Abstract - The calculation of spectral dependence of pZnTe-nCdSe heterojunction collection factor and short circuit current for different values of surface recombination rate and junction depth was carried out. The photosensitivity of the studied heterojunctions covers the wavelength region of 0.56-0.85 µm and is determined by the electron-hole pair generation in the component materials. The spectrum form as well as monochromatic sensitivity of ZnTe-CdSe heterojunction depend on the components thickness and their doping level. At the optimum conditions the spectral sensitivity is 0.35 A/W, quantum efficiency is 0.92. At reverse biases along with the photocurrent absolute value increase, the shift of short wavelength maximum to lower energies region is observed. The voltage dependence of this shift is in satisfactory agreement with the Frantz-Keldysh theory.

1. INTRODUCTION

ZnTe-CdSe heterojunctions, formed by the materials with the close values of lattices (discrepancy ~0.3%) are of great interes for production of solar cells (Buch et al., 1976; Gashin et al 1997), of luminescent diodes for visible region of spectrum (Fedotov et al. (1971), Gashin et al. (1977)), of electrons flux detectors (Gashin et al., 1983) and so on. The parameters of the given devices considerably depend on the photosensitivity spectral distribution. By coming from that the theoretical and experimental investigation of ZnTe-CdSe heterojunctions photosensitivity spectra and determination of their control methods are of great interest.

2. THEORETICAL CONSIDERATIONS

The short current and collection factor spectral sensitivity of ZnTe-CdSe heterojunction (HJ) for different component materials thicknesses was calculated by using different values of measured minority charge carriers diffusion length.

A plane ZnTe-CdSe HJ situated at a distance \( l \) from the semiconductor heterostructure of thickness \( d \) is considered. At this the contribution of generation both in ZnTe as well as in CdSe is considered. The problem consists of determination of the part of free charge carriers which when reaching junction participate in photocurrent.

Thus at the illumination through the wide band gap component (ZnTe) at the photons energies complying with the condition \( E_g(CdSe)=1.7eV<\hbar\nu<2.26eV=E_g(ZnTe) \) the generated in the photocell current consists of holes, minority charge carriers in n-CdSe, current as electron-hole pairs are generated only in this material.

At \( \hbar\nu>2.26 \) eV the photocurrent is determined both by the holes current from n-CdSe as well as electrons current from p-ZnTe.

Let us consider the first case: \( 1.7eV<\hbar\nu<2.26eV \). By neglecting the photons absorption by free carriers in p-ZnTe and considering only interband absorption one can consider, that the light falls directly on to potential barrier. The photocurrent \( I_{p} \) can be determined as:

\[
I_{p1} = I_0 Q_{p1} \tag{1}
\]

where: \( Q_{p1} \) - collection factor, \( I_0 \) - maximum current, which can be excited by the photons of the given wavelength, i.e. at \( Q_1 = 1 \).

\[
I_p = eN_0(1-R) \tag{2}
\]

where: \( N_0 \) - number of photons of the given energy falling on 1 cm² per time unit, \( R \) - reflection coefficient.

For the collection coefficient in the case of photons absorption in the depletion region (Tuzzolino et al., 1962):

\[
Q_{p1} \equiv 1 - e^{-\alpha W} \tag{3}
\]

where: \( \alpha \) -absorption coefficient, \( W \) - depletion region width.

In the second case, when \( \hbar\nu\geq2.26eV \), the component of the holes photocurrent from n-CdSe according to (Loferski and Wysocki, 1961) at \( L = b - 1 \) will be

\[
I_{p2} = I_0 Q_{p2} \tag{4}
\]

\[
Q_{p2} = \frac{1}{\alpha \left(1 - \frac{\nu_p}{\nu^2}\right)} \left( \beta y \nu_p e^{-\nu_p} - \nu y e^{-\nu y} - \alpha e^{-\alpha W} \right) \tag{5}
\]

where:

\[
\beta = e^{-\nu_p} (h + \alpha) - e^{-\nu y} (h + \nu_p)
\]

\[
\gamma = e^{-\nu y} (h - \nu_p) - e^{-\nu_p} (h + \alpha)
\]

\[
\Delta_p = e^{-\nu y} (h + \nu_p) - e^{-\nu_p} (h - \nu_p)
\]

\[
h = S/D_p; \quad \nu_p = (D_p \tau_p)^{1/2} = L_p^{-1}
\]

\( S \) - is surface recombination rate.

\( D_p \) - is holes diffusion coefficient.

The electron current component from p-ZnTe is
\[
I_{\text{ph2}} = I_0 Q_{\text{ph2}}
\]
\[
Q_{\text{ph2}} = \frac{1}{\alpha} \left( 1 - \frac{V_n^\alpha}{\alpha^2} \right) \left( \beta_n V_n e^{\gamma_n} - \gamma_n V_n e^{\beta_n} - \alpha e^{\alpha} \right)
\]
where:
\[
\beta_n = \alpha e^{-(\gamma_n+\alpha)} - \gamma_n e^{-(\beta_n+\alpha)}
\]
\[
\gamma_n = -\alpha e^{-(\gamma_n+\alpha)} - \gamma_n e^{-(\beta_n+\alpha)}
\]
\[
\Delta_n = 2 \nu_n c (V_n b - V_n l)
\]
\[
\nu_n = (D_n \tau_n)^{1/2} = L_n^{-1}
\]

\(L_n\) - is electrons diffusion length in ZnTe.

The calculation of photocurrent dependence on wavelength \(\lambda\) is carried out by approximating Sun radiation to the radiation of the black body (Ambrozeak, 1970):
\[
N_\text{ph}(\lambda) = 2 \pi c \lambda^{-3} \left( \exp \left( \frac{hc}{kT_\lambda} \frac{1}{\lambda} - 1 \right) \right)^{-1}
\]
at \(T_\lambda = 5800\) K; by assuming, that the interband absorption coefficient of semiconductor is described by the expression (Kireev, 1975).
\[
\alpha(\lambda) = \frac{e^2}{\pi \hbar^2 c^2 m_p^* m_n^*} \left( \frac{\hbar c}{\lambda} - E_g \right)^{1/2}
\]

The parameters of the sun radiation depending on absorption conditions in the atmosphere are given in the paper (Loferski and Wysocki, 1961), and in (Ambrozeak, 1970) the data on photons amount with the given energy is the Sun spectrum are given, which is necessary for calculation of spectral sensitivity.

The calculation was carried out for different combinations of \(l, b, h\) parameters. For the determination of \(\alpha(\lambda)\) dependence the data for \(m_p^*, m_n^*\) and \(E_g\) of ZnTe-CdSe HJ components were taken. The values of minority carrier diffusion length in ZnTe and CdSe were determined experimentally and are \(L_p = 0.76\) \(\mu m\) for CdSe and \(L_n = 1.14\) \(\mu m\) for ZnTe.

In Fig. 1. the plot of collection factor dependence on radiation wavelength is given. From the calculated plot one can see that, at the constant values \(b = 20\) \(\mu m\) and parameter \(h = 1.0\), the increase of the transition layer thickness \(l\), leads to the gain factor decreases up to zero in the short wavelength region at \(l\) higher than 10 \(\mu m\). The plot, according to the results of collection factor calculated dependence on wavelength, when the transition layer thickness is maintained constant \(l = 5\) \(\mu m\) and \(h = 1.0\) (Fig. 1.) shows, that the collection factor in the region 0.55 eV < \(h\) < 0.73 eV increases with the total thickness increase. The obtained results are in rather good agreement with the experiment.

**3. EXPERIMENTAL RESULTS**

In Fig. 2. the short circuit spectral dependencies of a thin film HJ is given, where curve 1 is for illumination from ZnTe side, and curve 2 - from CdSe side. From figure, one can see, that at the illumination from CdSe side the curve has a single maximum at 0.76 \(\mu m\), stipulated by electron-hole pairs generation in CdSe. As CdSe band gap is 1.72 eV and its thickness of 8 \(\mu m\) is relatively high, and ZnTe band gap is 2.26 eV, than CdSe does not transmit the active for ZnTe light. At the illumination from ZnTe side as the residual absorption coefficient is ~ 10 \(cm^{-1}\) (Reynolds et al., 1967) - the light active for CdSe is transmitted without absorption. In this case the spectral sensitivity curve covers the wavelength region 0.56-0.85 \(\mu m\) with two specific maxima at 0.62 \(\mu m\) and 0.76 \(\mu m\), which correspond the fundamental absorption region of ZnTe and CdSe.

We have investigated the influence of substrate temperature during CdSe layer epitaxy on the shape of spectral sensitivity of ZnTe-CdSe thin film HJ. In Fig. 3. the photosensitivity spectra of thin film HJ, grown in a single experiment and situated successively along deposition zone are given. In the case of high electron concentration in CdSe ~ (2.4 \(\times 10^{17}\) \(cm^{-3}\)) (layers are fabricated at low substrate temperatures ~ 616°C), all space charge is practically situated in ZnTe and photosensitivity is
determined by the electron-hole pairs generation in it (curve 6).

The redistribution of electron-hole pairs generation region occurs with the substrate temperature increase. In the case of high CdSe layers deposition temperature of about 680 °C and, hence, low electron concentration in CdSe (5.9 \times 10^{15} \text{ cm}^{-3}) the photosensitivity is mainly determined by electron-hole pairs generation in CdSe (curve 1).

So, the possibility of ZnTe-CdSe HJ photosensitivity spectral characteristic shape control, by deposition temperature selection, is shown.

The investigation of spectral dependencies of crystal-layer ZnTe-CdSe HJ fabricated by vapor phase epitaxy, had shown that the shape of these characteristics depends on cadmium selenide layer thickness (Gashin and Simashkevich, 1973). By selection of epitaxial layer thickness it is possible to obtain the characteristic with the uniform sensitivity in the 0.56-0.74 \mu m region (Fig. 4., curve 1). In the case of ZnTe-CdSe HJ fabricated by gaseous phase epitaxy in H₂ flow, at any illumination conditions the main contribution in photosensitivity is brought by electron-hole pairs generation in ZnTe (Fig. 4., curves 2,3). This is related to the fact that during CdSe layer deposition a high resistivity layer is formed, due to mutual diffusion of component-materials atoms, which determines the HJ photosensitivity.

Investigations of temperature shift of long wavelength and short wavelength edges in V_{oc} spectral dependence for ZnTe-CdSe HJ fabricated by CdSe layers vapor phase deposition on to ZnTe crystal, two types of samples were used: one with the low CdSe layer thickness (d = 0.45 \mu m), for which photosresponse is mainly stipulated by the absorption in ZnTe, and other, with higher thickness of CdSe layer (d = 9.2 \mu m), as a result of which, at the illumination through this layer a single long wavelength maximum is observed on the characteristic which at 300 K is situated at 0.74 \mu m, and maxima stipulated by electron-hole pairs generation both in ZnTe as well as in CdSe are shifting in the shorter wavelength region with the temperature decrease. The maxima temperature shift dependence for these samples is given in Fig. 5. As one can see these dependencies are rectilinear, and shift coefficient of short wavelength maximum with temperature equals \~ 6.2 \times 10^{-4} \text{ eV/K} and for long wavelength one \~ 4.5 \times 10^{-4} \text{ eV/K}.

These values are close to ZnTe and CdSe band gap temperature dependence, i.e. these stipulates the shift of maxima in sensitivity spectral dependence of ZnTe-CdSe HJ.

For the investigation of temperature influence on ZnTe-CdSe HJ spectral characteristic shape, the samples with the uniform sensitivity in 560-740 nm region were chosen. In Fig. 6. I_{sc} spectral dependencies at 300 and 77 K for one of samples are brought. Along with the shift of the entire characteristic to shorter wavelengths at temperature decrease, the relatively photosensitivity decrease in the long wavelength region is observed.

![Fig. 3. Photosensitivity spectral dependence for ZnTe-CdSe thin film HJ obtained at different substrate temperature, °C: 1-720; 2-696; 3-673; 4-658; 5-636; 6-615.](image1)

![Fig. 4. ZnTe-CdSe heterojunction photosensitivity spectral distribution.](image2)

![Fig. 5. Temperature dependence of photosensitivity maxima shift.](image3)

![Fig. 6. Short circuit current I_{sc} spectral dependence of ZnTe-CdSe heterojunctions at different temperatures T, K: 1- 80; 2 - 300.](image4)
This is related to the fact that temperature variation leads to space charge redistribution between HJ components. Indeed, at room temperature, as calculation shows this HJ is rather symmetrical: \( W_p = 1.6 \times 10^{-5} \) cm, \( W_p = 0.9 \times 10^{-5} \) cm. At the temperature decrease from 300 K to 77 K the holes concentration in ZnTe crystals, used as substrates, decreases more than by four orders of magnitude, at the same time the electrons concentration in CdSe layers by 10 times. As a result the entire space charge is situated in ZnTe and the most efficient separation of electron-hole pairs occurs in it. Besides, the holes mobility in ZnTe increases by 10 times, when as the same time in CdSe only by three times. Therefore along with the space charge redistribution with temperature decrease the diffusion length increases, but its sharper increase in ZnTe enhances the generated in ZnTe carrier separation.

At the same time with the investigation of \( I_{sc} \) and \( V_{oc} \) spectral dependencies of ZnTe-CdSe HJ, the quantum efficiency spectral distribution was studied (Fig. 7.). Quantum efficiency \( \beta \) is determined by the number of non-equilibrium charge carriers, generated by a single absorbed photon and is given by formula (Landsman et al., 1971).

\[
\beta = \frac{I_{sc}hc}{e\lambda \gamma P(1-R)}
\]

(10)

where: \( h \) - is Plank constant; \( c \) - light speed; \( P \) - falling radiation energy; \( \gamma \) - separation factor; having a value less than unity and is a function of charge carriers diffusion length, surface recombination rate, light absorption coefficient; \( R \) - reflection coefficient.

Based on the data on radiation flux power, reflection coefficient and \( I_{sc} \) without consideration of separation factor \( \gamma \) the \( \beta = f(\lambda) \) and \( I_{sc} = f(\lambda) \) dependencies where plotted (recalculated to the same falling energy). The maximum value of the effective quantum efficiency is 0.71. This value is understated, as \( \gamma \) is always less than unity. The carried out estimated calculations show that \( \beta \) reaches 0.86 - 0.92.

Fig. 7. Quantum efficiency Q and short circuit current \( I_{sc} \) spectral distribution of ZnTe-CdSe heterojunction.

The applied bias to HJ leads to the change of its spectral photosensitivity (Fig. 8a.). At direct biases the photoresponse value decreases. In that case the external electric field direction is opposite to the barrier field. This leads to the effective field value decrease and hence to gradual cessation of electron-hole pairs separation. When a reverse bias is applied photosensitivity increases with the bias increase. The reverse bias leads to the space charge region widening and, hence, photoresponse increase due to the increase of charge carriers amount generated in the contact field region.

At the same time with the photocurrent value increase with reverse bias increase, the short wavelength maximum shift in the long wavelength region is also observed, which is related to the electron-hole pair generation. The shift dependence \( \Delta \omega \) of this maximum on electric field \( E \) value in ZnTe can be sufficiently described by the law (Fig. 8b.).

\[
\Delta \omega \sim E^{2/3}
\]
which may be stipulated by the direct absorption edge shift under the influence of electric field according to Frantz-Keldysh theory (Aven and Cuzano, 1964). The estimation of the shift value by formula:

\[ \Delta \hbar \omega = \left( \frac{eEh}{m^*} \right)^{2/3} \]  

(11)

where: \( E \) - is electric field strength; \( h \) - Plank constant; \( m^* \) - reduced effective mass by the order of magnitude coincides with the experimental shift value (\( \hbar \omega \sim 10^{-2} \) eV).

4. CONCLUSIONS

By using the results of calculation of ZnTe-CdSe heterojunction short circuit current dependence on layers thickness and doping level, the optimum conditions for fabrication of photosensitive heterojunctions were determined. ZnTe-CdSe heterojunctions with the uniform distribution of photosensitivity in the wavelength region 0.60-0.80 \( \mu \)m with quantum efficiency of 0.92 electron/photon, monochromatic sensitivity 0.35 A/W and efficiency of light conversion into electric one of 7.2% were fabricated.

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REFERENCES


