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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 shielded. Both effects do not take place under the conditions of three-dimensional localization of excitons in a dense array of quantum dots and a significant exciton gain can be produced [7]. Under such conditions the refractive index in this spectral range is intensely modulated because the refractive index and the gain coefficient are subject to the Kramers – Kronig relation. Nonlinear effects can be produced under intense modulation of the refractive index in the cavity, in particular, self-adjustment of the cavity modes [8]. Under such circumstances there is no need for the stringent requirement that the cavity wall thickness be such that the cavity mode should coincide with the gain peak, since the latter condition is automatically satisfied in a certain spectral range. In experiments, this effect was observed as a shift of the lasing mode with an increase in the excitation density [9]. The gain coefficient obtained with an InGaN/GaN active region has been assessed from the results on the effects of lasing and mode shifting. Both estimates were about $\sim 10^5$ cm^{-1}, demonstrating that our understanding of the processes in the active region was adequate.

Since the gain coefficient of the active region is so high, DBRs with moderate reflection coefficients between 80 and 90% could be used in GaN-based VCSELs. Using this active region and such DBRs, we were the first to produce vertical-cavity emission of laser radiation with optical pumping at room temperature [10]. More interesting for practical purposes is injection pumping when the structure carries a current. For this purpose we grew resonance InGaN/GaN/AlGaN LEDs which have all the VCSEL components. A narrow cavity mode is seen in the radiation spectrum of the resonance LEDs. If the structure parameters are upgraded, this mode can become a lasing line. Therefore, the next logical step of our development work is to fabricate an injection InGaN/GaN/AlGaN vertical-cavity surface-emitting laser diode.

GaAsN solid solutions can be employed for fabricating other similar devices. This semiconductor system exhibits a rather atypical dependence of the energy gap width on the composition, which is such that the energy gap width can even be negative. The entire radiation spectrum from the ultraviolet to the infrared ranges can be covered by such devices. Infrared-emitting devices are fabricated from GaAsN with a very high content of GaAs, while we mostly used GaN doped with small amounts of arsenic. The structure is fabricated by depositing a GaAs layer on the GaN buffer layer and growing a GaN layer over the deposited layer. After the last layer is grown, GaAs is etched off and arsenic is dissolved in the GaN layer [11]. In optical experiments such structures exhibited a wide radiation line varying in color from orange to violet, so that these material can be potentially useful for fabricating devices emitting light over a wide spectral range.

In conclusion, let us summarize the main research results:

— a process has been developed for fabricating efficient AlGaN/GaN DBRs;

— the InGaN/GaN active region has been demonstrated to produce a high gain;

— nonlinear effects of self-adjustment of the microcavity modes have been analyzed;

— for the first time, vertical-cavity lasing at room temperatures has been achieved for InGaN/GaN/AlGaN structures;

— preliminary studies of the GaAsN structures have been performed.

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