Remembering Zhores Alferov

Father of the semiconductor laser, Nobel Prize laureate and director of the Ioffe Institute in St Petersburg, Zhores Alferov was a much-loved scientist and educator whose research changed the modern world.

Sergey Ivanov

On 1 March 2019, Zhores Ivanovich Alferov, a leading expert in the field of semiconductor physics and quantum electronics and author of over 500 scientific papers, more than 50 patents and several books, sadly passed away. An outstanding Soviet and Russian scientist he was a winner of the Lenin and State Prizes, the highest awards in Soviet Union and Russia, and was awarded the Nobel Prize in Physics in 2000 for his research into semiconductor heterostructures. Alferov was a vice president of the Russian Academy of Sciences, a foreign member of the Academies of Sciences of US, Poland, Korea, China, and a well-known public and political figure. He was also a long-standing, loyal member of the Ioffe Institute, devoting 50 years of his life to the institute and rising to become its director from 1987 to 2003, managing it through one of the most difficult periods for Russian science.

Alferov was born on 15 March 1930, in Vitebsk, USSR (now Belarus) and after graduating from a high school in Minsk (currently the capital of Belarus) he entered the Faculty of Electronic Engineering of the Leningrad Electrical Technical Institute (LETI). Alferov graduated from LETI with honors in 1952, and then moved to the Ioffe Institute, where he remained until 2003.

Throughout his life Alferov was engaged in research into the physics and technology of semiconductors. In the early 1950s he started his research career at Ioffe in the laboratory of Vladimir Tuchkevich (director of the Ioffe Institute from 1967–1986), where he investigated silicon and germanium high-power diodes, transistors, and tiristors, which had been discovered a few years earlier in the US by William Shockley, John Bardin and Walter Brattain — earning them the 1956 Nobel Prize in Physics. Then in the early 1960s, Alferov's attention turned to direct-gap III–V semiconductor compounds, which had been discovered independently by scientists at Ioffe (Nina Goryunova[1] and Anatolii Regel'[2]) and Siemens in Germany (Heinrich Welker)[3].

Alferov decided to tackle the formidable challenge of how to realize high-quality, defect-free heterostructures and heterojunctions. In March 1963, Alferov and Rudolf Kazarinov, an Ioffe theoretician who later joined Bell Telephone Laboratories, filed a patent[4] that described the idea of creating a semiconductor laser diode based on a double heterostructure, an idea that was also independently published later that same year in the *Proceedings of the IEEE* by Herbert Kroemer in the US[5]. The initial technological efforts of Alferov's team at Ioffe were focused on the use of vapour-phase epitaxy (VPE) to fabricate GaAs–GaAsP double-heterostructure laser diodes, but a large lattice mismatch resulted in laser diodes that operated only at low temperatures[6].

Zhores Alferov was awarded the Nobel Prize in Physics in 2000 together with Herbert Kroemer and Jack Kilby for "fundamental work that laid the foundations of modern information technology particularly for developing semiconductor heterostructures used in high-speed and optical electronics". Image courtesy of the Ioffe Institute, St Petersburg, Russia.

While the lattice-matched GaAs–AlAs system would, in principle, make an 'ideal' heterojunction, the approach was at first rejected because AlAs was known to be chemically unstable and to decompose in a humid atmosphere. However, in 1966, Alferov learnt that small AlGaAs bulk crystals synthesized in Goryunova's lab at Ioffe had remained stable for several years. He thus immediately switched his team to the growth of lattice-matched AlGaAs-based heterostructures by a modified liquid-phase epitaxy (LPE) method. The team's studies were successful and within months their results were published[7] around the same time as similar independent results achieved by Hans Rupprecht, Jerry Woodall and George Pettit at the IBM Thomas J. Watson Research Center in the US[8].

Then in 1970, after three years of intense research, the world's first stripe laser diode based on the AlAs–GaAs double-heterostructure system, operating in continuous-wave mode at room temperature with a threshold power density below 1 kA cm^{-2}, was reported by Alferov's group[9]. Similar results obtained independently by Izuo Hayashi and Morton Panish at Bell Telephone Laboratories[10] were reported a month later in *Applied Physics Letters*. The achievement of continuous-wave lasing at room temperature caused an explosion of interest in the physics and technology of semiconductor heterostructures, and in 1971 many universities, industrial laboratories in the USA, the USSR, Great Britain, Japan, Brazil and Poland started research into III–V heterostructures and various electronic and photonic devices based on the system.

These achievements were documented in Alferov's habilitation at Ioffe, which he defended in 1970. In the same year, Alferov took a six-month internship in the laboratory of Nick Holonyak at the University of Illinois (USA), where he was awarded the Stuart Ballantine medal of the Franklin Institute for his work — the 'little Nobel prize' as it is called.

In 1972, Alferov became a corresponding member, and in 1979 at the age of 49, an academician of the Academy of Sciences of the USSR. Throughout his career Alferov invested great efforts in the development and use of semiconductor devices based on III–V heterostructures, including laser diodes operating in a wide spectral range (650–1,500 nm), high-power AlGaAs lasers, high-voltage AlGaAs rectifiers, efficient light-emitting diodes, photodetectors and photovoltaic converters of solar radiation. The latter proved to be indispensable as a

Zhores Alferov's great team at the Ioffe Institute in 1970 who used LPE to fabricate the first continuous-wave AlGaAs double-heterostructure laser diode operating at room temperature. From left to right: Dmitri Garbuzov, Viacheslav Andreev, Vladimir Korol'kov, Dmitrii Tret'yakov, Zhores Alferov. Image courtesy of the Ioffe Institute, St Petersburg, Russia.

spaceship power supply, and when the first Soviet orbital station Mir launched in March 1986 it was equipped with solar cell batteries developed in Alferov's lab by his co-worker Viacheslav Andreev.

In the 1970s the era of new epitaxial nanotechnologies, namely molecular beam epitaxy (MBE) and metal–organic vapour-phase epitaxy (MOVPE), invented in the US by Alfred Cho[11,12] and Harold Manasevit[13], began. This made it possible to introduce a new degree of freedom — quantum-size effects — in designing novel semiconductor heterostructures for electronics and photonics. A decade of optimization of these fabrication technologies and device designs eventually led to the development of the separate confinement heterostructure (SCH) and AlGaAs laser diodes with a quantum-well active region. In 1982, Bell Labs reported such a laser that featured an extended graded-index waveguide (GRIN-SCH) and claimed the lowest ever reported threshold current density $J_{th} = 160$ A cm^{-2} (ref. [14]).

Following these achievements, Alferov initiated the work in three directions: modification of LPE reactors to fabricate low-dimensional structures; organization of two groups dedicated to MBE and MOVPE; and to build close interactions with industrial and academic institutions in the USSR to design and fabricate Soviet epitaxial systems.

I joined the MBE group in Alferov's laboratory at the Ioffe Institute, headed by Piotr Kop'ev, in 1980 along with Nikolai Ledentsov and Victor Ustinov, all of us being graduate students or research assistants. After five years, I became responsible for MBE growth. Alferov understood well that we had started about eight years later than our US competitors working in the lab of Morton Panish (Bell Telephone Labs) and was always extremely patient and attentive to our failures and problems in developing MBE technology. But his energy and focus on developing novel laser diodes inspired us to work day and night to develop a thermodynamic description of numerous phenomena in MBE, including segregation of main elements and impurities, and defect formation[15]. This knowledge allowed us to predict optimized growth conditions for a laser diode structure, and in 1987 we demonstrated an ultralow-threshold AlGaAs GRIN-SCH laser diode with $J_{th} = 52$ A cm^{-2}, which remained the world record for all kinds of semiconductor laser diode for more than seven years[16]. This research served as a basis of my PhD thesis.

A logical continuation of this research and knowledge of MBE was the development of self-organized InGaAs quantum dots in collaboration with TU Berlin in 1994[17]. Simultaneously, in 1993–1995, Alferov decided to extend the activity of our MBE group to wide-gap II–VI materials and put me in charge of the development of room-temperature blue–green ZnMgSSe/ZnCdSe SCH quantum-well laser diodes lattice-matched to GaAs (ref. [18]). Alferov suggested that a superlattice waveguide could be an efficient means to accommodate residual stress in the SCH quantum-well laser structure, and he was proved correct. Later, in collaboration with the group of Andreas Waag from Gottfried Landwehr's department of the University of Wuerzburg we succeeded in fabricating the world's first room-temperature II–VI laser diodes with self-organized CdSe/ZnSe quantum dots, by applying our SCH superlattice quantum-well concept to the active region[19].

For many years, semiconductor self-organized quantum dot structures became the object of intense research in hundreds of laboratories around the world due to their unique fundamental and applied properties. These developments gave birth to a new field of modern optoelectronics, quantum nanophotonics, with the goal of realizing optical systems for quantum computing and quantum cryptography.

My group and I highly appreciated Alferov's decision to expand growth studies beyond the III–V material system as later it allowed us to be involved in the extremely interesting field of II–VI diluted magnetic nanoheterostructures for spintronics. It also led to the invention of new multifunctional hybrid III–V/II–VI heterostructures containing a coherent heterovalent interface in the active region of photonic and spintronic device heterostructures[20,21].

During this period, one can confidently say that Alferov created a new research direction into the physics and technology of semiconductor heterostructures, which became the basis of modern micro- and optoelectronics, solar energy, telecommunications and information technologies. Because of the impact of this research, Alferov together with Herbert Kroemer and Jack Kilby were awarded the Nobel Prize in Physics in 2000 for "fundamental work that laid the foundations of modern information technology particularly for developing semiconductor heterostructures used in high-speed and optical electronics". These discoveries have radically changed the face of the modern world.

More recently, Alferov's main scientific interests have been pursued at Academic University (established in 2002 on his initiative) where he focused on the integration of optoelectronics based on III–V nanoheterostructures with silicon microelectronics in a single epitaxial heterostructure, as well as on the development of multielectrode electronic biosensor devices based on semiconductor and metal nanoheterostructures with microfluidic life support systems for robotic medical applications. I have full confidence that if he had been given at least another decade or two of active research, we would have heard about great achievements from his new laboratories in these important-for-humanity areas as well.

Now I digress from the scientific interests and achievements of Alferov and take a broader look at his importance, describing his impact on those he worked with, whom he taught, inspired and supported with his limitless energy and attention. He was a truly great man — a teacher in science and life, who personified an exciting and important era in Soviet and world science and was one of its brightest representatives. He was also a true patriot of his country, and his importance for the Ioffe Institute, where he worked for 50 years, cannot be overestimated. Through his students, Alferov inspired a whole galaxy of talented and enthusiastic physicists and technologists, enabling the Ioffe Institute to become one of the world's leading research centres in semiconductor electronics and photonic nanotechnology. He always set himself, his colleagues and his students extremely high goals, namely achieving and advancing world-leading research, a work ethic that is still alive today at Ioffe. He ran the Ioffe Institute for 15 years, which included the hardest years of perestroika and post-perestroika devastation, when science in the country was dying and many gifted scientists were lost to business activities or leaving the country. During this period, he managed not only to keep all the important areas of research at the Institute, but also continued to develop them, using his numerous international links and authority. He strengthened international ties, secured funding from abroad and taught us how to work in the international community. He taught us the spirit of true internationalism, that all scientists are people with a similar worldview, that there are no enemies in science, but only colleagues and rivals. This ethos has helped many Russian scientists to successfully settle and work in the world's largest companies and universities abroad, while maintaining a connection with the alma mater. It also helped those at Ioffe to stay and successfully continue to work at home, even in those difficult years.

Back in 1993, under the chairmanship of Alferov and his colleague and friend, the Nobel laureate Leo Esaki (Japan), the country's first annual international symposium on nanostructure physics and technology was organized, which brought together leading foreign and Russian scientists to discuss topical problems of this important area of world science. Later, Alferov made great efforts to support the international authority of Russia in the scientific world. At his suggestion, the president of the Russian Federation established the international prize 'Global Energy', which is annually awarded to three Russian and foreign scientists who have made an outstanding contribution in the area. Alferov also initiated the St Petersburg scientific forum 'science and society', where many Nobel laureates in physics, chemistry, physiology, medicine and economics meet each year to discuss human progress.

Alferov was a teacher. In his native University LETI, he invited leading theoreticians, experimentalists and technologists of the Ioffe Institute to give lectures to students and set up a department of semiconductor optoelectronics to train a new generation of researchers, many of whom became prominent scientists. Later, he established a faculty of physics and technology at the Peter the Great St. Petersburg Polytechnic University, and finally, the lyceum Physical-Technical School (in 1987) and Academic University (in 2002), as a two-stage system of training talented youth for working in science, where he invested all his experience, love and hope for the future.

His name and image will forever remain in our hearts, we will pass on this memory of the great teacher, the creator, educator and champion to our students and continue to implement his goal of turning Russia into an advanced scientific and technological country. Everyone who knew Zhores Alferov deeply grieves this irreparable loss. ❐

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