# Solid state physics and its role in science and in practice

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The celebration of the 250th anniversary of the USSR Academy of Sciences has turned into a national holiday. All were greatly impressed by the brilliant speech of Leonid Il'ich Brezhnev at the solemn session of the members of the Academy of Sciences and of the Soviet elite, when the Academy was awarded the second order of Lenin. In this speech, L. I. Brezhnev has shown what he expects of the scientists of the party as the 25th congress approaches—an ever deeper and bolder investigation of new processes and phenomena, an active contribution to the matter of scientific and technical progress, thoughtful analysis of the problems faced, responsible recommendations concerning the best solutions for them in order to increase the might of the country, to improve the nation's standard of living, and in the interests of building communism.

Much is entrusted to Soviet scientists, and this obligates us to solve all the better and all the more effectively the fundamental problems that influence radically the scientific and technical potential of our country. Scientists must have a clear outlook on the most important trends of scientific research and be able to assess their significance to the scientific and technical progress of the country. One such trend is solid phase physics. It was just to this problem that a lecture "Solid State Physics" was devoted at the Anniversary Session of the USSR Academy of Sciences.

Scientific and technical progress is based on the accomplishments of the present-day science. But while industry cannot develop successfully in our days without science, science depends to no less a degree on industry. The greater the help that industry renders sciences, the higher the practical significance of the research. It can be stated without exaggeration that the rate of scientific and technical progress depends in many respects on the level of commercial instrument construction and the production of new materials, and this level is determined in turn by the progress made in solid-state physics; consequently, solid state physics plays a primary role in modern technology, and is the foundation of scientific and technical progress.

Research on solid state physics started to develop rapidly in our country after the Great October socialist revolution, especially in the Leningrad Physico-technical Institute, which was organized in 1918. This institute trained a galaxy of talented physicists, whose work gained wide recognition. By now we have an entire army of highly skilled specialists in this important branch of science—members of academic establishments, higher institutions of learning, and commercial institutes.

The scientists of the USSR Academy of Sciences occupy a leading position in the development of basic research in solid state physics. Unfortunately, for lack of space, it is impossible to list here the academic institutes and mention the names of the researchers who made significant contributions to the solution of the problems referred to here.

Quantum theory of solid state physics was relatively recently the domain of only theoretical physicists. The situation has by now been radically changed, inasmuch as the quantum properties of solids are widely used in the development of electronic instruments that play an essential role in engineering. This pertains primarily to electronic computers. The first vacuum-tube computers, which came into being about 20 years ago, were cumbersome, not very reliable, and consumed much electricity. They could perform only several thousand operations per second and were used mainly as high-speed calculators. The colossal progress in the study of the quantum properties of solids has made it possible to develop a new elemental basis for computers. The third-generation computers are based on solid-state microelectronics with low degree of integration, while those of the fourth generation use considerably integrated circuitry. The transition to microelectronic circuits has made it possible to increase the speed of the machines to several million operations per second, even hundreds of millions in multiprocessor computers.

To perform logical operations and to store information, the computer must have a memory. The larger the memory, the more effective the computer utilization. The memory of modern machines is designed to store tremendous blocks of information. If it were printed, this information would occupy millions of pages of printed text. The transition to a new elemental base has led to a radical decrease in computer dimensions, and to a considerable lowering of the energy consumed per operation.

The elements of which computers are constructed must not only be fast in operation and consume little energy, but also be highly reliable. The use of solid-state microelectronics has solved this problem too. It should be mentioned that striking success in the development of integrated circuits of high reliability is by far not easy or simple. The vigorous development of solid state physics, which began in the 50's, was connected with the major accomplishments of semiconductor engineering—the development of electronic elements, transistors, which have replaced the vacuum tubes in the second-generation computers. The first transistors had short service lives and were characterized by a considerable scatter of their parameters. A thorough study of the processes that occur in transistors helped overcome these difficulties.

By now many theoreticians and experimenters are engaged in the field of solid state physics. Armed with modern instruments and equipment, they are studying the properties of semiconducting films of thickness frequently smaller than the wavelength of light. The work begins with depositing on a substrate a number of films, each of which must be of definite thickness and composition, and must be a single crystal. It is necessary to watch carefully that the films do not become contaminated, for even a trace of extraneous impurity affects their properties significantly. Ultrapure raw material is used for the film. The very technology of obtaining films with the required characteristics is very complicated. Therefore a person engaged in microelectronics must be both a good physicist and a good technologist. Unfortunately, the scientists that produce the new unique elements for microelectronics frequently remain in the shadow, even though it is on the basis of just these elements that many important systems are built. The entire point is that the system is capable of clearly demonstrating its merits, while the elements of which it consists can be frequently discerned only with the aid of a microscope, and explanations are of little help in this case.

In our days engineering is developing at so furious a rate, that one speaks of the possibility of creating automata or robots capable of performing not only physical but also creative labor. The question is even raised whether computers will have conscience, morals, etc.

Without going into a detailed consideration of these problems, I shall note that there is a radical difference between a modern computer and the human brain. The difference begins at the very base, the very foundation of these systems, namely their elemental base, consequently from the principle of construction of logical operations, of the operation of the memory, and of the methods of image recognition. It is here that the main difference lies between the artificial intellect and the live one. It is interesting that attempts were made to use certain principles inherent in living matter for the construction of computers. This trend received the name "bionics." It has not yielded as yet, however, any noticeably practical results. Therefore the development of computers goes its own way, and this tendency will remain in the nearest future. A computer made up of solid-state electronic elements will not be able even in the future to encompass all the aspects of the brain's activity, although it will imitate well many of its features. But the value of computers lies mainly in the fact that they do have a rich memory and can perform complicated calculations with colossal speed. If one speaks, for example, of control systems, then a computer is capable, on the basis of input data, to arrive at a complicated decision within a negligible time interval, something man cannot do at all.

In spite of the outstanding advances in the development and improvement of computers, their third generation no longer satisfies present-day requirements with respect to operating speed and memory volume. How can the operating speed be increased? It is necessary for this purpose, besides increasing the operating speed of the logical elements themselves, that the transmission of a signal from one element to another occupy less time. This time depends only on the distance between the elements. To reduce it, the logical elements must be placed very close to one another or, as it is called, to increase the level of integration of the logical circuits. But an increase in the integration level increases the heat dissipated by the elements as they operate, and leads to their early deterioration. It is therefore necessary to produce logical elements that consume little energy. There are various ways of solving this problem. One of them is to operate the computers at low temperature. But this will call for a rebuilding of the elemental base, and will entail large expenditures. Another way is to produce new logical elements, that consume less energy and, in addition, can withstand relatively heavy work loads. On this basis it will be possible to construct high-power integrated circuits that function reliably at ordinary temperature. It must be emphasized that the larger the computer, the more reliable must its elements be.

The memory, as already mentioned, is an essential part of the computer and accounts for 60–80% of its total cost. The memory must operate at high speed and have a large capacity. This has not yet been attained in a single device. A hierarchy of memory devices was therefore developed, starting with ultrafast ones of low capacity and ending with slow ones having a large capacity. At the present time the memory is based mainly on magnetic properties of solids, but for high-speed devices one used semiconducting integral circuits. The presence of a hierarchy of memory devices complicates the computers. A tremendous number of physicists are at work in the entire world on the task of developing high-speed memories. The new memory systems must be small and inexpensively mass-produced. I shall dwell on only three types of memory that seem promising: optical—using holography, magnetic—using cylindrical magnetic domains, and semiconducting.

In the development of holographic memory devices there is one unsolved problem—the medium in which to record and read the holograms. The medium must permit multiple re-recording, be reliable, consume little energy, etc. With a medium having the required characteristics at our disposal, holographic memory devices would find extensive applications in computers. To this end, various photochromic, photoplastic, and thermoplastic materials are being studied, together with magnetic films and ferroelectrics. So far, however, none of the investigated materials satisfies the imposed requirements.

A real revolution in electronics would result from the use of cylindrical magnetic domains. They require unprecedently low energy per bit, $10^{-13}$ J. A magnetic-domain memory can be used, for example, in telephones, in miniature computers, in associative-memory devices, and in analog memories. Owing to the large endurance to radiation, they will find extensive use in electronic apparatus of space ships.

Intensive development of semiconductor memories of various types is still continuing. Highly promising among them is a memory with charge coupling. Research in this direction, which started relatively recently, influences the development of not only computer technology, but of radio electronics as a whole. In these devices the carriers of the information are small-radius space-charge regions moving under the influence of an electric field.

In addition to the already mentioned trend, we shall note the possibility of constructing a computer memory on the basis of the relatively recently discovered photoferromagnetic effect and the so-called Josephson effect.

There are no grounds for doubting that the nearest future will bring machines that process large bulks of information, which should be fed to the computer via transmission lines of high carrying capacity. To this end it is necessary to replace the present-day system of cable connection by the most promising optical communication lines. Low-loss lightpipes are already in existence—the intensity of the propagating light decreases only by one-half in a 1-km path. These lightpipes are glass fibers about 0.1 mm thick, they do not require the use of expensive metals in short supply. The recently developed semiconductor heterolasers can be successfully used here as the radiators. It is appropriate to mention here that the heterojunction devices, first produced by Soviet scientists, play an important role in electronics. In addition to radiators, other devices are also necessary: photoreceivers, relays, converters, switches, etc. Integrated optics already serves as a basis for the development of various highly-reliable devices for optical communication lines, in which all elements should operate without failure for many years. When laser communication reaches the mass production stage, every home can be equipped with a small computer assembly performing the duties of a video-telephone and a television set, and will also be able to communicate with a large computer to obtain required information. The research in the field of solid state has brought about a revolution in the radio-electronic industry, where solid-state devices are replacing vacuum tubes. For example, successful work is being done on the development of solid-state screens for television and video-telephone, for the purpose of decreasing the weight and dimensions of these devices. Solid-state elements play an important role at present in high-power semiconductor conversion techniques. Apparatus has already been developed to transmit electric power at 1.5 million volts dc. This is of primary significance for electric-energy transmission over large distances.

The development of quantum electronics also depends in many respects on the level of work done on solid-state physics. Thus, quantum amplifiers in the radio band, in which ruby crystal serve as active elements, have record-high sensitivity. These amplifiers are used for communication with space ships.

High-power neodymium-glass lasers are used for thermonuclear fusion research. It is just with such lasers that it is proposed to realize in the near future a controlled thermonuclear reaction. This promising trend in the work on the problem of controlled thermonuclear fusion could result only from the tremendous progress made in the development of solid-state lasers with nanosecond and picosecond pulse durations. But one must not think that demonstration of the feasibility of obtaining thermonuclear energy with the aid of a laser will make it possible to construct power-generating equipment immediately.

The existing lasers still do not have the required characteristics. New ideas are needed here. A commercial laser setup should deliver about 100 million pulses without going out of order, and its components not only must withstand such an operating regime but also, no less importantly, retain their high optical qualities. The laser efficiency must exceed 10%, and the laser pulse waveform must be exactly controllable in time.

The results of computer experiments, i.e., of complicated computer calculations, make now for considerable optimism with respect to the feasibility of using lasers for controlled thermonuclear fusion. This optimism is caused by the fact that it is proposed to use the laser radiation not merely to heat the plasma, as was originally thought, but to effect a two-step process. First, a deuterated target in the form of a small sphere will be strongly compressed by the reaction of the matter evaporated from its surface when the latter is exposed to the laser radiation from all sides. At the end of this process the target will become rapidly heated to 100 million degrees, and this will create the conditions for the ignition of the thermonuclear reaction. The entire process will last only a billionth of a second. It is proposed to use as targets hollow multilayer spheres, with the aid of which it is possible to obtain, in principle, a high gain (ratio of the yield of the thermonuclear reaction to the laser radiation absorbed by the target). However, instability makes it impossible to obtain high gain. I stopped to discuss this process also in order to demonstrate how, by using laser compression, it is possible to obtain in principle matter of very high density (in this case presumably 1 kg/cm$^3$). This offers solid-state physics new possibilities, which expand considerably once we are able to obtain even higher densities. Theoretically there is no limit to the field of activity here—after all, the matter in neutron stars has a density equal to hundreds of millions of tons per cubic centimeter.

It is difficult to say whether physicists will ever be able to realize such a condensation of matter under laboratory conditions. At present the density is increased by using high pressures. Calculation shows that hydrogen, which is solid only at infralow temperatures, with an approximate density 0.1 g/cm$^3$, turns into metallic solid hydrogen with a density 10 g/cm$^3$ under pressure of several million atmospheres, and may possibly become superconducting. It is not clear, however, whether it can remain stable under ordinary conditions. Experiments on the production of metallic hydrogen are already underway, and the first results have already been obtained.

Pressures lower than those mentioned also are capable of altering the characteristics of a solid. For example, hydrostatic compression at a pressure higher than 10 thousand atmospheres greatly increases the plasticity of substances, and this is not only of theoretical but also of great practical interest. The point is that many materials are too brittle to be used in modern technology. Hence the idea of producing a new progressive technology through the use of high pressures to obtain materials with improved properties. This problem was solved through creative collaboration between physicists, engineers, and designers. The new technology, called hydroextrusion, not only makes it possible to impart to materials the required shape but, by changing their internal structure, greatly increases their strength, impact viscosity, plasticity, resistance to corrosion, magnetic properties, etc. Specialists in the field of solid state physics pay much attention to the synthesis of new crystals and compounds with a great variety of characteristics. Modern technology cannot get along without ultrahard materials. Much progress was attained in their development. Large polycrystalline diamonds and cubic boron nitride are produced by our industry and are used in a great variety of tools. These materials are synthesized under high pressures. Pressure is now coming into use to produce other crystals and compounds with improved properties. Thus, synthesis at pressures of several hundred atmospheres greatly improves the quality of a number of semiconductors, and the productivity of the process itself is appreciably improved.

The quality of a material depends not only on the purity of the initial substances, but also on its homogeneity. It is especially difficult to satisfy these conditions in the synthesis of high-temperature materials, particularly because they become contaminated by the materials of the crucible in which they are fused. These difficulties were overcome quite recently by a highly promising method, developed by Soviet physicists, of melting in a cold container. This method, in conjunction with high pressures, makes it possible to produce a new extensive class of materials for the most advanced branches of industry. The production of a number of such materials is already being learned. This short and incomplete survey, in which many important branches of solid-state physics were not considered, was principally intended to demonstrate not only the variety but also the importance of basic research in this field. We have in mind the discovery not of new laws, but of new properties and phenomena based on quantum solid-state theory. This requires, as a rule, ultrapure materials and a subtle original technology, the development of which may take many years. Without such research, however, further development of solid-state physics is impossible. On the other hand, the discovery of new laws, or the better understanding of space and time, should be expected from elementary-particle physics and from astrophysical research. But even the progress in these sciences is based on the attainments of solid-state physics.

Translated by J. G. Adashko