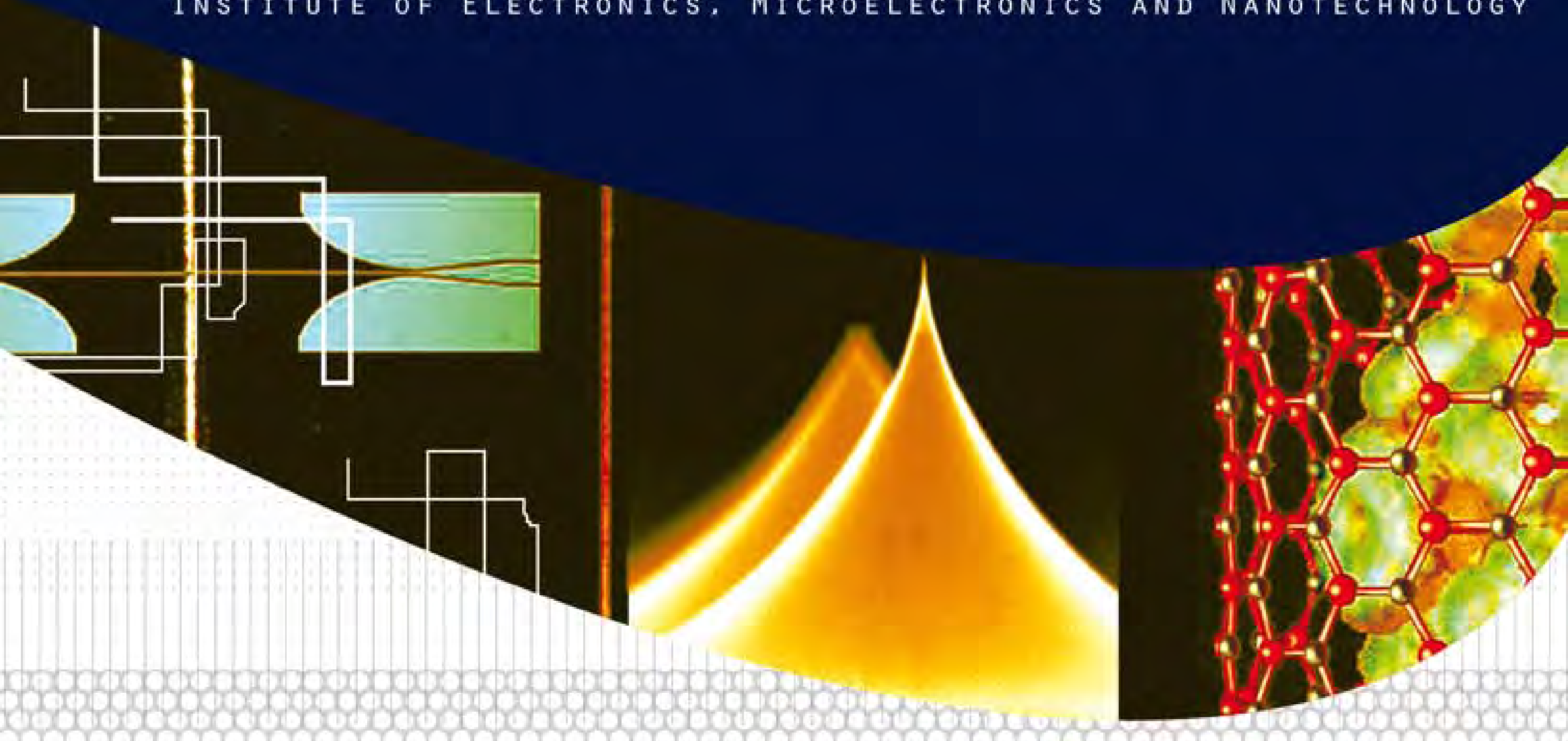
IEMN Project for 2010 - 2013

INSTITUTE OF ELECTRONICS, MICROELECTRONICS AND NANOTECHNOLOGY



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I Presentation of IEMN

I.1 Introduction

IEMN project for the period 2010-2013 has to consider the regional, national and international contexts.

The regional context : IEMN is partner of two important projects of the state region project contract (CPER) covering the period 2007-2013: The Ambient Intelligence campus and the international campus on security in transport. As a consequence all the scientific activity included in these two projects will continue up to 2013. It is worth noting that IEMN – owing to these activities - begins to develop promising partnerships with regional industrial and trading companies grouped in the 'pôles de compétitivité' PICOM, MAUD and I-TRANS. Another parameter is the creation of a large institute called 'IRCICA' which is devoted to ICT (from basic physics to ubiquitous computing) located on the USTL campus. IEMN is strongly involved in this project gathering 7 laboratories of the USTL campus.

The national context : The creation of ANR and the evolution of the internal structure of CNRS are two important factors that are to be taken into consideration in our strategy. The main consequence of these two factors is that the recurrent support of IEMN is decreasing continuously while the support of well defined scientific projects is increasing through call for proposals. **The main consequence is that the scientific strategy becomes more and more a research group strategy and less a coherent laboratory strategy**. Due to the lack of recurrent support it becomes difficult to propose and support internal research projects. The novel IEMN organisation which will be described later will try to solve, at least partly, this difficulty. It should also be noted that in France as in the other european countries, the number of high skilled french students which are applicant for a PhD is decreasing. As a consequence, our recruitment has to be more international. To do that, the complete change of our website presenting our activity for international students is one response.

The international context : Two main factors have to be taken into consideration. The development of intense research activities in Asia (China, India, Korea…) with important manpower and the rapid evolution of the micro and nanoelectronic business in Europe. The first factor requires us to increase our collaborations in Asia: a project of international laboratory with NTU (Singapore) will be described later. The second factor needs **a complete revision of our scientific policy in micro and nanoelectronics** with for instance the development of activities on the 'intelligent object' concept as well as in the field of energy harvesting. All these evolutions will be described in the scientific part of this report.

According to these different constraints and uncertainties as well as the analysis we have made of IEMN scientific activity during the period 2004-2007, it was decided not to change significantly our management and scientific policies in the future. However, although our project is mainly based on continuity with the past period, we propose some improvements in different fields described below in order to reduce the impact of some identified weaknesses**.**

I.2 Management and organization

Since the creation of IEMN in 1992, the management has been based on three departments (DHS, ISEN and DOAE).These departments were the trace of the three laboratories which decided to merge in 1992. After more than 16 years of evolution, the necessity of the department existence is less and less effective. Many research groups are not associated with only one department but are now composed by scientists that are associated to CNRS and universities (USTL or UVHC) or ISEN. This is a clear indicator of the success of the IEMN model as proposed by its creators. We are now convinced that our management has to fit more efficiently with its scientific organization that is based on five research axis:

- **Physics of nanostructures**
- **Micro and Nano Systems**
- **Micro- Nano- and Optoelectronics**
- **Communication Systems and Application of Microwaves**
- **Acoustics**

So, **we proposed to diminish the administrative role of the department and to increase the research axis one** as follows:
Each research axis is leaded by a scientist in charge of:

- The scientific animation (meetings, seminars).
- The human resources and investment policy (what are the new equipments we need, what are the students, post-docs, engineer, technicians we need to reach the axis scientific objectives).
- The connection between the laboratory management committee and the scientists of the research axis. The representation of the axis activity for visitors (scientist, faculties, industry, funding, agencies, …)

This management evolution was initiated during the year 2008 and we would like to completely adopt the scientific activity based management on january 1st, 2010 at beginning of the new four years contract.

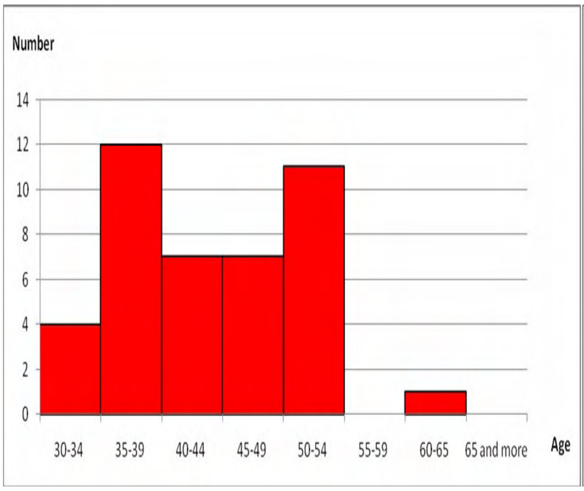
I.3 Director and deputy director change

IEMN deputy director, Dr Didier Stievenard, is in place for 11 years and IEMN director Prof. Alain Cappy leads the laboratory for 7 years. **Both decided not to renew their mandate at the IEMN direction.**
The laboratory council proposed that the new direction could be Dr Lionel Buchaillot, senior scientist at CNRS as director and Prof. Gilles Dambrine as deputy director.
The present IEMN direction fully agrees with this proposal of the laboratory council and is ready to organize the transition as soon as possible. The future direction will have the mission to put in place the new laboratory management based on the research themes rather than the original department based organization described before.

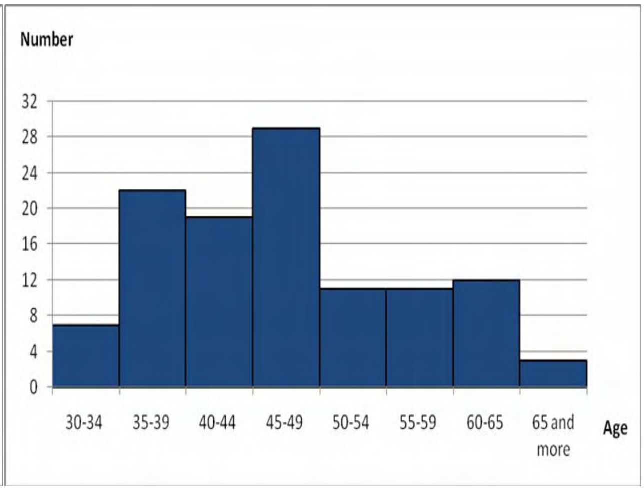
1.4 Human resources

During the 2004-2008 period, the number of **permanent** positions has slightly increased at IEMN . The increase was about 10 % for the professors/associate professors, 20 % as for CNRS scientists while the number of engineers and technicians remains almost constant during the same period. The main consequence of the constant number of administrative and technical permanent staff is that IEMN had to recruit many engineers and technicians with non permanent status to accompany the growth of the scientific staff.

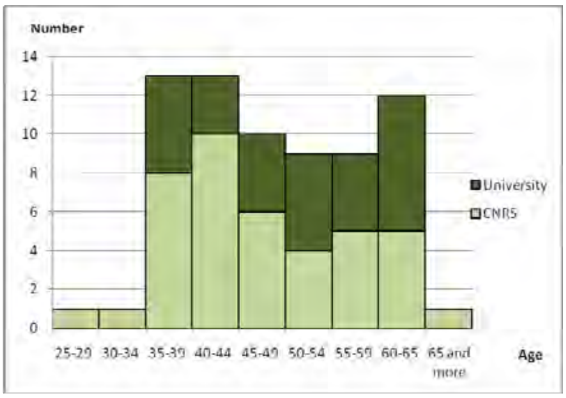
The histograms of ages for the different personnel categories in january 2010 are given below:



CNRS scientists



Professors and associate professors



Engineers and technicians

It is clear from these figures that no significant retirement departure of CNRS scientists will occur in the next years while about two professors/asociate Professor and two engineers and technicians will leave IEMN each year in the period 2010-2013. Our human resource strategy has to take this fact into account.

According to these data and also to our scientific project, it is possible to define our strategy in the human resource domain as follows.

- First, the growth of IEMN personnel is not our objective. With about 500 persons including students, IEMN can be efficiently managed, that could not be the case with 600 persons or more. Our increase in the period 2010-2013 will be light and restricted to few professors, associate professors and CNRS scientists who ask to joint IEMN in 2010. As it will be explained below, all these people have been working with IEMN for a number of years and their skills and competences are very well suited with our scientific strategy.
- Second, our priority is to attract the best master students, PhD students and post docs because they are the main research force and the future IEMN scientists. So, we have to increase our attractiveness by several means: better education by our personnel, customized following of each student, keeping of our infrastructure and equipments at the best european level, and, last but not least, an improvement of our communication policy especially through our new web site.
- As far as the engineers and technicians are concerned, our priority is to keep, or even slightly increase, the permanent position in the common services that are the technological and measurement facilities as well as in the central administration. It should be emphasised that a number of administrative positions are non permanent and supported by the laboratory with a significant risk of turn over and consequently loss of expertise and know how. **Stabilisation of these personnel with permanent positions is a real concern.**

Teams joining IEMN in 2010

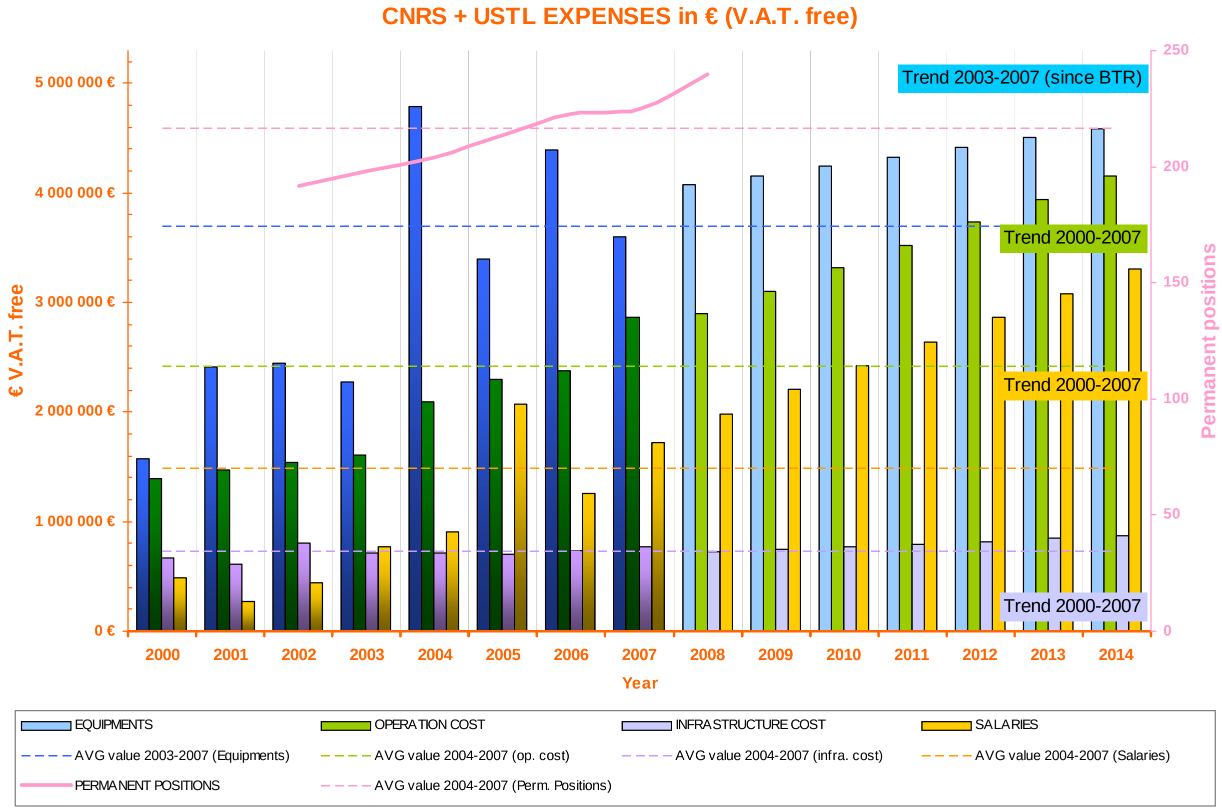
Two teams will join IEMN in 2010. The research team FILMS, presently members of the 'Laboratoire de Mécanique de Lille' and the team GEPIFREM which is an independent laboratory ("équipe d'accueil") of USTL.
The team FILMS is constitued by four persons: One professor (A. Merlen), two associate professors (F. Zoueshtiagh and M. Baudouin) and one CNRS junior scientist (P. Brunet). The scientific activity of this group is mainly devoted to fluid dynamics. Alain Merlen's team has been collaborating with IEMN for several years and 10 common papers were already published including 3 in 2007 and 1 in 2008. Presentation of the FILMS team is given in annex 1.

The team GEPIFREM is constituted by six persons: two Professors (P. Supiot and C. Mutel), two associate professors (C.Vivien and C. Foissac), one Research Engineer (to be recruited) and one technician (C. Malas). The scientific activity of this team is devoted to polymer deposition by low temperature plasma and plasma diagnostics. Philippe Supiot's team has also collaborations with IEMN for several years with recently 1 common paper and 4 common international conferences (1 under refeering). Presentation of GEPIFREM team is given in annex 2.

Why the integration of these teams? For the FILMS team, the collaboration with the AIMAN group led by P. Pernod is now so tight and their scientific objectives are now so common that it is clearer to integrate this team within the AIMAN group. For GEPIFREM, the activity of this team is process engineering oriented and centred on plasma techniques. We do believe that according to the past and the good collaboration between GEPIFREM and IEMN technological activity, the integration makes sense and is a good opportunity for both parts.

1.5-Financial resources

To reach our scientific objectives, the budget control is essential. The figure below presents a projection of the four expenses categories (investments, operation cost, infrastructure cost and salaries) for the period 2010-2013. This projection was calculated according to the variations observed during the preceding period and linear extrapolation. This projection was considered as reasonable at least as general trends and as minimum objectives in the case of equipments.



- **Investment** bar corresponds to small, medium or large equipments. Most of the budget is used for our technological and characterization facilities and our near field microscopy and telecom platforms. To allow a continuous upgrade of our equipments the equation is rather simple. About 30 M€ equipments (price 2008) are gathered in our facilities and platforms. If we consider that the average lifetime of equipments is 10 years we need about 3M€ a year for the replacement of old equipments without any significant improvement of the facilities and platforms capabilities. To allow the development of new experimental techniques and new fields of research the extra investment annual cost is about 1.5 M€ as shown in the investment projection (blue line) in the figure. How to get this budget each year? The situation was significantly changed since the beginning of the Basic Technological Research (BTR) programme aiming to improve the quality of the academic clean room facilities in France. Since the beginning of the BTR programme in 2004, IEMN invests 7.6 M€ in the technological facilities that is about 1.9 M€ each year (VAT included). Many old machines were then replaced that explain, at least partly, the improvement of the scientific IEMN production in the last years. The importance of this programme was huge and it is of primary importance for IEMN that this specific support continues in the future, through the 'large equipment' project called RENATECH for instance. For the other experimental domains (electrical characterization, near field microscopy and telecom) the main source of funding for the medium and large equipments is the CPER (Region State Project Contract) that was signed for the 2007-2013 period and thus that will continue up to 2013. In conclusion, if BTR programme continues with the same level of funding, IEMN could maintain its objectives in terms of state of the art equipment quality.

The extension of the central laboratory: a priority project for the next years. The past and scheduled increase of the number of scientists at IEMN leads to a severe lack of room to welcome new people and new experimental laboratories in good conditions. The extension of the central laboratory with additional offices and laboratory rooms is the unique solution for IEMN to allow its future development and good working conditions. The budget for this extension is estimated to 3 M€ for 1500 m^2 of additional surfaces.

- **Operation cost** bar corresponds to the cost of the scientific activity (consumables, travel and subsistence….) A significant part of this operation cost can be related to the technological facilities. The projection for the next years shows a slight increase related to the growth of IEMN staff. The main part of the funding comes from research contracts provided by national and international funding agencies. Our objectives in the next years will be to limit the increase of this operation to the minimum keeping in mind that the research quality is the unique goal.

- **Infrastructure cost** bar corresponds to buildings maintenance and basic expenses to allow these buildings to be usable (electricity, heating, clean room air conditioning…). Infrastructure cost was almost constant during the last years and for the projection, the live cost (3 % a year) was only taken into consideration

- **Salaries** bar corresponds to non permanents positions: administrative and technical staff directly paid by IEMN (about 0.5 M€ a year) as well as post-docs other non permanent scientists. As for the operation cost, this cost is directly related to the scientific activity and it is not surprising that the two increase slopes are similar. The incomes for the salaries came mainly for research contacts.

As explained in the 'Activity report 2004-2008' document, IEMN budget is more and more dependent on research contracts since the annual support (CNRS and ministry of research) is decreasing. The main difficulty is now to promote new research activities not supported by contracts. We believe that this trend is very risky for the future and that IEMN direction should have the possibility to directly support some research activity. In addition, since the use of the funding of more and more research contracts is dedicated (i.e. EU projects) and the level of overheads too low (i.e. ANR contacts), it is more and more difficult to pay common expenses as the infrastructure or some administrative non permanent positions. This deep change in the laboratory financing mode is dangerous and it could have a very negative impact on the scientific activity and could introduce many difficulties for our financial department to pay the common expenses.

1.6 Animation and education policy

In large multi site laboratory like IEMN, efficient scientific and technological animation is a requirement but also not easy to set up. Three levels of animation, already effective will be developed. The first level concerns the research group (IEMN is constituted by 18 research groups) and is under the responsibility of the group leader. The second level concerns the 5 research axis (Physics of nanostructures, Micro and Nano Systems, Micro- Nano- and Optoelectronics, Communication Systems and Application of Microwaves and Acoustics). Each axis responsible has the duty to organise the scientific animation of his axis trough meetings and seminars. From these scientific exchanges at the axis level, the investment and human resource policies are proposed to IEMN direction. The last animation level concerns the whole institute and is organized by the direction of the institute. This concerns general meetings when important questions have to be discussed, workshops on specific topics as well as annual events such as the research forum or the PhD open day. These event organizations will continue over the 2010-2013 period.

<u>IEMN education plan for 2010-2013</u>

Each year about 50 persons follow specific training to improve their personal skills and competences in different fields: scientific, technical, management, safety and security, english, software……. This continuous education program will continue in 2010-2013 and four main domains are already defined;

- Adaptation to the job: individual education for new personnel. Knowledge of the environment
- Evolution of the jobs: new skills and competences
- Personal evolution: individual education plan to prepare competition for better position
- Needs for development of new competences asked by the management

Education also concerns master students, PhD students and post-doc. To allow an efficient link between education and research, master student (M1 or M2) will be soon integrated in research groups and actual research subjects will be proposed to them. In this field, our policy is to increase research activity of undergraduate students as it is done in many countries. For PhD students, we will continue to push them to follow some master courses to complete their knowledge in specific domains and to follow the seminars and PhD or 'habilitation' defences (about 35-40 a year) that are probably a mine of information that is not enough used. For post-docs, it is important to propose them a high level education in new research field or new technique to complete their knowledge and to facilitate their employment in academic laboratory or industry.

1.7 International collaboration

IEMN's international relations objective is to further promote its research and teaching cooperation with universities and research laboratories around the world. This is done under various schemes jointly funded by national and international agency research programs, internally funded projects, collaboration through the strengthening and in certain cases initiation of new Mixed International Units sponsored by CNRS and the linking to partners from the industry. IEMN's strong link to USTL and other universities of the Northern France Region eases the establishment and maintenance of strong research and teaching partnerships. A good example of the international relations strategy is the pursuance of double degrees at the graduate level that leads to Masters and/or doctoral degrees. Partnerships of this type have for example been established with Georgia Tech at the Masters level and are also explored at the doctoral level. A similar strategy was adopted in the relations with NTU in Singapore and the University of California in Irvine. The availability of graduate students playing an active role in research conducted at IEMN, while at the same time interacting with international partners provides a unique way for strengthening the research cooperation links between partners, while at the same time allowing them to grow and expand towards new heights. The benefit for the participating student is undoubtedly significant since they obtain a global view of science and culture that is nowadays indispensable for a successful career. The establishment of further partnerships will best serve the international research and teaching perspectives of IEMN worldwide.

1.8 Valorisation and industrial partnership

A large part of IEMN scientific activity is performed in tight collaboration with industry. This will continue in 2010-2013 and our objective is mainly to improve the quality of our partnership rather than increase or decrease the quantity of industrial partners. In order to achieve this goal, the 'industrial relation' direction will be reinforced in the frame of the 'Carnot Institute ' in particular. The role of this direction will be slightly changed to meet with the Carnot requirements, especially the definition and application of an actual partnership strategy consisting in associating the industrial partners in some of our scientific objectives. In addition, IEMN has to be more concerned with the social needs (health, energy, sustainable development,…) to open new fields of collaboration.

In fact, IEMN has to work with two different type of industrial partner: SMEs and more particularly local SMEs and large national and international companies.

The SME case is probably the most difficult. We will continue to actively participate in professional organisms like 'Electropôle' representing the regional SMEs working in the field of electronics in a wide sense. We will also continue to propose to these SMEs regular seminars of technological survey called ' Club Pionniers' that allow to improve the innovation culture and to prepare new collaboration programmes, especially in the frame of the regional 'pôles de compétitivité'.

For the large companies, we will continue to promote the idea of common laboratory IEMN-Industry that has proved to be very efficient in the past, especially for patenting.

1.9 Hygiene and safety

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, IEMN aims to create in the area a laboratory of European size. For this reason, 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.

This team has as a permanent goal of implementing the means necessary 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 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.

<u>Identification and analyses of specific risks met in the unit : priorities adopted for the 4 years to come</u>

Chemical risk management.

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 vapors and gases at the equipment level and to prevent reactions between incompatibles. They incorporate exhaust abatement systems to minimize environmental emissions.

<u>To be done in the next four years:</u>

- IEMN will establish procedures to minimize waste at the stage of generation and to increase the safety of the workers (handling and operating instructions).
- In the case of the most commonly used chemicals, IEMN is studying the installation of automated chemical delivery systems to minimize the need for handling and manually pouring chemicals. The increased degree of automation will decrease worker's risk of contact with chemical or physical hazards.
- New safety equipments and instructions will be established to improve the management of the risk due to nanomaterials.
- IEMN will further develop individual exposure record sheets and make sure of medical aptitudes for each station.
- IEMN is working on the possibility to use central abatement systems with common pumping and exhaust systems in order to further reduce environmental impact (greenhouse effect, power consumption…).

Ionizing radiation risk.

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).

<u>To be done in the next four years:</u>

- An engineer from IEMN will soon follow the training course "PCR sources sealed and generating of rays".
- The declaration of the equipment at IEMN will be carried out thereafter.

Remaining security issues and plans to solve them.

Occupational health and safety evaluation document (DUER).

The evaluation of the occupational health and safety lies within the scope of the general obligation which falls to the director to take all measures necessary to ensure the safety and to protect health of all the staff.

IEMN has not currently prepared this paper document yet. Nevertheless, a reflection on the method, the hierarchy and the identification of the risks was already carried out.

A working group, to be setup soon, will have to lay down the rules for the identification of risks and the method of its deployment.

It should be noted that the deployment of the software DUER from the CNRS during 2008 will be the occasion to vitalize all of the main actors for the drafting of the DUER.

The mobilization of the personnel is an essential condition in order to have a first version together with a program of preventive actions as soon as possible.

II IEMN SCIENTIFIC PROJECT

Introduction

IEMN's scientific objectives are determined taking into account national and international context. Skills of the laboratory are identified within the framework of the five scientific axes where researchers have already determined short and mid term actions. Medium and long term evolution of microelectronics industry is not very clear in Europe and this fuzzy future raises fundamental questions on the role of IEMN in this domain. Our scientific policy tries to take this situation into consideration.

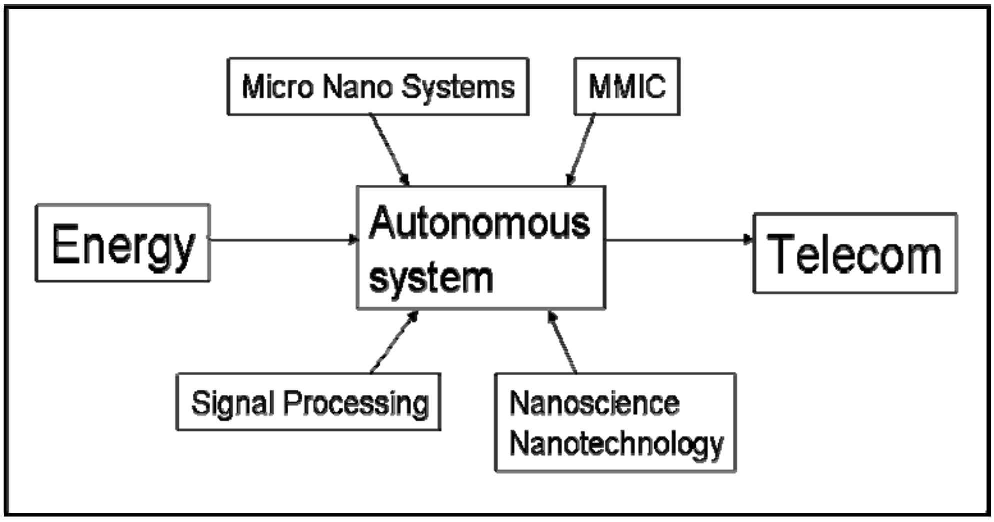
Our vision is to strengthen our specificities while beeing complementary with other national and european actors. To achieve this goal, we have to increase our collaborations:

- at national level by means of the networks of microelectronics facilities (BTR) and through ANR’s projects;
- at international level by creating new alliances with the major industrial and academic actors of microelectronics. Particularly, IEMN has to take advantage of its long experience of high frequency electronics, including high speed technologies and micro- and mm-wave metrology. In this specific domain, IEMN has to continue to bring specific and additional contributions at the best level thanks to this unique experience and the associated technological and experimental facilities.

According to ENIAC Strategic Research Agenda (SRA), the nanoelectronic era can be divided in three main technological domains: ‘More Moore’ characterized by the continuation of Moore’s law, ‘beyond CMOS’ that corresponds to more disruptive technologies which could complement or replace silicon technologies and finally ‘More than Moore’ which corresponds to semiconductor-based devices that convert non-digital-real-world as well as non-electronic information such as mechanical, thermal, acoustic, chemical, optical and biomedical phenomena to and from the digital domain.
The analysis of the scientific and industrial national and international (european) environment leads us to orientate IEMN activity toward "beyond CMOS" and "More than Moore" domains.

For the "**beyond CMOS**" domain, nanoscience and nanotechnology are for sure of great interest for most of the fields in which IEMN is involved. Indeed, the trend is to investigate physical phenomena occurring at ultimate dimension of the matter and devices as well. On that subject, recent work on nanowires and nanotubes as part of a transistor is a good illustration. Therefore, considering the near field microscopy platform and the capabilities of the clean-room facility, IEMN is likely to play a major role at the innovation stage by strengthening efforts in theoretical, applied physics and nanodevice concepts.
Despite being far from an industrial-like technological centre, IEMN can provide industry with new semiconductor materials (III-V and II-VI compounds) fully engineered by its researchers. From the evolution of the microelectronics industrial european landscape, IEMN must consider its role as a promoter of new and original solutions. Since the core of the processors in terms of downscaling is no longer a unique manufacturer affair (especially in Europe) but relies on joint venture, a laboratory like IEMN is naturally orienting its research towards alternative and complementary parts of future electronics circuits and systems.

In the ‘**More than Moore’** domain, interdisciplinary projects involving several research groups in IEMN have already begun : micro and nano systems for instance pave the way to a new generation of electro-mechanical devices able to replace and enhance the performances of key components such as filters, time reference, and so on… Research on so-called "smart devices", namely autonomous micro objects able to transmit and receive information (complete ICT system or intelligent objects), is a current reality within a few IEMN groups and acts as a collaborative stimulant outside IEMN's walls. It implies to find original solutions for low power electronics, sensors and actuators, and energy scavenging.



This diagram shows a schematic autonomous system federating IEMN skills for a telecom application purpose. The "Energy" block needs the commitment of several research groups, both inside and outside IEMN, in order to meet the future requirements

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Telecom will continue to be an important research area at IEMN since it gathers a significant workforce on a federative topic: digital communications and signal processing for safety in terrestrial transportation systems (communication, localization and electromagnetic compatibility), broadband communication and ambient intelligence (wireless sensors networks, internet of things, high data rate WLAN/WPAN, smart antennas using MEMS devices and software designed radio and radars). This successful activity is related to a number of academic and industrial collaborations in the frame of national or EU projects.

Acoustics is an IEMN's asset when is applied to fundamental understandings of modern devices such as bulk acoustic wave resonators and participates to the abovementioned "more than Moore" approach by providing acoustical development to MEMS/NEMS components. Based on IEMN experience in non-destructive control, another acoustic prospect is the application of this expertise to biological matter.

Reading the previous section could comfort the reader in the position that IEMN is essentially supporting an industry-driven or project-driven research. However, it is definitely not exclusively the case. Indeed, we do believe that even for applied science, which is mainly where IEMN is acting, fundamental research must be performed in order to keep the proposition and innovation force that is the key of a research laboratory when compared to a R&D private laboratory. Indeed, there is a constant need for fresh ideas in order to fuel our industrial partners within the framework of collaborative programs. The lack of fundamental research would level industrial R&D with research performed in public laboratories resulting in a situation where collaboration is useless.
BioMEMS is a typical illustration of this situation where researchers are supported by national or international programs whom industrial partners are in a stand-by position in the case if outcomes would be promising. In the same field, same companies are eager to use robust microfluidic devices to the benefit of all.

In conclusion, the general scientific policy of IEMN can be summarized as follows: a well-balanced research boosted by advanced topics in phase with major actual industrial concerns

II.1 Physics of nanostructures

Introduction

The prospective of the theme 1 is presented using a scientific view and not through the activity of the research groups because a majority of the subjects are treated by two or three groups together. Six topics are presented :

- Molecular Nanostructures and Devices
- Physics and thermochemical growth and for semiconductor based devices
- Zero-dimensional semiconductor nanostructures
- 2D systems, surfaces and interfaces
- Phononic Crystals
- Nano Photonics and Plasmonics

One important feature of this theme is that we have a good equilibrium between theorists and experimentalists. This allows i) to perform fundamental descriptions (electronic structure, optical properties, quantum transport, …) of materials and nanostructures, ii) to introduce new concepts for innovative devices and applications. This is illustrated for molecular devices, smart textiles, III-V heterostructures based devices, graphene on SiC for nano-electronic, nanowires based devices, super-crystals, phononic crystals and plasmonic circuits.

Even if the study of individual nanostructures is important for the understanding of the physical and chemical mechanisms involved in new nanostructures, for the next years, we will study more complex systems, obtained by self-assembly of organic and inorganic nanostructures, as illustrated by the projects on molecular switch and memory, nanocomputing building block, solar cells based on nanoparticles associated with nanowires and finally super-crystals (3D nanoparticles systems). For the physical characterization of the samples, two equipments are planned for the next months : a low temperature cryostat (4 K) with a 7 T magnetic field for quantum transport in nanowires and a four probes UHV system, (four STM in parallel), for electrical characterization of nanostructures, correlated with atomic scale studies.

II.1.1 Molecular Nanostructures and Devices

Our recently started and futures projects will concern:
- Electronic properties and transport in molecular nanostructures and molecular devices.
- Multi-scale molecular materials: from thin films to supra-molecular architectures such as self-assembled monolayers, self-organized nanowires, etc…
- Electronic properties of organic materials for plastic and textile electronics.

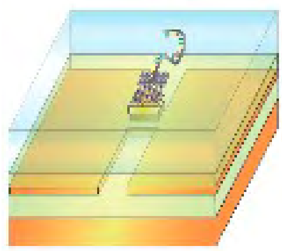
1.Fluctuations, noise and vibronic coupling in molecular junctions

(coll: D. Cahen, Weizmann Institute, Rehovot-Israël; A. Kahn, Princeton Univ.)

Beyond the measured static electronic transport in molecular junctions, dynamic phenomena such as noise (low frequency, RTS) and electron-molecular vibration coupling need to be better studied, better understood. Based on our recent work (as in the recent literature on molecular electronics), we will pursue on the following open questions.
- Understanding the magnitude of the electron-vibronic coupling as observed by inelastic electron tunneling spectroscopy (IETS). We will focus on the respective contribution of the molecule body vs. the electrode/molecule interface.
- Nature and origin of the noise in molecular junctions. The challenge is not only to make the distinction between the contributions of interfaces and molecules, but more to identify the electronic source of noise (e.g. traps, charge fluctuations) vs. those that are molecular by nature (e.g. conformational fluctuations).

2.Real time detection of charge state of a single redox molecule

(coll: NTT-BRL, group of A. Fujiwara, Japan)

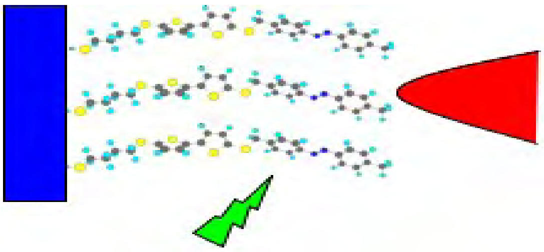


Shematic view of the hybrid SET-molecule device

Redox molecules are suitable candidates for molecular memories. For a single molecule, the time domain (dynamics) change of the charge state has never been observed experimentally. To detect a single redox molecule, it is essential to use a sub-electron sensitivity electrometer. Recent results of the NTT group showing the transfer and ultimate single electron detection at room temperature with silicon SET have opened the door to further studies. By

coupling this SET and molecular-scale device, our project, in collaboration with the NTT group aims to:
- Study of the redox charge state dynamics of a single molecule, which would be helpful to understand and design future molecular memories.
- Investigation on noise (e.g. RTS-like) due to discrete fluctuations of the redox state.
This study will be extended to others charged molecules (e.g. DNA).

3. Self-organized dynanic conjugated nanostructures, molecular switch and memory



(coll: J. Roncali, CIMMA-CNRS, Angers ; S. Palacin, J.P. Bourgoinn, V. Derycke, CEA-Saclay, G. Bidan, CEA-Grenoble ; L. Patrone, L2MP-CNRS ; B. de Salvo, CEA-LETI)

Optically stimulable molecular junction

This project aims at developing optically stimulable nano-structured surfaces by grafting self-assembled monolayers (SAMs) of conjugated systems bearing electronic properties that can be changed reversibly by optical stimulation. The active systems will consist of an oligothiophene chains, likely to undergo conformational changes, coupled with

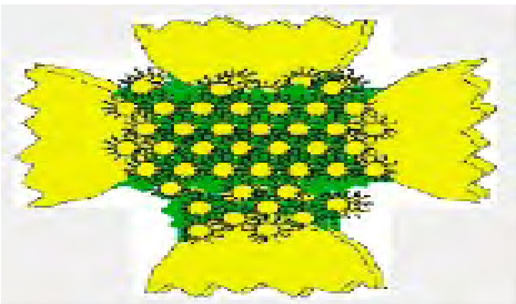


photo-izomerisable azobenzene derivatives attached in a loop side at two specific points along the chain. We will study the physical and electrical properties of the SAMs (XPS, AFM, STM and C-AFM) with a peculiar attention to the photo-induced changes in the electronic structure and conductivity.
We will also continue our work on molecular RTD-memories based on the sequential synthesis of self-assembled molecular quantum wells, and on hybrid optically-gated CNT-polymer FET.

4. Nanocomputing building block with acquired behaviour
(Coll. : V. Derycke, J.P. Bourgoin, CEA-LEM-Saclay; C. Gamrat, CEA-LIST-Saclay; M. Welland, Cambridge univ., G. Wendin, Chalmers univ. ; B. Linares-Barranco, IMSE-Séville)

Typical illustration of a NAB device made of gold NPs and organic molecules

The project aims at exploring the feasibility of a so-called nano-computing block (NAB) that would be built by interconnected molecular electronics nano-scale devices. The project aims at showing that such a NAB can acquire a specific computing function by means of a post-fabrication adaptation process (learning, reconfiguration). The project aims at showing that the acquired functionality will be exploitable within a realistic computing system. Our aim is to design and study a spiking formal synapse made of a bottom-up assembly of semiconducting organic molecules and functionalized nanoparticules. For that, we will take profit of chemical approaches using the grafting of molecules and or functionalized nanoparticules in nano-gap electrodes. We have already obtained encouraging preliminary results on a large-scale device (micron-size).

5. Dynamic behavior of nano-scale organic memory and transistor
(coll : D. Zender, univ. Reims ; A ; Mortreux,ENSCL ; J.P. Simonato, CEA-LITEN ; J. Buckley, CEA-LETI)
Despite the progress made in this field, our knowledge of the interface between inorganic materials and organic semiconductors or between organic materials and organic semiconductors is rather poor. Increasing this knowledge can open the door to new functionalities and devices. This is the place where this project starts. We intend to investigate the charge trapping dynamics and interfacial phenomena in OFET and OM by combining new electrical characterization tools (derived from those used for Si-CMOS), especially in the dynamic range, and SPM-based techniques to observe dynamic electron transport behavior at the single nano-object level. The project also deals with the fabrication of a new class of conjugated polymer based devices. These polymers are synthesized by alkyne metathesis polymerization and grafted directly on the surfaces with an expected local order that can leads to high transistor performances. Similarly, we will study new hybrid nano-composite based materials (based on nano-objects such as carbon nanotubes, C_{60} derivatives and nanoparticles) for memory devices.

6. Nano-organics for smart textiles
(coll: V. Koncar, ENSAIT; M. Bouazaoui, PhLAM; D. Deguillemont, IFTH)

The overall objective is to develop new approaches to obtain intelligent textile combining three innovative functions (mechanical sensor, thermal self-regulation, chemical detection). This multi-sensitivity will be ensured by the integration of CPC (conductive polymer composite) based on carbon nanotubes (CNT) in textile fibers. Under this framework, we will study the electronic transport properties of these CPC-CNT materials and fibers and investigate mechanical sensors based on them. Moreover, these approaches need to develop sol-gel techniques to deposit conducting electrodes (e.g. ITO) on textile fibers. We will also investigate flexible OFET directly integrated on a single textile fiber.

Supports. ANR-PNANO (projects OPTOSAM, MEMO), EU FP6-NMP (project INTELTEX), EU FP7-ICT-FET (project NABAB)

II.1.2 Growth and physics for semiconductor based devices

The epitaxy (MBE and CVD techniques) and physics activities are oriented towards Sb based heterostructures for opto and mocroelectronic devices, graphene on SiC and silicon and III-V nanowires with various targeted applications (biodetection, solar cell and electronic and spin transport). Finally, theoretical studies of the optical properties of Boron Nitride nanotubes will be led for UV-lasing nanodevice applications.

1. Sb-based heterostructures for opto and microelectronic devices

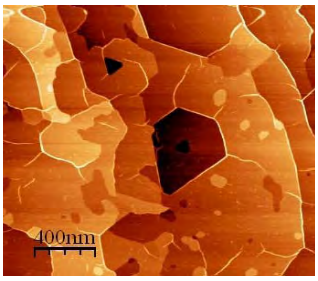
(coll: J. Grahn, Chalmers Univ; S. Huant, Néel Institute; V. Bayot, UC Louvain)

A new type-I heterostructure with AlInSb barriers and a InGaSb channel will be developed, exhibiting a conduction band offset higher than 0.6 eV and an electron effective mass close to that in InAs. We have already obtained preliminary results comparable with Intel-QinetiQ performances obtained on AlInSb/InSb heterostructures. Nevertheless, much remains to be done to improve the buffer layer by favouring 90° interface misfit dislocations. We will also develop HBT structure using InGaSb as base material, since it exhibits a high hole mobility compared to other alloys. This type of structure is currently investigated by NRL team in US. Both field effect and bipolar devices will be developed in collaboration with the "ANODE" group at IEMN. Finally, metamorphic LT grown GaAsSb layers on GaAs will be investigated as short carrier lifetime photoconductive materials. The goal will be to address wavelength in the 1-1.1µm range. A DGA PREI project has just started on this topic, in collaboration with the "Optoelectronic" group at IEMN.

Supports: ANR-PNANO (project MICATEC), DGA (PREI 'Nanophotoswitch')

2. Epitaxial growth of graphene on SiC substrates

(coll: L. Lévy, Néel Institute; T. Poiroux, CEA-LETI)



AFM image of a 1550°C graphitized Si-face SiC (6H) substrate (height scale: 2nm)

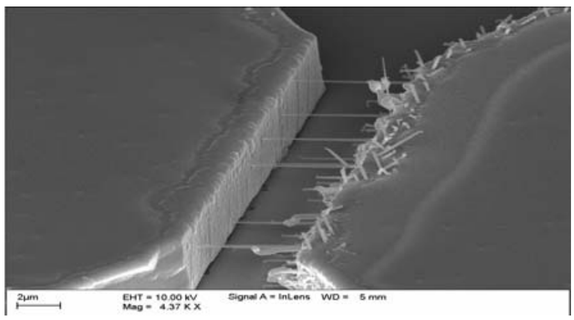
Growth and structural characterization of graphene will be performed by the "EPIPHY" group, in collaboration with the Néel Institute for low temperature transport measurements (through the ANR project XP-graphene). Besides the high temperature surface graphitisation of SiC, a second approach will explore the direct growth of graphene by molecular beam epitaxy. This should first involve growth on SiC substrates followed by attempts on other 'simpler' substrates (noticeably silicon). This experimental study will be supported by Molecular Dynamic simulations led in the "Silicon Microelectronics" group. Once high quality two-dimensional material will be synthesized, a variety of devices will be fabricated using the most advanced nanofabrication techniques by the "ANODE" group (nanowires, transistors, tunnelling devices…).

Supports: ANR PNANO (project XP-Graphene)

3. Semiconductor based nanowire devices

(coll : Y.M. Niquet, S. Roche, CEA-Grenoble ; X. Blase, Institut Néel; M. Bescond, LM2NP, Marseille, O.Melnyk IBL Lille ; R.Boukerhoub IRI Lille, P. Perrot, Lille1 Univ., P.Pareige Rouen Uni., G.Patriarche LPN Marcoussi, UTH Zurich)

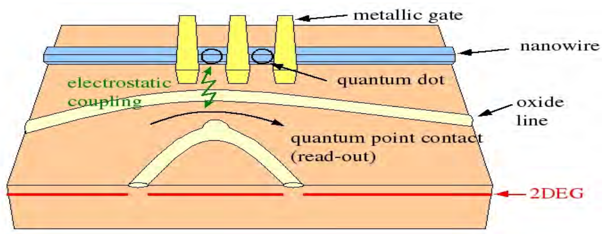
We will pursue the effort in nanowire CVD growth and extend it to heterostructure growth. A wide variety of binary, ternary and quaternary elemental composition and non-stoichiometric composition are conceivable by the chemical processes. The research work done in the field of silicon nanowires by S(V)LS is a good example to illustrate the benefits of a chemical approach to optimize the other elaboration processes (VLS by CVD, MBE…). On this basis, we will extend the growth to III-V nanowires by MBE to avoid the observed carbon contamination of MOCVD wires. We will focus on small bandgap semiconductors such as InAs and InSb which exhibit high electron mobility, suitable for high frequency, low power applications. However, the use of these nanowires will not be restricted to electronic applications only. We will investigate several ways of initiating the growth, with or without a catalytic nanoparticle, as well as several solutions for increasing the mobility and controlling the doping in these structures which remains a very critical aspect in the nanowire field. We are currently investigating growth conditions required to produce NW heterostructures and core-shell structures in the Si/Ge system and will also consider heterostructures for III-V materials.



To go from nanowires to high technology electronic devices, our strategy is to create platforms by lithography patterning on which diffusion length of reactive species is controlled during the subsequent reactive treatment leading to the growth of aligned and linear nanowires. Depending mainly on the choice of the orientation and template substrate, nanowires can be oriented. In this way, we are going to develop the localized growth of silicon nanowires between trenches of Si(110)-O-I wafers in order to get nanowires connected to electrodes and used for the electrical detection in real time of biomolecular interaction (antigene-antibody or enzyme (heparanase) - polysaccharide (heparin) involved in the cancer metastasis) in collaboration with the IBL and IRI laboratories.

Localized CVD growth of silicon nanowires between two electrodes

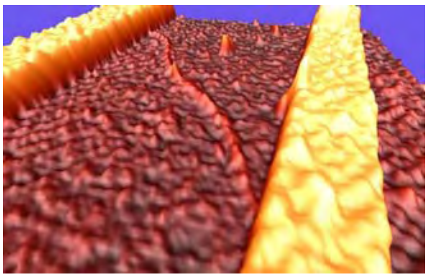
We will also investigate nanostructures based on low band-gap III-V materials for electronic and spin transport due to the high mobility, strong spin-orbit interaction, strong quantum confinement. The electronic properties will be investigated in a field-effect transistor geometry by low-temperature magneto-transport measurement in a dedicated helium cryostat.



We will then realize a confinement along the nanowire in order to reach the limit of quantum dots. Due to the low carrier effective mass, we expect to observe effects of quantum confinement at higher temperatures compared to materials usually used, which is necessary for using such properties in future electronic devices.

Scheme of a nanowire-based single electron device with a nearby charge read-out. Quantum dots are formed in the nanowire by depletion with metallic gates. The underlying two-dimensional electron gas is locally oxidized to form a quantum point contact. The conductance of this quantum point contact is very sensitive to the charge in the quantum dot.

We will develop combined electrostatic and transport measurements to image the transport properties of 1D systems (carbon nanotube and/or silicon nanowire field effect transistors), and 1D systems coupled with 0D nanostructures. The prototypal device will consist in a one dimensional channel (carbon nanotube or a semiconducting nanowire) coupled to a 0D nanostructure acting as a discrete charge storage node.



Electrostatic scanning probe techniques (electrostatic and Kelvin force microscopies) will be developed in a vacuum environment (i.e. in a regime of non-contact atomic force microscopy), with the aim to image the transport in the interacting 0D/1D devices with sub-10 nm spatial resolution, and with, ideally, single electron charge sensitivity. Self-assembled devices will also be considered.

AFM image of a 3D semiconductor SWCNT (1µm length). This system will be used to prepare coupled 1D/0D nanodevices

As a long term prospective, we will combine semiconducting nanowires with silicon, metallic or II-VI nanoparticles to get low cost, high yield solar cells. The fabrication and the optimization of the solar cells will need a complete physical characterization of the nanowires using i) STS spectroscopy (in order to measure the nanowire bandgap and the electronic properties of dopants in homo or heterojunction,) ii) 3D atomic tomography to get direct of measurement the spatial distribution of dopants in the nanowires.

Theoretical works on transport properties of semiconductor nanowires will concern the prediction of resistivity and mobility as functions of doping and environment (gate, dielectric). A first step is to consider the elastic scattering on donor and acceptor impurities, including the effect of screening induced by free carriers in a self-consistent approach. A second step concerns inelastic scattering by emission or absorption of phonons. Phonons and electron-phonon couplings will be calculated using atomistic methods. Optical properties of semiconducting nanowires will be considered, focusing on excitonic effects which are strongly enhanced in 1D systems. Our aim is to understand optical absorption and luminescence spectra and, ultimately, this knowledge will help in the design of opto-electronic devices. We will develop a code that solves the Bethe-Salpeter equation (Schrödinger equation for the interacting electron-hole pair) in the tight-binding approximation. The code will be able to handle nanowires with large unit-cells (several hundred atoms) and eventually will be extended also for the calculation of optical excitations in large bio-molecules.

After studying theoretically electronic excitations in pure Boron Nitride nanotubes (BNNTS), our next step will consist in studying the optical properties of BNNTs in the presence of defects. This will be important for the interpretation of luminescence in BNNTs which we presume to be mostly related to defect states. Our results will guide experiments on the use of BNNTs as UV-lasing nanodevices

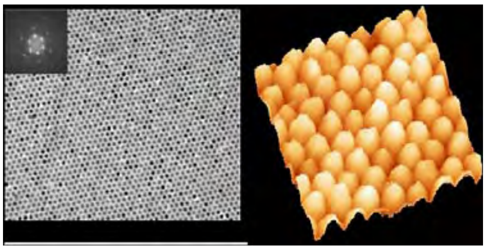
Supports. ANR-PNANO (QUANTAMONDE), ANR – PNANO (NANOBIODETECTION), ANR-JC (NANOFILOUS)

II.1.3 Zero-dimensional semiconductor nanostructures

1. Individual colloidal nanocrystals
(coll : D. Vanmaekelbergh, Debye Institute, Utrecht)

An important part of our experimental and theoretical efforts will be maintained on zero-dimensional (0D) semiconductor nanostructures, in continuity with our previous works on individual objects but with a clear evolution towards coupled or heterogeneous nano-structured materials. Scanning Tunneling Spectroscopy (STS) experiments on individual colloidal nanocrystals will be pursued, in particular on recently synthesized Si nanocrystals to identify the mechanisms (electron-phonon coupling, fluctuations of the environment, inter-valley couplings…) at the origin of the broadening of quantized levels.

2. Heterogeneous nanocrystals and binary super-lattices
(coll : D. Vanmaekelbergh, Debye Institute, Utrecht; Z. Hens, Gent University; S. Turrell, O. Robbe, LASIR, Villeneuve d'Ascq)



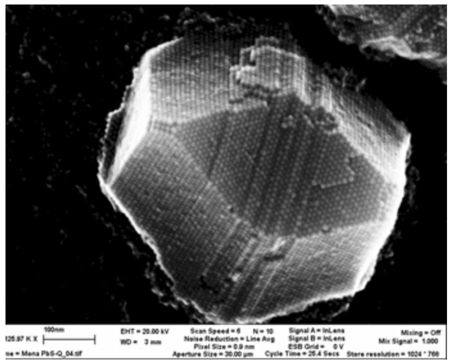
Top-left: monolayer of nearly spherical PbSe quantum dots showing long-range order over a distance of several micrometers. Top-right: STM image of a monolayer of PbSe quantum dots on Au(111).(Vanmaekelbergh et al., HERODOT project)

We will perform deepened studies on two types of systems: 1) heterogeneous nanocrystals made by the heterojunction between two semiconductor nanocrystals; 2) super-lattices formed by the 2D spontaneous organization of an ensemble of nanocrystals, including binary super-lattices composed of two types of nanocrystals. Electrostatic Force Microscopy (EFM) and Scanning Tunneling Microscopy (STM) measurements combined with theoretical calculations will be undertaken to determine the band offsets, the charge transfers and the couplings between the various constituents.

Transport properties of 2D networks of nanocrystals will be studied, and the possibility to dope these systems will be considered.

Supports. EU-FP7-Marie Curie (HERODOT 2008-2011).

3. Super-crystals



TEM image of a three-dimensional super-crystal of CdS nanocrystals (H. Weller, Univ. Hamburg, private communication).

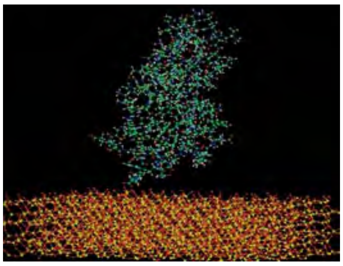
Optical properties of 3D ordered assemblies of nanocrystals (the so-called super-crystals) will be calculated in order to evaluate their performances as composite materials (or meta-materials) for applications in photonics, optoelectronics and photovoltaics. Theoretical works will deal with the mechanisms of relaxation of hot carriers in nanocrystals, problems that remain poorly understood at the moment.

4. Charge injection spectroscopy with elementary charge resolution

We will develop EFM in a ultra-high vacuum environment, in which the EFM measurements can be carried out with the cantilever tip in Van der Waals force gradients. This will enhance the charge detection sensitivity, with the aim to perform charge injection spectroscopy with elementary charge resolution. Charge transfers from doped nanostructures will also be considered.

II.1.4 2D systems, surfaces and interfaces

(collab. avec IPCMS Strasbourg, UCB Lyon, RPI New York (USA), Univ de Cagliari (Italie), ENEA Rome (Italie))



Snapshot of a steered-molecular dynamics simulation of an Ig fragment of the NCAM adhesion protein interacting with a SiO2-glass surface (red=oxygens, yellow=Si atoms) at T=300K

In a more general perspective of basic research, the atomic and molecular scale modelling of the interactions between macromolecular clusters and surfaces is aimed at determining the relative role of non-bonding forces, as a function of the macromolecule and surface structures. Such studies are motivated by the understanding of molecule-surface recognition mechanisms: dispersion (van der Waals) forces, dipolar and multipolar electrostatics, entropic forces (configurational elasticity, depletion and excluded volume interaction). Possible applications range from the self-assembly of molecular monolayers in nanostructure fabrication; characterization of thermal and electrical properties of non-bonded systems; immobilization of peptides and biomolecules on semiconductors; studies of the molecular mechanisms of cell-cell, cell-tissue and cell-surface adhesion.

Concerning the high-k oxides, we will study buffer oxides, i.e. oxides grown on silicon allowing a subsequent growth of III-V layer. The effort will be devoted to the electronic structure of the interfaces. *(Collaboration with INL, Lyon)*

II.1.5 Phononic Crystals

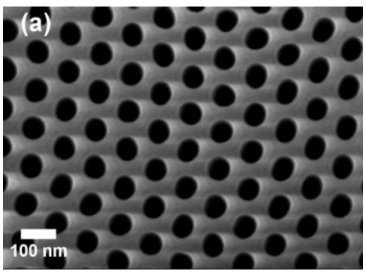
1.Thin films, surfaces and interfaces

(coll: B. Bonello, INSP Paris ; P. Deymier, Arizona, Tucson (USA))

We have recently demonstrated the possibility of absolute band gaps in the band structure of free or supported phononic crystal slabs. This will be exploited to study the functionalities of these structures for tunable filtering (guiding, selective filtering, multiplexing structures, slow-waves). Some of the theoretical works will be compared with laser interferometric experiments by B. Bonello et al (INSP, Paris). We shall also study the surface and interface modes of phononic crystals as possible means for confinement and guiding parallel to the surface, as well as for the purpose of selective transmission between two substrates.

2. Phonon-photon interaction

(coll: G. Fytas and A. Sato, Max Planck at Mainz ; C. Sotomayor, ICN, Barcelona ; E.H. El Boudouti, Oujda, Marocco)



Scanning electron microscope of anodic aluminum oxide membranes with aligned cylindrical nanopores (G. Fytas et al., unpublished data).

In the hypersonic regime, the phononic band structure can be investigated in comparison with Brillouin/Raman scattering. The purpose is to demonstrate the possibility of tailoring phonon dispersion in nanoporous membranes and the tunability of the anisotropic high frequency sound propagation using infiltration and physical stimuli. Besides, a detailed theory of light scattering in these nanostructured materials is lacking and needs to be developed. On the other hand, the enhanced phonon-photon interaction in slow-wave structures and in simultaneously phonon-photon cavities has not yet been studied in 2D structures. This would be interesting for the purpose of designing new compact acousto-optic devices, but also as a source of high frequency phonons. A FET OPEN pre-project TAIL PHOX (Tailoring photon-phonon interaction in silicom phoxonic crystals) proposed under FP7-ICT has been successful and should be proposed as a full project.

3 Negative refraction and focusing

(coll: O. Poncelet, LMP, Bordeaux ; B. Morvan, Le Havre)

Up to now, these phenomena have been studied in phononic crystals constituted by solid inclusions in a fluid (air or water). We are interested in solid phononic crystals, not studied before, which should be more interesting for technological applications. However, in this case, both longitudinal and shear waves are present and should be treated simultaneously. More details are given in “Axe 5”.

Support : ANR SUPREME (superlentille à refraction negative à base de métamatériaux et de cristaux photoniques).

4 Heat management

(coll: C. Sotomayor, ICN, Barcelona ;J. Ahopelto, VTT, Finland)

Thermal transport in nonmetallic nanostructured materials can be strongly affected by the specific phonon dispersions as well as different scattering mechanisms. Since the end of 2007, we are involved in a FP7-ICT project with 14 partners entitled Nanopack (Nano Packaging Technology for Interconnect and Heat Dissipation). The aim is to develop new materials and technologies for improving thermal transport and reducing interface resistances in nanodevices. Our task is to evaluate the effect of phonon dispersions on thermal transport in two types of structures (SOI and nanoparticles on SOI) and also elaborate theoretical tools to investigate light scattering in these structures. This topic will also meet the objectives of the project "Super-Crystal" dealing with the physical properties of a periodic arrangement of nanoparticles, in particular dispersion of phonons as well as phonon-phonon and phonon-electron interactions involved in heat transport.

Supports. FP7-ICT project Nanopack

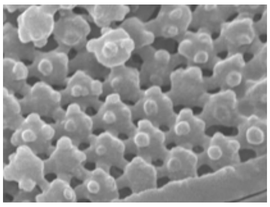
II.1.6 Nano Photonics and Plasmonics

1 Photonics

(coll: J.P. Vigneron, Namur, Belgium ; E.H. El Boudouti, Oujda, Marocco)

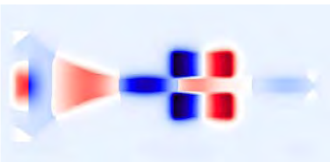
In continuation of our interreg project PREMIO with J.P. Vigneron (Namur) dealing with tunable filtering in micro waveguides coupled to lateral stubs, we intend to investigate similar phenomena in InP based 3D waveguides drilled with holes. The ability of such structures to guide, filter and multiplex light will lead to many applications for optoelectronic devices.

With our experience in simulation techniques, we shall collaborate to a project dealing with the biomimetic approach of metamaterials. The concept is to explore and exploit the diversity and complexity of natural nanostructured materials for inventing and developing artificial metamaterials.



TEM image of a natural photonic nanostructure

2 Plasmonic circuits



Rejective" plasmonic filter

We have started studying the propagation of light in plasmonic waveguides constituted by a metal-insulator-metal structure. Such a structure can drastically squeeze the light when the thickness of the dielectric is of the order of a few 10nm. We shall investigate the effect of cavities, either inside or in the vicinity of the waveguide, on the transmission coefficient. From this, one can imagine different filtering operations, separating different signals in a Y-shaped waveguide, or channel drop tunneling between two parallel waveguides. We would like also to investigate the band structure of a 2D plasmonic crystal made of drilled holes in a thin metallic (Ag, Au) film deposited on a dielectric substrate.

3. Nanostructured metamaterials from atomistic simulations of Super-Crystals

The idea is to solve Maxwell equations in which the electromagnetic response of a material is not given as usual by its bulk-like response, but by the (possibly non-local) response calculated with an atomistic description. The performances of super-crystals as photonic metamaterials in the optical range will be assessed. Three systems will be studied in particular: 1) nano-transmission lines; 2) nano-antennas using a semiconductor nanocrystal as a light emitter or detector; 3) 3D super-crystals with potentially negative refraction. The main objective is the prediction of new materials and functionalities

II.2 Micro and Nano Systems

Introduction

Prospects in the Micro Nano Systems (MNS) field are presented hereafter as four categories in accordance with those found in major MNS international conferences. Provided that the manpower devoted to the MNS field remains constant or increases, which is likely to happen, IEMN has a key role to play in Europe. Indeed, assets such as solid-state and bioMEMS experiences combined to material engineering are gathered in the same laboratory that is a rare condition in Europe for the MNS research field. If one considers the 1600 m^2 clean-room facility and the characterization platform, one can state that IEMN is an ideal place to make research on MNS. In addition, the commitment of IEMN researchers is already determined for most of the following perspectives described hereafter since they will benefit from financial supports obtained for the next 4 years after peer-review evaluation of their projects.

II.2.1 Solid-State Micro Nano Systems

Active probes for Atomic Force Microscopy
Collaborations: CPMOH (Bordeaux I); CRETA (Grenoble)

Context:
AFM systems have been widely used for 20 years in numerous academic, research and industrial work. They give access to microscopy images with a nanometric resolution and derives techniques allow many physical characterization and spectroscopies. Many labs are currently trying to use the oscillating mode of AFM to probe biological nanosystems and their dynamics in liquid environment. However, AFM performances are intrinsically limited in the framework of this nano-bio convergence by the AFM oscillator. Therefore, we propose to change the whole AFM oscillator and to choose a vibrating mode reducing the drag force that appears when the probe is operated in a liquid medium. In addition, an electrical sensor will replace the optical system in order to simplify the frequency and the amplitude measurements. The project is supported by the European Research Council (ERC) through a Starting Grant and by the French National Agency for Research (ANR PNANO) for the next 5 years.

Next 4 years actions:
The project is based on a simple idea; however, several levels of difficulties must be overcome to reach the target. The project is made of several stages corresponding to intermediate goals. The final goal is to record an image as the result of specific interactions between the active probe and either a chemical or a biological system in liquids that induce variations of the force of a few picoNewton and produce relevant information on species properties at a resolution better than the nanometer. A first requirement is to insert conveniently the nano-sensor in a commercially available AFM experimental set-up. The following obstacles need to be cleared:

High aspect ratio tips will ensure that the interaction occurs only between the surface and the probe apex. To achieve this goal, the preferred option is to grow a single wall or a carbon nano tube (CNT) with a low number of walls at the tip apex. An alternative option is to carve a tip by using a focused ion beam to get a silicon cylinder.
Bulk modes or contour modes are likely to reduce the hydrodynamic drag but it is not yet shown experimentally in a liquid medium.
A model dedicated to the computation of the hydrodynamics functions giving the motion of the squeezed film between the oscillating tip with a radius of a few nanometers and a surface roughness in the range of the nanometer will be developed.
The ultimate purpose is the real time imaging of molecular dynamics, which requires the association with an appropriate electronic circuit.

Potential impact:
This project aims at conferring unprecedented performances to AFM systems, allowing time-resolved force spectroscopies in a liquid medium. The main impact is foreseen in the promising field of the nano-bio convergence. Indeed, accessing the dynamics of most nanobiological systems remains today impossible.
More generally, AFM systems will benefit from the new generation of AFM probes fabricated in this project. The expected performances are far beyond the state-of-the-art of the conventional cantilevers based AFM involving a strong impact in applied physics and instrumentation.
In addition, nano probes fabricated in this project offers new wide range applications for bulk mode resonators requiring fundamental studies to be carried out and therefore yielding publications of papers in high standard scientific journals as well as patents.

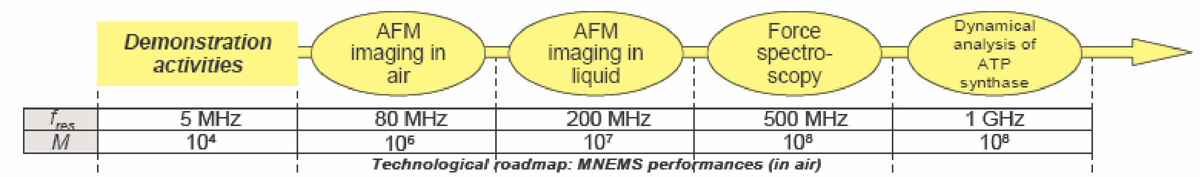


Figure: Roadmap for the next generation for AFM probes.

Micro strain gauges for electrical detection AFM
Collaborations: LPMC (École Polytechnique, Palaiseau); University College London (UK)

In order to perform atomic force microscopy (AFM) in "non standard" modes e.g; in a liquid medium, electrical detection of sub-nanometre deflections will be essential. Applications of AFM in liquid media are predominantly in the Life Sciences, e.g. molecular and cellular interactions. In order to achieve this, we are developing highly original micro strain gauges based on the effect of giant piezoconductivity which is observed in hybrid metal/semiconductor (MSH) systems. An MSH on cantilever structure would allow one to avoid the inherent problems incurred using lasers for optical AFM detection and also avoid reducing the spring constant of MEMS structures. We have demonstrated silicon based MSH devices having a very high gauges factor ~1000 compared to bulk silicon ~100 and we are currently working on full MSH integration into cantilever based systems.

Resonators for RF communications and timing
Collaborations: STMicroelectronics (Crolles); NXP Semiconductors (Caen)

Micro and nano resonators are among possible technical solution to replace quartz in electronics systems where they could serve either as filter parts or as time reference. IEMN has a 9 years experience in this field and the next 4 years action plan includes research on the design of in-IC and above-IC resonators. Collaborations with STMicroelectronics (STM) and NXP Semiconductors have been fruitful in those approaches leading to high frequency and high quality factor devices. The joint laboratory with STM is likely to yield original vibrating nano devices at the vicinity of 100 MHz. Research activities will stress on the improvement of the boundary conditions of resonators in order to decrease the losses occurring at the anchors. To achieve this goal, acoustics modeling will allow undertaking the design of Q-optimized anchoring for the next generation of resonators. IEMN has acquired specific software (MICROSONICS) that is dedicated to the simulation of losses due to acoustic radiations.

Bio-inspired Microsystems
Shimoyama and Pister, respectively at the Institute for Industrial Sciences of the University of Tokyo and at the Berkeley Sensors and Actuators Center at Berkeley, have first investigated this research topic. Each of them with a different objective, the first aiming at the artificial control of micro robots or insects, while the latter was more concerned with the whole autonomy of communicating mobile objects. At IEMN, major efforts will be devoted to the design of an efficient weight/power ratio actuator as well as to the design of an artificial wing mechanism having the capabilities to lift up a micro object

II.2.2 BioMEMS and Fluidic

Collaborations: Institut Pasteur de Lille, Unité de Glycobiologie Structurale et Fonctionnelle (UMR 8576 – Villeneuve d'Ascq), Unité de Biomécanique et de Bioingénierie (UMR 66000 – Compiègne) and Laboratory of Integrated Micro Mechatronic Systems (UMI 2820 - Tokyo).

Context:
Our group has been created in July 2007. Several members of the group have been studying on microfluidic devices and bio sensors since 2002. Our expertise is ranging from basic technologies to applied research. Our group is an intense user of the micro and nano-manufacturing facilities as well of the characterization station. Furthermore, we are currently setting up a cell culture laboratory in order to enable rapid testing of our micro devices before their use by our partners. A CNRS research engineer will have the responsibility for managing the operations of this laboratory.
On the fundamental aspects of our research, we are interested in liquid/surface interactions in the frame of Electro Wetting (in particular superhydrophobic surfaces). The recent breakthrough obtained concerning ElectroWetting On Dielectric (EWOD) on superhydrophobic surfaces has to be explained and optimized. In a close collaboration with the 'Institut de Recherche Interdisciplinaire (IRI)" and the FILMS Team (Group AIMAN), our objective is to realize and characterize different types of superhydrophobic surfaces for EWOD in order to develop a new model (based on Wenzel and Cassie-Baxter theories). This model will allow us to optimize the reversible electrowetting effect in particular on surfaces containing multi scale roughness.
Most of our devices are based on the engineering of the electric/electromagnetic fields in micro environment. Understanding the interactions between electrical energy and living micro-organisms is mandatory to design new devices for our long term objective. Living cells can be considered as micro electrical plants. We are involved in the development of models taking into account the actual tri-dimensional geometry of the cells and the non-uniformity of their components (cytoplasmic membrane, nucleus, etc …). Beyond a general electrical model of the cells, we are interested in defining the effects of the measurement set-up and geometry of the device on the measured electrical signature.
For the rapid prototyping of the devices, we are using polymer microfabrication methods like PDMS molding. However, for very high frequency studies (i.e.: 100 GHz-10 THz), most polymers do not have optimal electromagnetic properties (i.e.: high dielectric losses). That is why we have been involved in the development of a deposition process for polymerized TetraMethylDiSiloxane (pTMDS) using "cold" plasma technique in collaboration with the 'laboratoire de génie des procédés d'interactions fluids réactifs – matériaux' (GéPIFREM). The next step is to build a new plasma reactor in the clean room facilities of IEMN to intensify the research activity on this topic.

Next 4 years actions:
Our final objective is to propose an innovative concept for the analysis of cells functions on chip. This means having modules to culture, manipulate and analyze cells from tissue to single cells.
Thanks to our expertise in droplet motion using either EWOD or Surface Acoustic Waves (SAW), we have started various projects using digital microfluidics. We will study liquid/surface interaction on hydrophilic micropatterns embedded on the superhydrophobic surfaces made of silicon nanowires. We will also work on the ability to carry and culture a limited population of cells in calibrated droplets. We will study different technical solutions to reach the single cell resolution.

To pave the way to kinetic cells studies, we will look at the miniaturization of several analytical techniques. First, we will pursue the development of a matrix-free desorption/ionization mass spectrometry (DIOS-MS) platform in close collaboration with the group Biointerfaces of IRI. Second, we will work on the miniaturization of the surface plasmon resonance technique with the 'Laboratoire de Physique des Lasers, Atomes et Molécules' (Phlam). In both cases, we want to show that digital microfluidic can improve biodetection. Finally, with the same objective, we will work on sensors using piezoelectric micro cantilever in microfluidic environment.
Lots of work has already been performed on linear dielectric spectroscopy. It is really a very sensitive, label-free and low cost technology. However, biological cells are non-linear systems. That is why non-linear dielectric spectroscopy is likely to produce qualitative and hopefully quantitative information on the dynamical status of the cellular system under studies. We will work on this technique at micro scale.
In the same way, we will design micro device to measure and analyze the low frequency electrical noise of a cellular system. Noise analysis on microelectronic devices has shown to provide lots of information on the characteristics of the devices. We would like to apply this technique to biological systems.
The work on the Tera-Hertz probes will be continued with two objectives. First, we will broaden the frequency range (currently limited to 0.2 THz) to 3 THz using new THz sources. This goal will require designing new propagation guides working in microfluidic environment and allowing nanometer size probing. Second, we will study the arraying of this THz probe to evaluate its capability to be part of high density cell chip. Indeed, we have already demonstrated that the splitting of gold planar nanowire in two parts allows a very good transmission of the electromagnetic wave on both wires.
Finally, we have a rising activity on the development of new contrast agents for x-ray in vivo imaging of biological cells. These contrast agents are micro sized metallic particles with specific shapes. The research work will be focused on the functionalization of these particles to enhance the cellular uptake and control the toxicity.

Long-term actions:
If we reduce our scope to the engineering of chips for cells analysis, BioMEMS technology provides new capabilities to control accurately the micro-environment of the living organisms and to sense cells with higher spatial and time resolution. Whatever the application, our approach is to design and test low cost solutions for the culture and analysis of cells on chip. This means that we do not compete for the lowest detection limit, for the highest density integration or smallest sensor size. We are more interested in looking for reliable portable solutions allowing time-resolved in-situ analysis allowing rapid diagnostics.

Only very few products have label-free detection methods (i.e.: ACEABIO, BIACORE, MOLECULAR DEVICES). However, they work on large size samples (million of cells). As a consequence, the long-term objective is to design cell chips having various culture formats (i.e.: single cells, planar cluster of cells, 3D tissue), being able to perform statistical and multiparametric analysis thanks to several thousand parallel bioreactors and giving access to the kinetic of the biochemical reactions occurring at the level of the cells.

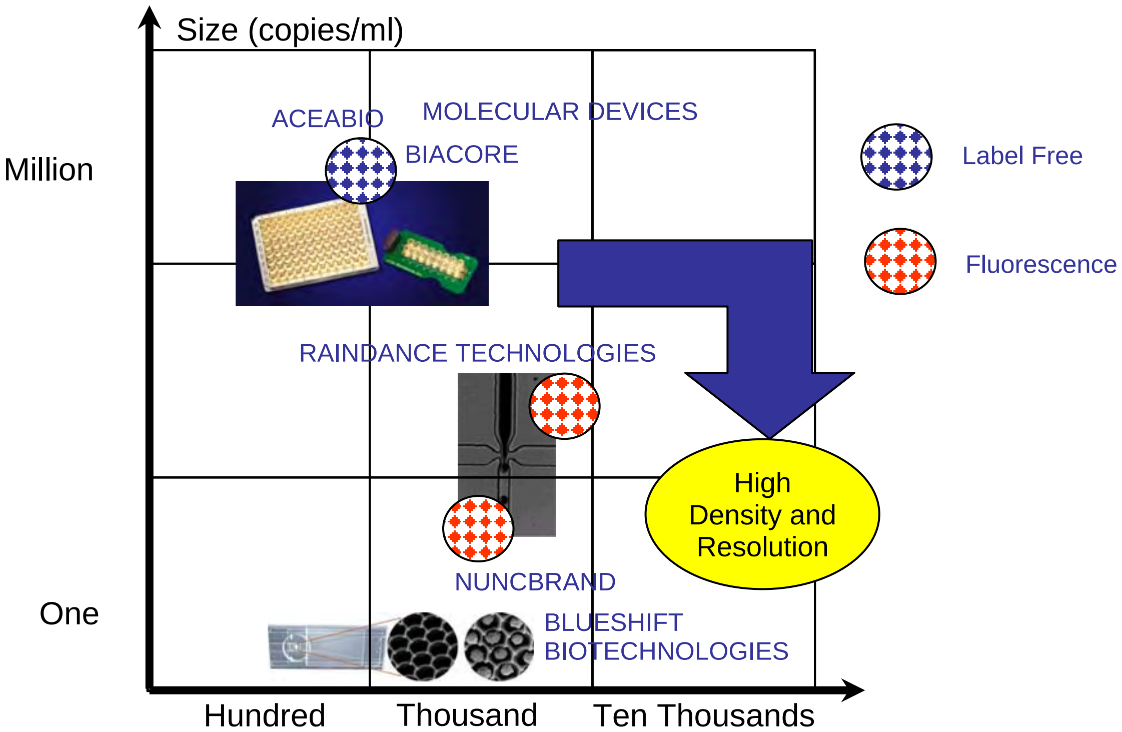


Figure: Cells on-chip through size versus density figures. High resolution (single cell) prefers fluorescence based analysis, label-free methods are mainly implemented on large size systems.

Micro electrospray emitters for mass spectrometry.

Mass spectrometry allows the detection of bio molecules, proteins and peptides, and in particular large bio molecules. Today, one of the great challenges of Life Sciences is a comprehension of how proteins function in living organisms. Our study here is the design, fabrication and characterisation of micro electrospray ionisation emitters for mass spectrometry. The goal is to develop micro electrospray ionisation emitters which have (i) a very ionisation efficiency allowing high sensitivity for mass spectrometry (<1 fmol/µL) (ii) a high reproducibility from device to device and finally (iii) compatibility with laboratory on a chip. A high ionisation efficiency permitting high sensitivity will allow the detection of samples having limited volume and low concentration; a good device to device reproducibility will eliminate measurement uncertainty and finally lab on a chip compatibility will allow integration of on-chip biochemical processes prior to electrospray ionisation

II.2.3 Microsensors, Microsources

The knowledge of the group gained in the field of the thermal microsensors will be further developed and used taking into account the current specific needs in Microsystems field: it appears obvious and challenging to continue our research in view of developing microsources of energy. Miniaturisation and efficiency of such sources appear to be critical points to control.

A first way to address the work on microgenerators is based on thermoelectric transduction using the patented original structures of the thermal microfluxmeters developed at IEMN these last years (see first part of this document & former reports). Within this context, the effort will be principally related to the search and the implementation of new families of thermoelectric materials with stronger coefficient of merit: this can be made possible through the use of nanostructured and/or low dimensional material systems, as was theoretically predicted at MIT in the 90's then recently validated experimentally.

A second way to contribute to the development of energy microsources, is even more innovating as it has not been explored at all so far: it consists to design and realise a planar thermodynamic micromachine generating a mechanical relaxation obtained by thermodynamic conversion of a temperature gradient, working, for example, according to the Stirling cycle. This kind of concept is challenging in that it requires investigating theoretically & experimentally the feasibility of several aspects.

It should be noted that if one wants to satisfy a criteria of sustainable development (and it is our objective), it would be necessary to be able to develop microgenerators for which the temperature difference to be supplied could use permanent natural phenomena, such as human body or of other non-polluting thermal energy sources.

Of course, improvement of existing microsensors performances and development of industrial applications will be continued in the framework of "Carnot Institute" as, for example, low-cost IR imager, humidity measurement system, or static anemometer.

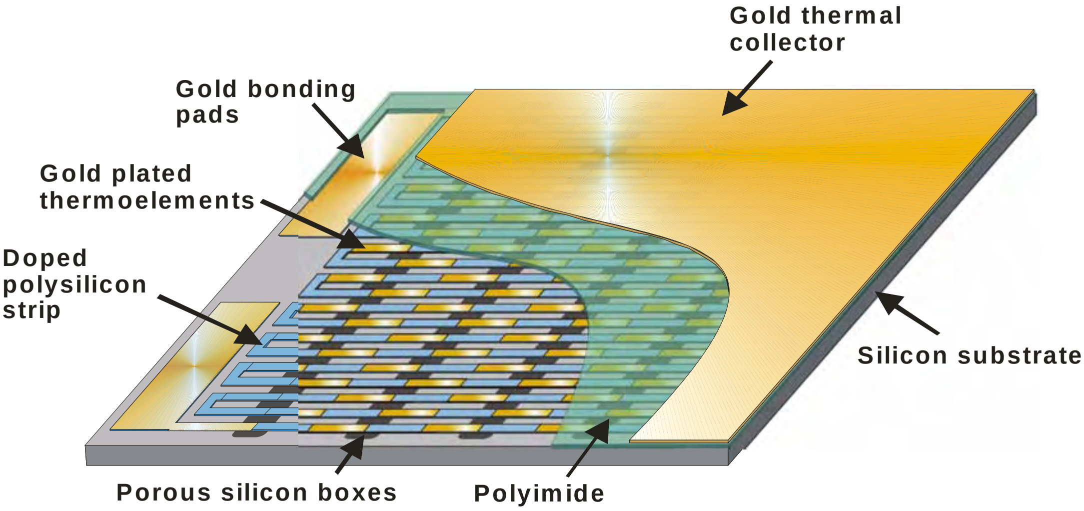


Figure: IEMN's original patented structure.

II.2.4 Coupled Multiphysics Actuation and Materials for Micro Nano Systems

Collaborations: Laboratoire de Mécanique de Lille (LML, UMR CNRS 8107 and specifically the "FILMS" Team), ONERA-DAAP, Dassault, MBDA, EADS, SNECMA, Rolls Royce, Ecole Centrale de Lyon, Renault, PSA, IRCICA, …

2.4.1. Thin films Characterization

Context:

In 2000, IEMN began a research activity on MEMS reliability and two thesis related to this topic were defended: the first one dealt with the evolution of the material properties of poly crystalline materials such as silicon and gold with respect to the number of cycles. This fatigue study was completed by another thesis on creep induced by an indentation process.

Next 4 years actions:

In collaboration with the Laboratoire de Mécanique de Lille (Lille) and the Laboratoire de Mécanique des Solides (École Polytechnique, Palaiseau), we plan to study thoroughly the mechanical properties of thin film material by combining different characterization techniques: tensile testing with an image correlation and nano indentation. Inverse modeling will serve as a tool in order to determine material behavior laws. The aim is to provide to the MEMS designer predictive information on the device characteristics when submitted to a cyclic loading.

2.4.2. Micro-Magneto-Mechanical Systems (MMMS)

Context:

Most of the work dedicated up to now in MEMS devices was made in the microscopic scales and primarily using electrostatic effects. If many MEMS solutions were proposed in the field of sensors, there is still a lot of efforts to do in the field of actuators, because there are plenty applications requiring forces, torques, and displacements in dynamic regimes not available with existing devices. This is in particular the case when microactuators are needed with effects in the macroscopic world. For this kind of intermediate range situated between the MEMS present characteristics, and the one available using conventional macro-technology, solutions based on magneto-dynamic effects are particularly adapted. Very few teams in the world are developing this kind of approach. France is in a good position with developments in the G2ELab in Grenoble on the one hand, and in our group IEMN /LEMAC where dynamic modes using couplings between different physical effects are stimulated and complementary applications targeted.

Next 4 years actions:

The goal of the work is the elaboration of completely integrated magnetic micro-actuators with large forces, torques or displacements and dynamic modes using mechanical resonances or couplings between different physical effects. Three applications detailed below were already selected and will be developed with emphasize on specific designs and the integration of all the elements of control.

The first demonstrators concern arrays of Microvalves for active flow control. There are strong needs in aeronautics and automobile industry for reduction of oil consumption, and greenhouse gas emission. Based on the successful demonstrators already elaborated in collaboration with the new IEMN team “FILMS” (see section 5) which placed the LEMAC in a world leader position, we will concentrate our research on: a) the increase of functionalities of the microvalves by the insert of integrated sensors allowing the control and/or closed loop drive, b) the development of new integrated fabrication processes improving fabrication of large numbers of microvalves and reducing power consumption, c) the adaptation of the microvalves to real environments for the two targeted fields of applications.

The second ones concern highly integrated matrix of micro-actuators for tactile interfaces. The goal here is to provide new computer interfaces providing tactile sense as complements of visual and audio informations. A completely integrated matrix including sensors will be developed.

The third one concerns soft reconfigurable RF antennas. In the perspectives of distributed sensors in large numbers or smart dusts, it is desirable to have orientable antennas with large deflections and frequency tunability. Our goal is to elaborate ultra-soft antennas working in the millimetric band, using PDMS and our magnetic actuating methods. These antennas are supposed to be part of the communication system of the smart dusts.

2.4.3. Active Multiferroic Nanostructures & resulting MMMS devices

Collaborations: Moscow Institute of Radio-Engineering, Electronics and Automation (MIREA Russia), Groupe de Physique des Matériaux (GPM, UMR CNRS 6634), IMO Hasselt universiteit (B)

Context:

One of the new and strong trends that recently appeared in the field of Micro-Electro-Mechanical Systems (MEMS) is the search for integration of new functionalities within the devices. Active materials such as piezo-electric / electrostrictive films on the one hand, and magnetostrictive films on the other, already provided these last years some interesting solutions, widening the potentialities of former MEMS devices.

In parallel, in the field of bulk active materials, the years 2000s shown a new interest for multiferroics, and among them specially magneto-electrics combining ferro-electric and ferro-magnetic orders, because it was demonstrated that magneto-electric interaction mechanism via the mechanical deformation of coupled giant magnetostrictive and piezoelectric materials is more efficient than the earlier studied mechanisms.

Within the general context described above, and based on this concept of laminated multiferroics, we proposed in IEMN/LEMAC the first magneto-electric hybrid structures combining nanostructured films with giant magnetostriction and piezoelectric films deposited on a silicon cantilever. An additional originality is the artificial induction of a critical state within the magnetic field providing very new properties of the multiferroic structure and enhancing the magneto-electric coefficient that achieved the record value in resonant mode of 50 V/cm.Oe.

Next 4 years actions:

The goal of the work is the Elaboration and analysis of new active multiferroic nanostructures with artificially induced critical states (instabilities), resulting from exchange, magneto-elastic and magnetostatic interactions between the nanolayers. These nanostructures will provide very specific properties non-available in already known active materials (i.e. single-crystals, alloys, composites...), and will be used to provide new concepts and new functionalities in the field of MEMS, with as a target the elaboration of a completely integrated MEMS demonstrator (MEMS actuators with integrated sensors, MEMS energy harvesting and remote energy feeding). This supposes the development of solutions for complete integration of the nanostructures within autonomous MEMS devices.

Some examples of targeted demonstrators are: MEMS actuators with integrated sensors, MEMS energy harvesting (vibrations) and remote energy feeding, matrix of MEMS magnetic sensors for imaging…

II.2.5 Fluids, Interfaces Liquids, Microsystems

The new FILMS team will join permanently IEMN in January 2010. It is specialized in fluid mechanics and acoustics, has the theoretical, numerical and experimental tools (high speed cameras, fluorescence microscope, etc.), to address fundamental problems in small-scale fluidics and their interactions with large scales. The integration of FILMS into IEMN offers the convergence and the synergy of different groups in an interdisciplinary field of research between hydrodynamics and microsystems or small scale living systems, inside the same laboratory. Collaborations are already active with BioMEMS, ULTRA-MAT/LEMAC or Silicon microsystems groups in IEMN or with IRI. Those latter as well as the participation of the team to the LEMAC from the origin, allow FILMS for being at the centre of a microfluidic pole. This situation concentrates most of the competences in IEMN, in an exceptional way, around the topic micro-fluidics and its associated technological support.

Next 4 years actions:

The first (Fluids) continues the recent advances on the particles segregation by an oscillatory flow or acoustic waves inside microchannels, with an extension towards biological particles for which applications are numerous.

Interaction with ultrasound and non-linear acoustics for fluidic metrology will be deepened in the frame of LEMAC. In addition to the French-Russian relationship, collaborations with ESPCI (laboratoire PMMH), with Angers, Liège, Warwick or Florida Universities already exist and others are planed particularly for the biological aspects (INSERM Marseille)

The second direction (Interfaces-Liquides) concerns works on droplets, bubbles and thin films. It mainly focuses on wetting problems of drops containing micro-particles and particularly on the issues of interactions between particles and the triple contact line. Particular attention will be given to contact lines during drop motions which displacements will be obtained by means of surface acoustic/ultrasounds waves or by micro actuations (electro wetting with BioMEMS paragaph 2 …). The problems related to drop motions will coupled with the wetting effects of surfaces with nanotextures.

Numerous international collaborations and publications (Universities of Bristol, Michigan, Paris 7 (PMMH, MSC), Sherbrooke) show that the group possesses an advanced expertise on the subject.

The third direction (Microsystems) concerns the fluidics of micro actuators dedicated to flow control, and in particular the optimization of the micro-valves developed in the frame of ULTRA-MAT/LEMAC group (paragraph 4.2).

The next 4 years will be focussed on the actuation power reduction and the system integration at smaller scales. This will allow the actuators fabrication only by means of micro-technology processes. A new design of “magneto-dynamic polymer” will be then tested. Numerous collaborations (Russian Academy of Science, Mac Gill, ONERA-DAAP…) and the industrial supports (automotive and aeronautics) have lead to middle term projects of industrial production and implementation on cars and aircrafts. LEMAC group has won a high-ranking European reputation in this field and its micro-valves were successfully tested in many European wind tunnels.uropean wind tunnels.

II.3 Micro/Nano- & Opto- Electronics

Introduction

The research activities in the field of nano and opto electronics are continuing toward the technological and conceptual limits. New systems of materials, novel architectures of nano devices and associated fabrication flow are investigated to open new ways of research and applicative fall downs in the microwave, THz and optical spectral range.
The three first topics concern the electronics part of these prospective for high power (wide bandgap material), ultra low consumption (narrow bandgap material) microwave applications and non conventional nanometer scale MOSFETs respectively. The next topic corresponds to the future works and new concepts on metamaterial for microwave to medium infrared domains. The next three topics concern the photonics part of these prospective dealing either with opto-electronics as well as acousto-optics (generation, detection, switching, routing, …) or photonics from THz to optical wavelengths. And finally, the last topic points out the physical based modelling activity both for electronics and optoelectronics nano devices and advanced technological process.

II.3.1 Wide Bandgap Devices for Microwave Power Amplification and Detection

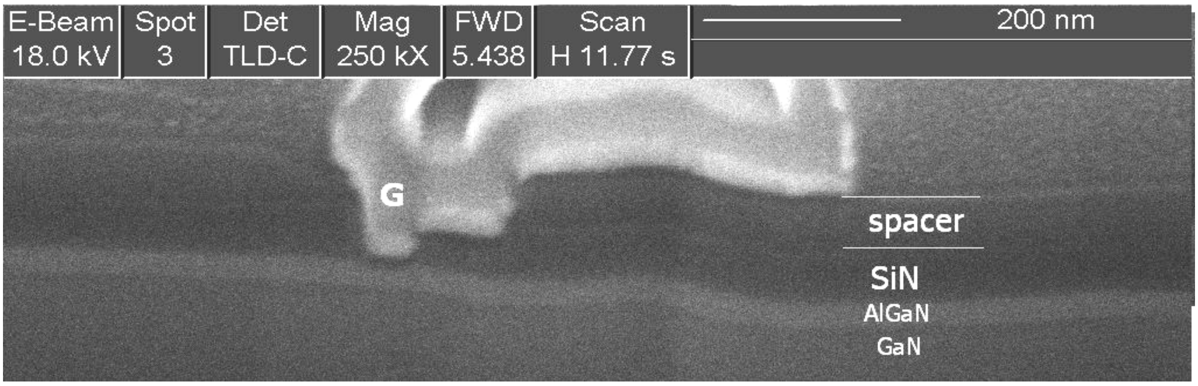
The main activity regards the design and fabrication of transistors for microwave power applications. A second aspect concerns the analysis of GaN capabilities for robust receiver chains. In this field, two goals are planned in the future :
- The development of an activity focused on devices working at frequencies higher than 20 GHz. It was shown that gallium nitride based transistors constitute a promising way for high microwave power and high frequency applications.
- Investigations on processing regarding new wide bandgap materials to predict their capabilities and the novelty they can bring compared to GaN semiconductor mainly in term of microwave power.

Short term actions:
HEMTs working up to 94 GHz will be studied for military or telecommunication applications. This activity needs to develop specific process taking into account of the devices sizes. The goal is the fabrication of 50-70nm transistors based on standard or advanced material such AlInN/GaN epitaxies. The device capabilities linked to the limitative effects at high frequency, the microwave power and the linearity will be investigated (collaboration with PICOGIGA).
Devices on free-standing or massive GaN substrates will be also studied as well as new composite substrates such as GaN on poly SiC where the surface material constitutes the best base for low cost epitaxies. The goal consists to get reproducible structures with less defects and to demonstrate high quality devices with high yield associated to high reliability (Collaboration with PICOGIGA).
It is planned to continue the analysis of the electrical and thermal behaviors of composite substrates to demonstrate their capabilities and limitations. Measurement will be also performed to study the gallium-nitride based transistor reliability (CARDYNAL contract).
AlGaN/GaN HEMTs on diamond substrate will be studied. The goal consists to improve the thermal dissipation for high power devices (MORGAN contract).
Studies are also started regarding the GaN based receiver chain (limiter + LNA) capabilities in S-band for radar applications (DTC contract).
Besides, RTDs on GaN templates will be fabricated and measured by C-AFM to demonstrate the advantages of the gallium nitride semiconductor. Simulations will be also carried out to help the device design (TRANSNIT contract).
Advanced semiconductors will be also investigated such as B(Al,Ga)N to fabricate new photo (transistors) detectors (GABORE and HIPPoPP contracts).
Investigation of THz detectors and emitters using the plasma wave behavior of 2D electron gas in AlGaN/GaN heterostructures will be continued (TERAGAN contract).

Long term actions:
Advanced semiconductors will be also studied such as B(Al,Ga)N to fabricate new transistor types such as MISHEMTs (GABORE and HIPPoPP contracts).
Diamond based process will start for applications in harsh environment. In this frame, investigations on delta-doped MESFETs based on diamond are planned (DELTADIAM project).
Another important activity was developed recently to demonstrate the wide bandgap possibilities in the following fields:
- Solar-blind deep-ultraviolet (DUV) photodetectors operating at high temperature and in harsh environments

presenting extremely low dark current, high breakdown voltage, and high responsivity.
- Development of devices based on nanowires for the fabrication of sensors.
- Design and fabrication of resonant tunneling diodes (RTD).
- Study of plasma wave devices for THz applications.

Long term issue will concern the development of new devices based on gallium nitride nanowires for detection or microwave applications.



FIB view of a double field plate Γ gate transistor with a gate foot length of 40nm.

II.3.2 Nanometer devices for high frequency low power electronics

Future wireless and sensing applications in the field of ambient intelligence will require high performance and ultra low power consuming electronics. To this aim, we are going to investigate other material and device architectures than conventional silicon CMOS.

MOSFET on narrow bandgap III-V material
State-of-the-art:
A first action concerns the fabrication of MOSFET on narrow band gap material. Although this field of research is increasing in several groups in United States (Perdue University, INTEL, Freescale, IBM), such a research does not exist in France; some activities are carried out at the European level (Qinetic in association with Intel, Glasgow University in collaboration with Freescale; Chalmers in association with IEMN). The main idea is to decrease the DC power consumption without degrading the frequency capability, which is possible by reducing the drain voltage down to few kT/q while keeping high the cut-off frequency. We hope to achieve this objective thanks to the high electron transport properties of antimonide based material.
Short term actions (collaborations with Chalmers, ESA, CNES, Thales Alenia Space)**:**
At the fabrication level, there are two critical steps that we have to investigate: the first ones concerns the deposit of high quality thin film gate oxide on III-V material, the other is the optimization of a self-aligned process to reduce as much as possible the access resistances. Simulations and electrical characterizations will be also necessary to improve the knowledge of fundamental behaviour of such III-V MOSFET under weak bias condition. Existing collaborations with European groups (Chalmers, Helsinki) and French partners (CEA-LETI) will be strengthened. More applicative research in this field of antimonite based transistors will be also carried out for low power cryogenic HF electronics for space applications. Such action will be supported by the French (CNES) and European (ESA) space agencies.
Long term actions:
According to the results obtained during this first phase, validating or not the interest of such devices for the ultra low consumption HF applications, we could focus on the problematic concerning the hetero-integration on silicon.

High frequency capability of 1D-electronic devices
State-of-the-art:
Since the few last years, some groups in the world (Irvine Univ. of California, Standford, Harvard, Lund Univ., Duisburg Univ.) are going to investigate the mechanisms and properties of carbon nanotubes or semiconductor-based-nanowires under high frequency regime. The main applicative interest is to use in one hand the very high electrons and holes mobility to achieve high frequency potentialities and in other hand, the versatility of nanotubes / nanowires to be integrated in many kind of substrates (hard or flexible dielectrics).

Short term actions (collaborations with CEA Saclay, ENS, Duisburg Univ., Néel Institute)**:**
A second objective concerns the high frequency dynamic properties of 1D-electronics devices and their potentialities to realize high frequency low consumption electronics on flexible substrate (plastic). In this topic of research, we would like to add complementary studies on existing

national and European actions by focusing on the high frequency properties of such technology. For the same motivations, we will continue to investigate carbon nanotubes based devices in collaboration with CEA Saclay and ENS and we will extend such study to narrow band gap nanowires. A collaborative action in InAs based-nanowires is going to be effective with a group of the University of Duisburg. A long term issue should be to develop a fabrication process of flexible HF electronics by deposit of CNTs and/or nanowires in solution without critical nanolithography steps. In a short term issue, we will fabricate elementary devices (dipoles, transistors) to allow high frequency characterizations in order to carefully understand and model the intrinsic and parasitic properties under dynamic regime of such nanodevices. In a similar objective, we plan to study the potentialities of graphene for electronic device applications, together with the EPIPHY group (material growth) and in collaboration with the Néel Institute for low temperature transport experiments (through the ANR project Xp-Graphène). Our objective is to optimize the fabrication process to achieve graphene-based-nano-ribbons with less than 10nm of width.

Long term actions:
For this topic, our focused target could be: open the way of new technological approaches at IEMN by using 1D-electronic devices and concepts based on printed electronics on flexible substrate (plastic…).

High frequency capability of advanced vertical transport based transistors
State-of-the-art:
Transistors operating at very high frequencies (500 GHz - 1 THz) are required for high speed telecommunication or THz-wave generation/detection systems. However, today's best performances obtained with heterojunction bipolar transistors (HBT) hardly reach cut-off frequency Ft of 500 GHz, due to the intrinsic limitations of electron transport in theses devices. Recently, higher frequencies of Ft=700 GHz have been obtained with a new device design, using indium rich InGaAs material.

Short term actions (collaborations with IES Montpellier, IMS Bordeaux, III-V Lab, OMMIC)**:**
One first project focuses on advanced technological activities required to achieve InP Heterojunction Bipolar Transistor (HBT) with high reliability level enabling the future development of the robust integrated circuits (ICs) working at 112 Gb/s for Ethernet optical transport network. InP HBT technology has successfully demonstrated its ability to provide large-signal processing for the higher clock-rate ICs operating at up to 50 GHz clock. Our objective is mainly to fabricate alternative Antimonide based HBT reported on AlN substrate to increase its thermal properties.
In a second project we propose a more drastic change by using InAs material - which offers more than a factor of 2 increase in intrinsic electron velocity as compared to InGaAs - in an innovative InAs/AlSb quantum hot electron transistor (QHET). This original vertical transport device has the potential to efficiently exploit the unrivalled transport properties of InAs. The aim of the project is to design, fabricate and study high speed prototype QHET and to evaluate the potential of this innovative technology for high frequency applications.

II.3.3 Non conventional nanometre-scale MOSFETs architectures

Research projects in the field of non-conventional MOSFET architectures encompass two types of objectives. The first one considers three-dimensional integration of active functions at both the front-end and back-end level: it belongs to high-risk research that also holds the potential of major innovations in the field of device processing and circuit design. The second type proposes to further pursue investigations in a field that has considerably gained in maturity and interest over the last few years: metallic source/drain MOS architectures for which our group has demonstrated state-of-the-art results.

Three-dimensional CMOS integration
Conventional planar CMOS integration has limited floorplanning choices which severely limit potential improvement of system performance. In particular, as circuit size grows, interconnect lengths and associated loading effects are identified as the major problem to face in order to keep on track of the ITRS requirements in terms frequency performance. Three-dimensional (3D) device integration appears as the most promising solution to limit latency due to interconnections. It also bears the promise to dramatically enhance chip performance, functionality, and device packing density. Short and middle terms solutions rely on heterogeneous layer transfer of functional circuits. At longer term, 3D integration must be envisioned at the front-end level as well as in the free volume left unoccupied between interconnection lines (back-end). Before in-chip 3D integration can be realized, key technology challenges must be addressed, in particular: i) device architectures with independent gate and source/drain control to build enhanced stacked functions at the front-end level, ii) growth of high

crystalline quality silicon on a dielectric amorphous surface to generate active semiconductor layers in the back-end layers.

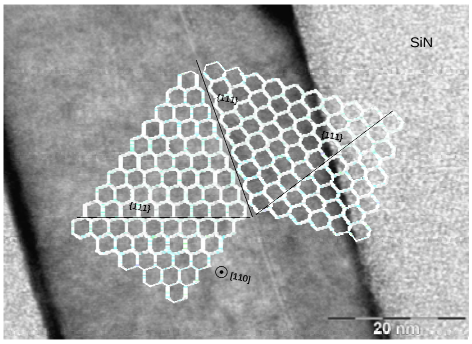
To tackle the first challenge, a mid/long-term objective is to propose integration schemes that enable the 3D stacking of transistors with independent source/drain/gate commands. In parallel to these technology-oriented investigations, a complementary design-oriented action will investigate the added value brought by 3D integration at the front-end level with respect to the following criteria: function enhancement at circuit level, area/function, power consumption, performance gain.

To tackle the second challenge, the catalytic VLS (vapour/liquid/solid) growth technique, well known to produce nanowires, will be coupled to a tunnel of confinement in order to produce nanometre thick crystalline ribbons with a well controlled orientation and placement. For the sake of illustration, the Figure placed bellow shows the result of preliminary work carried out in our group. Starting from a SiO_2 substrate, the first step has consisted in the fabrication of a SiN tunnel at the extremity of which a catalyst slug (Au) is placed. After a CVD growth based on catalytic SiH_4 decomposition, high resolution TEM characterization has confirmed the formation of a crystalline silicon blade in the initially empty volume of the tunnel cavity.

The integration of nanowires/nanoblades in vertical MOSFET structures will be considered as well. The demonstration will be proposed on vertical Si NWs obtained by a top-down approach but should be extended to bottom-up NWs growth with materials of IV or III/V group.

Metallic source/drain MOS architectures

In order to further pursue down-scaling of MOSFETs in the sub-32 nm range of gate lengths, novel devices that hierarchically combine alternative materials as well new architecture concepts such as multi-gated channel (fins or wires) have been proposed. Considering that the aforementioned innovations are expected to contribute to a higher current drive at shallower junction depth and reduced silicide thickness, extremely severe constraints are placed on the junction and contact technologies. In order to address this challenge, one alternative is to implement metallic S/D combined to a dopant segregation strategy at reduced thermal budget. The expected benefit is to considerably reduce the specific contact resistance of the metal/semiconductor junction while keeping activated dopants sharply localized at the interface. It is worth mentioning that Schottky architecture involves a low temperature process (<500°C) that enables the integration of MOSFETs in the back-end layers. It is therefore an indispensable building block for the integration of MOS structures in the back-end layers, as described previously. In addition, the effect of strained semiconductor will be thoroughly studied in the frame of the NANOSIL NoE: carrier injection from a metallic junction should benefit from band splitting and from the corresponding Schottky barrier height reduction.



High-resolution TEM characterization showing twined crystalline domains grown in the tunnel of confinement after catalytic CVD growth

II.3.4 Metamaterial technologies

Let us recall that the research activity on metamaterial concerns three spectral regions and the prospects in each frequency range are the following:

In connection with the microwave spectrum at short term, the main objective is to extend the studies to millimetre-wave range targeting notably the 60 GHz (in-door telecommunication systems), the 77 GHz (automotive applications) frequency bands along with the defence applications targeting the 94 GHz frequency windows. Tuneable metamaterials by means of a ferroelectrics BST technology or a Liquid crystal technology will be preferably developed. For the latter, an Applied Physics Letter in connection with metamaterials infiltrated by nematic compounds was just published in May 2008. For the former, the technological effort concerns at short term the development of quartz and BCB technologies at W band (75-110 GHz). At last, we plan the development of metamaterial antenna arrays for space applications. With respect to the state of the art on this topic, the novelty stems from the use of isotropic BST ceramic cubes.

For Terahertz, the central axis will concern the experimental demonstration of an electromagnetic cloak based on Mie resonance in cube-shaped high-κ inclusions. Also, the fabrication of a front-side illuminated device is in progress. In contrast to the edge-illuminated devices, following the requirement of an orthogonal orientation of the magnetic

field with respect to the current loop planes, we recently designed a sub-wavelength aperture device. The characterization of this kind of devices will be performed by a Time Domain Spectroscopy Technique in collaboration with the University of Littoral Côtes d'Opales (Physics department in Dunkerque).
At Infrared, most of the research will be oriented at mid and longer terms to the design and the fabrication of metamaterials in the optical range. Superlensing in the near field and hyperlensing in the far field are the targeted applications with two technological options. For MIR spectroscopy, a novel semiconductor based approach will be investigated. It is based on the resonant transmission on sublambada hole arrays. This work is carried out in collaboration with the epitaxy group at IEMN and III-V lab of Thales Alcatel group. For hyperlens, a planar technique requires to develop conformal mapping in order to design the gradient necessary for the magnification effect generally induced by metamaterials grown on curved surfaces. This work is a part of a proposal on the fabrication of an hyperlens at mid infrared.

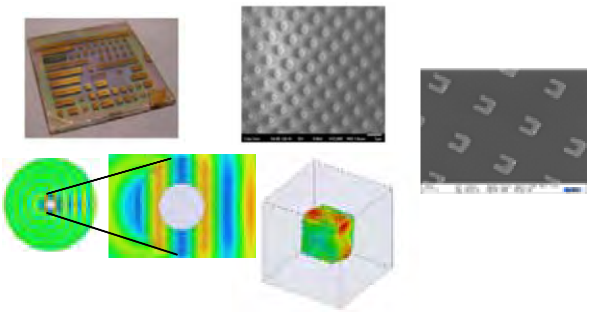


Fig. 1 : Quartz technology for millimeter wave metamaterials, Gold nano spheres, nir arrays, radar cross section and Mie resonances in BST cubes

For NIR, the chosen option is the development of wire or sphere clusters self assembled on pre-etched templates. The figure hereafter illustrates the quartz MMIC-type technology; a nanosphere cluster array fabricated in the framework of collaboration with the University of Boulder a scaled FSS operating at 1. 5 µm. Mapping of the H field in BST cube and E field of a cloak for the calculation of the radar cross section illustrate the modelling issues with special attention to the dispersion diagram in self assembled artificial media.

At longer term, we have the feeling that the concepts, developed via the metamaterial technology for electromagnetic waves, are quite general and that many unique properties, such as the achievement of negative index, can be extended to other kinds of waves notably acoustic waves. First contacts were taken with the Acoustic ISEN Group (Mrs Hladky) with a first practical application involving a flat focusing acoustic lens. Cloaking recently demonstrated at the University of Valencia Spain could also be considered. Also, preliminary contacts were established with the EPHONI physic group which has already a strong expertise in phononic crystals. At last, let us recall that the topic of left handed metamaterials is also one of the key subjects of the research programme of IRCICA. Non-linear optics can be envisaged in the framework of a left handed material system along with the so-called rainbow–devices recently proposed in the literature.

II.3.5 Optoelectronic generation and detection of terahertz signals

For the short term perspectives, we plan to continue our efforts in the development of passive and active terahertz devices. For the passive devices, we will focus on **plasmonic** structures such as planar Goubau-lines and their electromagnetic field confining properties and also on the **TEM-Horn Antenna**. Both of them will be used in several applications. This antenna will also be improved by replacing the currently used dielectric parallelepiped placed at the end of the antenna by a cylindrical lens (higher gain is expected). Applications, such as gas-spectroscopy, of this kind of antenna combined to **quantum cascade lasers** will be explored in collaboration with the group of Carlo Sirtori (Paris). Preliminary results have already been demonstrated.
For the active devices part we will work on the thermal aspect: the optical power density focused on ultrafast photodetectors used to generate THz signals (**LTG-GaAs photoswitches** and **UTC photodiodes**) is several hundred kW/cm^2. The semiconductor is heated at a temperature well above the room temperature (>100 °C). Higher efficiency and higher generated THz power will be possible only if the active layers are bonded on substrates with high thermal conductivity. Two ways will be explored: Van der Waals bonding (with classical spiral or dipole antennas) and metallic bonding (with the horn antenna approach).
Some of more long term perspectives concern the development of new activities around nano-objects. (i) We will combine our knowledge and technology skills to develop **near-field THz microscopy**. The Goubau lines and the Franz-Keldysh effect can be combined to improve the spatial resolution of such instruments and to reach the nanometre range. (ii) As sensitive detectors are still lacking in the THz range, we will investigate, in collaboration with T. Melin and D. Hourlier (IEMN), the properties of **silicon nanowires at THz frequencies** and their use as bolometer detectors.

II.3.6 Microwave- and Nano-photonics

Our research on microwave-photonics - mainly focused up to now on photodection and switching functions - and on nano-photonics - mainly focused on filtering and switching functions - started to be merged and extended to the realisation of novel functionalities with the goal of increased performance compared to the state of the art results. Potentialities of new materials and device architectures, i.e. use of plasmonics, will be jointly explored. On the other hand, the use this latter technique for biologic instrumentation will be growing.

Microwave photonics
State of the art
Microwave photonics domain requires specific developments linked either to the analogue properties of the transmitted signals or the optical configurations of its functionalities, if both are not jointly concerned! New device topologies and materials are then investigated in order to fulfil the requirements of the application fields. This can be achieved grouping the expertise and skills of different teams working in diverse research domains. It means, on one hand, that a strong effort is devoted to the optical and microwave properties of new materials (GaAsSbN/GaAs,GaN, InN,...), that is made under different collaborations (Nanyang Technological University at Singapore, IMRE at Singapore, GES at University of Montpellier, University of Darmstadt, L2E University of Paris 6). On the other hand, device design and fabrication follow the same way and joined activity with high expertise partners (Alcatel-Thales III-VLab, 3S Photonics, TAS, L2E) allows reaching the desired performance.

Short term actions (supported by DGA and Thales Airborne Systems; collaboration with L2E, Thales Airborne Systems, Alcatel-Thales III-VLab, 3S Photonics)**:**
<u>Photodetection</u>
The optical summation of RF signals was demonstrated at IEMN using several PIN photodiodes monolithically integrated with optical waveguides and at III–VLab with a hybrid microwave circuit including several PIN photodiodes. Next steps will be, in collaboration the III-VLab, to try to integrate InP Uni Traveling Carrier (UTC) photodiodes with dielectric nanowaveguides.
<u>Optical switching</u>
In our first actions we will study new InP heterostructures (quantum well based,…) and devices architectures to fulfil the requirements of low propagation loss and efficient optical index variations. The coupling to the fibre will also be considered. Optical switches and switching matrixes will be optimized and fabricated with the goal of low insertion loss, low consumption and high crosstalk (Thales Airborne System and DGA supports, TAS collaborations).The monolithic integration of the InP switching active region with dielectric nanowaveguides will also be studied (collaborations with TAS and 3S Photonics, PNANO ANR submitted).

Specific properties of photoconductive detectors on LT GaAs materials are now well known and more recently L2E (Paris 6) and TAS applied them to demonstrate a very high speed photoswitching of microwave signals. Here the goal of a more or less middle term research project supported by a DGA PREI in collaboration with TAS and L2E, is to try to use nanophotonics to extend the microwave bandwidth up to 20 GHz, keeping a 40 dB microwave isolation. Also, an extension to longer optical wavelengths (1.3µm, 1.55µm) is explored through the study of GaAsSb based epitaxies to get high resistivity and ultra short photoresponse properties. GaAsNSb heterostructures grown lattice matched to GaAs substrates (collaboration with Professor YOON Soon Fatt at NTU in the frame of a Collaboration Research Agreement and the CINTRA Project) are also explored as a potential material for such applications.

Long term actions:
We already started a collaboration with Nanyang Technological University (Prof. YOON Soon Fatt), to study the potentialities of GaAsSbN material grown lattice matched on GaAs substrate, for long wavelength (1.3µm, 1.55µm) photodetection. Efforts will be pursued on waveguide PIN photodiodes and avalanche effects in these devices. These actions with NTU are developed in the frame of collaborations with Thales (TAS, Thales@NTU), within a Collaborative Research Agreement between Thales - NTU- and IEMN signed in April 2007 on “Advanced optoelectronics and photonic devices for microwave applications”, and within the CINTRA (CNRS, IEMN, NTU, Thales, Research Alliance) project that we hope to start as soon as possible.
Optical switching functions will be investigated under the same collaborative action on GaAsNSb materials and jointly with Darmstadt University (Professor Dimitris PAVLIDIS) and IMRE at Singapore (Professor CHUA Soo Jin) (also in the frame of the CINTRA Project) concerning GaN based materials. This research will be primarily motivated by the knowledge of the optical and electro-optic properties (complex optical index, variations under free carrier injections…). Concerning new materials, InN, a new material which bandgap allows long wavelength (1.55µm, 1.3µm) photodetection with submicron penetration length for fast photoswitching of microwave signals (collaboration GES at University of Montpellier, L2E at Paris 6, TAS, PNANO ANR submitted) was also recently launched.

Nano photonics/Plasmonics
State of the art:
Nanophotonics in information and communication as well as in health care and life sciences is still a hot topic for the upcoming years (see for example, OPERA^{2015} data records). The development of nanoscale optical structures has enabled tremendous control over the propagation and manipulation of light waves. High index contrast waveguides and passive devices afford increased non-linear effects and compactness.

The development of nanoscale plasmonic devices with dimensions smaller than the wavelength of light allows reaching properties that can be exploited to gain an even higher degree of control over light-matter interactions and opens the door to the development of a myriad of new device architectures whatever the application field is. Moreover, their small size directly results in higher operating speeds and facilitates an improved synergy with electronic components.

Short term actions (collaborations with LPN, L2E, GET/INT, TAS, TRT, Alcatel Thales III-V Lab., Univ. de Rennes I, LAAS / CNRS, Selex Sistemi Integrati, CNR-IFAC, IRI, Univ. Mons (BE), Univ. Liège (BE), Univ. Lille 2)

Nanophotonics

The realisation of microwave photonic delays using slow optical waves is studied using either III-V/polymer nanostructured wires (DGA PREI, Eurofinder) or GaAs based membrane photonic crystals (PNANO ANR). One challenge will be to transform passive devices into active electro-optic devices. The nanometric dimensions allow achieving low required current to induce variable delays.

Photoswitching will also be investigated using nanophotonics structures (see paragraph dedicated to microwave photonics).

Plasmonics

Plasmonics, that we used right now in bulk films for biologic species detection will be investigated in integrated optics conformation for two completely different applications.

The first one will be the continuation of biologic instrumentation activity and it will be addressed commonly with the joint integration of microfluidics. Integrated optics and plasmonics offer great flexibility in instrumentation design, particularly for parallel or improved sensibility detections. When coupled to microfluidics, potentialities are increased tenfold since volume as well as homogeneity of solutions can be controlled improving so the repeatability of measurements.

The second will use the plasmon resonance to modulate an impinging optical signal in the telecommunication wavelength range. Most of the methods developed for microwave modulation of an optical signal are limited by the power needed and low efficiency of the electro-optic modulation (for example $LiNbO_3$ based modulators), by the nonlinearities (electroabsorption based modulators…) or the reliability (polymer based electrooptic modulators…). The new way proposed here is to take advantage from plasmonic effects to develop a high speed, high efficiency, high linearity electrooptic modulator (submitted DGA PREI).

Long term actions:

Interdisciplinary research mixing microfluidics, nanophotonics and plasmonics, leading to the "lab on chip" concept, will be targeted. Obviously, this is no more related to this single group activity but will involve other research group from the Institute as well as from University of Lille I but also from other laboratories as IRI and instrumentation oriented laboratories from University Lille 2 (Medicine).

The possibility performing nanophotonics using new materials will be explored in the frame of the CINTRA Project.

II.3.7 Opto-Electro-Acoustic advanced devices

As can be seen from the number of recently published papers, research activities in the domain of acousto-optic are regaining a great interest. The main reasons are: first, the tunability of bulk acousto-optic devices over a wide spectral range is convenient for optical communication systems, especially as regards network re-configurability. Second, new materials are now available with good optical and acoustical properties and third, the development of efficient micro- and nano- technologies leads to the possibility of designing new acousto-optic structures.

At short term, the future broad band optical network will require active selective couplers (add drop). Acousto-optic devices can offer a competitive solution for CWDM applications. In particular we are investigating a polarisation insensitive equaliser for Coarse Wavelength Division Multiplexing in the 1550 nm optical range. The design of the device is in progress based on a specific anisotropic interaction in two tellurium dioxide crystals in tandem. Next, the characterisation will be undertaken for a 4-wavelengths multiplex. This work is carried out in collaboration with the MV Lomonosov Moscow State University.

Owing to the recent progress in materials and structures, we plan to develop research activities for medium and long term range in the domain of planar acousto-optic interaction in semiconductor new materials and new structures. It is well known that the acousto-optic interaction offers the ability to functionalize an optical source. On the other hand, III-nitride materials have recently been reported to be promising for acousto-optic interaction. Such materials could allow to functionalise blue laser diodes. First the acoustic and optical properties of multilayer structures have to be studied. A PHC alliance program is starting with University of Bath, covering this topic. Moreover, slow mode devices such as photonic or phononic band gap structures could lead to an enhancement of the acousto-optic figure of merit. The benefits of these structures could enable the development of acousto-optic devices with size and consumption reduced by an order of magnitude compared with classical techniques. An ANR project has been proposed, with 5 academic and industrial partners, it deals with “phoXonic” structures on $LiNbO_3$.

II.3.8 Modelling for nano & opto devices and advanced technologies

Modelling of Nano and Opto devices
Physical simulation tools are essential to support the development of modern electron devices, to understand in depth their behaviour and to devise optimisation strategies.

State-of-the-art
Although commercial softwares take an increasing place, they are still far from meeting all needs, especially when innovative or exotic devices are considered. Therefore, most of laboratories have developed their own numerical simulation codes in relation with their specific fields of interest.
Monte Carlo (MC) simulation codes of electronic devices are widely spread in the scientific community. In particular, IEF (Paris), IES (Montpellier), IEMN (Lille), IMEP (Grenoble), CEA-Leti, to cite only French teams, have worked extensively on MC simulation. Among cutting edge issues, one may mention the account of quantum transport, the realistic 3D description of devices, and the modelling of contacts. The application of MC method to optoelectronic devices is less frequent. Only a few groups have developed a MC simulator of Quantum Cascade Lasers, among them MIT, several teams in Italy and Germany and only IEMN in France.
More “macroscopic” models based on conservation equations are useful because they are able to describe both the device and the circuit level. We plan to include electromagnetic phenomena in such models, a task which can be viewed as a first step towards global multiphysics simulation, which remains a very challenging goal.
Modern microelectronics makes use not only of semiconductors but also of ferroelectric systems which are essential for micro and nanoscale memories. This field of research is especially developed in Asia (Fujitsu, Samsumg, Seoul and Tokyo Universities...) and USA (Berkeley, HP) although some activities are also carried out in Europa (MULTICERAL project). We are developing space and time dependent models in order to investigate dynamical properties of devices based on nanostructured ferroelectrics layers.

Short term actions .
The actions which are currently in progress cover a wide range of topics. They will be continued and, as often as possible, we will try to make them converge towards “multiphysics simulation”.

- We are currently developing a particle model of lasers, and primarily of quantum cascade lasers, which describes electromagnetic properties of the resonant cavity as well as electron transport in the active “gain region”. Such an approach is essential to simulate realistically the laser in operation in static and dynamic conditions. The main difficulty is that the various phenomena occur on very different time scales. We are developing a collaboration with Warsaw University of Technology on this topic.
- Our activity on physical macroscopic models of semiconductor devices and circuits will be mainly focused on the development of a 2D time-domain electromagnetic general simulator. It requires both electrostatic and electromagnetic solution of Maxwell equations. The transport modelling will be based on conservation equation sets derived from Boltzmann equation, from drift-diffusion to energy-momentum by order of increasing accuracy. The first applications will be focused on THz devices based on wave propagation, such as distributed GaN Gunn diodes, plasma wave devices and travelling wave “Pierce-like” structures.
- We will continue to develop our simulator of ferroelectric thin films and nanostructures, based on a self-consistent resolution of Ginzburg-Landau, Landau-Khalatnikov and Maxwell equations. Using this model, we plan to investigate the lateral size effect and the dynamics of domain structure. This work is undertaken in collaboration with University of Picardie and Cambridge University.
- In parallel, new operations will also be launched. The first one consists in developing a 3D Monte Carlo simulator of nanoelectronic devices. Thanks to a realistic description of device geometry and special effort on contact modelling, it is expected to provide reliable information on dynamic operation, an essential topic for high speed nanodevices. Ballistic devices, such as Y-switches, widely studied at IEMN, will be used as a test bed.

Long term actions

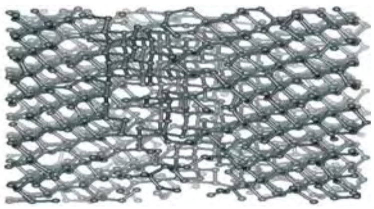
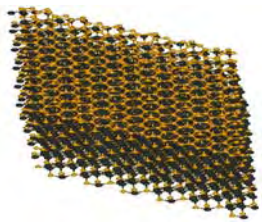
- We plan to study the mechanisms of electron conduction in ferroelectric systems, a topic which is crucial for understanding reliability in ferroelectric memories. At longer term, devices which combines ferroelectric and semiconducting properties may be considered.
- A major advance in nanotechnology is the recent development of “bottom-up” techniques, to fabricate nanowires. We plan to investigate devices based on III-V nanowires. To this aim, our 3D simulator will be completed in order to account for the specific material properties of these systems and for quantum effects.
- Another operation which is planned is the study of optoelectronic devices, such as uni-traveling-carrier diodes, based on dilute nitrides.
- Finally, we also intend to extend our energy-momentum modelling capability in order to study thermoelectric semiconductor devices for direct heat/electricity conversion.

Modelling of advanced technologies:
State of the Art/Context:
In order to continue the downscaling below the 32 nm node of electronic devices, intense research activities are being performed worldwide to develop new alternative architectures or processes. Advanced processes based on stress engineering (SiGe embedded source/strain), high mobility materials (germanium) or low-dimensional devices are under study. Such a level of complexity implies huge challenges on standard process simulations and it is expected

that more fundamental methods like molecular dynamics in a multi-scale framework could provide more physical understanding at the atomic level and support these developments.

Short term actions :
The simulations at the atomic level will be devoted to the application to FinFET nanodevices. Indeed in such low-dimensional architectures, a competition was observed between solid phase epitaxy and random nucleation. The consequence is that silicon grains may be formed and degrade the performance of the transistor. As conventional techniques of characterisation are not adapted to these structures, simulations are expected to help the understanding of the mechanisms that lead to the formation of grains and to propose guidelines to avoid them. This action takes place in the PULLNANO project in collaboration with NXP at IMEC.

Long term actions :
On the long term, new materials for microelectronics will be studied. The first material is Ge used to form source/drain junctions in GeOI devices. The interest for Ge is motivated by the four times higher low-field hole mobility in comparison to Si or GaAs, the lower band gap of germanium (0.66 eV) in comparison to silicon (1.12 eV), which should allow further scaling of the supply voltage, and the possibility to overcome the problem of the unstable Ge oxide using high-k dielectrics. The simulations will be applied to the recrystallization of amorphous Ge and the diffusion of dopants. This activity could be carried out in the framework of the PNANO ANR PRODIGE deposited this spring in collaboration with LETI, CEMES and LAAS. The second material is graphene on SiC, studied in the perspective of high mobility properties. Atomistic simulations will be carried out in collaboration with the EPIPHY group to understand the formation of graphene by heating and help to define guidelines to the optimisation of graphene-based devices.

	
Random nucleation growth in amorphous silicon structure of 2000 atoms : 3 grains could be identified	*Atomistic structure of a graphene plane on a SiC substrate used to simulate the graphitization.*

II.3.9 Microwave and millimeter wave advanced instrumentation for the characterization of innovative thin film materials and nano-devices

In the field of microwave and millimeter wave characterization the research activity generally encompasses either the measurement systems development or characterization methods. At IEMN, research efforts are made to investigate both aspects and to tackle the problems as a whole. The targeted applications of this work are diverse providing solutions for applications in fields as varied as industrial, scientific and medical. A few trends in each part of this body that would shape the future research have been identified.

On the system side, actions will be pursued to develop a millimeter wave microscope, based on the association of a six-port reflectometer and an electromagnetic probe, for the characterization of surface and subsurface materials in a non-contact, non-invasive and non destructive way. Within this activity of microwave systems development, an articulation will concern the challenge that consists of measuring the electromagnetic properties of nano-objects, in particular in the microwaves domain. To that end the definition and the realization of a system based on a new concept of microwave instrumentation that leans on our experience within the group in the achievement of S-parameters measurement systems will be part of the research program.
From the characterization methods point of view, studies will be launched with regards to many questions that need to be answered along the way when dealing with innovative materials. These issues include microwave characterisation of materials of different natures, shapes and sizes such as very high dielectric thin film materials for microelectronic applications, electro-optic polymer for broadband optical modulators or compact powdered materials for sintering control by microwave radiometry applications. So, a key objective in these research initiatives, led in collaboration with other groups, will be the understanding and the modelling of electromagnetic waves interactions with these kinds of materials

II.4 Communication Systems and Applications of Microwaves

Introduction

The future works of this axis will concern further development and improvement of the studies already undertaken, but also some new emerging activities like for example the use of microwave Time Reversal technique combined with UWB radio technology to improve communication and localization systems for underground trains or the development of solid state microbatteries for wireless sensors networks coupled to photovoltaic recovery devices compatible with the new SIP approach. The up-grade of our Telecom/CEM platform will also receive some deal of work. It is rather difficult to define quite exploratory work in the technological field of ICT but our aim is to develop innovative concepts at both circuit and system architecture level and hardware/software interface level. As previously mentioned we are also willing to validate the new concepts by operational demonstrators using our technological platform. Even though these future developments are not independent we will summarize them in 2 major topics

II.4.1 Telecommunication for Transport Systems

1) New adaptive coding and modulation techniques for MIMO based communication systems dedicated to enhance vehicle to infrastructure link performances

1.1) Joint source channel coding (JSCC) for MIMO-OFDM video transmission in urban transportation systems

Video surveillance constitutes nowadays a real challenge for security in urban transportation systems. In particular, it is of great interest to be able to quickly inform, in a reliable way, a distant control center of dangerous or critical situations (attacks, accidents) occurring on an urban bus. Previous works have shown that MIMO-OFDM technologies offer an efficient solution to this problem, allowing robust transmission of high data rate streams over wireless channels. We consider in our research project the benefit of a joint source channel coding (JSCC) approach in a MIMO-OFDM video transmission scheme, in order to optimize the end-to-end video transmission quality by applying unequal error protection (UEP). The specific case of correlated channels which is frequently found in transportation applications will be taken into account. Different JSCC architectures will be proposed for real time video surveillance, and evaluated in terms of coding efficiency, reconstructed video quality, error robustness and complexity. The transmission chain is based on the IEEE 802.16d standard; it consists in a 2x4 MIMO system associated with OFDM physical layer. Different UEP strategies will be considered in order to strengthen transmission against channel distortions by the joint optimization of the source and channel coding parameters using full or partial channel state information (CSI).

1.2) Adaptive OFDM techniques for MIMO communication vehicle to infrastructure link in high mobility context

Our studies will investigate the performance of combining powerful coding technique with high spectral efficiency modulation, especially turbo coded M-QAM modulation based OFDM system over a time varying channel when the receiver moves at a very high speed. OFDM is also being pursued for dedicated short range communications for road side to vehicle communications and as a potential candidate for the fourth generation (4G) mobile wireless systems. But fast time varying channel (in high speed case) produces a loss of orthogonality between carriers and causes Inter Carriers Interferences (ICI). To cope with these effects, more efficient signal processing as adaptive coding technique and Modified Gabor Wavelet Transform would be studied.

Channel models as Zeng's model will be used to evaluate the performances of the complete system. A part of this study will be dedicated to analyse the problems of synchronisation and equalisation techniques for this type of communication. The final objective concerns the effect of high mobility on the association of MIMO and OFDM techniques.

2) UWB radio technology and Time Reversal (TR) technique to enhance underground train–to–wayside communication and localisation systems

We propose to combine UWB radio technology and Time Reversal (TR) technique for underground train-to–wayside communication systems. Time Reversal channel pre-filtering facilitates signal detection and helps reducing interferences with preserving the important low-cost advantage of UWB. We will analyse the efficiency of this approach in underground area for both communication and localisation. To evaluate the performances of the systems, we will perform both simulation and measurements in a real tunnel environment.

3) Analysis of electromagnetic noise, noise modelling and channel coding in presence of impulsive noise

This study deals with the analysis of the noise characteristics and the impact of impulsive noise on the performances of communication systems. First, low frequencies, typically fewer than 100 MHz will be considered, the main application dealing with power line communication in vehicle and in aircraft as well. Then ambient noise whose frequency content extends to few GHz will be analyzed. In the transportation domain, studies will be devoted to impulsive noise generated by the catenaries because they strongly affect the reliability of the GSM-R communication systems.

3.1) Power line communication in road/rail vehicles – Noise analysis and channel coding

Noise can be numerically modelled from a statistical approach. In this case, for each temporal characteristics as pulse duration, spectral content, pulse amplitude, etc., one tries to determine a known distribution function fitting, as well as possible, the distribution of the experimental data. However, such an approach is rather heavy to implement. Few simplest models have already been proposed in the literature, the most known being the Middleton’s model. However, it has been elaborated for studying the interaction between noise and analog communication system and first trials have shown that it seems not suited for digital communication. A challenging task is thus to find new models that can be easily implemented in communication simulation software for accurately predicting the communication performances. Then the robustness of turbo codes, LDPC (Lox Density Parity Check Code), hybrids or non binary, will be studied.

3.2) Power line communication in aircraft (European project TAUPE)

Reducing the cabling weight and its space allocation, simplifying the installation and the maintenance and facilitating retrofitting in aircrafts without jeopardizing the overall safety are today key issues:

- To support the All Electric Aircraft and the More Composite Aircraft regarding the limitation to the current increase of the wires’ amount
- To retrofit and maintain current airlines fleets regarding the reduction of costs
- To address the Work Programme regarding Cost Efficient Air Transport (reduce fuel consumption through systems weight saving, space allocation, simplification and retrofitting)

The main objective is to provide a fully optimized avionic architecture for power and data transmission (mixing A/C power and communication networks) that will demonstrate on System Integration Benches (SIB) the feasibility of transmitting power and data on unique path wires.

From the resulting fully optimized avionic architectures mixing A/C electrical and communication networks, *TAUPE* will also deliver specifications for harness wiring and network equipments and requirements for systems qualification that will allow easy and secured power and data transmission on unique path wires. Test Readiness Level (TRL) 4 is targeted: components and breadboard validation in laboratory environment where the basic technological components (optimised Chipsets, adapted repeater, customized modems, wiring network and specific bridges) are integrated in System Integration Benches (SIB: reference applications in aircraft wiring architecture) to demonstrate that the components and the breadboard are working together.

3.3) Impulsive noise analysis for wireless communication : Application to railway systems

Similar approaches can me made for characterizing the impulsive noise in the GHz band. As an example, in the frame of the « Pôle de compétitivité I-Trans », a series of experiments is planned for recording, in time domain, the pulses radiated by the sparks occurring between the catenaries and the pantograph. Modelling the disturbing voltage produced by these pulses will then allow predicting their impact on the GSM-R link. Another more general aspect of this research deals with the modelling of the complete power infrastructure of the railway system in order to be able to predict the electromagnetic compatibility with all ground-train safety communication systems

4) Reverberation chambers: Increase of the useful frequency band and simulation of multipath environment

Preliminary studies have shown that the lowest working frequency of a reverberation chamber may be reduced by a factor of 2, by using a combination of wires running along the walls of the room. Furthermore, it seems that the amplitude calibration may be deduced from the distribution of the magnetic field or current density measured on the walls of the room. These two possibilities for both increasing the useful frequency band of the chamber and simplifying the calibration procedure will be investigated.

Lastly, the studies on the reverberation chambers as a mean to simulate a multipath environment will be developed. The possibility of changing the delay spread inside the room, while keeping constant the statistical characteristics of the room, for testing SISO or MIMO systems will be emphasized. The validity of such tests must also be deeply studied. Indeed, it must be noted that, in usual loaded rooms, the power delay profile is a continuously decreasing function instead of a number of taps related to the number of scatterers, as it occurs in real environment.

II.4.2 Digital Communication Systems, millimeter wave Wireless Sensors Networks and very high data rate WLAN/WPAN.

4.2.1: Indoor broadband digital communications – From physical propagation channel to associated communication systems

Research on digital communications will mainly focus on sensor networks, high or low rate. Interference and sensor to sensor radio channel modelling are main challenges to propose efficient communication schemes. Theoretical approaches based on new distributions that overcome the limitations of second order statistics will be developed along with practical solutions able to give a quick but reliable idea of the phenomena involved in the communication link. The study of new solutions for high rate robust transmissions as well as optical communications will be also proposed. The three constraints: reliability, physical security and energy dissipation will be considered although they do not lead to identical solutions. The multihops scenario but also cooperative strategies are one important aspect that will also be studied. Several topics can be identified:

- Most classical studies are based on second order statistics. Moreover, the central limit theorem and the finite variance of studied phenomena often lead to Gaussian distributions. However, new communication schemes are not well modelled by these usual approaches. Random variables with infinite second order moments are better suited. Indeed, when variance is finite, probability density functions are rapidly decreasing and events with “high” values are highly improbable. This is a strong limitation when rare events are the ones we want to represent. The signification on probability density functions is that they need to be “heavy tailed”. Such considerations naturally lead to α-stable distributions.

Sensor networks represent a difficult challenge for capacity and performance evaluation: the number of sensors, the *ad hoc* configuration, the ultra wide band and the millimetre wave make classical models not adapted and simulation prohibitively complex. The α-stable approach should allow fast simulations, a useful comprehension of physical phenomena and accurate models. Two topics will be of particular interest to us:

➢ **Ultra Wide Band (UWB) channel at extremely high frequencies:** when the central frequency of the considered channel becomes high, the stationary areas become very small, making impossible numerous enough channel measurements to obtain reliable estimation of correlation functions. Besides, when the channel band becomes “ultra” wide (several GHz), the time resolution becomes very high and scatterers are correlated. Consequently the channel is no longer stationary in the frequency domain. New approaches are then needed to model it. The model proposed by the IEEE 802.15.3a standards task group, based on the Saleh and Valenzuela approach, is difficult to use for theoretical performance analysis and development of adapted digital communication and signal processing solutions. We propose a new solution assuming that the channel can be considered as an α-stable non-stationary process.

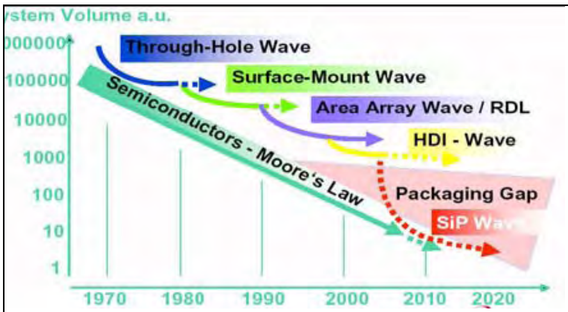
➢ **Multiple access interference (MAI) in an *ad hoc* network with time hopping**: *ad hoc* configuration and time hopping strongly modify the nature of the MAI. MAI is conditioned by the presence of strong interferers that importantly disturb the communication. Such events in *ad hoc* scenarios are rare: pulses need to superimpose and the power of the interfering pulse has to be high. Besides, directive antenna can reduce the MAI but increase its impulsive nature. The resulting noise is no longer Gaussian and new models have to be found. We can theoretically prove that the α-stable distribution can model the MAI in a Poisson field of interferers. This consideration then leads to new receiver strategies or to the use of new metrics for error correcting decoders.

- We will also further develop a fast simulation tool for a complete sensor network based on system-C AMS (ANR WASABI project). The application is a car to car propagation channel and physical layer model and the main constraint is complexity. The case of multihops transmissions, with a specific focus on the impact of front-end architecture, will be studied.
- The study of robust multimedia communication systems for wireless networks will be investigated (ANR TOSCANE project): in this case, we will develop new communication systems based on the capabilities of emerging scalable transmission schemes to adapt to channel varying conditions.
- Another topic concerns opportunistic commu-nications in multi-user OFDMA cellular networks, where joint scheduling among users and power control in a multi-cellular context is still an open problem. Some key words relative to our approach of the problem are: fairness among users, allocation of users to base stations, virtual MIMO.
- The design of efficient optical CDMA codes for optical communications by combining 1D, temporal spreading and frequency hopping scheme, should enable to increase the number of end users.
- New spatial multiplexing for RoF applications: the so-called mode group diversity multiplexing (MGDM) technique is investigated to further propose multi-services on a single MMF network.
- The extension of techniques previously developed to other application areas including in particular transportation systems.

In the medium and long term, we will strengthen the research activity of the Institute in **ubiquitous and pervasive communication** infrastructures

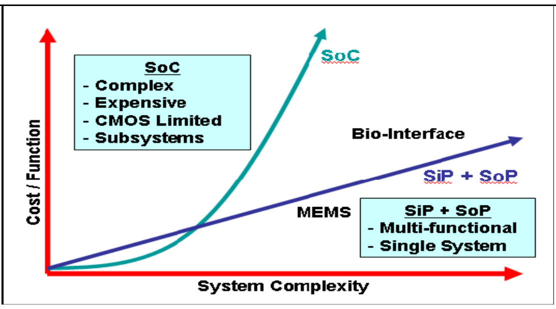
4.2.2: Autonomous ultra low power and miniaturized intelligent millimetre wave SIP radio modules for sensors networks.

The physical and economical limits of the Moore's Law will probably be reached within the ten coming years. To partically overcome these fundamental limitations ENIAC has proposed the More than Moore concept which relies on an heterogeneous integration of passive and active circuits of various technologies in Systems in Package (SiP) to offer more functionalities in reduced weight and size 3D modules. These modules can integrate sensing and communication capabilities together with some embedded intelligence and microsources of energy. The challenge of combining digital, analogue and RF functions in a single piece of silicon and optimizing this for different process technologies has proved to be difficult and extremely costly. Although major advances are continuing to be made in the semiconductor industries, for highly complex systems containing multifunctional components (digital, analogue, RF, MEMS, optics,…), the system on chip (SoC) option will be very costly if it can be achieved at all. The figure below shows how SoC for highly complex systems can become prohibitively expensive while SiP technology provides a complete functional system in one module that can be process like a standard component during board assembly, at the prize of more complex multiphysics 3D simulations including thermal, mechanical and electrical aspects.



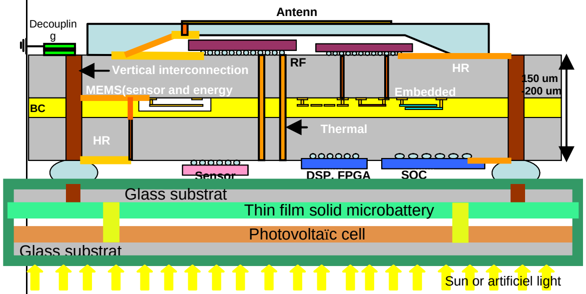
Packaging Waves (1970–2020)

(source IZM Fraunhofer)



Cost of SoC .vs. SiP (source IZM Fraunhofer)

Our goal is clearly to develop this SiP concept for sensors networks nodes and WLAN radio modules in the millimetre wave range (60 GHz and 140 GHz) including antenna array of sufficient gain which supports beam forming/ switching to achieve reasonable link budget for transmissions over 10 to 30 meters distance. MEMS devices will be used for the antenna configurability (STREPS MEMSPACK and MEMS4MMIC 2008-2010). In parallel with this SiP integration two key points will sustain this work: miniaturization and low-power operation. In addition for autonomous sensors networks we intend to develop microsources of energy combined with photovoltaïc recovery process. The figure below shows a possible approach that we will investigate based on our experience in packaging technology using either glass, HRS or BCB.



Conceptual drawing of SIP

To achieve ultra low power radio module, in addition to low power designed hardware architectures, we will also have to improve our ARM-FPGA hardware/software platform in 2 main directions:

- ✓Optimization of the multi-hop routing algorithms taking into account the use of beam forming antennas and adjustable transmission power
- ✓Optimization of the sleep-awake protocol to let sleep the maximum number of nodes when they have not to receive or transmit data while keeping the network connectivity.

This work will be developed in collaboration with the LIFL.

4.2.3: Microbatteries and photovoltaic energy scavenging for Wireless Sensors Networks.

In the future, the use of wireless intelligent and autonomous access point will need the investigation of micropower source. To supply this access point, we will perform the technological fabrication of a **Lithium ion thin film solid microbattery on a glass substrate** composed of two electrodes and an ionic oxide glass based solid electrolyte (LiPON). The miniaturization of the micropower source (volume # cm^3) is necessary to be compatible with the heterogeneous integration (System in Package concept). The micobattery's activity will be divided in two points:

✓The electrode part: During the discharge, the insertion of the lithium ion in the anode increase dramatically its volume inducing short circuits and so its death. Reducing the volume of the anode without the degradation of its performance is a key point. By the use of an anode based on silicon nanowires (or other material) allows obtaining a structure of electrode owning an empty rate up to 80%. The storage of the lithium ion around the nanowires would enhance the life time of this energy storage system. Using IEMN technological facilities, we will develop the growth of the silicon nanowires on glass substrate.

✓The electrolyte part: As mentioned previously, the solid electrolyte of the micropower source is based on an ionic oxide glass kwown as LiPON. The study of the deposition parameters of the electrolyte layer on a glass substrate will be investigated. The physicochemical characterization of the LiPON electrolyte layer constitutes the second application field of the research work.

In order to provide autonomous wireless access points, the micropower sources need to be charged. The high density of light energy (indoor or outdoor) in the environment (1000µW/cm^2 up to 100000µW/cm^2) has lead us to develop a scavenging system based on the conversion of the light in a unbiased PN junction (photovoltaic cell): this small size scavenging system (cm^3) uses the photovoltaic effect and allows the charge of the microbattery.

In order to be compatible with the integration of the thin films technology on glass substrate, we will not work with the crystalline silicon (c-Si) material line (thickness of absorbing layer # 100µm because of its bad absorbing behaviour). Moreover, the crystalline silicon material line does not allow to cover all the wavelengths of the solar spectra (ex: outdoor applications) and high energy photon (λ<400nm) and IR photon (λ>1100nm) are lost. Two types of thin films material line (thickness less than 10µm) allowing the deposition on glass substrate and covering a wide range of wavelengths will be investigated:

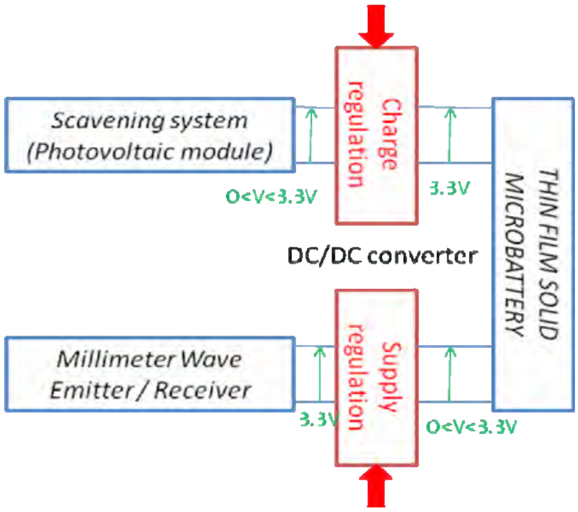
✓The amorphous silicon (a-Si:H) PIN photovoltaic cell but with limited efficiency (5 to 8%).

✓The chalcopyrite Cu – III – VI_2 material line in a multi-junction device ($CuInSe_2$: first absorbing layer and $CuGaSe_2$: second absorbing layer) to increase the efficiency (15 to 20%) of the photovoltaic cell (gap engineering) by the use of absorbing layers dedicated to a specific spectral range.

This new thematic research at IEMN/IRCICA will induce the development of new clean rooms equipments (PH_3 and B_2H_6 gas lines for the doping of the a-Si:H and coevaporation process for the growth of CIS/CGS photovoltaic cells). To demonstrate the feasibility of the coupling on glass substrate between LiPON solid microbattery and thin films multi-junction photovoltaic cells, we have firstly initiated some collaboration with others laboratories or industrials partners to obtain a-Si:H and CIS/CGS photovoltaic modules allowing the charge of the energy storage device.

For in-building non illuminated applications, we propose to optically deport the solar energy from outdoor to dark room by the use of a large core/high numerical aperture optical fiber pulled in the IRCICA photonic technological platform by the research team on photonic crystal fibers.

In addition a collaboration between two teams of researchers from the federation IRCICA (IEMN and L2EP labs) has begun concerning the charge regulation of the micropower source and the small size photovoltaic module as well as the regulation of the supply of the millimetre wave emitter/receiver and the energy storage device as depicted below. The use of static DC/DC converters allows the regulation of the energy's supply. As these converters are just composed of diodes and transistors, the integration of these devices on the glass substrate will be investigated.



4.2.4: Digital communication and very high data rate 60 GHz WLAN/WPAN.

1) Cognitive radio systems

New research efforts are targeted at cognitive radio systems in the extended GHz frequency range (400MHz – 10GHz). Applications as well as frequency bands and standards proliferate, radios able to adapt to various requirements and able to exploit opportunistically unused bands, eventually as a secondary user, are more than ever needed. Among the many bottlenecks is the RF interface that needs to sense the spectrum, withstand strong interferers and transmit in a wide range of frequencies. Wideband receiver front ends are becoming available, however not with sufficient immunity to interferers. Wideband transmitters are still lacking completely. The proposed research is to exploit a highly digitized multi-path transmit and receive architecture to increase performance through digital processing. This work builds on the results and experience gained in the digital transmitter architecture. Contacts have been set up with CARNOT partner institutes in this perspective.

2) Very high data rate WLAN/WPAN.

Many multimedia applications call for wireless transmission at Gb/s or multi-Gb/s transmission over short distances (<10 m). Sufficient spectral resource is available around 60 GHz with a frequency band of the order of 7 GHz allocated for unlicensed use such as wireless high-definition multimedia interface (HDMI) with targeted data rates up to 10 GB/s with a scalability to 20 Gb/s for higher resolution and color depths. The IR-UWB technique is limited to data rates of the order of 1 Gb/s. To achieve higher data rates the use of OFDM with MQAM sub carrier modulation is an obvious option. By limiting the constellation size to QPSK the resolution on the digital logic including ADCs and DACs can be reduced and the requirement on the phase noise of the LO can be relaxed. In addition a large sub carrier spacing (≥ 1.5 MHz for a 1024 FFT size) reduces drastically the OFDM sensitivity to RF impairment such as phase noise and I/Q imbalance.

Unfortunately due to large peak to average power ratio of the OFDM signal the power efficiency of the transmitter will be reduced and high ADC resolution will be required.

We intend to study, design and realize such OFDM/QPSK architectures with direct conversion (homodyne conversion) to suppress image frequencies and thus the critical image rejection filtering which makes this architecture suitable for multi-band, multi-standard operation. An intermediate solution could be to apply concepts and high-speed digital techniques developed for mobile communication to millimetre wave systems in order to reach digital modulation of IF signal at higher frequencies without prior conversion to the analog domain. ADC in the receive path is a critical point and it will need innovative architectures to meet the targeted performance at acceptable power levels. To integrate this system in a cost effective way the targeted technologies are very advanced CMOS processes (45 nm and beyond).

The transceiver architecture will in addition involve agile antennas with MEMS beam forming controled via the MAC layer.

This work will be developed in the framework of 2 MEDEA+ projects SIAM and Qstream in collaboration with ST-M, NXP,TH, IMEC, CEA-LETI, IMS, LAAS, LEST, … and of two SREPS MEMSPACK and MEMS4MMIC in collaboration with IMEC, VTT, University of Perugia, OMMIC, IMST, FhGISIT, …

II.5 Acoustics

Introduction

The research activities developed in the field of acoustics will continue toward the theoretical and experimental study of acoustic wave generation in various media mainly for non destructive testing applications and material characterisation. The field of acoustic Microsystems will be strongly developed in order to investigate new application in the field of BIOMEMS and of integrated non destructive testing acoustic method.The different topics concern the prospective for non destructive testing, acoustic Microsystems, materials for MEMS and NEMS, non linear magneto-acoustics, phononic crystals and ultrafast acoustics.
Research projects will be mainly developed in the field of non-destructive testing through a multiscale approach. In the low acoustic frequency range, mainly residual stresses measurement using longitudinal creeping waves and complex matrix materials characterization material such as water saturated porous medium and heterogeneous materials will be studied. Improvement will be also studied in the field of non linear non destructive characterization and imaging using non-linear magneto acoustic technique.
On the other hand, high frequency acoustic waves will be applied to study films adherence on substrates. Hypersonic phononic crystals and nanometer scale characterization will also be developed using terahertz acoustic waves. Integration of acoustic sensors through Microsystems approach for health monitoring and acoustic sensors network will be also investigated. The research field of acoustic Microsystems dedicated to biological applications and acoustic waves resonator and filters will be strongly developed using our know-how to make high frequency ultrasonic transducers (ZnO,LiNbO3, AlN, sputtering and diffusion bonding techniques).
Finally, acoustic waves propagation and interactions models with periodic structures or defects will also be improved and applied to phononic crystals, negative refraction and non linear acoustics.

II.5.1 Non Destructive Testing

For the next four years, our research project will mainly relate to the two following points:

Characterization of thin films by surface and guided acoustic waves generated and detected by laser sources.
General context and objectives
The use of coatings and thin layers deposited on substrate is common in many fields. In micro-electronics, for example, the desired electric, magnetic, or mechanical properties are often obtained by depositing thin films having these properties on silicon substrates. The elastic characterization of these films is primarily justified by the need to analyze the adherence of the layer on the support, by the need to estimate the residual stress state within the layer, and by the wish to have an indicator of its damage, caused by microscopic cracks or micro-porosities.
The laser-ultrasonics technique was widely used these last years for the non-contact characterization of layer on substrate structures. However, for layer thicknesses of the same order as those met in micro-electronics, the majority of the achieved works using this technique only exploit the bulk waves by analyzing the reflected waves at the interface between the film and the substrate. Acoustic frequencies at several tens or hundreds of GHz are then in general excited using a femtosecond laser.
Our approach consists in investigating the resonance phenomenon of the layer on substrate structure by using the surface and guided acoustic waves. The main advantage of these waves lies in their capability to interrogate very wide and sometimes inaccessible parts of the structure. The other advantage of this approach is to reduce the acoustic frequencies compared to those required by the use of bulk waves. Thus, the use of a picosecond laser should be widely sufficient in most cases. One of the objectives of the suggested work will be to improve the models used until now in order to take into account some wave-defect interactions. From a practical point of view, the use of two pulse lasers (nanosecond and picosecond) will allow to validate the theoretical developments in a frequency broad band. This work will be achieved in collaboration with Professors W. Lauriks and C. Glorieux of the Leuven University within the framework of a PHC Tournesol project.

Ultrasonic estimation of residual stresses
General context and objectives
Two subjects will be considered. The first relates to the analysis of the residual stresses influence on the piezoelectric answer of thin layers. The theoretical part of this study will be based on the experience gained in acoustoelasticity theory and in the use of the polynomial method for solving the propagation equations. The experimental part will relate to the realization of thin piezoelectric layers and their electric and acoustic characterizations. This work should be carried out in collaboration with LPM Laboratory of Sfax University (Tunisia)

The second study, concern the development of residual stress determination methods for thermoplastic injected polymer parts. This subject is of great interest in many industrial fields. Indeed, the stresses generated during parts manufacturing influence negatively the mechanical behaviour and the dimensional stability and they may also relax. Therefore it is important to have methods enabling to assess the stress level and its evolution during the product life. The international and national state of the art shows that the research works on the possibility of using ultrasounds to evaluate residual stresses are essentially related to metallic materials. The ultrasonic methods have also a strong potential of application in the case of thermoplastic polymers. However, numerous scientific challenges have to be solved. Our approach firstly consists in theoretically showing the sensitivity of ultrasonic waves with the stress fields within the polymer parts. The program will be mainly based on an analysis about the propagation and penetration of surface acoustic waves such as longitudinal creeping waves, also called L_{CR} waves (Longitudinal Critically Refracted waves) because in some papers, it has been shown that these waves are particularly sensitive to the stress. Moreover, the scientist community has different points of view to describe these waves. One of the scientific challenges consists in studying the characteristics of the L_{CR} waves and their interactions with stressed thermoplastic materials. This work should be carried out within the framework of ANR-Blanc program deposited in 2008, in partnership with The EMD (Ecole des Mines de Douai) and CETIM (CEntre Technique des Industries Mécaniques)

Complex materials characterisation

Context

Our goal is to study the ultrasonic characterization of liquids saturated poro-viscoelastic materials and foam. Subject which has been extensively studied since 1955 (Biot phenomenological theory) is not achieved since several parameters appearing in this theory cannot be easily measured and have to be considered as adjustment parameters. Today growing tendency is to use F.E.M. to compute these unknown parameters.

Objectives

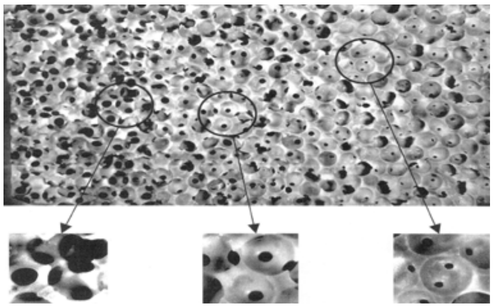
The originality of our approach lies in:

- multi-scale experiments using high signal to noise methods in high frequency experiments and self-made low frequencies and small dimensions transducers.
- use of F.E.M. to evaluate effective elastic constants of the porous material
- availability of ad hoc sample with a perfect control of its structure and geometry

We plan to start with periodic materials (easier implementation and understanding, gain in calculation time) and to reach progressively a random material.

We will focus particularly on the effects of the closing of pores on the wave propagation and on the effective elastic properties of the material.

Works on foam are essentially performed for food industry application for which only few ultrasonic characterizations are made in the world. Yet it seems that is the unique way to characterize them without modification of the chemical kinetic.



Collaboration

Works about porous materials will be realized in close collaboration with:

LOMC (University of Le Havre) in the FANO CNRS research group.

Balamand University (Lebanon) for which we have obtained a CNRS financial support.

LAMIH (University of Valenciennes) in the CISIT-CPER program on transportation safety (skull characterization during damage tests).

LMP (University of Valenciennes) which will realize porous synthetic materials.

Works on foam characterization will be performed in collaboration with INRA and will be applied to dough fermentation characterization.

Microsystems approach for Structural Health Monitoring

In the last fifteen years, research on the potential development of integrated systems for in-service inspection (real-time damage detection) of aeronautical structures has emerged. The common terminology for such systems is Structural Health Monitoring (SHM). In this context, studies on SHM systems based on the integration of thin piezoelectric transducers in the structures have led to promising results, which our team has significantly contributed. This contribution consists in the modelling of a complete SHM system (emitter, receiver, wave propagation and defect detection).

It is now more and more apparent in the literature that the transfer to implementation in real conditions is now a major concern for researchers. In this scope, our team has recently initiated works on acoustic methods making realistic, in a medium-term basis, the development of miniaturised, autonomous (in the sense of power as well as decision-making), embedded health-monitoring sensors. The principle is to develop "acoustic ambient noise" imaging techniques adapted to the particular problem of in-service inspection of aeronautical structures. Such techniques, which have been first investigated in underwater acoustics and seismology, should allow monitoring a structure by using sensors only, and without artificial emitters. Then, on one hand, the required power needed could be significantly reduced and on the other hand, power harvesting will allow to driving the sensor. Moreover, The miniaturisation could be conceivable while keeping the sensor autonomous

In parallel, it will be necessary in the next few years to go beyond the purely acoustic part of the problem, by addressing more precisely the following points:

- test the appropriateness of existing micro systems technologies to the problem,
- envisage possibly more suited technologies,

■ take into account the "communicating sensor" aspect (data reduction, networking),
■ develop embedded electronics for control, data processing, storage and communication
■ readapt acoustic models to the constraints entailed by sensor integration.

A number of these tasks lying at the interface of different topics, our team will naturally have to collaborate with other research groups (either inside or outside IEMN : CISIT….) specialised in micro technologies, sensor networks, advanced processing

II.5.2. Acoustic Microsystems

5.2.1 Acoustic Wave Resonators and Filters

Our research focuses on the development of multifrequency and multiband "single-chip" resonant platform for wireless communication without calling for supplementary technological facilities thanks to the combination of BAW and MEMS technologies.

Research Overview

The main goals are fully-integrated CMOS-compatible RF solution with prescribable bandshapes and center frequencies along with reduction of size, power-consumption and price, requirements that state-of-the-art resonator technologies such as SAW and BAW cannot meet altogether.

The objectives to meet in the LF, IF and RF bands will be :

- Low insertion loss
- High quality factor
- High rejection
- High roll-off
- Low motional resistance for devices readily matched to 50 RF systems
- Low Temperature Coefficient of resonant Frequency.

For classical piezoelectric bulk acoustic wave RF resonators, the resonant frequency is set by the thickness of the piezoelectric film. This mode of operation results in a single frequency per piezoelectric film deposition and moreover is not scaleable to IF frequency. Our research aims at designing a new class of piezoelectric MEMS resonators that effectively uncouple the resonant frequency of the device from the thickness of the piezoelectric layer. Two solutions will be studied :

Contour-extensional modes resonators that have their fundamental frequency set by either their in-plane dimensions or by selectively patterning the transduction electrodes and routing the electrical excitation waveform

Resonators built on a conventional BAW stack which make use of a lateral coupling through Lamb modes. For the filter to be able to operate at several frequencies that are not the overtones of the fundamental frequency a new design is needed employing either multi-modes or continuous spectrum with adequate isolation and transmission control mechanisms.

International State-of-the-art

Electrostatically-transduced resonators allow high quality factors and high frequencies (up to GHz by employing overtones) but suffer from large motional impedances that make their interface with 50 RF systems troublesome.

Piezoelectric actuation in Aluminum nitride contour-mode resonators allow low motional resistance (25 to 200) while maintaining high quality factors (1000-4000) and high frequencies (up to 1.2GHz) but call for a reduction of the electrical feedthrough capacitance between input and output.

Research Objectives

Fully understand the physical and electrical responses of the resonators
Develop semi-analytical models and associated softwares
Develop a full 3D FEM-BEM modeling
Study the thermal stability
Study the influence of second order effects and parasitics over the resonator and filter performances
Automatically extract models for 3D components (VHDL-AMS)
Design, fabricate and test prototypes to assess accuracy of the models
Some of the above objectives are part of the theme "BAW and MEMS" of "Axe 3" from the joint Laboratory IEMN-ST.

5.2.2 Acoustic BioMEMS

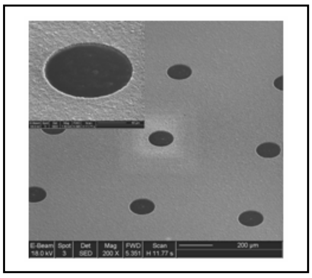
Context

This activity deals with high frequency acoustic characterization (around 1 GHz) in microfluidic channel. In fact, individual elements necessary to lab-on-chip devoted to this activity have to be fabricated and integrated. These characterisations concern elastic properties of biological cells, interfaces properties and molecules properties in liquid solution.

Using acoustic microscopy techniques up to 800MHz acoustic frequency, our laboratory already perform acoustic measurements using external lens and transducers. The new idea in the international context is to integrate these different elements on a wafer to achieve a mechanical, biophysical and chemical characterization in a lab-on-chip. It makes it possible to minimize the volume of the biological sample to be characterized, to develop parallel investigation of biophysical properties of cells or molecules (classical advantages of Lab-On-Chip) but also to reproduce a vascular environment for the biological cells to be characterized (an important point is to develop a user friendly prototype for the biologists).

Moreover, some acoustic characterization or actuation has been achieved in lab-on-chip but using lower frequencies (1MHz-50MHz). Some very recent works validate also the interest to develop 3D acoustic measurement system in order to characterize in situ 3D cells clusters (LIMMS).
The development of this activity will be made in collaboration with the IEMN BioMEMS group.

Objectives
The main elements to be fabricated (considering microfluidic requirements) and to be integrated in a lab-on-chip configuration are the following ones:
- **Ultrasonic transducers** are obtained with thin ZnO or AlN layer sputtering techniques (high frequency but only Z orientation) but also thanks to single crystal (especially $LiNbO_3$) bonded and thinned. This last method makes it possible to choose the crystalline orientation of the bonded single crystal and so to generate also shear waves. The group has developed for many years a competence to thin such single crystal until 4 µm in thickness on a squared centimeter. The aim concerning that part is to be able to thin again the single crystal transducers bonded on thin wafer on a larger area. Our goal will be also to test the ability of this technique to develop high frequency composite transducers in the gigahertz frequency range.



Lithography of a photodefinable nanocomposite. Opened holes (150 µm diameter) in a 40 µm thick layer. The insert shows the zoom on a hole.

- **Mechanical impedance matching** with nanocomposite made of polymer and nanoparticles. The aim is to get specific mechanical impedance depending on the concentration of the nanoparticles in the composite (photodefinable SU8 / TiO_2 / $SrTiO_3$ based nanocomposite were obtained with rather low losses). This makes it possible to create the most efficient matching layer between the substrate and water and also to develop high frequency composite transducers

- **Deflection or focusing functions thanks to specific lab-on-chip configuration** on silicon (patent application under study) development for high frequency local mechanical characterization. The application concerns also really local micromixing in a few squared micron areas (possible with the wavelength at 1 GHz)
- **Electronic function integration**: amplification, large bandwidth matching or optical switch development using GaN (piezoelectric) to integrate this function with acoustic characterization in order to solve the problem of electronic switched multiple transducers array and also connecting problems.
Some specific technological means devoted to acoustical microsystem fabrication will be developed in IEMN OAE department during the CISIT program dedicated to integrated sensors for bones characterization during crash.

Collaboration
The development of these different elements will be achieved in collaboration with the Physics department of Wuhan university (Pr XZ Zhao and a post doc position in IEMN).Financial supports have been asked through 2 programs:
The first one was presented to the PCV ANR call: the project concerns the adhesion properties measurement of biomaterials for endovascular stents fabrication (collaboration with H.F. Hildebrand (INSERM EA 1049) for biomaterial development and with P. Woisel (UMR CNRS 8009) for surface chemistry). Furthermore, this program will be proposed for a PPI program presented by the UVHC
The second one was presented to regional (ARCIR) call in collaboration with INRA: acoustic characterization of the interface between specific materials and viscoelastic products.

II.5.3. Realization and characterization of multi-functional materials for wireless telecommunication, MEMS, NEMS

MIMM team's main activities are based on the realization and characterization of multi-functional materials for wireless telecommunication, MEMS, NEMS,.... as a consequence we take interest in the relation between the growth conditions (and post annealing) and the structure (orientation, thickness,..), micro structrure (grain size, stresses, interfaces,..) and the electrical properties of the films.

New materials will be studied:
Lead free piezoelectric material which presents piezoelectric activity similar to the PZT one:
BNT-BT growth by conventional sputtering (ceramic target) and co sputtering, which will be developped for MEMS applications.
AlN film growth (with different orientation) for specific acoustic applications.
Ferroelectric materials, which we worked on lately, for micro waves applications.
In the next few years, our objective will be to reinforce this study and in particular to compare the wellknown BST material with the BZN which presents as an advantadge lower losse at high frequency, although its accordability will have to be improved thanks to dopant introduction. The micro waves characterization will be made at the IEMN institute where will be developped models explaining the dielectric behavior of ferroelectric films at high frequency. The variable capacitance is the main application, used, for instance, in mobile phone.

Many labs work on piezoelectric nano-strutures. The objective is to observe and to understand the dimensional effect on the piezoelectric activity of the material, this is why, we developped a FIB process. Typically the dimension of the PZT nano structure is about 100nm. We would like to reduce it to 10nm only by using a FIB process while improving the piezoelectric measurement technics (PFM). We think (as observed by some authors) that the piezoelectric activity can disappear when the structure is too small. We will try to explain the phenomena through physical models based on domain wall motion and will work on the active thickness effect on the piezoelectric response. Being in the NEMS context is crucial to study the electrical behavior of very thin films (< 50nm).

II.5.4. Nonlinear Magneto-Acoustics

Context / Positioning
Among the recent advances which attracted great attention in the field of ultrasounds, we can find on the one hand the Time Reversal (TR) and Wave Phase Conjugation (WPC) processes, and NonLinear Acoustics (NLA) on the other hand. Both of these concepts greatly enlarged the potentialities of ultrasounds in the field of non-destructive and medical imaging, or more generally of characterization of media. The parametric Magneto-Acoustic Wave Phase Conjugation (MAWPC) is a unique technique, jointly developed by IEMN an its Russian partner of the Wave Research Center of the Prokhorov General Physics Institute (RAS), which provides simultaneously coherent amplification of acoustic waves (similarly to LASERs in optics) and WPC. For this reason, it is naturally adapted for the combination of the WPC and NLA potentialities, thus leading to investigations of totally new fundamental physical phenomena and providing ways for the proposal of new concepts in the field of ultrasonic imaging and characterization.
But investigations of parametrical phenomena in the field of nonlinear magneto-acoustics is not limited to MAWPC, and studies on three-boson bound states and coupled excitations in solids began in our group this last year. It was demonstrated the explosive mechanism of the phonon triad excitation in EPAF crystal under electromagnetic pumping and predicted the phenomenon of "peaking and localization" of the triad of travelling magnetoelastic waves.
Our group and its Russian partners all integrated in the European Laboratory "LEMAC" are the world leaders in the field of Nonlinear Magneto-Acoustics and its applications to nonlinear ultrasonic imaging, **fluidics** and characterization.
Goal of the work
The work in this area for the future years will be first concentrated on the investigations of MAWPC for NL imaging and characterization of complex and moving media, with the development of new concepts of ultrasonic systems for Nondestructive, medical and industrial applications. New active materials for improved conjugators will be investigated, simulation methods dedicated to MAWPC and its specific applications will be **improved and** developed, prototypes for specific applications will be elaborated. For this last point, partnerships within European projects or with industrials are now solicited. Two new directions will also be developed : the first one concerns the adaptation of MAWPC to ultrasonic investigations without contacts and velocity measurements of air flows because of a large area of potential applications, and the second one concerns the increase of functioning frequency in order to adapt MAWPC to MEMS **characterizations.**
Finally, we will continue the investigations of three-boson bound states and coupled excitations in solids, and search for applications

II.5.5 Phononic crystals and negative refraction

Background

There is a growing interest in the study of phononic crystals, which are composite materials made of a periodic arrangement of several elastic materials. Their dispersion curves may present, under certain conditions, absolute forbidden bands e.g. frequency domains where the propagation of elastic wave is prohibited whatever the direction of propagation of the incident wave. This property confers them potential applications in a wide frequency range. If the presence of a band gap opens up potentialities for filtering applications, it is also possible to use unusual properties in the pass bands of the dispersion curves. Following recent works on ultra refractivity in photonic crystals [1,2], researches are carried out on phononic crystals presenting a negative refraction that can focus acoustic waves [3,4]. These systems use particularities of dispersion curves, which can exhibit branches with negative slopes. The potential applications of such devices are of main interest, in particular because they can reach the diffraction limit, i.e. the resolution can be smaller than half wavelength, as previously highlighted in photonic crystals [2]. This point is very important, because, at identical resolution, a lower frequency could be used, thus attenuation will be lower. Therefore, the use of a negative refraction flat superlens seems to be a very advantageous solution for very high resolution devices.

Objectives

To our knowledge, recent works on negative refraction of acoustic waves are devoted to phononic crystals made of solid inclusions in a fluid matrix. The work that will be performed on this topic concerns the study of negative refraction of elastic waves that can occur in simple phononic crystals with an elastic matrix (periodic arrangement of holes in an elastic matrix). The two main objectives of the study are:

- Use of theoretical models to study the negative refraction of elastic waves
- Experimental evaluation of the potentialities of the devices: fabrication of a flat “superlens” and tests on the focalisation under the diffraction limit.

Description of the work and collaborations

First, dispersion curves of elastic phononic crystals will be studied and conditions in which negative refraction can appear will be identified. Then the wave propagating inside the phononic crystal and inducing a negative refraction will be characterized. Experiments will also be performed, in the frame of FANO (Fédération Acoustique du Nord Ouest), where Phononic Crystals is one of the five topics. The teams involved in this project are LOMC (Laboratoire Ondes et Milieux Complexes FRE CNRS 3102, Université du Havre) and the Laboratoire Image et Cerveau (Université de Tours). First flat lens will be fabricated and then experiments will be performed with a view to reach the diffraction limit.

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II.5.6. Ultrafast acoustics

In the future, we will first concentrate our efforts towards a THz acoustics. Twenty years ago, H. Maris invented the picosecond ultrasonic technique by demonstrating the opportunity to generate and detect picosecond acoustic pulses using a femtosecond laser. Up to now, two main limitations can be identified. First using a thin metallic layer as transducer the frequency content of the strain pulse cannot reach higher frequencies than 250 GHz. Second only longitudinal acoustic waves are excited in the usual geometry. Due to that a complete mechanical characterization of thin layer is not permitted, in other words no information concerning the in-plane properties can be measured using picosecond ultrasonics.

Thanks to nanostructures we think that we could overcome both difficulties. Indeed, we have recently shown that quantum dots can be a very efficient source of coherent acoustic phonons. As their height is close to a few nanometers, we suspect that the acoustic pulse emitted by such a plan is much higher in frequency than what is usually done using metallic thin films. Semiconductor nanostructures could thus be the needed transducer for emitting THz acoustic waves. Simultaneously, we will examine the impact of organization on the elastic properties of collections of nanostructures. An artificial crystal made of nanostructures constitutes what is called an hypersonic phononic crystals which means that the elastic properties of the whole are dependent both on the Recent results we obtained on two-dimensionnal lattices of metallic dots have revealed individual and collective vibrational modes. These results suggest that using a nanostructured transducer could offer an unique way of reaching in-plane elastic properties in thin films using a conventional picosecond ultrasonic setup.

There is another fundamental interest in studying hypersonic phononic crystals. For reaching the hypersonic range, dots must be arranged with a lattice parameter which falls typically in the sub-micronic range. Due to that such crystals also present some photonic or plasmonic properties. Combining periodic effects both for acoustics and optics is promising for demonstrating new effects such as giant acousto-optic couplings.

Secondly, we will examine the thermal properties at nanoscale. Thermal energy in solids is transported primarily by electrons and phonons. The electronic contribution is important for materials with a large number of free carriers, such as metals. On the other hand, the thermal conductivity of dielectric materials and many semiconductors is determined mainly by the phonons. Modifying the acoustic properties of an object in the hypersonic range would also have a large impact in its thermal properties. For example some nanotechnology objects like carbon nanotubes or nanoparticles are more and more suggested as promising entities for elaborating new materials for low thermal resistance interfaces. Within the FP7 project NANOPACK we will develop new methods for measuring thermal properties at nanoscale and pursue some fundamental researches in order to get a better understanding of the role of acoustic phonons in thermal management

ANNEX 1: PRESENTATION OF THE TEAM
Fluides-Interfaces Liquides- Micro-Systèmes (FILMS)

National and international context

The recent upsurge of interest for investigating liquid flows at smaller and smaller scales, has appeared about a decade ago. Historically, it is partly explained owing the progresses of technologies in micro-fabrication, surface treatments and in electrical or magnetic active materials, enabling the fabrication of accurate actuators. At the same time, the technologies of visualisation has greatly improved as well: high-speed or high-resolution cameras, better and better microscopes, ... This has let a huge space of investigation for teams like FILMS, to try and understand the physical mechanisms that rule flows at small scales, where analytical approaches can sometimes be carried out - due to the absence of inertial terms in the momentum equations. On the other side, unexpected effects like the influence of confinement, the slip near walls or the huge viscous stress, make the situations sometimes more complex than in large-scale flows. In short, microfluidics opened a new type of problems requiring specific experimental and theoretical methods. Microfluidics does not only offer challenging issues for fluid dynamics or applied mathematics. Its field of applications is very large from flow control to medicine. (Sensors and actuator for flow control, multiphase flows in micro engineering, peculiar fluid structures (foams, micelles, vesicle) medicine delivery or fuel-cells…..

Traditionally, the research groups focusing on microfluidics have emerged from two types of background:
1 - teams traditionally specialized in the physics of liquids and soft-condensed matter. In the past, many of these teams had strong background in either the physics of instabilities chaos or pattern formation (where the complexity comes from the flow itself), either in complex fluids (including particle-laden fluids and granular matter) where the complexity comes from the the peculiar rheological properties. This community has borrowed tools from statistical physics and multi-scale approaches. Recently, a significant part of this community oriented their research in the physics of living organisms (animal and vegetal growth, morphogenesis) or biofluidics.
2 - teams with a strong engineering background. More focused on applications and processes (heat/energy transfer, flow-focusing, ...), they also generally benefit from better facilities in the fabrication of actuators and micro-channels. LETI in CEA Grenoble, IEMN in Villeneuve d'Ascq or LASS in Toulouse, are examples of such teams in France. In an international context, it is striking to note that the general scopes of the teams in the different countries roughly follow their traditional strong fields of investigation: many French teams focused on fundamental issues, with experiments and simple models, whereas in the United-Kingdom the main contributions have emerged from the community of applied mathematicians who tackled problems through pure analytical solutions. In Japan and Korea, microfluidics is translated in a very technological aspect, with the realisation of complex and accurate experimental devices, whereas in the United States both aspects are well balanced.

Specificity of FILMS team

From its beginnings, team FILMS tries to merge these two aspects not only because of the personal background of its members but also because of the vicinity with IEMN. The team is already associated to IEMN since January 2008 after long term collaboration. For instance, within the last 3 years, the collaborations between members of FILMS and teams at IEMN have produced 15 published results in leading international journals. It must also be underlined that A. Merlen is co-creator the Joint European Laboratory LEMAC with Philippe Pernod and Vladimir Preobrazhenski of AIMAN team at IEMN. For these reasons (and others) FILMS intends to join the IEMN in 2009, detaching from the Laboratoire de Mécanique de Lille (LML) where no collaboration remains active.

Generally, FILMS tries to adequately mix fundamental aspects and the use of means of high level of microtechnologies (acoustic actuators, nanowires-covered 'superhydrophobic' surfaces, ...) taking advantage of IEMN clean-rooms that are of the most sophisticated in France. Obviously all the technological fabrication cannot be performed by members of the team but by specialists of IEMN. Nevertheless, the access to the clean room is now possible to the members of the team for simple fabrication and, moreover, for a deeper understanding of the technological processes and constraints which is necessary for an accurate development of research linked to Microsystems. Very few laboratories in France can combine these strengths: the LPCMN in Lyon 1 is one of those. Other laboratories of soft-condensed matter generally have more limited technological means.

Amongst this national and international context and regarding the recent production and history of the team, the general scopes of the research in the FILMS team are to investigate:
- problems coupling phenomena at liquid interfaces and microflows of complex fluids.
- out-of-equilibrium phenomena, i.e. unstable or chaotic flows with natural applications in transfer and mixing.
- the influence of micro-actuators (acoustical, ultrasonic, magnetic, ...) on fluid flows.

All this is characterized by small scales in space and time.

Main equipments & Characteristics .
During the last quadriennal, the team has progressively gathered an important experimental adapted to its scientific objectives.

- Black/White CCD camera : high sensitivity 25 ips and low light observations
- B/W high speed CCD camera : 200 ips and low light, moderate speed observations
- B/W high speed CMOS camera: 2000 ips and high light, high speed observations
- Microscope: fluorescent and direct light for micro-PIV and microfluidics observations
- Gated Image Intensifier: observations under dark conditions and high speed video recording in fluorescent microscopy"
- Home made shaker enabling large amplitude (up to 12 cm) oscillations (used particularly for mixing and interfacial behaviour under oscillations…)
- Electromagnetic shaker enabling large frequency (up to 1 kHz) oscillations (used particularly for mixing and interfacial behaviour under oscillations…)

These tools were obtained through the financial support of MESR (PPF with IEMN and ESPCI-PMMH), CNRS (PIR and PEPS) and industrial contracts.

Through the PPF, the team has access to a holographic microscope at PMMH. The team participated to the "plateforme de métrologie optique SPI" building an ultra high speed CCD shadowgraph camera. Two high-performance PC enable both image treatment and code developments for scientific computing.

Permanent links with teams AIMAN, "Microsystèmes silicium" and "microfluidique" of IEMN give access to sets of microchannels, microvalves for flow control and acoustical, ultrasonic micromechanical electrical or magnetical systems.

Main actions for the next quadriennal

General strategy

- Improve the coherence.

The team was recently formed, it is necessary to merge all the backgrounds of the members: Alain Merlen (1991), Farzam Zoueshtiagh (2003), Philippe Brunet (2007), Michael Beaudoin (2008). This has already been done between A. Merlen and F. Zoueshtiagh (Common papers published) and is on the way with P. Brunet (Common communication accepted and papers in preparation). M. Baudoin has been appointed Maître de Conférences in September 2008. His background in acoustics (PhD LMM P6) and microfluidics (Post doc Ladhyx) covers the different research activities of the team. Moreover, whereas F. Zoueshtiagh and, partly, P. Brunet are experimentalists, M. Beaudoin brings missing numerical skills to the team. Therefore, his integration appears natural and straightforward. However, the difficulty is not to reach the integration but to maintain the equilibrium between individual and collective production as well as to canalize scientific curiosity to a limited fan of realistic possibilities.

- Improve the impact.

The impact of the team on the scientific community is relatively weak. This is due to different factors: the age of most of the members, the dispersion and evolution of the activity, the size of the target communities. The difficulty here is to maintain equilibrium between risky and innovative activities (like micro-valves for flow control...) and academic production on topic widely spread among the community (like instabilities, microchannel flows, particle separation). This can be improved during the quadriennal since many links with the national and international community in flow control and microflows have been settled. Nevertheless, one interesting direction should be more deeply investigated: the use of microsystems to control generic unstable flows instead of industrial ones. A link has still to be built with the community of the"theoretical flow-control".

Detailed actions

1) Dynamics of two-phase flow in complex micrometric channels (FILMS/ IEMN bioMEMS, Ladhyx) (Fluides)

Particles separation in oscillatory flows in microchannels (With IEMN microfluidique):

We have recently experimentally shown that micron sized particles could cluster in oscillatory flow conditions even at very low Reynolds number in a microchannel. A theoretical and numerical investigation of this clustering will give indications on the influence of different parameters such as friction or particle density involved in this phenomenon. As a direct result, we could therefore understand the separation process and design a microfluidic system for collecting separately different types of particles. This could interest medical/pharmaceutical industries as it would constitute an alternative to existing flow-based separation techniques such as field-flow fractionation or split flow lateral thin cell fractionation.

Micrometric network (With Ladhyx) :

Although many studies are dedicated to two-phase non mixing fluid flows in simple geometry at the micrometric scale, few deal however with two-phase flows in complex networks. A good understanding of their physics is essential as it might be used to improve our knowledge of various systems: for example biological systems such as lungs (and especially the phenomenon of airway reopening). M. Baudoin started a study on this topic during his postdoctorat at Ecole Polytechnique with Professors Charles Baroud and Paul Manneville, mainly centred on the understanding of airway reopening. FILMS could contribute to the field thanks to the capabilities of IEMN to perform MEMS mimicking nature for fundamental experiments. Mixing and miscible interface behaviour (FILMS, univ. of Florida / ENSAM Angers) : One of the challenges in microfluidics is to enhance mixing at their associated low Reynolds numbers. Recently, we have been able to show the development of Faraday instability between two miscible liquids using large scale (centimetric) oscillations. Now the idea is to use tools available at IEMN (electro-magnetic actuators) in order to develop Faraday instability in microchannels and in turn enhance the mixing between two liquids at micron scales. Numerical investigations carried out in collaboration with the University of Florida and ENSAM Angers presently provide tools to investigate an optimized micro-system in which the mixing is enhanced. Such system will have an important industrial interest and if successful, we will seek industrial contact and patent declaration through "IEMN transfert".

2) <u>Droplets dynamics on surfaces (Interfaces Liquides)</u>

Superhydrophobic surfaces (With IEMN/IRI)

The combination of micro or nano-texturation with an ad-hoc chemical treatment makes a surface super-hydrophobic, i.e. highly repellent to water. The dynamical spreading of water on such surfaces offers various interesting issues that we have started to investigate recently : the impact of a drop on such surfaces can show instabilities and capillary break-up, as well as surface protrusion. To understand the underlying mechanisms has a crucial importance for the design of self-cleaning surfaces and to lab-on-chip benches. Indeed, for this last application, super-hydrophobic surfaces are very convenient surfaces for micro-drop displacements, as water drops ‘roll’ on them with almost no-friction providing that water does not protrude the surface. We gather experimental and theoretical approaches to optimise the robustness of such surface, and the first obtained results (in both drop impact and electrowetting siuations) showed an up-to-now unreported high resistance against impalement thanks to multiple
layered nano-texturation.

Micro-manipulation of drops and particle-laden drops by Surface Acoustic Wave or electrowetting (FILMS/Microfluidique IEMN)

We have experimentally observed that micron and nano size particles deposited on a substrate could be collected by the movement of a drop more or less efficiently. The motion of the drop is obtained by different means like of electrowetting or surface acoustic waves. Particularly, in the case of surface Acoustic Waves, nonlinear effects such as acoustic radiation pressure or streaming can be used to manipulate drops at the micrometric scale or even to induce an inner flow. In the case of drops with different miscible phases, their mixing can be accelerated by this flow and, for particle laden-drops, the radiation pressure can modify the repartition of the particles. Another mechanism to be clarified is the effect of micron and nano size particles on a drop's contact line. Theoretical and numerical tools under study will greatly help in understanding and predict the particles behaviour with respect to drop speed, substrate texture, particles shape and/or density, etc. The expected results could have direct implications in designing lab on chip systems for particles collection on a surface.

3) <u>Miniaturization of micro-valves for flow control (FILMS/AIMAN) (Micro-Systèmes</u>).

The limitation for miniaturization comes from the high forces (relatively to the size) needed to act on the flows inside the micro-valves. New designs will be drawn in order to avoid any action on high-pressure area. Another solution will to be take advantage of fluid/structure interactions or bistable equilibrium inside the micro-valves. If the objective is reached, the micro-valves could be fabricated entirely in micro-fabrication processes and not in an hybrid way and therefore could be adaptable to mass production. In that case the technological activity could be relayed by the industry and the team could focus its aims on the use of such microactuators in fundamental experiments on flow control (transient growth, absolute or
convective instabilities etc...)

4) <u>Development of tools (transverse activity)</u>

Development of a FMM (Fast Multipole Method) based code

The main purpose of M. Baudoin recruitment was to reinforce the theoretical and numerical skills of the team. As an important part of the team activity is dedicated to the study of twophase flow at small scales and the development of acoustic tools for droplet micromanipulation, a FMM (Fast Multipole Method) based code might be of primary interest. First it could be used to compute multiple scattering inside complex media. For example, some composite media manufactured for the WPC (Wave Phase Conjugation) activity (to obtain specific magneto-acoustic properties) might induce multiple scattering of the acoustical wave. Then the acoustic field generated by the Surface Acoustic Waves inside the particleladen droplets could be computed, which would give fundamental information on the observed patterns. And finally, the FMM algorithm might be inserted inside a more general two-phase flow code to compute some complex flows at the micro-scale.

Development of original measurement methods.

The FILMS activity is linked with the development of visualisation and quantitative measurement method. The most specific are:

- the development of a ultra high speed CCD shadowgraph camera in the frame of the “plateforme de métrologie optique CNRS” (in collaboration with AIMAN team)
- the development of a phase conjugate velocimetry based on the property of focussing and time reversal of the phase conjugation method. Unlike LDA or PIV this method enables a measurement of a liquid velocity without any particle seeding. The spatial resolution is of the order of a few wave length of the conjugated ultra sonic beam. With classical US sources, this means around one millimetre resolution, but increasing the frequency this can becomes a non intrusive flow meter for microchannels. The interest is that the method does need transparent wall and is applicable in 3D. (With AIMAN team, Ioffe Inst. and Russian Acad. Sc.)

ANNEX 2: PRESENTATION OF THE TEAM GEPIFREM
Plasma processes and materials

Teachers – Researchers : Céline VIVIEN (MC), **Corinne FOISSAC** (MC), **Brigitte MUTEL** (Pr2)**, Philippe SUPIOT** (Pr2)

BIATOS: 1 IGR-Scientific instrumentation (future recruitment), **1 AdT Christian MALAS, 1 AdT-Secretary/Financial Management** (half-time, future recruitment).

Different collaborations have demonstrated the complementarities of our approach and that of the IEMN, especially in recent years, of the team led by Bertrand Bocquet ("Microfluidics Microsystems and THz"). This positive context gave us arguments to join this institute within the frame of reinforcement of its know-how in "process development", including plasmas. For this moment, the integration of our team, renamed "Plasma Processes and Materials", is based mainly on the continuation of ongoing projects:
- ANR BLANC "Control of properties of plasma deposited thin or thick films for a multifunctional use (CFPO)" (2006-2009)
- PPF "BioMEMS for THz spectroscopy: Design and Evaluation" (2006-2009)
- ANR BLANC "Catalyst deposit for micro- and milli-structured reactors (MILLICAT)" (2006-2010)
The **CREST label** (ministry agreement) obtained by our present laboratory, the GePIFReM EA 3571, in 2006 adds a dimension of openness and transfer which will be integrated into the overall framework of the IEMN.

The micro-and nano-structures can take several forms: a thin layer, a multilayered film, a massive composite, a quasi-1D or -3D arrangement, or a powder. In a number of cases, plasmas provide an elegant and efficient response to the realisation of complex structures at scales which often depend on a given integration need. The fields of wave propagation systems design (co-planar lines operating in the area 1GHz-1THz), of MEMS and bio-MEMS (micro-reactors, local immobilisation of enzymes on a surface) are compatible with the development of new plasma processes, due to the flexibility of these latter. In addition, the choice of plasma and process parameters for nanotechnology requires fundamental research on the media used. The mastery of the material properties must be based on an understanding of the stages of its manufacture when the process moves from micro-metric scale to nano-metric scale or vice versa. Crossed approaches to uncouple the problems will guide the work of the team in the following way:

- **Characterization of synthesized or processed Materials** from a physical-chemical point of view (composition, structure and links, surface energy…) but also from that of properties associated with their future use (optical, electrical and electronic properties, porosity, Adhesion-wettability, hardness). The aim of finding correlation between these properties and information from gas phase diagnostics is imperative.

- **Diagnostics of the gas phase** (Emission Spectroscopy Optics, Laser Induced Fluorescence, UV-Visible – IR Absorption, electrical measurements, mass-spectrometry…) on discharges (plasma), afterglows and growth mediums of film and processing.

- **Developing tools for monitoring conditions of synthesis** (Interferometry, Mie scattering, in-situ Plasmon Resonance spectroscopy …) for the plasma reactors design and their online control.

This context helps to develop a research program on two main themes:

Plasma assisted deposition of multifunctional materials

Efforts will focus on **RPECVD assisted synthesis of polymers** films satisfying the constraints of a multifunctional material for purposes ranging from MEMS design for biological analysis (ultra-thick layers) to interfacial layers growth (thin film), for example for catalytic microstructured reactors (ANR MILLICAT). But others aspects will be considered. They include:

- **research of deposition conditions to improve the surface state** (lower roughness) through AFM and SEM studies according to process parameters like microwave input power, gas flow ratios and pressure. A reactor installed at the LCI-IEMN for obtaining a larger surface deposit (4" wafer) will allow a test of the process in a clean room, including stages of dry assembling. A work of understanding (flow and kinetic modelling, experimental probing) on the process of undesirable powder growth, will be undertaken in collaboration with proper teams (request for PPF support). In addition, conditions leading to super-hydrophobic materials of interest for micro-fluidic applications will be scanned.

- **seeking new siloxanes-based precursors** compatible with our deposition technology (cyclical siloxanes, DVS-BCB) to reduce the value of the dielectric constant but especially dielectric losses. Deposition rates comparable to those obtained with the TMDSO will allow design (thick layers) of bio-reactor and microwave devices (context of ANR Blanc CFPO, PPF IEMN-GéPIFRéM-ProBioGem-…). Work has begun, but a validation through testing of the corresponding wave propagation devices will be undertaken.

- **studying the growth of films on substrates showing a well defined geometry** (1D, 2D, 3D) through conditions (plasma pulsed or not, ALD like mode) for obtaining thin or ultra-thin layers (10-1000 nm) from the current process. This work will be done under the GDR "SURGECO", including the themes "Trenches and Via" to which we contribute. One particularly striking point is the design of a sub-micron- and micron-scaled mask for patterning. This mask could be used as a national reference for comparative studies of films growth (MEB study after cleavage analysis, simulation MC) for different materials. The study of film growth around these patterns will constitute the basis of the technological development of new types of MEMS. A work in collaboration with the IMN (NANTES) will be undertaken. The practical realisation of the mask could be attributed to the IEMN (Central technological). As an extension, growth in porous structures will also be addressed (request for PPF support).
- **development of materials (metal oxides, metals)** adapted to the realisation of components and nano-structures is also a research axis that can contribute to short-term progress within the IEMN. The ALD will be the main technique for this purpose, especially for deposition onto nano-wire or nano-tubes.
- **studying of etching of the deposited organosilicon layers** is required to master their forthcoming local patterning (micro-channel ratio aspect) and the surface roughness. An optimisation work remains to be done on that matter to fulfil the constraints of use of these etched structures.

Surface modification and bio-molecules hanging

Plasma assisted surface modification is an important task because it helps to improve the interface properties (even on structures 3D geometry) but to reach further integration in the process of MEMS design. Apart from the surface treatments in remote N_2 or N_2/O_2 plasma afterglows, commonly used by the team, more targeted approaches, particularly for biological applications (a highly selective in relation to bio-molecules (proteins, peptides …)) will be developed .

- **Amine Functions :** The use of amino monomer is a well known manner to create amine functions on a surface by plasma techniques. Namely, allylamine (AA) is polymerised under pulsed discharge mode for grafting of DNA. The fragility of AA molecule is such that it is preferable to make the process at low energy. Work started on this topic have shown us that it was possible to obtain a PECVD film (denoted plasma polymerised AA: ppAA) with densities of primary amine functions at least equal to that given in the literature. The use of RPECVD in nitrogen post-discharge is compatible with low energy requirements and allows to consider new developments involving, in particular, the so-called short-lived afterglow on which our group has a good knowledge. Others precursors are considered, especially the Amino-PropyleTetraEthoxysilane which is commonly used for the hanging of enzyme by classical biochemistry.
- **Carboxylic Functions**: Regarding carboxylic groups, the use of acrylic or maleic acids will be considered using the same approach. The validation of grafting will be carried out in conjunction with the laboratory ProBioGem (USTL).
- **Biomolecules hanging:** Once stages of surface preparation of materials (presence of amine/carboxylic functions) will be achieved, a significant advance in the design of BioMEMS would be the local grafting of biomolecules.