From the outset we mention that the article on "Quantum Electronics and Photonics in Belgium" by Irina Veretennicoff which was published in Physicalia Magazine Vol. 27 (No. 3), 295-301 (2005) as part of the same series of articles on "Research in Physics in Belgium" covers topics that are partly complementary to the present overview.

Since the invention of the transistor, more than half a century ago, devices made out of semiconductors have transformed our society. For example, the internet revolution has become possible thanks to microelectronics. Microelectronics continues to be one of the most rapidly evolving generic technologies. The development in microelectronics also leads to the rapidly expanding field of microsystems with interesting applications in medicine, pharmacology, automotive, space, …

Parallel to the economic importance of semiconductors there has been a lot of new physics that has emerged from it. Think about the quantum Hall effect (Nobel prize physics in 1985) and the fractional quantum Hall effect (Nobel prize in physics in 1998).

The importance of materials based on semiconductors is due to the fact that small fractions of dopants are able to alter the electronic, magnetic or optical properties of the host material. For example, it is possible to change the resistivity by orders of magnitude, e.g. by adding dopants one can go from an insulator to almost a metal.

In Belgium the largest research centre devoted to semiconductor research and development is IMEC [1] located in Leuven. The Interuniversitair Micro-Elektronica Centrum (IMEC) was setup in 1984 by the Flemish government as part of a comprehensive program in the field of microelectronics. This centre has close ties with industry and universities.

At IKS/KULeuven [2] the technique of ion implantation is used to dope semiconductors like e.g. Ge, GaN and SiGe. Ion implantation is one of the most well established techniques in industry for semiconductor doping since it allows a precise control of the amount of introduced material, allowing even to overcome material solubility limits. However, a major disadvantage of this technique is the damage introduced in the crystalline lattice when the incoming high-energy particles displace the host atoms from their positions. Structural and chemical characterization is done at EMAT/UAntwerpen [3] through transmission electron microscopy (TEM) and electron energy loss spectroscopy (EELS). Theoretical support for the interpretation of the EELS data is given by TSM/UAntwerpen. At IKS/KULeuven [2] High Resolution X-ray diffraction (HRXRD) and Rutherford backscattering spectrometry (RBS) is
used. These structural data are complemented by electrical (deep level transient spectroscopy) and optical (cathodoluminescence, photo luminescence,...) investigations, in order to unravel the relation between structural and functional properties.

Silicium based materials

Si has been and still is ‘the’ material used in the semiconductor industry. Integrated circuits (ICs) based upon silicon MOSFETs can perform functions such as computing, signal processing, and information storage efficiently and cheaply, and are, thus, used in virtually every electronic device produced today. Over the past three decades, by reducing transistor gate lengths with each new generation of manufacturing technology, steady improvements in circuit performance (speed) and cost per function have been achieved. However, continued transistor scaling will not be as straightforward in the future as it has been in the past because fundamental materials and process limits are rapidly being approached. In the future, bulk-Si MOSFETs will require high-permittivity (high-κ) gate dielectrics and metal gate electrodes, as well as low-resistance ultra shallow junctions, in order to meet the stringent specifications of the International Technology Roadmap for Semiconductors (ITRS).

Techniques such as semiconductor band-gap and strain engineering to improve device transconductance and on-state current is an alternative. Advanced MOSFET structures such as the ultrathin-body (UTB) silicon-on-insulator (SOI) single-gate transistor and the double-gate (DG) transistor can be scaled more aggressively than the classic bulk-Si structure and, hence, may be adapted for IC production as early as the 45-nm technology node (15-nm physical gate length).

IMEC [1] developed a new, cost-effective process for the growth of high-quality strained Si layers on ultra-thin SRB layers (220 nm instead of the traditionally used 3 to 5 µm). A NiSi process was developed, which was compatible with 45 nm node requirements, and SiGe SRB layers. The formation of ultra-shallow junctions was also studied, using solid phase epitaxial regrowth (SPER), flash anneal and dynamic surface anneal (DSA).

At SP/KULeuven [4] the work on crystalline-semiconductors focuses on the fundamental characterisation (atomic nature, electrical aspects, thermal behaviour) of imperfections and traps with crucial impact on the electrical behaviour of semiconductors and advanced semiconductor/insulator heterojunction structures. This is addressed through synergetic combination of interface-specific experimental methods sensitive to local atomic structure (low-temperature electron magnetic resonance), to the fundamental (extended) electron state spectrum (internal photoemission -IPE), and to localized electron states (interface trap spectroscopy based on capacitance-voltage and conductance-voltage measurements). Information of band structure and band offset is inferred from internal photo-emission and photo-conductivity spectroscopy.

Various nm-thin dielectric films are deposited on traditional c-Si using various state-of-the-art techniques such as chemical vapour deposition, pulsed-laser and atomic layer deposition, and molecular-beam effusion. SP/KULeuven [4] studied layers as SiO₂, Si₃₄O₂₂N₈, high-dielectric constant (k) binary metal oxides HfO₂, ZrO₂, Al₂O₃, Sc₂O₃, La₂O₃, ternary Hf-Ti, Hf-Sc, Hf-La, and Hf-Ta oxides and ternary rare-earth metal oxides GdScO₃, DyScO₃, LaScO₃, LaAlO₃. The work addresses fundamental aspects of the newly composed structures, such as electronic band gaps and band off sets (i.e., relative energies of the conducting species within the various stacked layers) and the atomic nature of inherently occurring (interface) defects and traps, as well as on technological aspects dealing with electrical performance. The effort fits within the context that as a result of the continuous scaling of metal-oxide-silicon (MOS) based devices, the technological necessity has emerged to replace the conventional high performance SiO₂ and SiON insulators by a material with higher dielectric constant in future
generations of semiconductor electron devices. The research on high-k insulators is extended by SP/KULeuven to other semiconductors exhibiting electrical performance superseding Si, such as strained-Si, SiGe alloys, Ge, GaAs and SiC.

Since many years silicides have been used in VLSI (Very Large Scale Integration) technology as a contact material or in source, drain and gate areas of microelectronic components. With the ongoing reduction in device dimensions the demands on these silicides become more and more severe. The conventional transition metal-silicides (TiSi₂, CoSi₂) loose the properties for which they were initially chosen as contact or source material at linewidths below 40 nm. However, the quantum effects resulting from these decreasing dimensions are not only a part of the problem, they also provide a way to overcome the limitations of the currently used techniques. The research at IKS/KULeuven deals both with the improvement of the currently used materials and techniques by introducing ternary silicides as well as with the formation of nanostructures which have potential in new (quantum) applications.

The research group semiconductor/metal contacts (SMC) of the department of Solid-state Science at the University of Gent [5] studies the formation and properties of metal-Si compounds. These silicides are used for contacts in Si-based micro-electronics. They collaborate with IBM Research and the National Synchrotron Light Source in Brookhaven National Lab, which allows them to perform in-situ measurements during the solid-state reaction between a metal film and a semiconductor, i.e. during contact formation. They used this experimental set-up to study e.g. the effect of alloying elements on the formation and stability of CoSi₂ and NiSi. They have also an interest in the fabrication and characterization of nano-scaled contacts to semiconductors, using electron and/or ion beam based lithography (FIB/FE-SEM), electrochemical deposition and conducting probe AFM (CP-AFM).

The photonics group INTEC [6] develops low loss passive nanophotonic circuits in Silicon-on-Insulator (photonic crystals, photonic wires, ring resonators…) by means of deep-UV lithography in collaboration with IMEC [1]. These photonic structures have features down to about 100 nm with an accuracy better than 10 nm. Special attention is given to the reduction of loss mechanisms and to the coupling between the nanophotonic circuit and the outside world.

Si clusters are produced with a laser vaporization source at VSM/KULeuven [7] and characterized by mass spectroscopy. The optical properties are studied through photoluminescence in the presence of very high magnetic fields using the pulsed magnetic field facility of VSM/KULeuven.

A further activity of the SP/KULeuven group is the study of the localized state density in amorphous semiconductors of the silicon and chalcogenide groups, by means of steady-state and transient photoconductivity techniques.

At the Institute for Materials Research (IMO, Hasselt University) and the IMOMEC division of IMEC, [14] a plurality of reliability related issues of microelectronic devices are studied such as electromigration, hot carrier degradation, time-dependent dielectric breakdown and metal interdiffusion. Another important topic is the study of grain growth in submicron dual damascene electrochemically deposited copper interconnects. Specialized analytical techniques have been developed to study the dynamic behaviour of the grain growth process. The focus is on a physical understanding of the grain growth mechanism.
Germanium

Recently, germanium has regained much interest in the semiconductor industry because of its promising properties: it has 3 times higher mobility than silicon thus making it more suitable for high-speed circuits; dopant activation in germanium can be done at lower temperatures, therefore making low-temperature processing possible; germanium has the same lattice parameter as GaAs thus enabling on-chip integration of GaAs active optical components with Ge CMOS circuits.

IMEC (and also SP/KULeuven) studies the deposition of high-k materials (HfO₂) on Ge surfaces, the formation of capacitors, junctions and diodes.

SMC/UGent is interested in the formation and properties of germanides and carbides for contacting Ge- and C-based semiconductors (SiGe, Ge, diamond, SiC or carbon nanotubes).

III-V semiconductors

Si has an indirect band gap and consequently is not suitable for optical applications. Currently, III-V semiconductors are used in most solid-state lasers.

For fundamental research GaAs has been the most wide spread material because it can be grown epitaxially on AlGaAs resulting in heterostructures with record high mobilities.

The magnetic field dependence of the electrical and thermodynamic properties of a two-dimensional gas of charge carriers is investigated by PCPM/UCL [8], with special emphasis on the integer and fractional Hall effect, spin textures, composite fermions and the metal-insulator transition. Ballistic nanojunctions are produced by DICE/UCL [9] to study rectification and universal conductance fluctuations.

The magnetic field dependence of the optical properties of quantum wells, quantum wires and self-assembled quantum dots are investigated by VSM/KULeuven [7]. Theoretical support is provided by CMT/UAntwerpen [10] where the energy levels of shallow impurity states, excitons, charged exciton and biexciton energies are calculated using the stochastic variational technique and quantum Monte Carlo.

Spin related phenomena provide opportunities for the realization of new electronic devices. Two-dimensional electron/hole systems (2DESs/2DHSs) in GaAs-based heterostructures are the best choice for understanding the role of discrete degrees of freedom for quantum transport, as they combine low disorder and a simple/non-trivial band structure. Magnetotransport studies on these systems are performed by DICE/UCL [9] in order to measure the spin polarization of two-dimensional (2D) carriers and to observe spin-resolved ballistic transport. The theoretical description of spin phenomena due to the Rashba and Dresselhaus spin-orbit effect are done at CMT/UAntwerpen [10].

SMC/UGent [5] investigates the influence of inhomogeneities on the current-voltage characteristics of metal/semiconductor (GaAs, InP and GaP) contacts.

INTEC [6] develops membrane-type III-V semiconductor devices (mostly InP) for light emission (LEDs and laser diodes), bonded to other III-V substrates or to Silicon by means of BCB-bonding. Components and systems for nonlinear all-optical signal processing are studied by INTEC in collaboration with the OptIQ/ULB center [18]. Common efforts are concentrated on the temporal dynamics of these devices at a picosecond scale, as well as their transverse spatial self-guiding behavior.
Electron-phonon interaction is investigated theoretically by TFVS/UAntwerpen [11] and CMT/UAntwerpen [9] with special emphasis on many-particle effects, like e.g. hybrid magnetoplasmon-phonon modes and screening of the polaron and its effect on cyclotron resonance. Modeling of self-assembled quantum dots and quantum rings is done by CMT/UAntwerpen [10] and TFVS/UAntwerpen [11] which is based on a calculation of the strain and subsequently \( k \cdot p \)-theory is used to obtain the electronic structure.

Optical (surface) plasma resonant phenomena in nanolayers of highly n-doped III-V semiconductors are theoretically and experimentally investigated by LAMI/VUB [12] for the spectral range of CO\(_2\) lasers (9-11 μm). Such phenomena are exploited for the development of novel modulators, Q-switches, detectors and cameras for the given spectral range. Directly related to these investigations are the study of ultra sensitive calibration techniques for the determination of non-equilibrium non-auto-compensated IV-doping densities in III-V’s, which is done in collaboration with IMEC [1].

GaN has attracted widespread attention due to its large band gap and hardness. Furthermore, GaN is a suitable material for the fabrication of optical components that operate in the blue to ultraviolet region of the electromagnetic spectrum, and for microwave and high-power applications. The growth of GaN was initially done at INTEC-IMEC (Gent) but is currently performed at IMEC (Leuven). Ion implantation of different type of dopants occurs at IKS/KULeuven [2]. Structural characterization is done by EMAT/UAntwerpen [3].

TSM/UAntwerpen compute electron scattering data in ternary semiconductors, which are needed for accurate compositional analysis of semiconductor nanostructures such as In\(_x\)Ga\(_{1-x}\)As, Cd\(_x\)Zn\(_{1-x}\)Se,… In particular structure amplitudes, Debye-Waller factors and static displacements effects are calculated by using both first-principles electronic structure calculations and large-scale calculations based on empirical interatomic interaction potentials. In this way accurate data for quantitative analysis with electron microscopy are obtained of these materials

**II-VI semiconductors and wide band gap materials**

The II-VI semiconductors are gaining an increased interest due to their possible usage as yellow/green/blue solid-state optical emitters. Quantum dots made out of such semiconductors are characterized by EMAT/UAntwerpen [3] and studied optically by FUNDP [13]. Ordered operator calculus is used by TFVS/UAntwerpen [10] to investigate the exciton-phonon coupling leading to non-adiabaticity. This theoretical study allows to interpret the photoluminescence and Raman spectra of spherical quantum dots and quantum-dot quantum wells.

At the Institute for Materials Research (Hasselt University) and the IMOMEC division of IMEC [14] several wide band gap materials are studied, including diamond, AlN and BN. Most important are thin films of epitaxial and polycrystalline diamond, which are grown by microwave-enhanced chemical vapour deposition. The focus lies on the (opto-) electronic properties of these films, which are tuned by varying the deposition parameters and/or adding doping gasses to create p- or n-type conductive films. IMO-IMOMEC is e.g. one of the few laboratories in the world that are able to grown p-doped n-type diamond. The growth of thin nano- and ultrananocrystalline diamond films allows to study the grain-size dependence of several characteristic properties. The nitrides AlN and BN are prepared by magnetron sputtering. Especially h-BN is interesting as this material has potential in laser applications.
Besides structural and morphological methods such as SEM, EBSD and XRD, highly sensitive spectroscopic techniques based on photocurrent (PC, CPM, FTPS) or thermal deflection (PDS) enable to study the defect-related DOS in the band gap.

**Diluted magnetic semiconductors**

These materials belong to the larger program of ‘spintronics’. The goal of this program is the manipulation, transport and storage of “spins” and their implementation in nanoscale electronic devices and systems. In particular, III-V semiconductors doped with Mn are promising because they are ferromagnetic. MBE-growth of III-V semiconductor heterostructures, including ferromagnetic semiconductors, epitaxial magnetic films, and epitaxial half-metals, … is realized at IMEC [1]. They have also optical and magnetotransport measurement setups, ultrafast (spatially resolved) magnetization probes at room and low temperature (Kerr, transport), optical detection of electrical spin injection, … The magnetic, electrical and optical properties are investigated at VSM/KULeuven [7] and modeled by CMT/UAntwerpen [10].

**Organic semiconductors**

Organic materials will not replace silicon technology, it is expected that organic conductors will lead to innovative device concepts. They will have mechanical flexibility, tunable functionalities and relatively simple process technologies. At IMEC [1] materials and technologies are developed to increase the mobility of organic materials. For this, crystalline organic conductors in single crystal and thin film form are studied using molecular layer epitaxy in UHV system and a vapor phase deposition.

At IMO/UHasselt [14] the growth, the physico-chemical material properties, morphology and device characteristics, fundamental electro-optical material properties, stability of organic based electronic material systems and lifetime prediction are made. These materials are also studied for biosensor applications.

IMO-IMOMEC studies organic semiconductors like conjugated polymers and fullerenes at molecular level, as thin films, and in the form of devices. Prototype solid state devices include PLEDs, polymer/hybrid solar cells, transistors, biosensors and chemosensors. Research subjects are morphology, physico-chemical and electro-optical material properties, device characteristics, and the assessment of the long-term device stability. Recently, also nanostructured hybrid films and devices (e.g. Grätzel-type solar cells), based on the combination of organic semiconductors and inorganic semiconducting nanoparticles, became a central topic of research at IMO-IMOMEC.

**Modelling**

A large expertise is available in Belgium on modeling of semiconductors and of devices based on semiconductors. In addition to the one mentioned above we mention: 

*Ab initio* calculations are done at UCL [15] were the effort is mostly focused on code development of the ABINIT software [16]. This software package is used by CMT/UAntwerpen [10] to model the electronic structure of low dimensional semiconductors, e.g. quantum wires.

A model for (hot) free electron absorption in (an)isotropic (non)-parabolic multi-valley (Γ,L,X) III-V semiconductors based on quantum mechanical second order perturbation theory has been developed at LAMI/VUB [12]. Linear and non-linear phenomena are described taking into account screened impurity, acoustic, (non)-equivalent intervalley, thermal and hot
optical phonon assisted absorption processes. Thermo-opto-electronic properties e.g. photon-induced Seebeck effects have been modeled in the same framework.

Within the "Reliability, Electrical Characterization and Modeling (REM)" division of IMEC [17], the modeling group provides theoretical and numerical support in the areas of submicron CMOS technology and nanoelectronics. The modeling activities can roughly be divided into ab-initio calculations and quantum transport modeling. The modeling on nanowire-based structures is in collaboration with CMT/UAntwerpen [10]. Quantum transport modeling is done in collaboration with TFVS/UAntwerpen [11].