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The semiconductor revolution in the 20th century

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Abstract. This review is based on the plenary lecture presented by the author at the German – Russian Scientific Symposium 'Chemistry Shaping the Future' held in November, 2012, at the Central House of Scientists in Moscow. The review considers the background and milestones of the revolutionary development of semiconductor electronics in the 20th century, including the discovery of the transistor and semiconductor laser. The role of heterostructures and quantum size effects is highlighted. The significance of semiconductor solar energy converters for solving energy problems is discussed. The bibliography includes 32 references.

I. Introduction

Today the German – Russian Symposium 'Chemistry Shaping the Future' is held in the framework of the Year of Germany in Russia, and earlier, in April, 2012, I delivered a lecture at the German National Academy of Sciences Leopoldina in Halle in the framework of the Year of Russia in Germany.

Our relations with Germany started long ago, and the creation of the St Petersburg Imperial Academy of Sciences, now the Russian Academy of Sciences, was a result of a very intensive correspondence between Peter I the Great and Leibniz and, then, Wolf.

This review focuses on research into semiconductors inspired by my teacher Abram Fedorovich Ioffe — a disciple of the first Nobel Prize winner Wilhelm Röntgen, who worked in Munich. Röntgen considered Ioffer as his possible successor, but Ioffe decided to return to Russia to develop science and especially physics in his country. Nowadays, we speak a lot about innovations. In this respect, the twentieth century witnessed two absolutely successful innovative projects, which can be treated differently, namely, the Manhattan Project in the United States and the nuclear programme in the Soviet Union. These projects have led not only to the creation of nuclear weapons but also to the successful development of science and technology in the countries and worldwide. The success of large innovative projects is always determined primarily by the people who perform them. In this regard, staffing for the Manhattan Project was, to a certain extent, facilitated by Adolf Hitler, who forced talented scientists from Germany and other European countries to immigrate to the United States, where they occupied key positions in the implementation of the Manhattan Project. The staffing problem of the Soviet atomic project was solved by Abram Fedorovich Ioffe since Ya B Zel'dovich, Yu B Khariton, I V Kurchatov, A P Aleksandrov, L D Landau, and many other participants in this project were scholars of Ioffe's school of physicists. And finally, today, as we participate in a symposium on chemistry, I want to note that one of the first students of Ioffe was N N Semenov, the first Nobel laureate in our country, who was awarded the prize in chemistry for his research into the theory of chemical chain reactions.

The most difficult times, from my point of view, came to our science about 20 years ago, when the budget of my home Ioffe Physical Technical Institute, of which I was the director at that time, was cut immediately 20-fold. At that time, a huge role for us was played by the international scientific cooperation and our participation in international projects, including those with German scientists. As for my laboratory at the Physical Technical Institute, it was of great importance for us to carry out joint researches started long before that with the Institute of Solid State Physics at the Technical University in Berlin, which was then headed by the prominent German physicist Prof. Dieter Bimberg (now he is a foreign member of our Academy of Sciences). This joint project, like many other international projects, led to new, very important results, such as new methods for producing quantum dots in semiconductors and semiconductor quantum dot lasers. And I was infinitely happy when

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in 2001 the State Prize of the Russian Federation for this work was shared by us and Prof. D.Bimberg. Moreover, in the early 1990s, together with Prof. D Bimberg we formed the startup company Innolume in Dortmund, which is now actively collaborating with the later formed company Optogan producing LEDs in Russia. This once again underlines the importance of international scientific cooperation.

II. Studies of semiconductors in the 1930s

At the beginning of the twentieth century, Ioffe clearly understood the meaning of quantum physics and its role primarily in the development of new technologies. It was no coincidence that systematic study of semiconductors began at the Physical Technical Institute as early as in the late 1920s.

Speaking about this period, it is important to remember Oleg Vladimirovich Losev, a brilliant engineer and inventor and a genius physicist. His findings published almost 100 years ago, in the early 1920s, formed the basis of modern semiconductor electronics. His discovery of crystadyne, which was the first crystal amplifier and oscillator, and the invention of the first semiconductor LED generating visible light when a current flows through a metal whisker contact, the crystal detector with silicon carbide and zinc oxide, could be the basis of the development of semiconductor electronics.[1] However, it did not happen, and for a very simple reason — the level of technology and the level of semiconductor research at those days prevented the development of the real base of microelectronics and optoelectronics in the future. Although this belongs to history by now, we can be proud of the unique achievements of O V Losev.

Of paramount importance for the development of semiconductors and semiconductor electronics was the study published in 1932 by V P Zhuze and B V Kurchatov[2] on the electrical conductivity of cuprous oxide, where extrinsic and intrinsic conduction in semiconducting crystals was shown, as well as the study by Ya I Frenkel and A F Ioffe,[3] where the role of tunneling phenomena in semiconductors was demonstrated for the first time, which later formed the basis of many semiconductor devices and respective physical theories.

Judging by the volume of studies conducted at the Physico-Technical Institute, one could expect that the discovery of the transistor would happen here. However, immediately after the end of the Second World War, the principal investigators of semiconductors and other leading experts in physics, chemistry and materials science were recruited to solve the atomic problem.

III. The discovery of the transistor

Due to the exceptional importance of the discovery of transistors, I would like to say a few words about the history of this problem. During the war, vacuum electronics has been used for the solution of radar problems, and the rapid development of radar has boosted the development of microwave technology of detecting microwave signals again with crystal detectors, as it once was done by O V Losev. In addition, the technology of production and the use of germanium and silicon have been tremendously advanced. In 1945, Bell Labs Research Director Mervin Kelley hired John Bardeen (W Shockley, in my opinion, was already working in the company), Gerald Pearson and a number of other scientists, and the research team was formed with the task of making electronic telephone switches, which were desperately needed at that time. Moreover, Mervin Kelly (as I was told by John Bardeen) further stressed that it would be extremely important if, in ongoing research, evidence of applicability of the principles of quantum mechanics to the condensed state would be found. That is when the research director of the company puts this kind of problem before the research team, it is safe to say that the company will continue to develop, since solution of technical and technological problems and the development of basic research are planned simultaneously. It is no accident that 16 employees (if I remember correctly) of Bell Laboratories have won Nobel Prizes, mainly in the post-war years.

The transistor effect was discovered in 1947 by John Bardeen and Walter Brattain. Then, point-contact transistors and p–n junction transistors were discovered, and the theory of p–n junctions was put forward by William Shockley.[4] In 1956, W Shockley, J Bardeen and W Brattain were awarded with the Nobel Prize in physics for their researches on semiconductors and their discovery of the transistor effect. In his Nobel lecture on semiconductor researches that led to the creation of point-contact transistors, John Bardeen, first of all, pointed to Wilson's band theory of semiconductors, Frenkel's theory of photoelectric phenomena and parallel and independent studies of the theory of rectification in contacts developed by Mott, Shockley and B I Davydov at the Physico-Technical Institute.[5]

I remember the first international conference on the physics of semiconductors I attended, which was held in Prague in 1960. The conference was opened by the lecture of A F Ioffe (unfortunately, the last in his life) — brilliant, both in the form and content, in which he expounded a very brief history of the development of research on the physics of semiconductors. An excellent detailed lecture on the phenomena of avalanche breakdown in p–n junctions in silicon was given by William Shockley, and at the close of the conference, John Bardeen delivered a lecture. He is a unique figure in the history of semiconductor physics and physics in general, the only scientist in the history of physics who has won two Nobel Prizes, the first one for the discovery of transistors and the second one for the creation of the theory of superconductivity. Immediately after this conference, J Bardeen visited the Physical Technical Institute. In his talk, he said that science is international by its nature. Scientists know this very well, but it is also necessary to constantly mention this to the general public. Semiconductor physics is international. This is demonstrated by that its practical foundations have been created by people like Wilson and Mott in Great Britain, Wagner and Schottky in Germany, Ioffe and Frenkel in the Soviet Union. And I, then a young Soviet scientist, was infinitely glad to hear these words from a person who even then was the No. 1 figure in semiconductor physics.

In 1964, the Nobel Prize in physics was awarded to Charles Townes and two outstanding Soviet scientists — Nicholai Gennadievich Basov and Aleksandr Mikhailovich Prokhorov — for fundamental work in the field of quantum electronics, which has led to the construction of oscillators and amplifiers based on the maser-laser principle. In his Nobel lecture, A M Prokhorov emphasized that it took a considerable period of time — 5–7 years — after the

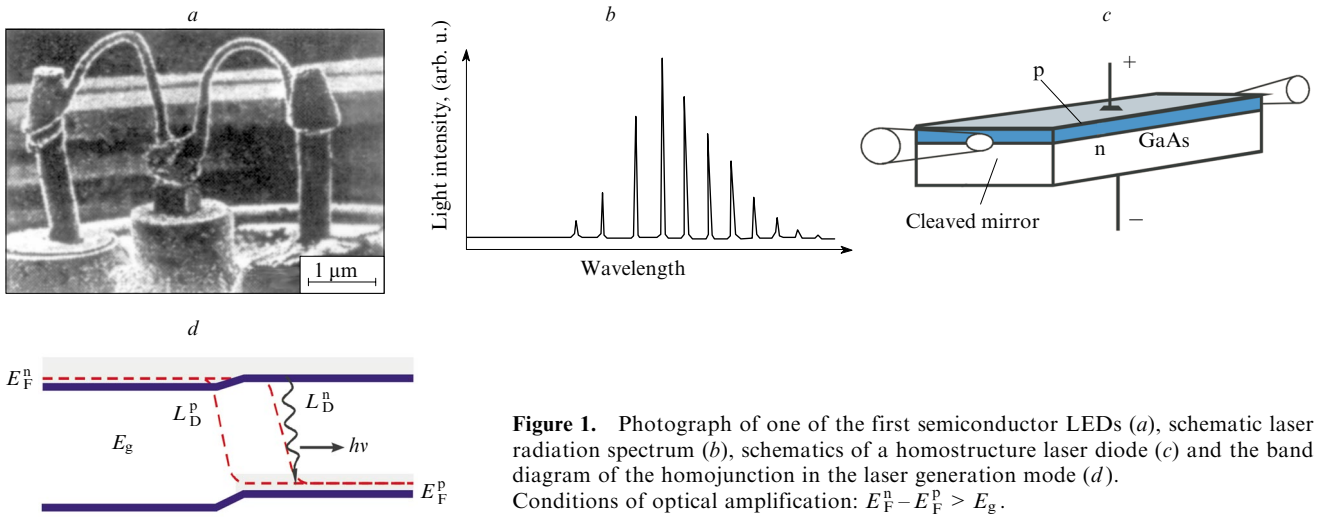


Figure 1. Photograph of one of the first semiconductor LEDs (*a*), schematic laser radiation spectrum (*b*), schematics of a homostructure laser diode (*c*) and the band diagram of the homojunction in the laser generation mode (*d*).
Conditions of optical amplification: $E_F^n - E_F^p > E_g$.

creation of masers to go from masers to lasers, the significance of which was estimated at once. To do this, two very important tasks — the creation of the laser cavity and methods of population inversion — had to be solved. The solution to both of these problems was proposed by N G Basov and A M Prohorov.[6] One can say that the discovery of the laser-maser principle was the basis of semiconductor optoelectronics; in this respect, of paramount importance were the works of N G Basov, O N Krokhin and Yu M Popov[7] carried out in the Soviet Union, who in 1961 offered a p–n junction injection laser, a semiconductor laser, and the work by M Bernard and G Duraffourg[8] in France. These works have stimulated many studies, including ours. This year we celebrate 50 years since the creation of semiconductor lasers and semiconductor light-emitting diodes (Fig. 1), which, as a development of the previously mentioned works by O V Losev, were invented at the appropriate technological level by Prof. Nick Holonyak at the University of Illinois in 1962.

Semiconductor research in 1962, including our studies[9] on heterostructures (Fig. 2),[10] was an impetus for the development of semiconductor optoelectronics. The same year witnessed the publication of the work accomplished at the Physico-Technical Institute by A A Rogachev and coworkers,[11] who observed for the first time efficient quasi-interband or interband radiative recombination in GaAs p–n junctions. This work immediately attracted much attention, since it demonstrated the real possibility of using a definite semiconductor material and p–n junctions in this material to create semiconductor lasers. Almost at the same time, with a difference of just a few days, there appeared the works of Robert Hall of General Electric in Connecticut,[12] Nick Holonyak of General Electric in Syracuse,[13] a group of the Lincoln Laboratory and Marshall Nathan[14] of IBM, and after about a month, the work of N G Basov and B M Vul[15] of the Physical Institute of the Academy of Sciences of the USSR. Thus, the first semiconductor lasers were created. Meanwhile, the laser created by Nick Holonyak was based on gallium arsenide–gallium phosphide solid solutions and simultaneously emitted visible light. Whereas conventional p–n semiconductor lasers worked only at low temperatures, this LED was able to operate even at room temperature. That is why I say that we are celebrating the 50th anniversary of the LEDs.

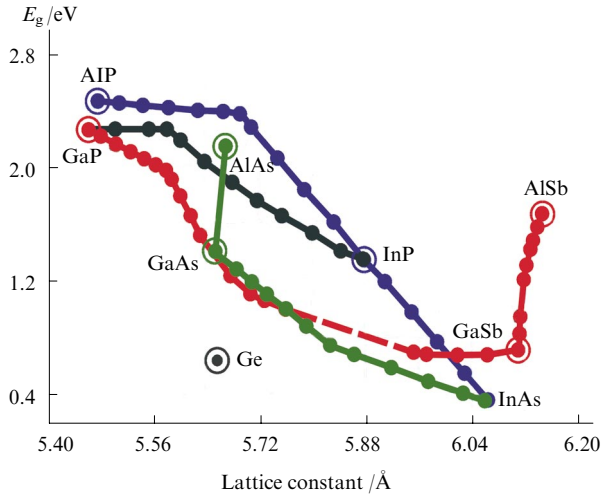


Figure 2. Band gap (E_g) vs. lattice constant for some semiconductor materials and their alloys.[10]
$T = 300$ K.

The Nobel Prize in Physics in 2000 was awarded jointly to me and Herbert Kroemer, a German theoretical physicist who quite early left Germany for the United States, where he still works. Back in the mid-1950s, he published the first theoretical works[16,17] dealing with semiconductor heterostructures and, first of all, heterostructure transistors (Fig. 3).

On the Award Ceremony, the Chairman of the Nobel Committee for Physics Prof. Tord Claeson stressed that the prize was awarded for contributions to early developments of microelectronics and photonics, focusing on integrated circuit and semiconductor heterostructures. At the same time, he noted that studies of semiconductor heterostructures had previously won two Nobel Prizes — for the discovery of the quantum Hall effect (Klaus von Klitzing, Stuttgart),[18] and for the discovery of the quantum Hall effect (Horst Stormer, Robert Laughlin and Daniel Tsui).[19] These works were based on studies of low-dimensional electron gas, and, thus, heterostructures have become labo-

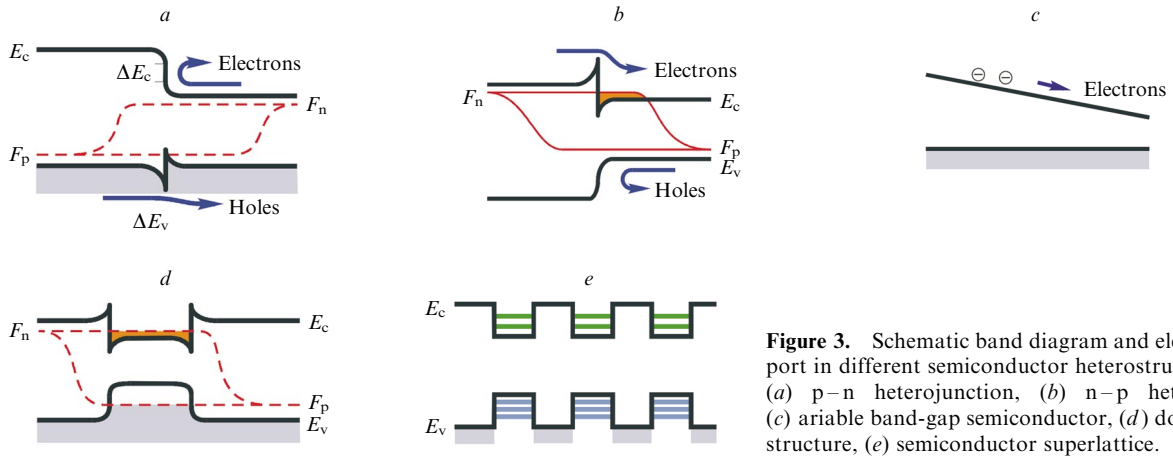


Figure 3. Schematic band diagram and electron transport in different semiconductor heterostructures. (*a*) p–n heterojunction, (*b*) n–p heterojunction, (*c*) ariable band-gap semiconductor, (*d*) double heterostructure, (*e*) semiconductor superlattice.

ratories for research rather than only the material for the creation of new instruments.

IV. Invention of silicon integrated circuits

The first integrated circuit was proposed in 1958 by Jack Kilby (Texas Instruments). However, the technology of silicon microelectronics and silicon chips was practically developed by Robert Noyce. It was he who proposed the first real technology of silicon chips, while working for Fairchild Semiconductor (Fig. 4).[20] When discussing the problem of Skolkovo, I usually say that Skolkovo should be no territory, but a certain ideology of commercialization of research projects, no matter where breakthrough technologies have been created, directly in Skolkovo or elsewhere, say, in Sosnovka in St Petersburg. Silicon Valley in the United States has received this name after it became the birthplace of silicon integrated circuits invented by Robert Noyce.

Figure 5 was taken by me from the lecture of Prof. S M Sze (when he worked for Bell Laboratories).[21] In my opinion, this figure is an interesting illustration of the title of my lecture 'The semiconductor revolution in the 20th century.' The lecture entitled 'Problems of submicron lithography' was delivered by Prof. Sze in 1982 at the Solid State Device Conference in Tokyo and was devoted to the analysis of changes in the social structure of the society in connection with the development of microelectronics. As the diagram of the labour force distribution in the United States shows, before 1905 the United States was an agricultural country, since a large part of the working population was employed in agriculture. From 1905 to about 1955, the United States was an industrial country, since a major part of the working population was employed in industry. Since 1955, the United States and then many other countries are, as we say, post-industrial states, the information commun-

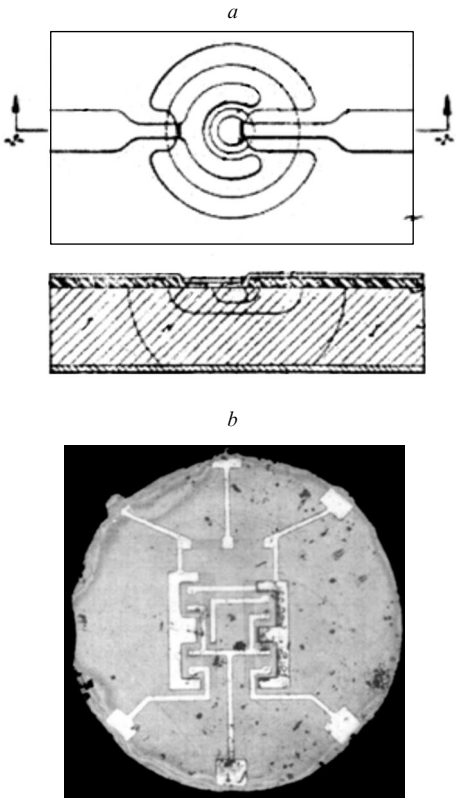


Figure 4. Schematic representation (*a*) and appearance (*b*) of the first integral curcuit of R Noyce.[20]

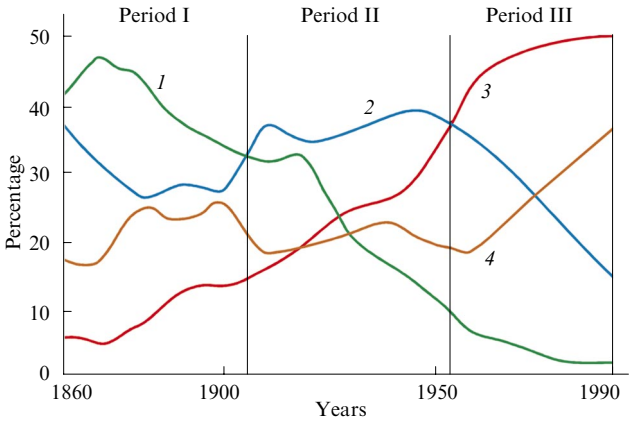


Figure 5. Change in the percentage of different groups of the working population in the United States. (*1*) Agriculture, (*2*) industry, (*3*) information, (*4*) service.

ity, since most of the working population is employed in the process of obtaining, using and processing information. We are talking about the information explosion, and primarily the development of microelectronics and computer technology has helped to cope with this huge amount of information.

In modern microelectronics, so-called Moore's law† is well known, which shows how the sizes of devices in this area change (Fig. 6).[22] For example, vacuum tubes are 100 million nanometers in size, and modern microelectronic chips are of a size of a few tens of nanometers. Nowadays, Intel launches the production of 22-nm chips, and 32-nm chips are already in production. This naturally leads to a dramatic increase in the density of the components, and we are approaching the time when Moore's law is no longer valid since, at such density and size, one switching in the integrated circuit will be performed by a few dozens of electrons, which can lead to rather frequent and uncontrolled failures and errors.

Another direction of development pertains to semiconductor heterostructures, where basic physical phenomena occur. They have a long history of application. Such a fundamental phenomenon as unidirectional injection in heterojunctions was proposed by W Shockley in his first transistor patent.[4] Then, these issues have been theoretically considered by H Kroemer[16] and our team.[9] In 1963, H Kroemer[23] and we[9] suggested so-called double heterostructure, which has been crucial for the development of semiconductor laser technology; then, so-called semiconductor superlattices have played an important role (see Fig. 3).[24] The first theoretical work in this area was performed by Academician L V Keldysh in 1962,[25] however, the first real heterostructure superlattices were produced by L Esaki and R Tsu in 1970.[24] Developing this technology and these physical notions, Leo Esaki once gave a very good definition of heterostructures, saying that whereas conventional materials are 'God-made crystals', the heterostructures, with their unique properties not exhibited by natural materials, should be called 'man-made crystals'.

However, to realize the theoretically predicted unique properties, it was necessary to find a suitable heterostructure. As often happens, this problem was solved independently and roughly at the same time in two laboratories — in my laboratory at the Leningrad Physico-Technical Institute[26] and at the IBM Watson Research Center in Yorktown Heights by H Rupprecht,[27] who later worked at the Fraunhofer Institute. It was precisely those works that enabled the fabrication of what we call ideal heterostructures based on gallium arsenide and aluminium arsenide. On the basis of these materials, the first family of heterostructures has been created, and their crucial properties have been achieved for most of semiconductor devices. As early as in 1968, we demonstrated a laser operating at room temperature,[28] whereas p–n junction lasers can work only at very low temperatures (Fig. 7). By the way, the first laser could be made for the near-infrared region and it would be even a little more efficient, but for financial reasons, our first so-called room temperature laser operated in the visible red region.

† Gordon Moore, a co-founder of Intel Corporation

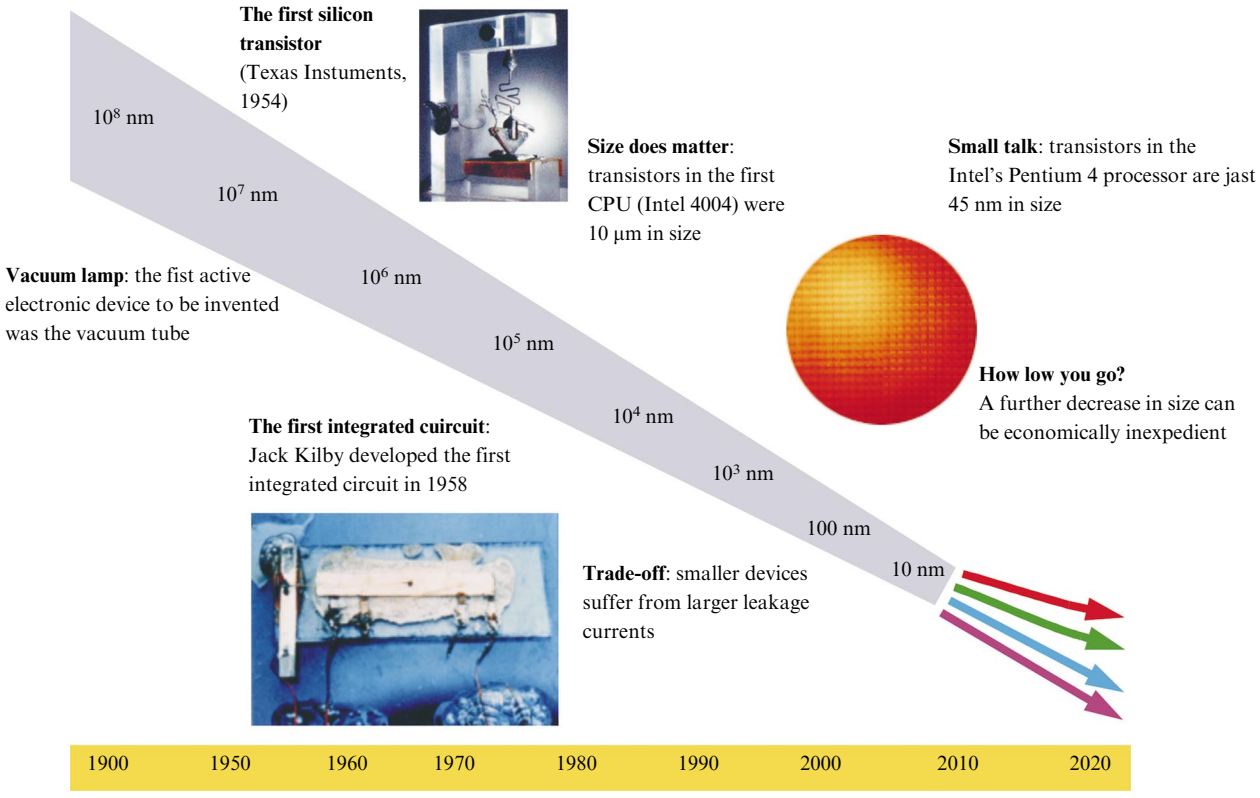


Figure 6. Illustration of Moore's law: evolution of the size of the working unit of electronic devices.[22]

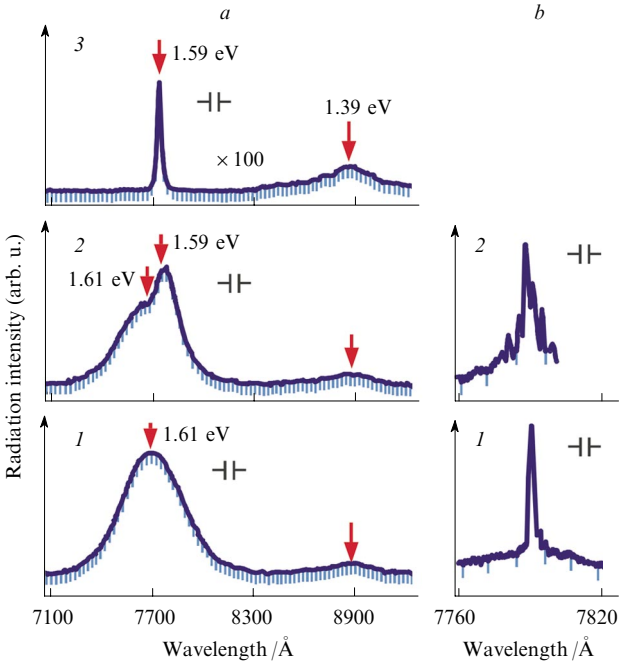


Figure 7. Emission spectrum of the first low-threshold $Al_xGa_{1x}As$ DH laser operating at room temperature (300 K).[10]
J_{th} = 4300 A cm^{-2}. Current I/A: 0.7 (*1a*), 8.3 (*2a*), 13.6 (*3a*); 13.6 (*1b*), 18 (*2b*). $s = 2.2 \times 10^{-3}$ cm^2. DH is double heterostructure.

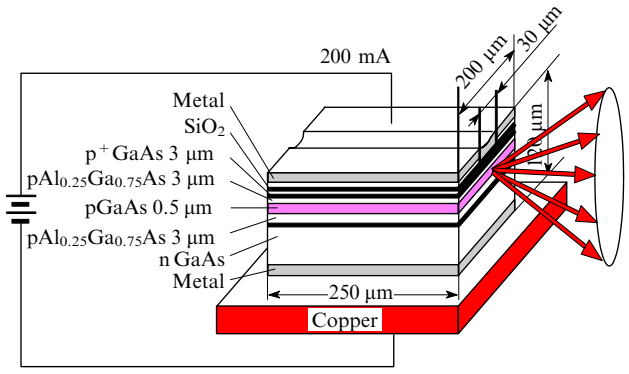


Figure 8. Schematic of the first injection DH laser operating in the CW mode at room temperature.[10]

Figure 8 shows the first CW semiconductor laser crucial for the design of first fibre-optic lines of communication, which have been successfully developed.

Almost immediately heterostructures were used to produce solar cells with significantly higher efficiency. This technology has been used in the large-scale production of solar panels for the Soviet spacecrafts in the 1970–1980s. Nowadays, low-orbiting spacecrafts use silicon solar cells, and for satellites in high orbits where high-energy particle fluxes are much stronger, heterostructure solar cells are much more reliable and efficient. In particular, the Mir space station had heterostructure solar panels with a total area of 70 m^2.

Heterostructures have enabled the development of fast electronics, ultrafast transistors, especially so-called HEMTs (high electron mobility transistors), which are today the major component of all mobile phones and bipolar transistors (Fig. 9).

The most efficient LEDs based on heterostructures have also rapidly developed. As I already mentioned, much of the progress in this field has been due to the works of my grandstudents, first in Germany and then in Russia, where some of them have returned. Their example has confirmed that today the most efficient form of business is scientific business based on research and development in which they have actively participated.

I have already mentioned that heterostructures became laboratories for researching low-dimensional electronic systems, including a two-dimensional electron gas in quantum wells, a one-dimensional electron gas in quantum wires and a zero-dimensional electron gas in artificial atoms —

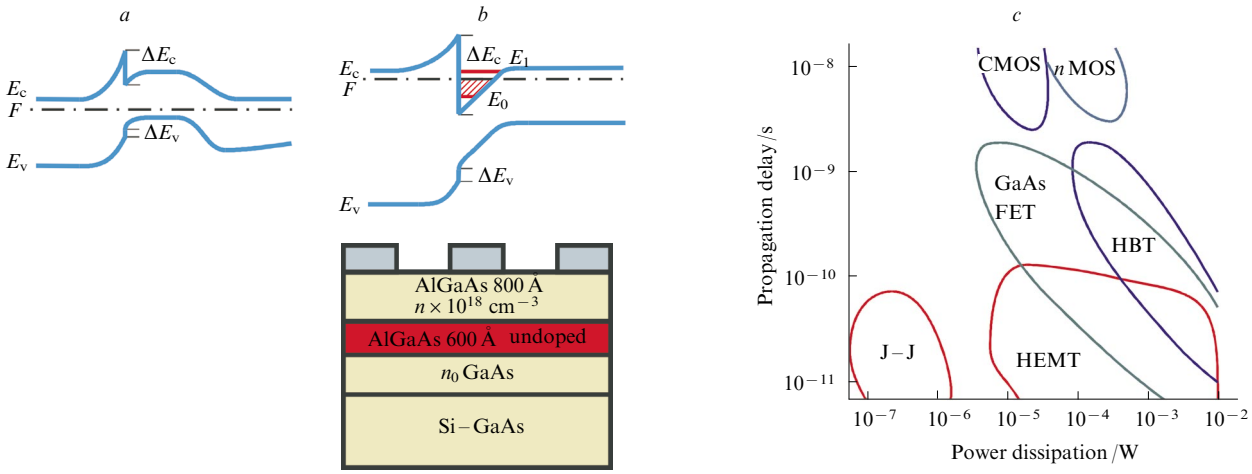


Figure 9. Band diagram of the heterobipolar transistor (*a*) and field effect transistor with a 2D electron channel (*b*), and the plots of switching time *vs.* switching power for different types of fast devices (*c*).
CMOS is complementary metal oxide semiconductor, HBT is heterojunction bipolar transistor, HEMT is high electron mobility transistor, FET is Schottky-barrier gate field-effect transistor, J–J is Josephson effect device.

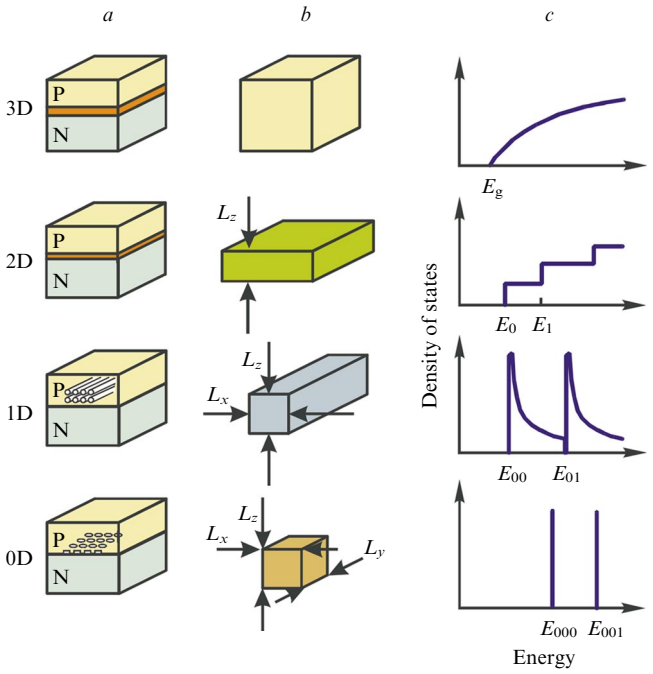


Figure 10. Schematic representation of lasers (*a*), laser active region (*b*) and corresponding density of states patterns (*c*) for different dimensionality of the active region: three-dimensional (3D is bulk material), two-dimensional (2D is quantum wells), one-dimensional (1D is quantum wires) and zero-dimensional (0D is quantum dots).

quantum dots (Fig. 10). Here is an example that I often cite to the students of our Academic University, which demonstrates the following, from my point of view, principal thing. Once the President of the Royal Society of London and Nobel Laureate in chemistry, the late George Porter, with whom I had the pleasure of knowing, said that when a distinction is made between fundamental and applied research, we must not forget that all research is applied, the only difference is that some of applications arise quickly and some, centuries later. From my point of view, the practical meaning of his words is that all of the development of civilization is associated with the development of science, but the scientific discoveries and scientific researches become a powerful engine of progress when they give rise to technologies. The last decades have witnessed unique progress in technologies based on scientific discoveries and research. However, when the technological level suffices not to apply new scientific discoveries, they remain unrealized, waiting in the wings, as it was with the results of O V Losev.

Figure 11 shows the so-called quantum cascade laser, the most efficient type of semiconductor laser emitting mid-infrared light (5–10 μm). In order to make it possible for them to operate even at liquid nitrogen temperatures and especially at room temperature, it was necessary to have a fruitful idea. Such an idea was put forward in 1971 at our Institute by theoretical physicists Rudolf Kazarinov and Robert Suris,[29] who predicted the possibility of stimulated emission in semiconductor superlattices. However, the level of technology at that time was obviously insufficient. The idea is simple, as they say, take it and implement it; but the level of our technology at that time did not permit doing so.

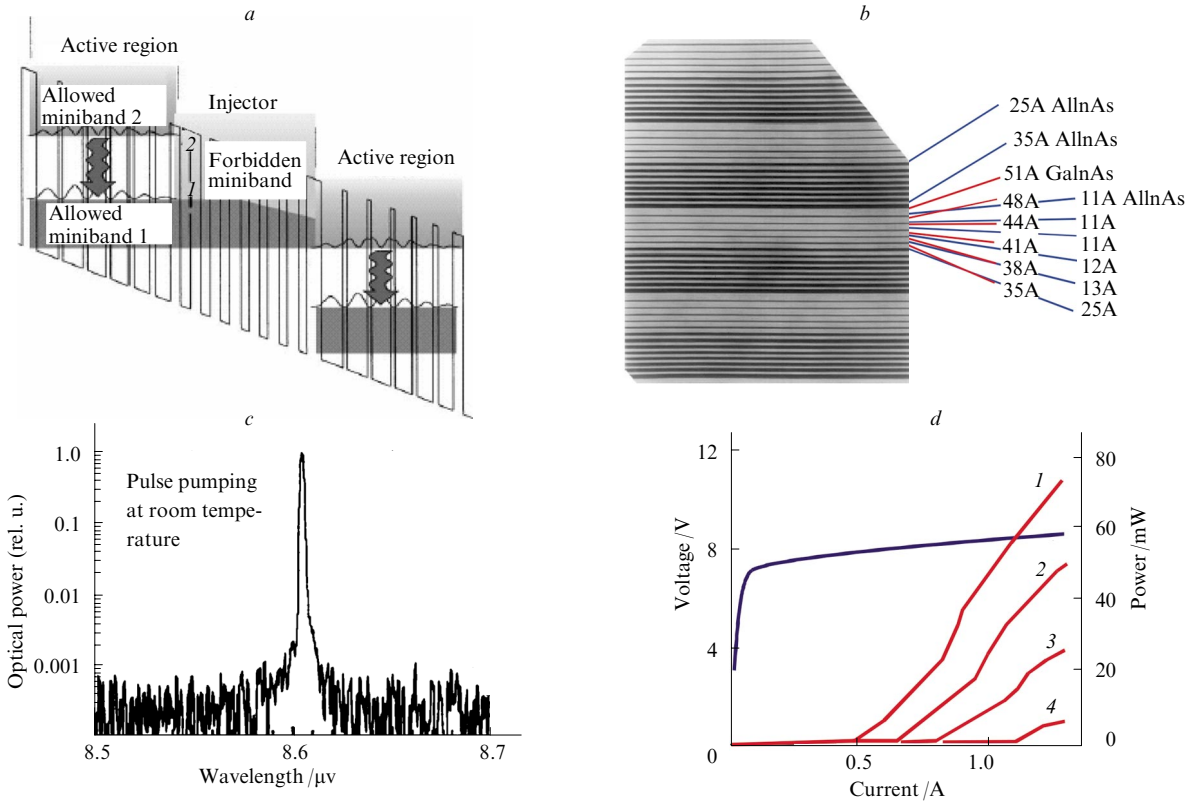


Figure 11. Quantum cascade laser: representative band diagram (*a*), cross-section microphotograph (*b*), room-temperature emission spectrum (*c*) and voltage–current and light–current curves at different temperatures, K (*d*): 80 (*1*), 150 (*2*), 200 (*3*), 250 (*4*).

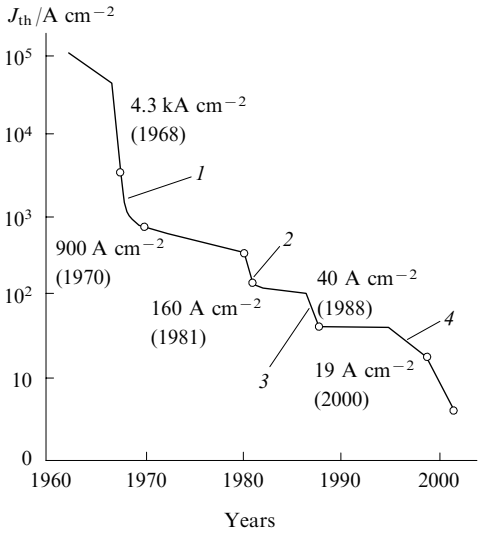


Figure 12. Evolution of the threshold current of semiconductor lasers (J_{th}).[10]
The figures denote sharp decreases in the threshold current caused by the impact of double heterostructures (*1*), heterostructures with quantum wells (*2*), heterostructures with quantum wells confined by short-period superlattices (*3*), heterostructures with quantum dots (*4*).

Only 23 years later, in 1994, due to the development of molecular beam epitaxy technology controlled by modern computers, did Federico Capasso at Bell Labs create the first quantum cascade lasers,[30] which are nowadays widely used in environmental applications and medicine.

Figure 12 presents the general history of semiconductor lasers. Semiconductor lasers were invented in 1962 in several laboratories at the same time. At room temperature, they had a threshold current density of 100 kA cm^{-2} at which lasing began. They burned out before they started operating. Heterostructures greatly reduced the necessary threshold current density so that lasers operated at room temperature, even in the CW mode. In the laboratory of low-dimensional electron gas, quantum wells and then quantum dots have reduced the required threshold current density to such a small value that today we do not even think about what threshold current density is necessary for semiconductor lasers. Thus, the development of the semiconductor laser technology over the past decades has led to that it has become dominating in optoelectronics.

V. Conclusions. Problems and directions of innovative development

In the last part of this review, I would like to focus on today's energy challenges, on how these challenges are met today and how, from my point of view, they will be solved. This has something in common with the issues addressed by the previous speaker Prof. Hans-Jörg Bullinger, the President of the Fraunhofer Society in Munich. This is a 'sha-green skin' (Table 1). Although the figures in this table may not be very accurate, and depletion of energy sources — oil, gas, coal, nuclear energy in thermal reactors — can occur within other periods of time, it will certainly happen.

I believe that a crucial alternative to the conventional energy sources is photovoltaics. It is precisely photovoltaics

Table 1. Data on different types of energy carriers.

Energy carriers	Total thoughout the world		
	reserves (known and extractive) /GW per year	consumption rate /GW	period of exhaust /years
Oil	200 000	4600	40–50
Gas	150 000	2200	60–70
Coal	1 000 000	3000	300–400
Nuclear power (thermal reactors)	90 000	750[a]	120
Total	1 440 000	11 000	130
Nuclear power (fast reactors)	15 000 000	11 000[a]	1500

[a] Calculated value.

that provides a solution to the energy challenges of the future. In a general sense, this implies the conversion of solar energy into electricity. This conversion can be achieved by various methods and with different efficiency. Among these methods, the photovoltaic method is, in my opinion, the most efficient one. Despite the fact that today it accounts for only 2% of the total energy consumption, it is the most promising method.

First heterostructures for solar cells were produced in 1969.[31] Then, they have appeared one after the other in the 1970s–1980s. In the 1990s, there was fruitful cooperation between the laboratory headed by V M Andreev, one of my disciples at the Physico-Technical Institute, and the Fraunhofer Institute in Freiburg. Their efforts have resulted in the design of Fresnel lenses for concentrated use of solar radiation. Heterostructures are a very expensive material; however, when the sunlight is concentrated by a factor of hundreds, the cost of this expensive material and the converter as a whole is negligible. The use of such a sequence — a cascade photovoltaic converter (Fig. 13) — can greatly improve the theoretical efficiency for them. The theoretical efficiency of heterostructure solar cells is 87%, whereas for the cascade cell containing only three p–n junctions, the theoretical efficiency is 65%. By now, the 44% efficiency has been actually achieved; unfortunately, this did not happen in Russia or Germany, but rather in the United States. This has been achieved, but there will be more. That is why, in this regard, heterostructures are most efficient.

Figure 14 shows the development of photovoltaic solar energy conversion in the past years.[32] The total capacity of photovoltaic power stations put into operation in 2011 was 30 gigawatts, which corresponds to 5 or 6 nuclear power plants. The percentage of electricity generated by photovoltaic power plants is currently growing very rapidly.

What are the rivals to semiconductors? The most potent rivals are polymeric materials. In 2000, the Nobel Prize in Chemistry was awarded to three outstanding scientists — Alan Heeger (United State), Alan MacDiarmid (United States) and Hideki Shirakawa (Japan) for the discovery and development of conductive polymers. In his Nobel lecture, Alan Heeger underlined that the most important is that conducting polymers offered the promise of achieving a new generation of polymers — materials which exhibit

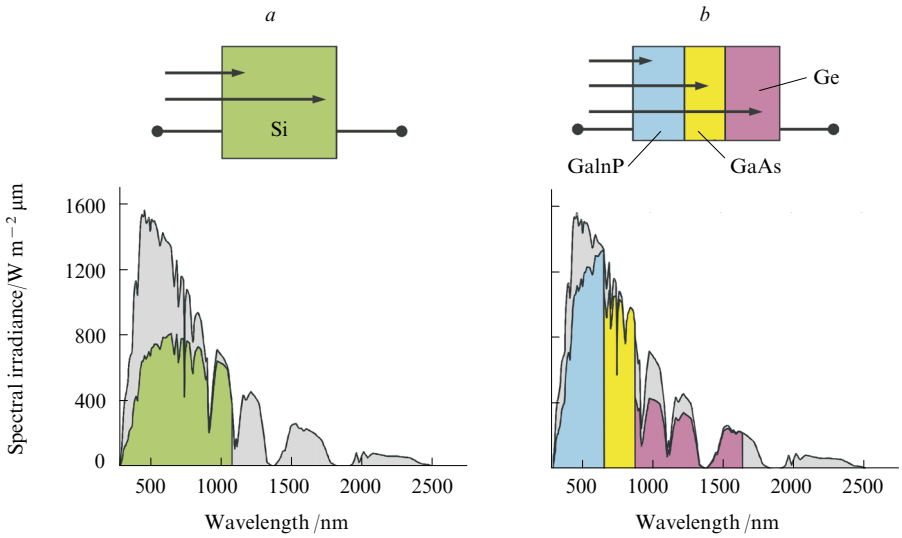
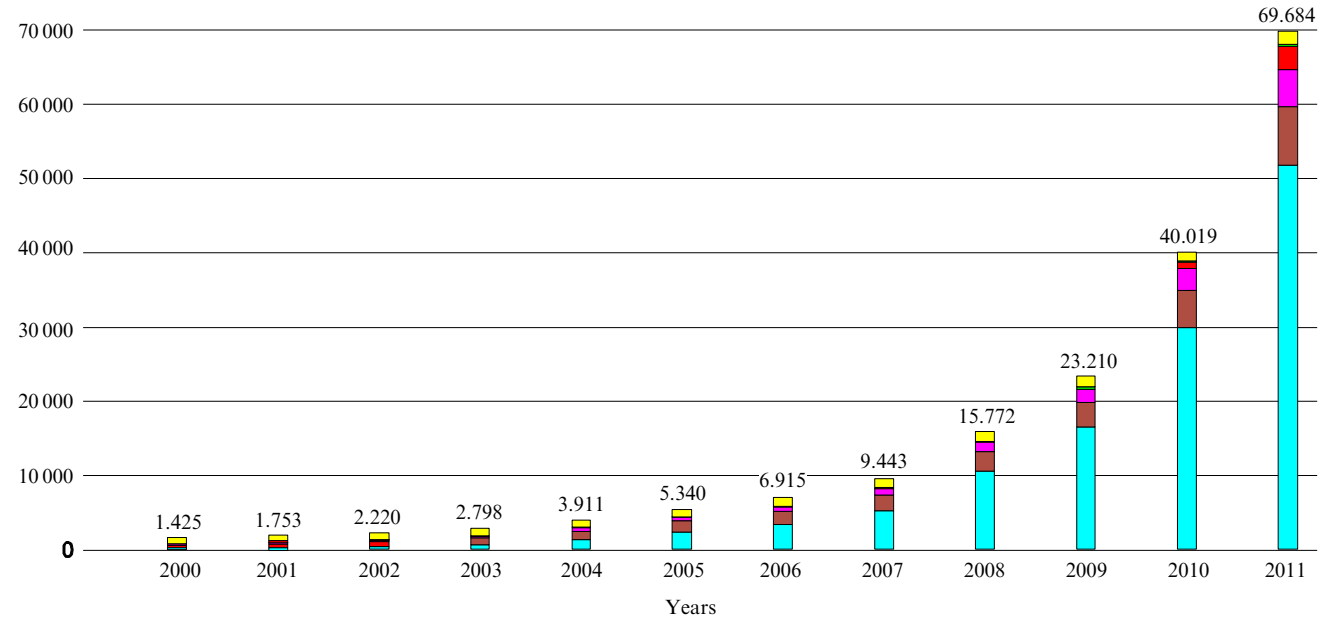


Figure 13. Principle of action (top) and the portion of the solar radiation spectrum used for photovoltaic conversion (bottom) for single-cascade (*a*) and three-cascade (*b*) solar cells.

electrical and optical properties of metals or semiconductors and which retain the attractive mechanical properties of polymers. By now, an efficiency of 13% has been achieved for polymer solar cells (Alan Heeger just held a lecture at the St Petersburg Scientific Forum). Whereas photovoltaics has developed very rapidly owing to the so-called one hundred thousand, half a million, and one million roofs programmes, polymer solar cells can be developed in a



Other countries	751	807	887	964	993	1.003	1.108	1.150	1.226	1.306	1.209	1.717
Middle East and Africa	–	–	–	–	–	–	–	–	–	21	205	336
China	19	39	45	55	64	68	80	100	145	373	893	3.093
America	146	177	222	287	379	496	645	856	1.205	1.744	2.820	5.053
Asia-Pacific countries	355	491	677	902	1.178	1.475	1.797	2.080	2.643	3.409	5.116	7.769
Europe	154	248	389	590	1.297	2.299	3.285	5.257	10.554	16.357	29.777	51.716
Total	1.425	1.653	2.220	2.798	3.911	5.340	6.915	9.443	15.772	23.210	40.019	69.684

Figure 14. Evolution of the world's annual production of solar photovoltaic power systems in 2000–2011 (MW year^{-1}).[32]

project of the billion windows type, since these polymeric materials can be applied to windows — they are transparent and at the same time generate electricity. For us, this is a very serious competitor, and we are working together to advance this technology further and further.

I recall that in 1988 the Bundestag of Germany invited me to give a lecture on the photovoltaic method of solar energy conversion at the Bundestag session in Dusseldorf. Later on, the Bundestag passed very important laws that encourage the development of solar energy engineering, including semiconductor solar energy conversion.

It is unfortunate that, being a deputy of the State Duma for many years, I did not succeed in convincing it to adopt similar laws in our country.

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