Investigation of \( \text{In}_{0.7}\text{Ga}_{0.3}\text{As}/\text{In}_{0.7}\text{Al}_{0.3}\text{As} \) metamorphic HEMT-heterostructures by photoluminescence spectroscopy

D. S. Romanovskiy\(^1\), S. A. Tarasov\(^1\), G.B. Galiev\(^2\), S.S. Pushkarev\(^2\)

\(^1\)Saint-Petersburg Electrotechnical University “LETI”, Prof. Popova 5, St. Petersburg 197376, Russia
\(^2\)Institute of Ultrahigh Frequency Semiconductor Electronics, Russian Academy of Sciences, 117105 Moscow, Nagorny proezd, 7 (5).

E-mail: DSRomanovskiy@gmail.com

Abstract. Low-temperature photoluminescence and photoreflectance have been studied in several metamorphic HEMT- (MHEMT-) heterostructures with the same active regions and different buffer layer designs grown by solid-source molecular beam epitaxy. The indium mole fraction in \( \text{InAlAs/InGaAs/InAlAs} \) single quantum well (QW) is 0.7. It was found that structures with step-graded metamorphic buffer have better quality. Also it was shown that mismatched superlattices in metamorphic buffer can influence on the half-width of photoluminescence spectra. The possible attribution of photoluminescence and photoreflectance spectral lines and their thermal behaviour are critically discussed.

Metamorphic epitaxial heterostructures with quantum well \( \text{InAlAs/InGaAs/InAlAs} \) for high electron mobility transistor (HEMT) grown on GaAs substrates have recently attracted considerable attention [1]. Such heterostructures have the following advantages in comparison with heterostructures on InP substrates: lower substrate cost, less substrate brittleness, and high flexibility for bandgap engineering. On the one hand the range of indium mole fraction 0.3–0.5 in quantum well is available only with GaAs substrates. On the other hand the range of indium mole fraction 0.5–1.0 may be achieved by using metamorphic technology either on InP substrates or on GaAs substrates, but as it was mentioned above GaAs substrates are more paying.

Metamorphic technology employs in the case of epitaxial growing of layers mismatched with substrate by the lattice parameter. It consists in epitaxial growing of thick transition layer with gradually varying composition between substrate and active region of HEMT-heterostructure concluding quantum well, doping layer and contact layer. This layer is named metamorphic buffer (MB), its thickness is about 1 micron or more. Usually the InAlAs compound is used for this purpose due to good isolated properties, but also InGaAlAs compound may be employed [2].

In lattice-mismatched structures consisting of layers with a thickness in excess of the critical thickness for plastic relaxation, misfit dislocation networks are formed. MB behaves as a virtual substrate that can be designed in order to accommodate the lattice parameter of the topmost structure to that of the underlying substrate. MB allows the reduction, by means of magnitude, of the dislocation density by confining them in definite regions of the structure, which can be kept apart from the active layers of the device. MBs may have constant or graded composition, either in a steplike or in a continuous way. Superlattices (SLs) composed of very thin alternate compressive strained and tensile strained layers are capable of blocking threading dislocations generated in metamorphic buffer thus preventing their penetration into the active region [3, 4]. It was demonstrated that threading dislocations bend near the strained superlattices and spread in the lateral direction after that [5]. In this...
study efficiency of step-graded and continuous MBs with internal strained superlattices has been investigated.

The heterostructures used in this study (hereinafter referred to as «samples») were grown by conventional molecular beam epitaxy on GaAs substrates. Their construction shown in figure 1 is typical for metamorphic HEMT-heterostructures with the exception of upper layer: instead of doped contact layer n-InGaAs the undoped protective layer i-InGaAs was grown for the correct measurement of electrophysical parameters. Samples possess different design of metamorphic buffer as shown on figure 2. Sample 895 was grown on GaAs substrate 2° misoriented from (1 0 0) plane towards [0 1 1] direction, other samples were grown on GaAs (1 0 0) substrates.

| Layer                                      | Thickness, nm |
|--------------------------------------------|---------------|
| In$_{0.7}$Ga$_{0.3}$As (protecting layer)  | 7             |
| In$_{0.7}$Al$_{0.3}$As (barrier)          | 22            |
| Si (delta-layer)                           | –             |
| In$_{0.7}$Al$_{0.3}$As (spacer)           | 6             |
| In$_{0.75}$Ga$_{0.25}$As (quantum well)   | 16            |
| In$_{0.7}$Al$_{0.3}$As (barrier)          | 46            |
| In$_{x}$Al$_{1-x}$As, $x = 0.75 \rightarrow 0.70$ (inverse step) | 50            |
| In$_{0.7}$Al$_{0.3}$As (smoothing layer)  | 115           |
| 50 In$_{x}$Al$_{1-x}$As (MB)              | $h_{MB}$      |
| {AlGaAs/GaAs} × 5 (SL1)                   | 2.0/1.5       |
| In$_{0.7}$Ga$_{0.3}$As (substrate)        | –             |

**Figure 1.** General construction of heterostructures

An arrangement of the photoluminescence (PL) apparatus [6] employed in this study is shown in fig. 3. A MDR-2 monochromator scanned the sample over a range of 0.5–1.1 eV. An InGaAs detector was employed. In order to suppress the effect of second order diffraction, a long path filter was set in front of monochromator. Samples were excited using an Nd:YVO$_4$ laser with 5320 Å wavelength that was chopped at 218 Hz. For low-temperature measurements samples were mounted in a variable-temperature closed cycle helium cryostat (10 K < $T$ < 300 K).

In additional to the PL research MHEMT-heterostructures have been investigated by photoreflection technique (PR). It is possible by adding to PL system a tungsten lamp with direct current supply. Care is to be taken to overlap laser’s and lamp’s spots on the sample and to focus reflected lamp beam into the monochromator. See more details in figure 3.

Electrophysical parameters measured from Hall effect with Van der Pau technique are summarized in table I.

| sample | $\mu_e$, cm$^2$/V·s | $n_S$, $10^{14}$cm$^{-2}$ |
|--------|---------------------|---------------------------|
| 300 K  | 77 K                |                           |
| 830    | 10500               | 33300                     | 1.45 | 1.38 |
| 888    | 11900               | 47100                     | 1.56 | 1.47 |
| 889    | 11600               | 44200                     | 1.53 | 1.45 |
| 895    | 11400               | 38700                     | 2.16 | 2.11 |
Figure 3. Simplified laboratory setup for PL and PR studies. Light scheme of PR technique is used (1 – monochromator, 2 – laser, 3 – sample in cryostat, 4 – lock-in amplifier, 5 – chopper, 6 – detector, 7 – spin controller, 8 – computer, 9 – lamp)

As we can see from spectra in figure 4 the highest intensity shows sample 889 with step-graded metamorphic buffer. There is a 5% difference in indium mole fraction between buffer layers. So we can suppose that it is the most successful construction of metamorphic buffer: it locks the most of dislocations from substrate and has minimum residual strain at the top. This supposition is agreed by Hall measurements (see table I).

Figure 4. PL spectra of MHEMT-heterostructures with different buffer constructions ($T = 77$ K)
One can see that the most intensive peak of sample 888 has greater energy position in comparison with other samples for about 0.1 eV. That might mean lower indium concentration in quantum well region of sample 888. The difference in indium concentration between sample 888 and the other samples is about 1–2%, which is normal for molecular beam epitaxy method.

**Figure 5.** Relative spectra of MHEMT-heterostructures at 300 K (solid lines) and at 77 K (dashed lines) a – 830, b – 888, c – 889, d – 895

The main peaks near 0.70 eV and 0.84 eV correspond to transitions from 2-nd electron confined state to the 1-st hole confined state in QW and from conduction band to the valence band in upper region of MB respectively. These peaks become more intensive at lower temperature, whereas the feature at 0.65 eV originate hypothetically from 1-st electron confined state to the to the 1-st hole confined state transitions have an opposite behavior (see figure 5). Moreover, the lower temperature, the lower intensity it has. In our opinion this is due to a strong localization of the 1-st electron confined state carriers in QW [7]. At lower temperatures localization of electrons and holes on the 1-st electron confined state becomes stronger so the probability of the radiative recombination decreases proportionally.
Sample 889 with step-graded metamorphic buffer has the minimum half-width of spectral line. It is probably due to deficiency of great defect concentration and non-radiative centers in the barrier material near the interface [8]. So, we suggest that this sample has the best quality of interface and minimum defect states in barrier layers.

Also sample 889 has much better temperature dependence of PL intensity. Figure 6 shows absolute spectra of two samples at two different temperatures. As mentioned earlier, sample 889 has much greater intensity at both temperatures. Moreover, as compared to sample 830 the increase in intensity at lower temperature is greater too: about 10 times for sample 889 and only 2 times for sample 830. It may be due to a lot of thermal independent defects and misfits in sample 830. If so, the decrease of temperature will slightly influence on radiative transition probability. On the other hand, if sample 889 has much more perfect structure and phonon scattering is the main nonradiative transition mechanism the temperature decrease will drastically improve the probability of radiative transitions from the first level in QW, as shown in figure 6 b.

Figure 6. Comparison of PL spectra intensity at 300 K (solid line) and 77 K (dashed line): a – 830, b – 889

Figure 7. Typical PL spectra of MHEMT-heterostructures at different temperatures
Figure 8 shows PR spectral line obtained at 11 K. One can see a lot of features (inflection points) that are similar to PL peaks. However there are a lot of PR features in energy region, where none of PL features observed. It is probably due to much higher sensibility of PR technique as compared to PL. Thereby PR features in non-PL energy regions may provide some additional information about subband transitions in QW or about interband transitions in MB material.

Conclusions

We have performed PL and PR investigation of metamorphic HEMT-heterostructures with In mole fraction ~ 0.7 in channel region. Transitions from conduction band to valence band in thick layers and from 1-st and 2-nd electron subband to heavy-hole subband in QW were observed in PL and PR spectra. The transition energies measured from PL spectra in good correlation with those calculated using the effective mass approximation. PL spectra show that the most successful heterostructure is sample 889 with step-graded metamorphic buffer. It has more pronounced temperature dependence of PL intensity, higher electron mobility $\mu_e$ and 2D electron concentration $n_S$. Also sample 889 with step-graded metamorphic buffer has the minimum half-width of spectral line. It is probably due to deficiency of great defect concentration and non-radiative centers in the barrier material near the interface. So, we suggest that this sample has the best quality of interface and minimum defect states in barrier layers.

PR spectra obtained are in good correlation with PL spectra. There are a lot of inflections at the energies similar to PL peaks. Also one can see a lot of PR features where none of PL peaks can be seen. It is normal state of things for PR. However some more evidence is required to analyze these spectra.
References

[1] New semiconductor materials. Biology systems. Characteristics and properties. [www.matprop.ru].

[2] Patent US 6818928 B2. Quaternary-ternary semiconductor devices / W.E. Hoke, P.S. Lyman ; Raytheon Company (US). – Appl. No. 10/310207 ; filling data 05.02.2002 ; publication date 16.11.2004.

[3] I.J. Fritz, P.L. Gourley, L.R. Dawson, J.E. Schirber. Electrical and optical studies of dislocation filtering in InGaAs/GaAs strained layer superlattices // Appl. Phys. Lett. – 1988. – Vol. 53. – P. 1098–1100.

[4] Patent US 7009224 B2. Metamorphic long wavelength high-speed photodiode / R.H. Johnson, J.K. Guenter, J.R. Biard ; Finisar Corporation. – Appl. No. 10/413186; filling data 14.04.2003 ; publication date 07.03.2006.

[5] G.B. Galiev, I.S. Vasil’evskii, S.S. Pushkarev, E.A. Klimov, R.M. Imamov, P. A.Buffat, B. Dwir, E. I. Suvorova. Metamorphic InAlAs/InGaAs/InAlAs/GaAs HEMT heterostructures containing strained superlattices and inverse steps in the metamorphic buffer // J. Cryst. Growth. – 2013. – Vol. 366. – P. 55–60.

[6] S. A. Tarasov, I. E. Gracheva, K. G. Gareev, O. E. Gordyushenkov, I. A. Lamkin, E. A. Mën’kovich, V. A. Moshnikov, A. V. Presnyakova. Atomic Force Microscopy and Photoluminescence Analysis of Porous Metal Oxide Materials // Semiconductors, 2012, Vol. 46, No. 13, pp. 1584–1588.

[7] PL features of heterostructures In₀.₅₃Ga₀.₄₇As/In₀.₅₂Al₀.₄₈As with double-side doping/A.F. Tsatsunlicov, V.M. Ustinov, A.U. Egorov et al.//Fizika I Tekhnika Poluprovodnikov. – 1996. – Vol. 30. – issue 10.– P. 1814–1821.

[8] The effect of potential fluctuations on the optical properties of InGaAs/InAlAs superlattices [Текст] / L.C. Pocas, E.M. Lopes, J.L. Duarte et al.//Journal of Applied Physics. – 2005. – Vol. 97. – P. 103518.