Electronics and Photonics

by Andrew M. Hoff and Jerzy Ruzyllo

Over the past five decades a steady increase in both the quantity and capability of electronic and photonic components that we may interact with on a daily basis has occurred. A stroll through an airport departure terminal at nearly any time of year effectively demonstrates this point. People may be observed communicating with others by cell phone, working on laptop computers, or checking the time on digital watches. Children surround a portable DVD player to watch their favorite computer-animated movie, while others play with miniature hand-held video games as their parents listen to music from pocket-sized MP3 players. Clearly the information age, that some believe began its steady rise with the demonstration of a solid-state electronic component in a New Jersey laboratory in December of 1947,[1] has now become a global phenomenon. Electronic computer systems that occupied large rooms and used massive amounts of power were once accessible only to large business concerns or to government entities. Present day computer systems with greater functionality run for hours on sets of rechargeable batteries and fit nicely on a person's lap. Electronic and photonic components constitute and support a major portion of the global economy and strongly contribute to the effectiveness of business, education, healthcare, and entertainment sectors.

The ECS Electronics and Photonics Division finds itself in the center of the action on the semiconductor electronics and photonics arena since the invention of the transistor followed by the invention of the light emitting diode. In this brief overview, the technical and scientific foundations upon which the presence of this Division is established as well as the Division's mission and goals are presented.

Electrons and Photons

A fundamental ability to control the properties of materials and material systems forms a basis for the development and manufacture of electronic and photonic devices and systems. The difference between these two is that in the former electrons act as the information carriers, while in the latter the same function is performed by photons. An electron is a negatively charged particle in an atom and carries the smallest, or elemental, electric charge. A photon is basically a packet of electromagnetic energy that can be tailored to perform various functions in information processing systems.

Semiconductor material and device designs are selected in accord with the needs of either electronic or photonic functions. In the electronic case, the prime selection criteria include the width of the energy gap, the electron mobility, thermal conductivity, and certain manufacturability related properties. For photonic systems the key parameter is not only the width of the energy gap but also type of gap, either direct or indirect (Fig.1). Whereas historically, electronic and photonic functions were performed separately by designated devices made out of either electronic semiconductors or photonic semiconductors, the present trend toward a merger of these two functions in a single material system is irreversible. Whether in present day imaging system performance (in which the display quality is critically dependent on thin film transistors (TFTs) integrated with each pixel); or in solar cells (where an electrical signal results from the conversion of radiated energy); or in future generations of integrated circuits (where optical waveguides may one day replace electrical interconnect lines while the underlying transistors carry out electronic operations), electrons and photons are destined to interact closely within the same material system, or within the same device.

Electronic and Photonic Materials and Devices

The basic materials and processes employed to fabricate individual or discrete semiconductor electronic components have been known and in use since the late 1950s. By that time silicon had become the substrate material of choice because of its adequate electronic properties, availability, and, very importantly, the ease of formation of its high quality native oxide, SiO_2. Methods of surface preparation such as cleaning the silicon surface to remove yield-limiting trace impurities,[2] doping, and pattern definition, were in development along with high temperature chemical process techniques that formed a passivating and durable layer of SiO_2 glass on the surface of the single-crystal silicon.[3] The importance of silicon in electronics was further enhanced when, in the late 1950s two engineers working independently in Northern California and in Texas, respectively, developed schemes to integrate multiple electronic components within a single semiconductor body. This innovation, the integrated circuit or IC, formed the foundation for an unprecedented growth of semiconductor electronics.[4]

The following decades have produced a continuous stream of innovations aimed at addressing the challenge of

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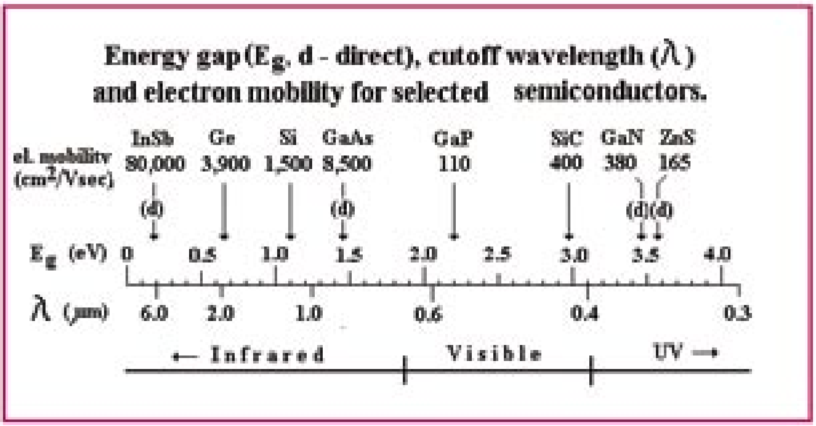

Fig. 1. *Selected semiconductors and properties determining their usefulness in electronic and photonic applications.*

providing ever-increasing capability or functionality in a given area of substrate material. Over this period the dominant semiconducting substrate material has remained silicon for the majority of ICs manufactured; although compound semiconductor materials, primarily GaAs, continued to increase in usage in various electronic applications such as wireless communication, microwave, and high-speed digital systems. For all semiconducting substrates the planar technology of manufacturing devices dominated over this period. The fabrication scheme employed for a typical circuit involves a detailed sequence of additive and subtractive layer formation and patterning steps. State-of-the-art complementary metal-oxide-semiconductor, or CMOS, circuits employ twenty or more layers and masking steps to obtain the final device. Innovations in both the materials employed (such as the increasingly broad use of SiGe in both bipolar and unipolar silicon devices), and in the fabrication approaches to forming ever smaller structures in the layers, have enabled manufacturers to provide increasingly complex and capable digital and analog devices. Progress in manufacturing tools including, in particular lithographic tools, is allowing still higher resolution of the pattern transfer process. Current geometries of cutting edge ICs are in the 65 nm range and are bound to get even smaller. In this sense, semiconductor technology entered the realm of nanotechnology several years ago and continues to serve as a technology driver for emerging scientific and technical domains such as spintronics and bioelectronics. In addition, silicon is broadly used to fabricate microelectromechanical systems (MEMS) in which the favorable electronic and mechanical properties of silicon are merged to carry out unique functions.

Single crystal silicon is certainly a work horse of semiconductor electronics. In addition to its dominant role in IC technology, silicon is also used in a broad range of discrete device applications. Silicon appears as thin films of amorphous or polycrystalline form in TFT technology, in solar cells, and in other applications. As the range of electronic applications continues to expand, however, the need to supplement silicon with other semiconductors is evident. For instance, SiGe is needed to introduce electron-accelerating strain in the Si lattice, whereas germanium itself, with its superior electron mobility over Si, may see a resurgence on the semiconductor arena. In addition to Ge the wide-bandgap silicon compound, silicon carbide (SiC) (Fig.1), has steadily emerged as a prime candidate for high-power, high-temperature device applications despite continued problems with substrate quality and a high density of interface traps at the SiO_2-SiC interface in MOS devices.

A few years after the breakthrough invention of the IC, a development important to photonic applications took place when a physicist in upstate New York demonstrated the first solid-state visible light emitting diode (LED) using compound semiconducting material.[5] Since then an avalanche of progress involving III-V compounds including GaAs, InP, and GaP, has occurred culminating in the development of a blue semiconductor laser using GaN (Fig. 1).[6] An advancing understanding of the physics and chemistry of III-V compounds and progress in vacuum technology, that allowed for the development of very-high-precision deposition techniques such as molecular beam epitaxy (MBE), have yielded both lattice-matched as well as lattice-mismatched or strain-layer superlattices and complex heterostructures with highly engineered bandgaps. This capability has enabled advanced photonic devices such as LEDs and lasers, as well as electronic structures, *e.g.*, heterostructure bipolar transistor (HBT) development. In addition to light emission technologies, this new generation of III-V and II-VI compounds now provides for the effective detection of light over a broad spectrum of wavelengths culminating in the detection of UV radiation due to the mastering of wide-bandgap compounds such as GaN and ZnS (Fig. 1).

Over the course of electronic and photonic device manufacture, the respective materials, *e.g.*, Si in the former case and GaAs in the latter, had been considered entirely incompatible with each other both from the chemical composition viewpoint (Ga and As are dopants in silicon while Si is an amphoteric dopant in GaAs) and from a crystallographic structure viewpoint. This paradigm is slowly changing not only due to the earlier mentioned emphasis on the merger of electronic and photonic functions that will blur the boundaries between these two domains; but also due to the likely merger of high-electron mobility compounds such as GaAs and InSb (Fig. 1) with silicon in next generation CMOS IC technology, where for an increased mobility of electrons the channel can conceivably be made out of III-V compound semiconductor.

Until recently all functional semiconductor materials originated from the semiconductor series of the periodic table. They are available as bulk wafers or as thin films deposited primarily on mechanically stable and limited-size substrates. A new breed of semiconductor materials, known as organic semiconductors, consisting primarily of carbon, hydrogen, and oxygen, is bound to overcome these limitations and expand semiconductor electronics and photonics into new areas. Regarding this expectation, organic semiconductors may be deposited inexpensively on large substrates, most thin-film organic semiconductors maintain their properties even if their substrates are drastically flexed or deformed, and they are capable of emitting light in the visible region. The emergence of such large-area plastic electronic and photonic structures allows us to anticipate an exciting future of these technical domains.

Progress in Semiconductor Electronics and Photonics Continues

Progress in electronics and photonics is as much dependent on continued trends as it is on single developments such as the emergence of specific technical solutions. The list of both is long. Here are a few examples of the trends and specific technical breakthroughs needed to sustain the desired progress in semiconductor electronics and photonics.

Early circuit structures employed layers with vertical and horizontal dimensions relative to the plane of the substrate surface on the order of micrometers whereas present-day circuit dimensions have been scaled down to the nanometer region. Among the various improvements mentioned earlier, MBE was instrumental in assuring control over vertical dimensions while control of the horizontal dimension in conventional technology still depends on the resolution of lithographic processes. The use of resolution enhancement techniques such as phase shift masks, immersion lithography, as well as a new generation of photoresist and excimer lasers, allows photolithography to remain effective down to the 45 nm resolution level. Furthermore, innovative approaches to the fabrication process, the selection of the materials employed, and new MOSFET designs (Fig. 2) were developed to achieve dimensional scaling and improved circuit performance. Chemical mechanical planarization (CMP), which had been used extensively in the production of the initial high quality silicon substrate wafers, was applied to the planarization of the dielectric and metallic films used to interconnect the millions of transistors in the substrate body. CMP processing provided many benefits such as an increase in the maximum number of interconnecting layers on a circuit, an improvement in the reliability of the overall interconnect structures, and an improvement in the manufacturing yield and productivity.[7]

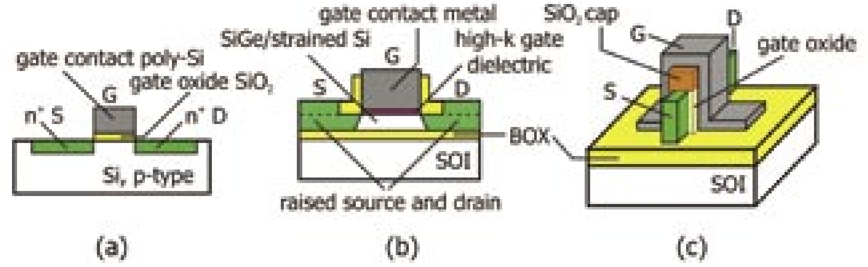

Fig. 2. *MOSFET evolves over the years to meet growing performance requirements. Structure of the contemporary high end MOSFET (b) differs significantly from an original (a). Future generation MOSFETs, such as (c) FinFET shown must be modified further.*[8]

The need for control of the quantum transport of charge carriers in electronic materials has led to both reliability issues and to opportunities regarding the gain of MOS transistors. As the dielectric thickness of the gate oxide layer between the control gate and the conducting channel of the field effect transistor has decreased, quantum mechanical tunneling or leakage of carriers between the gate electrode and channel has occurred. New higher dielectric constant insulator materials which allow a thicker film to be used and still induce an equivalent charge in the channel to that formed by a thinner glass insulator, are being evaluated as a replacement for the SiO_2 glass films that have been in use for forty years. This transition will likely be accompanied with a switch from poly-Si gate contacts in next generation CMOS to metal gate contacts. As mentioned earlier, to further address the transport control of carriers in the channel of MOS devices, strain is being applied as a tool to improve the conductivity of the channel. Finally, as the charge needed to represent a digital zero or one in memory devices approaches the limit of a single electron, quantum structures are being applied to provide multiple electronic states in the same area, *e.g.*, a two state structure provides twice the memory density in the same area.

Over the past fifteen years, the shrinking or scaling of dimensions in electronic and photonic structures has challenged manufactures to search for alternative dimensional measurement approaches. Higher precision relative to the dimensions being acquired is needed to quantify and monitor the progress and outcomes of the fabrication processes at numerous stages in the layer sequence. For example, glass films intended to be 1 nm thick must be measured with a precision of 1% or less. In addition to dimensional metrology, measured parameters regarding the quality or cleanliness of both the surface and bulk regions of device structures and substrates is now being driven well below the part per billion level using X-ray, electron beam, and photon sampling of the surface/bulk regions of the materials. At present the silicon substrate diameter used in manufacturing is in transition from 200 to 300 mm and is expected to move to a diameter of 450 mm within the next ten years. The expense of the larger substrates is causing manufacturers to search for in-line metrology solutions that may be applied to product materials rather than to process witness substrates that were once commonly used in manufacturing. In addition, new metrology approaches are being sought that will provide quantitative electrical properties of device layers and structures prior to completion of the overall device structure.

Exciting developments resulting from a broader application of bottom-up processes should add new flavor to the next-generation implementation of electronic and photonic device functions. In this regard the accomplishments of surface science and solid-state chemistry could be effectively translated into the technology of self-assembled monolayers, or SAMs, which are bound to play key roles in future electronic and photonic applications.

This section has mentioned a few technical developments that either have or will play a critical role in allowing for the sustained growth of the electronics and photonic industries. However, additional advancements are needed. In this regard, ECS assists in the creative process by maintaining an intellectual environment that supports such progress and innovation.

Electronics and Photonics at ECS

Technical societies have been formed to facilitate effective interchange of information and ideas between members of the global scientific and technical community. ECS and its constituent Divisions, including the Electronics and Photonics Division, provide such an important service to the global community by broadly disseminating information. Timely publication of information is accomplished both in print and in electronic media and in particular at meetings of the Society held twice a year where topical symposia are an important venue for dissemination of new knowledge and methods of interest to meeting attendees. The Electronics and Photonics Division sponsors or co-sponsors over 40 such symposia. These symposia cover a broad range of topics related to state-of-the-art semiconductor electronics and photonics. A majority of these symposia are internationally established and are traditionally attended by top scientists and researchers from around the world. Part of the success of these endeavors is that the list of symposia is continuously updated to reflect emerging needs and trends in electronic and photonic materials, process technologies, and device structures.

With a membership of around 2,000, the Electronics and Photonics Division at ECS has a critical mass sufficient to play a lead role in the international solid-state science and technology arena. More important than the number of members, however, is that scientists, researchers, and engineers from around the world

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associated with this division, represent the highest level of professional competency. Incidentally, one important function of the Electronics and Photonics Division at ECS is to identify and to recognize leaders in the field by awarding one of them every year with a prestigious Divisional award. It is in this environment in which less experienced members of the community, graduate students in particular, should find great opportunities to learn and to expand their professional horizons.

Summary

Electronic and photonic devices and systems have developed into a dominant global industry over the past fifty years. As we move forward in the new millennium, the structures and materials used to manufacture devices and systems will likely change significantly from those that have supported this revolution until now. Through its publications, symposia, and other means of knowledge dissemination the Electronics and Photonics Division of ECS intends to continue contributing to the development of future information and communications systems. We are counting on the next generations of scientists, researchers, and engineers to continue this mission for many years to come. ■

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