THE WAY TO QUANTUM DOT LASERS

N.N. Ledentsov

A.F. Ioffe Physical-Technical Institute
Institut für Festkörperphysik, Technische Universität, Berlin

Николай Николаевич Леденцов – главный научный сотрудник ФТИ им. А.Ф. Иоффе РАН, профессор, член-корреспондент РАН, лауреат Государственной премии РФ. Основные научные интересы – получение и исследование свойств эпитаксиальных наногетероструктур и приборов на их основе.

The fact that tiny coherent insertions of the semiconductor material having a small band-gap in a wide band-gap matrix, or quantum dots (QDs), may completely reshape modern micro- and optoelectronics became evident many years ago. Several competing approaches were tested on the way of practical realization of QDs, including those based on different processing techniques, on direct growth methods and on combination of both. Initially, the research was concentrated on processing techniques. The breakthrough occurred, however, when direct growth effects, people were initially fighting with (surface faceting, formation of islands, phase separation of alloys, etc.), were intentionally used for fabrication of nanostructures. Here I report on the history of quantum dot laser, and our experience and efforts in growth and studies of QD heterostructures at the Zhores Alferov's laboratory of Ioffe institute in close collaboration with the group of Prof. D.Bimberg at the Technical University of Berlin.

1. INTRODUCTION

Semiconductor is the key element of modern electronics. Probably, the most important property of semiconductor is the ability to realize high current flows of charge carriers through the crystal. This property is directly related to a high density of states in the conduction and the valence band, and, consequently, to a high density of atoms in the crystal. High absorption or gain coefficients in the solid state, taken together with the possibility of high current flows through the medium, made it possible realisation of compact and efficient photodetectors, light-emitting diodes (LEDs) and lasers. The key advantage of the high density of atoms in the crystal has its own price, however. As opposite to the case of a diluted gas of atoms, the atoms in a crystal are strongly bound to each other. The interactions between closely spaced atoms in bulk crystal makes broadening of the electronic spectrum unavoidable. At high temperatures, lattice vibrations (phonons) can easily stimulate transitions of charge carriers in the energy range defined by the lattice temperature and/or scatter their direction. Higher scattering rates at higher temperatures mean also lower mobility of charged carriers and result in other disadvantages in device characteristics.

To improve the performance of the device, one needs to modify the density of states in such a way, that the density of states has a maximum near the top of the valence band and the bottom of conduction way is made as high as possible. Then, the impact of the high-energy continuum states will be reduced and the device performance will be improved. If the carrier motion in a solid state is limited in a layer of a thickness of the order of the carrier de Broglie wavelength (or mean free pass, if it is smaller), in agreement with quantum mechanics one should observe effects of size quantization and the density of states may be indeed dramatically modified (see Fig. 1). The ultimate case of size quantization in solids is realized in a quantum dot (QD), which keeps the basic properties of the atom, while it provides a geometrical size allowing practical application of atomic physics to the field of semiconductor devices.

2. QUANTUM WELL HETEROSTRUCTURES

Studies of size quantization effects became popular already by the end of 50-ies – beginning of 60-ies (see e.g. for a review [1]. Ultrathin layers of metals and semimetals were mostly investigated. The real success came when the idea of size quantization was applied to double heterostructures, which was proposed by Alferov and Kazarinov [2] and Kroemer [3] and, later, demonstrated as an active medium of diode laser by Alferov et al [4, 5]. Immediately after it became possible to create ideal semiconductor double hetrojunctions, an idea of using the ultrathin layer periodic structures, or artificial superlattices, has been proposed for electron transport devices in 1969 – 1970 [6].

I must stress here one detail, extremely important for understanding the vision of Prof. Zh.Alferov. The importance of the idea of L.Esaki and R.Tsu was not recognized at once. As Prof. L.Esaki told us, Physical Review rejected their paper. At the same time, Zhores Alferov and his colleagues in 1971 grew in a multichamber VPE reactor of special design a multilayer $GaP_{0.3}As_{0.7}$/GaAs superlattice and observed the effects related to the appearance of the subbands for electrons [7]. Of course, lattice matched

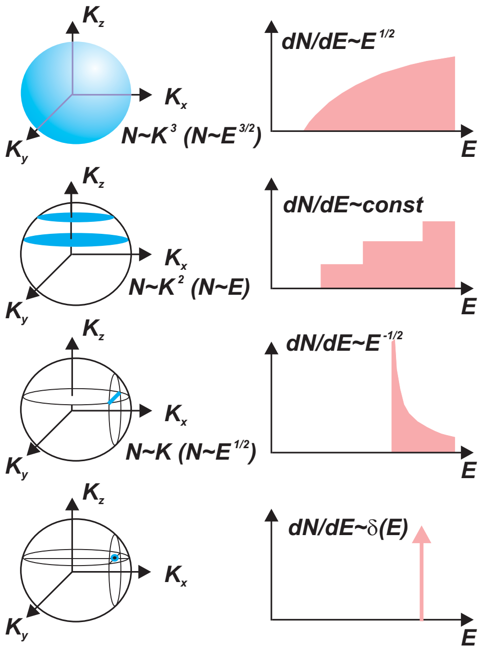

Fig. 1. Density of states for carriers in structures with different dimensionalities

materials and advanced growth tecniques like Molecular Beam Epitaxy (MBE) or Metal-Organic Chemical Vapor Deposition (MOCVD) were necessary to realize the idea in a full way. In 1974, Chang et al. observed the effect of resonant tunnelling proving the application of quantum mechanics to describe transport phenomena in ultrathin semiconductor GaAs/AlGaAs heterostructures. R.Kazarinov and R.Suris at Ioffe Institute have predicted another principally important effect in 1970. They considered the possibility to create an unipolar long-wavelength laser using radiative transitions between electron size quantization subbands. The laser of this kind has been created (so-called "cascade" laser) one quarter of a century later. Importance of using the quantum size effects in lasers has been recognized in 1974 – 1975.

In 1974, Dingle et al. directly observed the effects of size quantization in optical spectra of quantum wells [8]. The step-like character of the absorption spectrum related to the specifics of the density of states in quantum wells has been demonstrated (see Fig.1). A decrease in the GaAs layer thickness resulted in shifting the steps towards higher photon energies. Optical studies underlined also a tremendously increased role of excitonic effects. In 1975, Dingle and Henry proposed the idea to "exploit quantum effects in heterostructure semiconductor lasers to produce wavelength tunability" and achieve "lower lasing thresholds" via "the change in the density of states which results from reducing the number of transnational degrees of freedom of the carriers" [9]. Dingle and Henry [9] did not restrict their patent exclusively to quantum wells, and pointed, that the singularity in the density of states occurs when the dimensionallity of the system is lower than two (see Fig.1 and Fig.5 in [9]). They also understood the importance of the Coulomb interaction effects and wrote that "the combination of confinement and Coulomb attraction between the electron and hole increases the strength of the optical absorption and emission processes and hence the laser gain". The authors additionally wrote that "the interaction of carriers with the lattice, with impurities and with other carriers tend to alter the energetics of the band edge transitions" and can "alter the density of states significantly by producing a distribution of band gap energies", but concluded that "Neither of these two effects should substantially diminish the change in the density of states which results from reducing number of translational degrees of freedom of the carriers". Further concentration of the efforts regarding QW's was merely related to the fact, that the technology available at that time permitted only research on the structures with ultrathin layers. In 1975, photo-pumped operation at low temperature was realized [10], and, soon after that, room-temperature operation was reported [11]. The threshold excitation densities were very high (corresponding to current densities of 75 – 300 kA/cm^2), and most of the researchers remained rather skeptical towards using the QWs in lasers. Nevertheless, injection lasing in QWHS laser with threshold current density of only few kA/cm^2 at room temperature was demonstrated soon and improved temperature stability of the threshold current as compared to conventional DHS laser was found. At the same time, for quite a significant time, the device parameters of QW lasers remained much inferior with respect to conventional DHS lasers. Practical application of QWHS lasers started much later.

Looking from now one can imagine that the development of the QW laser was easy, that the researchers and the industry recognized immediately its tremendous advantages. This is not completely so. I remember a seminar held at the Ioffe Institute in 1980. I was a student at the Professor Alferov's Educational Department those days, and also had a practical work in his laboratory. The seminar was devoted to size quantization effects and their potential use in double heterostructure lasers. The results of the famous team of Prof. Holonyak were reported. I remember that there was a lot of scepsis concerning the applicability of quantum wells in lasers. The comments were: "these devices will not be able to operate at high powers", "there will be a problem of carrier capture in these ultrathin layers", "everybody knows that one should avoid additional interfaces and here you have essentially, an interface", and so on. I was very much in favor of QW lasers, as I was writing a student report on the recent advances in quantum size effect and its device applications. My enthusiasm was, probably, forgivable for a third-year student. I clearly remember that everybody was shocked when Prof. Alferov stood up and concluded, "in several years from now all our laboratory will concentrate on quantum size heterostructures and their application in lasers".

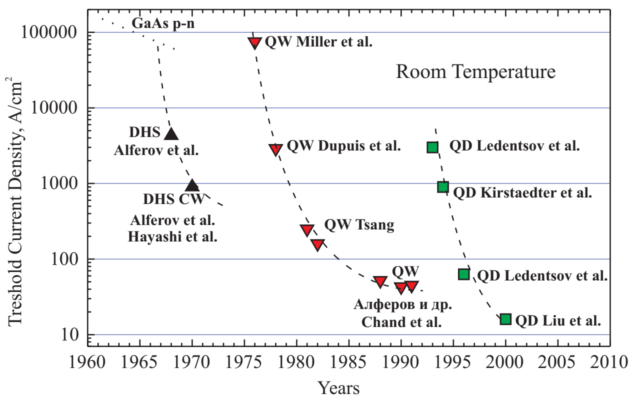

Fig. 2. Development of heterostructure lasers

I would like to stress, that this happened before the strong reduction of the threshold current density in multiple-QW 18 and single-QW separate-confinement heterostructure lasers was demonstrated [12] (see Fig. 2).

3. APPEARANCE OF MBE TECHNOLOGY AT THE IOFFE INSTITUTE

Another clear example of the vision of Prof. Alferov was the development of molecular beam epitaxy (MBE) at the Ioffe institute, and in the Soviet Union, in general. It took a lot of his organizational and administrative skills to get our first Riber1000 MBE machine to gain experience, and, on the basis of this experience, to initiate the production of MBE equipment in the country. The background of these activities was his vision and clear understanding of the future of micro- and optoelectronics. I was happy to be the first student of the new MBE group, who joined in 1979 the initial team led by Dr. P.Kop'ev, currently a professor and a Head of the Nanoheterostructures Center of the Ioffe Institute.

Prof. Alferov personally brought me to a small room where several prominent, even not very friendly-looking at me people were sitting. This his decision was my destiny, I can't explain it in the other way. Everything was perfect in those days, even we had no MBE machine, initially. Finally, it was delivered and installed by Riber, and my first practical work in the MBE area was devoted to MBE substrate preparation, and technical support of the MBE process. Later, after the first GaAs samples, which were able to emit light, appeared, it became necessary to make also photo- and, later, electroluminescence characterization, and I was moved to this direction. Dr. Kop'ev was walking with me along the corridors of the laboratory building of Abraham Ioffe institute trying to get back his own spectrometers, oscilloscopes, power supplies, once temporary given to friends, and now "busy in some high-priority areas, which can't be disturbed in favor of some trash technology".

One must admit, that the first samples were really bad. The other members of the laboratory were participating in industrial projects, gaining publications, extra remunerations, attending conferences, even in "foreign countries" (after approval of numerous Communist Party Committees of different levels). We had to try again and again to understand the reasons of our problems and just trying to reach the quality level of the very initial Liquid Phase Epitaxy (LPE) period. Our salary level was rather low (I started with 100 roubles per month, e.g. order of magnitude smaller value as compared to my monthly reward as a construction worker in the Northern part of Russia during my summer vacation time). However, the level of research around us in the laboratories of the Ioffe Institute was extremely high: very important experimental studies of optical properties of semiconductors were held in the Department led by Prof. B.P. Zakharchenya, many advanced devices were under development in our Zhores Alferov's Department, such as, e.g. heterostructure solar sells (Mir space station used the solar sells developed at the Ioffe institute for about 15 years and the capacity decreased by only 15% during this period), high power heterostructure transistors, and, of course, excellent heterostructure lasers, of different kinds and colors. A pleiad of world recognized theorists worked at the Ioffe Institute: V.I. Perel', M.I. Dyakonov, M.G. Skobov, E.L. Ivchenko, G.E. Pikus, A.E. Efros, O.V. Konstantinov and many others. All these people were easily reachable for students and the scientific atmosphere was very democratic and open.

As I said, the first stages of development of our MBE technology were very tough. On the other side it motivated deeper understanding of MBE growth process, and resulted in a series of works devoted to thermodynamics of MBE growth, doping and segregation processes. This period also gave us a key to future understanding of basic phenomena in self-organized growth, which we consider as predominantly thermodynamically-driven process. For the improvement of our MBE growth, the younger generation of researchers contributed a lot. It occurred in a very funny way. We (Victor Ustinov, Sergei Ivanov and myself) understood that the key point for the success in MBE is the maintenance of the ultrahigh vacuum conditions in the MBE chamber, possible only under continuous filling of the cryoshrouds with liquid nitrogen and continuous growth. Together with Sergei Ivanov and Victor Ustinov, we, during a vacation time of one of the fathers of Soviet-Russian MBE Boris Melt'ser (who is a very distinguished person with extraordinary contributions to the technology) and taking the advantage of some temporary carelessness of the Head of the group Dr. Kop'ev started day-and-night weekly MBE growth (it was not officially permitted). We worked up to 30 hours without interruptions and were replacing each other for sleep only. It was necessary to carry heavy tanks with liquid nitrogen to the forth floor (the cargo elevators were not available after 5 p.m. and the angry security ladies were not permitting us to use conventional elevators, which was certainly strictly prohibited). It was also necessary to arrange all the characterization measurements, and it is not easy when you have mostly three persons for all the tasks. Later, this style of work got the official approval from our senior colleagues, and we continued together.

Finally, the growth quality was improved, and we've got our first QW injection lasers. Later, we started to use the concept of GaAs QWs confined by short-period superlattices as an active medium of the device and soon reached very low threshold current densities of 40-50 A/cm^2 at room temperature [13, 14] in 1988 – 1989. It is funny to remember, but it was again very difficult to convince people to use this short-period superlattice approach, even the improvement in optical properties and in the temperature stability of the luminescence were very convincing. The main argument against was that "the shutters will be broken". Similar thresholds (~50 A/cm^2) were later reported for AlGaAs lasers with strained InGaAs quantum wells by Chand et al. in 1990. The very important point is that this MBE technology, initiated by Prof. Alferov, gave an access to modern quantum size effect structures to a wide community of the Ioffe Institute researchers, and the obtained experimental results stimulated significant interest shown by leading Ioffe Institute theorists. I would like to stress again, that the vision of Prof. Alferov was a necessary precondition for all the following developments of Quantum Size Heterostructure Physics at the Ioffe Institute.

4. CHANGING DIRECTIONS

In the middle of the 80-ies "of the last century", a sweet but short era of early "Perestroika" started. The world became bright and promising. On the other hand, thanks to the President Reagan's "Star Wars" program, a lot of new equipment became available, and we still use the advantages of this short but decisive moment. Here, Professor Alferov again demonstrated his outstanding vision and organizational skills. We have got several modern MBE machines and, also, MOCVD equipment. Russian-made MBE machines of generally comparable quality also became available at this time, and also due to activity of Prof. Alferov, who initiated and got the governmental support for the development of MBE equipment in our country. During this short but great period visits of foreign scientists became more often at this time. A large delegation of American scientists came to us, including the future Nobel Prize Laureate Horst Störmer, heterostructure heroes Morton Panish, Jeffry Woodall and many others. A Nobel Prize Laureate Prof. Leo Esaki and his beautiful wife Masako also visited us. I accompanied them to Moscow and we had several discussions, which turned out to be very important to me later. I remember we were talking in a plane about the possibility of the appearance of a hump in the conduction band at the n-AlGaAs-n GaAs single heterojunction. After some discussion, Prof. Esaki concluded that this hump may, probably, evolve or may not evolve, but this is not very important. What is important is to "foresee the change". His main idea was that everybody moves in some generally accepted direction (he draw a line), but nothing is forever in this world, and there must be a turn (he draw a line orthogonal to the first one). The key point is to foresee the turn and to start moving in the direction, different from the commonly accepted. Then you can really get the great result (and he drew a third line from the starting point of the first line to the end of the second). It might be possible to argue or to disagree (e.g. "who knows what is the direction of the turn"), but the triangle itself was very convincing, and I agreed immediately, as also a hero of one of the most popular Russian books in a similar situation. I still remember these words of Prof. Esaki concerning the necessity to "foresee the change". The key point is to foresee the turn and to start moving in the direction, different from the commonly accepted.

My thoughts were directed towards quantum wires and quantum dots. This mostly came from my identity as an optics and laser person, certainly having a general interest in intriguing optical properties of these nanostructures and their applications. On the other hand, my MBE background was telling me that there must be direct growth techniques to produce these structures.

5. QUANTUM WIRES AND DOTS: FIRST ATTEMPTES

One should note that, already in the beginning of the 80's the progress in QWHS lasers on one side, and experimental advances in crystal growth on misoriented [15] or patterned [16] substrates revived interest to heterostructures with size-quantization in more than one direction. Influence of high magnetic fields on the characteristics of DHS lasers was considered experimentally and theoretically [17] and the results were interpreted as originating from the magnetic-field-induced modification of the density of states. In 1982, Arakawa and Sakaki 18 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 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 to 313°C. There were pessimistic predictions as well. In 1988, Vahala introduced the inhomogeneity of QDs into the consideration. Also the influence of doping on transparency current was treated. He concluded "For high gain operation a medium composed of quantum boxes does not offer significant advantages over a conventional bulk semiconductor unless quantum box fabrication tolerances are tightly controlled". Benisty et al. proposed that the low luminescence efficiency of QDs produced by ion-etching of QW samples, results from the lack of matching energies for phonon relaxation of carriers in QDs ("phonon bottleneck effect in a QD").

Our first attempts to fabricate quantum wires and dots were related to the following idea. If one deposits a submonolayer of AlAs on a GaAs surface, an array of AlAs islands should be formed. In the case of a vicinal stepped surface, the islands can be attached to steps. If now one grows a GaAs layer on top of an AlGaAs stepped surface, deposits a submonolayer AlAs coverage and increases the temperature up to the value when the evaporation rate of GaAs becomes significant, one may selectively etche the GaAs regions, which are not covered by AlAs, which has much higher temperature stability. If the structure with the remaining GaAs domains is covered by AlGaAs, quantum wire-like GaAs domains may be formed. We grew such a structure on a vicinal GaAs (100) substrate in 1990 and it, indeed, demonstrated significant in-plane polarization anisotropy, expected for the quantum wire case. This was measured by Dr. Uraltsev, who, unfortunately left us in his most productive age. Until recently, this way of creation of quantum wire or quantum dot structures was not explored by us further, until very recently, and with a very different motivation.

In 1989, Prof. Alferov was awarded with the Alexander Karpinsky Prize from the Stiftung F.V.S. and its founder Alfred Toepfer. The advantage of this Prize for me was that it is shared in two parts. One part goes to the main Award Recipient, and the second part goes to the second Recepient, nominated by the main Laureate. The "junior" award was a stipend to perform research work in Germany. I am very proud that Prof. Alferov selected me among many talented young people working those days (as also now) in his laboratory. I chose the Max-Planck-Institut fur Festkorperphysik (MPIF) in Stuttgart, with fascinating world leading scientists, such as Nobel Prize Laureate, frequent guest of the Ioffe Institute, Prof. Klaus von Klitzing, Professor Manuel Cardona, Professor Hans Joachim Queisser, and many others. The famous MBE laboratory of MPIF led those days by Dr. Klaus Ploog (now Professor, director of Paul Drude Institute in Berlin) was considered as one of the world leading in MBE technology. I should mention, that the amount of the award was not enough to spend the whole year at MPIF, and I am very greatful to the Max-Planck-Society and personally to Prof. Klaus von Klitzing and Prof. Klaus Ploog, for their arranging a possibility to find an additional support, and provide me with all the necessary conditions for successful work. It was really a very productive and exciting time. It is also important to say that, starting from this period in my life Germany appears as a second country extremely important to my life. Initially, I came to Dr. K.Ploog with an idea of continuing growth on vicinal substrates using AlAs masking and selective thermal etching technique. Probably the idea smelled a bit like Santa-Barbara's business (UCSB), and he was not very supportive of it, arguing that the steps on vicinal surfaces are kinked, and it will be not possible to produce good enough structures. Then I concentrated on optical spectroscopy of localized states, which I started at the Ioffe institute. This experience was very important for further understanding the optical properties of real self-organized quantum dots; for example, the phonon-related exciton relaxation mechanism was first revealed for localized states in short-period superlattices.

We came in a close touch with Richard Nötzel, those days a PhD student at the MBE lab. His task was MBE growth of GaAs and GaAs-AlAs superlattices on high-index (311)A surface. After first studies of optical properties, it became clear, that we have something really extraordinary. Strong optical anisotropy, giant anisotropy in the degree of optical orientation of excitons, giant (-X mixing in type-II superlattices pointed to the growth mechanism, which is very different from that for (100)-oriented surfaces. Reflection-high-energy electron diffraction (RHEED) studies for (311)A and (211)B substrates demonstrated that the surfaces are periodically nanofaceted [19, 20] even it was possible to grow mirror like multilayer structures and get fairly narrow photoluminescence (PL) peaks. The answer was that the surfaces are nanoscopically faceted and this faceting is well-ordered, the effect predicted a decade before the discovery by A.F. Andreev and V.I. Marchenko. Observation of nanoscopically-ordered faceted surfaces was the first clear manifestation of the self-organized growth mechanism in semiconductors. When I came in December 1990 to Ioffe Institute for Christmas vacations and, certainly, visited Prof. Alferov, I was happy to discuss with him these results. He immediately understood and recognized the importance of this discovery, which also shed light later on the reasons of size and shape ordering of self-organized quantum dots in Stranski-Krastanow and Volmer-Weber growth. For the most extensively studied (311)A growth it was concluded that flat (311)A GaAs or (311)A AlAs surfaces splits to hill and valley structure with lateral periodicity of 3.2 nm and a corrugation height of 1.02 nm (6 monolayers in the (311) direction). Moreover, it was assumed that during the epitaxial growth of AlAs on GaAs and vice versa, the surface corrugation undergoes a phase change with one material filling initially the grooves in the other. The phase-changed surface faceting is established after six monolayers of GaAs or AlAs are deposited on top of the AlAs or GaAs surface, respectively [2,3]. The experimental results were driven mostly from the data derived in reflection high-energy electron diffraction (RHEED) experiments and optical studies. The use of self-organized growth of ordered nanostructures on corrugated surfaces is of particular importance for applications in opto- and microelectronics, such as lateral superlattices for infrared intersubband photodetectors with normal incidence, FIR emitters, high-frequency two and three-terminal devices based on lateral Esaki-Tsu superlattices, lasers, including cascade lasers, and so on. Unfortunately, this discovery was doubted by some researchers, who studied "some" structures on (311)A surfaces. The growth conditions should be certainly properly controlled to ensure no facet bunching due to poor vacuum or contaminations on the surface. It is even sadder, that all the partners of the discovery except of myself rejected the initial idea. More recently, the proposed growth mode was confirmed using high-resolution transmission electron microscopy (HRTEM) and HRTEM image processing [21]. The GaAs-rich and AlAs-rich regions are laterally periodic with 3.2 nm and the corrugation height for each interface is – 1.02 nm. The GaAs and AlAs regions are vertically correlated and phase shifted with respect to each other, as it was originally proposed in Refs. 19, 20. The angles of the corrugation are revealed in many parts of the image and fit (~40° and ~140° with respect to the flat (311) surface) to the originally proposed [19, 20] interface structure. Intensity spots due to the lateral periodicity of 3.2 nm and a checkerboard arrangement of the spots, evidencing the reversal of the phase of the surface corrugation during the GaAs and AlAs growth, were confirmed by Fourier transforms of the experimental HRTEM images [21]. One should note, that the HRTEM studies of the (311)A GaAs-AlAs superlattices are complicated by the fact that, the favorable chemically sensitive (002) reflection is not available in the [$\bar{2}$33] zone axis. Moreover, the contrast may be based only on the different extinction lengths of the 000-reflection in GaAs and AlAs, resulting in the different amplitudes of the corresponding reflection (A_{000}). Additionally, there exists the difficulty of the proper sample preparation along the [$\bar{2}$33] zone axis, the relatively small lattice fringe distances of the (311) and (220) planes, fast AlAs oxidation, the change of the image pattern induced by small sample thickness, changes and the interface nonuniformity along the thickness of the HRTEM sample which may mask the interface structure.

Fortunately, an excellent team of electron microscopy exist at the University of Karlsruhe led by Prof. Dagmar Gerthsen. They do fantastic work, and in many directions they are ahead of the average level by a decade. We closely cooperate with this team in several directions. It was clearly shown that the GaAs-rich and AlAs-rich regions are laterally periodic with 3.2 nm and are vertically correlated and phase shifted as it was originally proposed. The probability of facet irregularities is relatively low in this case. We note again that the in-plane GaAs-rich layer contrast modulation corresponds to the roughly estimated compositional modulation of up to 40 – 50%. The angles of the corrugation (black arrows) are revealed in many parts of the image and fit (~40° and ~140° with respect to the flat (311) surface) to the originally proposed interface structure.

To ensure validity of the interface model, the Fourier transform images of the processed HRTEM pictures has been obtained. They were shown to be in full agreement with the initial concept of corrugated SL (appearance of satellite streaks, checkerboard arrangement of the streaks in ideal agreement with the ideal model interface structure, etc.) The experimental image also contains disorder-induced tilted streaks, corresponding to the facet angle of the CSL (40^o) in agreement with pioneering publications in 1991.

I am completely sure that the interest in corrugated superlattices will be revived in the near future and will bring a lot of exciting results and device applications.

In summer 1991, I was invited by Prof. Bimberg from Technical University of Berlin to make a seminar on my results of optical studies of corrugated superlattices on high-index GaAs surfaces. It was again a destiny. We met with Prof. Bimberg for the first time, and the possibility of future cooperation was established.

6. MOVING TO QUANTUM DOTS

After my Alexander Karpinsky Research Fellowship was over in 1991, I returned to the Ioffe Institute and continued work on corrugated superlattices. We decided to use the structures with GaAs islands locally-inserted in the AlAs barrier, separating the two neighboring GaAs layers [52, 53]. Local coupling results in creation of QD-like localized states. We realized intense GaAs-"cluster" (quantum dot)- related luminescence [22, 23].

Funding dropped by more than order of magnitude. For the Ioffe Institute, this period was particularly difficult, as the industry was also ruined, and the Institute had traditionally good links with electronic industry (e.g. first Soviet transistors were developed at the Ioffe Institute in a team of Prof. Alferov). We were getting significant additional funding from industry before the collapse. It was the most difficult time for Prof. Alferov, the whole goal of his life was questioned. The industries he invested so many efforts in (electronics, analytical instrumentation, semiconductor laser technologies) were dying. The Institute was also at the edge of collapse, many scientific schools around us disappeared forever. At the same time we never interrupted our work at Ioffe. This is, again, a desert of Prof. Alferov, and the reason of his heart problems in the middle of 90-ies. Fortunately, he has got a very timely help in Germany (hospital in Buch, near Berlin), as was kindly arranged by Prof. Bimberg. Help of the international scientific community, international governmental and private funds became particularly important at this moment, and we will never forget friends, who was remembering us during this hard times. A very important help came from George Soros, who established an International Science Foundation (ISF) and supported Science in the former Soviet Union. More than 700 scientists of the Ioffe Institute received grants of urgent aid of $500 (a very considerable amount of money for that period). Me and many other scientists from the Ioffe Institute additionally got $1000 per person for their research teams, and the Institute, additionaly, got 10000$ for every group reward. Later, we also won several research projects from ISF.

Prof. Alferov went to USA trying to get some urgent support for the institute, which was a key institution in the developing of the Soviet atomic bomb (Prof. Kurchatov, head of the Soviet Atomic Bomb project worked with Abraham Ioffe). Surprisingly, the institution, which provided a significant help, was Pentagon.

Later, INTAS (International Association, created for the promotion of Science in the former Soviet Union states) and NATO provided significant support. The support was not enough to upgrade the equipment, but it helped tremendously to keep our research on track and just to feed scientists and their families.

Particularly strong role belongs here to Germany, with which Russia had traditionally the strongest scientific links, starting from Lomonosov and Euler times. Abraham Ioffe was a student of Roentgen and established our Physical-Technical Institute as some analogue of the Physikalishces-Technisches Staatsanstalt, established by Werner von Siemens in Berlin. Alexander von Humboldt Foundation, Volkswagen Foundation, Max Planck Society, DAAD, DFG, BMBF did a lot to support our science at that time, as they do also now.

7. InAs/GaAs SYSTEM

In 1993, we have got a NATO linkage grant for cooperation with Dr. Clivia Sotomayor Torres from Glasgow University (currently a professor at the University of Wuppertal, Germany) for studying QDs and QWs. We were pushing research on monolayer and submonolayer (SML) InAs isertions in a GaAs matrix grown at the Ioffe Institute. We concluded the InAs SML insertions represent one-monolayer-high anysotropic islands, essentialy two-dimensional chains of InAs molecules placed on top of GaAs surface [24]. The SML research became later particularly important in the case of wide gap matrices, where Bohr radii are smaller, and the confinement potentials may be very deep. HREM studies, single PL lines from single QDs up to high temperatures, magnetooptical data, all confirmed the QD-nature of SML insertions (for a review see [25, 26]).

8. STRANSKI-KRASTANOW QUANTUM DOTS

We were also working on InGaAs/GaAs structures with highly strained InGaAs layers [27]. As also many others we observed a transition from 2D-like layers to 3D islands. We grew the structures at relatively low substrate temperatures which made possible to avoid extensive defect formation and realize high density arrays of QDs. We reported first lasing in self-organized QDs in a paper submitted in 1993 [28]. Prof. Alferov was very supportive of this our activity. Again, as opposite to many of his highly reputed friends, who were considering quantum dots by self-organized growth approach as a not very promising technology and just wasting of time.

In 1994, we have got a joint Volkwagen project with the Technical University of Berlin. The Institute for Solid State Physics led by Prof. Bimberg was certainly a world-leading place in characterization of nanostructures. This team pioneered low-temperature cathodoluminescence studies with high spectral, lateral and time-resolution, and applied this technique to characterization of interfaces in quantum wells and to quantum wires, formed in

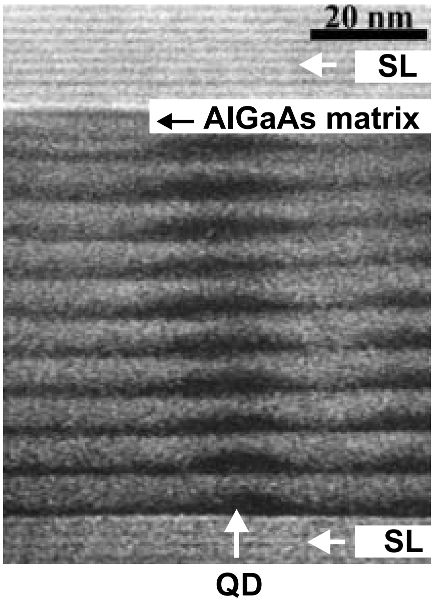

Fig. 3. Transmission electron microscopy image of the active region of high-power laser using InAs quantum dots in an AlGaAs matrix

V-grooves. Later, Dr. Jurgen Christen (currently a professor at the University of Magdeburg in Germany) gave the first evidence of sharp emission lines in the CL spectra of Ioffe QD structures. The team also developed ultrahigh sensitivity calorimetric absorption technique, which was very useful, particularly at the initial stage of our QD research. Heterostructure laser growth using advanced MOCVD and advanced characterization techniques of the devices were also available. Exciting work in modeling of electronic spectrum of strained quantum wires was performed by Dr. Marius Grundmann (currently a professor at the University of Leipzig) and Oliver Stier. Both later contributed very significantly to understanding of electronic spectrum and relaxation pathways in QDs.

This was an excellent fit to our good technological facilities and experience at Ioffe, but our somewhat limited facilities in characterization and numerical simulation. It is also very important to stress, that the progress in nanotechnology is not possible without cooperation in many fields, particularly without advanced structural characterization techniques, such as image-processed HRTEM and HRTEM modeling. In addition to the University of Karlsruhe (Prof. Dagmar Gerthsen, Dr. Andreas Rosenauer, Dmitry Litvinov), we cooperated very closely with the Max Planck Institute for Microstructure Physics (Prof. U. Gosele, Dr. Werner, Dr. N. Zakharov). Several TEM experts from the Ioffe Institute worked at these places for quite a long time: Sergei Ruvimov (now is working in a company in USA), Alexander Kosogov (now in Canada), Ilya Soshnikov, Nikolai Cherkashin, Youri Musikhin. Excellent characterization facilities existing were an excellent fit to our good technological and laser experience at Ioffe.

This concentration of efforts and broad cooperation resulted in a number of serious advances in quantum dot growth and, first of all, in realization of first QD injection lasers demonstrating the theoretically-predicted properties [29].

Experimental and theoretical studies of self-organized growth in the InAs/GaAs and other III-V systems were reported in number of publications (see for a review Ref. 30). We believe, as also for the case of ordered surface nanofaceting, formation of two-dimensional islands, SOG of SK QDs can be well described by quasi-equilibrium models (see e.g. 30, 31), while the kinetics plays a significant role mostly at the initial stages of QD formation.

9. EVOLUTION OF QUANTUM DOT LASERS

It was quickly recognised that the main obstacle for QD laser operation at elevated temperatures is related to temperature-induced escape of carriers from QDs, insufficient modal gain at room temperature, and large size dispersion of small QDs formed at the first stage of SK growth mode. Several approaches were proposed to improve the laser performance:

(i) We proposed to improve the laser performance by increasing the density of and simultaneously the localization energy of QDs using strongly electronically-coupled QDs 32, 33.

(ii) We proposed lasers with QDs placed in a QW (e.g. InGaAs QDs inside GaAs/AlGaAs QW [34]) to decrease the density of the extended cavity states and reduce the carrier leakage from QDs at high temperatures.

(iii) We proposed to use the matrix material having a higher band-gap energy (e.g. InAs QDs in an AlGaAs matrix 33, see Fig. 3).

(iv) We proposed to increase the density of large QDs by using a concept of "seeding" 35, using an array of very small stressors having a very high density (e.g. InAlAs stressors on AlGaAs surface).

(v) We proposed the stressor-activated spinodal decomposition technique. This approach is based on overgrowth of small elastically-relaxed islands by the alloy layer, made of lattice-mismatched components [36]. This process results in an increase in the volume of the quantum dots while keeps their high density.

(vi) We found that overgrowth of InAs SK islands by ultrathin AlAs layers results in replacement of In from the wetting layer by Al and in increase of the volume of QDs.

(vii) We were first to demonstrate that QD lasers, after the lasing in the near infrared range starts, emit strongly enhanced, as compared to the QW case, spontaneous far infrared radiation [37].

(viii) We demonstrated that, for multiple stacking of InGaAs/GaAs QDs, lateral quantum wire-like structures are formed in the upper rows, exhibiting strong in-plane optical polarization anisotropy in PL [38].

As a result of all these developments, low threshold (~70 A/cm^2, l=2 mm, uncoated), high power (~3 – 4W CW) lasers were realized in a spectral range from 0.94 to 1.31 μm. A quantum efficiency up to 95% and a wall-plug efficiency up to 51% were obtained. One can give here just several examples, and more information can be found in recent review articles [39, 40]. The differential efficiency was 56% for 1.9-mm cavity lengths (uncoated) and was weakly temperature-dependent. Narrow 7 μm-wide stripes were also fabricated from similar wafers. Low threshold single-transverse-mode kink-free operation up to 120 mW was demonstrated for uncoated facets (see also Fig. 4).

Another important issue in the realization of long-wavelength GaAs-based QDs is the GaAs-based

VCSEL emitting at 1.3 µm [41], which is urgently needed for telecom. CW operation of the 1.3 µm QD VCSEL was first realized in [42]. Devices, fabricated from our wafers operate at room temperature and above with threshold currents below 2 mA, operation voltage below 2V, and differential efficiencies of about 60 % in the CW mode [42]. The threshold current variation across the wafer was 10% and the wavelength variation was 1.28-1.306 µm. Maximum output power at 25°C heat sink temperature was 0.65 mW (see Fig. 5). Preliminary lifetime tests demonstrate no degradation of the threshold current of the device.

The recent progress in QD lasers is, indeed, very exciting. The threshold current density of double heterostructure injection laser based on QDs is recently reduced to 16 A/cm^2 at room temperature [43], about three-times better than for the best QW devices.

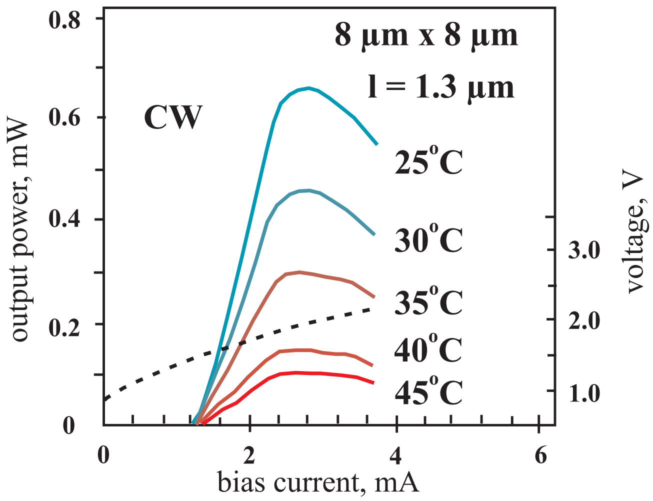

Fig. 5. Characteristics of the GaAs-based CW VCSEL emitting at 1.3 µm

10. CONCLUSIONS

Just several years ago, there was a lot of skepticism towards the SOG QD concept [44]. As opposite, in his opening plenary talk "Quantum dots heterostructure lasers: state of the art and future prospects" given at the Photonics West Conference in San Jose in January 1999, Prof. Alferov said that the future of heterostructure lasers [45] will belong to quantum dots lasers very soon. Once he made a similar forecasts for double heterostructure lasers, and, later, for quantum well lasers, when these were only under development. I strongly believe that the latest forecast will have the same future, as his double heterostructure and quantum well predictions. In his Nobel Lecture he again underlined the role of QDs in heterostructure lasers of the near future.

In this paper, I wanted to describe our way towards QD lasers. As it becomes clear, the most of our developments would be impossible without vision and active support of Prof. Alferov, particularly, in decisive moments. We all congratulate Professor Zhores Ivanovich Alferov with his Nobel Prize 2000, the last Nobel Prize of the Millenium.

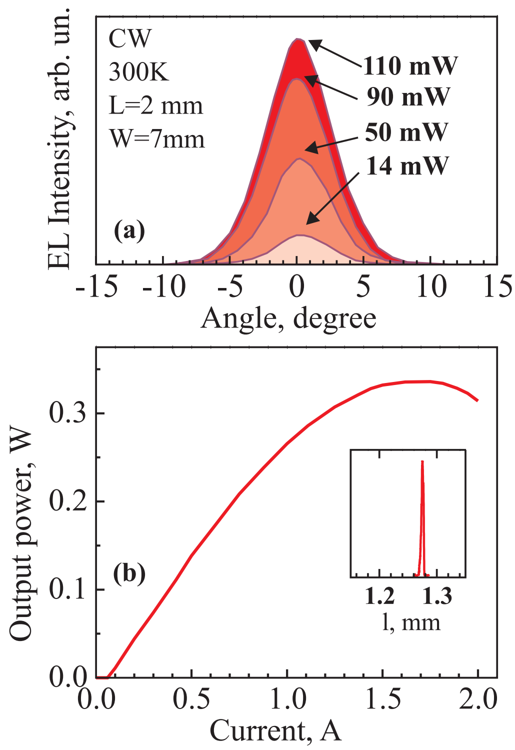

Fig. 4. High-power CW operation and narrow far-field pattern for 7 µm-wide stripe QS laser emitting near 1.3 µm

REFERENCES

1. V.N. Lutskii, Phys. stat. sol. (a) **1**, 199 (1970).
2. Zh.I. Alferov and R.F. Kazarinov. Authors Certificate No 27448, Application No 950840 with a priority from March, 30, 1963.
3. H. Kroemer, - Proc. IEEE **51**, 1782 – 1784 (1963).
4. Zh.I. Alferov, V.M. Andreev, E.L. Portnoi, M.K. Trukan, Fiz. Tekhn. Poluprov. **3**, 1328 – 1331 (1969) (submitted December 30, 1968). Sov. Phys.-Semicond. **3**, 1107-1110 (1970).
5. Zh.I. Alferov, V.M. Andreev, E.L. Portnoi, M.K. Trukan, Fiz. Tekhn. Polupr. **3**, 132 (1969) Sov. Phys. Semicond. **3**, 1107 (1970).
6. L. Esaki and R. Tsu, IBM J. Res. Develop. **14**, 61 (1970).
7. Zh.I. Alferov, Yu.V. Zhiljaev, Yu.V. Shmartsev, Fiz. Tekhn. Poluprov. (Sov. Phys. - Semicond.) **5**, 196 (1971).
8. R. Dingle, W. Wiegmann, and C.H. Henry, Phys. Rev. Lett. **33**, 827 (1974).
9. R. Dingle and C.H. Henry, "Quantum effects in heterostructure lasers" U.S. Patent No. 3982207, **21**, September, 1976.
10. J.P. van der Ziel, R. Dingle, R.C. Miller, W. Wiegmann, W.A. Nordland, Jr. Appl. Phys. Lett. **26**, 463 (1975).
11. R.C. Miller, R. Dingle, A.C. Gossard, R.A. Logan, W.A. Nordland, Jr., and W. Wiegmann, J. Appl. Phys. **47**, 4509 (1976).
12. W.T. Tsang, Appl. Phys. Lett. **40**, 217 (1982).
13. Zh.I. Alferov, A.M. Vasiliev, S.V. Ivanov, P.S. Kop'ev, N.N. Ledentsov, B.Ya. Meltser and V.M. Ustinov, Pis'ma v Zh.Tekhn.Fiz. **14**, 1803 (1988) - Sov. Phys. - Tekhn. Phys. Lett. **14**, 782 (1988).
14. Zh.I. Alferov, S.V. Ivanov, P.S. Kop'ev, N.N. Ledentsov, M.E. Lutsenko, M.I. Nemenov, B.Ya. Meltser, V.M. Ustinov and S.V. Shaposhnikov, Fiz. Tekhn. Poluprov. **24**, 152 (1990) Sov. Phys. Semicond. **24**, 92 (1990).

15. P.M. Petroff, A.C. Gossard, R.A. Logan, and W. Weigman, Appl. Phys. Lett. **41**, 635 (1982).
16. E. Kapon, M.C. Tamargo, and D.M. Hwang, Appl.Phys. Lett. **50**, 347 (1987).
17. H.A. Bluyssen and L.J. Ruyven, IEEE J.Quant. Electron. **QE-17**, 2191 (1981).
18. Y. Arakawa and H. Sakaki, "Multidimensional quantum well lasers and temperature dependence of its threshold current" Appl. Phys. Lett. Vol. **40**, 939 (1982).
19. R. Nötzel, N.N. Ledentsov, L. Däweritz, M. Hohenstein and K. Ploog, Phys. Rev. Lett. **67**, 3812 (1991).
20. R. Nötzel, N.N. Ledentsov, L. Däweritz, K. Ploog "Method of fabricating a compositional semiconductor device" US patent US5714765, issued 3.02.1998, priority 29.01.1991.
21. N.N. Ledentsov, D. Litvinov, A. Rosenauer, D. Gerthsen, I. P. Soshnikov, V.A. Shchukin, V.M. Ustinov, A.Yu. Egorov, A.E. Zukov, V.A. Volodin, M.D. Efremov, V.V. Preobrazhenskii, B.P. Semyagin, D. Bimberg and Zh.I. Alferov, J. Electron. Mat. (2001) *(in print)*.
22. Zh.I. Alferov, A.Yu. Egorov, A.E. Zhukov, S.V. Ivanov, P.S. Kop'ev, N.N. Ledentsov, B.Ya. Meltser and V.M. Ustinov, Semicond. **26**, 959 (1992).
23. P.S. Kop'ev and N.N. Ledentsov, Abstracts of Invited Lectures and Contributed Papers, the International Symposium "Nanostructures: Physics and Technology". St. Petersburg, Russia, June 13 – 18, 1993. Ed. P.S.Kop'ev. p. 26.
24. P.D. Wang, N.N. Ledentsov, C.M. Sotomayor Torres, P.S.Kop'ev and V.M. Ustinov, Appl. Phys. Lett. **64**, 1526 (1994), ibid. **66**, 112 (1995).
25. N.N. Ledentsov, et al. Thin Solid Films. **367** (1 – 2), 40 (2000).
26. I.L. Krestnikov, N.N. Ledentsov, A. Hoffmann, D. Bimberg, Phys. stat. sol. (a) **183** (2), 207 (2001).
27. L. Goldstein, F. Glas, J.Y. Marzin, M.N. Charasse, G. Leroux, Appl. Phys. Lett. 47, 1099 (1985).
28. N.N. Ledentsov, V.M. Ustinov, A.Yu. Egorov, A.E. Zhukov, M.V. Maximov, I.G. Tabatadze, P.S. Kop'ev, Fiz. Tekhn. Poluprov. **28**, 1484 (1994) Semiconductors **28**, 832 (1994) (Submitted December 29, 1993).
29. N. Kirstaedter, N.N. Ledentsov, M.Grundmann, D. Bimberg, V.M. Ustinov, S.S. Ruvimov, M.V. Maximov, P.S. Kop'ev, Zh.I. Alferov, U. Richter, P. Werner, U. Gosele, J. Heydenreich, Electron. Lett. **30**, 1416 (1994).
30. D. Bimberg, M. Grundmann and N.N. Ledentsov, "Quantum Dot Heterostructures" John Wiley & Sons, Chichester, 328 (1999).
31. V.A. Shchukin, N.N. Ledentsov, P.S. Kop'ev, and D. Bimberg, Phys. Rev. Lett. **75**, 2968 (1995).
32. N.N. Ledentsov, M. Grundmann, N. Kirstaedter, O. Schmidt, R. Heitz, J. Böhrer, D. Bimberg, V.M. Ustinov, V.A. Shchukin, P.S. Kop'ev, Zh.I. Alferov, S.S. Ruvimov, A.O. Kosogov, P. Werner, U. Richter, U. Gösele and J. Heydenreich, Solid State Electronics **40**, 785 (1996).
33. N.N. Ledentsov, V.A. Shchukin, M. Grundmann, N. Kirstaedter, J. Böhrer, O. Schmidt, D. Bimberg, S.V. Zaitsev, V.M. Ustinov, A.E. Zhukov, P.S. Kop'ev, Zh.I. Alferov, A.O. Kosogov, S.S. Ruvimov, P. Werner, U. Gösele and J. Heydenreich, Phys. Rev. B, **54**, 8743 (1996).
34. M.V. Maximov, I.V. Kochnev, Yu.M. Shernyakov, S.V. Zaitsev, N.Yu. Gordeev, A.F. Tsatsul'nikov, A.V.Sakharov, I.L. Krestnikov, P.S. Kop'ev, Zh.I. Alferov, N.N. Ledentsov, D. Bimberg, A.O. Kosogov, P. Werner, and U. Gösele, Jap. J. Appl. Phys. **36,** part 1, 4221 (1997).
35. M.V. Maximov, D.A. Bedarev, A.Yu. Egorov, P.S. Kop'ev, A.R. Kovsh, A.V. Lunev, Yu.G. Musikhin, Yu.M. Shernyakov, A.F. Tsatsul'nikov, V.M. Ustinov, B.V. Volovik, A.E. Zhukov, Zh.I. Alferov, N.N. Ledentsov and D. Bimberg, Proceedings ICPS24, *Jerusalem, August 2 – 7*, 1998, *D. Gershoni, Ed.* (World Scientific, 1999).
36. Yu.M. Shernyakov, D.A. Bedarev, E.Yu. Kondrat'eva, P.S. Kop'ev, A.R. Kovsh, N.A. Maleev, M.V. Maximov, V.M. Ustinov, B.V. Volovik, A.E. Zhukov, Zh.I. Alferov, N.N. Ledentsov, D. Bimberg, Elecrtonics Letters **35**, 898 (1999).
37. L.E. Vorob'ev, D.A. Firsov, V.A. Shalygin, V.N. Tulupenko, Yu.M. Shernyakov, N.N. Ledentsov, V.M. Ustinov, and Zh.I. Alferov, JETP Letters **67**, 275 (1998).
38. P. Yu, W. Langbein, K. Leosson, J. M. Hvam , N. N. Ledentsov, D. Bimberg, V.M. Ustinov, A. Yu. Egorov, A. E. Zhukov, A. F. Tsatsul'nikov, and Yu. G. Musikhin, Phys. Rev. B **60**, 16680 (1999).
39. N.N. Ledentsov, M. Grundmann, F. Heinrichsdorff, D. Bimberg, V. M. Ustinov, A. E. Zhukov, M.V. Maximov, Zh.I. Alferov and J. A. Lott, IEEE J. Sel. Top. in Quantum Electronics, **6**, 439 (2000).
40. N.N. Ledentsov, V.M. Ustinov, V.A. Shchukin, D. Bimberg, J.A. Lott, and Zh.I. Alferov, SPIE Proceedings, Vol. 4287 In-Plane Semiconductor Lasers V (Editor L.J. Mawst and R.U. Martinelli), paper [4287-13] (2001).
41. J.A. Lott, N.N. Ledentsov, V.M. Ustinov, N.A. Maleev, A.E. Zhukov, A.R. Kovsh, M.V. Maximov, B.V. Volovik, Zh.I. Alferov, and D. Bimberg, Electr. Lett. **36**, 1384 (2000).
42. J.A. Lott, N.N. Ledentsov, V.M. Ustinov, N.A. Maleev, A.E. Zhukov, A.R. Kovsh, M.V. Maximov, B.V. Volovik, Zh.I. Alferov, and D. Bimberg, LEOS2000, 13 – 16 November 2000, Puerto Rico, IEEE Annual Meeting Conference Proceedings, Vol 1, 304.
43. G.T. Liu, A. Stintz, H. Li, T.C. Newell, A.L. Gray, P.M. Varangis, K.J. Malloy and L.F. Lester, IEEE J. Quan. Electron. **36**, 1272 (2000).
44. B.G. Levi, Phys. Today, **49** (5), 22 (1996).
45. Zh.I. Alferov and N.N. Ledentsov, SPIE Proceedings Vol. 3625, Physics and Simulation of Optoelectronic Devices VII, Eds: P. Blood, A. Ishibashi, M. Osinski, 2 (1999).

InAs/InGaAs quantum dot lasers. To cite this article: V V Korenev et al 2018 J. Phys.Â Modulation p-doping as the way to attain multi-state lasing in. short-cavity InAs/InGaAs quantum dot lasers. V V Korenev1,2, A V Savelyev1, V G Dubrovskii3, S Breuer4, M V Maximov1,2, A E. Colloidal Quantum Dots (CQDs) are semiconductor nanoparticles that can generate vivid and saturated colors of light efficiently, which are used to make display screens of many electronic devices. Though CQDs should be promising as laser materials, they are not yet practical since they need to be powered by another source of light energyâ€"a method known as optical pumping.Â "Our successful experiment brings us one step closer towards developing single-material full-color lasers that can be electrically pumped. That achievement would eventually make it possible to put lasers on chip integrated systems used in consumer electronics and the Internet of Things (IOTs)" said Asst Prof Dang, from the School of Electrical and Electronic Engineering (EEE).