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# Epitaxial heterostructures of the active region for near-infrared LEDs

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The influence of AlGaAsP, GaAsP and AlGaAs/GaAsP compensating layers on the optical quality of the active area based on InGaAs/GaAs quantum wells for LEDs emitting at a wavelength of 940 nm has been studied. Heterostructures with multiple quantum wells have been grown by MOVPE technique using various approaches to compensating structural stresses. An increase in photoluminescence intensity by more than 32% was demonstrated when using AlGaAs/GaAsP compensating layers.

**Keywords**: quantum wells, LED, InGaAs, epitaxy, heterostructures.

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Light emitting diodes (LEDs) operating in the near infrared range (700−2500 nm) play an important role for a number of applications. These include optical diagnostics, biomedical imaging, optical communications, night vision systems, security systems and data storage [1]. Recently, their application has been extended to optical sensors in wireless devices, time-of-flight sensors, and aerial drones [2]. The use of multiple quantum wells (MQW) as the active area of LEDs offers several advantages over double heterostructures (HS), in particular, it improves their internal quantum efficiency [3]. However, the MQW layers, particularly $In_xGa_{1-x}As$, in the active area of the LED have a lattice mismatch with the GaAs substrate, leading to limitations in improving the IR LED output power [4]. It has been demonstrated in a number of studies that the use of layers in the active area of the MQW that compensate for the stresses caused by mismatch can significantly improve the performance of devices [5–7].

In this work, a comparative study of the effect of compensating layers (CLs) of different types, in particular AlGaAsP, GaAsP and AlGaAs/GaAsP combination, on the photoluminescent properties of MQW $In_xGa_{1-x}As$ emitting at a wavelength of 940 nm is carried out.

The investigated HSs were grown by metal-organic vapor phase epitaxy (MOVPE). As reference samples, two HSs based on MQW without CL, emitting at wavelengths of 850 and 940 nm, were created. Both structures included wide-band AlGaAs barriers 200 and 50 nm thick, with an active area of several QWs between them. In the case of HS at 850 nm, it consisted of six QWs $In_{0.11}Ga_{0.89}As/Al_{0.20}Ga_{0.80}As$ (sample A). In the case of the QW at 940 nm — of $In_{0.14}Ga_{0.86}As/GaAs$ (sample B). The QW thicknesses were 3 and 7 nm for samples A and B, respectively. The thickness of the AlGaAs spacer layers varied from 15 to 30 nm. The obtained HSs were investigated by analyzing the photoluminescence (PL) spectra, which were recorded at two optical excitation densities by a Nd : YAG laser with an emission wavelength of 532 nm.

The value of the maximum intensity of PL (IPL) for the LED emitting at 840 nm is almost 3 times the result from sample B (see Figure 1). If we estimate the value of the total stress in both HSs by the product of the mismatch value of the lattice constant ($da/a$) and the value of the thickness ($h$) of the active area layers (QW and spacer layers), this value will be 2 times greater for the B sample: $+135000$ ppm · nm versus $+63000$ ppm · nm for sample A, respectively. The significantly increased stress in HS may explain the low maximum IPL of sample B.

To increase the PL intensity of the MQW at 940 nm and improve the structural quality of the HS, it is necessary to minimize the total stress. One way is to reduce the concentration of In in QW. However, according to calculations based on the solid-state QW model [8], in this case, an increase in the QW thickness to 10 nm or more would be required to maintain the target wavelength of 940 nm. This value is already close to the values of the critical thickness of the InGaAs [9] pseudo-morphic layer, at which the stressed layer will relax with the formation of mismatch dislocations at the layer boundary. This will lead to the degradation of the electrophysical properties of the material and the appearance of spreading dislocations in the HS, which will affect the parameters of the device, as shown, for example, in the work [10]. Thus, the most promising approach, as discussed earlier, is the use of stress-compensating layers. Sufficiently thick compensating layers will also act as spacer layers (spacers) separating QWs in the array.

$Al_{0.25}Ga_{0.75}As_{0.96}P_{0.04}$ and $GaAs_{0.94}P_{0.06}$ the layers that replaced the AlGaAs spacer layers in the HS and introduce a compensating tensile strain, are chosen to compensate for the compressive strain in the InGaAs QW.

The lattice mismatch ($da/a$) between $Al_{0.25}Ga_{0.75}As_{0.96}P_{0.04}$ and GaAs substrate is approximately $-2000$ ppm. To use such a layer as a compensating layer (with replacement of the AlGaAs spacer layer), while maintaining the emission wavelength at 940 nm, according to the solid-state model calculation [8], an increase in the In concentration in the InGaAs QW to 17% is required. The calculated QW thickness was 4.6 nm. The following expression from the continuum elasticity theory [11,12] is used to calculate the optimal CL thickness more accurately:

$$t_b = t_{sl}\left[\frac{A_{sl}a_b^2(a_0 - a_{sl})}{A_b a_{sl}^2(a_b - a_0)}\right], \tag{1}$$

where $t_b$ and $t_{sl}$ — the thicknesses of the CL and the QW stressed layer, $a_b$ and $a_{sl}$ — their lattice constants, $a_0$ — the lattice constant of the substrate, $A_b$ and $A_{sl}$ — the stiffness constants depending on the stiffness coefficients $C_{11}$ and $C_{12}$ according to the formula:

$$A_i = C_{11,i} + C_{12,i} - \frac{2C_{12,i}^2}{C_{11,i}}. \tag{2}$$

Following this calculation, the optimal CL thickness of $Al_{0.25}Ga_{0.75}As_{0.96}P_{0.04}$ should be 48 nm. A series of HSs with MQW $In_{0.17}Ga_{0.83}As/Al_{0.25}Ga_{0.75}As_{0.96}P_{0.04}$, in which the thickness of the CLs varied from 30 to 75 nm (sample C series), were grown and their PL was measured. The dependence in Figure 2 shows that the range of optimal thicknesses of CL $Al_{0.25}Ga_{0.75}As_{0.96}P_{0.04}$ CL is 45–50 nm, which is in full agreement with the results obtained using the continuum elasticity theory.

The approach of using the CLs $Al_{0.25}Ga_{0.75}As_{0.96}P_{0.04}$ described above has the following drawback. Firstly, the thickness of the spacer layer (45–50 nm) is large enough to create an effective active area of the LED (electron-hole overlap and radiative recombination rate decreases). Second, the large concentration of In (17%) in the QW leads to conditions close to the critical thickness, which can also adversely affect the optical quality of the HS.

However, using $GaAs_{0.94}P_{0.06}$, the lattice mismatch $da/a$ between the CL and the GaAs substrate is smaller and is approximately −4000 ppm, which allows a significant reduction in the thickness of the CL compared to the HS $In_{0.17}Ga_{0.83}As/Al_{0.25}Ga_{0.75}As_{0.96}P_{0.04}$, described above. According to the solid-state model calculation, when the AlGaAs spacer layers CL $GaAs_{0.94}P_{0.06}$ are replaced, the thickness of the QW will be 7 nm at an In concentration of ∼ 14%. Calculation by formula (1) predicts a CL thickness $GaAs_{0.94}P_{0.06}$ of 14 nm.

Based on these calculations, an HS containing MQW $In_{0.14}Ga_{0.86}As/GaAs_{0.94}P_{0.06}$ was grown (sample D). In addition, the approach proposed in [13] was taken into account, where a combined barrier consisting of layers $AlGaAs/GaAs_{0.94}P_{0.06}$ was proposed as a CL. The authors of the work [13] note that a thin AlGaAs layer can be used to reduce the sharp unbalanced strain from two adjacent InGaAs and GaAsP layers. Using a similar approach, we grew HSs with MQWs $In_{0.17}Ga_{0.83}As/Al_{0.20}Ga_{0.80}As/GaAs_{0.94}P_{0.06}$ (series E samples). The PL spectra from HSs emitting at 940 nm are shown in Figure 3, and the parameters are summarized in the table.

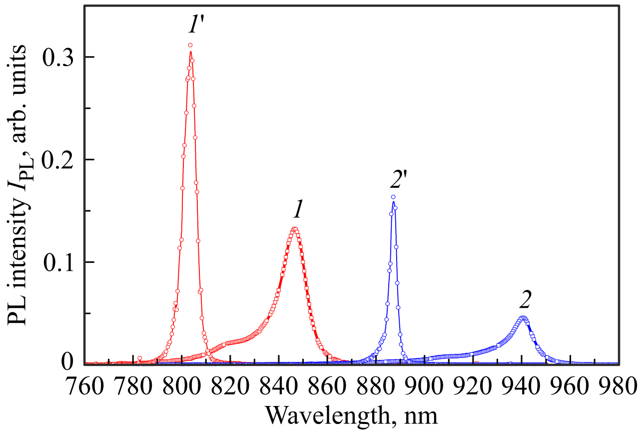


**Figure 1.** PL spectra for samples A and B at room temperature (*1, 2*) and at liquid nitrogen temperature (*1′, 2′*).

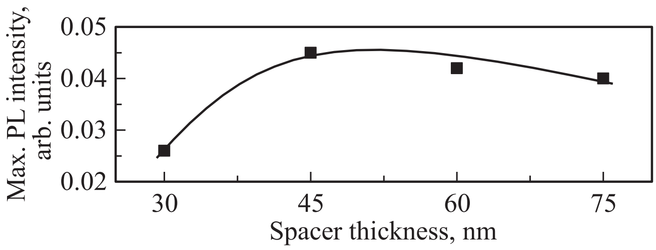


**Figure 2.** Dependence of the IPL maximum on CL thickness in a series of MQW $In_{0.17}Ga_{0.83}As/Al_{0.25}Ga_{0.75}As_{0.96}P_{0.04}$ samples (sample C series).

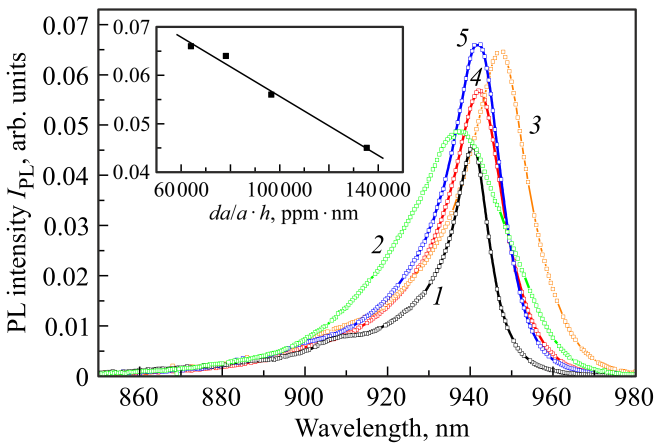


**Figure 3.** PL spectra at room temperature for samples *1* — B, *2* — C, *3* — D, *4* — E1, and *5* — E2; inset — dependence of the IPL maximum at room temperature on the product of $da/a$ by layer thickness. (The colored version of the figure is available on-line).

An increase in the maximum $I_{PL}$ from samples with compensating layers E1 and E2 compared to sample B is observed (Figure 3, curves *4, 5* and *1*, respectively). The E2 sample with 18 nm thick $GaAs_{0.94}P_{0.06}$ CLs showed a 32% increase in IPL maximum. The estimated value of the

Growth and optical parameters of experimental heterostructures

| HS | QN | $t_{QW}$, nm | CL | $t_{QS}$, nm | $da/a \cdot h$, ppm $\cdot$ nm | max $I_{PL}$, arb.units |
|---|---|---|---|---|---|---|
| A | $In_{0.10}GaAs$ | 3 | $Al_{0.2}GaAs$ | 30 | +63000 | 0.132 |
| B | $In_{0.14}GaAs$ | 7 | GaAs | 14 | +135000 | 0.045 |
| C | $In_{0.17}GaAs$ | 4.6 | $Al_{0.25}GaAsP_{0.04}$ | 45 | +17500 | 0.048 |
| D | $In_{0.14}GaAs$ | 7 | $GaAsP_{0.06}$ | 14 | +78000 | 0.064 |
| E1 | $In_{0.14}GaAs$ | 7 | $Al_{0.2}GaAs/GaAsP_{0.06}$ | 4/10 | +96500 | 0.056 |
| E2 | $In_{0.14}GaAs$ | 7 | $Al_{0.2}GaAs/GaAsP_{0.06}$ | 4/18 | +64000 | 0.066 |

total stress (as a product of $da/a$ over the thicknesses of the active area layers) of sample E2 is almost identical to the similar estimated value of $da/a$ for sample A (+64000 ppm). The dependence of IPL on the estimated value ($da/a \cdot h$) for all investigated HSs clearly demonstrates the influence of stresses in the HS on its optical quality (see inset in Figure 3). However, it should be noted that, despite the relatively low value of $da/a \cdot h$ for the best sample of the C series, its $I_{PL}$ only slightly exceeds the level of the reference sample B. Thus, the pit thickness close to the critical value (at high indium concentration in InGaAs solid solution) affects the optical quality of HS even more than the mechanical stress factor.

## Conflict of interest

The authors declare that they have no conflict of interest.

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