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THE MECHANISM OF CURRENT TRANSPORT IN THE STRUCTURE Al-*p*-CdTe-Mo WITH DIFFERENT THICKNESS OF THE BASE

Sh. A. Mirsagatov[1], A. K. Uteniyazov[2]
[1]*Physical technical institute of the Academy of Sciences of Uzbekistan, Tashkent,*
[2]*Karakalpak State University, Nukus,*
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In this paper the mechanism of current's transport in the structure Al-*p*-CdTe-Mo is studied, when the thickness of the base $w \leq 10$ μm. The results of study of current-voltage characteristics of the structure Al-*p*-Cd-Te-Mo with different thicknesses of the base and the influence of the thickness of the base on the mechanism of current's transport are given. The above results at current densities ~$8.62 \cdot 10^{-8}$–$4.36 \cdot 10^{-5}$ A/cm^2 and ~$5.08 \cdot 10^{-7}$–$2{,}44 \cdot 10^{-5}$ A/cm^2 for samples No. 1 and No. 2, respectively, were obtained by the theory that takes into account only duffusion components of the current and the applied voltage to the base of the diode structures. At high current densities ~$4.36 \cdot 10^{-5}$–1.95 A/cm^2 and ~$2.44 \cdot 10^{-5}$–3.98 A/cm^2 for samples No. 1 and No. 2, respectively, results were obtained by the theory of the drift current transport mechanism, taking into account the possibility exchange of free carriers inside the recombination complex.
Keywords: film, Schottky barrier, diode structure.

МЕХАНИЗМ ПЕРЕНОСА ТОКА В СТРУКТУРЕ Al-*p*-CdTe-Mo С РАЗЛИЧНОЙ ТОЛЩИНОЙ БАЗЫ

Ш. А. Мирсагатов, А. К. Утениязов

В работе исследуется механизм переноса тока в структуре Al-*p*-CdTe-Mo, когда толщина базы $w \leq 10$ μm. Приведены результаты исследований вольт-амперных характеристик структуры Al-*p*-CdTe-Mo с разными толщинами базы и влияния толщины базы на механизм переноса тока. Соответственно для образцов № 1 и № 2 при плотностях тока ~$8{,}62 \cdot 10^{-8}$–$4{,}36 \cdot 10^{-5}$A/cm^2 и ~$5{,}08 \cdot 10^{-7}$–$2{,}44 \cdot 10^{-5}$A/cm^2 результаты получены по теории, в которой учитываются только диффузионные составляющие тока и падение приложенных напряжений на толщине базы в диодных структурах. При больших плотностях тока ~$4{,}36 \cdot 10^{-5}$–1,95 A/cm^2 и ~$2{,}44 \cdot 10^{-5}$–3,98 A/cm^2, соответственно для образцов № 1 и № 2, результаты получены по теории дрейфового механизма переноса тока, учитывающей возможность обмена свободными носителями внутри рекомбинационного комплекса.
Ключевые слова: пленка, барьер Шоттки, диодная структура.

МЕХАНІЗМ ПЕРЕНЕСЕННЯ СТРУМУ В СТРУКТУРІ Al-*p*-CdTe-Mo З РІЗНОЮ ТОВЩИНОЮ БАЗИ

Ш. А. Мірсагатов, А. К. Утеніязов

У роботі досліджується механізм перенесення струму в структурі Al-*p*-CdTe-Mo, коли товщина бази $w \leq 10$ μm. Наведено результати досліджень вольт-амперних характеристик структури Al-*p*-CdTe-Mo з різними товщинами бази та впливу товщини бази на механізм перенесення струму. Відповідно для зразків № 1 і № 2 при щільності струму ~$8{,}62 \cdot 10^{-8}$–$4{,}36 \cdot 10^{-5}$A/cm^2 і ~$5{,}08 \cdot 10^{-7}$–$2{,}44 \cdot 10^{-5}$A/cm^2 результати отримані по теорії, в якій враховуються тільки дифузійні складові струму і падіння прикладених напруг на товщині бази в діодних структурах. При великій щільності струму ~$4{,}36 \cdot 10^{-5}$–1,95 A/cm^2 і ~$2{,}44 \cdot 10^{-5}$–3,98 A/cm^2, відповідно для зразків № 1 і № 2, результати отримані з теорії дрейфового механізму перенесення струму, що враховує можливість обміну вільними носіями всередині рекомбінаційного комплексу.
Ключові слова: плівка, бар'єр Шотткі, діодна структура.

INTRODUCTION

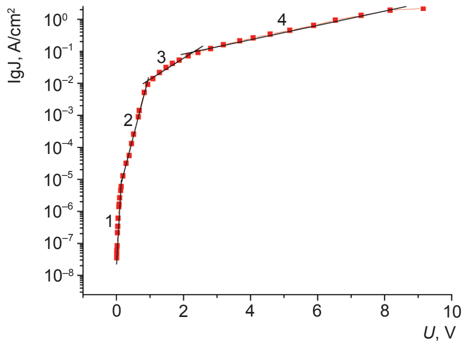
Cadmium telluride is widely used to create *X*-ray detectors and those of γ-radiation. The monocrystal CdTe and $Cd_{1-x}Zn_xTe$-detectors have already demonstrated their advantage over Si and GaAs-detectors and have been successfully used for spectrometry and γ-radiation. In the last years, detectors with Schottky barrier [1–3], based on CdTe and $Cd_{1-x}Zn_xTe$ began intensively developed. The essential advantage of such detectors are small reverse currents ($\sim 10^{-7}$ A) and high operating temperature ($T \geq 300$ °K). In addition, detectors based on the diodes with Schottky barrier can detect high-energy photons with energies up to 1 MeV and higher within energy limit [4].

For the first time we obtained in [5] injection photodetector based on *p*-type conductivity coarse-film cadmium telluride with the thickness of the base $d \geq 50$ μm, and in [6] current transport mechanism of injection of photodetectors was examined. Resistance of the base of these photodetectors was close to the intrinsic conductivity.

The aim of this study is to investigate the influence of the thickness of the base on the current transport mechanism.

The studied film structures were prepared using formerly developed technology described in [7].

Current-voltage characteristics were studied at the forward (when the «+» was applied to Mo) and reverse (where «–» was applied to Mo) directions at the wide range of current and voltage changes. Total analysis of the current-voltage characteristics shows that they possess rectifying properties and their rectification coefficient defined as the ratio of forward current and reverse one at the fixed voltage (5 V), is more than four orders of magnitude. Figure 1 shows the dependence of current-voltage characteristics for direct current in semi-log scale for the two types of samples. Current-voltage characteristics of these samples fit well into direct lines of fig. 2. Consequently, they are described by dependence of type $J \sim AV^{\alpha}$. Seguence of the current-voltage characteristics' parts of the sample are different at forward current and at reverse one.



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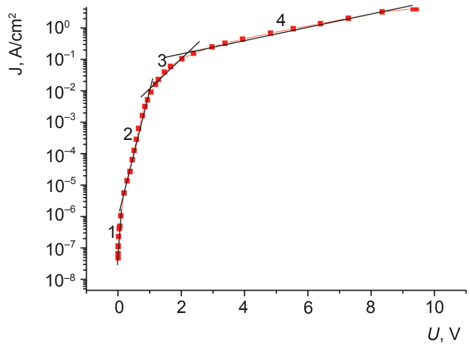

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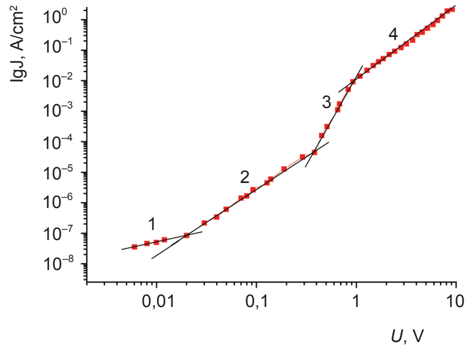
Fig. 1. Direct branch of the CVC for typical Schottky barrier diodes (Al-*p*-CdTe-Mo) in semi-log scale in the dark at $T = 300$ K. The area of Al-contact $S \approx 0.07$ cm², (a – $w = 8$ μm, $\rho \approx 2 \cdot 10^8$ Ω·cm, base — sample No. 1, b – $w = 10$ μm, $\rho \approx 2 \cdot 10^7$ Ω·cm, base — sample No. 2)



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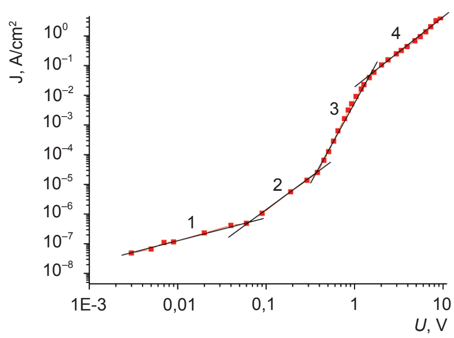

b

Fig. 2. Direct branch of the CVC for typical Schottky diodes (Al-*p*-CdTe-Mo) in double logarithmic scale in the dark at $T = 300$ K. The area of Al-contact $S \approx 0.07$ cm², (a – $w = 8$ μm, $\rho \approx 2 \cdot 10^8$ Ω·cm, base — sample No. 1, b – $w = 10$ μm, $\rho \approx 2 \cdot 10^7$ Ω·cm, base — sample No. 2)

EXPERIMENTAL RESULTS AND DISCUSSION

Direct branch of CVC measured in the dark at room temperature is shown in Fig.1. As the figure shows the direct branch of the CVC consists mainly of four parts, which are described by the following exponential functions:

1) $I = I_{01}\left[\exp\left(qV/c_1kT\right)-1\right]$, where $c_1 = 1$ and $I_{01} = 2.61\cdot10^{-9}$ A;

2) $I = I_{02}\left[\exp\left(qV/c_2kT\right)-1\right]$, where $c_2 = 4.05$ и $I_{02} = 1.59\cdot10^{-8}$ A;

3) $I = I_{03}\left[\exp\left(qV/c_3kT\right)-1\right]$, where $c_3 = 23.98$ and $I_{03} = 1.96\cdot10^{-5}$ A;

4) $I = I_{04}\left[\exp\left(qV/c_4kT\right)-1\right]$, where $c_4 = 73.62$ and $I_{04} = 1.93\cdot10^{-3}$ A for the sample No. 1 and

1) $I = I_{01}\left[\exp\left(qV/c_1kT\right)-1\right]$, where $c_1 = 1$ and $I_{01} = 3.32\cdot10^{-9}$ A;

2) $I = I_{02}\left[\exp\left(qV/c_2kT\right)-1\right]$, where $c_2 = 4.08$ and $I_{02} = 6.43\cdot10^{-8}$ A;

3) $I = I_{03}\left[\exp\left(qV/c_3kT\right)-1\right]$, where $c_3 = 16.96$ and $I_{03} = 6.72\cdot10^{-5}$ A;

4) $I = I_{04}\left[\exp\left(qV/c_4kT\right)-1\right]$, where $c_4 = 78.96$ and $I_{04} = 3.86\cdot10^{-3}$ A for the sample No. 2.

In the first part of the CVC the current is probably limited by the thermal electron emission [8]. Since ideal factor for both samples is equal to one, $C = 1$ and the potential barrier's height is calculated as it is described in [6], equal respectively to $W = 0{,}84$ eV and $W = 0{,}83$ eV for samples No. 1 and No. 2.

The second part of the characteristic (see. Figure 1) is probably described as in [6] by the theory of V. I. Stafeev [9], because in it value of the exponent (c) more than 2 and it is equal to 4.05 and 4.08 for samples No. 1 and No. 2 respectively. Current-voltage characteristics is described [9]:

$$I = I_0\left(e^{\frac{qV}{ckT}}-1\right), \tag{1}$$

where
$$C = \frac{2 + bCh\frac{w}{L_n} + b}{b+1}$$

and

$$I_o = \frac{kT}{2q(b+1)}\frac{S}{\rho L_n}\frac{ch\frac{w}{L_n}}{\mathrm{tg}\left(\frac{w}{2L_n}\right)}, \tag{2}$$

here $b = \mu_n/\mu_p$ — the ratio of electron's and hole's mobilities. At the second part have been also identified the pre-exponential factors, they are $1.59\cdot10^{-8}$A and $6.43\cdot10^{-8}$A. Using the above mentioned experimental data and formulas (1) and (2) values of the diffusion length of minority carriers-electron L_n, mobility product for the lifetime of the electron — $\mu_n\cdot\tau_n$ and the resistivity of the base — ρ, were determined for the values $w \approx 8$ μm, $w \approx 10$ μm for samples No. 1 and number 2, respectively, $b = \mu_n/\mu_p = 10$ [8] and $T = 300$ K. Table 1 gives also the parameters calculated from the third and fourth parts of CVC from formulas (1) and (2) to compare the results.

Table 1

Parameters, determined from the first parts of the CVC

Number of sample	C	W/L	L_n, μm	$\mu_n\tau_n$, cm²·V⁻¹	τ_n, s	I_0, A	ρ, Ω·cm
1	4.05	1.87	4.27	$7.01\cdot10^{-6}$	$7.01\cdot10^{-8}$	$1.59\cdot10^{-8}$	$2.48\ 10^{10}$
	23.98	3.91	2.04	$1.6\cdot10^{-6}$	$1.6\cdot10^{-8}$	$1.96\cdot10^{-5}$	$1.53\cdot10^{8}$
	73.62	5.07	1.57	$9.56\cdot10^{-7}$	$9.56\cdot10^{-9}$	$1.93\cdot10^{-3}$	$4.95\cdot10^{6}$
2	4.08	1.88	5.3	$1.08\cdot10^{-6}$	$1.08\cdot10^{-8}$	$6.43\cdot10^{-8}$	$4.86\cdot10^{9}$
	16.96	3.55	2.81	$3.04\cdot10^{-6}$	$3.04\cdot10^{-8}$	$6.72\cdot10^{-5}$	$2.55\cdot10^{7}$
	78.96	5.14	1.94	$1.45\cdot10^{-6}$	$1.45\cdot10^{-8}$	$3.86\cdot10^{-3}$	$2.15\cdot10^{6}$

Results of Table 1 shows that at increasing current density the diffusion length of minority carriers (electrons) L_n decreases and, accordingly, mobility product for the lifetime of electrons — $\mu_n \cdot \tau_n$, decreases. This experimental result is explained by rechanging recombination centers and as a result, decreasing lifetime of minority nonequilibrium carriers too. Researhed diode structure at high current densities transforms to the diode structure with a thick base. If it is so, the current–voltage characteristic of this diode structure at high current densities should be described well by dependence of the current on voltage of type $J \sim V^{\alpha}$ voltage. Indeed, built in double logarithmic current-voltage characteristics at current densities ~$4.36 \cdot 10^{-5}$–1.95 A/cm^2 and ~$2.44 \cdot 10^{-5}$–3.98 A/cm^2, respectively, for samples No. 1 and No. 2, 3 and 4 parts (See Figure 2) are described well by the dependence of the current on the voltage of type $J \sim V^{\alpha}$. According to the theory [10], CVC's part with a sharp increasing current appears when together with point impurities and defect-impurity centers complex recombination systems involve in recombination processes. They can be such complexes as «negatively charged acceptor + positively charged intercenter» or «positively charged donor + negatively charged vacancy», causing by recombination-stimulated processes [11, 12], «small donor + vacancy» appearing from the decay of complex systems [13, 14] and so on.

So in highly compensated p-CdTe film, together with simple point defects complex recombination systems are too.

In this case, the rate of recombination is described by [10]:

$$U = N_R \frac{c_n c_p \left(np - n_i^2\right)}{c_n \left(n + n_1\right) + c_p \left(p + p_1\right) + a\tau_i np}, \quad (3)$$

where N_R — concentration of recombination centers (complexes); n, p — concentration of electrons and holes; n_i — intrinic concentration in the semiconductor; c_n, c_p — coefficients of capture of electrons and holes; n_1, p_1 — equilibrium concentrations of electrons and holes on conditions when Fermi level coincides with the level of impurities (so-called statistical Shockley-Read factors); τ_i — time taking into account the inertia of those or other processes of electronic exchange within the recombination complex; a-coefficient depending on the specific type of impurity or defect-impurity complexes (see [10]). According to the theory [10], CVC's parts of type $J \sim V^{\alpha}$, where $\alpha > 2$, are realized when the recombination of nonequilibrium carriers is delayed, that is, involving complexes in which the electronic exchange takes place. In this case, in the denominator of (3) inequality

$$c_n \left(n + n_1\right) + c_p \left(p + p_1\right) < a\tau_i np \quad (4)$$

is realised and CVC has the following analytic expression:

$$V = \frac{(b+1) w^2 N_R}{N_A \mu_n \tau_i} + \frac{w\sqrt{J}}{q\mu_n (b+1) C} - \frac{2(b+1) w^2 N_R c_n}{N_A \mu_n a\tau_i C\sqrt{J}} = A + B\sqrt{J} - \frac{D}{\sqrt{J}}. \quad (5)$$

In this case, N_A – the concentration of shallow acceptor centers and the parameter C is related to the concentration of electrons [10, 15]:

$$n(0) = C\sqrt{J}\,. \quad (6)$$

From (5) we can determine such parameters as $N_R / \tau_i, n(0), \frac{c_n}{a\tau_i}$ (τ_i— delay time within the complex, N_R the concentration of complexes). Equating straight line for two given data points (J_1, V_1 и J_2, V_2), we define the value of the voltage

$$V = V_1 - \frac{V_1 - V_2}{J_2 - J_1} J_1, \quad (7)$$

which then equate to the value

$$A = \frac{(b+1) w^2 N_R}{N_A \mu_n \tau_i}$$

of the formula (5). To determine the parameters of the sharp increase of current we choose three experimental points (V_1, J_1), (V_2, J_2), (V_3, J_3) and then we compose two equation for them to determine coefficients B and D

$$B = \frac{V_2 - V_1}{\sqrt{J_2} - \sqrt{J_1}} - \frac{D\left(\frac{1}{\sqrt{J_1}} - \frac{1}{\sqrt{J_2}}\right)}{\sqrt{J_2} - \sqrt{J_1}}, \quad (8)$$

$$D = \frac{(V_3 - V_2) - (V_2 - V_1)\frac{\sqrt{J_3} - \sqrt{J_2}}{\sqrt{J_2} - \sqrt{J_1}}}{\left(\frac{1}{\sqrt{J_2}} - \frac{1}{\sqrt{J_3}}\right) - \left(\frac{1}{\sqrt{J_1}} - \frac{1}{\sqrt{J_2}}\right)\frac{\sqrt{J_3} - \sqrt{J_2}}{\sqrt{J_2} - \sqrt{J_1}}}, \quad (9)$$

which can be equated to their analytical value from the formula (5). Using the formula (5) $\mu_n C$ is determined, and using the formula (6) we can estimate the concentration of injected electrons $n(0)$ at the beginning and at the end of these parts of CVC. All parameters calculated from the parts of CVC are given in Table 2.

Experimental results show that at changing current density concentration of recombination centers taking part in the processes of current transport is changed. This implies that at low current densities CVC is described well by current-voltage characteristics, which takes into account the diffusion component of the current. At the same time for large current densities CVC is described well by drift current component. Jf we could have the theory of the current-voltage characteristics, taking into account both the diffusion and drift current components, we would get the full dynamics of the current's dependence on voltage.

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Table 2

Parameters determined from the CVC's parts of type $J \sim V^{\alpha}$

Number of sample	Branchesd CVC	N_R/τ_i, cm³·s⁻¹	$n(0)$, cm⁻³	N_A, cm⁻³	$C_n/a\tau_i$, cm⁻³
1	$J \sim V^{6}$	$1.72\cdot10^{15}$	$7.6\cdot10^{9}$–$1.12\cdot10^{11}$	$3.12\cdot10^{8}$	$2.21\cdot10^{9}$
	$J \sim V^{2.44}$	$4.65\cdot10^{15}$	$8.39\cdot10^{12}$–$1.22\cdot10^{14}$		$2.41\cdot10^{12}$
2	$J \sim V^{5.53}$	$2.21\cdot10^{16}$	$3.17\cdot10^{9}$–$1.33\cdot10^{11}$	$6.25\cdot10^{9}$	$6\cdot10^{8}$
	$J \sim V^{2.42}$	$9.6\cdot10^{16}$	$6.74\cdot10^{11}$–$8.6\cdot10^{12}$		$4.65\cdot10^{11}$