

Study of Surface States of In-nITO-pCdTe Structures Based On Large-Block Polycrystalline Films pCdTe

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Annotation. In this work, we study the change in the degree of compensation of surface states (In+Sn) at the interface of the nITO-pCdTe structure and the resistance of the near-surface layer of the pCdTe semiconductor. The temperature $I - V$ characteristics were investigated in the temperature range (273–373)K. The values of the impurity activation energy for ITO / pCdTe were determined and the values of the spectral distribution of the collection coefficient $Q(\lambda)$ and photosensitivity S_{λ} of the ITO / pCdTe structures were determined. Analysis of the dependences $V(\psi_s)$, $N_s(\psi_s)$ shows that in the modes of accumulation and depletion, the recharging of defects occurs in the near-surface layer of the semiconductor and at the interface.

Keywords: Polycrystalline, resistivity, layer, oxide, temperature, surface states, potential, characteristic.

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I. Introduction

It is known that in polycrystalline semiconductors the kinetic parameters, including the lifetime of minority charge carriers, are mainly determined by defects on the N_{ss} surface, of which the intergranular surface states play a decisive role. Many authors have experimentally discovered a non-monotonic dependence of the short-circuit current I_{sc} in germanium Ge [1] and silicon Si [2 – 4] solar cells and collector current in CdTe bipolar phototransistors [5]. One of the main results of this circle of studies is an increase in I_{sc} and a decrease in the open circuit voltage V_{oc} , as well as a decrease in the collector current in CdTe bipolar phototransistors with a monotonic increase in the concentration of deep defects N_t . However, in solar cells [6, 7], created on the basis of large-block polycrystalline films of pCdTe, in contrast to the above-mentioned works, not only the short-circuit current I_{sc} increases, but also the efficiency η with an increase in the concentration of deep impurities, of the type considered in [8].

It was shown in [8, 9] that the nature of the above dependences is the same and is associated with an increase in the lifetime of minority charge carriers with an increase in the degree of compensation, which leads to a change in the thickness of the space charge layer in structures, and in polycrystals, in addition to a change in the layer space charge, the potential in grain boundaries changes. The induced carrier concentration on the surface of the pCdTe films was created using an In-nITO-pCdTe MOS structure.

II. Experiment

The In-nITO-pCdTe MOS structure is created by sputtering a specially prepared indium + tin alloy (In + Sn) onto the surface of large-block pCdTe films with a columnar grain structure by magnetron ion sputtering of MSIR in an oxygen-containing medium [10]. Note that the same pCdTe films grown on a molybdenum Mo substrate by a gas transport method in a stream of hydrogen H_2 were also used to create solar cells. The collecting ohmic top contact was a W-shaped contact deposited in a vacuum of 10^{-4} Torr from pure indium In. The resistivity of the films pCdTe $\rho \approx 10^3 - 10^4$ ohms * from to, and the thickness of them was $d \sim 70 \mu m$. The films consist of blocks of microcrystal's with a columnar structure of cubic grains oriented in the growth direction and misoriented in azimuth. The grain sizes range from 100 to 150 μm , so that the grains cover the entire film thickness. Conducting wide-gap n-type semiconductor films with a composition of a mixture of tin oxide SnO_2 + and indium oxide In_2O_3 -ITO had a transmittance of 88%, a thickness of $\sim 0.5 \div 0.7 \mu m$ [11]. In this work, transparent conducting layers of indium and tin oxides were obtained by the method of magnetron ion sputtering. When this target served disc of indium and tin alloy (95% + 5%), respectively, and that an increase in specific power of discharge resistivity and adsorption coefficient Decrease the - creases, This is apparently

due to alleviating pollution - nennosti films of foreign matter. It follows that with the - resistance layer of In₂O₃ + SnO₂ (ITO) strongly depends on the impurity concentration.

When spraying layers ITO on polycrystalline CdTe in a target used respectively pure Alloy In + Sn with different ratios of tin and indium. The photosensitivity spectra were recorded on a ZMP-2 monochromator with a quartz prism. A DKSSH-1000 xenon lamp operating in the mode of the minimum allowable power (650W) was used as a radiation source. The radiation is calibrated in absolute units using a thermo element with an RTE-9 quartz window. In fig. 1 shows the spectral distribution of the collection coefficient and photosensitivity of the structures of the ITO / pCdTe structure. The short-wavelength edge of photosensitivity (S_λ) already at λ = 300 ÷ 400 nm reaches 0.1 ÷ 0.2 A / W.

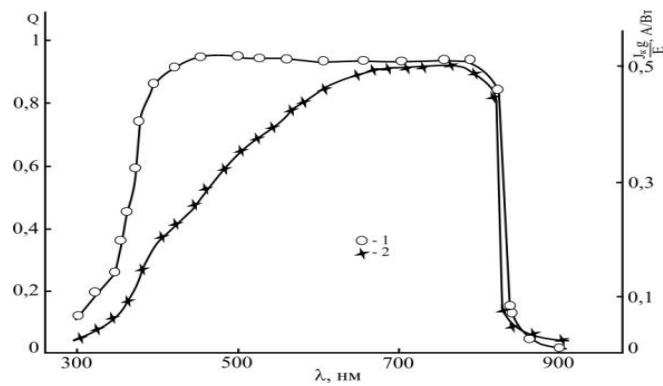


Fig. 1. Spectral distributions of the collection coefficient $Q(\lambda)$ and photosensitivity S_{λ} of the ITO / pCdTe structures, 1-spectral distribution of the collection coefficient $Q(\lambda)$; 2- photosensitivity S_{λ} structures.

In fig. Figure 2 shows the I – V characteristic of a typical sample of the ITO / pCdTe structure at a constant in the temperature range 263–393 K. As can be seen from this figure, the I – V characteristic at room temperature is described by three exponential dependences:

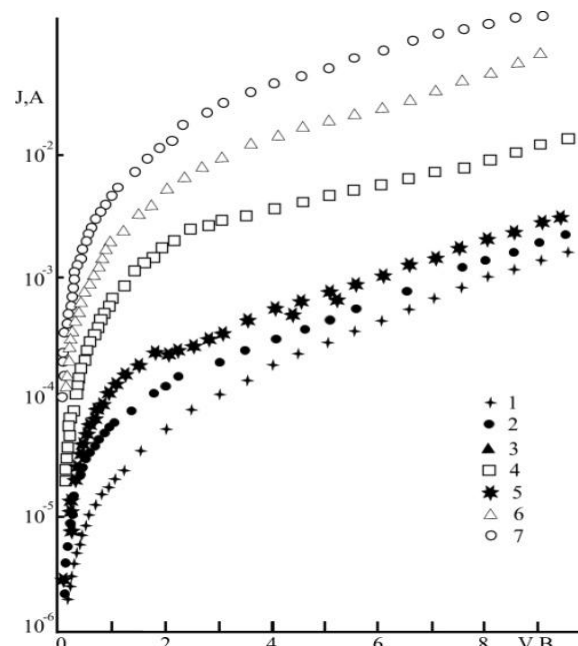


Fig. 2. I - V characteristic of a typical sample of the ITO / pCdTe structure at a constant in the temperature range 263 ÷ 393 K; 1 - 263K; 2-273K; 3-300K; 4 - 333 K; 5 -353 K; 6 - 373 K; 7 - 393 K;

$$I = I_{01} \exp eV / C_1 KT \text{ (where } C_1 = 3 I_{01} = 2 \cdot 10^{-6} \text{ A / cm}^2 \text{);}$$

$$I = I_{02} \exp eV / C_2 KT \text{ (where } C_2 = 20 I_{02} = 3.5 \cdot 10^{-5} \text{ A / cm}^2 \text{);}$$

$$I = I_{03} \exp eV / C_3 KT \text{ (where } C_3 = 120 I_{03} = 6.2 \cdot 10^{-4} \text{ A / cm}^2 \text{);}$$

Note that the forward branch of the I – V characteristic for some samples with the ITO / pCdTe structure has two distinct portions of the exponential dependence.

Table 1 shows the $\rho_{\text{subtraction}}$ for the investigated ITO / pCdTe structures in the temperature range 273 ÷ 373 K. The results of these calculations show that in this way the determined value of ρ of the base is in satisfactory agreement with the resistivity of the initial film of cadmium telluride. The plotted temperature dependence for these calculated ρ makes it possible to determine the value of the impurity activation energy is 0.44–0.02 eV for ITO / pCdTe .

The analysis of the results calculated for the ratio $\frac{I_{02}}{C_2}$, L_n and the base resistivity allows us to conclude that in the second section of the I – V characteristic of the ITO / pCdTe structures, the current is limited by recombination in the pCdTe semiconductor thickness.

Table 1.
The main parameters of the I - V characteristics calculated for the structures under study
ITO / pCdTe in the temperature range 273 ÷ 393 K

ITO / pCdTe structure					
T, K	C_2	$I_{02}, \frac{A}{cm^2}$		L, mkm	$\rho, \Omega m$
300	37	$5,5 \cdot 10^{-3}$	3.7	19	$2.3 \cdot 10^3$
323	33.5	$7.6 \cdot 10^{-3}$	3.6	19,4	$1.5 \cdot 10^3$
343	36.4	$3.3 \cdot 10^{-2}$	3.7	19	$4.3 \cdot 10^2$
373	25	$8 \cdot 10^{-2}$	3.3	21,2	$1.16 \cdot 10^2$
393	28	$8.7 \cdot 10^{-2}$	3.2	22,3	$1.1 \cdot 10^2$

The study of the capacitance-voltage characteristic of the investigated pCdTe / nCdS structure can bring some clarity to these issues. The C-V characteristic was recorded in a wide frequency range $f = 10 \text{ kHz} \div 10 \text{ MHz}$. Studies have established that C-V characteristics in the frequency range $f \leq 10 \text{ kHz}$ and $f \leq 465 \text{ kHz}$ have different patterns and capacitance values. Therefore, the study of C-V characteristics was focused at test signal frequencies $f = 10 \text{ kHz}$ and $f = 465 \text{ kHz}$. C-V characteristic pCdTe / nCdS structure at the frequencies $f = 10 \text{ kHz}$ and $f = 465 \text{ kHz}$ is similar to C-V characteristic of the PMOS strukutry semiconductor base p - type and behaves as an MOS semiconductor structure with a base n - type.

In Fig. 3, the experimental (2) and calculated (1) C-V characteristics are taken at a test signal frequency $f = 1 \text{ MHz}$ at room temperature e.

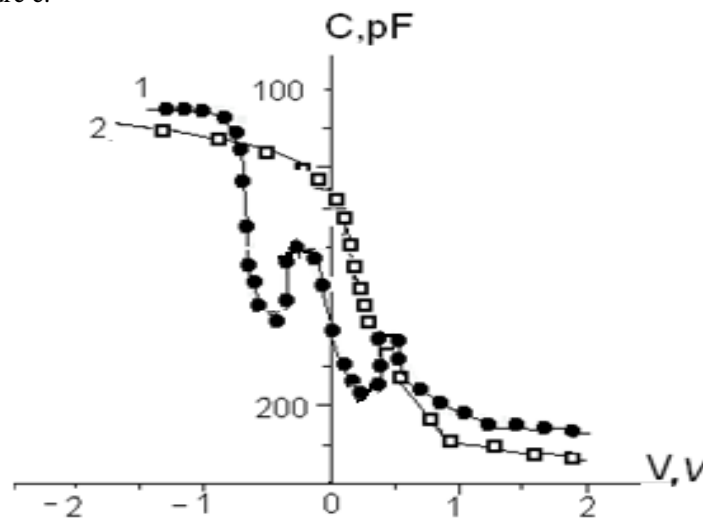


Fig. 3. Experimental (1) and calculated (2) C-V characteristics of the MOS structure In-nITO-pCdTe $f = 1 \text{ MHz}$ at room temperature.

To construct the calculated C-V characteristic, the concentration of equilibrium charge carriers of holes was determined from the experimental C-V curve. The concentration of equilibrium charge carriers p_0 , determined from the flat-band capacitance and the slope of the capacitance-voltage characteristic, turned out to be 10^{12} cm^{-3} [10,12], which is three orders of magnitude less than the equilibrium concentration of holes in the

pCdTe film itself. This concentration of holes is characteristic of the near-surface layer of the pCdTe film. The near-surface pCdTe layer with such a p_o concentration is formed during the formation of the In-nITO-pCdTe MOS structure due to the diffusion of Sn and indium In atoms, which are donor impurities for cadmium telluride [13]. The calculated voltage-voltage characteristic was constructed as in [12, 14]. The rise of the “jump” and the dip of the “well” of the capacitance on the experimental capacitance-voltage characteristic (Fig. 4) were analyzed in detail in [15] and they are explained by the presence of deep acceptor centers with the activation energy $E_{ak} \approx E_v + 0.5$ eV in the space charge layer and $E_{ak} \approx E_v + 0.16$ eV at the insulator-semiconductor interface. The latter are filled when the majority of charge carriers accumulate at the oxide-pCdTe interface, while others are emptied in the depletion mode. Comparison of the results of the experimental and calculated capacitance-voltage characteristics for the structures under study shows that the MOS structures under study have a complex structure. Since the experimental C-V characteristic in the region of strong enrichment and depletion lies on the left, and in the transition region it is to the right of the calculated C-V characteristic. This behavior of the experimental capacitance-voltage characteristic is possibly related to the charge exchange of the effective density of surface states N_{ss} . From the shift of the experimental C-V characteristic along the voltage axis relative to the calculated one, the total captured charge Q_{ss} by the surface states N_{ss} and the value of the surface potential ψ_s corresponding to a given bias on the upper metal electrode were found. The real position of the surface potential is determined from the value ψ_s of the ideal capacitance-voltage characteristic at the same value of the capacitance of the experimental and calculated C-V curves. In this way, the found dependence of ψ_s on the applied potential V is shown in Fig. 3, and the dependence of N_{ss} on ψ_s is shown in Fig. 4.

A general analysis of the dependences $V(\psi_s)$, $N_s(\psi_s)$ shows that, in the modes of accumulation and depletion, the recharging of defects occurs in the near-surface layer of the semiconductor and at the interface. The $V(\psi_s)$ dependence in the accumulation mode behaves anomalously with an increase in the negative bias, and the edge of the valence band begins to bend down instead of up. This trend continues to the value $V = -0.42$ V, which corresponds to 0.077 eV, after which the surface potential changes its direction of change with a further increase in negative bias and acquires a negative value at $V = -0.72$ V.

As for the density of surface states, it reaches its maximum value of $\sim 1.85 \cdot 10^{10} \text{ cm}^{-2}$ at $V = -0.69$ V ($\psi_s = 0.016$ eV), then, with an increase in the enrichment mode, it begins to sharply decrease and at $\psi_s = -0.1$ eV ($V = -0.75$ V) equals zero. After that, it acquires an acceptor nature and begins to increase strongly. The considered anomalous behavior of the dependences $V(\psi_s)$, $N_s(\psi_s)$ in the enrichment mode is explained by the recharge of deep local centers on the surface and in the near-surface layer of the semiconductor. Indeed, the beginning of the section of anomalous behavior of the dependences $V(\psi_s)$, $N_s(\psi_s)$ coincides with the beginning of the section of the decay of the “well” capacity on the C-V characteristic (Fig. 1, curve 1), where deep acceptor centers are filled. Moreover, as long as the concentration of accumulated holes is less than the concentration of deep centers, the filling process continues, and the capacitance decay region remains on the C-V characteristic. The trapping of holes by negative acceptor centers N_{ssa} neutralizes them, therefore, leads to a change in the difference between the donor and acceptor surface states, as a result of which the effective density N_{ss} increases. According to the estimate given in [16], this deep acceptor level has an activation energy $E_{ak} = 0.16$ eV, which is very close to $E_{ak} = 0.15$ eV [7,16] of the interstitial tellurium atom Te_i .

The dynamics of changes in ψ_s in the range $V = -0.29$ V \div -0.42 V (Fig. 4) shows a decrease in the conductivity of the near-surface semiconductor layer, instead of its growth in the enrichment mode. This dependence $V(\psi_s)$ indicates the presence of deep acceptor centers in the near-surface layer. In addition, it should be noted that, in thermodynamic equilibrium at the oxide - pCdTe interface, there is a significant number of indium atoms In and tin Sn, as evidenced by the downward bending of the valence band edge E_v by $\psi_s = 0.06$ eV. In this case, the effective density $N_{ss} = 5.8 \cdot 10^9 \text{ cm}^{-2}$ has a donor type. The effective density N_{ss} in the mode of flat zones ($\psi_s = 0$) retains the donor nature and is characterized by the value of $N_{ss} = 7 \cdot 10^9 \text{ cm}^{-2}$. In addition, it follows from this figure that the value of N_{ss} at $\psi_s = -0.1$ eV and $\psi_s = 0.13$ tV is equal to zero.

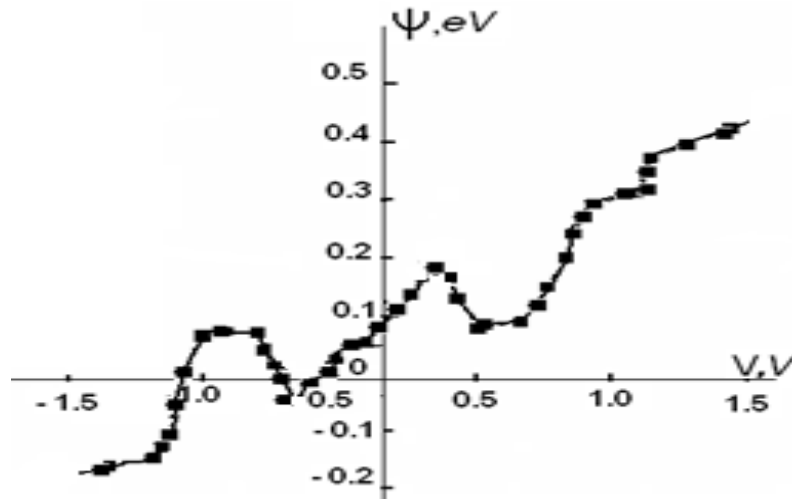


Fig. 4. Surface potential versus applied voltage at the top metal electrode of the In-nITO-pCdTe MOS structure.

In the depletion mode, due to the recharge of the deep acceptor level with $E_{ak} \approx 0.5$ eV, the surface potential in the voltage range 0.26V-0.39V (Fig. 4) decreases instead of increasing. Further, with an increase in V , ψ_s increases again and at $V = 1.8V$ ψ_s becomes equal to 0.5 eV. As for the dynamics of changes in N_{ss} (Fig. 3), in the process of decreasing ψ_s , it also rapidly decreases in value, which becomes equal to zero at $\psi_s = 0.13$ eV, then acquiring an acceptor nature, it rapidly increases to $N_{ssa} = 4.1 \cdot 10^9 \text{ cm}^{-2}$ ($\psi_s = 0.08$ eV), and enters a plateau in the entire range of the depletion mode up to $\psi_s = 0.29$ eV. In the inversion mode, the effective density N_{ssa} slowly increases and becomes equal to $N_{ssa} = 1.1 \cdot 10^{10} \text{ cm}^{-2}$ at $\psi_s = 0.5$ eV.

Thus, it has been shown that the charge exchange of deep acceptor levels at the oxide-semiconductor pCdTe interface and at the surface layer is accompanied by a change in the degree of compensation of surface states, thereby causing a non-monotonic dependence of the capacitance on voltage.

The relationship between the dependence of the degree of compensation on the change in the lifetime of minority nonequilibrium current carriers has also been studied experimentally. At the extreme points of the dependence of the effective density of surface states N_{ss} on the surface potential ψ_s , the lifetime of minority nonequilibrium current carriers was measured.

The following points were taken from the dependence $N_s(\psi_s)$: $\psi_s = -0.1$ eV and $\psi_s = 0.13$ eV, at which $N_s = 0$. The points were also taken: $\psi_s = -0.2$ eV and $\psi_s = 0.08$ eV, at which the effective values of the acceptor and donor surface states reach the highest values and are respectively $8.5 \cdot 10^{10} \text{ cm}^{-2}$ and $6 \cdot 10^{10} \text{ cm}^{-2}$.

III. Conclusion

The measurements of the In-nITO-pCdTe MOS structure show that indeed at the points where $N_s = 0$ the lifetime of minority nonequilibrium current carriers reaches a large value and is equal to $\sim 10^{-6}$ s. At stress values when N_{sa}, N_{sd} have the highest values $\tau = 5 \cdot 10^{-7}$ s and $\tau = 10^{-7}$ s, respectively. It is shown that, in the In-nITO-pCdTe MOS structure, the recharging of surface states in grain boundaries leads to a change in the recombination parameters. It was found that point compensation of impurities in the grain boundaries of polycrystalline pCdTe is accompanied by a sharp increase in the time of nonequilibrium current carriers. MOS structures based on large-block polycrystalline films of cadmium telluride In-nITO-pCdTe MOS structures are very sensitive to external influences.

It should also be noted that the PS concentrations calculated by the same method from the C-V dependence, which was measured at two frequencies of 10 and 465 kHz, have different values at the same value of ψ_s . At a signal frequency of 10 kHz, the N_{ss} value is almost an order of magnitude higher than N_{ss} obtained at 465 kHz. This result indicates that the PSs of the structures under study are not the same by their nature and differ from each other in micro parameters, i.e. by the depth of occurrence, by the values of the cross section for the capture of electrons and holes.

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