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The Role of Dmitriĭ Nikolaevich Nasledov in the Formation and Development of the Physics and Technology of III–V Semiconductors

O. V. Emel'yanenko, N. M. Kolchanova, M. P. Mikhaĭlova, and Yu. P. Yakovlev

Ioffe Physicotechnical Institute, Russian Academy of Sciences, Politekhnicheskaya ul. 26, St. Petersburg, 194021 Russia

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Studies of III–V compounds in the Soviet Union were started in the early 1950s at the Ioffe Physicotechnical Institute, USSR Academy of Sciences. Dmitriĭ Nikolaevich Nasledov, a deputy director of the institute and the head of the semiconductor laboratory, decided to uphold the efforts of N.A. Goryunova in her studies of indium antimonide and to expand these studies to the entire class of III–V materials (III = In, Ga, Al; V = Sb, As, P). It required great scientific courage and foresight for D.I. Nasledov to make such a decision. The only other laboratory in the world which was engaged in studies of III–V compounds at that time was the laboratory headed by Professor Welker (Federal Republic of Germany). All scientists in the field of semiconductors concentrated almost exclusively on germanium and silicon. It seemed that these elemental semiconductors, which brought electronics to a new level, could not be surpassed by any compound semiconductor. However, time showed that this notion was not true.

The first significant report on studies of III–V semiconductors (InSb, InAs) at the Physicotechnical Institute was delivered by Nasledov at the First All-Union Conference on Semiconductors (Leningrad, 1956) [1]. He mentioned (among other phenomena) that neither electrical conductivity nor the Hall voltage depend on temperature in new III–V compounds. Many scientists considered this observation strange and even accidental. However, it was found shortly afterwards that the above temperature independence is the consequence of profound degeneracy in the electron gas, which is typical of heavily doped (then, simply "impure") III–V crystals. Fundamentally new phenomena in these crystals gave rise to a new field in the physics of semiconductors, specifically, the physics of heavily doped semiconductors. The contribution of the laboratory headed by Nasledov to this field is reported in [2, 3].

In general, the issue concerning the potentialities of doping and purification was central to the fate of the new compounds. Deviations from stoichiometry, high reactivity of constituents (As, P), and uncertainty in the pattern of incorporation and removal of impurities sometimes created an impression that all efforts were vain. All the problems that were encountered had to be solved for the first time. Close cooperation between physicists and chemists in the laboratory headed by Nasledov played an important role in the scientific progress; the team of chemists was headed by Goryunova. Physicists developed the zone-melting (purification) and Czochralski methods [4], whereas chemists quite successfully grew ingots in cells.

By the end of the 1950s and the beginning of the 1960s, the joint efforts yielded the first results. The purification, doping, and growth of III–V crystals could be performed as in the case of Ge and Si; other technological problems were also solved step by step. The world's purest InSb crystals were grown and studied; these crystals featured an electron concentration of $n \approx 10^{12}$ cm^{-3} and an electron mobility of $\mu \approx 10^6$ cm^2 V^{-1} s^{-1} at a temperature of $T = 77$ K [5]. The team headed by O.V. Emel'yanenko continued to study transport phenomena in a wider class of III–V compounds. The results of studying the impurity band [6, 7], the discovery of a giant magnetoresistance when charge carriers move via impurities [8], the investigation of the metal–semiconductor transition in various materials, and the determination of the origin of negative (quantum) magnetoresistance (discovered by the Emel'yanenko team even earlier, in 1958 [2]) were of greatest interest [9]. In all of these studies, the simplicity and accuracy of analysis relied on the basic special feature of III–V compounds (consisting in the sphericity of the conduction band, which represents the simplest model of a semiconductor's energy-band structure). The impurity properties, transport phenomena, and photoelectric properties of InSb, InAs, GaAs, AlSb, and InP were studied [10–15]. Diffused and fused *p–n* junctions and also photodiodes based on *n*-GaAs [16–18] were fabricated and studied. These and other results have shown conclusively that III–V compounds have a much wider range of controllable semiconductive properties in comparison with Ge and Si and are much more attractive for both the technology and physics of semiconductors.

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The number of researchers engaged in the studies of III–V semiconductors has steadily increased. The team investigating III–V sermiconductors at the Physocotechnical Institute was transformed into the laboratory of electronic semiconductors in 1957. Centers of research in the field of III–V semiconductors were founded in other cities of the USSR (Baku, Kishinev, Ordzhonikidze, and so on) under the guidance of Nasledov. Institutes in Moscow and Ukraine, as well as foreign laboratories, became involved and competed in this field. Under these conditions of growing competition, the laboratory headed by Nasledov obtained striking results that clearly showed the intrinsic worth of III–V semiconductors. Specifically, it was shown in 1962 that the luminescence spectrum of GaAs *p–n* junctions narrows appreciably with increasing current, which can only be attributed to the appearance of stimulated emission [19–21]. This was the first observation ever of stimulated emission from semiconductors.[1] Gallium arsenide, as well as a number of other III–V compounds, has a spherical conduction band with a center at the same point, $k = 0$, as for the valence band. This important special feature of III–V semiconductors distinguishes them from a great many indirect-gap semiconductors (including Ge and Si) and brings the probability of obtaining recombination radiation in the former close to 100%.

D.N. Nasledov, S.M. Ryvkin, A.A. Rogachev, and B.V. Tsarenkov were awarded the Lenin Prize in 1964 for their studies that led to the development of semiconductor lasers. In the laboratory headed by Nasledov, a new, revolutionary line in solid-state physics and technology was initiated; this line was related to optoelectronics, and a major contribution was made by the team headed by Tsarenkov. In order to fabricate optoelectronic devices based on binary compounds and graded-gap III–V structures, the method of liquid-phase epitaxy (LPE) for both the open and closed systems was developed by A.T. Gorelenok and Yu.P. Yakovlev at Nasledov's laboratory at the Ioffe Physicotechnical Institute [22, 23]. In the following years, the LPE method was widely used at other semiconductor laboratories at the same institute. Studies of radiative recombination and those aimed at the fabrication of lasers and light-emitting diodes (LEDs) based on GaAs and GaP and of graded-gap *p–n* structures in systems of GaAlAs and GaAlSb solid solutions were actively pursued by the team headed by Tsarenkov. The first surface-barrier structures based on III–V compounds were fabricated by Yu.A. Gol'dberg and E.A. Posse; the characteristics of these structures were consistent with an idealized theoretical model.

A high level of research and development (R & D) in the field of light-emitting devices at the laboratory headed by Nasledov provided the basis for the commercial production of these devices. The Council of Ministers of the USSR decided in 1960 to intensify the efforts aimed at developing devices based on GaAs and GaP. The laboratories headed by Nasledov and Goryunova (Ioffe Physicotechnical Institute) and the Start plant were included into the R & D program. A short time later, researchers and technologists of the Start plant (S.S. Meskin, V.N. Ravich, L.M. Kogan, I.T. Rassokhin, and A.L. Gofshtein-Gardt) with the creative support of scientists from Nasledov's laboratory (B.V. Tsarenkov, A.T. Gorelenok, A.N. Imenkov, V.V. Evstropov, and Yu.P. Yakovlev) developed the commercial production technology for (the first in the USSR) lasers based on GaAs and also LEDs for the infrared (GaAs) and visible (GaP) regions of the spectrum.

Studies on the recombination of nonequilibrium charge carriers and the development of important components (photodetectors and photoemitters) for optoelectronics became one of the leading lines of research in the laboratory headed by Nasledov [24–27].

Between 1964 and 1966, D.N. Nasledov, Yu.S. Smetannikova, and Yu.G. Popov discovered and studied a new physical phenomenon (oscillations of photoconductivity and photomagnetic effect) in InSb narrow-gap semiconductors at low temperatures [28]. As was shown by I.N. Yassievich [29], the oscillations were caused by illumination-induced heating of the electron subsystem. Between 1966 and 1968, D.N. Nasledov and N.M. Kolchanova discovered the heating of an electron subsystem in GaAs and GaSb wide-gap semiconductors. These studies on the heating and cooling of electron–hole plasma received international recognition and have been widely cited in articles and monographs.

Extensive studies of the photoconductivity and photomagnetic effect in all III–V compounds were undertaken in laboratories with the aim of determining the lifetime of carriers and ascertaining the recombination mechanisms of nonequilibrium charge carriers. The response speed, detectability, and photosensitivity were the parameters that were of prime interest to designers of new photodetectors and, consequently, to the scientists at Nasledov's laboratory. The studies on photoelectric phenomena in III–V semiconductors found practical applications: the first (in the USSR) InSb and InAs photodetectors for the middle-infrared region of the spectrum were developed (studies by the team headed by S.V. Slobodchikov and M.P. Mikhaĭlova) and were then produced on a commercial scale by the Institute of Applied Physics.

In the 1960s, not only was the scope of studies in Nasledov's laboratory widened, but new experimental methods were also rapidly introduced. Nasledov's laboratory promptly responded to intense worldwide interest in oxygen and iron-Group impurities, which made it possible to obtain semi-insulating GaAs single crystals. In a very short period of time, Nasledov's laboratory became one of the well-known leading teams in the sci-

[1] The lasing effect in GaAs was also reported by Hall *et al.*, Phys. Rev. Lett. **9**, 366 (1962).—*Translator's note.*

entific world concerned with this line of research. At that time, Nasledov made an unexpected but quite reasonable decision: he decided to join the forces of his laboratory at the Ioffe Physicotechnical Institute (N.M. Kolchanova and G.N. Talalakin) with the department headed by V.F. Masterov at the Leningrad Polytechnical Institute. This collaboration made it possible to widen the range of experimental methods and use new methods for comprehensive and in-depth studies of deep-level centers, first in GaAs and then in other III–V compounds. The employment of resonance-based methods (electron spin resonance and nuclear magnetic resonance) made it possible to make considerable and rapid progress in understanding the aforementioned centers. Ferromagnetic properties of GaAs crystals doped with Fe were discovered and studied at that time [30–32]. The assertion that the ordering of impurity atoms belonging to the Fe Group is caused by the exchange interaction via the host atoms without the involvement of conduction electrons was bold and innovative.

Returning to the scientific activity of Nasledov's laboratory, we may state that the 1960s and 70s were fruitful years of learning for the scientists at this laboratory. Nasledov allowed his coworkers more and more freedom in their research; he believed that self-realization was the best method for the mobilization of creative energy. The stored potential yielded striking results, which contributed to the international science and technology of III–V semiconductors in diverse fields.

At that time, Nasledov's laboratory became a genuine training center for scientists: hundreds of postgraduate students, as well as candidates and doctors of science from every part of the Soviet Union, from Novosibirsk to Riga and Vilnius, began working at this laboratory. Research workers from Nasledov's laboratory, who joined it upon graduation from university, have become self-reliant scientists, who are well-known for their contribution to the science and technology of III–V semiconductors in the USSR and around the world. The list of references in this article gives only a rough idea of this process. Below, we list the most outstanding young scientists who gained experience under Nasledov's guidance and went on to collaborate with Nasledov as heads of individual teams working in different lines of research. They were G.N. Talalakin (purification, doping, and growth of crystals, first by zone melting and then by liquid-phase epitaxy); Yu.M. Burdukov (solution of the same problems by the Czochralski methods); O.V. Emel'yanenko and T.S. Lagunova (fundamental studies of transport phenomena in III–V compounds, solid solutions, and structures on them); B.V. Tsarenkov, A.N. Imenkov, V.V. Evstropov, T.N. Danilova, and Yu.P. Yakovlev (fundamental studies and practical applications of *p–n* junctions in GaAs, photodiodes, and emitters based on graded-gap III–V compounds); N.V. Zotova (formation of InAs *p–n* structures and studies of their electroluminescence); M.P. Mikhaĭlova, Yu.S. Smetannikova, S.V. Slobodchikov, N.M. Kolchanova, and M.A. Sipovskaya (fundamental studies of photoelectromagnetic properties of III–V compounds); and A.A. Gutkin and V.E. Sedov (development and studies of photodiodes based on GaAs). Studies of InSb and GaAs growth technology were awarded State Prizes (for Nasledov and Burdukov). The laboratory headed by Nasledov was repeatedly a participant and prize winner at the Exhibition of Economic Achievements of the USSR, where new structures and devices developed under the guidance of Nasledov were exhibited.

The school of semiconductor science and technology founded by Nasledov put the Soviet Union in the forefront in mastering of III–V compounds. The papers delivered by Nasledov at international conferences attracted much interest.

In 1968, 25 years since the foundation of the Physicotechnical Institute, Doctor of Science (physics and mathematics) Zh.I. Alferov, now a Nobel Prize holder, mentioned the decisive pioneering role of Nasledov in studying and mastering III–V semiconductors, in their technical applications, in fabricating the first semiconductor lasers, and in the development of optoelectronics. In particular, Alferov wrote [33]: "Following the discovery of the semiconducting properties of III–V compounds, scientists from the Physicotechnical Institute took great efforts in the systematic study of the phenomena related to charge transport in these compounds. A natural consequence of these studies at this institute was the creation of the physical prerequisites for the development of an injection laser and a number of other semiconductor devices based on III–V compounds. Nasledov and his coworkers deserve the main credit for these achievements."

It has been 25 years since Nasledov's death. A new laboratory of infrared optoelectronics was founded based on his laboratory. This laboratory is headed by Yu.P. Yakovlev, professor and doctor of science (physics and mathematics); he was a coworker of D.N. Nasledov. In the 1950s, the main objects of investigations performed by Nasledov and his colleagues were the binary III–V compounds, whereas multinary compounds based on III–V semiconductors are now used to solve fundamental and application-oriented problems. Years have passed, the technology has changed, and the range of problems, narrowed. However, traditions established in the middle of the last century have been preserved.

In the 1950s, Nasledov boldly started to study the unknown class of III–V compounds; in the early 1990s, a similar courage, combined with foresight, was exercised by the scientists and technologists of the laboratory when they brought Nasledov's studies to a new level, with the aim of developing quantum-confinement devices based on multinary III–V compounds. As before, enormous scientific potential ensured that the scientific level of the laboratory (in the very difficult conditions of perestroika) remained high; moreover, the laboratory gained wide recognition not only in the commercial market of light-emitting semiconductor devices but also in the scientific community.

Now, the main line of activity of the laboratory is the development and study of optoelectronic devices (lasers, light-emitting diodes, and photodiodes) for the middle-infrared region of the spectrum (λ = 2–5 μm) on the basis of III–V compounds. The spectral range of 2–5 μm includes a multitude of main absorption lines of natural and industrial gases, such as H_2O, CH_4, CO_2, CO, NH_3, HF, N_2O, and so on; as a result, the use of nondestructive optical methods for the detection of gas molecules in the atmosphere and the determination of their concentration on the basis of coherent and noncoherent emission sources ensure a promising outlook for the monitoring and protection of the environment. The spirit and style of Nasledov's scientific activity, i.e., a sophisticated approach to the problem under investigation, have been preserved in the laboratory. The technology of growing multilayered heterostructures by liquid-phase epitaxy and vapor-phase epitaxy from organometallic compounds is being developed. The transport properties of narrow-gap multicomponent solid solutions based on GaSb and InAs are being studied. Noncoherent and coherent sources of radiation operating in the spectral range of 2–5 μm at room temperature are being developed and studied. Tunable diode lasers, which have been used with good results in diode-laser spectroscopy for the detection of minute amounts (from 1 ppm to 1 ppb) of contaminating substances in a surrounding medium, are being developed. High-efficiency LEDs operating in the spectral range of 2–4 μm and with an emission power exceeding 1 mW in the continuous mode have been developed; these LEDs are being successfully used in portable gas analyzers. In addition, long-wavelength lasers (λ = 3.3 μm) with an emission power of 6 W have been developed [34]. *p–i–n* diodes and avalanche diodes operating in the spectral range of 1.2–2.4 μm have been fabricated for the first time; these diodes are based on GaInAsSb/GaAlAsSb solid-solution structures and have a quantum efficiency of 0.6–0.7 electron/photon [35]. Thus, the pioneering effort that was started by the prominent scientist and our teacher, Professor Nasledov, with his colleagues more than 50 years ago has found its logical continuation at the Ioffe Physicotechnical Institute in present scientific activity aimed at the development and investigation of nanooptoelectronic devices for the visible and middle-infrared regions of the spectrum. In honoring Nasledov for his prominent scientific achievements, let us follow his motto: "Stay the course!"

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