Double Heterostructure Lasers: Early Days and Future Perspectives

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Invited Paper

***Abstract*—A short historical review of the physics and technology of heterostructure lasers based on double heterostructures is described. Recent progress in quantum dot laser structures and future trends in the development of the physics and technology of these new types of heterostructures are discussed.**

***Index Terms*—Heterostructure, quantum dot, quantum well, quantum wire, semiconductor laser, superlattice.**

I. Introduction

IT would be very difficult today to imagine solid-state physics without semiconductor heterostructures. Semiconductor heterostructures and especially double heterostructures, including quantum wells, quantum wires, and quantum dots, currently comprise the object of investigation of two thirds of all research groups in the physics of semiconductors.

While the feasibility of controlling the type of conductivity of a semiconductor by doping it with various impurities and the concept of nonequilibrium carrier injection are the seeds from which semiconductor electronics has sprung, heterostructures provide the potential means for solving the far more general problem of controlling fundamental parameters in semiconductor crystals and devices, such as the width of the bandgap, the effective masses and mobilities of charge carriers, the refractive index, and the electron energy spectrum.

The development of the physics and technology of semiconductor heterostructures has brought about tremendous changes in our everyday lives. Heterostructure-based electron devices are widely used in many areas of human activity. Life without telecommunication systems utilizing double-heterostructure (DHS) lasers, without heterostructure light-emitting diodes (LEDs) and bipolar transistors, or without the low-noise, high-electron-mobility transistors (HEMTs) used in high-frequency devices, including satellite television systems, is scarcely conceivable. The DHS laser is now found in virtually every home as part of the compact-disc (CD) player. Solar cells incorporating heterostructures are used extensively in both space and terrestrial programs; for fifteen years the "Mir" space station has been utilizing solar cells based on AlGaAs heterostructures.

Manuscript received October 9, 2000. This work was supported by Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg, Russia.

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Publisher Item Identifier S 1077-260X(00)11559-X.

II. DHS Concept and its Application for Semiconductor Lasers

The idea of using heterostructures in semiconductor electronics emerged at the very dawn of electronics. Already in the first patent associated with p-n junction transistors, Shockley [1] proposed the application of a wide-gap emitter to achieve one-way injection. Some of the most important theoretical explorations in this early stage of heterostructure research were carried out by Kroemer, who introduced the concept of quasi-electric and quasimagnetic fields in a graded heterojunction and hypothesized that heterojunctions could possess extremely high injection efficiencies in comparison with homojunctions [2], [3].

The next important step was taken several years later, when we and Kroemer [4], [5] independently formulated the concept of DHS-based lasers. In our patent, we noted the feasibility of attaining a high density of injected carriers and population inversion by "double" injection. We specifically mentioned that homojunction lasers "do not provide continuous lasing at elevated temperatures," and to demonstrate an added benefit of DHS lasers, we explored the possibility of "increasing the emitting surface and utilizing new materials to achieve emission in different regions of the spectrum."

At the beginning theoretical research significantly outpaced its experimental implementation. In 1966, we predicted [6] that the injected-carried density could well be several orders of magnitude greater than the carrier density in a wide-gap emitter (the "super-injection" phenomenon). At the same year, in a paper [7], we generalized our conception of the principal advantages of DHS for various devices, particularly for lasers and high-power rectifiers:

"The regions of recombination, light emission, and population inversion coincide and are concentrated entirely in the middle layer. Owing to potential barriers at the boundary of semiconductors with different bandgap widths, even for large displacements in the direction of transmission, there is absolutely no indirect passage of electron and hole currents, and the emitters have zero recombination (in contrast with p-i-n, p-n-n$^+$, n-p-p$^+$, where recombination plays a decisive role).

"Population inversion to generate stimulated emission can be achieved by pure injection means (double injection) and does not require a high doping level of the middle region and especially does not require degeneracy. Because of the appreciable difference in the dielectric constants, light is concentrated entirely in the middle layer, which functions as a high-Q wave-

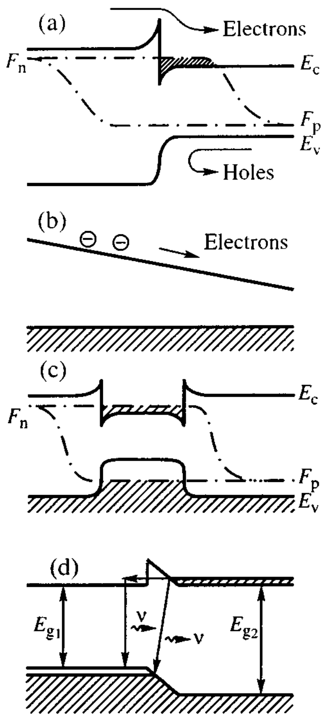

Fig. 1. Main physical phenomena in classical heterostructures. (a) One-side injection and superinjection. (b) Diffusion in an imbedded quasielectric field. (c) Electron and optical confinement. (d) Diagonal tunneling through a heterojunction.

guide, and optical losses in the passive regions (emitters) are therefore nonexistent."

The following are the most important physical phenomena predicted in heterostructures:

1) superinjection of carriers;
2) optical confinement; and
3) electron confinement (Fig. 1).

At that time, there was widespread skepticism regarding the feasibility of fabricating an "ideal" heterojunction with a defect-free boundary, especially one that exhibited the theoretically predicted injection properties. The actual construction of efficient, wide-gap emitters was regarded as a sheer impossibility, and many viewed the patent for a DHS laser as a "paper" patent.

Mostly due to this general skepticism there existed only a few groups trying to find out the "ideal couple," which was, naturally, a difficult problem. There should be met many conditions of compatibility between thermal, electrical, 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 "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 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 preparation and study of these heterojunctions one had to overcome a certain psychological barrier. AlAs had been synthesized long ago, but many properties of this compound remained unstudied since AlAs was known to be chemically unstable and decompose in moist air. The possibility of preparing stable and adequate to applications of heterojunctions in this system seemed to be not very promising.

Initially, our attempts to create DHS were related to a lattice-mismatched GaAsP system, and we succeeded in fabricating by VPE first DHS lasers in this system. However, due to lattice mismatch the lasing like that in homojunction lasers occurs only at liquid nitrogen temperature.

From a general point of view, at the end of 1966, we came to a conclusion that even the small lattice mismatch in heterostructures $GaP_{0.15}As_{0.85}$–GaAs does not permit us to realize potential advantages of the DHS. At that time, Tret'yakov showed that small crystals of $Al_xGa_{1-x}As$ solid solutions of different compositions, which had been prepared two years ago by cooling from the melt, were put in the desk drawer by 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 preparation of durable heterostructures and devices. Studies of phase diagrams and the growth kinetics in this system and development of LPE method especially for heterostructure growth soon resulted in fabricating the first lattice-matched AlGaAs heterostructures. When we published the first paper on this subject, we were lucky to be the first to find out a unique, practically an ideal lattice-matched system for GaAs, but as it frequently happened the same results were simultaneously and independently achieved by Rupprecht and Woodall at T. Watson IBM Research Center [8], [9].

Then the progress in the semiconductor heterostructure area was very rapid. First of all, we experimentally proved the unique injection properties of wide-gap emitters and superinjection effect [10], the stimulated emission in AlGaAs DHS [11], established the band diagram of $Al_xGa_{1-x}As$–$GaAs_x$ heterojunction, carefully studied luminescence properties, diffusion of the carriers in a graded heterostructure and very interesting peculiarities of the current flow through the heterojunction—that is similar, for instance, to diagonal tunneling-recombination transitions directly between holes of the narrowband and electrons of the wide-band heterojunction components [12]–[15].

At the same time, we created the majority of most important devices with realization of the main advantages of the heterostructures concepts:

1) low threshold at room temperature DHS lasers [16] (Fig. 2);
2) high effective SHS and DHS LED [17];
3) heterostructure solar cells [18];
4) heterostructure bipolar transistor [19];
5) heterostructure p-n-p-n switching devices [20].

Most of these results were achieved afterwards in other laboratories in 1–2 yr and in some cases even later. However, in 1970, the international competition became very strong. Later on, one of our main competitors, (Hayashi), who was working

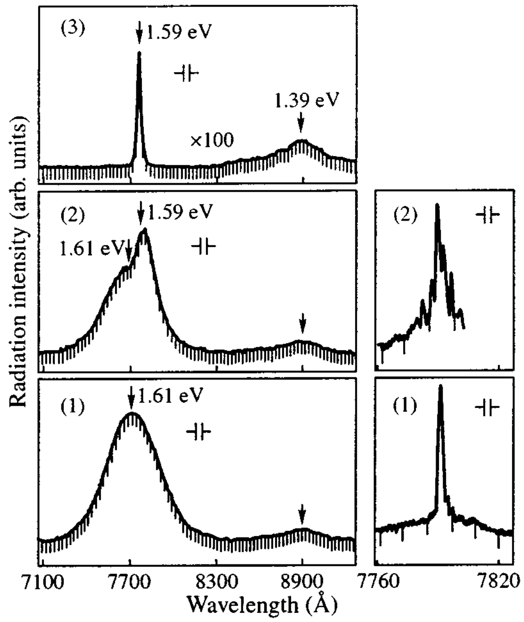

Fig. 2. Emission spectrum of the first low-threshold Al_xGa_{1-x} DHS laser operating at room temperature (300 K), $J_{th} = 4300$ A/cm^2. The current rises from 1) 0.7 A to 2) 8.3 A, and then to 3) 13.6 A.

together with Panish at Bell Telephone Laboratories in Murray Hill, wrote [21] "In September 1969 Zhores Alferov of the Ioffe Institute in Leningrad visited our laboratory. We realized he was already getting a J_{th} (300) of 4.3 kA/cm^2 with a DHS. We had not realized that the competition was so close and redoubled our efforts … Room temperature CW operation was reported in May 1970 … ". In our paper published in 1970 [22], the CW lasing was realized in stripe-geometry lasers formed by photolithography and mounted on copper plates covered by silver (Fig. 3). The lowest J_{th} at 300 K was 940 A/cm^2 for broad area lasers and 2.7 kA/cm^2 for stripe lasers. Independently, the CW operation in DHS lasers was reported by Hayashi and Panish [23] (for broad area lasers with diamond heatsinks) in a paper submitted only one month later than our work. The achievement of the "CW" at room temperature produced an explosion of interest in physics and technology of semiconductor heterostructures. If in 1969 AlGaAs heterostructures were studied just at a few laboratories over the world, mostly in the U.S.S.R. and the U.S.A. (Ioffe Institute, "Polyus" and "Quant"—industrial Labs., where we transferred our technology for applications in the U.S.S.R.; Bell Telephone Laboratory, D. Sarnoff RCA Research Center, T. T. Watson IBM Research Center in the U.S.A.), at the beginning of 1971 many universities, industrial laboratories in the U.S.A, the U.S.S.R., U.K., Japan, Brazil, and Poland started investigations of III–V heterostructures and heterostructure Devices.

At this early stage of the development of the 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 done in our laboratory in 1970. On paper [24], 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. As a practical example of utilizing this idea, we considered different InGaAsP compositions and soon this material was recognized among the most important ones, for many different practical applications, especially for lasers in infrared region for fiber optical communications [25] and the visible [26]–[29].

Main ideas of a semiconductor distributed-feedback laser were formulated by us in the patent in 1971 [30]. In the same year, Kogelnilk and Shank considered a possibility of replacing the Fabry–Perot or similar types of the resonator in dye-lasers with volume of periodical inhomogeneities [31]. It is necessary to note that their approach is not applicable to semiconductor lasers, and all laboratories that carried out research in DFB and DBR semiconductor lasers used the ideas formulated in [30]:

1) Diffraction grating is created not in volume, but on a surface waveguide layer.
2) Interaction of waveguide modes with surface diffraction grating is giving not only distributed feedback but also highly collimated light output.

Now, these principles are widely used in telecommunication diode lasers.

The discovery of the first "ideal" AlGaAs heterostructures [8] and the demonstration of the first lasers operating at room temperature [16] experimentally confirmed predicted earlier physical phenomena and became the basis for modern optoelectronics.

Particularly important was continuous wave (CW) operation at room temperature [22]. The latter event represented a principal point for semiconductor lasers: Fiber-optical communication systems were born due to this achievement.

The creation of DHS lasers led not only to new light-emitting device concepts and new physics but, also, to important technological peculiarities:

1) fundamental need for structures with well-matched lattice parameters;
2) the use of multcomponent solid solutions to match the lattice parameters;
3) fundamental need for epitaxial growth technologies.

Because of electron confinement in double heterostructures, DHS lasers have essentially become the direct precursors to quantum-well structures, which have a narrow-gap middle layer with a thickness of a few hundred angstroms, which is an element that has the effect of splitting the electron levels as a result of quantum-size effects. However, high-quality DHS with ultrathin layers could not be attained until new methods were developed for the growth of heterostructures. Two principal modern day epitaxial growth techniques with precision monitoring of thickness, planarity, composition, etc., were developed in the 1970s. Today, molecular-beam epitaxy (MBE) has grown into one of the most important technologies for the growth of heterostructures using III–V compounds, primarily through the pioneering work of Cho [32]. The basic concepts of metal-organic vapor-phase epitaxy (MOVPE) were set forth in the early work of Manasevit [33] and have enjoyed widespread application for the growth of heterostructures from III–V compounds, particularly in the wake of a paper by Dupuis and Dapkus reporting the successful use of this technique to create a room temperature injection DHS laser in the system AlGaAs [34].

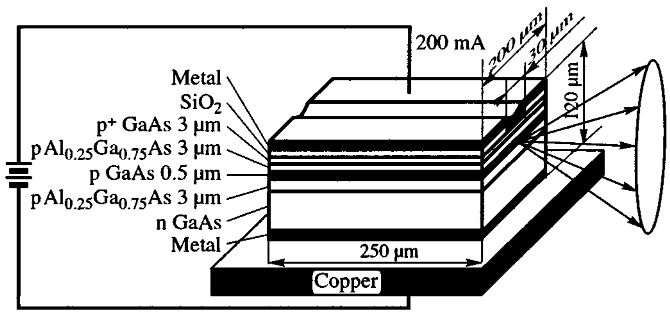

Fig. 3. Schematic view of the structure of the first injection DHS laser operating in the CW regime at room temperature.

The distinct manifestation of quantum-well effects in optical spectra of GaAs–AlGaAs semiconductor heterostructures with an ultrathin GaAs layer (quantum well) was demonstrated by Dingle *et al.* in 1974 [35]. The authors observed a characteristic step structure in the absorption spectra and a systematic shift of the characteristic energies as the thickness of the quantum well was decreased.

Lasing by means of quantum wells was first accomplished by van der Ziel in 1975 [36], but lasing parameters fell short of average DHS lasers. It was 1978 before Dupuis and Dapkus, in collaboration with Holonyak, reported the first construction of a quantum-well (QW) laser with parameters to match those of standard DHS lasers [37]. The term "quantum well" first surfaced in this paper. The real advantage of QW lasers was demonstrated much later by Tsang of Bell Telephone Laboratories. Through a major improvement in MBE growth technology, it was possible to lower the threshold current density to 160 A/cm^2 [38].

The most complex QW laser structure, consolidating a single quantum well and short-period superlattices (SPSs), was grown in our laboratory in 1988 [39]. We obtained threshold current densities $J = 52$ A/cm^2 and, after a certain optimization $J = 40$ A/cm^2, which was the world record for semiconductor injection lasers until the late 1990s and affords a good demonstration of the effective use of quantum wells and superlattices in electron devices.

The concept of stimulated emission in superlattices, set forth by Kazarinov and Suris [40]–[42], was made a reality by Capasso *et al.* [43], [44] almost a quarter-century later. The previously proposed structure was substantially optimized, and the cascade laser developed by Capasso gave birth to a new generation of unipolar lasers operating in the mid-IR range.

From a certain standpoint, the history of semiconductor lasers is the history of the campaign to lower the threshold current, as is graphically illustrated in Fig. 4. The most significant changes in this endeavor did not take place until the concept of DHS lasers had been introduced. The application of SPS quantum wells actually brought us to the theoretical limit of this most important parameter. Subsequent possibilities associated with the use of new structures utilizing quantum wires, and quantum dots will be discussed in the next section of the article.

Applications of the quantum-well and superlattice heterostructures in semiconductor lasers permitted:

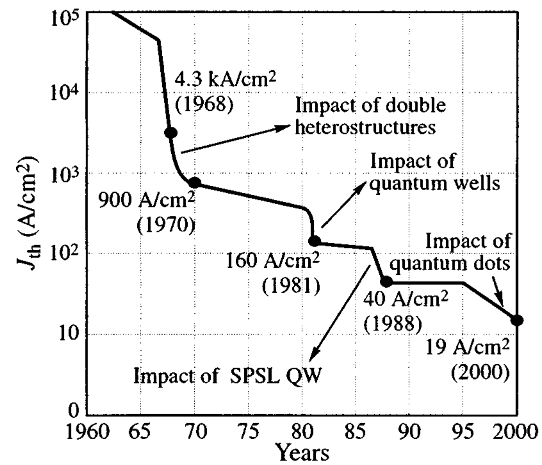

Fig. 4. Evolution of the threshold current of semiconductor lasers.

1) shorter emission wavelengths, lower threshold current, higher differential gain, and weaker temperature dependence of the threshold current in semiconductor lasers;
2) infrared quantum cascade lasers;
3) lasers with quantum wells bounded by short-period superlattices;
4) optimization of electron and optical confinement and of the waveguide characteristics in semiconductor lasers.

There were important technological consequences:

1) no need to carefully match lattice parameters;
2) fundamental need to use slow-growth technologies (MBE and MOVPE);
3) submonolayer growth method;
4) suppression of the propagation of mismatch dislocations during epitaxial growth;
5) radical diversification of materials available for heterostructure components.

III. Quantum-Dot Heterostructure Lasers

The principal advantage application of quantum-size heterostructure for lasers originates from the noticeable increasing of the density of states with reducing of the dimensionalities for electron gas (Fig. 5).

During the 1980s, progress in two-dimensional (2-D)-quantum-well heterostructures physics and its applications attracted many scientists to studying systems of far

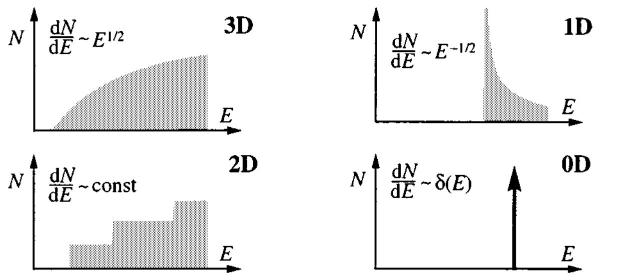

Fig. 5. Density of states for charge carriers in structures with different dimensionalities.

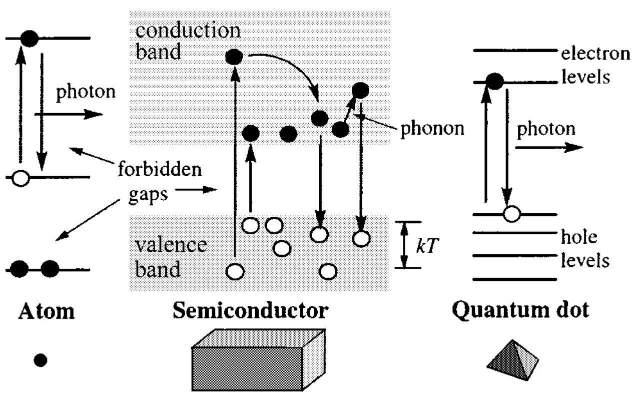

Fig. 6. Schematic representation of energy diagrams in case of (left) a single atom, (center) a bulk crystal, and (right) a quantum dot.

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. In addition, being confined in all three directions, quantum "dots"—"artificial atoms" with a totally discrete energy spectrum—are created (Fig. 6).

Experimental work on fabrication and investigation of quantum wire and dot structures began more than 15 yr ago. In 1982, Arakawa and Sakaki [45] theoretically considered some effects in lasers based on heterostrustures 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 conventional laser reflecting the reduced dimensionality of electronic state." The authors performed experimental studies on a QW laser placed in high-magnetic fields directed perpendicular to the QW plane and demonstrated that the characteristic temperature (T_0) describing the exponential growth of the threshold current with temperature increases in magnetic field from 144 °C to 313 °C. They pointed to a possibility to weaken the threshold current dependence on temperature for QWR lasers and full temperature stability for QD lasers (Fig. 7). By now there is a significant number of both theoretical and experimental papers in this field.

The first semiconductor dots based on II–VI microcrystals in glass matrix were proposed and demonstrated by Ekimov and Onushchenko [46]. However, since the semiconductor quantum dots were introduced in an insulating glass matrix and the quality of the interface between glass and semiconductor dot

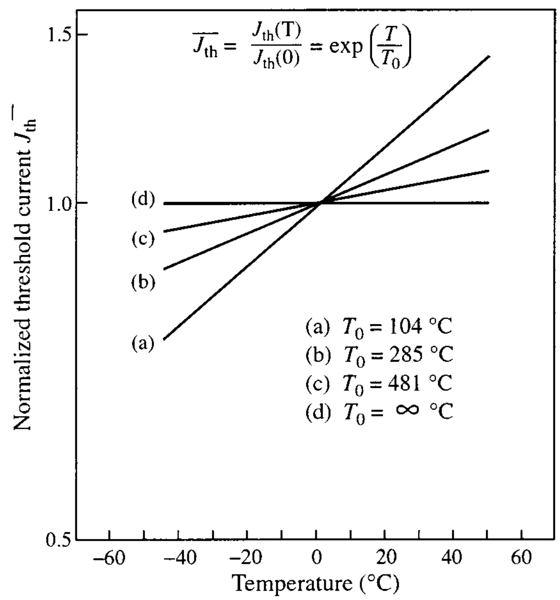

Fig. 7. Normalized temperature dependence of the threshold current for various DHS lasers. (a) Bulk (b) with QWs (c) with QWs, (d) with QDs.

was not high, both fundamental studies and device applications were limited. Much more exciting possibilities appeared since three-dimensional (3-D) coherent quantum dots had been fabricated in semiconductor matrix [47].

Several methods were proposed for the fabrication of these structures. Indirect methods, such as the post-growth lateral patterning of 2-D quantum well often suffer from insufficient lateral resolution and interface damage caused by the patterning procedure. A more promising way is the 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 of the Ioffe Institute and Berlin Technical University—last year, we carried out this research in close cooperation—contributed significantly to the last direction.

Finally, we came to the conclusion that the most exciting method of the formation of ordered arrays of quantum wires and dots is the self-organization phenomena on crystal surfaces. Strain relaxation on step or facet edges may result in formation of ordered arrays of quantum wires and dots both for lattice-matched and lattice-mismatched growth.

The first very uniform arrays of 3-D quantum dots exhibiting also lateral ordering were realized in the system InAs–GaAs both by MBE and MOCVD growth methods [48], [49].

Elastic strain relaxation on facet edges and island interaction via the strained substrate are driving forces for self-organization of ordered arrays of uniform, coherently strained islands on crystal surfaces [50].

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 energy of interface γ_{12} is lower than the substrate surface energy $\gamma_2 + \gamma_{12} < \gamma_1$, i.e., if the material 2 being deposited wets the substrate, then we have the 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

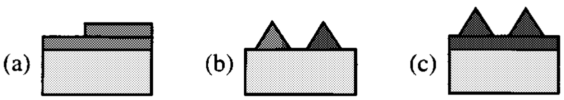

Fig. 8. (a) Frank–van der Merve. (b) Volmer–Weber. (c) Stranski–Krastanow growth modes.

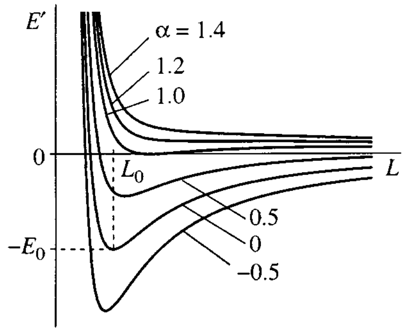

Fig. 9. Energy of a sparse array of 3-D coherently strained islands per unit surface area as a function of island size. The parameter α is the ratio between the change in the surface energy upon island formation and the contribution from island edges to the elastic relaxation energy. When $\alpha > 1$, 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.

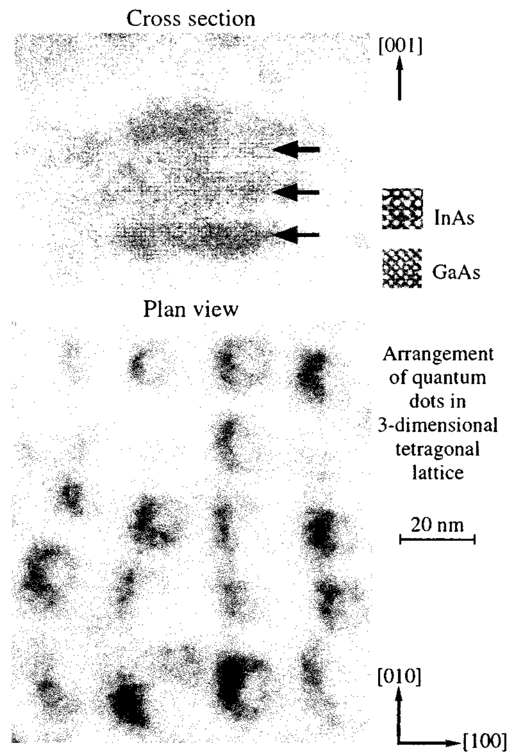

Fig. 10. Vertical and transverse ordering of coupled QDs in the system InAs–GaAs.

Volmer–Weber one where 3-D islands are formed on a bare substate.

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 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. 8). The characteristic size of islands is determined by the minimum in the energy of an array of 3-D coherently strained islands per unit surface area as a function of the island size (Fig. 9) [50]. Interaction between islands via elastically strained substrate would results in lateral-island ordering typical of the square lattice.

Experiments show in most cases 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. 10) Shape of quantum dots can be significantly modified during regrowth or post-growth annealing or by applying complex growth sequences. Short period alternating deposition of strained materials leads to a splitting of QDs and to formation of vertically coupled quantum dot superlattice structures (Fig. 10) [51]. Ground-state QD emission, absorption, and lasing energies are found to coincide [48]. Observation of ultranarrow (<0.15 meV) luminescence lines from single quantum dots [48], which do not exhibit broadening with temperature, is the proof of the formation of an electronic quantum dot.

Quantum dot lasers are expected to have superior properties with respect to conventional QW lasers. High differential gain, ultralow threshold current density, and high-temperature stability of 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. Overheating of facets being one of the most important problems for high-power and high-efficiency operation of AlGaA–GaAs and AlGaAs–InGaAs lasers, may thus be avoidable.

Since the first realization of QD lasers [52], 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 QDHS laser operation at room and elevated temperatures was connected to temperature-induced evaporation of carriers from QDs. Different methods were developed to improve the laser performance:

1) the increase of the density of QDs by stacking of QDs (Fig. 11)
2) the insertion of QDs into a QW sheet;
3) the use of a matrix material with a higher bandgap energy.

As a result, we got many parameters of QDHS lasers that were better than ones for QWHS lasers based on the same materials. As an example, the world-record threshold-current density of 19 A/cm^2 has been recently achieved [53]. Further, the cw-output power up to 3.5–4.0 W (CW) for a 100-μm strip width, the quantum efficiency of 95%, and the wall-plug efficiency of 50% were obtained [54].

Significant activities in theoretical understanding of QD lasers with realistic parameters have been performed. For a QD size dispersion of about 10% and other practical structure parameters, the theory [55] predicts typical threshold-current densities of 5 A/cm^2 at room temperature. The value of

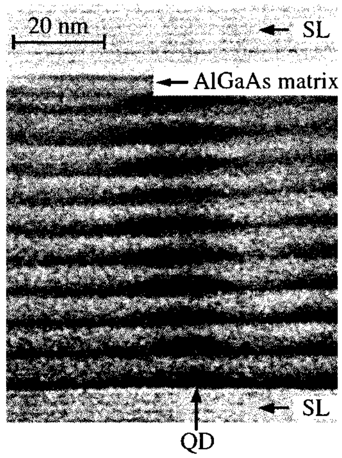

Fig. 11. Transmission electron microscopy image of the active region of high-power QDHS laser.

10 A/cm^2 at 77 K [56] and even 5 A/cm^2 at 4 K [57] have been experimentally observed.

In view of advanced device applications of QDs, the incorporation of QDs in vertical-cavity surface-emitting lasers (VCSELs) seems to be very important. QD VCSELs with parameters, which fit to the best values for QW devices of the similar geometry, have been demonstrated [58]. Recently, very promising results for 1.3-μm QD VCSELs on a GaAs substrate to use in fiber optical communications have been obtained [59].

In a free-standing 3-D 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 range of 1.3–1.5 μm using a GaAs substrate and to develop wavelength-multiplexing systems on the base of QD VCSELs in the future.

IV. Future Trends

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

However, from a general and more deep point of view, heterostructures (concerning all of them: the classical, QWs and SLs, QWRs, and QDs) are the way of creation of new types of materials—heterosemiconductors. By using Esaki's words—instead of "God made crystals," we create by ourselves—"Man made crystals."

The classical heterostructures, quantum wells, and superlattices are quite mature and we exploit many of their unique properties. Quantum wires and dots structures are still very young: Exciting discoveries and new unexpected applications are awaiting us. Even now, 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 "indepth.

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

As for as in depth, it is necessary to mention that degree of ordering depends on very complicated growth conditions, materials constants, and concrete values of the surface free energy. The way to resonant tunneling and "single" electron devices including optical one, is a deep-detailed investigation and evaluation of these parameters in order to achieve the maximal possible degree of ordering. In general, it is necessary to find out more strong self-organization mechanisms for ordered arrays of QDs creation.

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

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