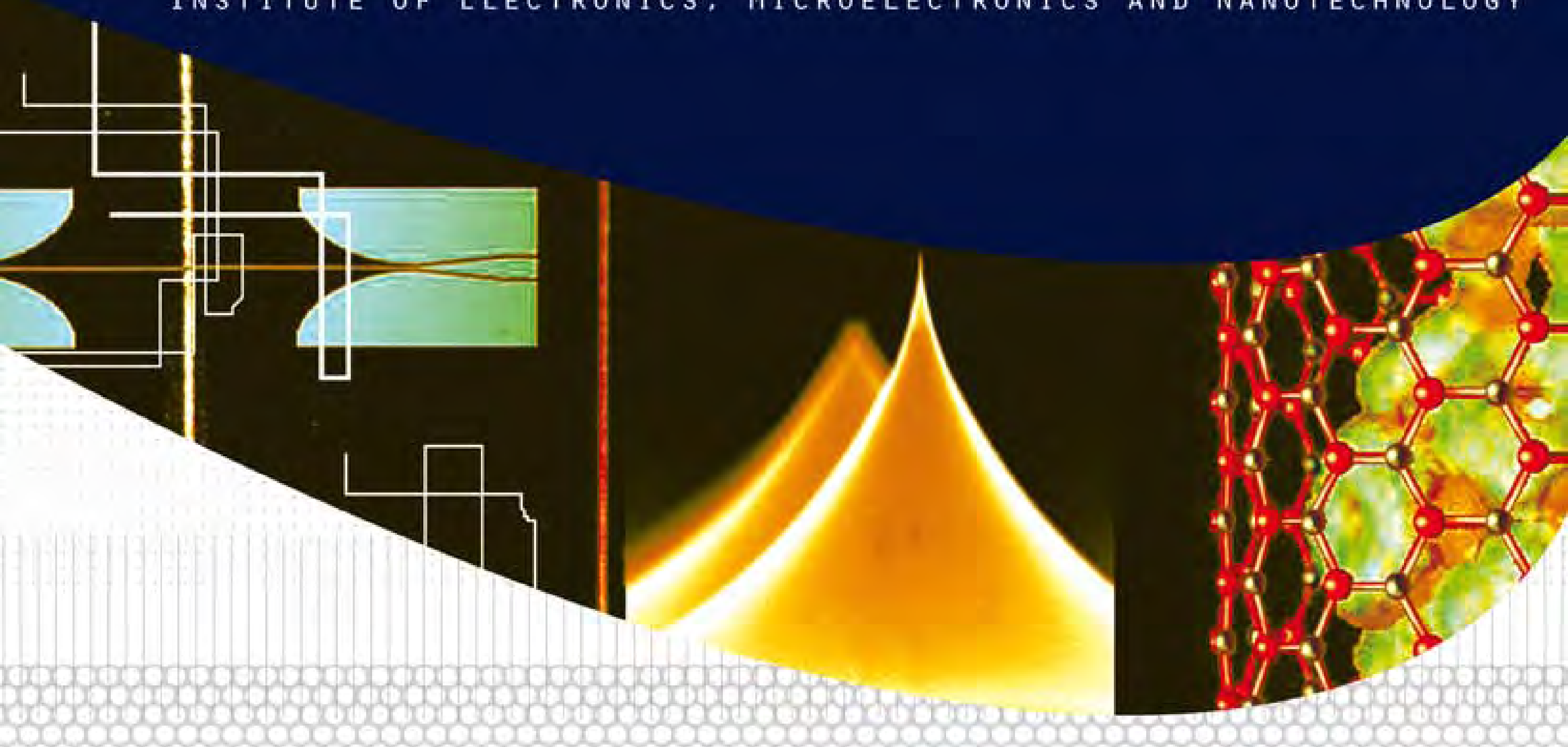
Activity Report
2004-2008

INSTITUTE OF ELECTRONICS, MICROELECTRONICS AND NANOTECHNOLOGY



CNRS USTL UVHC ISEP INSTITUT CARNOT IEMN

iemn UMR CNRS 8520 Recherche Formation Transfert

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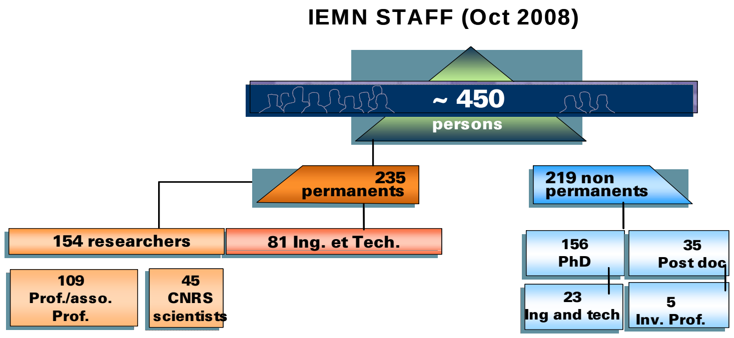
I.1-Introduction

IEMN, the Institute of Electronics, Microelectronics and Nanotechnology, (http://www.iemn.univ-lille1.fr/) is a research institute created in 1992 by the National Centre for Scientific Research (CNRS), two universities and one engineer school of France northern region: the University of the Sciences and Technologies of Lille (USTL, www.univ-lille1.fr), the University of Valenciennes and Hainaut Cambrésis (UVHC, www.univ-valenciennes.fr) and the Institut Supérieur d'Electronique et du Numérique (ISEN, www.isen.fr) respectively. Three missions have been assigned to IEMN in 1992:

- Research at the best international level
- Education, mainly through Master and PhD
- Innovation and transfer to industry, in particular regional SMEs

IEMN is located in several buildings in Villeneuve d'Ascq, Lille and Valenciennes. The central laboratory building is the largest one and it regroups all the main technological facilities and the institute administration. The other units located on the USTL, UVHC campus and in Lille ISEN building are also devoted to research and contain different equipments allowing us to make a link between the education at master and engineer levels and research. As far as the recruitment of brilliant PhD students is a key problem for any laboratory, IEMN staff is strongly involved in master and engineer degrees to maintain an efficient link between education and research.

I.2 Staff



Nowadays IEMN institute has a total staff of about **450 persons** (500 with master students) including **109** professors and associate professors, **45** CNRS researchers, about **100** engineers and administrative agents, about **156 PhD** students as well as **40** post doc and invited professors **Very open to international collaborations, more than 100 foreigner scientists coming from 20 different countries are currently working at IEMN.**

Variation of permanent and non permanent staff (**excluding undergraduate students and trainees**) between 2004 and 2008

Category	**2004**	**2008**
Professors and associate professors	**98**	**109**
CNRS scientists	**37**	**45**
Engineers and technicians-(permanent)	**79**	**81**
Engineers and technicians-(contract)	**15**	**23**
PhD students	**135**	**156**
Post doc	**15**	**30**

This table shows a small increase of the IEMN personnel during the period 2004-2008. In particular, we should mention that the team EPHONI with 5 permanent positions and two PhD working on phononics joined IEMN in 2006. The 10% increase of associate professors and professors was possible thanks to the support of the USTL and UVHC to IEMN. We also prepared a number of candidates to the CNRS competition and an average of two applicants succeeds in this very difficult competition each year. The significant increase of the post doc number is especially due to the creation of the National Research Agency (ANR).

Recruitment policy

For all the new personnel recruited at IEMN (PhD, professors and associate professors, engineers and technicians), we have tried to select the best candidates. For national competition, we prepared our candidates for the selection committee and, as a result of this policy, 8 new CNRS scientist joined IEMN within the last four years. We were also very open to external recruitment, that are PhD who obtained their master out of Lille and scientists and associate professors getting a permanent position at IEMN while having obtained their PhD in another university. **During the last four years about 50 % of the new recruited associate professors and 75% of the CNRS junior scientists came from another university in France or abroad.**

I.3 Scientific activity

IEMN scientific activity which covers a large domain going from the physics of materials and nanostructures to instrumentation can be divided into five major scientific domains:

Physics of Nanostructures

This scientific activity concerns the study of thin layers, heterostructures, nanostructures and nanodevices, new materials that can have a great potential for new applications in electronics, optoelectronics and nanotechnology. It covers theoretical and experimental researches as well.

Micro and Nano Systems

These activities concern microactuators and MEMS, microsystems for telecommunications, microfluidics for biological sciences, thermal micro-sensors, integration of piezoelectric materials in Microsystems and Magneto-Mechanical Microsystems (MMMS).

Micro- Nano- and Optoelectronics

For the micro and nanoelectronics part, the main objectives concern the design, fabrication and characterization of advanced semiconductor devices, as well as molecular devices. Our goal is the improvement of the frequency, noise or power performance. In optoelectronics, our main activity is oriented towards classical functions: photo detectors, switches, lasers, and new functions: opto-microwave transducers and adders at optical telecommunication wavelengths, searching for high speed, low noise, low consumption, low losses,…,

Communication Systems and Application of Microwaves

This wide activity with ambitious goals deals with signal processing, design of new circuits and system architectures, technological developments and electromagnetic compatibility for new applications.

Acoustics

This activity is shared into different topics, such as ultrasonic non-destructive evaluation techniques, design of efficient tools for optimization of acoustic antennas in two or three dimensions as well as the development of new electro-active devices.

Our research policy aims to maintain certain equilibrium between:

- Long term research corresponding to about 30 % of the activity aiming to identify, understand and analyze new phenomena or new behaviours which could be used in the electronic and optoelectronic components and devices in more than ten years
- Medium term research corresponding to about 50 % of the activity. By working in close relation with national and international large companies, development of high performance components and devices and even systems helping the companies to maintain a favourable position in the international market in the next five-ten years.
- Short term research, about 20 % of the activity. Fabrication of prototypes for applications in less than five years in domains like telecommunications, health, food testing and transport. Transfer to regional SMEs and IEMN start-ups.

I.4 Technological facilities and platforms

The main part of IEMN research activity is performed within common technological resources consisting in technological and characterization facilities as well as near field microscopy and telecom platforms and allowing the fabrication as well as the physical and electrical characterization of state-of-the-art components, devices and microsystems. A complete description of these facilities and platforms can be found at www.iemn.univ-lille1.fr/en/facilities. During the period 2004-2007, the quality of the facilities and platforms were significantly improved thanks to three important national and regional programs: the Basic Technology Research network (www.iemn.univ-lille1.fr/en/facilities/technological-plateform.html), the research reinforcement plan in the Nord-Pas de Calais Region and finally the State Region Project Contract CPER. About 4 M€ were invested each year to make IEMN one of the best equipped micro and nanotechnology centre in Europe.

The main mission of the **technological facilities** consists in supporting the IEMN research teams for their technological projects. In addition, within the National Technological Network for Basic Technological Research (BTR) programme, IEMN became in 2003 a National Platform, opened to the academic laboratories as well as national and international industrial laboratories. Approximately 200 research projects are performed each year in the 1600 m² ISO 5 / ISO 7 clean rooms supervised by 26 engineers and technicians. The technological facility is organized into four main resources: materials, deposition, etching and lithography. The main equipments are given in the table below. A team is also entirely devoted to the realization of complete devices or MEMS/NEMS. This need is expressed either within the framework for common laboratories (Thales or ST Microelectronics, for example), or within the BTR network.

Technological facilities main equipments	
Material 3 scientists 6 engineers 1 technician	**MBE growth:** 3 RIBER growth chambers **Ion Implantation:** 1 EATON GA204 ion implanter, 2 RTA **LPCVD:** 5 TEMPRESS tubular furnaces,1 furnace for nanowires **Sputtering:** 4 equipments for magnetic and piezo materials **Organic materials platform:** 3 glove boxes with spinning coater and evaporator. **Material characterization:** Surface characterization (ESCA), DDX, Hall effect, femtoseconde laser…
Lithography 6 engineers	**E-Beam:**1 LEICA EBPG 5000+, 1 VISTEC EBPG-5000plusES **Optical lithography**:3 mask aligners, 1 double face aligner,1 substrate bonder
Deposition Etching 6 engineers 2 technicians	**Wet etching**: 5 chemical benches for Si, 4 chemical benches for III-V compounds **Dry etching**: XeF2 etching,1 STS ICP for Si deep etching, 1 OXFORD RIE-ICP for III-V compounds,1 OXFORD RIE etching, 1 IBE etching, PECVD: 1 OXFORD PECVD system **Metallization:** 3 UHV evaporators,1 automatic UHV evaporator, 2 sputtering equipments, 1 multi cathode sputtering equipment, 1 evaporator for polymers,1 RTA
Process control and assembly 5 engineers	**Sample cleaning, dicing, polishing, bonding:** supercritical CO2 drying, chemical and mechanical polishing and lapping, 2 wafer dicing saws, 2 bonding machines **Characterizations:** 3 profilometers, optical microscopes, reflectometer, spectroscopic ellipsometry, 2 SEM, 1 near field microscope, 1 large field AFM

The characterization facilities aim for measuring the electrical parameters of devices over a wide frequency range (from DC to THz) and temperature range (from 30 K to 600K). A summary of the equipment available is given below

Characterization facilities main equipments	
4 engineers	12 vector network analyzers from 30 kHz to 325 GHz 1 large signal network analyzer 1 THz electro-optic bench 2 noise figure meters 8 pulse generators 4 analog signal sources 6 DC source monitoring

These facilities are unquestionably unique in France and among the two or three best microwave characterization academic centres in Europe. Moreover, its expertise in ultra-high frequency device characterization is internationally recognized and allows an important role in the joint laboratories between the IEMN and several companies such as THALES and ST Microelectronics and also foreign research institutes. The technical team appointed to this joint facility is composed of three engineers, who have experience in (the) electrical device characterization and microwave measurements. The first target of this joint service is to carry out the full electrical and microwave characterization of devices fabricated at IEMN in order to perform a feedback for the technological process.

The near field microscopy platform relies on the two principal techniques which are the Scanning Tunnelling Microscopy (STM) and Atomic Force Microscopy (AFM) working under ambient or ultra high vacuum (UHV) conditions. The development of these techniques coincides with the emergence of the new domains of Nanoscience and Nanotechnology. In addition of getting an atomic resolution image, STM provides access to the spectroscopy of local electronic density of state and measurement of the band structure of nanoobjects like islands, nanocrystals or quantum dots. The equipments consist of 3 UHV STM, with temperature measurements ranging from 4 to 500 K and 5 AFM which give also nanometric physical characterization particularly in the domain of electrostatic force, charge and local conductivity of silicon nanocrystals, carbon nanotubes, nanowires….

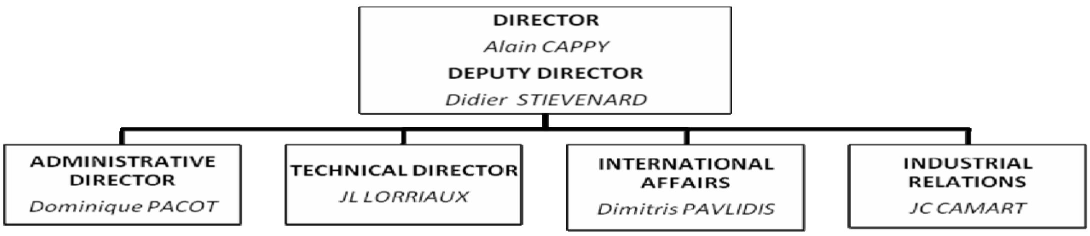
The telecom platform offers a large set of advanced scientific equipments for the development of new radio modules and communication systems, up to the millimetre wave range, in particular for wireless ad hoc or mixed radio-fiber networks for smart objects and sensors, towards an ambient intelligence. It provides large facilities for time domain and frequency vectorial analysis and characterization of innovative analog or digital communication sub-systems and systems up to 110 GHz. It is fully complementary to the characterization platform which deals with device and circuit characterization while the telecom platform aims at the generation and analysis of complex signals (UWB, OFDM, CDMA, QAM…) to demonstrate new concepts for wireless communication links including radio channel sounding.

The technological and characterization facilities mission is not only to support the institute research teams but also national and international academic and industrial laboratories as well as local SMEs. In particular, to support the national R&D effort, IEMN facilities are used by our start-ups and also by different companies in the frame of our **common laboratories.** Common laboratories are long term agreements between these companies and IEMN to develop common research on well defined subjects needing the use of IEMN facilities. In addition to these common laboratories, IEMN is strongly involved in collaborations with national or european companies in the III-V, Si and microsystems business in the frame of national or european contracts. The quality of the IEMN-industry partnership was recently recognized through the attribution of the label '**Carnot Institute '** to IEMN.

I.5 Management and organization

At IEMN creation 16 years ago, the laboratory was organized in three departments corresponding to the three laboratories that gathered together. Nowadays, the notion of department is less and less effective and IEMN is mainly organized in two levels that are the administrative and the scientific levels.

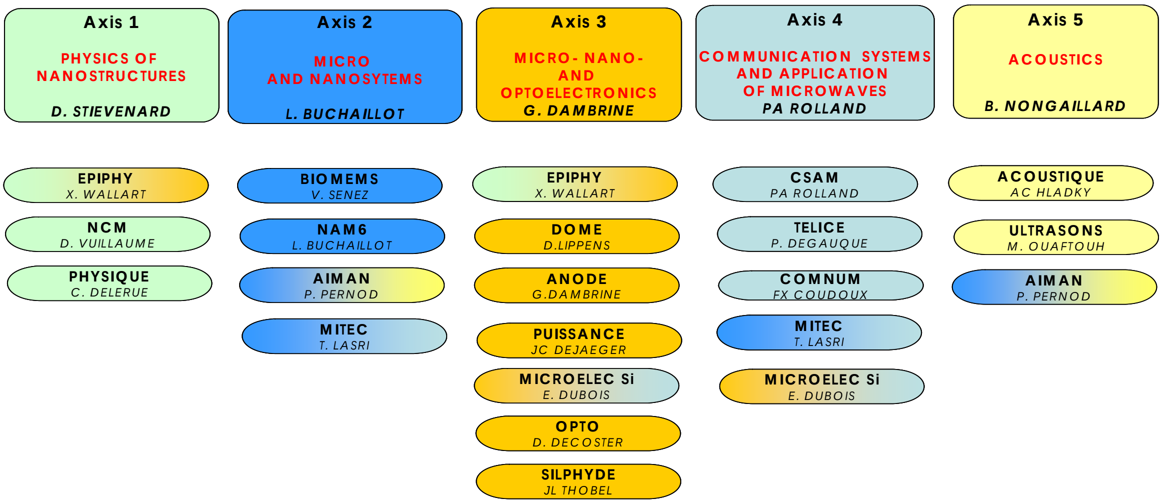
Administrative level:



In connection with the director and deputy director of the laboratory, three directions were put in place
The administrative direction has in charge all the financial aspects, the human resources and the communication of the institute
The technological direction has in charge the infrastructure and the technological facilities and platforms.
Tow external relation directions have in charge the **international affairs** and the **industrial relations**, especially in the frame of the Carnot Institute network

Scientific level

The scientific activity is organized in five research axes and 18 research groups. Each of the five research axes has a scientific responsible having in charge the scientific animation and the scientific policy definition of the axis scientific domain. These responsible were appointed recently (2008) and their role will be significantly increased in the future. This point will be described in detail in the 'IEMN project for 2010-2013 documents.
The figure below shows the repartition of the groups in the five different research axes.



A research group gathers about 5 to 15 professors, associate professors and/or CNRS scientists and about the same number of PhD students and post docs. Four groups (EPIPHY, AIMAN, MICOELEC Si and MITEC) are working at the interface between two axis or have activities within two axis. The scientific activity of each research group is described below: more information can be obtained in the group web sites.

EPIPHY (Epitaxy and physics of nanostructures, 9 permanent positions): epitaxy of III-V materials and growth of nanowires, physics of heterostructures, terahertz devices (http://epiphy.iemn.univ-lille1.fr)
NCM (Nanostructures and molecular devices, 5 permanent positions): molecular electronics (http://NCM.iemn.univ-lille1.fr)
PHYSIQUE (Physics, 15 permanent positions): 0D, 1D and 2D nanostructures, nanodevices, phononics and nanophotonics (http://physique.iemn.univ-lille1.fr)
BIOMEMS (MicroElectroMechanical Systems for biology, 10 permanents positions): microfluidics, THz spectroscopy, lab-on-a chip (http://biomems.iemn..univ-lille1.fr)
NAM6 (Nano and Micro Systems, 5 permanent positions): RF MEMS, micro and nano resonators, micro and nano electro spray, bio-inspired MEMS (http://nam6.iemn.univ-lille1.fr)
AIMAN (Pulse acoustics and nonlinear magneto acoustics,7 permanents positions): magnetomechanical microsystems, non linear magneto acoustics, multiferroics (http://aiman.iemn.univ-lille1.fr)
PUISSANCE (Power devices, 7 permanent positions): power amplifier, large gap materials (http://puissance.iemn.univ-lille1.fr)
ANODE (Advanced nanometer devices, 10 permanent positions): III-V low power devices, mm and submillimeter waves, CNT based transistors (http://anode.iemn.univ-lille1.fr)
DOME (Quantum micro and optoelectroniques devices, 6 permanent positions): metamaterials
MICROELECTRONIQUE SILICIUM (Silicon microelectronics, 6 permanent positions) : advanced MOS devices, modeling and simulation, circuit design, software radio (http://microelectronique.iemn.univ-lille1.fr)
OPTOELECTRONIQUE (Optoelectronics, 13 permanents positions) : microwave photonics, nanophotonics, optical waveguides (http://optoelectronique.iemn.univ-lille1.fr)
SILPHYDE (Physical device modeling, 5 permanents positions): Monte Carlo modeling, device simulation (http://silphyde.iemn..univ-lille1.fr)
CSAM (Circuits, systems and microwave applications, 8 permanent positions): smart object communications, 60 GHz WLAN, UWB (http://CSAM.iemn.univ-lille1.fr)
COMNUM (digital communications, 12 permanent positions): digital communications, indoor broadband communications, propagation channel (http://comnum.iemn.univ-lille1.fr)
MITEC (Microtechnology and Instrumentation for Thermal and Electromagnetic Characterization, 9 permanent positions) : non destructive control, thermal microsensors (http://mitec.iemn.univ-lille1.fr)
TELICE (Telecommunications, interferences and electromagnetic compatibility, 7 permanent positions): EMC, communication in transportation systems (http://telice.iemn.univ-lille1.fr)
ACOUSTIQUE (Acoustics, 5 permanent positions): picosecond acoustics, phononic cristals, BAW (http://acoustique.iemn.univ-lille1.fr)
ULTRASONS (Ultrasonics, 21 permanent positions): non-destructive control, health-monitoring structures (http://ultrasons.iemn.univ-lille1.fr)

Each research group is leaded by a senior scientist who defines, in agreement with group members, the scientific strategy and assigns the financial and human resources to the research projects in which the group is involved. The group leaders are the contact point between the direction of the laboratory and the scientists and they are members of the laboratory council.

In 2007, we began some actions to improve the quality control of the research. We introduced in each research group a laboratory book and an improvement of our information system is currently performed especially to avoid the lost of information in the technological and characterization facilities.

I.6 Budget-Financial information

The table below gives an overview of the revenues and expenses during the period.

Annual direct support	2004	2005	2006	2007
CNRS+USTL+UVHC+ISEN	**3 185 904**	**3 223 417**	**3 178 440**	**2 786 078**

Research contracts				
CPER (state, region, FEDER)	2 076 972	2 981 524	2 890 002	1 406 789
BTR	2 000 000	1 136 200	2 870 400	1 601 468
EU (without FEDER)	1 076 422	1 274 838	986 224	853 330
Ministry of research and other ministries (defence, industry…)	1 299 703	2 180 037	965 463	821 506
National Research Agency (ANR)		83 207	800 845	1 353 833
Other contacts (industry, international programs, Carnot institute, miscellaneous)	1 862 956	1 306 541	1 645 882	1 305 400
Total resources from contracts	**8 316 053**	**8 962 347**	**10 158 816**	**7 342 326**
Total revenues: annual direct support + research contracts	**11 501 957**	**12 185 764**	**13 337 256**	**10 128 404**

Expenses	2 004	2 005	2 006	2 007
Investments	5 846 604	4 126 047	5 415 067	4 384 453
operation cost	2 778 252	2 913 298	3 108 108	3 693 083
Infrastructure cost	1 458 268	1 498 661	1 431 597	1 494 750
Salaries	1 196 947	2 419 782	1 586 365	2 035 085
Total	**11 280 071**	**10 957 788**	**11 541 137**	**11 607 370**

Some explanations to read these tables:
The annual direct support is the funding that IEMN receives each year through its parent organisations. This income is directly managed by the laboratory except some infrastructure costs that are directly supported by CNRS, USTL, UVHC and ISEN CPER is a seven years contract (2007-2013) between the french state and the region council. BTR is the national programme for the development of basic technological research. EU means european contracts (mainly FP6 and FP7). Investments concerns all the equipments for the research, operation cost concerns the research expenses (consumables, travel and subsistence…), infrastructure cost concerns the maintenance of the different buildings and some common expenses (electricity, heating, cleaning….) while salaries only concerns the non permanent positions that are directly paid by IEMN with our own resources.

These tables lead to some comments:
- First, the annual direct support (excluding the salaries of the permanent positions not shown in the table) decreases by about 13,5% while the personnel increases by about 20 %. The decrease was continuous and very significant in 2007. As a consequence it is more and more difficult to support internal research programs as to cover infrastructure and common expenditures.
- Second, the CPER and BTR programs contribute significantly to the total budget even if these funding sources are not regular and can vary by about 45 % from one year to the next one. Since these programs are mainly devoted to investment, it is difficult to define medium term investment strategy.
- Third, the contract funding is stable (the increase in 2005 is only due to one large MOD contract). It should also be noted that the ANR becomes a very significant source of funding with, in 2007, about 15 % of the budget.

If we now consider the expenses, we should note a strong correlation between the CPER+BTR programs and the expenses of investment. The running and salary costs increased while the infrastructure cost remains almost constant.

To complete these tables we should mention that the salaries of the permanent positions (CNRS scientists, professors and associate professors, engineers and technicians, PhD grants directly funded by the ministry of research are not included in the budget because all these salaries are directly paid by the ministries. This total direct salary support is 19 M€ that is about twice the budget excluding salaries, about 10 M€, as shown in the table. **As a consequence the total IEMN budget (salaries of permanent and non permanent personnel, investments, operation costs, infrastructure costs) is close to 30 M€.**

In research contract domain, two points should be noted: first a more and more important part of revenues is coming from ANR. Mid 2008, **42 ANR projects** (12 with IEMN as coordinator, 30 with IEMN as partner) were selected (note that 9 projects beginning in january 2008 and 9 selected in 2009 are not included in the 2007 budget). Secondly, IEMN was involved in **23** FP6 and FP7 EU **projects during the 2004-2008 period** with 13 projects (4 IP, 1 NoE, 6 STREP, 2 collaborative projects) still active in 2008, two of them with IEMN as coordinator. Finally, contracts make up about 29 % of IEMN's total budget. This ratio, 11 points higher than CNRS global ratio, illustrates IEMN's ability to promote his projects among the funding agencies and his partners.

Financial means repartition

For many years, our policy in terms of financial means repartition is unchanged. Part of the annual direct support is used for the common expenses (infrastructure cost, salaries of administrative non permanent staff …) and the remaining (about 0,50 M€) is distributed to the research groups according to their size and to allow a minimum funding for each scientist. The annual large funding coming from BTR and CPER is mainly used for the common equipments in our facilities and platforms. CPER is also used in a less extent to support specific research activities with post-docs and engineers. If we now consider the research contracts obtained by the research groups, part of the budget of each contract is deducted to support the central administration and also to support IEMN scientific policy as it is defined by the five research axes.

I.7 International cooperation

Scientific relationship with international renowned laboratories is an important objective for IEMN researchers. As for the industrial relationships, we prefer to collaborate with some selected research centres such as the Universities of Michigan, Illinois or Georgia Tech in the United States as well as all the European leading institutions in the field of micro and nanotechnologies. Over the last four years IEMN has continued its relations with Japan through the LIMMS (Laboratory for Integrated MicroMechatronics Systems) and the CIRMM (Centre for International Research in MicroMechatronics), as well as with Belgium through the European Laboratory on Microelectronics and Microsystems (LEMM) between IEMN and the Catholic University of Louvain (UCL). A new European Laboratory in nonlinear Magneto-Accoustics (LEMAC) has also been initiated between IEMN and the General Physics Institute of Russian Academy of Sciences. Furthermore, IEMN continues to enhance its international relations with the US and Asia. A strong collaboration has been developed between IEMN, THALES and Nanyang University of Technology (NTU) in Singapore that addresses the aspects of optoelectronics and nanoelectronics. IEMN's aim for a leading role in global science has greatly benefited through the rapid development of international projects in recent years not only due to contributions from the director of international relations but also thanks to the dynamism of many IEMN scientists.

An important mission in the development of international relations is the establishment of university and industry partnerships. To achieve this objective, contacts have been established with European and American universities involving collaboration in research and teaching. These include joint programs and partnerships with universities and research centres such as Georgia Institute of Technology, University of Michigan, University of Illinois in Urbana Champaign, Imperial College, U.K., Technische Universität Darmstadt, Germany and the University of California, Irvine.

A major effort has been placed on the establishment of a European Campus referred to hereafter as the European Campus Northern France (ECNF). It initiated a program consisting of 42 fellowships for transatlantic exchanges of students at the graduate level. This program is jointly funded by the "Fund for the Improvement of Postsecondary Education" (FIPSE) of the Department of Education in the US and the "Directorate General for Education and Culture" (DG EAC) of the European Commission. It has as main objective the development of an "EC-US Graduate Curriculum on Electronic Devices and Micro-Electro-Mechanical Systems for Biological/Biomedical Applications". ECNF associated students will be able to pursue graduate studies in electrical engineering by following courses and gaining research experience from the affiliated institutions. They will spend part of their time at ECNF attending courses offered by European and US Faculty or in some cases through the Internet. They will also attend courses in the US and in partner European Universities.

A major international partnership was established with the Georgia Institute of Technology through a formal agreement. The inauguration of the double Masters degree between USTL and Georgia Tech was celebrated in june 2008 at ECNF's headquarters. IEMN hosted several faculties and visitors from Georgia Tech. Cooperative research projects have also been defined and introductory sessions were organized jointly by Georgia Tech and IEMN/USTL for students on the degree options offered.

Support to ECNF's international activities was also provided through a newly awarded Partner University Fund (PUF)/FACE program, which promotes the development of a dual USTL-Georgia Tech Masters degree. Fellowships are provided under this program for both European and US students.

I.8 Industrial relations

As far as the industrial collaborations are concerned, IEMN cannot reply positively to any industrial solicitations. Therefore, the following partnership policy is applied to avoid any risk of dispersion :

▪ To develop specific partnerships with a limited number of companies, leaders in their business, by creating joint IEMN-industries common laboratories.

▪ To create IEMN-industry research teams by receiving engineers and scientists from industry in our facilities. Three common laboratories IEMN-industries were thus created in the past:

- o THALES TRT (now called III-V Lab) for design, realization and characterization of microwave power devices using gallium nitride (2002-2006)
- o ST Microelectronics for millimetre wave applications of Si devices, MOS devices for the future and integration « above IC » of BAW (Bulk Acoustic Wave) filters (since 2003)
- o RIBER for industrial applications of MBE and the growth of new III-V alloys (2002-2006)

▪ To set a tight and continuous collaboration with french and european industries of our research domain thanks to national (National Research Agency) or european (FP, EUREKA, MoD...) contracts, and to encourage staff exchanges (engineers from industry, PhD ….)

▪ To develop a close connection with regional SMEs and IEMN start-ups. This specific partnership, although delicate for an academic laboratory, is a success thanks to the creation of a specific service « IEMN-Transfert » having a role of interface between IEMN and SMEs. IEMN-Transfert should also answer to the SMEs demands as well as to place human and material resources at their disposal through research contracts, studies or services.

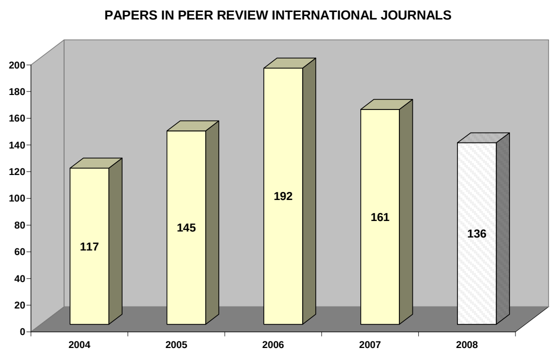
The results of the industrial collaborations during the last four years are contrasted. On one hand, IEMN obtained some success with **the creation of three start-up companies** that created more than 15 positions, some of them for former IEMN PhD students, and also with the label 'Carnot Institute' obtained in 2006 by IEMN and which is a recognition of the quality of the research carried out with private companies. On the other hand, two of the common laboratories with industry were stopped. With RIBER, the company modified its R&D strategy in the field of III-V materials and consequently, the strong collaboration with IEMN was stopped. Concerning TIGER, the common laboratory with THALES-ALCATEL III-V Lab the collaboration continues and we are involved together in several research programmes but it is difficult to sign a new common laboratory agreement for administrative reasons and also because III-V Lab engineers, previously working at IEMN returned to Marcoussis III-V Labs. However, new research work between IEMN and III-V Lab began in 2006 in the field of antimonide based HBT. It should be emphasized that the IEMN-ST collaboration is extremely successful. **For the years 2004-2007, this common laboratory scientific production is 27 papers in international journals, 97 communications in international conferences, 29 patents and 34 theses already finished or in progress. Taking the dramatic success of the first four into consideration, it was decided by both parties that the IEMN-ST common laboratory will be pursued up to 2012.**

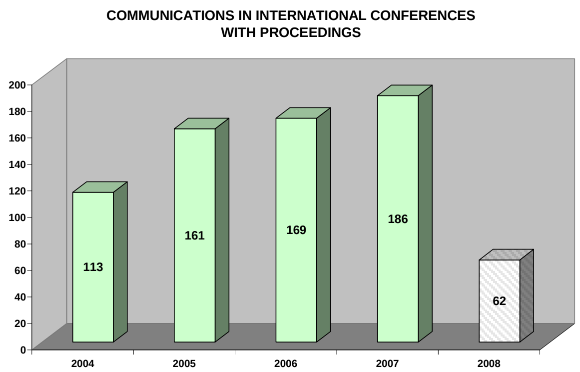
I.9 Scientific production

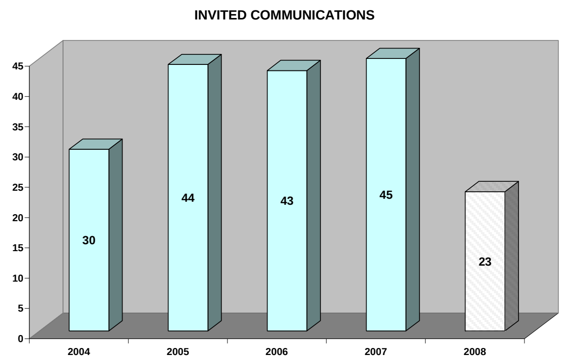
The results presented in the second part of this report concern only the outstanding results obtained during the last four years. The entire scientific production with the complete references is given in detail in a separate document. A synthesis of the scientific production is given in the table and figures below. In this table, we reported the total production in terms of peer review papers in international journals, international conferences, invited conferences and patents during the period 2004-2007 compared with the previous four years period 2000-2003

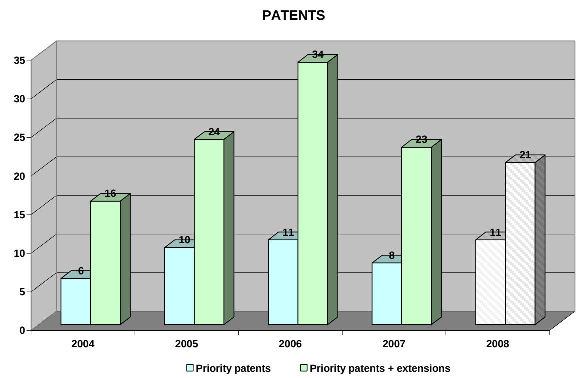
Category	**Total 2004-2007**	**Total 2000-2003**
Papers in international journals (data base ISI WoK)	**610**	**404**
Communications in international conferences	**614**	**390**
Invited talks	**161**	**111**
Priority patents (+ extensions)	**35 (+ 62)**	**~20**

It is noteworthy that the production increases in each category including patents. **This clearly indicates that the scientific activity was improved in the last four years both in fundamental/long term research and in applied/short term research**. In addition, the IEMN policy based on the equilibrium between fundamental and applied research was successful at least as far as the scientific production is concerned.
The variation of the scientific production as a function of time is given in the figures below. For peer review journals and patents, a constant increase can be observed from 2004 to 2006. The production of year 2008, limited to the period january-july in the figure, seems to be also very good for both papers and patents. For the communications in international conferences, a constant increase could be observed while the number of invited communications is mainly constant over the 2004-2007 period.









The table and figures gives an overview of the total production including high impact factor journals and other less renowned journals. In order to analyze more quantitatively IEMN scientific production, we have reported in the table below the production in some selected high impact factor journals and compared the period 2004-2007 with 200-2003

Journal	Impact factor	Number of papers: 2004-2007 (+2008)	Number of papers: 2000-2003
Science	22	3 (+1)	0
Nature physics	12	1	0
Nano Lett.	10	6 (+2)	2
Phys. Rev. Lett.	7	16 (+5)	9
Appl. Phys. Lett.	4,0	43 (+14)	27
Optics Express	3,7	3(+3)	0
Phys. Rev. B	3,1	32 (+15)	22
IEEE Elect. Dev. Lett.	2,7	12 (3)	13
J. Appl. Phys.	2,3	34 (+4)	21
IEEE Trans. Electron. Dev.	2,0	15 (+3)	9
IEEE Trans. MTT	2,0	9(+2)	5
IEEE Photonics Tech. Lett.	2,0	6(+1)	1
Total		180 (+53)	108

The conclusion is quite clear. For almost each journal the number of published papers is significantly higher in 2004-2007 than during the preceding period 2000-2003.

It should be emphasized that IEMN production constitutes a significant part of total french production in several journals for the 2004-2007 period: 34% for IEEE-EDL, 18% for IEEE-TED, 10% for IEEE-MTT, 6% for Nanoletters, 4 % for APL and 3% for JAP.

This clearly shows that the quality of the research activity was significantly improved in the four last years.

I.10 National and international responsabilies of IEMN

- **Nanoscience competence centre**

In order to promote and develop French Nanosciences and Nanotechnology at national and international levels, the CNRS together with the Ministry of Research have initiated a national organization through the creation of six Nanosciences Competence Centre – Ile de France, Rhone-Alpes, Grand-Est, Grand Sud-Ouest, PACA and nord ouest (see http://www.nanomicro.recherche.gouv.fr/ and http://www.cnrs.fr/mppu/cnano.htm). It represents a total of 4100 researchers. IEMN was responsible of the creation of the Nord-Ouest Nanoscience Competences Centre (http://www.iemn.univ-lille1.fr/en/cnanono.html).

The main objectives of these centres are : to promote nanosciences and facilitate scientific exchanges within each region, to facilitate access to nanotechnology centres, to facilitate cross disciplinary projects, to contribute to nanosciences and society research & debate, to contribute to the training of graduated students, to open nanoscience labs to undergraduate students, to popularise nanosciences, to build a bridge between research and local industry and to encourage European collaboration and exchange, in close collaboration with NanosciEra.

The North West Centre includes 30 laboratories, 1 main Technological Centre (IEMN), 15 Universities, 8 Engineer Schools and 570 researchers.

- **Thematic Research networks (GdR)**

Among the scientific structuration of research in France, an important one is the GdR. It is an official entity where national collaborations are fostered between groups or laboratories working on a common topic. IEMN is leader of 3 GdR (DFT++, MNS and Nanoelectronics) and has created one (GdR Nanowires).

DFT ++

The GdR “DFT++” was created in 2006, following the “GDR DFT”. Its objectives are to animate the scientific community in electronic structure theory centred on the density functional theory (DFT), to contribute to the resolution of theoretical issues in the fields of nanostructures and complex materials, and to participate to the development of methodologies and softwares required to treat these problems. The “GDR DFT++” is interdisciplinary, organizing common meetings between chemists and physicists. It gathers more than 300 researchers belonging to ~60 academic and industrial laboratories, demonstrating the growing importance of electronic structure simulations in a wide range of scientific fields. Web site: http://www.isen.fr/~gdr-dft

MNS

The GdR “MNS” is dedicated to Micro and Nano Systems. 300 researchers from 40 laboratories are involved in this thematic network where activities are split in 4 groups working on the following topics: Micro and Nanotechnology; Micro and Nano Systems for Biology and Chemistry; Smart Dust; Tests, Characterisation and Reliability. Each group is aiming at fostering scientific exchanges through the organisation of meetings where presentations are made by young researchers. One possible output of the groups is a collaborative project submitted to the National Research Agency for the peer-review process. To summarize, the GdR MNS animates the scientific community and organizes an annual meeting. (http://www.lirmm.fr/mns/)

Nanoelectronics

The GDR “Nanoelectronics” includes activities from the CNRS departments ST2I, MPPU and Chemistry with 40 laboratories. There are three main topics (“Silicon and IV-IV devices”, “III-V nanoelectronics up to terahertz applications” and “Molecular electronics”) and three cross topics (Technology and Materials Characterisation and Simulation-Architectures »). (Web site : http://www.iemn.univ-lille1.fr/en/gdrnano.html)

Nanowires

This GDR (2974) is financially supported by the French CNRS and CEA, mainly. It was created in 2006. Today (end of 2007), it represents a network of 33 French academic research teams (and about 120 researchers). Each of them is involved in one or several of our research themes. We organize annual meetings where physicists, chemists, biologists, engineers and technologists are welcome to interact by presenting their scientific results, exchanging information and initiating new collaborations. Schools are also organized to introduce the topic to students and to new members willing to get involved in this research. We are open to collaborations and exchanges with other countries. In particular, the GdR could become a E-GdR (European GdR), where each European partner could receive support from its own funding councils (http://www.iemn.univ-lille1.fr/en/gdrnanofil.html).

For the **international** responsibilities, IEMN is active in the ‘Scientific Community Council’ of the European Technology platform ENIAC especially in the redaction of the annual Strategic Research Agenda of ENIAC. Many IEMN members have participated to TPC of major international conferences (IMS, MEMS, IEDM, EuMW, MRS, IPRM, WCU, ESSDERC-ESSIRC) and also acted as reviewer for many international journals.

I.11 Award and distinctions

During the 2004-2008 period, some IEMN scientists and IEMN results were distinguished by national and international awards and distinctions.

ERC grant

B. LEGRAND, selected for a junior grant in the field of MEMS/NEMS by ERC, 2008

Individual awards

B. DUBUS, prize Chavasse SFA (Acoustics French Society) 2007
C. DELERUE, prize Ancel SFP (Physics French Society) 2007
D. TROADEC, 'cristal' medal of CNRS 2008
P. PERNOD, Doctor Honoris Causa, university MIREA, Russia 2007
V. PREOBRAZHENSKY, French Acoustics Society medal 2005 and prize L. Mandelshtam of the Russian academy of science 2006

Best paper awards

N. TIERCELIN, P. COQUET, R. SAULEAU, V. SENEZ, H. FUJITA Millimeter wave planar antennas printed on micromachined ultra-soft PDMS substrate . Proceedings of the 4th ESA Workshop on Millimetre Wave Technology and Applications : circuits, systems, and measurements techniques, MilliLab, Espoo, Finland, february 15-17, 2006, 331-336 **Award** for this work given by YOKOSUKA RESEARCH PARK (consortium gathering major ICT japanese scientists and companies).

A. TALBI, O. DUCLOUX, N. TIERCELIN, Y. DEBLOCK, P. PERNOD and V. PREOBRAZHENSKY, "Vibrotactile using micromachined electromagnetic actuators array," J. Phys.: Conf. Ser. 34, pp. 637-642, 2006, **Best Poster award**

VOLATIER A., CARUYER G., PELLISSIER-TANON D., ANCEY P., DEFAY E., DUBUS B.
UHF-VHF resonators using Lamb waves cointegrated with FBAR resonators
Proceedings of the 2005 IEEE International Ultrasonics Symposium, Rotterdam, The Netherlands, september 18-21, 2005, 902-905. **Best Student Paper Award**

GOUDEMAND C., COUDOUX F.X., GAZALET M., CORLAY P.
QoS optimization of MPEG-2 video transmission over ADSL channels using hierarchical modulations
Proceedings of the 5th WSEAS International Conference on Multimedia, Internet and Video Technologies, MIV'05, Corfu Island, Greece, august 17-19, 2005, 80-84, **Best Student Paper Award**

A. RENAUDIN, E. GALOPIN, V. THOMY, C. DRUON, F. ZOUESHTIAGH
Creeping, walking and jumping drop
American Physical 2006 , Society, Division of Fluid Mechanics. **Winning contribution to the Gallery of Fluid Motion**

O. DUCLOUX, Y. DEBLOCK, A. TALBI, N. TIERCELIN, P. PERNOD, V. PREOBRAZHENSKI, A. MERLEN :
Magnetically actuated microvalve for active air flow control
IMEMS Singapour 2006. **Best Poster award**

EGOT S., BARANOWSKI S., KLINGLER M.
Modeling automotive electronic equipment in a realistic sub-system
Proceedings of the 7th EMC Europe International Symposium on Electromagnetic Compatibility, EMC Europe 2006, Barcelona, Spain, september 4-8, 2006, 1041-1045, **Best Paper Award**

TREIZEBRÉ A., BOCQUET B.
BioMEMS for cell investigation at millimeter and submillimeter wavelength
Proceedings of the 12th International Symposium on Antenna Technology and Applied Electromagnetics, ANTEM-URSI 2006, Montreal, Canada, july 16-19, 2006, **Best Student Paper Award**

DEVULDER M., DEPARIS N., TELLIEZ I., PRUVOST S., DANNEVILLE F., ROLLAND N., ROLLAND P. A.
UWB transmitter in BiCMOS SiGe 0.13 µm technology for 60 GHz WLAN communication
Proceedings of the 2007 IEEE International Conference on Ultra-Wideband, ICUWB 2007, Singapore, Singapore, september 24-26, 2007, 432-435. **Best Paper Award**

SOPHIE BARBET, RAPHAËL AUBRY, DOMINIQUE DERESMES, MARIE-ANTOINETTE DI FORTE-POISSON, HEINRICH DIESINGER, THIERRY MELIN, DIDIER THERON
Poster : "Kelvin Force Microscopy on GaN Wide Gap Materials"
2007 MRS Fall Meeting Boston, November 29, 2007. **Best Student Poster Award**

EMERY P. , DEVOS A.
Acoustic attenuation in silica in the 100-250GHz range using colored picosecond ultrasonics
Proceedings of the 12th International Conference on Phonon Scattering in Condensed Matter, PHONONS 2007, Paris, France, july 15-20, 2007 . **Best paper award**

B. GEYNET, P. CHEVALIER, F. BROSSART, G. DAMBRINE, F. DANNEVILLE, A. CHANTRE
A selective epitaxy collector module for high speed Si/SiGe HBTs
Proccedings ISTDM 2008, pp112-113 **Best Student Poster Award**

I.12 Education and training

With 50 Master of Research students and more than 150 PhD students, IEMN is a major educational player in Microtechnology, Nanotechnology and Telecommunications research areas.
IEMN personnel is strongly involved in LMD and engineers degrees. Among the most important responsibilities assumed by IEMN personnel, one should mention.
- The direction of the 'Science for Engineers' doctoral school gathering about 500 PhD supervisors and more than 800 PhD students
- The direction of the Engineer school 'Polytech lille' with 1200 students
- The direction of the Engineer school 'Telecom Lille1'with 600 students
- The direction of the Enginees school 'ENSIAME' with 500 students
- The direction of the "Valenciennes institute of sciences and technologies"
- The direction of five master degrees

Master of Research degrees at IEMN

IEMN is involved in three Master of Research degrees which are the MNT master, the ATC master and the Ultrasonics and Telecoms master.

- MNT (Micro and NanoTechnology) is a multidisciplinary Masters program geared towards design, fabrication and characterization of Micro and Nano based technologies. The Master degree is structured around a core syllabus with two optional specializations (Micro or Nano).
- ATC (Advanced Technologies for Communication and mobility) is also a multidisciplinary Masters degree, but it specialises in the fields of ICT between software and hardware.
- The Ultrasonics and Telecoms Masters degree teaches ultrasonic techniques as well as high bandwidth local networks and optical telecommunications.

The first two Masters degrees (the MNT and the ATC) are taught at the University of Science and Technology of Lille, and the Ultrasonics and Telecoms Master is taught at the University of Valenciennes and Hainaut Cambrésis. IEMN personnel is also significantly involved in several engineer schools: ISEN, Polytech'lille, TELECOM Lille1, EC-Lille

Keywords:

MNT Master: Electronics, Microsystems, Microfluidics, Biotechnology, Active smart materials, Nanotechnology, Biology and Photonics.
ATC Master: Information, Communication, Hardware/Software interfacing, Signal processing.
Ultrasonics and Telecoms Master: Ultrasonics, Electro and Acousto-optic components, Acoustics and piezoelectric materials, Microtechnology and Telecommunications.

It should be noted that IEMN CNRS scientists are also strongly involved in the different engineer schools and masters degrees. In 2007, IEMN CNRS scientists gave about 600 hours of courses, 600 hours of exercises and 300 hours of laboratory in the different schools and universities.

International education for our master students is an important objective and several international programmes were put in place.
First, a major international partnership was also established with the Georgia Institute of Technology through a **double Master degree agreement**. This agreement allows for IEMN students to follow some courses at USTL and some at GT (Lorraine or Atlanta Campus) to obtain the two master degrees after only six months additional education time. 4 students was or are presently engaged in this double degree.

Second, eleven master students participated to transatlantic exchanges for a length of stay of four to six months in renowned US universities (Georgia Institute of Technology, University of Michigan, University of Illinois in Urbana Champaign).
Third, IEMN and the University of Michigan agreed to have a senior level course (Introduction to MEMS) developed in Michigan that is offered as part of the Masters on Micro and Nanotechnology (MNT). Part of this course is provided through the web as it is for the University of Michigan students. The rapidly increasing popularity of the course is clearly demonstrated by its evolving enrolment, which has gone from 5 to 35 in three years. The course involves several specific lectures to have a real contact between students and a MEMS specialist in order to explain in more depth the subjects provided by the course given on the web.

PhD study at IEMN

The research teams at IEMN are attached to the regional doctoral school ED-SPI (the school of science for engineers). The number of new PhD students is given below for the 2004-2007 period.

Year	**2004**	**2005**	**2006**	**2007**
New PhD	**45**	**42**	**47**	**42**

As shown in the table the number of new PhD student is roughly constant. **As in several laboratories of the same field of research it is more and more difficult to attract high level and interested students**. Each year, we can deplore that some PhD grants are not used due to the lack of candidate with good academic records. For the future, the search of PhD student will be certainly a big issue.
In parallel, the laboratory has settled multiple initiatives for the promotion of doctoral studies. In fact, with more possibilities for education and training proposed by the ED-SPI, the laboratory will strives to instil a multidisciplinary culture into doctoral students.
Among the different methods put in place to reach this objective is the organisation of weekly seminars covering research taking place at IEMN. These seminars can also be given by external specialists and academics. In addition, we offer our doctorate students the possibility of taught courses during the first and second year of their PhD program, up to a maximum of 3 courses during 2 years among those offered by the MNT and ATC Masters degree programs.

To facilitate meetings and exchanges between doctoral students, we have created an Open Day for students that take place at the beginning of every academic year. During this event the second year doctoral students present their work from their first year using posters and the third year doctoral students organise a guided visit of the laboratory facilities for the students beginning a PhD. The goal of this event is to improve the integration of new PhD students, cultivate inter-communication and to reinforce the cohesion of our doctoral program.

In addition, the IEMN prize is a new method destined to add value to thesis work. This distinction aims at identifying one or two doctoral students every year for exceptional quality of work produced during their PhD.

Finally, every spring we organise the IEMN research forum. This event has the objective of demonstrating the opportunities available in Doctorate and Masters Research at the laboratory. This permits potential students to meet the supervisors of different proposed subjects described on poster stands. The research forum equally includes a conference given by a renowned personality and a series of visits. Our current doctorates perform most of the organisation and presentation of this forum at the IEMN.

It can be noted that several of our PhD students share their time between the laboratory at the IEMN and our numerous industrial partners (STMicroelectronics, THALES, etc.). The number of PhD students pursuing this form of doctoral training is growing steadily. A new program “Doctorat-Conseil” established by the ministry gives the opportunity to the PhD students to spend 32 days/year in a company working on a particular topic. Two of our students are enrolled in 2007 in this program with two of our start-ups as partner companies.

The laboratory may also support the creation of “Start-Up” small business companies. Some of IEMNs past PhD graduates have gone on to launch notable start-ups (e.g. DELFMEMS and MC^2).

Short courses and focused schools

In 2005, under the initiative of the MPPU CNRS Department, a national school on Nanosciences and Nanotechnology : from concepts to application, was organized at IEMN. About 45 participants from the BTR network reached Lille for this 5 day training. After Lille, Grenoble and Toulouse have organized this type of school.
Strongly involved in the development of scanning probe microscopes (SPM) since the beginning of the 90's, IEMN has transferred its expertise through short courses. The three day course, given in the french language, is intended to scientists, technicians, engineers, who desire an introduction to SPM or who want to broaden and update their knowledge on the

increasingly use of scanning probe microscopes in physics, chemistry, biology, and in numerous industrial sectors (semiconductors, data storage, biomaterials, food,.). 161 people have attended these short courses since 1999 and come mainly from french research institutions (CNRS, CEA, INRA, ...) or major companies commercializing electronic, material or food products (Thales, NXP, Jobin Yvon, Saint Gobain, Atofina, Cray Valley, Nestlé, Mars Inc.). Since 2008, a more specialized short course dealing with the electrical mode in SPM has also opened.

Training of IEMN personnel

Each year about 90 trainings for scientists as well as for engineers and technicians are followed by IEMN personnel. The duration of these trainings can vary from half a day to 7 days with an average of 2 days. The main topics of these trainings concerns an improvement of technical skills (software tools, talk in english, personal efficiency, authority, management….) and security (fire, gas, first aid..). For the engineers and technicians, the topic trainings are discussed each year during the 'annual activity interview' that was put in place for all the administrative and technical personnel since 2007. This interview between each personnel and his direct responsible allows to detect the possible difficulties in accomplishing the missions that were trusted and to collect the training and educational needs. IEMN also organised for the scientists, engineers and technicians preparation sessions for the national or local competitions for permanent positions. We do believe that this preparation is a reason for our success in the CNRS scientist competition (eight new positions during the period 2004-2008) and in the promotion of many IEMN agents.

1.13 Hygiene and safety

The IEMN aims to be a structure that gathers regional research in the field of electronics in the broad sense i.e. from the nanosciences to instrumentation and therefore also from the most theoretical aspects to their applications, the IEMN aims to create in the area a laboratory of european size. For this reason, the IEMN must develop a policy of Hygiene, Safety and Environment to the height of its scientific objectives.
This action is concretised initially by the implication of the scientific teams in the evaluation, at the earliest possible stage, of the risk factors inherent in any research.
It has as a permanent goal of implementing the necessary means which makes it possible to ensure the best control of these risks, on all workstations, in all our achievements and during the control of all our projects.
Although our activities are not regarded as generators of strong pollution, we have the will to be the most exemplary possible to ensure environmental protection by minimizing the depletion of natural resources and by limiting the residual impact of all our operations.
But beyond these aspects of Safety and Environment, the respect of the men and women who create the success of the IEMN requires that we still reinforce in their connection with Hygiene and Safety.
In the continuation of this document, we present the last and future actions of Safety and Hygiene. Knowing that our will for improvement is permanent, we will engage annually on progress objectives by implementing specific action plans.

Operation for hygiene and safety

• Two engineers are in charge of hygiene & safety rules at the IEMN. They were trained in 2007, and appointed in february 2008. The missions of each one of them were presented to laboratory.
• A special committee of hygiene and safety meets once per year. The last one took place in july 2008.
• We have 19 first-aiders on-site.
• We have a network of guides and fire marshals for the follow-up of the evacuations. A fire drill took place on may 21, 2008.
• We will soon have a "qualified person in protection against radiation", of which training took place in june 2008.
• Training on sensitive safety issues within the laboratory are regularly given to new scientists (PhD, post doc, CNRS junior or senior researchers, Prof. and Ass. Prof…..)
• An elaborate personnel training program at the beginning of the year near our supervision by the CNRS and the USTL.
Before any intervention by external companies, a common visit of the laboratory makes it possible to identify the possible hazards and a prevention plan formalises the necessary measures for the operation.

Identification and analyses of two specific risks met; chemical and ionizing radiation risks

Our activities in the fields of microelectronics and nanotechnologies use many chemicals. They are typically process-related and do not remain in the final manufactured product. The risk management measures related to the use of chemicals applied in IEMN are widely inspired by that used in the Semiconductor Industry (which often exceed regulatory requirements). These hazardous chemicals can be categorized as follows:

- Aqueous solutions (acids, bases) used to chemically etch or clean the wafers.
- Organic compounds (generally solvents) used to clean the wafers and as part of photolithography processes.
- Metallic compounds (copper, aluminium compounds) used to plate wafers or to provide electrical connections.
- Specialty gases (silane, arsine, fluorocarbons…) as precursors for thin film growth and dry etching.

IEMN set up measures for tracking and controlling chemicals. The chemical stock is reduced as much as possible and is stored in a secure exterior area or in safety cabinets. Chemicals can only be used in dedicated areas fully equipped with collective protections (extraction hoods) while the staff ought to wear individual protections (glasses, gloves, air purifying respirators or even breathing apparatus). Environmental spill prevention methods, such as double-containment, minimize risk of soil exposure. Waste management measures include a complete collection and segregation of solid and liquid wastes, further shipped to approve treatment facilities.
Hazardous gases are only used in closed sub-atmospheric gas systems, whereas most high-pressure gas cylinders are kept outside of the building in secure cabinets. The few gases stored inside the working area are enclosed in gas cabinets designed with safety features appropriate for these applications (fire safety, negative ventilation, exhausting of potentially hazardous leaks and gas leak monitoring). Exhaust systems are designed to remove chemical vapours and gases at the equipment level and to prevent reactions between incompatibles. They incorporate exhaust abatement systems to minimize environmental emissions.

Main achievements during the last four years:

- The chemical storage room, located outside of the main building, has been secured and upgraded (locked area with integrated fire protection system, ventilation and temperature control).
- A new clean room dedicated to organic chemistry is being built in addition to the existing lithography clean room and to the two inorganic chemistry clean rooms.
- Most of carcinogenic, mutagen and reprotoxic chemicals have already been substituted or banned from IEMN.
- Two more point of use abatement systems (dry scrubbers) has been installed to treat toxic and greenhouse gases (5 scrubbers).

In the field of ionizing radiations, IEMN is holding several X-ray tubes, but also equipments which use high voltage generators (susceptible to radiate X-rays). These equipments are hold in secured areas only accessible to authorized and trained workers. Controls and measurements have shown good safety conditions and that the ionizing radiation emissions are below the background level (even so, workers are wearing personal dosimeters). Achievement during the last four years: One person is being trained to radioprotection and will be soon in charge of it.

I.14 Conclusion : swot analysis

IEMN-Strengths: stability of the laboratory and common view of the personnel**.** Quality of personnel. Highly skilled engineers and technicians. Quality of scientific production. Large scientific activity from basic physics to industrial applications. Strong interaction with industry through long term agreement and start-up creation. Support from parent organizations (CNRS, universities) in IEMN development. International recruitment (more than 20 % of the personnel), large research activities in hot topics such as nanoscience and nanotechnology, efficient interaction between physicists and engineering scientists, flexibility of research groups, 3" clean-room facility (allowing fast response-time process evolution), national and international activity of IEMN's researchers (conference programme comities, paper review boards, agency scientific councils…..), multi site laboratory allowing a good connection with students from the different universities and engineer schools.

IEMN-Weaknesses: multi site laboratory limiting interactions between scientists. Buildings fully occupied reducing the possibilities of development. Equipment sharing involving reproducibility and reliability problems. Large variety of research projects going from nanophysics to integrated circuits and MEMS in the same technological facilities, 3" clean-room facility (implying supplying troubles). Difficulty in attracting brilliant PhD students. Lack of efficient information system. Lack of monitoring tools for management. Heterogeneous administrative and financial rules

IEMN-Opportunities. Dynamics between the large technological facilities created by the BTR network. Possibility of national and international (european) recognition of the network as a ‘large equipment’. New themes of research such as energy or ambient intelligence.

IEMN-Threats: Reduction in funding for investment (BTR, CPER). Renewal of old equipment and process capability improvement difficult without specific state support. Permanent increase of the running, infrastructure and maintenance costs needing more and more research contacts, decrease of student interests for science and engineering, no clear future for microelectronic industry in Europe, strong research policy change of our main industrial partners, university of Lille not selected in the ‘large campus’ national programme.

II Scientific report

Introduction

IEMN scientific activity which covers a large scientific domain as well as theoretical, experimental or technological researches is divided into five major scientific axes:

1-Physics of Nanostructures
2-Micro and Nano Systems
3-Micro-Nano- and Optoelectronics
4-Communication Systems and Application of Microwaves
5-Acoustics

The scientific report, presented in the next pages, describes the main achievements of the last four years for each of the five research axes. In each axis, some research operations were defined corresponding to a specific topic that can involve scientists for several groups. The staff, objectives, outstanding results and collaboration were reported for each operation. Some important papers related to the work are also specified in the text. It should be emphasized that all the IEMN scientific activity is not reported here but only its main achievements.

II.1 Physics of nanostructures

Introduction

This theme includes the most advanced researches of IEMN, involving “Physics” (including four teams), “Epiphy” and “Nanostructures and Molecular Devices” group activities. Nevertheless, a good equilibrium is maintained between advanced and applied researches, illustrated with many industrial contracts. These activities concern studies of thin layers, heterostructures and nanostructures (1D, 0D) of materials of high interest and technological breakdown for electronics, opto-electronics and nanotechnologies. They include theoretical and experimental research in several directions :

- Growth and physics of 3/5 heterostructures and isolated or self-assembled nanostructures (0D, 1D, 2D) of semiconductors
- Simulation of the growth of heterostructures and nanostructures
- The electronic structure of high k dielectrics
- Optical spectroscopy, STM and EFM spectroscopies mainly in nanostructures
- Physics of surfaces, nanoparticles and silicon semiconductor nanowires for bio-detection
- Dynamics of organics or biomolecular molecules in interaction with surfaces
- Materials and nanostructures for molecular electronics
- Physics of waves in micro and nanostuctured materials : photonics and phononics.
- Active nanostructures and films for MEMS

For the theoretical works, the main used techniques are the multi-scale simulation, the molecular dynamics for the analysis of molecules-surface interaction, and *ab-initio* (LDA) and semi-empirical (tigh binding) techniques applied to the electronics structures of nanostructures and high k dielectrics. For the experimental works, we have important technical facilities : three MBE machines devoted to III-V semiconductors growth and recently also for graphene, one CVD oven, an ESCA machine, 7 near-field microscopes – 4 in air ambient, 3 in UHV systems-, femto-second laser source,…

The report is organized around scientific themes, and a brief summary of the objectives of each one is given hereafter :

- *Molecular electronics* : we contributed to knowledge development by studying the fundamental electronic properties and transport of various molecular devices based on self-assembled monolayers, small ensemble of molecules, supramolecular assembly of molecules and nano-objects, and we established proof of concept for new devices

- *MBE :* growth and physical characterization of III-V based heterostructures for opto and microelectronic applications, including both field effect and bipolar devices. We have developed metamorphic growth of heterostructures on InP for field effect devices, heavily carbon doped material for HBT’s base as well as an original experimental setup for MBE flux measurements.

- *Zero-dimensional (0D) semiconductor nanostructures :* experimental and theoretical studies of zero-dimensional (0D) semiconductor nanostructures have been undertaken to probe their electrical, electronic and optical properties at the level of individual nano-particles

- *One-dimensional nanostructures* : it is an interdisciplinary area covering chemistry, physics, biology, materials and electronic engineering issues. It aims to understand the fundamental properties of 1D nanostructures (semiconductor nanowires, carbon or boron nitride nanotubes) of interest for electronic applications, and comprises both theory and experimental work (synthesis and characterization).

- *2D systems, surfaces and interfaces* : the main objective is to understand fundamental physical and chemical phenomena involving mainly a semiconductor surface as a starting material. Atomic-level properties of semiconductor surfaces have thus been investigated as well as the formation of thin oxyde layers or complex molecular adsorbate systems on top of these surfaces.

- *Phononic crystals and Nanophotonics* : phononic crystals can found potential applications for manipulating the sound, (tunable filtering and sound isolation). We have studied defect modes (guides, cavities, surfaces) and thin film modes in phononic crystals, and of locally resonant structures in relation with sound isolation. Future promising applications ranging from phonon-photon interaction in cavities and slow-wave structures, negative refraction and wave focusing, heat management, are currently being explored.

- *Active nanostructures and films for MEMS* : The general goal of this subject is the elaboration of active ferroelectric, ferromagnetic and multiferroic materials and nanostructures for MEMS (nanostructures with giant magnetostriction and artificially induced critical states and resulting multiferroics, on the one hand, and piezoelectric thin films etching, on the other hand)

II.1-1 Molecular Nanostructures and Devices

Permanent Staff: N. Clément, C. Dufour, D. Guérin, S. Lenfant, K. Lmimouni, D. Vuillaume
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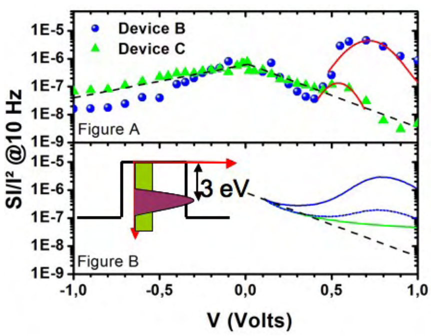
Objectives :
Our main objectives focus on molecular electronics, especially hybridized with silicon, and organic electronics. We contributed to knowledge development by studying the fundamental electronic properties and transport of various molecular devices based on self-assembled monolayers, small ensemble of molecules, supramolecular assembly of molecules and nano-objects, and we established proof of concept for new devices.
Read more: www.iemn.univ-lille1.fr/fileadmin/Commun_Recherche/NCM/documents/activity_report_2004-2008.pdf

Outstanding results
1). Fundamental transport properties in molecular junctions.
Electronic transport (ET) in molecular junctions and devices has been widely studied from a static point of view. However, this approach is non sufficient for a complete understanding of ET. It is only recently that dynamic phenomena (noise, fluctuations…) have been investigated. While it is obvious that 1/f noise will be present in molecular junctions as in almost any system, only a detailed study can lead to new insights in the transport mechanisms, defect characterization and coupling of molecules with electrodes. We reported (with Weizmann Inst.) the observation and detailed study of the $1/f^{\gamma}$ tunnel current noise through $Si/C_{18}H_{37}/Al$ junctions. The normalized noise current power spectra (S_I/I^2) showed noise bumps over a certain bias range and we proposed a model that includes trap-induced tunnel current, which satisfactorily describes the noise behavior.



Spectral density of tunnel current noise vs. bias voltage. Comparison between experiment (A) and model (B).

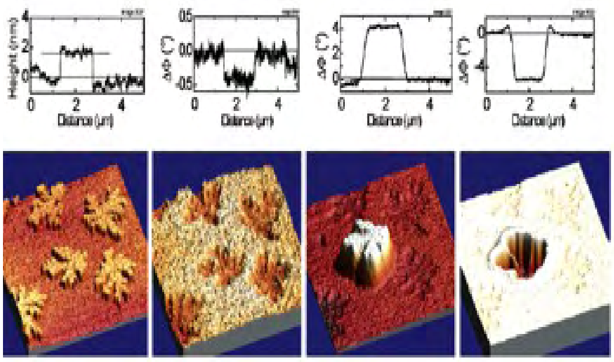
The background noise is associated with a low density of traps uniformly distributed in energy that may be due to Si-alkyl interface defects or traps in the monolayer. The local increase of noise for bias > 0.4V is ascribed to a trap distribution peaked in energy, probably induced by the metal deposition on the monolayer **[N. Clement et al, Phys. Rev. B 76, 205407 (2007)]**.

We have reported the synthesis and study of ET in molecular rectifying diodes made on silicon using sequential grafting of self-assembled monolayers of alkyl chains bearing a π group at their outer end. We have examined to what extent the nature of the π end-group (change in the energy position of their molecular orbitals) drives the properties of these molecular diodes. For all the π-groups investigated, we have observed rectification behavior. The current-voltage curves were analyzed with a simple analytical model, from which we extracted the energy position of the molecular orbital of the π-group in resonance with the Fermi energy of the electrodes. We concluded that Fermi level pinning at the π-group/metal interface is mainly responsible for the observed absence of dependence of the rectification effect on the nature of the π-groups, even though they were chosen to have significant variations in their electronic molecular orbitals **[*S. Lenfant et al, J. Phys. Chem B 110, 13947 (2006) ; ibid, Nano Lett. 3, 741 (2003)*]**.

2). Molecule-electrode interface issues.
Controlled and well-defined molecule/electrode interfaces are very critical issue in molecular electronics. Gold electrodes were deposited by nano-transfer printing (nTP) on a thiol-functionalized self-assembled monolayer (SAM) on silicon substrate. WE reported a generic sequential chemical route to incorporate thiol groups (–SH) on a preformed self-assembled monolayer on silicon. Temperature dependent measurements showed that the Au-nTP junctions exhibited a purely temperature-independent tunnel behavior, while a slight temperature-dependent behavior was observed at a low bias (< 0.5 V) for the junctions with evaporated Au electrodes **[*D. Guérin et al, J. Phys. Chem. C 111, 7947 (2007)*]**. We also demonstrated (with BARC-Mumbay) that a dense "carpet" of thiol groups at the interface avoids diffusion of gold into the molecule even for a 3 carbons chain. For this short molecule, we observed pure tunnel conduction with barrier height of about 2.1 - 2.6 eV and an effective mass $m^* = 0.16\ m_e$ (m_e = mass of the electron). This extends the demonstration of the excellent tunnel dielectric behavior of these organic monolayers down to 3 carbon atoms with a thiol/Au bond at the interface **[*D.K. Aswal et al, Small 1, 725 (2005)*]** and allowed us to carefully study interactions between electrons and molecular vibrations (by IETS) in these silicon-molecular hybrid junctions.

3) Local probe studies of injection and delocalization of charges in organic nanostructures.
We reported how electrons and holes, which are locally injected in a single pentacene monolayer island, stay localized or are able to delocalize over the island as a function of the molecular conformation (order vs. disorder)

of this island. Charge carriers were locally injected by the apex of an atomic force microscope tip, and the resulting two-dimensional distribution and concentration of injected charges were measured by electrical force microscopy (EFM) experiments.



From left to right: AFM image of a pentacene monolayer island, EFM images before charge injection, after hole and electron injections demonstrating the ambipolar behavior of the nanostructure.

We showed that in crystalline monolayer islands, both electrons and holes can be equally injected, at a similar charge concentration for symmetric injection bias conditions, and that both charge carriers are delocalized over the whole island. On the contrary, charges injected into a more disordered monolayer stay localized at their injection point. These results provide insight into the electronic properties, at the nanometer scale, of organic monolayers governing performances of organic transistors and molecular devices **[*T. Heim et al, Nano Lett. 4, 2145 (2004)*]**. We have carried out similar experiments on other nanostructures (DNA, single organic crystals, supra-molecular nanowires).

4) Molecular self-assembled devices.

We reported (with Itodys) on an organic field-effect transistor built on a SAM made of bifunctional molecules comprising a short alkyl chain linked to an oligothiophene moiety that act as the active semiconductor. The SAM was deposited on a thin oxide layer (alumina or silica) that served as the gate insulator. Platinum-titanium source and drain electrodes were patterned through e-beam lithography (L = 15 nm to 1 µm). For L < 100 nm, a few devices offered a mobility of ~ 10^{-3} cm^2/Vs., with an on-off ratio reaches 1800 at a gate voltage of -2 V. This result demonstrated field-effect in a single organic monolayer. Interestingly, the device operates at room temperature and very low bias, which may open the way to applications where low consumption is required. [M. Mottaghi et al, Adv. Func. Mater. 17, 597 (2007)].

5) Organic devices including nano-objects.

Organic devices have gained a very great interest both for the understanding of their electronic properties and for applications in low-cost, large-area, and flexible electronics. Several groups have reported memory devices made of metal nanoparticles (NPs) embedded in organic materials. These devices used a vertical structure where the active layer (an organic semiconductor including metal nanoparticles) is sandwiched between two metal electrodes. However, we demonstrated that this approach suffers from drawbacks (filamentary conduction) induced by the metal deposition on top of the active organic layer **[*D. Tondelier et al, Appl. Phys. Lett. 85, 5763 (2004)*].** We reported (with CEA-LIST) on a horizontal three-terminal structure (transistor), which is not sensitive to that drawback. We demonstrated an organic memory-transistor device based on a pentacene-gold nanoparticles active layer. Gold (Au) nanoparticles are immobilized on the gate dielectric (silicon dioxide) of a pentacene transistor by an amino-terminated self-assembled monolayer. Under the application of writing and erasing pulses on the gate, large threshold voltage shift (22 V) and on/off drain current ratio of ~$3x10^4$ are obtained. Charge retention times up to 4500 s are observed. The memory effect is mainly attributed to the Au nanoparticles **[*C. Novembre et al, Appl. Phys. Lett. 92, 103314 (2008)*]**.

We demonstrated (with CEA-LEM) that spectacular photoinduced modifications of the electrical characteristics of CNTFETs are achieved by coating the transistor with photoconducting polymers. Depending on the applied gate bias, the device can be optimized as a memory element or as an optical switch (optically driven current modulator). We proposed a mechanism based on the trapping of photogenerated electrons at the nanotube/gate dielectric interface. These trapped electrons act as an “optical gate” for the nanotube transistor that is significantly more efficient than the conventional electrostatic gate. Finally, we demonstrated that this device is a very sensitive charge sensor to study the charge distribution and dynamics in polymer thin-film transistors **[*J. Borghetti et al, Adv. Mater. 18, 2535 (2006)*]**.

Acknowledgments – Collaborations

Coll.: V. Derycke, J.P. Bourgoin - LEM-CEA (Saclay), S. Palacin - SPCSI-CEA (Sacay), D.K. Aswal, J. Yakhmi - BARC (Mumbay), A. Kahn - Princeton Univ., D. Cahen - Weizmann Institut (Rehovot), G. Horowitz - ITODY-CNRS (Paris), C. Gamrat - LIST-CEA (Saclay), D. Zander, C. Petit, G. Salace – CReSTIC (Reims).

Supports: PNANO, ACI-nanoscience, IFCPAR, EU.

II.1-2 Epitaxy and physics of III-V semiconductor based heterostructures

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Objectives
We aim to develop MBE growth and physical characterization of III-V based heterostructures for opto and microelectronic applications, including both field effect and bipolar devices. We have developed metamorphic growth of heterostructures on InP for field effect devices, heavily carbon doped material for HBT's base as well as an original experimental setup for MBE flux measurements.
We also model the strain effect in heteroepitaxial growth**.**

Outstanding results
1) Metamorphic modulation-doped heterostructures on InP
InAs has been studied as the active material of metamorphic $In_{0.8}Al_{0.2}As$/InAs modulation-doped heterostructures grown on InP. We show that the main limitation of these structures is the plastic relaxation of the 10-15 nm thick InAs channel compressively strained to the underlying InAlAs buffer. The best results are obtained with a composite channel made of 7nm InAs inserted in an $In_{0.8}Ga_{0.2}As$ layer. In this case, the electron mobility reaches 21 500 and 179 000 cm^2/V.s. at 300 and 77K respectively for a sheet carrier density of 9 10^{11} cm^{-2}. These values are among the highest ones ever reported for such metamorphic structures. [***X. Wallart et al., Appl. Phys. Lett. 87, 043504 (2005)***].
A new MBE growth chamber installed at the beginning of 2005 has been the starting point for the growth of antimony based semiconductors at IEMN. III-V materials containing Sb offer the opportunity to grow modulation doped heterostructures with very high room temperature electron

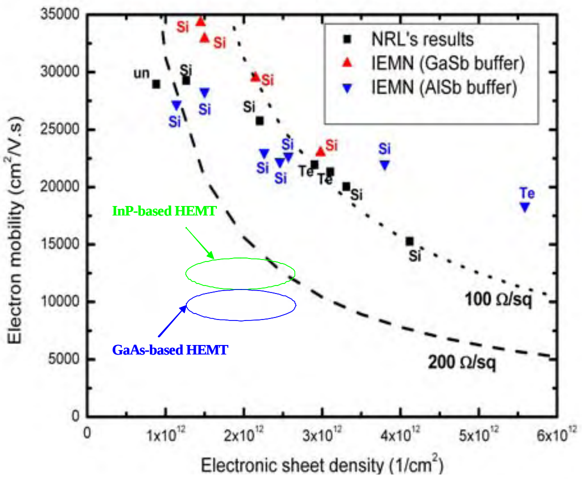

*Figure 1: electron mobility in the AlSb/InAs system compared to values from the NRL (after B. Bennett et al., SSE **49**, 1875 (2005))*

mobility. This property is essential to make high speed and low power consumption field effect transistors. We began with the growth of AlSb/InAs heterostructures on InP. As no semi-insulating lattice matched substrate exists for these materials, a metamorphic approach is required. For the delta-doping, we used a Si doping plane inserted in a 6 ML thick InAs layer first. We then turned to the use of Te as n-type dopant with GaTe as the source material. Two kinds of buffer (GaSb or AlSb) were studied. With the former, we obtained the best results, close to state of the art ones, since the electron mobility exceeds respectively 30 000 and 200 000 cm^2/V.s. at 300K and 77K (figure 1). For devices, an insulating buffer is needed which requires the use of AlSb. In this case, a sheet resistance as low as 70 Ω was achieved associated with an electron mobility of 22 000 cm^2/V.s. and a sheet carrier density of 3.8$10^{12}$/cm^2 at 300K [***L. Desplanque et al., J. Crystal Growth 301-302, 194 (2007); M.Borg et al., IPRM 07 Proceedings,67 (2007)*****]**.

2) Heavily C-doped InGaAs and GaAsSb as base materials for HBTs on InP

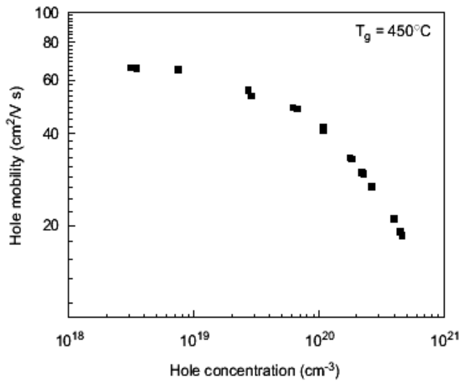

Figure 2 : hole mobility versus concentration for lattice matched GaAsSb on InP.

HBTs require heavily p-doped base layers. We have developed carbon doping using a CBr_4 source. On GaAsSb lattice matched to InP, we have obtained record hole mobility and doping levels up to 4 10^{20}/cm^3, promising low base sheet resistance (figure 2) [***D. Yarekha et al., J. Crystal Growth 301-302, 217 (2007)***].
The electron lifetime has been measured by time-resolved differential transmission experiments in heavily carbon-doped p-type InGaAs and GaAsSb, grown lattice-matched on InP by molecular beam epitaxy. It is found inversely proportional to the square of the doping in both alloys, which is typical of Auger recombination dominated processes. As expected, this point only depends (see figure 3), on the activated dopant density (see figure 3). It appears that the electron lifetime is almost twice larger in GaAsSb than in InGaAs for large p-type doping, thus confirming that GaAsSb is a strong contender for the base material of double heterostructure bipolar transistors grown on InP [***D. Vignaud et al., Appl. Phys. Lett.**, **90**, **242104 (2007)***].

3) Real-time in-situ flux monitoring by wavelength-modulated atomic absorption spectroscopy in molecular beam epitaxy

A flux monitoring set-up has been developed, based on wavelength-modulated atomic absorption spectroscopy (WMAAS) in-situ real-time measurements. It is particularly suited for element III fluxes monitoring during the growth of

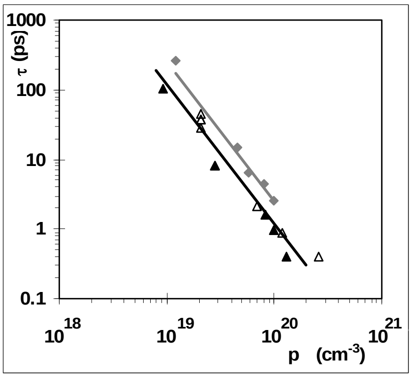

Figure 3 : The measured electron lifetime in InGaAs:C (filled triangles), InGaAs:Be (empty triangles) and GaAsSb:C (lozenges).

III-V semiconductors and heterostructures inside a MBE chamber. Measurements have been carried out for the Ga element at 403.3 nm (see figure 4), with a growth rate in the range 0.027-1.5 ML/s on GaAs. The WMAAS signal shows a linear dependence on the growth rate over the whole range studied here. For the particular case of Ga, it is shown that WMAAS measurements at the 4f or 6f even harmonics show the best signal-to-noise ratio characteristics. The uncertainty and low flux limit are measured to be below 0.01 ML/s, allowing precise measurements even at such very low atomic fluxes. [D. Vignaud, J. Vac. Sci. Technol, B25, 1398 (2007)].

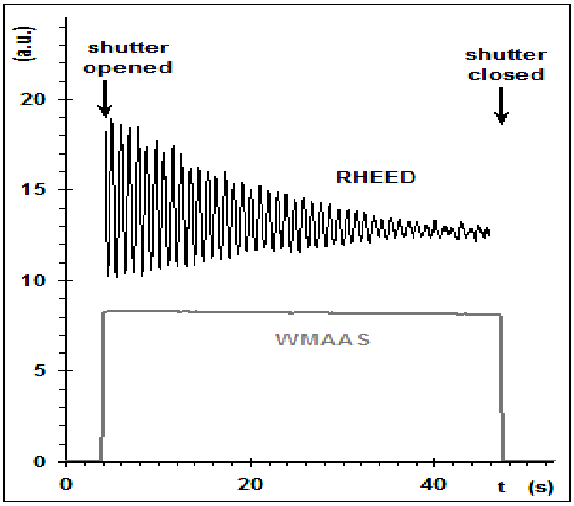

Figure 4: Simultaneous recordings of RHEED intensity oscillations and 2f WMAAS signal, for a Ga cell temperature of 960°C (RHEED growth rate 1.05 ML/s).

4) Modelling of strain in heteroepitaxy

i) growth of nanostructures on "patterned" substrates

In order to improve lateral organization of "self assembled" quantum dots, patterned substrates, as a nanomesa array, can be used. This idea has been experimentally investigated for several systems: Ge/large Si quantum dots, InAs/GaAs nanomesas and InAs/InP nanomesas. From the quasi equilibrium model, neglecting kinetic limitations, we have calculated how design parameters of the substrate can improve the organization of nucleating dots. Especially it appears interesting to take advantage of stressors, inserted up enough in the nanomesas, for an earlier nucleation of quantum dots as well as a stronger localization near the edges of the mesas. This study has been first performed in the framework of NanoQUB for InP substrates, and then extended to the other substrates [***C. Priester et al., Mater. Res. Soc. Symp. Proc., 901E (2006)-Ra13-03.1-6, A. Turala et al. IPRM 06 Proceedings, 2006, 214-217, A. Turala et al., IEEE LEOS Proceedings 2006, 189-190***].

An other interesting point was the description of elastic interaction at the early stages of organic nanocrystals growth on a passivated Si substrate : a simple search of "quasi-coincidences" leads to the observed orientations of PTCDA nanocrystals and explains quantitatively their elongation versus their orientation [***F. Vaurette et al., Phys. Rev. B75, 235435 (2007)***]

ii) role of strain for several alloy 2D-growth.

We have investigated the incorporation behavior of Tl in InAs and GaAs. Indeed, it is difficult to incorporate Tl in InAs whereas it is easier in GaAs, though the mismatch is lower for InAs. We have found two joint explanations: a higher tendency to get an ordered alloy in GaAs:Tl than in InAs:Tl, and the role of surface dimers, with a strong Tl surface segregation [***R. Beyneton et al.,Phys. Rev. B72, 125209 (2005)***].

For GaInNAs alloys on GaAs substrate, a Valence Force Field description has shown atomic distances are not directly determined by the nature of second or third nearest neighbors nor local or average alloy concentration and that N atoms tend to desert In rich areas [***C. Priester et al., Mater. Res. Soc. Symp. Proc.,891, 497 (2006)***].

iii) elastic relaxation in several quantum dot systems

As rather usual now, we have provided calculated elastic deformation fields – for GaN/AlN dots or InAs/InP wires for simulating diffraction spectra to some ESRF users [***A. Letoublon et al., Phys. Rev. Lett., 92, 186101 (2004); A. Mazuelas, Phys. Rev. B73, 045312 (2006)***]

Acknowledgments – Collaborations

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II.1-3 Zero-dimensional semiconductor nanostructures

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Objectives

Experimental and theoretical studies of zero-dimensional (0D) semiconductor nanostructures have been undertaken to probe their electrical, electronic and optical properties at the level of individual nano-particles.

Highlights

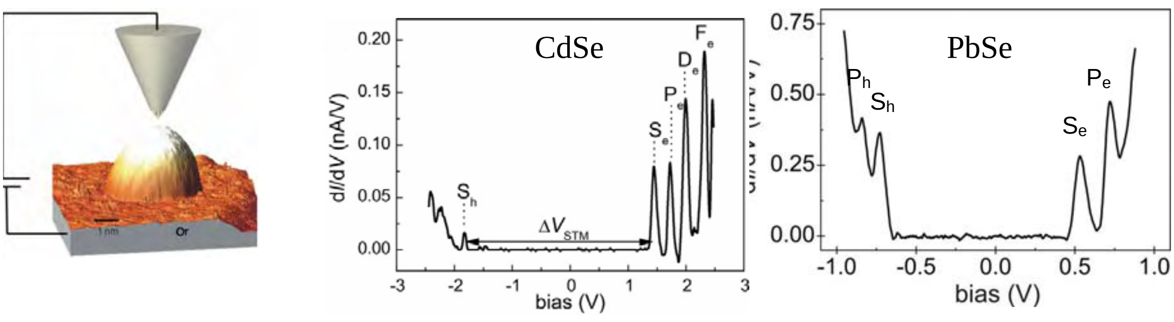
Silicon nanoparticles have been studied as discrete charge storage nodes by electrostatic force microscopy (EFM) and charge injection techniques. The amount of charge stored in a nanoparticle can be quantitatively measured from EFM signals [**T. Mélin et al., Phys. Rev. B 69 035321 (2004)**], and electrostatic interactions dissociated using spectroscopic techniques, enabling in particular to identify weak dipole-dipole interaction terms at the nanometer scale [**T. Mélin et al., Phys. Rev. Lett. 92 166101 (2004)**]. We have then studied the mechanisms governing the charge injection. The separation of surface and volume charge injection processes has been evidenced from the hysteretic behaviour of the nanoparticle charge-voltage characteristics [**H. Diesinger et al., Appl. Phys. Lett. 85 3546 (2004)**]. The mechanisms responsible for charge injection in the nanoparticle volume have been attributed to tunnel transport through the nanoparticle oxide interfaces [**S. Barbet et al., Phys. Rev. B 73 045318 (2006)**].

Colloidal semiconductor nanocrystals (NCs) are processible from solution onto rigid or flexible substrates, thus making them quite appealing for the fabrication of low-cost electronic devices. While these devices are expected to consist of NC solids, with the expectation that the properties of such solids will be much improved over the combined properties of the individual NCs, key questions exist regarding their electronic structure and the transport properties of such thin films. Thanks to the spatial resolution of scanning tunnelling microscopy, the electronic characterization of PbSe and CdSe individual NCs were performed to study the energy level, the spatial extent and shapes of the NC states and the carrier-carrier interactions in NCs [**P. Liljeroth et al., Phys. Rev. Lett. 95, 086801 (2005)**]. When this technique is applied to an array of NCs, we could follow the transition from a collection of non-interacting NCs to the regime where bulk solid-state properties emerge as the interparticle distance decreases, due to the electronic delocalization and coupling between neighbour PbSe NCs [**P. Liljeroth et al., Phys. Rev. Lett. 97, 096803(2006)**].

The main theoretical studies on 0D nanostructures have dealt with the optical properties of PbSe NCs that receive increasing interest because their gap varies from the infrared to the visible [**G. Allan et al, Phys. Rev. B 70, 245321 (2004)**]. Calculations of the optical absorption spectra versus NC size demonstrate quantum confinement effects at different points in the Brillouin Zone [**R. Koole et al, Small 4, 127 (2008)**]. Predictions of two-photon absorption spectra are found in excellent agreement with experimental ones, uncovering forbidden optical transitions [**J.J. Peterson et al., Nano Letters 7, 3827 (2007)**]. We have also studied electron-electron interaction processes (e.g. the impact ionization) that were recently invoked to explain the generation of multiple excitons after absorption of a single photon in PbSe NCs [**G. Allan et al., Phys. Rev. B 73, 205423 (2006); Phys. Rev. B 77, 125340 (2008)**].

Acknowledgments – Collaborations

D. Vanmaekelbergh, Utrecht University. T. Baron, LTM CNRS. T. Krauss, Rochester University.



Scanning tunnelling microscopy and spectroscopy of isolated CdSe and PbSe nanocrystals deposited on a gold surface at 5K

II.1-4 One-dimensional nanostructures

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The activity on one-dimensional nanostructures at IEMN is an interdisciplinary area covering chemistry, physics, biology, materials and electronic engineering issues. It aims to understand the fundamental properties of 1D nanostructures (semiconductor nanowires, carbon or boron nitride nanotubes) of interest for electronic applications, and comprises both theory and experimental work (synthesis and characterization).
Chemical kinetics and thermodynamics in Si/Ge nanowire growth
Even though much progress has yet been achieved, many fundamental and technological questions still need to be solved. This concerns both the basic growth mechanisms as well as the oriented and location controlled growth.
We discuss from a thermodynamics/kinetics point of view the growth of nanowires by the two most used processes, i.e. SLS and VLS and to point out the origin of the supersaturation and the conditions in which nanowires can be obtained.
Whatever the process, the driving force needed to trigger the SiNW precipitation is the supersaturation of liquid alloy Au-Si or Au-Ge. Equilibrium between phases can be expressed in one of two ways: either the total Gibbs free energy of the system is minimized or the chemical potentials (μi) of each component in coexisting phases are equated. It must be pointed out that, in the nanomaterial properties, surface energy cannot be neglected, because of the large surface/volume ratio.

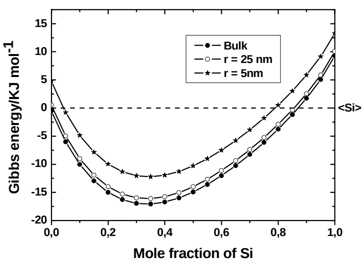

Figure 1: Gibbs energy of Au-Si liquid alloy at 1100°C

We have calculated and constructed the binary phase diagrams of Au-Si and Au-Ge nanosystems involved in the growth of nanowires [***D. Hourlier et al, J. P. E.D., vol 28 ,(2) 150 (2007)***]. Gold forms a simple and deep eutectic system with silicon and germanium. However, the eutectic temperature and the eutectic composition depend on the size and the shape of the solid / liquid system considered. The surface contribution increases the Gibbs energy of the droplet, and, as a consequence, decreases its thermodynamic stability (Fig1).

The important phenomenon, which deserves attention because of its occurrence in phase diagrams of nanosystems, is that the solubility of any particle (stable or metastable) is always higher in a macroscopic liquid than in a nanometric liquid.
In the SLS process, our model demonstrates, for the first time, how and from where supersaturation is reached. The supersaturation is not due to the migration of silicon from the wafer as claimed by many researchers, but to the existence of SiO volatile species resulting from the metastable equilibrium $SiO_{2,\ amorphous}$ /Si $_{wafer}$. More interesting is that the partial pressure P_{SiO} does impose a minimum radius of the first generation of nanowires in the range of 5 nm. After that, other generations of nanowires will grow due to the new metastable equilibrium $SiO_{2,\ amorphous}$ /Si $_{nanowire}$ [**D. Hourlier et al, C. R. Chimie, vol 10, 658 (2007)**]. We are currently investigating growth conditions required to produce NW heterostructures and core-shell structures.

Nanowire growth and fabrication of nanowire-based devices

A bottom-up approach was first used on self-assembled titanium silicide nanowires grown on a Si(111) surface. Electrical measurements with atom probe contact as well as scanning tunneling sepctroscopy were performed and showed the metallic behaviour of the NWs. In addition, scanning tunneling spectroscopic measurements obtained on the NWs at temperatures below 25 K yielded a rectifying behaviour. NWs are electronically decoupled from the Si surface on a voltage range of several hundreds of meV at low temperatures. The Schottky barrier height between the NWs and the Si surface was precisely determined and equal to 0.23eV [***T. Soubiron et al., Appl. Phys. Lett., 90 102112 (2007)***]. Second, silicon nanowires were grown using mainly CVD techniques. As one of the bottle neck of nanowire electronic properties is the determination of the doping level, we have developed a controlled process which allows the growth of a reduced number of nanowires on top of micropilars (Fig.2, scale bar 1μm). These NWs are used in atomic 3D tomographic experiments in the GPM (Rouen). Schottky diodes made by self-assembling of silicon nanowires assisted by collagen were also successfully obtained.

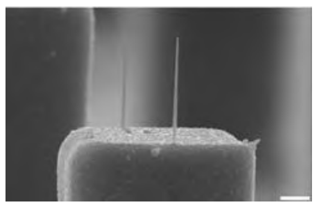

Figure 2 : Localized growth on a micropilar

For the top-down approach, we fabricated and characterized silicon nanowires made with lateral sizes down to 10 nm. Transport characterization allowed us to highlight a depleted area at the interface Si/native SiO2. The associated depletion width, the surface state density as well as the doping level of the nanowires were determined. Bulk phonons scattering was evidenced. Finally, three applications were developed: a decoder (using local etching), a current switch (using cross-bar structures with lateral gates) and a bio-sensor for ovalbumine detection.

Fundings : ANR-PNANO, DGA REI 0534048

Theory of the electronic structure of semiconductor nanowires

On the theoretical side, the electronic structure of semiconductor nanowires has been calculated using a tight binding method [***Y.M. Niquet et al., Phys. Rev. B 73, 165319 (2006)***]. The confinement leads to opening of the gap, but it is shown that dielectric confinement induced by the mismatch between dielectric constant of the wire and its surrounding largely dominates over quantum confinement. Quite similar effects explain that the ionization energy of dopants in freestanding nanowires strongly increases with respect to its bulk value, and doping becomes difficult in nanowires with diameter below 10 nm [***M. Diarra et al., Phys. Rev. B 75, 045301 (2007)***]. The doping is more efficient in nanowires surrounded by a gate oxide (SiO_2, HfO_2) due to an efficient screening of the potentials, but strong polaronic effects occur in that case [***M. Diarra et al., J. Appl. Phys 103, 073703 (2008)***].

Theory of Raman and optical absorption spectroscopy of boron nitride nanotubes

Using the techniques of many-body perturbation theory for the inclusion of electron-electron correlation and of electron-hole interaction, we have shown that the spectra of bulk hexagonal BN and of the tubes are dominated by strongly bound excitons. We have observed a strong effect of the dimensionality on the excitonic binding energy which increases considerably while reducing the dimensionality (from 0.7 eV in bulk BN, via 2 eV in the 2-dimensional single sheet to more than 3 eV for the 1-dimensional tubes)[**L. Wirtz et al., Phys. Rev. Lett. 96, 126104 (2006)**]. In collaboration with the LEM at ONERA, Chatillon, we calculated the Raman spectra of BN tubes. The characteristic dependence of the high frequency phonon modes on the tube radius enabled us to distinguish the spectral signature of BN tubes from the signature of crystalline hBN particles. These results are important for the analysis of the raw-soot of BN nanotubes and for a controlled purification/separation of the tubes from their by-products [**R. Arenal et al., Nano Lett. 6, 1812 (2006)**].

Electrostatic properties of individual carbon nanotubes

Electrostatic properties of single-separated multiwalled carbon nanotubes (MWCNTs) and single-walled nanotubes (SWCNTs) deposited on insulating (SiO_2) layers have been investigated by charge injection and electric force microscopy (EFM) experiments. We have observed delocalized charge patterns along the MWCNTs and SWCNTs upon local injection from the EFM tip, corresponding to (i) charge storage in the nanotubes and to (ii) charge trapping in the oxide layer along the nanotubes. The two effects have been distinguished [**M. Zdrojek et al., Phys. Rev. Lett. 96, 039703 (2006)**] for CNTs showing abrupt discharge processes in which the charge stored in the CNT is field emitted back to the EFM tip, while trapped oxide charge can subsequently be imaged by EFM, clearly revealing field-enhancement patterns at the CNT caps [**M. Zdrojek et al., Appl. Phys. Lett. 86, 213114 (2005)**]. The electrostatics of individual MWCNT and SWCNTs have then been analyzed from their linear charge densities measured as a function of the nanotube diameters. The results differ from classical capacitive predictions by one order of magnitude and correspond to a response of nanotubes in the external electric field generated at the microscope EFM tip. The fact that MWCNTs can hold an out-of-equilibrium charge is attributed to the charging of the inner-shells of the MWCNT, as a result of the MWCNT finite transverse polarisability and of the intercalation of semiconducting and metallic shells in the MWCNTs (coll. A. Mayer, Univ Namur) [**M. Zdrojek et al., Phys. Rev. B, 77, 033404 (2008)**].

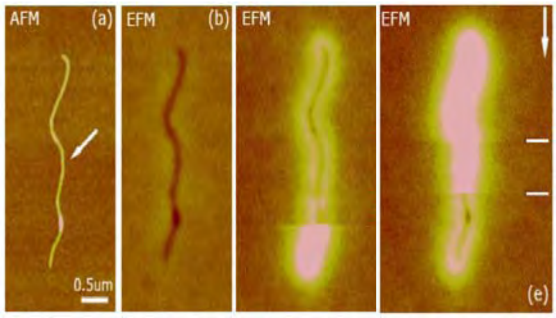

Figure 3 : AFM (a) and EFM (b) image of a MWCNT with 18nm diameter prior to charge injection. (c) and (d) are EFM images (20Hz scale) recorded after charging injection, and showing abrupt discharge events (labelled d_1,d_2 and d_3) and halos of residual oxide charge surrounding the MWCNT.

II.1-5 2D systems, surfaces and interfaces

Permanent Staff: F. Cleri, C.Delerue, D. Deresmes, I. Devos, B. Grandidier, T. Melin, J.-P. Nys, D. Stievenard, D. Théron
Non Permanent Staff: S. Barbet, M. Berthe, P. Boulenc,Y. Coffinier, A.-Q. Lequang, R. Stiufiuc

Objectives
Surfaces and interfaces exibit properties and behavior that are very different from the adjacent bulk phase. Atoms and molecules are typically present in concentrations different from either the bulk materials and arrange themselves differently, creating two-dimensional layers that have varying degrees of geometrical order. Mechanical, electrical and optical properties are therefore altered considerably at surfaces and interfaces, given them a central role in technological applications ranging from microelectronic devices to biochips. Since these applications use semiconductor materials, our research activities focussed on the understanding of fundamental physical and chemical phenomena involving mainly a semiconductor surface as a starting material. Atomic-level properties of semiconductor surfaces have thus been investigated as well as the formation of thin oxyde layers or complex molecular adsorbate systems on top of these surfaces.

Outstanding results
1) Impurities and point defects at semiconductor surfaces
Semiconductor devices approaching the scale of the semiconductor lattice, the precise atomic configuration of their structure will become critically important to their macroscopic properties. In particular, the number and position of the dopant atoms in the semiconductor materials and the nature of point defects at interfaces will lead to fluctuations in device electrostatics and electron tranport. As a result, we investigated subsurface acceptors positioned below the GaAs (110) surface by scanning tunneling spectrocopy at low temperatures to determine how the surface modifies the electronic structure of single dopants. We also probed the spatial extend of the acceptor level wave functions and showed asymmetric states that deviate from the hydrogenic states [***G. Mahieu et al., Phys. Rev. Lett. 94, 26407, 2005***], suggesting an anisotropic local coupling between neighboring magnetic dopants in magnetic diluted semiconductors. To further understand tunneling spectroscopy through a single quantum level such as an acceptor state, we chose to study transport through an isolated Si dangling bond as a model system. Such adatom can be found on the B-doped Si(111) √3x√3R30 surface and has a state energetically localized in the energy gap. Although this state was decoupled from any other electronic state, we were able to drive current of a few nA, demonstrating polaronic conduction : the electrons can be transferred through this single quantum state due to their non radiative recombination with valence band holes thanks to vibrational emissions [***M. Berthe et al., Phys. Rev. Lett. 97, 206801, 2006***].

2) Interfaces between High-K and silicon
After the epitaxy of LaAlO3 on a TiO2-terminated {100} surface of SrTiO3, a high-mobility electron gas may appear. Its origin is a subject of debate between the interface polarity and unintended doping. Here we have relaxed a superstructure representing the interface in order to demonstrate the oxidation change of the Ti atoms at the interface. The obtained relaxations are in good agreement with HRTEM at Unité Mixte CNRS /Thalès [***J.-L. Maurice, Materials Science and Engineering B 144, 1, 2007***].
We investigated the use of a γ-Al2O3 buffer layer between the high-k LaAlO3 and the silicon substrate. We firstly studied the structural matching of γ-Al2O3 (001) with a Si(001)-p(2x1) reconstructed surface. According to experimental data recorded at INLyon and computations in the density functional theory framework, we explained the Si dimer breaking and found stable interfaces between γ-Al2O3 and Si which encounters surface reconstruction changes. These interfaces satisfy the criterion of an insulating buffer layer [***P. Boulenc et al., Microelectronics Reliability, 47, 709, 2007***].

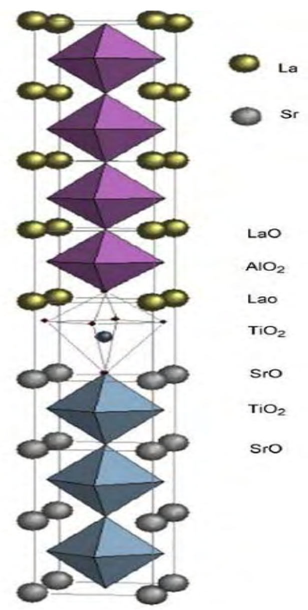

Fig 1: One half of the unit cell used in the calculations after relaxation. It shows that the interface is strongly elongated, and the TiO6 interfacial octahedron is so distorted, that the oxygen cage around the Ti ion is now a pyramid

3) Organic-semiconductor interfaces

In order to provide a theoretical basis for the analysis of a molecular device comparable to those under investigation in the ANR MEMO project, we performed DFT calculations for a dense monolayer of phenyl-terminated alkyl chains chemisorbed onto the Si:H(100) surface. Different adsorption sites and interface bonding schemes were characterized for the reconstructed surface, as a function of H pressure. A strong intermolecular screening of the electrostatic interactions within the layer, already reported in several organic-inorganic systems, was found. This implies that the conductivity gap approaches the HOMO-LUMO gap. The HOMO position, independent on the bonding, is dictated by the Si-molecule electron affinity difference, ultimately establishing an interface dipole. A substantial reordering of molecular levels with respect to the Fermi level of Si is also observed, as a function of the different bonding arrangements [**J. Phys. Chem. B 2006**]. Then, by means of a combination of *ab-initio* and empirical MD simulations, we studied the thermal evolution of benzene- or anthracene-terminated alkyl chains on Si(100). By monitoring the internal degrees of freedom of the molecules as a function of temperature, we demonstrated a transition to a free-rotor phase at about 400 K. Above this temperature other internal molecular degrees of freedom are also active, with a substantial increase in the monolayer roughness. Such findings correlate to experiments of metal evaporation on the monolayer surface, during the fabrication of molecular devices [**Appl. Phys. A 2007**].

4) Electrical Detection of biological interaction in a nanogap

Starting from Si surfaces, we also characterized the immobilization of biological probes, which are linked by chemioselective methods developped at the Institut of Biology in Lille. Along with these characterizations, we understood the physical mechanisms ruling the behaviour of a liquid in nanostructured surfaces and find out strategies in the design of new interfaces from a silicon surface to enhance the optical signal emitted by the optical biological receptors adsorbed on the Si supports [**C. Olivier et al., Langmuir 22, 7059, 2006; Y. Coffinier et al. , Surf. Sci. 601, 5492, 2007]**. We then took advantage of these supports to detect the interaction of the probes with biolomolecular receptors through optical (infrared, fluorescence) or electrical detection means [**L. Marcon et al., Biosens. Bioelectron 23, 81, 2007**].

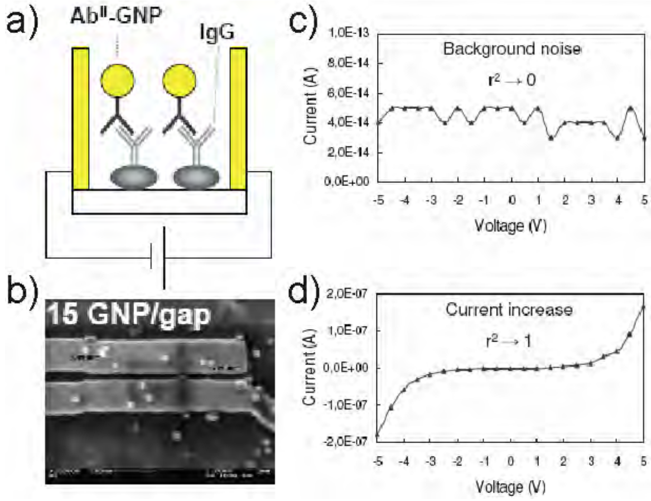

Fig 2 : E lectrical Detection of biological interaction in a nanogap: (a) detection scheme, where goat antibodies are immobilized and able to capture immoglobulin G (IgGs) from a human serum. The captured IgGs are further reacted with secondary antibodies labeled with gold nanoparticles (GNPs). Few GNPs are observed in the nanogap (b) and induce a significant change in the I(V) characteristic (c and d).

Fundings – Collaborations

- Minefi 2008 with STMicroelectronics
- ANR PNANO *Interaction polypeptide3D, ,* ARC-ir *Puces nano-3D* and ANR PNANO *NANOBIODETECTEUR* with Institut of Biology in Lille (IBL), Institut Pasteur Lille, Institut de Recherche Interdisciplinaire (IRI)
- Chaire Internationale Région Nord-Pas de Calais (F. Cleri), 2006
- Collaboration ANR PNANO *MEMO*, led by D. Vuillaume

II.1-6 Phononic Crystals and Nanophotonics

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Non Permanent Staff : M. Beaugeois,Y. El Hassouani, H. Larabi, A. Noual, R. Sainidou

Objectives

Phononic crystals are heterogeneous materials constituted by a periodical repetition of inclusions in a matrix. Associated with the possibility of absolute band gaps in their band structures, these materials can found potential applications for manipulating the sound, in particular in the fields of tunable filtering and sound isolation. Some of the authors were among the first to initiate this topic. Our recent activity has dealt with the theoretical study of defect modes (guides, cavities, surfaces) and thin film modes in phononic crystals, and of locally resonant structures in relation with sound isolation. Future promising applications ranging from phonon-photon interaction in cavities and slow-wave structures, negative refraction and wave focusing, heat management, are currently being explored.

The simulation tools developed in the above topic have also been adapted to study the propagation of light in InP based micro waveguides, especially in view of searching new filtering and demultiplexing devices based on the effect of one or several stubs (small lateral resonators) attached to the waveguide on the transmission spectra.

Finally, we present some analytical results in quasi-1D structures (chains containing loops or side resonators), either as a support to interpret numerical calculations or as new predictive models for further explorations.

Outstanding results

1) Phononic crystals.

- We have investigated theoretically and with ultrasonic experiments the propagation of acoustic waves in 2D phononic crystals containing guides, cavities and coupled guide-cavities. We give a summary of the main results published in several papers. A guide created by removing a row of cylinders allows propagation of acoustic waves inside the band gap of the phononic crystal. A high level of transmission can still be obtained with a bent waveguide provided the bent is designed appropriately. The transmission through the guide is modified by introducing a cavity either inside or in the vicinity of the guide: the same cavity acts as a *selective* filter in the first case and a *rejective* filter in the latter. With a guide constituted by a set of coupled cavities one can obtain propagation inside a narrow band (*slow modes*). We have proposed a first model of a demultiplexing device [***Y. Pennec et al., App. Phys. Lett. 87, 261912 (2005)***], based on the mechanism of resonant tunneling, that allows a selective transfer of a wave between two parallel coupled waveguides (Fig.1). Ultrasonic experiments were performed in all the above structures at Institut Femto (Besançon) with a crystal constituted by steel cylinders immersed in water.

- We have also investigated phononic crystals with hollow cylinders and shown the existence of narrow and sharp peaks in their transmission spectra inside a band gap. The peaks can be tuned by changing the radius of the cylinders or the nature of a fluid filling the holes. A guide made of such cylinders allows a selective transport of a wave. This property can be used to realize a demultiplexer when parallel guides of different constitution are inserted in the phononic crystal [**Y. Pennec *et al.*, Phys. Rev. E 69, 046608 (2004)**].

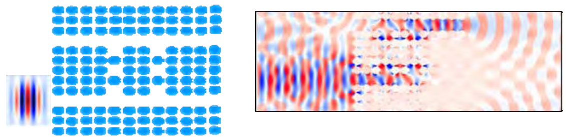

Figure 1: Map of the displacement field during the selective transfer of a wave between two coupled parallel waveguides inserted in a 2D phononic crystal.

- We have studied the *Lamb modes* in a slab of phononic crystal and demonstrated that an absolute band gap can occur only if the thickness of the slab is of the same order as the period of the lattice. This is related to the constraint imposed by the free surfaces on the values of the wave vector parallel to the cylinders. Moreover, we have shown that this property may still hold when the slab is deposited on a substrate, for example in the case of a phononic crystal made of holes in piezoelectric PZT deposited on a silicon substrate [***J. O. Vasseur et al., Phys. Rev. B 77, 085405 (2008) and J. App. Phys. 101, 114904 (2007)***]. This opens the feasibility of filtering functionalities, such as guiding and multiplexing described above, in suspended and supported membranes (Fig. 2). With micron size structures, they can be promising for high frequency (GHz) telecommunication applications

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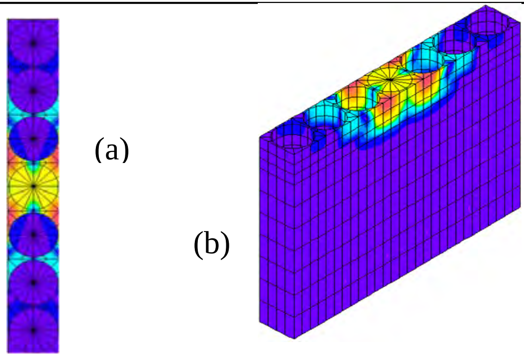

Figure 2: Elastic displacement field for a waveguide mode falling in the absolute stop band of a structure made of an air holes/PZT phononic crystal plate deposited on a homogeneous Si substrate (a) top view, (b) side view.

- We have also investigated the surface modes in a 3D phononic crystal and shown the richness of the surface modes, as compared to the 2D case, in the absolute band gap. In particular, these modes can be tuned by changing the geometrical and physical parameters of the inclusions in the vicinity of the surface [***R. Sainidou et al., Phys. Rev. B 77, 094304 (2008)***].

• We have studied phononic crystals with locally resonant structures in which the inclusions are constituted by cylinders coated with a soft (rubber) material. In these structures low frequency local resonances cut the normal acoustic branches leading to the bending of the latter, opening of gaps and drops in the transmission coefficient (*Fano resonances*). Such gaps appear at frequencies situated one to two orders of magnitude below the Bragg gap, and are useful for sound isolation with a sample whose size remains much smaller than the wavelength. We considered for the first time the case of multi-shell cylindrical inclusions [***H. Larabi et al., Phys. Rev. B 75, 066601(2007)***] and shown the possibility of increasing the number of low frequency gaps and their widening.

2) Nanophotonics.

• We have studied the propagation of light in 2D semiconductor (InP based) micro waveguides coupled to one or several lateral stubs. The advantage of the stub with respect to the usual micro-ring or disk resonators resides in its very small size which is comparable to the width of the waveguide (about 0.5 μ). The technological processing of these structures was performed in the Nanophotonic group of IEMN (Fig. 3)

• With a single stub, we have shown that the transmission spectrum displays one or several very narrow dips provided the stub is coated with a thin metallic film to avoid the light to escape. This property was first demonstrated with a perfect metal coating and recently extended to the case of real metals (Ag and Au) to show that such a device can be used in the infrared and near optical domain useful for telecom applications.
The frequencies of the zero of transmission can be tuned with the geometrical parameters of the stub. The quality factor of the dips is increased when the waveguide is separated from the stub by a small air gap. We showed that the interaction between several stubs produces a widening of the zeros of transmission into band gaps.

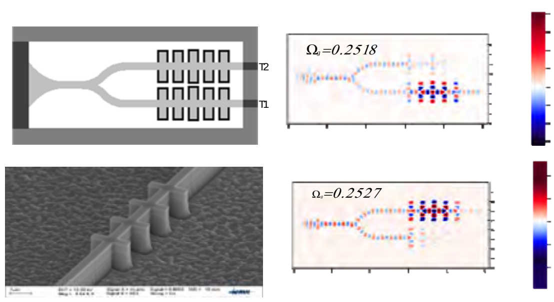

Figure 3: Y-shaped waveguide demultiplexer: each branch of the Y-waveguide transmits one specific frequency corresponding to the resonance state of the defect stub contained in this branch.

Inserting an appropriate defect stub between a set of periodical stubs leads to a tunnelling transmission, with a narrow peak inside the gap which can be useful for selective filtering. We used this filtering process to investigate the possibility of a new device for wavelength demultiplexing based on a bent Y-shaped component (Fig. 3) [***Y. Pennec et al., J. Optics A: Pure and Applied Optics 9, 431 (2007)***]. Currently, similar problems are investigated in sub-wavelength plasmonic waveguides.

3) Photon, phonon, electron and magnon circuits using quasi 1D structures.

• We have developed predictive analytical models in monomode waveguides coupled to dangling resonators (stubs) or containing loops. As mentioned above, such structures can display zeros of transmission and band gaps and become useful for filtering functionalities.

• In the field of photonic, we have shown theoretically and experimentally (using simple experiments with coaxial cables) the possibility of both superluminal propagation as well as negative group velocity. The former (more usual) phenomenon is obtained inside a band gap, whereas the latter can happen in the vicinity of a zero of transmission when an asymmetric loop is inserted in the waveguide [***E.H. El Boudouti et al., J. App. Phys. 95, 1102 (2004)***]. This is due to a drop in the phase at the frequency of the zero of transmission, in analogy with the Bohm-Aharonov effect in electron circuit.

• We have studied the possibility of sharp resonances, resulting from geometrical effect, in the transmission spectrum of an electronic circuit consisting of *a single symmetric or asymmetric loop with dangling resonators at its ends*. The different lengths in the structure, and thus the zeros of transmission of the loop and of the dangling resonators, are chosen appropriately in order to obtain simultaneously a large stop band and an internal resonance of the structure falling inside. Asymmetric or symmetric Fano resonances are obtained depending on whether the frequency of the resonance falls near a zero of transmission or is squeezed between two zeros of transmission [***A. Al Wahsh et al., Phys. Rev. B 75, 125313 (2007)***].

•The propagation of an electromagnetic wave through a chain of metallic nanoparticles coupled through their surface plasmons is studied by considering a dipole interaction model. It is shown that if the infinite linear chain is coupled to a finite vertical chain, the transmission spectrum can exhibit either zeros or peaks of transmission depending on the number of the clusters in the vertical chain, their separation and their plasmon frequencies [***L. Dobrzynski et al., J. Phys. Cond. Matt. 18, 9047 (2006)*** and ***Phys. Rev. E 69, 035601 (2004)***]. Similar effects have been investigated in dipole coupled magnetic clusters.

Acknowledgments-Collaborations
A. Khelif, V. Laude (FEMTO, Besançon), P. Deymier (Tucson, Arizona), J.P. Vigneron (Namur, Belgium) and Interreg contract PREMIO (Pôle de REcherche en MIcro-Optique), E.H. El Boudouti, D. Bria (Oujda, Morocco), H. Al Wahsh (Cairo, Egypt).

II.1-7 Active nanostructures and films for MEMS

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Non Permanent Staff: A. Ostaschenko, S. Hage Ali

Objectives:
The general goal of this subject is the elaboration of active ferroelectric, ferromagnetic and multiferroic materials and nanostructures for MEMS. During the period of report, the activity was concentrated on: nanostructures with giant magnetostriction and artificially induced critical states and resulting multiferroics, on the one hand, and piezoelectric thin films etching, on the other hand.

Outstanding results:
1) Multiferroic Nanostructures based on piezo / giant magnetostrictive multilayers with induced critical states
Recent studies show that magneto-electric interaction obtained via mechanical deformation of laminated bulk multiferroics fabricated by glued alternating Terfenol-D and PZT or PMN-PT layers, provide better magneto-electric coefficient than the earlier studied mechanisms. On the basis of our background on active nanostructures with giant magnetostriction and induced Spin Reorientation Transition (SRT), we recently demonstrated the first transfer of this concept in film forms for adaptation to MEMS devices **[A. Ostachenko & al., Phys. Solid State, 50, 446, 2008]**. The originality comes from the use of nanostructures with artificially induced critical states, resulting from exchange interactions between the nanolayers. For this reason, the magnetic nanostructure is analysed in details using Tomographic Atomic Probes (LaTAP) in collaboration with GPM in Rouen (Fig. 1).

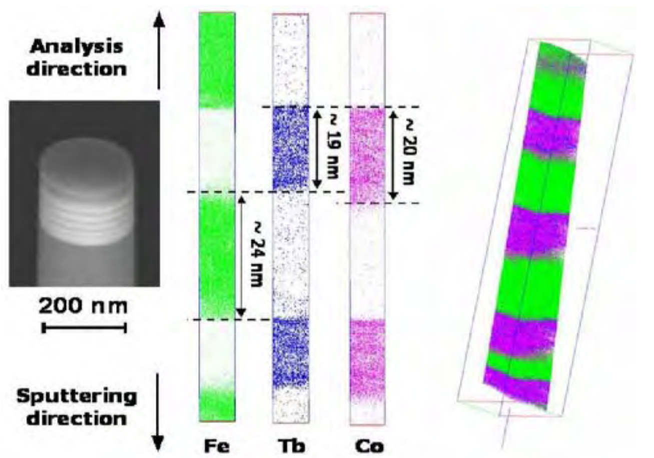


Figure 1 : Analysis of TbCo/FeCo multilayers of IEMN by the LaTAP Probe from GPM

1.1) Hybrid film / bulk multiferroics
The first structures considered were nanolayers such as $N*((Tb_xFe_{1-x})_{4,5nm}/Fe_{6,5nm})$, $N*((Tb_{0,4}Fe_{0,6})_{4,5nm}/(Fe_{0,6}Co_{0,4})_{6,5nm})$ and $N*((TbCo)_{4,5nm}/(FeCo)_{6,5nm})$ deposited by magnetron sputtering under magnetic field on bulk PZT beams, then on bulk PZT layers (150µm thick) bonded on Silicon (50µm thick) (fig.2) **[N. Tiercelin & al., APL, 92, 2008]**. For a 500nm active magnetic layer, 300 times thinner than the PZT substrate, and when an instability of SRT type is used, a $580mV.Oe^{-1}.cm^{-1}$ value was achieved in resonant mode. Fig. 3 shows the fairly good agreement between the magnetic field dependence of the ME voltage and the angle amplitude at the end of the actuator, showing that the ME voltage can be used as an indicator of the actuator position.

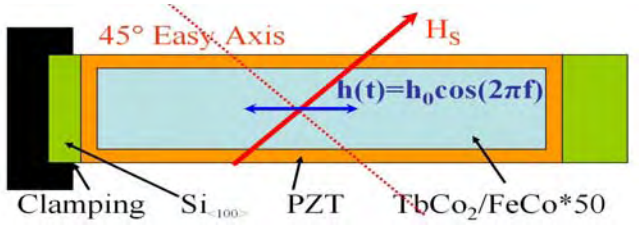


Figure 2 : magnetic field configuration for the clamped PZT beam coated with an active magnetic film and placed on a silicon substrate. Hs is the polarizing field. h(t) is the excitation field.

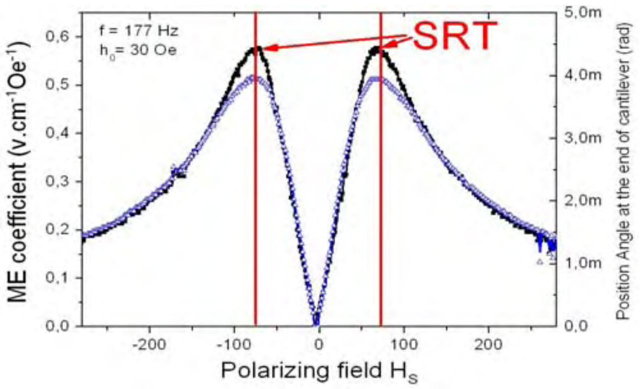


Figure 3: Measured ME coefficient (solid square) and bending angular position (hollow triangle) for the first resonance mode of a PZT on substrate clamped beam.

1.2) Film / film multiferroics on cantilevers
We elaborated the first magneto-electric film/film nanostructure with induced Spin Reorientation Transition on silicon substrates: $((TbCo_{5nm}/FeCo_{5nm})_{x50}/AlN_{3\mu m}/Pt/Si_{50\mu m})$ (fig. 4) **[N. Tiercelin & al., E-MRS, 2008]**. As shown on Figure 5 the magneto-electric coefficient reaches the record value of **$50V.cm^{-1}Oe^{-1}$** for the longitudinal vibration mode at 35 kHz at the SRT point (Hs ≈100 Oe) (**highest value found in literature: $10V.cm^{-1}Oe^{-1}$** for bulk laminate composites (PMN-PT/Terfenol D)).
These active nanostructures can provide totally new capabilities and functionalities, giving rise to new concepts in the field of MEMS.

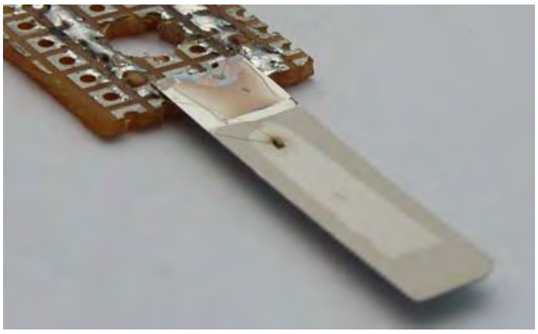


Figure 4: AlN 3µm and 50x($TbCo_{2}$ $_{5nm}$/$FeCo_{5nm}$) on 50 µm Silicon.

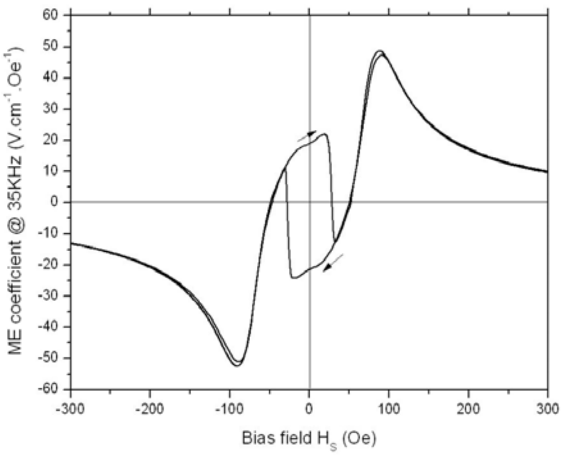


Figure 5: Dynamic ME coefficient @ 35KHz (longitudinal mode) vs. polarizing magnetic field

2) PZT films etched by focused Ga+ ion beam: study of ion damage and post annealing treatment effects

We have got a great experience on the growth of ferroeletric and piezoelectric thin fims. Now, our main objective is to study the dimension effect of the films on the structural, micro strutural and electrical properties. Our major works are first to realize very thin films (thickness in the order of 50-100 nm), and secondly to fabricate films with finished lateral dimension. We focused our work in a first time on PZT films, deposited by sputtering on silicon substrates metallized with Pt or LNO. For very thin film the influence of the bottom electrode is very strong as well on the film orientation as the film micro structure (grain size). The lateral size to fabricate PZT "island" has been obtained by Focused Ion Beam (FIB with Ga^{+} ions). More precisely, we used a commercial DualBeam (FEI STRATADB 235) to etch different sizes of islands (from 1µm to 150nm diameter) on these Pt (LNO)/PZT/Pt layers. In the first step, we used a 100 pA ion beam to make island of 1.5µm diameter, and in the second step we decreased island dimensions with lower ion beam intensity (10pA). An example of PZT island (on Pt) is shown fig. 6, the island diameter is of the order of 200nm.

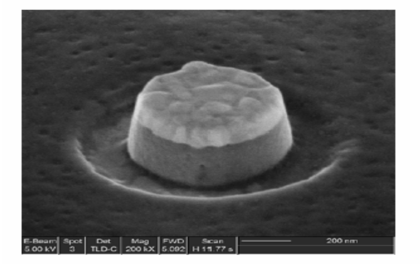


Figure 6: Scanning ion-beam image of PZT island with the lateral dimension of 200 nm. before and after annealing treatments

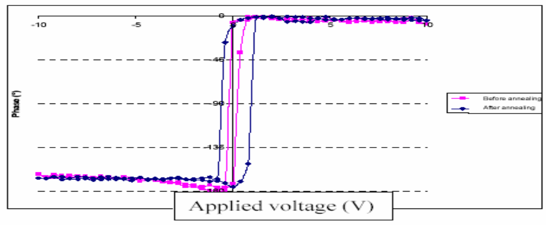


Figure 7 : PFM signals of PZT islands

An Atomic Force Microscopy was used to investigate the surface morphology and the electrical properties of the islands. Hysteresis piezoelectric loops have been recorded in the piezoelectric force microscopy mode. In this work, a conductive Pt-Ir-coated silicon tip with a spring constant of 40 N/m and resonant frequency of 320 kHz is used. The conductive probing tip with an apex diameter about 30 nm is positioned over the centre of a selected PZT island and a dc bias voltage Vdc coupled with an ac signal is applied between the tip and the grounded bottom electrode. We have systematically compared the piezoresponse of the PZT films before and after etching. It is found that some degradations are induced in the etching process by Ga+ implantation, surface amorphisation,... We have also investigated the effect of annealing treatments on the piezoelectric response. The piezoelectric response of the PZT islands is completely recovered after annealing (fig. 7 is relative to the PFM signal of a 200nm PZT island). The piezoelectric seems to disappear for PZT island dimension lower than 100nm. We try now to understand the physical phenomena.

Finally, we have also investigated switching properties of ferroelectric thin films by using a simulation tool based on phase transition and electromagnetism theories. Results show that the contribution of the surface to free energy strongly influence the shape of the current versus time curves. That is especially usefull to characterize the thin films. Publications relative to this work are :

[A. Ferri & al., Integr. Ferro, 91, 80, 2007], **[R.H. Liang & al., Microelectronic engineering, 85, 670, 2008]**

Acknowledgments – Collaborations

• Magneto-electrics : GPM – Rouen University (Fr), IMO – Hasselt universiteit (B), Moscow Institute of Radioengineering, Electronics and Automation (Ru)

• Piezo-electrics : LCPIA: Univ. Lens (Rachel Desfeux), LAAS Liviu Nicu). A pnano project has been submitted with the LAAS this year on this project.

II.2 Micro and Nano Systems

Introduction

Micro and Nano Systems (MNS) is one of the five main research themes at IEMN where it began in the mid-90s. Now, it has evolved towards a federating subject involving several research teams and widely covering topics such as sensors and actuators finding applications in thermal management, fluidic, biology, and nanotechnologies while maintaining more fundamental research activities on thin film materials and actuation modes. Service of IEMN's clean-room facility is used for the fabrication of the devices. Preliminary characterization of MNS is done on standard equipments whereas advanced performances assessment is often realized on specific test benches. Prior to the presentation of outstanding results and achievements, let us briefly introduce the context for each of the MNS domains investigated in our Institute.

- *Micro and Nano Resonators:* Microsystems have a major role to play so as to form a continuous nano-micro link and to thus assure the connection between the nanotechnologies and the macroscopic applications by developing a set of consistent and useful functions at the microscopic scale. In this context, the microdevice will either feature a nanometric part, or it will produce or detect displacements or forces of magnitude compatible with the manipulation and characterisation of nano-objects. These nanometric devices are integrated onto vibrating cantilevers for applications in the field of atomic force microscopy with very high lateral resolution.
- *RF MEMS:* In collaboration with STMicroelectronics and NXP Semiconductors, devices have been successfully fabricated in industrial facilities with different approaches: above-IC and in-IC. IEMN has also studied Bulk Acoustic Wave (BAW) filters and proposed original designs that have been patented. Together with DELFMEMS Company, a RF switch has been fabricated; it is based on a design less sensitive to temperature variation than widely spread clamped-clamped based devices.
- *Microsystems Microfluidics and THz:* The investigation of living cells is a very important topic today. Our research domain is the observation and the quantification of the biochemical information transfer between the liquid environment of a cell and its progression towards the nucleus..The technological means for reaching this objective is the design of specific BioMEMS, including planar THz electromagnetic functions coupled with microfluidic circuits.
- *Electrospray Emitter Tips:* Silicon microtechnology is utilised to form rigid cantilever and mechanical structures for lab on a chip interfaces, notably nanoelectrospray emitter tips, such emitter tips are capable of emitting droplets having a diameter of microns or even nanometres. Indeed, we have also recently developed a device which is capable of depositing minuscule volumes (sub-attolitre) of liquid. Characterisation of the devices designed and fabricated at IEMN involves collaboration with the Astbury Centre for Structural Microbiology at the University of Leeds, United Kingdom in order to perform nanoelectrospray ionisation-mass spectrometry (nanoESI-MS).
- *Digital microfluidics for biologic applications:* EWOD (Electro-Wetting-On- Dielectric) and SAW (Surface-Acoustic-Waves) actuated devices for digital microfluidics devoted to biologic applications. In such a context, the droplets are envisioned as mobile laboratories. This point of view allows the making of prototypes for protein analysis by Mass Spectrometry of MALDI type but also the analysis of the behavior of a single cell under stimuli for which the expressed proteins are potential markers. A reusable base is dedicated to droplet actuation and guiding while the disposable cover is reserved to the biochemical fonctionalizations which allow interaction with the droplet biologic contents.
- *Magnetomechanical microsystems (MMMS):* MMMS are micro-systems based on coupled magnetic and mechanical effects. The specificity is to search, or artificially induce, magnetic or mechanical instabilities, in order to improve the performances or add new functionalities to the devices. This activity is a part of the theme entitled "nonlinear magnetoacoustics of condensed matter". The activity concerns the elaboration of active magnetic films with induced instabilities of structural or spin reorientation phase transition types. At the vicinity of these instabilities, non linear dynamic magneto-optic and magnetoelastic properties are studied.
- *Heat Flux Microsensors:* Heat flux sensors are practically unused in industry and not at all in consumer applications such as electric household appliances, automotive, home automation. The Micro-Thermics team has developed and patented a new heat flux microsensor entirely produced in silicon technology that makes it possible to manufacture it in very large numbers for a very low price. By using micromachining, more than 200 cells can be implemented on a 5x5 mm² microfluxmeter that allows high sensitivity (typically 5 V/W)

II.2-1 Droplet-based microfluidics on superhydrophobic surfaces and fluidic addressing

Permanent Staff: V. Thomy, J.C. Camart, C. Druon, P. Tabourier
Non Permanent Staff: J. Carlier, F. Caron, E. Galopin, A. Renaudin, N. Verplanck

Objectives

Discrete microfluidics (droplet-based) is a field showing an upsurge scientific activity. Among the two droplet motion techniques developed in our team (ElectoWetting On Dielectric - EWOD and Surface Acoustic Waves - SAW), we are interested both in liquid/surface interactions (in particular superhydrophobic surfaces) and in Lab-on-Chip development for biological applications (Mass Spectrometry and Surface Plasmon Resonance).

Outstanding results

1) EWOD on superhydrophobic surfaces

We have developed, for the first time, a strategy to achieve effective reversible electrowetting of liquid droplets in air on superhydrophobic silicon nanowire surfaces. The superhydrophobicity was achieved using a combination of surface roughness and hydrophobization through surface coating with a fluoropolymer C_4F_8. The surface roughness combined with the low surface energy induced by the surface coating ensured air trapping between the substrate and the liquid droplets, necessary to achieve superhydrophobicity. An effective way to dynamically turn the properties of superhydrophobic nonuniform textured surface by reversible electrowetting in oil and for the first time in air, without any additional energy to the system, was demonstrated. The decrease of the contact angle upon applied voltage is equal to 58° in oil (state of the art) and to 23° in air for a saline solution of 100 mM KCl. This result shows, for the first time, the possibility to achieve total reversible electrowetting operation on superhydrophobic surface in air **[N. Verplanck et al. Nano letters 7, 813 (2007)].** This effect is ascribed to the high heterogeneity of the surface and air trapped under the droplet preventing to reach the Wenzel configuration.

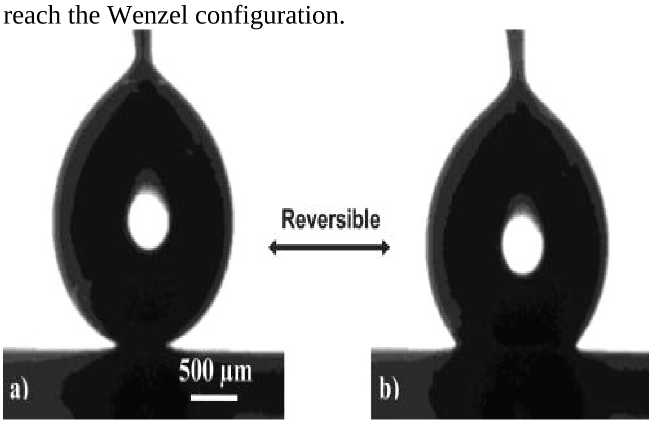


Figure 1 : Reversible electrowetting of a saline water droplet (5µL, 100mM KCl) in air environment: a) θ=160° @ 0V, b) θ=137° @ 150V$_{RMS}$.

2) SAW based microfluidic platform for SPR detection

We have developed a surface acoustic wave (SAW) echo method to move and to locate a microdroplet from a single interdigital transducer (IDT) **[F. Zoueshtiagh et al. Physics of Fluids 19, 091111 (2007)]**. A prototype working at 20 MHz demonstrates the ability of this method to achieve the aimed biological applications with a submillimeter accuracy positioning. The tested platform fitted with one IDT built on a $LiNbO_3$ substrate allows the tracking of water droplets actuated by SAW running free or squeezed under a cover for biological treatments in a lab on chip. **[A. Renaudin et al. Journal of Applied Physics 100, 116101 (2006)]**.

We have also showed that this system permits the enhancement of biosensing performances inside a droplet, by the continuous renewal of the analyte-carrying fluid near the sensing SPR surface (high influence of the transport of analyte to the sensing surface). A SAW based microstirring layout technology was adapted to obtain reproducible vortex-like circular flows with a controlled flow speed. Mean flow speeds up to 1.8 mm.s^{-1} have been measured using a Particle Image Tracking technique. The results allowed us to report on a proof-of-concept of a droplet based Surface Plasmon Resonance (SPR) system coupled to the same SAW microfluidic platform. Efficiency of SAW microstreaming coupled to SPR biosensing was demonstrated by improving the accuracy of kinetic parameter estimation in mass transport limited regime: a streptavidin binding was monitored in static mode under SAW streaming mode. **[E. Galopin et al. Biosensors and Bioelectronics 23, 746 (2007)].**

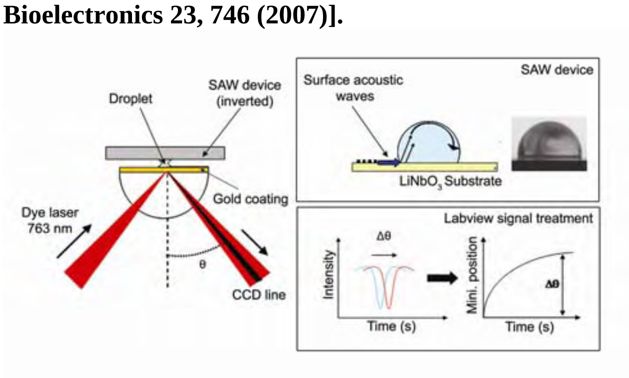


Figure 2: Experimental set-up of the droplet-SPR layout. $LiNbO_3$ substrate on top slide enables SAW microstreaming during real time monitoring of interactions.

Acknowledgments – Collaborations

R. Boukherroub (IRI USR 3078, Silicon nanowires growth), F. Zoueshtiagh (LML UMR 8107, Particle Image Tracking technique), M. Bouazaoui (PhLAM UMR 8523, optical bench for SPR detection).

II.2-2 Magneto-Mechanical Microsystems

Permanent Staff: P. Pernod, V. Preobrazhensky, N. Tiercelin, A. Talbi
Non Permanent Staff: L. Gimeno, R. Viard, S. Hage Ali, J. Streque

Objectives:
The general goal of this subject is to investigate the wide range of possibilities of magnetism and magnetic materials for the elaboration of micro-mechanical systems. The first direction deals with nanostructures with giant magnetostriction and induced critical states and their combination with piezoelectric thin films in order to elaborate new concepts of Microsystems with enlarged functionalities. The details on this activity are reported in the paragraph "Materials and nanostructures for MEMS" of Axis 1 of the present report. The second direction of activity, reported here, concerns magneto-dynamic micro-actuators. During the period of report, the work of LEMAC was concentrated on three applications : 1) Microvalves for aerodynamic active flow control, 2) High density arrays of micro-actuators for tactile interfaces, 3) Reconfigurable RF-antennas based on MEMS magnetically actuated PDMS micro-structures. Some results about the microvalves were selected as outstanding results and are presented below.

Outstanding results : Self oscillating micro-valves and derived magneto-dynamic configurations
An original actuation technique of MicroMechanical Valve based on an artificially induced self-oscillation due to an instable fluid-structure interaction has been proposed and investigated **[O. Ducloux & al., APL, 91(3), 2007]**. This technique provides high velocity pulsed air microjets at the output the micro-valve, with no necessary electrical energy feeding. Oscillations of the microjet velocities are between almost 0 and > 100 m/s, and frequencies are easily tunable in wide ranges (several hundred Hertz to > 2 kHz) using additional miniaturized permanent magnets. These characteristics are compatible with the typical specifications of flow control in aeronautics (for airwings and engines) or also for automobiles.

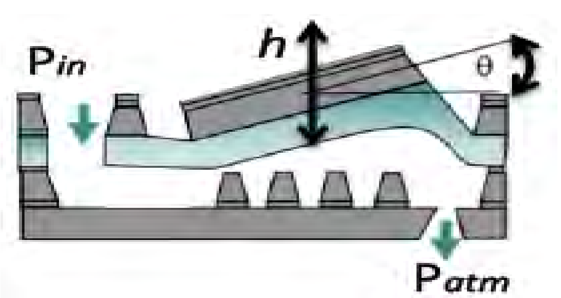


Fig. 1 : Scheme of the self-oscillating micro-valve based on a fluid-structure coupling

The structure, presented on fig.1 consists in a rigid silicon pad processed on a flexible membrane, both located over a silicon microchannel. Internal micrometric walls create a pressure distribution within the internal flow, at the origine of the strong mechanical coupling between the fluid and flexible membrane dynamics which present oscillating instabilities in some ranges depending on the inlet pressure, and the design of the microvalve (see fig. 2). Some specific packagings of the microvalves, compatible with experiments in wind tunnels were developed and arrays of such devices were tested at the output of a cold airplane engine for aeroacoustic control (OSCAR project).

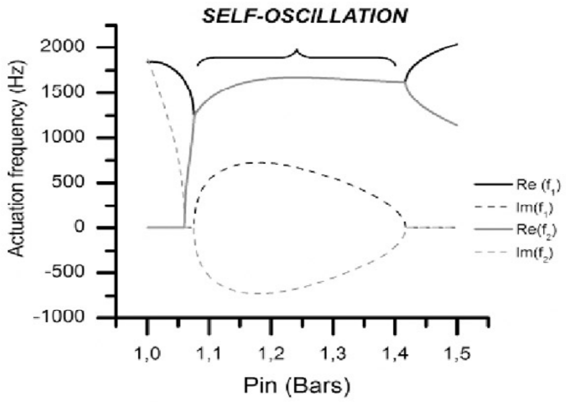


Fig. 2 : Theoretical and experimental analysis of the self-oscillating range of the micro-valve

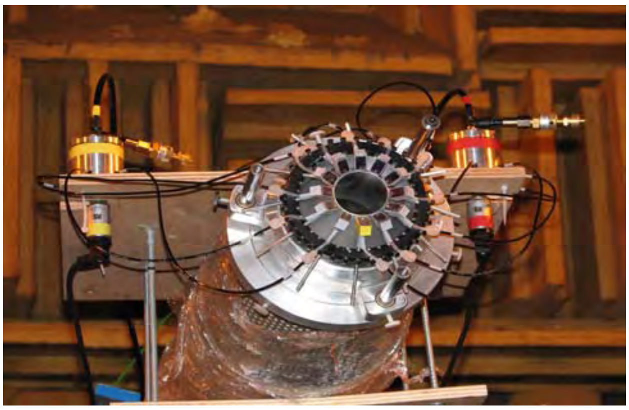


Fig. 3 : Photography of an array of 12 self-oscillating microvalves mounted at the exit of an airplane engine for acoustic noise reduction (tests in the anechoic room of Ecole Centrale de Lyon / OSCAR project)

Acknowledgments – Collaborations
The work on microvalves was made in close collaboration with the Laboratory of Mechanics of Lille, ONERA, and within several projects : GDR CNRS « contrôle de décollements », the Interreg IIIa and ADVACT European projects, and from DGA.

II.2-3 Micro and Nanofabricated Nanoelectrospray Ionisation Tips

Permanent Staff: S. Arscott, B. Legrand, L. Buchaillot
Non Permanent Staff: C. Descatoire

Objectives

Following pioneering work begun in the 1980s, John B. Fenn was awarded the 2002 Nobel Prize in Chemistry for electrospray ionization (ESI)-Mass Spectrometry (MS). Since, ESI-MS has become one of the instrumental techniques used in molecular biology; applications include Genomics and Proteomics. Commercial ESI-MS has sensitivity in the range of nmol-pmol/µL using very low flow rates ~1 nL/min; so why miniaturize? Sensitivity and detection limit are linked to ionization efficiency. Current non-micro fabricated ESI emitter tips produce micro sized charged droplets; following emission of these droplets, via the formation of a Taylor cone (application of ~1kV) and the break-up of a jet at the tip of the cone, the emitted droplets loose charge either by Coulombic fission (*charge residue model*) or direct ion formation from the droplet surface (*ion evaporation model*). The ionisation efficiency of the technique is low i.e. a few percent, since the initial droplets are large and few biomolecules are exposed to charge at the surface of the droplet. By ejecting smaller droplets, one should observe a boost in the ionisation efficiency and hence the sensitivity due to the increased surface-to-volume ratio of the droplets. Also, current non-microfabricated ESI tips are not at all compatible with Laboratory-on-a-Chip systems; microfabricated tips would be compatible with such technologies and benefit from batch production leading one day to possibly full miniaturisation of Mass Spectrometry; integration would also bring benefits in terms of analysis such as zero-dead-volume (analysis of reduced sample volumes would benefit from this) and reduced time scales e.g.; between sample mixing and identification (protein folding studies would benefit from this).

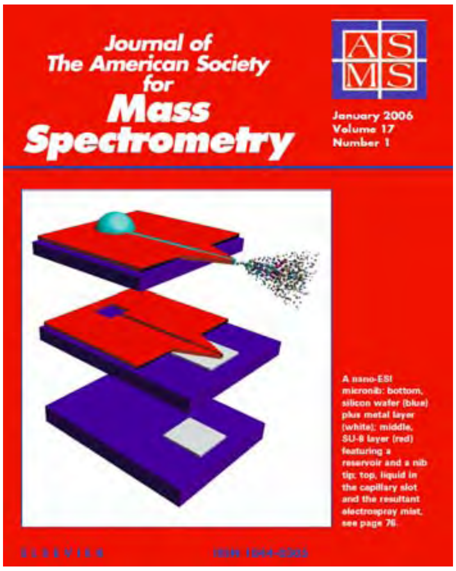


Figure 1 Front cover of JASMS

Outstanding results

IEMN have been designing, building and characterising (in collaboration with A.E. Ashcroft, *Astbury Centre for Structural Molecular Biology, University of Leeds*) micro and nanofabricated ESI tips for 6 years now. At IEMN we have achieved a number of notable scientific successes: i.e. **patenting** of an original microfluidic slot-based ESI tip, **16 publications** in international journals, **a front cover** of the prestigious *Journal of American Society for Mass Spectrometry*, **13 international conferences** and a **book chapter**. In a recent review on the topic entitled '*A decade of microfluidic analysis coupled with electrospray mass spectrometry: An overview*' the output of our laboratory made up **9.7 % of all international scientific production** in the period 2002-08, making IEMN very much a **world leader** in this subject over the past years. several challenges have been addressed in the period (i) the invention of a microfabricated ESI tip compatible with Lab-on-a-Chip (ii) an understanding of the physics of capillary filling in complex geometries (collaboration with R. Blossey, *IRI*) (iii) a microfluidic-microelectromechanical modelling of devices taking capillary forces into account (iv) fabrication of ESI tips having nanometre scale dimensions (v) characterisation of nanodroplet emission (vi) fmol/µL characterisation of micro and nanofabricated ESI tips using Mass Spectrometry.

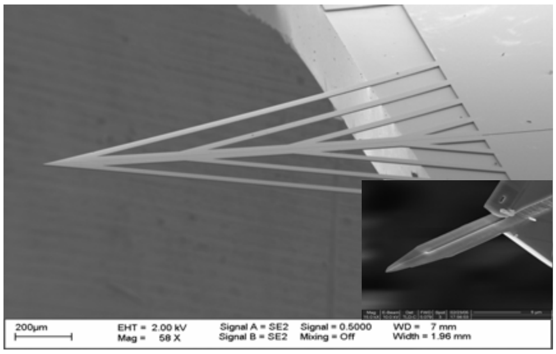


Figure 2 SOI based nanoESI tip (tip = 2×5µm). Inset: nanotip (tip = 21×300nm)

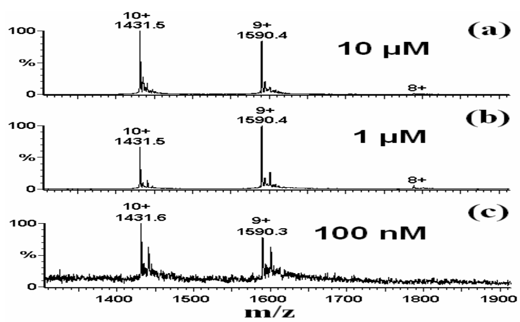


Figure 3 Mass spectra demonstrating fM/µL detection

II.2-4 RF MEMS: electromechanical and Bulk Acoustic Wave resonators

Permanent Staff: B. Dubus. L. Buchaillot, B. Legrand, M. Faucher
Non Permanent Staff : A. Volatier, C. Durand

Objectives

The objective is to propose an orginal cost-effective approach aiming at i) the integration of high frequency tunable resonators for filter applications and ii) the replacement of quartz as a time reference by in-IC electromechanical resonators.

Outstanding results

1) Switchable and tunable BAW resonator

Classical Bulk Acoustic Wave (BAW) filters exhibit a fixed central frequency determined mainly by the piezoelectric layer thickness. As BAW frequency specifications are in the 0.1% range, each layer of the stack should be controlled in the same range. This accuracy is not reached by any deposition technique which is in the 1% range on a whole wafer. Therefore, a trimming step is mandatory to reach sufficient wafer yield. Providing tunability to BAW technology could save trimming steps and offer solutions like tunable or switchable RF filters. We report the realization and the radio-frequency characterization of a tunable strontium titanate electrostrictive Solidly Mounted Resonator [**A. Volatier, et al - Appl. Phys. Lett. 92, 032906 (2008)**]. For a 430 nm thick strontium titanate layer, the resonance frequency at 2.2 GHz can be switched on with a bias voltage of 2 V and tuned +/-0.85% with a bias voltage between 2 and 30 V. No hysteresis is observed. The resonator tunability is found to be affected by: i) the variation of coupling factor versus bias which is the dominant effect; ii) the variation of strontium titanate stiffness at constant electric displacement. From these results, the concept of a switchable Coupled Resonator Filter constituted by an electrostrictive layer acoustically coupled to a classical piezoelectric layer has been patented [**A. Volatier et al. – french patent FR2905207 (2008)**].

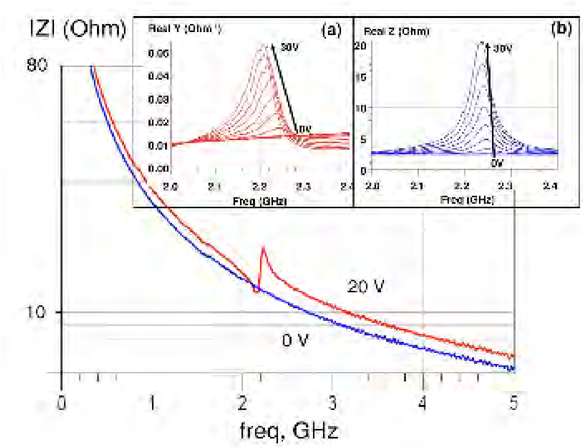


Figure 1: Impedance and admittance of strontium titanate Solidly Mounted Resonator vs. electrical bias.

2) For the first time, an in-plane Nano-Electro-Mechanical (NEM) resonator based on a Resonant Suspended Gate (RSG) MOSFET principle, and integrated in a Front-End process has been demonstrated. Advanced Silicon-On-Nothing (SON) technology based on industrial 8 inch tools is used to fabricate RSG-MOSFETs with high in-IC integration capabilities (figure 2).

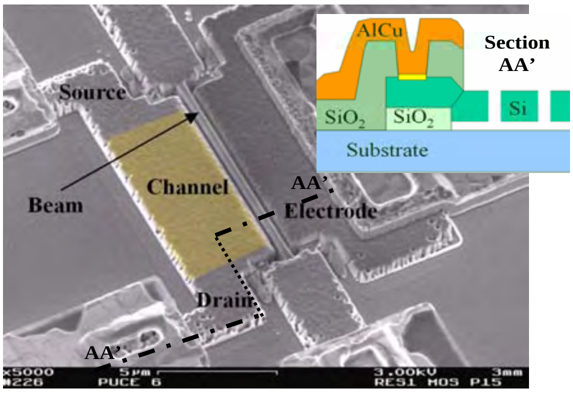


Figure 2: SEM picture of a C-C beam resonator, drive and sense electrodes. Inset shows a cross-section of the device.

Figure 3 shows the transmission curves measured with the same device at the resonance frequency. The fundamental resonance frequency was measured to be 14.33 MHz and 14.31 MHz with capacitive and MOS detection respectively in good agreement with analytical and FEM simulations. The extracted motional resistance R_m is 736 kΩ and the C_0 capacitance is 21.5 fF. The MOSFET detection yields a +4.3 dB signal amplification compared to the capacitive detection, due to the MOSFET intrinsic gain.

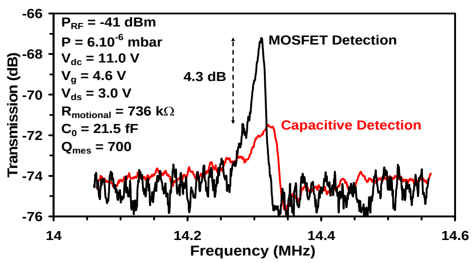


Figure 3: Capacitive and MOSFET detection comparison on the dynamic response of the NEMS (L=10µm, w=165nm, d=120nm)

[C. Durand et al. – Proc. IEEE MEMS 1016 (2008)]

Acknowledgments – Collaborations

E. Defaÿ, M. Aïd, E. Ollier, F. Casset, Ph. Robert: CEA-LETI, Grenoble – P. Ancey: STMicroelectronics, Crolles.

II.2-5 THz BioMEMS for proteomic and cell investigations

Permanent Staff: N.E. Bourzgui, C. Vanoverschelde, B. Bocquet
Non Permanent Staff: V. Mille, A. Treizebré, A. Abbas

Objectives

The study of biological molecular interactions is one of the understanding key of systemic biology. This last one broadens the field of molecular biology to the study of molecular assemblies where cell membrane activity is a well example. The field of non-ionizing electromagnetic radiation contributes as investigation means. The THz range appears more and more interesting allowing free-label investigations on living matter. We have demonstrated that THz measurements on aqueous solutions are possible by using original BioMEMS.

Outstanding results

1) Context

The optical domain is currently used in biological characterization but it requires fluorescent tags. They can modify biomolecular interactions. Microwave or radiofrequency spectra give us global information and suffer lake of spatial resolution. The intermediate frequencies between these two domains, called THz gap, are still little used. Its principle interest lies in the THz photon energy which is at the same level of low binding energy inside biomolecules. We can so probe directly the protein interactions by analyzing the conformation changes. First analyses are carried out on lyophilized samples but biologists are interested in non-invasive and free-label observations on liquid phases. The strong absorption of T-rays in aqueous solutions requires working on small volumes as microfluidic circuits.

2) THz probes with Planar Goubau Line (PGL)

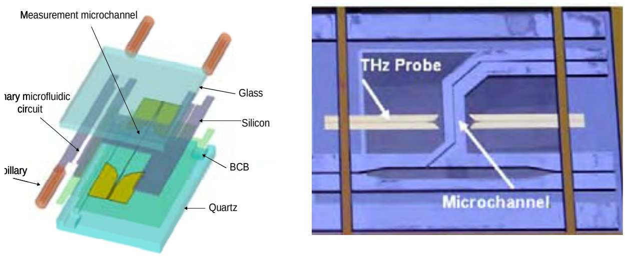
We have demonstrated that THz propagation is possible on a planar metal wire put down a dielectric substrate. The propagation mode is the same as a Goubau mode. A strong difficulty lies in the excitation of this mode. We have designed a coplanar–PGL transition for transferring THz signals generated by the measurement systems (VNA or electro-optic bench) to the BioMEMS [**A. Treizebre et al, IEEE MWCL, Vol.15, n°12, pp.886- 888, 2005**]. More recently, we have improved this transition in terms of large bandwidth, low losses and high efficiency close to 75%.

3) Nanometer PGL

The challenge is to probe a part of the cell membrane. Molecular assemblies occur during a biochemical event with a size around 1 µm. Note that this spatial resolution is quite different from the THz wavelength. We have solved this problem by using nanometre wires. For example, a wire of 100nm width gives us a spot of 2.2µm [**A. Treizebré et al., Int. J. Nanotechnology, Vol.5, n°6/7/8, 784, 2008**].

4) Technological realization

The compatibility between THz propagation and microfluidic circulation requires a mixed technology based on quartz, silicon and polymer. We have fabricated a BioMEMS which includes microfluidic circuit and THz probe as described on the figure 2. A first microchannel is dedicated to the supply of biochemical product while a derivative microchannel of 50µm width is used for the cell immobilization and the measurements.



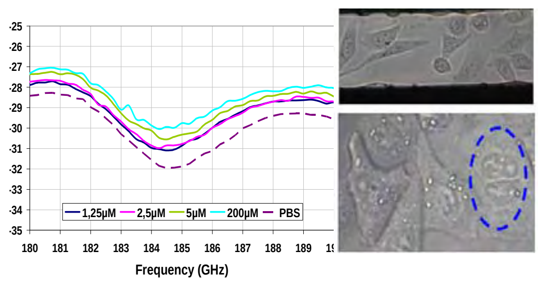
(a) (b)

Figure 1: (a) Scheme of the BioMEMS (b) THz BioMEMS realized in a mixed technology

5) Cell growth and measurements

A first step concerns all proteins which take place in the cellular communication because no database exists at these frequencies. A first very interesting result is shown on the figure 3a for the lactoferrin. We obtain a very good discrimination of low concentration solutions at the µM level (65µg/ml). A first explanation could be that lactoferrin trap a metallic molecule.

Measurements on cells will follow. We have demonstrated recently that CHO cells growth inside the measurement channel (Fig.3b).



(a) (b)

Figure 2: (a) Measurements on lactoferrin in 180 to 190 GHz frequency range and (b) cell growth and division inside a microchannel of 50µm width

Acknowledgments – Collaborations

D. Legrand & J. Mazurier (UGSF, UMR CNRS 8576), E. Leclerc (Univ. Compiègne, UMR CNRS 6600), C. Slomianny (LPC, EMI INSERM 0228)

II.2-6 Unpackaged thermal microsensors

Permanent Staff: P. Godts , D. Leclercq, K. Ziouche
Non Permanent Staff: M. AitHammouda , M. Haffa

Objectives

Heat flux measurements may induce many applications like infrared contactless temperature measurement, detection of human presence or real-time recording of the enthalpy flow associated with the phase changes.

However heat flux measurements are far from widespread in consumer applications because no low-cost sensors exist. This is why we conceived package-free microsensors entirely realised using silicon technology and based on patented original concept.

In this aim, we took again the physical problem at the base and imagined a silicon compatible structure patterned with thermal surface discontinuities. An e.m.f. proportional to the measured flux is generated by a planar periodic thermopile.

A most important feature of this paradigm is the possibility to produce sensors of various shapes and areas that lead to develop versatile thermoelectric microgenerators.

Outstanding results

Entirely developed at I.E.M.N., these new heat flux microsensors are constituted of several hundreds of doped polysilicium microthermocouples laid out on the substrate in which porous silicon boxes were initially processed (Fig. 1) [**K. Ziouche et al, European Patent N° 05370028.2, (2005)**]. Since no packaging is necessary, the sensor area can be dimensioned according to the expected responsivity required by applications (typically 3x3 mm² to 10x10mm²).

A mathematical model has been established and validated in order to optimise the principal characteristics versus dimensions of micro-thermocouples and porous silicon boxes [**M. AitHamouda, Thesis (2007)**].

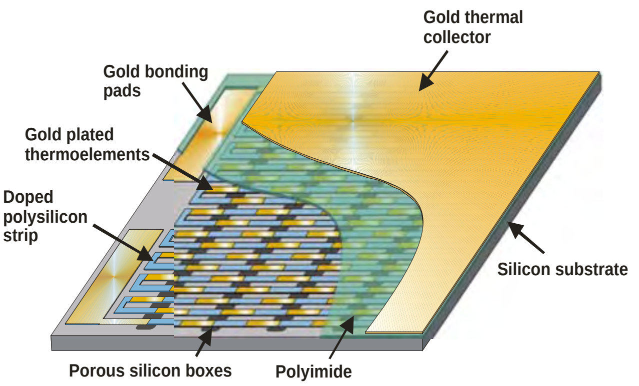


Figure 1: Cut-away view of a heat flux microsensor

These very robust quasi-monolithic planar microsensors sensors can be used as well in scientific equipment as in consumer applications. The very high responsivity (0.15V/W for a 5x5 mm² sensor) makes possible measurements of very tiny power such as evaporation enthalpy flow of water droplets. Due to their large versatility, various innovative measurement methods were carried out and corresponding devices were developed such as contactless temperature measurement in dirty environment, water detection through a metallic wall, characterisation of *ultrasonic transducers...*

Infrared microsensors arrays are also package-free thanks to an original thermally balanced design of each pixel (Fig. 2) [**M. Boutchich et al, Sens. Actuators, A Phys., 121, 1 (2005), 52-58**]. Infrared absorbent (polyimide) and reflecting (gold) rectangular areas were deposited on the top of each pixel to generate temperature gradients. Each detector was a thermopile build up by a series of 300 polysilicon/gold microthermocouples suspended on independent stress-compensated SiO2/Si3N4 membranes.

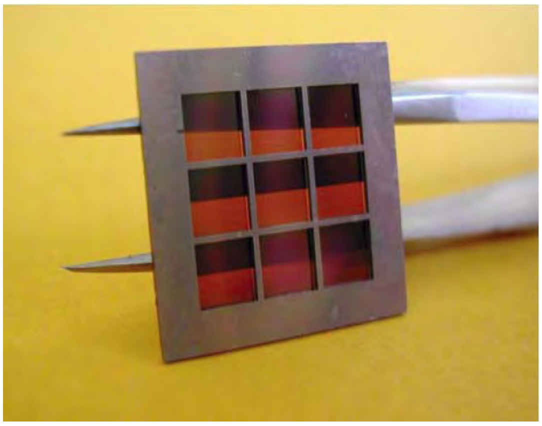


Figure 2: 3x3 pixels infrared array (back side)

The IR detection mapping results from the Seebeck e.m.f. delivered by the individual thermopiles. Wide dimensions (10x10 mm²) and low resolution (9 to 25 pixels) arrays were achieved [**M. Haffar et al, SENSOR 2007, Nürnberg, May 22-24, (2007), 217-222**]. Associated to a very low cost Fresnel lens, they permit to realise an IR camera dedicated for instance to remote monitoring or house automation. The specific detectivity (D*= 2 10^{7} cm.$Hz^{1/2}$.W^{-1}) for a 3x3mm² pixel is suitable for consumer applications. The most advantage of these sensors is the ability to detect even motionless person unlike pyroelectric arrays.

Acknowledgments – Collaborations

Most of these works were supported by “OSEO-ANVAR” and “Région Nord-Pas-de-Calais

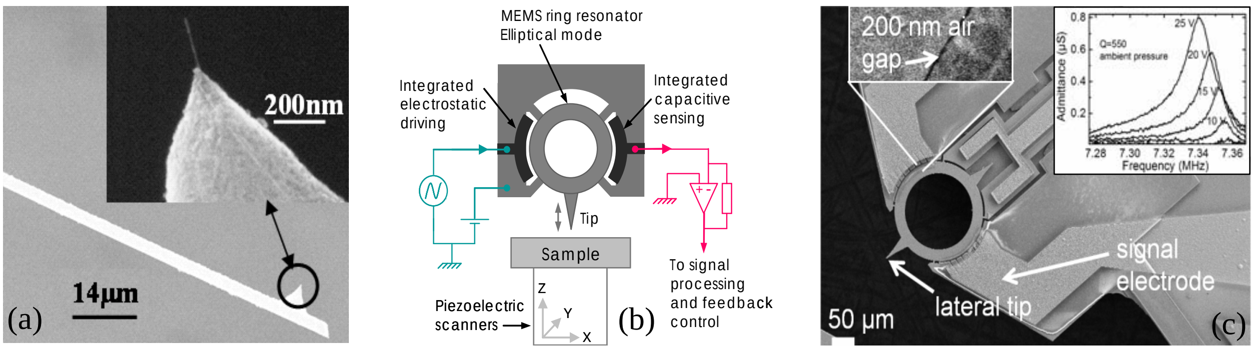
II.2-7 Vibrating Micro and Nanosystems for Atomic Force Microscopy

Permanent Staff: L. Buchaillot, M. Faucher, B. Legrand
Non Permanent Staff: E. Algré, A.-S. Rollier, B. Walter

Objectives

Atomic Force Microscopy (AFM) is of major interest in the field of life sciences and biochemistry. It is foreseen to give access to real time observation of biological and biochemical nanosystems, which could open new horizons in the understanding of fundamental mechanisms involved for example in cellular biology. However the performances of conventional AFM probes are strongly degraded once placed in a liquid due to the mass of liquid put into motion by the vibrating cantilever. Much effort is currently devoted at the international level to overcome this limitation. In this context, we work on the integration of MEMS and NEMS technologies in the AFM probes. In particular we work on the integration of the actuation and detection, on the grafting of carbon nanotubes (CNT) at the tip apex and on the use of bulk mode MEMS resonators as a new generation of AFM probes.

Outstanding results



(a) SEM image of a AFM cantilever with a CNT grafted at the tip apex. (b) Schematic of the concept of an AFM probe based on a MEMS resonator with integrated actuation and detection. (c) SEM image of a prototype of a AFM probe based on a MEMS ring resonator. Inset: resonator frequency response in air.

1) Cantilevers with an integrated actuation

We obtained results concerning the use of integrated electrostatic and piezoelectric actuators with an AFM cantilever. We demonstrated that electrostatic actuation is feasible in liquids at the microscale both in static and dynamic modes ***[B. Legrand et al., Appl. Phys. Lett., vol 88, 034105, 2006]***. On the other hand, the PZT piezoelectric material has also been used in thin films to successfully drive the vibration of the cantilever in air and in liquids. An analytical modelling have been developed to predict the resonance frequency and quality factor of the cantilever in liquids, taking into account the hydrodynamic and squeezing effects ***[A.-S. Rollier et al., Proceedings of DTIP 2006, 244, 2006]***.

2) Carbon nanotube AFM tips

CNT have been successfully grafted on micromachined silicon nanotips as shown in Fig. (a), with an outstanding yield of 60 %. CNT growth is based on the HFCVD technique and has been made by A.-M. Bonnot from LEPES in Grenoble. AFM images at the nanoscale with an enhanced lateral resolution have been obtained using such CNT nanotips on microcantilevers, in collaboration with the CPMOH in Bordeaux ***[A.-S. Rollier et al., Proceedings of IEEE MEMS 2007, 851]***.

3) MEMS and NEMS resonators for GHz AFM probes. By taking advantage of the 7-year expertise of IEMN in the field of MEMS resonators in the range 1MHz-1GHz, we propose a very innovative approach to overcome the current limitations of the AFM probes. The concept is presented in Fig. (b). It aims at introducing MEMS bulk mode resonators as AFM probes. Main features are: ability to reach resonance frequencies of the AFM probes up to the GHz, minimization of the hydrodynamic effects, and easy integration of actuation and detection based on the capacitive effect.
Overall performances in terms of force sensitivity and time resolution are expected to be 2 to 3 orders of magnitude above those of current commercial AFM probes, and the concept of the probe has been patented ***[M. Faucher et al., French patent 0703161, 2007]***. A prototype of the probe has been fabricated and characterized in air and with the tip immerged in a liquid (see Fig. (c)) ***[M. Faucher et al., Proceeding of IEEE Transducers 2007, 2267]***.

Acknowledgments – Collaborations

Some parts of this work have been carried in collaboration with the LEPES in Grenoble and the CPMOH in Bordeaux. From 2008, this research activity is supported by an ANR project and has also been granted by the European Research Council in the frame of the “Starting Grants” program.

II.3 Nano/Micro & Opto-Electronics

Introduction

The research activities of this task concerns advanced devices in the fields of the micro and Nano-electronics, Optoelectronics and Photonics. Up to now, the technological limitations are not completely achieved in terms of dimension, materials, device architectures and co-integration. Moreover, this domain of research is going to change while electronics, photonics and Electromagnetism sciences are going together to create new advancements. Conventional top-down technological approach is continuing to reach nanometer dimensions, but bottom-up ones is also investigate by using 1D-electronics materials.
These works are strongly oriented to the medium and long term and are in agreement with the national and international strategic and economic criteria. Indeed, whole of these research activities are supported by the national research networks (ANR, DGA) and by the European research frameworks (FP6, FP7, ESA, MOD…). The striking results described after this introduction are scheduled from the micro/nano electronics to photonics via the THz domain. Let us introduce the context for each topic of this domain.
- **Micro and nano-electronics**: the main objectives concern the fabrication of advanced nano-electronic devices, and the improvement of the frequency limitations toward THz in the field of low noise and low power consumption (detection, amplification…), power (generation, amplification…) and high speed digital applications. The studies concern the optimization of the technological processes, the physical and electrical (DC and high frequency) simulations and characterizations

High power electronics: the activity concerns wide bandgap semiconductors such as gallium nitride and more innovative materials (BN and diamond). The goal is the fabrication of power chips and power amplifiers for military and telecommunication applications. State of the art performance was obtained for devices on Si(111) substrates at 18GHz with a microwave power density of 5.1W/mm associated to a PAE of 18% and a power gain of 9dB.

Low power consumption electronics: we develop devices based on new materials system or new architectures like double gate HEMTs, ballistics devices and plasma wave transistors. State-of-the-art results on microwave properties of carbon nanotubes based transistors have been also obtained. For instance, we obtained an intrinsic current gain cutoff frequency of 30 GHz establishing state-of-the-art high frequency potentialities of CNTFETs.

Non conventional nanometre-scale MOSFETs: Thanks to technological facilities and associated expertise, we study and fabricate alternative MOS architectures to overcome roadblocks associated to the ITRS end-of-roadmap. The present research theme focuses on the design and the fabrication of metallic Schottky source/drain (S/D) MOSFETs, the design of a new FinFET architecture and the study of impact-ionization MOSFET (I-MOS) to overcome the subthreshold slope limitation of MOSFETs (60mV/dec). The microwave properties of aggressively scaled Schottky S/D MOSFETs are also analysed by complementatry modelling and experimental approaches.

Metamaterial: At the boundaries of electronics, electromagnetism and photonics, this activity is strengthened and significant results was obtained since the last four years. This topic tends to address crucial breakthroughs like the demonstration of negative refraction at microwave frequencies, a novel approach for cloaking at Terahertz frequencies or still the experimental verification of focusing by a Photonic crystal. In this last aspect, outstanding results were achieved experimentally and theoretically in the field of left-handed electromagnetism.
- Optoelectronics and photonics: this thematic includes generation and detection of terahertz (THz) signals for spectroscopy, imagery, and telecommunications is investigated along an optoelectronic approach by combining laser sources and ultra-fast optoelectronic devices.

Optoelectronics: Microwave photonics affords new potentialities in the optical processing of microwave signals. We applied it mainly to the optical beam forming of wide instantaneous bandwidth phased array antennas. Specific devices have been so studied and fabricated; as high speed optical switching matrices and detectors.

Nanophotonics: using III-V semiconductor material line allows the mixing of passive and active functionalities. We capitalize on the compactness and the high optical confinement of these circuits i) to decrease surface areas requested for passive integrated optics circuits, ii) to decrease interaction volume required for electro-optic functions and iii) to increase non-linear effects.
- Modelling: besides of all these experimental topics, this activity is to develop physical models and to implement them in simulation tools. All important aspects of micro and nanoelectronics have been considered: technological fabrication processes, physical mechanisms of device operation and performance of devices and circuits. A wide variety of devices have been studied: field effect transistors, ferroelectric memories, semiconductor lasers.

II.3-1 Wide Bandgap Devices for Microwave Power Amplification and Detection

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Non Permanent Staff : H. Barkad, M. Benali, B. Benbakhti, S. Boulay, F. Carosella, A. Curutchet, N. Defrance, M. Elkhou, J.C. Gerbedoen, M. Mattalah, A. Minko, V. Raballand, X. Tang, S. Touati, N. Thouvenin, M. Werquin

Objectives

This task consists to develop devices based on wide bandgap semiconductors mainly for microwave power applications. It is based on physical simulation, technological processing, electrical and microwave measurement and power performance determination. During the last four years, the activity was based on wide bandgap semiconductors such as gallium nitride and more innovative materials (BN and diamond). The goal is the fabrication of power chips and power amplifiers for military and telecommunication applications. A large part of the activity was developed in the frame of TIGER, a common laboratory between THALES III-V LAB and IEMN. It is a research field very competitive, studied since several years by the most famous laboratories all around the world in USA, Europe and Japan. The second topic regards X-UV photodetectors for solar observation missions.

Outstanding results

1) Physical-thermal simulation

In order to study the physical behaviour and the determination of the temperature in devices, a physical-thermal model was developed. This model is shared in two parts: a 2D energy-balance physical model describing the electrons transport in the active area of the device and a thermal model determining the lattice temperature in the device (active area and substrate). It is based on the resolution of the heat equation.

The model was used to simulate TLM structures in order to analyze the saturation phenomenon of the current. It is shown that only the determination of the temperature in any point of the device, conditioning the dependence of the electrons velocity according to this temperature, permits to understand the experimental observations. A good agreement is observed between experimental I(V) characteristics and the temperature determination by Micro-Raman and the theoretical predictions. [***B. Benbakhti et al, IEEE-ED, 53, (9), 2237-2242 (2006)***].

2) AlGaN/GaN HEMTs

AlGaN/GaN HEMTs were fabricated and measured for power applications. The activity is performed on epitaxies grown by MOCVD or MBE on different substrates such as SiC and Si(111) or advanced possibilities such as Si(001) or reported substrates. State of the art performance was obtained for devices on Si(111) substrates at 18GHz with a microwave power density of 5.1W/mm associated to a PAE of 18% and a power gain of 9dB (Fig.1). **[*D. Ducatteau et al, IEEE-EDL, 27, (9), 7-9 (2006)*].**

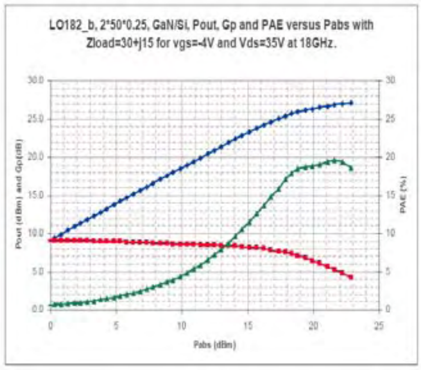

Fig.1: Power performance of AlGaN/GaN device on Si(111) substrate

In order to increase the breakdown voltage, field plate (FP) transistors were studied. Two configurations are possible: a FP based on additional electrode (Fig.2) and a topology based on a Γ shape.

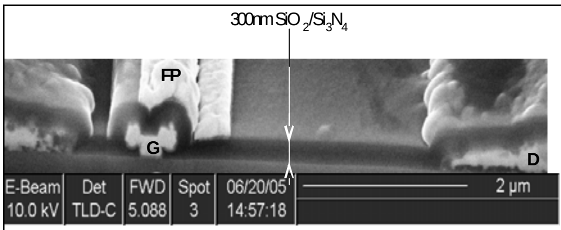

Fig.2: Field plate transistor

Both topology optimizations were carried out by means of a 2D-Energy-Balance model and permit to determine the best compromise between the breakdown behavior and the microwave capabilities. At 10GHz, for a FP HEMT on SiC substrate a maximum output power density of 10.4W/mm is obtained with a PAE of 39% and a power gain of 13dB.

The first results obtained from AlGaN/GaN HEMTs devices on MBE and MOCVD epitaxial structures grown on "composite" substrates were obtained. These substrates are based on innovative structures in which a thin top single crystal layer Si <111> (SopSiC) or SiC (SiCopSiC) is transferred onto a thick polycrystalline SiC wafer with a thin SiO_2 intermediary insulating layer. The fabrication of the transistors is based on a process flow closed to those of devices on Si or SiC substrates. In a first step, the device processing was based on optical lithography to demonstrate the device feasibility and in a second step e-beam lithography was performed (0.25µm gate length). Pulse measurements were carried out in order to study the trapping effects. The results obtained on 0.25µm gate length devices show a good behavior. Power measurement performed on 2µm gate length transistors permitted to demonstrate the first results obtained on these new devices. At the bias point V_{DS}=25V and V_{GS}=-2.5V, under class A operation, an output power of 23.6dBm is obtained corresponding to a power density of 1.15W/mm. The maximum PAE is 28% and the linear gain is about 11dB. The results show the capabilities of such composite devices, providing HEMT devices for microwave power applications. **[*V. Hoel et al, EL, 44, (3), 238-239 (2008)*]**.

In order to improve the frequency device performance, a technology based on Ge spacer gate was developed. It is associated to the Γ shape nitride gate technology. permitting to decrease the parasitic capacitances. Device fabrication is similar to the process commonly used. The difference takes place on the gate processing where a gate recess is associated to the SiN gate technology. The gate foot is recessed by digital etching followed by annealing to repair damage due to the etching. A 40nm thick germanium sacrificial layer is then deposited by evaporation on the SiN layer and removed by a wet chemical etching solution based on H_2O_2 after the Γ gate realization. Thus, the gate obtained is unstuck from the SiN layer (fig.3). Gate metallization used is based on evaporated Pt/Ti/Pt/Au.

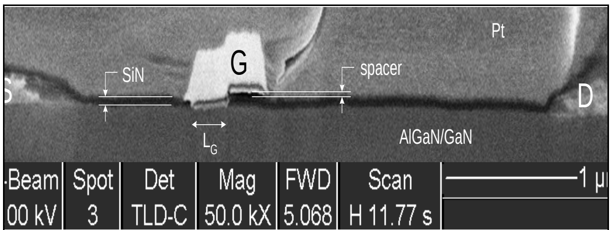

Fig.3: SEM image of the cross section of Ge spacer gate based on SiN technology

Good results were obtained for devices on Si(001) substrate interesting for the fabrication of low cost devices because it is widely used in the silicon mainstream technology and it permits the fabrication of mixed integrated circuits. **[*S. Boulay et al, IEEE-ED, 54, (11), 2843-2848 (2007)*]**. At the bias point V_{DS}=30V and V_{GS}=-2V corresponding to class A operation, an output power density of 2.9W/mm associated to a maximum Power Added Efficiency (PAE) of 20% and a linear gain of about 7dB is obtained.

3) Photodetectors based on wide bandgap semiconductors

Solar-blind deep-ultraviolet (DUV) photodetectors operating at high temperature and in harsh environments were fabricated from various wide band gap semiconductors such as Al(Ga)N,BN and diamond. Deep-ultraviolet solar-blind photodetectors based on high-quality cubic boron nitride (*c*BN) films with a metal/semiconductor/metal (MSM) configuration were fabricated. The design of interdigitated circular electrodes (Fig.4) enables high homogeneity of electric field between pads.

The DUV photodetectors present a peak responsivity at 180 nm with a very sharp cutoff wavelength at 193 nm and a visible rejection ratio (180 versus 250 nm) of more than four orders of magnitude. The characteristics of the photodetectors present extremely low dark current, high breakdown voltage, and high responsivity, suggesting that *c*BN films are very promising for DUV sensing. **[*A. Soltani et al, APL, 92, 053501, (2008)*]**.

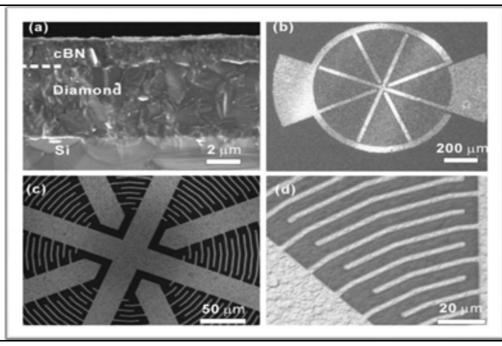

Fig.4: SEM cross-sectional morphology of the cBN/diamond composite film and image of a 1 mm diam. cBN photodetector.

In the VUV wavelength range of interest, the diamond photodetector is sensitive with a maximum response of 48 mAW^{-1} at 210 nm with a corresponding external quantum efficiency of 42%, homogenous and stable under short irradiation. It indicates a rejection ratio between 200 and 400nm of more than four orders of magnitude. AlN MSM devices are sensitive and stable underbrief VUV irradiation. They show a rejection ratio between 200 and 360nm of more than four orders of magnitude and demonstrates the advantages of wide band gap material based detectors in terms of high rejection ratio and high output signal for VUV solar observation missions.

4) Traps analysis in wide bandgap semiconductors

Different measurement methods such as photoluminescence, pulsed I(V) versus temperature, photoionization, time domain measurements using a large signal network analyzer (LSNA) and admittance determination were used to characterize the traps behavior in HEMTs (at the interface Schottky contact/AlGaN) and photodetectors (at the surface of the widegap semiconductor). This study permits to get an understanding of the physical mechanisms and to improve the technological process and the device epitaxy. A model on the photoluminescence procedure was carried out to study free surfaces. It is shown that the minimum trap density is $1.3x10^{10}$ $cm^{-2}eV^{-1}$ on a hBN/InP MISFET device. **[*M. Mattalah et al, Thin Solid Films, 23997, (2007)*]**.

Acknowledgments – Collaborations

This task is supported by french MOD (DGA KORRIGAN), the research ministry (ANR: TRANSNIT and CARDYNAL, RNRT : ANDRO), the European Community (IST : HYPHEN, ULTRAGAN, REX : TARGET). The main collaborations are THALES (III-Vlab, TRT, TAS, TAD), UMS, PICOGIGA, IRCOM, CRHEA, QINETIQ, IEF, CEA, GORGIA-TECH, LMOPS, IMO, ROB, IMS, INL.

II.3-2 Advanced millimeter- and submillimiter- waves III-V devices

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Objectives
Objective of this activity is to develop high frequency devices for integrated circuits working at mm-wave and sub-mm-wave frequencies. Applications are oriented low power consumption and low noise. We develop devices based on new materials system or new concepts. During 2004-2007, we work on submicron HBT, Double gate HEMTs, ballistics devices and plasma wave transistors. Since 2006, we began an activity on new materials system, based on antimonide compounds.

Outstanding results
A new concept concerns study and fabrication of double gate HEMTs (DG-HEMT), based on transferred substrate technique. Gates in DG-HEMTs are placed on each side of the conductive channel. For these "alternative" devices, the reduction of short channel effect particularly restrictive for high working frequency in sub-100nm gate length HEMTs, is waited. Better charge control efficiency and no effect of carrier injection in the buffer (no buffer is used in this structure) should allow surpassing the performances of current HEMTs. We develop all the technological process on InAlAs/InGaAs materials. Figure 1 represents cross section of a 30nm InAlAs/InGaAs DG-HEMTs. This is the first III-V DG-HEMT using transferred substrate technique ever realized.

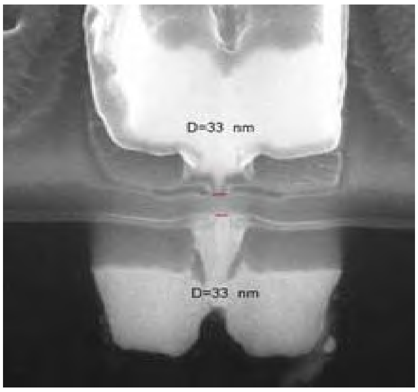

Figure 1 : 30nm gate length InAlAs/InGaAs DG-HEMT

In comparison with single gate HEMTs, a 30% improvement of maximum oscillation frequency is achieved in a single command DG-HEMT [**N. Wichmann et al, EDL 26, 9, pp.601, 2005**]. Double gate HEMT with double gate commands have also been realized (gate can be biased separately). Frequency performances are similar than single HEMTs. However double command offers the possibility to shift the threshold voltage, without any change in electrical performance and the technology is the same for the enhancement- and depletion-mode transistor. Moreover this technology will allow to develop a velocity modulation transistor, in which the current is modulated by velocity without carrier variation, leading to a strong reduction of the intrinsic gate capacitance. Technology is basically similar than the double-gate process, except for the channel, which consist on a high mobility and a low mobility channels. First VMT has been fabricated using InGaAs material for the high mobility channel. Lowering mobility in the other channel is achieved by a compensated doping. To confirm advantage of VMT, microwave three-ports device is on development.

During the same period, work has been made on TBJ (Three terminal Ballistic Junction) for rectifying applications, and current switching by the addition of a Schottky gate on a TBJ. Concept is based on ballistic transport of the carrier. Using InGaAs material, with mobility higher than 10 000cm²/Vs, a mean free path of 100nm is possible at room temperature. Defining topology with dimension lower than the mean free path, a quasi-ballistic transport can be achieved. Monte Carlo simulation predicts THz cutoff frequency. We develop a complete technological process with few hundred nanometers dimensions (figure 2), and 20 nanometers in resolution (alignment and dimension). Functionality (rectifying effect) up to 94GHz has been experimentally observed at room temperature [**S. Bollaert et al, Thin Solid Films, 515, 10 (2007) 4321**]. However, cutoff frequency of this nano device is limited to few hundred GHz. Indeed frequency performance is limited by the high impedance level of these nanometer devices (few kΩ) associated with the parasitic capacitance.

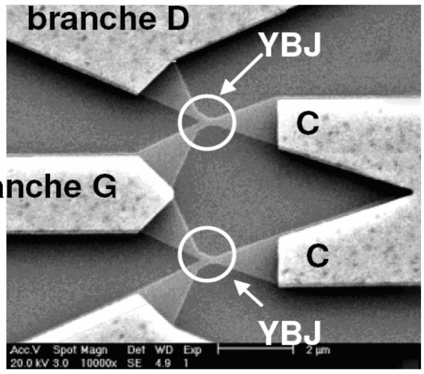

Figure 2 : T-Branch Junction TBJ

The SHBT is a device of choice for very high speed electronics. It has the world record of cut off frequency. At IEMN we have developed an aggressive technological lateral scaling to reach deep submicron device. Figure 3 represents 0,25-µm device and its Ft is 400 GHz. The Double HBT InP/GaAsSb/InP is more interesting thanks to the high breakdown voltage. The recent optimisation of the InP/GaAsSb E-B junction by the incorporation of Al in the emitter (giving AlInP) has permitted to improve drastically the current gain useful for future high frequency performances [**E. Mairiaux et al., IPRM 2008**].

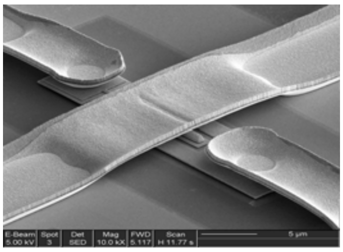

Figure 3 : 0,25 µm Heterojunction Bipolar Transistor on InP

Since 2006, we began an activity on antimonide based devices. Our preliminary results were on AlSb/InAs HEMTs with gate length of 100nm (figure 4), with a best f_T of 200GHz **[S. Bollaert et al, CICL, EuMIC 07]**. Electron mobility in this material is higher than 20 000cm²/Vs. Thus, frequency performances are still high even at very low V_{ds} of few hundred mV. At 200mV, cutoff frequency is kept at 150GHz. Main objective of this new material system should be the reduction of power consumption for autonomous system as sensors network. Indeed huge mobility obtained in antimonide system is attractive at low voltage drain.

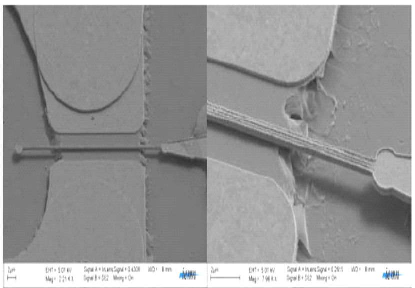

Figure 4 : AlSb/InAs HEMT with 100nm air-bridge gate

Plasma wave in two-dimensional electron gas (2DEG) in a nanometer size high electron mobility transistor (HEMT) were proposed by Dyakonov and Shur as a new way to realize THz emitters or detectors. Plasma wave are oscillations of electron density in time and space. In gated 2DEG of a FET, dispersion relation of plasma wave is linear and given by this expression:

$$w = sk \text{ with } s = \sqrt{q^2 n_s d / m^* \varepsilon} \quad (1)$$

where s is the plasma wave velocity. Plasma wave velocity is 10 times higher than the electron drift velocity. Thus, in submicron gate length, THz frequency can be reached. By adjusting the applied gate voltage, sheet carrier density can be fixed, allowing the tune of the detection or emission of electromagnetic radiation in the THz range. In a FET, the channel acts as a resonant cavity for the plasma wave. Quality factor of the cavity is an important parameter for resonant detection or for emission. Quality factor depends on the collisions time of electron in the cavity. To obtain high quality factor, ballistic or quasi-ballistic regimes is necessary. The condition of emission or resonant detection is given by this expression:

$$w\tau >> 1 \quad (2)$$

where w is the angular frequency and τ the momentum relaxation time. This expression means that electron scattering has to be reduced during the propagation of the plasma wave along the FET channel. Indeed scattering will damp the plasma wave. Therefore, high mobility materials will be suitable for resonant detection or emission. III-V materials are good candidate for this purpose. We develop works on InAlAs/InGaAs and also on AlGaN/GaN HEMTs. We have two materials systems: one with a high mobility (InGaAs i.e. low effective mass) and one with a large sheet carrier density (GaN). Mobility difference in these material systems is related to the effective mass (momentum relaxation τ almost similar). First THz emission has been observed at 4K on a 60 nm gate length InAlAs/InGaAs HEMTs realized at IEMN [**W. Knap et al, APL 84, 13, p2331, 2004**]. Since 2004, we develop a dedicated technology, in which we try to improve the condition of emission by insertion of MIM capacitance according to the theory of Dyakonov. This advanced device should allow the tuning of the emission frequency. No clear observation of tuned emission has been yet demonstrated. The physical origin of emission could have several explanations: emission due to the access region of the transistor (deep water, no gate) or other instability (Gunn effect?). For detection, the situation is clearer. Resonant detection at 2.5THz in 50nm gate length InAlAs/InGaAs has been observed up to 80K, in photovoltaic mode [**A. El Fatimy et al., APL 89, 131926 2006**], when no drain current was applied. By adjusting the drain current, it is possible to increase the quality factor of the cavity. Thus in the same device, resonant detection at 600GHz occurs at room temperature, if a drain current is applied, meaning that the device is close to instability **[F. Teppe et al., APL 89, 222109 2006**]. In photovoltaic mode, responsivity is 1V/W at 2.5THz with a NEP of 10^{-9}W/Hz$^{0.5}$. Recently, tunable resonant detection of an optical beating by plasma wave in our HEMT has been observed at room temperature [**J. Torres et al., APL, Vol. 89, 2006**]. So our transistor can act as a mixer-detector for THz signal. The same works are undergoing on wide band gap devices. THz emission on AlGaN/GaN field effect transistors at room temperature on SiC substrate have been demonstrated **[N. Dyakonova et al., APL 88, 141906 2006**]. Detection of subterahertz and terahertz radiation by HEMT AlGaN/GaN transistors in the 0.2–2.5 THz frequency range has been also reported. These experiments were performed in the temperature range 4–300 K. For the lowest temperatures, a resonant response was observed. The resonances were interpreted as plasma wave excitations in gated two-dimensional electron gas. Non-resonant detection was observed at temperatures above 100 K. The estimated noise equivalent power show that these transistors can be used as efficient detectors of terahertz radiation at cryogenic and room temperatures. [**A. El Fatimy et al, El, Vol. 42, 2006**].

Acknowledgments – Collaborations

Authors wish to thank colleagues from University of Salamanca, University Catholic of Louvain, University of Chalmers. These works have been partly supported by IRCICA, European Community (FET OPEN Nanotera). Plasma wave task was supported by the research ministry (ANR Teragan, ACI Teratop). We wish to thank GES group from University of Montpellier, for THz mmeasurements.

II.3-3 Carbon based nano electronics for high frequency applications

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Non Permanent Staff: J.-M. Bethoux, A. Le Louarn, L. Nougaret.

Objectives

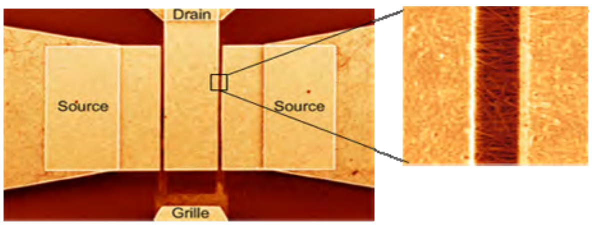
Carbon nanotubes (CNTs) exhibit a number of remarkable electronic and mechanical properties that make them most attractive for micro and nanoelectronic applications. Using a semiconducting single-walled nanotube (SWNT) to model the channel of a field-effect transistor (FET), a recent theoretical study predicted that this device family may be faster than conventional field-effect devices and suitable for high-frequency (HF) operation. Experimental verification, however, remains very challenging. This is one of our objectives in this research field.

Outstanding results

In this work [***J.M. Bethoux and al. - IEEE Trans on Nanotech, Vol. 5, No. 4, 335, (2006)***], we report measurements on CNT-FETs consisting of a small network of typically 10–50 single-wall carbon nanotubes (SWNTs) assembled thanks to nanolithography and self-assembling deposition via silica surface treatment. Two port S parameters of CNT-FETs are measured with a standard HF on-wafer station. As compared to similar works, we have extracted for a first time an electrical HF model of CNT-FETs.

The frequency limitation (0.8 GHz) has been attributed to the high input parasitic (capacitances, resistances). Consequently, much higher HF performances are clearly at hand by optimizing contact resistances and parasitic capacitances. The parallel layout of CNTs has been demonstrated to be an efficient way to probe HF properties via standard VNA measurement.

Based on this result, the new appropriate device structure has been developed in the first time to lower input parasitic such as gate resistance, source to gate and gate to drain capacitances.



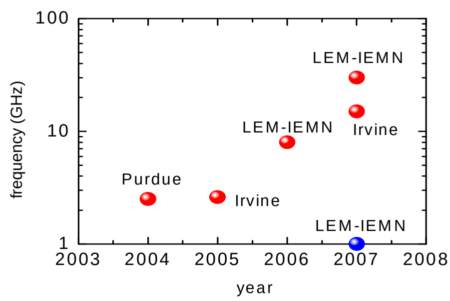
Scanning electron microscopy _SEM_ images of the two-finger back-gate CNTFET active region

The CNFETs fabricated, although based on a random network of CNs, allowed us to achieve, [***J.M. Bethoux and al. - IEEE Electr Dev Lett, Vol. 27, No. 8, 681, (2006)***], the state of the art in term of current gain cutoff frequency of 8 GHz, and the MSG of 10 dB at 1 GHz, after full de-embedding. Noticeably, these performances are still dominated by parasitic elements.

So by improving deposition technique, the CNTs density has been strongly improve, while keeping the parasitic capacitances to an almost unaffected level. We obtained an intrinsic current gain cutoff frequency of 30 GHz establishing new state-of-the-art high frequency potentialities of CNTFETs [***A. Le Louarn and al., Appl. Phys. Lett. 90, 233108 (2007)***].

The device showed a maximum stable gain above 10 dB at 20 GHz. The parameters of an equivalent circuit model of multi-tubes CNTFET at 20 GHz are determined, which open the route to the modeling of nanotubes-based high frequency electronics.

This process has been also transferred with success on flexible substrate [***N. Chimot and al., Appl. Phys. Lett. 91, 153111 (2007)***]. The demonstrated performances show that CNT devices are very promising candidates for low cost, high flexibility, and HF electronic applications on flexible supports.



State of the art in term of current-gain cut-off frequency
Red: Rigid substrate
Blue: Flexible substrate

Transistor on flexible substrate

Acknowledgments – Collaborations

This work is supported by the French ANR under Contract No. ANR-2005-055 HFCNT. Authors wish to thank colleagues of LEM-CEA Orsay (J.P. Bourgoin group), LPA – ENS (C. Gattli group), IEF Orsay: (P. Dolfus group).

II.3-4 Non conventional nanometre-scale MOSFETs architectures

Permanent Staff: E. Dubois, G. Larrieu**.**
Non Permanent Staff : N. Breil, C. Charbuillet, F. Fruleux, X.L Han, A. Lecestre, J. Penaud, F. Ravaux, D. Yarekha.

Objectives
Projections of the international technology roadmap for semiconductors (ITRS'07) indicate that many architectural and technological roadblocks must be solved in order to pursue downscaling of CMOS technologies towards 10 nm gate long devices. To contribute to this quest, the present research theme focuses on three major directions: i) the design and the fabrication of metallic Schottky source/drain (S/D) MOSFETs, ii) the design of a new FinFET architecture that considerably relaxes processing constraints due to its highly three-dimensional topology and iii) the study of impact-ionization MOSFET (I-MOS) to overcome the fundamental *'kT/q'* thermodynamic barrier that limit the subthreshold slope of MOSFETs above 60mV/dec**.**

Outstanding results
1) Metallic Schottky source/drain MOSFETs
Over the last decade, the development of metallic source/drain (S/D) has emerged as a potential performance booster because of the increasing impact of S/D resistance on transistor performance, especially in the case of ultra-thin SOI and multiple-gate thin body MOSFETs. The implementation of a dopant segregated band-edge silicide using the so-called implantation-to-silicide (ITS) scheme and low temperature activation (500°C) has been demonstrated. A new state-of-the-art current drive performance has been established for SB-MOSFETs at 25 nm of gate length: Ion of 530 µA/µm at Vg=Vd=-1.1V. Fig.1 also demonstrates that metallic S/D competes with best unstrained channel SOI p-FET technologies. A record RF performance for a 30-nm p-type unstrained thin-film fully depleted SOI SB MOSFET has been demonstrated with a f_T of 180 GHz **[G. Larrieu, et al – IEDM Tech. Dig. 2007, IEEE Trans. Electron Dev. 52, 2720 (2005)]**.
Beyond device integration, a soft and scalable etching procedure that selectively eliminates Pt without altering PtSi has also been proposed to facilitate the integration and the scalability of PtSi on ultra-thin silicon layers. The selective etch is based on the low temperature transformation of the excess Pt into a more reactive PtxGey phase that is easily etched in a Sulfuric Peroxide Mixture (SPM). The mechanism of Pt_xGe_y alloying has been studied based on X-Ray Diffraction (XRD) analysis. The innocuousness of the germanidation-based selective etch on the integrity of the PtSi/Si junction is consolidated by Schottky barrier measurements. **[N. Breil, et al – IEEE Electron Dev. Lett. 29, 152 (2008)- Appl. Phys. Lett. 91, 232112 (2007)]**. This work was performed in the frame of the METAMOS European project (STReP)

2) Spacer-First Damascene-Gate FinFET Architecture featuring Stringer-free Integration
A new Damascene-gate FinFET process that inherently suppresses stringers resulting from gate and spacers patterning has been developed. The so-called spacer-first integration scheme relies on the engineering of a hydrogen silsesquioxane (HSQ) layer by electron beam lithography followed by two selective compartmentalized development steps to successively release the Damascene-gate cavity and the source/drain (S/D) contact regions. In contrast to the existing gate-first and gate-last integration approaches, the resulting FinFET process does not impose any restriction or interdependency on the sizing of the fins, gate, spacers and source/drain regions. A complete morphological and electrical validation has been proposed in the particular case of wrap-around self-aligned metallic Schottky S/D contacts. **[F.Cornu-Fruleux, et al - IEEE Electron Dev. Lett. 28, 523 (2007)].**

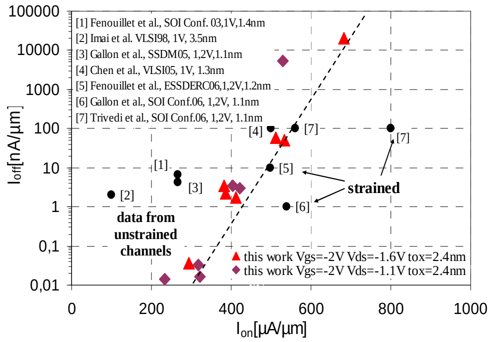


Fig. 1 : Ion-Ioff state-of-the art of S/D p-MOSFET on SOI substrate indicating that Boron DS p-MOSFETs is leading the SOA of both SB and conventional unstrained thin-film SOI technologies.

3) Ultra-High current drive in 30nm gate I-MOS
An I-MOS transistor with 30nm gate length has been fabricated. It presents the best characteristics ever reported for a MOS device: a low breakdown voltage (5.3V) and a low equivalent resistance (66Ω.µm). As the devices do not show any saturation, the very high drive current (up to 4680µA/µm) is only limited by the contact resistance. **[C. Charbuillet, et al – IEDM Tech. Dig. 2006].**

II.3-5 Advanced mm-wave Silicon devices

Permanent Staff: G. Dambrine, F. Danneville
Non Permanent Staff : G. Pailloncy, C. Pavageau, S. Pruvost, A. Siligaris, F. Gianeselo, B. Martineau, R. Valentin, B. Geynet, N. Waldhoff

Objectives

The aim of the activity is to study the high frequencies (HF) performances (current and power gain cut-off frequencies, respectively f_t and f_{max}, Minimum noise figure NF_{min}), HF properties (through extrinsic/intrinsic elements extraction) of advanced mm-wave Silicon devices, corresponding to mainstream CMOS/BiCMOS Technology as well as alternative architectures. Some linear, noise and nonlinear HF models are also developed and used to design elementary demonstrators (low noise amplifiers, mixers).

Outstanding results

1) HF Properties of SiGe HBTs, Si Bulk (at 78K), SOI and Schottky Barrier MOSFETs (at 300K)

The main small signal and HF noise characterizations are carried out at ambient temperature (300 K), nevertheless, for space communications and radio astronomy, there is a strong interest to study the properties of SiGeC HBT and Si MOSFETs at cryogenic temperatures (78K). For a 0.13 µm BiCMOS SiGeC technology, f_{max} of 292 GHz and NF_{min} of 1.5 dB (f = 40 GHz) have been reported. It was shown as well that a proper choice of dc collector current and device geometry lead to easier noise matching **[S. Pruvost et al, Elec. Dev. Lett., 26, 105 (2005)]**. 65 nm technology node n-MOSFETs was also investigated and, compared to ambient temperature, improvements of 34% on f_t (reaching 300 GHz) and 78% on f_{max} (reaching 335 GHz) were observed while a NF_{min} as low as 0.6 dB was measured at 40 GHz (1.5 dB at 300K). These outstanding HF performances were explained through an improvement of intrinsic transconductance but also a decrease of extrinsic source/drain (S/D) and gate resistances **[A. Siligaris et al, IEEE Tran. Elec. Elec. Dev., 53, 1902, (2006)]**.
In order to investigate the linearity properties of the SOI MOSFET technology, a large signal model intended to Partially Depleted devices, including the so-called kink effect (KE), was developed. It was in particularly shown that the KE degrades device intermodulation, acting as slow memory effect **[A. Siligaris et al, IEEE Tran. Elec. Elec. Dev., 52, 2809, (2005)]**.
The control of S/D contact resistances is a real challenge for up-coming 18 nm CMOS technology node, and Low Schottky Barrier (LSB) S/D architecture MOSFETs constitute a solution to reduce them. Using a dedicated RF layout, p-type LSB MOSFETs fully processed within the laboratory (academic environment) were studied **[R. Valentin et al, in Proc. of SiRF2007, 32]**; a 30-nm gate long device featuring an outstanding f_t of 180 GHz (Fig. 1) was recorded, which constitutes the best result reported in literature for unstrained channel fully depleted SOI p-MOSFETs **[G. Larrieu et al, in Proc. of 2007 Int. Elec. Meet. Conf, 147]**.

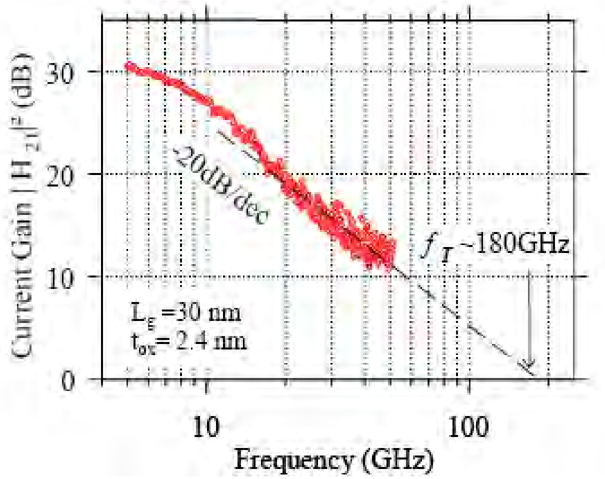


Fig. 1 : On-wafer S-parameters of a 30 nm DS p-MOSFET are measured, up to 50GHz with Vg=Vd=-2V.

2) Design of Demonstrators

Using RF models developed for SOI MOSFETs on High resistivity substrates, several demonstrators in mm-wave range were realized. First, Distributed Amplifiers were designed using 130 nm technology; an average gain of 7 dB along with a unity gain bandwidth of 51 GHz were achieved, which corresponds to the best tradeoffs for a CMOS technology in terms of gain, bandwidth, and power consumption for this technology **[C. Pavageau et al, IEEE Tran. on MTT, 56, 587, (2008)]**. Second, low noise amplifier (LNA) using 65 nm technology, operating at 80 GHz, were realized. This 3 stages LNA featured a Gain of 7.2 dB along a noise figure of 5.7 dB (power consumption is 70 mW and occupied area 0.98 mm^2), performances which are among state-of-the-art results **[B. Martineau et al, in Proc. of 33rd ESSCIRC, (2007)]**.

Acknowledgments – Collaborations

Activities related to mainstream technology devices and demonstrators design were made in collaboration with STMicroelectronics (common research lab).
Activity on LSB MOSFETs is made within the framework of European Contrat METAMOS (METAllic source/drain architecture for advanced MOS technology), STREP Call FP6-2004-IST-NMP-2.

II.3-6 Metamaterial technologies

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Non Permanent Staff: M. Bouzouad, C. Croënne, N. Fabre, S. Fasquel, M. Foulon, G. Houzet, D. Gaillot, A. Lucas, A. Marteau, and F. Zhang

Objectives
The main objectives of this work were first to design and fabricate metamaterials which are artificial electromagnetic metal-dielectric micro/nanostructures, and secondly to experimentally demonstrate their unique properties through negative refraction, focusing or cloaking experiments. This work was conducted in the DOME (Dispositif Opto-et Micro-Electronique quantique) group which addresses a large part of the electromagnetic spectrum from microwave, to infrared via the Terahertz spectral regions. Here, we exemplify three breakthroughs which concern (i) the demonstration of negative refraction in composite metal dielectric metamaterials operating at microwave frequencies, (ii) a novel approach for cloaking at Terahertz frequencies based on Mie Resonances in high-κ BST ferroelectrics and (iii) the experimental verification of focusing by a Photonic crystal nanopatterned in an InP-based semiconductor slab.

Negative refraction in omega-type prism-like microstructure
Fig. 1 illustrates the so-called split ring resonator and wire arrays along with the transmission line approaches which were developed at microwave frequencies. The main breakthrough was achieved with the experimental demonstration of a selective-angle device with the goal to realize a novel frequency discriminator based on ultra-refraction. The underlying idea is to synthesize a negative-zero-positive index artificial medium so that changing the frequency leads to a broad angle- selectivity around the normal to the titled interface of a wedge-type device.

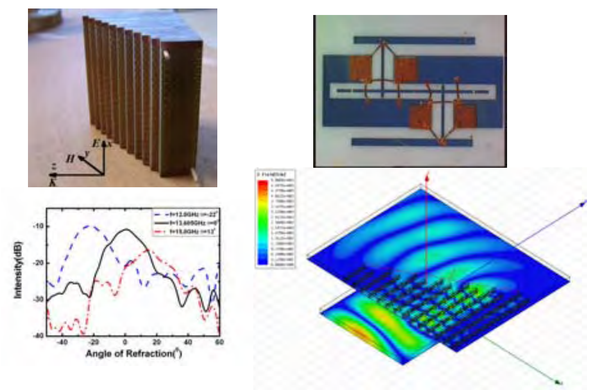

Fig. 1 Illustration of metamaterial technologies with a free-space wedge-type prototype and a composite Left Right Handed transmission line.

The experimental demonstration was successfully implemented firstly owing to ab-initio (all details of structuring are included) full-wave 3-D analysis of the scattering of light with a prism-like microstructure. The composite left- and right- handed character was achieved by balancing the magnetic and plasma frequencies from the retrieval of the dispersion of the effective permittivity and permeability values. Experimental assessment was achieved by developing a novel characterization technique mimicking free- space conditions with a parallel plate waveguide configuration. A comparison of theoretical and experimental results was just accepted in JAP [F. Zhang et al JAP in press]. In parallel, we studied the possibilities to tune the dispersion characteristics by means of voltage-controlled thin Ferroelectric (BST) films and by infiltrating Liquid crystals (LCs) in voids fabricated inside the metamaterials. Many tuneable microwave applications notably composite phase shifters (Fig. 1) were reported by the group in the IEEE Transactions series. The last paper, written in collaboration with the University of Littoral concern the dispersion characteristics of BST films [L. Burgnies et al IEEE Tans on AP, vol.57, 4, 2008]. The studies on LCs are currently carried out in collaboration with the University of Tsinghua (Beijing University).

Cloaking in High κ BST dielectrics
Fig. 1 illustrate the last breakthrough recently published [D. Gaillot et al. Optics Express, vol. 16, 3986,2008]. With respect to the split ring resonator technology corresponding to the microwave region, the basic idea is to induce an artificial magnetic response via Mie resonances. The artificial magnetic dipole relies on vortex-like current in dielectric rods or sphere depending on the dimensionality of the system. There is not need to shape the current loop with concentric split ring resonators. It results from this a great simplification of the basic cell which permits to envisage an operation at Terahertz frequencies. In practice, the requirement of a strict localization of the field within the dielectric core necessitates to use high permittivity materials such as BST cubes which are imaged (inset FIR) and were fabricated at the University of Tsinghua and whose scattering characteristics were calculated at IEMN. From the modelling of the cloak, the key difficulty was to model the ultra-refraction of light within the cloak designed with gradients of permittivity or permeability. This work was carried out in the framework of two contracts with the DGA and ESA on Terahertz metamaterials. Fig. 2 shows the solved transverse electric field component for a 2-D cloak made of dielectric rods with a permittivity of 200. The calculation can be conducted by assuming homogeneous multilayers or by full wave analysis of the microstructure as performed for the prism. For the former approach, we are using an original approach which consists to sum up the local field components. The method applied to double

negative media was just published (C. Croënne et al Proceeding of the EuMa, vol.4, 95, 2008].

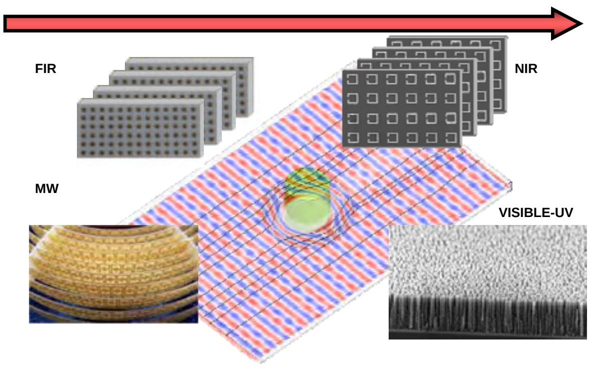

Fig. 2: Illustration of the modelling of EM Cloaks and of various technologies (SRR–dielectric rods–C shaped inclusion FSS – wire clusters).

Above the far infrared spectral region, ferroelectrics exhibit relaxation phenomena and thus loose their properties of high κ materials. To overcome such a difficulty, we considered the stacking of Frequency Selective Surface arrays made of C-shaped current (MIR/NIR inset). The arrays which are shown here were fabricated by e-beam lithography at IEMN and characterized by FTIR experiments. A review on this research axis was just published [D. Lippens et al., CR Phys, in press]

Focusing via photonic crystal slab

Outstanding results were achieved experimentally and theoretically in the field of left-handed electromagnetism following our previous work [M. Perrin et al JOPA, Vol.7, S3, 2005].

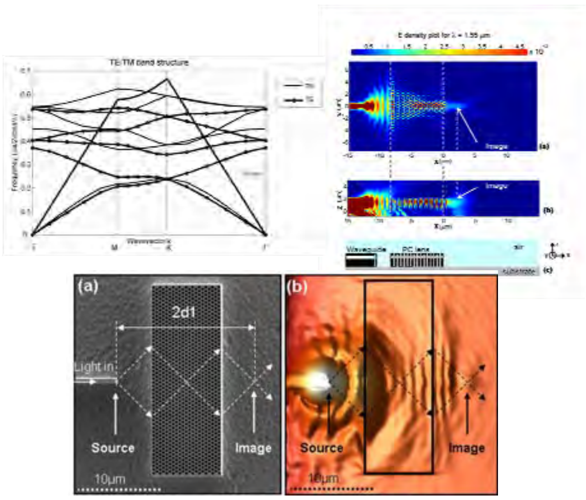

Fig. 3 Negative index PC technology (band diagram, FDTD modelling and NSOM experiment)

The basic idea is to take advantage of the band folding of band in the first Brillouin zone of Photonics crystals (PC) as it can be understood from the dispersion characteristic displayed in Fig. 3. We just showed that such a dispersion characteristic can be interpreted in terms of the frequency dependence of the refractive index and Bloch impedance and of the dispersion of the effective permittivity and permeability. The main conclusion of this study published in Physical Review (C. Croënne et al PRB, Vol. 7, 125333, 2008) is that, while a matching of the negative index can be achieved, there is a fundamental intrinsic incompatibility on the Bloch impedance matching. On this basis, full wave simulation by using FDTD codes were carried out in order to fulfil the conditions of high transmissivity and an original solution based on Fabry-Pérot resonances was recently published [N. Fabre et al, Optics communications in press]. With respect to the modelling effort, it was also demonstrated the possibility of a cloaking device which exhibits a butterfly-shaped PC cloak [O.Vanbésien et al., Optics A, vol. 47, 1358, 2008]. The main difficulty of the experimental verification of negative refraction is the fabrication of the nanostructure but also the characterization of the devices. These two difficulties were solved over this last few years with the development of a new structuring technique of the photonic crystal which replaced those studied during S. Fasquel's thesis. The main improvements were the use of a novel HSK-resist and of ICP-etching technique instead of a DRIE processing stage [N. Fabre et al Opto-electronics review, vol. 14, 225, 2006]. From this experimental side, the main breakthrough stems from the successful characterization of a lens (SEM photograph in Fig.3) by the NSOM (Near field Scanning Optical Microscopy) of the University of Bourgogne. The source was integrated by implementing a narrow ridge waveguide which plays the role of a point source. The electric field intensity was recorded by a mapping of the electric field component by using a chemically etched silica fibre. Well-resolved focus can be seen in the image plane and within the flat lens in agreement with the ray tracing optics by assuming index matching. The resolution was interpreted by 3-D full wave of the whole device (source and lens) and experimentally determined to be 0.8 λ_0. These results which are to the best of our knowledge at the state-of-the art with respect to sub-wavelength focusing in PC flat lens will be presented at the San Diego CLEO conference [N Fabre et al.] and are under review for a letter revue paper.

Acknowledgments – Collaborations
The works on omega-type prism is carried out in the framework of a CNES contract, on cloaking is funded by DGA and ESA, on focusing by ANR projects (Metaphore and Fani PNANO projects). The collaborations with the Universities of Dijon (ICB), Calais (LEMCEL), CEA Le Ripault, Tsinghua and Xian in China, Altanta (Georgia Tech) and Boulder in the US are acknowledged.

II.3-7 Optoelectronic Generation and Detection of Terahertz Signals

Permanent Staff: T. Akalin, G. Ducournau, J.-F. Lampin, E. Peytavit.
Non Permanent Staff : A. Beck, O. Offranc.

Objectives
Generation and detection of terahertz (THz) signals are the new frontiers for high speed electronics and the interest for this subject is growing rapidly since applications emerge: spectroscopy, imagery, teledetection and telecommunications. We follow an optoelectronic approach: it combines laser sources and ultrafast optoelectronic devices for the generation and the detection of THz signals. This activity is in close connection with the MBE activity of IEMN since devices are based on III-V epilayers: low-temperature-grown (LTG) GaAs, AlGaAs and heterostructures: uni-travelling-carrier photodiodes (UTC-PD). We also work on new THz transmission lines (Goubau lines) and THz antennas.

Outstanding results
1) THz time-domain measurements
We have developed and improved a new ultrafast sampling method for THz signals. It is based on an optical electroabsorption phenomena: the Franz-Keldysh effect. We have shown that LTG-GaAs is a good material for the sampling of THz pulses via this effect. Subpicosecond pulses are generated by a photoconductor (also fabricated with LTG-GaAs) illuminated by femtosecond laser pulses. The problem is that the generation and the sampling need two different photon energies (one below the bandgap and the other above the bandgap). It was solved by using one wavelength but two materials: LTG-GaAs for the generation and LTG-AlGaAs for the sampling [**L. Desplanque, et al., Appl. Phys. Lett. 84, 2049 (2004)**]. A Van der Waals bonding technique was used in order to place the 2-µm thick layers on coplanar transmission lines. State-of-the-art results were obtained: a risetime from 10 to 90 % of 490 fs and a spectrum that extends up to 2.5 THz with high dynamic range. This method is suited for the time-domain characterization of integrated passive and active THz devices.
2) New THz waveguides
We have also designed original and highly efficient THz-pulse launching structures on a plasmonic waveguide. This is a similar approach to the one developed at microwave frequencies for the excitation of Goubau-Lines with horn antennas. Both waveguides are composed by a single metallic conductor. We have a planar topology which is compatible with classical microelectronic devices. We have also fabricated filters with corrugated waveguides which are also interesting for their electromagnetic field confining properties. Low-loss bendings on these waveguides and plasmon jumping effects have also been demonstrated at THz frequencies by means of simulations and experiments. [**T. Akalin et al., Joint 32nd IRMMW and 15th IEEE Terahertz Electronics Conference, Cardiff (2007)**].
3) THz UTC-PD
In collaboration with the HBT activity (M. Zaknoune), we have developed an activity on these high-speed photodiodes which are very interesting for generating THz signals with 1.55 µm lasers (more compact and cheaper than 0.8 µm sources). With 7.5 µm-diameter InGaAs/InP UTC-PD, we have measured 3.6 ps pulses with our sampling method [**A. Beck et al., Joint 31st IRMMW and 14th IEEE Terahertz Electronics Conference, Shanghai (2006)**]. New processes are under development: integration with horn antenna, transfer of epilayers on silicon substrates.

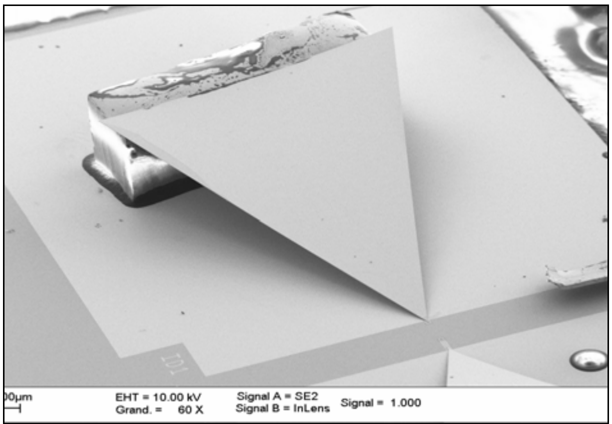

Figure 1: THz horn antenna monolithically integrated with a LTG-GaAs interdigitated photoconductor.

4) Integrated THz horn antennas (HA)
We have developed a new kind of integrated THz antenna: for the first time a large bandwidth HA was fabricated for the 100 GHz – 1 THz band. It has several advantages compared to the classical approach: high gain, large bandwidth, low dispersion and it radiates directly in the air (the radiation is not trapped into the substrate). It is a 3D structure (figure 1) which is fabricated using standard lithography and then lifted and bonded on a 800 µm-thick PTFE parallelepiped. It was monolithically integrated with a LTG-GaAs photoconductor and we have demonstrated its efficiency with state-of-the-art results for CW (1 µW at 780 GHz) and pulsed THz generation (5.6 µW of mean power) [**E. Peytavit et al., Electron. Lett. 43, 73 (2007)**]. This structure was patented [**J.-F. Lampin et al., brevet n°0610164, 21 novembre 2006**].

Acknowledgments – Collaborations
This work is supported by CNRS and DGA (contract 06.34.021). G. Mouret (LPCA, Dunkerque), J. Mangeney (IEF, Orsay), S. Barbieri (LPA, Université ParisVII)

II.3-8 Microwave- and Nano-photonics

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Non Permanent Staff: M. Carette, N. Choueib, J-R. Coudevylle, S. Ginestar, D. Lauvernier, M. Lesecq, S. McMurtry, A. Pagies, C. Rodriguez, N. Saadsaoud, G. Ulliac, M. Zegaoui

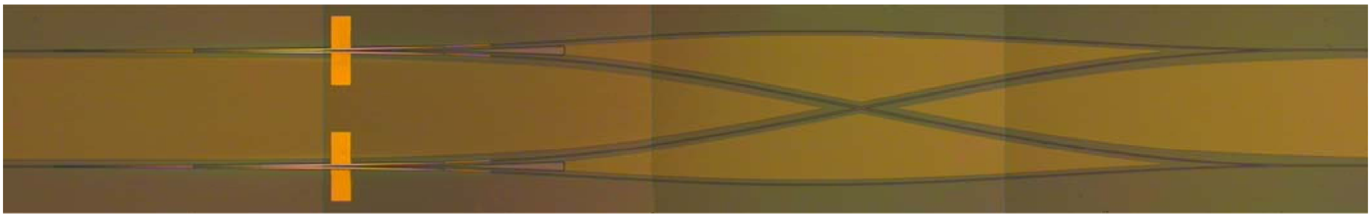


Figure 1: 2x2 switching matrix made of 2 DOS switches and passive recombination photonic circuit

Objectives
Microwave photonics affords new potentialities in the optical processing of microwave signals. We applied it mainly to the optical beamforming of wide instantaneous bandwidth phased array antennas. Specific devices have been so studied and fabricated; as high speed optical switching matrices and detectors.
Nanophotonics using III-V semiconductor material line allows the mixing of passive and active functionalities. We capitalize on the compactness and the high optical confinement of these circuits i) to decrease surface areas requested for passive integrated optics circuits, ii) to decrease interaction volume required for electro-optic functions and iii) to increase non-linear effects.

Outstanding results
Microwave-photonics
High speed optical switches
We previously demonstrated high speed (1ns), low noise, and very low crosstalk (-40dB at 1.55µm wavelength) InP Digital Optical Switch (DOS) components.
We designed and fabricated 1→4 switches aswell as 2x2 switching matrixes (*Figure1*) that are based on this elementary DOS structure .Nevertheless, th DOS structure has been redesigned to flawlessly fit with interconnecting passive photonic circuit that is required to build a matrix. Crosstalk value close to -30 dB has been achieved on a 2x2 switching matrix for a driving current around 55 mA (@ 1.55µm wavelength) [*J. Chazelas et al – Patent INPI 06-11276 (2006)*].

2) Multiple optical inputs - single electrical output photodetector
Always dealing with the optical processing of microwave signals within an optical beamforming structure, the electrical summation of optically carried microwave signals is required. It has been demonstrated that separate optical absorption and joined electrical launching structures can realize this adding function with low degradation of noise properties, at least much less than what is commonly achieved with pure electrical coupling circuitry. A specific detector has been designed and fabricated. It is composed of several (up to 8) evanescently coupled PIN detectors, each of them being implemented on top of an integrated optics waveguide (*Figure 2*). The detector has so up to 8 optical inputs and a single electrical output which is constituted by a common interconnection bridge between all detectors.

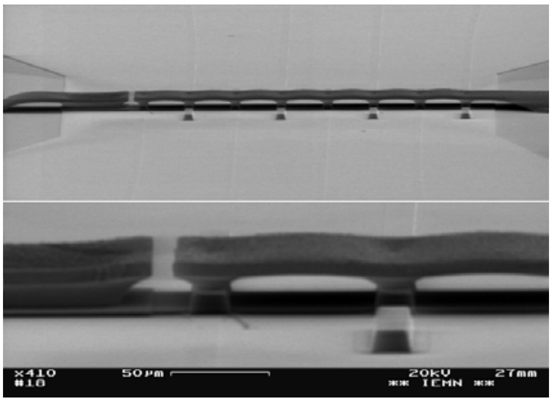


Figure 2: Top: 8-input integrated optics photoreceiver including 8 optical waveguides and 8 evanescently coupled PIN detectors. Bottom: details of interconnection bridge

We got the summation of two detected RF signals of same amplitude: a power increase of 6 dB can be noticed comparing output RF power when 1 channel is active to the case where both are. This was accompanied by a 3 dB increase of the output noise level validating the fact that we got an increase in the signal to noise ratio by almost 3 dB which effectively corresponds to the case of two channels. Saturation current has not clearly been pointed out up to photocurrent value in the order of 20 mA for 2 impinging optical beams and the detection bandwidth is 20 GHz for a 8-input device[*J-P. Vilcot et al, SPIE, Vol. 6343, 63432-E1-E6 (2006)*]
Nanophotonics

3) Filters based on InP optical wires
Optical filters have been investigated under an innovative topology which issues from the microwave world: it

consists in a lateral resonator (stub) which shall be metallised for better operation (*Figure 3*). Modelling on this structure has been made in collaboration with B. Djafari-Rouhani research team (see operation 1.6) [*Y.Pennec et al, Journal of Optics A: Pure Applied Optics, Vol. 9, S431-S436 (2007)*].

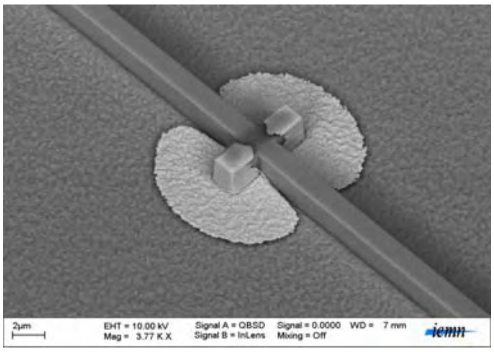


Figure3: "Stub" based optical resonator

4) Tunability of microdisks resonators

More conventional micro-rings and micro-disks that are coupled to input/output waveguides by a 100nm wide gap have been fabricated. Active functionalities have been added under either optical or electrical control. Optical control is easily achievable from a technological point of view since it does not require any specific device modification. We use it on a 15µm diameter InGaAsP/InP micro-disk resonator. It was illuminated by a 980 nm wavelength laser; 20mW impinging power focused on the micro-disk induced a 3 nm wavelength tuning [*M. Beaugeois et al, Optics Letters, Vol. 32, 35-37 (2007)*]. Electrical control requires device design modification, mainly relative to the adding of electrodes. An air-bridge technique has been fitted to contact tiny pad surfaces on the high optical wires (*Figure 4*). A tunability of resonance frequency by 8 nm under 80 mA drive current has been achieved.

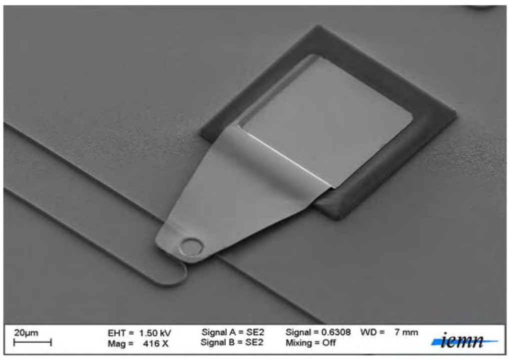


Figure 4: 15µm diameter microdisk resonator with electrical resonance wavelength tuning.

5) Optical switch based on optical wires

Using almost the same technology that in §4 but applied to optical switching, a 1→2 optical switch has been designed and fabricated (*Figure 5*). Characterization shows a -20dB crosstalk under 100mA drive current (@ 1.55µm wavelength) [*M. Lesecq et al, Optics Express, Vol. 16 (2008)*].

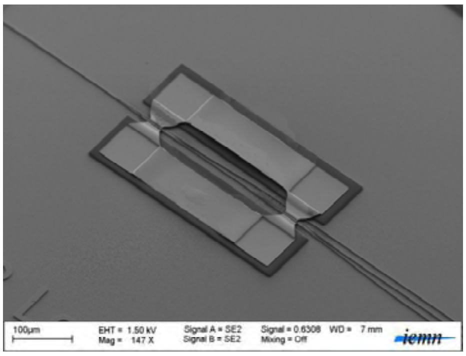


Figure 5: Optical switch based on 1µm-width optical wires.

6) III-V/polymer nanowires

The previously launched studies using GaAs core structures have been characterized. Propagation loss value around 5dB/mm has been recorded for a 300nm square semiconductor core embedded in BCB and 90°-bend excess loss below 1dB for a 5µm curvature radius. Spot size converters were added in waveguide designs by the way of reverse tapers (80nm x 300nm). Total coupling losses have been measured to be around 6.5dB and 12dB for respectively TE and TM modes showing a better efficiency of these structures for TE mode (linked to asymmetric design of these) [*D. Lauvernier et al, Optics Express, Vol. 15, 5533-5341 (2007)*]. GaAs has been replaced by InP as core material, owing to a different plasma chemistry, sidewall roughness has been decreased and propagation loss as low as 1dB/mm has been reported. Two particular applications of these nanowires are currently under investigations; the first one deals with an all optical switch and the second one with a variable delay functionality. The optical switch function is based on absorption saturation and the delay function on slow wave properties of Bragg structures (*Figure 6*).

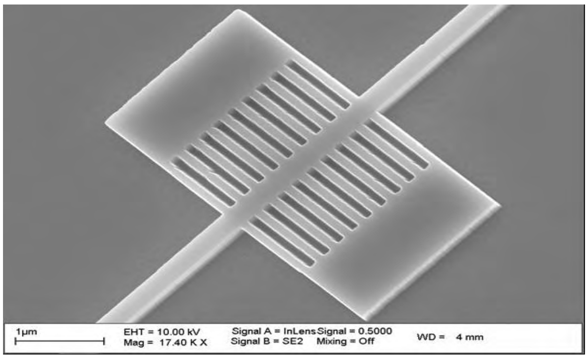


Figure 6: Slow wave nanowire based structure incorporating sidewall Bragg grating.

Acknowledgments – Collaborations

M. Bouazaoui, B. Pinchemel: PhLAM/IRCICA – J-P. Vigneron: LPS – FUNDP (Namur)

Thales Airborne Systems, French Ministry of Defence (DGA branch), Interreg IIIa French-Belgium programme and ANR

II.3-9 Modelling of technologies and advanced devices

Permanent Staff: L. Baudry, C. Dalle, F. Dessenne, C. Krzeminski, E. Lampin, J.-L. Thobel.
Non Permanent Staff: O . Bonno, Q. Brulin, V. Cuny, A. El Moussati, E. Lecat.

Objectives
The objective of this activity is to develop physical models and to implement them in simulation tools. All important aspects of micro and nanoelectronics have been considered: technological fabrication processes, physical mechanisms of device operation and performance of devices and circuits. A wide variety of devices have been studied: field effect transistors, ferroelectric memories, semiconductor lasers...

Outstanding results
1) Simulation at the atomic level for nanodevice processing
Standard simulations of the microelectronic technologies are carried out using continuous models implemented into finite element solvers. Several studies have been performed on dopant diffusion ***[E. Lampin et al., J. Appl. Phys. 94, 7520 (2003)] [E. Lampin et al., Solid State Electron. 49, 1168 (2005)]*** and oxidation modelling ***[C. Krzeminski et al., J. Appl. Phys. 101, 064908 (2007)]*** to improve the predictivity of process simulators. However, for nano-devices, additional insight and understanding at the atomic level is mandatory to simulate the complex processes developed by laboratories at the state-of-the-art of the ITRS Roadmap. In particular, a multiscale approach is being developed and atomistic molecular dynamics has been applied to various challenging issues. Boron diffusion effects have been investigated at the atomic level in silicon and the migration length estimated in excellent agreement with various continuous model ***[V. Cuny et al., Europhys. Lett. 76, 842 (2006)]***. The method has also been applied to simulate the recrystallization of an amorphous / crystalline silicon stack, a key process for the formation of ultrashallow junctions for below-32nm technology nodes. The simulations have been exploited to systematically extract the recrystallization velocity. A potentiality to simulate the solid or the liquid phase epitaxy using the appropriate interatomic potential was demonstrated [***C. Krzeminski et al J. Appl. Phys. 101, 123506 (2007)***].

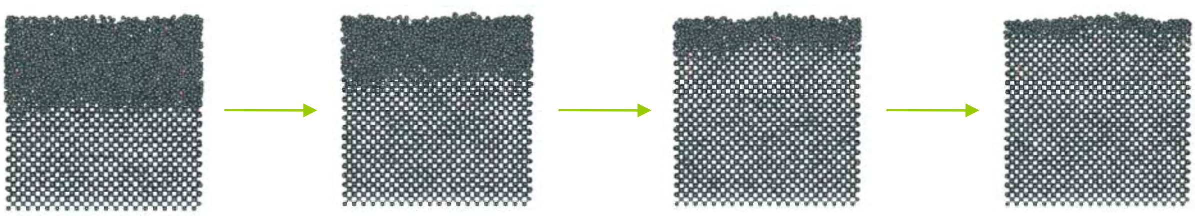
2) Modelling of ferroelectric thin films for device applications
We have developed a comprehensive model of ferroelectric thin films, based on Landau-Khalatnikov and Ginzburg-Landau theories and accounting for their semiconducting properties. We have applied it to study the electric field distribution inside a ferroelectric capacitor and we found a highly non linear behaviour which affects both static and dynamic properties. ***[L. Baudry, J. Appl. Phys. 97 024104, (2005)]***

3) Monte Carlo simulation of Quantum Cascade Lasers (QCLs)
We have developed a Monte Carlo model of electron transport in QCLs, paying special attention to screened carrier-carrier scattering.. Thanks to this model, we have shown that a careful optimisation of the so-called “resonant phonon” QCL allows it to operate at frequencies as low as 1 THz. This confirms that QCLs are good candidates to fill the “terahertz gap” [***O. Bonno et al., Physica E, 33(1), 13—16 (2006)***].

4) Macroscopic modelling of devices and circuits
2D time-domain Maxwell/transport models have been developed. The test-bed application is the mm-wave silicon distributed IMPATT diode. FDTD high order explicit approximations have been implemented for compatibility with parallel computing.
[A. El Moussati and C. Dalle, J. Comput. Electron. DOI 10.1007/s10825-008-0235-1 (2008)]

Acknowledgments – Collaborations
EC projects IST 2000-30129 FRENDTECH, SASEM 2001-32674, NanoCMOS (IP), PullNANO (IP), common laboratory STMicroelectronics-IEMN.

Non conventional nanometre-scale MOSFETs architectures



Recrystallization of an amorphous Si layers formed on a crystalline substrate. Molecular dynamics simulation.

II.4 Communication Systems and Applications of Microwaves

Introduction

This theme gathers four research groups on a main federative topic, digital communications and signal processing for 3 major applications :

- Safety in terrestrial transportation systems
- Broadband communications and millimeter wave WLAN
- Software designed radio and radar

In addition to this main research activity some efforts are devoted to microwave and millimeter wave detection, imaging and non destructive characterization.

This theme is mainly oriented towards applied researches even though a great deal of work concerns theoretical developments and simulations to implement new concepts. A good balance is achieved between theoretical work and experimental validation and demonstration absolutely necessary in this field of applied research. For this last purpose the researchers can rely on an advanced Telecommunication platform, unique in the french academic laboratories which involves up to date CAD tools and instrumentation/characterization facilities at a system level. Concerning MMIC tests, MEMS realization and millimeter wave subsystems assembly the researchers can use the IEMN characterization and technological facilities, so they can manage their projects from end to end which constitutes a rather unique feature for an academic laboratory.

This theme addresses numerous applications and covers a wide frequency band from base band up to millimeter wave frequencies (140 GHz). The report will focus on the most significant results split in five operations and a brief summary of the objective of each one is given below :

- Communication, localization and Electro Magnetic Compatibility (EMC) in transportation systems.

This topic aims at optimizing digital communications in a transportation environment which remains a challenging issue. This wide subject covers both in-vehicle, road-to-vehicle, vehicle-to-vehicle, train-to-train and train-to-ground configurations. Improved MIMO or UWB techniques have been studied for communication, localization and anti-collision either for road vehicle and trains. For high speed train, communications special coding and modulation schemes have been developed while for in-vehicle PLC techniques were investigated together with the associated EMC aspects.

- Indoor broadband digital communications : (optical fiber, DSL, PLC).

This research work focuses on multimedia networks integrating both wirelines (optical fiber, DSL PLC) and 60 GHz wireless access networks. Two main topics are investigated : Characterization and modelling of physical propagation channels and corresponding design and implementation of innovative communication concepts.

- Global smart object communication (SOC), wireless sensors networks (WSN) and very high data rate WLAN/WPAN (HDMI)

This multidisciplinary work is developed in close collaboration with the laboratory of fundamental computing science of Lille (LIFL) and addresses not only the physical layer but also the hardware/software interface. To reduce size (SOC and WSN) or to insure very high data rates (HDMI) the 60 GHz band was considered. To achieve ultra-low power Impulse UWB technique was used together with beam forming antennas based on MEMS switches and phase shifters. To increase the connectivity of the 60 GHz wireless network radio over fiber systems were also developed and demonstrated. O-level packaging technologies were also demonstrated in view of a heterogeneous integration.

- Digital circuits and communication

With the technologies progress this work focuses on moving from configurable analog and RF circuits to digital hardware and even software design. This concerns reconfigurable analog and BAW filters and oscillators, digital generation of RF signal and ultra wide band high resolution electrical samplers.

- Non destructive characterization

In this operation microwave and millimeter techniques are used to perform quantitative characterization of subsurface defects in dielectric materials at micrometer scale for example or to monitor the temperature inside powder materials by microwave radiometry.

II.4.1 Communication, Localisation and Electromagnetic Compatibility in Transportation Systems

Permanent staff: S. Baranowski, I. Dayoub, B. Demoulin, V. Degardin, P. Degauque ,Y. ElHillali, L. Kone, M. Lienard, A. Rivenq, J.M. Rouvaen, Ch. Semet and E. Simon
Non permanent staff: G. Andrieu, N. Ben Slimen, M. Chennaoui, O. Delangre, S. Egot, M. A. Lamari, S. Leman, G. Moniak, A. Nasr, F. Rouissi, L. Sakkila, P. Stefanut , J. Zaidouni

Objectives

Optimizing the performance of a communication link in a transportation environment remains a challenging topic. This is a very wide subject covering both in-vehicle and road-to-vehicle, train-to-train and train-to-ground configuration. During these last 4 years DOAE/COMNUM, DHS/TELICE and DHS/CSAM groups have combined their efforts for studying communication techniques based either on MIMO (Multiple Input Multiple Output) or UWB (Ultra Wide Band) approaches, and localization and distance measurement techniques either for road vehicles or trains. Anti-collision radars have been developed and, for UWB systems, a special attention was devoted to optimize the codes, taking the multi-user aspects into account. In the transportation domain, high bit rate communication to high speed train (HST) is also a challenging research and special coding and modulation techniques were studied. The idea of having a laboratory set-up for simulating a multipath environment and testing communication systems in a well defined structure being attractive, the possibility of using reverberation chambers was investigated. Lastly, for in-vehicle data transmission, power line communication techniques were studied, while electromagnetic compatibility (EMC) aspects have also been taken into account.

Outstanding results

To clearly point out the main achievements, we successively consider the research areas mentioned above

1) Communication and localization in tunnels

If we first consider the possibility of increasing the performance of the link, MIMO is a promising technique (fig 1 and 2). However, in a long tunnel, the number of reflecting objects between, or near, the transmitter and the receiver is often quite low. In such situations, the concept of spatial diversity must be replaced by the concept of modal diversity We have thus investigated the possibility of using the modal theory of the electromagnetic propagation in rectangular or circular tunnels, to satisfactorily interpret experimental results, including polarization **[*M. Lienard, et al., C. R. Acad. sci., Sér. IV , vol.7, 726, 2006*].**

A methodology combining ray theory and modal theory has been proposed to determine the amplitude of the modes excited by a single vertical dipole and to determine the number of "active" modes at the receiving points and the correlation distance between receiving antennas. [***D. G. Dudley et al., Invited paper IEEE AP Mag., vol. 49, 11, 2007***]. The frequency range under consideration is, in this case, between 2 GHz and 5 GHz. By assuming identically excited modes in a tunnel of rectangular shape, the upper bound of MIMO channel capacity has also been determined. The calculation is based on the equivalence between the eigenvalues associated with the channel transfer matrix and the weights of the modes propagating in the tunnel.

Figure 1: MIMO measurement system

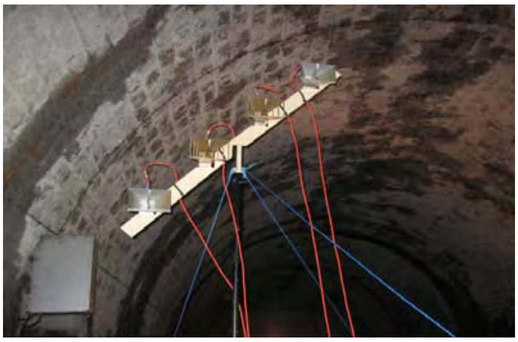


Figure 2: Fixed MIMO transmitting array in tunnel

A system allowing data to be exchanged between two successive trains in a tunnel, while simultaneously measuring the distance between them, would help to optimize train traffic in very long tunnels, without lowering safety standards. A study including both theoretical and experimental phases was conducted, to design and optimize such a system and focused on the Channel Tunnel, where a minimum range of 5 km is necessary for operational use. The solution retained for measuring distance was based on spread spectrum techniques, transponders being located in each train. This method allows the double objective of distance measurement and data transmission to be attained. A prototype, operating in the 2.2/2.4 GHz frequency band, was constructed and tested in diverse sections of the Channel Tunnel. **[*M. Lienard et al., IEEE Trans. on Vehicular Techno., vol. 53, 705, 2004*].** This system was also tested successfully on shorter distances in underground rail system tunnels, whose geometry is much more complex, as in the Paris and Lille subway lines **[*M. Lienard et al., Eur. J. of Transport and Infrastructure Research, vol. 4, 405, 2004*]**

In collaboration with INRETS, we have also designed and developed another type of original radar and achieved a mock-up to provide data communication between road or railway vehicles (fig3). It is based on the principle of cooperative radar using a transponder inside targets. It uses a numerical correlation receiver and has a broad band of about 100 MHz for high data flow communications. [***Y. El Hillali et al., EURASIP J. of Embedded System, vol. 2007, 37, 2007***]

Three original multiplexing methods have been implemented, in real-time using FPGA devices, to multiplex data communication, localization and allow multi-users access. These methods are Sequential Spreading Spectrum technique, Code Position Modulation and Cyclic rotation Modulation, respectively. [***L. Sakkila et al., IEEE Intelligent Transport. Systems Newsletter, vol. 9, 2007***].

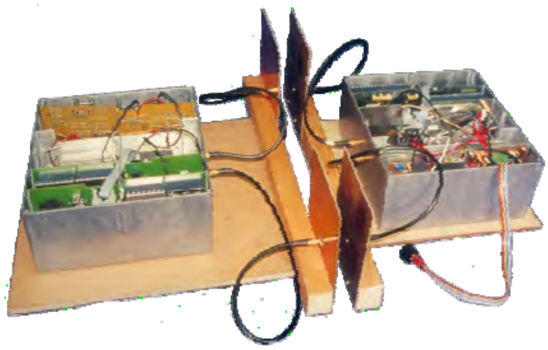


Figure 3: Radar and data transmission at 2.4 GHz

2) Communication to high speed train

There are not a lot of studies dealing with the problem of high data rate services both in uplink and downlink directions in the case of high-speed trains. In collaboration with INRETS, we have investigated the performance of combining powerful coding techniques with high spectral efficiency modulations. We focused especially on turbo coded 16-QAM modulation based OFDM system (classical FFT or using Gabor's wavelets) over a time varying channel when the receiver moves at a very high speed. The performance of such a system have been analyzed with a new Rayleigh fading channel simulator using the Zheng's model. BER improvements have been demonstrated for high data rate video transmissions [***M. Chennaoui et al., Proc. IEEE Intelligent Transp. System Symp., 2005***]. The bit error performance improvement has been demonstrated for high bit rate transmission using video sequences.

3) Short range inter-vehicles communication and localization technique

The classical multi-band UWB system consists in dividing the bandwidth into several sub-bands and using a frequency hopping technique to address each sub-band. The frequency hopping depends on pseudo-random code sequences. Original mathematical tools called Modified Gegenbauer Functions (MGF) have been used to ensure UWB multi-user communications and localisation systems. It is shown that MGF offer better performance for multi-user UWB communication [***F. Elbahhar et al., Wireless Personal Com., vol. 34, 255, 2005***]. The orthogonality of these MGF is exploited to construct a multi-band UWB localization and communication system and to reduce the Multi-User Interference (MUI) for inter-user asynchronous communication. In this scope, only a few trains (typically 6) will be allowed to communicate information (data or video) with a sufficiently low BER, on the order of 10^{-4} (error control codes may be applied to further decrease transmission errors). Moreover the distance between a train and a preceding one must be known to a precision in the meter range over distances higher than one hundred of meters; this calls for a signalling pulse width of the order of 10–20 ns, enabling in turns communication at a data rate reaching 25–50 Mbits/s, which will be sufficient for the considered communication application.

For automotive applications, as urban collision avoidance and parking aid, the needed range is by far much smaller and Ultra Wide Band (UWB) techniques can be used. A pulsed UWB radar system has been studied for this application. Trial experiments have been successfully realised in order to implement signature analysis for obstacle classification and recognition. [***F. Elbahhar et al., I.E.E. Proceedings – Communications, vol. 152, 229, 2005***]

We have also designed and achieved a multifunctional architecture by exploiting the emerging BiCmos technologies (from STMicroelectonics) in the millimetre-wave frequency band near 80 GHz. Directions of the targets are obtained using two or more separated sensors associated to localization techniques i.e. measurements of Angles of Arrivals (AOA), Time of Arrival (TOA), Time Difference Of Arrival (TDOA) or multilateration techniques. This UWB multifunctional architecture fullfill several requirements:

- One chipset for Short Range Radar (SRR) in the 76-77 GHz frequency band and Long Range Radar (LRR) the 77-81 GHz frequency band.
- Long range localisation and communication abilities with data rates around 5 Mbps between cooperative vehicles.

The phase method is used for Direction Of Arrival (DOA) and TOA estimations that are used for localisation purpose based on the hybrid technique named DOA/TOA. Results have shown a promising solution for an inter-vehicle localisation system in particularly and for localisation applications in general. [***V.Y Vu et al. Proc. Int. Symp. on Intelligent Signal Processing and Com. Systems, 875, 2006***]

Numerous algorithms based on correlation matrix eigenvalues have been developed to estimate the number of paths in a multipath environment. To improve their efficiency, the use of the interlacing properties of the eigenvalues both of a Hermitian matrix and of its main submatrices was proposed. [***Nasr et al. Electronics Letters, vol. 43, 1443, 2007***].

4) Reverberation chambers for simulating a multipath environment

Reverberation chambers (RC) have been used since many years for electromagnetic compatibility (EMC) applications. But nowadays, this test facility has attracted attention from the wireless community as a way to easily characterize antennas for mobile terminals and to test wireless systems, a RC being a way to create either a multipath Rayleigh fading environment or a Ricean environment. In the EMC standards, the RC characteristics are usually defined in the frequency domain, in terms of RC quality factor, modes density, modes bandwidth, to mention only few of them. In time domain, a decay time is introduced. In order to apply this concept of RC to the modelling of propagation channel, the relationship between these characteristics and both the channel coherence bandwidth and the rms delay spread has been found. In some cases, the delay spread in the RC appears to be too large and the use of absorbing panels placed in the room was investigated.

A new testbed aiming to test wireless systems has been proposed. **[*M. Lienard et al., Electronics Letters, vol. 40, 578, May 2004*]**. It is made of two reverberation chambers coupled through a waveguide whose transverse dimensions can be changed (fig 4). By changing the waveguide dimensions, one can control several features of the wireless channel. Indeed, depending on the transverse size of the guide, compared to the wavelength, one can modify the number of propagating modes and thus the rank of the channel transfer matrix. Furthermore, with such a technique, the propagation characteristics in the vicinity of the transmitter and of the receiver can me modified separately. Extensive theoretical and experimental works were carried out to show the interest of such a laboratory set-up

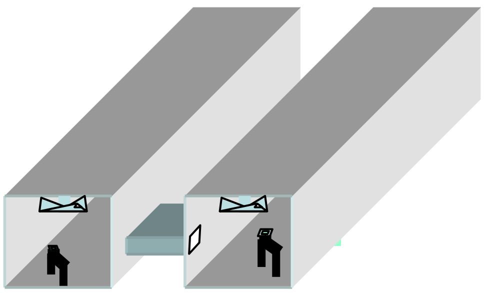


Figure 4: Principle of the laboratory set-up

5) In-Vehicle Power line communication

Over the last few decades, electronic systems have been used more and more in vehicles. Data transmission on dedicated communications networks and twisted wires leads to complex network architectures, with the result of increasing the weight of the cable harness and the number of connections, making it harder to insure the reliability of the combined systems. One possible medium-term solution is to use the DC power network as the physical support for transmission. This method, often called Power Line Communication, is currently being developed primarily for use in indoor applications. However, in-house and in-vehicle network architecture and noise characteristics are quite different. Therefore, the statistical properties of the in-vehicle channel transfer function were studied and extensive impulsive noise measurements were taken at various connection points in different new up-market cars to analyze the distribution of disturbing pulse characteristics, both in a stationary vehicle and in a vehicle moving normally in traffic. Probability density functions have also been proposed. A channel model, including noise and transfer function, was elaborated to be included in communication software for optimizing the channel coding and predicting the performance of the link. **[*V. Degardin et al., Proc. of IEEE/ISPLC Int Symp., 222, 2006***

6) Electromagnetic Compatibility: Coupling to cable network – Automotive applications

At the design step of the car, placement of the cables in the car body requires a specific topology both of the harnesses and of the connected printed circuits boards to reduce the voltage amplitude induced by electromagnetic fields radiated by wireless communication equipments in the 100 MHz - few GHz frequency range. A new model, taken into account all the electric and electronic parameters of the electrical architecture of a car has been developed. It is based on the combination of various concepts: non uniform transmission lines theory, transfer impedance concept, equivalent electric schema, associated to random variations of some parameters **[*S. Egot et al., Best paper award, Proc. Int. Symp. on EMC Europe, 1041, 2006*]**. Very good agreement was observed between measured and predicted results, as shown in Fig. 5.

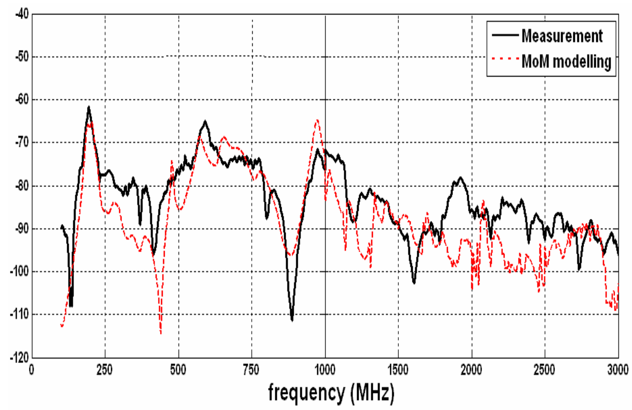


Figure 5: Disturbing voltage at the input of an on-board equipment illuminated by a disturbing wave

To simplify the calculation, one can proceed in two steps. First, determine the incident field on the cable structure by using a full wave method and then calculate the induced current and voltage by introducing a new concept of equivalent cable. In thius case, we have proposed to decrease the complexity of the cable bundle by introducing the concept of equivalent wires. **[*G. Andrieu et al., IEEE Trans. on EMC, vol. 50, 175, 2008*]**

Acknowledgments- Collaborations

Strong collaboration with: Alstom, SNCF, RFF, Eurotunnel, FCI automotive, PSA and Valeo. Few students from Politecnica di Cartagena, Politecnico di Torino and Université libre de Bruxelles prepare their Ph.D part time at IEMN to get a “double” diploma.

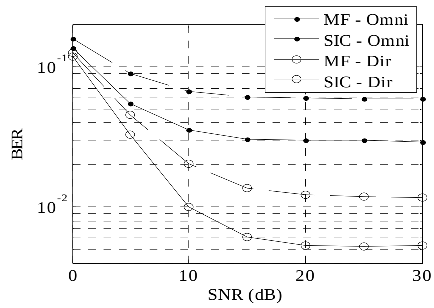
II.4.2 Indoor Broadband Digital Communications – From Physical Propagation Channel to Dedicated Communication Systems

Permanent Staff: A. Benlarbi, L. Clavier, P. Corlay, F.-X. Coudoux, I. Dayoub, M. Gazalet, M. Gharbi, J.M. Rouvaen, Marie Zwingelstein-Colin.
Non Permanent Staff: H. ElGhannudi, A. Boé, R. Okouyi, M. Bocquet, D. Bueche, C. Goudemand, M. Ramon, Z. Abdelouhaib, S. Fady, M.E. Romaric, O. M'Foubat Anicet, S. Hassane, A. Mazen

Objectives
Research on indoor broadband digital communications focused on multimedia networks integrating both wireline (optical fiber, DSL, PLC) and 60 GHz wireless access networks. Several technological challenges have been identified and studied. Characterization and modeling of physical propagation channels is one of the research topics. Based on the channel models developed, we design and implement innovative communication systems at the physical level. In what follows, we successively consider these two research areas and point out the main results obtained by IEMN.

Outstanding results
1) Propagation media
Radio channel: based on indoor Ultra Wide Band (UWB) measurements, we characterized the 60 GHz channel and proposed statistical models. This constitutes a hard point because classical hypothesis are not valid anymore. We searched for new solutions, based on α-stable random processes, which overcome the limitations of actual models.
We also developed a location strategy involving enhanced time difference of arrival to increase the estimation accuracy. Our technique is based on mm-wave up-converted UWB interferometer and allows mitigating the multipath propagation. Experimental results show the simultaneous localization of multiple objects with an error less than few centimeters. It also allows weak multipaths channel sounding by canceling dominant paths ***[A.Benlarbi et al, Elec. Lett. 42, 435 (2006)]***.
Power Line Cable: we proposed indicators to predict the true performance of channel estimators using pilot frequencies. They give an accurate idea of the BER degradation due to imperfect channel estimation (better than classical MMSE criterion) and subsequently allows efficient bit loading strategies in multi-carrier transmission systems ***[D.Bueche et al, ETT 17, 591 (2006)].***
Optical fiber: we investigated multimode optical fiber as a means of transportation for distributing jointly radio signals, and Gigabit Ethernet. In particular, we have shown that the standard optical fiber (50 µm heart – standard SX 50/125, mainly used in Europe) allows transmission distances larger than 100m. With the optimized fiber, transmission distances up to 600m can be envisaged.

2) Digital communication systems
Multiple Access: CDMA and UWB impulse radio systems have been studied. Simple UWB architectures allow high data rates. For dense networks, an *ad hoc* approach induces space diversity and is more efficient. We also demonstrated the benefits of directive antenna and multiple users detectors (fig. 1) ***[A. Boé et al, Proc. EuMA 3, 228 (2006)]***.



gure 1: DS-CDMA BER with omnidirectional (omni) or directive (dir) antennas, matched filter (MF) or serial interference canceller (SIC) (ad hoc network, 80 interferers, 8 Mbits/s per user).

DMT/OFDM: we validated a multi-carrier transmission system, which fulfils bit rate and reliability constraints inherent to multimedia communications.In particular, a robust transmission scheme was proposed based on the use of embedded multicarrier modulations for unequal protection of transmitted data against channel errors ***[C. Goudemand et al, IEICE Trans. Comm. E.89-B, 2071 (2006)]***.
RoF-Optical CDMA: we proposed innovative methods for blind modulation discrimination and equalization based on non-linear non-convex cost functions for radio communications ***[I. Dayoub et al, Wir. Pers. Comm. 41, 225 (2007)]***. Moreover, we recently devised a linear receiver using the parallel interference cancelling (L-PIC), dedicated to transmission over purely optical or hybrid radio on fiber networks using optical CDMA codes. It outperforms conventional receivers.

Acknowledgments – Collaborations
TELECOM Institute (F), University of Kent (UK), Univ. of Concordia (Canada), SUPCOM Tunis.

II.4.3 Smart objects communication, sensors networks and 60 GHz high data rate WLAN / WPAN

Permanent Staff: A. Benlarbi, L. Clavier, M. Fryziel, C. Lethien , C. Loyez, N. Rolland, P.A. Rolland, S. Seok
Non Permanent Staff: A. Boé, M. Bocquet, N. Deparis, M. Devulder, J. Lin

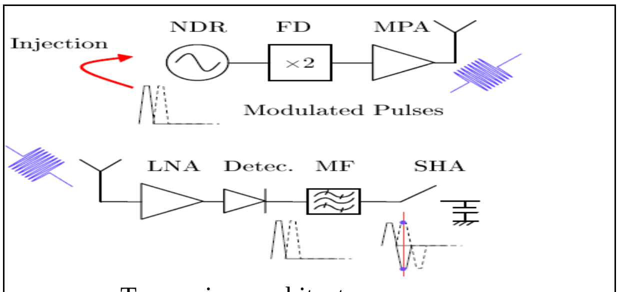
Objectives

This multidisciplinary work is developed in close collaboration with the laboratory of fundamental computing science of Lille (LIFL) in framework of the IRCICA Research Federation. IEMN is in charge of the physical and MAC layers while LIFL provides the communication middlewares and the routing algorithms using adaptative antennas. IEMN was among the first laboratories to propose in 1995 the use of the 60 GHz radio channel in combination with radio overfiber (RoF) networks for indoor communications. This work was extended to smart objects communication (SOC) in 2001 then to wireless sensors networks (WSN) in 2005 and finally to very high data rate WLAN / WPAN for wireless High Definition Multimedia Interface (HDMI) in 2006 with a major objective to create a generalized ambient intelligence.
In addition IEMN was a pionneer for the development of 60 GHz Impulse Radio Ultra Wide Band (IR UWB) communications for SOC and WSN as a friendly alternative to single or multi-carrier transmission techniques previously deployed with M-QAM modulation schemes. All the active and passive MMIC building blocks were designed, realized and tested using 0.2 and 0.1 µm GaAs P-HEMT technology (OMMIC foundry) and more recently 0.13µm BiCMOS technology (ST-M foundry). Complete functional 60 GHz communication systems were demonstrated over short distances ($\leq 10m$) with data rate up to 2Gb/s. In this report we will only focus on the most significant achievements concerning low-cost, ultra-low power radio modules and RoF networks as well as 0-level packaging as a first step towards Systems In Package (SIP).

Outstanding results

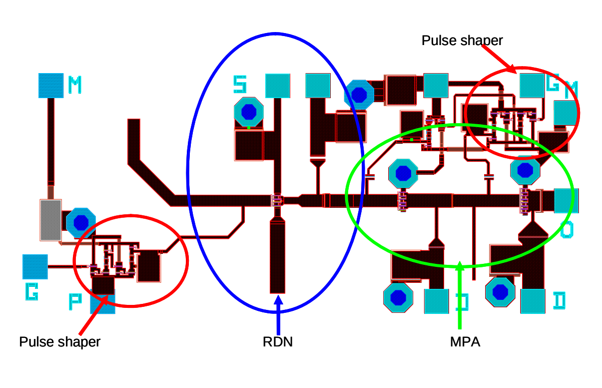
1) 60 GHz Ultra low-power IR-UMB transmitter with infinite ON/OFF dynamic for sensors networks and high data rate WLAN

UWB-IR technique with Pulse Position Modulation (PPM) for data transmission and Time Hopping Code Division Multiple Access (TH-CDMA) is used for communication between sensors network nodes because of its simplicity, its low power consumption, and its low sensitivity to fading and to the non linearities of the transmitter. In addition this technique when used with a non-coherent correlation detection does not need stable Local Oscillators (LO). To reduce the power dissipation the circuit described below was used for a 60 GHz IR-UWB transmitter.

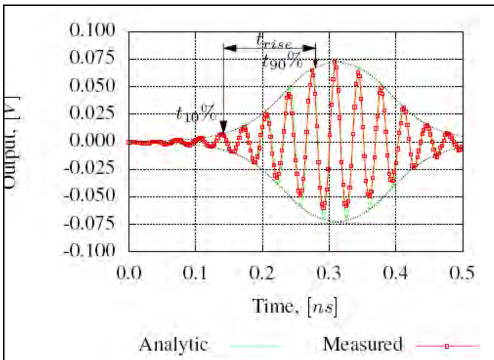


Transceiver architecture

A CMOS clock with a frequency ranging from 100 MHz to 1 GHz triggers a sub-ns pulse generator (50 pS to 1 nS, typically 300 pS) offering PPM and TH facilities which in turn switchs ON/OFF a negative differential resistance low external Q oscillator based on a 0.1 µm PHEMT technology via a pulse shaping circuit to achieve very short rise and fall times (typically 15 pS). Due to the rich harmonic content of such a pulse, the oscillator can be injection locked (ILO) on one of the numerous harmonic components of the pulse spectrum. Two kinds of harmonic ILO's were successfully tested : a 30 GHz ILO locked on the 60^{th} harmonic component of a 500 MHz clock followed by a frequency doubler and a 60 GHz ILO locked on the 60^{th} harmonic of a 1 GHz clock. Phase noise level as low as -110 dBc/Hz were measured @100 kHz offset from carrier for a 3dBm output power at 60 GHz. The 60 GHz ILO is followed by a MPA buffer amplifier also pulsed biased ON/OFF by a sub-nS pulsed generator triggered by the same reference clock. The output power of this MPA using also 0.1 µm PHEMT is 18 dBm at 1 dB compression.



60 GHz Transmitter layout using a pulsed ILO.



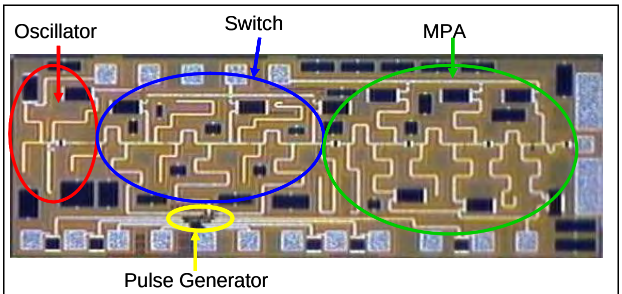
30 GHz output generated waveform

Deparis and al "60-GHz UWB-IR transceiver with pulsed-injected locked oscillator ". ECWT 2007, Munich, Germany, 280, 2007]

In addition to its compactness and its low power dissipation this original architecture exhibits an infinite ON/OFF switch ratio which limits the interference in multi users environment. This transmitter was used for a 4 m transmission together with a receiver involving a specific demodulation scheme. Up to 2 Gb/s data rates were demonstrated using burst mode transmission with a Bit Error Rate lower than 10^{-6}. For low data rate sensor networks the DC power Consumption can be kept below 100 µw for the transmitter and could be drastically reduced with CMOS technology. Note that this coherent transmitter could also be used with more sophisticated modulation schemes (BPSK, QAM) but at the price of more complex demodulation circuits.

2) 60 GHz IR-UWB transceiver in BiCMOS SiGe 0.13 µm technology

IEMN has already designed, realized and assembled complete and functional 60 GHz IR-UWB radio modules using P-HEMT technology. However despite the low-power design the DC consumption and the cost could be too high for autonomous objects. Thus we have investigated the full integration of the transceivers in a single MMIC chip using the ST-M 0.13 µm BiCMOS technology to reduce size, cost and consumption. Since the aim was to demonstrate the feasibility of such an integration a simple architecture with a 60 GHz SPDT switch was used. The corresponding MMIC circuit (size 2.15*0.75 mm^2) is illustrated below.



D*evulder M and al "UWB transmitter in BiCMOS SiGe 0.13 µm technology for 60 GHz WLAN comm.-unication" IEEE ICUWB 2007, Singapore, 2007].*

The main characteristics of the transmitter and the receiver are: * Transmitter : P out $_{-1dB}$ = 8 dBm, ON/OFF switch ratio = 40 dB, maximum data rate for single carrier operation 1 Gb/s.

* Receiver: LNA gain = 19 dB, NF = 6dB, detector sensitivity = 1 mV/µW. The overall consumption of this transceiver is close to 300 mW under CW operation and can be thus drastically reduced using burst transmission with low burst repetition factor. This work was presented at the IEEE International Conference on Ultra Wide Band, ICUWB 2007 Singapore and received the Best Paper Award.

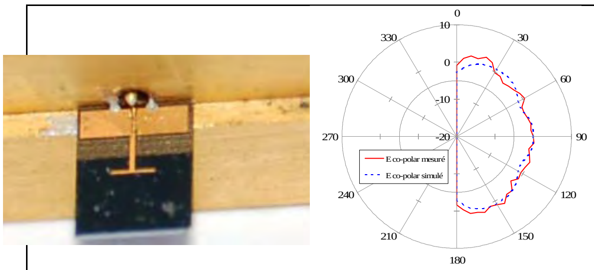
3) Smart Antennas

To obtain sufficient link budget for transmission over 10 meters distance antennas beam forming or beam switching is necessary to achieve space division multiples access which result in energy saving and in drastic reduction of the complexity of the routing algorithms mainly for sensors networks. Two kinds of antennas were developed:

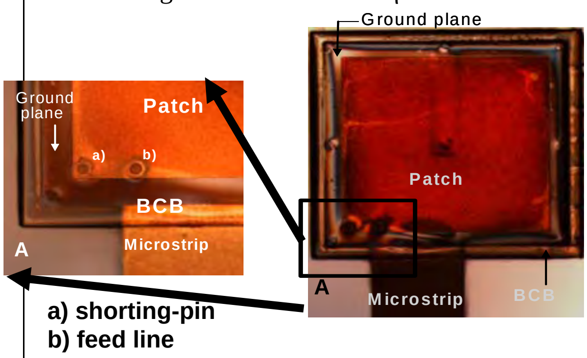
◆ Yagi antennas printed on high k substrates (Si or GaAs) offer reduced size, adjustable radiation pattern and high efficiency (>85%) if TE mode surface waves are used to couple the antenna elements. In addition these antennas have a balanced feed which makes them easy to integrate with differential PAs and LNA.***[BOE and al "Smart antenna based on RF MEMS switches and printed Yagi-Uda antennas for 6O GHz ad hoc WPAN. » 36th European Microwave Conference, Manchester, Sept 2006]***

◆ PIFA patch antennas printed on low K substrate (BCB for example in our SIP approach) vertically fed by via holes also offer reduced sizes an easy design but a low directivity. In this case the surface waves excitation must be minimized to obtain high antenna efficiency.

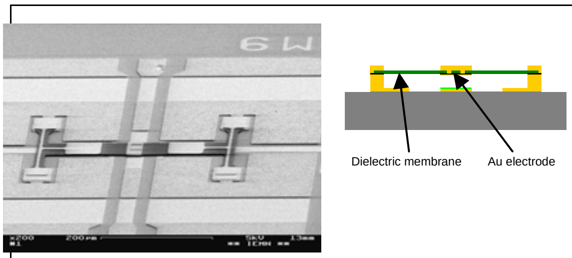
To achieve antenna diversity or beam steering MEMS switches or MEMS phase shifters are used. These MEMS functions were specifically developed for this application and will be further improved in the STREPS MEMSPACK and MEMS4MMIC.



60 GHz Yagi antenna on AsGa. η measured=85%

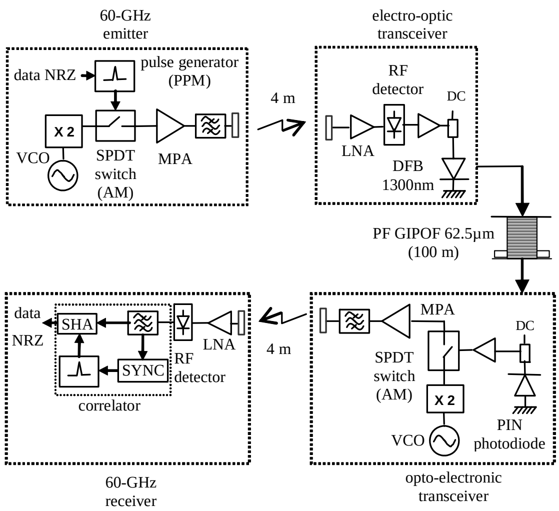


60 GHz PIFA antenna on top of a SIP



60 GHz capacitive MEMS with a dielectric membrane

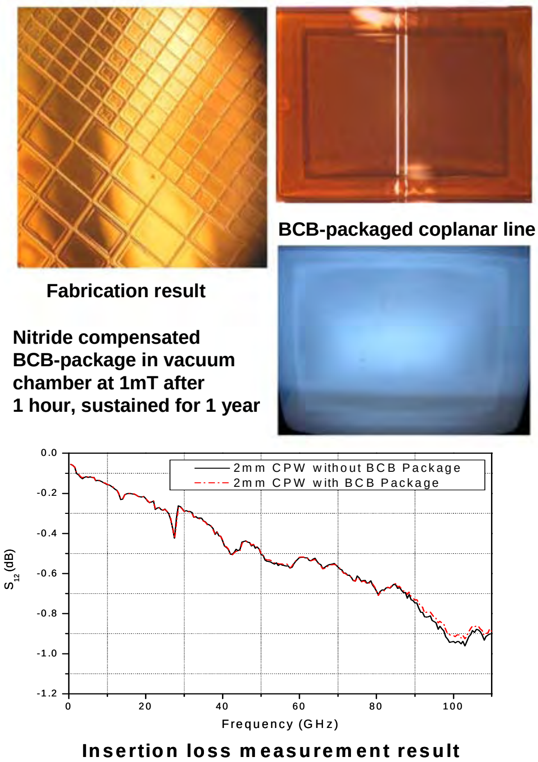
4) Increase of the connectivity of 60 GHz wireless networks using Radio over Fiber (ROF) System
An efficient 60 GHz RoF communication system was developed to extend the connectivity of 60 GHz wireless networks to a whole building. It is based on a reduced complexity architecture as depicted below and uses on-the-shelf commercial optical components. The MMIC transmitter using P-HEMT technology consists of a PPM-TH sub-ns pulse generator which modulates the 60 GHz source via a SPST switch followed by a medium power amplifier delivering 16 dBm output power. The optical transmission is based on the modulation of the intensity (IM) of a distributed feedback (DFB) laser operating at 1300 nm and on a direct detection (DD) technique in a large area PIN photodiode. For the optical transport of the sub-ns we used a perfluorinated gradex index polymer optical fiber PF GIPOF. The receiver includes a low noise amplifier (LNA@NF=6dB G=40dB) and a correlation detector which consists of matched filter and fast sampling and hold amplifier (SHA) triggered by a second pulse generator synchronized with the incoming signal using a specific synchronization technique. This quite simple and low-cost RoF system was successfully used for multihop point to point transmission with data rates up to 200 Mb/s and BER lower than 10^{-6}.



[C. Loyez and al. "An impulse system for 60-GHz wireless networks based on polymer optical fiber". IEEE Photonics Technol. Lett., 19, 24 (2007)]

In addition optically powered remote radio units was experimentally demonstrated with multimode glass optical fibers using WDM technology (WDM 850/1300 nm). This power over fiber technique includes a photovoltaïc converter (unbiased), a photo diode and a LNA. This simple approach could be quite interesting in situations where providing remote electrical power is difficult, expensive or hazardous.

5) 0-level packaging technology for mm. wave applications
For a global radio coverage of 60 GHz ad hoc networks we have developed smart Yagi antenna arrays with beam steering or switching facilities based on capacitive MEMS switches. However MEMS contains fragile movable parts and cannot be used without a package to protect them during at least wafer handling and wafer dicing. Thus we have developed o-level packaging technologies based either on pyrex glass or BenzoCycloButene (BCB) film using a wafer level BCB bonding technique to encapsulate RF MEMS and RF MEMS based MMIC functions. Note that to be compatible with a MEMS above IC approach the technological processes never exceed a temperature of 250°C. The figure below shows an example of 0-level BCB film package with vertical and horizontal interconnects and the additional losses induced by such packaging measured on CPW lines up to 110 GHz. One can see that the losses induced by the packaging are negligible (<0.02dB) up to 110 GHz which shows that this technique is quite suitable for microwave and mm. packaging.



[SEOK S., and al "Design, fabrication, and measurement of benzocyclobutene polymer zero-level packaging for millimeter-wave applications" IEEE Trans. Microwave Theor. Tech., 55, 5 (2007)].

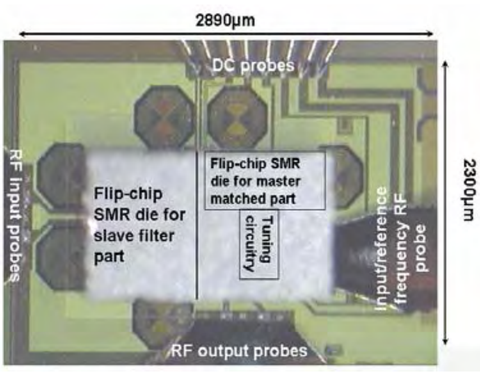
Acknowledgments – Collaborations
DGA, OMMIC, ST-M, CEA-LETI ,XLIM IMEC, VTT, Universitu of Perugia, NoE AMICOM

II.4.4 Digital circuits and communication

Permanent Staff: Andreas Kaiser, Nathalie Rolland, Bruno Stefanelli
Non Permanent Staff: Hassan Elaabbaoui, Antoine Frappé, Axel Flament, Benoit Gorisse, Jean Gorisse, Crépin Nsiala-Nzeza.

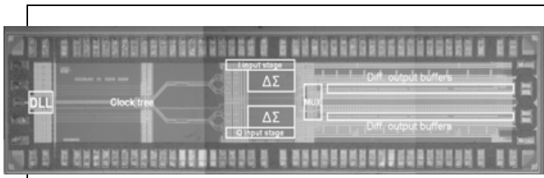
Objectives
This operation groups several research actions aiming at the introduction of flexibility and programmability into radio interfaces. With progress of the technologies, the focus is moving progressively from reconfigurable analog and RF circuits to digital hardware and even software.

Outstanding results
1) Reconfigurable analog base-band filters.
Order reconfiguration and digital tuning (patents pending) of wide-tuning range Gm-C base-band filters have been demonstrated in a 0.12µm CMOS process from STMicroelectronics at 1.2V supply voltage. A continuous tuning range of greater than 10 covers all standards for mobile communications.
2) Tuneable BAW filters and oscillators.
For the first time tuneable RF band filters using BAW resonators, active inductors and varactors have been demonstrated. The tuning range is sufficient to correct typical process impairments while sustaining the high linearity and low noise of passive filters. Compact integration is achieved through flip-chip SiP assembly of BAW resonators and IC components (0.25µm Si-Ge BiCMOS). Automatic tuning has been implemented through an amplitude locked tuning loop in a master-slave architecture. An integrated reference oscillator at 2.14 GHz with state of the art performance has been designed with minimal silicon area thanks to the SiP assembly.



Tuneable 2.14 GHz BAW filter with on-chip automatic tuning. Razafimandimby &al, ESSCIRC 2007

3) Digital generation of RF signal
Using high-speed digital logic, an all-digital flexible signal generator based on delta-sigma modulation has been designed in STM 90nm CMOS. RF carriers up to 1 GHz (3GHz in the 1st image band) can be synthesized directly in the digital domain. Non-conventional design of the modulator allows placement of NTF zeros onto critical frequencies such as nearby receive-bands of other standards. Semi-digital filtering of the quantization noise produced by the delta-sigma modulators has been demonstrated with a SiP assembly of a 65nm CMOS chip and a 5 channel power combiner in Integrated Passive Devices (IPD) technology. A peak output power of 18 dBm at 1V can be reached with 50Ω load. Integration of this approach associated with high-performance BAW filters into a multi-standard DCS/UMTS transmitter is the goal of the IST-MOBILIS project.



Digital Δ–Σ modulator in 90nm CMOS for direct generation of RF signals. A. Frappé & al. RFIC 2008

4) Ultra wide band high resolution electrical samplers
In close collaboration with CEA-LETI and CEA-DAM IEMN has designed and realized in GaAs PHEMT technology high resolution and ultra wide band digitizers (DC-8GHz BW, 6 ENOB and 60 dB DR) based on propagation lines and limited to single shot analysis of fugitive signals. To increase both temporal analysis window and sampling performance (goal 10 ENOB at 8 GHz BW and 40Gs/s sample rate,French MoD support), a promising new star architecture (patent pending) has been explored with InP Double Heterojunction Bipolar Transistors (DHBT) from OMMIC. It is divided into six blocks, each including two sampling channels, a clock propagation line to the next element and an inverter. Time-interleaved sampling occurs at 3.33 Gs/s, re-sampled to form 24 outputs at 1.67Gs/s, which can then be digitized with commercial 10 bits ADCs. Based on preliminary experimental results on InP DHBT trigger structures, system simulations predict a 3 dB bandwidth of 20 GHz, THD below -58 dB up to 10 GHz (ENOB > 9.5) and a 15 fs rms jitter (assuming an ideal clock). These results are much better than any other reported ones. New sampling blocks are now in foundry.

Acknowledgments – Collaborations
European Commission, ANR, ANRT, STMicroelectronics, EPCOS SA, AVIZA Technologies, CEA-LETI, CEA-DAM, DGA, Alcatel Thales3-5 lab, VTT, Université Pierre-et-Marie-Curie, IMS, XLIM, LAAS, University of Madrid, ENST, ENST Bretagne, C3SS-Supelec, Universitatea Politehnica of Bucarest.

II.4.5 Microwave and Millimeter Wave Non Destructive Characterization

Permanent Staff: L. Dubois, P.Y. Cresson, D. Glay ,T. Lasri, A. Mamouni, J. Pribetich
Non Permanent Staff: O. Benzaim, N. Bernardin, K. Haddadi, M. Maazi, C. Ricard, MM. Wang

Objectives

In this operation, research activities for the development of new characterization tools based on microwave and millimeter wave techniques are carried out. Hence, two main research topics are developed to perform quantitative characterization of the structures of interest. The first one concerns the analysis of subsurface defects at ever-smaller scales (micrometer) while the second one is related to the temperature monitoring inside powder materials by microwave radiometry.

Outstanding results

All the actions undertaken in this field require a specific development that encompasses the conception and realization of microwave or millimeter wave systems, the development of sensors, a modeling part (electromagnetic wave propagation modeling and/or thermal modeling) and the development of signal processing tools to retrieve the parameter of interest. In this context demonstrators have been realized for different applications.

On the industrial applications side, systems operating in the microwave or millimeter wave bands have been proposed to bring solutions in Non Destructive Testing fields. In that context, answers have been brought for the contactless characterization of subsurface defects in dielectric materials ***[M. Maazi et al - Sensing and Imaging - Int. Journal, Springer New York Publisher, vol. 7, n° 4, pp 125-154, (2006)].***

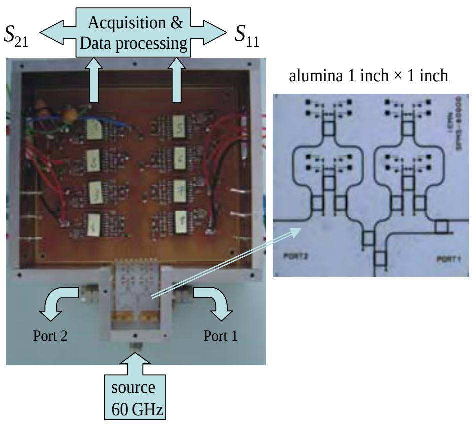


Fig. 1: Millimeter wave system operating at 60 GHz

The second outstanding result is taken in the microwave radiometry theme of our research activity. Actually, this technique appears to be an interesting measurement method in microwave sintering of metal matrix composites. The trend is to detect and avoid detrimental local overheating. This task is still challenging because the available commercial temperature measurement devices are not very efficient in the temperature monitoring inside heated parts. Experiments performed on powdered materials submitted to a high gradient of temperatures have proved the ability of contact-less microwave radiometry to follow internal thermal trajectories up to 1000°C. A radiometric device operating at 3.3 GHz has been implemented in a microwave oven designed at the EMPA (S. Vaucher, Switzerland). Very good results have been obtained even for fully metal powders when heated up to 600°C **[S. Vaucher et al – Physica B 398, pp 191-195 (2007)].**

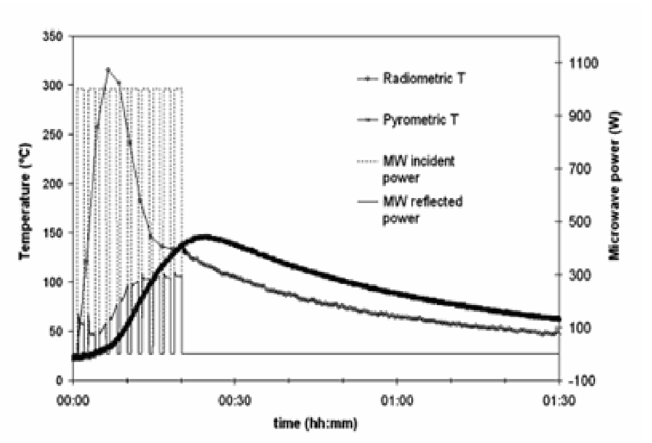


Fig. 2 : Comparison of temperature measurement obtained from an IR camera and a microwave radiometer for an aluminium powder sample placed inside an insulation layer.

Among the biomedical topics that have been handled a study devoted to the design and modeling of a specific microwave applicator for the treatment of snoring through a localized thermotherapy has been successfully completed **[P.Y. Cresson et al – IEEE Transactions on MTT, vol. 54, n°1, (2006)].** Studies on microwave dosimetry have also been tackled.

Acknowledgments – Collaborations

CEA-CESTA, CEA-LETI, Lille-Hospital (CHRU), Air Liquide, EMPA (Switzerland

II.5 ACOUSTICS

Introduction

The activity of the acoustics theme is provided by a group of 17 full-time equivalent researchers allocated on the three IEMN sites. The research groups “Acoustique ISEN”, “Ultrasons DOAE” and AIMAN are concerned with this activity. The whole activity of the acoustics theme includes, in the same time, works on physical acoustics, modelling and applications in industrial fields such as electronics, transports and biology. The works developed concern not only theoretical and fundamental approaches but also technological innovations in the field of sensors and associated instrumentation systems.

The activities can be divided in non destructive testing and material characterization on a wide dimension scale, modelling and design of acoustic wave resonators and filters using bulk, surface acoustic waves or phononic crystals and non linear magneto-acoustics.

Health monitoring structures: Structural Health Monitoring (SHM) systems based on the integration of thin piezoelectric transducers in the structures has led to promising results. The contribution consists in the modelling of a complete SHM system (emitter, receiver, wave propagation and defect detection). An original and simple 3D modelling has been proposed.

Acoustoelasticity and laser ultrasonics, applications to non-destructive testing: The research activities developed in NDT are mainly undertaken in the areas of acoustoelasticity and laser-ultrasonics. In the first area, the research was focused on the estimation of residual stresses in materials such as glass and in aeronautical engine ball bearings. The second area studied some properties of acoustic waves at the air-solid interface and their potential applications.

Design and implementation of low-frequency acoustic technique for non-intrusive fouling monitoring in plate heat exchanger: original compact and low frequency acoustic sensors have been developed for food products and food making process characterization.

Ultrafast acoustics: nanoscale acoustics using ultrashort laser pulses: femtosecond laser pulses provides picosecond ultrasonic pulses in order to study the elastic properties of very thin films and phonon emission from semiconductor quantum dots.

Phononic crystals and application to filtering: propagation of elastic waves in periodic structures led to band-gaps depending on the geometry and shape of the periodic elements. Filtering is then possible for electronic circuits applications.

Nonlinear magneto-acoustics: this activity is devoted to the study of magneto-acoustic waves phenomena in parametrically active materials. Application to phase conjugation is presented.

Acoustic Wave Resonators and Filtersthe research aims at modelling, designing, fabricating and characterizing flexible fully-integrated "single-chip" radiofrequency systems that can cover IF and RF frequencies. Advantage is taken of the ability of microelectromechanical (MEMS) resonators to provide high on-chip Q-factors using fabrication techniques that are compatible with modern IC processes.

Among results, only outstanding ones will be presented later on. They well illustrate the diversity of the activities as well as their originality.

Theoretical approaches, know-how and experimental means are gathered inside a network dedicated to acoustics and named 'Fédération d'Acoustique Nord-Ouest'(FANO) supported by the CNRS.The laboratories located in Le Havre, Le Mans, Tours, Poitiers and IEMN are concerned with this research network.

II.5-1. Health Monitoring Structures

Permanent Staff: J. Assaad; S. Grondel, E. Moulin
Non Permanent Staff: N. Abou Layla**.**

Objectives
For a few years, Lamb waves have been seriously considered as a potential technique for integrated damage assessment (or health monitoring) systems. This technique can consists in using thin piezoelectric transducers embedded within the plate-shaped structures to be monitored. Theoretical and experimental studies are based upon transient analysis.

Outstanding results
In order to help optimize such a system, a hybrid finite element - normal mode expansion modelling technique adapted to this type of transducers has been developed. This technique is used for viscoelastic (lossy) materials. For this purpose, simplifying assumptions have been proposed and validity conditions have been established and verified. Moreover, predicted results have been successfully compared to experimental ones.
[**L. Duquenne et al., , J. Acoust. Soc. Am. Vol. 116, 133, 2004]**. In order to take into account the finite length of an actual transducer, an original and simple 3D modelling, based upon the separation of the excited wave from the source diffraction, have been proposed [**E. Moulin et al, J. Acoust. Soc. Am., Vol. 119, 2575, 2006**.].
Finally, the scattering of the fundamental Lamb modes from discontinuities in isotropic plates is studied. Both finite element method and modal analysis are used to quantify power coefficients of the scattered waves from symmetrical and asymmetrical notches (Fig. 1), down- and up- steps. Mode conversions phenomena are only observed for the asymmetrical steps and notches case [**F. Benmeddour et al., NDT&E international, in press**].

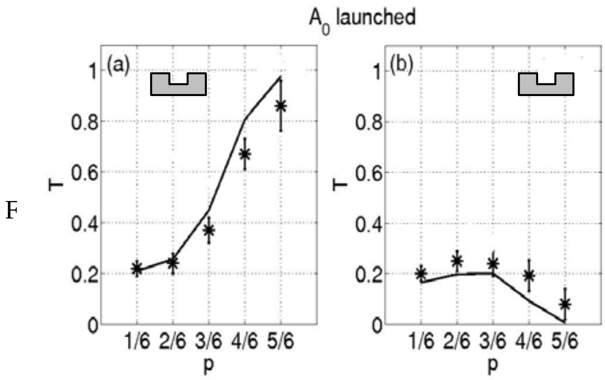


Fig.1*: Experimental results of the A0 (a) and S0 (b) power transmission coefficients when the launched (at the edge of the plate) Lamb mode A0 interacts with asymmetrical notches with different depth 2dp (2d being the thickness of the plate).*

Acknowledgement-collaboration
GDR2501, C. Paget ; Airbus (England). D. Osmont ONERA

II.5-2 Acoustoelasticity and laser ultrasonics: applications to non-destructive testing

Permanent Staff: M. Duquennoy, F. Jenot, M. Ouaftouh, M. Ourak
Non Permanent Staff : D. Devos

Objectives
The research carried out within the framework of this operation concerns the theoretical and experimental study of the interactions of ultrasound waves with different material characteristics or with defects. This research was carried out from our developments undertaken in the areas of acoustoelasticity and Laser-Ultrasonics.

Outstanding results
1) Ultrasonic non-linearities and residual stress
The characterisation of the state of stress, within the materials, is proving to be more and more necessary in the development of devices on a macroscopic and microscopic scale, as the performance of the mechanical parts is intimately linked to the distribution of their internal stress. Over the past four years, an important study has been devoted to the estimation of residual stress in amorphous media. On a

theoretical level, the acoustic non-linearities linked to the presence of stress were taken into account within the framework of the theory of acoustoelasticity. We have shown that it is possible to analyse the inhomogeneity of the residual stress in the thickness by exploiting the Rayleigh wave "dispersion", and on the surface using velocity variation for a given frequency [**M. Duquennoy et al, J. Acoust. Soc. Am., vol.119, 3773-3781 (2006)**]. To do this, different stress profiles (parabolic, linear,…) were considered and a finite elements model of the stress distribution due to thermal quenching was developed in collaboration with a team from the LAMIH (UMR-CNRS 8530). The good correlation (qualitative and quantitative) between the measured results and the model has shown the pertinence of our study and the performances of ultrasonic waves for the estimation of stress (fig.2). A second important point of our research concerned the estimation of stress in aeronautical engine ball bearings that are under very severe stress. In this case, the determination of the residual stress profiles was carried out on the first 60 microns under the surface with an extremely fine interval of 5 µm [**S. Desvaux et al, NDT & E Intern., vol.37, 9-17 (2004); vol.20, 9-24 (2005); J. Appl. Mech., vol.73, 342-346 (2006)**].

2) Laser ultrasonics
Some properties of acoustic waves at the air-solid interface were studied using laser-ultrasonics to optically excite and detect these waves [**F. Jenot et al J. Appl. Phys., vol.97, 094905 (2005)**]. In comparison with the leaky Rayleigh wave, a large amplitude was observed for the acoustic disturbance which is composed of Scholte and lateral waves. However, it was apparent from theoretical results taking source terms into account that the normal displacement of these waves could not be the larger in such an interface. Another explanation for the high intensity fluctuation measured was the optical heterodyne detection of the refractive index variation induced in the fluid. It was clearly shown that the transmitted, reflected or diffracted acoustic fields provide useful information about the position or the size of structures intercepting the propagation path. This suggests a lot of new applications in sizing of structures where non-contact measurements on inaccessible parts would be necessary. We were also interested in the characterization of thin films by laser-ultrasonics. In collaboration with Leuven University, different structures like gold layer deposited on silicon were studied in order to determine the film thickness or its elastic constants.

Acknowledgments – Collaborations
Laboratorium voor Akoestiek en Thermische Fysica (Leuven University), LAMIH (UMR-CNRS 8530), SKF (Rouvignie), Centres de recherche de St Gobain (Aubervillier), Glaverbel (Jumet, Belgique), Prelco (Rivière du Loup, Québéc).

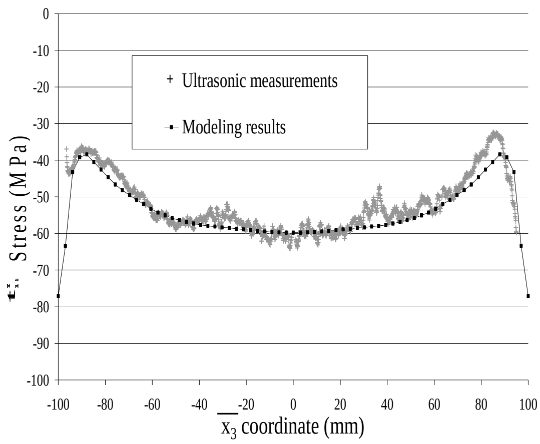


Fig.1*: Evolutions of the stress along the line in a flat glass for the ultrasonic measurement and the modelling.*

II.5-3 Design and implementation of low-frequency acoustic technique for non-intrusive fouling monitoring in plate heat exchanger

Permanent Staff: G. Nassar, B. Nongaillard**.**
Non Permanent Staff : B. Merheb**.**

Objectives
Food industry has a significant need for sensors making it possible to characterize the elaborated products and the manufacturing processes.¶ The first often have complex structures very absorbing with respect to the acoustic waves and the seconds present many stages of manufacture in which many physical parameters give rise to changes in the qualities of the product manufactured.¶ One of the significant parameters consists in the elastic properties of the product often measured through tests of rheology and often accessible through acoustic measurements. ¶We developed a set of sensors characterizing the dairy gel during the cutting step,

cheeses with strong opening and the bread dough during the phase of kneading then of fermentation.¶ We present here another aspect relating to the characterization of the manufacturing process, more particularly the in situ follow-up of the fouling of plate heat exchangers (PHE).¶ This work led us to develop a specific sensor and measurement method which provides new information useful for processing plans.

Outstanding results

A low frequency acoustic method was implemented for the purpose of non-intrusive monitoring of the PHE fouling in situ. A mechanical impact is used to generate acoustic vibrations over a frequency range between 100 Hz and 20 kHz, and multiple compact low frequency acoustic sensors are used to receive the transmitted acoustic vibrations. By analyzing the evolution of the acoustic wave parameters (e.g. power and delay), an indicator of the fouling rate is obtained for each zone inside the exchanger. The results of this analysis show that low-frequency acoustic waves are sensitive to PHE fouling and cleaning. Moreover, the evolution of the acoustic response (power or delay) depends on where the sensor is located on the exchanger **[B. Merheb et al, Journal of Food Engineering 82 (2007) 518–527]**. The decrease in acoustic power in fig. 3 is attributed to the growth of fouled layers. The response of the sensor S0 is different of that of the S2 sensor. This indicates that the rate of deposit is more important at the inlet of the PHE. The rise of the pressure drop confirms the global growing of deposit. Furthermore, during the cleaning phase, the acoustic power suddenly increases to rich its original value.

This non-intrusive acoustic technique can be used to monitor fouling and cleaning in real time, in plate heat exchanger.

Acknowledgments – Collaborations

*In collaboration with INRA-LGPTA, Villeneuve d'Ascq, France. (G. Delaplace, J-C Leuliet)

**This work has been supported by the FEDER & the Region Nord Pas-de-Calais.

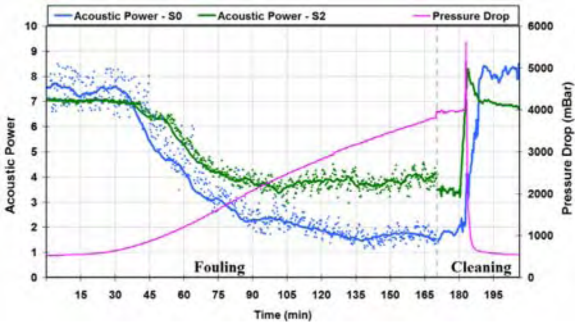


Fig.1: Evolution of the power of the acoustic waves received by 2 different sensors during the fouling experiment on a V2 PHE.

II.5-4 Ultrafast Acoustics: nanoscale acoustics using ultrashort laser pulses

Permanent Staff: A. Devos.
Non Permanent Staff : G. Caruyer, R. Côte, J.-F. Robillard, P. Emery, P.-A. Mante

Objectives

Femtosecond laser pulses in a pump-probe scheme offer an unique way of performing acoustic experiments in a frequency range which is inaccessible by conventional techniques (>100 GHz). This so-called ultrafast acoustics or picosecond ultrasonics provides a suitable method for studying the elastic properties of sub-micron films, hetero-structures and nanostructures. An experimental setup has been developed in our lab since 1999. Since then, we are particularly interested in the laser-wavelength effects on acoustic signals.

Here we focus on two recent advances: first an improvement of the picosecond acoustic technique for thin films metrology and the demonstration of a strong acoustic phonon emission from semiconductor quantum dots.

Outstanding results

1) Thin film Metrology

We explored from both the theoretical and experimental points of view the influence of the laser wavelength on the strain pulses detected in thin transparent layers using ultrafast acoustics. From a theoretical analysis of the displacement detection involved in such experiments, we predict amplitude and sign changes in the detected signals as the laser is tuned. Experimental results performed on various samples and at different wavelengths are found to be in excellent agreement with the theoretical description [**A. Devos et al. Phys. Rev. B 74, 064114 (2006)**].

From this, we proposed an improvement of picosecond acoustics dedicated to thin film metrology: we reached a much higher measurement accuracy and more physical parameters are extracted using several laser wavelengths. The potentiality of the improved technique has been demonstrated on Bulk Acoustic Wave resonators (BAW). A BAW resonator is something like a quartz resonator but works in the radio-frequency range using a micronic piezoelectric layer. The control of the frequency is a challenging question for the mass production of such devices promising object for RF filtering in mobile phone. A BAW resonator is a complex stack of thin layers composed of various materials. Furthermore, its resonance frequency is directly related to the thickness and mechanical properties of the materials, especially the piezoelectric layer. But performing mechanical measurements at such a scale is not so easy and we may say that BAW resonators constitute a challenging object for thin film metrology.

We have shown that ultrafast acoustics suits very well the mechanical characterization of these objects and that measurements can be pursued in realistic structures. More precisely, the high sensitive phenomenon described here could be very useful for in-line control of the thin piezoelectric layer. [**A. Devos et al. Patent WO 2006/136690**]

2) Quantum dots as a promising THz acoustic emitter

We performed ultrafast acoustic experiments in InAs/InP semiconductor self-assembled quantum dot (QD) layers. The sample reflectivities revealed strong echoes. A comparison between one- and two-color experiments and a fine analysis of the echo shape attest that a high magnitude acoustic phonon wave packet emerges from each single QD layer. This conclusion is supported by a numerical modeling which perfectly reproduces our experimental signals only if we introduce a strong acoustic generation in each QD layer. We explain such a strong emission thanks to an efficient capture of the carriers by the QDs [**A. Devos et al. Phys. Rev. Lett. 98, 207402 (2007)**].

This result demonstrates that QD is a very efficient acoustic phonons emitter which may also reaches the THz range needed for nanoscale acoustic transduction.

Acknowledgments – Collaborations

ST Microelectronics and CEA LETI (BAW project), FOTON, INSA Rennes (QD epitaxy), CEMES, Toulouse

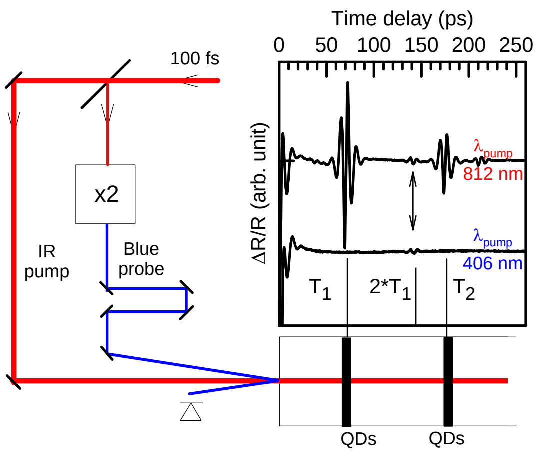


Fig.1: *Experimental setup and measured reflectivities on a 2 QD layers sample. The two sharp structures at T1 and T2 delays correspond to phonon wavepackets emitted from each QD layer detected only when* using *the infrared pump.*

II.5-5 Phononic crystals: application to filtering

Permanent Staff: A.-C. Hladky-Hennion, B. Djafari-Rouhani, B. Dubus, Y. Pennec, J. Vasseur
Non Permanent Staff: M. Bavencoffe, F. Duval**.**

Objectives

The propagation of elastic waves in periodic structures has received a great deal of interest for the last two decades. Among all the periodic structures, phononic crystals particularly attractive because they are exhibit absolute band gaps i.e. frequency bands in which the propagation of elastic waves is forbidden in all directions. These band-gaps arise under certain conditions, depending on the properties, the geometry and the shape of the inclusions. Thus, filtering is a possible application of phononic crystals and is presented here for two different cases.

Outstanding results

One-dimensional phononic crystals

The propagation of elastic waves through a one-dimensional chain of beads with grafted stubs is experimentally as well as numerically investigated. The results obtained by the two approaches are well correlated and show that the stub introduces a dip in the spectral response of the chain, which is related to the excitation of a stub mode (Fig. 5). It has shown that the frequency of the dip is mainly determined by the interaction of the waveguide with the first bead in the stub. The results allow potential applications for the filtering and multiplexing of elastic waves **[A.C. Hladky-Hennion et al, Phys Rev B, 77, 104304 (2008)]** (See also operation 1.7 Phononic crystals and Nanophotonics).

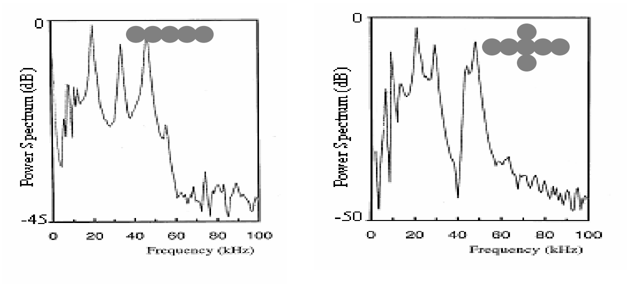


Fig. 1. *Experimental power spectrum of a chain made of five identical steel beads, without and with a symmetric stub grafted at the middle of the chain.*

Piezoelectric phononic crystal plates

Recently, the existence of absolute band gaps has been theoretically demonstrated for guided elastic waves in a piezoelectric plate on a substrate [**J.O. Vasseur et al, J. Appl. Phys., 101, 114904, (2007**)], which is a geometry of interest for possible co-integration on silicon chip. The aim of this study is to evaluate its consequences on the signal transmission through the phononic crystal, by taking into account the whole structure, containing the phononic crystal as well as the emission and reception devices. These numerical calculations also show that, even if the main part of the elastic energy is localized in the phononic crystal layer, a part of the waves can propagate in the substrate, which can degrade the filtering capability of the device. The filtering capabilities of the phononic crystal are validated by the modeling of the whole structure, including the PZT plate with five rows of holes, the silicon substrate, and the interdigitated electrodes (IDEs) for the signal generation and reception. The emission and reception IDEs are identical. The frequency of interest is 1.5 GHz, which is exactly at the middle of the absolute band gap. The signal received on the reception IDE is analyzed and presented in the frequency space (Fig. 6). The signal is compared to the signal get when the PZT layer is without holes. With holes and at 1.5 GHz, an important attenuation (17.1 dB) is observed on the frequency response curve (Fig. 6) because this frequency is in the absolute bandgap of the phononic crystal **[A.C. Hladky-Hennion et al, Proc. IEEE Ultrasonic Symp.620 (2007)]** (See also operation 1.7 Phononic crystals and Nanophotonics).

Acknowledgments – Collaborations

M de Billy, Institut Mécanique Jean Le-Rond d'Alembert, Université Paris 6

B. Morvan, LOMC, Université du Havre

This work was supported by the French Ministry of Industry (Nano2008 program) and by STMicroelectronics Company, Crolles, France.

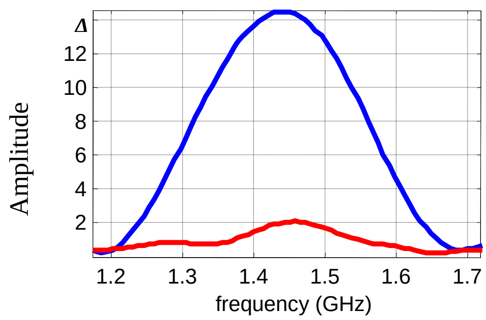


Fig. 2. *Frequency spectrum on the reception IDE. Blue curve: device without holes, red curve: device with 5 infinite rows of holes.*

II.5-6 Nonlinear magneto-acoustics

Permanent Staff: P. Pernod, V. Preobrazhensky, O.Bou Matar
Non Permanent Staff: Yu.Pyl'nov, A.Brysev, L.Krutyansky, M.Ivanov, N.Smagin, P.Shirkovsky, V.Rudenko

Objectives

This chapter contains the results of studies of new magneto-acoustic wave phenomena in parametrically active materials obtained in the laboratory LEMAC last year. In the first paragraph the first results of experimental observation and theoretical description of the new parametric phenomenon that is the three phonon coupled excitation in solid are reported. The new method of phase conjugation for low frequency ultrasonics using Brillouin scattering of acoustic waves is reflected in the second paragraph.

Outstanding results :

1)Explosive instability and localization of three-phonon excitations

The study of supercritical parametric excitations of ultrasound waves in magnetic media is one of priority directions of LEMAC activity. In the classical meaning parametric instability of ultrasound in magnets suppose generation of coupled phonon pairs by RF magnetic field. In the present study we observed for the first time, on an example of antiferromagnetic crystal α-Fe_2O_3, the supercritical generation of coupled triad of phonons under RF magnetic pumping in solid **[V. Preobrazhensky & al., JETPh Letts, 86(5), 348, 2007]**.

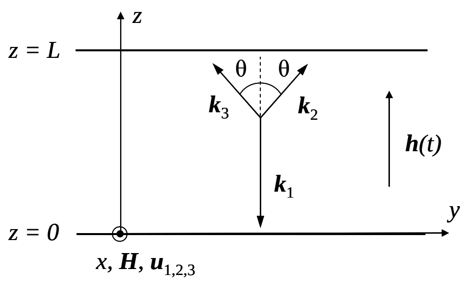


Fig.1 *Three- phonon coupling of traveling waves*
Energy and pulse conservation conditions:
$\Omega_P = \omega_1 + \omega_2 + \omega_3$; $k_1 + k_2 + k_3 = 0$.

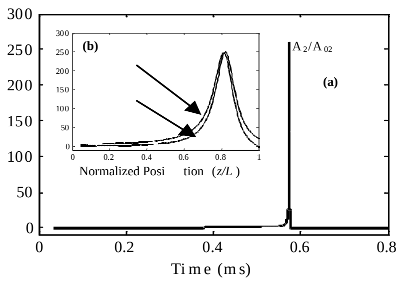


Fig.2 *"Peaking and localization" of acoustic field*

The specific feature of observed phenomenon, marking it out from classical parametric instability, is the development of singularity of acoustic field at a finite duration of pumping that is typical for explosive instabilities. The theoretical analysis show that three-phonon explosive instability of traveling ultrasound waves (see fig.7) is accompanied by space-time "peaking and localization" of acoustic field (fig.8). The phenomenon under consideration is expected to be used for large band and high power formation of scanning and phase conjugate ultrasound beams.

2) Phase conjugation of the Stokes component of Brillouin scattering of ultrasound**.**

The range of studies in the field of wave front reversal of ultrasound and its applications in nonlinear acoustic imaging and diagnostics is continuously extending. Parametric wave phase conjugation (WPC) is now one of two main principle of ultrasound wave front reversal on level with multi-channel electronic time reversal technique. The efficiency of supercritical parametric WPC, providing wave front reversal with giant amplification, increases with increasing of carrier frequency of ultrasound. Last year application of high frequency (HF) parametric WPC for phase conjugation of low frequency (LF) wave was demonstrated experimentally (fig. 9) and described theoretically. For WPC of the LF wave, magnetoacoustic parametric interaction combined with Brillouin scattering of HF phase conjugate waves was used successfully **[Yu. Pyl'nov & al., Phys. Wave Phenomena, 15(2), 111, 2007].**

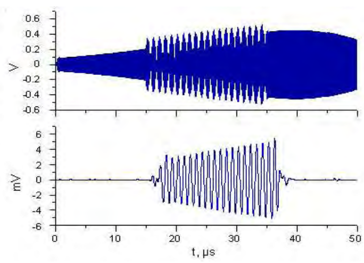


Fig. 3 *: Oscillograms. a) Mixed HF and LF signals.*
b) LF signal emitted by the parametric antenna

Acknowledgments - Collaborations :

Wave research center of A.M. Prokhorov GPI (Russian Academy of Science), Moscow Institute of Radioengineering, Electronics and Automation (MIREA), Taurida University. Work made in the frame of the European Laboratory LEMAC, ECO-NET and PHC programs.

II.5-7 Acoustic Wave Resonators and Filters

Permanent Staff: B. Dubus, T. Gryba, J.E. Lefebvre, V. Zhang.
Non Permanent Staff : L. Elmaimouni, A. Raherison.

Objectives
Trends in telecommunications standards call for smart mobile terminals with more and more sophisticated functionalities without size, cost and electrical consumption increase. Design of selective acoustic wave filters compatible with standard IC-technology remains an important topic for theoretical and applied research. We address both physics and engineering issues i) by developing semi-analytical models and associated softwares helping at designing Surface and Volume Acoustic Wave (SAW and BAW) resonators and filters and ii) by designing, fabricating and characterizing filters on Silicon to validate solutions to industrial key issues.

Outstanding results
i) Semi-analytic models. All the acoustic devices, resonators, filters, rely on the use of plane multilayered structures. With some approximations justified by the physical behaviour of studied structures, a quite general semi-analytical Stroh formalism-based impedance matrix modelling is developed. It allows to take into account, for the layers and the possible semi-infinite substrate, any type of material, metallic, dielectric, piezoelectric. This model, unlike usual scalar models, takes into account all the possible acoustic waves in the direction studied. The matrix approach is combined with a network approach where any layer and the possible semi-infinite substrate are represented by an equivalent network with all the advantages associated to a representation through cascadable equivalent circuits. Introducing the impedance matrix allows the model to be free from the numerical instability suffered by the transfer matrix method. The obtained tool is powerful and efficient, able to model any structures involved in BAW resonators and filters, Film Bulk Acoustic Resonator, Solidly Mounted Resonator and Coupled Resonator Filter. **[V. Zhang et al, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, accepted November 7, 2007].**

	1st short circuit	1st open circuit	2nd short circuit	2nd open circuit
FEM	0.99	1.29	2.47	2.49
Experimental	0.91	1.22	2.45	2.51
Polynomial	0.94	1.26	2.43	2.45

Table : Resonant frequencies of a 1.53x0.61mm^2 resonator: FEM and experimental results taken from literature.

Finite lateral dimensions of the structures can give rise to parasitic lateral resonances able to affect resonators and filters performances. A semi-analytic polynomial-based model allowing bidimensional modelling of the BAW structures studied is developed. Results for a rectangular resonator demonstrate bidimensional potentialities of that polynomial modelling:

ii) Filters for industrial applicability
Coupled Resonator Filter for W-CDMA applications
Bulk Acoustic Wave (BAW) filters are usually based on ladder or lattice topology with BAW resonators electrically coupled. These filters are only fully single-ended or balanced whereas standards like GSM or W-CDMA require mode conversion and impedance transformation. We report the design, manufacturing and characterization of BAW Coupled Resonator Filter (CRF) for W-CDMA applications [**A. Volatier et al – IEEE 2006 Ultrason. Symp. (2006), 829-832**]. Aluminum nitride resonators with molybdenum electrodes are acoustically coupled through a W/SiO_2 multi-layered stack and insulated by a fully dielectric SiN/SiOC Bragg mirror. This configuration provides galvanic insulation between input and output making CRF suitable for single-to-balanced conversion. Measurements of both single-ended and single-to-balanced filters display bandwidth and out-of-band attenuation close to W-CDMA specifications (fig10).

Acknowledgments – Collaborations
Part of the BAW works was performed by B. Dubus and V. Zhang under the joint Lab of IEMN-ST.
F. Ratolojanahary: univ Fianarantsoa (Madagascar).
E. Defaÿ, M. Aïd : CEA-LETI, Grenoble – P. Ancey, J.-F. Carpentier : STMicroelectronics, Crolles.

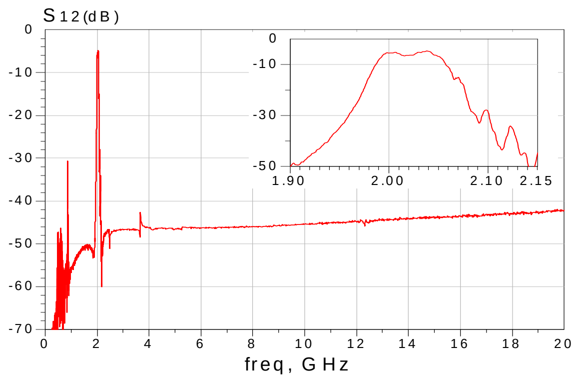


Fig.1 *Coupled Resonator Filter transmission response realizing Single-to-differential and 50-to-200 conversions*