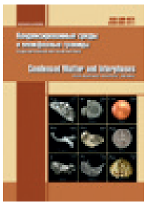

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Electrophysical properties of PIN photodiodes of the 2.2-2.6 µm range based on InGa(Al)As/InP heterostructures with a metamorphic buffer layer

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Abstract

Due to a large number of applications in the near and short-wave IR spectrum and a relatively high detectivity, PIN photodiodes based on epitaxial InGa(Al)As/InP heterostructures are of a great scientific interest. The operational spectral range of such photodetectors is up to 2.6 µm. However, to reach such wavelengths it is necessary to synthesize heterostructures with metamorphic buffer layers. In our study, we investigated the current-voltage and capacitance–voltage characteristics of PIN photodiodes based on InGa(Al)As/InP heterostructures with an original metamorphic buffer layer and an $In_{0.83}Ga_{0.17}As$ absorbing layer grown by means of molecular beam epitaxy.

The photodiode chips were formed using standard post-growth processing techniques. The diameter of the photosensitive area of the obtained diodes was 140 µm. The dark currents and the shunt resistance were ~ 300 nA and ~ 25 kΩ at the voltage of -10 mV respectively.

Therefore, the suggested metamorphic buffer layer effectively eliminates threading dislocations in the active area of the heterostructure. The obtained heterostructures with metamorphic buffer layers can be used to produce IR photodetectors for the spectral range of 2.2-2.6 µm.

Keywords: Molecular beam epitaxy, Metamorphic buffer layers, Near IR photodetectors, Current-voltage characteristic, Capacitance–voltage characteristic, Dark currents

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1. Introduction

IR photodetectors attract attention due to the specifics of their spectral range, namely the high contrast of short-wave IR radiation in the Earth's atmosphere. They also have numerous applications in the atmospheric window in a range of 1–3 µm, including in satellites, night vision equipment and thermal visors, lidars, fluid and gas spectroscopy, etc. [1]. Therefore, the development of effective near IR photodetectors is a promising area.

At the moment, the most well-studied is the wavelength range of up to 1.7 µm, with the leading position occupied by photodiodes based on $In_{0.53}Ga_{0.47}As/InP$ lattice-matched heterostructures, which are characterized by lower dark currents and higher mobility of charge carriers as compared to photodiodes based on germanium (Ge). However, the 1.9–2.7 µm spectral range (in between the strong absorption spectra of water vapor) is often more preferable. In this case, analogous to the short-wave range, PIN photodiodes based on heterostructures with active $In_xGa_{1-x}As$ ($x > 0.53$) layers grown on indium phosphide substrates demonstrate good performance. Their cut-off wavelengths can be up to 2.6 µm [2; 3]. However, during the transition from the lattice-matched heterostructure to the layers enriched with indium, the dark currents of photodiodes grow rapidly by several orders of magnitude, which results in an abrupt drop in their detectivity [4]. Nevertheless, InGa(Al)As nanoheterostructures on InP substrates can compete with HgCdTe and InAsSb materials in the 2.2-2.6 µm spectral region because this technology makes it possible to synthesize perfect crystalline semiconductor structures with highly homogeneous parameters and to use mature post-growth processing techniques to form crystal photodiode. Photodetectors based on InGa(Al)As/InP are highly effective at room temperature. Therefore, they require neither active, nor passive cooling, which helps to make the final devices smaller and more attractive commercially.

As compared to photodetectors based on $In_{0.53}Ga_{0.47}As/InP$ lattice-matched heterostructures, photodetectors based on InGa(Al)As in the 2.2–2.6 µm spectral region are more difficult to produce, because they require very thick (about 1–2 µm) active layers with a high (up to 83%) concentration of indium. The pseudomorphic epitaxial growth of such layers on InP is impossible due to the strong elastic strain [5]. To grow relatively thick $In_{0.83}Ga_{0.17}As$ layers on InP substrates, it is necessary to artificially match the crystal lattice parameters of the material and the substrate.

The misfit dislocations occurring during the epitaxial growth are extended charged defects of the crystal structure and result from elastic deformations taking place during the growth of layers with different parameters of their crystal lattices. Dislocations always have a negative effect on the properties of active optoelectronic devices, including photodetectors. Specifically, they reduce the breakdown voltage and increase the leakage current within the whole reverse bias range [6]. In the active area of photodiodes, dislocations can act as conductive channels between *p*-type and *n*-type regions, i.e. as a *p-n* junction barrier. Furthermore, dislocations result in a number of traps in the band gap for charge carriers acting as parasitic recombination centers. One solution to this problem involves introducing transitional epitaxial layers of variable compositions between the InP substrate and the active area of InGaAs, i.e. using the so-called metamorphic buffer layer [7]. The main purpose of growing metamorphic structures is to slow down the penetration of dislocations into the buffer layers and to obtain a strain-free active area with a low density of defects in the crystal structure [8–10]. Metamorphic buffer layers prevent the penetration of dislocations into the active areas of photodiodes with an $In_{0.83}Ga_{0.17}As$ absorbing layer, thus reducing the dark currents. Together with shunt resistance and the capacitance of photodiodes, dark currents are critical for the detection and identification of small optical signals with high signal-to-noise ratio.

Therefore, it is important to obtain InGa(Al)As/InP heterostructures for PIN photodetectors characterized by a high structural quality and low dark currents and functioning in the spectral region of up to 2.6 µm. To obtain such a heterostructure, we suggested a design for InAlAs metamorphic buffer layers and performed the epitaxial growth of the test samples with an active area of a high structural quality [11]. In the present study, we investigated the effect of the suggested structure of the metamorphic buffer layer on the electrophysical properties of crystal PIN photodiodes.

2. Experimental

The sample heterostuctures with metamorphic buffer layers for PIN photodiodes were grown by means of molecular beam epitaxy on n^+-InP (100) doped epi-ready substrates using a Riber MBE49 industrial molecular beam epitaxy setup. The heterostructure obtained for PIN photodiodes is demonstrated in fig. 1. It contained a p^+-$In_{0.83}Al_{0.17}As$ region, a 1500 nm thick n^--$In_{0.83}Ga_{0.17}As$ layer serving as an IR absorption i-region, a 2 µm thick n^+-InAlAs graded metamorphic buffer layer of variable composition, and a 100 nm thick $In_{0.52}Al_{0.48}As$ lattice-matched layer. The layers between the substrate and the active InGaAs area were doped with silicon (n^+), and the contact layers were doped with beryllium (p^+). The InGaAs region was doped to the degree of $(0.5–2)·10^{16}$ cm^{-3}. The $In_xAl_{1-x}As$ metamorphic buffer layer was formed by linearly increasing the molar fraction of In from 0.52 to 0.86 at a constant temperature of the substrate with three thin inserts [InAs/InAlAs]×3 every 0.5 µm. At the end of the formation of the graded layer, the structure was annealed at a maximum temperature, and the temperature of the substrate holder was then lowered. The technology of the epitaxial growth of metamorphic buffer heterostructures for PIN photodiodes is detailed in [11].

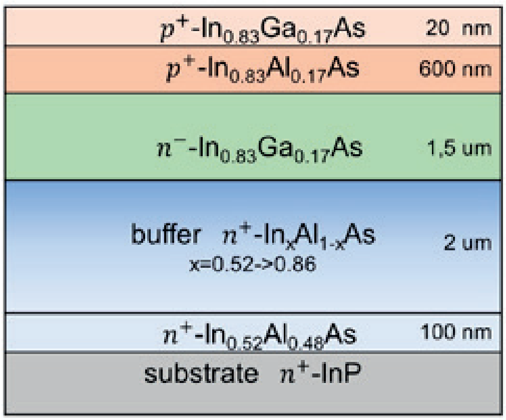

Fig. 1. The heterostructure obtained for PIN photodiodes

Fig. 2 presents the diffraction pattern of the studied sample. The diffraction pattern demonstrates peaks of the InP substrate, the InGaAs layer, and the InAlAs metamorphic buffer with a linear composition gradient. The X-ray diffraction was performed using a DRON-8 diffractometer with a Bartels monochromator and the radiation at the X-ray tube of $CuK\alpha_1$ = 0.15406 nm. The diffraction maximum of the InGaAs layer corresponds to the reference maximum of a completely strain-free layer with a composition of about 83%.

In order to perform electrophysical measurements of the heterostructure by means of double photoresistive mask lift-off photolithography, we formed p- and n-type ohmic contacts based on a Ti/Pt/Au metal system and anode-cathode contact pads based on the V/Au metallization. The diameter of the photosensitive area of the diode was 140 µm. An optical microscope image of the obtained crystal photodiodes is presented in fig. 3. The crystals were then studied by means of electrophysical methods using a SUSS MicroTec PM 8 microprobe unit at the temperature of 295 K.

3. Results and discussion

3.1. Current-voltage characteristics

The effectiveness of the suggested design of the metamorphic buffer layer can be assessed based on the dark current-voltage characteristics of the resulting photodiode. The dark current-voltage characteristics of several photodiodes from the middle of the wafer are shown in fig. 4. They were obtained using an Agilent B1500A semiconductor device parameter analyzer in the forward bias range V from -1 to 0.25 V with a 5 mV step. The figure demonstrates strictly asymmetric forward and reverse branches, which is common for diodes. The reverse current branch initially located in the third quadrant was projected to the positive semiplane for the convenience of presentation on a logarithmic scale. The most rapid increase in the dark current is observed at low reverse voltage bias range of up to 100 mV. The reverse branch corresponds to low dark currents: ~ 10 uA at reverse voltage bias of 1 V and ~ 300 nA at 10 mV respectively.

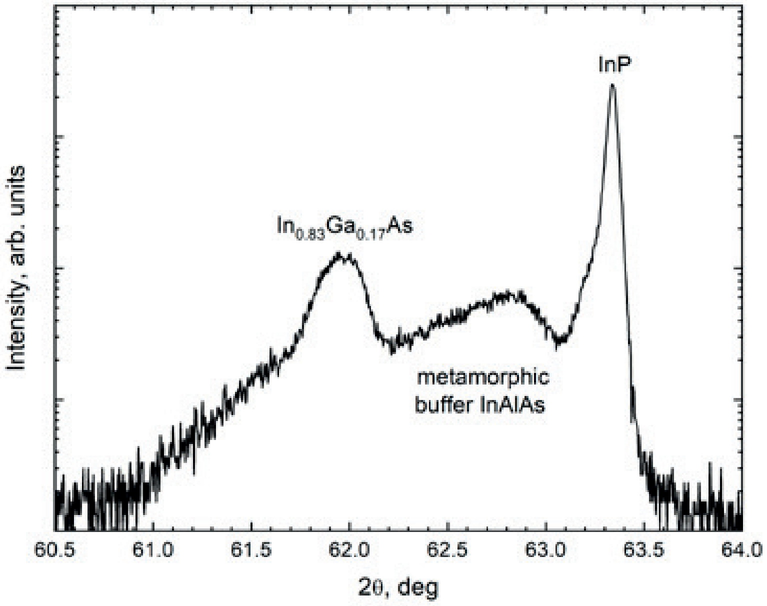

Fig. 2. X-ray diffraction pattern of the heterostructure with regard to the symmetric InP (004) reflection

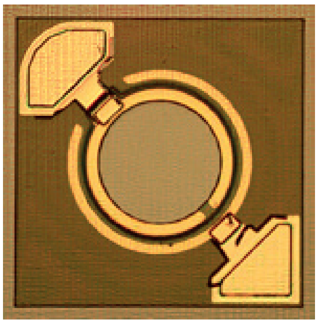

Fig. 3. An image of a PIN photodiode crystal

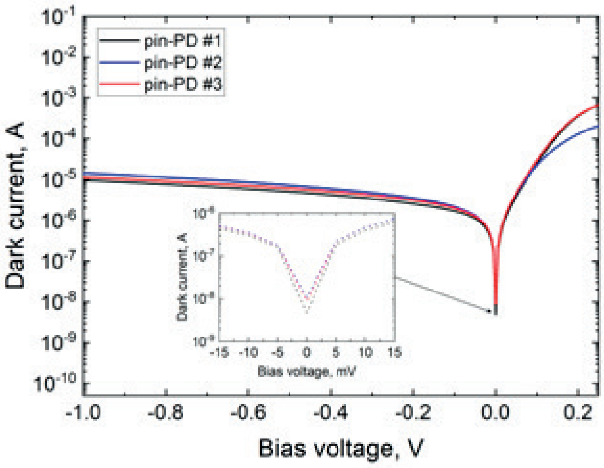

Fig. 4. The dark current-voltage characteristics of crystal PIN photodiodes at 295 K

The shunt resistance of the photodiode is the resistance of the unbiased *p-n* junction. It is usually measured based on the current value at the reverse bias of 10 mV < kT/q at room temperature T = 295 K (where k is the Boltzmann constant, q is the elementary charge) in accordance with the Ohm's law: $R_0 = \frac{dU}{dI}$. The calculated shunt resistance was on average ~ 25 kΩ, which corresponds to the product of R_0A ~ 4 Ohm·cm^2, where A is the junction area of the photodiode.

When the crystal PIN photodiodes are subjected to IR radiation with a wide spectrum and the maximum intensity in the region of 2.5 μm, the current values of the reverse branch grew by about an order of magnitude. This indicated effective formation of electron-hole pairs in the i-region of the photodiode. Therefore, the obtained heterostructure can be used to produce photodetectors of near IR radiation.

The dark current is an important parameter of photodetectors affecting the signal-to-noise ratio and detectivity. There are several major dark current mechanisms reported for photodiodes: the diffusion current mechanism, the generation-recombination current in the depletion region, and the deep level tunneling mechanisms [3]. Surface leakage at the sidewall of mesa can also contribute to the dark current [12]. For a better understanding of the processes occurring in photodiodes it is necessary to determine the dominant mechanism based on the dependence of the dark current on the temperature. This is generally an exponential dependence $I_T \sim \exp(-E_a/kT)$. However, the activation energies E_a in the exponent differ depending on the dark current mechanism. For the diffusion current, the activation energy is about the band gap of the semiconductor material E_g , for the generation-recombination current it is about $E_g/2$, and for the deep level tunneling and surface leakage the activation energy is E_g /4 [12]. The existing literature focuses on the dominating nature of generation-recombination currents and trap-assisted tunneling [2, 3]. Indeed, at high concentrations of indium, the InGaAs solid solution becomes a narrow-bandgap material. This can be one of the reasons for the increase of the share of the generation-recombination currents as compared to lattice-matched heterostructures. However, a large number of dislocations characteristic of heterostructures with metamorphic buffer layers can result in additional levels in the band gap. Therefore, the contribution to the dark current is of mixed nature. In our study, we observed a four-time decrease in the dark current at the voltage of -10 mV during the thermoelectric cooling of crystal PIN photodiodes by 10 degrees (fig. 5). To refine the dark current mechanism, further research is required in a larger temperature range of up to 77 K.

3.2. *Capacitance–voltage characteristics*

Standard capacitance–voltage characteristics of PIN photodiodes were determined by means of microprobe analysis using an Agilent E4980A precision LCR meter at frequencies of 200 kHz and 1 MHz in the reverse bias range from 0 to 3 V. Typical capacitance–voltage characteristics are presented in fig. 6. Fig. 6 demonstrates that capacitance–voltage profile curves are practically identical at different frequencies. The capacitance of bias-free photodiodes was about 14 pF and then decreased following an increase in reverse voltage. In the reverse bias range of up to 2 V curves $1/C^2(V)$ are linear with the slope coefficient practically independent of the frequency of the signal (fig. 7), which can indicate the abrupt nature of the obtained *p-n* junction [13].

4. Conclusions

In our study, we produced PIN photodiode chips of the near IR spectrum based on InAlAs/$In_{0.83}Ga_{0.17}As$/InP heterostructures with a metamorphic buffer layer. The measurements of the electrophysical properties of the chips with the sensitivity area of 140 μm gave the following results: the dark current was ~ 300 nA at the reverse bias of 10 mV, the shunt resistance was ~ 25 kΩ, and the shunt capacity was ~ 14 pF. Relatively low dark currents indicate effective resistance to the penetration of dislocations in the active area of the heterostructure, which are the main sources of noise and leakages.

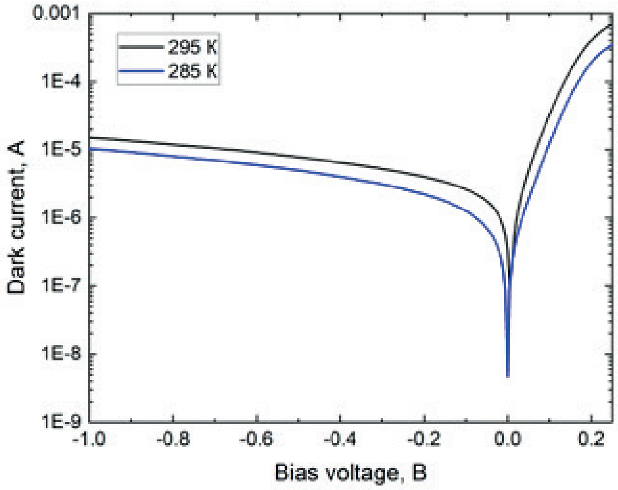

Fig. 5. The dark current-voltage characteristics of a crystal PIN photodiode at various temperatures

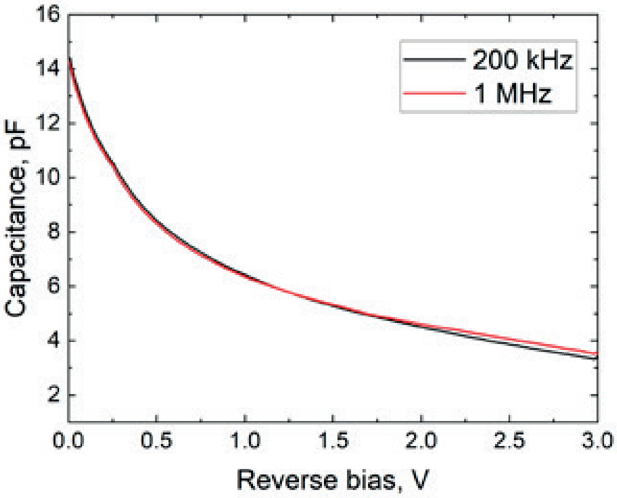

Fig. 6. The capacitance–voltage characteristics of crystal PIN photodiodes at 295 K

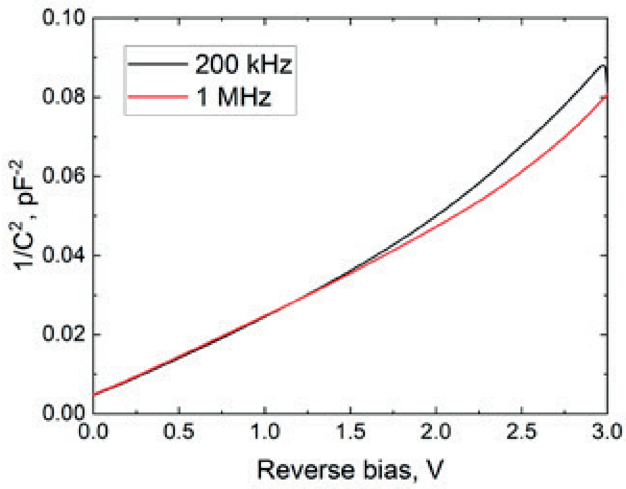

Fig. 7. Dependence of $1/C^2$ on the voltage for crystal PIN photodiodes at 295 K

The results demonstrate that the suggested metamorphic buffer layers of the heterostructure can be effectively used for the production of PIN photodiodes in the spectral range of 2.2-2.6 μm.

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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