Semiconductor Physics, Quantum Electronics & Optoelectronics, 2010. V. 13, N 4. P. 444-447.

PACS 73.40.Cg, Gk, Lq

Electrical properties of n-SnS_2/n-$CdIn_2Te_4$ heterostructure

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Abstract. Using the method of deposition over the optical contact, the authors created n-SnS_2/n-$CdIn_2Te_4$ heterojunction and investigated temperature evolution of its current-voltage characteristics under the forward bias $U \leq 3$ V. Analyzing temperature dependence of the curves obtained, the main mechanisms of current transport through the semiconductor contact were determined, allowing prediction of successful possible applications of the heterojunction studied under high temperatures and elevated radiation due to the parameters of the base semiconductors and the diode structure itself.

Keywords: heterojunction, n-SnS_2/n-$CdIn_2Te_4$, optical contact, current-voltage curve, current transport mechanisms.

Manuscript received 30.12.09; accepted for publication 02.12.10; published online 30.12.10.

1. Introduction

At the modern development stage of electronics, it is especially timely and important task to create devices able to operate under the significant fluxes of ionizing radiation, and also at the elevated temperatures without additional cooling. Among these devices, one should mention rectifying structures based on layered semiconductors and materials with the stoichiometric vacancies (see, e.g., paper [1] and references therein). This is caused by the fact that layered semiconductors (including SnS_2) possess many unique physical and chemical properties [2]. In particular, predominant Van-der-Waals binding between the layers allows the possibility to obtain thin and quite elastic plates with mirror-smooth and practically ideal surface [2, 3] by simple material chipping from the monocrystalline ingots. Another technologically-important detail concerns the ability to create heterojunction to the layered semiconductors by deposition over the optical contact. This method does not require high-temperature treatment and yields good adhesion of the junction components, approaching bulk durability of the contacting materials [4].

The beneficial peculiarities of materials with the so-called defect semiconductor phases (including $Hg_3In_2Te_6$ and $CdIn_2Te_4$) is the large concentration of stoichiometric vacancies (up to $\sim 10^{21}\,cm^{-3}$ [5]), which causes high semiconductor stability towards the action of ionizing radiation [1, 6]. The latter phenomenon attracts significant interest to the defect phases as promising materials for creation of the photosensitive structures, able to operate under high temperatures without any additional cooling.

This paper presents the results concerning technology for n-SnS_2/n-$CdIn_2Te_4$ heterojunctions using the methodology of deposition over optical contact, as well as the detailed study of their current-voltage characteristics (CVC) under the forward bias. Using the Anderson model [7] for the sharp heterojunction, we have estimated the height of the potential barrier within heterostructure, determined the dominating current transport mechanisms of transformation between them upon application of a different voltage. The obtained results allowed to conclude that n-SnS_2/n-$CdIn_2Te_4$ heterojunctions could be used for efficient substitution of the traditional silicon-based photodiodes in the devices intended for applications under extreme environment conditions.

2. Research objects and methodology

The studied heterojunctions were formed on the base of non-doped SnS_2 and $CdIn_2Te_4$ single crystals, grown by the modified Bridgman method from stoichiometric melt. The samples of $CdIn_2Te_4$ and SnS_2 displayed *n*-type conductivity with the carrier concentration and mobility ($T = 300$ K): $n \approx (1 \div 9) \times 10^{13}\,\text{cm}^{-3}$, $\mu_n \approx (130 \div 140)\,\text{cm}^2/(\text{V}\cdot\text{s})$ for $CdIn_2Te_4$ [8] and $n \approx (1 \div 3) \times 10^{15}\,\text{cm}^{-3}$, $\mu_n \approx (80 \div 95)\,\text{cm}^2/(\text{V}\cdot\text{s})$ for SnS_2, respectively.

The substrates were made from 500-900 μm thick monocrystalline plates of *n*-$CdIn_2Te_4$, subjected to mechanical and chemical polishing with further careful rinsing [9] to achieve the surface quality required for construction of a heterojunction. *n*-SnS_2 plates with the area of several square millimeters were obtained by chipping off the thin layers (~10 μm) from the monocrystalline sample. The resulting plates had mirror-smooth and perfect surfaces, making no additional treatment required. The freshly-chipped *n*-SnS_2 plates were put on the top of *n*-$CdIn_2Te_4$ substrates and pressed together, joining both materials into a strong optical contact due to adhesion phenomena. Further, ohmic contacts to heterojunction were created by fusion of indium.

CVC of *n*-SnS_2/*n*-$CdIn_2Te_4$ heterojunctions were measured in DC mode under a forward bias; the resulting curves featured pronounced rectifying characteristics in all the temperature range studied (250-332 K). The rectification coefficient, determined for $U = 1$ V, was decreasing from 1600 down to 250 upon device exposure to higher temperatures. The prepared heterojunction exhibited a high quantum efficiency within the energy range 1.3-2.1 eV. Upon illumination from the *n*-SnS_2 side (light source with a power 90 mW/cm^2), open circuit voltage of 0.56 V was reached.

3. Results and discussion

Our analysis of the temperature influence on the heterojunction CVCs confirmed the possibility to describe the properties of *n*-SnS_2/*n*-$CdIn_2Te_4$ structure using the model of a sharp heterojunction suggested by Anderson [7, 10]. The obtained current-voltage plots were typical for the isotype semiconductor heterostructures. In particular, it was found that for the voltages $0.95\text{ V} < U < 3.0\text{ V}$ one can describe the current with a linear dependence:

$$I \sim C \cdot (U - U_0), \tag{1}$$

where U_0 = (0.78±0.01) V is a cut-off voltage determined by extrapolation of the linear CVC segments (Fig. 1) to an intersection with the voltage axis.

It is important that for $0.95\text{ V} < U < 3.0\text{ V}$ the temperature dependence of the current at a fixed voltage (inset to Fig. 1) obeys the formula:

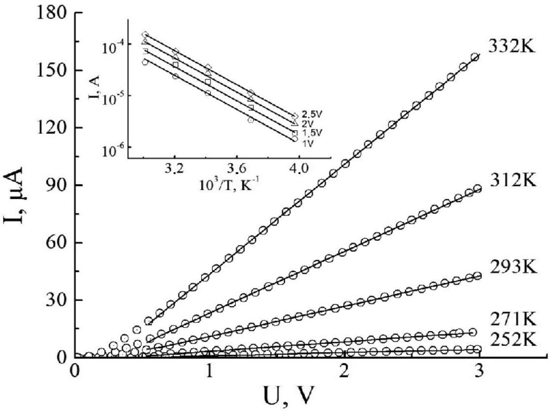

Fig. 1. Current-voltage characteristics for a forward-biased *n*-SnS_2/*n*-$CdIn_2Te_4$ heterojunction at the different temperatures. The inset shows the current as a function of reverse temperature at a fixed voltage.

$$I \sim \exp(-E_a / kT), \tag{2}$$

where E_a = (0.35±0.01) eV is the activation energy, which reasonably correlates with E_a = (0.42±0.03) eV for the intrinsic defects in $CdIn_2Te_4$ [8]. It is worth mentioning that the activation energy for *n*-SnS_2 defects, accordingly to the paper [11] and references therein, is within the range 0.20-0.26 eV. Thus, the obtained E_a value confirms that the specific resistivity of heterojunction investigated is determined by the resistance of $CdIn_2Te_4$ substrate, and its temperature dependence is caused by the presence of an energy level formed by the intrinsic defects in the band gap of the base semiconductor.

The detailed analysis of the influence caused by the temperature on the CVC measured has shown that forward-biased *n*-SnS_2/*n*-$CdIn_2Te_4$ structure ($U < 0.75$ V) is governed by two current transport mechanisms: generation-recombination (I_{gr}) and tunneling (I_t) ones. However, it was found that in a certain voltage intervals only one of these mechanisms is dominating.

For the direct biases $0\text{ V} < U < 0.32\text{ V}$, generation and recombination of carriers significantly overcomes tunneling, so CVC of the device can be successfully described with the formula [7, 10]:

$$U = n\,\frac{k_0 T}{e}\,\ln\left(\frac{I}{I_{gr}^0} + 1\right). \tag{3}$$

Here, n is the non-ideality coefficient.

$$I_{gr}^0 \approx \exp\left(-E_g(0)/(n k_0 T)\right). \tag{4}$$

I_{gr}^0 is a cut-off current determined at $U \to 0$ V for the material with a bandgap $E_g(0)$ at $T \to 0$ K, all other designations are common.

Performing the calculations in accordance to (3) for the different temperatures (Fig. 2), we determined the value of non-ideality coefficient as n = 2.0±0.1. Plotting the experimental dependence $\ln I_{gr}^{0}(T)$ (inset to Fig. 2) allowed to find the activation energy $E_g(0) = (1.1\pm0.1)$ eV, which fits into the interval $E_g(CdIn_2Te_4) = (0.9\div1.24)$ eV usually mentioned in the literature (e.g. the paper [12] and references therein). This result proves that the most possible model for generation-recombination processes in the heterojunction studied involves carrier recombination over the slow recombination centers, located at the boundary between the semiconductors. Such centers could appear as a consequence of misfit dislocations, caused by broken bonds of both SnS_2 and $CdIn_2Te_4$ due to a significant mismatch of crystalline lattice parameters in the base materials.

For the bias 0.35 V < U < 0.71 V, tunneling current transport becomes significantly prevalent [7, 10], which is confirmed by the semi-logarithmic scale plots of CVC for n-SnS_2/n-$CdIn_2Te_4$ heterojunction, yielding a set of parallel segments (Fig. 3).

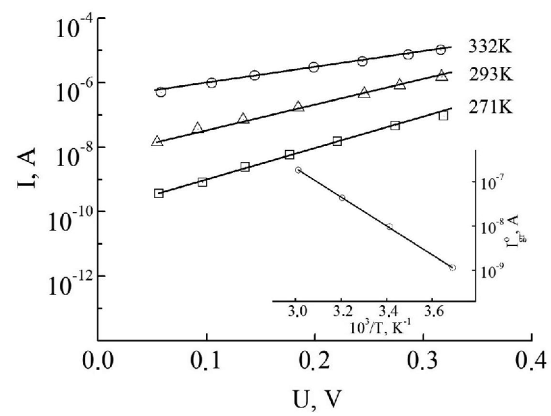

Fig. 2. Current-voltage plots for n-SnS_2/n-$CdIn_2Te_4$ heterojunction in the case of dominating generation-recombination transport. The inset shows the cut-off current I_{gr}^{0} as a function of the reverse temperature.

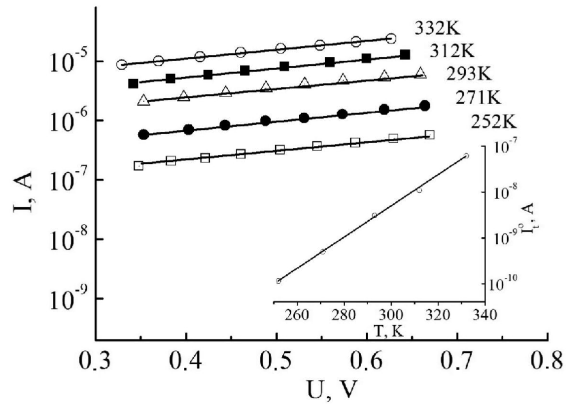

Fig. 3. Current-voltage plots for n-SnS_2/n-$CdIn_2Te_4$ heterojunctions for tunneling carrier transport. The inset displays the cut-off current I_t^0 as a function of the temperature.

In this case, CVC can be successfully described with the expression [7]:

$$I_t = I_t^0 \cdot \exp(\alpha U + \beta T), \quad (5)$$

where $I_t^0 = B \cdot \exp(-\alpha U_d)$ is a cut-off current at $U = 0$, U_d is a diffusion potential difference, B is a constant determined by heterojunction parameters, α and β are the parameters independent on voltage and temperature, correspondingly. For the tunneling current, the tangent of the slope found from the semi-logarithmic CVC plot yields $\alpha = 26.19\ \mathrm{V}^{-1}$. The dependence of cut-off current I_t^0 on the temperature also reveals linear character upon plotting in the semi-logarithmic scale (inset to Fig. 3), displaying a slope $\beta = 7.72\cdot10^{-2}\ \mathrm{K}^{-1}$.

Our analysis (Fig. 4) suggests that for $U > 0.75$ V current-voltage plots obeys well the following expression [10], corresponding to over-barrier current:

$$\ln I - \frac{eU}{k_0 T} = \ln I_{b0} - \frac{eI}{Ck_0 T}, \quad (6)$$

with the same constant C as that in formula (1) and cut-off current I_{b0} (for $U = 0$ V). The temperature dependence of the latter is determined as [10]:

$$I_{b0} = A\cdot T^2 \cdot \exp\left(-\frac{e\varphi_b}{k_0 T}\right). \quad (7)$$

Here, $e\varphi_b$ is the energetic barrier height; the value A is determined by heterojunction model (effective masses of the carriers, area of the contact, etc.) and is usually chosen to be a fitting parameter. Curves $\ln I - eU/(k_0T) = f(I)$, plotted for the different temperatures (Fig. 4), feature several straight segments. Extrapolating the latter to the intersection with the ordinate axis, we plotted experimental temperature dependence of cut-off, which can be also brought to straight-segment form upon using the coordinates $\ln I_{b0} = f(10^3/T)$ (inset to Fig. 4).

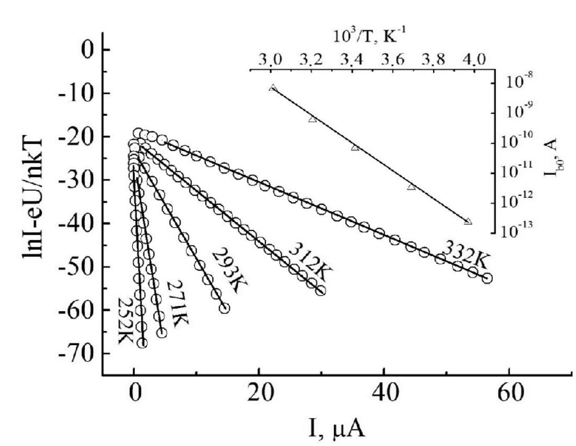

Fig. 4. Current-voltage characteristics of a n-SnS_2/n-$CdIn_2Te_4$ heterojunction for over-barrier current transport under different temperatures. The inset shows the cut-off current $I_{b0}(T)$.

The slope of the latter plots corresponds to the height of a energetic barrier $e\varphi_b$ = (0.85±0.02) eV of the structure. It is worth mentioning that the obtained $e\varphi_b$ for *n*-SnS_2/*n*-$CdIn_2Te_4$ heterojunction is higher than that for *n*-InSe/*p*-CdTe ($e\varphi_b$ = 0.71 eV) and *n*-InSe/*p*-GaSe ($e\varphi_b$ = 0.73 eV) [13, 14]. The latter suggests promising perspectives for applications of *n*-SnS_2/*n*-$CdIn_2Te_4$ heterojunction in IR-devices, intended for a stable operation under the elevated temperatures and high incident radiation.

4. Conclusions

Therefore, the results of a complex study of current transport mechanisms taking place in isotype *n*-SnS_2/*n*-$CdIn_2Te_4$ heterojunction created by the deposition over optical contact proves the significant advantages of this structure and suggests its possible applications as an analogue of *n*-InSe/*p*-CdTe and *n*-InSe/*p*-GaSe heterojunctions. Investigations of temperature dependences of current-voltage characteristics revealed that *n*-SnS_2/*n*-$CdIn_2Te_4$ junction is characterized by several current transport mechanisms upon application of a direct bias $U < 0.95$ V, including generation-recombination, tunneling and over-barrier currents. All three mechanisms were thoroughly studied, determining the voltage ranges for which each of them becomes predominating. On the base of the results obtained, it is possible to predict good perspectives for *n*-SnS_2/*n*-$CdIn_2Te_4$ junction in the devices intended to operate under high temperatures and radiation fluxes.

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