PHOTORECEIVERS WITH SELECTIVE AND MODULATED SENSIBILITY

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INTRODUCTION

The III-V semiconductor compounds wide use for making various optoelectronic active elements, as laser, photodiode, light-emission diode, etc. GaAs, InP, GaP and their related solid solutions are more used. Photoreceivers on the basis of III-V homojunctions possess high efficiency, but they have wide photosensibility spectrum. Unlike the binary compounds quaternary solid solutions have possibility to vary the band-gap in a large interval and allow to form heterostructures with peculiar photoelectrical properties [1]. The semiconductor heterostructures on the basis of quaternary solid solutions InGaAsP are successfully used for preparing the photoreceivers for IR spectral range 0.9 – 1.65 μm. They ensure higher conversion efficiency, lower dark currents and a higher work frequency. Moreover, the $In_xGa_{1-x}As_yP_{1-y}$ multiplayer heterostructures can realize some devices with novel characteristics and parameters.

1. THE PHOTODIODE WITH SELECTIVE SENSIBILITY

To obtain selective photosensibility we made double heterostructures by liquid phase epitaxy on the InP substrate (figure 1). The first at the substrate layer with band gap E_{g1} determines red boundary of sensibility and second (frontal) layer with band gap E_2 limits sensibility at short-wave side.

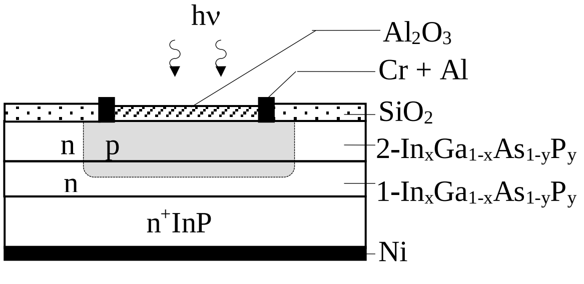


Figure 1. The structure of selective photodiode.

High-energy radiation ($h\nu > E_{g2}$) is absorbed completely into frontal layer if its thickness d is more than $1/\alpha$, where α is light absorption coefficient, and d is more than diffusion length of minor charge carriers generated into frontal layer. Radiation with photon energy more than E_{g1} and less than E_{g2} ($E_{g1} < h\nu < E_{g2}$) is absorbed into first active layer and generates nonequilibrium charge carriers, which are separated by internal electric field of p-n junction and form photocurrent.

The photosensibility spectra of selective photodiode on the basis of double heterostructure InP - $In_{x1}Ga_{1-x1}As_{y1}P_{1-y1}$ - $In_{x2}Ga_{1-x2}As_{y2}P_{1-y2}$ with various thickness of frontal layer optimised for receive optical signals transferred through the atmosphere on a big distance is presented in figure 2. This structure have values of band gap $E_{g1} = 1.12$ eV for active layer, $E_{g2} = 1.18$ eV for frontal layer and spectra maximum for $\lambda = 1.06$ μm [2].

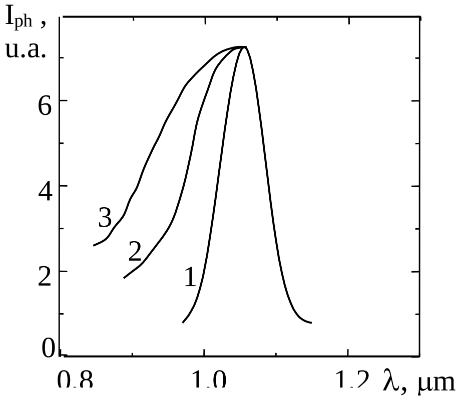
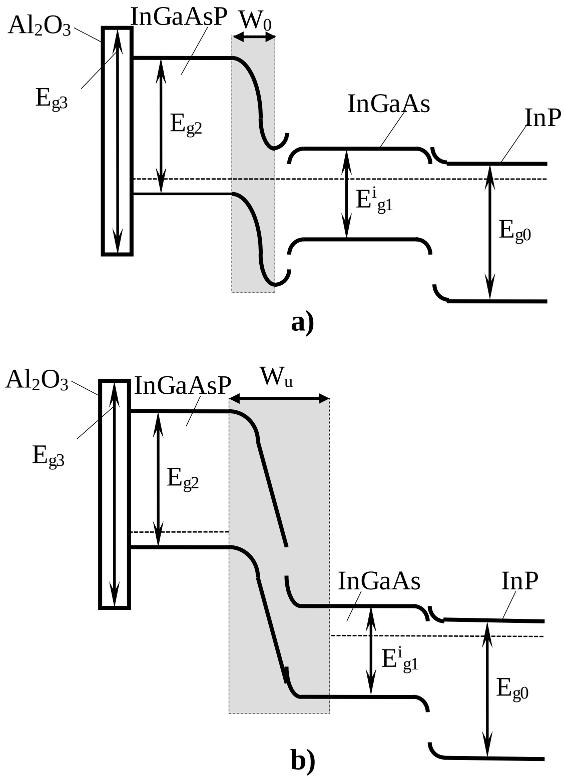


Figure 2. Photosensibility spectra of selective photodiode with thickness of frontal layer d:
1 - 7 μm; 2 - 4 μm; 3 - 2.5 μm.

The spectra semi-width depends on thickness of frontal layer and for structure with 7 μm thickness of frontal layer is 75 nm. The $In_xGa_{1-x}As_yP_{1-y}$ multiplayer heterostructures can be optimised and accommodated, varying the coefficients “x” and “y”, to receive radiation with spectra maximum in interval 0.9 μm < λ < 1.65 μm and the spectra semi-width can be reduced to 20 – 30 nm.

2. THE PHOTODIODE WITH MODULATED SENSIBILITY

One of important characteristics of photodiode for optic communication is possibility to have control over photodiode sensibility easy and quickly. Heterostructures on the basis InP – InGaAs – InGaAsP allow to make photodiode with modulated photosensibility and new functional properties. Liquid phase epitaxy was utilized to obtain the semiconductor heterostructures. The photodiode consists of n^+-InP substrate, InGaAs layer with band gap E_{g1} = 0.75 eV, InGaAsP layer with E_{g2} = 1.12 eV, Al_2O_3 antireflection layer with wide band gap E_{g3} and ohmic contacts. The p-n junction is realized by Zn diffusion through the opened in SiO_2 windows and is placed in frontal layer near the heterojunction. Figure 3 shows the energetic diagrams of photodiode without any polarization voltage (figure 3,a) and for reverse polarization voltage more than any “threshold” one U_{thr} (figure 3,b). In the case “a” charge carriers generated in active layer with E_{g1} cannot be separated due to a potential barrier in the valency zone between InGaAs layer and InGaAsP one. Only for $U_{rev} > U_{thr}$ the space charge region W extends also into the InGaAs photoactive layer, the potential barrier decreases to disappearance.



a)

b)

Figure 3. The energetic diagrams of photodiode.
a) without any polarization voltage;
b) for reverse polarization voltage.

Thus, the photocurrent generated in active layer by optic communication signal with λ = 1.3 µm or λ = 1.55 µm (regions II and III) increases quickly from the zero to its maxim value at exceeding $U_{rev} \geq U_{thr}$ (figure 4). Dotted lines show characteristics for classic photoreceiver (with illumination I, without illumination 0). For first time, it was realized a photodiode whose photosensibility can be modulated by a polarization voltage with modulation degree of 100 % [3]. The new photodiode can be successfully utilized in optoelectronic systems to receive, to code and to processe the optic information [4].

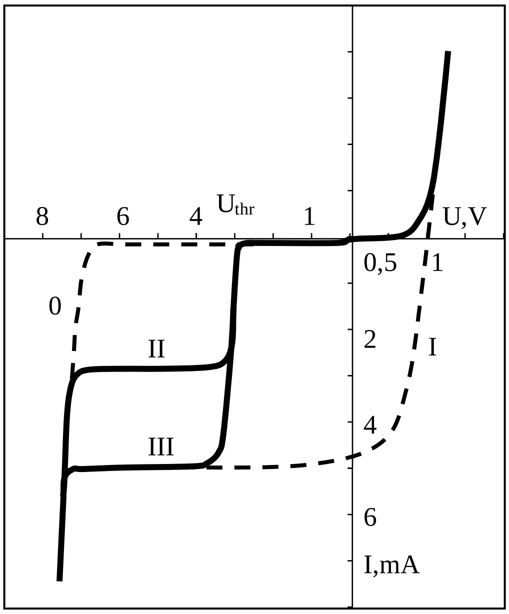


Figure 4. Volt-current characteristics of photodiodes with modulated sensibility (II, III) and classic (I).

3. THE PHOTODIODE WITH MODULATED SENSIBILITY FOR RECEIVE TWO WAVELENGTH

On the basis of photodiode with modulated sensibility can make selective photodiode with possibility to receive simultaneously two optic signals with different wavelength and to modulate photosensibility for each of them by supply voltage. The design of this photodiode (figure 5) is similar to described above structure only in addition contains on the back side the active layer with band gap $E_{g4} < E_{g1}$ and thickness less than diffusion length of minor carriers and back layer with E_{g1} where was formed second p-n junction with space charge region W_2. The space charge region of first p-n junction into layer with E_{g2} is W_1. The energetic diagrams of this structure are presented in figure 6.

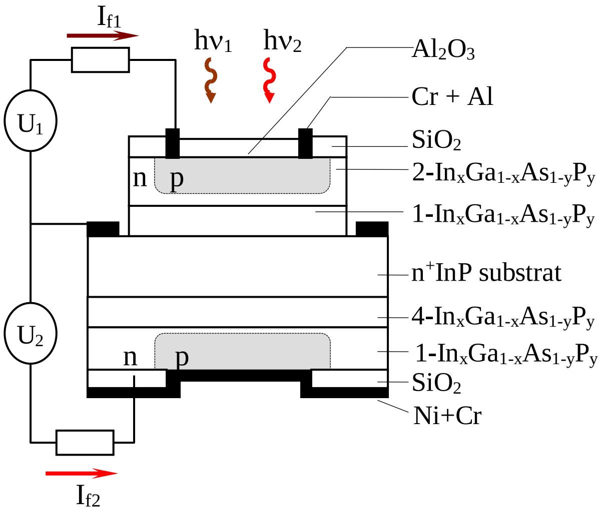


Figure 5. The photodiode with modulated sensibility for receive two wavelength

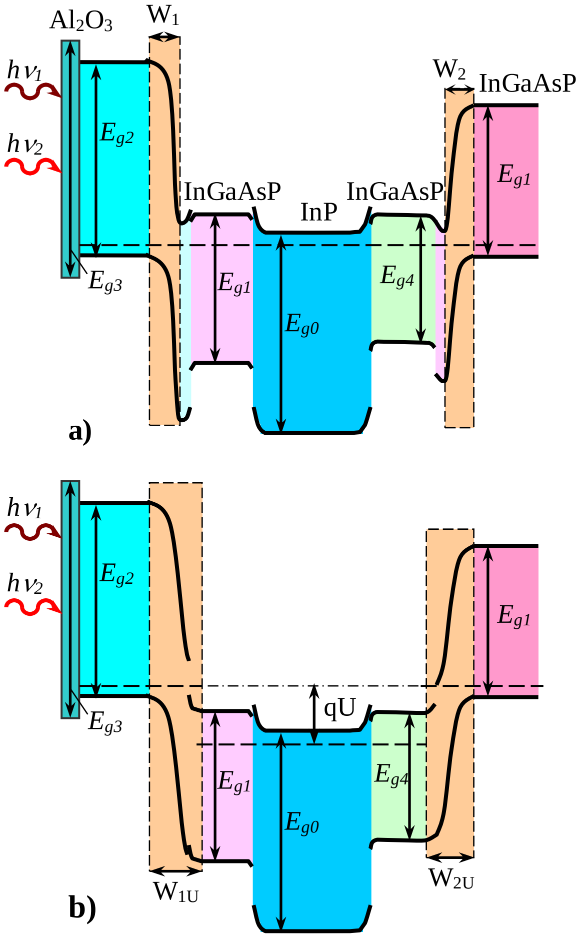


Figure 6. The energetic diagrams of selective photodiode with modulated sensibility to receive two optic signals with different wavelength.
a – without any polarization voltage;
b - for reverse polarization voltage more than threshold voltage.

Optic signals with photon energy $h\nu_1 = E_{g1}$ and $h\nu_2 = E_{g4}$ are introduced into photodiode structure through the antireflection layer with band gap E_{g3}, which ensures minim optic loses. Selectivity of photodiode is ensured by absorption of photons with energy $h\nu > E_{g2}$ at the surface of frontal layer, which don't participate in formation photocurrents of p-n junctions, as since thickness of frontal layer with E_{g2} is more than diffusion length of minor charge carriers, and photons with energy $h\nu < E_{g4}$ go through the semiconductor structure without absorption. The optic signal with photon energy $h\nu_1 < E_{g2} < E_{g3}$ is absorbed into first active layer with E_{g1} and other optic signal with photon energy $h\nu_2 < E_{g1} < E_{g2} < E_{g3}$ propagates through structure and is absorbed into second active layer with E_{g4}. Generated nonequilibrium charge carriers cannot be separated due to potential barriers φ_b into valency zones and in this case photocurrents through both p-n junctions is equalled zero. At the reverse polarization of p-n junction $U_{rev} > U_{thr} = q\varphi_b$ the potential barrier disappears (figure 6,b) and generated charge carriers is separated by electric field of p-n junction forming current proportional intensity of incident signal. Thus, we modulate output signals (currents through the p-n junctions) with modulation degree of 100 % by change reverse polarization on the p-n junctions in very small interval about values $U_{rev} = U_{thr}$ (figure 7).

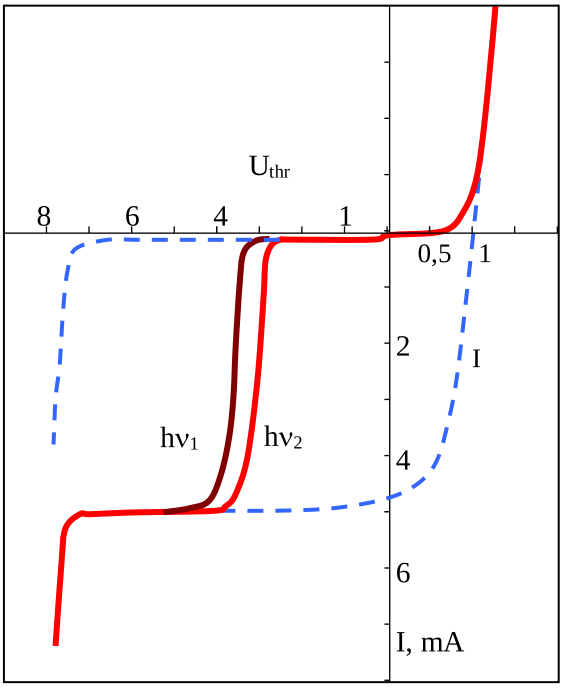


Figure 7. Volt-current characteristics of selective photodiode with modulated sensibility, which receives simultaneously two optic signals with different wavelength. ($h\nu_1$, $h\nu_2$) and classic (I).

4. PHOTORESISTOR WITH MODULATED SENSIBILITY

The classic photoresistor is manufactured by form of a p-type or n-type semiconductor layer with 1-10 μm thickness on a semiconductor substrate. The ohmic contacts formed as a grid have the distance between the strips of the grid less than the diffusion length of minor charge carriers, which is 2-4 μm for holes and 5-10μm for electrons (depending on the doping level of active layer, which variable between $10^{16} – 10^{18}$ cm^{-3}).

A supply voltage is applied to contacts. Without optic flux, a current, named dark current, appears in the active layer under the influence of applied voltage. Dark current decreases the photoresistor detectivity, determined by the noise currents:

$$\overline{i_n^2} = 2q\left(I_{ph} + I_d\right)\Delta f$$

where: I_{ph} – photocurrent , I_d – dark current, Δf – the transparency band of the frequencies.

At illumination of the photoresistor with an optic flux, excess charge carriers generated inside the active layer are separated by the electric field created by the external source of voltage. Separated charge carriers form a photocurrent proportional to the intensity of the incident optic flux.

Disadvantages of the classic photoresistor are:

- the photocurrent is formed by the minor charge carriers, which reduce the photocurrent value;
- the contact grids occupy more than 50% of the active area. To exclude the optic flux loses, it is necessary to use heterostructures which allow to light up the active layer from the back side of the structure;
- the active layer thickness can’t be less than 1/α, α - the absorption coefficient of the optic radiation. This determines the big values of the dark current, which limits the photoresistor’s detectivity.

The new photoresistor (figure 8,a) is manufactured on basis of the III-V semiconductor compounds, for example GaAs, and consists from a semi-isolator substrate and a p-type or n-type active layer. SnO_2 layer of n^+-type is deposited by the pyrolysis method between the ohmic contacts, which are connected to the supply voltage U_1. The energetic diagram of heterostructure SnO_2-semiconductor is presented in figure 8,b.

The heterostructure is reverse polarized by the source of voltage U_2. The thickness of the space charge region W of the heterojunction depends on the height of the potential barrier φ_b, on the reverse polarization voltage value U_2 and on the acceptor (or donor) dopant concentration N_a (N_d) of the active layer, by the relation:

$$W = \left[2\varepsilon_0\varepsilon_s\left(\varphi_b - U_2\right)/qN_d\right]^{\frac{1}{2}}$$

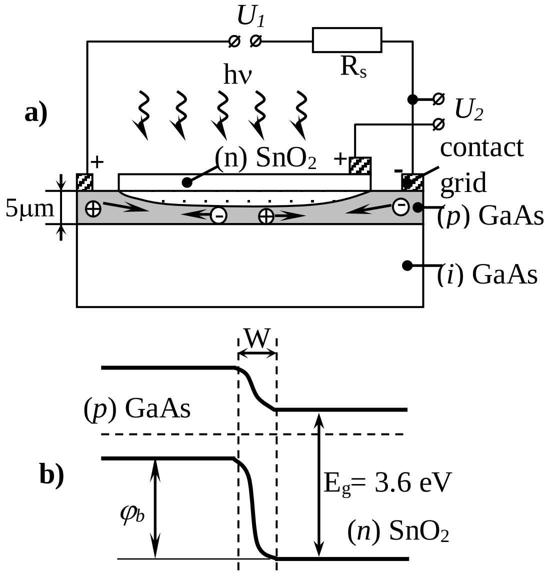


Figure 8. Structure (a) and energetic diagram (b) of photoresistor without any polarization voltage.

At the certain value of the polarization voltage U_2 the space charge region extends into the whole thickness of the active layer and blocks channel for the dark current generated by the supply voltage U_1 (figure 9,a).

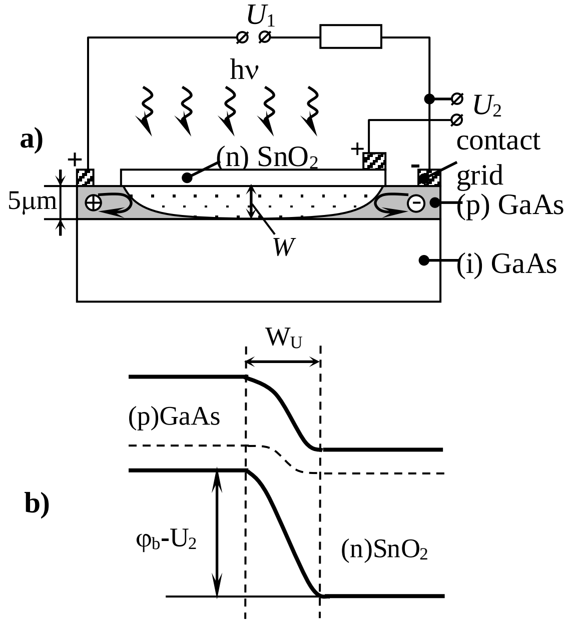


Figure 9. Structure (a) and energetic diagram (b) of photoresistor at reverse polarization voltage ($U_2 \geq U_{thr}$).

Excessive charge carries generated by the optic flux absorbed inside the active layer GaAs are separated by the internal electric field of the GaAs-SnO_2 heterojunction. So, only excessive major charge carriers form the photocurrent in the channel. The total photoresistor current consists from the major charge carriers injected by the external voltage source U_1 and the major charge carriers injected by the optic flux. This way, the losses at the charge carriers recombination inside the active layer's volume are reduced to zero. The distance between the contact grid's strips can be much bigger than the diffusion length of minor charge carriers because the minor charge carriers generated by the optic flux do not determine the photocurrent value. The distance between the contact grid's strips influences on the time of response only, which is equal with the drift time of the excessive major charge carriers inside the electric field formed by the source U_1.

Another major advantage of photoresistor is the possibility to vary channel thickness for current, including it's blocking, by the reverse polarization voltage U_2. Figure 10 presents the dependence of the photoresistor current for U_1=const and for different values of the heterojunction polarization voltage U_2. The space charge region W extends through the whole active layer thickness at the threshold reverse polarization voltage U_{thr}. Total photoresistor current is equal to zero for $U_2 \geq U_{thr}$, but for $U_2 < U_{thr}$ the total current consists from the dark current I_d, which value depends on channel thickness for current (is function of U_2), and from the photocurrent I_{ph}, which value is proportional with the intensity of the incident flux.

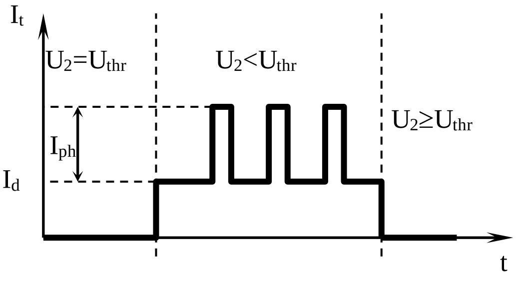


Figure 10. Photoresistor current for various polarization voltages.

CONCLUSION

The scientific investigations demonstrate that III-V compound heterostructures permit manufacturing of photodiodes with unique functional properties:

- exclusion of optic background influence and detecting of signals with certain wavelength only;
- photosensibility modulation on 100 % by polarization voltage;
- detecting simultaneously two or more optic signals with different wavelength.

The presented photoresistor as distinct from the classic photoresistor has the following advantages:

1. The photocurrent's value doesn't depend on the recombination processes inside the active layer volume;
2. The dark current can be reduced to minimum by making a thin channel for current;
3. The resistor photosensibility can be modulated by polarization voltage of the GaAs-SnO_2 junction. This allows to detect selectively the optic signals with different modulating frequencies from a wide packet of signals transmitted by the optic fibers or by other mediums.

Bibliography

1. Dorogan V., Syrbu N., Vieru T., etc. *Variable composition layers in the optoelectronic devices structure based on A^3B^5 compounds.// Romanian Journal of Optoelectronics.- V.6, Issue 1, 1998, Bucharest, Romania, P.20-23.*

2. Dorogan V.,Bejan N., Vieru T., Coseac V., Secrieru V.. *Selective reception of optic signals transfered through atmosphere.// Ist Internation. Conf. on Information Tecnologies. 11-13 April, 2001, Chisinau, Moldova, V.2001, N.1, P.95.*

3. Dorogan V., Brânzari V., Vieru T., Coseac V., Necşoiu T., Savastru R. *Fotodiodă selectivă.// Brevet de invenţie nr. 876 G2 - Buletin Oficial de Proprietate Industrială, Nr.11, 1997, P.22.*

4. Dorogan V., Bejan N., Vieru T., Coseac V., Prodan I. *A new structure of p-i-n photodiode for optic communications.// Ist Internation. Conf. on Information Tecnologies. 11-13 April, 2001, Chisinau, Moldova, V.2001, N.1, P.96.*