energy for this amplification is the photon. Further amplification can be achieved by an array of photochromes embedded in the polyacetylene chain. This is a schematic process of soliton amplification.

Technological applications of molecular electronics

The following is a partial listing of some of the applications of molecular electronics.

1. Analogue and digital computers.
2. Interfacing with biosensors
   - artificial intelligence
   - pattern recognition
   - robotics.
3. Quantum mechanical electron tunnelling.
4. Molecular state elements.
5. Molecular switches
   - organometallic
   - molecular/intramolecular rearrangement
   - donor/acceptor complexes.
6. Molecular switching and proton engineering.

Possibility

The subject of molecular electronics is not just an extension of electronics. It is in fact, the future of electronics. When electronic devices can be conceptualized at molecular levels and when such chips can be interfaced with biological items, it will be almost like keying on to the functions of the brain. The bioprocessor can not only perform, but it can also regenerate itself. The biochip implants can take over the functioning of the nervous systems. When these things happen, they may be the limits of technology.

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Semiconductor physics—Where do we go?

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The current trend in semiconductor physics and devices are reviewed. The Indian scenario and its limitations are pointed out.

Semiconductor materials form the heart of electronics. Semiconductor devices perform the functions of rectification, detection, mixing, amplification, blocking and switching. These also act as sensors for converting physical parameters like temperature, pressure, light into electrical signals and innumerable others. The advancements in semiconductor technology are responsible for the fast growth of electronics industry with improved reliability, efficiency and convenience of electronics systems used in communications, computers, defence, entertainment, medical, etc.

Current trends in research in the area of semiconductor physics involve tailoring of properties by combining different materials. Such heterostructures allow bandgap engineering resulting in devices with increasing frequency for microwave devices, increasing power handling for industrial applications and improved line shapes for lasers, in addition to improved reliability and performance. This has required multidisciplinary research in materials, basic physics, device physics, epitaxial technology, process instrumentation, characterization techniques, etc. Here we first briefly glimpse the current trends in semiconductor research, and mention the status in India. We shall finally discuss the difficulties faced by us and look into the future of Indian scenario.

Current trends

III–V materials are aimed at very high performance electronics and opto-electronics. The most important compound semiconductor materials are GaAs, InP, GaP and InSb. The first two are available in wafers up to 3" diameter, which are often used for epitaxial growth of the crystal structure containing the active zone of the electronic or optoelectronic component. Epitaxial structures involve ternary or quaternary alloys, the most frequently used being Ga_{1-x} Al_x As/GaAs in electronic applications (such as HEMT—High Electron Mobility Transistor) or optoelectronic applications (LED, lasers) and Ga_{1-x} In_x As_{1-y} P_y/InP in near-infrared opto-electronics (lasers for long-distance telecommunications).

By passing from one compound to another and especially by using an alloy of given composition, electronic characteristics can be tailored to specific applications. However, the crystallographic characteristics must also be adjusted very accurately, hence the added importance of epitaxial growth. The spectacular success of the (Al, Ga) As/GaAs system is largely due to the very low variation in crystal unit cell size for all forms of this alloy. In the other cases, optimum adjustment of structural properties requires the use of a quaternary alloy.

III–V semiconductor materials cover technological fields with widely differing impacts. They have found applications in solar cells for space, lasers for communications, detectors for infrared range useful for defence, high frequency mm wave devices for communications and fast switches for computers. This wide range of applications has been possible due to the advancements in epitaxial technologies which permit monolayer growth and lithography which allows definition of 0.1 µm features. As a general rule, below 2 GHz, silicon still maintains a strong position in transistors and hyper-frequency ICs. On the other hand, beyond 2 GHz specialized applications (e.g. electronic equipment for military or civilian radar systems, direct TV reception from geosynchronous satellites), are being provided by new GaAs components with much improved performance. For example, very low noise HEMT for ultra-rapid switching in computers, and MMIC (monolithic microwave integrated circuit) technology are now routinely used.

II–VI and pseudo II–VI or IV–VI materials are not extensively used although their electronic properties are not intrinsically inferior – these semiconductor families show record electronic mobility levels at low temperature, but it is difficult to obtain high crystal grade epitaxial layers due to the high ionicity of the materials. On the other hand, owing to their direct bandgap structure these materials also have specific applications in opto-electronics and solar photovoltaic cells. In the far-infrared, lead chalcogenide-based alloys (Pbs, PbSe, PbTe) frequently combined with tin telluride have been used for producing tunable lasers for very high resolution spectroscopy and also for local oscillators in heterodyne sensing.

Cadmium telluride (CdTe) and related mercury cadmium telluride crystals are currently the most important for infrared detection and night vision systems. These have unmatched performance for the atmospheric window around 10 µm wavelength. Recently focal plane arrays have been demonstrated using MCT. Other materials important for the infrared detection include InSb and InAs. For fibre optical communication systems again heterostructures based in InP/In GaAs Sb are used.

In photovoltaic applications, II–VI and pseudo II–VI semiconductor materials are likely to compete with the very new a-Si:H system. This may occur in a certain type of application where the 'cost benefit' energy conversion ratio is more sensitive to performance (high yield, stability of the material). R & D projects in the US suggest that there is a promising outlook for a new system based on thin poly-crystal layers, referred to as CdS-CIS, a heterojunction consisting of cadmium-sulphide and I–III VI_2 alloys based on mixed copper and indium selenide, $CuInSe_2$ which is in fact the alloy $Cu(Ga, In)Se_2$. The applications slot concerned is the terrestrial solar energy sector, and is mainly filled by c-Si (single or multiple crystals).

However silicon remains the most important semiconductor material today. In recent years it has regained a lot of ground lost to III–V materials earlier. Combined with germanium, strained layers, silicon goes faster and now competes well in the 100 GHz range. On the other hand SiGe alloy structures are also competing for the long wavelength infrared detection application with the MCT.

Indian scenario

Semi-insulating gallium arsenide single crystals have been grown and cut into wafers for use in the MMW devices at SPL, Delhi and Anna University, Madras. BARC, Bombay and IIT, Kharagpur are also involved in crystal growth of various semiconductor materials. CdTe crystals have been grown at SPL, Delhi for making focal plane array detectors. A new material called porous silicon is also being studied at SPL, TIFR, IISc and other laboratories. Emission of visible light from this material has attracted world wide attention. Single quantum well laser structures and superlattices have been grown at SPL and TIFR. Some of these structures at SPL have shown lasing action at 801 mm with peak power greater than 5 W under pulsed conditions in broad area diodes. MODFETs have also been fabricated. Also epitaxial layers of MCT on CdTe have been grown at SPL by LPE and MOCVD. Work on materials for VLSI applications is being carried out at NPL, New Delhi. LSI and thin films work is being done at IIT, Delhi, Madras, Bombay and CEERI, Pilani. Purification of indium, gallium and $PoCl_3$ is being done at C-MET and NFC.

Additionally, characterization of materials developed is extremely important. Extensive facilities for this have been created at SPL, NPL, CEERI Pilani, and TIFR. Several universities (Cochin, Pune, BHU, Delhi), IITs and IISc have set up special techniques. CAT, Indore and CSIO, Chandigarh are engaged in the development of equipments needed for semiconductor materials/devices processing. Pune University is working on the development of ion implanter. Further, excellent theoretical work is being carried out at Calcutta, Madurai and several other institutions. Table 1 gives a sample of the activities in various institutions.

Table 1. Sample of the research activities at some of the institutions in India in semiconductor physics and device-related subjects. (This is only illustrative and not an exhaustive listing)

Institution	Research activity
CEERI, Pilani	Multi-level interconnect of LSI/VLSI oxides over doped polysilicon for EPROM 3 µm CMOS technology
IISc, Bangalore	Polycrystalline silicon, defects in semiconductors, metal semiconductor interfaces, parasitic effects in CMOS devices, functional devices for microelectronics
IIT, Madras	Solar grade silicon, oxidation kinetics, MBE of GaAs
IIT, Bombay	MOS for radiation effects in ICs, plasma oxidation, dielectric breakdown in MOS devices
IIT, Kanpur	aSi H, MIS interfaces
IIT, Kharagpur	Crystal growth of InP, GaSb, MOCVD of III-V compounds
SPL, Delhi	MMW GaAs Gunn diodes, GaAs HEMT, GaAs digital ICs and MMICs, laser diodes, focal plane array detectors, silicon impatt diodes

Limitations

It is clear that the level of research in the area of semiconductor physics, materials and devices in India is much below the international level both in terms of quality and quantity. It is also evident from the small number of publications in journals and the few papers being presented in international conferences of repute. Individuals have excelled but that does not say much about the system.

The primary reason for this situation is the nature of the subject which is capital-intensive and multidisciplinary. Research in semiconductor physics and materials requires facilities which would cost easily in crores. Device research is even more expensive. Then operation and maintenance of these equipments and facilities also costs considerable amounts. This also requires infrastructure for power, skilled people, etc. As a result only a few institutions in the country are able to afford any semblance of experimental research in this high technology area. One possible solution to this will be to have central facilities where sophisticated work can be carried out by workers from various universities and institutions. These work centers should be funded liberally and assured continuous funding. Such centres are common in western countries where it has been recognized that it is not possible to have such facilities in every university.

A major problem faced by the few institutions that do have some experimental research is the shortage of trained manpower. That our University system is not giving adequate training is now widely accepted. Lack of research environment in most universities means that we do not get graduates with suitable specialized training. The manpower shortage is further increased due to brain drain. As a result, the few graduates that we get from the few institutions which have any programmes in the area of semiconductors get very attractive offers from abroad and go away. This problem is recently aggravated further by the government policy of ban on recruitment due to which we are unable to find young people for our laboratories. This has resulted in inverted pyramid structures in most organizations leading to poorer performance.

Our industries are also responsible for not promoting research in the institutions in this applications-oriented area. Industries have their own problems due to which they are not interested in sustained R & D either in-house or sponsored.

Conclusions

Overall the condition of research in the area of semiconductor physics, materials and devices is not as healthy as it should be mainly due to lack of funding, manpower and infrastructure. However recently funding has improved resulting in new facilities like MOCVD being created at several places. Due to export restrictions being imposed by western countries, some other agencies like ISRO have realized the importance of research in these areas. We expect the future to be brighter.