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Molecular beam epitaxy of metamorphic buffer for InGaAs/InP photodetectors with high photosensitivity in the range of 2.2–2.6 um

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Abstract

The present work is concerned with finding optimal technological conditions for the synthesis of heterostructures with a metamorphic buffer for InGaAs/InP photodetectors in the wavelength range of 2.2–2.6 um using molecular beam epitaxy. Three choices of buffer structure differing in design and growth parameters were proposed.

The internal structure of the grown samples was investigated by X-ray diffraction and transmission electron microscopy. Experimental data analysis has shown that the greatest degree of elastic strain relaxation in the InGaAs active layer was achieved in the sample where the metamorphic buffer formation ended with a consecutive increase and decrease in temperature. The said buffer also had InAs/InAlAs superlattice inserts.

The dislocation density in this sample turned out to be minimal out of three, which allowed us to conclude that the described heterostructure configuration appears to be the most appropriate for manufacturing of short wavelength infrared range pin-photodetectors with high photosensitivity.

Keywords: Molecular beam epitaxy, Metamorphic buffer, Short wavelength infrared range photodetectors, X-ray diffraction analysis, Transmission electron microscopy

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1. Introduction

In the recent years short wave infrared range (SWIR) photodetectors for 1-3 um are actively investigated. This band includes several atmospheric windows, which opens a lot of opportunities for utilizing it in the satellite observation, night vision and thermal imaging devices, lidars, absorption spectroscopy of gases and liquids, including CO_2, etc. [1]. One of the well-established material systems for SWIR photodetectors is $In_xGa_{1-x}As/InP$ with $x \geqslant 0.53$. The absorption layers of $In_{0.53}Ga_{0.47}As$ composition are epitaxially grown lattice-matched to the InP substrate and can be used for detector manufacturing with 1.7 um cutoff wavelength. To further extend the operating range in the long-wave direction it is necessary to increase indium mole fraction in the active layer, which results in a compressive elastic strain being introduced. The degree of layer to substrate lattice mismatch can be as high as ~ 2 % for the detectors with operating wavelength of 2.5 um. In this case the value of dark current dramatically increases, which greatly inhibits the device's performance. Nevertheless, extended wavelength SWIR photodetectors based on the InGaAs/InP heterostructures are successfully implemented using a transition layer approach known as metamorphic buffer [2].

The idea behind the metamorphic buffer is to create either an abrupt or a smooth transition from one material's lattice constant (substrate in this case) to the lattice constant of another material being used in the active layer. Buffer design and material parameters are being chosen to prevent dislocations propagating into the active layers of the heterostructure. Aside from application in extended wavelength SWIR photodetectors this technology is also used for manufacturing of a wide variety of semiconductor structures, such as high electron mobility transistors [3], lasers [4], solar energy convertors [5].

In the course of this paper a search for optimum molecular beam epitaxy (MBE) growth conditions of a metamorphic buffer for the high sensitivity 2.2–2.6 um photodetectors with InGaAs absorption layer on InP substrates. The InGaAs solid solution with indium mole fraction x=0.83 was chosen as the active layer material. The buffer configuration was chosen to be linearly graded with a lattice mismatch "overshoot" relative to the active layer's lattice parameter, since such a buffer can compensate partial relaxation of the layer [6]. An employment of the linearly graded buffer is more effectively inhibits the dislocation propagating into the active region when compared to the step-graded buffer [7], and also allows one to achieve small surface roughness. Moreover, the lack of an abrupt composition variation in the buffer layer leads to a lesser probability of a three-dimensional growth mode [8].

The buffer and upper cap layers were formed using InAlAs solid solution. Heterojunction-based photodetectors demonstrate better performance compared to their homojunction counterparts in the same wavelength range. For example, a zero-bias resistance area product R0A increases at least an order of magnitude in the heterostructure-based design [9], which on its own contributes to the increase in detectivity [10].

The present work is concerned with finding optimal technological conditions for the synthesis of heterostructures with a metamorphic buffer for InGaAs/InP photodetectors in the wavelength range of 2.2-2.6 um using molecular beam epitaxy.

2. Experimental

In order to study the effect of metamorphic buffer growth modes on the quality of the InGaAs absorption layer and the density of threading dislocations, three heterostructures (#1, #2 and #3) were manufactured. Three samples were grown by molecular beam epitaxy on semi-insulating "epi-ready" InP (100) substrates using the industrial MPE Riber MBE49 setup. Benefits of the setup include the use of high purity materials, availability of precision growth control methods and ultra-high vacuum during synthesis, which ensures high quality structures. The possibility of abrupt interruption and subsequent continuation of the material flow to the substrate makes it possible to obtain sharp heterointerfaces, and the high temperature stability of two-zone effusion sources of group III metals and an arsenic cracking source ensures the consistency of the composition. The quality of the grown layers was controlled *in situ* by the reflection high-energy electron diffraction system (RHEED).

Each test sample contained 500 nm $In_{0.83}GaAs$ active layer and InAlAs graded buffer. The design of the test structures is shown in Fig. 1.

At the beginning of the growth InP substrate was annealed, and then a smoothing 100 nm thick lattice-matched $In_{0.52}AlAs$ layer was grown. Then a 2 um $In_xAl_{1-x}As$ metamorphic buffer was formed by gradually increasing the In mole fraction from 0.52 to 0.87 with a 4 % excess in indium content relative to the active layer. Gradient buffer growth was carried out by reducing the aluminum source temperature. In addition to that, the synthesis differed for three samples in temperature conditions and the presence (or absence) of additional inserts. The metamorphic buffer in all three structures was formed at the temperature of ~ 400–410 °, the subsequent layers at ~ 490 ° with a flow ratio of group V/III materials ~ 10. Such conditions, on the one hand, can contribute to the relaxation of the crystal lattice due to the low temperature of the substrate [11, 12], and also allow the majority of dislocations to be kept in the buffer layer and reduce their spread to the upper layers. On the other hand, these growth conditions can prevent the three-dimensional growth, as would be evidenced by the point diffraction pattern.

In contrast to structure #1, sample #2 undergone a peak temperature increase to ~ 520 ° at the end of graded layer growth. Then the temperature was decreased to 100 ° for an exposure period of 20 minutes followed by a rise to 520 ° for 1 minute. Lastly, after that the active layer was deposited at a temperature of 490 °. Sample #3 was obtained using the same growth conditions as #2, but additionally contained three InAs/InAlAs superlattice inserts in the buffer layer with a spacing of 500 nm in-between.

During the metamorphic layer deposition, the growth pattern was controlled by RHEED. At the beginning of the buffer synthesis, as the In fraction increased, (1x1) surface reconstruction appeared, when the RHEED streaks thickened and blurred. However, in the process of layer growth the thickening gradually disappeared. Towards the end of the buffer growth, and then for the InGaAs layer as well, a striped diffraction pattern with rather narrow streaks was seen and (4x1) surface reconstruction occurred. Thus, during the metamorphic buffer formation, a significant improvement in the surface quality of the epitaxial layer was observed, which indicates the relaxation of the graded layer, as strain increased with thickness.

The internal structure of the obtained samples was characterized by X-ray diffraction and transmission electron microscopy (TEM). X-ray diffraction studies were carried out on a DRON-8 diffractometer with a Bartels monochromator and a sharp-focus X-ray tube with Cu$K_{\alpha1}$ radiation, λ = 0.15406 nm. TEM studies were carried out on a Zeiss Libra 200FE microscope with a dark field detector. Samples for TEM measurements were prepared using standard thinning processes.

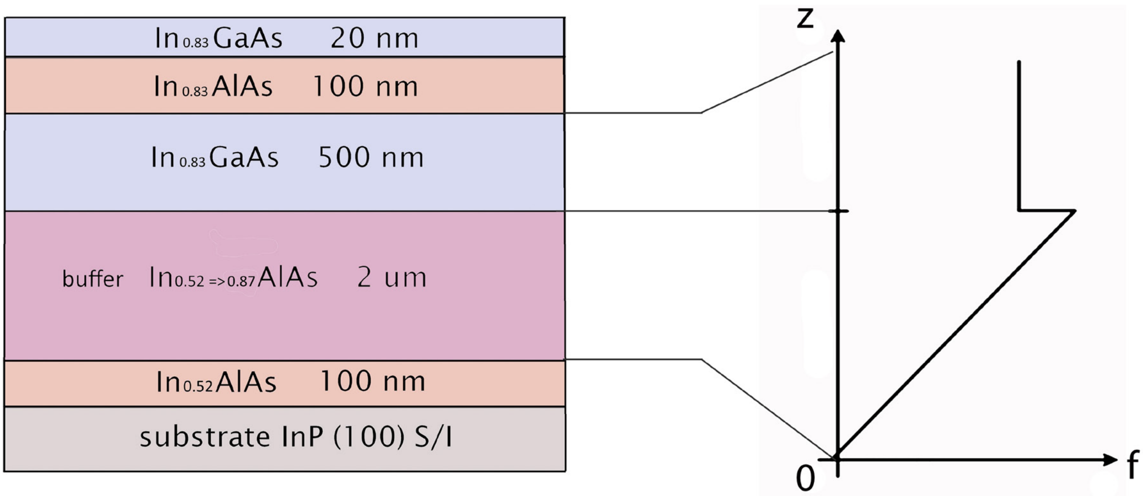

Fig. 1. Test samples layer composition and schematical representation of a graded buffer with a mismatch “overshoot” relative to absorption layer, where *f* – lattice mismatch, *z* – distance from the substrate interface

3. Results and discussion

3.1.X-Ray diffraction studies

Fig. 2 shows the X-ray diffraction curves from the test structures. Each curve contains diffraction peaks from the InP substrate, InGaAs absorption layer and linearly graded metamorphic buffer positioned between the first two. To the right of the substrate peak the diffraction maximum from the InAlAs smoothing layer can be seen. In structure #3, the intensity of the diffraction maximum from the test InGaAs layer is 2.5 times higher relative to the two other samples, while the full width at half maximum of this peak is the smallest being 0.39° (versus 0.47° and 0.51° for #1 and #2, respectively). The InGaAs diffraction maximum of sample #3 nearly coincides with the calculated maximum from a completely relaxed layer of ~ 82 % In composition, which is close to the target composition. This allows us to make a conclusion that in the sample #3 the metamorphic buffer is completely relaxed and further growth of the active layer took place in the absence of internal strain. In samples #1 and #2, the peak is shifted to the left, which may be due to the presence of residual strain in the layer and thus incomplete relaxation.

3.2. TEM studies

Fig. 3 shows dark-field TEM [110] plane cross-sectional images of the experimental samples. Structural areas of linearly graded metamorphic buffer and $In_xGa_{1-x}As$ active layer with In molar fraction c x = 0.83 are indicated on the TEM images. Observed structural defects can be identifies by the two main types – misfit dislocations and threading dislocations. In Fig. 3 a), corresponding to the sample #1, a large number of threading dislocations are observed in the metamorphic buffer layer. Moreover, dislocations are also present in the absorption layer InGaAs, which is unacceptable for the device performance. The observed threading dislocations are predominantly 60-degree dislocations with Burgers vectors $b = a/2 <110>$, where a – unit cell parameter. In other words, these are dislocations parallel to [110] and [$1\underline{1}0$] directions [13]. Besides that, 90-degree threading dislocations with Burgers vectors $b = \sqrt{2}\,a/2$ can be also seen in the InGaAs active layer. Some of the dislocations spread over the entire thickness of the active and upper cap layers and propagate to the surface.

Sample #2 (see Fig. 3 b) is characterized by a lower density of threading dislocations compared

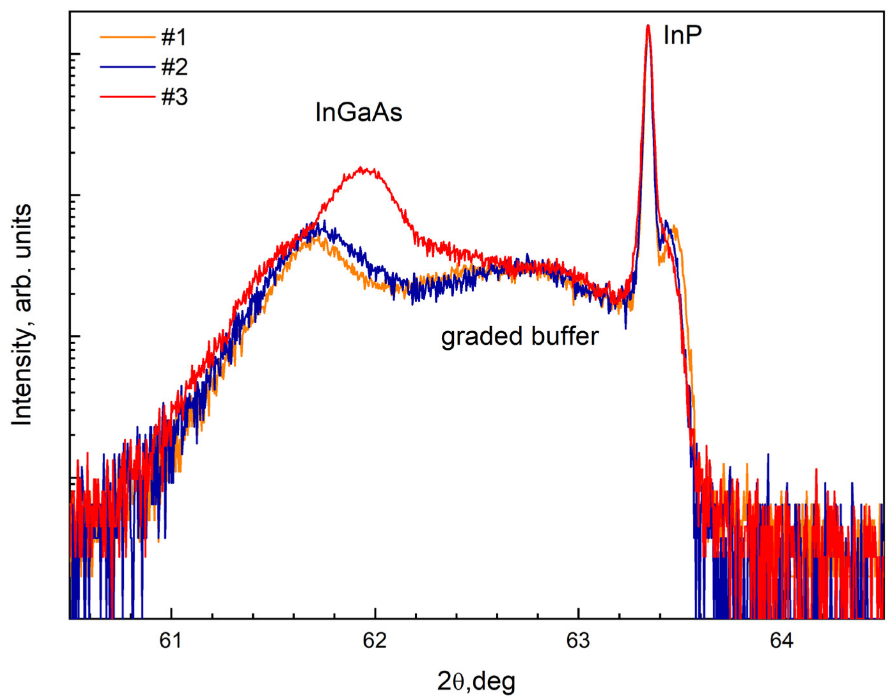

Fig. 2. X-ray diffraction curves of the test structures in relation to the symmetric InP (004) reflection

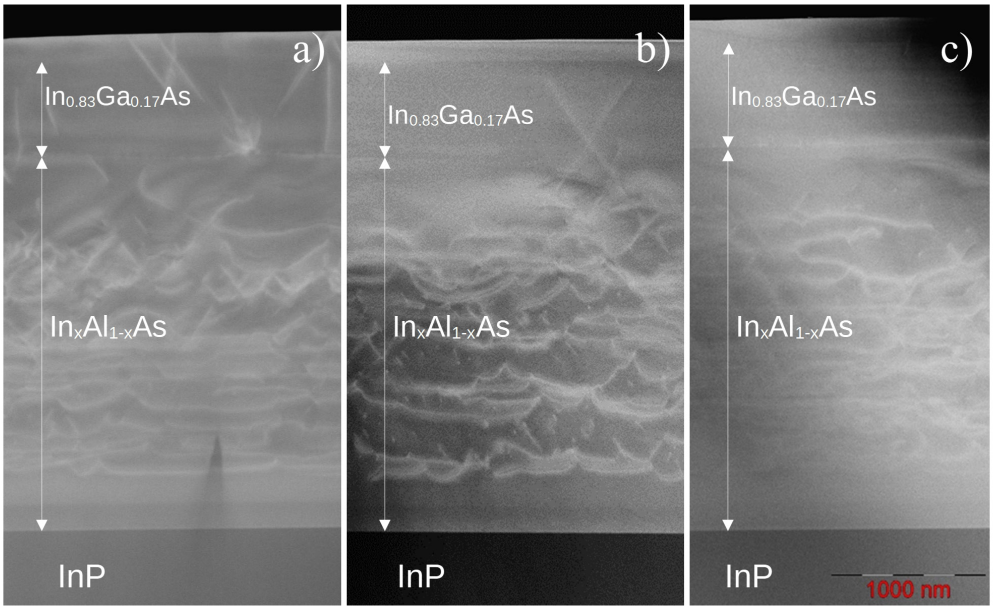

Fig. 3. TEM images of the test structures in the [110] section plane: a) sample #1, b) sample #2, c) sample #3

to sample #1. Nevertheless, one can notice the propagation of 60-degree dislocations from the metamorphic buffer to the active region. Misfit dislocations are also clearly distinguishable on the figure. The distribution of misfit dislocations over the buffer layer is almost uniform up to thicknesses of about 1500 nm. In the upper part of the buffer layer the formation of misfit dislocations stops. This result is consistent with the theoretical predictions for a metamorphic ~1400 nm thick $In_xAl_{1-x}As$ buffer (with a maximum $x = 0.87$) with a linear gradient profile [14].

Fig. 3 c) shows the TEM image of sample #3. Contrasting inserts, typical for superlattices, are distinguished in the buffer area. Moreover, threading and misfit dislocations are also observed in this sample. The threading dislocation density decreases in the direction of epitaxial growth until the dislocations finally disappear in the upper part of the buffer layer. Based on the image analysis, it can be concluded that there is a dislocation-free area in the buffer near the interface. Thus, putting InAs/InAlAs inserts in the buffer layer could be useful to inhibit the nucleation and propagation of dislocations.

4. Conclusion

In the scope of this work, we studied several various approaches to the MBE growth of linearly graded metamorphic buffers $In_xAl_{1-x}As$ for the implementation of InGaAs pin-photodetectors sensitive in 2.2–2.6 um wavelength range on InP substrates. Employing methods of internal structure analysis, such as X-ray diffraction and transmission electron microscopy, conclusions about the effectiveness of the three certain buffer designs for the formation of strain-free absorption layer were drawn. The most optimal metamorphic buffer configuration was determined. The main design feature is the inclusion of three InAs/InAlAs superlattice inserts in the metamorphic buffer with 500 nm spacings between them. At the same time, after the graded buffer growth, the temperature of the substrate was subsequently raised and lowered. It is shown that heterostructures with this buffer are characterized by the lowest of the three test structures threading dislocations density in the active layer.

Thus, the fundamental possibility of MBE synthesis of strain-free InGaAs/InP heterostructures with a metamorphic buffer was shown. The authors suggest to follow the technological parameters of the MBE process given in the text during the growth of SWIR photodetector heterostructures with high photosensitivity in the range of 2.2–2.6 um.

Contribution of the authors

The authors contributed equally to this article.

Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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