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Structural and morphological characterization of InGaAs/InP 2.5 μm photodetector heterostructures with different metamorphic buffer layer profiles

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Abstract. $In_{0.83}Ga_{0.17}As$/InP PIN-photodiode heterostructures with different metamorphic buffer layers' profiles have been grown by molecular beam epitaxy. Cross-section transmission electron microscopy images have been investigated to estimate the density of threading dislocations. Heterostructures' surface and its roughness have been researched by atomic force microscopy. The lowest dislocation density and surface roughness were observed in the heterostructure with a linear-graded metamorphic buffer layers (MBLs). MBLs were designed with a In mole fraction gradient of 0.18 rel. units/μm. Epitaxial growth was concluded with a final in situ high-temperature annealing step. Potential distribution of the heterostructures' cleaved surface has been researched by Kelvin probe force microscopy.

Keywords: metamorphic buffer layers, infrared photodetectors, molecular beam epitaxy

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Материалы конференции
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Структурные и морфологические особенности гетероструктур InGaAs/InP фотодетекторов с длиной волны отсечки 2.5 мкм с различным профилем метаморфного буферного слоя

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Аннотация. $In_{0,83}Ga_{0,17}As/InP$ PIN-фотодиодные гетероструктуры с различными профилями изменения состава метаморфных буферных слоев были выращены методом молекулярно-пучковой эпитаксии. Изображения просвечивающей электронной микроскопии в геометрии поперечного сечения были проанализированы для оценки плотности прорастающих дислокаций. Рельеф поверхности гетероструктур и шероховатость были исследованы с помощью атомно-силовой микроскопии. Среди исследованных образцов минимальными значениями плотности дислокаций и шероховатости поверхности характеризуется гетероструктура с метаморфным буферным слоем линейного профиля с градиентом состава 0,18 отн. ед./мкм, рост которого завершался in situ высокотемпературным отжигом. Распределение потенциала по поверхности скола гетероструктур было исследовано методом сканирующей Кельвин-зонд-микроскопии.

Ключевые слова: метаморфные буферные слои, инфракрасные фотодетекторы, молекулярно-пучковая эпитаксия

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Introduction

InGaAs/InAlAs/InP photodetectors operating in the spectral range of 2.2–2.6 um are valuable for applications like infrared spectroscopy, gas analysis, and night vision [1]. The goal of achieving high performance in this spectral range requires the use of $In_{0.83}Ga_{0.17}As$ absorption layer. However, the lattice constant mismatch of 2.1% between the $In_{0.83}Ga_{0.17}As$ absorption layer and the InP substrate makes it necessary to use metamorphic buffer layers (MBLs).

The mismatch of epitaxial layers' lattices leads to an increase in the threading dislocations density. In the present work, the influence of the MBLs' profile on the crystalline quality of the heterostructures has been investigated.

MBLs with continuous linear composition gradients, commonly used for the growth of InGaAs layers high in In content on InP and GaAs substrates, are reported to improve dislocation suppression, reduce dark currents [2], and decrease overall surface roughness [3]. Alternatively, in other work a step composition gradient achieved minimal surface roughness [4].

An interesting variation, not yet studied for InGaAs/InP metamorphic growth, is a square-root graded, or so called convex graded MBLs [5], where the composition changes non-linearly (steep grading near the substrate and moderate grading near the active region). This design was shown to enhance stress relaxation in highly mismatched InGaAs/GaAs heterostructures. We also investigated a step-linear MBLs. Furthermore, the thermocycling process during step-linear sample growth was performed after every step, which might be another mechanism for reducing dislocation density [6].

Materials and methods

The semi-industrial molecular beam epitaxy Riber49 setup was used to manufacture PIN-photodiode heterostructures. Three structures were grown on N^+-type “epi-ready” InP (100) wafers. These samples differed in their MBLs’ profiles, and in this work they are labelled S-1, S-2 and S-3.

N^+-$In_xAl_{1-x}As$ metamorphic buffer layers with In mole fraction changing from 0.52 to 0.83 were used in all heterostructures. They were formed after a thin 100 nm lattice-matched $In_{0.52}Ga_{0.48}As$ layer. MBLs’ width was 2 um in all structures, and MBLs’ growth temperatures were maintained at 450–490 °C. Structure S-1 included convex-graded MBLs, where In mole fraction changed as $x = 0.52 + 0.219\sqrt{z}$ where z is MBLs’ width in um. Sample S-2 was made with linear-graded MBLs. In heterostructures S-1 and S-2 MBLs growth was followed by *in situ* thermal annealing with peak temperature rise up to 530 °C for 30 seconds and slow cooling to 50 °C over 25 minutes for an exposure period of 20 minutes. Structure S-3 was manufactured with step-graded MBLs consisting of five 200-nm-wide steps separated by 100-nm transition regions where In mole fraction changed linearly. The thermocycling process for sample S-3 involved a 100 °C temperature decrease over 2.5 minutes, then a return to the growth temperature over 2.5 minutes, which was repeated after every step. After MBLs, 1.5 um $In_{0.83}Ga_{0.17}As$ active layer was grown. The absorption layer was slightly n-doped using silicon (Si). At the end, 0.6 um p^+-type contact layers doped with beryllium (Be) were formed on the top of the heterostructure.

In other studies, the application of inverse step is demonstrated [2]. We suppose that the inverse step similarly improves characteristics of heterostructures with different MBLs, Therefore, we find it necessary to first optimize the metamorphic buffer layers design and then apply the inverse step.

The cleavage of samples was done with a sharp scalpel from the substrate side of the samples. The cleaved surface was examined far enough from the edge of the samples so that the mechanical effect of the cleavage process had a minimal effect on the chipped surface.

Transmission electron microscopy (TEM) images were acquired with a JEM-2100F (Jeol) 200 kV Field Emission analytical electron microscope. Both the (001) heterostructure surface and the (110) cleavage surface morphologies of the samples were analysed by atomic force microscopy (AFM) under ambient conditions on a NTegra Aura setup (NT-MDT, Moscow, Russia), operating in semi-contact mode, using NSG11 probes with a stiffness coefficient of 5N/m and a radius of curvature of the probe needle tip of 10 nm. For the study of the cleaved surface potential distribution a Kelvin probe force microscopy (KPFM) using conductive probes was applied.

Results and discussion

TEM images of analysed structures are presented in Fig. 1. All images demonstrate high dislocation density in the MBLs of approximately ~ 10^{11} cm^{-2}. The dislocation densities in the active layer of heterostructures were calculated for samples S-2 and S-3. For S-2 its value is ~$5\cdot10^8$ cm^{-2} and for S-3 it is ~$5\cdot10^9$ cm^{-2}. Dislocation density for S-1 cannot be estimated due to the poor quality of the respective TEM image. Therefore, further research on the dislocation density in S-1 is required. In previous studies, a dislocation-free region was observed [7]. The current images, however, do not show it. The dislocation density values, presented in literature for similar metamorphic heterostructures, are typically ~10^7 cm^{-2} [2]. In our work, this value is higher, which may be due to the absence of an inverse step in the MBLs, and can be further improved.

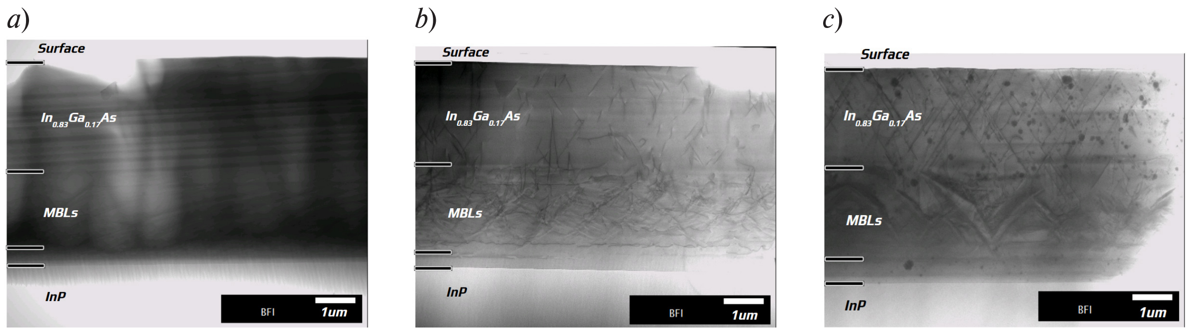

Fig. 1. TEM images of heterostructures S-1 (*a*), S-2 (*b*) and S-3 (*c*)

AFM images of heterostructures' surface, which are shown in Fig. 2, were analysed. Surface roughness was measured as root-mean-square (RMS). It is demonstrated that sample S-2 has the lowest RMS of 17.3 nm. In other studies, this value for MBE-grown linear MBLs is about 10–20 nm [2], which is in good agreement with our work. Non-linear MBLs on GaAs substrates demonstrate RMS of 1–2 nm for 10×10 μm^2 surface area [5]. Therefore, it was expected that convex-graded MBLs on InP substrates would also show the best results. However, this structure revealed a much higher RMS value, suggesting that further research on the optimal growth conditions of InP-based convex-graded MBLs is required.

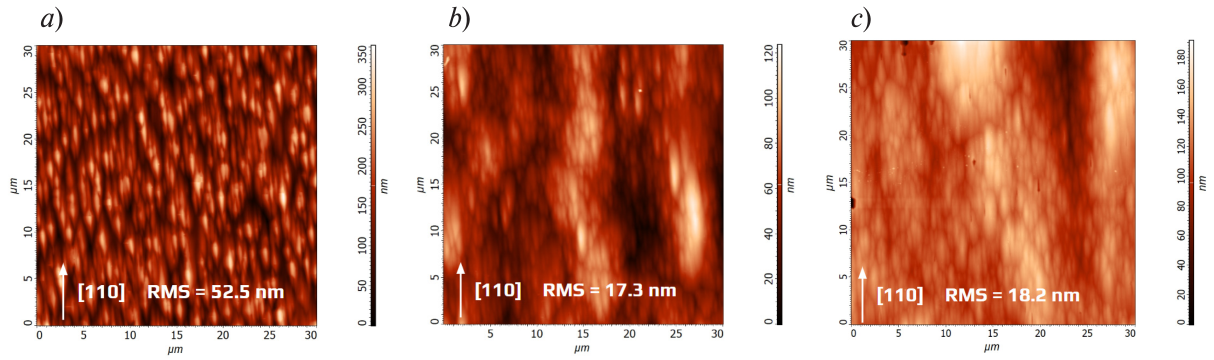

Fig. 2. AFM images of heterostructures' surface S-1 (*a*), S-2 (*b*) and S-3 (*c*)

All images reveal typical anisotropic features of the metamorphic structures' surface along the [110] direction [2]. We can conclude that usage of linear-graded MBLs not only decreases the dislocation density, but also leads to a better surface quality.

AFM and KPFM were used to better understand the cleavage morphology of three samples (Fig. 3).

Sample S-1 (Fig. 3, *a*–*d*) demonstrates a good correspondence between the heterostructure layer thicknesses observed in the AFM and KPFM images. The crystalline quality can be evaluated from images of the cleaved surface topography. The surface features, which appear as diagonal stripes, most likely, follow threading dislocations. A reduction of dislocation density is observed near the upper interface of MBLs. However, it is continued with a sharp increase in the absorption layer. A dislocation-free area can be seen only in *p*-layer.

Images of the heterostructure S-2 (Fig. 3, *e*–*h*) do not demonstrate diagonal surface irregularities, which can be associated with lower dislocation density. Nevertheless, this sample has a rougher cleavage surface. Profiles of surface topography and electric potential correlates, but there are some differences. For example, from 2 to 4 um potential remains almost constant, while surface height changes.

Analysis of sample S-3 (Fig. 3, *i*-*l*), similar to S-1, demonstrates surface features indicative of threading dislocations. In the active region, larger stripes are visible, but with a lower density, which may confirm the better compensation of elastic strain and the annihilation of threading dislocations. Irregularities are observed at the heterointerface between the metamorphic buffer layers and the active region on both AFM and KPFM images, which might show the formation of misfit dislocations [8].

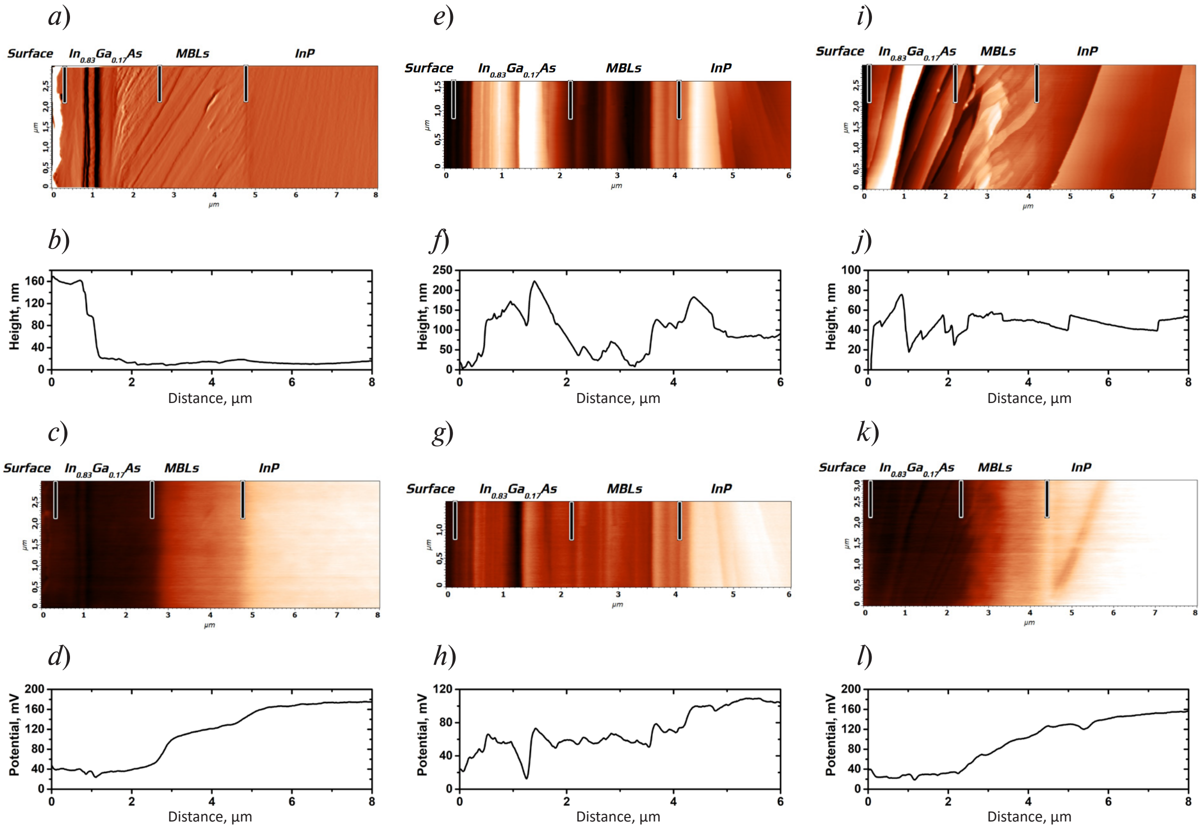

Fig. 3. AFM and KPFM measurements on the surface cross-section of samples S-1 (*a*–*d*), S-2 (*e*–*h*), S-3 (*i*-*l*)

In our work, we used the KPFM method to clearly illustrate the shape of the potential distribution on the law of change of the In mole fraction.

The electric potential profiles for all three samples show a decrease from the *n*-doped InP substrate to the *p*-layer. Local changes of a slope of the curve are noticeable, which might be connected with the band structure [9]. We believe that such a study of the cleavage potential can be used for the modelling of the band structure of the corresponding structures.

Conclusion

$In_{0.83}Ga_{0.17}As/InP$ PIN-photodiode heterostructures with different metamorphic buffer layers' profiles have been researched. It is demonstrated that the structure with a linear-graded buffer has the lowest dislocation density of ~$5\cdot10^8$ cm^{-2} in the active layer and the least surface roughness (RMS = 17.3 nm). The cleavage topography and electric potential distribution of three samples were researched.

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