

Features of current transport in Al–Al₂O₃–p–CdTe–Mo structure

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Abstract. The results of studies of the current-voltage characteristics of the Al–Al₂O₃–p–CdTe–Mo structure in the forward direction of the current in the dark and under light illumination have been presented. These characteristics have four sections of the power-law dependence of the current on the voltage in the form $J \sim V^n$. It has been shown that the Al–Al₂O₃–p–CdTe–Mo structure can be considered as a n^+ – p diode structure with a long base, in which the current transport processes are described by the drift model of ohmic relaxation under conditions of non-equilibrium carriers recombination occurring through a pair two-level recombination complex.

Keywords: injection, pair two-level recombination complex, rapid current increase.

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1. Introduction

In recent years, there observed in the growing interest to creation of devices based on A²B⁶ semiconductors, since they have several advantages over silicon, which remains the main material of modern instrument-making industry. One of the main advantages of these semiconductors is a larger spectral range, since the materials have a band gap corresponding to the full spectrum of visible and partially ultraviolet light. In particular, injection photodiodes with high spectral sensitivity are being developed on the basis of CdTe [1-6].

At the same time, it should be emphasized that materials of the type A²B⁶ and, first of all, CdTe, despite these advantages, have a number of significant disadvantages, the main one of which is the presence of a large number of impurities and defects of various nature. Due to this, the processes of injection and photoelectric amplification in them will have a number of features, the study of which is the purpose of this paper.

2. Samples and measurement procedure

The p -CdTe film structures with a columnar grain structure were prepared on a Mo substrate by sublimation in hydrogen flow. The MOS structure was created by

sputtering aluminum in vacuum ($\sim 10^{-5}$ Torr) [7] onto the surface of the obtained p -CdTe films. p -CdTe films had the resistivity $\rho \approx 10^9\text{--}10^{11} \Omega \cdot \text{cm}$ and a minority carrier (electron) lifetime $\tau \approx 10^{-8}\text{--}10^{-7}$ s. The performed X-ray diffraction analysis showed [8, 9] that the thin Al₂O₃ oxide layer with the thickness close to 30 nm is formed in the technological process. This layer plays a very important role in operation of the obtained structure; it is due to it that the obtained structure is not a simple metal-semiconductor structure, but is a MOS structure, *i.e.*, Al–Al₂O₃– p –CdTe–Mo (Al – metal, Al₂O₃ – oxide, p -CdTe – semiconductor, Mo plays the role of an ohmic contact). It is known that Al₂O₃ oxide can be considered as a wide-gap n -type semiconductor. Thus, the obtained Al–Al₂O₃– p –CdTe–Mo structure can be represented as a $R_{oh}\text{--}n^+\text{--}p\text{--}R_{oh}$ structure with a long p -base, the scheme of which is shown in Fig. 1.

It is well known that a long base is the base with the ratio $\frac{d}{L_n} > 1$ (d is the base length, *i.e.*, in our case, d is the p -CdTe layer thickness, L_n – diffusion length of minority carriers (electrons). To estimate the ratio $\frac{d}{L_n}$, it is necessary to determine the lifetime of minority carriers (electron) τ_n .

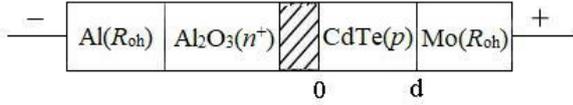


Fig. 1. Scheme of Al–Al₂O₃–p–CdTe–Mo structure.

The value of τ_n was determined from relaxation of non-equilibrium current carriers at a low level of excitation, both in the absence of voltage and under various applied voltages [2]. Non-equilibrium carriers were excited by an electric signal that was supplied from the calibrated pulse generator G5-55 of the U-shape with the amplitude 60...80 mV and duration 100...200 μ s. The steepness of these pulses was no more than $2 \cdot 10^{-9}$ s, duty cycle not less than $5 \cdot 10^{-4}$ s. For example, for the end of the section of sharp current increase at the constant voltage $V = 1.2$ V the electron lifetime $\tau_n \approx 10^{-7}$ s. Then, we use the well known expression

$$L_n = \sqrt{D_n \tau_n}, \quad (1)$$

where $D_n = \frac{kT}{q} \mu_n$, electron mobility for CdTe $\mu_n = 100 \text{ cm}^2 \cdot \text{V}^{-1} \cdot \text{s}^{-1}$, $\tau_n \approx 10^{-7}$ s and $d = 10 \text{ }\mu\text{m}$ – base length.

Thus, for our structure the relation $\frac{d}{L_n} \approx 20$, which makes us to assume the drift injection models.

3. Results

To ascertain mechanisms of current transport when applying direct bias voltage, we studied the current-voltage (I – V) characteristics in the dark and under light, when the structure is illuminated by monochromatic light with the wavelength $\lambda = 950$ nm. The measurement results are shown in Fig. 2.

From this figure, it can be seen that the dark and light CVCs are described approximately by the same laws. The dark CVC (curve 1 in Fig. 2) has four sections, which are described by power-law dependences of the current on voltage of the form $J \sim V^\alpha$ with different values of the exponent α . At low voltages ($V < 0.1$ V), there is the section of the linear dependence $J \sim V$, then $J \sim V^2$, followed by the section of the sharp increase of current $J \sim V^{5.5}$ and, finally, the second quadratic section $J \sim V^2$. The light current-voltage characteristic (curve 2 in Fig. 2) has almost all the same sections, only the currents are now 2 orders of magnitude larger. The dark I – V characteristic begins at $J \approx 10^{-8} \text{ A/cm}^2$, and the light current-voltage characteristic begins at $J \approx 10^{-6} \text{ A/cm}^2$.

Since both of these I – V characteristics begin with Ohm's law $J \sim V$, and then the power dependence $J \sim V^2$ follows, we can conclude that the n^+ – p junction does not make a significant contribution, the main part of the

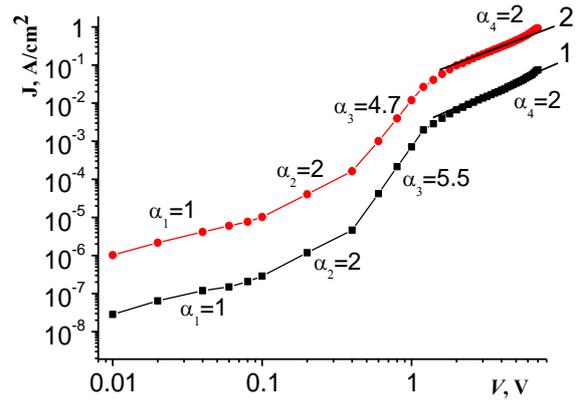


Fig. 2. Dependences of the current density J of the Al–Al₂O₃–p–CdTe–Mo structure on the forward bias voltage in the dark (1) and that under light (2), when the structure is illuminated by monochromatic light with the wavelength $\lambda = 950$ nm, $T = 300$ K.

voltage is applied to the base. And since in our case the estimates give the ratio $\frac{d}{L_n} \approx 10 \dots 20$, at first glance, the

Lampert theory of drift currents that explains the dependence of $J \sim V^2$ by the ohmic relaxation of the space charge is suitable. However, the subsequent CVCs do not fit in the framework of this model. Apparently, a complex system of impurities and defects begins to play its role; it causes changes in the laws of recombination and, as a result, changes in the laws of current transport, both in the dark and under light. In what follows, we will try to analyze this situation from the theoretical point of view.

4. Theoretical consideration and discussion

Since CdTe, like other semiconductors of the A²B⁶ group, contains many impurities and defects of various kinds, we consider recombination of non-equilibrium carriers that occurs not through a simple single-level Shockley–Read trap, but through a pair recombination complex. Attempts to create recombination statistics of this kind have been made repeatedly for various models of recombination complexes. These can be donor-acceptor pairs, complexes of the types impurity + vacancy complexes, impurity + interstitial defect, or defects of the Frenkel pair type arising as a result of recombination-stimulated processes. In [10], various models of such complexes were collected. In this case, the scheme of recombination occurring through such a two-level complex will be approximately the same for all models. It is shown in Fig. 3.

It was also shown in [10, 11] that for all these models, the recombination rate can be written as:

$$U = N_R \frac{c_{n1} c_{p2} (pn - n_i^2)}{c_{n1}(n + n_{11}) + c_{p2}(p + p_{12}) + \tau_{ii} c_{n1} c_{p2} pn}, \quad (2)$$

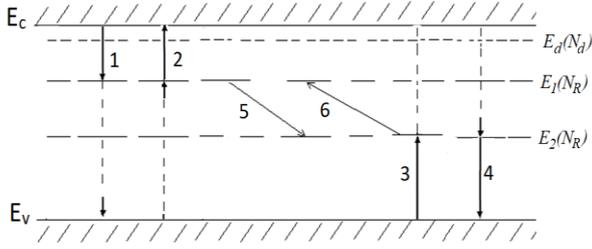


Fig. 3. Scheme of the recombination through a pair two-level recombination complex. Dashed lines show unaccounted transitions. 1 – $c_{n1} N_R (1-f_1)$, 2 – $c_{n1} N_R f_1 n_{11}$ – exchange between the level E_1 and the conduction band. 3 – $c_{p2} N_R f_2 p$, 4 – $c_{p2} N_R (1-f_2) p_{12}$ – exchange between the level E_2 and the valence band. 5 – $c_{12} N_R f_1 (1-f_2)$, 6 – $c_{12} N_R f_2 (1-f_1) e^{\frac{E_2-E_1}{kT}}$ – exchange between the levels E_1 and E_2 , where $(c_{12})^{-1} = \tau_{ii}$ is the time of intra-complex exchange. It is assumed that the difference $E_1 - E_2$ is very small, so $e^{\frac{E_2-E_1}{kT}}$ can be ignored.

where N_R is the concentration of impurities at the levels E_1 and E_2 (it is assumed to be the same), n and p are the concentrations of free electrons and holes, respectively; c_{n1} – electron capture coefficient for the level E_1 , c_{p2} – hole capture coefficient for the level E_2 , n_i – intrinsic concentration, n_{11} and p_{12} are analogues of Shockley–Read statistical factors for the levels E_1 and E_2 :

$$n_{11} = N_c e^{-\frac{E_c - E_1}{kT}}, \quad (3)$$

$$p_{12} = N_v e^{-\frac{E_v - E_2}{kT}}, \quad (4)$$

where $\tau_{ii} = \frac{1}{c_{12}}$ is the time of intra-complex exchange of

electrons between the levels E_1 and E_2 , *i.e.*, time determining the inertia of intra-complex exchange. Let's consider how these processes can affect the rate of recombination. Analyzing the formula (2), we can distinguish 4 main cases, namely:

1. It can be seen from (2) that the time τ_{ii} defines the latter term in the denominator. When this term is small, *i.e.*, the condition

$$c_{n1}(n + n_{11}) + c_{p2}(p + p_{12})c_{n1}c_{p2}\tau_{ii}n \gg \tau_{ii}c_{n1}c_{p2}\tau_{ii}np \quad (5)$$

takes place, and the expression for the recombination rate (2) takes the form:

$$U \approx N_R \frac{c_{n1}c_{p2}(np - n_i^2)}{c_{n1}(n + n_{11}) + c_{p2}(p + p_{12})}, \quad (6)$$

i.e., it is not practically different from the usual expression of the classic Shockley–Read statistics.

Accordingly, under conditions of quasi-neutrality and a sufficiently high level of injection, when

$$n \approx p > n_{11}, p_{12}, \quad (7)$$

$$U \approx N_R c_{eff} n, \quad (8)$$

$$\text{where } c_{eff} = \frac{c_{n1}c_{p2}}{c_{n1} + c_{p2}}.$$

Accordingly, the lifetime of minority carriers (electrons) $\tau_n = \frac{n - n_n}{U}$, when using the expression for the recombination rate (8), takes the form

$$\tau_n = \frac{1}{N_R c_{eff}}, \quad (9)$$

i.e., is a constant that does not depend on the level of excitation. However, with increasing the excitation level, the latter term in the denominator of expression (2) can begin to play a noticeable role.

2. Inequality (5) still holds, but the latter term in the denominator (2) is already noticeable. Then under conditions (7)

$$U \approx N_R c_{eff} n (1 - c_{eff} \tau_{ii} n), \quad (10)$$

i.e., with an increase of excitation level the recombination rate begins to decrease and electron lifetime

$$\tau \approx \frac{1}{N_R c_{eff}} + \tau_{ii} \frac{n}{N_R}. \quad (11)$$

It no longer remains constant but increases slightly with increasing the excitation level. But these changes are still insignificant.

3. With a further increase of the injection level, the sign of inequality (5) may change to the opposite one:

$$c_{n1}c_{p2}\tau_{ii}np > c_{n1}(n + n_{11}) + c_{p2}(p + p_{12}). \quad (12)$$

In this case, the recombination rate U (2) under conditions (7) takes the form:

$$U \approx \frac{N_R}{\tau_{ii}} \left(1 - \frac{1}{c_{eff} \tau_{ii} n} \right), \quad (13)$$

i.e., the recombination rate decreases with increasing the excitation level. In this case, the electron lifetime

$$\tau \approx \frac{\tau_{ii}}{N_R} n \left(1 + \frac{1}{c_{eff} \tau_{ii} n} \right). \quad (14)$$

It means that the lifetime changes with increasing the injection level.

4. And finally, when the latter term in the denominator (2) is very large, the recombination rate of non-equilibrium carriers will reach full saturation

$$U \approx \frac{N_R}{\tau_{ii}}. \quad (15)$$

Moreover, the lifetime of minority carriers (electrons) is as follows:

$$\tau \approx \frac{\tau_{ii}}{N_R} n, \quad (16)$$

i.e., the electron lifetime increases linearly with increasing the excitation level.

Thus, consideration of recombination processes occurring through the two-level recombination complex, which allows one to take into account the inertia of electronic exchange, leads us to a fundamentally new result – with increasing the excitation level, when processes of intra-complex exchange of carriers within the complex begin to play a significant role, the recombination rate of non-equilibrium carriers reaches full saturation, and the carrier lifetime increases linearly with increasing the excitation level. Let's recall that in the classic Shockley–Read statistics, the recombination rate increases linearly with increasing level of excitation, and the lifetime remains constant.

We now proceed directly to elucidating the features of current transport in this structure. It is well known that the main equation of the problem, which describes the distribution of concentration of non-equilibrium carriers in the p -base of the diode structure, can be written as follows (see, for example, [12, 13]):

$$D_n \frac{d^2 n}{dx^2} - \frac{J}{q(b+1)^2 n^2} \times \left[N_a \frac{dn}{dx} - \frac{dE}{dx} \frac{dn}{dx} + n \frac{d}{dn} \left(\frac{dE}{dx} \right) \right] - U = 0, \quad (17)$$

where the first term describes the ambipolar diffusion of non-equilibrium carriers, the second one describes their ambipolar drift, and the third one describes the recombination rate. It is also well known that an analytical solution of the equation (17) is impossible, therefore, two main injection models are usually considered: 1) the diffusion model, when field terms in (17) are neglected, and 2) the drift models, when the first term describing diffusion in (17) is neglected. The drift models are usually realized in structures with a longer base, when the ratio of the base length to the diffusion length $\frac{d}{L} \gg 1$. Since, as noted above $\frac{d}{L_n} \approx 10..20$, we will focus on the drift models.

It is known that there are 2 drift models: the ohmic relaxation model of the space charge and the dielectric

relaxation model of the space charge. The ohmic relaxation model is realized in a p -semiconductor, when the injected space charge is less than the charge of uncompensated acceptors:

$$qN_a \gg \frac{dE}{dx}. \quad (18)$$

In this case, the equation (17) can take a very simple form:

$$- \frac{JN_a}{q(b+1)^2 n^2} \frac{dn}{dx} - U = 0. \quad (19)$$

Now we need to consider the solution of this equation for four values of the recombination rate obtained above, and to find the corresponding I – V characteristics. Here, as usual in drift models, the voltage on the injecting n^+ - p junction will be small as compared to the voltage on the long p -base, so that the I – V characteristic will be determined by the usual expression:

$$V = \int_0^d E dx, \quad (20)$$

and the injecting n^+ - p junction will determine only the concentration $n(0)$ at the boundary of the space charge of the junction and the quasi-neutral p -base (see Fig. 1), and we will consider this junction to be non-ideal, so, respectively (see details in [12]):

$$n(0) = C \sqrt{J}, \quad (21)$$

where $C = \frac{n_n}{qV_p^*(b+1)}$, V_p^* is the parameter related with the non-ideal nature of the n^+ - p junction (see, for example, [12]).

In this case, the expression for the electric field is used:

$$E \approx \frac{J}{q\mu_p(bn+p)}, \quad (22)$$

since the Dember component of the field

$$E_d = \frac{D_n \frac{dn}{dx} - D_p \frac{dp}{dx}}{\mu_n n + \mu_p p}$$

is usually neglected when

calculating the drift models. It should be noted that the subsequent results are very similar to those obtained in [10] for p - i - n structures under similar conditions. Small differences are caused by the fact that in our case the base is of the p -type, and minority carriers are, respectively, electrons, not holes. In addition, in [10] for simplicity of calculations, it was assumed that $c_{n1} = c_{p2}$. We abandoned this assumption.

So, we consider 4 cases of the dependence of the recombination rate on the injection level.

1. When the intra-complex electron exchange plays no role, since it has a very fast ($\tau_{ii} \rightarrow 0$) recombination rate, U (6) is not practically different from the expression in the classical Shockley–Read statistics, and the solution of equation (19) and the corresponding I – V characteristic are well known (see, for example, [13]):

$$J = \frac{9}{8} q \mu_n \mu_p N_a \tau_n \frac{V^2}{d^3}. \quad (23)$$

2. When the influence of inter-level, intra-complex exchange is still small, but the inertia of this process begins to become apparently little, the recombination rate takes the form (10), and the I – V characteristic, as shown in [10] in detail, has the form:

$$J = M(J) q \mu_n \mu_p \tau_n N_a \frac{V^2}{d^3}, \quad (24)$$

but since the factor $M(J)$ is very weakly dependent on the current, the I – V characteristic is almost unchanged.

3. When the latter term in the denominator of expression (2) becomes so significant that intra-complex exchange is predominant and the recombination rate is described by the expression (13), the solution of equation (19) has the form:

$$n = \frac{1}{\tau_{ii} c_{eff}} \left\{ 1 - \frac{1}{\tau_{ii} c_{eff} n(0)} \exp \left[- \frac{q(b+1)^2 N_R x}{\tau_{ii}^2 c_{eff} N_a J} \right] \right\}. \quad (25)$$

The CVC calculated using the formulas (20), (22) and (25) has the form:

$$V = \frac{(b+1)d^2 N_R}{N_a \mu_n \tau_{ii}} + \frac{d\sqrt{J}}{q \mu_n (b+1)C} - \frac{(b+1)d^2 N_R c_{eff}}{N_a \mu_n \tau_{ii} C \sqrt{J}}. \quad (26)$$

As it was analyzed in detail in [10], the dependence of type (26) allows one to obtain a sharp increase of the current in the form $J \sim V^\alpha$ and α can be significantly greater than 2. It was shown using numerical comparison with the experimental results obtained for various semiconductors, in particular, for A^2B^6 semiconductors on the example of CdS–CdTe structures [14].

4. When the intra-complex exchange is highly pronounced and the recombination rate takes the form (6), *i.e.*, reaches full saturation, the concentration distribution has the form:

$$n = \frac{n(0)}{1 + q(b+1)^2 N_R \tau_{ii}^{-1} n(0)x} \quad (27)$$

and the CVC takes the form:

$$J = \frac{q^2 \mu_n^2 (b+1)^2 c}{d^2} (V - V_0)^2, \quad (28)$$

$$\text{where } V_0 = \frac{(b+1)d^2 N_R}{2N_a \mu_n \tau_{ii}}.$$

So, the drift model of ohmic relaxation that we chose during recombination through the pair two-level complex has three main voltage dependences on the current with increasing the injection level: $J \sim V^2$ (23), then the sharp increase of current (26) and again $J \sim V^2$ (28).

Thus, the assumption of recombination, occurring not through the simple single-level Shockley–Read traps, but through complex pair recombination complexes, the inertia of the intra-level exchange of which increases with increasing the excitation level, well explains the change of the I – V characteristic observed in the Al–Al₂O₃–*p*–CdTe–Mo structure.

Now we consider a semiconductor model with the pair two-level recombination complex under photoexcitation conditions. It is presented in Fig. 4.

Transitions 1 to 6 coincide with the same transitions shown in Fig. 3. The figure also shows all possible transitions of photoexcited carriers. Dotted lines indicate non-accounted transitions in this consideration. The considered transitions are 7 – $A\Phi_A N_R f_1$ and 8 – $B\Phi_B f_2$.

Here, Φ_A and Φ_B are the intensities of the fluxes of quanta (photon/cm²·s) with the energies sufficient to photoionize the center. The coefficients $A = \lambda_A \sigma_1$, $B = \lambda_B \sigma_2$ are proportional to the capture cross-sections of these quanta by impurity recombination centers located at the levels E_1 and E_2 , respectively (λ_A and λ_B are their quantum efficiencies, σ_1 and σ_2 – capture cross-sections of the corresponding fluxes of quanta A and B by these centers).

As it was analyzed in detail in [15], impurity photoexcitation in this case changes the analogs of the Shockley–Read statistical factors (3) and (4), which we introduced earlier when considering recombination through the two-level recombination complex:

$$n_{11}^* = n_{11} \left(1 + \frac{A\Phi_A}{c_{n1} n_{11}} \right), \quad (29)$$

$$p_{12}^* = p_{12} \left(1 + \frac{B\Phi_B}{c_{p2} p_{12}} \right). \quad (30)$$

Since we still neglect the direct interaction of the level E_1 with the valence band and the level E_2 with the conduction band, for simplicity of calculation, we do not present statistical factors n_{11} and p_{12} and the corresponding n_{11}^* and p_{12}^* .

From the foregoing, it is clear that the recombination rate of non-equilibrium carriers under conditions of additional impurity photoexcitation takes the form:

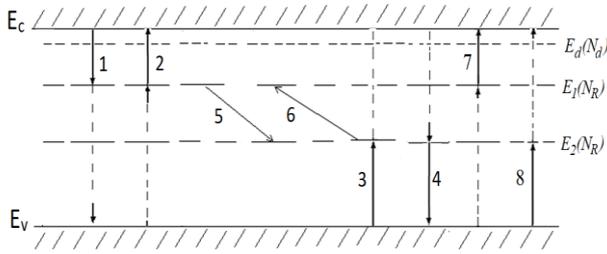


Fig. 4. Scheme of energy transitions in a semiconductor with photosensitive two-level centers forming a pair recombination complex.

$$U = N_R \frac{c_{n1}c_{p2}(pn - n_i^2)}{c_{n1}(n + n_{11}^*) + c_{p2}(p + p_{12}^*) + c_{n1}c_{p2}\tau_{ii}np}. \quad (31)$$

Further, we can re-analyze this expression under conditions of quasi-neutrality and a high level of excitation, which now instead of (7) will look like:

$$n \approx p > n_{11}^*, p_{12}^*, \quad (32)$$

where n_{11}^* and p_{12}^* are described using the formulas (29) and (30).

Since as the result of the action of impurity illumination $n_{11}^* > n_{11}$ and $p_{12}^* > p_{12}$, then all the above CVCs $J \sim V^2$, $J \sim V^{4.7}$ and again $J \sim V^2$ will be repeated in the same sequence, but now at higher excitation intensities, which is confirmed by the course of the light current-voltage characteristic in Fig. 2 (curve 2).

5. Conclusions

These studies show that Al–Al₂O₃–p–CdTe–Mo (Al – metal, Al₂O₃ – oxide, p–CdTe – semiconductor, Mo plays the role of an ohmic contact) structure can be considered as a n⁺–p diode structure with a long base, in which the current transport processes have been determined using the drift model of ohmic relaxation under conditions of recombination of non-equilibrium carriers occurring through the pair two-level recombination complex. Taking into account the inertia of the electronic exchange processes inside this complex, it is possible to explain the successive changes in the I–V characteristic $J \sim V^2$, $J \sim V^{5.5}$ and again $J \sim V^2$ both in the dark and in the light under conditions of impurity photoexcitation.

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Особливості перенесення току в структурі Al–Al₂O₃–p–CdTe–Mo

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Анотація. Наведено результати досліджень вольт-амперних характеристик структури Al–Al₂O₃–p–CdTe–Mo у прямому напрямку струму в темряві та при освітленні. Ці характеристики мають чотири ділянки степеневі залежності струму від напруги у вигляді $J \sim V^\alpha$. Показано, що структуру Al–Al₂O₃–p–CdTe–Mo можна розглядати як структуру n^+p діода з довгою базою, в якій процеси токоперенесення описуються дрейфовою моделлю омичної релаксації за умови рекомбінації рівноважних носіїв, що відбувається через парний дворівневий рекомбінаційний комплекс.

Ключові слова: інжекція, парний дворівневий рекомбінаційний комплекс, швидке збільшення струму.