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Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (31 January, 2001)

On January 31, 2001 the Division of General Physics and Astronomy of the Russian Academy of Sciences held a scientific session at the P N Lebedev Physical Institute. The following reports were delivered at the session:

(1) **Alferov Zh I** (A F Ioffe Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg) "Semiconductor heterostructures: new physics and technology";

(2) **Kop'ev P S** (A F Ioffe Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg) "Heterostructures with Short-Period Superlattices";

(3) **Ustinov V M, Maleev N A, Zhukov A E, Kovsh A R, Sakharov A V, Volovik B V, Tsatsul'nikov A F, Ledentsov N N, Alferov Zh I** (A F Ioffe Physico-Technical Institute, Russian Academy of Sciences, St. Petersburg), **Lott J A** (Air Force Institute of Technology, Department of Electrical and Computer Engineering, Ohio, USA), **Bimberg D** (Institut für Festkorperphysik, Technische Universität Berlin, Berlin, Germany) "Vertical-cavity emitting devices with quantum-dot structures";

(4) **Krestnikov I L, Lundin V V, Sakharov A V, Bedarev, D A, Zavarin E E, Musikhin Yu G, Shmidt N M, Tsatsul'nikov A F, Usikov A S, Ledentsov N N, Alferov Zh I** (A F Ioffe Physico-Technical Institute, Russian Academy of Sciences, Saint-Petersburg). "Heterostructures based on nitrides of group III elements: Technical processes, properties, and light-emitting devices".

Given below are the shortened versions of reports 3 and 4.

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Vertical-cavity emitting devices with quantum-dot structures

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In recent years, a significant progress has been made in the research on semiconductor heterostructures with ensembles of self-assembled quantum dots (QD) not only yielding more knowledge of their fundamental physical properties but also making it possible to employ them in practice for manufacturing semiconductor sources of light. One interesting application involves using QD arrays as active layers in microcavity light-emitting diodes (MCLED) and vertical-cavity surface-emitting lasers (VCSEL). The essential advantages of these devices are determined by the low beam divergence, the high temperature stability of the wavelength, and the planar technology and on-wafer testing [1].

Even though the MCLED and VCSEL devices have been successfully developed for the spectral ranges at 850 and 980 nm, a number of fundamental problems have to be resolved before developing similar devices for the wavelength ranges at 1.3 and 1.55 μm which are of practical significance [1]. The distributed Bragg reflectors (DBR) formed of alternating layers of two materials with different indices of refraction (the thickness of each layer is a quarter of the resonance wavelength adjusted for the index of refraction) serve as mirrors in vertical-cavity devices. High-performance DBRs for the MCLEDs and VCSELs operating in the 850/980 nm range are formed by alternating AlGaAs and GaAs layers. Significantly, the device structure can be grown within a single epitaxy process. Light-emitting devices for the 1.3/1.55 μm range are traditionally manufactured of InAlGaAsP/InP materials which do not make it possible to fabricate high-quality vertical cavities within a single epitaxy process because of the small difference between the indices of refraction (significantly smaller than for AlGaAs/GaAs materials) of the layers of InGaAsP, InAlGaAs, and InP and the low thermal conductivity of the quaternary compounds. Therefore, there is an ongoing demand for new semiconductor materials suitable for fabricating long-wavelength VCSELs on GaAs substrates. Currently the greatest interest is drawn to InGaAsN and GaAsSb quantum-well structures and QD-array In(Ga)As structures [2].

Recently the authors were involved in a demonstration of lasing at a wavelength of 1.3 μm for a VCSEL on a GaAs substrate with a QD InAs/InGaAs-based active region [3]. The present paper briefly describes the main results of our research and development work on long-wavelength (in the range of 1300 nm) vertical-cavity surface-emitting devices with QD array active regions.

It has been demonstrated that the optimal conditions of molecular-beam epitaxy (MBE) make it possible to fabricate structures with several InAs/InGaAs QD layers which have a high surface QD array density and exhibit bright photoluminescence in the 1.3-μm wavelength range without an increase in the line half-width in comparison with the structures which include only one QD layer [4, 5]. Stripe lasers with such active regions exhibit low-threshold lasing (< 80 A cm^{-2}) and a high output power in the continuous-wave mode (> 2.5 W) [6].

The first step in the development of the long-wavelength vertical-cavity surface-emitting devices on GaAs substrates was the development and analysis of vertical-microcavity

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structures containing InAs/InGaAs QDs and MCLEDs fabricated with them which had exhibited a narrow electroluminescence line in the 1265 – 1325 nm wavelength range [7]. These devices employed hybrid optical microcavities formed using a lower AlGaAs/GaAs DBR (which was an *n* type conductor or undoped) and upper dielectric DBR. The attempts to achieve lasing in this structural design proved to be unsuccessful, however.

Let us consider the essential factors that must be taken into consideration when a design is selected for fabricating long-wavelength VCSELs with InAs/InGaAs QD active regions. Lasing starts when a balance is reached between optical gain and the total optical losses including the output losses and internal losses in the laser structure [1]. One should take into account the fact that in the VCSELs the optical wave penetrates to a certain depth into the DBR, that is, the effective cavity length differs from the geometric distance between the reflectors. In addition, for small-thickness active layers one should take into account the arrangement of the active region with reference to the spatial distribution of the amplitude of the standing wave of the optical field in the vertical microcavity.

The essential feasibility of fabricating VCSELs with various optical resonators can be assessed in the first approximation from the experimentally observed parameters of stripe lasers with the same active region [8]. InAs/InGaAs QD structures are known to exhibit gain saturation with an increase in the pumping current, which is due to the finite surface density of QDs [2]. The highest measured optical modal gain for long-wavelength edge-emitting lasers based on three InAs/InGaAs QD layers was not higher than 10 – 12 cm^{-1} for an internal optical loss of 1.5 ± 0.3 cm^{-1} [6]. It has been demonstrated [8] that VCSELs with an active region consisting of three InAs/InGaAs QD layers start lasing at $R > 0.9994$ if zero internal loss is assumed, and at $R > 0.9997$ if an internal loss is 2 cm^{-1} ($R = \sqrt{R_1 R_2}$, where R_1 and R_2 are the reflection coefficients for the upper (output) and lower mirrors). It can be seen that lasing is achieved when very high mirror reflection coefficients are combined with low internal optical losses.

The significant optical losses in doped semiconductor mirrors [9] make it practically unfeasible to use the traditional design with upper and lower contacts at *n*- and *p*-type doped mirrors for fabricating long-wavelength QD VCSELs. The optimal design seems to be the one with the upper and lower undoped Al_xO_y/GaAs DBRs, which can be manufactured by selective oxidizing of the AlGaAs layers in an atmosphere saturated with water vapor [10]. The large difference between the refraction indices of the layers for the oxidized mirrors makes it possible to achieve a wide spectral range with high optical reflection levels.

The VCSELs with InAs/InGaAs QD active layers were grown by the MBE technique in a Riber-32P apparatus with a solid-state As^4 source. Figure 1 presents a schematic and the main parameters of a typical VCSEL. Two Al_xO_y apertures produced by partial oxidizing of the AlGaAs layers not only limit the current but also provide a redistribution of the optical field in the cavity. In comparison with a cavity using semiconductor DBRs, the optical field amplitude in the active region increases significantly and its penetration into the mirrors decreases [8]. For devices with an 8 × 8-micron oxidized aperture, the threshold current is 1.8 mA for the highest external incremental efficiency of 43% (for radiation output through the upper mirror) [3]. This is the best published result for VCSELs on GaAs substrates operating in the range of 1.3 μm. The highest continuous-wave output power at the room temperature is greater than 0.6 mW for the best devices [11]. The internal optical loss of 0.04 ... 0.05% per photon pass corresponds to the best published results for the VCSELs of all types [12].

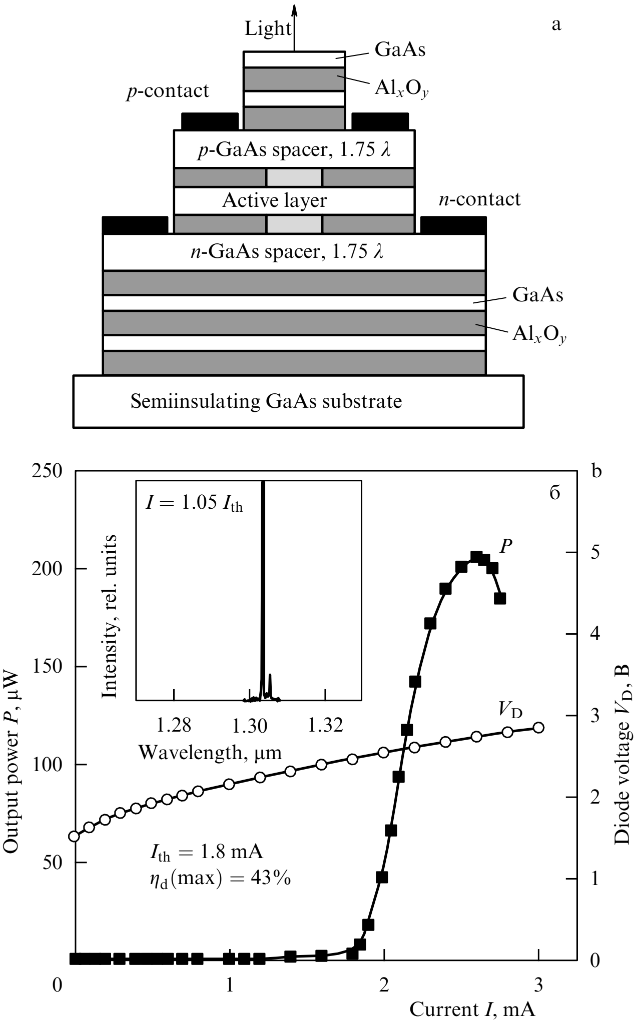

Figure 1. Schematic of (a) the cross section and (b) the main parameters of the VCSEL with an active region of three layers of InAs/InGaAs quantum dots.

In conclusion, the research results presented in this paper demonstrate the feasibility of fabricating a new generation of efficient long-wavelength (the 1.3 μm range) vertical-cavity surface-emitting lasers with arrays of self-assembled quantum dots.

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Heterostructures based on nitrides of group III elements: technical processes, properties, and light-emitting devices

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Optical and magnetooptical data-recording and data-reading systems account for approximately 20% of the rapidly growing market for semiconductor lasers (6 billion dollars and 108% growth in the year 2000). Light-emitting devices with the smallest possible radiation wavelengths are required for fabricating these systems. Indeed, when CD-ROM devices using 780-nm radiation were replaced with 650-nm devices (DVD-ROM systems), the data-recording density was increased 20 times. A further decrease in the wavelength of the semiconductor lasers will make it possible to record up to 150 Gbytes of data on a single compact disk.

These are the reasons for an enhanced interest in wide-band compounds, in particular group III element nitrides, because gallium nitride, which is the main compound of this group, has an energy-gap width of 3.42 eV corresponding to the ultraviolet spectral range. The use of the AlGaN and InGaN solid solutions makes it possible to control the energy-gap width by respectively increasing or decreasing it. Therefore, the group III nitrides allow us to emit radiation in a wide spectrum from the ultraviolet to the red ranges. Thus, GaN-based light-emitting devices can be employed not only in data-recording and storage systems but also for designing white-light sources, high-resolution projection TV systems, traffic lights, beacons, signal lights, medical apparatus, and so on.

Light-emitting diodes (LEDs) and stripe lasers fabricated on the basis of GaN are at present commercially available. Therefore, we believe that a research subject of interest is the development of vertical-cavity surface-emitting lasers (VCSELs) using the materials of this group [1] while the development of the LEDs and stripe lasers was just the first step toward the goal. VCSELs have a number of advantages, for instance, a high degree of integration, temperature stability, low threshold currents, and a good-quality radiation pattern; that is why there is considerable interest in them. The mirrors in the VCSELs fabricated with group III nitrides are the AlGaN/GaN distributed Bragg reflectors (DBRs), between which there is a GaN microcavity with an InGaN/GaN active region. The problems of fabricating such structures and studying their properties are discussed in the present report.

As no lattice-matched substrate is available for growing gallium nitride, we make use of a complicated two-stage technique of metalorganic chemical vapor deposition on sapphire substrates (MO CVD). The first stage conducted at a low temperature (about 550 °C) consists in nitridization of the substrate and deposition and annealing of an AlGaN nucleation layer. The second stage conducted at a high temperature (about 1050 °C) consists in the growth of a Ga(Al)N buffer layer, which provides for planar growth and blocking of the faults growing from the sapphire/Ga(Al)N interface, and in the growth of the epitaxial structure [2].

As the difference between the refraction indices of AlGaN and GaN is very small, when we fabricate AlGaN/GaN DBRs we must employ a large number of quarter-wave-length AlGaN/GaN pairs to obtain even low reflection coefficients (about 80 – 90%). In contrast to the AlAs/GaAs system, the AlN/GaN system is not lattice-matched, and the large number of layers in the structure gives rise to very high mechanical stresses, which cause cracking and, accordingly, degradation of the electrical and optical properties of the structure.

To prevent cracking, the DBRs can be grown directly on the sapphire substrate. The problem of lattice matching does not arise under these conditions because each layer is thin enough to withstand the stress and the lattice parameter of the entire structure is the arithmetical mean of the lattice parameters of GaN and AlGaN. However, the DBR bulk contains faults which grow from the interface with the substrate because of the absence of a buffer layer. Therefore, in our opinion, the best fabrication technique involves using an AlGaN buffer layer whose lattice parameter is equal to the averaged lattice parameter of the DBR lattice. This technique produces a structure with compensated stresses in which a defect-free DBR is obtained. The structures grown using this technique exhibit a reflection coefficient of more than 90% in the ultraviolet spectral range. Apart from having good optical properties, these structures have a high conductivity providing an ohmic-type current – voltage characteristic with a resistance of 50 Ω and exhibit no degradation on passing high-density currents. Therefore, an AlGaN/GaN DBR can be used both as a mirror and as an emitter of charge carriers into the active region [3].

InGaN/GaN superlattices fabricated by thermal cycling of the substrate are used as the active regions. The indium incorporation into the growing layers depends cardinally on the substrate temperature and, even if all flows in the reactor are maintained at a constant level, thermal cycling gives rise to a structure in which the indium content varies periodically along the growth direction [4], although the real growth processes are much more complicated [5]. High-resolution transmission electron microscopy demonstrates that the structure is not uniform in the indium content in the lateral direction. Indium-rich (up to 60% content) nanodomains with a characteristic size of 3 – 10 nm are found instead of homogeneous quantum wells. The domains effectively localize carriers in all three directions and act as quantum dots in this system [6].

Exciton absorption might prove to be very high in the wide-band compounds. But in the bulk material or in a quantum well the exciton states do not contribute to the gain, first, because they are heated up and cannot undergo radiative recombination, and, second, because they are