# Flagship Project on Flexible Electronics

## I- Context, challenges and objectives

Foldable, thin, light-weight, stretchable, stackable, high performance – that's the promise that flexible electronics and integration of highly heterogeneous functional and structural materials holds today. As recently reported in the *'Assembly and Packaging'* chapter of the International Technology Roadmap for Semiconductors (ITRS) last edition, *'Flexible electronics is projected to grow into a multibillion-dollar industry over the next decade and will revolutionize our view of electronics. [...] It will enable a broad range of devices and applications not possible today.'* This last statement widely recognizes that foldable systems-in-the-foil (SiF) are particularly well suited to the development of nomadic and space-weight-and-power (SWAP) constrained applications featuring ubiquitous intelligence such as wireless sensor networks (WSN), micro-aerial vehicles, embedded defense and security chips, lab on chip, environment monitoring and smart textiles. To realize those objectives, advanced very thin film and flexible/conformable electronics and microsystems comprising digital, embedded memories and analogue signal processing, RF circuitry, antennas, sensors, actuators, microfluidics need to be developed.

Over the past decades, the quickly growing field of macroelectronics has given rise to numerous applications that partially fill this demand. Displays, solar cells, lightning constitutes the most mature sectors in this field but a fourth essential segment related to logic control, memory, analogue electronics, MEMS and detection systems is still far from minimal targets to envision the heterogeneous integration multifunctional systems on flex. Beyond the enthusiastic application perspectives of flexible electronics, it is however noteworthy to realize that flexible macroelectronics is today quasi-exclusively synonymous with organic semiconductors and high-throughput printing techniques whose major deficiencies lie in extremely poor carriers mobility (<1 $cm^2.V^{-1}.s^{-1}$) and coarse patterning resolution (~10µm at best). By way of example, the first pentacene-based organic microprocessor published by IMEC in 2012 features 8-bit logic operation, comprises 4000 transistors and operates at 70Hz. Although it constitutes a remarkable result, this level of performance is still far from competing with the first Intel 4004 microprocessor demonstrated some 40 years ago.

Low cost and large surface is therefore no advantage to address certain application classes for which increased complexity and bandwidth above a few MHz are needed. If today's organic macroelectronics with its unique mechanical properties arouses high expectations in terms of innovation, one has to accept that current capabilities limit its use to applications where high performance is not required. There is, however, no doubt that the advantage of multiple possible form factors and weight/space savings of flex, on one hand, and high frequency performance at reasonable cost, on the other hand, is already creating convergence toward high value applications and products. Although flexible macroelectronics and More-than-Moore high performance microelectronics develop on separate tracks, both share a common goal toward increased functionality, complexity and high-frequency performance.

Beyond the frequency/speed issue, another recurrent roadblock that illustrates shortcomings associated to the heterogeneous co-integration of multifunctional systems stems from the necessary combination of markedly different material classes and functional blocks coming from incompatible processes. One essential technological prerequisite is therefore to introduce processing techniques that manage to conciliate conflicting constraints in terms of thermal budgets, shape complexity, chemical compatibility, contamination issues, mechanical stress and, last but not least, cost effectiveness.

Based on the above analysis and accounting for the areas of excellence owned by the laboratory, two distinctive trademarks have been identified to judiciously position IEMN contribution into the broad topic of flexible electronics:

i) the development high performance multi-Ghz flexible electronics
ii) the heterogeneous integration of smart materials and functional blocks onto mechanically flexible substrates.

Building on this strategy, a research program tackling four major challenges has been elaborated whose objectives are detailed as following:

**Challenge I - Engineering HF materials for flex-compliant systems:** This challenge focuses on the integration of active materials and interconnections that feature electrical and mechanical properties that comply with the requirement of high frequency operation.

**Challenge 2 – High-frequency, ultra-thin devices/circuits layers on the foil:** The main objective of the device/circuit workpackage is to develop multi-GHz flexible technologies based on complementary active materials covering Si, GaN, AlInAs/GaInAs and graphene.

**Challenge 3 – Multifunctional sensors and actuators:** This workpackage targets the development of smart sensing and actuation devices that takes advantage of mechanical compliance of constituting materials (e.g. reconfigurable antenna, haptic interface, touch screen).

**Challenge 4 – Integration of heterogeneous flexible systems:** This activity concentrates efforts on heterogeneous co-integration of new functional materials, sensors, actuators and high-performance electronics into advanced multifunctional systems (e.g. WSN, microdrones).

## II- Background

### Genesis of the project

Accounting for the rising activity on mechanically flexible materials and devices carried out in various IEMN groups in the late 2009, the laboratory has launched in 2010 a Flagship project on Flexible Electronics. The main objectives of this initiative were fourfold:

i) to enhance the generic topic on Flexible Electronics with both innovative and groundbreaking ideas
ii) to better integrate this activity involving 10 IEMN groups into a coherent, complementary and sound research program at the laboratory scale
iii) to structure and enhance the visibility of this program as a flagship topic of the CPER-CIA project (Governmental/Regional /FEDER, Campus Intelligence Ambiante, phase 2, 2010-2013)
iv) to feed the LEAF Equipex proposal, i.e. an equipment-oriented project, with a mature and well organized scientific and technological content.

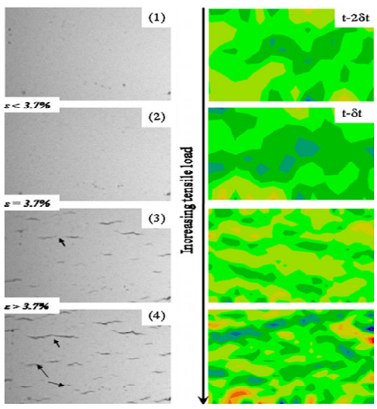
**The LEAF Equipex project:** Considering that flexible electronics is a broad and rapidly moving field, the positioning of IEMN contribution to this topic was of utmost strategic importance. It therefore appeared important not only to introduce groundbreaking ideas for improving the current state-of-the-art of flexible electronics but also to push innovation by shifting the research value chain from the supply of crude hardware to the demonstration of smart integrated systems. One important feature that accompanies this type of evolution is that tremendous added value can be obtained at the system level from the introduction of a very small number of innovative i) process steps or ii) processing tools or iii) new materials with remarkable properties. Consistent with this rationale and with the scientific program developed hereinbefore, the objective of the LEAF project has therefore been focused on the introduction of laser micromachining techniques for structuring materials (patterning, scribing, drilling, cutting, milling at micron scale) using a dry, safe and low temperature direct write photo-thermal ablation technique. (http://leaf-equipex.iemn.univ-lille1.fr/)

## III- A glimpse of results

The objective of this section is not to give an exhaustive description of results obtained in the Flagship project on Flexible Electronics but rather to outline a selection of outstanding results covering the 4 challenges complementarily to groups' reports.

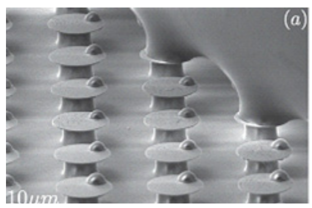
***Damage and defects in flexible and stretchable interconnects*[(a)]**
Flexible electronics – unlike their rigid counterparts - implies that potentially large mechanical stress and strains will be put on systems and individual components which make up those systems. Hence, a study of damage and defect formation in metals and semiconductors is essential in an understanding of the behaviour of such systems. Our goal here was to study defect formation in metals/semiconductors at high strains. This was performed through the fabrication of flexible samples using microelectronics and microsystems materials/thin films. The formation and evolution of microscopic defects in metal and semiconductors films was studied (thickness µm → nm) using digital image correlation under uniaxial tensile loading. By analyzing the heterogeneous strain field during the deformation process, we have shown a link between heterogeneities and cracks initiation[(b)].

(a) NAM6 group
(b) T. Roland et al., J. Micromech. Microeng. 2, 125005 (2011).



(left) Evolution of crack network on a metallic film and (right) Strain field during the tensile test.

***Micro/nano texturation for optimized ink-jet printing on polymers*[(c)]**
We have been the first to report on a polydimethylsiloxane (PDMS) molding process to achieve flexible and transparent superomniphobic surfaces. This type of surfaces supports a metastable Cassie state with a wide range of liquids (surface energies ranging from 72.2 to 24mN/m) but they also exhibit large contact angle (CA) hysteresis, in contradiction with the widespread idea that Cassie state reduces hysteresis. A comparison of our results with a recent theoretical prediction confirms a 1D wetting model for which apparent CA are related to linear surface fraction of liquid-solid contact along the contact line[(d)]. As a consequence of this high CA hysteresis, the right figure shows that when droplet contact-line recedes with weak mechanical retention, a minute amount of liquid is left on top of the



SEM images of droplet on an inclined omniphobic surface.

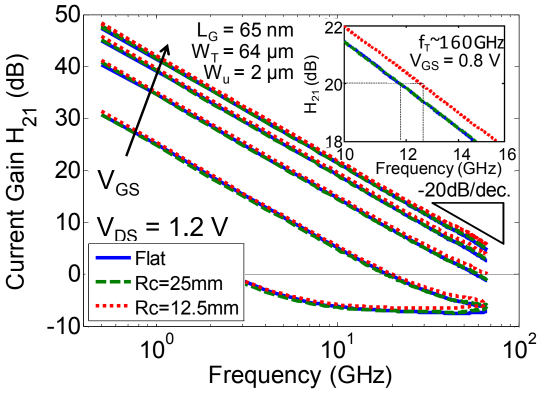
posts. This results offer an original way to deposit controlled amounts of liquid at well-targeted location[e] for optimizing printing of electronic circuits on flexible substrate.

(c) BiOMEMS group
(d) R. Dufour et al., Langmuir, 26, 22, 17242-17247 (2010)
(e) R. Dufour et al., Small, 8, 8, 1229-1236, (2012)

### *Record high-frequency flexible electronics: SOI-CMOS, AlInAs/GaInAs HEMTs & AlGaN/GaN HEMTs[f]*

Many emerging applications related to ultra-light communicating flexible systems require frequency performance similar to those achieved by state-of-the-art rigid semiconductor technologies. Starting from standard state-of-the-art mature technologies, methods based on extreme thinning of the initial substrate and subsequent bonding of circuit dies on plastic films have resulted in mechanically flexible electronics reaching the 150 GHz frequency range and beyond. This strategy referred to as ultimate thinning and transfer bonding (UTTB) has been developed in three different flavors:

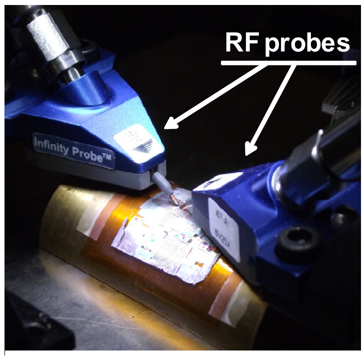
i) The first is based on a 65nm SOI-CMOS technology for which we have developed a methodology relying on neutral plane engineering to provide high performance stability upon bending, by locating the active layer at the neutral fiber of the flexible system. Following this approach, record frequency performance of flexible n-MOSFETs featuring $f_T/f_{MAX}$ of 150/160 GHz[g], have been obtained with variations less than 5% even under aggressive bending down to a radius of 12.5 mm[h].




HF characteristics of UTTB n-MOSFETs under flexure: using neutral plane engineering the unity current gain cut-off frequency ($f_T$) is weakly impacted by strain.

ii) AlInAs/GaInAs high electron mobility transistors (HEMT) take advantage of narrow bandgap III-V materials and still remains today the active device that has the best frequency and low-noise performance. This type of device is especially attractive for medical imaging, security, spectroscopy, radiometry, aeronautics and for wireless communication applications beyond 300 GHz. Cutoff frequencies $f_T$ = 160GHz and $f_{MAX}$ = 290GHz[i] measured on 100nm gate length AlInAs/GaInAs HEMTs establish a state-of-the-art for this technology on flex and make it possible to envision the 0.75-1 THz range for 30nm HEMTs.

iii) For applications requiring large bandwidth, high operating frequency and microwave power, GaN-based technologies are extremely attractive for providing high efficiency solutions in receiver and emission chains. New opportunities in terms of high performance, low cost, and lightweight circuit integration can be brought by applying the UTTB philosophy to GaN technologies[j]. We have shown that a rise in the 2-DEG density is experimentally observed in 120nm AlGaN/GaN transistors on a flexible substrate under 0.88% tensile strain. This phenomenon is attributed to the modification of the piezoelectric field within the barrier. Cut-off frequencies $f_T/f_{MAX}$ of 32/52 GHz have been established for the first time for GaN power device without major deviation under bending[k].

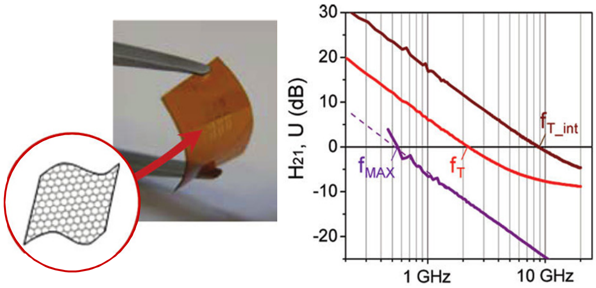



Flexible a UTTB chip under HF probing in bent configuration. Same methodology was used SOI-CMOS, AlInAs/GaInAs and GaN HEMT.

(f) SILICON MICROELECTRONICS, ANODE and PUISSANCE groups
(g) A. Lecavelier et al., Electron Dev. Lett. 32, 1510-151 (2011)
(h) A. Lecavelier et al., J. Appl. Phys. 113, 152701-1-9 (2013)
(i) J. Shi et al., Appl. Phys. Lett. 99, 203505-1-3 (2011)
(j) M. Lesecq et al., Electron Dev. Lett. 32, 143-145 (2011)
(k) N. Defrance et al., Trans. Electron Dev. 60, 1054-1059 (2013)

### *Flexible GHz single-layer graphene transistors[l]*

Solution-based single layer of graphene developed at Northwestern University has been used to fabricate graphene field effect transistor on a flexible substrate. We have obtained high value of extrinsic and intrinsic current gain cut-off frequency, 2.2GHz and 8.7GHz, respectively. These figures are quite stable under strain down to the radius curvature of 12.5mm[m]. This result establishes the state-of-the-art in the field of flexible carbon RF electronics, and places solution-based graphene at the top of the short list of materials that are suitable for large area / low cost fabrication methods.




Graphene FET on kapton using solution-based graphene monolayer, and measured HF performance

(l) CARBON group
(m) C. Sire et al., Nano Lett. 12, 1184-1188 (2012)

***Ultra-soft polymer-based MEMS*** [n]

Ultra-soft metal/polymers active structures with unique mechanical properties for innovative circuits and MEMS have been developed[o]. This approach enables the realization of soft moving parts such as membranes, hinges or cavities compatible with micro-machined silicon, metallization and addition of magnetic elements. Applications were developed and patented in several fields, such as integrated high density tactile interfaces, micro-valves and micro-pumps for fluidic applications as well as agile millimeter wave antennas and phase shifters. The right figure shows the brightest results on this last subject[p]:

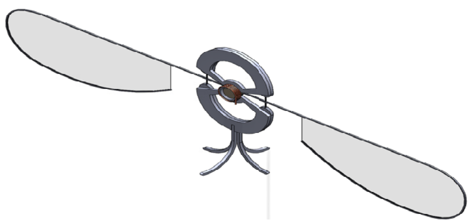

mm-wave devices on soft polymer membrane, from left to right: pneumatic tunable patch antenna, phase shifter, beam steering antenna.

- a suspended patch antenna with pneumatic actuation showed 8% tuning capability around 53GHz .
- a phase shifter with moving ground plane showed a state-of-the-art figure of merit of 118°/dB(insertion loss).
- a directive antenna capable +/- 90° mechanical beam steering with a constant gain at 57GHz was realized.

(n) AIMAN-FILMS group
(o) J. Streque et al., J. Micromech. Microeng. 22, 095020-1-10 (2012)
(p) S. Age-Hali et al. IEEE Antennas Wirel. Propag. Lett. 9, 1131-1134 (2010)

***Flying wing nano air vehicle*** [q]

To date, microsystem technology has not been used for designing flying wing nano air vehicle (FWNAV) and to artificially create hovering insect flight. Our FWNAV called Objet Volant Mimant l'Insecte (OVMI) has reached a certain maturity in the fabrication process using successive SU-8 layers[r] as well as in its aero-elastic modeling. Furthermore, this prototype is, to our knowledge, the first one at the real size of insects able to create lift with the help of passive torsion and without any articulation. To achieve this goal, a wing resonant actuation concept in combination with a resonant-like thorax is used and the obtained mode-shape is quite similar to the flapping motion of insects[s]. To actuate the wings, an electromagnet is currently used due to its wide availability. The OVMI prototype weights 22 mg (the world's lightest) and flaps at about 30Hz, but higher actuation frequencies are actively sought. However, a better understanding of the phenomena on its wing is mandatory so as to accelerate its development to get it airborne and also to optimize performance.

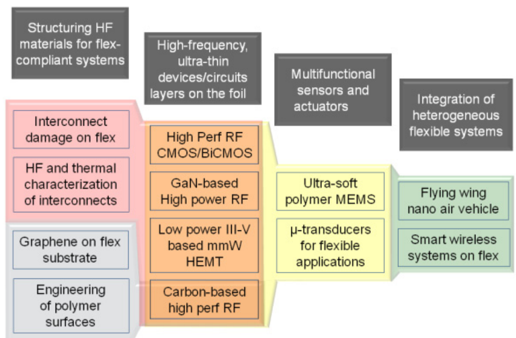


Design of OVMI prototype fabricated with SU-8

(q) MAMINA group
(r) T. Dargent et al., J. Micromech. Microeng. 19, 085028-1-10 (2009)
(s) X.Q. Bao et al. J. Micromech. Microeng. 21, 125020-1-16 (2011)

## IV- Future directions

Building on the dynamics created by the CPER-CIA project over the last three years and on the synergy created by the LEAF Equipex project, the Flagship project on Flexible Electronics will strengthen its activity in each of the identified challenges, namely, i) Structuring HF materials for flex-compliant systems, ii) High-frequency, ultra-thin devices/circuits layers on the foil, iii) Multifunctional sensors and actuators and iv) Integration of heterogeneous flexible systems. The overall Flagship project organization is schematically described in the right figure with a structure consistent with the four identified challenges.




Overall organization of the Flagship project on flexible electronics

### Challenge I - Structuring HF materials for flex-compliant systems

***Interconnect damage on flex:*** Interconnect aging under aggressive bending and stretching condition will be pursued through the development of test protocols able to couple mechanical monotonic or cyclic loadings with optical and electrical measurements. A special focus will be done on optical metrology (visible and infrared wavelength) and digital image correlation.

***HF and thermal characterization of interconnects and plastic substrate:*** Electrical properties of the flexible substrates must be characterized with accuracy in the entire operating frequency band up to 220GHz. To that end, methods are being developed to determine the permittivity and loss tangent. De-embedding techniques applied to S-parameters measurements and numerical analysis based on spectral domain approach and finite element are used to predict the complex permittivity behavior. A special effort will also be devoted to the design, fabrication and characterization of flex-compliant interconnect network and HF transmission lines using e.g. meandering redundant interconnect meshes to provide robustness and viability.

***Graphene on flexible substrate:*** Because graphene growth on large area by CVD on metals is now well mastered and documented, the next step is to develop the technological processes required to transfer this 'wonder' material on whatever substrate while preserving its properties. Another goal is to grow other 2D materials such as BN to develop vertical or lateral graphene/BN heterostructures also on flex substrates.

***Engineering of polymer surfaces:*** Polymer microprocessing is becoming a major issue for new electronic applications on flexible media. In the field of inkjet printing, efforts will be focused on understanding the physics of droplets impact and evaporation on textured surfaces. Complementarily, process developments will be undertaken for polymer surface micromachining by femtosecond laser ablation which appears to be a very attractive and compelling technology for fast development of polymer microsystems.

## Challenge 2 – High-frequency, ultra-thin devices/circuits layers on the foil

***High performance CMOS/BicMOS on flex***: After demonstrating record cut-off frequencies of 150/160 GHz for RF 65nm SOI-CMOS technoly on flex, first coming efforts will focus on the integration of complex circuit blocks such as LNAs operating in W band (75-110GHz) on flex. The thinning and transfer-bonding methodology will be extended to fully depleted SOI 28 nm and 0.5 THz BiCMOS technologies within the frame of the ST-IEMN common laboratory. At system level, the heterogeneous assembly and interconnection of independent building blocks on flex (CMOS microcontroller and RF communication, sensors, antenna…) will be undertaken using pick-and-place techniques coupled to structuring techniques such as photo-thermal ablation within the framework of the LEAF Equipex project.

***GaN-based high power RF:*** One main objective in the collaborative framework of the FLEXIGaN consortium will be to obtain, on the one hand, flexible GaN-based HEMTs delivering 2W/mm up to X band and, on the other hand, InGaN/GaN-based flexible LEDs with an external quantum efficiency of 5%. Convergence to produce high speed/high performance flexible autonomous power RF tags is also targeted for logistic tracking, preventive maintenance and objects traceability where high power is also required.

***Low power III-V based mmW HEMT:*** Increasing the coupling between the incoming high frequency signal and the device is today a challenge for high sensitivity detector. Plastic is a low permittivity material and better coupling of the antenna on this material is expected. The trend of this activity will be to develop a detector for millimeter and sub-millimeter wave combining a HEMT acting as a detector and an antenna.

***Carbon-based high performance RF***: Flexible graphene electronic is developing based on two main material synthesis routes: (i) CVD graphene transfer on flexible substrate, and (ii) solution-based graphene. Combining several technological paths (conventional, ink-jet printing, laser technologies), the objective is explore the fabrication of interconnects, devices, circuits and systems covering a large frequency bandwidth on the flexible substrates in a heterogeneous assembly approach.

## Challenge 3 – Multifunctional sensors and actuators

***Ultra-soft polymer MEMS***: Tunable reflect array structures are of particular interest for radar and communication purposes as they offer beam-patterning capabilities. The approach of independently moving and addressing reflectors is a promising alternative to conventional MEMS switches having reliability issues. Two main research directions will therefore be followed: (i) to push the mm-wave 60 GHz flexible devices to practical electronics (ii) to transpose the solutions in the higher frequency range for components such as phase shifters, tunable filters, beam steering antennas and reflect-arrays at 110 GHz and above, up to 240 GHz. Work on flexible sensors and actuators, in particular for tactile interfaces and microfluidics, will target the elaboration of conformable arrays. This activity involves collaborations with Georgia Tech. and CINTRA-CNRS in Singapore.

***Micro transducers for flexible applications***: Research on compact and efficient micro-transducers on flexible substrates is poorly covered internationally but essential for flexible smart systems like the flying wing micro drone. Over the last few years, innovative electro-active polymers (EAP) that have a macromolecular architecture of interpenetrating polymer networks (conducting IPN) have been developed. State-of-the-art results have been obtained for small self-standing micro-beams of conducting IPN featuring 5V supply voltage, displacements at the beam tip of several hundred micrometers, and forces of about ten µN. In collaboration with CNES and ST, future work will concentrate on the integration of conducting IPN in ambitious and innovative demonstrators such as haptic surfaces for flex phone, microfluidic microreactor, a micro-gripper force feedback.

## Challenge 4 – Integration of heterogeneous flexible systems

***Flying wing nano air vehicle***: The global objectives for the next five years are to produce sufficient lift forces to enable flight and at the same time to design and implement electronic functionalities necessary for a remotely flight control. Further developments are first based on the use of previously developed modeling and experimental framework to optimize the structure design and the electromagnetic actuation in terms of weight and power consumption. In a second step, the aim will be to determine the optimal kinematics to produce the necessary forces to propel an artificial Insect. In a third step, the research will focus on the choice and the minimization of electronic components such as microcontrollers and accelerometers or gyroscopes to allow the maneuverability of the artificial insect.

***Smart sensor and actuator wireless systems***: This activity tackles the heterogeneous co-integration of new functional materials, sensors, actuators and high-performance electronics into advanced multifunctional systems. The central objective is not to develop energy autonomy in ultra low power smart communicating objects but rather to enhance their functionality with the additional property of mechanical flexibility. One emblematic example is the artificial insect eye capable of imaging with hemispherical field of view, low aberrations and infinite depth of field while transmitting data in real time. Although the list is not exhaustive and likely to be enhanced over the lifetime of the project, the following examples of systems are believed to introduce significant innovation to pending technical problems: i) reconfigurable antennas (frequency agility, beam-steering, polarization diversity) that will be heterogeneously co-integrated with HF circuits for short range wireless links (W-HDMI,WPAN,WSN) ii) wearable haptic interface with local signal processing and wireless communication, iii) micro-drone that co-integrate electronics, sensing and actuation for autonomous navigation.

## V- Scientific production

The publication activity is spread over the 10 groups contributing to this Flagship project, namely, AIMAN, ANODE, BIOMEMS, CARBON, EPIPHY, MAMINA, MITEC, NAM6, PUISSANCE and SILICON MICROELECTRONICS. The following table gives a concise picture of scientific production since the structuration of the activity on Flexible Electronics.

| **Flagship on Flexible Electronics (Jan. 2010 - Jun. 2013)** | | | |
|---|---|---|---|
| Peer-reviewed international journals | 37 | Patents | 4 |
| Peer-reviewed international conferences with proceedings | 36 | PhD thesis defended | 11 |
| Invited talks | 12 | PhD thesis on-going | 6 |

## VI- Associated research projects

If the scientific and technical content of this Flagship project initially served to feed the LEAF Equipex proposal, it is now worth noting that LEAF reciprocally served as a lever to obtain an additional funding envelope of 700k€ over the 2014-2015 period from regional council/MESR/FEDER to support the activity on flexible electronics. Associated to this global dynamics, a substantial number of national and international collaborations have been developed by IEMN groups contributing to the Flagship project on Flexible Electronics. Whereas the exhaustive list of collaborating partners is beyond the scope this document, most important national and international projects are detailed hereafter[1]:

- ST/IEMN common laboratory: to enhance mature silicon-based technologies with mechanical flexibility
- ANR REFLEX : to develop inkjet printing process for biopolymers
- ANR LIVE-CAMS : to design and fabricate micro-valves for aerodynamic flow control
- ANR GRACY: to develop graphene-based low noise amplifiers
- COST ESNAM: European Scientific Network for Artificial Muscles
- ANR IN-ART and EADS foundation: high efficiency electro-active polymers for flapping micro air vehicles
- ERC UPTEG: to develop mechanically-flexible membrane-based thermoelectric converters
- FET GRAPHENE FLAGSHIP: to explore the potential of graphene for RF applications on flex
- ANR FLEXIGaN: to develop power GaN-based HEMTs operating in X band and InGaN/GaN flexible LEDs
- ANR CLEAR-FLIGHT: to pursue work on flying wing nano air vehicle in continuation to ANR IN-ART

## VII- Technological platform and infrastructure

Beside the deployment of the LEAF femtoseconde laser micromachining platform, companion equipments will contribute to considerably enhance our technological resources and expertise for advanced assembly, interconnect and packaging associated to flexible electronics technologies. Additional equipments comprise: i) a high precision grinder for substrate thinning, ii) spin-etching and chemical mechanical polishing for high uniformity stress relief, iii) nanosecond laser for light-to-heat debonding of temporary carriers, iv) a high precision die placement and bonding platform including chip flipping and v) a fully automated 3D interferometric microscope for routine analysis of laser ablated patterns.

A new building will be erected in 2014 in order to extend surface associated to technical platforms. It consists of three stories of research laboratories with approximately 1260 m$^2$ of work area and 200 m$^2$ for technical support. Both the new space and the clean room surface left by moving some pieces of equipment will make new area readily available for the installation of the technological platform of the Flagship project on Flexible Electronics.