Current-voltage characteristics of the injection photodiode on based of M(In)-nCdS-pSi-M(In) structure

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Abstract

The direct volt-ampere characteristic of the M(In)-nCdS-pSi-M(In) structure was studied at room temperature. It is found that the current-voltage characteristic of such structures has a power-law dependence of the current on the voltage.

Key words: electron exchange, bipolar drift length, bipolar diffusion length.

There are well known data on formation of injection photodiodes based on A^2B^6 connections, in particular based on sulfide and cadmium telluride and its solid solutions [1-4]. The Ni-nCdS-n$^+$CdS – structure based on CdS mono-crystals is considered to have photocurrent strengthening when it is illuminated with λ = 0.22 microns light since there is an injection of the majority charge carriers in a high-resistance n-area from non-illuminated side of n $^+$-n-transition [1]. The injection photo-detector with internal strengthening based on the cadmium sulfide, working at room temperature in a wide range of spectrum is not created yet. Such injection photo-detector with increased output parameters can be created on the p-i-n-based structures. For A^2B^6 semiconductors, including CdS, it is technologically difficult to obtain p-type conductivity and p-i-n-structure on its basis because of self-compensation effect. To avoid this problem we created M(In)-nCdS-pSi-M(In) structure with heterojunction. The high-resistant strongly compensated weak n-type CdS-layer plays role of i-layer here. The choice of pSi-nCdS heterojunction was previously described [5].

It is known that injection and accumulation properties of the barriers determine the current-voltage characteristics of the structure. Therefore, it was investigated by the direct current-voltage characteristic structures in the dark, which is illustrated in Fig.1 for the half-logarithmic scale. Straight direction of a current in structure is considered when pSi contact is able to applied to potential "+" and potential "-" as backward. The analysis of C-V demonstrate that the structure possesses rectification properties and its rectification coefficient "K" (defined as the relations between a direct and inverse current in the presence of fixed voltage U=20V) and forms $\approx 10^5$. The analysis of direct current-voltage characteristics of M(In)-nCdS-pSi-M(In) structures have shown that it consists of four plots at the room temperature.

The first, second, fourth parts are described by the exponential dependence of current on voltage and have the following analytical expression

$$I=I_0 [\exp (qV/(c\,kT)) -1] \quad (1),$$

where c is the indicator of exponents, I_0 is the pre-exponential factor, q is the

charge of electron, and k is the Boltzmann constant, T is the temperature in Kelvin, V is the bias voltage. Note that the values of parameters "c" and "I_0" have different values for each area of C-V. The third area of C-V describes the sublinear dependence of the current on voltage.

Here, we will analyze only the fourth part, since the first, the second, and the third parts were analyzed in detail in our previous work [6].

As was noted above, the fourth part of C-V is defined by the exponential dependence $I=I_{04}exp\ (qV/kTc_4)$, where $c_4 = 68$, $I_{04} = 1.9 \bullet 10^{-7}$ A/cm^2. Substituting these experimental data into expressions (2) and (3), we determine the relations of base thickness for the diffusion length of holes w/L=8.5, and L=0.24 μm, and the resistivity of the base ρ=1.9•10^7 Ω • cm. L, ρ

$$V = V_0 exp\ (aIw), \qquad\qquad (2)$$

$$where\ a=1/2qD_pN_t \qquad\qquad (3)$$

In the expression (2) V_0 preexponential multiplier factor $V_0 = \dfrac{D_{eff}}{\mu_p} \dfrac{b+1}{b(b\gamma+b+1)} \dfrac{p_{sb}^2}{N_t p(w)}$,

where D_{eff} is the coefficient of bipolar diffusion: $\gamma = \dfrac{N_t}{p_{1t}}$ - the f actor of adhesion, psb is the concentration of nonequilibrium holes at the cathode (about M(In)- nCdS - contact): p(w) is the concentration of nonequilibrium holes at the anode (contact nCdS - pSi). In equation (3), D_p is the coefficient of diffusion of holes, N_t is the concentration of adhesion levels, I is the current density. being evaluated by the fourth part of C-V, strongly differs for the same value estimated with the help of the second part. The difference between these values can be explained by the changes of base properties with increasing current density in the structure. After sublinear part C-V due to the highly compensated recombination centers of recharges decreases the lifetime of minority carriers - holes and the structure acquiring the properties of "long" diodes[7], in which the current is mainly determined by the drift mechanism. To confirm the above

identified value of bipolar diffusion and drift mobility of the fourth part of C-V. As was shown in experiment, the bipolar diffusion length for the fourth part of strict C-V is two times less than L by size at the second part and it is equal to 0.24 μm. In case of $\mu \bullet \tau$ product it is reduced four times. Further, assuming that the mobility and lifetime of the plasma of electron-hole pairs are equally reduced twice from the expression $L = (D \bullet \tau)^{0.5}$, where $D_a = 3,3 \bullet 10^{-1} cm^2 \bullet s^{-1}$ is determined with the following values: $L = 0,24$ μm $\tau = 1,75 \bullet 10^{-8} s$. Since $D_a = (kT/q) \bullet \mu_D$ we find that the mobility of bipolar diffusion of free carriers is $\mu_D = 12,5$ cm^2/V•s. And, the mobility of bipolar drift of the free carrier is defined in the following way. It was admitted that on this strict of C-V delineating such structure it is called as a drift current, and so the voltage and current at the end of the fourth part of C-V (V= 20 V, I = 0,18 A/cm^2) was defined as the base resistance structures. Further assuming that the centers of the sticking holes ($N_t = 2 \bullet 10^{10}$ cm^{-3}) that play a decisive role in modulating the bipolar process of the drift velocity on the sublinear part of C-V, all filled and the concentration of electron-hole plasma is not less than 10^{11} cm^{-3}, which is significantly higher than the concentration of the adhesion centers. Then, using the formula R=ρd/S; where d≈2μm (the thickness of the base), ρ is the resistivity of the base and S=0.1 cm^2 active area of the structure, the size of the bipolar drift mobility $\mu_a = \sim 112$ cm^2/V•s. It is known that in the injection diodes are a significant part of the utilized potential drops at the base of the structure, so for simplicity it was assumed that the applied potential V = 20 V to the structure, equally distributed between the injecting contact, M(In)- nCdS and base (nCdS). In this case, the bipolar drift velocity of holes is considered as $v_a \approx 5,6 \bullet 10^6$ cm/s. For such a bipolar velocity of the drift, length of drift bipolar holes is $L_{dr} \approx 5.6 \bullet 10^{-2}$ cm at the value $\tau \approx 10^{-8} s$ (the lifetimes of electron-hole plasma), which is more higher with three orders of magnitude than the bipolar diffusion length (L=0.24 μm). Above evaluation shows growth dynamics of the bipolar drift, which fully confirms that in the fourth part of the C-V drift mechanism is predominant.

The fourth part of C-V is also well described by a power law of the type I~V$^\beta$, where $\beta \approx 6.2$. At sufficiently high injection levels, the concentration of

nonequilibrium carriers in M(In)-nCdS strongly increases and, therefore, even in the asymmetric transition it starts playing a prominent role for the second component of current, i.e. the drift current [8]. In this case, a decisive role even at the boundary layer, space - charge starts playing a carrier drift in the electric field. Conductivity thickness increases slower than the growth rate of current and voltage-current characteristic is described by a power law type [8]:

$$I = (9/8)q(n_o-p_o)\mu_n\mu_p\tau \, (V^\beta/w^3) \, S \qquad (4)$$

where, n_o, p_o are the equilibrium concentration of electrons and holes, $\mu_n\mu_p$ - mobility of electrons and holes, τ is the lifetime of electron-hole plasma, $\beta \approx 2-4$.

Further, the product $\mu_n\mu_p \approx 4 \bullet 10^7 \, (cm^2 \bullet V^{-1}s^{-1})^2$ was calculated on the basis of equation (4) for the given values: $\rho \approx 2 \bullet 10^{10}$ Ω. cm, $n_0 \approx 10^6 \, cm^{-3}$ and $\mu_n = 289 \, cm^2 \bullet V^{-1} \bullet s^{-1}$ [9], and the values of current $I = 0.18 \, A \bullet cm^{-2}$ and $V = 20 \, V$. Thus, obtained value of $\mu_n\mu_p$ is larger with four orders than their values according to the literature data [10]. Moreover, this difference is obtained in the case in which $\mu_n = 289 \, cm^2 \bullet V^{-1} \bullet s^{-1}$ and $\mu_p = 8 \, cm^2 \bullet V^{-1} \bullet s^{-1}$ as single crystals CdS [9]. In addition, the final evaluation indicates that there is conductivity modulation of the base, where the main role is performed by the rapid growth of the bipolar drift mobility of the nonequilibrium carriers with current. This is because the mobility of the bipolar electron-hole plasma according to [10]:

$$\mu = \frac{n - p\dfrac{dn}{dp}}{n\mu_n + p\mu_p}\mu_n\mu_p \qquad (5)$$

which has a value in the numerator, depending on the difference of concentrations of charge carriers. In the fourth part of the C-V the change probably occurs in the numerator of expression (5) leading to a sharp increase in the mobility of the bipolar electron-hole plasma. The reason may be levels of adhesion to holes, being active.

According to the theory [11], section of the power current-voltage type $J - V^\beta$, β>2 follows the part of the exponential dependence of the type $J - \exp^{\frac{eV}{ckT}}$ and index of power is not greater than four.

However, due to the structure of the M(In)-nCdS-pSi-M(In) plot type $J - V^{\beta}$ occurs after sublinear part of C-V and $\beta \approx 6.2$ at the room temperature. Such C-V structure can also be explained in the frame of the theory of the drift mechanism of current transfer taking into account the possibility of exchange of free carriers inside a recombination complex. Due to the structure of the M(In)-nCdS-pSi-M(In) base is heavily compensated high-resistivity polycrystalline film of cadmium sulfide. Obviously, in these films may be point defects, such as vacancies of atoms of cadmium (Cd) and sulfur atoms (S). In addition, in the initial powders of the compounds CdS, from which the polycrystalline CdS film was obtained, according to TU, there are a few chemical elements: In, Al, Ag, Cu, Fe and etc.. Therefore, forming complexes of various types should be expected in the database (CdS). In the form of compounds, CdS volatile components are the atoms of cadmium. Therefore, in the sublattice of atoms of cadmium are easily formed by their singly and doubly charged vacancies. Doubly charged vacancies of atoms of cadmium in most cases form complexes with positively charged impurity of type $(V_{Cd}^{2-}\,\mathrm{Cd}^+)^{-1}$ and neutral sulfur atoms of type $(V_{Cd}^{2-}\,\mathrm{S}*)^{-2}$. In addition to these mentioned above, complexes have a large probability of formation of such defacto-impurity complexes to negatively "charged acceptor + positively charged ion of introduction" or "positively charged donor + negatively charged vacancy" that can play a decisive role in recombination processes. For these recombination processes in the base of the structure occurs not only through simple recombination centers [12], but also through defecto-impurity complexes. In this case, the expression for the rate of recombination is undergoing fundamental change and takes the form as follows [11]

$$U = N_R \frac{c_n c_p (np - n_i^2)}{c_n (n - n_i) + c_p (p - p_i) + \alpha \tau_i np} \tag{6}$$

where N_R is the concentration of recombination centers (complexes), n, p are concentrations of electrons and holes, n_i is its own concentration in the semiconductor, c_n, c_p are the capture coefficients of electrons and holes, n_1, p_1 are equilibrium concentrations of electrons and holes under conditions when the Fermi

level coincides with the impurity level (called static factors Shockley-reed), τ_i is time taking into account certain processes of electron exchange inside a recombination complex, and β is the coefficient depending on the specific type of impurity or defect-impurity complexes (see[11]).

Despite the different type of complexes, they follow one General pattern – recombination of nonequilibrium electrons and holes with delay, and given the inertia of the electron exchange inside a recombination complex causes to the appearance of the last term in the denominator of expression (6), which at a sufficiently high level of excitation may be crucial. According to the theory [11], areas of C-V $J \sim V^\beta$, where β >2, can be realized when the recombination of nonequilibrium current carriers happens with delay, i.e. with participation of complexes for an electronic exchange. In this case, in the denominator of the expression (6) is realized inequality

$$c_n(n+n_1)+c_p(p+p_1)<\alpha\tau_i np \qquad (7)$$

and C-V, and has the following analytical expression for the structure of p-type base:

$$V = \frac{(b+1)w^2 N_R}{bN_a\mu_n\tau_i} + \frac{w\sqrt{J}b}{q\mu_n(b+1)C} + \frac{2(b+1)w^2 N_R c_p}{bN_a\mu_n\beta\tau_i C\sqrt{J}} = A + B\sqrt{J} - \frac{D}{\sqrt{J}} \qquad (8)$$

Since the investigating structure was created on the basis of the highly compensated cadmium telluride, therefore, the concentration of shallow acceptors $N_A=N_a-N_d$. The parameter C was related with the concentration of electrons on the border n-CdS oxide n-SiO with the expression [11]

$$p(0) = C\sqrt{J} \qquad (9)$$

The dependence (7) allows to describe any value of the slope of the C-V type $J \sim V^\beta$, including the site of sharp growth. A comparison of the return part of C-V dependence $J \sim V^{\beta\approx4.7-4.8}$ with the expression (7) allows to determine parameters such as N_R/τ_i, $p(0)$, $\frac{c_p}{\alpha}$ (τ_i – time delay inside the complex, N_R is the concentration of complexes). For this, the equation of a straight line is made for the given

experimental points. For example, making the equation of the straight line for the two experimental points (J_1, V_1 and J_2, V_2) determine the value of the voltage,

$$V = V_1 - \frac{V_1 - V_2}{J_2 - J_1} J_1 \tag{10}$$

For which it can equate to $A = \frac{(b+1)w^2 N_R}{N_A \mu_n \tau_i}$ from the equation (8). Further substituting the value w=120 μm, b=10, $\mu_n \approx 100 \frac{cm^2}{V \cdot s}$ and N_A=1.5·10^{10}cm^3 into (7) we easily define expression $\frac{N_R}{\tau_i}$. For determination of other parameters, the sharp growth of current was chosen by three experimental points (V_1, J_1), (V_2, J_2), (V_3, J_3), for which three equations is applied to determine the coefficients B and D

$$B = \frac{V_2 - V_1}{\sqrt{J_2} - \sqrt{J_1}} - \frac{D(\frac{1}{\sqrt{J_1}} - \frac{1}{\sqrt{J_2}})}{\sqrt{J_2} - \sqrt{J_1}} \tag{11}$$

$$D = \frac{(V_3 - V_2) - (V_3 - V_2)\frac{\sqrt{J_3} - \sqrt{J_2}}{\sqrt{J_2} - \sqrt{J_1}}}{(\frac{1}{\sqrt{J_2}} - \frac{1}{\sqrt{J_3}}) - (\frac{1}{\sqrt{J_1}} - \frac{1}{\sqrt{J_2}})\frac{\sqrt{J_3} - \sqrt{J_2}}{\sqrt{J_2} - \sqrt{J_1}}} \tag{12}$$

which are then equated to their analytical values given in equation (8) allowing to estimate the values $\mu_n C$, $n(0)$, N_R/τ_i and the value $\alpha\tau_i/c_n$ being respectively equal to N_r/τ_i 3,5·10^{14}cm^{-3} s^{-1}. $n(0)_n$=1,4·10^{14}cm^{-3} and $n(0)$=1,3·10^{16} cm^{-3}. In this way, specific values of the concentration ratio of the complexes on the delay in complexes and the concentration of the injected nonequilibrium electrons at the beginning and at the end of the segment, the sharp growth of current is reasonable side-altars, as evidenced by the correctness of the assumption. This leads to the conclusion that the recombination processes predominantly involved intrinsic complex systems for the electronic exchange, as a result inertia can be appeared in the structure. In this case, we are not able to say exactly that complexes are involved in the recombination processes. As was estimated, the value $\alpha\tau_i/c_n$ =9·10^{-10}cm is the integral value, where α is a coefficient, depending on concrete type of impurity or defacto - impurity complexes. In this case, to make

full clarity on this issue, it is essential to know the type of the complex, which occurs mainly through recombination processes being unknown at the moment.

Analysis of strict C-V, structures of M(In)-nCdS-pSi-M(In) shows that it has quite a complex mechanism of current transfer, as evidenced by the sequence of sections: $I=I_{01}exp(eV/ckT)$, where $c\approx 1$. $I_{01}exp(eV/ckT)$, where $c\approx 3.6$ $I \sim V^{0,1}$ and $I \sim V^{6,2}$ at the room temperature (see Fig.1). This sequence parts of the C-V does not match the sequence C-V, for which it has taken into account the influence of the inertia chelated electronic exchange on the processes of recombination and current transfer [13]. The theory offered in [13] solves the basic equation

$$D_n \frac{d^2 n}{dx^2} - \frac{jN_a b^2}{q(b+1)^2 p^2} \frac{dp}{dx} - U \qquad (13)$$

where the recombination rate U described by the expression (5) and not considered by the diffusion term of the equation. In this respect, an analytical solution of the equation (7) was obtained for long diodes with non-injecting contact. Further, the patterns of current flow for four cases will be discussed since the last term in the denominator of the expression (6) increases with increasing of excitation level.

The direct sequence parts of C-V shows that the investigating complex structure and with increasing current density can change the mechanism of current transfer. At low current densities of the resistance, the thickness of the space charge is decisive in the resistance structures, and the transfer mechanism is the thermionic emission. At the second part of the C-V, a significant part of the voltage falls to the thickness of the base structure, and the current in structure is restricted by the recombination. And, in the recombination processes, determining role plays a critical role simple - point recombination centers. Third sublinear part of the C-V is characterized by the recombination processes in a large part affected by the participation of complex systems; consequently, the lifetime of nonequilibrium carriers is larger than their flight time. This phenomenon leads to change of distribution profile of nonequilibrium carriers resulting in a counter-

diffusion and drift flows, which leads to the appearance of sublinear part of the C-V. The appearance at the C-V area, a sharp growth of current is obvious that becomes extremely important in the presence of high concentrations of the injected nonequilibrium carriers 10^{14} cm^{-3} to 10^{16} cm^{-3} participating in complexes in the recombination processes.
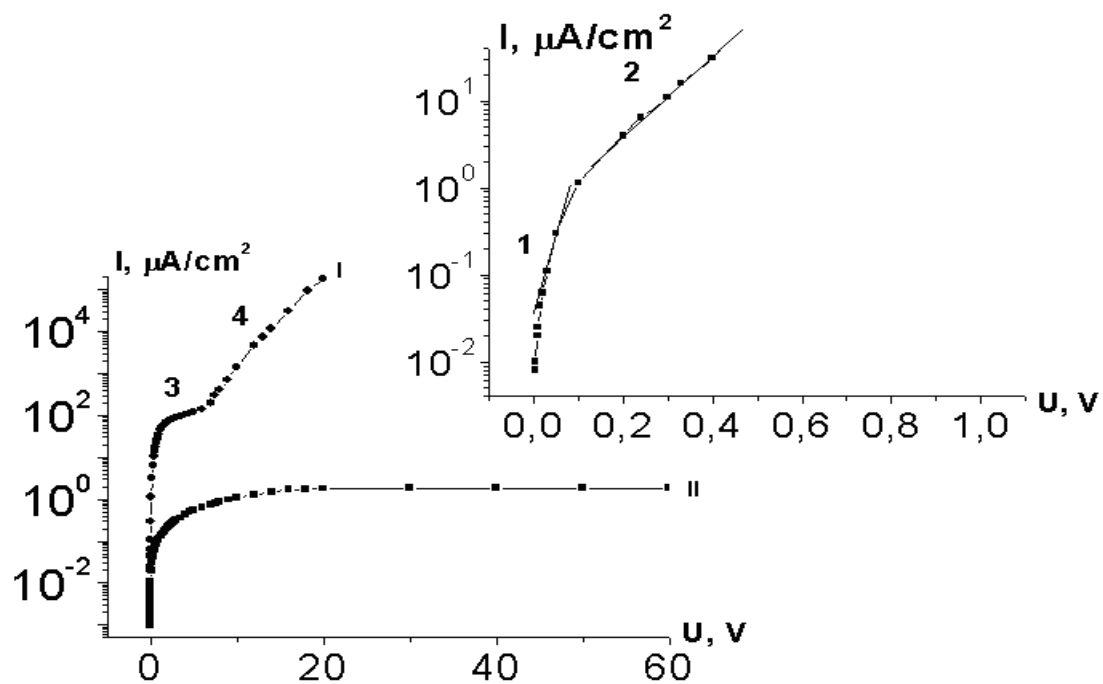
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FIGURE CAPTIONS

Fig.1. The structures of voltage - current characteristic in semi-logarithmic scale in the dark: (I) strict branch, (II) reverse branch. The third (3) and four (4) areas has been indicated on the strict branches (I), and the first (1) and second (2) parts has been shown on the strict branches in the plot.

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