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The barrier capacitance of n-SnS_2/n-$CdIn_2Te_4$ heterojunction

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We report the electrical study results for the n-SnS_2/n-$CdIn_2Te_4$ structure formed by deposition over optical contact. The measured current-voltage and capacitance-voltage (C-V) curves are typical for an abrupt heterojunction. According to the C-V curve analysis, higher voltage frequencies lead to lower barrier capacitance. This effect may be caused by intrinsic structural defects producing localized donor states in the band gap of $CdIn_2Te_4$. The observed electrical properties can be explained by frequency-dependent recharging processes of such deep donor centers.

Keywords: heterojunction, barrier capacitance, capacitance-voltage curve, structural defects.

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Introduction

The stability of semiconductor devices to the effects of ionizing radiation largely depends on the properties of the materials from which they are made. In most semiconductors (Ge, Si, and others), radiation exposure causes irreversible changes to their basic parameters, such as the conductivity and mobility of charge carriers. In this regard, attention is drawn to semiconductors with increased radiation resistance, in particular, those containing a large concentration ($\sim 10^{21}$ cm^{-3}) of stoichiometric vacancies. Such can be In_2Te_3 type semiconductors and their analogs, one of which is $CdIn_2Te_4$, a compound from the CdTe–In_2Te_3 system. It was shown [1] that the electrical properties of $CdIn_2Te_4$ remain unchanged when exposed to γ-radiation up to doses of $1 \cdot 10^8$ R. This property is favorable for the creation of $CdIn_2Te_4$-based photovoltaic devices operating in conditions of increased radiation. The spectral range of photosensitivity of $CdIn_2Te_4$ with a maximum at $\lambda = (0.5\text{-}0.6)$ μm coincides with the spectrum of solar radiation [2], which is important for the creation of solar cells.

In this work, we present the results of the study of the current-voltage (I-V) and the capacity-voltage (C-V) curves, including frequency dependence of the barrier capacitance in the n-SnS_2/n-$CdIn_2Te_4$ heterojunction at room temperature. The temperature dependences of the I-V characteristics were considered in [3].

I. Experimental results

The n-SnS_2/n-$CdIn_2Te_4$ heterojunction is an isotypic n-n-junction of two semiconductors with different band gaps – 2.07 eV (SnS_2) and 1.27 eV ($CdIn_2Te_4$) and dielectric constants $\varepsilon_1 = 9$ and $\varepsilon_2 = 11.7$ [4] respectively. These semiconductors have different crystal structures: SnS_2 is a lamellar tin disulfide with lattice parameters of the trigonal system (lattice parameters are $\alpha = 3.65A$, $c = 5.88A$) [5] and $CdIn_2Te_4$ with a defective tetragonal structure (lattice parameters are $\alpha = 6.205A$, $c = 12.405A$) [6]. Such a heterojunction, like Schottky diodes, is a device with minority charge carriers [7].

The SnS_2/$CdIn_2Te_4$ heterojunction was formed by deposition over optical contact [8], which is a relatively simple low-temperature method that eliminates cross-doping and makes it possible to obtain abrupt heterojunctions. Obtained by the Bridgman method, SnS_2 and $CdIn_2Te_4$ crystals have electron concentration and mobilities of $n = 4 \cdot 10^{15}$ cm^{-3}, $\mu = 95$ $cm^2/(V \cdot s)$ and $n = 3 \cdot 10^{12}$ cm^{-3}, $\mu = 132$ $cm^2/(V \cdot s)$ respectively.

Plane-parallel $CdIn_2Te_4$ substrates were previously mechanically and chemically polished to achieve a mirror-smooth surface with minimal microrelief. Thin plates with a thickness of the order of 10 μm were separated from the

SnS_2 single crystal of layered structure, without being subjected to any additional treatment. The obtained SnS_2 plates were placed on top of $CdIn_2Te_4$ substrates and slightly pressed. Due to the elasticity of the SnS_2 plates, sticking and adhesion of surfaces of semiconductor surfaces was strong enough for producing solid heterojunction structure.

The dark current-voltage curves of SnS_2/$CdIn_2Te_4$ heterojunctions were studied at constant current and at room temperature. A typical current-voltage curve (Fig. 1) has pronounced rectifying properties. The rectification factor, defined as the ratio of forward current to reverse current at $U = 1V$, is

$$K = \frac{I_f}{I_r}\bigg|_{U=1V} = 1 \cdot 10^3$$

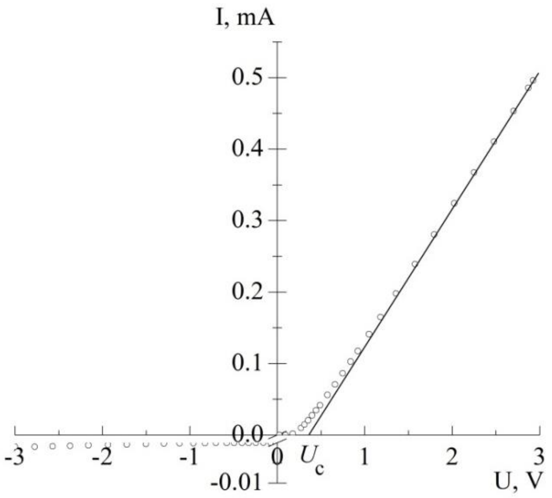

Fig. 1. Dark current-voltage curve of the SnS_2 / $CdIn_2Te_4$ heterojunction.

When direct voltage is applied at $U < U_c$ (U_c is the contact potential difference), the I-V curve is described by an exponential dependence of the type

$$I = I_0 exp\left(\frac{eU}{kT}\right), \quad (1)$$

where $I_0 = 1.3 \cdot 10^{-9} A$ is the saturation current.

At direct biases exceeding the contact potential difference $U > U_c$, the I-V characteristic has a linear section, the slope of which is determined by the resistance of the base material of $CdIn_2Te_4$ ($7.5 \cdot 10^3$ Ohm). By extrapolating the linear section of the I-V curve to the intersection with the voltage axis, the contact potential difference is determined $U_c = 0.36V$.

Capacitance-voltage curves (Fig. 2) depend on the circular frequency $\omega = 2\pi/T$ (T is the oscillation period) of the voltage. As one can see from the figure, with an increasing reverse voltage U the barrier capacitance C decreases, which is caused by an increase in the width of the space charge region (SCR) W of the heterojunction by analogy with a flat capacitor $C = \varepsilon\varepsilon_0 S/W$, where ε is the relative dielectric constant, ε_0 is the electric constant, and S is the transition area. In this case, the dependence of the capacitance on the frequency of the alternating signal ω is observed, namely, with increasing ω, the capacitance decreases. Similar dependences are known for inhomogeneous systems [9].

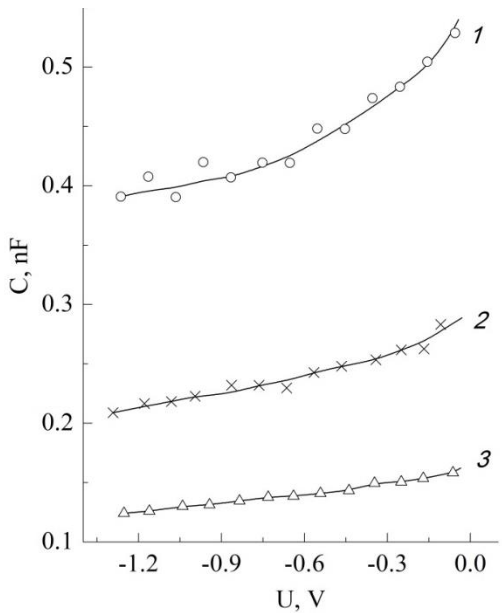

Fig 2. Capacitance-voltage curves of the SnS_2 / $CdIn_2Te_4$ heterojunction measured at different voltage frequencies ω: 10 kHz (1), 20 kHz (2) i 30 kHz (3).

The dependence of the capacitance C on the applied reverse bias U can be represented as

$$\frac{1}{C^2} = \frac{2(U_C - U)}{e\varepsilon\varepsilon_0 S^2 N_D} = \frac{2U_C}{e\varepsilon\varepsilon_0 S^2 N_D} - \frac{2U}{e\varepsilon\varepsilon_0 S^2 N_D}, \quad (2)$$

The dependencies $1/_{C^2} = f(U)$ shown in Fig. 3 are linear functions typical of an abrupt heterojunction. Having determined the slope of the straight lines (Fig. 3), donor concentrations N_D were estimated. Extrapolating the lines to the intersection with the voltage axis ($1/_{C^2} = 0$) the values $U_C = f(\omega)$ (barrier cut-off voltage) were obtained. By the intersection of the dependences $1/_{C^2} = f(U)$ with the ordinate axis at $U = 0$, the capacitance $C = f(\omega)$ and width of the space charge region $W = f(\omega)$ were determined. The resulting values are shown in Table 1. It should be noted that these parameters are inter-related. For example, when the barrier cutoff voltage $U_C = f(\omega)$ is higher than the cut-off voltage U_C determined from the I-V curves at $\omega = 0$. As the frequency ω increases, the cut-off voltage U_C increases, which correlates with the change of other parameters listed in the table.

Table 1.

Parameters of n-SnS_2/n-$CdIn_2Te_4$ heterojunction

ω, kHz	U_c, V	N_D, cm^{-3}	C, F	W, μm
10	0.65	$9.8 \cdot 10^{13}$	$6.2 \cdot 10^{-10}$	2.6
20	1.22	$4.3 \cdot 10^{13}$	$3.0 \cdot 10^{-10}$	5.3
30	1.48	$1.6 \cdot 10^{13}$	$1.7 \cdot 10^{-10}$	9.6
0	0.36	$3.0 \cdot 10^{12}$	$1.5 \cdot 10^{-10}$	10.9

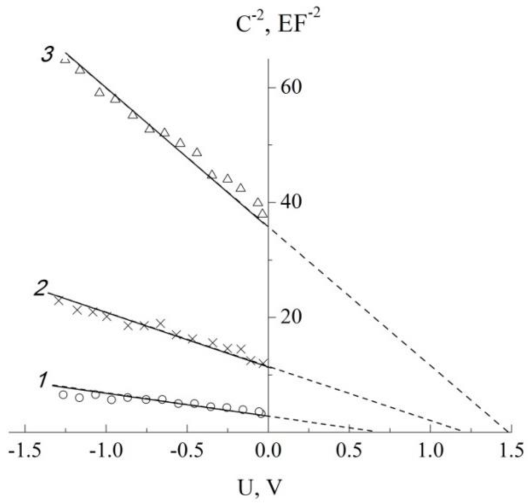

Fig. 3. Curves of $\left({}^{1}/_{C^2} = f(U)\right)$ plotted for different values of voltage frequency ω: 10 kHz (1), 20 kHz (2), 30 kHz (3).

II. Discussion of results

The space charge region (SCR) is formed when two semiconductors with different carrier concentrations are put in contact; inter-diffusion of carriers produces in-built electric field and the energy barrier, which are absent in quasi-neutral regions outside the SCR. When alternating voltage is applied to the device, free electrons (but not heavier ions) will manage responding to it. In this case, the C-V curve makes it possible to determine the concentration of free electrons, but not the concentration of donors using formulas:

$$C = \left(\frac{e\varepsilon\varepsilon_0 S^2 N_D}{2U_C}\right)^{1/2}, W = \left(\frac{2\varepsilon\varepsilon_0 U_C}{2N_D}\right)^{1/2}, \qquad (3)$$

By using the value of contact potential difference U_C obtained from analysis of I-V curves (Fig. 1) and considering N_D to represent the equilibrium electron concentration at room temperature, possible values C and W were estimated in the absence of an alternating electric field ($\omega = 0$). The obtained results (shown in the bottom row of Table 1) correspond to the situation when deep defective levels practically do not affect the barrier properties of the heterojunction. A similar situation takes place in the study of C-V characteristics at sufficiently high frequencies (of the order of 1 MHz) [9, 10], when deep discrete levels do not have time to recharge over the period of oscillation. With a decrease in frequency ω (increase in the oscillation period), the filling of deep discrete levels manages to change significantly over the oscillation period. The longer the oscillation period is, the faster is the rate at which the deep impurity centers are emptied and the barrier capacity of the heterojunction increases, which is observed experimentally.

The effect of intrinsic structural defects on the properties of $CdIn_2Te_4$ is apparent from the studies of the intrinsic absorption edge [2]. The presence of defects defines the exponential nature of the distribution of the density of states responsible for the "tail" of the conduction band. As it was shown in Ref. [11], a wide impurity band is observed in the $CdIn_2Te_4$ photoluminescence spectrum at a photon energy of $h\nu = 0.95 eV$ associated with impurity states located in the band gap of semiconductor. These states are responsible for electric properties of the material, and, in the first place, they define its conductivity and the behavior of $C = f(\omega)$.

Conclusion

The increase in the barrier capacitance $C = f(\omega)$ of the n-SnS_2/n-$CdIn_2Te_4$ heterojunction with decreasing frequency ω is due to the high density of charged deep impurity levels in the band gap of $CdIn_2Te_4$. Under the action of applied alternating electric field these levels are emptied, releasing electrons and thus increasing the positive charge associated with donor impurity levels. As a consequence, the width of the space charge region $W = f(\omega)$ decreases, and the capacitance $C = f(\omega)$ increases.

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Бар'єрна ємність гетеропереходу n-SnS_2/n-$CdIn_2Te_4$

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Наведено результати дослідження електричних характеристик гетеропереходу n-SnS_2/n-$CdIn_2Te_4$, отриманого методом посадки на оптичний контакт. Показано, що вольт-амперні характеристики та вольт-фарадні характеристики (ВФХ) є типовими для різкого гетеропереходу. Виявлено частотну залежність ВФХ: зі збільшенням частоти змінної напруги бар'єрна ємність зменшується. Залежності ВФХ від частоти обумовлені наявністю власних структурних дефектів та пов'язаних із ними локалізованих донорних станів у забороненій зоні $CdIn_2Te_4$. Одержані результати пояснюються залежними від частоти процесами перезарядки глибоких донорних центрів.

Ключові слова: гетероперехід, бар'єрна ємність, вольт-фарадна характеристика, структурні дефекти.