Physics – Uspekhi **37** (5) 555 – 558 (1995)

PACS numbers: 85.30.-z; 72.80.-r; 01.10.Fv

Semiconductors in the modern world†

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Abstract. Some of the most important achievements in modern electronics and energetics, based on the physics of semiconductors, are discussed very briefly.

1. Introduction

At the end of the twentieth century we are flooded with information, which affects us all. This has become possible because of the developments in solid-state 'semiconductor' electronics.

The best known semiconductor devices and their applications are as follows:

(1) computers and memory systems;

(2) displays, i.e. luminescent or other visible (to the human eye) controlled images, which help us to grasp the data received by a computer or recorded with the aid of optical devices;

(3) colour television screens, which make it possible to observe images with the human eye on the basis of cathodoluminescence, an effect thoroughly studied by physicists; luminescent screens consist of semiconductor films prepared by a careful technological treatment;

(4) solar cells, providing a dependable and ecologically clean source of electric energy;

(5) detectors and dosimeters for monitoring and determination of the intensity of harmful radiation.

There is an analogy between the lever of Archimedes or the method of controlling the flow of water by opening and closing a gate or lock, the processes in a vacuum triode invented a long time ago by Lee de Forest, and the action of the transistor discovered by Bardeen, Brattain, and Shockley. It is appropriate to recall that 'crystal detectors', similar to hot-cathode vacuum diodes, were already in existence at the beginning of the twentieth century. Crystal detectors with a point contact between a needle (point) made of a hard metal and a semiconductor crystal were unreliable and temperamental. The parallel development of the technology of vacuum devices has made the then available semiconductor devices uncompetitive, particularly in connection with the military requirements in the field of radio communications or wireless during the First World War in 1914 – 1918.

I feel it right to mention here the pioneering work of the Russian physicist and inventor Oleg Vladimirovich Losev, carried out in Petrograd (Leningrad) and published in 1923 – 1928. He discovered the generation of hf oscillations of the current and the emission of light (luminescence) by silicon carbide (SiC) crystals containing spontaneously formed barriers between the regions with very different electrophysical and optical properties. These barriers are now called p – n junctions.

One cannot exclude the possibility that if there had been more effective exchange of scientific information between Russia, Western Europe, and the USA, solid-state (semiconductor) electronics could have made a much earlier start than it actually did.

It is convenient to consider the following 'triads' of solids:

Metals	Semiconductors	Insulators
(iron, aluminium)	(silicon)	(diamond, glass)

The main property separating metals, on the one hand, from semiconductors and insulators, on the other, is the *susceptibility* to the excitation of their electron subsystems by such agents as light (photons) or 'hard' radiation, i.e. high-energy charged particles, or strong electric fields. The outstanding Russian physicist Abram Fedorovich Ioffe regarded as a semiconductor any system in which excitation can create a large number of nonequilibrium charge carriers. Many observations support his view: the processes in a gaseous plasma and the electronic phenomena in liquids are in many respects similar to the processes occurring in classical semiconductors such as silicon and germanium.

For about the last forty years semiconductors have been regarded as a separate class of materials. Much progress has been made, initially in the field of their theory.

The transport of charge carriers and the thermoelectric processes were first explained qualitatively. The laws governing the 'primary' photoelectric effect, now called photo-ionisation, were verified experimentally by Pohl and Gudden. They used insulating crystals, including natural diamonds. An exact correspondence had been found between these phenomena and Einstein's concept of the photoionisation of isolated atoms. However, many of the 'secondary' effects, such as the influence of chemical impurities on the photoconductivity, have long remained unpredictable.

† Paper presented at the general meeting of the Academy of Sciences of Athens, 18 October 1994.

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Received 4 January 1994
Uspekhi Fizicheskikh Nauk **165** (5) 591 – 594 (1995)
Translated by A Tybulewicz

The next stage in the development of the subject was a consequence of the demands made by military technologies, which has led to the current level of semiconductor applications, resembling the success in the construction of aircraft during the First World War. The discovery and further progress in radar were followed by a major effort to improve solid-state detectors of small electromagnetic signals. It had been found that excellent devices can be constructed from germanium single crystals. Germanium (Ge), a relatively rare element in the Mendeleev periodic system, crystallises in a very simple structure, similar to that of diamond and silicon.

Pure germanium is very expensive, but near-perfect Ge crystals can be grown in vacuum at about 960 °C. In Russia I was probably one of the first to construct the apparatus for growing germanium single crystals. They were grown earlier by our colleagues at the Bell Laboratories in the USA. Germanium soon became the main material used in the manufacture of transistors, diodes, and photoelectric devices. However, its intrinsic properties, governed by the band gap close to 0.7 eV, limit the range of temperatures in which germanium devices can be used to about +30 °C: at higher temperatures they are practically unusable.

This has stimulated a search for other semiconductors and among these silicon soon proved to be the best. The technology for growing large silicon single crystals is very complex. Nevertheless, it is at present (1994) possible to grow enormous cylindrical silicon single crystals with a diameter up to 150 mm and more than 50 cm long. These single crystals represent the most perfect and pure material formed by a very advanced technology. However, cutting of these crystals into thin wafers, from which integrated circuits (used in particular in computers) are made, requires the use of a very expensive technology (discs impregnated with diamond crystallites), since silicon single crystals are very hard.

An alternative approach to the fabrication of silicon devices is the very interesting field of semiconductor technology. It is based on the epitaxial growth of semiconductor films. It is very likely that in ten or twenty years the growth of enormous silicon crystals and their cutting into thin wafers will be replaced by the epitaxial technology.

2. Silicon as the main semiconductor material

Silicon seems to have been created by nature to become the basis of modern solid-state electronics, as iron has long been the main material in the fabrication of tools, vehicles, and weapons. Like iron, silicon does not exist in nature in its free state: much work and skill is needed to prepare it. However, grown silicon crystals become covered by a naturally formed thin film of a glassy oxide and remain stable in a wide range of temperatures up to 600 °C. Back in the mid-fifties devices made of silicon became superior in their parameters to germanium devices. At present, over 98% of 'units' of semiconductor electronic devices are made of silicon.

3. Size of semiconductor devices and the task of their miniaturisation

Since the discovery of the transistor in 1948, it has become evident that the size of a semiconductor diode or triode can be hundreds or thousands of times less than the size of a vacuum device used for the same purpose. Moreover, a semiconductor device does not have a hot cathode and the thermal energy dissipated during its operation is small. Specialists remember enormous computers (called calculating machines in the early fifties) with thousands of vacuum tubes (valves), requiring powerful ventilation systems for heat removal. During the first 20 years of the development of their manufacture, semiconductor devices and products based on them (such as radio receivers) contained tens of separate transistors and diodes connected by wires. The making of such products required much time, including primitive manual operations. When I visited a radio engineering factory in Japan in 1962, I was greatly impressed by a workshop where hundreds of girls sat for hours looking through a binocular microscope and controlling manually a micromanipulator.

The idea of planar two-dimensional technology was formulated back at that time and it was soon put into practice. The new technology requires complex and expensive consecutive processes, i.e. production lines similar to the conveyor belts used in car manufacture. Over 200 operations are needed to fabricate an integrated circuit on a small single-crystal silicon wafer or chip (this word is now used also in Russia) with an area of about 1 cm^2 and about three tenths of a millimetre thick. The integrated circuits fabricated in this way are the 'heart' of the personal computer and they may contain hundreds of thousands of active components such as transistors, diodes, and capacitors.

4. New trends in solid-state electronics: the use of accelerated ions and electrons

One of the major problems in integrated circuit technology is the reduction in the size of the active components and a corresponding increase in the number of components on a chip. There are several ways of achieving this and one of them involves the use of accelerated beams of ions of the necessary chemical impurities. The initial method for the local introduction of impurities (doping) involved masking, i.e. the formation on the surface of a semiconductor of a necessary protective-film template which leaves open the regions that have to be doped. This is followed by thermal diffusion and removal of the mask by chemical etching. These operations, which have been developed technically and are used at present, are complex and are not always sufficiently reproducible.

It has been proposed and demonstrated experimentally that a pure beam of accelerated ions can be used for local introduction of the required impurities into the surface layer of a semiconductor or some other material.

The initial attitude of the technologists to this method has been very cautious and frequently sceptical because of the radiation damage to the structure of the material, which is unavoidable when ions are implanted. Fortunately, it was soon discovered that the initial perfect crystal structure of silicon, germanium, and to some extent that of other semiconductor materials can be restored and that the ion implantation method is effective and practical. Thousands of specially adapted ion accelerators, usually called 'implanters', are currently used in countries with a highly developed electronic industry.

In addition to the use of accelerated ions, there are potential applications for laser radiation pulses and electron beams in the modification of the properties of semiconductors.

5. Power consumption of semiconductor devices

One of the main features of modern semiconductor electronics is the high efficiency of transistors and other devices in combination with an extremely low power consumption. Electronic watches, portable radios, and calculators run for about a year on a miniature chemical battery or they can be operated by a solar cell. Less than half the consumed energy is dissipated in the environment.

6. Current applications of solar cells and future trends

The first 'photovoltaic' devices, based on utilisation of the internal photoionisation in nonmetallic materials, were made and used successfully well before the development of modern semiconductor technology, particularly that of silicon devices. The devices have been made of silicon and also of cadmium sulfide (CdS) by trial and error, and they have proved successful. However, their energy efficiency does not exceed 0.5%. A decisive step forward in solar energy technology was made in the middle fifties by G L Pearson and his colleagues in the USA. They used silicon single crystals with p–n junctions. According to the theoretical predictions, the ultimate efficiency of conversion of solar radiation energy into electric power is very high and can exceed 30%. Silicon solar cells were made at the P N Lebedev Physics Institute in Moscow and improved at a technological centre near Moscow.

The second of the Russian satellites carried prototype silicon solar cells and at present such electric power sources are employed universally in space research. The initial technology of their fabrication has included cutting of large single crystals into thin wafers, which results in considerable waste of materials.

Some years ago an alternative method for the fabrication of large-area silicon films was developed by Spear and Le Comber in Great Britain. They synthesised amorphous silicon from a gaseous plasma containing materials with this element. Like crystalline silicon, the amorphous material has tetrahedral bonds between the atoms and there is no 'long-range order' characteristic of crystalline substances. The great majority of calculators, including those used in shops selling sausage and other products, are driven by solar cells made of amorphous silicon. The Japanese electronic industry has rapidly mastered the technology of amorphous silicon and has made considerable progress in this field.

At present, silicon solar cells are used very widely and this has stimulated a healthy enthusiasm among those who believe in further expansion of the range of their applications. However, it is difficult to imagine that future solar cells will compete with internal combustion engines of cars or with the dangerous nuclear reactors used to generate electric power.

7. Luminescence of semiconductors

The remarkable phenomenon of luminescence, i.e. 'athermal' emission of light, has been known from time immemorial. In contrast to light emitted by burning wood or an exploding volcano, there are other quite different light sources. We can imagine the lightning hurled by Zeus to be a consequence of the luminescence emitted by a gaseous plasma excited by powerful electric currents in the terrestrial atmosphere. Among natural phenomena, not requiring the action of gods, one might mention the well-known chemiluminescence of decomposing wood or the luminescent organs of glow-worms, which delight people even in cold Russia, and the light emitted by some sea animals which many lucky people have been able to observe in the Black Sea near the shores of the Crimea. The luminescence, i.e. 'nonthermal' emission of light by excited semiconductors, has now been explained in detail by current theoretical concepts. In the case of semiconductors this phenomenon is initiated by the generation of 'excess' carriers, i.e. those which are in thermodynamic non-equilibrium, similar to nonequilibrium electrons in a vacuum.

This process can be started by ionising radiation, for example, by accelerated-electron beams or x-rays, or by what is known as injection of nonequilibrium carriers across a barrier in a semiconductor structure.

All the currently used television sets use fast-electron excitation of thin semiconductor films, carefully selected and fabricated by an expensive and complex technology to ensure that colour pictures appear on the screen. A gradual changeover is likely to flat electroluminescent screens, which will not require the use of electron beams in vacuum.

8. Particle detectors and dosimeters

For a long time the nature and energy of 'hard' nuclear radiations such as alpha particles, fast electrons, and gamma quanta, have been determined and measured by devices related to vacuum tubes. These devices are efficient and reliable, but they have a large working volume and require high potentials (voltages) for their operation. The idea of a solid-state ionisation chamber has been implemented, to the best of my knowledge, by van Heerden in the middle forties: he used natural diamond crystals which are almost perfect insulators under equilibrium conditions. Ionisation by high-energy particles or photons generates a large number of charge carriers and an electric current pulse passes through a crystal if it is subjected to an electric field. The van Heerden device was the first solid-state ionisation chamber. Its working volume was less than one-thousandth of the volume of the corresponding vacuum ionisation chamber. Silicon, germanium, and other semiconductors are used at present systematically as working materials in various types of detectors of high-energy particles and photons, and in dosimeters.

9. Main difficulties hindering applications of semiconductors in technology

As pointed out earlier, one of the attractive aspects that has made transistor fabrication possible has been the relatively simple technique for growing near-perfect germanium crystals. In the case of silicon, this technique has proved much more complex and very much more expensive, but the main difficulties have been overcome. The technology of the closest analogues of silicon, which are primarily diamond-like semiconductors synthesised by Hilsum in

Great Britain and by Nasledov and Goryunova in Russia, is even more complex. Much effort and expense has been needed to synthesise III–V compounds, particularly gallium arsenide (GaAs).

As one might expect, the existence of many types of point defects and the possibility of phase transitions, have a strong influence on the perfection of the crystal structure. At present, the technical feasibility of utilising semiconductor compounds is greatly limited compared with the wide range of technologies of silicon devices.

Other difficulties and limitations of future practical applications of semiconductors are primarily due to the meta-stability of the majority of semiconductor devices. The users expect their devices to work for at least a decade. This aspect has frequently proved decisive. It is for this reason that many of the attractive directions for the development of physics and technology of semiconductors have gradually died out.

Semiconductors, like the cells of living organisms, are very sensitive to the action of hard radiation such as gamma rays or neutrons. These phenomena are being investigated systematically and their effect on semiconductors is very great. The main processes that create radiation damage in solids have often been described quantitatively. This frequently makes it possible to predict the behaviour of a semiconductor device as a function of the conditions during the action of radiation.

Acknowledgements.
I am grateful to Professor P C Euthymiou, of Athens University, who was the first to propose the cooperation of Greek and Russian specialists in solid-state physics in 1978, and also to Professor K Alexopoulos who gave me the extremely difficult task of presenting a paper at a general meeting of the Academy of Sciences of Athens in October 1994.