IMM

Istituto per la Microelettronica e Microsistemi

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1. GENERAL INFORMATION

The Institute for Microelectronics and Microsystems (IMM) is one of the Institute of the Italian National Council of Research (CNR) founded in 2001 as a consequence of the re-organization process of the CNR scientific network. The Institute, whose headquarters is in Catania, is organized on five different departments placed in: Bologna (ex LAMEL), Catania (ex IMETEM), Roma (ex PSM), Lecce (ex IME) e Napoli (ex IRECE). The Institute has been founded to create a big scientific structure covering strongly competitive fields such us microelectronics, sensors, and microsystems. These fields are experiencing a continuous expansion, which requires a high level of innovation.

The research activity of the Institute, carried out by 69 Researchers and 37 Technicians, with expertise on physics, chemistry, and electronic engineer, covers all the path from the understanding of basic phenomena up to the design and realization of innovative microelectronics and multifunctional devices. Possible applications are in the field of *telecommunications*, *computer science*, *automotive*, *environment control*, etc.

The Institute maintains strong collaborations with others Research Laboratories, University, Microelectronics Industry, and Manufactories interested to applications of sensors and microsystems. IMM is involved in numerous national or international scientific project in collaboration with Industry (STMicroelectronics, Alenia, Philips, Olivetti, …) and with other important European laboratories (CEA LETI, IMEC, Fraunhofer Institutes, …). The staff of Institute consists also of 13 administrative units (see Fig. 1).

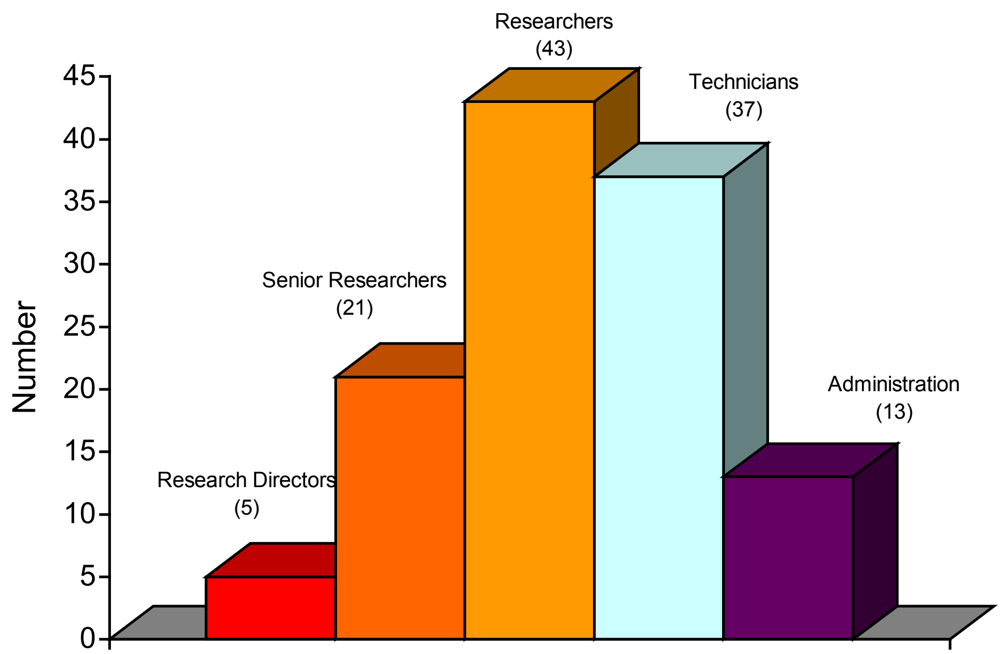

Figure 1 Number of the IMM personnel units as a function of the different professional positions.

The headquarters of IMM is now in Catania in the premises of STMicroelectronics. Within the National agreement called *Intesa di Programma* between CNR and Ministero dell'Istruzione dell'Università e della Ricerca (MIUR), a financial budget of 6 Millions of Euro has been assigned to realize the IMM building in the Industrial area of Catania on a surface of about 20.000 m^2.

The total financial budget of IMM is equal to € 8.648.000. This budget is divided among the different income typologies as illustrated in figure 2 .

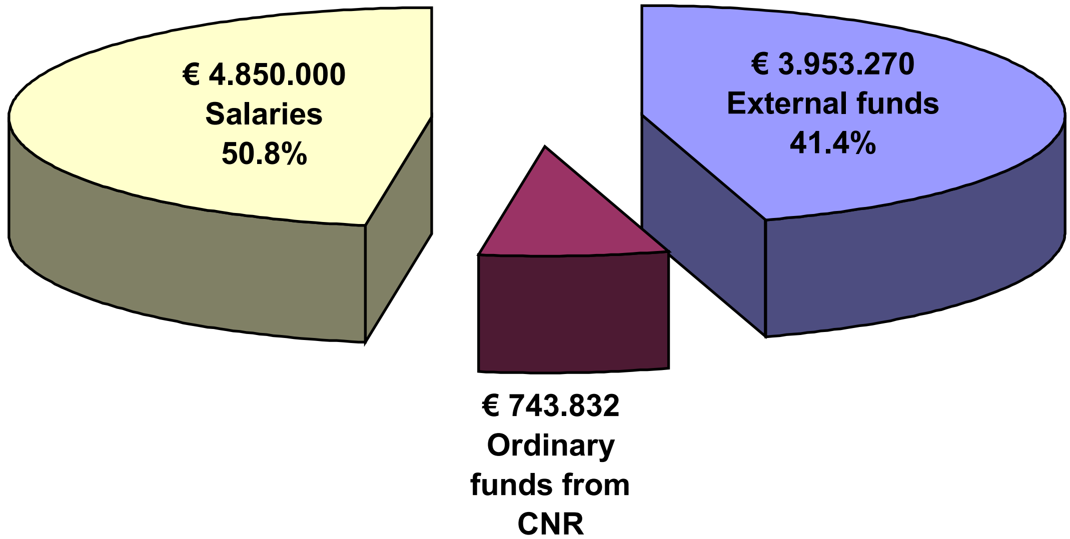

Figure 2 Financial budget of IMM divided among the different income typologies. Salary expense is also evidenced. External funds cover 39% of the total budget.

The external funds come from contracts with Industry, with other National Research Institutions, and from projects financed by MIUR and by European Union, according to the repartition shown in figure 3.

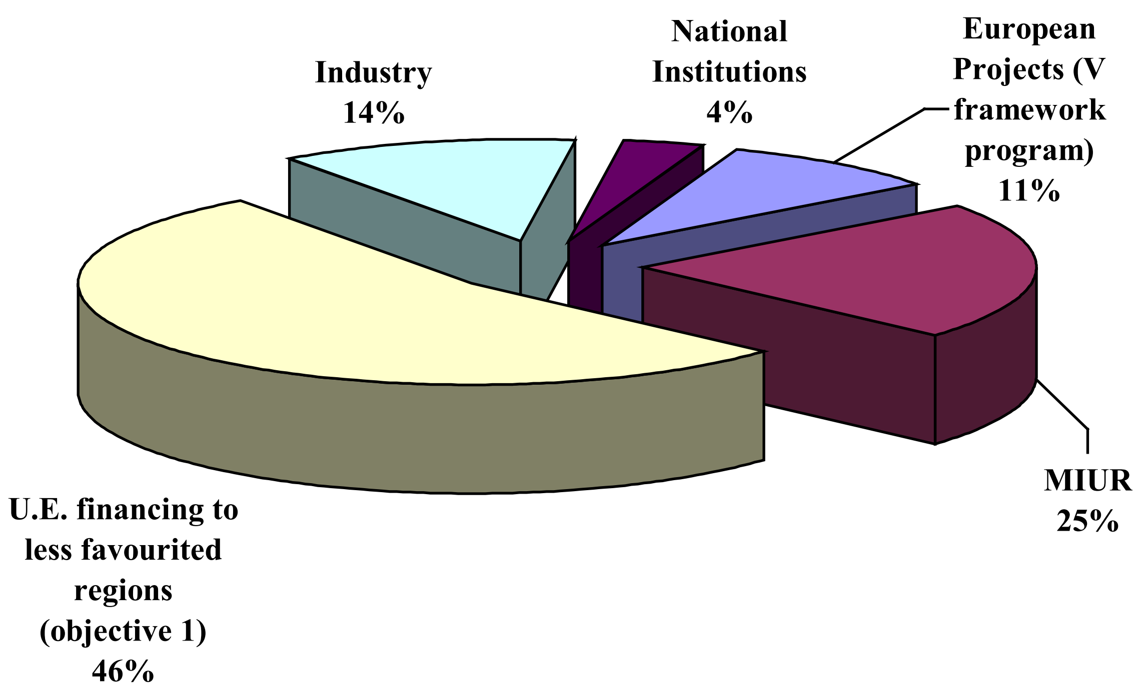

Figure 3 Repartition of the external funds as a function of the different sources: Industry, other National Research Institutions, European projects and MIUR projects.

2. RESEARCH ACTIVITY

The research activity of IMM is organized on four different main research lines: I) materials and processes for microelectronics; II) sensors and microsystems; III) optoelectronics and photovoltaics; IV) development of advanced characterization techniques for material and process analyses.

2.1 MATERIALS AND PROCESSES FOR MICROELETTRONICS

2.1.1 Ion implantation and doping diffusion in Si

Within this activity we investigate the processes for silicon doping whose main objective is the realization of doped layers with superior electrical performances.

We follow theoretical and experimental approaches to study radiation damage, impurity diffusion by thermal processes, and the electrical activation of doping species.

By excimer laser irradiation of silicon implanted with B^+ at energies of the order of 1 keV, we realize ultra shallow junctions (< 50 nm) with low sheet resistance values (< 500 Ω/□) and with doping profiles characterized by a strong gradient (< 2 nm/decade). This process is also simulated by considering both the thermal evolution of irradiated Si and the doping diffusion and segregation during anneal. The integration of such processes within the present ULSI technology will be investigated within the European project FLASH.

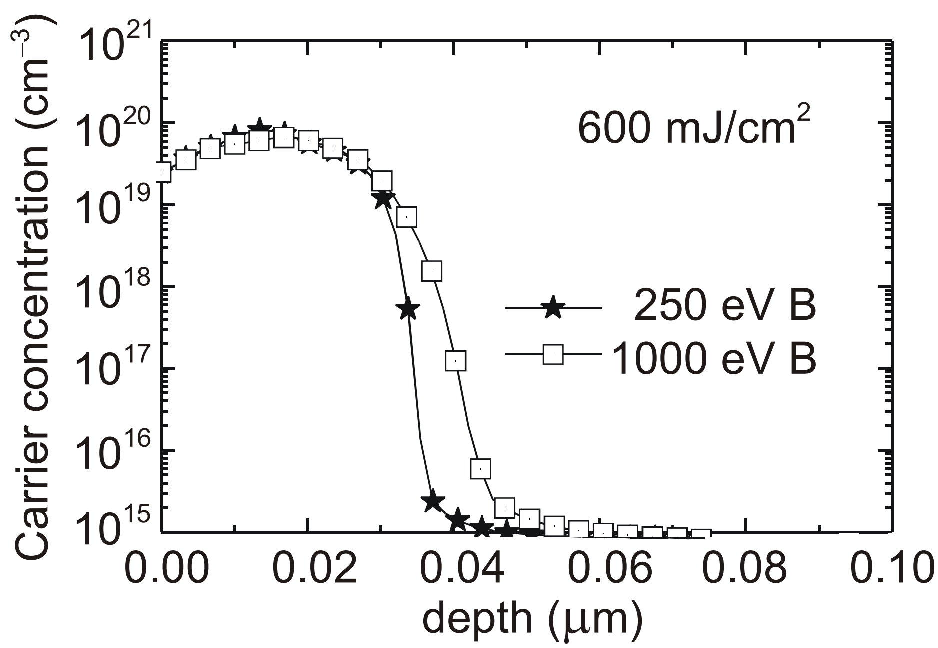

Figure 4 Carrier concentration profiles in silicon implanted with B at energies of 250 or 1000 eV to a dose of 1×10^{15} cm^{-2}. Samples were irradiated by excimer laser at an energy density equal to 600 mJ/cm^2. The obtained junction depths are less than 50 nm!

Doping deactivation in Si, induced by cluster formation, is investigated both for As and B. The influence of point defects on this process is investigated by producing a controlled excess of interstitials or vacancies by implantation of Si^+ ions at different energies and doses. As far as arsenic is concerned we observe a tight correlation between doping concentration and the annealing kinetics of damage. In the case of B we observe the formation of B-I clusters which induce a reduction of the electrical activity, a supersaturation of interstitials, and, as a consequence, a reduction of the doping diffusion.

For the 130 nm technology (IMPULSE project) we need to use implants at very low energy (< 1 keV). In order to measure such shallow profiles we optimized the Spreading Resistance Profiling technique. We introduced specific conditioning procedures of the instrumentation and accurate measurement methodologies which allow us to obtain carrier concentration profiles with a very high depth resolution and with an extremely good concentration sensitivity and accuracy.

In the next future microelectronics requires doping processes which imply the use of non conventional species (In, N) too. For this reason we are investigating the diffusion phenomena of these elements. In the case of indium we study the mechanism responsible for the damage formation during ion implantation, to calibrate the parameters of the Monte Carlo simulation of impurity profiles and as-implanted damaging. We have already determined some parameters controlling In diffusion in Si, by significantly improving the accuracy of the profile simulations under thermal treatment. Moreover, we have demonstrated that we can also improve the electrical activation of In in Si (by almost one order of magnitude) by introducing controlled quantities of C, thanks to the formation of In-C complexes which introduce an acceptor level in Si band gap at 0.111 eV from the valence band. As far as nitrogen is concerned we have evidence that diffusion in Si is governed by the oxygen concentration present in the material.

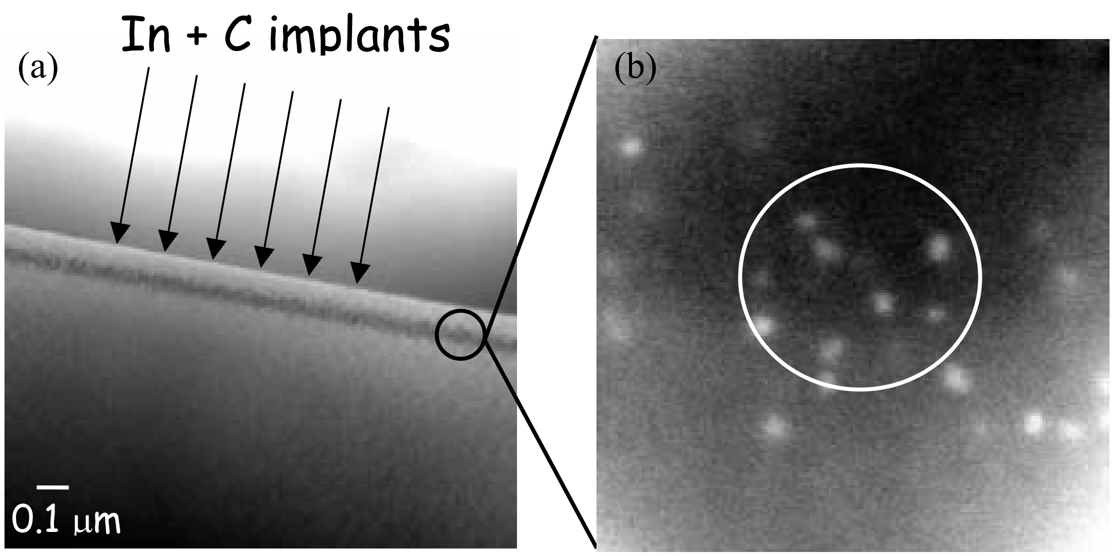

Figure 5 (a) Cross sectional transmission electron microscopy (TEM) of a silicon sample co-implanted with In and C. The band located at a distance of about 100 nm from the surface is formed by coherent precipitates. (b) Detail of the precipitate region obtained by using energy filtered TEM. The image was taken using only the electrons whose energy is reduced by the plasmon loss due to interaction with silicon carbide. The image contrast demonstrates that the observed precipitates are nanometer clusters of SiC.

Finally, the experimental activity and the phenomenological models are integrated by theoretical studies at atomic level by molecular dynamic and static (ab-initio and Tight Binding) and by kinetical Monte Carlo simulations. In particular, these methods are used to investigate the energetic and kinetics of boron-defects systems at different time scales (formation and evolution of metastable aggregates and complexes). Furthermore, we started an activity to investigate the migration mechanism of indium in silicon. A theoretical and experimental activity (financed by a FIRB National project) will be focused to the interpretation of structural measurements (ion-channeling and X) in implanted Si samples and based on atomistic models of defects.

2.1.2 Non volatile memories based on silicon nanocrystals

We are prosecuting the activity started on 2000 for the realization of prototypes of MOS capacitors and non volatile memories with *n* channel MOSFET and with the "single electron" stack: Si / SiO_2 / *Si nanocrystal layer* / CVD dielectric / polySi gate and metals (WSi_2). We have already realized several versions of capacitor and transistor prototypes. On these samples we are performing a strong electrical characterization activity. In particular we are investigating the programming and the erasing characteristics by direct tunnel, charge retention, and we are also performing first reliability tests. The obtained results are quite encouraging. Samples are nor yet optimized, with relatively low nanocrystals densities (~ 3×10^{11} cm^{-2}). Using control oxide thickness of the order of 7−8 nm we observe a shift of the threshold voltage of about 1 V between written and erased states. These values are in line with the best literature data, indicating that it is possible to realize structures with threshold shifts useful for most applications even if Si nanocrystals are trapping only few electrons (between 0 and 5).

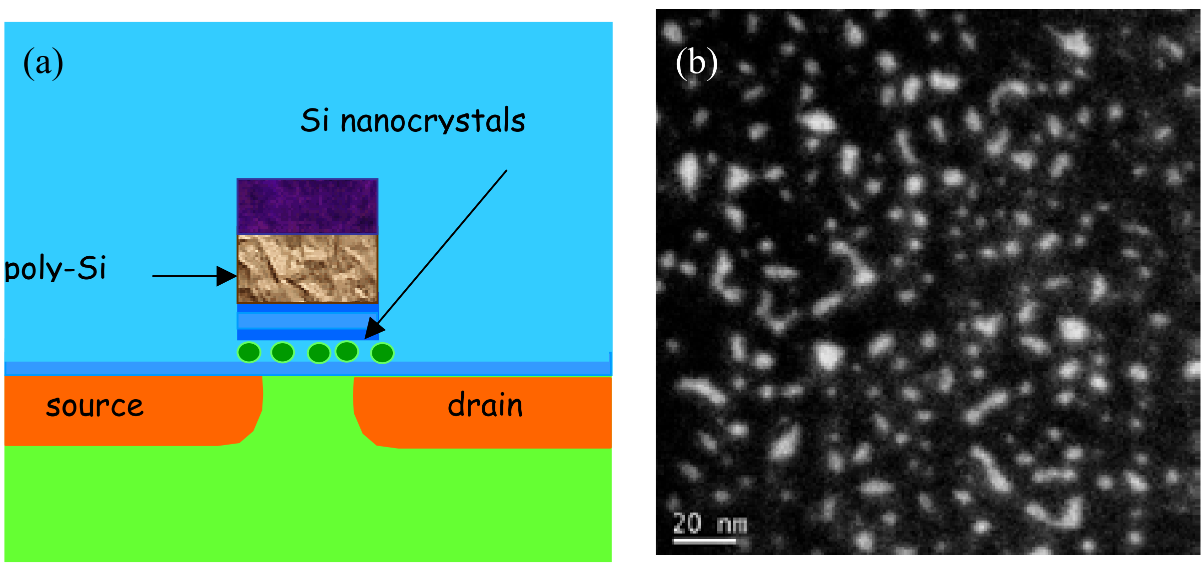

Figure 6 (a) Schematic of a FLASH memory with Si nanocrystal. The nanocrystal layer substitutes the silicon polycrystalline layer routinely used as floating gate in this technology. (b) Plan view EFTEM micrograph of the Si nanocrystals. Their diameter is of the order of few nanometers.

Moreover, compared to the standard Flash the programmable voltage can be strongly reduced. The programming and erasing times are of the order of milliseconds under control gate voltages of about 10 V. This is a big advantage with respect to the standard flash memories based on NAND architectures (present in all the main technological roadmaps) which need larger operation voltage. Finally, we started the characterization of the charge retention and of the resistance to drain and gate troubles. Preliminary measurements on memory array clearly indicate that our prototypes exhibit very long life times under drain stress.

2.1.3 Advanced metalization on Si and electromigration phenomena

Within this research line we have accurately determined, without any complex model, the growth velocity of the titanium silicide C54 phase, the material most frequently used as contact in the Si device technology. We are able to simulate the transition from the C49 to the C54 phase on both unpatterned samples and on sub-micrometer structures. Moreover, we observed that the addition of a tantalum thin film at the Si/Ti interface induces the formation of a new hexagonal C40

$TiSi_2$ phase that rapidly transforms to the finale C54 phase. This process allows us to extend the use of $TiSi_2$ also for contact lines as narrow as 0.1 μm. We are performing an accurate structural and electrical study of the different $TiSi_2$ phases. These study is also extended to Si nanoclusters dispersed in a $TiSi_2$ matrix. For the first time, we can observe the phase transition in any individual cluster.

Moreover, we are intensively investigating the phase transition responsible for the formation of $CoSi_2$ with emphasis to the thermal stability and to its dependence on the presence of cavities formed by the ion implantation. This process was patented. It is very important for applications to power devices where the silicide films of the gate undergo high temperature processes needed for the doping electrical activation. By using our proposed process it is possible to avoid $CoSi_2$ agglomeration responsible for a strong increase of the film resistance and, as a consequence, for the worsening of the device performances.

Finally, we investigate the properties of the most commonly used diffusion barrier in the microelectronics field: titanium nitride (TiN). This barrier is routinely realized by reactive sputter in presence of argon, nitrogen and oxygen in order to obtain films characterized by the optimum stochiometry. The structural properties of the barrier and its capability to stop the aluminum diffusion depend on the process parameters. In this study we optimize all the different parameters involved is such a way to obtain a reliable process with an increase of the device life time.

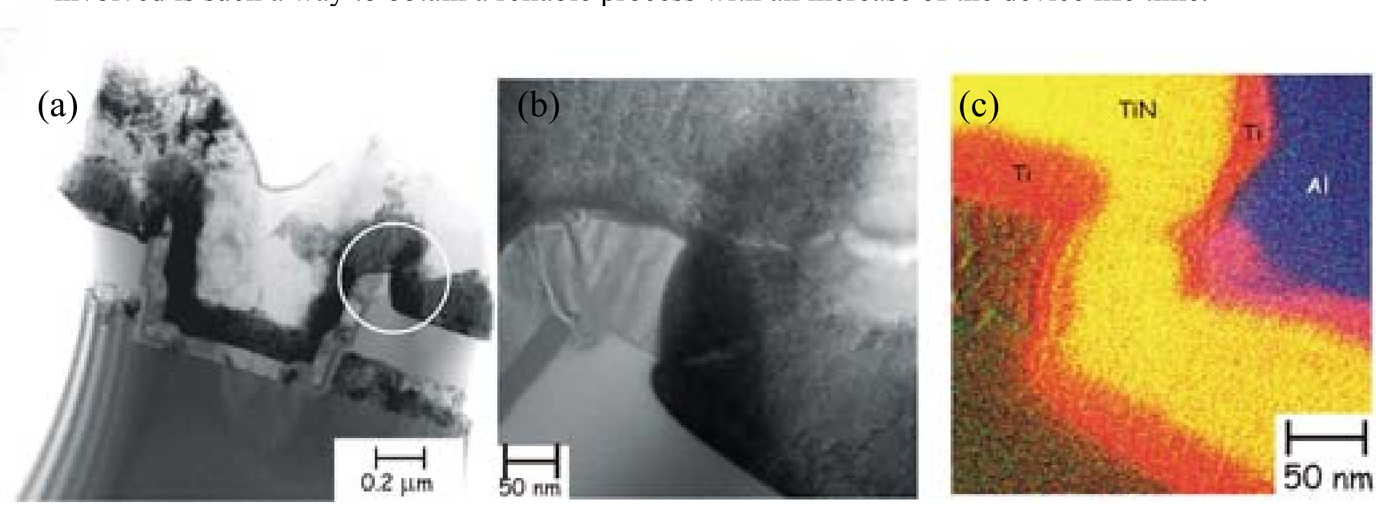

Figure 7 (a) Cross sectional TEM micrograph of the emitter contact in bipolar silicon transistor. (b) Particular of the region inside circled in (a). (c) The same region observed by using the energy filtered TEM. The different layers forming the diffusion barrier are clearly visible between silicon and aluminum metalization.

As far as the multilevel metalization reliability is concerned, the activity is carried out in collaboration with ST. By using the methodologies and measurement systems developed by IMM, we completed the experimental characterization of the electromigration phenomena in 0.13 μm flash memories flash. We also designed new test structures (Al-Cu metalization lines with W visa for the 0.1 μm technology), by varying the visa geometry and the total length. The aim of this activity is the implementation of new layout rules for short metalization lines (10 μm) which are possibly more reliable according to the Blech model. Further developments are in the field of "damascene" copper.

2.1.4 Development of processes for SiC devices

In IMM silicon carbide (SiC) is investigated for both basic research and for the development of new technological processes to realize advanced devices. As far as the basic physics is concerned, we have measured the <0001> channel stopping power by RBS in the 4H−SiC polytype. It has been demonstrated that the measured value is significantly less than the same channel of the

6H−SiC polytype. This difference is explained by taking into account the different electron distribution of the two polytypes along the same crystallographic channel.

The fundamental Richardson constant has been determined for 4H−SiC and titanium or nickel barriers, and related silicides. This value is different from the universal one. The difference has been explained for all the investigated cases by taken into account the model of inhomogeneous barriers.

We have developed a quantitative method for the determination of carrier profiles in SiC with high spatial resolution (20 nm) and sensitivity (10^{15} − 10^{19} cm^{-3}) based on scanning capacitance microscopy. The capability to form high quality silicon oxide at low temperature with reproducible thickness allows us to realize the optimum experimental conditions needed by the developed dC/dV conversion models. This method has been applied to determine carrier profiles in 6H−SiC which have been related to the residual damage for implants of Al and N. In the case hot implants of nitrogen we identified the occurrence of two regimes, with or without the formation of extended defects, respectively. In the first case (for a dose < 10^{14} cm^{-2}) electrical activation depends on the annealing temperature and on the heating ramp. The threshold temperature to activate this phenomenon is 1300 °C. For hot implants of Al^+, and for doping concentrations below 5×10^{19} cm^{-3}, we found the minimum temperature at which we have to maintain the sample during the implantation in order to obtain the complete doping electrical activation after the post thermal treatment. Moreover, we started the investigation of the surface damage induced by anneals at high temperatures. The realization of n^+/p diodes with field oxide allowed us to demonstrated that the surface damage (microstep) can produce detrimental effects on the device performance.

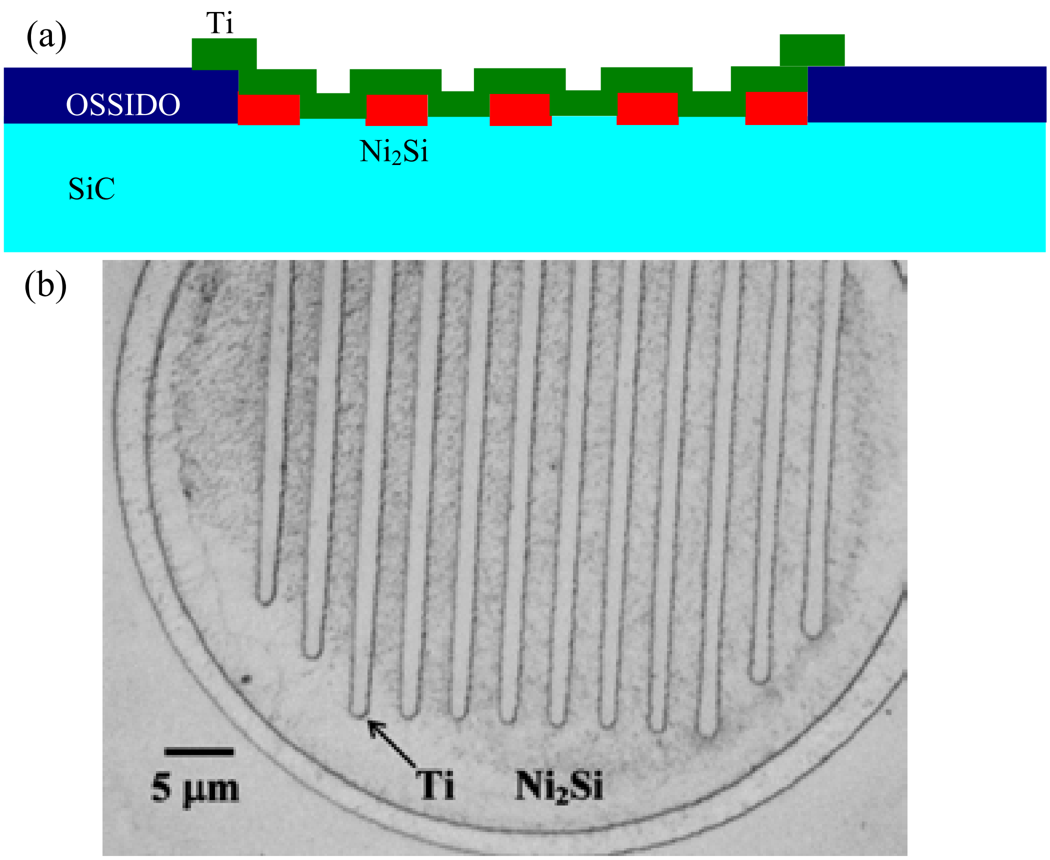

Figure 8 (a) Schematic of the SiC Schottky diode with a double metalization (Ni and Ti). (b) Plan view optical micrograph showing the realized working structure.

We optimized the realization of linear contacts p and n type area doped by ion implantation or during epitaxy. Either on 4H−SiC or 6H−SiC wafers, the developed metalization allow us to obtain contact resistivity of the order of 10^{-6} $\Omega\cdot cm^2$ for doping level of about 10^{19} cm^{-3}. Moreover, a simulation code has been developed to elaborate the contact resistance measurements on TLM structures (transmission line model). The model takes into account border effects around and below the metal contacts.

We realized power devices working at 4 A, 600 V with Ni Schottky contact and field plate border termination onto a B-implanted layer. Thousands of these devices were realized and tested on wafer or in "package" by static (V_f = 2.5 V @ 4 A, V_{BD} = 600 V, n = 1.04, ϕ = 1.5 eV) and dynamic measurements (t_{rr} = 7 ns, Q_{rr} = 9 nC). We also realized diodes characterized by a low power dissipation by Schottky contacts with double carrier. We demonstrated that the current flow of these devices is controlled by the metal with the lowest barrier while the inverse current is determined by the metal with the highest barrier. The results were interpreted on the basis of the physical model describing the pinch-off of the low barrier under inverse polarization.

2.1.5 Devices based on carbon nanotubes

We started an activity for the growth of matrix of parallel carbon nanotubes (CNT), with controlled diameter and morphology, embedded in a porous alumina support. Porous alumina is formed by an ordered matrix of pores or nanometer nanochannels, parallel and perpendicular to the surface. It is the nanotemplate within carbon nanotube can be grown by chemical vapor deposition. We have already designed an experimental reactor that will allow us to explore a wide range of deposition conditions. ST in Catania has expressed a strong interest for this activity. CNT will be developed and characterized in view of two possible applications: *i*) as charge collector in a radiation detector with a high spatial resolution (project NANOCHANT – INFN) to be employed for High Energy Physics experiments or for nuclear medicine; *ii*) as electron emitters with high emission current density and low threshold field, to be used as cold cathodes instead of the usual microtip cathodes in memory or display devices (project FISR – MIUR).

2.2 INTELLIGENT MICROSYSTEMS AND MICROSENSORS

Microsystems (MS) are integrated microstructures fabricated by using micro- nanometer technologies and chemical micromachining of silicon or other materials (metals, insulators, semiconductors) which can incorporate mechanical, optical, electronic, magnetic, chemical, or biological functions. They exhibit sensorial capabilities, data elaboration, autocalibration and actuation on a single or multiple chip. Microsystems include both MEMS (micro-electro-mechanical-systems) and MOEMS (micro-optical-electromechanical systems).

Intelligent microsensors (MSI) are devices which can transform on of the possible input energy (thermal, magnetic, chemical, mechanical, shining, or electrical) in a standard electro/optical signal for successive elaboration, calibrations or drift corrections. They can be organized on sensorial matrixes for more complex operations including input data classification and recognition or statistics.

The research activity of IMM in these fields is very interesting and attractive. The IMM structure allow to all the research groups the opportunity to reach a critical mass for an effective participation to all the National and International calls.

2.2.1 Present situation and trend for the applications

The design, realization and testing techniques for MS or MSI are experiencing a rapid continuous evolution, by promising new micro- and nanometer technological solutions for new devices and for new integrated systems with a higher level of complexity and functionality, such as reactors or micromachines with the capability of independent movement induced by transponder and with a generalized sensing and actuation capability.

Nowadays a large number of MS and MSI have been industrially produced or realized as prototypes: gyroscopes and accelerometers for inertial measurements, ink jet devices and flow sensors (microfluidics), optical switches, displays and magneto-optical heads, pressure devices, radiofrequence device, drug microdispenser, etc.

On medium and long period we expect further developments of these components with optimized technologies and with new applications for the realization of efficient microengine, microrelays, microspectrophotometers, anticollision devices, multiple optical switches, pace-makers, lab on chip equipped with polyfunctional microcontrollers and new microsystems to control the microspaces cooling.

In the future nanotechnologies will provide new materials for fabricating microsystems (e.g. to reduce surface abrasion or adhesion in the absence of lubrication), tailored membrane or complex structural elements for mechanical sensors and for optoelectronic-photonic devices.

Although the Scientific Community agrees about the potential impact of the MEMS and MEOMS technologies, the wide scale trading of this products is retarded for the heterogeneous nature of these technology, involving fabrication processes, design, testing (electrical or non-electrical input and output), and packaging. Frequently, any category of these devices is nowadays a custom product that must be fabricated on big volumes to be competitive. For medium or small volume production proper infrastructures and optimum business-model do not exist.

2.2.2 Fabrication technologies for microsystems

Nowadays the technologies which are used to realize MS are essentially the ones coming from silicon based microelectronics (silicon dioxide and integrated circuits), with the addition of the chemical etching technology of silicon and other materials (micromachining). Lithography, routinely used in the VLSI technology, is also employed for microsystems but with less stringent problems related to the scaling. Finally, silicon and polycrystalline silicon deposition techniques, thermal evaporation and sputtering of metals and semiconductors, all the different CVD deposition techniques, chemical and/or physical etching eventually assisted by photons, and, very important, the new packaging techniques are intensely used in the MS technology.

Chemical micromachining of silicon offers the opportunity to realize MS which are organized on the surface (surface micromachining), or in the bulk (bulk micromachining), or in both. The minimum sizes are below 1 micron even if thin films, few nanometer thick, can be also used. Within this context the realization of MS must take into account problems related to the integration of CMOS circuits (on the same chip or in multichip systems) to be employed as local interface and to introduce in the devices a certain level of intelligence. Also important are the technique to solder silicon wafers and other materials. Nowadays the chemical micromachining techniques refer to a large number of materials (Si, GaAs, InP, AlN, GaN), insulators (oxides, nitrides, oxynitride, polymers), and metals including the catalytic ones. The dimensional accuracy that can be obtained are very good while, in some case, the reliability of the mobile components of MSs is not satisfactory, especially in the cases where these components are fabricated using materials not fully compatible from the thermal and chemical point of view.

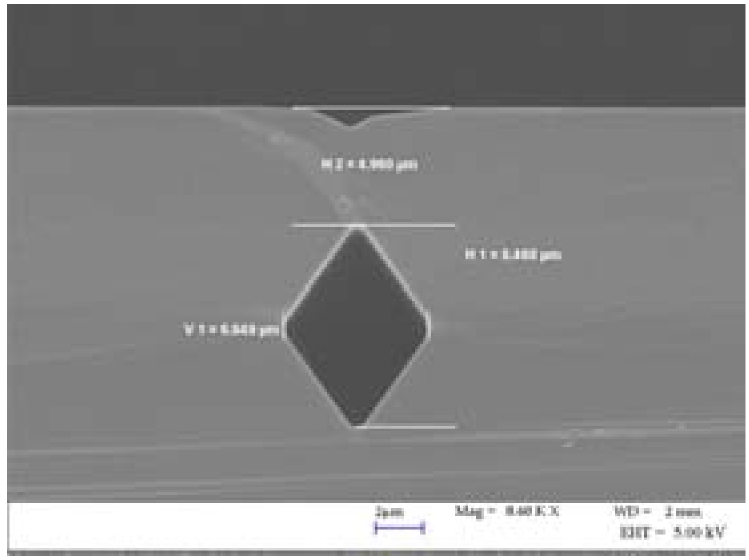

Figure 9 Scanning electron microscopy (SEM) in cross sectional of a microchannel fabricated within a monocrystalline silicon wafer.

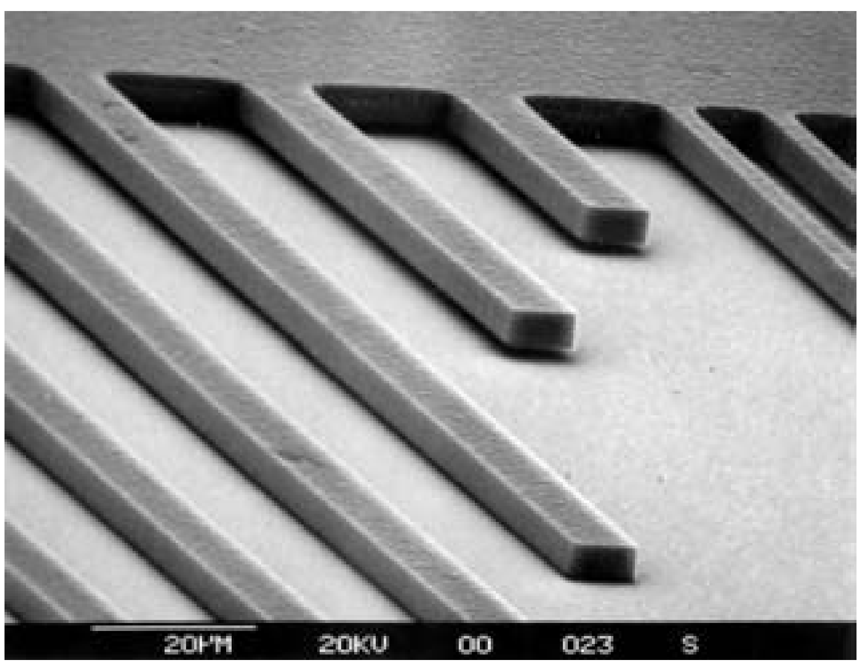

Figure 10 SEM micrograph showing a sequence of micro cantilevers fabricated using polycrystalline Si.

In the near future these technologies will be based on new polymeric materials and on mixed structures for the realization of very complex systems which will be able to execute both electronic and polyfunctional activity. A big effort will be devoted to the performance improvement of the mobile parts and of the actuators. Further application fields will be the bioMems devices, microinjectors, fluid microdispenser, and the diagnosis instrumentation for invasive or non invasive medical sectors.

In parallel, the metrology technology will be strongly developed. This technology is necessary to calibrate the MS responses when stimulated by physical, chemical, or biological parameters.

2.2.3 Fabrication technologies for intelligent microsensors

As far as intelligent microsensors (MSI), the technology is essentially the same used for microsystems with the addition of materials which are chemically sensitive to chemical and/or biological parameters and of new piezo-piro materials such as AlN, GaN etc., necessary to realize sensors sensitive to physical parameters. Sensor matrixes with the related techniques for deconvolving and predicting the input status are technologically important. It should be not neglected the activity for the development of protocols to simplify dialog between MSI and telecommunication systems. In the near future we expect major improvement in the field of physical MSI for pressure and temperature measurements, for radiation, flux, and magnetic field detection, or for humidity, deformation, acceleration, viscosity measurements. The chemical MSI must be improved in terms of a better accuracy in measuring concentration of aggressive and corrosive gases. These MSI must exhibit a better accuracy in realizing smell images of smells or chemical compositions of industrial interest, or volatile mixtures interesting for the air quality. The biological MSI will improve as sensors for DNA segments, as enzymatic sensors, and as sensors for general biochemical species.

In the next future most of the MSIs must be improved from the stability and performance point of view (better sensitivity and resolution). We will consider new materials: mesoporous structures, mixed insulators incorporating micro and nanometallic spheres, materials with memory capability. The interaction between sensorial systems and telecommunications will be much stronger. The optimum design of interfaces between materials characterized by good cross-sensitivity will be a very relevant activity in order to improve the reliability and the ratio between cost and performance.

2.2.4 List of activities

We now list the research products of IMM in the field of Sensors and Microsystems.

IMM-Section of Bologna

I) Silicon based microsystems, equipped with heater and with a tin oxide sensitive layer
II) Integrated system for integral monitoring containing separation units as microsystems
III) Miniaturized gas chromatographic system, oriented to the palm-top solution
IV) Gas sensor with a photo-acoustic transduction
V) Inkjet print heads structure
VI) Interferometer array based on MacZender structure
VII) Micro thruster

IMM-Section of Roma

I) Electronic nose
II) Manipulation of chemically sensitive materials for quartz micro balance
III) Porfirine array as optical and mass sensors
IV) Microthermocouple with high response speed
V) Mesoporous materials with high surface area as humidity or alcohol sensors
VI) Tunable oscillators with low phase noise in the 4-40 GHz band
VII) Millimeter wave filters for frequencies around to 40 GHz
VIII) Millimeter wave antenna (38 GHz)
IX) Microswitches for space applications

IMM-Section of Napoli

I) Systems realized with porous silicon microcavities for the identification of organic substances and DNA fragments
II) Temperature microsensor integrated in silicon
III) Electromagnetic field sensor
IV) Optical fiber Bragg sensors
V) Tunable $LiNbO_3$ acoustic-optical filters for deformation measures

IMM-Section of Lecce

I) Gas sensors based on metallic oxides obtained by sol-gel technology
II) Sensor array based on metallic oxides
III) Systems based on surface plasma resonance
IV) Resistivity sensors based on polymeric films and macro molecules

IMM-Section of Catania

I) Micro fuel cell
II) Micro channel buried in Si
III) Si-based magnetic microtraps
IV) Si-based electrocatalic membranes

2.3 OPTOELECTRONICS E PHOTOVOLTAICS

The realization of optic devices acting as interfaces between microelectronic circuits and optical fiber could be a fundamental breakthrough in several application fields. Silicon is indubitably one of the most promising materials for this kind of application. In fact, it allows making use of the mature and reliable microelectronic technology in order to realize low-cost chips where electronic and optic devices are monolithically and usefully integrated.

The so-called *fiber-to-the-home* (FTTH) applications and, in general, the realization of fast and robust Local Area Network (LAN), could significantly benefit from the use of optical devices which fabrication is fully compatible with the standard microelectronic technology. In particular, this feature could allow a tremendous reduction of the fabrication costs and, consequently, the overcoming of the most important impediment that now limits the commercial success of large scale optical network. A typical example in the telecommunication field is the *fiber-in-the-loop* application, where, once again, economic considerations suggest the exploitation of *low-cost-low-performance* silicon-based optoelectronic user terminal, as wavelength tunable optical filters, photodetectors, modulators and switches with data rate in the range 1÷10 Mbit/s. This viewpoint can make affordable, for the telecom companies, the conversion of the existing copper-based network in an optical one, permitting, in the future, that the customer upgrades to a high-performance wide-band optical link.

At the same time, the use of optoelectronic integrated circuits in the telecommunication field, is intimately associated with the need of integration between photonic devices on the chip with the intention to realize optical interconnections on a chip and between chips, ensuring performances that could be considerably better than those of the existing microelectronic circuits, so opening new perspectives to their integration, beyond the metallic interconnections physical limits.

Moreover, silicon could be a very promising material in several application fields, such as sensors, microdevices, microsystems and smart structures. Even the traditional research activity on photovoltaics, historically developed inside the IMM, can broaden toward the microsystems, providing the remote power supply for multi−function chips that can operate without electrical wires. In brief, it is probable that, taking advance of the last research results, in the near future the silicon technology will provide a significant contribution to the photonic diffusion in all the application field that, up to now, are typically based on electronic devices and systems, with considerable advantages.

In this framework IMM performs several research activities in the optoelectronics and photovoltaic filed, simultaneously developing some parallel researches on different materials, compatible with microelectronic technologies, and special devices, to be integrated in hybrid solution, with the aim to realize high performances photonic circuits.

2.3.1 Optoelectronics: silicon based devices

The Institute for Microelectronics and Microsystems plays a very important role in the national and international landscape in the field of the design, fabrication and characterization of photonic devices based on the technologies of the crystalline, micro−crystalline and amorphous silicon. Cooperation with important Italian and foreign research centers recently allowed the realization of optical waveguide both single−mode and multi−mode, working at the typical wavelengths of the optical telecommunication systems, characterized by optical losses lower than 1 dB/cm. The most important feature of such structures is the fully compatibility with the standard microelectronic fabrication processes, as these employed in the realization of bipolar and CMOS devices. Moreover, it has been demonstrated, in these host structures, the realization and the operation of micrometer optical modulators and switches. The optical radiation control in these devices is basically performed by thermo−optic and plasma dispersion effect. The devices were fabricated taking advantage of the numerous possibilities offered by the silicon technology, ranging from mono−crystalline silicon structures, grown by epitaxy, to micro−crystalline or hydrogenated amorphous silicon structures, deposited by PECVD at low temperature (< 200 °C), whose realization is fully compatible with the standard devices process flow. A preliminary activity, evidently required for the originality of the research, is the characterization of the materials and the effects employed for the devices fabrication and operation. An example is the characterization of the thermo−optic effect in micro−crystalline silicon and in hydrogenated amorphous silicon compounds. Analysis are currently carried on the characterization of the photo−induced absorption effect in amorphous materials, focused on the realization of all−optical modulators and switches. Almost all the recent activities in the mentioned fields are developed in strong cooperation between the different Sections of the Institute. A last example, following this trend, occurs from the design and the preliminary realization of resonant cavity enhanced photodiodes with tunable wavelength response, based on the micro−crystalline silicon technology.

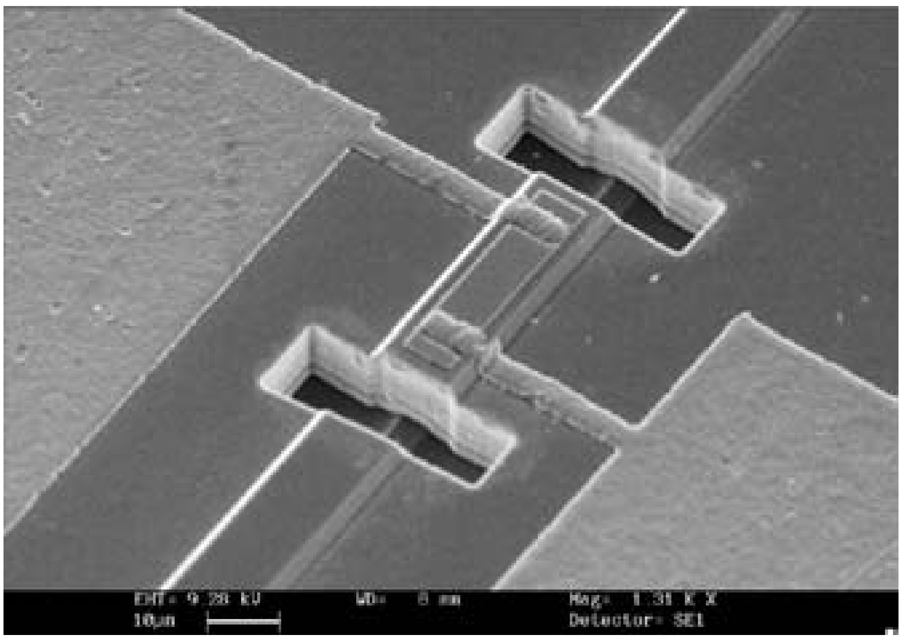

Figure 11 Scanning electron micrograph of a thermo-optical modulator integrated on fiber and compatible with the Si technology.

Complementary with the above mentioned research activities, and very interesting for its importance, is the research activity developed in IMM on the realization of silicon optical sources, overcoming the intrinsic limit of this material due to its indirect band−gap. In particular, it has been defined the synthesis process for silicon nanocrystals imbedded in a silicon dioxide matrix, starting from SiO_x thin films deposited by means of PECVD. The materials produced by this innovative technology show photo−luminescence and electro−luminescence at room temperature, in the visible or near infrared range, with high quantum efficiency and stability, non−common characteristic for silicon based materials. Applications and perspectives for these materials received an additional incentive from the discovery that the emission at 1.54 μm from erbium ions embedded in a silicon dioxide matrix, can be amplified up to 100 times in presence of silicon nano−crystals.

In relation with the major achievements reached in the last two years in this field, it is worthwhile to notice the realization of resonant micro−cavities based on silicon nano−crystals, and electro−luminescent devices based on silicon nano−crystals and ion erbium doped silicon nano−crystals, where, optimizing the active material properties, it is possible to reach stability and quantum efficiency performances so high to prefigure practical use in optical interconnection systems, or in the realization of optical amplifier integrated in waveguides.

In the same direction is addressed the preliminary research on the realization of nano–crystalline alloys of silicon carbide, starting from micro–crystalline films deposited by PECVD and then re–crystallized by UV laser radiation.

As last activity of particular importance and originality can be mentioned the study on the immobilization of proteins on silicon, with the aim to realize biochip with logical and sensing functions.

In conclusion, the research activities in this field have as principal objective to demonstrate the realization, with compatible processes, of active optical circuits, integrated with electronic analog and digital circuits.

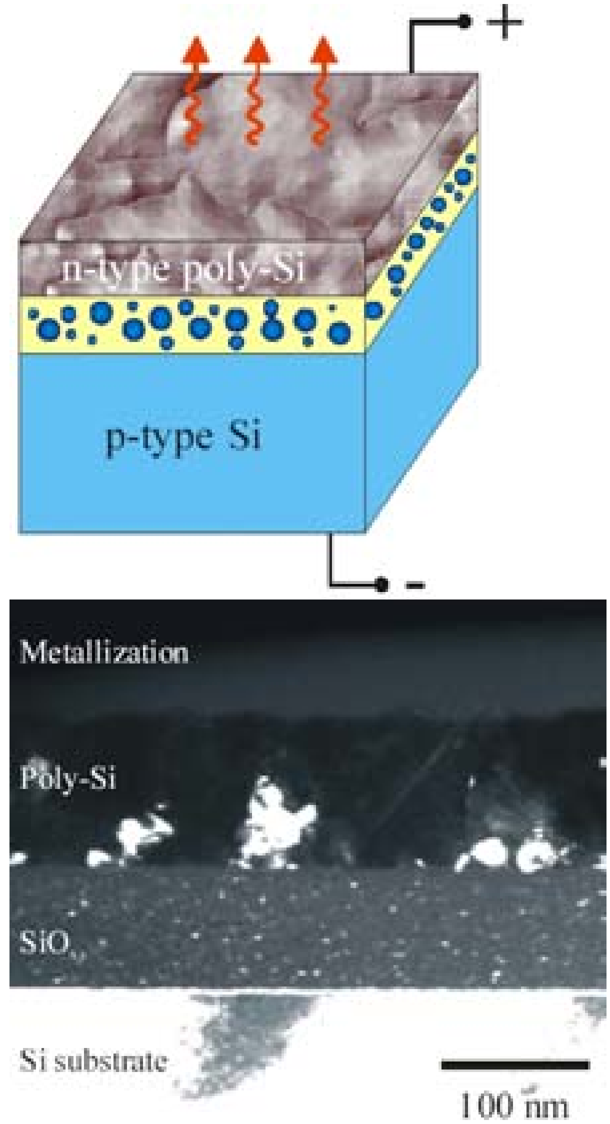

Figure 12 (a) Schematic of the Si nanocrystal electroluminescent MOS device realized at IMM. (b) TEM Cross-sectional micrograph of the same device.

2.3.2 Optoelectronics: III-V and $LiNbO_3$ based devices

Several research activities, not less important, are finalized to the realization of photonic devices characterized by high performances, which can be integrated in hybrid silicon based optoelectronic circuits. Among these researches, can be mentioned the realization of resonant photodiodes based on heterostructures in III–V materials, for optical telecommunication applications. On the same time, it has been developed integrated detectors for X rays, in bulk GaAs. With the aim to favor the compatibility with the microelectronic processes, are of particular importance the studies on the synthesis of nano–crystals of the II–VI and II–V groups, starting from colloidal solutions. Purpose of that research is the realization, on silicon or glass substrates, of light emitters based on colloidal quantum–dots in resonant micro–cavities.

Moreover, an established know-how is present in the Institute in the field of the design and the realization of electro–optic devices both in lithium niobate waveguide structures and bulk material, characterized by very high operation frequencies and independence from the radiation optical wavelength. Particularly innovative is the research activity focused on the fabrication of devices and circuits based on photonic crystal structures. This kind of components, together with applications in the telecommunication field, is very interesting in the middle IR wavelength range, for laser spectroscopic applications.

2.3.3 Photovoltaics: heterojunction based cells on silicon and in micro–crystalline silicon

This activity is one of the most established in the Institute. At this moment, it is mainly focused on the realization of heterojunction based cells, characterized by high efficiency and low fabrication costs. These devices are realized by means of low temperature (< 250 °C) PECVD deposition on mono−crystalline silicon substrates. The original results achieved allow the fabrication of triple−layers cells (micro−crystalline p−type / amorphous p−type / amorphous intrinsic) which reach an open circuit voltage of 638 mV, without contact passivation. Another characteristic of the realization process is the use of the very high frequency (VHF) PECVD, which permits a good control on the micro−crystalline layer quality. It is possible to reach an efficiency of about 14 % on flat silicon substrate that is on the same order of the best results reported in literature. The next objectives are: the use of textured silicon substrates, in order to increase the short circuit current, and the use of micro−crystalline instead of amorphous silicon, in order to reduce the emitter absorption. This development will require the solution of difficulties related to the interaction between hydrogenous rich plasma and amorphous silicon.

Moreover, is in an advanced phase the development of p−i−n devices in micro−crystalline silicon, deposited by PECVD, for the realization of low cost cells, on industrial substrates.

2.3.4 Photovoltaics: high efficiency cells in III−V semiconductor and thermo−photovoltaics

The activity is prevalently carried out in the European Project THE REV (A Thermo−photovoltaic Power Generator for Hybrid Electric Vehicles), coordinated by the IMM. This activity consists in:

i) Design and characterization (EBIC, SNOM) of photovoltaic cells based on InGaAs Multi-Quantum Well, on GaAs and InP substrates. Special structures, with balanced strain, grown on *virual substrates*, realized in cooperation with the NNL laboratory in Lecce (ASI financial support), are to be patented.
ii) Realization, structural characterization (XRD, SEM), and optical characterization at room temperature (CL and PL), and at high temperature (emissivity measurements at 1000−1500 K) of selective emitter based on rare earth. A particular class of these devices has to be patented.

Finally, the participation of the Institute in a spin−off initiative promoted by the Imperial College − Innovation is in definition, finalized to the commercial exploitation of the research results obtained in the last years in the cooperation between the former IME−CNR and the Imperial College.

2.4 DEVELOPMENT OF CHARACTERIZATION TECHNIQUES

The development of materials, processes, and advanced devices for microelectronics and microsystems requires a huge effort in the field of the characterization techniques. On this research line IMM dedicates 19% of its human resources distributed uniformly on two big research area. The first is in the field of the *development and/or improvement of methods for two- and three dimensional characterization in advanced microelectronic structures*, the second is in the field of the *characterization of the fundamental properties of advanced nanostructured and functional materials*.

2.4.1 The characterization laboratories

The distribution of the main characterization laboratories on the different Sections of the Institute is shown in Tab. I.

	Catania	Bologna	Napoli	Lecce	Roma
ELECTRON MICROSCOPY	×	×	×	×	
SCANNING PROBE MICROSCOPY	×			×	
OPTICAL CHARACTERIZATION	×	×	×	×	
ION BEAM MEASUREMENTS		×			
X-RAY DIFFRACTION AND REFLECTION		×			
ELECTRICAL MEASUREMENTS	×	×	×	×	×

2.4.2 Development of techniques based on electron microscopy

The Institute has strong expertise in the filed of Electron Microscopy. Three new advanced transmission electron microscopes (TEM) are present in Bologna and Catania (FEI Tecnai F20 with FEG source in Bologna, a Jeol JEM 2010 and a Jeol JEM 2010F with FEG source in Catania), whilst a scanning electron microscopy (SEM) with FEG source has been recently installed in Lecce. Two more SEM microscopes with LaB_6 source are working in Napoli and in Bologna. The activity is very intensive and microscopists of the Bologna, Catania and Lecce Sections are involved in specific research projects finalized to the development of new contrast techniques to analyze the chemical-structural properties of materials and devices, and in research project concerning all the other research activities of the Institute where high resolution investigations are required. Let's to mention the European Project STREAM (V framework program), coordinated by the Section of Bologna, referring to the development of methodologies to analyze the strain components in ULSI devices using

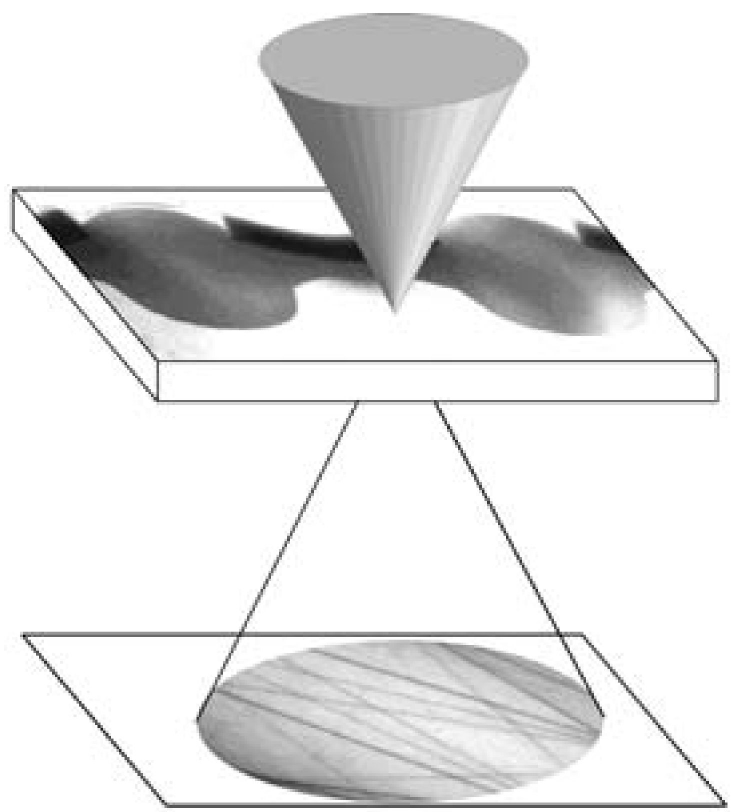

Figure 13 Principio di funzionamento della tecnica di analisi CBED. Il fascio elettronico convergente viene spostato sul campione sottile. Il pattern di diffrazione che si ottiene può essere interpretato per misurare il campo di strain in dispositivi ULSI.

Convergent Beam Electron Diffraction (CBED). As far as the structural characterization is concerned the Section of Bologna is involved in the development of Electron Crystallography techniques which are of interest for the investigation of complex materials (compound crystals, modulated structures) and compound exhibiting a crystalline order on sub-micrometer scale.

Besides the structural characterization of materials and CBED, the microscopy groups of IMM are involved on the development of methodologies for the high resolution profiling of chemical species and dopants in semiconductors. In Bologna we explore strategies based on the phase contrast and electron holography (in collaboration with the Physics Department of the University of Bologna), and on the Z contrast in STEM micrographs taken in dark field at high energy (200 keV) or in bright field at low energy (below to 30 keV). These activities will be financially supported by a FIRB National Project in the next three years and will involve also the Section of Lecce for the Z contrast at low energy. In Catania we intensively work on the develop of characterization techniques for the two-dimensional delineation of junctions by selective chemical etch coupled to TEM analyses, also by means of the energy filtered transmission electron microscopy (EFTEM).

2.4.3 SCM and SNOM microscopy

A very effective profiling technique with high sensitivity and resolution is the one developed in Catania based on capacitance scanning measurements (SCM - Scanning Capacitance Microscopy). On this field IMM is partner of an European Project (HERCULAS) whose funds can be used to support both research activity and mobility of young researchers throughout the European Union.

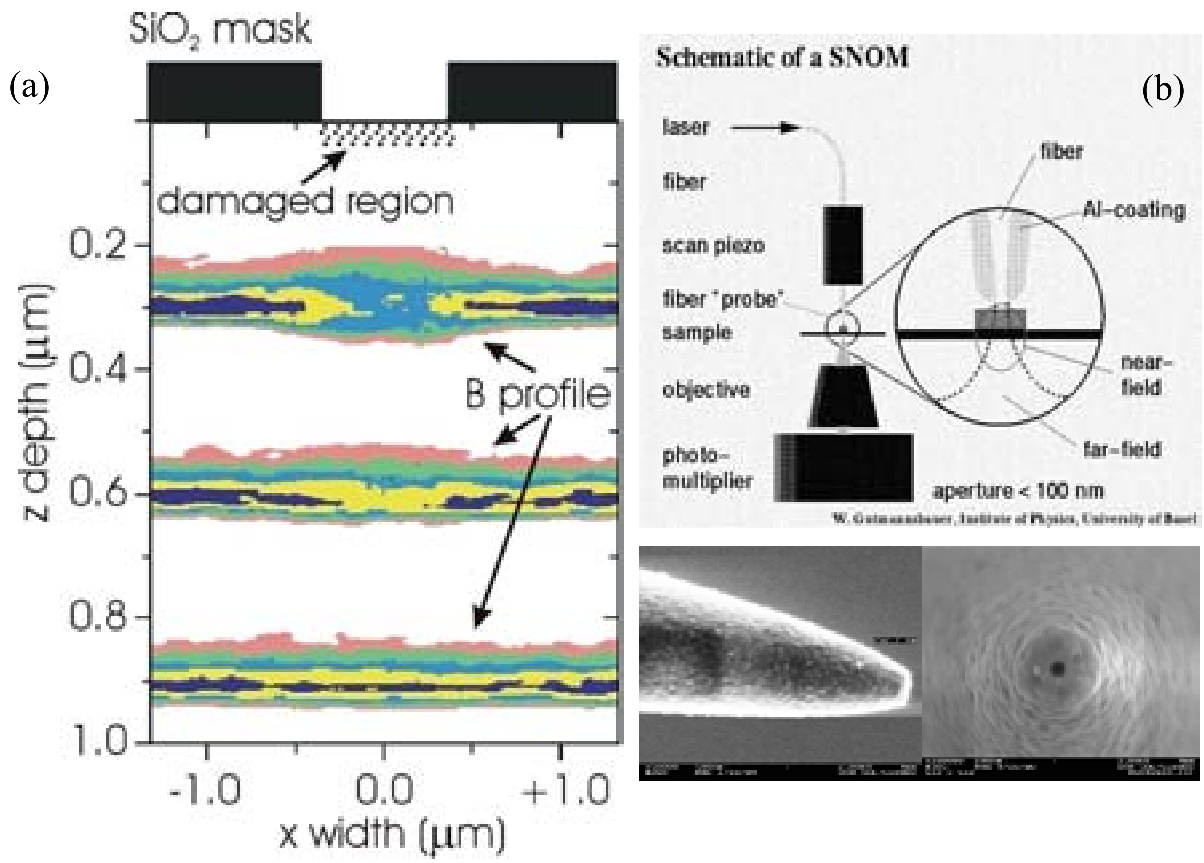

Figure 14 (a) Two dimensional boron concentration profiles in Si obtained by SCM. Dopant has been located at three different depths by MBE. A Si implant produced a damaged region confined around the window defined by the SiO_2 mask. It was thus possible to investigate the boron - defects interaction. (b) Schematic of the SNOM apparatus in Lecce. The scanning electron micrographs show the probe dimensions.

In general, scanning probe microscopy is a very consolidated technique both in Catania and in Lecce. In Lecce, within a project financed by 'INFM, a Near field Scanning Optical Microscopy (SNOM) apparatus has been developed and successfully used to characterize InGaAs quantum dots in GaAs.

2.4.4 Damage profiling: RBS, X-ray diffraction and reflection, TEM weak beam contrast

These activities are performed at the Bologna Section where a well consolidate expertise exists in the field of the *Rutherford Backscattering Spectroscopy* (RBS). The RBS group of the Section of Bologna, together with the Simulation and Modeling group, developed methods to accurately determine the damage profiles induced by ion implantation in Si and in SiC.

The Section of Bologna is also involved on the characterization techniques based on TEM weak beam contrast to investigate lattice defects and on the developments of analytical methods based on triple crystal X-ray diffraction. On this latter field, Bologna is involved in a very significant activity based on the use Sincroton light facility in Grenoble and in Trieste. At the present, the X-ray group is involved on the European project IMPULSE, financed by the V network program and coordinated by the Section of Bologna. The final objective of this project is the characterization of ultra shallow junctions (90 nm) realized by ion implants and rapid thermal anneals for devices of the next generation.

2.4.5 Development of optical characterization techniques

Section of Lecce is involved in an activity concerning the time resolved optical spectroscopy on semiconductor nanostructures, such as colloidal CdSe, CsSe/ZnSe, or ZnSe/ZnS quantum dots/rods and core/shell, or self-organized InGaAs/GaAs quantum dots. During 2002 a pulsed laser (80 fs) has been installed in Lecce. The clock frequency is 5 KHz and the energy of every pulse is about 1 mJ at 810 nm. This system consists in an Femtosource s20 seed oscillator (FEMTOLASER produktions GmbH) pumped by a 5 W green laser (COHERENT Inc) and by an amplifier Concerto (THALES Laser S.A). By a optical parameter amplifier Topas (LIGTH CONVERSION) the wavelength can be tuned in the range 1.1 – 3 μm, extendable from visible to far infrared using second and third armonic generator crystals.

At the Section of Napoli interferometer techniques have been developed to investigate the thermo-optical effect. This Section is also active in the field of the digital optical holography to measure MEMS profiles and deformations under static or dynamic regime. This activity is strongly related to the development of new microsystems. The technique allows us the free contact three dimensional characterization of MEMS with high lateral (< 1 μm) and depth (< 5 nm) resolution.

2.4.6 Electrical characterization

In the field of electrical measurements, many activity are in progress in Catania and Bologna to investigate the conduction mechanisms of ultra thin dielectrics and to study electromigration phenomena in metal interconnects. The Catania and Bologna laboratories are equipped with several KEITHLEY, AGILENT, and network analyzers. They are also equipped with thermal chucks working from −60 to 200 °C and DLTS instruments. Laboratories for the electrical characterization of sensors and microsystems are present in Napoli, Lecce and Roma, too. The scientific production during 2002 has been mainly concentrated on the ultra-thin oxide characterization.