Metamorphic InGaAs photo-converters on GaAs substrates

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Abstract. Metamorphic heterostructure photoconverters (PC) based on InGaAs have been grown on GaAs substrates by the MOCVD technique. It has been shown that using the multilayer metamorphic buffer with layer thickness of 120 nm and In composition step of 2.5 % provides a good quality of the bulk layers grown on the buffer with up to 24 % of In. A PC with photosensitivity up to 1350 nm and the quantum efficiency of 80 % in the range of 1050–1100 nm have been made. The 34.5 % efficiency of laser radiation conversion at 1064 nm has been demonstrated.

1. Introduction
To date, solar cells (SCs) based on III-V heterostructures are the most effective devices in the field of converting renewable energy into electricity. The efficiency of the modern monolithic metamorphic triple-junction GaInP/GaAs/GaInAs SCs exceeds 44 % [1] and that of mechanically stacked 4-junction GaInP/GaAs-GaInAsP/GaInAs SCs is 46 % [2].

Application of the metamorphic growth of the wide band gap GaInP/GaInAs tandem [3-5] allows raising the SC efficiency compared to a pseudomorphic structure [6]. In this case, the lattice mismatch between subcells and a germanium substrate is compensated by a composition gradient set of metamorphic buffer layers. After relaxation of the buffer layers, a transition to a new lattice constant takes place and dislocations turn up on heterointerfaces. Owing to this, only the buffer layer remains strongly defective and penetration of dislocations into photoactive layers appears to be very little.

Another area of application of metamorphic PCs is wireless fiber optic systems for transmitting laser radiation power or information data. For this, one can use conventional 800–1300 nm lasers having different applications in medicine, industry and telecommunication systems. Laser photoconverters (LPC) for this wavelength range is the most in demand as an optical pair to a conventional powerful solid-state laser on Nd:YAG irradiating at 1064 nm. For this purposes a Si based LPC with about 40 % conversion efficiency for 1064 nm has been demonstrated [7]. However, the efficiency was low without using very complex special pyramid-like profiling of facial surface and maximal conversion efficiency was demonstrated at low radiation power. So, the development of efficient III-V LPC also promising for SHF applications is in great demand for modern optoelectronics.

In the present work, metamorphic InGaAs heterostructures with a wide composition range have been fabricated on GaAs substrates by the MOCVD technique, and PCs based on them have been created.
2. Experimental setup
Metamorphic PC structures were grown in a low pressure MOCVD reactor under 100 mbar on \( n^- \)GaAs (100) substrates misoriented by 6° towards the [111] direction. Metal alkyls were used as sources of the III-group atoms: threemethylgallium, threemethylaluminum, threemethylindium. Arsine was used as a source of As atoms. Monosilane and diethylzinc were used to dope layers with \( n^- \)type and \( p^- \)type impurity, respectively.

The PC structure represents a \( p^-n \) diode with a back surface barrier and a wide-band gap window (figure 1). Variation of the In portion in the layers of In\(_x\)Ga\(_{1-x}\)As metamorphic buffer (MB) was carried out stepwise with a step \( x \sim 2.5 \% \) at a thickness of one sublayer of \( \sim 120 \text{ nm} \). A set of In\(_x\)Ga\(_{1-x}\)As structures with In concentration \( x \) of the order of 10, 14, 19, 24 and 29 \% has been created with a number of sublayers in the MB region of 4, 6, 8, 10 and 12, respectively. The PCs based on these structures have been fabricated (figure 1).

Spectral dependencies of the quantum efficiency (QE) and reflection were recorded on a specialized installation in a widen wavelength range up to 1400 nm [8]. Study of structural parameters of PC structures was performed with using a raster SEM CamScan Series 4 DV100.

3. Results and discussion
Growth of MB layers of thickness greater than the critical one and relaxation of elastic stresses were resulting in forming the large amount of misfit dislocations, which were turning up on the buffer interfaces (figure 1, right). In the picture, a dislocation grid lying predominantly in the interfaces between layers with a different In content is clearly seen.

Application of MB has allowed obtaining a satisfactory In\(_x\)Ga\(_{1-x}\)As LPC surface morphology with the In content up to 24 \%, which is confirmed by the surface SEM pictures (figure 2a, b and c). Raising the In concentration \( x \) up to 29 \% resulted in a sharp deterioration of the surface morphology (figure 2d). This indicates insufficient relaxation of the elastic stresses in the MB layers and one can expect an increase of the defect concentration in the LPC photoactive layers.

It has been proved by investigations of the QE of the PCs created on the base of the grown structures (figure 3). Increase of In concentration resulted in broadening of the spectral response band.
because of decreasing the band gap of PCs. At the same time, the changing of QE in the range of 400–600 nm due to increase of absorption in a window layer has been observed.

Figure 2. Pictures of metamorphic In$_x$Ga$_{1-x}$As LPCs surface with the In concentration $x$: (a) – 10 %, (b) – 19 %, (c) – 24 %, (d) – 29 %, obtained by the SEM.

Figure 3. Spectra of the internal QE for In$_x$Ga$_{1-x}$As PC with the In concentration $x$: 1 – 0 % (pure GaAs), 2 – 10 %, 3 – 14 %, 4 – 19 %, 5 – 24 %, 6 – 29 %.

The maximum level of the QE spectra depended weakly on the In concentration at $x < 25$ % and was more than 90 % (figure 3, curves 2-5). Further increase of the In concentration $x$ up to 29 % resulted in a drastic drop of the maximum level of QE spectrum down to 81 % (figure 3, curve 6). It
was caused by an increase of defects concentration in the photoactive layers due to insufficiently effective relaxation of stresses.

The QE in the range of 800–1000 nm depends weakly on the In concentration (figure 4, curves 1,2) while for longer wavelengths, the dependency becomes much stronger. However, the developed structures give a possibility for creating effective LPC for wavelengths of up to 1100 nm. For 1064 nm the LPCs with the In concentration $x \sim 24\%$ will have the highest efficiency since such LPCs ensure the maximum QE of about 80 % (figure 4, curve 3). The weak dependence of the QE on In composition for wavelengths of 810 and 980 nm (figure 4, curves 1 and 2) will also allow creating wide band LPCs based on a structure with the In content $x \sim 24\%$ for effective conversion of laser beams in the range of 800–1100 nm.

It should be noted that for effective conversion of radiation at wavelengths in the range greater than 1250 nm it is necessary to raise the In concentration $x$ up to 30 % and higher (figure 4, curve 4). However, the developed MB technology does not allow suppressing defect penetration in photoactive LPC layers. Thus, it is necessary to optimize the design of MB and conditions for its growth to create effective LPCs for the given wavelengths.

PCs fabricated of a structure with the In content $x \sim 24\%$ have demonstrated a high value of the efficiency for the 1064 nm wavelength (that of the Nd:YAG laser) which was 34.5 % at the radiation density of 3–4.5 W/cm² (figure 5). Further decrease of efficiency at higher radiation density occurs due to increase of series resistivity losses at higher photocurrent.

**Figure 4.** Dependencies of internal QE on In$_x$Ga$_{1-x}$As LPC composition at wavelengths of conventional powerful lasers.

**Figure 5.** Dependence of the efficiency of converting 1064 nm laser beam on its power.

### 4. Conclusion
Investigations of metamorphic LPCs based on In$_x$Ga$_{1-x}$As fabricated by the MOCVD on GaAs substrates have been carried out. It has been shown that the use of a multilayer metamorphic buffer region with a step by layer thickness of 120 nm and by In content of 2.5 % ensures good relaxation of elastic strain and an effective turn up of dislocations on heterointerfaces up to the In concentrations $x \sim 24\%$. With increasing the indium concentration up to 29 %, such buffer does not allow growing bulk layers with a satisfactory surface morphology. LPCs based on In$_x$Ga$_{1-x}$As layers with the In concentration $x \sim 24\%$ demonstrated the maximum internal QE of about 95 % with its further decrease down to 80 % in the wavelength range of 1050–1100 nm. The 1064 nm laser beam conversion efficiency was 34.5 % at the radiation density of 3–4.5 W/cm².

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