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High efficiency (EQE = 37.5%) infrared (850 nm) light-emitting diodes with Bragg and mirror reflectors

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Developed and investigated are IR (850 nm) light-emitting diodes based on AlGaAs/Ga(In)As heterostructures grown by the MOCVD technique with multiple quantum wells in the active region and with a double optical reflector consisted of a multilayer $\mathrm{Al_{0.9}Ga_{0.1}As/Al_{0.1}Ga_{0.9}As}$ Bragg heterostructure and an Ag mirror layer. Light-emitting diodes with the external quantum efficiency EQE = 37.5% at current densities greater than $> 10\,\mathrm{A/cm^2}$ have been fabricated.

Keywords: IR light-emitting diode, AlGaAs/GaAs heterostructure, Bragg reflector, InGaAs quantum wells.

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1. Introduction

Internal optical losses in AlGaAs/GaAs light-emitting diodes (LEDs) are reduced either by removing the growth GaAs substrate after the growth process [1–5] or by forming a Bragg reflector (BR) based on a multilayer $\mathrm{Al_{0.9}Ga_{0.1}As/Al_{0.1}Ga_{0.9}As}$ heterostructure between the substrate and the active LED region [6,7].

The reflection coefficient of Bragg reflectors is high (on the order of 90%) only for rays within a small solid angle on the order of ± 20 ang. deg [8]. This is the reason why the maximum external quantum efficiency values for AlGaAs/GaAs LEDs based on heterostructures with BRs do not exceed 10% [6,7].

High-efficiency IR LEDs based on MOCVD AlGaAs/GaAs heterostructures are fabricated [4,9] by „transferring“ the grown heterostructure to a carrier wafer with a mirror silver layer, which serves as a reflector, deposited onto the heterostructure surface. The growth GaAs substrate is then subjected to selective etching. The internal coefficient of reflection of the generated isotropic radiation ($\lambda = 850$ nm) in such structures with an Ag reflector is $\sim 90\%$ almost for all rays incident on the Ag reflector surface at various angles. This translates into a considerable enhancement of the external quantum efficiency in AlGaAs/GaAs IR LEDs with a „back“ Ag reflector [4,9].

In the present study, the results of development of LEDs ($\lambda = 850$ nm) with a double (selective Bragg and wideband mirror) reflector are reported.

2. Light-emitting AlGaAs/Ga(In)As heterostructure

LEDs were fabricated based on AlGaAs/Ga(In)As heterostructures (Fig. 1) formed MOCVD on *n*-GaAs substrates that are removed in the post-growth LED fabrication procedure. The active region of LEDs contains six GaInAs quantum wells, each with a thickness of 3 nm, confined between wide-bandgap *n*- and *p*-bounding $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{As}$ ($x = 0.2-0.4$) layers. Quantum wells provide an opportunity to raise the carrier density in a thin layer and enhance electron–hole overlapping. This, in turn, helps increase the radiative recombination rate and, consequently, the internal quantum efficiency. The use of multiple quantum wells allows one to keep the ground energy level of a quantum well acting as a dominant recombination channel even at high pumping levels [9].

A Bragg reflector was grown between the active region and the back surface of the structure to enhance the efficiency of light extraction from the crystal. In contrast to laser structures, which require the BR to be adjusted to a certain wavelength, LEDs are more efficient with BRs that feature a relatively broad spectral reflection range (40–80 nm).

3. Optical characteristics of the Bragg reflector

In the present study, the BR was formed from AlGaAs layers with the greatest possible difference in refraction indices: the lower index (n) of wide-bandgap $\mathrm{Al_{0.9}Ga_{0.1}As}$ was contrasted with the higher refraction index of narrow-bandgap $\mathrm{Al_{0.1}Ga_{0.9}As}$. $\mathrm{Al_{0.1}Ga_{0.9}As}$ was used instead of GaAs to minimize the absorption of radiation (850 nm) in the BR. The reflection coefficient may be increased not only by choosing the layers with a profound difference in refraction indices, but also by increasing the number of periods. The BR in the developed LED structure contained 15 pairs of p-$\mathrm{Al_{0.9}Ga_{0.1}As}$/$p$-$\mathrm{Al_{0.1}Ga_{0.9}As}$ layers.

Figure 2 presents the reflection spectra of three BR heterostructures with the reflection maximum shifting within

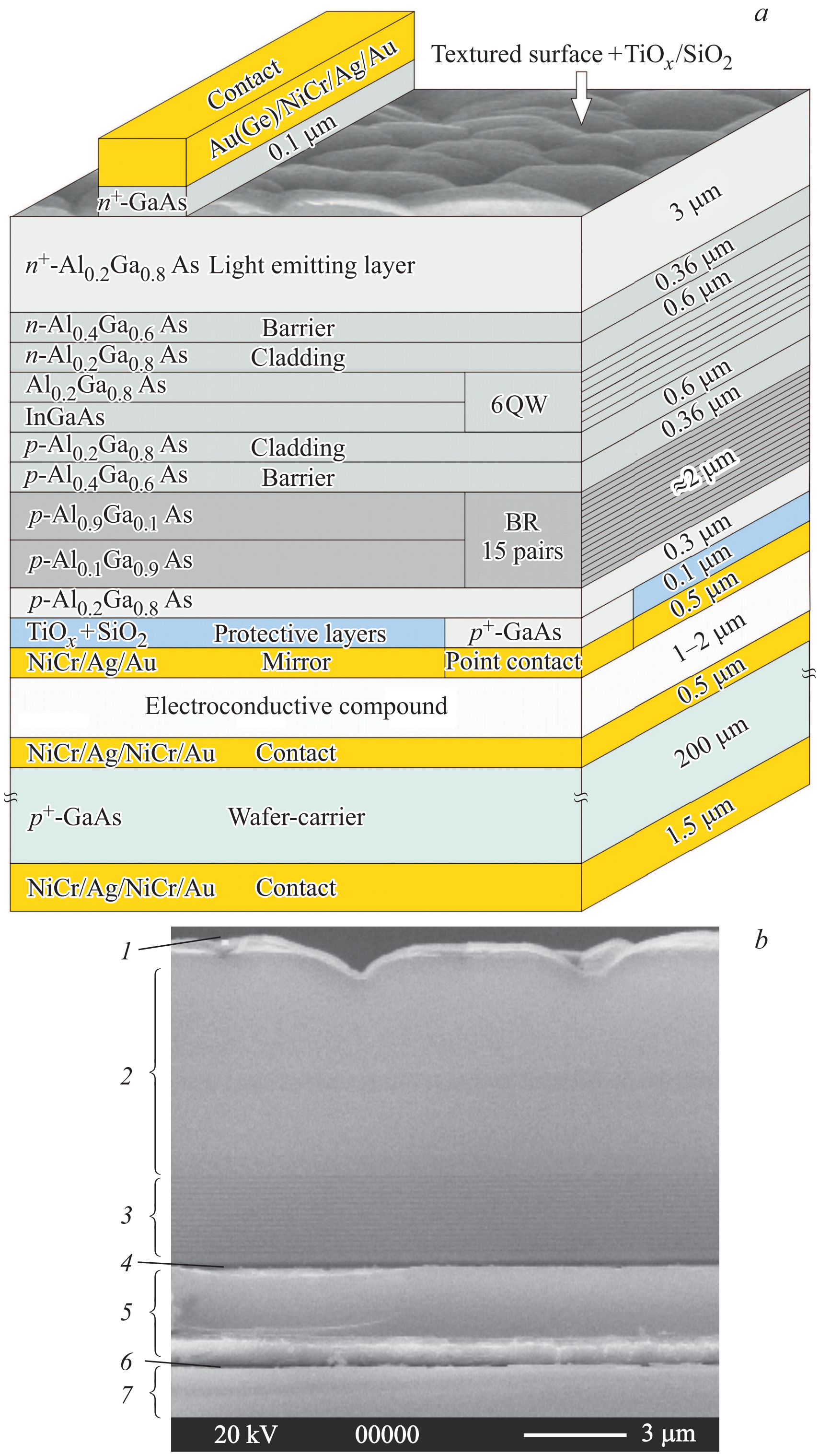

Figure 1. Diagram (*a*) and cleavage surface (*b*) of a light-emitting diode imaged with a scanning electron microscope after transfer of the heterostructure to the carrier wafer (p^+GaAs), removal of the growth n-GaAs substrate, texturing of the light-output surface, and deposition of the antireflective coating and Ohmic contacts. *1* — textured surface, *2* — heterostructure layers, *3* — BR, *4* — mirror reflector, *5* — silver-containing compound, *6* — contact to the p-GaAs substrate, *7* — p-GaAs substrate.

the range of $\lambda = 800-920$ nm for rays incident on the BR surface perpendicularly to the planes of epitaxial structure layers and at angles on the order of ±20 ang. deg relative to the normal [8]. Radiation ($\lambda = 850$ nm) generated in the active LED region and incident on the BR at large angles may be reflected efficiently by thicker BR layers. The

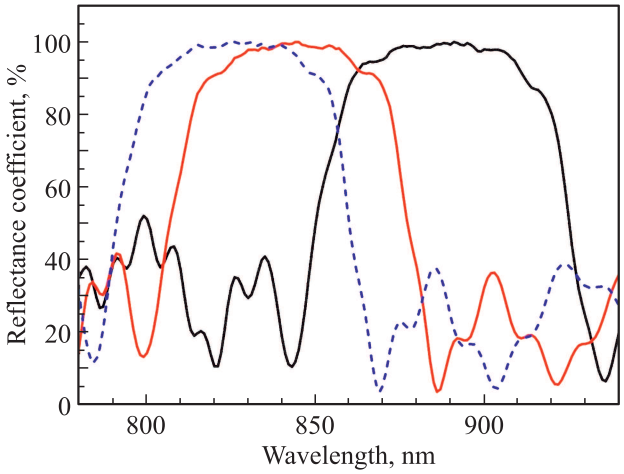

Figure 2. Reflection spectra of structures with Bragg reflectors containing 15 pairs of $Al_{0.9}Ga_{0.1}As-Al_{0.1}Ga_{0.9}As$ layers of various thickness.

BR reflection maxima for rays incident on the BR at near-right angles shift in this case toward higher wavelengths. Structures with two-section BRs may be used to broaden the reflection spectrum and, consequently, extend the range of reflection angles. However, it was found that structures with a greater number of BR layers and a higher overall BR thickness are characterized by higher Ohmic losses [10]. Multiple potential barriers formed by layers with different bandgap widths interfere with the propagation of carriers in BR structures and raise the series resistance (especially when *p*-type layers are used [11]). The problem of efficient transport of holes with their high effective mass [12] in *p*-type BR layers is indeed an important one, and the associated increase in series resistance induces additional heating and, consequently, has a negative effect on the device operation.

Experimental LED samples were fabricated based on structures with single-section Bragg reflectors with the maximum reflection within the 830–870 nm wavelength range. A mirror Ag reflector was introduced into the LED structure in the course of post-growth processing to enhance the efficiency of light extraction from the crystal.

The designed LED heterostructure features additional reflection from the BR due to the effect of total internal reflection from an array of BR $Al_{0.9}Ga_{0.1}As/Al_{0.1}Ga_{0.9}As$ layers, which is characterized by an „average“ AlAs content of 50% and effective refraction index $n \simeq 3.3$. The AlAs content in the $Al_xGa_{1-x}As$ medium (out of which the radiation incident onto the BR came) was approximated in the examined heterostructure by $x = 20\%$; i.e., the AlAs content was assumed to be the same as that in the frontal light-output structure layer. Calculations performed with account for the results reported in [7] demonstrated that the angle of total internal reflection of „lateral“ rays from the $Al_{0.2}Ga_{0.8}As/Al_{0.5}Ga_{0.5}As$ interface is ~ 20 ang. deg. The fraction of generated isotropic radiation undergoing total internal reflection from this heterointerface is 35%.

4. Post-growth technology

The procedure of LED fabrication based on the grown heterostructures (Fig. 1) involved the following operations:

– fabrication of point contacts 10 μm in diameter with a pitch of 75 μm to the surface p^+GaAs layer;

– removal of the p^+GaAs contact layer at sites without point contacts to form transparent windows for the generated radiation;

– deposition of a dielectric coating (e.g., TiO_x/SiO_2, Si_3N_4) at sites without contacts for protection and to moderate the degradation of optical properties of the back mirror;

– deposition of an Ag layer with a thin (1–2 nm) adhesion NiCr layer, which serves as the back mirror, with subsequent sputtering of a „protective“ gold layer;

– flipping and fixing of the structure with a silver-containing compound on the p^+GaAs carrier wafer with contact layers deposited in advance on the front and back surfaces;

– selective etching of the *n*-GaAs growth substrate;

– etching of the n^+GaAs layer at sites without contacts to reveal the light-output surface;

– texturing of the light-output surface;

– formation of an antireflective coating based on $TiOx/SiO_2$ or Si_3N_4 layers;

– fabrication of strip contacts to the n^+GaAs layer;

– mounting of the fabricated LED chips on a heat-sink circuit board and mounting of a silicon hemisphere.

Texturing of the light-output surface, which was done to enhance the efficiency of LED radiation extraction, was performed by wet chemical etching with a solution based on hydrofluoric acid, ammonium fluoride, and hydrogen peroxide. Hemispheres 0.2–0.5 μm in height forming as a result of this process provided the maximum enhancement of electroluminescence intensity and LED efficiency. The dielectric antireflective coating deposited onto the textured surface acts as a protector and suppresses the Fresnel reflection of outgoing radiation.

5. LED characteristics

The power-current characteristics and the external quantum efficiency (EQE) of light-emitting diodes fabricated in accordance with the growth and post-growth procedures detailed above were examined to analyze the electroluminescence properties of LEDs. Measurements were carried out with 0–200 mA pulsed currents flowing through the studied samples.

Figure 3 shows the current dependences of the output optical power (curve *1*) and EQE (curve *2*) of a light-emitting diode with an area of 1 mm^2. The maximum obtained EQE value was 37.5% in the current range of 100–200 mA.

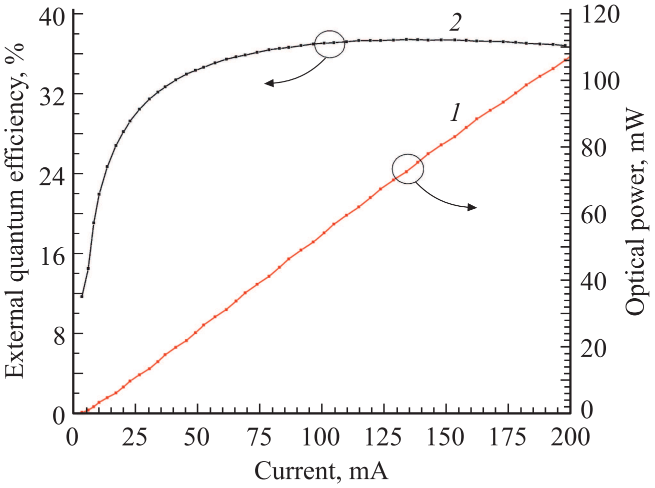

Figure 3. Power-current characteristic (*1*) and current dependence of the external quantum efficiency (*2*) of a light-emitting diode with a double (BR + silver mirror) reflector.

6. Conclusion

AlGaAs/Ga(In)As heterostructures for LEDs ($\lambda = 850$ nm) with a double (BR + silver mirror) reflector were fabricated by MOCVD. It was demonstrated that the Bragg reflector structure ensures both mirror reflection of rays incident on the BR at near-right angles and total internal reflection of „lateral" rays incident on the BR at angles ~ 20 ang. deg to the plane of heterostructure layers. A post-growth technology of LED fabrication, which involves transferring the structure with a mirror (Ag) layer onto the p^+GaAs carrier wafer with subsequent etching of the growth n-GaAs substrate, texturing of the light-output surface, and deposition of an antireflective coating and Ohmic contacts, was developed.

The measured external quantum efficiency of the fabricated LEDs was as high as EQE = 37.5%. This value exceeds considerably the efficiency of devices based on similar heterostructures including either a Bragg reflector [7] or a mirror (silver) reflector [9].

Conflict of interest

The authors declare that they have no conflict of interest.

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