Photosensitive AlGaAs / GaAs Structures Grown by Molecular Beam Epitaxy

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AlGaAs / GaAs photosensitive structures were grown by molecular beam epitaxy and photodetector devices were fabricated. The structures were characterized by reflection high-energy electron diffraction (RHEED), reflectance anisotropy spectroscopy (RAS) and atomic force microscopy (AFM). Spectral characteristics of p-i-n structures were calculated. It is shown that obtained structures have atomically smooth surface and abrupt heterointerfaces. Room-temperature I-V measurements of fabricated photodetectors showed low dark current I_d = 3.38 nA at reverse bias U_{rev} = 5 V.

Keywords: Molecular beam epitaxy, AlGaAs / GaAs, Photodetector, Ultraviolet, Scintillator.

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1. INTRODUCTION

During the last few years semiconductor GaAs detectors have considerable interest as an alternative to Si and Ge detectors for the detection of luminescent light of scintillators [1-4]. Scintillation detectors are used in cosmic ray experiments, particle accelerators, neutrino physics and many others. Usually a scintillation detector system consists of a scintillator and a photodetector. Optical fibers are used to deliver light from any area of scintillator to photodetector. Polystyrene scintillator lights at a maximum wavelength approximately 400-450 nm, but transfered light from the fibers has 476 nm wavelength. Photoelectronic multiplier is usually used for detection luminescent light [5]. Therefore it has many disadvantages. For example, using high voltages (1000 V), needs for magnetic shielding, high cost. So we suggest to use semiconductor photodetector instead a photoelectronic multiplier. The application of the photodetectors based on AlGaAs / GaAs heterostructures makes it possible to improve the detector properties. We can achieve maximum matching between photosensitivity and luminescence spectrum by varying the band gap of the wide-gap window and of the photoactive region containing *p-n* junction. The large values of the band gap for the *p-n* junction material provide low dark current at room and higher temperatures.

In this paper we demonstrate *p-n* AlGaAs / GaAs photodiode and *p-i-n* AlGaAs / GaAs structure grown by MBE for detection the luminescent light of polystyrene scintillator.

2. AlGaAs / GaAs PHOTOSENSITIVE STRUCTURES GROWTH

2.1 *p-n* AlGaAs Photodiode Structure

A cross-sectional diagram of the structure is shown in Fig. 1. Epitaxial layers were grown on (100) oriented n^+ GaAs substrate doped with silicon to $1.5 \cdot 10^{18}$ cm^{-3}, with dislocation density < $1 \cdot 10^4$ cm^{-2}, 400 μm thickness and 40 mm in diameter. As the initial materials we used high-purity Al 5N8 (99,9998 %) produced by Ulvac Materials, Inc., Japan; high-purity Ga 8N (99,999999%) and high-purity As 7N (99,99999%) produced by Furukawa Denshi Co., LTD., Japan. A thin GaAs buffer

contact layer p^+ GaAs (Be)	$2 \cdot 10^{18}$ cm^{-3}	45 nm
"window" p^+ AlAs (Be)	$2 \cdot 10^{18}$ cm^{-3}	50 nm
p $Al_{0.35}Ga_{0.65}As$ (Be)	$5 \cdot 10^{17}$ cm^{-3}	500 nm
n $Al_{0.35}Ga_{0.65}As$ (Si)	$5 \cdot 10^{17}$ cm^{-3}	500 nm
buffer n^+ GaAs (Si)	$1.5 \cdot 10^{18}$ cm^{-3}	200 nm
substrate n^+ GaAs (Si)	$1.5 \cdot 10^{18}$ cm^{-3}	400 μm

Fig. 1 – A cross-sectional diagram of the *p-n* photosensitive structure

layer is grown on the top of the GaAs substrate to achieve atomically clean and smooth surface for subsequent growth. Next a 1 μm thick *p-n* $Al_{0.35}Ga_{0.65}As$ junction is grown. It is the active region where incident light is absorbed and generate electron-hole pairs. These optically generated carriers are separated due to the internal electric fields and contribute to output current. Next a 50 nm "window" p^+ AlAs is grown. This window layer transmits the optical photons of interest to the $Al_{0.35}Ga_{0.65}As$ active region. This design allows to reduce the influence of surface recombination. In fact, surface recombination effect is the main challenge in fabricating AlGaAs / GaAs devices for near ultraviolet light detection. Since surface recombination velocity for untreated GaAs is about 10^5 cm/s, almost all shortwave radiation is absorbed in near-surface layer and does not contribute to photocurrent. The top layer is p^+ GaAs contact layer doped with Be to $2 \cdot 10^{18}$ cm^{-3}. It provides a high-quality ohmic contact with low resistance.
Then *p-n* photodiodes with circular mesa active region were fabricated. An AuGe / Au contact is deposed on the bottom side of the wafer and a Ti / Pd / Au/Ti alloy is deposed on the top surface. Photolithography is

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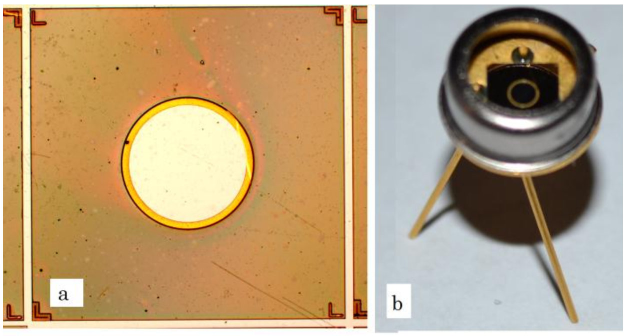

Fig. 2 – 4 × 4 mm chip with active region 1.5 mm in diameter (a) and packed chip (b) of *p-n* photodetector

used to define the top contacting ring (Fig. 2). After this contacting ring is formed, the top GaAs layer is selectively removed by reactive ion-beam etching. The chips were mounted on TO-39 package and covered by cap with glass window.

2.2 n^+-p-i-n^+ AlGaAs Photosensitive Structures

n^+-p-i-n^+ AlGaAs / GaAs heterostructures were grown partially by MOCVD and MBE (see Fig. 3). Thick layers were grown by MOCVD [6] because MBE growth speed is very low (about 1 μm/h). At the same time it is problematically to get high-quality ternary alloys by MOCVD [7]. This structure supposed to work as a transistor with floating base. In this case incident radiation goes through emitter to base and to i-GaAs layer. Optical generation of electron-hole pairs take place in different regions of the structure depending on the incident radiation wavelength. According to the mathematical modeling results the highest contribution of optically generated charge carriers to the photocurrent observed at absorption in i-GaAs layer. Therefore 400 nm wavelength light completely absorbs in *p*-GaAs base layer. So it is reasonable to grow a thinner base region in future.

Using of n^+ InGaAs contact layer significantly reduces the resistance of ohmic contact to the emitter.

contact layer n^+ $In_{0.53}Ga_{0.47}As$ (Si)	10^{19} cm^{-3}	40 nm	MBE
contact layer n^+ GaAs (Si)	$4 \cdot 10^{18}$ cm^{-3}	40 nm	MBE
emitter n^+ $Al_{0.25}Ga_{0.75}As$ (Si)	10^{19} cm^{-3}	100 nm	MBE
buffer p GaAs (Be)	$5 \cdot 10^{17}$ cm^{-3}	300 nm	MBE
base p GaAs (C)	$5 \cdot 10^{17}$ cm^{-3}	0.72 μm	MOCVD
i-GaAs	10^{13} cm^{-3}	42 μm	MOCVD
buffer n^+ GaAs (Si)	$7 \cdot 10^{17}$ cm^{-3}	5 um	MOCVD
substrate n^+ GaAs (Si)	$2 \cdot 10^{18}$ cm^{-3}	500 μm	MOCVD

Fig. 3 – A cross-sectional diagram of the n^+-p-i-n^+ photosensitive structure

3. MODELING OF SPECTRAL RESPONSE OF PHOTOSENSITIVE STRUCTURES

Spectral characteristics were calculated by solving the basic system of differential equations: the Poisson equation, the continuity equation and the transport equation for electrons and holes. System of equations was solved numerically by finite difference method using a tridiagonal matrix algorithm.

Calculations of spectral response were carried out for a *p-i-n* GaAs structure. It consists of a 0.82 microns thick top *p*-GaAs layer doped to of $5 \cdot 10^{17}$ cm^{-3}; 45 microns thick *i*-GaAs region with electron density $1 \cdot 10^{14}$ cm^{-3} and heavily doped n^+-substrate from the back side of the structure. Surface recombination rate was taken as $2 \cdot 10^6$ cm/s. Fig. 4 shows a spectral response of described structure. For clarity contribution of different regions is shown.

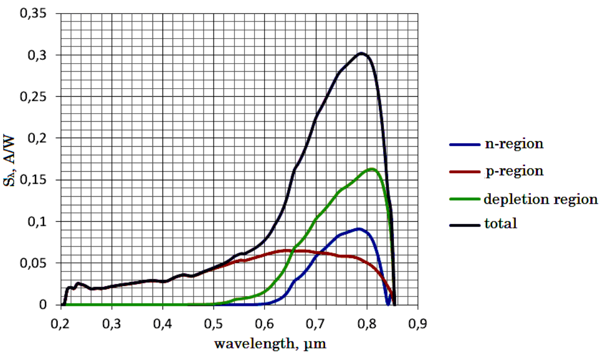

Fig. 4 – Calculated srectral response of p-i-n GaAs structure

Fig. 4 shows that the photosensitivity of the structure from the short-wave edge is determined by electrons in *p*-region, and from the long-wavelength edge by charge carriers generated in the depletion region and holes in the lightly doped *i*-region. Thus blue-shift of spectral response can be achieved by reducing surface recombination rate and by increasing mobility and lifetime of electrons in *p*-region. Also modeling of *p-i-n* heterostructure with *p*-$Al_xGa_{1-x}As$ layer was performed. Calculated characteristics are shown in Fig. 5.

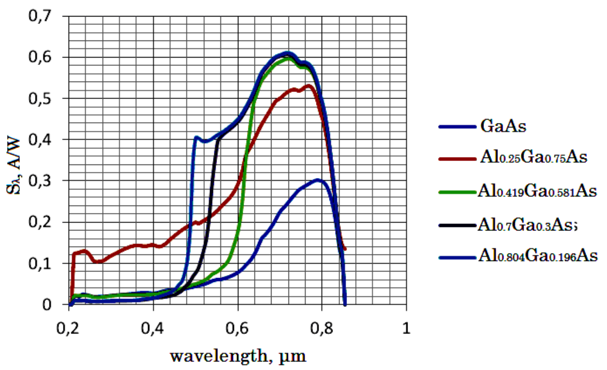

Fig. 5 – Calculated srectral response of *p-i-n* AlGaAs heterostructure with different mole fraction of Al

Calculated spectral characteristics are shifted to the short-wave range and overall sensitivity increases. At the same time we can see that the greatest increase in sensitivity at wavelengths less than 0.4 microns take place not for the widest bandgap material. Someone may find it strange, but the fact is that in the more widebandgap-materials the electron mobility decreases sharply (from $3.1 \cdot 10^3$ cm^2/V·s for $Al_{0.25}Ga_{0.75}As$ to $5.4 \cdot 10^2$ cm^2/V·s for $Al_{0.419}Ga_{0.581}As$) for the same surface recombination rate and lifetime of charge carriers.

4. EXPERIMENTAL RESULTS

RAS spectra were recorded during the whole growth process. Detector voltage versus growth time at 500 nm wavelength is shown on Fig. 6. You can see signal decay during the growth of p-n junction, but after correcting substrate temperature from 550 to 545 °C it became stable. So we have grown a high quality structures with abrupt heterointerfaces.

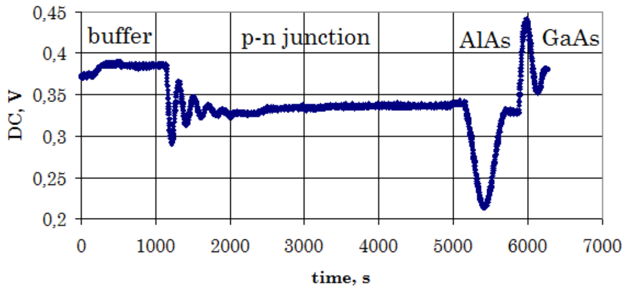

Fig. 6 – Detector voltage versus growth time dependance for p-n structure growth

AFM image is shown on Fig. 7. The average roughness value is 0.5 nm which indicates to atomically smooth surface.

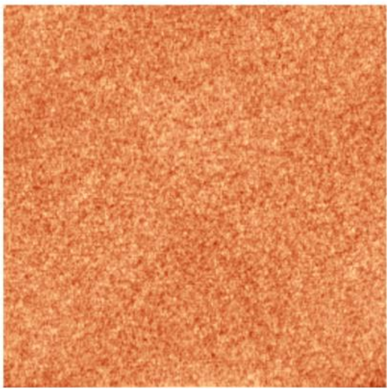

Fig. 7 – 10 × 10 μm AFM image of *p-n* structure surface after growth

Current-voltage characteristics of fabricated *p-n* photodiodes were measured. Best samples demonstrated low dark current $I_d = 3.38$ nA at reverse bias $U_{rev} = 5$ V.

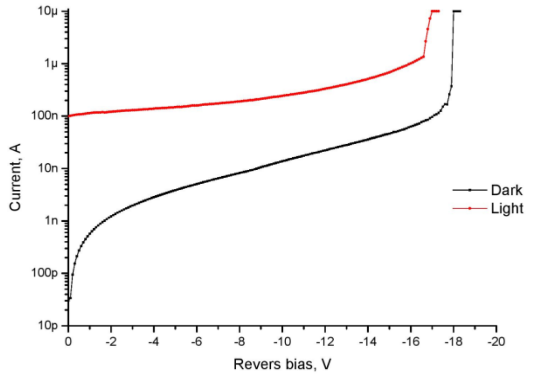

Fig. 8 – I-V measurements of fabricated *p-n* photodiode

5. CONCLUSIONS

High quality photosensitive AlGaAs / GaAs structures were grown by molecular beam epitaxy. Fabricated on their basis p-n photodetectors demonstrated low dark current $I_d = 3.38$ nA at reverse bias $U_{rev} = 5$ V.

Results of mathematical modeling of the spectral response shown that AlGaAs / GaAs structures may be highly sensitive in short-wavelength range. So they can be used as detectors of luminescent light of scintillators.

In the near future we plan to fabricate phototransistors on the basis of grown n^+-p-i-n^+ structures and to measure spectral responses of obtained photodetectors.

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