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AN ANTHOLOGY OF THE DISTINGUISHED ACHIEVEMENTS IN SCIENCE AND TECHNIQUE. PART 42: ELECTRONICS: RETROSPECTIVE VIEW, SUCCESSES AND PROSPECTS OF ITS DEVELOPMENT

***Purpose.** Preparation of brief scientific and technical review about sources, retrospective view, basic stages, achievements, problems, trends and prospects of development of world electronics for period of 20th-21st centuries. **Methodology.** Known scientific methods of collection, analysis and analytical treatment of the opened scientific and technical information of world level in area of a vacuum electronics, semiconductor electronics, vacuum microelectronics and nanoelectronics, and also optical electronics. **Results.** A brief analytical scientific and technical review is resulted about the primary and present states, achievements, trends and prospects of development of electronics in the developed countries of the world. From positions of approach of the systems advantages and lacks of semiconductor microelectronics are described as compared to a vacuum electronics. Considerable progress is marked in development of semiconductor element base (microtransistors, microprocessors, microcontrollers and other) for creation of different electronic devices and computing engineering. Information, touching the determining deposit of electronic companies of the «Silicon Valley» in the USA in providing of technological breach in area of modern microelectronics, production of computers and their microprocessors, software and creation of devices of mobile communication development, is resulted. The basic problems of space microelectronics are affected. The possible ways of further development are indicated in the world of electronics, including vacuum microelectronics and nanoelectronics, and also optical electronics. The special attention is turned for urgent development of high-efficiency protective facilities specialists against cyber attacks hackers on the computer systems. In a review an accent is done on the sharp necessity of acceptance the proper services of drastic measures for a fight with cyber terrorism. **Originality.** Systematization of the scientific and technical materials touching world history of development and creation of modern element base of a vacuum electronics and semiconductor microelectronics known from the sources opened in outer informative space is executed. Possible new perspective directions of development in the modern world of microelectronics are formulated. **Practical value.** Popularization and deepening for students, engineer and technical specialists and research workers of front-rank scientific and technical knowledge in the topical area of development, creation and application in the modern technique of the different setting of high-computer-integrated electronic devices, extending their scientific range of interests and further development of scientific and technical progress in society.* References 34, figures 22.
Key words: **vacuum electronics, radio lamp, solid state microelectronics, transistor, integrated circuit, microprocessor, vacuum integrated circuit, vacuum microelectronics and nanoelectronics, trends and prospects of electronics development.**

Приведен научно-технический обзор о ретроспективе, успехах, тенденциях и перспективах развития мировой электроники. Рассмотрены основные этапы развития электроники, связанные с изобретением радиолампы, транзистора, интегральной схемы и высокоинтегрированного микропроцессора. Отмечен вклад электронных компаний «Кремниевой долины» США в технологический прорыв в микроэлектронике. Описано состояние работ в области вакуумной микроэлектроники и наноэлектроники. Библ. 34, рис. 22.
Ключевые слова: **вакуумная электроника, радиолампа, твердотельная микроэлектроника, транзистор, интегральная схема, микропроцессор, вакуумная интегральная схема, вакуумная микроэлектроника и наноэлектроника, тенденции и перспективы развития электроники.**

Introduction. For mankind in the 20th century, the time came when the further development of scientific and technological progress in society became unthinkable without electronics. As is known, by «*electronics*» we mean that area of science and technology that covers the study and practical use of electronic and ionic phenomena occurring in vacuum, gases, liquids, solids and plasmas, and also on their boundaries [1]. That is why electronics is engaged in the study of the interaction of electrons and ions with electromagnetic fields and methods of creating electronic devices for the conversion of electromagnetic energy mainly for the transmission, reception, processing and storage of information [2]. Electronics has become the basis of modern automation, radio engineering, electrical engineering, energy, cybernetics, information technology and other important scientific and technical fields of knowledge. Without electronics, research at a high scientific level in the field of the microworld (for example, plant and animal cells, atoms and molecules of matter), and the macrocosm (for example, objects of the nature of the planet Earth, the secrets of near and far space) have become impossible. Without extensive use of electronics, they do not do without the development and creation of most complex military and civilian facilities (for example, aircraft, rocket and space technology, power stations, audio, television, and video equipment, etc.). Electronics and its successes in all industrialized countries of the world are given increased attention. According to the level of development in the country of electronics and, accordingly, the electronic industry, experts make a reasoned assessment of its scientific and technical potential and economic opportunities in the medium and long term [2]. The emergence of electronics was preceded by the invention at the end of the 19th century (May 7, 1895) by our former compatriot, Professor of Physics Department of the St. Petersburg Electrical Engineering Institute A.S. Popov (1859-1906) wireless radio communication [2, 3]. We would like to point out that the remarkable achievements of the talented Italian engineer and businessman G. Marconi (1874-1937) awarded in 1909 by the Nobel Prize in Physics [4] contributed to the significant development in the world of radio communications. Radio and radio transmitters immediately found application in military affairs and, first of all, in the Navy [2, 3]. It was then that for practical implementation of actual applied radio engineering tasks, a corresponding elemental base was required, and the study and creation of which was done in detail by electronics.

The goal of the paper is the preparation of a brief scientific and technical review on the sources, main stages, achievements, current trends and prospects of development in the electronics world on the basis of published in open press materials.

1. The stage of the birth of electronics and the invention of a radio lamp. The creation and development of the elemental electronics base in the world actually began with the invention of an electronic lamp (EL) in the early 20th century. So, in 1904, John Fleming received a British patent for «*A device for the conversion of alternating current into direct current*» [2, 5]. It was this two-electrode vacuum device - the diode and served as the opening on the Earth of the age of electronics. Therefore, this electronics is usually called «*vacuum electronics*» [5]. EL or simply a radio lamp is known to be an electrovacuum device that operates by controlling the intensity of the flow of free electrons moving inside a vacuumed sealed glass cylinder between the metal electrodes. These electrons in EL arise because of the phenomenon of their thermionic emission from the surface of a metal cathode heated by direct (alternating) heating current to high temperature (about (800-3000) °C) [2, 5]. It should be noted that the author of the discovery of the phenomenon of thermionic emission from a hot electrode is the famous American electrical engineer and inventor Thomas Edison (1847-1931), who in 1883, in experimental studies, as far as possible, to increase the lifetime of a light bulb containing a carbon filament in a pumped glass flask, recorded the passage of an electric current in a vacuum from the filament of a lamp to a flat metal electrode located near a given filament [5]. Then the importance of the significance of this seemingly local electrophysical phenomenon, but as it turned out in the future of a fundamental scientific discovery, he did not fully understand. But as an experienced inventor, just in case, he still patented it in the US. Over time, it was this discovery that became the basis for the operation of all types of EL and, in fact, the basis for all vacuum electronics up to the creation of semiconductor devices. J. Fleming used this «Edison effect» when creating his electrovacuum diode, which played a prominent role in the history of radio engineering. The main drawback of the Fleming diode was its inability to amplify electrical signals. In 1906, an American engineer Lee de Forest introduced a third electrode to the EL in the form of a control metal grid and invented in this way an electrovacuum triode shown below in Fig. 1 [5, 6].

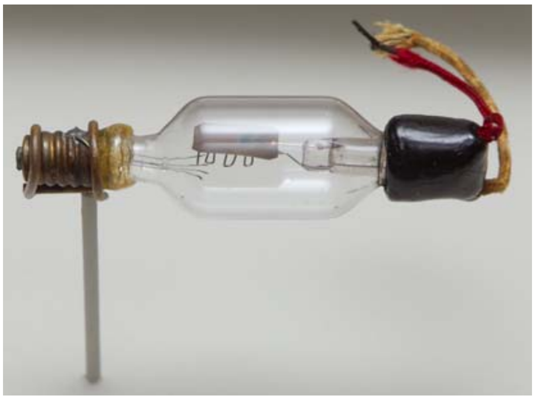

Fig. 1. General view of the triode created by Lee de Forest [5, 6]

The «Forest triode» became the first amplifying lamp and the basis for further improvement of EL with a heated cathode [7]. This EL due to the supply of its control electrode of an alternating electric potential could work as an amplifier of electromagnetic oscillations [7]. In 1913, based on the «Forest triode «, the first autogenerator was created [5, 7]. A major contribution to these pioneering developments for the needs of radio engineering with the use of a tube triode for the generation of electromagnetic oscillations was made by A. Meissner [8]. EL and the lamp amplifiers created on their basis became actively used on radio stations. Under the leadership of the well-known Russian radio engineer M.A. Bonch-Bruevich (1888-1940) at the Nizhny Novgorod Radio Laboratory in 1919 the first Russian radio lamp was created, called «Babushka» («Grandmother») (Fig. 2) [9].

Fig. 2. General view of the first Russian powerful radio lamp «Babushka» («Grandmother») (Nizhny Novgorod Radio Laboratory, 1919) [9]

Later on, after tube diodes and triodes, such types of EL were created: [7] tetrodes (1913), pentodes (1929, Fig. 3), hexodes (1932), heptodes, octodes and nonods. These types of EL differ in design from each other, primarily by the number of metal grids (from two to seven) [5, 7]. ELs using a filament inside the cathode are called indirectly incandescent lamps, and ELs made with a filament in the form of the cathode itself have been called direct-burning lamps. EL cathodes, as a rule, are activated by metals having a small work function of electrons. In EL direct heating for this purpose, radioactive thorium is used, and in indirect filament lamps - barium [7]. On the inner surface of the EL glass, one can see a brilliant coating-getter intended for the adsorption of residual gases in its internal vacuumed volume and the indication of the vacuum in it (when the air enters the EL, the getter becomes white [7]). The peak of «flowering» in the world of vacuum electronics came in 1930-1950.

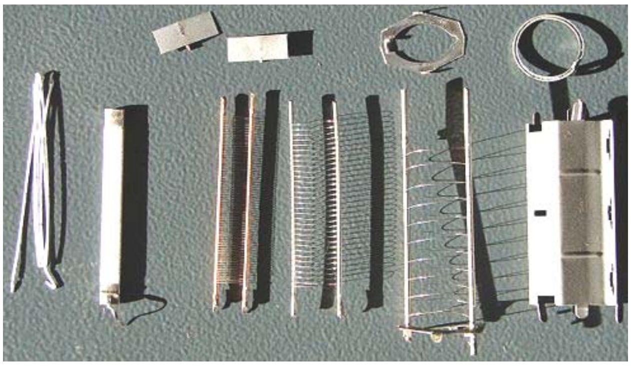

Fig. 3. External view of individual elements of the modern electrovacuum pentode (from left to right: filament, heated cathode, three metal grids, anode, at the top of the mentioned EL elements - details of their attachment) [7]

We point out that in 1913 G. Marconi patented the construction of the anode of a radio lamp in the form of a hollow metal cylinder of various configurations surrounding an internal coaxially placed cathode [7]. In this regard, EL already in the 1930s almost acquired the external view that it now has (Fig. 4). In high-power radio tubes with a high current density of the cathode, purely metallic cathodes perform their refractory tungsten. The anodes in such ELs are most often made in the shape of a box (see Fig. 3, 4) surrounding the cathode and the grid, from nickel or molybdenum (sometimes from tantalum) [7]. The grid in EL is a lattice (see Fig. 2) or a spiral made from a thin refractory metal wire wound around the cathode. A slight change in the difference between the electrical potentials between the control grid and the cathode leads to large changes in the anode current in the external circuit of the EL.

Fig. 4. General view of a modern vacuum radio lamp [7]

Let us pint out the advantages and disadvantages of tube electronic amplifiers using radio tubes in their circuits. The main advantages of amplifiers on EL should be attributed [6, 7]:

- simplicity of circuits (in tube amplifiers, in comparison with semiconductor amplifiers an order of magnitude smaller than composite elements and parts, EL provide more amplification than transistors);
- high reliability in operation (the output parameters of EL depend little on external factors such as temperature, pressure, optical and ionizing radiation, EL are insensitive to electric overloads in their circuits);
- good compatibility with the load (lamp stages have a large input resistance, which helps reduce the number of active elements in the amplifier and reduce losses on them);
- ease of maintenance (with the failure of the EL it is much easier to replace than the transistor);
- absence at their output of certain types of distortion inherent in transistor cascades.

The main disadvantages of electronic amplifiers on radio tubes include the following [6, 7]:

- relatively low efficiency (in used ELs, in addition to powering the anode, it is required to heat the cathode due to the filament, which leads to additional costs of electricity);
- greater inertia in preparation for operation (all EL require preheating);
- certain limitations on safety in their operation (electronic circuits using EL require the use of voltage in their circuits, which is hundreds and thousands of Volts);
- limited lifetime (over time, the cathode EL loses its emissive properties in the emission of free electrons, a relatively high probability of burning the cathode filament EL);
- fragility of their EL with a glass cylinder.

Despite these disadvantages, ELs continue to be actively used and at present when creating electronic circuits of the following techniques [7]:

- powerful broadcasting transmitters having an output power from hundreds of Watts to several Megawatts (electronic circuits of such radio devices use powerful and super-power radiolamps with air or water cooling and a filament current in EL cathode circuits of 100 A and more);
- objects of military equipment that are resistant to the damaging effect of a powerful electromagnetic pulse of natural (from lightning discharges) and artificial (from nuclear explosions) origin;
- rocket and space technology exposed to long-term exposure to radiation fluxes when flying in open space conditions (the radiation degradation of semiconductors limits their use in spacecraft electronics);
- high-quality audio equipment.

Note that the introduction of any gas in the EL degrades its technical characteristics. Nevertheless, radio engineering practice required gas discharge devices in which the control of their electrical ion current is carried out by the voltage applied to their metal electrodes. Such ion devices have been called «thyratrons» one of whose representatives is shown in Fig. 5.

The thyratron is a sealed glass cylinder filled with a gas (usually an inert gas, hydrogen or mercury vapor) and containing at least three electrodes - a cathode, an anode and a grid - inside it [10]. The grid in the thyratron is used to ignite a gas discharge in the space between the cathode and the anode. For this purpose, a high impulse voltage is applied to it from the power supply. The ionized gas (plasma) arising from this electric spark discharge in the closed thyratron volume conducts an electron-ion current between the cathode and the anode. In this way a three-electrode gas-discharge thyratron switches on and off the pulse current in its anode circuit. In high-current circuits of high-voltage pulse technology using powerful capacitive energy storage (CES) to supply high pulsed currents (HPC) of the nano and microsecond range to electrical loads, three-electrode electronic devices that were termed «trigatrons» were widely used [11]. Usually their working chamber is filled with a gas dielectric (Fig. 6). More rarely it is filled with a liquid dielectric. Trigatrons are one of the varieties of a controlled spark switch [12].

Fig. 5. General view of a large hydrogen thyratron used in pulse electrical circuits of modern radars (manufactured by General Electric, USA) [10]

Fig. 6. General view of the powerful trigatron type CV100 [11]

Trigatrons use a cold cathode. A microsecond voltage pulse with an amplitude of up to ±100 kV is applied to their control (initiating) electrode (an analog of the grid in thyratrons) from the generator of igniting electrical signals, causing the appearance of one of its main spark-discharge electrodes in the local zone and, accordingly, the initial ionization of the plasma channel of the gaseous dielectric surrounding it. As a result of a sharp decrease in the electrical strength of its main insulating gap between the cathode and the anode of the trigatron, an electric breakdown of the working dielectric medium takes place and, accordingly, a discharge of the previously charged CES to the load. The amplitudes of commutated trigatrons of HPC range from tens to thousands of kiloamperes [11, 12]. This type of electronic devices is also used as high-current high-voltage switches in the discharge circuits of generators of high and ultrahigh impulse voltages, performed according to the classical Arkadyev-Marx scheme, in high-voltage devices of high-current accelerators of charged particles and electrodynamic guns [11, 12].

A successful combination of controlled spark switches - trigatrons and thyratrons have become such gas-filled lamps with a cold cathode as «krytrons» [13]. The krytrons (Fig. 7) are characterized by a fast switching on of the electric circuit in order to transmit a powerful signal with high current and high voltage through it. The first samples of krytrons were created in the USA by the firm EG&G Corporation for transmitters of military aircraft radars [13].

Fig. 7. General view of the krytron-key type KN2 «Krytron» (manufactured by EG&G Corporation, USA) [13]

Unlike most gas discharge devices, in krytrons an electric arc discharge is used to initiate a high-current spark discharge between the cathode and the anode of these gas-filled lamps. In this connection, the krytrons have four electrodes: two main or main (cathode and anode), a grid and a keep-alive electrode [13]. In the krytron, the keep-alive electrode to which a small positive-polarity voltage is applied is located next to the cathode, which has a negative electric potential. A high commutated voltage in the krytron is applied to the anode. After the appearance of an electric arc discharge between the keep-alive electrode and the cathode and the initial ionization in this local gas zone, a positive voltage pulse is applied to the control grid in its glass mesh balloon, resulting in a high-current electric spark discharge between the anode and the cathode of the krytron [13]. Electrical breakdown of the insulating gap between the anode and the cathode of the krytron and ensures fast switching of its high-current circuit with load. To facilitate the ionization of the gas of the krytron, an isotope of radioactive nickel-63 emitting β-rays (electrons) is placed in its glass cylinder [13]. The krytrons created in the second half of the 1940s were used in industrial pyrotechnics and nuclear technology (for example, in high-current control circuits for the operation of electric nuclear detonators [13]) because of their stably high impulse responses compared to semiconductor devices. In connection with the possibility of using krytrons in electric circuits for the detonation of nuclear munitions [13, 14], very strict export restrictions have long been imposed on their export from the United States. At present, the American Company «Perkin-Elmer Components» produces gas-filled and vacuum krytron-keys [13]. The vacuum version of the krytron («sprytron») can operate under conditions of high radiation, when the semiconductor technology is working incorrectly and fails. In conclusion of this section devoted to ELs, let us dwell on such a gas-discharge device as a «xenon arc lamp» [15]. This lamp (Fig. 8) is a powerful source of artificial light, close in its spectral composition to daylight.

Fig 8. General view of a 15 kW xenon arc lamp used in a modern IMAX projector [15]

In this lamp, the electric arc brightly shines in a glass bottle filled with xenon. Its cylinder is made of heat-resistant quartz glass. The cathode and anode in such a lamp are tungsten electrodes doped with radioactive thorium to reduce the work function of electrons from them. The balloon is initially evacuated, and then xenon is fed into it. Pulsed xenon flashbulbs contain a third control electrode surrounding its glass cylinder [15].

2. The stage of development of microelectronics and the invention of a transistor. Electronic devices built on EL had such two significant drawbacks as: large weight dimensions and high levels of consumed electric power (energy) [2, 8]. These shortcomings were critical for the creation of computers, portable electronic devices, electronics for aviation and rocket and space technology. Therefore, semiconductor devices were objectively created and developed. The underlying electronics was called «*solid state electronics*» [2, 8]. Element base of this electronics at the initial stage of its occurrence began to be based on transistors and semiconductor diodes. As is known, a transistor is a semiconductor triode (Fig. 9) which is capable of controlling a significant current from its small input signal in its output circuit. This property of the transistor allowed it to be used to amplify, generate, switch and convert signals. Following the EL, the transistor became the basis for the circuitry of most electronic devices [16]. When and by whom was this device created, which made a «revolution» in electronics?

Fig. 9. General view of bipolar transistors of various designs using three electrodes on a single semiconductor crystal – the base, the control electrode – the emitter and the controlled electrode – the collector) [16, 17]

From the history of the invention of the transistor, it is known that since 1936 in the USA in the experimental development department of Bell Telephone Laboratories of a large Company American Telephone and Telegraph under the leadership of Joseph Becker, work was done to create solid-state amplifiers of electrical signals [17]. Until 1941 (before the start of World War II) it was not possible to produce a semiconductor amplifying device in Bell Labs. In 1945, after the war, under the leadership of theoretical physicist William Shockley in this laboratory, the research related to the creation of a field-effect transistor was resumed. After two years of failure, experimental physicist Walter Brattain working on December 16, 1947 with a germanium crystal unexpectedly received a steady amplification of the signal [17]. His subsequent research with theoretical physicist John Bardeen showed that they, in fact, invented a semiconductor triode, later called a «bipolar transistor.» Fig. 10 shows the external view of the investigated model of this transistor [17].

For the reader it is required to give a little explanation about the field (unipolar) and bipolar transistors. The «field effect transistor» uses a semiconductor (for example, a germanium or silicon crystal) of only one type of conductivity, having a thin channel, which is affected by the electric field of the gate electrode isolated from the channel [16]. A field-effect transistor, unlike a bipolar triode, is controlled not by current, but by the voltage applied to its gate. In the «bipolar transistor» semiconductors with both types of conductivity are used. It works by the interaction of two *p-n* junctions closely spaced on a single semiconductor crystal and is controlled by a change in the current through the base-emitter junction [16]. The output of its emitter is usually common for the control and output currents [3]. Do this so that in circuits with the use of a transistor it would be possible to gain amplification not only by voltage, but also by current. In addition, it should be pointed out that the scientific discovery of the *p-n* junction in crystalline silicon was made in 1940 by the employees of the American laboratory «Bell Labs»

Russell Ol and John Scuff [17]. These solid-state physicists have established that doping the surface of a silicon crystal with boron atoms leads to its positive *p*-conductivity, and phosphorus atoms to its negative *n*-conductivity. Thus, *p*-type silicon and *n*-type silicon were invented, which played a huge role in the development of solid-state electronics [17]. In this regard, it should be noted that in 1941, regardless of US physicists, the Ukrainian physicist V.E. Lashkaryov developed the theory of «blocking layer» and injection of charge carriers at the interface between copper and cuprous oxide [17]. The two types of conductivity found experimentally by means of a thermosonde in a copper-oxide element indicated the presence of a transition layer between them, which prevents the passage of current [17].

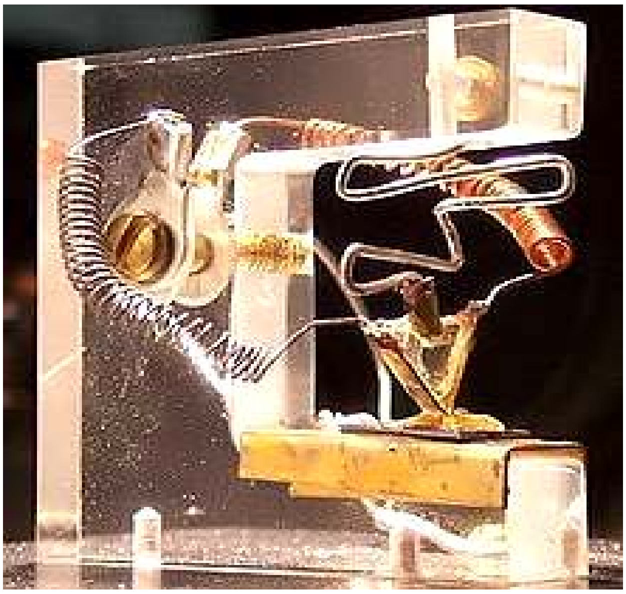

Fig. 10. External view of the modern layout of the transistor By J. Bardeen and W. Brattain (its original is not preserved) [17]

On December 23, 1947, a presentation of the existing original layout (see Fig. 10) of a new semiconductor product – a bipolar transistor to the leadership of the Bell Labs laboratory [17] was held. It is this date that is considered the birthday of the transistor. Having learned about this success of his colleagues, W. Shockley re-connects to semiconductor research and in a short time creates the theory of a bipolar transistor [17]. Fig. 11 shows the American scientists who discovered the transistor effect [17]. Note that at the end of June 1948 in the US Company where the first bipolar transistor was working the first radio transistor was manufactured [17]. However, the world sensation due to the invention in the US and the radio technical use of the transistor at that time did not take place. This was due to the fact that the first point-to-point transistors, in comparison with EL, had low output characteristics. Only in 1956 the scientific discovery of American researchers W. Brattain, J. Bardeen and W. Shockley was appreciated by the Swedish Academy of Sciences for its worth: its authors for the «*semiconductor research and discovery of the transistor effect*» were awarded the Nobel Prize in physics [4].

Fig. 11. Future Nobel Prize Laureates in Physics at the Bell Labs Laboratory (from left to right: John Bardeen, William Shockley and Walter Brattain, USA, 1948) [17]

We point out that the first point-like transistors, despite their small size and economy, were distinguished by a high noise level in useful electrical signals, low power, instability of the characteristics in time, and a strong dependence of the output parameters on temperature [17]. A point transistor, the zones of two *p-n* junctions closely spaced from each other in which a single-crystal germanium was performed on a single crystal, was sensitive to mechanical shocks and vibrations due to its nonmonolithicity. In 1951, the first flat bipolar transistor was constructed, constructively representing a monolithic germanium crystal [17]. At the same time, the first transistors on a silicon crystal appeared (Fig. 12). The output characteristics of such bipolar transistors began to compete successfully with EL parameters [17].

Fig. 12. General view of monocrystalline silicon grown in vacuum by technologists in materials science [18]

Bipolar transistors *p-n-p* (direct conductivity) and *n-p-n* (inverse conductivity) are known [19]. These transistors, in addition to the basic semiconductor material used most often in the form of a single crystal (a thin flat element from the large single crystal shown in Fig. 12), contain in their construction alloying additives (usually boron or phosphorus) to the base semiconductor, metal leads of the *base*, *emitter* and *collector* as well as the body (metal or ceramic) with insulating parts (see Fig. 9) [17]. The main types of semiconductors in them were silicon, germanium and gallium arsenide. We will point out that in bipolar transistors the charge carriers move from the emitter through a thin base to the collector. The base is separated from the emitter and collector by *p-n* junctions. Current flows through this type of transistor only when charge carriers are injected from its emitter into the base through the corresponding *p-n* junction. In the base they are not the main charge carriers and easily penetrate through its other *p-n* junction between the base and the collector. In the base of the transistor the charge carriers move due to the diffusion mechanism. In this regard, it should be fairly thin. The current control between the emitter and the collector of the bipolar transistor is performed by changing the voltage between the base and the emitter, on which the conditions for injecting charge carriers into the base depend [17, 19].

As for the history of the creation of field-effect transistors, we note that for the first time the electrophysical idea of control (regulation) in a semiconductor triode with an isolated gate electrode by a flux of main charge carriers (electrons) was expressed by J. Lilienfeld (US Patent No. 1745175 of 28.01.1930) [20]. However, the difficulties encountered in realizing this idea in practice made it possible to create the first operating field-effect transistor only in 1960. In 1966, Carver Mead, by shunting the electrodes of such a semiconductor device with Schottky diode, substantially improved the design of the field-effect transistor [20]. Field-effect transistors are classified into devices with a gate in the form of a *p-n* junction and with an isolated gate. The last transistors have received in electronics the name of MDS-transistors («metal-dielectric-semiconductor») [20]. Sometimes, MDS-transistors are also called MOS transistors («metal-oxide-semiconductor»). In addition, field-effect transistors with an isolated gate are divided into instruments with a built-in channel and devices with an induced channel [20]. We will point out that the channel in these transistors is the region through which the flow of their main charge carriers-electrons passes. The electrodes of field-effect transistors have the following names [20]: *source* – an electrode, from which the main charge carriers enter the channel; *drain* – an electrode through which the main charge carriers leave the channel; *gate*–- an electrode that serves to regulate the cross section of the channel. The conductivity of the channel under consideration can be either of the *n*-type or of the *p*-type. In this regard, the type of channel conductivity distinguishes between field-effect transistors with an *n*-channel and a *p*-channel. In a field-effect MOS transistor containing one semiconductor crystal (substrate), the current flows from the source electrode deposited on the highly doped region of the *n*-conductivity semiconductor crystal substrate to the drain electrode deposited on the heavily doped region of the semiconductor substrate with *p*-conductivity, through a channel located under the gate electrode. The distance between heavily doped source and drain regions is of the order of one micron. The surface of the semiconductor crystal between the source and the drain is covered with a thin layer (about 0.1 μm thick) of the dielectric. For a silicon crystal, SiO_2 is used as this dielectric, grown on the surface of a silicon crystal by its high-temperature oxidation [20]. A metal gate electrode is applied to the dielectric layer between the source and the drain. The channel exists in the doped parts of the semiconductor crystal substrate in the gap between the gate and the undoped semiconductor substrate, in which there are no charge carriers. Therefore, it (the substrate) can not conduct a current. Under the shutter, there is a depletion region, in which there are also no charge carriers, due to the formation of a Schottky contact between the doped region of the semiconductor crystal and the metal gate of the Schottky contact [20]. It turns out that in this type of field-effect transistor, the width of the channel is limited by the space between the substrate and the depletion region. The voltage applied to the gate increases or decreases the width of the depletion region of the device in question and thereby adjusts (changes) the channel width of such a transistor. In this way the current passing through its channel changes in this device.

In a field-effect transistor with a control *p-n* junction, a plate-crystal made of a semiconductor (for example, with *n*-conductivity) is used, at the opposite ends of which there is an electrode-source and an electrode-drain included in the controlled circuit of the device. Between these electrodes, a control gate electrode is placed on a region of a semiconductor with a different conductivity (for example, with *p*-conductivity). The power supply included in the input circuit of the device creates on its only *p-n* junction a reverse voltage. In the input circuit of such a transistor, the source of amplified signals is also included. When the input voltage changes on the gate, the reverse voltage on the *p-n* junction also changes. In our case, this will lead to a change in the thickness and, correspondingly, the cross-sectional area of the depletion layer region in the *n*-channel field-effect transistor through which the main carriers (electrons) flow [20]. By varying the cross-sectional dimensions of this channel, a current change is achieved in the output circuit of this type of semiconductor triode.

The main advantages of semiconductor triodes over vacuum ELs are [16, 17]:

- small size and weight, contributing to the wide development of miniature electronic devices;
- low cost, caused by automation of production and technological processes;
- low voltage level, which facilitates the use of transistors in small electronic devices, powered by batteries;
- absence of additional time to warm up their electrodes after switching on the device;
- low power dissipation (energy) indicators, which contribute to improving the energy efficiency of transistors and devices in general;
- high reliability in operation and great mechanical strength to shock loads and vibrations of individual semiconductor triodes and an electronic device as a whole containing a huge number of similar semiconductor devices;

• long service life, counted by dozens of years of continuous operation as part of the device;

• possibility of combination in work with additional electronic circuits and devices.

The main disadvantages of transistors in comparison with vacuum ELs are [17, 21]:

• operating voltage for transistors using crystalline silicon does not exceed 1 kV (when switching circuits with voltages greater than 1 kV, IGBT-transistors are now used);

• use of transistors in high-power broadcasting and microwave transmitters is technically and economically impractical (using high-power generator tubes, magnetrons, klystrons and moving-wave tubes for this purpose provides a better combination of high frequencies, high power and acceptable cost);

• transistors in comparison with EL are more vulnerable to the impact of such a damaging nuclear weapon as a powerful electromagnetic pulse;

• increased sensitivity to the damaging effects of radiation and cosmic radiation.

Note that the input impedance for field-effect MDS- transistors using an isolated gate electrode can be values that vary in the range (10^{10}-10^{14}) Ω. In field-effect transistors with a control *p-n* junction, these parameters are (10^{7}-10^{9}) Ω [20]. High input impedances for field-effect transistors make it possible to use them when creating high-precision electronic devices operating at low voltage with low energy consumption (for example, electronic clocks). A hybrid type IGBT transistor, combining the properties of bipolar and field-effect transistors, can be used in high-voltage technology [8, 20].

Over time, transistors have replaced vacuum EL throughout the world in most electronic devices. These semiconductor devices radically changed all electronics of our world. They became the element base on which «*microelectronics*» arose and integrated circuits and high-speed computers were created [22]. At the beginning of the 21st century, transistors became the most massive product produced by mankind. Note that in 2013 for every inhabitant of the planet Earth electronic industry of the world was released about 15 billion transistors, most of which were part of integrated circuits [16, 17].

3. Intermediate stage of development of microelectronics and the invention of an integrated microcircuit. We point out that in April 1954 the employee of the American Company Texas Instruments Gordon Teal manufactured the first silicon bipolar transistor. Until 1957, this US Company was the only supplier of silicon transistors in the world market of microelectronics [17]. The invention by Karl Frosch in the United States of the process of «wet» (using water vapor) thermal oxidation of silicon in order to obtain a thin SiO_2 layer on a semiconductor substrate made possible the release in 1958 of the «Bell Labs» of the first silicon MES transistors. In March 1959, Jean Ernie created the first silicon planar transistor, in which the meza-technology was replaced by a more promising planar technology for manufacturing transistors. The further development of the physics and technology of semiconductors led to the fact that silicon practically displaced germanium from microelectronics, and the planar process became the main technology of manufacturing transistors in the electronics world and made it possible to create monolithic integrated circuits (ICs) [17, 23]. The IC (Fig. 13) is an electronic scheme of arbitrary complexity made on a semiconductor substrate (crystal plate or film) and placed in a non-separable plastic (ceramic) housing [21, 23].

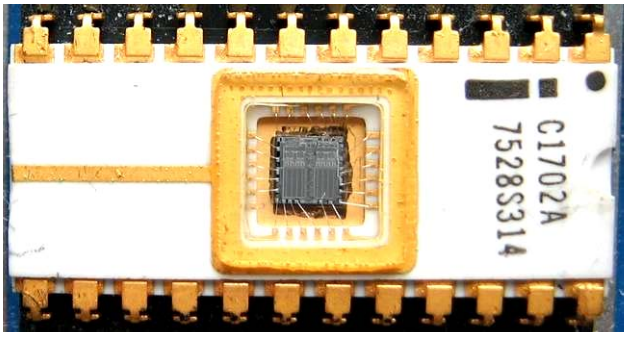

Fig. 13. External view of the IC used in space microelectronics with an increased level of radiation [21]

The vast majority of the IC in the world is manufactured in cases (see Fig. 13, 14) and is intended for their surface mounting on the boards of electronic devices. We will point out that an insignificant part of the IC, which is part of the microassemblies, is manufactured without these enclosures. Often, IC is also called a «chip» (from the English «chip» – «thin plate» [1]). British radio engineer Geoffrey Dummer on May 7, 1952 first put forward the idea of combining a set of standard electronic components in one monolithic semiconductor crystal [23]. This progressive idea for a number of years because of the insufficient level of development in the world of technologies for the production of semiconductor devices remained unrealized in practice. Only in the first half of 1959 there was a real breakthrough in the world semiconductor technology, carried out in practice by three practitioners from three private American Corporations who successfully solved three fundamental problems for the production of IC [23].

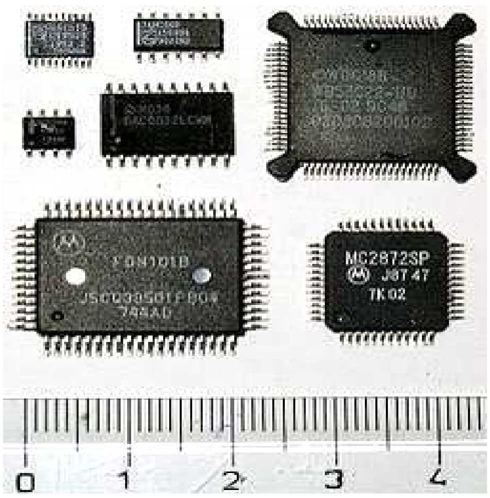

Fig. 14. General views of case ICs of various design and integration degree intended for surface mounting on electronic device boards [23]

So, American physicist and inventor Jack Kilby of Texas Instruments patented the principle of combining electronic components in IC with transistors made with layered *p-n-p* or *n-p-n* junctions (US patent was issued in 1964) [23, 24]. It should be noted that in 2000 J. Kilby (born in 1923) «*for his contribution to the discovery of the integrated circuit*» was awarded the Nobel Prize in physics [24]. Further, at this time, the American engineer Kurt Legovec of the Sprague Electric Company invented a method for electrical isolation of components formed on a single semiconductor crystal (he proposed to use *p-n* junctions as insulation) [23]. It was then that an American specialist Robert Noyce from «Fairchild Semiconductor» invented a method of electrically connecting the components of an IC (due to their metallization with aluminum) [23]. In addition, R. Noyce in those years proposed an improved version of the isolation of components of IC based on the latest planar technology by Jean Hoerni. On September 27, 1960, the group of Jay Last of Fairchild Semiconductor created the first workable IC on the ideas of R. Noyce and J. Hoerni.

Note that, depending on the degree of integration of electronic components in one semiconductor crystal (usually silicon, germanium, gallium arsenide or hafnium oxide), the following IC names are currently used [23]:

- small integrated microcircuit (MIMS), containing up to 100 electronic components;
- medium integrated circuit containing up to 1000 electronic components;
- large integrated circuit containing up to 10,000 electronic components;
- ultra-large integrated circuit containing more than 10,000 electronic components (further increase of electronic components in one chip with bringing their number to 10^9 or more does not change the name of this IC).

Let us emphasize the fact that, in fact, with the invention of IC in electronics, its new section, «microelectronics», objectively studying and manufacturing electronic components objectively appeared, whose linear geometric dimensions of the characteristic elements became a few microns or less. The technological process of manufacturing the IC as a semiconductor element base in microelectronics has been continuously improved and improved to this day [25]. This complicated and complex process includes the sequence of a number of technologies [25-27]: the production of high-purity semiconductor materials, the manufacture of miniature semiconductor elements (transistors, diodes, etc.), the quality control of their manufacture, the assembly of these electronic components and quality control of their assembly. According to the requirements of «electronic hygiene» in the working area of semiconductor wafer processing and in the operations of assembling IC crystals there should not be more than five dust particles with a size of 0.5 μm in 1 liter of air [18]. In the production of IC, the technology of doping a semiconductor crystal is used to obtain *p-n* junctions and photolithography, realized with the help of appropriate lithographic equipment. The resolution (in μm or nm) of this equipment determines the name of the specific technological process used in the manufacture of IC. Reducing the size of semiconductor structures in ICs leads to improved technical characteristics of semiconductor devices (for example, to reduce their power consumption, increase the operating frequency in their electronic circuits, increase their speed, reduce their cost, etc.) [28]. Therefore, the miniaturization of the semiconductor element base of microelectronics has become the main worldwide trend in the production of various electronic devices. Below are the main stages of development in the world of the technological process in the manufacture of IC [23]:

- stage with resolution (3-1.5) μm (1970s);
- stage with a resolution of (0.8-0.5) μm (1980s);
- stage with resolution (350-130) nm (1990's);
- stage with a resolution of (65-10) nm (2000's).

Let us note that in May 2011 Altera Company produced the world's largest IC consisting of 3.9 billion field-effect transistors [23], with the 28 nm resolution technology production process. In 2012, the smallest transistors in the IC contained a few atoms of matter. In one processor of a modern computer, they can contain more than a billion pieces. In the IC, electronic components of conventional electronics such as resistors, capacitors, inductors, diodes, transistors, insulators and conductors are used [28]. Only these components are used in the form of miniature devices made on a single semiconductor chip (Fig. 15) in the integrated version. In microelectronics, ICs are divided into digital, analog-digital and analog. Moreover, digital ICs consist of miniature transistors, and analog ICs contain miniature resistors, capacitors and inductors. Modern digital technology and the ICs used in it are mainly built on field-effect MDS-transistors performed on a single silicon crystal (chip). These transistors have become essentially a «brick» for building circuits of logic, memory and computer processors. The dimensions of modern MDS-transistors are from 90 to 8 nm [28, 29]. At present, up to several billion MDS-transistors can be located on a single semiconductor chip with an area of up to 1 cm^2 [28]. According to Moore law («*the number of transistors in the IC is doubled for every 18 months*»), a further increase in the degree of integration of transistors on a single chip is expected in the coming years [28].

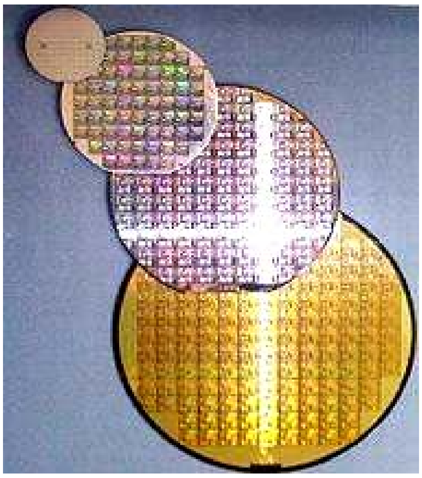

Fig. 15. Thin round silicon plates with prefabricated microcircuits before cutting them with a diamond microdisk into individual crystals of a given semiconductor [28]

4. The current stage of development of microelectronics and the invention of a highly integrated microprocessor. ICs have become the backbone of processors (from Latin «processus» – «advancement» [1]) which are the central part (the «heart») of all computers performing the information conversion programs specified by the program and managing the entire computing process in an electronic computer [28]. As is known, the «microprocessor» forms the core of the computer (Fig. 16), in which additional functions (for example, connections with its peripherals) are performed using specially designed chipsets [23]. The US Company Intel in 1971 was the first to manufacture IC (Intel 4004) which served as a microprocessor [23]. Another American Company IBM based on the advanced microprocessors 8088 and 8086 released their famous personal computers PC/XT series [23]. In the first computers, the number of chipset sets was up to hundreds of pieces. In modern computers, their number does not exceed three. Recently there has been a tendency of gradual transfer of the functions of the chipset (memory controller, etc.) to the microprocessor [23, 28].

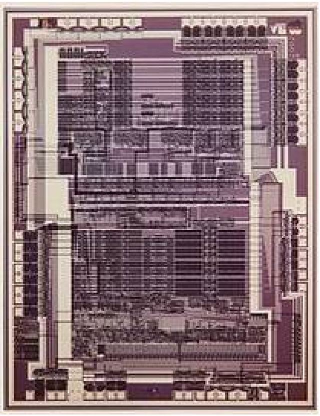

Fig. 16. External view of the internal filling of the modern microprocessor Apple of the US Company of the same name [18]

In this regard, the microprocessor with built-in operational and program memory devices, memory controllers, input-output devices and other additional functions is also called a «microcontroller» [28]. The main feature of the microcontroller is the possibility of programming the logic of its operation. The placement of a whole microprocessor on a single chip of an extremely large degree of integration (Fig. 17) containing hundreds of millions of electronic components led to a significant decrease in its cost [30]. The creation at the end of the 20th century of highly integrated microprocessors on a single crystal determined their wide application in personal computers.

At present microelectronics uses microprocessor systems, which are functionally complete products consisting of one or several microprocessors (microcontrollers, Fig. 18) [30]. In modern electronic devices, massively multi-core processors are also used which are CPUs that contain two or more processing cores on a single processor semiconductor (silicon) crystal [30]. In such a processor, several of its cores are integrated into one ultra-large integrated circuit. The concept of a «multi-core electronic device» can also be used to describe the operation of multi-core systems (for example, Intel MIC [30]).

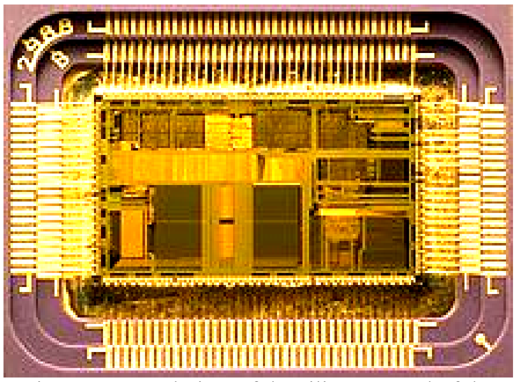

Fig. 17. General view of the silicon crystal of the microprocessor 80486DX2 in the case for a personal computer [30]

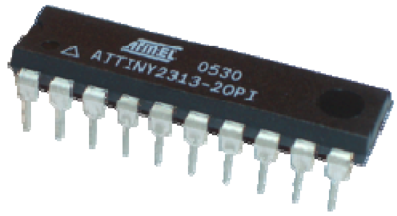

Fig. 18. External view of the modern microcontroller Attiny2313-20PI of the American Company Atmel [30]

The microcontroller (from the English «controller» [1]) is essentially an IC (see Fig. 18), designed to control the operation of various electronic devices. It is, by and large, a single-chip microcomputer. The first US patent for a microcomputer or microcontroller was issued in 1971 to employees of the American Company Texas Instruments, engineers M. Kochren and G. Boone [30]. They were the first to suggest not only a microprocessor on a single semiconductor chip but also a memory with digital I/O devices. In 1976, the American Company Intel released the microcontroller i8048. In 1980, this electronic Company created a microcontroller i8051, on the silicon chip of which placed 128 thousand field-effect transistors were placed. A successful set of peripherals, the ability to flexibly select external and internal program memory and an affordable price have ensured this microcontroller success in the electronics market. To date, there are more than 200 modifications of microcontrollers compatible with i8051, produced by two dozen companies in the world [30].

The continuous increase in the complexity of microprocessors has led the world of electronics to the fact that now one or more microprocessors are used as computational elements in all electronic devices, starting from a mobile phone and ending with mainframes and supercomputers [30]. The achievements of mankind in the exploration of outer space since the late 1960s are due to the use of computer equipment on board space vehicles. Thus, in the US NASA space program associated with the first landing of a man on the Moon (July 20, 1969 [31]), all on-board calculations for guidance, navigation and control on the Apollo 11 spacecraft were provided to small specialized microprocessors on a crystal of silicon of its on-board computer [30]. These electronic devices were designed and manufactured by the new «young» American Company Fairchild Semiconductor settled in the promising technological area of the United States. At the same time, another US company, Texas Instruments, developed and manufactured germanium ICs for Minuteman-2 intercontinental ballistic missiles [32].

4.1. The «Silicon Valley» of the United States and a technological breakthrough in microelectronics. The northern part of the state of California (near San Francisco) which currently holds about half of the US scientific and technical potential in the field of electronics and computer technology was named «Silicon Valley» [32]. It is the numerous electronic firms of the USA (Fig. 19) formed on the territory of the Silicon Valley, and made a decisive contribution to the beginning of the rapid development of world microelectronics in the 20th century. It was with them that the process of widespread use of ICs in military equipment and civilian technology began [32].

Fig. 19. General view of the buildings of some Companies that are part of the largest technology center in the US [32]

The emergence and active development of this high-tech center of the United States involves the concentration in this area (with the unofficial capital of San Jose) of leading American Universities, cities at a distance of less than an hour from each other, major sources of financing for new companies, and a Mediterranean-type climate . It is commonly believed [32] that the founders of the Silicon Valley were American scientists like William Shockley (Fig. 20) and Frederick Terman (Fig. 21).

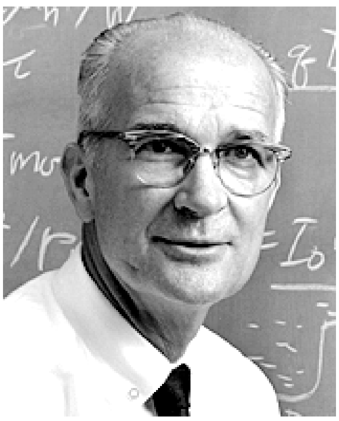

Fig. 20. One of the founding fathers of the Silicon Valley in the US State of California, Professor of Physics William Shockley [32]

It was in this region of the USA that, since the 1960s, the active use of silicon began with the world's most advanced production of semiconductor devices (transistors and ICs). Here in 1956, one of the co-authors of the discovery of the transistor effect, physicist W. Shockley, moved and founded his Company Shockley Semiconductor Laboratory in Mountain View which is developing a new technology for the use of silicon in the production of transistors [32]. Germanium by this time has proved to be an expensive semiconductor material in the production and not resistant to elevated temperatures.

Fig. 21. One of the founding fathers of the Silicon Valley in the US State of California, Stanford University Electrical Engineering Professor Frederick Terman [32]

The authoritarian style of the leadership of W. Shockley and his enthusiasm for his own development of a 4-layer semiconductor diode led to the fact that his eight most talented physicists and specialists (the «Traitorous Eight») left his Company and soon on the funds of his sponsor Sherman Fairchild created a new electronic Company, «Fairchild Semiconductor» [32]. For W. Shockley and his business, this event had a deplorable effect: soon the unprofitable Company «Shockley Semiconductor Laboratory» ceased to exist, and its leader was forced to leave for teaching as a Professor at the nearby Stanford University of the United States. It is important to note that W. Shockley, as the discoverer of the transistor effect, and the author of the most important work on the theory of semiconductors at the end of his life, considered his contribution to genetics as his main scientific achievement, paradoxically [32].

Fairchild Semiconductor Company, led by Robert Noyce, adhered to a new progressive socio-technical ideology: «*Inventions in technology can change the world*». Each of her employees thought about their personal contribution to the progress of microelectronics. This company has a new corporate culture in the development and production of semiconductor devices, which includes a democratic leadership style and strict labor discipline. Fairchild Semiconductor was a successful US commercial project in the field of microelectronics. It became the world leader in the field of creation of transistors and ICs based on silicon crystals. It was this company that laid the foundation for a number of new electronic companies in the Silicon Valley. So, two of the indicated «Eight» (Gordon Moore and Robert Noyce), having left the electronic Company Fairchild Semiconductor have created a new Company Intel which is engaged in the first stage with magnetic storage devices. Then at Intel followed R. Noyce's invention of the silicon IC and the creation on its basis of the first chip microprocessor (1971) which in the future will became the fundamental basis of all electronic devices of our time [32]. By 1980, the avalanche division of electronic companies in the Silicon Valley led to the creation of a California high-tech park (cluster) comprising 65 companies engaged in the development and production of computers and their components, especially microprocessors, as well as software, mobile devices and biotechnologies. As of 2006, Silicon Valley has become the third technology center in the United States (after New York and Washington) in the area of high technology. About 386,000 highly qualified specialists worked at this center at the indicated time, with an average annual income of about USD 80,000 [32]. Joint efforts of the Companies of the Silicon Valley in the 20th-21st centuries have made a real technological breakthrough in the field of microelectronics.

4.2. Nearest prospects, main trends and problems in the development of world microelectronics. Now in the world of electronics began to develop research on the development and creation of new vacuum micro devices on the basis of IC with field emission [33]. These new semiconductor devices have ultrahigh speed, high radiation resistance, low sensitivity to ambient temperature and high efficiency. This electronics was called «*vacuum microelectronics*», based on vacuum integrated circuits.

4.2.1. Vacuum microelectronics. It is believed that the functionality of vacuum IC will be significantly different from the capabilities of existing ICs. Vacuum microelectronics becomes one of the most important directions in the development of microwave electronics used in radar complexes, telecommunication devices and information processing systems [33]. This is due to the fact that traditional semiconductor technology is no longer able to provide highly reliable transmission, reception, storage and processing in real time of very large volumes of information in conditions of extreme environmental influences. For this reason, in the last decades in all the leading countries of the world intensive work has been carried out related to the study of the fundamental problems of vacuum microelectronics.

4.2.2. Vacuum nanoelectronics. In recent years, experts are increasingly focusing on electronics, which uses autoemission properties of carbon nanotubes (CNT). This new section in electronics was called «*vacuum nanoelectronics*» [33]. The main efforts in this field of electronics are now directed at the development and creation of flat screens of displays and TVs based on CNT. In 2005, Motorola Company announced the creation of a prototype display based on CNT. In 2006, Samsung Corporation demonstrated its prototype display on the basis of CNT, whose panel had a thickness of 30 mm [33]. It should be noted that in its development this corporation successfully cooperates with the American Company Carbon Nanotechnologies Inc., which supplies it with the specified nanotubes. Apparently, it is not «far off» the creation of flat panel TVs based on new technology in electronics. According to [33], the problem of the appearance in the everyday life of people of a display spatially and energetically interfaced with the IC is best solved by creating a flat cathodoluminescent screen with an auto-electronic nanostructured cathode. Therefore, we can say that vacuum microelectronics and vacuum nanoelectronics allow creating fundamentally new microwave vacuum lamps, as well as essentially new and highly efficient flat cathodoluminescent displays [33].

4.2.3. New trends in the creation of IC. In recent decades, the technology of fabricating high-mobility electron transistors (HMETs), which are widely used in microwave communication and radio observation devices, has been rapidly developing. On the basis of the HMET, both hybrid and monolithic microwave integrated circuits are created. At the heart of the HMET operation is the control of their conductive channel by means of a two-dimensional electron gas, the region of which is created under the contact of the gate electrode of the field-effect transistor due to the use of a heterojunction and a very thin dielectric spacer layer [20]. For the practical implementation of ultra-large integrated circuits, ultra-miniature field microtransistors are being created. They are manufactured using nanotechnology with a geometric resolution of equipment less than 100 nm. In such semiconductor devices, the thickness of the gate dielectric of the transistor reaches several atomic layers. Thanks to this, in modern microprocessors of the American Corporation Intel the number of electronic components ranges from tens of millions to two billion pieces [20].

4.2.4. Space microelectronics. To microelectronics intended for use in space and military purposes, there are increased requirements for [21]: reliability of IC (both semiconductor and shell), resistance to instantaneous gamma and neutron radiation, resistance to a powerful electromagnetic pulse of a nuclear explosion, stability to vibrations and mechanical overloads, resistance to high humidity and medium temperature (–40 °C to +125 °C). The biggest problem of space microelectronics is the protection of on-board electronic devices from the damaging effect of heavy space charged particles on them, which have a high energy, sufficient to «break through» their IC through with the formation of a powerful «train» of electric charges [21]. Fig. 22 shows a modern ultra-large integrated circuit for use on artificial satellites and spacecraft.

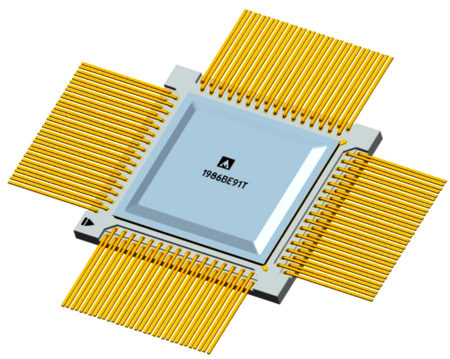

Fig. 22. External view of a ultra-large integrated circuit in cermet body intended for use in space [21]

In addition, it should be noted that around our planet there are two powerful belts of charged particles (the so-called Van Allen radiation belts) [21]: one at an altitude of about 4000 km, consisting of protons, and the other at an altitude of about 17,000 km with an electron flux. The level of cosmic radiation at altitudes (300-500) km above the Earth, where satellites and spacecraft usually fly, such that the annual dose of radiation there reaches 100 rad = = 1 J/kg = 1 Gray [34]. At altitudes of more than 1000 km, the annual dose of radiation can be 10,000 rads or more [21]. For conventional commercial IMS, the «lethal» dose of radiation is about 5000 rad. Therefore, in a few months of flight in such space conditions, conventional ICs will gain their «deadly» dose of radiation and fail. In this connection, for special spacecraft missions in high orbits (≥ 1000 km) and in outer space, special radiation-resistant ICs are needed for their electronic devices [21].

4.2.5. Optoelectronics. At the beginning of the 21st century, the evolution of solid-state electronics in the direction of miniaturization of electronic components gradually stopped and is now practically stopped [2]. This stop was predetermined by the attainment in this kind of electronics of the minimum possible sizes of semiconductor transistors, conductors and other components on a semiconductor crystal capable of removing (dissipating) the heat released to them when electric charges (current) flow through them and not be destroyed. These geometric dimensions in microchips reached units of nanometers, which led to the name of technology for their production - nanotechnology [18]. In this connection, it is possible that in the near future the next stage in the evolution of the world electronics will be «*optoelectronics*» in which a quantum quasiparticle without a rest mass appears as a photon, a much more mobile and less inertial in its physical nature, a representative of the microworld than a free electron («a hole») in a semiconductor crystal of solid-state electronics.

4.2.6. Cybersecurity. A world-class problem in microelectronics is the provision of cybersecurity of computer systems for both private and public Companies and individual computers. In recent years, cyberattacks of hackers around the world have acquired a massive and systemic character. Simple and reliable protective measures and solutions from such attacks in the field of cybersecurity currently do not exist.

Conclusions.

1. The completed scientific and technical review of development for the period of the 20th and 21st centuries of world electronics testifies to the enormous technological breakthrough of mankind in this very complex field of knowledge aimed at serving society. Electronics is on the «threshold» of new discoveries.

2. Electronics has penetrated almost all spheres of human activity. The technosphere of earthlings simply was not conceivable without electronic devices (for example, computers, microprocessors, etc.). The objective process of the development of our civilization has led to the complete dependence of man on electronics and on its scientific and technical achievements. Electronics brought people many benefits and amenities. But along with this, in the monopoly of electronics for mankind lies a hidden threat. Intentional or accidental inadvertent simultaneous failure of the main and back-up electronic devices of control systems at critical technical facilities (for example, nuclear power plants, nuclear facilities and military centers for strategic missile control) can lead to disastrous consequences for large regions of the developed countries of the world.

3. The problem of cybersecurity of electronic devices and computer systems for military and civil purposes is acquiring particular urgency and significance. The development and widespread adoption of effective measures and means to combat cyber-attacks (cyber-terrorism) in electronic practice should always be given the increased attention of the relevant services and specialists.

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