Photoconductivity of gamma-irradiated ZnSe (Te)/ZnO:O and ZnSe(Te)/ZnO:O,Zn nanoheterojunctions

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Abstract. Possibility of enhancing the photoconductivity of ZnSe (0.2%Te)/ZnO:O nanoheterojunction was investigated under effect of thermo-treatment in zinc vapor followed by 60Co gamma-irradiation in air to the dose of 106 Gy by means of generation of impurity-defect complexes. The obtained ZnSe (0.2%Te)/ZnO:O,Zn nanoheterojunction had an electron conductivity with the activation energy 0.33 eV that is caused by thermo-stimulated transfer of charge carriers on the stable resonance level $\Gamma = 5.76$ eV in the conducting band. The significant photoconductivity growth from $10^{-10}$ to $10^{-5}$ $\Omega^{-1}$ was achieved at 300 K, and also a broad band (480-1100 nm) light scattering at free carriers occurred due to formation of additional stable associates $(O_{Zn}^0,Te_{Zn}^0,V_{Zn}^{-})$, $(O_{Zn}^0,V_{Zn}^{-})$ or $(O_{Zn}^0,V_{Zn}^{-},Me^{III}_{Zn}Zn_{l})$ at the interface between the matrix crystal p-ZnSe(0.2%Te):O,Zn and nanocrystallite n-ZnO of 40 nm size, where amorphous phase layer of 1.2 nm was also grown.

1 Introduction

Scintillator ZnSe crystals with a high light yield have found wide application in X-ray tomography devices [1,2]. Schottky photodiodes Ni-ZnSe (Te,O)-In are used for UV radiation dosimetry radiometry [3]. Type II n-ZnO/p-ZnSe heterostructures have high photocatalytic activity and are used as photodetectors from 355 to 638 nm [4-6]. Nanowires a n-ZnO/p-ZnTe and n-ZnO/p-ZnS were proposed for photovoltaic devices [7]. The solar cell is composed of nanowires with a ZnO core and ZnSe shell with a size of 40 - 80 nm, where free electrons are in ZnO, and free holes are in ZnSe. In this case, the heterojunction can be associated with highly strained defects and a complex interface [8]. The X-ray diffraction pattern of the ZnSe film contains intense peaks (111), (220), (311), and (400) [9]. A compressed tablet of ZnSe nanoparticles with dimensions of ~ 35 nm according to the Scherer formula and ~ 50 nm according to scanning electron microscopy had photoconductivity at 301 - 371 K [10]. According to X-ray diffraction patterns of (GaAs) 1-xy (Ge2) x (ZnSe) y nano-heterostructures, the size of ZnSe nanocrystals was estimated at 59 nm, and for GaAs nanocrystals at 48 nm [11]. The thermodynamically stable ZnO/Ag nanocomposite with ZnO nanorods 30 - 70 nm possessed high photosensitivity, the concentration of uncompensated

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ionized donor impurity \( N_d \) increased from \( 2.4 \times 10^{14} \) to \( 5.6 \times 10^{17} \) cm\(^{-3} \) \([12]\). The values of \( N_d \sim 10^{16} \) cm\(^{-3} \) are typical for nominally undoped ZnO with a characteristic n-type conductivity caused by small donor defects in the form of oxygen vacancies and interstitial zinc \([13, 14]\). Concentrations of free charge carriers in ZnSe (Te) with thermodynamically stable low-mobile complexes \( V_{Zn} Te_{Se} \) are in the range of \(~ 1.2-1.6 \) \( 10^{17} \) cm\(^{-3} \) \([3]\). It has been shown that with a decrease in the size of ZnO particles within the limits of 63 - 315 \( \mu \)m, the response voltage of the I–V characteristic of the composite varistor increases from 20 to 150 V \([15]\). Isotropic heterostructures n-Ga\(^{+}\)–n\(^{-}\)-(ZnSe)\(_{1-x-y}\)(Si\(_2\))\(_x\)(Ga\(^{+}\))\(_y\) (\( 0 \leq x \leq 0.03, 0 \leq y \leq 0.09 \)) have rectifying properties in the voltage range \(~20+ 15\) V \([16]\). The temperature dependence of the electrical conductivity of a thin ZnS\(_x\)Se\(_{1-x}\) film at 300-500 K is associated with loosely coupled Mott-type transitions and decreases with increasing S content, while the crystals with activation energy \( (E_a) \) of hops increases from 0.13 to 1.89 eV with temperature \([17]\). ZnSe \( \rho =10^8 \) Ohm-cm of compensated electronic conductivity had \( E_a=0.66 \) eV associated with the Zn, donor \([18]\).

The problem is to create stable photoactive centers with a high concentration and photodiodes with high photoconductivity (PC) in the UV-visible range based on wide-gap direct-gap nanoheterojunctions (NHJ).

The aim of this work is to find the conditions for enhancing the photoconductivity of ZnSe(Te)/ZnO:O NHJ using heat treatment in zinc vapor and gamma irradiation in the presence of oxygen to create impurity defect complexes and controlled generation of carriers.

### 2 Experimental technique objects

Investigated were ZnSe crystals grown at the Research Institute "Monokristall", Kharkov. To create p-n-junction in ZnSe crystals, diffusion doping with an isovalent impurity of Te atoms was used, which led to additional generation of zinc vacancies - \( V_{Zn} \). During the oxidative treatment, additional centers of interstitial zinc, \( Zn_i \), were introduced and stable associates \( V_{Zn} Te_{Se} Zn_i \) were formed. Then, heat treatment was carried out in zinc vapor to increase the concentration of these associates \([19]\). As result of the oxidative heat treatment, the formation of NHJ ZnSe (Te) / ZnO: O was expected, and after heat treatment in zinc vapor, LHP ZnSe(Te)/ZnO:O,Zn, possessing photoconductivity. Some of the samples from each series were irradiated in the presence of atmospheric oxygen with \(^{60}\)Co gamma rays with an energy of \(~ 1.25 \) MeV and a power of 10 Gy/s up to a dose of \( 10^6 \) Gy at 300 K. It was assumed that at such high dose, the concentration of oxygen centers in the selenium sublattice, which leaves the crystal, would increase, presumably near the impurity center of large tellurium ion, which would lead to an increase in the concentration of impurity associates, \( (O_{Se}^{0} Te_{Se}^{0} V_{Zn}^{+}) \), \( (O_{Se}^{0} V_{Zn}^{+} Me_{Zn}^{3+} Zn_i^{-}) \) \([19]\).

Research methods. A description of the method for studying X-ray diffraction patterns is given in \([20]\). Table I shows the structural characteristics: the reflections of the matrix lattice (ZnSe) and the sizes of the nanocrystalline (NC) and amorphous (ZnO) phases on the nanometer scale, estimated by the Selyakov-Scherrer formula.

Optical density spectra (D) were measured on an SF-56A (LOMO) spectral device equipped with computer program for recording and processing the obtained spectra in the wavelength range from 190 to 1100 nm at 300 K with an error of 1%. All spectra are reproducible when measured three times. Table II presents the optical densities at the maxima of the absorption bands and the corresponding transition energies, energy levels in the conduction band. The levels and transitions were identified in accordance with theoretical calculations of the band structure of pure ZnSe taking into account the temperature in the sequence: \( A_{1,3,4} \), \( \Gamma_{6v} \), \( L_{1,5,4} \), \( M_{4v} \) etc. \([21]\). The concentration of optical and centers N (cm\(^{-3} \)) responsible for the isolated absorption band was calculated using the Smakula formula:
where \( n \) - is the refractive index for the wavelength corresponding to the maximum of the absorption band, in the case of \( E_g \) - the band for the ZnSe crystal \( n = 2.6645 \); \( f \) - is the oscillator strength for transitions with the participation of the zone is equal to 1; \( H \) - is the half-width of the band, (eV); \( K_{m} \) - is the absorption coefficient at the maximum of the band (cm\(^{-1}\)); \( N \) - is the concentration of electrons.

The electrical conductivity was measured by the current-voltage method at a direct current in cell with clamping Cu electrodes in the temperature range 90 - 390 K. In Arrhenius coordinates, the activation energy \( (E_a) \) of the electrical transfer process \( \rho(T) \) was determined from the relation:

\[
E_a = \frac{k \ln(\rho_1/\rho_2)}{(1/T_1^{-1} - 1/T_2^{-1})}
\]

The course of the peak dependence \( \sigma(T) \) is process of relaxation of the charge associated with electrically active defects. Because the area under the curve of the peak \( \sigma(T) \) in the region of its extremum is the value of the total charge accumulated during alloying, heat treatment or irradiation, then \( E_a \) can be calculated from:

\[
E_a = G \left[ \frac{kT_m(T_m - \Delta T)}{\Delta T} \right]
\]

where \( T_{max} \) - is the temperature at the maximum of the peak; \( \Delta T \) - is its half-width, and the coefficient \( G \), which depends on the order of the kinetics of the relaxation process and the value of the effective frequency factor (\( \omega \)), is equal to 1.42 at \( \omega \approx 10^{-12} \) s\(^{-1}\) for electrons and 1.5 at \( \omega \approx 10^{-8} \) s\(^{-1}\) for ions. Table III shows the characteristics of the electrical conductivity of ZnSe(0.2%Te)/ZnO:O, ZnSe(0.2%Te)/ZnO:O,Zn NHJ in the range of 90 - 390 K before and after irradiation.

Photo - Volt-ampere characteristics (VAC) were measured by the two contact method with indium contacts on standard devices: amplifier U5 - 4, voltmeters F - 116/2, Sh - 300, F - 136, power supply B5 - 50, at 300 K in the dark and under illumination with an incandescent lamp (continuous spectrum) with a brightness of 2280 lumens as measured by a Guarda FX-101 LUX METER. We studied the dependences of the dark and photo-current on the applied external voltage 0 – 100 V. Table IV shows the electro-optical characteristics of the investigated NHJ before and after irradiation. Photoconductivity was determined from the ratio, where \( R_l \) and \( R_d \) are resistance to light and dark, as described:

\[
\sigma_{FP} = \frac{(R_l - R_d)R_d}{R_l}
\]

### 3 Experimental results and discussion

X-ray structural analysis (XRD). We previously studied the crystal structure of ZnSe(0.2%Te)/ZnO:O and ZnSe(0.2%Te)/ZnO:O,Zn before and after irradiation. The X-ray diffraction patterns contained the ZnO (110) nanocrystalline phase and the reflection of the matrix lattice of the ZnSe crystal (220) [20], which is consistent with the spectrum of the ZnSe powder (111), (220), (311), and (400) [8].
Table 1. Structural characteristics - reflections of the matrix (ZnSe) and the size of the impurity (ZnO) phase of the NHJ ZnSe(Te)/ZnO:O, ZnSe(Te)/ZnO:O,Zn before and after irradiation.

<table>
<thead>
<tr>
<th>Structural characteristics</th>
<th>ZnSe(0.2 ves.%Te)-ZnO:O</th>
<th>ZnSe(0.2 ves.%Te)-ZnO:O,Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>pure</td>
<td>γ-ird.</td>
</tr>
<tr>
<td>Matrix phase reflex ZnSe</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td>Impurity phase reflex ZnO</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>The size ZnO (nm)</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Diffuse reflection size</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

In Table 1 shows the calculations of the sizes of ZnO nanocrystallites ~ 40 nm in ZnSe(Te)/ZnO:O NHJ, which do not change after heat treatment in zinc vapor and gamma irradiation. In the ZnSe(Te)/ZnO:O,Zn NHJ, the amorphous ZnO phase was also observed in the form of a diffuse band [20]. The sizes were estimated as ~ 0.9 nm, which after gamma irradiation increased to 1.2 nm. This occurs due to the radiolysis of selenium from the crystal surface, leading to an increase in the content and size of ZnO nanoparticles [22]. Our results are consistent with the literature data: where the nanowires of the ZnO core and ZnSe shell had dimensions of 40 - 80 nm and a length of up to 1 micron [8]. According to the Scherer formula, ZnSe powder nanoparticles had dimensions of ~ 35 nm, and in scanning electron microscope ~ 50 nm [10]. X-ray diffraction of nanoheterostructures (GaAs)$_{1-x}$(Ge$_2$)$_x$(ZnSe)$_y$ showed that the size of ZnSe nanocrystals is 59 nm, while GaAs nanocrystals are 48 nm [11]. In ZnO/Ag nanocomposites, ZnO nanorods had diameter of ~ 70 nm [12].

Fig. 1. Optical density spectra of NHJ - Left: ZnSe(Te)/ZnO:O (a); Right: ZnSe(Te)/ZnO:O,Zn (b) before and after irradiation with $^{60}$Co 100 MP gamma quanta.

In Fig. 1a,b shows the optical density spectra (D) of ZnSe(Te)/ZnO:O, ZnSe(Te)/ZnO:O,Zn NHJ before (1) and after gamma irradiation (2). The NHJ spectrum of ZnSe(Te)/ZnO:O (a, 1) contains the resonance levels (RL) $I_{6v} - 5.76$ (215 nm) eV and $L_{1,3v} - 4.85$ (255 nm) eV [21, 22], as well as the absorption edge $E_g=2.58$ eV (480 nm). The calculated value of the total population on the RL and $E_g$ (concentration of photoconductivity electrons) according to the Smakula formula (1) $N_e = 4.38 \times 10^{16}$ cm$^{-3}$ is given in Table 1.

Table 2. Energies (eV) and optical densities (D) of levels and calculations of electron concentration by the Smakula formula in NHJ ZnSe(Te)/ZnO:O, ZnSe(Te)/ZnO:O,Zn before and after irradiation.

<table>
<thead>
<tr>
<th>ZnSe(0.2%Te)/ZnO:O</th>
<th>γ-irradiation $^{60}$Co</th>
<th>ZnSe(0.2%Te)/ZnO:O,Zn</th>
<th>γ- irradiation $^{60}$Co</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{6v} = 5.76$ eV</td>
<td>-</td>
<td>$I_{6v} = 5.76$ eV</td>
<td>$I_{6v} = 5.76$ eV</td>
</tr>
<tr>
<td>$N_{\text{eff}} = 2.25 \times 10^{16}$ cm$^{-3}$</td>
<td>-</td>
<td>$N_{\text{eff}} = 2.44 \times 10^{16}$ cm$^{-3}$</td>
<td>$N_{\text{eff}} = 2.45 \times 10^{16}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>
Irradiation led to decrease in $N_e$ by an order of $4.6\times10^{15}$ cm$^3$ due to the destruction of the RL. HT in Zn (b, 1) vapors led to destruction of RL $L_{1,3\nu}$, as a result $N_e$ decreased to $2.78\times10^{16}$ cm$^3$ and ZnSe(Te)/ZnO:O,Zn NHJ was formed. Irradiation with gamma quanta of this NHJ (b, 2) led to an insignificant increase in $N_e=2.97\times10^{16}$ cm$^3$, an increase in scattering was also observed, independent of $\lambda$ in the range 480-1100 nm and associated with scattering on weakly bound carriers. This should increase the photoconductivity $N_e$, calculations of the concentration of photoconductivity electrons $N_e$ are consistent with the literature data on the concentration of uncompensated ionized donor impurity $N_d \sim 10^{16}$ cm$^3$ in an undoped nanostructured ZnO array with n-type conductivity due to small donor defects in the form of $V_0$ and Zn$_i$ [12-14].

In Fig. 2 a,b show the temperature dependences of the electrical conductivity $\sigma(T)$ in the range 90 - 390 K NHJ ZnSe(Te)/ZnO:O before (curve 1) and after (curve 2) irradiation, which can be conditionally divided into three temperature ranges, where both exponential and peak dependences are observed: in the low-temperature part (90 - 260 K) it has $(6.5 \div 21)\times10^{-13}$ Ohm$^{-1}$·cm$^{-1}$ with the activation energy of electrical transfer $E_a=0.01$ eV according to formula (2), that is electron hopping conductivity near the Fermi level. In the range 260 - 370 K, peak tunneling electrical conductivity is observed with $T_{\text{max}} = 328$ K, $E_a = 0.25$ eV according to formula (3), and $\sigma_{\text{max}}=3.9\times10^{-8}$ Ohm$^{-1}$·cm$^{-1}$ (Table III), which, according to - Apparently, it is associated with the thermally stimulated emission of charge carriers to the formed RL in the conduction band and the formation of stable associates $V_{\text{ZnTeSeZn}}$ [19].
Table 3. Characteristics of the electrical conductivity of ZnSe(Te)/ZnO:O, ZnSe(Te)/ZnO:O,Zn NHJ in the range of 90-390 K before and after irradiation.

<table>
<thead>
<tr>
<th>NHJ</th>
<th>Parameters</th>
<th>Electronic conduction</th>
<th>peak conductance</th>
<th>Ionic conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (K)</td>
<td>σ (Ohm(^{-1})·cm(^{-1}))</td>
<td>E(_a) (eV)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 – 260</td>
<td>(6.5 – 21)·10(^{-13})</td>
<td>370 – 390</td>
</tr>
<tr>
<td><strong>ZnSe(0.2%Te)/ZnO:O</strong></td>
<td></td>
<td>0.01</td>
<td></td>
<td>(14 - 9.2)·10(^{-10})</td>
</tr>
<tr>
<td>Irradiation</td>
<td>T (K)</td>
<td>σ (Ohm(^{-1})·cm(^{-1}))</td>
<td>E(_a) (eV)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>190 – 280</td>
<td>(3.1 – 0.5)·10(^{-12})</td>
<td>300 – 390</td>
</tr>
<tr>
<td><strong>ZnSe(0.2%Te)/ZnO:O,Zn</strong></td>
<td></td>
<td>0.03</td>
<td></td>
<td>5.6·10(^{-11})</td>
</tr>
<tr>
<td>Irradiation</td>
<td>T (K)</td>
<td>σ (Ohm(^{-1})·cm(^{-1}))</td>
<td>E(_a) (eV)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>210 – 270</td>
<td>10(^{-13}) - 2.2·10(^{-12})</td>
<td>370 – 390</td>
</tr>
</tbody>
</table>

Ionic electrical conductivity was observed at 370 - 390 K with \(\sigma = (14 \div 9.2)\cdot10^{-10}\) Ohm\(^{-1}\)·cm\(^{-1}\) and \(E_a = 0.71\) eV. After gamma irradiation with ZnSe(Te)/ZnO:O NHJ in the range 90 - 190 K, the value of \(\sigma = 3.1\cdot10^{-12}\) Ohm\(^{-1}\)·cm\(^{-1}\) did not depend on temperature, and at 190 - 280 K it began to decrease to 0.5·10\(^{-12}\) Ohm\(^{-1}\)·cm\(^{-1}\) \(E_a = 0.03\) eV in the region of electronic conductivity (curve 2), that is, carriers were localized on associates. In the range 300 - 390 K, ionic conductivity with the participation of Zn\(_i\) \(5.6\cdot10^{-11}\) Ohm\(^{-1}\)·cm\(^{-1}\) with \(E_a = 0.473\) eV is switched on (Table III) and the maximum intensity of electroluminescence (EL) is reached at 72 V [23]. Accordingly, \(N_e\) decreases to 4.6·10\(^{15}\) cm\(^{-3}\) at 300 K (Table 2). Fig. 2b shows the temperature dependence of the electrical conductivity of ZnSe(Te)/ZnO:O,Zn BHJ before and after irradiation. It can be seen that HT in zinc vapor led to an increase in the electronic conductivity at 90 K by four orders of magnitude, that is \(\sigma = 3.3\cdot10^{-9}\) Ohm\(^{-1}\)·cm\(^{-1}\) with \(E_a < 0.01\) eV. Further, in the range 180 - 390 K, there was a decrease to \(T_{\text{min}} = 302\) K and \(\sigma_{\text{min}} = 4.1\cdot10^{-10}\) Ohm\(^{-1}\)·cm\(^{-1}\) with \(E_a = 0.17\) eV (Table III), this may be due to an increase in the concentration of \(V_{\text{ZnTeSe}_i\text{Zn}}\) defects [23] and the formation of inclusions of the amorphous phase up to 0.9 nm (Table I). Decrease in \(\sigma\) (T) NHJ ZnSe(Te)/ZnO:O,Zn in 90÷390 K led to an increase in \(E_a\) from <0.01 to 0.17 eV, which agrees with the data on the electrical conductivity of a thin ZnS\(_x\)Se\(_{1-x}\) film, where it falls from 300 to 500 K with increasing S content, but \(E_a\) of hops increases from 0.13 to 1.89 eV [17]. After irradiation in ZnSe (Te)/ZnO:O,Zn, the value of \(\sigma\) does not depend on temperature in the range 90 - 210 K (possibly due to the tunneling of charge carriers). With an increase in temperature to 270 K, an increase in \(\sigma\) from 10\(^{-13}\) to 2.2·10\(^{-12}\) Ohm\(^{-1}\)·cm\(^{-1}\) is observed with \(E_a = 0.33\) eV. In the range 270 - 370 K, a peak growth of \(\sigma_{\text{max}} = 3\cdot10^{-9}\) Ohm\(^{-1}\)·cm\(^{-1}\) is observed at \(T_{\text{max}} = 356\) K, \(E_a = 0.57\) eV (Table III), which is apparently associated with thermally stimulated emission of carriers charges on a stable RL in the conduction band. Ionic conductivity with \(\sigma = (9.9 \div 13)\cdot10^{-10}\) Ohm\(^{-1}\)·cm\(^{-1}\) at 370 - 390 K and \(E_a = 0.71\) eV (Table I), probably associated with the movement of Zn\(_i^+\) along the boundaries of ZnSe with an amorphous ZnO nanophase up to 1.2 nm in size to complexes \([V_{\text{ZnTe}}^0]\), stable in the range 150 - 400 K [18, 19].
In Fig. 3 a,b show dark and photo - I - V characteristics for NHJ ZnSe(Te)/ZnO:O and ZnSe(Te)/ZnO:O,Zn. It can be seen that the high-resistance ZnSe(Te)/ZnO:O NHJ in the dark and under illumination had semiconductor structure, where the range of rectifying voltages ranged from -99 to +96 V with a blocking voltage in the dark to ±60 V, in the light from -70 to +80 V with (-38; +48) V. It is known that the section above the cut-off voltage determines collisional ionization processes according to the law I = KU^n, almost like in varistors, apparently due to the formation of deep, stable, electrically active centers (here with the formation of stable associates V_{Zn,Te} in ZnSe) [19], and is confirmed by the appearance of EL at 64 V [24]. ZnSe (Te) / ZnO: O NHJ has high resistance R_d = \pm 7.2 \cdot 10^9 \div -2.7 \cdot 10^{10} Ohm, which is consistent with specific resistance of \sim 10^9 Ohm-cm of tablet of pressed ZnSe nanoparticles [10], and a low photoconductivity \sigma_{ph} = 10^{-10} Ohm^{-1} according to the formula (4). Irradiation with gamma quanta led to a decrease in the range of rectifying voltages from -60 to +45 V with a blocking voltage to ±36 V, where at 42 V an EL appears, depending on the polarity [24]. According to the literature data, composite ZnO varistors have a high electric breakdown field strength in the range from 20 to 150 V [15], and in our case the ZnSe(Te)/ZnO:O NHJ had a value of 80 V, and after irradiation of 40 V.

For NHJ ZnSe(Te)/ZnO:O,Zn, the dark blocking voltage decreased to 6 V, respectively, R decreased by three orders of magnitude, due to an increase in the concentration of
V_{ZnTeSeZn} associates [19], and the voltage range of the rectifying property decreased from 17 +10 V, and EL appears already at 8 V [23], which may be associated with the formation of an amorphous ZnO phase with a characteristic size of up to 0.9 nm on the ZnSe surface. According to [16], the n-GaP-n’-(ZnSe)_{1-x-y}(Si_{2})_{x}(GaP)_{y} heterostructure in the range of rectifying voltages from -20 + 15 V gave visible glow from 10 V. After illumination, the I – V characteristic acquires photodiode structure, with $\sigma_{\text{PhC}}$ up to 2·10^{-8} Ohm^{-1} (Table IV). Gamma irradiation led to a decrease in the blocking voltage to 3 V in the range of 9 V with the formation of EL at 4 V, which may be due to the growth of the amorphous phase to 1.2 nm [24]. The destruction of the blocking barrier was observed in the light, while $\sigma_{\text{PhC}}$ increased to 9·10^{-6} Ohm^{-1}.

Table 4. Dark and light resistance, polarization (+ R/-R), photoconductivity (PhC) at 300 K NHJ ZnSe(Te)/ZnO:O, ZnSe(Te)/ZnO:O,Zn before and after irradiation.

<table>
<thead>
<tr>
<th>NHJ</th>
<th>Dark resistance $R_{d}$, Ohm</th>
<th>Polarization +R/-R</th>
<th>Light resistance $R_{s}$, Ohm</th>
<th>Polarization +R/-R</th>
<th>Photoconductivity $\sigma_{\text{PhC}},$ Ohm^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZnSe (0.2%Te)-ZnO:O</td>
<td>$+7.2 \cdot 10^{6}$</td>
<td>0.27</td>
<td>$+1.4 \cdot 10^{6}$</td>
<td>0.2</td>
<td>$+6 \cdot 10^{-10}$</td>
</tr>
<tr>
<td>$\gamma$-quanta</td>
<td>$-2.7 \cdot 10^{10}$</td>
<td></td>
<td>$-7 \cdot 10^{9}$</td>
<td></td>
<td>$-10^{-10}$</td>
</tr>
<tr>
<td>ZnSe (0.2%Te)-ZnO:O,Zn</td>
<td>$+2.3 \cdot 10^{6}$</td>
<td>0.07</td>
<td>$+2.2 \cdot 10^{6}$</td>
<td>0.08</td>
<td>$+2 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\gamma$-quanta</td>
<td>$-3.1 \cdot 10^{7}$</td>
<td></td>
<td>$-2.8 \cdot 10^{7}$</td>
<td></td>
<td>$-3 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>$\gamma$-quanta</td>
<td>$+1.6 \cdot 10^{4}$</td>
<td>0.42</td>
<td>$+1.4 \cdot 10^{4}$</td>
<td>0.54</td>
<td>$+9 \cdot 10^{-6}$</td>
</tr>
<tr>
<td>$\gamma$-quanta</td>
<td>$-3.8 \cdot 10^{4}$</td>
<td></td>
<td>$-2.6 \cdot 10^{4}$</td>
<td></td>
<td>$-1.2 \cdot 10^{-5}$</td>
</tr>
</tbody>
</table>

In Table 4 shows comparison of the values of photoconductivity ($\sigma_{\text{PhC}}$) at 300 K for NHJ ZnSe(Te)/ZnO:O $\sigma_{\text{PhC}}=6\cdot 10^{-10}$ Ohm^{-1}, which after irradiation increased by 30%; for NHJ ZnSe(Te)/ZnO:O,Zn $\sigma_{\text{PhC}}$ increased by 2 orders of magnitude ($2 \cdot 10^{-8}$ Ohm^{-1}) due to heat treatment and another 2 orders of magnitude to $9 \cdot 10^{-6}$ Ohm^{-1} due to irradiation.

4 Conclusion

The performed studies have shown the possibility of a significant increase in the photoconductivity of the initial ZnSe(0.2%Te)/ZnO:O NHJ using heat treatment in zinc vapor and gamma irradiation in the presence of oxygen by creating impurity defect complexes. The obtained NHJ ZnSe(0.2%Te)/ZnO:O,Zn possessed electronic conductivity with an activation energy of 0.33 eV, which is associated with thermally stimulated emission of charge carriers to a stable RL $\Gamma_{6v} = 5.76$ eV in the conduction band and with an increase in light scattering at 480-1100 nm by free media. At the same time, a significant increase in photoconductivity was achieved from $10^{-10}$ to $10^{-5}$ Ohm^{-1} at 300 K.

The results obtained on the structural, optical, and electrical characteristics make it possible to recommend thermally and radiation-treated ZnSe(Te)/ZnO:O,Zn NHJ for the manufacture of photodiodes. The authors are grateful to V.D. Ryzhikov for the provided samples of zinc selenide.

References

samples of zinc selenide. Photoconductivity was achieved from 10 complexes. The obtained NHJ ZnSe vapor and gamma irradiation in the presence of oxygen by creating impurity defect photoconductivity of the initial ZnSe(0.2%Te)/ZnO:O NHJ using heat treatment in zinc. The performed studies hav...treatment and another 2 orders of magnitude to 9 ZnSe(Te)/ZnO:O,Zn

...ZnSe(Te)/ZnO:O

...amorphous ZnO phase with a characteristic size of up to 0.9 nm on the ZnSe surface. According to [16], the n...ohm by free media. At the same time, a significant increase in

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