Nobel Lecture: The double heterostructure concept and its applications in physics, electronics, and technology*

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I. INTRODUCTION

It is impossible to imagine now modern solid-state physics without semiconductor heterostructures. Semiconductor heterostructures and, particularly, double heterostructures, including quantum wells, wires, and dots, are today the subject of research of two-thirds of the semiconductor physics community.

The ability to control the type of conductivity of a semiconductor material by doping with various impurities and the idea of injecting nonequilibrium charge carriers could be said to be the seeds from which semiconductor electronics developed. Heterostructures developed from these beginnings, making it possible to solve the considerably more general problem of controlling the fundamental parameters inside the semiconductor crystals and devices: band gaps, effective masses of the charge carriers and the mobilities, refractive indices, electron energy spectrum, etc.

Development of the physics and technology of semiconductor heterostructures has resulted in remarkable changes in our everyday life. Heterostructure electronics are widely used in many areas of human civilization. It is hardly possible to imagine our recent life without double heterostructure (DHS) laser-based telecommunication systems, heterostructure-based light-emitting diodes (LED's), heterostructure bipolar transistors, or low-noise high-electron-mobility transistors for high-frequency applications including, for example, satellite television. Double-heterostructure lasers now enter practically every house with CD players. Heterostructure solar cells have been widely used for space and terrestrial applications.

Our interest in semiconductor heterostructures was not occasional. Systematic studies of semiconductors were started in the early 1930s at the Physico-Technical Institute under the direct leadership of its founder, Abraham Ioffe. V. P. Zhuze and B. V. Kurchatov studied the intrinsic and impurity conductivity of semiconductors in 1932, and the same year Ioffe and Ya. I. Frenkel created a theory of rectification in a metal-semiconductor contact based on the tunneling phenomenon (Frenkel and Ioffe, 1932; Zhuze and Kurchatov, 1932a, 1932b). In 1931 and 1936 Frenkel published his famous articles where he predicted, gave the name, and developed the theory of excitons in semiconductors, and E. F. Gross experimentally discovered excitons in 1951 (Frenkel, 1931, 1936; Gross and Karryev, 1952a, 1952b). The first diffusion theory of p-n heterojunction rectification, which became the base for W. Shockley's p-n junction theory, was published by B. I. Davydov in 1939 (Davydov, 1939). Because of Ioffe's initiative in the late 1940s at the Physico-Technical Institute, research into intermetallic compounds was begun. Theoretical prediction of semiconductor properties in A^3B^5 compounds and their subsequent experimental discovery were done independently by H. Welker and (on the example of InSb) N. A. Gorunova and A. R. Regel at the Physico-Technical Institute (Goryunova, 1951; Blum *et al.*, 1952; Welker, 1953). We benefited a lot from the high degree of theoretical, technological, and experimental expertise in this area at the Ioffe Institute at that time.

II. CLASSICAL HETEROSTRUCTURE

The idea of using heterojunctions in semiconductor electronics was put forward at the very dawn of the electronic era. In the first patent concerned with p-n junction transistors, Shockley (1951) proposed a wide-gap emitter to obtain unidirectional injection. A. I. Gubanov at our Institute first theoretically analyzed current-voltage characteristics of isotype and anisotype heterojunctions (Gubanov, 1950, 1951) but the important theoretical considerations at this early stage of heterostructure research were put forward by H. Kroemer, who introduced the concept of quasielectric and quasimagnetic fields in a graded heterojunction and made an assumption that heterojunctions might exhibit extremely high injection efficiencies in comparison to homojunctions (Kroemer, 1957a, 1957b). In the same period there were various suggestions about applying heterostructures in semiconductor solar cells.

The proposal of p-n junction semiconductor lasers (Basov *et al.*, 1961), the experimental observation of effective radiative recombination in GaAs p-n structure with a possible stimulated emission (Nasledov *et al.*, 1962), and the creation of p-n junction lasers and LED's (Hall *et al.*, 1962; Holonyak and Bevacgua, 1962; Nathan *et al.*, 1962) were the seeds from which semiconductor optoelectronics started to grow. However, lasers were

*The 2000 Nobel Prize in Physics was shared by Zhores I. Alferov, Jack Kilby, and Herbert Kroemer. This lecture is the text of Professor Alferov's address on the occasion of the award.

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not efficient because of high optical and electrical losses. The threshold currents were very high, and low temperature was necessary for lasing. The efficiency of LED's was very low, as well, due to high internal losses.

The important step was made immediatly after the creation of *p-n* junction lasers when the concept of the double heterostructure laser was formulated independently by us and Kroemer (Alferov and Kazarinov, 1963; Kroemer, 1963). In his article Kroemer proposed to use the double heterostructures for carrier confinement in the active region. He proposed that "laser action should be obtainable in many of the indirect gap semiconductors and improved in the direct gap ones, if [it] is possible to supply them with a pair of heterojunction injectors."

In our patent we also outlined the possibility of achieving a high density of injected carriers and inverse population by "double" injection. We especially pointed out that homojunction lasers "do not provide cw at elevated temperatures," and an additional advantage of DH lasers that we considered was the possibility "to enlarge the emitting surface and to use new materials in various regions of the spectrum."

Initially the theoretical progress was much faster than experimental realization. In 1966 (Alferov *et al.*, 1966), we predicted that the density of injected carriers could exceed the carrier density in a wide-gap emitter by several orders of magnitude (the "superjunction" effect). The same year, in a paper submitted to a new Soviet journal, *Fizika i Tekhnika Poluprovodnikov* (*Soviet Physics Semiconductors*), I summarized our understanding of the main advantages of the double heterostructure for different devices, especially for lasers and high-power rectifiers:

> "The recombination, light-emitting, and population inversion zones coincide and are concentrated in the middle layer. Due to potential barriers at the boundaries of semiconductors having forbidden bands of different width, the through currents of electrons and holes are completely absent, even under strong forward voltages, and there is no recombination in the emitters (in contrast to p-i-n, p-n-n^+, n-p-p^+ homostructures, in which the recombination plays the dominant role) . . . . Because of a considerable difference between the permittivities, the light is completely concentrated in the middle layer, which acts as a high-grade waveguide, and thus there are no light losses in the passive regions (emitters)" (Alferov, 1966).

Here are the most important peculiarities of semiconductor heterostructures we emphasized at that time: (i) superinjection of carriers, (ii) optical confinement, and (iii) electron confinement.

The realization of the wide-gap window effect was very important for photodetectors, solar cells, and LED applications. It permitted us to broaden considerably and to control precisely the spectral region for solar cells and photodetectors and to improve drastically the efficiency of LED's. The main physical phenomena in double and single classical heterostructures are shown in Fig. 1. Then it was only necessary to find heterostructures in which these phenomena could be realized.

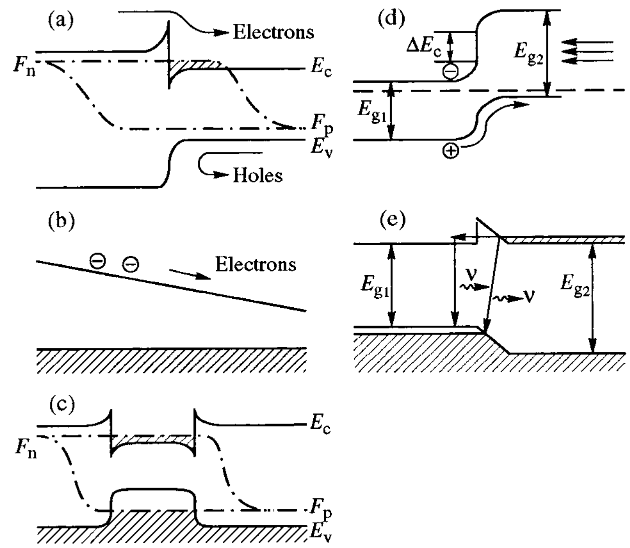

FIG. 1. Main physical phenomena in classical heterostructures: (a) One-side injection and superinjection; (b) diffusion in built-in quasielectric field; (c) electron and optical confinement; (d) wide-gap window effect; (e) diagonal tunneling through a heterostructure interface.

At that time general skepticism existed with respect to the possibility of creating the "ideal" heterojunction with a defect-free interface and first of all with theoretical injection properties. Even a very pioneering study of the first lattice-matched epitaxially grown single-crystal heterojunctions Ge-GaAs by R. L. Anderson (1960, 1962) did not give any proof of the injection of nonequilibrium carriers in heterostructures. Actual realization of an efficient wide-gap emitter was considered to be next to impossible, and the patent for the double-heterostructure laser was often referred to as a "paper patent."

Mostly due to this general skepticism there existed only a few groups trying to find the "ideal couple," which was, naturally, a difficult problem. Many conditions of compatibility needed to be met between thermal, electrical, and crystallochemical properties and between the crystal and the band structure of the contacting materials.

A lucky combination of a number of properties, i.e., a small effective mass and wide energy gap, effective radiative recombination, and a sharp optical absorption edge due to the "direct" band structure, a high mobility at the absolute minimum of the conduction band, and its strong reduction of the nearest minimum at the (100) point ensured for GaAs even at that time a place of honor in semiconductor physics and electronics. Since the maximum effect is obtained by using heterojunctions between the semiconductor serving as the active region and a more wideband material, the most promising systems looked at in that time were GaP-GaAs and AlAs-GaAs. To be compatible, materials of the "couple" should have, as the first and the most important condition, close values of the lattice constants; therefore heterojunctions in the system AlAs-GaAs were preferable. However, prior to starting work on the preparation and study of these heterojunctions one had to overcome a certain psychological barrier. AlAs had been synthesized long ago (Natta and Passerini, 1928; Goldschmidt, 1929), but many properties of this compound remained unstudied, since AlAs was known to be chemically unstable and to decompose in moist air. The possibility of preparing stable and adequate applications of heterojunctions in this system seemed to be not very promising.

Initially, our attempts to create double heterostructures were related to a lattice-mismatched GaAsP system. And we succeeded in fabricating by vapor-phase epitaxy the first DHS lasers in this system. However, due to lattice mismatch, the lasing, like that in homojunction lasers, occurred only at liquid-nitrogen temperatures (Alferov, Garbuzov, *et al.*, 1967). I would like to mention that, curiously, it was the first practical result obtained for a lattice-mismatched, even partially relaxed, system.

Our experience, which we got from studying the GaAsP system, was very important for understanding many specific heterojunction physical properties and the basics of heteroepitaxy. The development of the multichamber vapor-phase epitaxy method for the GaAsP system permitted us to create in 1970 superlattice structures with a 200-Å period and to demonstrate the splitting of the conduction band (Alferov, Zhilyaev, and Shmartsev, 1971).

But from the general point of view at the end of 1966 we came to a conclusion that even a small lattice mismatch in heterostructures $GaP_{0.15}As_{0.85}$-GaAs did not permit us to realize potential advantages of the double heterostructure. At that time my co-worker D. N. Tret'yakov told me that some small crystals of $Al_xGa_{1-x}As$ solid solutions of different compositions, which had been prepared two years ago by cooling from a melt, were put in a desk drawer by Dr. A. S. Bortshevsky and nothing happened to them. It immediately became clear that $Al_xGa_{1-x}As$ solid solutions turned out to be chemically stable and suitable for the preparation of durable heterostructures and devices. Studies of phase diagrams and the growth kinetics in this system and development of the liquid-phase epitaxy method, especially for heterostructure growth, soon resulted in fabrication of the first lattice-matched AlGaAs heterostructures. When we published the first paper on this subject, we felt lucky to be the first to find a unique, practically ideal lattice-matched system for GaAs, but as frequently happened, simultaneously and independently the same results were achieved by H. Rupprecht and J. Woodall at the T. Watson IBM Research Center (Alferov, Andreev, *et al.*, 1967; Rupprecht *et al.*, 1967).

From then on, progress in the semiconductor heterostructure area was very rapid. First of all, we experimentally proved the unique injection properties of the wide-gap emitters and superinjection effect (Alferov, Andreev, *et al.*, 1968a) and the stimulated emission in AlGaAs double heterostructures (Alferov, Andreev, *et al.*, 1968b), established the band diagram of the

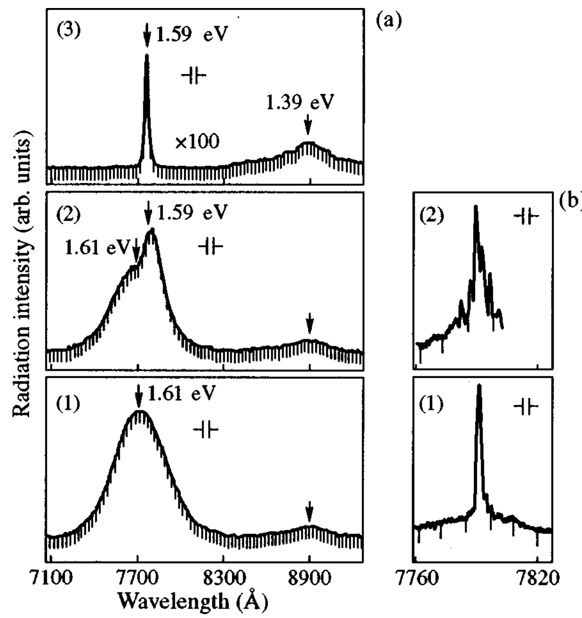

FIG. 2. Emission spectrum of the first low-threshold Al_xGa_{1-x} double heterostructure 1 $J_{th}=4300$ A/cm^2. The current rises (a) from (1) 0.7 A to (2) 8.3 A and then to (3) 13.6 A; $s=2.2\times10^{-3}$ cm^2.

$Al_xGa_{1-x}As$-$GaAs_x$ heterojunction, and carefully studied luminescence properties, diffusion of carriers in a graded heterostructure, and very interesting peculiarities of the current flow through the heterojunction. The current flow is similar, for instance, to diagonal tunneling-recombination transitions directly between holes of the narrow-band and electrons of the wide-band heterojunction components (Alferov, Andreev, Korol'kov, Portnoi, and Tret'yakov, 1969; Alferov, Andreev, Korol'kov, Portnoi, and Yakovenko, 1969a; Alferov, Garbuzov, *et al.*, 1969; Alferov, 1970).

At the same time, we created some important devices that realized the main advantages of the heterostructure concepts:

—DHS lasers with low threshold at room temperature. (Fig. 2) (Alferov, Andreev, Portnoy, and Trukan, 1969)

—Highly effective LED's using semiconductor heterostructures and double heterostructures (Alferov, Andreev, Korol'kov, Portnoi, and Yakovenko, 1969b)

—Heterostructure solar cells (Alferov, Andreev, Kagan, *et al.*, 1970)

—Heterostructure bipolar transistor (Alferov, Ahmedov, *et al.*, 1973)

—Heterostructure *p-n-p-n* switching devices (Alferov, Andreev, Korol'kov, Nikitin, and Yakovenko, 1970).

One of the first successful applications in industrial-scale production in our country was heterostructure solar cells in space research. We transferred our technology to the Quant company and, since 1974, GaAlAs solar cells have been installed on many of our sputniks. Our space station *Mir* (Fig. 3) used them for 15 years.

Most of these results were achieved afterwards in other laboratories in one to two years and in some cases

FIG. 3. Space station *Mir* equipped with heterostructure solar cells.

even later. But in 1970 the international competition became very strong. Later on, one of our main competitors, Izuo Hayashi, who was working together with M. Panish at Bell Telephone Laboratories in Murray Hill, wrote:

> "In September 1969 Zhores Alferov of the Ioffe Institute in Leningrad visited our laboratory. We realized he was already getting a $J_{\rm th}^{(300)}$ of 4.3 kA/cm^2 with a DH. We had not realized that the competition was so close and redoubled our efforts . . . Room-temperature cw operation was reported in May 1970 . . . " (Hayashi, 1984).

In our paper published in 1970 (Alferov, Andreev, Garbuzov, *et al.*, 1970), cw lasing was realized in stripe-geometry lasers formed by photolithography and mounted on copper plates covered by silver (Fig. 4). The lowest $J_{\rm th}$ density at 300 K was 940 A/cm^2 for broad-area lasers and 2.7 kA/cm^2 for stripe lasers. Independently, cw operation in DHS lasers was reported by Hayashi and Panish (Hayashi *et al.*, 1970; for broad-area lasers with diamond heat sinks) in a paper submitted only one month later than our work. Achievement of continuous waves at room temperature produced an explosion of interest in the physics and technology of semiconductor heterostructures. Whereas in 1969 AlGaAs heterostructures were studied in just a few laboratories, mostly in the USSR and U.S. (A. F. Ioffe Institute, Polyus, and Quant—industrial labs where we transferred our technology for applications in the USSR; Bell Telephone, the D. Sarnoff RCA Research Center, and T. J. Watson IBM Research Center in the U.S.), by the beginning of 1971 many universities and industrial labs in the U.S., the USSR, the United Kingdom, Japan, and even Brazil and Poland had begun investigations of III-V heterostructures and heterostructure devices.

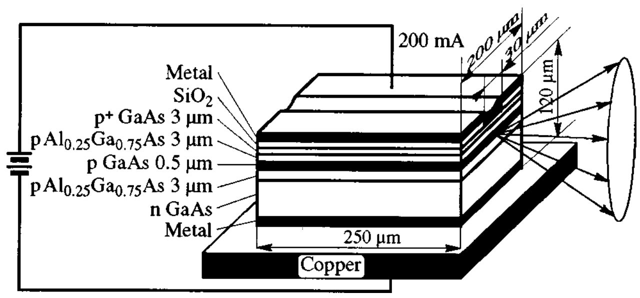

FIG. 4. Schematic view of the structure of the first injection DHS laser operating in the cw regime at room temperature.

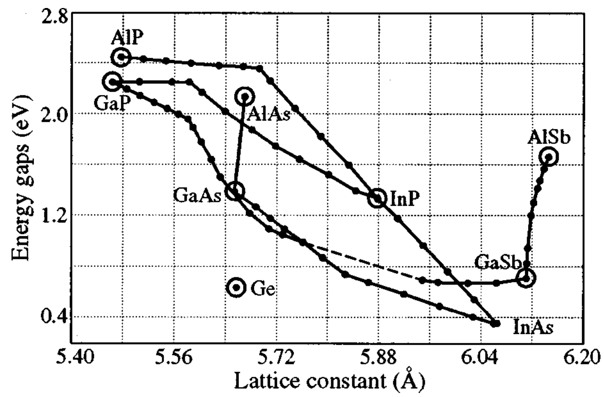

FIG. 5. Energy gaps vs lattice constant for III-V semiconductors. Lattice-matched heterojunctions: Ge-GaAs—1959. From Anderson, 1960, 1962. AlGaAs—1967. From Alferov *et al.*, 1967; Rupprecht *et al.*, 1967. Quaternary heterostructure (InGaAsP and AlGaAsSb): Proposal—1970. From Alferov, Andreev, Konnikov, *et al.*, 1971; First experiment—1972. From Antipas *et al.*, 1973.

At this early stage in the development of heterostructure physics and technology it became clear that we needed to look for new lattice-matched heterostructures in order to cover a broad area of the energy spectrum. The first important step was taken in our laboratory in 1970: in our paper (Alferov, Andreev, Konnikov, *et al.*, 1971) we reported that various lattice-matched heterojunctions based on quaternary III-V solid solutions were possible, which permitted independent variation between lattice constant and band gap. Later on G. Antipas and co-workers came to the same conclusions (Antipas *et al.*, 1973). As a practical example utilizing this idea we considered different InGaAsP compositions, and soon this material was recognized as being among the most important ones, for many different practical applications, including photocathodes (James *et al.*, 1973) and especially lasers in the infrared region for fiber-optic communications (Bogatov *et al.*, 1974) and the visible (Alferov, Arsent'ev, *et al.*, 1975a, 1975b; Hitchins *et al.*, 1975).

The early 1970s "world map" of ideal lattice-matched heterostructures is shown in Fig. 5. Only a decade later this "world map" was drastically changed (Fig. 6). Nowadays, it is necessary to add III nitrides.

The main ideas of a semiconductor distributed-feedback laser were formulated by us in our 1971 patent (Alferov, Andreev, Kazarinov, *et al.*, 1971). The same year H. Kogelnilk and C. V. Shank considered the possibility of replacing the Fabry-Perot or similar types of resonator in dye lasers with volume periodic inhomogeneities (Kogelnik and Shank, 1971). It is necessary to note that their approach is not applicable to semiconductor lasers, and all laboratories that carried out re-

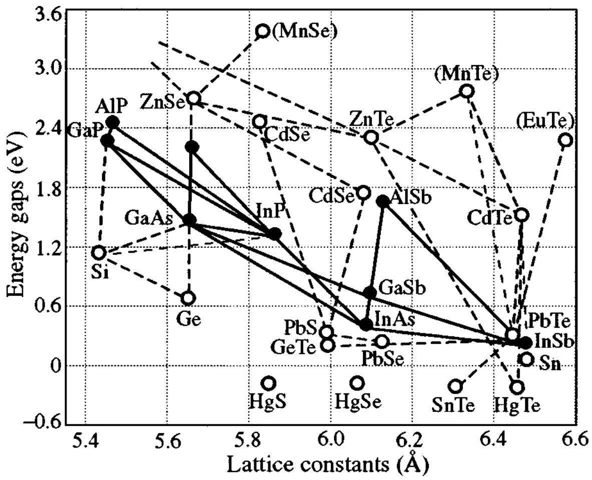

FIG. 6. Energy gaps vs lattice constants for semiconductors of IV elements, III-V and II(IV)-VI compounds, and magnetic materials in parentheses. Lines connecting the semiconductors, solid for the III-V's and dashed for the others, indicate quantum heterostructures that have been investigated.

search in distributed-feedback and distributed-Bragg-reflector semiconductor lasers used the ideas formulated in Alferov, Andreev, Kazarinov, *et al.* (1971):

(1) Diffraction grating created not in volume, but on a surface waveguide layer.

(2) Interaction of waveguide modes with a surface diffraction grating, which gives not only distributed feedback but also highly collimated light output.

A detailed theoretical analysis of the semiconductor laser with surface diffraction grating was published in 1972 (Kazarinov and Suris, 1972b). In this paper the authors established the way to obtain single-frequency generation. The first semiconductor lasers using surface diffraction gratings and distributed feedback were realized practically simultaneously at the Physico-Technical Institute (Alferov *et al.*, 1974, 1975), Caltech (Nakamura *et al.*, 1973), and Xerox Laboratory in Palo Alto (Scifres *et al.*, 1974).

In the early 1980s Kroemer and G. Griffiths (1983) published a paper that stimulated strong interest in staggered-lineup heterostructures (type-II heterojunction). Spatial separation of electrons and holes at the interface results in tunability of their optical properties (Alferov, Garbuzov, *et al.*, 1969; Baranov *et al.*, 1986). Staggered band alignment makes it possible to realize optical emission with a photon energy much smaller than the band-gap energy of each of the semiconductors forming a heterojunction. The demonstration of an injection laser based on a type-II GaInAsSb-GaSb heterojunction (Baranov *et al.*, 1986) showed promise for the creation of effective coherent light sources in the infrared optical range. Radiation in such a device is due to the recombination of electrons and holes localized in self-consistent potential wells at different sides of the heterointerface. Thus type-II heterostructures open possibilities both for fundamental physics and for device applications, which cannot be realized with type-I heterostructures in the III-V material systems. However, practical applications of these structures are still hampered by a poor understanding of their fundamental properties and scarcity of actual systems, which have been studied experimentally up to now.

To summarize this brief review of classical heterostructure development, we can classify the most important as follows:

CLASSICAL HETEROSTRUCTURES

I. Fundamental physical phenomena (Fig. 1)

- One-side injection
- Superinjection
- Diffusion in built-in quasielectric fields
- Electron confinement
- Optical confinement
- Wide-gap window effect
- Diagonal tunneling through heterostructure interface

II. Important applications in electronics

- Semiconductor lasers—Low threshold and continuous waves at room temperature, distributed-feedback and distributed-Bragg-reflector lasers, vertical surface emitting lasers, IR type-II heterostructure lasers
- High-efficiently LED's
- Solar cells and photodetectors, based on wide-gap window effect
- Semiconductor integrated optics, based on semiconductor distributed-feedback and distributed-Bragg-reflector lasers
- Bipolar wide-gap transistors
- Transistors, thyristors, and dynistors with photonic signal transmission
- High-power diodes and thyristors
- Infrared to visible converters
- Efficient cold cathodes

III. Important technological peculiarities

- Lattice-matched structures are necessary in principle
- Multicomponent solid solutions are used for lattice matching
- Epitaxial growth technology is needed in principle

Concluding this concise summary of the early development of bulk heterostructures, one may say that the invention of an "ideal" heterojunction and the introduction of the heterostructure concept into semiconductor physics and technology have led to the discovery of new physical effects, pivotal improvement in the characteristics of practically all known semiconductor devices, and the invention of new ones.

III. HETEROSTRUCTURE QUANTUM WELLS AND SUPERLATTICES

Owing to electron confinement, the double-heterostructure laser became an important precursor of the quantum well structure: when a middle layer had a thickness of some hundred angstroms, the electron levels would split due to the quantum size effect. The development of heterostructure growth techniques made it possibile to fabricate high-quality-double heterostructures with ultrathin layers. Two main methods of growth with very precise control of thickness, planarity, compositions, etc. were developed in the 1970s. A modern molecular-beam epitaxy method became practically important for III-V heterostructure technology due first of all to the pioneering work of A. Cho (1971a, 1971b). Metallo-organic chemical vapor deposition originated from the early work of H. Manasevit (1968) and found broad application in III-V heterostructure research after R. Dupuis and P. Dapkus (1977) reported the room-temperature injection of AlGaAs DH lasers which had been grown by the metal-organic chemical-vapor deposition method.

Clear manifestation of the quantum size effect in optical spectra of GaAs-AlGaAs semiconductor heterostructures with ultrathin GaAs layers (quantum wells) was demonstrated by Raymond Dingle *et al.* (1974). The authors observed a characteristic steplike behavior in absorption spectra and systematic shifts of the characteristic energies with a quantum well width decrease.

Studies of superlattices were launched by the work of L. Esaki and R. Tsu (1970), who considered the electron transport in a superlattice, i.e., at an additional periodic potential created by doping or changing the composition of semiconductor materials with the period bigger than, but comparable to, the lattice constant of a crystal. In this "man-made crystal," as Esaki called it, a parabolic band would break into minibands separated by small forbidden gaps and having Brillouin zones determined by this period. Similar ideas were described by L. V. Keldysh (1962) when considering the periodic potential produced on a semiconductor surface by an intense ultrasonic wave. At the Physico-Technical Institute, R. Kazarinov and R. Suris theoretically considered the current flow in superlattice structures in the early 1970s (Kazarinov and Suris, 1971, 1972a, 1973). It was shown that the current between wells determined by tunneling through the potential barriers separated the wells, and the authors predicted very important phenomena: tunneling under the electric field when the ground state of a well coincided with the excited state of the next well, and stimulated emission resulting from photon-assisted tunneling between the ground state of one well and the excited state of a neighboring well, which is lower in energy due to an applied electric field. At that time Esaki and Tsu independently considered resonant tunneling in superlattice structures (Tsu and Esaki, 1973).

The pioneering experimental studies of the superlattice structures were carried out by Esaki and Tsu: the superlattices were grown by vapor-phase epitaxy in the system GaP_xAs_{1-x}-GaAs. At the same time, in our laboratory we developed the first multichamber apparatus and, as was mentioned before, prepared a superlattice structure $GaP_{0.3}Al_{0.7}$-GaAs with the thickness of each layer 100 Å and a total of 200 layers (Alferov, Zhilyaev, and Shmartsev, 1971). Observed peculiarities of the current-voltage characteristics, their temperature dependence, and photoconductivity were explained by the splitting of the conduction band due to the one-dimensional periodic potential of the superlattice. These first superlattices were also the first strained-layer superlattices. E. Blakeslee and J. Matthews, who were working with Esaki and Tsu at IBM, succeeded in the mid-1970s in growing strained-layer superlattices with a very low concentration of defects. But many years later, after G. Osbourn's (1982) theoretical study at Sandia Lab and the first successful preparation of a high-quality strained-layer superlattice GaAs-$In_{0.2}Ga_{0.8}As$ by M. Ludowise at Varian, N. Holonyak at the University of Illinois achieved on those structures a cw room-temperature laser action (Ludowise *et al.*, 1983). It became clear that in a strained-layer superlattice the lattice strain became an additional degree of freedom, and by varying the layer thicknesses and compositions one could vary continuously and independently of one another the forbidden gap, lattice constant, of the overall superlattice.

In the early 1970s, Esaki and co-workers moved to molecular-beam epitaxy technology in AlGaAs systems (Chang *et al.*, 1973), and in March 1974 they submitted a paper on resonant tunneling (Chang *et al.*, 1974). It was the first experimental demonstration of quantum well heterostructure physics. They measured the tunneling current and conductance as a function of an applied voltage in GaAs-GaAlAs double barriers and found current maxima associated with resonant tunneling. Later in the same year Esaki and Chang (1974) observed resonant tunneling in a superlattice. The strong interest in resonant tunneling obviously was connected with its potential applications in high-speed electronics. In the late 1980s picosecond operation was achieved in a double-resonant tunnel diode, and oscillations up to 420 GHz were reported in a GaAs resonant tunnel diode at room temperature.

The restriction of electron motion to two dimensions in field-effect transistors had been recognized long ago (Shriffer, 1957) and that for trapped electrons in inversion layers was first verified in a magnetoconductance experiment by A. B. Fowler *et al.* (1966). Spectral effects due to spatial quantization were observed in thin bismuth films in 1968 by V. N. Lutskii and L. A. Kulik (Lutskii, 1970).

The pioneering work of Dingle *et al.* (1978) on modulation-doped superlattices demonstrated a mobility enhancement with respect to the bulk crystal and stimulated research on the application of high-mobility two-dimensional electron gas for microwave amplification. In France and Japan practically simultaneously new types of transistors based on a single nAlGaAs-nGaAs modulation-doped heterostructure were created that were labeled TEGFET's (two-dimensional electron-gas field-effect transistors) in France (Delagebeaudeuf *et al.*, 1980) and HEMT's (high-electron-mobility transistors) in Japan (Mimura *et al.*, 1980).

The first quantum well laser operation was demonstrated by J. P. van der Ziel *et al.* (1975), but the lasing parameters were much worse than for average DHS lasers. In 1978 Dupuis and Dapkus, in collaboration with Holonyak, first reported on a quantum well laser with parameters comparable to those of conventional DHS lasers (Dupuis *et al.*, 1978). The name "quantum well" was used in that paper. The real advantages of quantum well lasers were demonstrated much later by W. T. Tsang at Bell Telephone Laboratories. Thanks to many improvements in molecular-beam epitaxy growth technology and the introduction of an optimized structure (GRIN SCH), he found threshold currents as low as 160 A/cm^2 (Tsang, 1982).

We started to develop molecular-beam epitaxy and metal-organic chemical vapor deposition methods for growing III-V heterostructures only in the late 1970s. First of all, we stimulated the design and construction of the first Soviet molecular-beam epitaxy machine in our electronic industry. In a few years three generations of these machines were developed, and the last, which had the name "Cna," was good enough for our goals. (It was named for the nice river not very far from Ryazan, the city where NITI—the industrial laboratory of the Electronic Industry—was located; NITI carried out development of the molecular-beam epitaxy machine.) In parallel, later on, we started to develop a molecular-beam epitaxy system with NTO AN—the scientific instruments company of the Academy of Sciences in Leningrad. In the mid-1980s we got a few systems of this version. Both types of molecular-beam epitaxy systems are still working at the Ioffe Institute and other laboratories.

We developed the metal-organic chemical vapor deposition systems in our Institute and later, in the 1980s, a Swedish company, Epiquip, specially designed with our participation two systems for our Institute, which are still used in our research.

The strong interest in the experimental study of low-dimensional structures and the lack of equipment for molecular beam epitaxy and metal-organic chemical-vapor deposition growth technology stimulated our research on the development of liquid-phase epitaxy suitable for quantum well heterostructures.

However, until the late 1970s it seemed impossible to grow III-V heterostructures with an active-region thickness of less than 500 Å by liquid-phase epitaxy because of the existence near the heterojunction of extended interface regions with varying chemical compositions.

The situation was changed due to the work of Holonyak *et al.* (Rezek *et al.*, 1977) for superlatticelike InGaAsP structures, using a rotating boat system. In our laboratory we developed a new liquid-phase epitaxy method with the usual translational motion in a standard horizontal system for InGaAsP heterostructures (Alferov *et al.*, 1985) and a low-temperature liquid-phase epitaxy method for AlGaAs heterostructures (Alferov *et al.*, 1986a). These methods permitted us to prepare practically any kind of excellent-quality quantum well heterostructures with an active-region thickness of up to 20 Å and with the size of the interface regions comparable to one lattice constant. Of great practical importance for InGaAsP laser heterostructures was the creation of a record threshold current density for InGaAsP/InP ($\lambda = 1.3$ and 1.55 μm) and for InGaAsP/GaAs ($\lambda = 0.65 - 0.9\,\mu$m) single quantum well separate confinement lasers (Alferov *et al.*, 1986b, 1987). For high-power InGaAsP/GaAs ($\lambda = 0.8\,\mu$m) lasers a total efficiency of 66% with cw power 5 W for 100 μm width, a stripe-geometry laser was achieved (Alferov *et al.*, 1988a; Garbuzov *et al.*, 1988). In this laser the effective cooling of a semiconductor power device by recombination radiation was for the first time realized as had been predicted much earlier (Alferov, 1966). Garbuzov *et al.* (1990) noted an important characteristic of the InGaAsP heterostructure, its unusual resistance to multiplication of dislocations and defects (Fig. 7). It was this research that initiated the broad application of Al-free heterostructures.

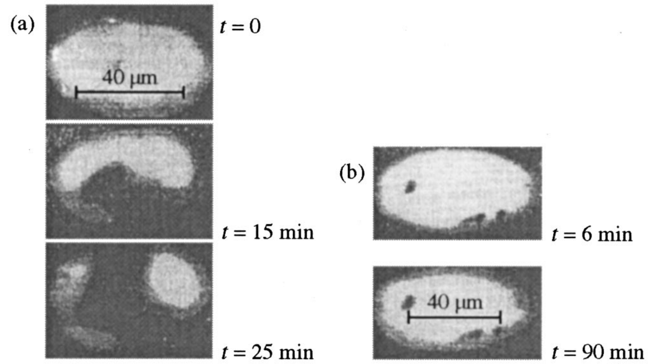

FIG. 7. Time evolution of a double heterostructure active region under high-level photoexcitation: (a) AlGaAs/GaAs, (b) InGaAsP/GaAs. Diameter of Kr^+-laser excitation beam −40 μm. Excitation level (a) 10^4 W/cm^2, (b) 10^5 W/cm^2.

A most complicated quantum well laser structure (Fig. 8), which combined a single quantum well with

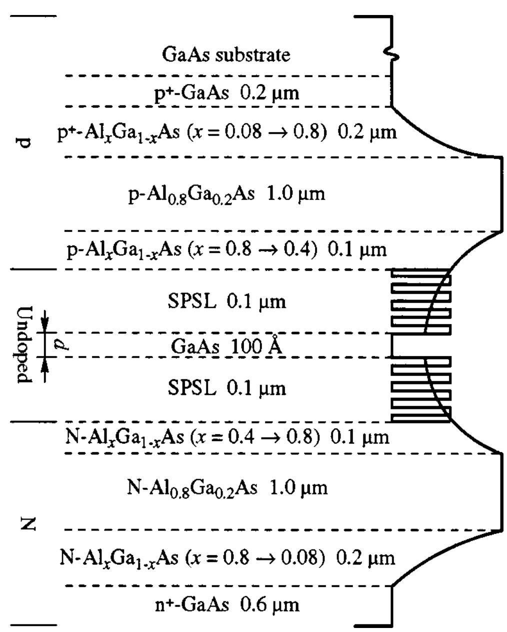

FIG. 8. Quantum well heterostructure laser, using short-period superlattices grown by molecular-beam epitaxy.

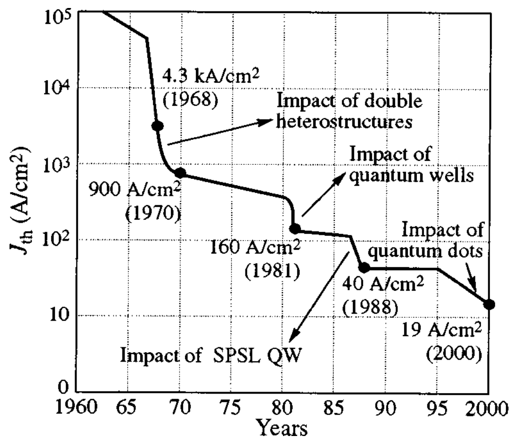

FIG. 9. Evolution of the threshold current of semiconductor lasers.

short-period superlattices, for the creation of GRIN SCH semiconductor heterostructures (the most favorable for the lowest J_{th}) was demonstrated in our laboratory in 1988 (Alferov *et al.*, 1988b). Using short-period superlattices, we achieved not only the desirable profile of a graded waveguide region, thus creating a barrier for dislocation movement to the active layer, but also the possibility of growing different parts of the structure at sufficiently large differences in temperature. In this way, we obtained both an excellent surface morphology and a high internal quantum efficiency on a planar GaAs (100) surface. The lowest $J_{th}=52\,A/cm^2$ and, after some small optimization, $40\,A/cm^2$ was for a long time a world record for semiconductor injection lasers and a good demonstration of the application of quantum wells and superlattices in electronic devices.

The idea of stimulated emission in superlattices which had been suggested by Kazarinov and Suris (1971, 1972a, 1973) was realized nearly a quarter of a century later after a proposal by Federico Capasso (Faist *et al.*, 1994). The proposed structure was strongly improved, and a cascade laser developed by Capasso gave rise to a new generation of unipolar lasers operating in the middle-infrared range.

The history of semiconductor lasers is, from a certain point of view, the history of the evolution of the semiconductor laser current threshold, which is shown in Fig. 9. The most dramatic changes took place just after the introduction of the DHS concept. The impact of short-period superlattice quantum wells led to a theoretical limit on this most important parameter. What can happen as a result of application of the new quantum wires and quantum dot structures will be discussed in the next part of our paper.

It may be that the crowning achievement of quantum well studies was the discovery of the quantum Hall effect (Klitzing *et al.*, 1980). This discovery and its comprehensive studies in AlGaAs-GaAs heterostructures, which shortly led to the discovery of the fractional quantum Hall effect (Tsui *et al.*, 1982), had a huge impact on solid-state physics. Observation of the effect, which deals only with fundamental quantities and does not rely on peculiarities of the band structure, carrier mobility, or densities in a semiconductor, has shown that heterostructures can be used to model some very basic physical effects. Recently many studies in this area have concentrated on understanding the condensation of electrons and the search for Wigner crystallization.

To summarize, the development of the field of heterostructure quantum wells and superlattices can be outlined in the same manner as that of classical heterostructure research:

HETEROSTRUCTURE QUANTUM WELLS AND SUPERLATTICES

I. Fundamental physical phenomena

- 2D electron gas
- Steplike density-of-state function
- Quantum Hall effect
- Fractional quantum Hall effect
- Excitons at room temperature
- Resonant tunneling in double-barrier structure and superlattices
- Energy spectrum in superlattices determined by choice of potential and strain
- Stimulated emission at resonant tunneling in superlattices
- Pseudomorphic growth of strained structures

II. Important consequences for applications

- Shorter emission wavelength, reduced threshold current, larger differential gain, and reduced temperature dependence of the threshold current for semiconductor lasers
- Infrared quantum cascade laser
- Short-period superlattice quantum well laser
- Optimization of electron and light confinement and waveguiding for semiconductor lasers
- 2D electron-gas transistors (high-electron-mobility transistors)
- Resonant-tunneling diodes
- Precise resistance standards
- SEED's and electro-optical modulators
- Infrared photodetectors based on quantum size level absorption

III. Important technological peculiarities

- Lattice match unnecessary
- Low-growth-rate technology (MBE, MOCVD) needed in principle
- Submonolayer growth techniques used
- Blockading of mismatch dislocations during epitaxial growth
- Sharp increase in the variety of heterostructure components

IV. HETEROSTRUCTURE QUANTUM WIRES AND QUANTUM DOTS

The principal advantage of using quantum-size heterostructures in lasers is the noticeable increase in the density of states when the dimensionality of the electron gas is reduced (Fig. 10).

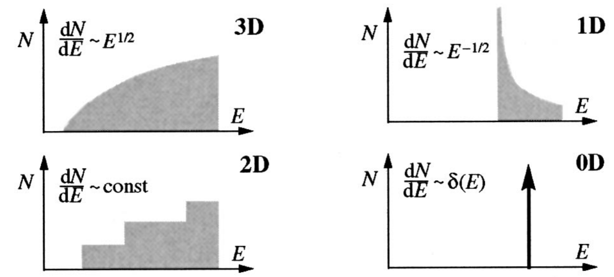

FIG. 10. Density of states for charge carriers in structures with different dimensionalities.

During the 1980s, progress in 2D quantum well heterostructure physics and its applications drew many scientists to the study of systems of far less dimensionality—quantum wires and quantum dots. In contrast to quantum "wells," where carriers are localized in the direction perpendicular to the layers but move freely in the layer plane, in quantum "wires" carriers are localized in two directions and move freely along the wire axis. With confinement in all three directions, quantum "dots"—"artificial atoms" with a totally discrete energy spectrum—are created (Fig. 11).

Experimental work on the fabrication and investigation of quantum wire and dot structures began more than 15 years ago. In 1982, Y. Arakawa and H. Sakaki (1982) theoretically considered some effects in lasers based on heterostructures with size quantization in one, two, and three directions. They wrote: "Most important, the threshold current of such a laser is reported to be far less sensitive than that of [a] conventional laser reflecting the reduced dimensionality of [the] electronic state." The authors performed experimental studies on a quantum well laser placed in high magnetic fields directed perpendicular to the quantum well plane and demonstrated an increase in the characteristic temperature (T_0) describing the exponential growth of the threshold current; the temperature increased in the magnetic field from 144 to 313 °C. They pointed to the possibility of weakening the threshold current dependence on temperature for quantum wire lasers and full temperature stability for quantum dot lasers (Fig. 12). By now there

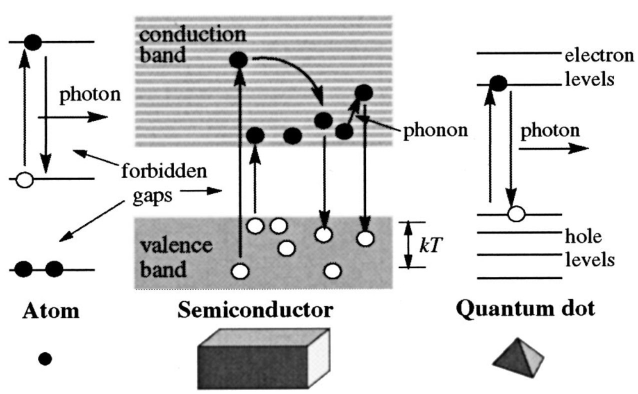

FIG. 11. Schematic representation of energy diagrams for a single atom (left), a bulk crystal (center), and a quantum dot (right).

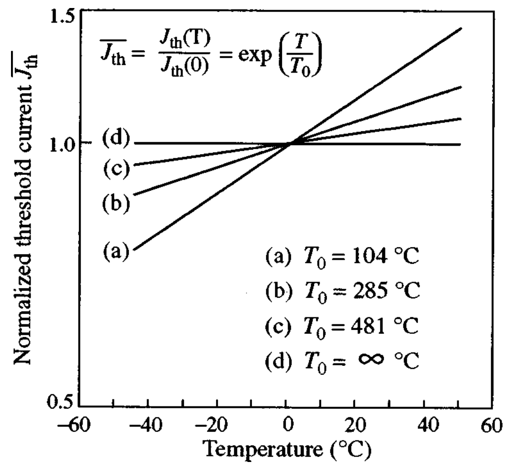

FIG. 12. Normalized temperature dependence of the threshold current for various DHS lasers: (a) bulk; (b) with quantum wells; (c) with quantum wires; (d) with quantum dots.

are many theoretical and experimental papers in this field.

The first semiconductor dots based on II-VI microcrystals in a glass matrix were proposed and demonstrated by A. I. Ekimov and A. A. Onushchenko (1981). However, since the semiconductor quantum dots were introduced in an insulating glass matrix and the quality of the interface between glass and semiconductor dot was not high, both fundamental studies and device applications were limited. Much more exciting possibilities appeared after three-dimensional coherent quantum dots had been fabricated in a semiconductor matrix (Goldstein *et al.*, 1985).

Several methods were proposed for the fabrication of these structures. Indirect methods, such as postgrowth lateral patterning of a 2D quantum well, often suffer from insufficient lateral resolution and interface damage caused by the patterning procedure. A more promising approach is fabrication by direct methods, i.e., growth in V grooves and on corrugated surfaces, which may result in formation of quantum wires and dots. The groups at the Ioffe Institute and Berlin Technical University—who have carried out this research in close cooperation over the past few years—have contributed significantly to the latter type of fabrication.

These groups came to the conclusion that the most exciting method for forming ordered arrays of quantum wires and dots is use of self-organization phenomena on crystal surfaces. Strain relaxation on step or facet edges may result in the formation of ordered arrays of quantum wires and dots for both lattice-matched and lattice-mismatched growth. The first very uniform arrays of three-dimensional quantum dots also exhibiting lateral ordering were realized in the system InAs-GaAs by both molecular-beam epitaxy and metal-organic chemical-vapor deposition growth methods (Ledentsov *et al.*, 1995; Alferov, Gordeev, *et al.*, 1996).

Elastic strain relaxation on facet edges and island interaction via the strained substrate are driving forces for the self-organization of ordered arrays of uniform, co-

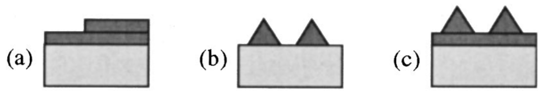

FIG. 13. Growth modes: (a) Frank–van der Merve; (b) Volmer-Weber; (c) Stranski-Krastanow.

herently strained islands on crystal surfaces (Shchukin *et al.*, 1995). In lattice-matched heteroepitaxial systems the growth mode is determined solely by the relation between the energies of two surfaces and the interface energy. If the sum of the surface energy of epitaxial layer γ_2 and the energy of the interface γ_{12} is lower than the substrate surface energy, $\gamma_2+\gamma_{12}<\gamma_1$, i.e., if the material being deposited wets the substrate, then we have Frank–van der Merve growth. Changing the $\gamma_2+\gamma_{12}$ value may result in a transition from the Frank–van der Merve mode to a Volmer-Weber one in which 3D islands are formed on a bare substrate.

In a heteroepitaxial system with lattice mismatch between the material being deposited and the substrate, the growth may initially proceed in a layer-by-layer mode. However, a thicker layer has a higher elastic energy, and the elastic energy tends to be reduced via the formation of isolated islands. In these islands the elastic strains relax and, correspondingly, the elastic energy decreases. This results in a Stranski-Krastanow growth mode (Fig. 13). The characteristic size of islands is determined by the minimum in the energy of an array of 3D coherently strained islands per unit surface area as a function of the island size (Fig. 14) (Shchukin *et al.*, 1995). Interaction between islands via an elastically strained substrate would result in lateral island ordering typical of a square lattice.

Experiments show in most cases a rather narrow size distribution of the islands, and on top of that coherent islands of InAs form under certain conditions a quasi-periodic square lattice (Fig. 15). The shape of quantum dots can be significantly modified during regrowth or postgrowth annealing, or by applying complex growth

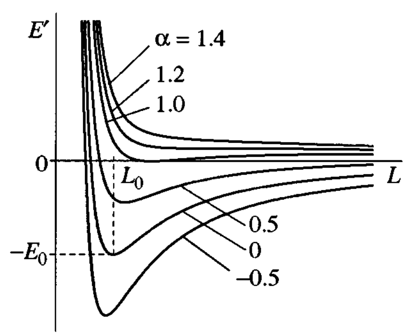

FIG. 14. Energy of a sparse array of 3D coherently strained islands per unit surface area as a function of island size. The parameter α is the ratio between the change in the surface energy upon island formation and the contribution from island edges to the elastic relaxation energy. When $\alpha>1$, the system tends thermodynamically toward island coalescence. When $\alpha<1$, there exists an optimal island size and the system of islands is stable against coalescence.

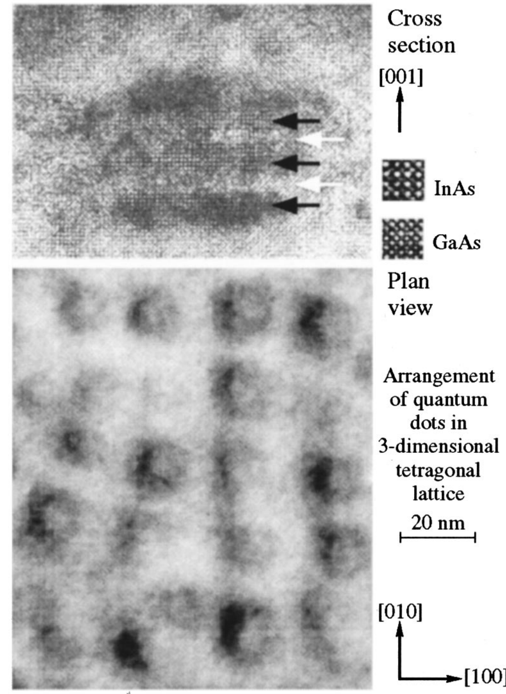

FIG. 15. Vertical and transverse ordering of coupled quantum dots in the system InAs-GaAs.

sequences. Short-period alternation in deposition of strained materials leads to a splitting of quantum dots and to formation of vertically coupled QD superlattice structures (Fig. 15; Alferov, Bert, *et al.*, 1996). Ground-state quantum dot emission, absorption, and lasing energies are found to coincide (Ledentsov *et al.*, 1995). The observation of ultranarrow (<0.15 meV) luminescence lines from single quantum dots (Ledentsov *et al.*, 1995) which do not exhibit broadening with temperature, is proof of the formation of an electronic quantum dot (Fig. 16).

Quantum dot lasers are expected to have properties superior to those of conventional quantum well lasers. High differential gain, ultralow threshold current density, and high-temperature stability of the threshold current density are expected to occur simultaneously. Additionally, ordered arrays of scatterers formed in an optical waveguide region may result in distributed feedback and/or in stabilization of single-mode lasing. Intrinsically buried quantum dot structures spatially localize carriers and prevent them from recombining nonradiatively at resonator faces. The overheating of facets, which is one of the most important problems for the high-power and high-efficiency operation of AlGaAs-GaAs and AlGaAs-InGaAs lasers, may thus be avoidable.

Since the first realization of QD lasers (Kirstaedter *et al.*, 1994), it has become clear that the QD size uniformity was sufficient to achieve good device performance. But even at that time, it was recognized that the main obstacle for QD heterostructure laser operation at room and elevated temperatures was the temperature-induced evaporation of carriers from quantum dots. Different methods were developed to improve the laser perfor-

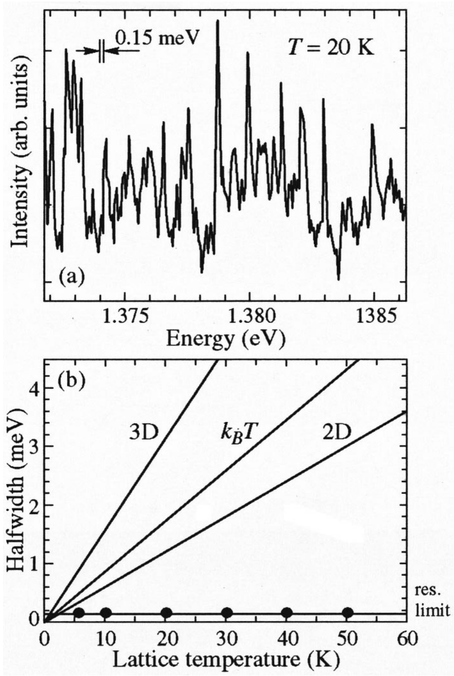

FIG. 16. (a) High-resolution cathodoluminescence spectrum of InAs-GaA; (b) temperature dependence of the full width at half-maximum of the cathode peak.

mance: (i) the increase of the density of quantum dots by stacking them (Fig. 17); (ii) the insertion of quantum dots into a quantum well sheet; (iii) the use of a matrix material with a higher band-gap energy. As a result, we got many parameters of QD heterostructure lasers better than those for quantum well heterostructure lasers based on the same materials. As an example, the world-record threshold current density of 19 A/cm^2 was recently achieved (Park *et al.*, 2000). Further, a cw output power up to 3.5–4.0 W (cw) for a 100-μm strip width, a quantum efficiency of 95% and a wall-plug efficiency of 50% were recently obtained (Zhukov *et al.*, 1999).

Significant efforts towards a theoretical understanding of QD lasers with realistic parameters have been undertaken. For a QD size dispersion of about 10% and other

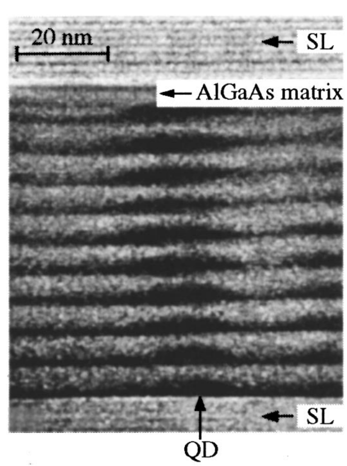

FIG. 17. Transmission electron microscopy image of the active region of high-intensity laser.

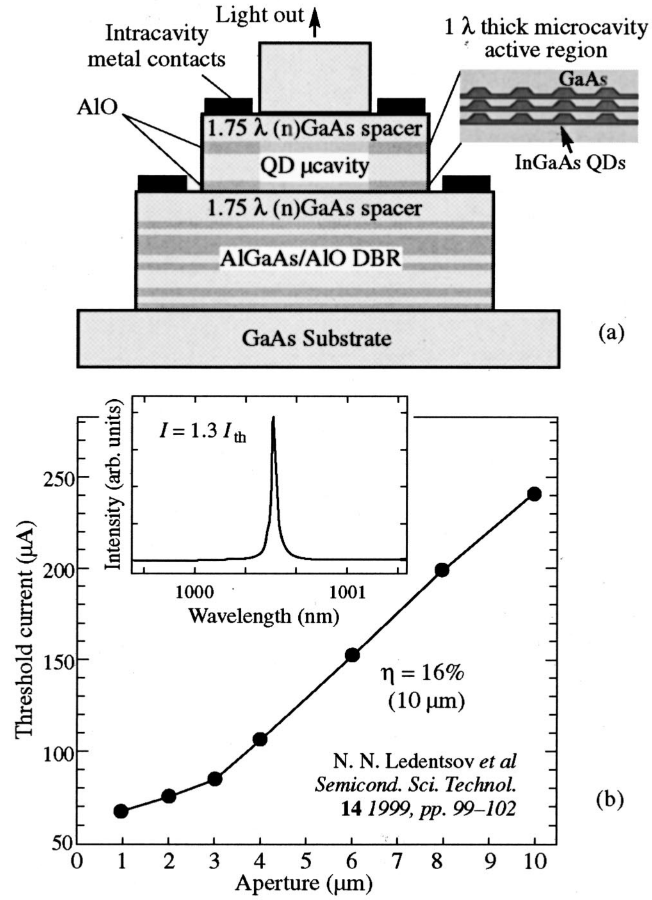

FIG. 18. (a) Schematic view of the quantum dot vertical-cavity surface-emitting laser structure. Basic advantages of quantum dots: (1) no interface recombination at oxide-defined apertures; (2) reduced lateral spreading of carriers out of the aperture region. Single quantum dot laser at ultralow threshold current is possible. (b) Dependence of the threshold current on the aperture size in a QD vertical-cavity surface-emitting laser. (i) Low threshold current densities (170 A/cm^2 at 300 K); (ii) low threshold currents at ultrasmall apertures; (iii) 1.3-μm range on GaAs substrate.

practical structure parameters, the theory (Asryan and Suris, 1996) predicts typical threshold current densities of 5 A/cm^2 at room temperature. The values of 10 A/cm^2 at 77 K (Zhukov *et al.*, 1997) and even 5 A/cm^2 at 4 K (Park *et al.*, 1999) have been experimentally observed.

In view of advanced device applications of quantum dots, the incorporation of quantum dots in vertical-cavity surface-emitting lasers seems to be very important. QD vertical-cavity surface-emitting lasers with parameters that fit to the best values for quantum well devices of similar geometry have been demonstrated (Fig. 18; Lott *et al.*, 1977). Recently, very promising results have been obtained (Fig. 19; Lott *et al.*, 2000) for 1.3-μm QD vertical-cavity surface-emitting lasers on a GaAs substrate to use in fiber-optic communications.

In a free-standing 3D island formed on a lattice-mismatched substrate, the strains can relax elastically, without the formation of dislocations. Thus a sufficiently large volume of a coherent narrow-gap QD material can be realized. This makes it possible to cover a spectral

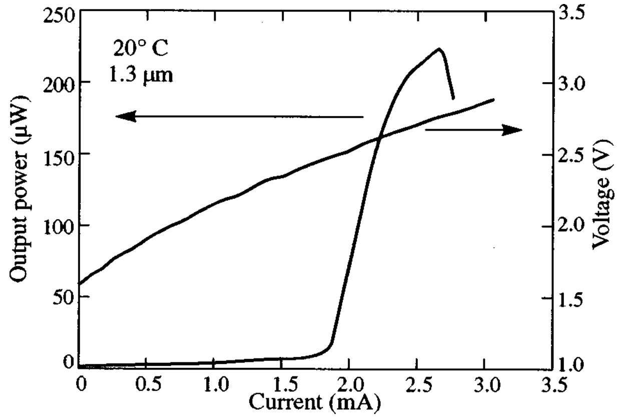

FIG. 19. GaAs-based QD vertical-cavity surface-emitting laser emitting at 1.3 μm.

range of 1.3–1.5 μm using a GaAs substrate and to develop wavelength-multiplexing systems on the basis of QD vertical-cavity surface-emitting lasers in the future.

It is very important to emphasize that we were able to realize the DHS concept for quantum wire and quantum dot structures because in both cases we have a narrow band-gap material in a wide-gap matrix.

Let us summarize again as we did for other parts.

HETEROSTRUCTURE QUANTUM WIRES AND DOTS

I. Fundamental physical phenomena

- 1D electron gas (wires)
- Density-of-state function with sharp maximums (wires)
- 0D electron gas (dots)
- δ-function type of density-of-state function (dots)
- Increasing binding energy of excitons

II. Important applications in electronics

- Reduced lasing threshold current and larger differential gain
- Reduced temperature dependence of threshold current (wires)
- Temperature stability of the threshold current (dots)
- Discrete amplification spectrum and a possibility of obtaining performance characteristics similar to those of solid-state or gas lasers (dots)
- Higher modulation factor in electro-optical modulators
- Possibility of creating "single-electron" devices
- A new possibility for the development of field-effect transistors

III. Important technological peculiarities

- The application of self-organization effects for growth
- Epitaxial growth in V grooves (wires)
- High-resolution lithography of heterostructure quantum well lasers

V. FUTURE TRENDS

Recently very impressive results for short-wavelength light sources have been achieved on the basis of II-VI selenides and III-V nitrides. The success in this research was mostly determined by the application of heterostructure concepts and methods of growth which had been developed for III-V quantum wells and superlattices. The natural and most predictable trend is the application of heterostructure concepts as well as technological methods and peculiarities of new materials. Different III-V, II-VI, and IV-VI heterostructures, developed in recent times, are good examples of this statement.

But from a more fundamental point of view, heterostructures (including quantum wells and superlattices, quantum wires, and quantum dots) offer a way to create new types of materials—hetero-semiconductors. In the words of Leo Esaki, instead of "God-made crystals" we create "man-made crystals."

The study of classical heterostructures, quantum wells and superlattices is quite mature and we are now exploiting many of their unique properties. The study of quantum wire and dot structures is still very young: exciting discoveries and new unexpected applications are awaiting us. Even at this early stage, however, we can say that ordered equilibrium arrays of quantum dots may be used in many devices: lasers, light modulators, far-infrared detectors and emitters, etc. Resonant tunneling via semiconductor atoms introduced in larger band-gap layers may lead to significant improvement in device characteristics. More generally speaking, QD structures will be developed both "in width" and "in depth."

In width means new material systems to cover a new energy spectrum. The lifetime limitations of the green and blue semiconductor lasers and even more general problems of the creation of defect-free structures based on wide-gap II-VI and III-V (nitrides) would be solved by using QD structures in these systems.

As to *in depth*, it is necessary to mention that the degree of ordering depends on very complicated growth conditions, materials constants, and concrete values of the surface free energy. To achieve resonant tunneling and single-electron devices, including optical ones, require a thorough investigation and evaluation of these parameters in order to obtain the maximal possible degree of ordering. In general, it is necessary to find stronger self-organization mechanisms for ordered arrays of quantum dots.

In the early 1980s I was invited to deliver a lecture about heterostructures and applications at the Amoco Photonic Center near Chicago.

The summary of my lecture was as follows:

(1) Heterostructures—a new kind of semiconductor material—expensive, complicated chemically and technologically, but most efficient

(2) Modern optoelectronics is based on heterostructure applications:

—The DHS laser—a key device of modern optoelectronics

—The heterostructure protodiode—the most efficient and high-speed photodiode

—Optoelectronic integrated circuits (OEIC's)—will solve problem of high information density of an optical communication system

(3) Future high-speed microelectronics will mostly use heterostructures

(4) High-temperature, high-speed power electronics—a new broad field of heterostructure applications

(5) Heterostructures in solar energy conversion: the most expensive photocells and the cheapest solar electricity producer

(6) In the 21st century heterostructures in electronics will reserve only 1% for homojunctions

And 20 years later I see no reason to change this summary.

It is hardly possible to describe even the main directions of modern physics and the technology of semiconductor heterostructures. There is much more than I have mentioned. Many scientists contributed to this tremendous progress, which defines to a great extent not only the future prospects of condensed-matter physics and semiconductor laser and communication technology, but also, in a sense, the future of human society. I would like also to emphasize the impact of scientists of previous generations who prepared our way. I am very happy that I had a chance to work in this field from the very beginning. I am even happier that we can continue to contribute to progress in this area now.

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