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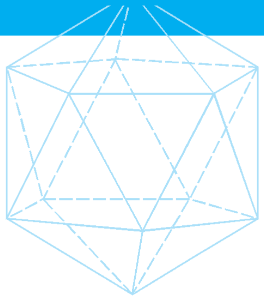

# Semiconductors in 21st Century — The First Decade

Based on the lecture delivered on February 25, 2010*

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## Introduction

As a class of materials, semiconductors played, and continue to play, an undeniably pivotal role in the explosive growth of our technical civilization over the last six decades. The main driving force behind this growth was the unprecedented progress in digital integrated circuits (IC) technology as described by Moore's law [1].

During recent years, departure from the pattern noted above can be observed. It is no longer that progress in semiconductor technology is driven solely by technical breakthroughs needed to sustain the growth of digital electronics. During the last ten years, the impact of digital electronics is increasingly accompanied by the accelerated growth of distinct, readily identifiable semiconductor technical domains which are only partially related, or not related at all, to logic and memory IC technology.

The purpose of this overview is to identify and to briefly discuss, in layman terms, selected technologies which are perceived to contribute the most to the recent expansion of priorities which define state-of-the-art semiconductor science and engineering.

To establish a foundation for the follow up discussion, a brief overview of the fundamental properties of semiconductors, key semiconductor materials, as well as their uses is presented. Then, trends in semiconductor science and engineering are discussed and emerging new directions are identified. Subsequently, a discussion of new generation technology drivers is presented, emphasizing the role of organic semiconductors, nano-ordered semiconductor material systems, carbon electronics, as well as photovoltaics, and MEMS/NEMS devices in defining emerging trends. The review is summarized by stressing the critical role semiconductors continue to play in supporting high-tech endeavors of the 21st century.

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* This text is also available on **www.semi1source.com/21stCentury**

# Overview of Semiconductors

For the sake of clarity of the forthcoming discussion, it is appropriate to introduce key concepts related to its scope by answering the following three basic questions.

## What Are Semiconductors?

The fundamental electrical property of any solid is its electrical conductivity, i.e. ability to conduct an electric current. As Figure 1 illustrates, insulators and conductors feature very low and very high conductivity respectively, regardless of external conditions such as temperature, or illumination. The electrical conductivity of theses materials, as predetermined by the nature of interatomic bonds which determine electron's freedom to move within a solid, cannot be altered. Metals for instance, can only be very good conductors.

What distinguishes electrical conductivity of semiconductors from metals and insulators is basically what defines semiconductors as a separate class of solids. First and foremost, in contrast to metals and insulators, electrical conductivity of semiconductors can be controlled by orders of magnitude (Fig. 1) by introduction of alien elements (doping). Furthermore, conductivity of semiconductors can be controlled by two types of carrier: negative electrons or positive holes. In addition, it depends on temperature, illumination, as well as electric and magnetic fields. Very importantly, and again in contrast to metals and insulators, when adequately processed, semiconductors can emit visible radiation. These outstanding characteristics allow a myriad of highly functional devices, both electronic and photonic to be made using semiconductors.

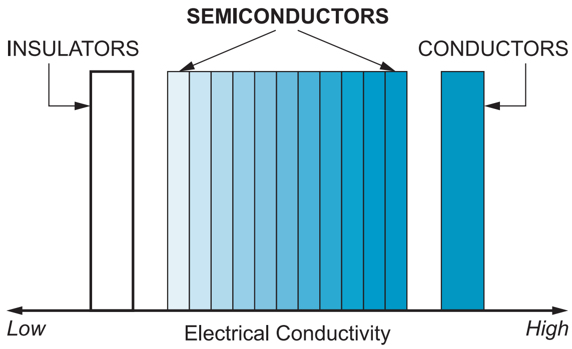

**Figure 1.** Electrical conductivity of solids

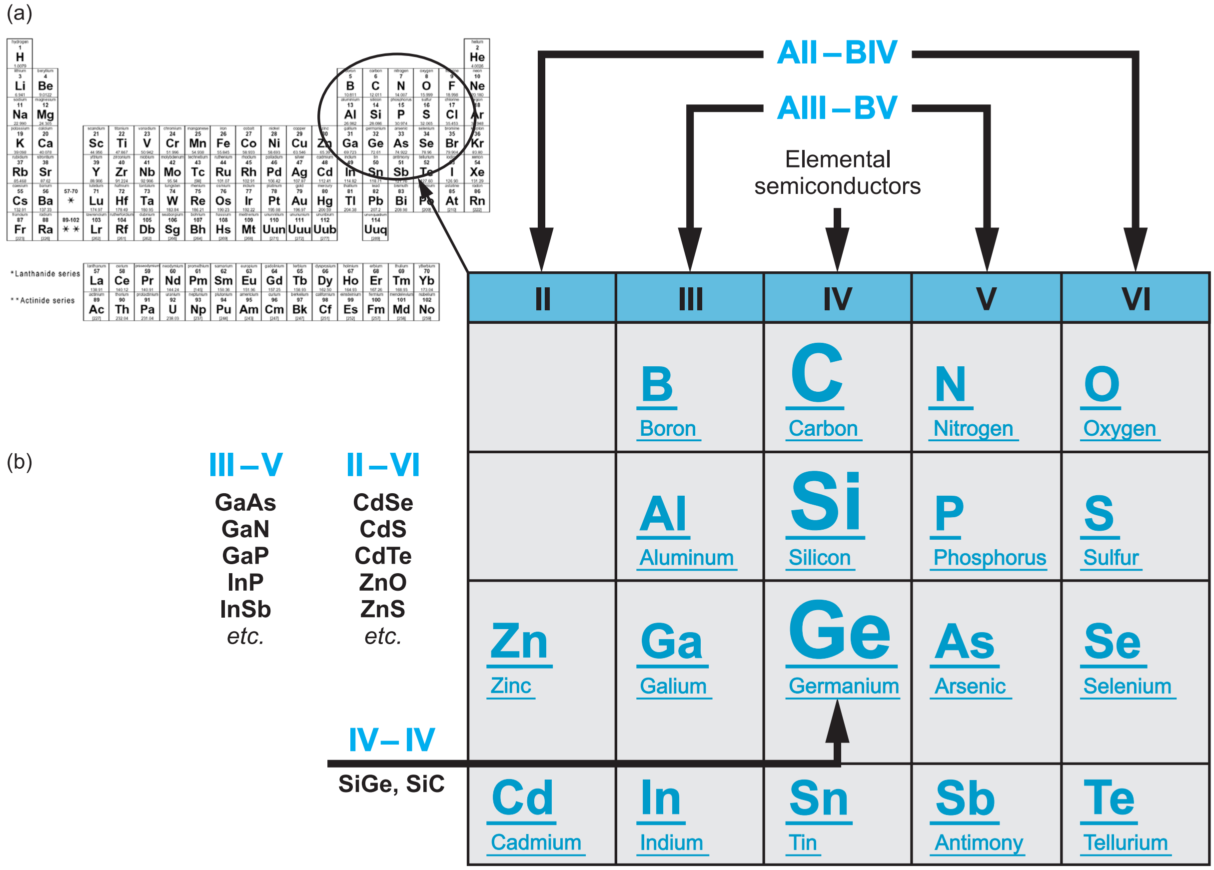

**Figure 2.** Materials displaying semiconductor properties

## What Materials Display Semiconductor Properties?

In the Periodic Table of the Elements (Fig. 2a) a section singled out in Figure 2b is often referred to as a “semiconductor periodic table”. All inorganic semiconductors either elemental in group IV, or compound synthesized from the elements from the group IV (e.g., silicon carbide, SiC), groups III and V (e.g., gallium arsenide, GaAs), as well as groups II and VI (e.g., cadmium selenide, CdSe) originate from this section of the periodic table.

In addition to a range of inorganic semiconductors identified in Figure 2b, selected organic compounds form a very distinct class of semiconductors featuring unique properties and offering a range of novel applications (see discussion later in this overview).

Semiconductors can be subdivided into classes featuring diversified properties based on the chemical composition, fundamental physical properties, as well as the extent of an order in the three-dimensional arrangements of atoms. In this last case ordered (crystalline) and disordered (non-crystalline, or amorphous) semiconductors are distinguished. In addition, the nano-ordered semiconductors featuring a highly ordered structure within extremely confined geometries, such as nanowires, nanotubes, and quantum dots, can be singled out.

Silicon (see Fig. 2b) is by far the most important and the most widely used semiconductor material. Its use continues to grow not only through the needs of ever progressing microprocessor and memory integrated circuit technology, but also through the growing needs of solar cells (photovoltaics) and Micro-Electro-Mechanical Systems (MEMS) applications. Among compound semiconductors, gallium (Ga) compounds with group V elements (Fig. 2b), gallium nitride (GaN) and gallium arsenide (GaAs) in particular, are the most important due to their usefulness in a range of electronic and photonic applications.

## How Semiconductors Are Used?

It can be safely assumed that with the exception of the most rudimentary ones, all instruments and any equipment which uses electricity to operate require semiconductor elements to be functional. From the most complex outer space instrumentation, weaponry, or information processing circuitry, to simple everyday tools and gadgets semiconductors are the foundation upon which the operation of almost everything electronic and photonic is based.

In order to implement the desired operations, semiconductor material is processed into a device which can perform in a controlled and predetermined fashion electronic (e.g. diode, transistor, monolithic integrated circuit), or photonic (e.g. Light Emitting Diode, or LED, laser) functions. Among many classes of semiconductor devices a select three, deemed the most important in terms of function, are shown in Figure 3. A transistor (Fig. 3a) is a device designed to amplify and/or switch an electrical signal and as such is a cornerstone of semiconductor device engineering. The transistor is a basic building block of all integrated circuits (IC), and hence, has been developed into by far the most complex and most important semiconductor device. Other than transistor, semiconductor diodes that can be used to either emit light of desired wavelengths (light-emitting diode in Fig. 3b) or convert light into electricity, as it is done in solar cells (Fig. 3c), are the other key semiconductor devices.

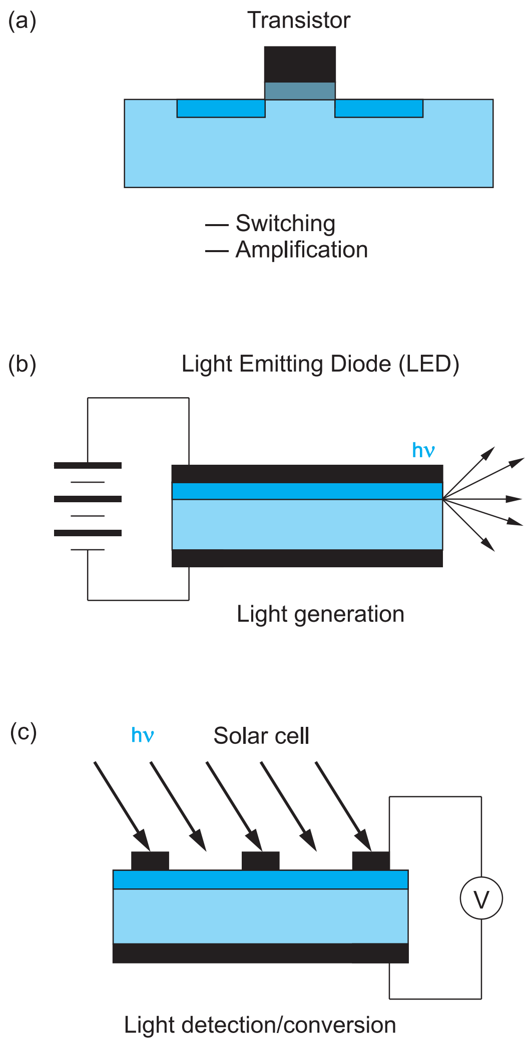

**Figure 3.** Key semiconductor devices (a) transistor used for switching and amplification of electric signal, (b) $p$–$n$ junction diode acting as an light emitter, and (c) $p$–$n$ junction diode acting as a solar cell

# Technology Drivers in 20th Century

Since the invention of the transistor in 1947 followed by the commercial introduction of integrated circuits (IC) some twenty years later, progress in semiconductor technology has been driven primarily by the need to process information faster and more efficiently. Processing information is all dependent upon devices which can be turned "on" and "off" fast enough so that corresponding sequence of "1"s and "0"s can be executed billions of times per second. Since the Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET) is the most effective device in carrying out these functions the progress in IC engineering was driven primarily by the improvements in MOS technology.

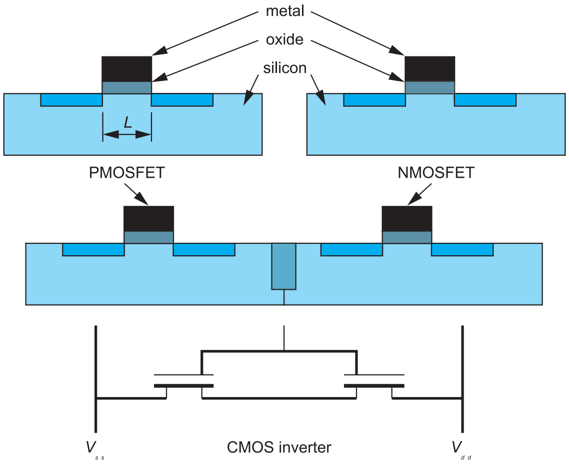

**Figure 4.** Complementary MOS structure, CMOS — an ultimate electric switch

To be exact, it is not a MOSFET either *n*-channel or *p*-channel (Fig. 4 a and b), but the combination of these two in the Complimentary MOS (CMOS) structure shown in Figure 4 c that is the focus of attention. CMOS shows superior characteristics in switching applications including very low energy needed to switch it from "on" to "off" state, and hence, very limited power dissipation, as well as essentially no current in the "off" state. In more general terms, digital applications involving logic and memory ICs were driving forces behind the dramatic progress in semiconductor science and engineering over the last fifty years.

During those years, progress in IC technology expressed in terms of the number of transistors per chip by Moore's law (Fig. 5) was dependant primarily on the continued reduction of transistor's geometry in CMOS cells with scaling down of the channel length *L* (Fig. 4) being a lead target. Technically, the reduction of transistor geometry was possible because we had ways to keep on reducing wavelengths λ of radiation used for photoresist exposure in the photolithographic processes defining transistor geometry. That was until λ was reduced to the 193 nm emission wavelengths possible with ArF excimer laser. As further reduction of λ was not feasible without overcoming significant technical and cost-related barriers, the 193 nm exposure length remained unchanged (Fig. 5)

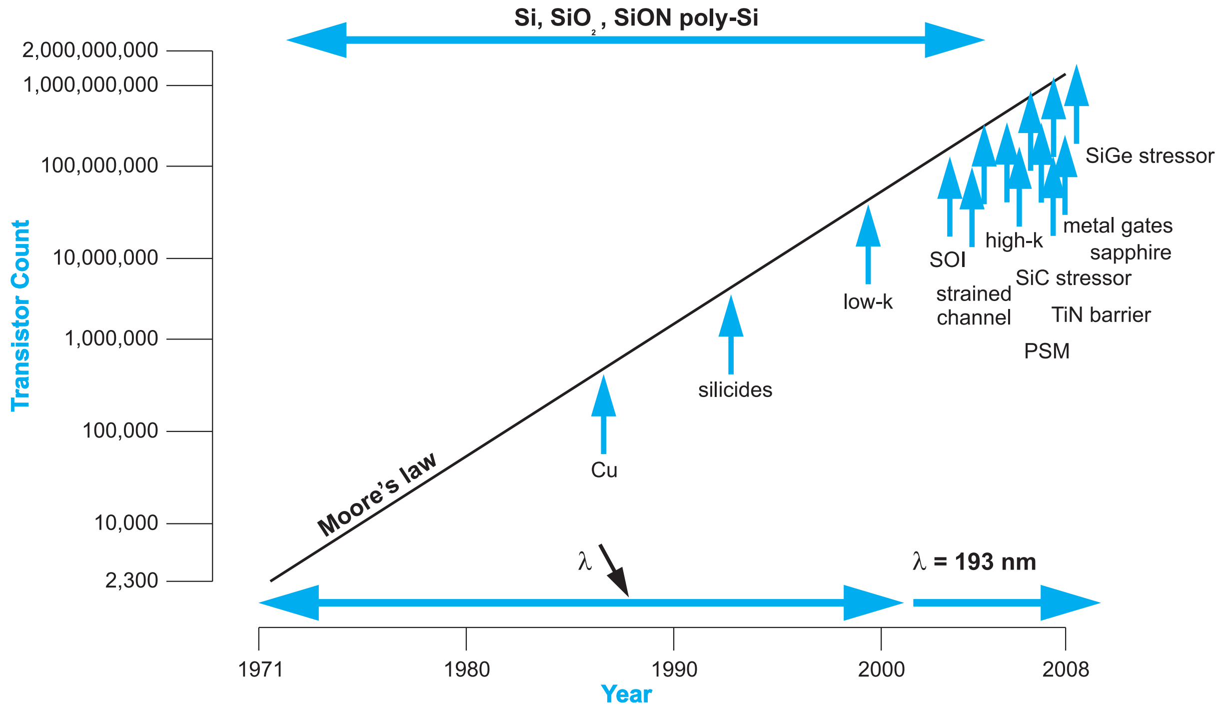

**Figure 5.** Recent progress in integrated circuit technology is driven primarily by material engineering solutions

and alternative ways of improving the performance of the CMOS were pursued.

While all this was happening not much was changing in terms of materials used to fabricate advanced ICs (with the exception of copper replacing aluminum as an interconnect material, Fig. 5) and device configuration. It was all based on silicon and its derivatives (single-crystal Si, poly-Si, $SiO_2$, $Si_3N_4$, SiON) while planar CMOS remained a benchmark in terms of device layout.

In parallel to the rapid growth of the electronic component of semiconductor device technology, impressive progress has also been accomplished at the photonic end of the semiconductor device spectrum. Over several years the driving force in this domain was an effort to develop blue light emitting diodes needed in addition to the longer wavelength LEDs developed earlier. This effort was punctuated by the successful development of blue LEDs formed on InGaN [2].

# Era of Materials

As discussed earlier, for over 30 years the progress in semiconductor technology was dependant mainly on the improvements in ICs manufacturing processes, photolithography in particular. At the same time, developments that were highlighting the advancements were basically synonymous with pushing the boundaries of high-end logic and memory IC technology toward faster more potent circuits.

During the last decade or so the paradigm has shifted noticeably. With the exposure wavelength used in photolithography remaining unchanged the progress in CMOS technology is currently accomplished primarily through innovative materials engineering solutions combined with broader than ever before selection of materials used to process high-end devices.

In conjunction with this renewed emphasis on materials major modifications of the transistor's structure are aggressively pursued.

As a result, it is mostly all about the materials and the elaborately configured material systems these days. In fact, the latest process technology related breakthroughs are almost entirely related to materials engineering. Figure 5 shows examples of materials related developments that took place in advanced ICs engineering during the last few years. Introduction of high-k gate dielectrics, accompanied by the need to address a range of challenges (e.g. [3]), use of SOI substrates and the use of stressors in the MOSFET channels are just a few highlights underscoring this trend.

# Technology Drivers in Early 21st Century

Figure 6 is constructed in order to illustrate developmental trends currently observed in semiconductor engineering. As the horizontal bars in this figure indicate, integrated circuit technology continues to play pivotal role in a key technology driver. The selection of materials used besides silicon is growing continuously, device design evolves and the focus is shifting from shear speed and power efficiency to more application specific solutions based on the range of materials and transistor layouts available.

At the photonics end of the spectrum, light emitting and detecting devices clearly continue as a self-contained technical domain with growing impact on an overall semiconductor business particularly through the increased role of semiconductor devices in display technology. The new emphasis in LED technology, which emerged during the last decade as a major force, is an urgent need to use LEDs in lighting applications as a replacement for highly inefficient incandescent and fluorescent bulbs. In this respect the development effort spreads over a range of device solutions including inorganic and organic LEDs as well as quantum dot based light emitters.

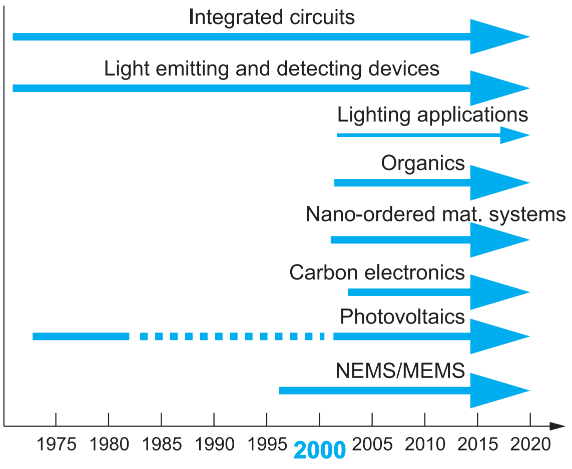

**Figure 6.** Technology drivers in semiconductor device engineering

During the last decade, several new, or renewed, applications of semiconductors have emerged as major players (see Fig. 6), and hence, can be seen as technology drivers in the early 21st century. Those emerging areas of semiconductor science and engineering are briefly reviewed below. It needs to be emphasized that the selection of those areas is based entirely on the Author's assessment of the observed trends and as such is open for discussion. Another point which should be stressed is that several among new technologies are pursued to overcome roadblocks digital IC technology will be facing in the future and not necessarily as self-contained technical domains.

## Organic Semiconductors

Until recently, all semiconductor materials used in commercial applications originated from the semiconductor series of the periodic table (Fig. 2) and were inorganic in nature. A new breed of cheap to process organic semiconductors, i.e. materials consisting primarily of carbon and hydrogen, show good promise in expanding applications of semiconductors into the areas in which conventionally thin-film inorganic semiconductors can not be used. An important factor distinguishing organic, or "plastic", semiconductors from their organic counterparts is that the former maintain their fundamental physical properties even if drastically bent. This characteristic opens up possibility of formation of low-cost functional semiconductor devices on flexible substrates.

From the point of view of physical properties, organic semiconductors differ in several ways from their conventional, inorganic counterparts. Just like other semiconductors, however, they do allow control of charge distribution using external electric field and they do have the capability to emit visible radiation. Consequently, several semiconductor device structures both photonic (LEDs, solar cells) and electronic (Thin--Film Transistors, TFTs) can be implemented using select organic compounds.

The fundamental difference between inorganic and organic semiconductors is in the charge transport mechanism. In the former case electrons moving in wide bands as delocalized plane waves are subjected to very limited scattering, and hence, feature relatively high mobility (e.g. $\sim 1.5 \times 10^3$ $cm^2V^{-1}s^{-1}$ in Si at room temperature). In the case of organic semiconductors, the charge transport is based on carriers hopping between localized states associated with organic molecules. In the process electrons undergo significant scattering which result in very low electron mobility in organic semiconductors ($\sim$1–3 $cm^2V^{-1}s^{-1}$).

The best promise for a breakthrough application that organic semiconductors show is in flexible displays as well as printed electronics and photonics. In the former cas, organic LEDs (OLEDs) (e.g. [4]) and TFTs, both needed to engineer high quality active matrix full-color display, are the center of attention. In OLEDs light generation is based on the decay to the ground state of excitons formed through interactions between electrons and "holes" rather than through the band-to-band recombination as is in the case of conventional LEDs. In organic TFT, similarly to conventional TFTs, transistor action is based on the field effect in which potential applied to the gate contact changes the conductivity of organic semiconductor between source and drain.

## Nano-Ordered Semiconductor Material Systems

As current technology allows us to manipulate a solid matter at the atomic and molecular level the formation and use of nano-scaled (nm = $10^{-9}$ m; size of the atoms varies depending on the element from 0.2 nm to 0.5 nm) material systems has become entirely feasible. Due to their physical properties being distinctly different from their bulk counterparts, the nano-ordered (see earlier discussion) semiconductor material systems offer a range of novel applications and have a potential for addressing challenges semiconductor technology, including digital ICs, will face in the future. As a result, nano-ordered semiconductors have emerged during the last decade as one among major technology drivers (Fig. 6) partially because of the role they are expected to play in resolving limitations of future generations digital electronics.

The starting point to understanding nano-ordered material systems is recognizing the fact that the fundamental properties of a solid confined to ultra-small geometries are different than the properties of the exact same solid in bulk form. Figure 7 a shows a crystalline bulk material, silicon for instance, featuring well defined physical characteristics governed by the laws

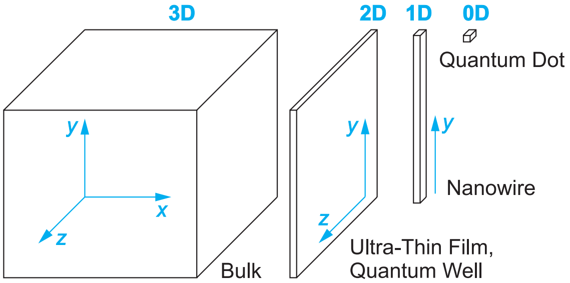

**Figure 7.** Physical properties of semiconductor material change as its geometry is scaled from 3D to 0D configuration

of classical physics. It is enough, however, that its one dimension is reduced to close to zero, effectively forming a silicon sheet a few atoms thick (Fig. 7b) that its properties change significantly. This is because 2D-confinement alters the distribution of energy levels which can be occupied by electrons in the atom, and hence, changes fundamental physical properties which now are defined by the laws of quantum physics. The same phenomena are further reinforced in the case of 1D confinement resulting in nanowire formation (Fig. 7c) and zeroD confinement leading to the formation of quantum nano-dots (Fig.7d). Those last show dependence of the bandgap on the size of the dot allowing tunability of basic properties of the material by changing the size of the dot. This particular characteristic is very useful especially in photonic applications (e.g. [5]).

The ability to form nano-ordered semiconductor structures shown in Figure 7 opened up new areas of application of semiconductor technology and established this particular technical domain among the key technology drivers in semiconductor technology in the early 21st century.

## Carbon Electronics

Due to manufacturability related issues, lack of substrates as well as lack of effective *n*-type dopants [6], bulk carbon in the highly ordered crystalline form (diamond) did not fulfill its promise of an excellent semiconductor. However, in the nano-ordered form, a range of carbon-specific material structures show great promise in a number of key applications.

Among the most exciting forms of nano-ordered carbon is its two dimensional version known as graphene. This unique structural configuration of pure carbon has the potential to have a real impact on how we will build active semiconductor devices in the future.

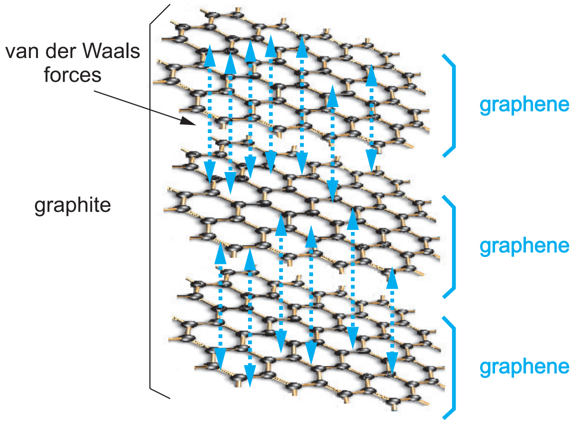

**Figure 8.** Weak van der Waals forces bind graphene sheets to form graphite

In terms of crystallographic structure, graphene is a two-dimensional part of the three-dimensional graphite, i.e. one atom thick planar sheet of carbon that is connected to adjacent sheets by relatively weak van der Waals forces (Fig. 8). Effectively then, graphite is a thick stock of graphene sheets each internally covalently bonded (a very strong bond) in the planar hexagonal configuration, but which are relatively weakly bonded between each other.

One of the many remarkable characteristic of this ultimate 2D material structure is that graphene displays excellent semiconductor properties. Particularly attractive is its very high carrier mobility in excess of 150,000 cm$^2$/Vs. Interestingly, early observations based on conductance measurements suggests that in graphene electron and holes mobilities should be almost the same. This is in contrast to conventional 3D semiconductors (Fig. 7a) in which electrons feature significantly higher mobility than holes..

Regarding electronic applications, graphene can be used to form ultra-fast transistors. A graphene based transistor featuring 100 GHz cut-off frequency has been recently demonstrated [7].

Graphene can be obtained by detaching, atomic layer by atomic layer, sufficiently large pieces of graphene from graphite and transferring them to other substrates, or, by far more effectively, by growing it on silicon carbide substrates. Rolled into a cylinder, graphene will form a single-walled carbon nanotube which form another unique carbon configuration with potentially important applications in semiconductor device manufacture.

## Photovoltaics

Photovoltaics constitute yet another technology driver in state-of-the-art semiconductor science and engineering (Fig. 6). The photovoltaic effect is the effect based on which solid state devices convert light into electricity. This effect is by far the most efficient when such devices are made out of semiconductors. Hence, the term “photovoltaics”, which refers to the technical domain concerned with the conversion of solar energy into electricity using photovoltaic effect, is essentially synonymous with semiconductor solar cells.

The photovoltaic effect was experimentally observed some 150 years ago [8]. Since then, during the last fifty years in particular, commercial attempts to use it as a vehicle allowing direct conversion of solar light into electricity were highly dependant upon cost and balance between supply and demand for energy derived from fossil fuels. The interest was always growing during energy crisises, e.g. in the early 1970’s

(Fig. 6) then dissipated after the oil market regained its balance.

The above scheme was decidedly altered during the last decade when, sparked by yet another energy crisis, the world-wide push toward the alternative to fossil fuel sources of energy firmly established photovoltaics as a rapidly growing segment of semiconductor industry. Currently, a large number of commercial enterprises manufacturing solar cells are fully functional around the world.

It should be emphasized that although shaped and processed differently, solar cell fabrication involves the same manufacturing methods and materials as most of the other semiconductor devices. With the technology and knowledge available today the efficiency with which solar cell converts light into electricity is proportional to the cost of its fabrication which in turn depends on the cost (quality) of materials used and complexity of manufacturing processes employed. Based on this paradigm, various classes of solar cells can be distinguished.

In terms of materials used silicon dominates solar cells industry while the selection of technology roughly comes down to the choice between thin-film solar cells using non-crystalline silicon, or CdTe for instance (solar cells based on organic semiconductors belong to this class), and crystalline semiconductor, again mainly silicon, in the form of very thin square substrate wafers. The former offers low-cost cells but at the expense of efficiency. The latter produces more efficient cells but at a higher cost. Figure 9 shows schematic diagram of the typical amorphous silicon thin-film solar cell featuring efficiency in the 6–8% range (Fig. 9a) and single-crystal multi-layer III–V based solar cell featuring efficiencies approaching 40% (Fig. 9b). Both approaches are needed and the choice depends on the type of application. Regardless of technology/materials used photovoltaics are certainly among key technologies determining how semiconductors are used now and will be used in the future.

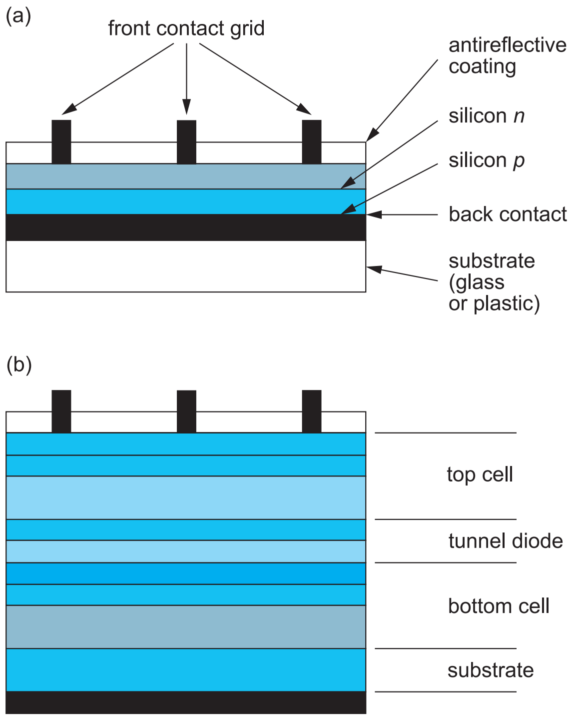

**Figure 9.** (a) Low-efficiency Si thin-film solar cell and (b) multi-layer multi-junction single-crystal III–V solar cell optimized for high efficiency

## MEMS/NEMS

Micro-electro-mechanical systems (MEMS) and follow-up generations of nano-electro-mechanical systems (NEMS) integrate mechanical and electrical functions using a somewhat modified, but otherwise standard CMOS IC manufacturing procedure. Such functional integration is possible only because silicon, besides discussed earlier advantageous electrical and cost/manufacturing related properties, also features outstanding mechanical properties. This combination is unique to silicon and cannot be reproduced using any other material.

As shown in Figure 6, growth of MEMS technology took off several years ago and is expected to continue to grow in years to come driven by the increasing complexity and functionality of MEMS/NEMS components of the complete Systems-on-Chip (SOC). Micro- and nano-sensors, including bio- and chemo-sensors, actuators, gyroscopes, accelerometers, etc. are just a few examples of MEMS devices.

While based on the Si IC manufacturing technology the MEMS fabrication processes are governed by needs which in some aspects require specialized approaches. For instance, very deep etches performed on silicon in the course of MEMS device manufacture need specialized dry etching tools. Also, MEMS release processes, not used at all in conventional IC manufacturing, call for oxide etching in intricate lateral geometries and as such required development of innovative solutions specific to MEMS manufacturing [9].

In summary, the ultra-small mechanical devices integrated on the same chip with controlling them electronic circuitry, constitutes yet another technical domain which continues to drive progress in semiconductor science and engineering. Further growth of this segment of semiconductor technology in inevitable and is expected to have a growing impact both technically and commercially.

# Concluding Remarks

This overview attempted to identify trends which emerged as forces driving progress in semiconductor science and engineering in early 21st century. The discussion presented leads to the conclusion that semiconductors now more than ever before continue to have a major impact on the evolution of our technical civilization. It is also quite evident that, although, several developments continue to be driven by the long-term needs of digital electronics, there is a range of new technologies which open up new areas of application for semiconductor materials well beyond today's uses. Some of them were briefly discussed in this overview.

Finally, it should be once again pointed out that this overview is concerned with new developments on semiconductor arena which are either commercialized already or are on the direct path to commercialization in the near future. Developments in several emerging domains such as spintronic, or use of semiconductors in broadly understood "bio" applications, are left to the future discussion. Their impact will be judged based on the future success of the process of conversion of the theoretical concepts into practical solutions.

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