11. Frenkel Ya.I. Collection. fav. tr. (Nauka, 1975) vol. 2, p. 217.
12. R.H. Hill. Phil. Mag. 23, 59 (1971).
13. N.G. Volkov, V.K. Lyapidevsky FTT. 14, 1337 (2012).

DOI: 10.34708/GSTOU.CONF..2021.52.60.004
УДК 541.128.7

HETERO TRANSITIONS BASED ON p - TiGaSe_2 - n - CuInSe_2

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Abstract. *The current-voltage and lux-ampere characteristics, as well as the photovoltage spectra and the lux dependence of the photovoltage in the gate and photodiode modes of the $p\text{-TiGaSe}_2$ - $p\text{-CuInSe}_2$ heterojunction obtained for the first time are studied. It was found that this heterostructure has a pronounced diode character. The $I - V$ characteristic of the structure under study is characterized by the fact that at low voltages it obeys well the law $I \sim \exp(eU / \beta kT)$. The photovoltage spectrum covers a wide range of wavelengths (0.55 - 1.85 μm). In this case, pronounced maxima are observed at $\lambda = 0.59$ and $\lambda = 0.95 \mu\text{m}$. The relaxation time τ determined from the kinetics of the photovoltage in the valve mode is $\sim 20 \mu\text{s}$.*

Keywords: *heterostructure, current-voltage characteristic, photovoltage, spectrum, single crystal.*

The study of this system was primarily stimulated by the fact that n - CuInSe_2 single crystals are characterized by the presence of a direct transition near 1.2 μm [1] and, therefore, are of great interest for creating solar energy converters. The physical properties of p - TiGaSe_2 single crystals are considered in [6-9].

To create $p\text{-TiGaSe}_2$ - $n\text{-CuInSe}_2$ heterojunctions, $p\text{-TiGaSe}_2$ single crystals with a carrier concentration of $\sim 10^{13} \text{ cm}^{-3}$ (at $T = 300 \text{ K}$) and $n\text{-CuInSe}_2$ single crystals with a carrier concentration of $\sim 10^{16} \text{ cm}^{-3}$ (at $T = 300 \text{ K}$) grown by the Bridgman-Stockbarger method. Before preparing heterojunctions, the surface of CuInSe_2 samples was etched with a solution of potassium dichromate in sulfuric acid and then washed with distilled water and pure alcohol. The surface of the $p\text{-TiGaSe}_2$ samples was not chemically treated. Ohmic contacts were obtained by applying a silver paste to the structures under study. The ohmicity of the contacts was preliminary checked by studying the structures $\text{Ag} - \text{TiGaSe}_2 - \text{Ag}$ and $\text{Ag} - \text{CuInSe}_2 - \text{Ag}$. It turned out that the current-voltage characteristics ($I - V$ characteristics) of these systems are symmetric and obey a linear law up to $\sim 15 \text{ V}$. At higher voltages, the symmetry of the $I - V$ characteristics of $\text{Ag} - \text{TiGaSe}_2 - \text{Ag}$ is somewhat violated.

Fig. 1. Schematic diagram of a characteristic curve R_{cr} **is the resistance of the**
 $p\text{-TiGaSe}_2 - n\text{-CuInSe}_2$ **heterojunction;**
 R_{cr} **- load resistance; $R_{l.r.} \ll R_{cr}$; H307 - plotter;**
CVG - sawtooth voltage generator. $U_{max} = 10 \text{ V}$, $f = 0.1 \text{ Hz}$

Fig. 2. Voltage-current characteristic heterojunction
 $p\text{-TiGaSe}_2 - n\text{-CuInSe}_2$ **at 300 K.**

Volt-ampere and lux-ampere characteristics, as well as in the dark, and the photovoltage spectra were recorded using a characteristic curve assembled on the basis of a plotter (Fig. 1), and the photovoltage spectra were recorded on an automated SDL-2 spectrometer adapted for these and other purposes.

In fig. 2 shows a dark $I - V$ characteristic taken at $T = 300 \text{ K}$ for the $p - \text{TiGaSe}_2 - p\text{-CuInSe}_2$ heterojunction. It can be seen from this figure that the $I - V$ characteristic has a clearly pronounced diode character with a forward direction corresponding to the positive potential on TiGaSe_2 . The $I - V$

characteristic of the structure under study is characterized by the fact that at relatively low voltages it obeys the exponential law $I \sim \exp(eU/\beta kT)$, where $\beta \approx 4$, and at higher voltages, a linear segment is observed. The detected linear section makes it possible to determine the cutoff current voltage, which in the considered case was $V_{oc} \approx 0.60$ V. It was found that with increasing forward bias, the differential resistance of the p - TlGaSe_2 - n - CuInSe_2 transition approaches the resistance of the TlGaSe_2 layer. It should be noted that at voltages $U > 10$ V, the linearity of the I - V characteristic is violated, which is apparently associated with the influence of current contacts. The thickness of the dielectric gap between the surfaces of the contacting materials (d), which was estimated by the method described in [2], is ~ 20 Å. In the opposite direction, at relatively low voltages, the $(I \sim U)$ characteristic obeys linear ($I \sim U$) and at high voltages - to quadratic ($I \sim U^2$) laws.

This structure has a fairly noticeable photosensitivity. Distribution curve of the spectral sensitivity of the p - TlGaSe_2 - n - CuInSe_2 heterojunction in the photovoltaic mode at room temperature is shown in Fig. 3. As can be seen from the figure, when the heterojunction is illuminated from the p - TlGaSe_2 side, the photovoltage spectrum covers a wide range of wavelengths (0.55 - 1.85 μm). In this case, pronounced maxima are observed at $\lambda = 0.59$ and $\lambda = 0.95$ μm , which are associated with the absorption of light in p - TlGaSe_2 and n - CuInSe_2 , respectively. The observed sharp drop in the photoemf in the short-wavelength region of the spectrum is explained by the fact that, in the samples under study, the diffusion length of nonequilibrium carriers in the direction perpendicular to the transition surface is less than the thickness of the TlGaSe_2 layer.

Fig. 3. Spectral distribution of the photovoltage of the heterojunction p - TlGaSe_2 - n - CuInSe_2 when illuminated from the side of TlGaSe_2 .

The apparent noticeable photosensitivity in the longer-wavelength region of the spectrum, where the photon energy is less than the band gap of n - CuInSe_2 single crystals, is apparently associated with the absorption of light by deep traps in TlGaSe_2 . The depth of these levels, determined from the red border of the spectrum, is ~ 0.67 eV. This value is in good agreement with the results of studies by other authors.

In fig. 4 shows the luxury dependence of the photovoltage in the valve (curve 1) and photodiode (curve 2) modes when excited by an ISSH-1003M flash lamp.

Fig. 4. a - luxury dependence of the photovoltage of the $p\text{-TlGaSe}_2$ - $p\text{-CuInSe}_2$ heterojunction in the valve (1) and photodiode modes (2); b - oscillogram of the photovoltage in the valve mode.

It was found that in both cases there is a power-law dependence $V_\phi \sim I^\alpha$, where the exponent $\alpha \approx 0.5$ in the valve mode and $\alpha \approx 0.8$ in the photodiode mode. The indicated value of α indicates that the separation time of nonequilibrium carriers is comparable with their lifetime [3]. The latter is also confirmed by an increase in the value of α in the photodiode mode, when the separation of carriers accelerated by an external field. The relaxation time τ , determined from the kinetics of the photovoltage in the valve mode (Fig. 5b), is $\sim 20 \mu s$.

References

1. Shay I.L., Tell B., Kasper H.M., Schiavone L.M. Electronic structure of AgInSe_2 and CuInSe_2 . // Phys. Rev. (B). Solid State. - 1973. - V.7. - No. 10. - part.1. - P.4485-4490.
2. Parkers J., Tomlinson R.D. and Hampshire M.J. Electrical properties of CuInSe_2 single crystals. // Sol. Stat. electronic. - 1973. - V.16. - P.773-777.
3. Parkers J., Tomlinson R.D. and Hampshire M.J. The fabrication of p - and n - type single crystals of CuInSe_2 . // J. of Cryst. Growth. - 1973. - V.20 - No. 4. - P.315 - 318.
4. Abdinov A.Sh. V.K. Mamedov Nurulaev Yu.G. Electrical properties of CuInSe_2 single crystals. // Dokl. AN Azerb. SSR. - 1980. - T. 36. - No. 10. - P.17-20.
5. Neuman H., Tomlinson R.D. and others. Electrical properties of the p-type CuInSe_2 single crystals. // Phys. Status Solidi. - 1979. - V.56. - No. 2. - P. k137-k 140.
6. Guseinov G.D., Seyidov F.M. et al. On the pseudo-binary system TlSe-GaSe // Journal of Physical Chemistry. - 1972. - No. 3.- P. 803-804.
7. Isayev T.J. and Hopkins B.H. Crystal growth, symmetry and physical properties of thallium, gallium disulphide TlGaSe_2 . // J. of Crystal Growth. - 1975. - V.29. - No. 1. - P.121-122.
8. Chervova A.A. On the band gap of TlGaSe_2 . // Sci. app. Gorky un-that, ser. phys.- 1972. - No. 149. - P.16-18.
9. Chervova A.A. Photoconductivity and thermally stimulated conductivity of TlGaSe_2 and TlInSe_2 . // Rukop. deposit. at VINITI. - No. 53-67 dated January 7, 1976. - P.10.
10. Sharma B.L., Purohit R.K. Semiconductor heterojunctions. Publishing house "Soviet radio". - Moscow. - 1979. —227p.
11. Ryvkin S.M. Photoelectric phenomena in semiconductors. // M.: Fizmatgiz. - 1963. —494p.