AlGaAs/GaAs photodetectors for detection of luminescent light from scintillators

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Abstract. The AlxGa1-xAs / GaAs photosensitive heterostructures were grown by molecular beam epitaxy. On their basis the discrete photodiodes (PD) and phototransistors (PT) operating in the visible (0.4–0.7 μm) wavelength range and having photosensitive area diameters of 1.5 mm and 180 μm correspondingly were created. The current-voltage and spectral characteristics of discrete PD and PT were measured and analyzed. Distinctive features of the proposed photodetectors are a high monochromasy with the maximal sensitivity of 0.13 A/W at λ = 530–570 nm and a low dark current of 4.7 nA and 530 pA at 5 V reverse bias for PD and PT correspondingly.

1. Introduction

During the last few years the semiconductor GaAs detectors have attracted a considerable interest as an alternative to the Si and Ge ones for the detection of the luminescent light of scintillators. Photodetectors for the 0.4–0.7 μm spectral range can be used as photosensors in scintillation detectors, which are used, for example, in experiments with cosmic rays. The acquisition of information on the particles falling on the Earth from space is an important research task. However, the fastest accelerators allow getting the particle energies of about 10^{13} eV, while the energy of the particles originating from outer space can reach 10^{17}–10^{19} eV. Besides, due to the sensitivity lack in the infrared range and a high sensitivity in the visible range such photodetectors can be used to control the backlight of liquid crystal displays.

The scintillation detector consists of a scintillator that emits photons when struck by ionizing radiation and a photodetector that converts the light from the scintillator into an electrical signal. In modern detectors optical fibers are used to improve the focusing of the light from the scintillator. Typically, the scintillators used for experiments in high energy physics emit photons at wavelengths from 375 to 430 nm. To detect this light the photomultiplier tubes (PMT) are used because their maximum spectral sensitivity is almost perfectly matches the maximum of the scintillator emission spectrum. However, PMTs have some disadvantages, that is why nowadays researchers and engineers are working on finding an alternative to replace the PMT. The most common alternatives are silicon p-i-n diodes [1] or silicon PMTs (SiPM) [2–4].
AlGaAs solid solutions are very promising to create photodetectors for this spectral range. GaAs has the maximum sensitivity at about 800 nm, but a high sensitivity in the visible range (400–500 nm) can be achieved by adding Al that results in an increase of the energy gap. When creating the photodetectors it has been assumed that the scintillation plate of the SC-301 type with the maximum in the emission spectrum at about 420 nm can be used. The wavelength of the light transferred to a photodetector is approximately 476 nm.

This paper presents the results of the investigation carried out with the aim to create high efficiency photodetectors (PDTs) operating in the visible (0.4–0.7 $\mu$m) wavelength range. The AlGaAs / GaAs PDTs for detecting the light from the scintillator are presented. Photodiodes and phototransistors based on AlGaAs / GaAs heterostructures (figure 1) were produced using the photolithography techniques with chemically-assisted ion beam etching.

Details of the creating and growth for these structures are described in [5–7]. Photodiodes with the circular mesa, the chip size of $4 \times 4$ mm$^2$ and the photosensitive window diameter of 1.5 mm (figure 2 (a)) were mounted by soldering into TO-39 coverage.

Phototransistors were produced in two ways: with and without the base mode. Figure 2 (b) shows a phototransistor chip with size of 600 $\times$ 600 $\mu$m$^2$ which has a round base contact with the bonding pad and the emitter contact; the diameter of the photosensitive window is 180 $\mu$m. Phototransistors chips were mounted by soldering into TO-18 coverage. Schematic cross-sections of finally made devices are shown in figure 3.
Figure 2. Chip view for the photodiode (a) and the phototransistor (b).

Figure 3. Cross section for the photodiode (a) and the phototransistor (b).

2. Results and discussion

The dark current and the breakdown voltage were measured by an Agilent B1500A semiconductor device analyzer. The reverse photodiode current-voltage (I–V) characteristic is presented in figure 4. The best samples demonstrated the dark current $I_d = 3.38$ nA at the reverse bias $U_{rev} = 5$ V. The I–V characteristic control was carried out at each stage of devices fabrication, from cutting wafers into chips to the packaging process.

Figure 4. Reverse photodiode I–V characteristic.
The measurements showed that after all production steps the dark current increased and the breakdown voltage decreased insignificantly (figure 5).

![Figure 5. Reverse photodiode I–V characteristics at wafer and after packaging.](image)

The phototransistor I–V characteristics measured at a floating base mode (with two contacts: to the emitter and to the collector) are shown in figure 6. Geometric parameters of samples are as follows: the base thicknesses are 1 μm for 531PT and 0.8 μm for 532PT, the i-layer thicknesses are 42 μm for 531PT and 45 μm for 532PT.

![Figure 6. Phototransistors I–V characteristics without base contact for different base thicknesses.](image)
The phototransistor dark currents were 0.1 nA at $U_{rev} = 20$ V for 531 PT and 0.03 nA for 532 PT; the breakdown voltage was $\approx 600$ V. Such small values of the dark current were achieved due to the plasma surface passivation and using a high quality insulating SiO$_2$. The observed difference between the dark currents can be caused by the fact that the buffer layer in the structure 531 is thicker (300 nm) than in the structure 532 (100 nm), therefore the base layers are of different thicknesses.

Spectral characteristics were measured using a “MDP” type monochromator and a system for measuring the spectral sensitivity of photodetectors TTM 3.435.088. Figure 7 shows the photodiodes spectral characteristics.

It is seen, that as the Al mole fraction increases by 0.05, the spectral sensitivity maximum shifts by 40 nm to shorter wavelengths. Besides, the sensitivity at a wavelength of 475 nm increases almost twice due to choosing the optimal composition and thickness of the active p-layer. To achieve a greater sensitivity at shorter wavelengths an antireflection coating on the “window” layer can be used. The maximum value of the absolute spectral sensitivity reaches 0.13 A/W.

Unfortunately, we were unable to measure spectral characteristics of phototransistors using the same equipment because the diameter of the incident light beam was 1.5 mm, while the diameter of the transistor photosensitive area was 180 μm. In further experiments such measurements will be made and analyzed.

3. Conclusion
Photodetectors for detecting light from the scintillator based on Al$_{x}$Ga$_{1-x}$As / GaAs heterostructures were produced. The performed measurements showed low dark currents at the level of 0.5 nA for phototransistors and 10 nA for photodiodes, as well as high breakdown voltages of about 600 V and 20 V correspondingly. Experimentally determined composition and thickness of layers in the studied heterostructure allowed us to increase the sensitivity at a wavelength of 475 nm almost twice. The absolute spectral sensitivity of photodiodes reaches 0.13 A/W at $\lambda = 570$ nm.

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