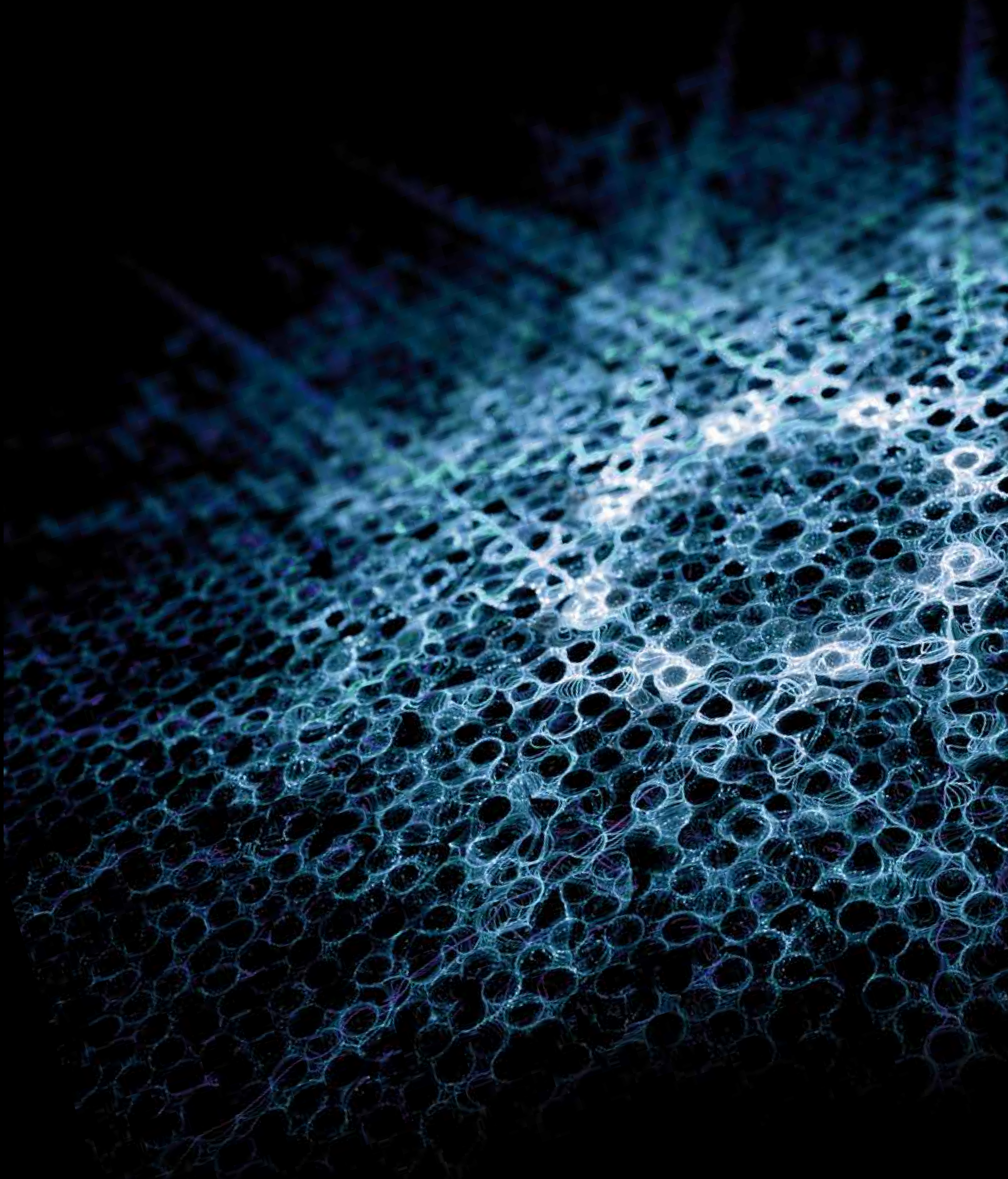

IMM Institute for Microelectronics and Microsystems

National Research Council of Italy

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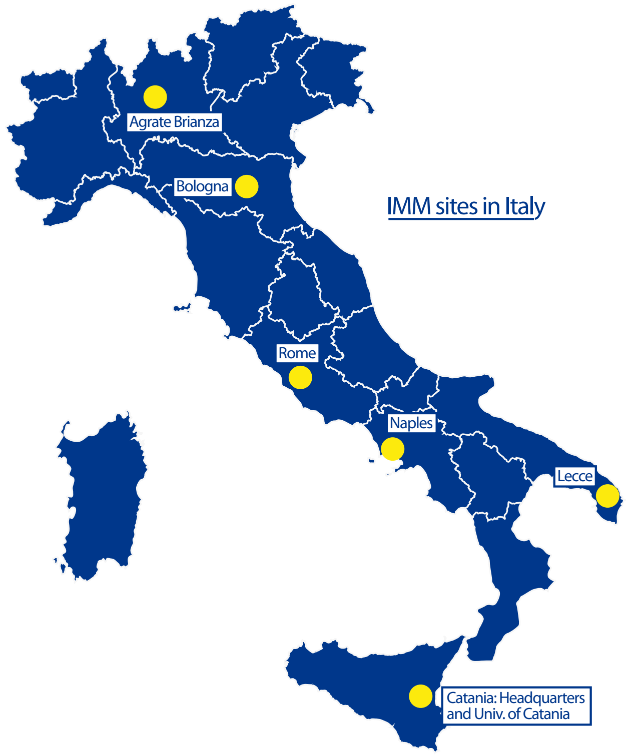
The Institute for Microelectronics and Microsystems (IMM),

belonging to the Physics and Matter Technologies Department of CNR, is organized in 7 Sections, located in Agrate Brianza, Bologna, Rome, Naples, Lecce and in Catania (the Headquarters and at the Univ. of Catania). IMM counts 195 people as permanent staff (117 as Researchers) plus temporary staff including 47 Post-Docs and 61 Ph.D. students (survey 2014).



The research activity

is focused on innovative solutions for micro and nanoelectronics, advanced materials and processes for smart components, optoelectronics and photonics, sensors and multifunctional micro/nanosystems. In particular, the main research areas are:

1) Nanostructured materials: Graphene and two dimensional materials beyond graphene, Semiconductor nanowires and nanomaterials, Oxide and metal nanostructures, Self-assembled nanosystems;

2) Materials and devices for Information Storage and Processing: Advanced contact schemes and doping strategies, Spintronic Devices, Nanomaterials for phase change memories, Memristive devices and neuromorphic computing, Quantum Information Processing;

3) MEMS and MOEMS: Metamaterials for RF and microwave applications, SiC films for sensors and freestanding MEMS structures, RF-MEMS switches, Silicon flexural resonators for strain sensors;

4) Flexible and Large area electronics: Inorganic flexible electronics, Graphene based devices, Organic electronics, Low temperature inorganic films for flexible sensors;

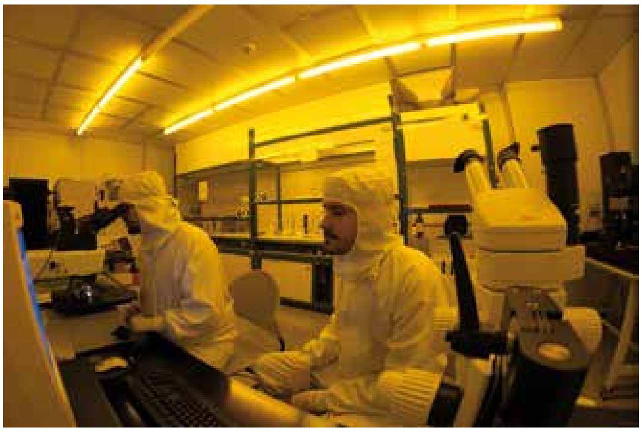
5) Materials and processes for RF and Power devices: hetero-epitaxial growth of 3C-SiC on Si, processing development for SiC and GaN devices;

6) Energy conversion devices: Materials for third generation solar cells, including silicon nanodots and nanowires, graphene, perovskites, Ultra-thin transparent and conductive films, 3C-SiC, Plasmonics, nano-rectenna;

7) Photonic materials and devices: Silicon photonics, Biomimetics and metamaterial-based devices for hybrid integration, Fiber optic based devices;

8) Sensors and multifunctional micro/nanosystems: Materials for sensing technology, Components for multifunctional sensing systems,

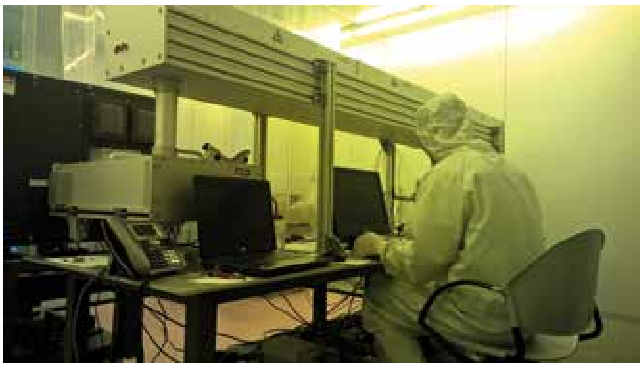
- *Micro-nanofabrication facility*



- *Micro-nanofabrication facility*

Integrated smart multifunctional micro/nanosystems;
9) Micro and Nanoscale characterization and imaging: Electron Microscopy Techniques, Scanning Probe Techniques, Light Microscopy Techniques, X-Rays and Ion beam techniques;
10) Theory, numerical simulation and modelling: Theory of coherent and correlated quantum systems, Density Functional Theory and ab-initio simulations, Simulations of processes and devices from the meso- to the macro-scale.

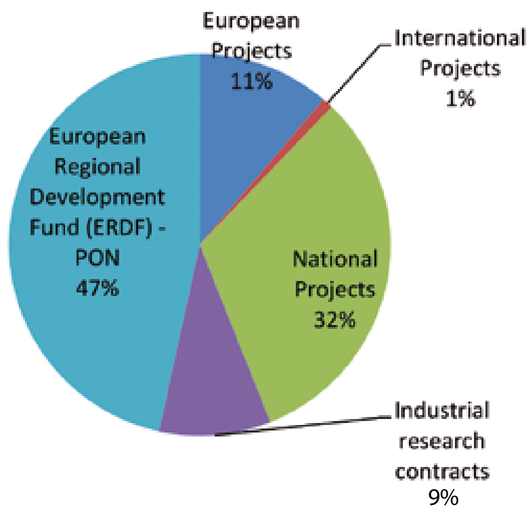
IMM activities span from material science and process development to device fabrication and system integration, thanks to the micro-nanofabrication facilities present at the different sites (clean-room areas totaling >1400 m^2). Through the participation to many European projects, IMM benefits from collaboration with prestigious international research institutions, such as Laboratoire d'Electronique de Technologie et d'Instrumentation (LETI), Interuniversity MicroElectronics Center (IMEC), European Synchrotron Radiation Facility (ESRF), Centro Nacional de Microelectrónica (CNM), and with many semiconductor industries, including STMicroelectronics (ST), Micron, Philips, SILVACO, AMD, ABB, Tower Semiconductor and Siemens. Particularly effective is the collaboration with STMicroelectronics, with two IMM Sections embedded in ST plants in Catania and Agrate Brianza, allowing the successful development of public-private initiatives. Furthermore, IMM has a close collaboration with many Universities (one of its Section being located within the Physics Dept. of the University of Catania) and also carries out an important role in the formation, coordinating many PhD and graduate student activities. As a result, IMM effectively bridges the Academic Institution research activities with the Industrial applications, as also clearly demonstrated by the location of some IMM Sections. It should be underlined that the strong interaction with companies does not prevent, but often promotes the development of basic research activities. Indeed, some challenges in nanoelectronics require "More than Moore" solutions, with expected long-term practical applications. The Institute is active in many emerging fields related to nanotechnologies (low-dimensional systems, new materials for memories and spintronics, graphene, etc.), sometime generating innovative know-hows also for non-electronic applications.
Due to the strong industrial interaction, IMM research programs include also specific aspects addressed by the Industrial partners. Particularly relevant is the participation to the projects, led by ST, and funded through the European Regional Development Fund (ERDF) regarding: the development of flexible electronics for smart disposable systems



- *Micro-nanofabrication facility*

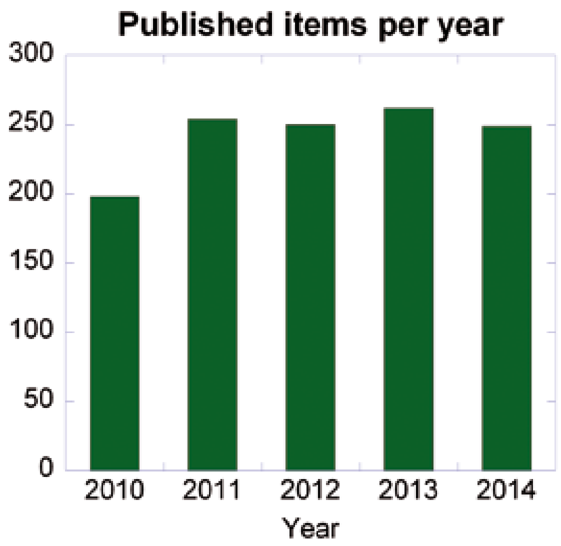
(PLAST_ICs); power electronics based on SiC and GaN for the control and conversion of electric power for automotive and industrial applications (AMBITION POWER); third generation photovoltaics (ENERGETIC); new PV-technologies for smart systems integrated in buildings; micro and nanotechnologies for advanced biomedical systems (HIPPOCRATES). Another relevant ERDF funded project is the Public-

Private Partnership for research, development and validation of innovative technologies and services for Ambient Assisted Living (INNOVAAL). IMM also collaborates with Alenia Aermacchi on several projects related to aerospace and is partner of a number of Technological Districts, stimulated by the Italian Ministry for University and Research. IMM is member of the Technological Districts "Micro and Nanosystems" in Sicily, "Hi- MECH (high mechanic technology)" in Emilia Romagna and the Aerospace District of the Campania.
IMM coordinates or is partner of several European projects and among these are worth mentioning those on: real neurons-nanoelectronics architecture with memristive plasticity (RAMP), water control (AQUASYSTEM) and the application of nanotechnology for water treatments (WATER); graphene and 2D semiconductors (EU GRAPHENE FLAGSHIP, 2DNANOLATTICES); MEMS for detection of illicit substances (DOGGIES, DIRAC); microelectrode arrays for brain signal recording and stimulation (CORTICONIC); synthesis and functionality of chalcogenide nanostructures for phase change memories (SYNAPSE); self-assembled structures for nanometrology and nanostructured devices (CRYSTAL,TREND); organic electronics (COSMIC), volumetric scanning microwave microscopy for non-destructive 3D nanoscale structural characterization (V-SMMART NANO); energy for a green society: from sustainable harvesting to smart distribution: equipments, materials, design solutions and their applications (ERG, funded by ENIAC JTU); development of a critical mass of Ambient Assisted Living applications, products and services (ReAAL); innovation for age-friendly environments in the European Union (AFE-INNOVNET)); the ERDF funded projects on MEMS for Aerospace (TASMA) and on smart systems enabling services in bio-imaging (RAISE) and in assisting individuals in monitoring their health conditions (AA@H, BAITAH) and remote rehabilitation system for Alzheimer patients (ALTRUISM). Thanks to the project Beyond-Nano, also funded by ERDF, IMM has recently installed a sub-Angstrom ARM200F Scanning TEM, which, thanks to its exceptional features, makes the facility one of the most powerful tool for structural analysis in Europe.



- *Distribution of external annual funding (averaged over the period 2011 - 2013).*

IMM has an annual operating budget, averaged over the last three fiscal years, around €24 million, including €9.8 million of personnel costs and €1.4 million of running costs supported by CNR and €12.8 million arising from European Regional Development Funds, European, International, National projects and Industrial research contracts.
Scientific results are presented to many International Conferences and around 250 articles are published by IMM researchers on JCR journals every year.



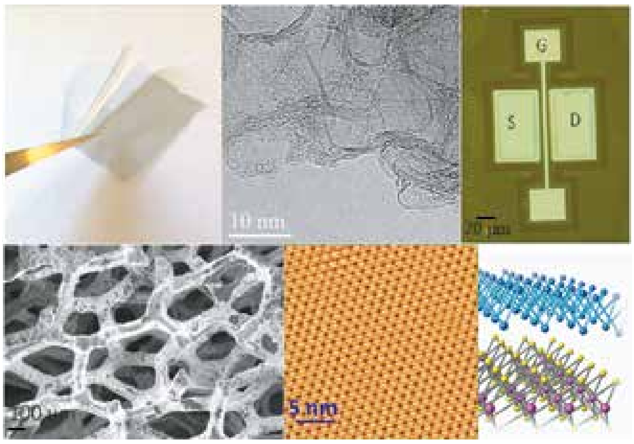
- Number of articles published on JCR Journals per year

Nanostructured materials

In order to tackle the numerous challenges in the nanotechnology field, the activity on nanostructured materials covers different topics including graphene and two dimensional materials beyond graphene, semiconductor nanowires and nanoparticles, oxide and metal nanostructures, and self-assembled nanosystems.

Graphene and two dimensional materials beyond graphene

Synthesis of graphene and carbon nanostructures is accomplished by means of chemical vapour deposition (CVD) on large area (up to 6 inches) for almost all variants and shapes of graphene, epitaxy on SiC(0001) susbtrates, and physical-mechanical methods (arc discharge, RF magnetron sputtering, chemical exfoliation). Graphene production is intended for integration into:



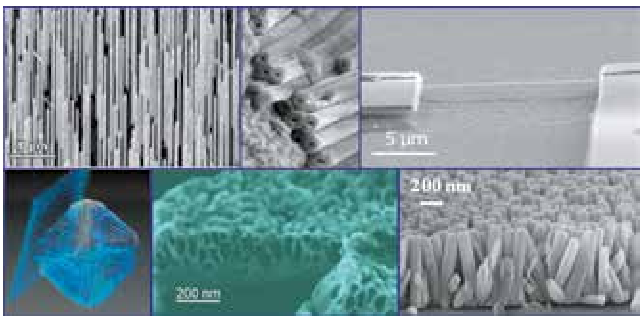
- *From left to right, Top: a graphene flake, graphene layers from arc discharge in liquid, a graphene transistor; Bottom: 3D graphene structure, atomic topography of silicene, model of a Si/MoS_2 hetrosheet.*

a) functional substrates (glass and flexible polymers) targeting transparent conductive electrodes for flexible and transparent capacitors and actuators, 3rd generation bulk and dye-sensitized solar cells and organic devices such as light emitting transistors;
b) technological processes for innovative MEMS and MOEMS devices with attention paid to thermal and thermoelectric properties aiming at graphene bolometers and thermopiles;
c) high power and high mobility field effect transistors and novel electronic device incorporating graphene/semiconductor heterostructures (e.g. graphene/AlGaN/GaN heterostructures).
d) three-dimensional structures for sensing and water purification devices.

2D materials beyond graphene are a new frontier for nanoelectronics which addresses an ultimate scaling of the device size features and paves the way to nonconventional functionalities. IMM is engaged to synthesize, characterize, and integrate into prototypical device structures new elemental 2D materials such as silicene (the silicon counterpart of graphene), 2D transition metal dichalcogenides (TDM) such as MoS_2, and van der Waals heterostructures.

Semiconductor nanowires and nanomaterials

Semiconductor-based nanowires (NWs), and nanoparticles (NPs) are synthesized and studied in terms of their electrical, structural and thermo-electrical properties for the production of novel custom devices. Semiconductor (Si, Ge, III-V and II-VI compounds) NWs with controlled characteristic sizes are produced by means of the metal-catalyzed growth via ion coupled plasma CVD and metallorganic chemical vapor epitaxy, plasma-enhanced CVD, and metalassisted chemical etching of a Si template. Main goals of this effort rely on the fabrication of gas sensors, exploiting the large surface-to-volume ratio, and of NW-based 3rd generation solar cells, and on the study of surface defects and confinement effects by means of electron paramagnetic resonance spectroscopy.



- *- From left to right, Top: GaAs-AlGaAs core-shell nanowires, TiO_2 nanotubes, a Si nanowire device; Bottom: a Si nanoparticle, Ge sponge-like structures, ZnO nanostructures.*

Polycrystalline Si NWs are also fabricated by a top-down technology in order to investigate their thermoelectric properties, namely thermal conductivity, electrical resistivity and Seebeck coefficient for applications in high-efficiency thermoelectric energy conversion. Si NPs are studied as a key material to establish a Si-based photonics. A high density plasma process was optimized to synthesise Si NPs without the need of subsequent thermal treatments.
Si nanocrystals embedded in a silica matrix are hence taken as a paradigmatic system for the nonlinear optics at the nanoscale with specific attention to the stimulated Raman scattering phenomena.
Nanoscale sponge-like structures are formed within the amorphous phase of germanium by ion implantation with heavy ions at room temperature. The porous structure provides an enormous surface-area-to-weight ratio for applications such as low cost chemical and biochemical-sensing devices, electrodes and photovoltaic applications.

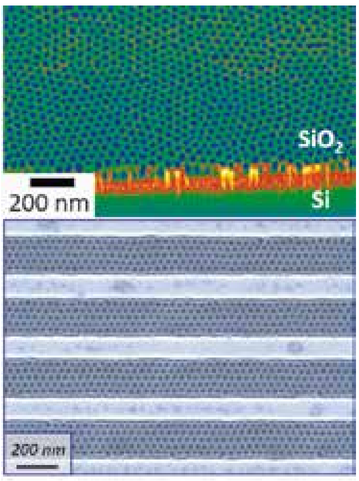
Oxide and metal nanostructures

The research activity on oxide nanostructures is mainly concerned with TiO_2 and ZnO. TiO_2 exhibits relevant properties in the photocatalytic degradation of water pollutants (both organic compounds and microorganisms). Nanometric TiO_2 films wrapping metallic (Au, Pt, Ag, Ru) nanoparticles, or TiO_2 nanotubes are synthesized for improving the efficiency of purification in the water treatment, thanks to electron scavenging effects or to an enhancement of the exposed surface. ZnO is an extremely versatile material that can be used as building block for piezotronics, biosensing and biomedical applications. Surface defect engineering in ZnO nanostructures leads to efficient and fast UV detection, gas and biomolecules sensing. In addition to TiO_2 and ZnO nanostructures, organic-inorganic hybrid perovskites such as lead iodide perovskites are also considered for their scalability to the nanoscale and excellent electrical conductivity. The study of conductive perovskites is mainly carried out on nanostructured blends made of TiO_2 mesoporous scaffold and perovskites active materials.

Metal nanostructures are basic components of complex nanodevices with improved functionalities and performances with respect to the traditional ones: ultra-small, ultra-fast, tera-bit level storage and ultra-low consumption nanoelectronic devices; ultra-sensing devices; ultra-efficient optoelectronic and solar-cell devices; nanovehicles for localized and efficient release of drugs.

Self-assembled nanosystems

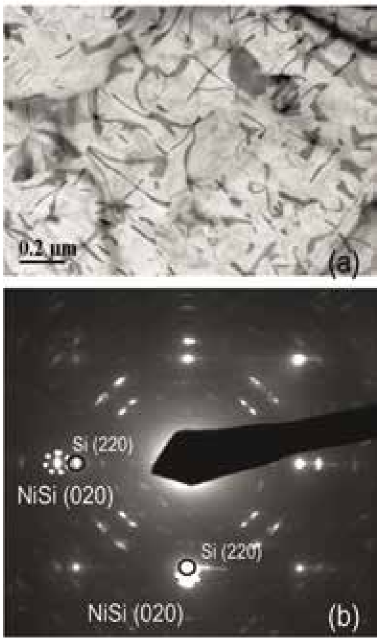
Self-assembly is expected to provide advanced bottom-up solutions for the synthesis and manipulation of new functional materials with characteristic dimensions well below 20 nm. The main interests are the fundamental issues related to the understanding of the self-assembly mechanism in polymeric thin films and the implementation of advanced nanolithographic technologies based on these materials. The latter objective is mainly pursued by developing a block copolymer based lithography enabling to tune dimension, positioning and doping of semiconducting and dielectric nanostructures and to functionalize self-assembled materials as active elements in low-cost electronic, optoelectronic or photovoltaic devices. In this context, self-assembling of diblock copolymers is specifically utilized for the low cost production of mesoporous material made of ordered vertical nanoholes, because they provide the same advantages of NWs but are more robust, thus allowing easy handling.



- *Nanohole patterns from self-assembling of block-copolymers.*

Materials and devices for Information Storage and Processing

Research activities at IMM address the scientific and technological challenges in information storage and processing based on memory and logic devices, as well as in biologically-inspired neuromorphic circuits and quantum computing paradigms, exploiting more than ten years experience in the field. IMM activities

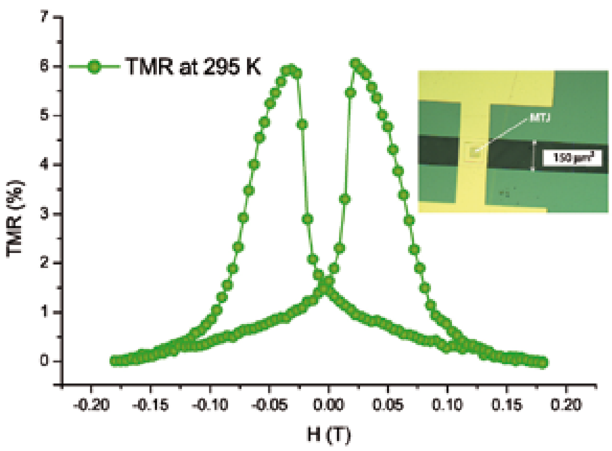


- *TEM image and diffraction of transrotational Ni-silicides*

span from materials and advanced characterization techniques, to nanostructures, novel technological processes, device prototyping, physical modelling and simulation. IMM is collaborating with leading industries in the field of semiconductor and micro-nanoelectronics at the national and international level and within European research projects. The final objective is to contribute to evolutionary and disruptive enabling concepts for devices at the nm scale towards novel digital and analog applications, low cost and low energy per unit function.

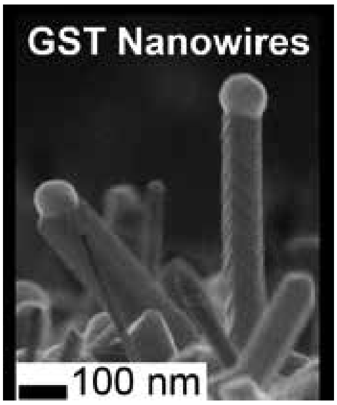
Advanced contact schemes and doping strategies. With the aim to address some of the crucial enabling steps for future CMOS based nanoelectronics, IMM is addressing the development of Ni-silicides for ultrascaled contacts in Si-based nanoelectronics. By investigating the crucial role of the early stages of the Ni-Si atomic interaction, a novel process has been developed to form **transrotational Ni-silicides** with thickness < 10 nm, high structural stability and quality of the interface, suitable for integration with ultra-shallow junction. From the electrical point of view, thin trans-NiSi layers offer resistivity values comparable to those of standard poly-NiSi phases (~20 µmohm×cm) and low contact resistance on a wide range of doping conditions. Another important step for future nanoscaled devices is the integration of alternative high-mobility channel materials in the Si platform, such as Ge. In this framework, IMM is currently investigating **advanced doping processes in Ge** to achieve high activation levels and shallow concentration profiles. In particular, the activity focuses on the mechanisms governing the dopant diffusion, their electrical activation/ deactivation, and the evolution of defects.

Spintronic Devices. Spin-dependent electronics (spintronics) is characterized by the use of both the spin and the charge of the electron to tune functionalities in electronic devices. IMM is addressing the development of atomic layer and chemical vapor deposition (ALD/CVD) methods for the synthesis of simple spintronic systems, such as **magnetic tunnel junction (MTJ)**, being core elements in several spintronic memory and logic devices.
We first reported the achievement of tunnel magnetoresistance (TMR) up to few % at room temperature in (Fe, Fe_3O_4)/MgO/Co patterned MTJs



- *TMR at 295 K of a Fe_3O_4/MgO/Co MTJ grown by CVD/ALD* grown fully by ALD/CVD, thus opening the path toward the cost-effective synthesis of materials and multialyers for spintronics on large substrate area, to favor an easier technology transfer.

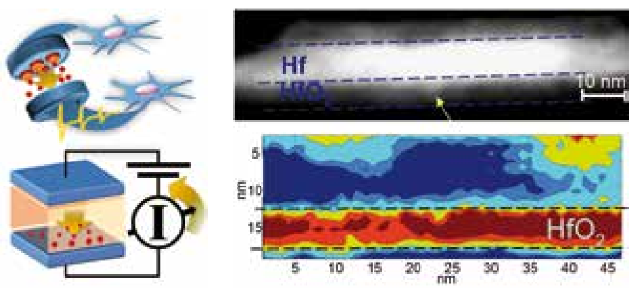
Manipulating domain walls (DW) in magnetic nanowires – racetrack memory – is an innovative approach to store information. Such concept can replace hard disk drivers thanks to the expected extremely high density and low power consumption. The IMM activity is addressed to the advanced structural and chemical characterizations of ultrathin (1 nm) CoFeB layers integrated in multilayer stacks for racetrack memory. The study contributed to the understanding of the basic mechanisms driving the forces originating the perpendicular magnetic anisotropy (PMA) and working in strong interaction with industrial partners, to optimize the integration of ultrathin CoFeB layer on top of 8" engineered Si wafers.



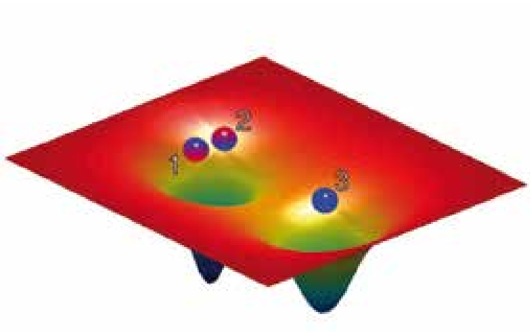
- *$Ge_1Sb_2Te_4$ single hexagonal crystals with 60 nm*

Nanomaterials for phase change memories. Phase Change Memories (PCM) are based on the reversible structural phase change induced in the active material, typically chalcogenide planar layers, by ns current pulses. Exploiting the very different electrical resistivity related to the amorphous and crystalline states, a binary information encoding is feasible and the PCM devices are already on the market. Among the various strategies to downscale the PCM memory cells and reduce power consumption, **phase change nanowires (NWs)** are very promising candidates due to the reduced programmed volume, possibility of tuning the material composition and of downsizing the electrode contact areas. IMM is involved in the synthesis and characterization of both thin films and nanowires of In-Sb-Te and Ge-Sb-Te, as well as in their advanced characterization including electro-thermal analysis. Self-assembled NWs (diameter around 30-80 nm) are grown by metallorganic chemical vapor deposition (MOCVD) and VLS, with various chalcogenides compositions. Recently, a functional PCM cell based on $Ge_1Sb_2Te_4$ single nanowire was demonstrated. Perspective of future work aim to control the NW positioning and the core-shell geometries for multi-level NW-based PCM devices.

Memristive devices and neuromorphic computing. Two-terminal devices exhibiting a digital or analog change of their resistance as a function of electrical pulses can be exploited for information storage (resistive switching memories RRAM), non-linear circuit elements with memory (logic in-memory devices beyond CMOS), and for developing memristive devices emulating the synaptic functionality of the brain for advanced neuromorphic systems. IMM is active in these fields since long time and is currently focusing on the switching mechanisms in oxide based memristive devices and their applications.
Structures down to the nanoscale are fabricated by exploiting advanced lithography techniques based on self-assembly strategies (block-copolymer) or by the synthesis of metal-insulator-metal nanowires. To address synaptic functionality, the devices are optimized for achieving analog



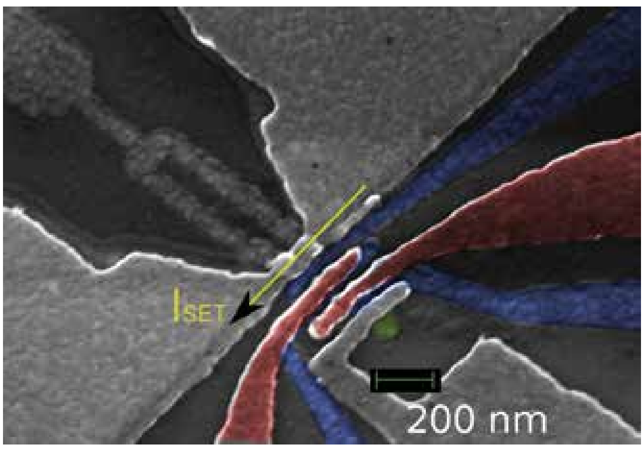
- *(Left) Memristive devices can be used to emulate the synaptic functionality.*
- *(Right) STEM dark field and electron energy loss spectroscopy of HfO_2 films.*



- *Sketch of the studied qubit, with three electrons confined in a double QD.*

control of their resistance as a function of train of electrical pulses and for mimicking the spike time dependent plasticity.
Finally, switching mechanisms are investigated at the nanoscale by means of high-resolution TEM analyses, providing effective local chemical and structural information for driving material optimization.

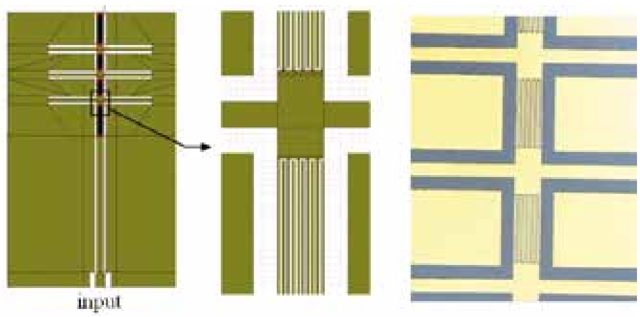
Quantum Information Processing. Quantum Information Processing deals with the exploitation of quantum behaviour in physical systems between states in which the logical information is encoded. Manipulation of these quantum states is at the base of quantum algorithms that ensure exponential reduction in computational time with respect to the classical counterparts. The scientific activities at IMM are related to the theoretical and modelling aspects of quantum information processing, as well as to the design and fabrication of devices and their functional characterization. The focus is on a qubit type defined on **spin states of three electrons in a silicon double quantum dot (QD).** The advantage in using this qubit relies on its intrinsic long coherence time, electrical state-manipulation and easy fabrication. From the viewpoint of theory and modelling, effective Hamiltonians are derived for a single qubit and for two coupled qubits, as well as a universal set of quantum gates to potentially obtain any quantum algorithm. A mechanism to connect remote qubits is developed by exploiting coherent transport by adiabatic passage. Further, silicon double QDs are designed to be electrostatically defined in a silicon nanowire, which is coupled to a Single Electron Transistor (SET) used as qubit state reader. Transport measurements performed at cryogenic temperatures (on single-qubit devices with minimum feature sizes of 45 nm) confirm the basic control of the dynamics of a single electron in the ms range at 4.2 K. Future perspectives are towards further improvements of single qubit devices and multiple qubit based systems.



- *SEM image of the qubit holder (double QD) and the qubit reader (SET)*

MEMS and MOEMS

Since several years MEMS is no longer considered "a field", but has become "an enabling technology" with widespread applications. Bringing the knowledge base of different disciplines into contact with MEMS technology, completely new sets of applications and opportunities were identified and became the subject of innovative and highly creative efforts. The circumstance that real products that address real markets could be manufactured at competitive prices, provides new lines of business based on paradigm-shifting device design. This trend has hugely enlarged the world of MEMS devices. In particular, the integration of micro-optics and MEMS has created a new class of microsystems termed MOEMS, which provide attractive solutions to a range of problems, when the requirements are high functionality, high performance and low cost. IMM activities on MEMS and MOEMS span from the study of new materials and/or novel deposition and characterization techniques, to the fabrication of devices with advanced functionalities.

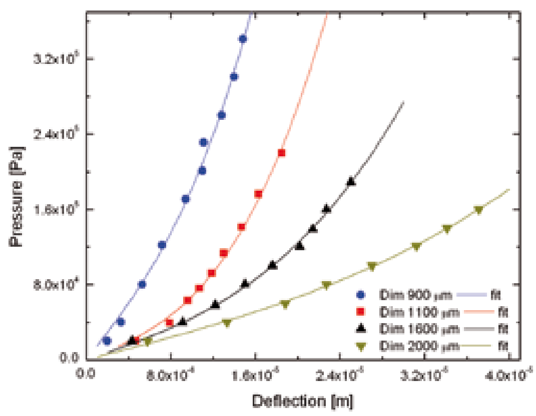


- *Layout of a coplanar guide (CPW) zeroth order metamaterial resonance antenna.*

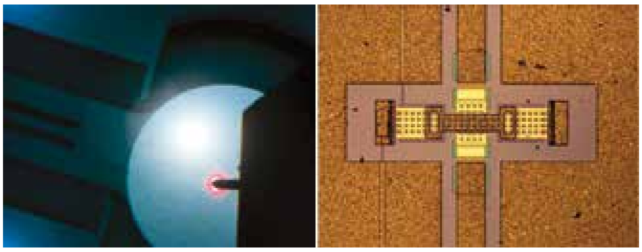
Materials

Starting from new materials, IMM develops a research activity on **Metamaterials**, or lefthanded materials (LHM), double negative (DNG), negative refractive index (NRI) materials, which are characterized by strong electrical and magnetic plasmonic resonances that lead to strongly dispersive permittivity and permeability in narrow frequency bands. In the resonance region, the permittivity and permeability can be less than one and even negative. These materials exhibit phase and group velocities of opposite signs and a negative refractive index in certain frequency ranges, both characteristics making them appealing for Radio Frequency (RF) and microwave applications, especially when size reduction and beam orientation over a wide range angle (forward and back radiation) are required. The feasibility of various metamaterial microwave components have been studied, like phase shifters, non-linear transmission lines, antennas and Sierpinski multi-band triangular resonators in coplanar waveguide configuration for applications up to 20 GHz.

Another activity is based on the study of the mechanical properties of **silicon carbide** (SiC) films for use in sensors or free-standing MEMS structures; one important issue is the residual stress field, which is normally created during the growth process and which can result in the unwanted deformation or failure of these structures. The built-in stress may change the mechanical response, the resonant frequency of thin-film structure, even leading to film cracking, buckling or delamination. A large effort of the IMM research group was in the study of the origin of the stress in this material and in the development of new processes that can reduce this stress and give the opportunity to use this material in new high temperature MEMS, as in cylinder pressure sensors. Still in the framework of new materials, IMM is committed in the development of ad hoc **atomic layer deposition** (ALD) processes



- *Deflection vs. pressure of a thin 3C-SiC membrane with different geometry.*

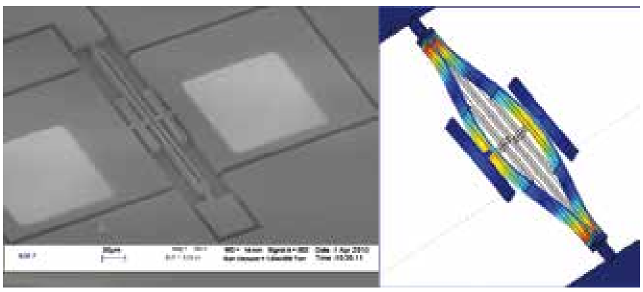


- *(Left) AFM characterization of a micromirror.*
- *(Right) Single-pole-single-throw RF-MEMS ohmic series switch.*

for the implementation of thin conformal layers into MEMS and MOEMS devices. ALD allows implementing at low cost novel materials with enhanced performances, such as innovative etch-resistant layers that improve the last steps of the process for the MEMS release, materials for magnetic sensing and low temperature transparent films with designed properties for the optimization of MOEMS.

Devices

Among MEMS devices developed at IMM there are **RF-MEMS** switches and Silicon resonators.
RF-MEMS are used for signal routing, redundancy logic, matrices, phase shifters. Their main advantages are in the all-passive environment, distortion free response and low-loss capabilities. Thanks to their small size and high reliability, these microwave and millimeterwave switch matrices are essential components in telecommunication systems, since they enhance satellite capacity by providing full and flexible interconnectivity between the received and transmitted signals. Several configurations have been studied and are currently under **space qualification to reach mechanically stable, low-loss, negligibly charged devices.**

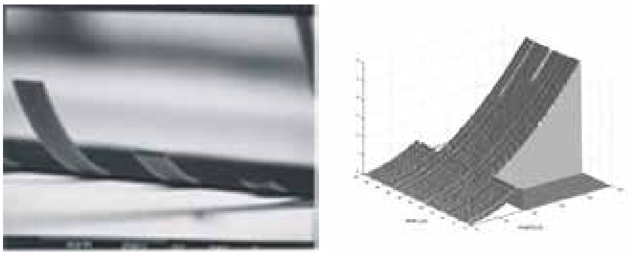


- *SOI flexural DETF resonator for strain sensing and 1st antisimmetric resonance mode.*

Silicon flexural resonators shaped as Double-Ended Tuning Forks (DETF) can be used as strain sensors by exploiting the dependence of the mechanical resonance frequency on the axially-applied force on the resonator. Micromechanical strain sensors on silicon chip are fabricated in vacuum at wafer level, yielding a strain resolution around 2 nanostrain on steel.

Characterization techniques

The **Digital Holographic Imaging** is a non-destructive, non-contact and non-invasive optical interferometric technique that can be efficiently employed as full-field technique for surface contouring and for measurement of surface displacement with a high vertical resolution. In particular, holographic imaging has been employed for detecting the three-dimensional features of

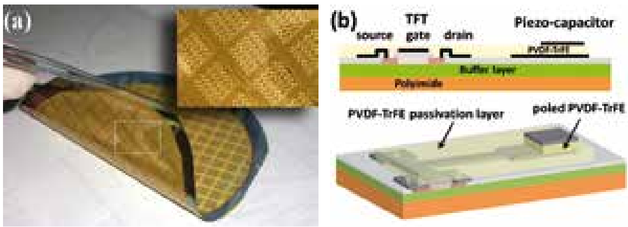


- *DH characterization of MEMS.*

microstructures (such as cantilever, RF-MEMS, micro-heaters) and quantitatively evaluate the out-of-plane deformations due to the residual stress introduced by fabrication processes and how external loads (such as temperature, pressure, applied voltage…) affect the deformation. In DH the fringe pattern is produced by interference between an object wave (the beam wave scattered by the object under investigation) and a reference wave. A CCD or a CMOS records this pattern, then the digitized interference pattern is numerically processed to retrieve the quantitative amplitude and phase image of the object under investigation.

Flexible and Large area electronics

Flexible and large area electronics has attracted a lot of attention since it allows the possibility to fabricate devices on arbitrary curved surfaces and movable parts. This opens the door to new applications in different areas of consumer electronics, such as flexible displays, bio-medical implantable devices, automotive applications, flexible sensors. Flexible



- *(a) Polycrystalline silicon transistors on flexible substrate.*
- *(b) Schematic of ultra-flexible tactile sensor.*

electronics is mainly developed on plastic substrates that require low temperature processes. This can be fulfilled by inorganic and organic materials and both technologies have been investigated at IMM. For inorganic materials, low temperature polycrystalline silicon (LTPS) devices have been developed and, more recently, graphene based devices started to be studied. For organic material, solution processed materials are applied to device manufacturing, on low temperature plastic substrates, by printing techniques. At the same time, **low temperature inorganic thin films** and nanostructured materials for **flexible sensors** are investigated, in order to integrate sensors with electronic devices and circuits on flexible plastic substrates.

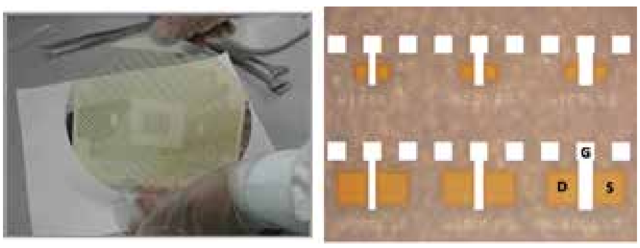
Inorganic flexible electronics

Low temperature polycrystalline silicon (LTPS) devices

IMM has developed a strong expertise in fabrication and characterization of devices and sensors for flexible electronics applications with particular focus on LTPS thin film transistors (TFTs). The key frame-based research activity includes device designing, low temperature fabrication techniques, excimer laser crystallization technique of amorphous silicon, electrical and mechanical testing. The LTPS platform is exploited for biomedical application, advanced robotics and aerospace prototypes (chemical and physical sensors, ultra-flexible tactile sensors, electrochemical devices based on nanostructured materials, implantable epicortical micro electrode arrays), as well as for advanced sensing systems based on wearable or deployable devices (short/long range localization sensor network embedded in smart clothes, stretchable pressure monitoring systems based on nanocomposite materials to be embedded in inflatable structures, etc.).

Graphene based devices

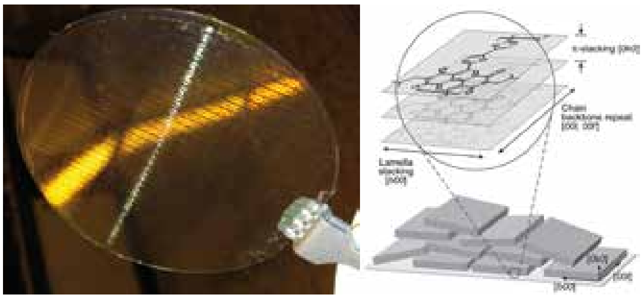
Graphene has been considered as a material of choice for flexible electronics, thanks to its unique combination of high electrical conductivity, optical transparency, mechanical robustness and flexibility. IMM is currently involved in the EU Graphene Flagship project and, specifically, in the WP8 “Flexible Electronics”, which aims at the demonstration of an integrated graphene-based hybrid system on a flexible plastics platform, including energy harvesting, battery, power management, interconnects, sensors, signal processing and RF connectivity elements. In this context, IMM is currently working with STMicroelectronics to the development of backgated graphene field effect transistor (FET) structures on a plastics substrate (PEN), which will represent the basis of the analog electronics and sensing elements. A clean (metal contaminations-free) and cost-effective transfer technology is under development at IMM, based on the electrolytic delamination of the graphene membrane from the copper foil, fully preserving copper for almost unlimited subsequent CVD growths.



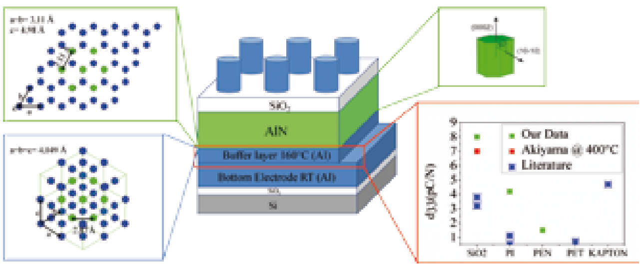
- *Graphene devices on flexible substrates.*

Organic electronics

Flexible and large area electronics requirements are well fulfilled by the properties of polymeric and small molecules organic materials, i.e. intrinsic flexibility, low cost process, compatibility with plastic substrate, biocompatibility and possibility to be printed. IMM is developing devices and circuits, based on solution processed semiconductor and dielectric organic materials, manufactured on flexible plastic substrates (PEN), with maximum process temperature of 100°C, by using printing techniques (inkjet printing, gravure). The developed high performance organic devices are analysed, also by using 2D numerical simulations, with particular attention to the effect of the device structure on electrical characteristics and to their reliability under bias stress and environmental conditions. Compact device models allow us to design organic circuit that are applied as frontend electronics for sensors pressure and gas sensors. The structural properties of organic semiconductors thin films are investigated by means of X-ray scattering techniques (X-ray diffraction in specular and grazing incidence geometries, wide angle X-ray scattering and X-ray reflectivity) and correlated with the electrical response of Organic Field Effect Transistors (OFET).



- *(Left) Organic transistors on flexible substrates.*
- *(Right) Schematic of the face-on molecular packing P(NDI2OD-T2) polymer inferred from X-ray measurement.*



- *Al/AlN-based devices, with highly c-axis-oriented hexagonal AlN layer, deposited by sputtering at low temperature.*

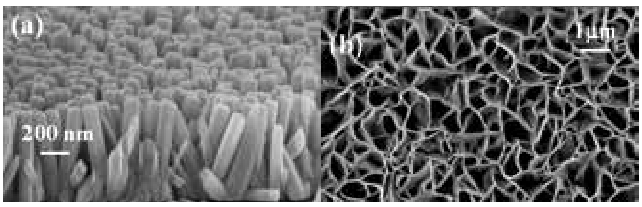
Low temperature inorganic films for flexible sensors

Al/AlN-based devices

AlN-based (inorganic) flexible pressure sensors represent a very attractive alternative to polymers-based piezoelectric devices, since, in spite of their relatively lower piezoelectric coefficients, they offer a number of advantages. In order to improve the piezoelectric properties of AlN layers, IMM is developing Al/AlN-based devices by using sputtering deposition at low temperatures (<160°C), with the intent of finding out a reliable strategy to implement piezocapacitors on flexible substrates. High piezoelectric performances are achieved which are competitive also on flexible substrates with respect to the actual literature results.

Low-cost ZnO nanostructures for flexible and disposable sensors

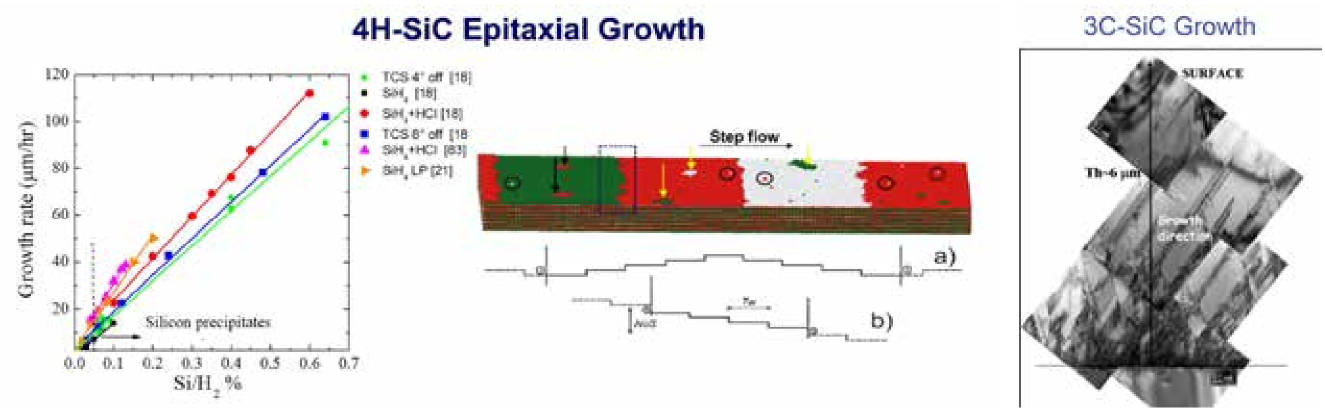
IMM has developed ZnO nanorods and nanowalls growth from aqueous solution on glass, metal or plastic substrates. Thanks to their large and reactive exposed area, these nanostructures can be successfully applied to many sensing purposes. Engineering of surface defects in ZnO nanostructures leads to efficient and fast UV detection, gas and biomolecules sensing. A flexible and disposable pH sensor has been recently demonstrated with the ZnO nanowalls connected to a thin-film-transistor in extended gate configuration.



- *ZnO nanorods (a) and nanowalls (b) deposited from aqueous solution on glass, metal or plastic substrates.*

Materials and processes for RF and Power devices

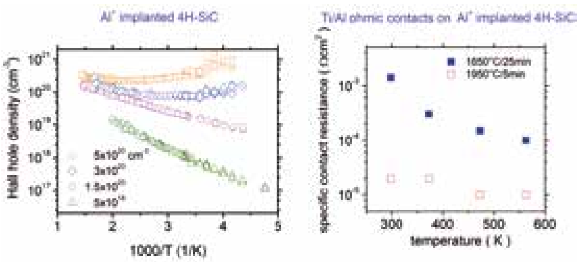
Today, the world average ratio of electricity to total energy consumption is about 20% and this ratio is expected to increase in the future. This steadily increasing need of electric power is a global concern, that must be faced through an improvement of the energy efficiency (reduction of power consumption) in power electronics devices and modules. *Power electronics* involves *conversion of electric power* using power semiconductor devices and circuits.
Si is the most commonly used semiconductor for power devices, but its maturity makes difficult to achieve further breakthroughs in the performances. In this context, the introduction of a new generation of high efficiency power devices based on wide band gap (WBG) semiconductors will enable to overcome wide band gap semiconductor devices. Fundamental issues and technological aspects related to SiC and GaN power devices (Schottky diodes, JBS, MOSFETs, HEMTs, MISHFETs, MOSHEMTs,..) are addressed, such us:
- epitaxial growth and physical characterization;
- metal/semiconductor interfaces (Ohmic and Schottky contacts);
- dielectrics/semiconductors interfaces
- ion implantation and activation, doping, oxidation
- post-oxidation of gate oxides and mobility in WBG devices;
- correlations between materials, processing and devices behavior.



- *Left: 4H-SiC growth rate for different processes; Center: Simulation of the growth process of 4H-SiC; Right: 3C-SiC layers grown on Si substrates.*

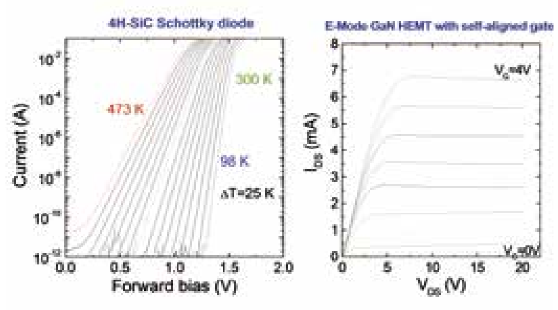
the physical limits of Si. Silicon carbide (SiC) is an old but emerging semiconductor, which is promising for advanced power devices because it has superior physical properties. SiC devices are also promising for high-temperature and radiation-resistant operation. Gallium Nitride (GaN) is also attractive as a material for high power and high frequency devices, owing to the similar band-gap and critical electric field strength, combined with the peculiar presence of the two dimensional electron gas with a high mobility. At present, growth and device-fabrication technologies for SiC are more mature, and SiC power devices exhibit better performance and reliability. IMM has a recognized experience in the development of advanced processing and characterization for

In the last ten years, IMM has been one of the main actors of the large evolution of the epitaxial processes of SiC. Important achievements on SiC homo-epitaxy have been the introduction of chloride precursors, the epitaxial growth on large area substrate with low defect density, the improvement of the surface morphology, the understanding of the CVD reactions and epitaxial mechanisms by advanced simulations. All these concepts are now widely used in SiC epitaxy and can be useful for epilayers of a new class of devices with high breakdown voltage (10 kV or more). The main problem of SiC technology is the high cost of the substrate and of the epitaxy with respect to Si. This cost can be reduced of more than an order of magnitude with the heteroepitaxial growth of 3C-SiC

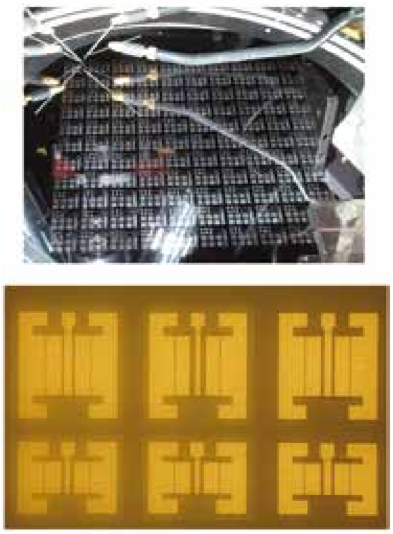


- *Temperature dependence of the electrical properties of Al-implanted 4H-SiC layers and Ti/Al Ohmic contacts*

on Si. This process is extremely difficult because of the large lattice and thermal expansion coefficient mismatch of the two materials.
Then the main effort of at IMM has been to develop new process and new substrate structures to solve these problems and obtain a good material with a low defects density and a low stress. The developed technology has been patented and is presently under consideration in several projects for new applications in the field of MEMS and photovoltaic devices.
The research activities on processing development for SiC and GaN are carried out on test patterns and devices fabricated in the IMM clean room facilities, characterized employing a large variety of techniques available in the Institute. Conventional characterizations are often combined with nano-scale electrical measurements carried out by scanning probe microscopy (SPM), to assess fundamental properties such as homogeneity of Schottky barrier, uniformity of dopant profiles, activation in nitrated interfaces, local breakdown events in gate oxides, etc. For SiC devices, Schottky and Ohmic contacts to p- and ntype implanted areas are important research topics. In ptype 4H-SiC(Al) material, very high active doping concentrations has been reached with a very weak temperature dependence of the hole concentration. The possibility of obtaining p-type SiC materials of very low conductivity permits to obtain Ohmic contacts of quite low specific contact resistance.
In the last years, important contributions to the understanding of the channel mobility in SiC MOSFETs has been also produced at IMM. Nano-scale resolution electrical characterization of SiO_2/SiC MOS structures subjected to different post-oxidation-annealing processes (N_2O, NO, $POCl_3$,…) allowed to quantify the role of the "counter doping effect" of N and P species introduced in the channel during these thermal treatments.
In the case of GaN, the development of advanced processing for enhancement-mode GaNHEMTs is being explored by several approaches (gate recession, fluorine incorporation, p-type gate, …). A gold-free technology (with Ti-, Ta-, W-based metallizations) has been developed on GaN and the transport mechanisms through these contacts have been investigated, considering the possible correlation with the material quality. The integration of novel high-k gate dielectrics and passivating layers (Al_2O_3, HfO_2, CeO_2, NiO,..) grown by Atomic Layer Deposition (ALD) is investigated to reduce the leakage current and the device power consumption, without significant shift of the threshold voltage.



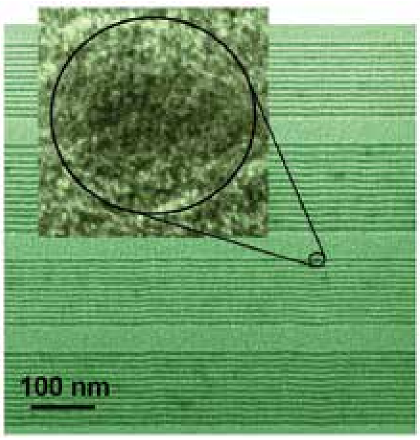
- *I-V characteristics of 4H-SiC Schottky diodes and AlGaN/GaN HEMTs*



- *AlGaN/GaN HEMT devices on Si substrate fabricated at IMM*

Energy conversion devices

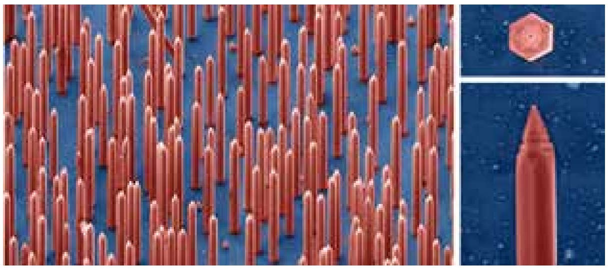
New Materials for Photovoltaics
Graphene (G) transparent conductive electrodes, obtained by transferring on the substrate our C-CVD grown G, have been successfully applied in photovoltaic devices. In third generation thin film solar cells the stability of G front contacts up to 1100 C has been demonstrated in preliminary p-i-n cells by comparison with ITO based devices. Using high quality G layers to prepare the photoanode of Dye Sensitized Solar Cells (DSSCs), the highest efficiency ever reported in the literature for this kind of device having G front contact have been obtained.



- *SiC / Si superlattice.*

Silicon nanodots in dielectric matrix find their interest in tunable absorbers for third generation solar cells. The idea is to achieve control the material band-gap through the control of the nanodot diameter, and set it to the optimum value for a top absorber of a multijunction, all-silicon solar cell. The figure illustrates the silicon nanodots as observed in transmission electron microscopy. The activity received support by FP7-NASCEnT.

Nanowires
Silicon NanoWires (NWs) provide a potential solution to increase the efficiency of solar cells, because thanks to their geometry and optical properties they can be used as light-trapping layers or as buildingblocks of core-shell radial junctions. One of the easiest methods to form NWs is the metal-catalyzed growth by ICP-CVD. Moreover, to fabricate the solar cells, a controlled method to form the p-n junction is needed. An innovative solution is based on the use of molecular doping technique. Junction

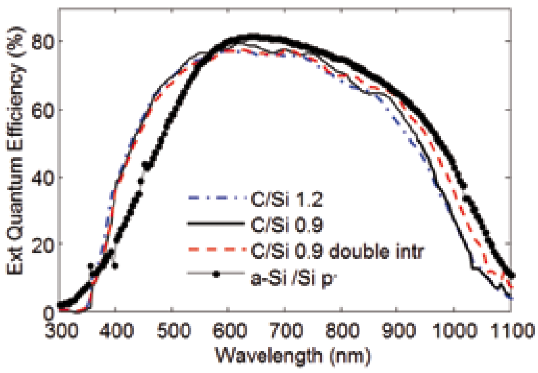


- Semiconductor nanowires.

depths in the tens of nm range for both p- and n-type doping with peak concentrations of 1×10^{19} cm^{-3} are obtained .

III-V and II-VI semiconductors nanowires
The 1D structure allows a more efficient light harvesting due both to the increased optical absorption related to the nanowire band structure and to the light trapping among the wires. Additionally the transport and collection of photogenerated carriers inside the core results greatly increased. Activity funded by Project Phashyn - Reti di Laboratori – Regione Puglia: III generation photovoltaic based on nanowires.

New Materials for Dye-Sensitized Solar Cells
TiO_2-coated AZO conductive films as TCO substrates are widely useful for all organic-based photovoltaic cells including not only dye-sensitized solar cells (DSSC) but also organic thin film cells and hybrid

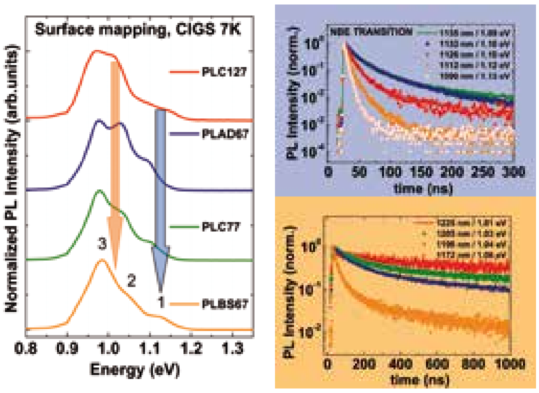


- *External Quantum Efficiency of SiC / Si heterojunction PV cell.*

solid-state solar cells. We focus on the fabrication of TiO_2/AZO multilayer structures for dye and perovksites solar cells at scaled thermal budget with some structural constraints: high transparency, high conductivity, high injection and collection efficiencies of the photogenerated carriers.

Ultra-thin Transparent Electrodes

The inclusion of a thin silver film within TCO layers is highly beneficial, allowing to strongly reduce the TCO thickness from the typically 1 µm used in thin film solar cells to about 50 nm, and, at the same time, to maintain a low electrical resistivity and high transmittance in the visible spectral range. Thermal stability of the TCO/Ag/TCO structures was

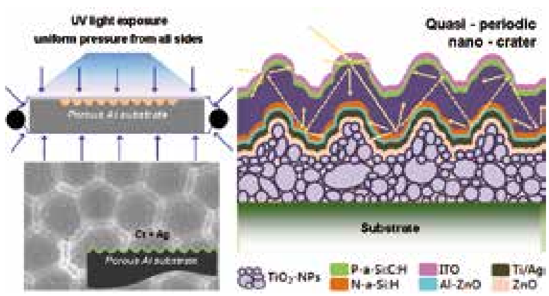


- *Photoluminescence spectra and transient in chalcogenide PV absorbers.*

investigated demonstrating an excellent behavior of the TCO film as a barrier to Ag diffusion. We also demonstrated that the energy density threshold for the scribing of the transparent contacts can be significantly reduced.

C-SiC/Si heterojunction cells

The 3C-SiC polytype is characterized by a bandgap of 2.3 eV and would be therefore suitable as transparent conductive 'window' layer of a silicon heterojunction (SHJ) solar cell. We have manufactured SHJ solar cells using polycrystalline 3C-SiC as window layer and Aluminum doped zincum oxide (AZO) as top electrode (TCO). When compared to SHJ solar cells manufactured by n-type amorphous silicon on p-type Si substrate, using the same TCO, the 3C-SiC/Si cells exhibit higher quantum efficiency in the range 400-550 nm, reasonably due to the lower reflection observed in this wavelength range.

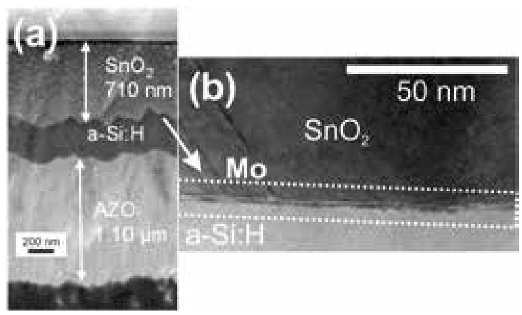


- *Bottom center: novel plasmonic resonator for thin film PV cells.*

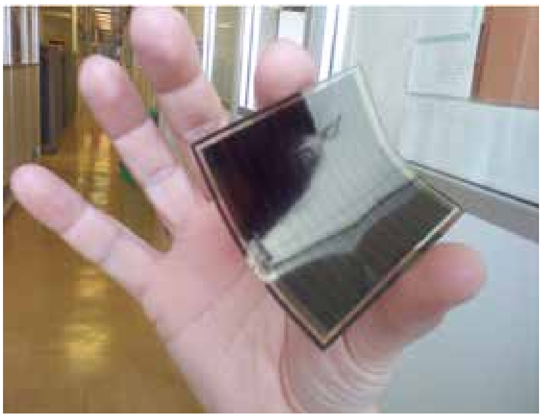
Advanced optical and electro-optical characterization

The core activity is focused both on the investigation of the main photo-excited carriers relaxation mechanisms through the energy levels and the determination of their time constants, and on the study of electron/hole transport in new nanostructured materials and devices. Activity funded by ERDF through the projects: SOLAR, Nanofluids for solar thermodynamic energy conversion; MAAT, III generation photovoltaic based on organic solar cells; INNOVASOL, III generation photovoltaic based on CdTe nanowires.

Plasmonics concepts have been applied to advanced light management concepts, in order to achieve efficient and cheap a-Si:H / uc-Si thin film solar cells (THINC project). The devices are fabricated on nanostructured back-reflectors obtained by nano-imprinted replica molding. The cells show a 28% Jsc enhancement with respect to the same cell deposited

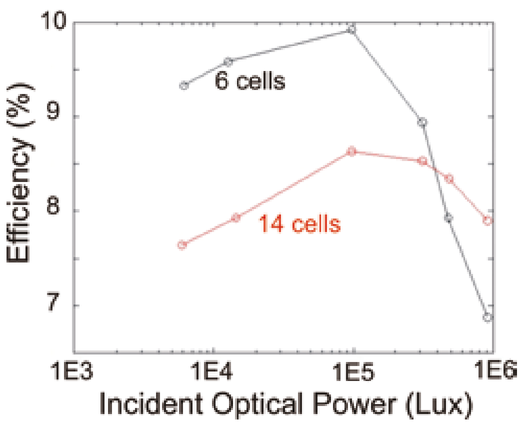


- *Ultra-thin Mo film for surface plasmon polariton modes for light trapping in thin a-Si:H cells.*



- *Amorphous-Si PV mini-module on flexible substrate (polyimide) realized in collaboration with STMicroelectronics.*

on a flat substrate. The novel cell structure is designed to couple plasmonic up-converters and plasmonic light trapping geometries. We have also studied metal nanoparticles (MNPs) integrated in plasmonic back reflector (PBR) structures aimed for light trapping in thin film solar cells. We show that the photocurrent enhancement achieved in the a-Si:H light trapping window (600 – 800 nm) stays in linear relation with the PBRs diffuse reflection. Moreover, in amorphous Si cells grown on SnO2:F (FTO) covered glass we have shown that ultra-thin Mo films in between the FTO and the ptype a-Si:H layer can be used to achieve light trapping in the a-Si:H solar cells through plasmonic surface modes. The ultra-thin Mo film produces surface plasmon polariton modes equivalent to guided modes in a waveguide.



- *Power Conversion Efficiency of the modules on the top figure as a function of illumination level.*

New Devices

PV devices

We have studied approaches to improve performances in hydrogenated amorphous silicon (a-Si:H) solar cells by using molybdenum as contact to the p-type a-Si:H layer. Mo is a refractory metal, and we have shown that compared to standard SnO2:F (FTO) contacts the a-Si:H cells have improved photocarrier lifetime and reduced contact resistance. These results have been used to fabricate (with STMicroelectronics) a-Si:H PV modules on polyimide flexible substrates. We are now focusing our efforts to the introduction of heterojunctions in silicon based solar cells, in collaboration with STMicroelectronics and 3SUN. These research activities are funded by two national MIUR-PON programs "Nuove Tecnologie Fotovoltaiche per Sistemi Intelligenti Integrati in Edifici" and "Tecnologie per l'ENERGia e l'Efficienza energETICa (ENERGETIC)", and by an European ENIAC JTU project, ERG.

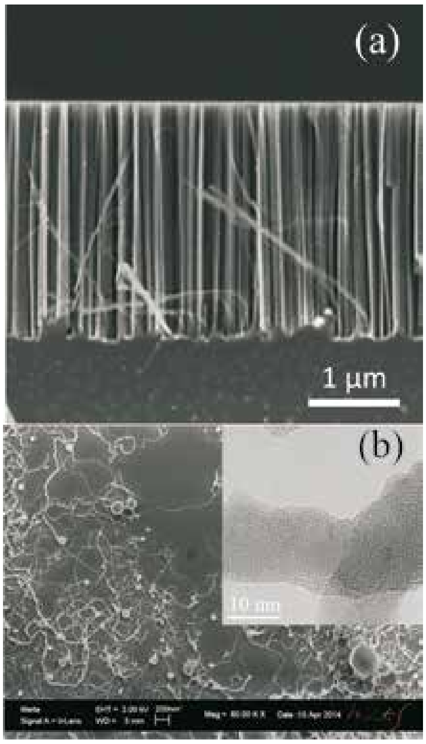
- *SEM micrographs of rectenna devices.*

Nano-Rectennas

The activity is focussed on the design and the fabrication of an innovative device to directly convert solar energy into electrical power based on optical rectified nano-antennas (nanorectenna).
The critical point is represented by the rectifier with the required electrical characteristics (non-linearity, asymmetry, good responsivity with no external bias applied, low impedance). Activity funded by POR Project "Rectenna".

Photonic materials and devices

Silicon photonics
The continuous miniaturization of Si electronic devices and the progressive trend towards nanometric dimensions set new scientific challenges. The shrinkage of devices dimensions and the consequent increase of their density on chip determine an unwanted raise of interconnection



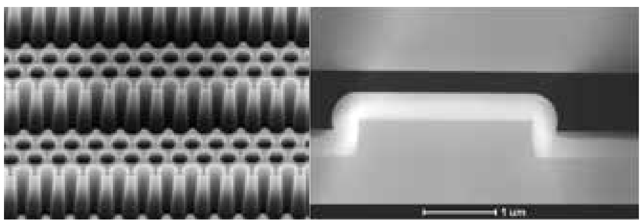
- *(a) SEM image of Si NWs produced by metal assisted wet etching;*
- *(b) SEM image of Si NWs and nanospheres produced by an induction plasma torch process. The inset is a high resolution.*

lengths with a consequent delay in the signal propagation and a huge amount of power density dissipated by joule effect that strongly limit further integration capabilities.
Similar considerations limit the development of efficient telecommunication systems and data centers where the new and unique opportunities given by silicon of integrating at low cost absorption free optical components and microelectronic circuits are incredibly pushing tindustrial research. Silicon photonics is offering a low cost solution to these problems and the Institute is strongly involved in this field, focusing the research on three main goals:

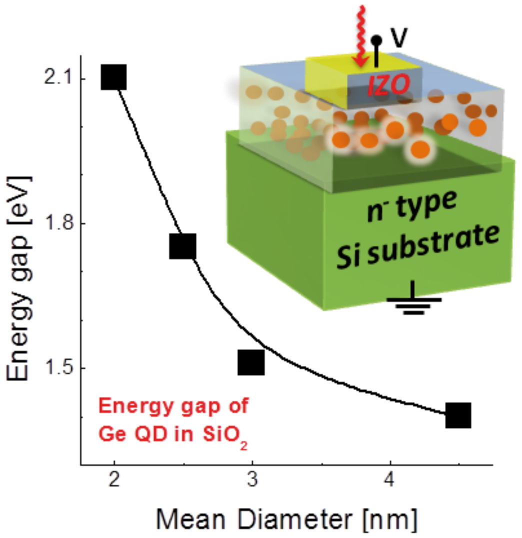
- to overcome the silicon intrinsic inability to emit light
- to develop new light manipulation techniques on chip at a sub-micron level
- to develop new families of photodetectors

1) A first approach is based on **light emission** in low dimensional Si structures, such as nanowires (NWs). They are produced by new processes allowing dense arrays with a tight control of NWs size. Another approach to light generation exploits the very high silicon optical non-linearities, and their huge increase in low dimensional structures, such as Si nanocrystals (Si-nc) embedded in a silica matrix (Si-rich-SiO2), where four-order-of-magnitude increase of the stimulated Raman gain, with respect to bulk crystalline Si, has been demonstrated, paving the way to the realization of extremely efficient silicon Raman lasers with technologies compatible to standard microelectronic. A third approach to light emission exploits new techniques to dope Si substrates with rare-earth (RE), such as Eu and Er, up to 10^{22} active impurities per cm^{-3} and beyond. The processes developed allow to optimize materials both for light amplification at 1.54 Pm and for light management, useful also for photovoltaic applications as downconverters in the infrared region and up-converters in the visible one.

2) The Institute has been historically involved in the realization of Si photonic integrated devices aimed at **light manipulation on chip,** demonstrating about 20 years ago the first realization of a VLSI-based optical micro-modulator operating at the optical communication wavelengths. The activity in this field is continuing looking at the development of new



- *(Left side) SEM images of a Si negative photonic crystal exhibiting "invisibility" at near infrared wavelenghts. (Right side) STEM image of a strained-Si rib structure.*

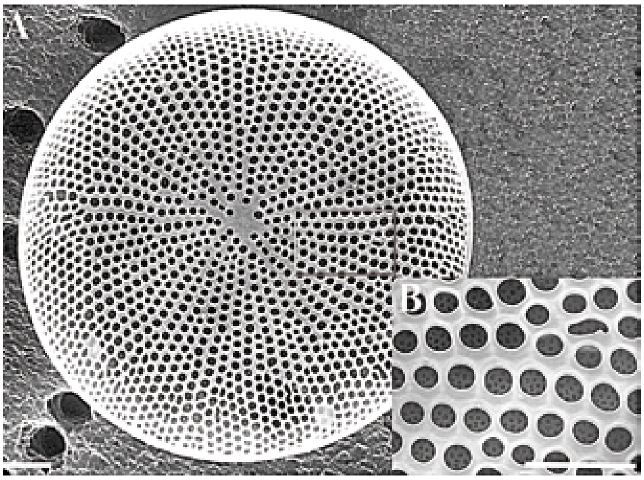


- *Measured energy gap as a function of the Ge QD mean diameter.*

technologies for light control at sub-micron scale, therefore representing the frontier of integrated photonics.
In our laboratories, photonic crystals, metamaterials and dielectric plasmonics are designed, fabricated and characterized with the aim of fabricating nanophotonic devices based on new concepts. Recent activities are dealing with the use of strained silicon for enhancing advanced optical capabilities, such as switching, in devices and subsystems for telecom and datacom applications.

3) Another crucial issue in Si photonics is **light detection.** By taking advantage of quantum confinement effects and of the high absorption coefficient in the solar energy range, Ge nanostructures can be successfully applied for light harvesting. We have demonstrated that the absorption efficiency significantly increases in very small quantum dots and that the optical bandgap of Ge NS can be varied from 0.8 up to 2.5 eV. By combining the modulation of light absorption and charge trapping effects in Ge quantum dots, a very high efficient light detector has been demonstrated operating in the visible range with responsivity as high as 10 A/W and internal quantum efficiency up to 1500 %. A second activity is dedicated to the development of devices with sensitivity down to single photon and timing resolution of few tens of picoseconds. Development of a dedicated CMOScompatible technology brought to fabrication of planar silicon SPAD devices and arrays with high performances in terms of large active area, high timing resolution, high detection efficiency and low intrinsic noise. These photodetectors exhibit single-photon sensitivity in the visible and near-infrared (400- 850nm) and find application in many fields such as Fluorescence Lifetime IMaging (FLIM), micro-array-based biological analysis, confocal microscopy, adaptive optics and quantum cryptography, to name a few. A third activity is related to the fabrication of near-infrared Si photodetectors based on the internal photoemission effect (IPE) in metal-semiconductor structures. Recent results in this field have brought to the first demonstration of a graphene-Si Schottky photodetector able to operate at 1550 nm, taking advantage of both IPE and the twodimensionality of the graphene active layer. The integration in high quality optical resonant structures is in progress.

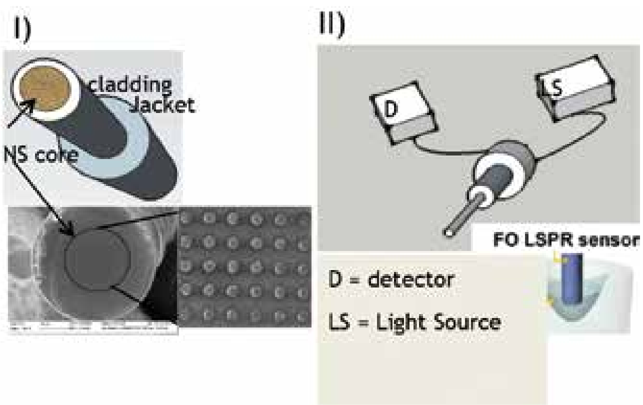
Biomimetics and metamaterial-based devices for hybrid integration
Nanophotonic structures developed with top-down processes in research labs recall the natural photonic structures of diatoms, ubiquitous, monocellular algae being responsible of about 20-25% of the global



- *SEM image of the frustules of a diatom (Coscinodiscuus Valesii).*

oxygen produced by means of photosynthesis, but living in environments where sunlight is not easily accessible. Their photonic nanostructure has been selected by evolution in order to exploit at maximum light collection. We are making biomimetic studies to understand the behaviour of this living organism as "living photonic crystals" able to concentrate sun light with incredible efficiency. The aim of this activity is both to understand the biological meaning of the optical properties of diatoms and to exploit these properties
in the design and fabrication of new bio-inspired devices, such as super-lenses and solar concentrators.
A second activity related to the study of photonic metemeterials is devoted to the realization of a new family of liquid-crystal plasmonic components characterized by unexpected performance in terms of tuning of the modal effective indices, effective areas and losses. The original concepts developed open new perspectives in the design of functional components for low power on-chip and intra-package interconnects, such as variable optical attenuators, phase shifters, directional couplers, and switches.

Fiber optic based devices
An emerging key enabling technology named "lab-on-fiber", based on the integration of sensors and devices onto the optical fiber tip promises advantages in simple, label-free, realtime detection



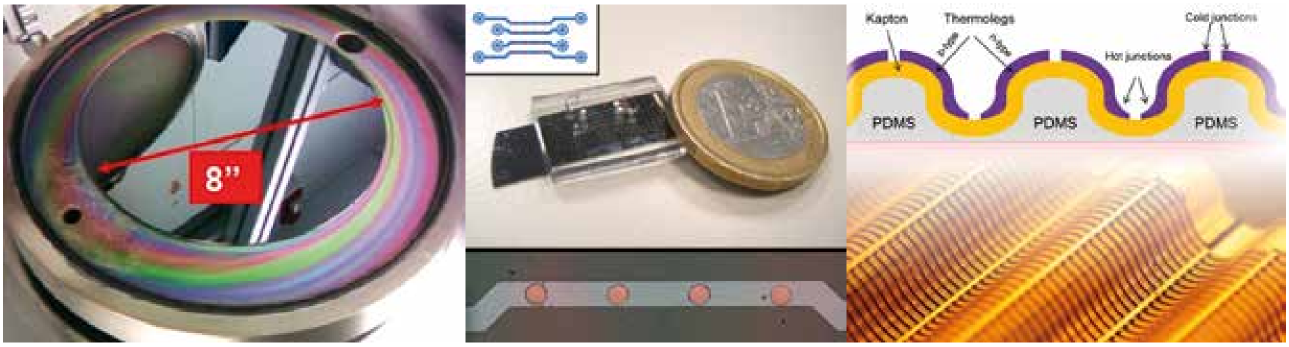
- *I) Schematic of a FO LSPR sensor with SEM images of the FO tip.*
- *II) Schematic of the optical measurements set-up.*

of analytes in extremely low sample volumes and in vivo. In this field, the Institute has demonstrated the direct realization onto a standard fiber tip of a new family of plasmonic devices exploiting Localized Surface Plasmon Resonance effect for bio-chemical sensing applications. First results in biomedicine, and in particular in the early detection of Papillifero Carcinoma of the thyroid gland have been obtained.
A more standard activity in the optical fiber field sees the Institute strongly involved in the fabrication of sensing systems for aerospace and environmental applications (more details are reported in the section devoted to sensing and microsystems). In this framework, it is worth mentioning the activity aimed at optimizing raman amplification, both for application to metrology and telecommunication within an EU-funded project for the deployment of a European-scale optical fibre network specifically dedicated to the long-distance transfer of ultra-stable optical frequencies among national metrological institutes.

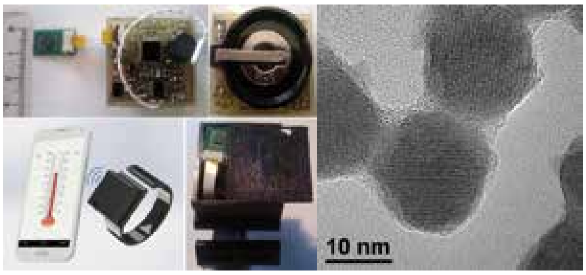
Sensors and multifunctional micro/ nanosystems

The development of future multifunctional sensing devices requires multidisciplinary integration of different technologies, including embedded electronics, microsystem technology, nanomaterials, analytical chemistry, signal processing and communication for autonomous sensor networks. The IMM activities on sensors and multifunctional sensing systems, carefully balanced between basic research and application-driven developments targeting technological transfer, are focussed on combining micro- and nano-fabrication of MEMS/NEMS components with broad expertise and capabilities in nanostructured materials in a frame of Smart Systems Integration (SSI). State-of-the-art development activities in these fields are promoted by close collaborations with national and international universities and research centres in the framework of international projects.

Research on development of **(Nano-) materials for sensing technology** includes low-dimensional carbon-based nanostructures (mainly carbon nanotubes (CNT) and graphene) used as sensing layers for CNT-FETs and chemiresistors for chemical and bio-sensing applications. For gas sensing applications, nanostructured metal oxides for highly sensitive gas microsensors are synthesized and deposited using various techniques, including reactive sputtering, rhetoaxial growth and thermal oxidation (RGTO) techniques, also targeting wafer-level deposition techniques on silicon micromachined ultra-low-power hotplates for batch fabrication and technological transfer. A different approach is based on the synthesis of colloidal metal oxides (SnO_2, TiO_2, ZnO, V_2O_5, In_2O_3, MoO_3, WO_3, etc.) as gas nanoparticles sensing layers by wet chemical procedures For these materials, to be deposited as MOX sensing layers by sol-gel processes, precursor molecular structure can be designed in order to provide well defined reactivity features. Great attention is devoted to the development of low cost and low temperature
processes for the manipulation and deposition of carbon nanostructures as sensitive layers of innovative devices. Electrophoretic and dielectrophoretic techniques are studied both theoretically and experimentally, being the control of dielectrophoresis forces the working principle of devices aimed at the cells' manipulation and sorting for medical applications (e.g. cancer diagnosis and/ or prognostic), designed and fabricated in our laboratories. Complex multiferroic materials like $ErFe_2O_4$ are grown using cost-effective wafer-level atomic layer deposition processes, with potential applications in diverse fields of modern technology, including gas sensing applications. The precise control of the structural properties within the polymorphic ternary phases allows to target some specific functionalities aiming at reaching a realistic technology transfer of multiferroics thin films. Hybrid functional interfaces for biosensors and biomedical applications are developed, and bioconjugation is achieved through wet and dry chemistry surface passivation procedures of most



- *Left: CVD/ALD conformal deposition of multiferroic material on large area; Center: Microarray device with hybrid functional interface; Right: Wearable thermoelectric energy harvester.*



- (Left) Near Field Communication-based wearable thermometer. First prototype in Polylactic Acid customized package and related use case on mobile app.
- (Right) SnO_2 nanoparticles for gas sensing.

common materials used in biomedics: glass, gold, silicon and silicon related materials, such as oxide, nitride and porous silicon.
Further developments in the field of innovative materials include fluorophores, such as the Ruthenuim trisbipiridine, for near infrared spectroscopy (NIRS) using silicon Photomultipliers and biocompatible insulating layers with high dielectric constant for capacitive biosensors by combining atomic layer deposition processes.

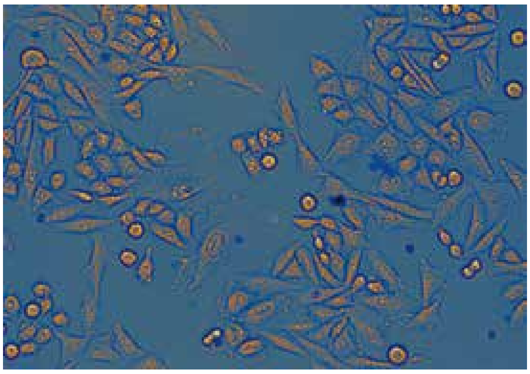
Several research groups are active in the field of **(MEMS-) components for multifunctional sensing systems.** Prototypes include microfluidic devices for Lab-on-chip (LoC) and Total-Micro-Analysis Systems (uTAS), including microvalves, micro and nanochannels and silicon micromachined analytical components like gas-chromatographic columns and thermally controlled multi-channel reaction chambers for biosensing applications. Portable or wearable sensing applications and ubiquitous sensing networks are addressed by MEMS ultra-lowpower hotplates, which can be coupled to micro powerharvesting devices for thermoelectric energy conversion. The latter devices are also suitable for

- SPR system.

powering medical implants.
In the field of biosensing, Ion sensitive field effect transistors (ISFET) as electrical biosensors are developed for detection of DNA hybridization (biomedical applications), molecular recognition (antigen-antibody pairing) or enzyme activity (used for water pollution studies).
For biohybrid systems connecting natural and artificial neurons, biocompatible transducers are under development, able to exchange electric signals with individual neurons in a reliable and non-destructive fashion. The possibility to measure very low magnetic fields opens the road to several applications, from magnetoencephalography (MEG), to low field magnetic resonance imaging (LMRI), Magnetocardiography (MCG) and recently to the magnetic marker monitoring method for tumour detection. For these applications, SQUIDs (Superconducting QUantum Interference Devices)

- Ultra-low-power MOX gas sensor array: size compared to a 1 eurocent coin (left), and sensor array flip-chipped on a flexible PCB (right)

based on Nb superconducting nano-Bridges are under development. The high sensitivity enables detection of few fT, and the sensitivity in term of magnetic moments can be of few Bohr magnetons, making possible the detection of a single Magnetic NanoParticle (MNP). An integrated optical electromagnetic field sensor suitable for sensing in the Fresnel region over a wide frequency range (ELF to UHF band) is also being realized. This device is based on an integrated interferometer driven by optical fibre transmission lines and suitable to monitor electromagnetic fields radiated by antennas also in near field region. The optical EMF sensor thereby results dramatically less invasive then a standard probe, and yield a new feedback signal of the radiated power. Finally, RF-MEMS, IR photodetectors and THz detectors are developed as



- *CHO-K1 cell culture on 10nm $AlHfO_2$ grown by ALD.*

micro-components for aerospace and radar airport security systems, while the research activities on silicon photomultipliers (SiPM) and Single Photon Avalanche Detectors (SPAD) target in particular the study of DNA hybridization in biomedical devices, photodetectors in near infrared spectroscopy, quantum cryptography and astronomical applications.

Most of the materials and devices previously described are finally exploited for the development of **Integrated smart multifunctional (micro- and nano-)systems.** Typical examples are application-specific miniaturized analytical gas sensing systems for in-field use, vincluding silicon micromachined fast gaschromatographic (GC) separation devices and selective pre-concentrators targeting sub-ppb detection limits. Applications include safety and security, environmental monitoring, food quality and safety and industrial monitoring. Still in the field of gas sensing, Electronic Noses and Sensor Arrays for monitoring VOCs and chemical species were demonstrated. These portable systems include an

- *Miniaturized GC for environmental BTEX analysis (left) and MEMS GC components (pre-concentrator, GC column, TCD).*

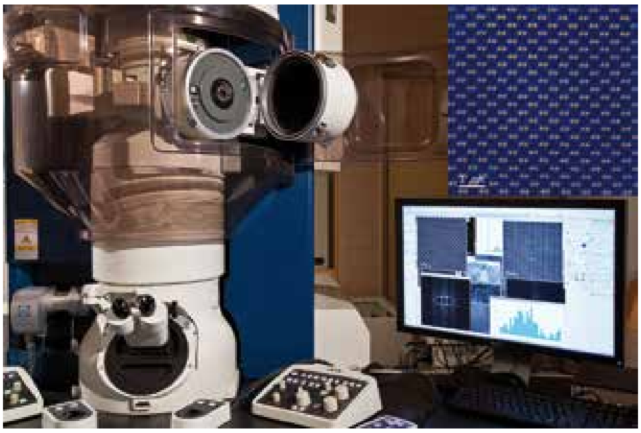
array of silicon micromachined gas sensors, sampling system, electronic and automated control, pattern recognition and signal processing units. The targeted application sectors are aroma monitoring in food safety and quality, breath analysis for lung diseases prevention and air quality.
Integration of both innovative and off-the-shelf devices enable multi-sensing solutions for Ambient Assisted Living (AAL), relying on smart signal and image processing. Several technologically advanced platforms were demonstrated as support of fragile/elderly people, aiming at improving the quality of life at home: capabilities include indoor people localization and tracking, remote acquisition of clinical signs (heart rate, breathe rate) and detection of falls through time-of-flight 3D cameras. Another class of integrated multifunctional sensors are the biosensing systems based on Plasmonic and Magneto-Plasmonic Surface Resonance, proposed for detection of biological molecules recognition, DNA sequences, etc. in food analysis, environmental

- *Electronic nose prototype (left) and zoom on the Sensor Array.*

and medical applications. Another class of integrated multifunctional sensors, making use of nanostructured magnetic/plasmonic materials, are the biosensing systems based on Plasmonic and Magneto-Plasmonic Surface Resonance, proposed for detection of biological molecules recognition, DNA sequences, etc. in food analysis, environmental and medical applications. Another class of integrated multifunctional sensors, making use of nanostructured magnetic/plasmonic materials, are the biosensing systems based on Plasmonic and Magneto-Plasmonic Surface Resonance, proposed for detection of biological molecules recognition, DNA sequences, etc. in food analysis, environmental and medical applications.

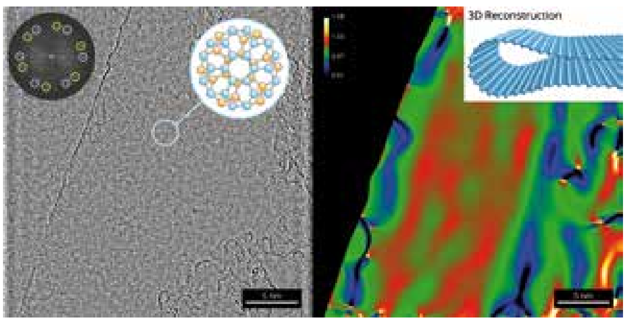
Micro and Nanoscale characterization and imaging

The research activities in this field are aimed to the application and the development of structural and analytical characterization techniques and innovative experimental methodologies to meet the current requirements of the sub-nm scale processes understanding and control in the nanoscience field.

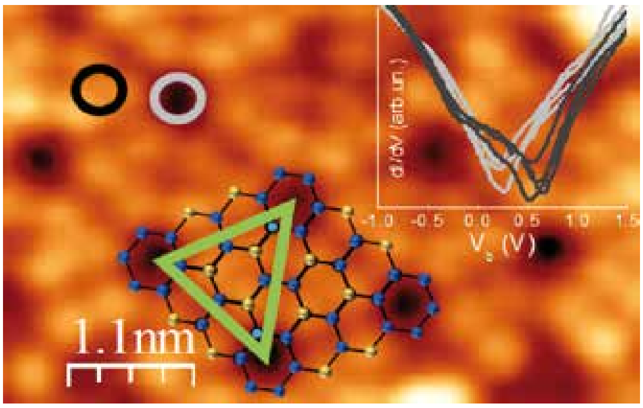


- *JEOL ARM200F at the Beyond Nano Microscopy Lab. On the right, structural image of a Si substrate.*

Electron Microscopy Techniques: Electron Microscopy (EM), that makes IMM, particularly the Sections of Catania, Lecce and Bologna, a reference at the National level, is currently applied, with several different techniques, to the study of a wide class of materials and devices for nanoelectronics and nanosciences. Examples are Convergent Beam Electron Diffraction (CBED) for strain analysis, High Resolution EM (HREM), Electron holography and Electron Tomography for studying nanostructured and 2D materials, Scanning Transmission EM (STEM), at low and at high energy, in combination with quantitative X-Ray microanalysis (EDX), and Energy Loss Electron Spectroscopy (EELS) for studying high-k oxides, ultrashallow implants in Si and SiC, and graphene membranes. Moreover, in-situ EM techniques are employed to characterize active individual nanostructures in real devices. Finally, innovative detection systems and techniques for SEM, are developed in collaboration with leading National and International companies. In this scenario, the Beyond Nano Microscopy Lab in Catania plays a leading role. Established in the framework of the Beyond Nano Project (funded by ERDF), a research infrastructure integrated with the best skills of southern Italy CNR's structures in the field of advanced materials and nanotechnology, the Electron Microscopy Lab is one of the largest facilities for Electron Microscopy in Italy. Build around a last-generation aberration-corrected JEOL ARM200F EM, equipped with state-of-the-art EDX and EELS spectrometers and capable to provide sub-angstrom resolution even at very low energy, it is aiming to be able to obtain simultaneously chemical and structural information down to the atomic scale, on graphene, polymers, bio- and multi-functional materials in a wide range of strategic areas, such as energetic efficiency, photovoltaic, safety, health and nanoelectronics.

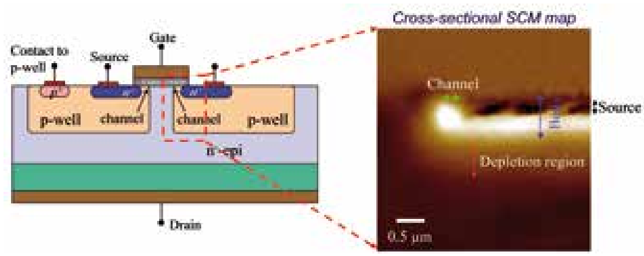


- *High Resolution image of a graphene layer folded over itself (left), Geometric Phase Analysis map and corresponding 3D reconstruction (right).*



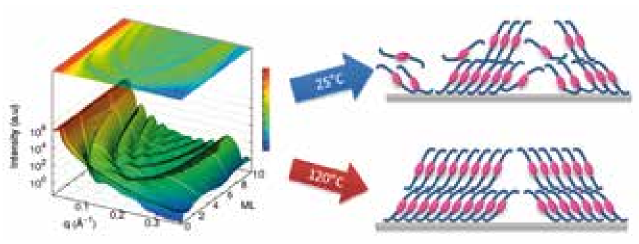
- *STM image of silicene with atomic arrangement; inset: STS spectra at two different locations as indicated by black and grey circles.*

Scanning Probe Techniques: The institute, in particular in the Sections of Agrate Brianza, Catania and Rome, a solid expertise in the field of Scanning Probe Microscopy (SPM). Scanning Capacitance Microscopy (SCM) and Scanning Spreading Resistance Microscopy (SSRM) techniques are



- *Schematics of a SiC power MOSFET and 2D carrier distribution in the channel region measured.*

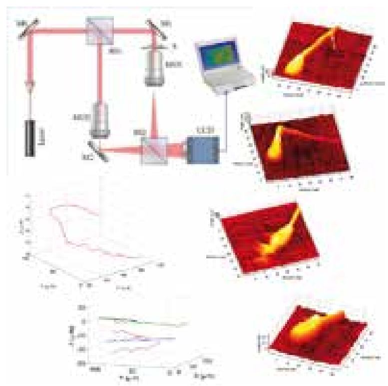
employed for 2D carrier and resistivity profiling in semiconductors, such as ultrashallow junctions in Si, SiGe heterostructures, and SiC, GaN and AlGaN/GaN compunds, for studying electrical activation of implanted dopants and 2D maps of carriers with nm resolution. Scanning Tunneling Microscopy (STM) in UHV and local elastic and inelastic Scanning Tunnel Spectroscopy (STS) down to 24 K are used for atomic resolution characterization of low dimensional systems. Magnetic Force Microscopy (MFM) and Piezoresponse Force microscopy (PFM) are employed for the recognition of magnetic, ferroelectric or piezoelectric nanodomains, while Kelvin Probe Force Microscopy (KPFM) is used for determination of electronic structure, chemical variations and distribution of the electrostatic potential at the surfaces. Conductive Atomic Force Microscopy (CAFM) is employed for exploring the local current



- *Evolution of molecular arrangement by in-situ XRD and XRR during molecular film growth.*

transport behavior in nanostructures and 2D materials, for testing the operation of nanodevices and investigating nanoscale inhomogeneities as source of macroscopic phenomena such as resistance switching of both memristors and resistive random access memories. Moreover, it is employed for the investigation of current transport phenomena at dielectric/semiconductor interfaces (tunneling, breakdown) and at metal/semiconductor contacts (probing lateral homogeneity of the Schottky barrier), and for the characterization organic/ polymeric systems, such us bulk-heterojunctions or dye sensitized solar cells. Finally, Scanning Microwave Microscope (SMM), an AFM modified to measure microwave signals in phase and amplitude, is employed for studying in a nondestructive way material properties such as dielectric constant and doping profile, or for imaging purposes of devices and biological tissues, allowing a subsurface characterization of buried structures also in topography free samples, with 5-10 nm spatial resolution.

Light Microscopy Techniques: In the field of Light Microscopy, IMM, and in particular the Section of Napoli, have made a strong effort in implementing new techniques for life science, suited for real time imaging with high 3D spatial resolution and chemical specificity of unlabeled living cells. Holographic Imaging (HI), a label-free, non-contact, non-invasive and high-resolution method, allows for the recording and the numerical reconstruction of the phase and



- *Three-Dimensional Imaging and tracking of bovine sperm cell.*

amplitude of the specimen's optical wavefront, therefore obtaining 3D quantitative sample imaging. Coherent Raman Microscopy (CRM), exploiting the non-linear interaction among pump and probe signals and the sample, shows much more intense signals respect to linear Raman microscopy in observing molecular and chemical structure of the sample, allowing the acquisition of images on a large area in a few seconds. In the future HI and CRM can be joined in order to get chemical selectivity, geometrical dimensions of investigated objects and faster imaging process. Moreover, new approaches have been developed for imaging systems based on the scanning of single elements (such as confocal or multiphoton microscopy) to overcome the limitation of the linear correlation of acquisition times and spatial resolution. Single pixel detectors have been used in place of the traditional multi-pixel detectors, together with global illumination with refreshing rates of the order of tens of KHz, therefore, exploiting the reciprocal nature of optical systems, and a global imaging system with increasing resolution capabilities as a function of the number and types of used optical probes is under development.

X-Rays and Ion beam techniques: X-Ray and ion-beam techniques complete the characterization capabilities of the Institute, within the Sections of Bologna and Agrate Brianza.
X-Ray scattering techniques, namely X-Ray Diffraction (XRD), Reflectivity (XRR), Grazing Incidence (GIXRD) and Small-Angle Scattering (GISAXS), with conventional X-Ray sources on a lab scale and synchrotron radiation (at the Elettra – Sincrotrone in Trieste and at the ESRF in Grenoble), are widely employed, from powders to nanostructured thin films characterization, with a particular focus on organic thin film transistors. Moreover, in-situ X-Ray scattering techniques are employed to study molecular self-assembly processes. Finally X-ray Computed Tomography (XCT) is developed and applied with synchrotron light to material science and cultural heritage. In particular, for the first time, it has been shown that X-ray phase-contrast tomography can allow to read the Herculaneum papyri rolls buried

- *The papyrus alphabet as revealed by the X-ray Phase Contrast experiment.*

by the eruption of Mount Vesuvius in 79 AD. These carbonized papyri are extremely fragile and are inevitably damaged or destroyed in the process of trying to open them to read their contents. The technique has allowed to decipher various letters hidden inside the precious papyri without unrolling them. This attempt, carried out in cooperation with ESRF and CNRS, opens up new opportunities to read many Herculaneum papyri, which are still rolled up, belonging to the only library passed on from Antiquity, thus enhancing our knowledge of ancient Greek literature and philosophy.
Moreover, IMM's scientists are part of the international "Mössbauer collaboration at ISOLDE-CERN" since 1998, focused in exploiting radioactive isotopes for emission Mössbauer spectroscopy (eMS) studies of materials for microelectronics and spintronics. Atomic-scale magnetism in magnetic semiconductors and oxides, in the regime of extreme dilution (3d-doping down to 10^{-5} at.%), not accessible with the laboratories and synchrotron methods, is under investigation. In 2014, two new experiments started, focused on the study of properties of Mn- doped (Al,Ga)N and Mn-based alloys, to correlate their atomic-scale properties with their macroscopic functionalities, and to contribute to their potential use in optoelectronics, spintronics, magnetic shape memories and magnetocalorics.

Theory, Numerical Simulation and Modelling

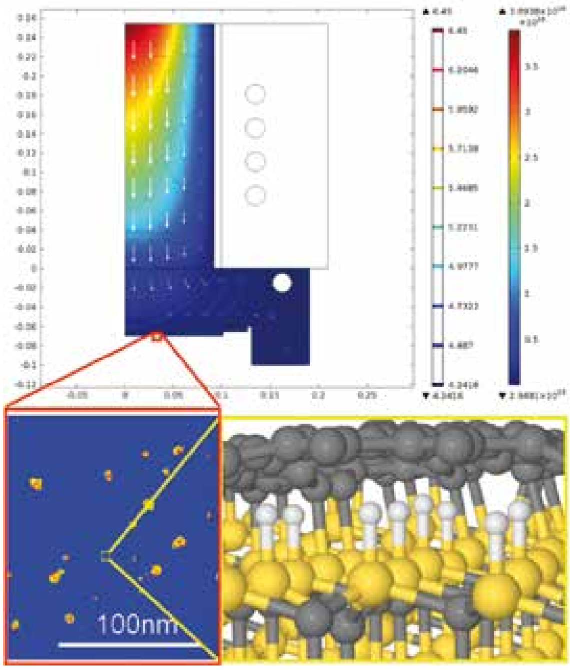
The theoretical-computational activity at IMM aims at bridging the gap between the atomic and quantum phenomena that rule interactions and processes at the nanoscale with the macroscopic dimensions of real materials, devices and applications. To this end several complimentary approaches are developed and employed, starting from quantum mechanics schemes for the description of materials and devices with an atomic resolution, all the way up to the realization of advanced algorithms for the simulation of real-world processes and devices within Continuum and Kinetic Monte Carlo (KMC) methodologies. The general objective is to create a common framework of skills to address the study of the structural and functional characteristics of materials at time and spatial resolutions that are comparable to those of actual processes and experiments. The research fields of interest are vast and include the structural prediction, electronic configuration, device simulation, quantum and classical transport, atomic diffusion and kinetics, process simulation, advanced numerical modelling and simulation of experimental techniques. The materials studied range from nanostructured and lowdimensional to thin films and wafers.

Theory of coherent and correlated quantum systems In coherent nanosystems

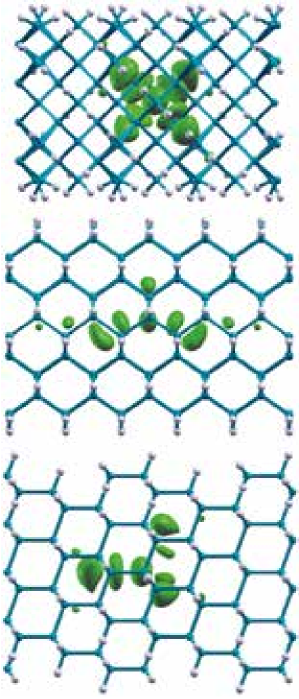
Quantum properties of matter are fully exploited for novel applications since nanosystems may behave like "artificial atoms", where the wave-like nature of the electrons, photons and phonons leads to the existence of quantum superpositions and entanglement. Quantum control of the phase-coherent dynamics of such systems means the ability of dealing with (prepare, mantain, manipulate, recover) extended quantum superpositions. IMM research focuses on the study of decoherence, the main obstacle for the functionality of quantum architectures, and on active and passive control methods which minimize its effects on hardware in the quantum computation framework. Several aspects of decoherence in quantum networks are also studied, from quantum control for entanglement recovery in distributed architectures to design of new materials in the quantum transport regime, where electrons in extended states are subjected to pure dephasing. The Density Matrix Renormalization Group approach is applied when electron (or particle) correlations are dominant, that allows for a calculation of both the static properties and of the real-time evolution of the system ruled by model-Hamiltonians (e.g. Holstein-Hubbard, Heisenberg). Such calculations are useful for the (i) description of superconductivity, quantum magnetism (ii) interpretation of these and new effects in the modern context of optical lattices, whose great benefit is to deal with controllable many-body systems in which the parameters, the initial states and the evolution protocol can nowadays be varied in an experimental range.

Density Functional Theory and ab-initio simulations

Density Functional Theory (DFT) is a widely used framework for quantitative calculations in realistic materials with moderate correlations. Developments of numerical methods are also performed from



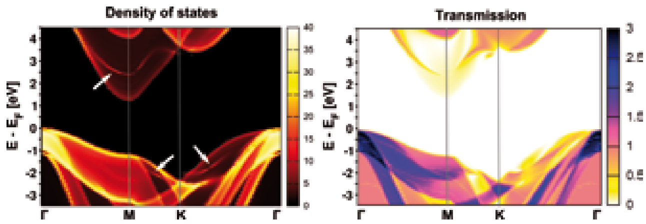
- *Multi-schemes simulation of the process of H intercalation for epi-graphene grown on SiC: continuum modelling of the equipment, KMC simulation of the growth process and DFT calculations of the structural.*



- *Delocalization of P donor wavefunction in H-passivated Si nanowires with different orientations.*

the adoption of the correct exchange-correlation functional and relative pseudopotential to the implementation of band-unfolding procedures and ab-initio based electron transport codes. The DFT activity at IMM is currently devoted to the simulation of nanostructures based on different materials: graphene, Si, SiC, transition metal oxides, perovskites etc. Several aspects are investigated and here we list the most significant ones:

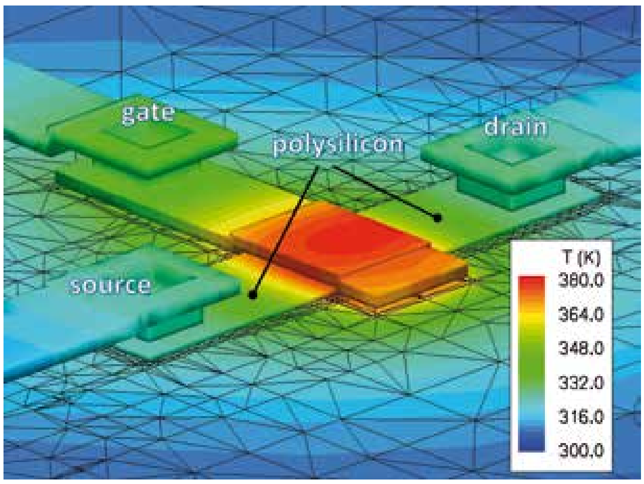
- Studies of the effect of impurities in H passivated Silicon and Germanium nanowires oriented along different crystallographic directions also in the presence of a uniaxial strain field;
- Computations of vvvv phase diagrams of Zirconia and Hafnia doped with transition metal impurities as a function of doping concentrations. Kerr effect in Mn doped GaAs ;
- Calculation of the structural and electronic properties in: epitaxial graphene grown on SiC substrates with different orientations, nitrogen- and boron-doped graphene . Comparisons with ARPES spectra;
- Estimation of internal potentials and charge (re)distribution in folded grapene sheets for a direct comparison with electron microscopy response;
- Calculation of the stability and degradation mechanisms in lead iodide perovskite solar cells.



- *Momentum-space projection of the density of states and the transmission coefficient for 3C-SiC with a double stacking fault.*

Simulations of processes and devices from the meso- to the macro-scale

Different approaches (KMC, continuum models, compact models) have been developed in order to reproduce the virtual version of processes and devices. In house model and code development and multi-scale paradigms are the characteristic aspect of this activity, although the original routines' integration on commercial tools (e.g. COMSOL or TCAD Synopsis) and their calibration and use is also pursued. In compact model formulation, applying dimensionality reduction techniques, it is possible to construct robust models that describe qualitatively



- *Temperature distribution inside the polysilicon avtive layer of a TFT biased in the selfheating regime.*

the dynamics of complex systems. Here we list some application of these classes of methods:

- Coupled continuum and KMC simulations of several advanced technological processes: laser anneling in sub-melting and melting regimes, plasma doping, etching and deposition, graphene synthesis and manipulation;
- Comparisons of Monte Carlo simulations with STEM based experimental intensities of emitted X-rays and transmitted electrons;
- Simulations of nanostructures and nanophotonic devices, as well as the modeling of new optics for x-ray synchrotron light;
- Simulations of microfluidic devices for sorting and manipulation of biological samples integrating electrical and optical functionalities;
- Two- and three-dimensional numerical simulations are used to analyze a number of specific aspects in the electrical characteristics polysilicon and organic TFT devices;
- Simulation of contact's effects in organic devices related to the presence of a metal/organic-semiconductor junctions. The distributed Schottky junction at metal/organic semiconductor interface has been characterized by 2D numerical simulations, thus validating the compact model for the circuit simulation;
- Low-dimensional models of the nervous system (perceptive systems, hearing and acoustic sensors).

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