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Effect of GaAsP barrier layers on the parameters of InGaAs/AlGaAs laser diodes emitting in the 1050 – 1100-nm spectral range

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***Abstract*. To improve the parameters of laser diodes emitting in the 1000 – 1070-nm spectral range and develop highly efficient laser diodes emitting in the 1070 – 1100-nm range, it is proposed to introduce GaAsP barrier layers into the active region of the quantum-well InGaAs/AlGaAs heterostructure, which compensate for enhanced mechanical stresses. This considerably improves the luminescence characteristics of heterostructures and changes conditions for generating misfit dislocations. The long-wavelength lasing at 1100 nm becomes possible due to an increase in the thickness of quantum wells and in the molar fraction of InAs in them. The manufactured laser diodes emitting in the 1095 – 1100-nm range have low threshold currents, the high output power and high reliability.**

Keywords: *heterostructure, GaAsP barrier layers, stress compensation, quantum well, laser diode.*

1. Introduction

Laser diodes (LDs) emitting in the 1050 – 1100-nm spectral range are widely used at present as master oscillators in solid-state and fibre laser systems, open atmospheric communication links, and in scientific research. The development of efficient LDs based on InGaAs/AlGaAs heterostructures in this wavelength range involves the problem of decreasing the concentration of crystal defects in the active region. Defects and, first of all, misfit dislocations appear because the lattice periods of the active-region (InGaAs) and substrate (GaAs) materials are different. To obtain lasing at a wavelength of 1050 nm and above, it is necessary to dope the heterostructure with In atoms at considerable concentrations. In this case, stresses produced in the heterostructure approach their critical values at which misfit dislocations are generated or exceed these values. Defects generated in the heterostructure considerably reduce the internal quantum yield, optical losses increase, and additional current leak channels appear.

There exist several ways for solving this problem. In [1], it was proposed to use stressed InGaAs buffer layers changing the distribution of mechanical stresses in the active region. Another method is based on a change in the standard epitaxial growth conditions and the use of new materials that favour the generation of misfit dislocations by kinetic methods [2]. In this paper, we employ the approach based on the compensation of mechanical stresses in the active region [3]. This method seems to be more promising because it only weakly changes the active region geometry, almost does not affect the transport of carriers, and does not require any considerable modification of the technological cycle.

The use of stressed GaAsP barrier layers with stresses opposite to those produced by the InGaAs layer allows the compensation for misfit stresses appearing in the active region, which improves the quality of heterostructure crystals, thereby increasing the LD efficiency. In addition, the emission wavelength of LDs can be increased compared to that of already available LDs.

2. Experimental

The InGaAs/AlGaAs heterostructures were grown by the method of MOS hydride epitaxy in a SIGMOS-130 horizontal quartz reactor with a rotating graphite substrate holder at the growth temperature 720 °C and pressure 60 Torr. $Al(CH_3)_3$, $Ga(C_2H_5)_3$, $In(CH_3)_3$, AsH_3, and PH_3 were used as sources of the III and V group elements, and hydrogen was used as a carrier gas. Epitaxial growth was performed on n-GaAs (100) substrates. A number of heterostructures with the InGaAs/GaAsP/AlGaAs quantum-well stressed active region were grown (Fig. 1). The thickness of the $In_xGa_{1-x}As$ quantum well (QW) was 60 Å and its composition x was varied from 0.8 to 0.35. The

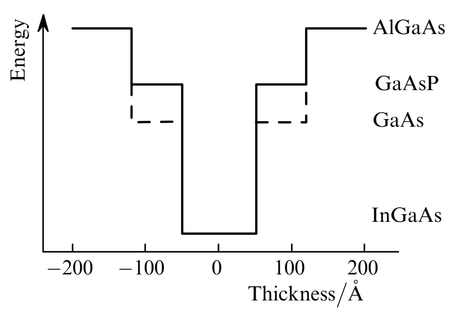

Figure 1. Energy diagram of the conduction band of the active region of InGaAs/GaAs/AlGaAs and InGaAs/GaAsP/AlGaAs heterostructures studied in the paper.

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composition of the $GaAs_{1-y}P_y$ barrier layer of thickness 70 Å was varied in the range $y = 0 - 0.12$. The QW and barrier were placed between $Al_{0.2}Ga_{0.8}As$ waveguide layers of thickness 0.15 μm and $Al_{0.3}Ga_{0.7}As$ emitter layers of thickness 1.5 μm. The heterostructure terminated in n- and p-GaAs contact layers of thickness 0.5 μm. The emission parameters of grown heterostructures were determined from photoluminescence measurements. Luminescence was excited at 532 nm by a solid-state laser. LDs fabricated from the above-described heterostructures emitted in the 1050 – 1100-nm region.

3. Results and discussion

The development of InGaAs/AlGaAs LDs emitting in the 1050 – 1100-nm region involves the control of mechanical stresses in the active region of the initial heterostructure. These stresses should not exceed a critical value at which the efficient generation of defects begins. Curve (*1*) in Fig. 2 shows the dependence of the critical QW thickness on the QW composition for the single-InGaAs/GaAs QW heterostructure calculated according to [4]. The region below curve (*1*) is 'allowed'. If the QW composition and width are in this region, misfit dislocations are not generated. Curve (*3*) in Fig. 2 shows the calculated dependence of the interband transition wavelength for the InGaAs/GaAs QW of the same geometry as that of the grown heterostructures: for the QW thickness of 60 Å (indicated by the dashed straight line), the molar fraction of InAs was varied in the range from 0.04 to 0.40. One can see from these dependences that when the QW thickness is 60 Å and the molar fraction of InAs exceeds 0.31 – 0.32, the heterostructure passes to the 'forbidden' region. In this case, the maximum photoluminescence wavelength of the heterostructure in the 'allowed' region with such an active region is 1045 – 1050 nm. The lasing wavelength of LDs fabricated from this heterostructure lies in the range 1065-1070 nm. The fabrication of a heterostructure LD on the 'allowed' region boundary is prevented by the generation of defects due to the errors of the epitaxial growth or under the action of subsequent technological operations.

These problems were solved in our study by using the compensation for stresses with the help of introduced GaAsP barrier layers. The lattice constant of the InGaAs QW is greater than that of the GaAs substrate, whereas the lattice constant of the GaAsP barrier layer is smaller. This results in the compensation of total mechanical stresses in the active region.

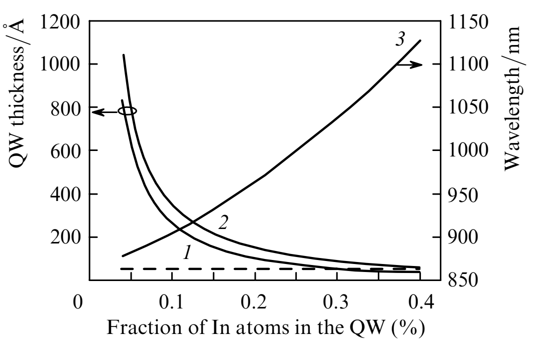

Figure 2. Critical thickness of the InGaAs/GaAs (*1*) and InGaAs/$GaAs_{0.88}P_{0.12}$ (*2*) QWs and the interband transition wavelength (*3*) as functions of the composition of the 60-Å thick InGaAs/GaAs QW. The horizontal dashed straight line indicates the QW thickness equal to 60 Å.

Figure 3 shows the calculated dependence of mechanical stresses and the experimental dependence of the photoluminescence intensity of the single-$In_{0.35}Ga_{0.65}As$/$GaAs_{1-y}P_y$ QW of thickness 60 Å on the molar fraction y of GaP in the barrier layer. The introduction of phosphorus into the barrier layer efficiently reduces the total stress in the heterostructure: for the molar fraction of GaP equal to 0.12, stresses are reduced by more than 40 %. The replacement of the GaAs barrier layer by $GaAs_{0.88}P_{0.12}$ reduces mechanical stresses below a critical value, thereby transferring the structure from the 'forbidden' to 'allowed' region. This is distinctly confirmed by the increase in the photoluminescence intensity with increasing the fraction of phosphorous atoms in the barrier.

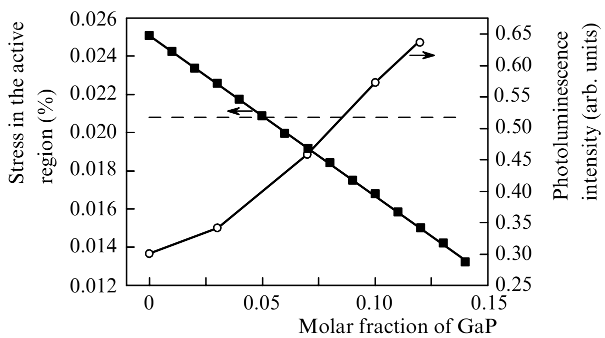

Figure 3. Dependences of mechanical stresses in the active region and the photoluminescence intensity of the heterostructure with the $In_{0.35}Ga_{0.65}As$/GaAsP QW of thickness 60 Å on the molar fraction of GaP in the barrier layer. The dashed straight line indicates the value of critical stresses in the QW.

The introduction of the stressed GaAsP barrier layer allows one to increase the QW thickness and the molar fraction of InAs in the QW compared to heterostructures with GaAs barrier layers. As a result, the critical conditions for the generation of misfit dislocations change. This fact is reflected in Fig. 2, where a new calculated dependence of the critical QW thickness is also presented for the heterostructure with the $GaAs_{0.88}P_{0.12}$ barrier layer [curve (*2*)]. According to the results obtained, the maximum achievable wavelength shifts to 1100 nm. The grown heterostructure exhibits intense photoluminescence with a maximum at 1097 nm.

Because GaAsP has a wider band than GaAs, the introduction of phosphorous atoms leads to a change in the band diagram of the active region. The height of barrier layers increases and the QW depth in the valence and conduction bands also increases. This is accompanied by the rise of the dimensional quantisation levels with respect to the QW bottom. As a result, the photoluminescence wavelength becomes shorter, which is undesirable. However, this effect is weak. Out experimental data show that the addition of 12 % of phosphorous atoms results in the shift of the photoluminescence wavelength only by 7 nm.

Note that the increase in the height of the barrier layer restricts the maximum molar fraction of GaP. The barrier potential should not exceed at least the waveguide layer level both in the conduction and valence bands. In this paper this level corresponds to the level of the $Al_{0.2}Ga_{0.8}As$ waveguide.

The barrier layer can be also restricted more rigidly because the energy jump at the waveguide-barrier interface affects the transport of carriers through the heterostructure. The requirements to the minimal value of this jump depend on the type of the device.

On the other hand, the maximum admissible content of phosphorous atoms in the barrier layer is restricted by the requirement of high quality of crystalline heterostructure. The GaAsP barrier layers are stressed, as the InGaAs QW, and the condition for the generation of misfit dislocations exists for them as well. Analysis of mechanical stresses produced during the heterostructure growth shows that the intense generation of defects can begin during the growth of the first (lower) barrier layer. Because the heterostructures under study contain a great amount of indium atoms, the compression stress from InGaAs exceeds the tensile stress from GaAsP at the beginning of the growth of the second (upper) barrier layer. This is clearly demonstrated in Fig. 3, where, despite the fact that both barrier GaAsP layers (upper and lower) are taken into account, mechanical stresses in the active region have the same sign as in the case of structures with conventional GaAs barriers.

Figure 4 shows the dependence of the critical thickness of a single $GaAs_{1-y}P_y$ layer grown on a GaAs substrate on the content y of phosphorous atoms. The dashed straight line indicates the fraction of phosphorous atoms at which the barrier-layer potential becomes equal to the waveguide potential in the conduction band. The potential jump at the AlGaAs – GaAsP layer interface is distributed equally between the valence and conduction bands. The GaAsP layers used in the paper are located in the 'allowed' region.

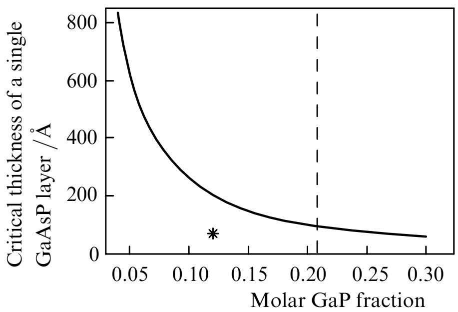

Figure 4. Dependence of the critical thickness of a single GaAsP layer grown on a GaAs substrate on the molar fraction of GaP. The dashed straight line indicates the composition of the barrier whose potential is equal to the potential of the $Al_{0.2}Ga_{0.8}As$ waveguide; the asterisk corresponds to the GaAsP barrier layer of thickness 70 Å with the maximum molar fraction of GaP equal to 0.12.

We found that the replacement of the GaAs barrier layer by GaAsP improves the luminescent characteristics of heterostructures emitting in the 1000 – 1070-nm region and allows us to grow heterostructures which can be used to fabricate LDs emitting in the 1070 – 1100-nm region and suited to modern requirements.

From the grown InGaAs/GaAsP/AlGaAs quantum-well structures, we fabricated test wide-contact LDs and single-mode diodes with a ridge mesa stripe of width 3 μm.

The study of lasing characteristics of wide-contact LDs made of heterostructures with stressed GaAsP barrier layers showed that the emission wavelength 1090 nm of these LDs was considerably longer than that of InGaAs/GaAs/AlGaAs heterostructure diodes and the threshold current density was lower by a factor of 1.5. The threshold current density for lasers with stressed barrier layers was lower than 600 A cm^{-2}.

The typical light – current characteristic of a cw single-mode mesa stripe LD with the cavity length 1000 μm operating at 25 °C is presented in Fig. 5. The minimal threshold current was 12 mA, while the scatter of threshold current values for 100 LDs did not exceed 16 mA. The single-mode cw output power exceeded 200 mW for the 300-mA pump current. The emission spectrum of the LD consisted of three – five longitudinal modes and had the FWHM of 4 – 5 nm. The experimental temperature dependence of the emission wavelength was 4 – 5 Å K^{-1}. The estimated service life of the LD at 25 °C was more that 10^4 h.

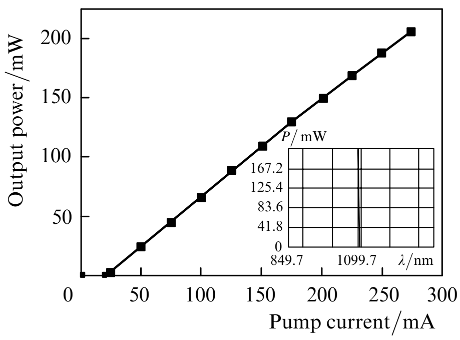

Figure 5. Typical light – current characteristic of LDs fabricated of InGaAs/GaAsP/AlGaAs heterostructures studied in the paper. The inset shows the emission spectrum for an output power of 200 mW (the resolution being 1 nm).

4. Conclusions

To improve the crystal structure of quantum-well InGaAs/AlGaAs heterostructures emitting in the 1050 – 1100-nm region, we have proposed to use stressed GaAsP barrier layers compensating for mechanical stresses in the active region. Our experiments have shown that this considerably reduces mechanical stresses in the heterostructure, resulting in the increase in the formation threshold of misfit dislocations and in the enhancement of the luminescence intensity. Single-mode LDs have been fabricated from the grown heterostructures, which emit in the 1050 – 1100-nm region, have low threshold currents (12 mA), high quantum efficiency (70 %), and improved reliability.

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