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Influence of the doping level in the absorption layer of InGaAs/InP 2.5 μm photodetectors on their electrical properties

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Abstract. $In_{0.83}Ga_{0.17}As/InP$ PIN-photodiode heterostructures with different doping levels have been grown by molecular beam epitaxy. Metamorphic buffer layers were applied to prevent misfit dislocations nucleation in active layers. Capacitance-voltage and current-voltage curves of fabricated photodiodes have been measured and analysed. The impact of various dark current mechanisms has been estimated after the measurements of current-voltage curves at different temperatures.

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

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Материалы конференции
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Влияние степени легирования активной области InGaAs/InP 2.5 мкм фотодетекторов на их электрофизические характеристики

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Аннотация. $In_{0,83}Ga_{0,17}As/InP$ PIN-фотодиодные гетероструктуры с различными концентрациями легирующей примеси в поглощающем слое были выращены методом молекулярно-пучковой эпитаксии. Метаморфные буферные слои использованы для уменьшения плотности дислокаций несоответствия в активной области гетероструктур. Были изучены вольт-фарадные и вольт-амперные характеристики полученных кристаллов фотодиодов. На основе вольт-амперных характеристик, полученных при разных температурах, был исследован вклад различных механизмов образования темновых токов.

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 have a wide range of applications. They can be used in infrared spectroscopy devices, gas and night vision sensors [1]. However, to achieve a high performance in this spectral range, $In_{0.83}Ga_{0.17}As$ absorption layer should be used. Since the absorption layer and InP substrate have a mismatch of 2.1% in the lattice constant, metamorphic buffer layers (MBLs) need to be implemented.

The properties of optoelectronic devices are closely connected with the density of misfit dislocations. In photodiodes, such defects can lead to a high value of dark current. Dark current is a noise, which decreases sensitivity of photodiodes at low luminous intensities [2].

MBLs could effectively suppress generation of misfit dislocations in the absorption layer, but it is necessary to find optimal design and growth parameters to achieve the best device characteristics. In the present work, influence of the doping level of the absorption layer on dark current has been investigated.

Materials and Methods

PIN-photodiode heterostructures were grown by molecular beam epitaxy using a semi-industrial Riber MBE49 setup. We used n^+-type "epi-ready" InP (100) wafers to grow two structures with different doping levels of the absorption layer, called S-1 and S-2.

At the beginning of growth, substrates were annealed. After that, a thin 100 nm lattice-matched $In_{0.52}Ga_{0.48}As$ layer was grown. Next, n^+-$In_xAl_{(1-x)}As$ metamorphic buffer layers were formed by gradually increasing indium (In) mole fraction at growth temperatures of 500–510 °C (thermocouple). MBLs contained three InAlAs/InAs superlattice inserts. Structure S-1 was made with an inverse step in MBLs: indium mole fraction was increased up to 86%. S-2 was manufactured without an inverse step, but $In_{0.83}Ga_{0.17}As/In_{0.83}Al_{0.17}As$ digital superlattice inserts before and after the absorption layer were formed. MBLs growth was followed by thermocycling process of peak temperature rising up to 630 °C and slow cooling down to 50 °C. The growth process of MBLs is described in more detail in [3]. 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). The doping concentration of the active layer was on the order of 10^{16} cm^{-3} in both samples, but its estimated value in S-2 was specially made 4 times higher than in S-1. At the end, 0.6 um p^+-type contact layers doped with beryllium (Be) were formed on the top of the heterostructure.

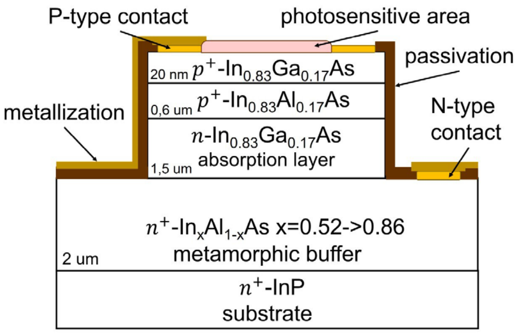

Fig. 1. Schematic structure of PIN-photodiode

Photosensitive areas with the diameter of 140 μm and contact areas were fabricated using a standard photolithography procedure. The overall photodiode mesa size was 325×325 μm^2. A schematic structure of produced PIN-photodiodes is presented in Fig. 1.

ECV profiles were measured by Electrochemical capacitance voltage profiler ECV Pro (Nanometrics, USA). The C–V curves were gained using LCR Agilent E4980A setup. The I–V curves at different temperatures were obtained using The Keithley 2400 measuring setup. The samples were cooled using Janis VPF-100 cryostat.

Results and Discussion

ECV measurements helped to calculate carrier concentrations in the active layer of two samples. In S-1 its value was $10{\cdot}2^{16}$ cm^{-3}, and in S-2 it was $8{\cdot}10^{16}$ cm^{-3}, which is 4 times higher, as expected. In p^+-type and n^+-type contact layers, respective main carrier concentrations were $2{\cdot}10^{18}$ cm^{-3}, showing that PIN structures were successfully manufactured.

I–V curves of both samples at room temperature of 300K are shown in Fig. 2. They are highly asymmetrical, showing a diode-like behavior. At reverse bias voltages less than 0.2 V, dark currents values of samples are different: in S-2 the dark current is higher by almost an order of magnitude. However, at higher bias voltages, the dark currents of structures are nearly identical, reaching the value of ~ $1.2{\cdot}10^{-5}$ A (which corresponds to dark current density of $7.8{\cdot}10^{-2}$ A·cm^{-2}) at a bias voltage of –1.0 V. This probably could indicate that high doping of active layers leads to an increase in diffusion dark current. But, as it was shown in [4], it is still necessary to slightly dope absorption layers. Therefore, for lowering dark current at small bias voltages doping concentration should probably be ~ $(1–2){\cdot}10^{16}$ cm^{-3}.

The suggested doping concentration value is close to the one recommended by some works [4]. However, it is much lower than in other studies, where the optimal doping concentration is claimed to be ~$(1–5){\cdot}10^{17}$ cm^{-3} for the lower leakage current [5].

It should be mentioned that the doping concentration is connected with the device capacitance. Consequently, it defines the response time and the thermal noise. Therefore, the impact of higher doping levels of the absorption layer on photodiode capacitance should also be researched. For this reason, capacitance-voltage curves were acquired to study manufactured PIN-structures S-1 and S-2.

The plot in Fig. 2 shows that $1/C^2$–V characteristics are highly linear, which may indicate an abrupt p–n junction [6]. As expected, higher doping concentration led to higher capacitance

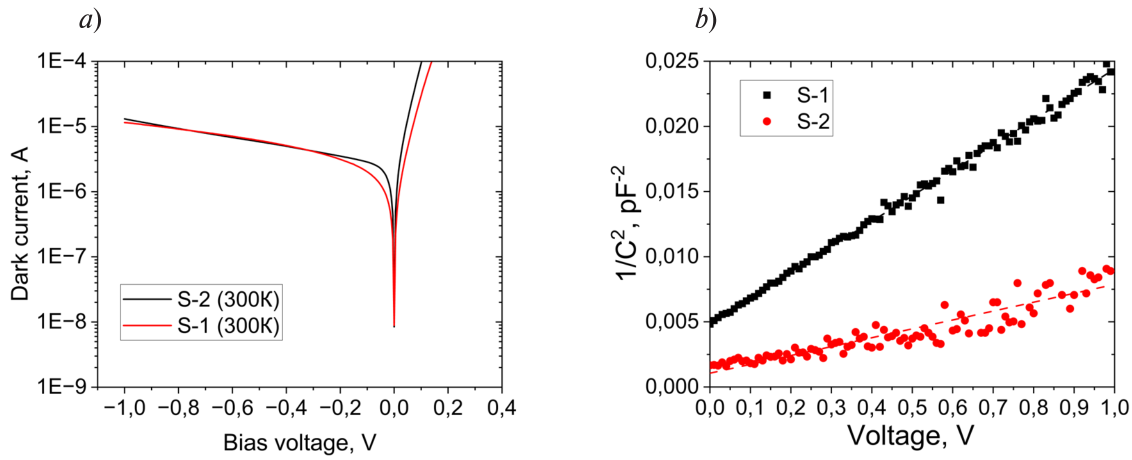

Fig. 2. *I*—*V* (*a*) and *C*—*V* (*b*) curves of samples

(lower $1/C^2$). Nevertheless, capacitance values for both samples were of the same order of magnitude: at a zero bias voltage it was 14 pF in S-1 and 24 pF in S-2. This might indicate that the doping level does not significantly affect the operating speed of manufactured pin-photodiode chips, which should be relatively high in both PIN-structures. Although, further measurements of response time are required.

Since sample S-1 had lower dark current, it was chosen for the investigation of current—voltage curves, obtained at different temperatures. Dark current decreases with temperature decline, showing the largest drop by more than two orders of magnitude at reverse bias voltages less than 0.4 V. It presumably indicates the high influence of diffusion dark current mechanism at lower reverse biases, which supports the idea of higher diffusion dark current in sample S-2 at room temperature. *I*—*V* curves obtained at different temperatures are presented in Fig. 3.

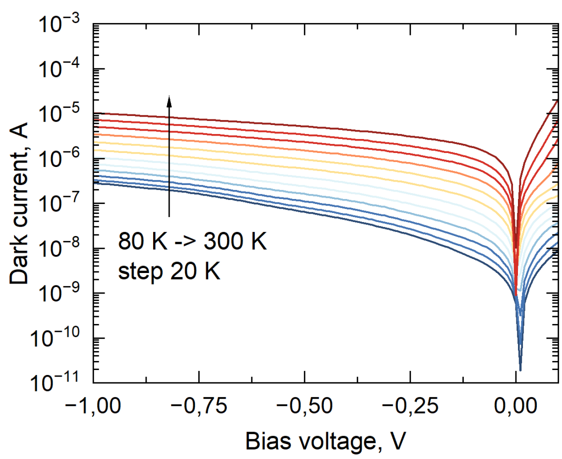

Fig. 3. Temperature dependence of *I*—*V* curves

Conclusion

$In_{0.83}Ga_{0.17}As$/InP PIN-photodiode heterostructures with different doping levels of the absorption layer and superlattice inserts have been studied. It was discovered, that doping concentrations of active layers should be ~ $(1 - 2)\cdot10^{16}$ cm^{-3} for achieving better performance. The value of the dark current was determined to be ~ $1.2\cdot10^{-5}$ A at a bias voltage of −1.0 V at room temperature. Capacitance-voltage measurements have shown that an increase of the doping concentration led to an increase of the capacitance from 14 pF to 24 pF. The influence of different dark current mechanisms was determined based on dark current temperature dependence.

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