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SEMICONDUCTORS IN THE MODERN WORLD

ΟΜΙΛΙΑ ΤΟΥ ΑΝΤΕΠΙΣΤΕΛΛΟΝΤΟΣ ΜΕΛΟΥΣ ΤΗΣ ΑΚΑΔΗΜΙΑΣ
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1. At the end of the 20-th century, the human beings both in highly developed and developing countries are strongly influenced, may be even submerged, into an enormous amount of information supplied by the devices based on the application of semiconductors. Let me begin by mentioning some of the most prominent fields:

1) Computers and storage of information;

2) Displays as «mediators» between the computer, human eye and human brain;

3) Color TV — in screens widely used today, the phenomenon of cathodoluminescence, well understood by physicists, permits the human eye to see the image. The luminescent screen consists of carefully chosen semiconductor layers;

4) Solar cells, as a dependable and ecologically clean source of electric energy;

5) Detectors and dosimeters for monitoring harmful radiations;

2. There seems to be an analogy between the lever of Archimedes or controlling the flow of water by shifting of a shutter, and the processes in a vacuum triode invented long ago by Lee de Forrest and the transistor action discovered and explained in 1948 by Bardeen, Brattain and Shockley. It is worth noting that «crystal detectors», similar to vacuum diodes with a hot cathode existed in the begin-

ning of our 20-th century. The crystal detectors with a point contact between a needle of hard metal and semiconducting crystal were tricky in operation and the simultaneous fast development of vacuum tubes' technology resulted in their dominance, first of all, in the field of military applications of «wireless», or radio, as we call it new.

I cannot abstain from mentioning Oleg Lossev's experimental results obtained in Russia in 1923-28, when he demonstrated both the generation of high frequency oscillations of current and emission of light in silicon carbide (SiC) crystals containing spontaneously grown barriers between the regions with completely different electrophysical and optical properties. Now we call them «p-n junctions».

One cannot exclude a possibility that, if there could exist at that time a better exchange of scientific information between Russia and Western Europe Countries and the USA, the solid state (semiconductor) electronics could have a much earlier start than it happened in real history.

3. One can consider now a «triada» of solids:

Metals	*Semiconductors*	*Insulators*
(Iron)	*(Silicon)*	*(Diamond, Glass)*

The main dividing line between the metals on the one hand, and both the semiconductors and insulators on the other hand, is determined by their susceptibility to an excitation of their electronic sub-system by such agents as light or «hard» radiation, such as charged particles of high energy, or by applying strong electric field. One of outstanding Russian physicists. Abraham F. Ioffe, regarded any material system that can be thus excited and to contain numerous «charge carriers», as a semiconductor. My opinion is that his arguments are justified, the gas plasma and electronic processes in liquids are in many respects similar to those in classic semiconductors such as silicon or germanium.

4. For about forty years after the semiconductors began to be regarded as a special class of materials many basically important achievements were made, first of all in the field of theory. The phenomena of thermoelectric effects and transport of charge carriers were qualitatively explained. The laws of «primary» photoelectric effect that we now call «photo-ionization» were proved experimentally by Pohl and Gudden, who used the insulating crystals, including natural diamond.

It was found that there exists a complete agreement between these phenomena and Einstein's concept of the photoionization of isolated atoms. However, many of the «secondary» effects, such as the influence of impurities on photoconductivity, remained unpredictable.

The next step leading to the modern level of semiconductors' applications was due to the requirements of military technology, similar to the success in airplanes' development during the World War I. After the invention and development of radiolocation, strong effort was made to improve the performance of solid-state detectors of weak electromagnetic radiation. It was found that excellent devices could be made by the use of germanium single crystals. Germanium, a rather rare element in D. Mendeleev Periodic System, crystallyzes, forming a very simple monoatomic lattice closely similar to that of diamond and silicon.

Pure germanium is very expensive, but excellent single crystals could be grown in vacuum at the temperature about 960° C. In my Country, I (most probably) was the first one to build the equipment for single crystals of germanium growing (as far as I know, they were first grown by the colleagues at Bell Telephone Lab in the USA). Germanium was the basic semiconductor used for various types of transistors, diodes and photoelectric devices. However, due to its intrinsic properties, which could not be changed (the so-called «width of the forbidden gap», about 0.7 electron-volts), the range of temperatures where germanium devices could be operated was limited: even at +30°C their performance decreased.

This fact resulted in the search of a better material, which turned to be silicon.

The art of obtaining large single crystals of silicon is quite complicated. At present (1994) they can be obtained as huge cylinders of ~150 mm (6 inches) in diameter, half a meter long. They are definitely the most perfect and pure crystals man has produced. But to cut this initial material into thin wafers for the production of «planar» integral schemes (IS), one has to use diamond-impregnated discs, as silicon is extremely hard.

An alternative approach to the production of thin layers of silicon, avoiding the necessity of cutting large crystals, is a fascinating field of modern semiconductor technology. It seems to be quite probable that in ten or twenty years the necessity of growing huge crystals of silicon and cutting them shall be supplanted by «epitaxial» technology.

5. Silicon as Semiconductor No 1.

Silicon exists as a substance specially created by Nature for the development of semiconductor electronics, similar to iron in the field of mechanical engineering. Like iron, it does not exist in a free state in nature, and has to be produced by man with the expenditure of skill and considerable energy.

However, once produced, it covers itself with a thin protective layer of oxide similar to glass that remains stable in a wide range of temperature, up to about 600°C. From the beginning, in early 50-ies, silicon devices have become superior to germanium devices, and at present, about 98% of all «units» in solid State electronics are based on silicon.

6. The size of a semiconductor device and the progress in miniaturization.

From the time of the invention of a transistor in 1948, it was evident that the size (volume) of a diode or triode is negligible compared to the volume of a vacuum tube needed for the same purpose. Besides this, no hot cathode is needed and so, practically no excess heat is created. People of my age remember huge computers containing thousands of vacuum tubes that needed special ventilation for heat removal. During the first two decades of semiconductor industry development, the final products like radio sets included several dozens of separate transistors and diodes, to be connected by wires. Their production was consuming much time and human effort.

So, the idea of a planar two-dimensional technology has appeared and materialized. This involved complicated and expensive production lines comparable to those used in modern automobile factories. The total number of operations required for the production of an «Integral Circuit» — IC — on a silicon «chip» which has an area about 1 cm^2 and a thickness of one third of millimeter, exceeds two hundred». The final IC, which constitutes the «heart», i. e. the active part of a personal computer, may have several hundred thousands of «active elements» like transistors, diodes and capacitors.

7. New approaches to semiconductor technology: the use of ion and electron beams.

One of the major problems of modern semiconductor IC-technology is to decrease the size of a unit (element), and thus to increase the number of elements on a chip. There are several ways to do this, and one of them involves the use of accelerated ions beam. The initial method of introducing the necessary chemical impurities locally included masking (covering) parts of the surface to be doped, subsequent thermal diffusion, and etching (removing) the mask.

These cycles of operation, which are, of course, used in many cases at present, are complicated and not always reproducible. Early enough it was suggested and experimentally proved that a clean beam of necessary ions can be used for local introduction of impurities near the surface of semiconductor or other solid material. Initial attitude of technologists towards this technique was quite cautious, even skeptical, due to an inevitable radiation-induced damage. Fortunately, it was found that in silicon, germanium and, to some extent, in other semiconductors the initial perfect structure of a crystal can be recovered, and thus the «ion implantation» is effective. It has also become economically profitable, and at present in the countries with highly developed electronic industry many hundreds of special ion accelerators, now often called «implanters» are constantly used.

There exists also the most interesting field of other uses of the ion beams, first of all of the electron beams and the laser treatment of semiconductors.

8. The energy consumption by semiconductor devices.

The main features of contemporary semiconductor devices that are most prominent: high efficiency of transistors and other devices and extremely low consumption of energy, needed for their action. An electronic watch, a portable radio or a small calculator run for a year on a miniature chemical cell or on a solar cell. Usually less than a half of the needed energy is spent for inevitable heat production.

9. The present field of solar cell applications and some trends for future.

First «photovoltaic» devices based on the well understood process of inner photoeffect in nonmetallic materials were developed and technically used for a long time before the advent of modern silicon technology. These devices made of selenium, cadmium sulfide etc had low energy conversion efficiency (less than 0.5%), but they were successfully used, for instance for the illumination intensity monitoring. The major step forward was the conversion of solar energy made in early 50-ies by G. Pearson and his colleagues in the USA, who were using single crystals of silicon.

According to theoretical predictions it was really found that the efficiency of solar light conversion to electricity was quite high, up to about 15%. The analogous cells were soon made by us in P. N. Lebedev Institute of Physics and improved in a technological center in Moscow. The second of the Russian satellites already carried experimental solar cells, and at present very large areas of them are common and indispensable in cosmic research.

The initial technique required the step of cutting of very large Si crystals into thin wafers by diamond-impregnated discs, a slow and expensive operation.

Some years ago an alternative way of producing large areas of silicon layers has become technologically feasible. In this case silicon is deposited in a thin layer as a result of chemical reactions in «gas plasma» containing chemical compounds including silicon as a component. In most cases these layers have the properties of amorphous material, i. e. they have a tetrahedral, homopolar nature but do not have the «long order» typical for the perfect single crystals. Most of the present day calculators used in every shop selling bread, tomatoes and oranges have simple solar cells based on amorphous silicon. Japanese industry has gained substantial money out of the production of amorphous silicon cells, necessary for popular small semiconductor devices.

As it could be expected from general theoretical considerations, the amorphous state of silicon and other semiconductors (and the state of usual glass we use so much) is metastable, i. e. after some time amorphous, noncrystalline material begins to crystallize. So, one must be cautious in using amorphous semiconductors in the devices destined to work for many years.

At present, silicon solar cells are widely used, and there is a considerable enthusiasm among those who believe in their future expanded field of applications. However, one can hardly foresee that the solar energy in future shall surpass the combustion engines for automobiles, or dangerous nuclear reactors.

10. The luminescence of semiconductors.

A brilliant phenomenon of luminescence, i. e. emission of light, was observed and admired by the human beings since prehistoric times. In contrast to the light emitted from burning wood or a volcano, there exist other, nonthermal sources of light. I dare to state that the light emitted by Zeus's lightnings was the gas plasma luminenscence due to the electrical currents passing in the Earth's atmosphere.

Returning to the terrestrial phenomena not involving the actions of Gods, one has to regard the well-known chemoluminescence of decaying wood or luminescent beetles that we admire even in our cold country —Russia—, and of sea animals that I have been admiring as a boy, swimming near Crimea in the Black Sea, as we call it.

At present the luminescence, i.e. the emission of light by excited semiconductors has been explained in detail by the concepts of modern theory. The process is *initiated by the generation of «excess», i. e. nonequilibrium charge carriers, similar to free electrons' in vacuum.*

To start this process, one can use ionizing radiations, such as fast electron beams, X-rays or the so-called injection through a barrier inside a semiconductor structure.

All modern TV sets involve the phenomenon of excitation of thin semiconductor layers, carefully chosen and produced by costly technology to create exciting color images on the TV screen. At present (1994) one may be at the brink of going over from the cathodoluminescence to the «flat» electroluminescent screens involving no electron beams in vacuum.

11. Particle counters and dosimeters.

For a long period the nature and intensity of «hard radiations»: a-particles, fast electrons and γ-quanta was detected and analyzed by the devices, to some extent similar to vacuum tubes. They were efficient and dependable, and required large space and high voltage to be operated. The idea of using a solid-state ionization camera, as far as I know, was first realized by Van Heerden, who has used natural diamond, that is a perfect insulator in a state of thermal equilibrium. The process of ionization by high energy particles or quanta produces a large number of charge carriers, and a pulse of electric current passes through the crystal if an electric field is applied to it. Van Heerden's device was an analog to a vacuum «ionization chamber». It required a working space approximately equal to 1/1000 of that of a chamber with the gas inside it.

At the present time silicon and other semiconductors are constantly used as the «working materials in various types of particle detectors and hard radiations' dosimeters.

12. The main difficulties peculiar to the application of semiconductors.

a) As it was mentioned above, one of the advantages efficiently used at the time of transistor invention has been a relatively simple technique of producing almost perfect crystals of germanium. Even in the case of silicon it has become more complicated and expensive, but the main difficulties have been overcome. The technology of the «relatives» of silicon, first of all, the semiconducting «diamond-like» crystals that were synthesized by C. Hilsum in Great Britain and by D. Nasledov and Nina Goryunova in Russia, is much more complicated. Great hopes and much effort was applied to the so-called $A_3 B_5$ *compounds, first of all,* *to gallium arsenide (GaAs). As it could be expected, a variety of «point defects» and that of the possibility of the phase transitions definitely influences the perfection of crystalline structure of crystals, and the technical uses of semiconductor devices based on these compounds are limited, as compared to the field of silicon-based devices.*

b) Other typical difficulties and limitations of the future uses of semiconductors are due, first of all, to the metastable state of most of semiconductor structures. It is well known that the consumers expect for the devices they need a lifetime not less than 10 years. This fact has been always decisive. Due to this, many of the initially attractive lines of physics and technology of semiconductors have gradually decayed.

c) Semiconductors, like the cells of all living creatures, are vulnerable to the influence of «hard» radiation, like γ-rays and neutrons. This phenomenon is constantly investigated, and it has to be considered seriously. The basic processes resulting in the «radiation damage» of solids have been described quantitatively. As the result, one can predict the behavior of a semiconductor device, depending on the conditions in which it is used, with certainty.

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