RELAXATION OF ANOMALOUSLY LARGE PHOTOVOLTAGES IN CADMIUM TELLURIDE FILMS

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Fig. 1

Figure 1: Fig. 1

Abstract

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1. The experimental material on the effect of anomalously large photovoltages (the ALP effect) in semiconductor films consists, in the overwhelming majority, of studies carried out under steady-state conditions. It is natural to expect that the study of transient processes will provide additional information on the physical nature of the ALP effect. Some, and moreover contradictory, data on the relaxation times of V_ϕ in ALP films are given in works ([1–5]). An estimate of the relaxation time of V_ϕ in cadmium telluride films was obtained experimentally by us in work ([6]), where, however, the question of the physical nature of the processes responsible for the measured τ remained unresolved. Below we present results obtained with the aid of a more accurate method, and also compare these results with theoretical concepts concerning the nature of the ALP effect in cadmium telluride films.

Fig. 1. *a*—*p*—*n*-junction model of an ALP film; one micro-photoelement is indicated by the dotted line: 1—*p*-region, 2—*n*-region; *b*—equivalent circuit of a micro-photoelement; *c*—equivalent circuit of an ALP film closed on an external load Z

2. As a result of works ([7,8]), it may be considered established that ALP films of cadmium telluride are multi-element structures consisting of a large number of micro-*p*—*n* junctions. A model of such a structure is shown in Fig. 1a. The dotted line shows the "elementary cell" of an ALP film (micro-photoelement). The equivalent circuit of such a micro-photoelement is presented in Fig. 1b. Here J_f is the photocurrent generator, characterized by its own relaxation time τ_0 ([9,10]):

$$J_f = XI; \qquad X = a/(1 + j\omega\tau_0); \tag{1}$$

$I = I_0 e^{j\omega t}$ is the intensity, and ω is the frequency of light modulation;

$$z_1 = r_1/(1 + j\omega\tau_1); \qquad z_2 = r' + r_2/(1 + j\omega\tau_2) \tag{2}$$

are the impedances of the photoactive and non-photoactive regions ($\tau_1 = r_1 C_1$; $\tau_2 = r_2 C_2$); r_1, r_2, and $r' = r'_1 + r'_2$ are the differential resistances of the p—n junction, of the n—p junction, and of the ohmic region; C_1 and C_2 are the differential capacitances of the p—n and n—p junctions. The equivalent circuit of an ALP film consisting of N such micro-photoelements is shown in Fig. 1c.

The photovoltage produced by the afn film across the load Z, and the current in the external circuit, are expressed by the formulas

$$V_\Phi = \frac{ZNz_1X}{Z + N(z_1 + z_2)} I; \qquad J = \frac{V_\Phi}{Z} = \frac{Nz_1X}{Z + N(z_1 + z_2)} I. \tag{3}$$

We shall consider as the load a parallel RC circuit

$$Z = R/(1 + j\omega\tau_3); \qquad \tau_3 = RC. \tag{4}$$

Under real conditions this is usually an ohmic load shunted by a parasitic mounting capacitance. The frequency-phase characteristics of the photovoltage and current have the form ($s = j\omega$):

$$\varphi(s) = \frac{V_\Phi}{I} = \frac{V_{\Phi 0}}{I_0} \frac{R + N(r_1 + r_2 + r')}{Nr'\tau_0\tau_1\tau_2\tau_3} \frac{\tau_2 s + 1}{(s - s_1)(s - s_2)(s - s_3)(s - s_4)};$$
$$\xi(s) = \frac{J}{I} = \frac{J_0}{I_0} \frac{R + N(r_1 + r_2 + r')}{Nr'\tau_0\tau_1\tau_2\tau_3} \frac{\tau_2\tau_3 s^2 + (\tau_2 + \tau_3)s + 1}{(s - s_1)(s - s_2)(s - s_3)(s - s_4)}. \tag{5}$$

Here

$$V_{\Phi 0} = \frac{RNr_1 a I_0}{R + N(r_1 + r_2 + r')}; \qquad J_0 = \frac{Nr_1 a I_0}{R + N(r_1 + r_2 + r')}; \tag{6}$$

and s_i are the roots of the equation

$$\tau_0\tau_1\tau_2\tau_3 Nr' s^4 + [\tau_0\tau_1\tau_2(R + Nr') + \tau_1\tau_2\tau_3 Nr'$$
$$+\tau_2\tau_3\tau_0 N(r_1 + r') + \tau_3\tau_0\tau_1 N(r_2 + r')]s^3 +$$

$$+[\tau_0\tau_1(R+Nr_2+Nr')+\tau_0\tau_2(R+Nr_1+Nr')$$
$$+\tau_0\tau_3 N(r_1+r_2+r')+\tau_1\tau_2(R+Nr')+\tau_2\tau_3 N(r_1+r')$$
$$+\tau_3\tau_1 N(r_2+r')]s^2+[\tau_0(R+Nr_1+Nr_2+Nr')$$
$$+\tau_1(R+Nr_2+Nr')+\tau_2(R+Nr_1+Nr')$$
$$+\tau_3 N(r_1+r_2+r')]s+[R+N(r_1+r_2+r')]=0. \quad (7)$$

We find the transient characteristics directly from (5) by means of the inverse Laplace transform ([11,12]). The relaxation curves of the photovoltage and current are described by the formulas

$$V_\Phi(t)=V_{\Phi 0}\frac{R+N(r_1+r_2+r')}{Nr'\tau_0\tau_1\tau_2\tau_3}\sum_p \frac{1+\tau_2 s_1}{s_1(s_2-s_1)(s_3-s_1)(s_4-s_1)}e^{s_1 t},$$
$$J(t)=J_0\frac{R+N(r_1+r_2+r')}{Nr'\tau_0\tau_1\tau_2\tau_3}\sum_p \frac{1+(\tau_2+\tau_3)s_1+\tau_2\tau_3 s_1^2}{s_1(s_2-s_1)(s_3-s_1)(s_4-s_1)}e^{s_1 t}. \quad (8)$$

Here $\sum_p$ denotes summation over all cyclic permutations of the four indices $1,2,3,4$ of the roots s_i. The p-transition model of an afn film is characterized by four relaxation times

$$\tau_i^*=-1/s_i \qquad (i=1,2,3,4), \quad (9)$$

which in the general case do not coincide with the times $\tau_0,\tau_1,\tau_2,\tau_3$.

3. Let us consider a simplified model of an afn film consisting only of photoactive elements ($r'=0;\ r_2=0$). The admissibility of this simplification is supported by the fact that the experimental value of the resistivity in afn films of cadmium telluride ($\rho\sim 10^8\div 10^9$ ohm/cm) ([13,14]) is of the same order of magnitude as ρ of pure CdTe ([15]). For such a model, (7) degenerates into a second-order equation, and

$$-\frac{1}{s_1}=\tau_0; \qquad -\frac{1}{s_2}=\tau^*=\frac{R_{\text{pl}}R(C_{\text{pl}}+C)}{R_{\text{pl}}+R}, \quad (10)$$

where $R_{\text{pl}}=Nr_1$ and $C_{\text{pl}}=C_1/N$ are, respectively, the dark resistance and capacitance of the film.

The transient characteristics of the photovoltage and current take the following form:

$$V_\phi(t)=V_{\phi 0}\left[\frac{\tau_0}{\tau_0-\tau^*}e^{-t/\tau_0}+\frac{\tau^*}{\tau^*-\tau_0}e^{-t/\tau^*}\right];$$

$$J(t) = J_0 \left[\frac{\tau_0 + \tau_3}{\tau_0 - \tau^*} e^{-t/\tau_0} + \frac{\tau^* + \tau_3}{\tau^* - \tau_0} e^{-t/\tau^*} \right], \tag{11}$$

where

$$V_{\phi 0} = \frac{RNr_1 aI_0}{R + Nr_1}; \qquad J_0 = \frac{Nr_1 aI_0}{R + Nr_1}. \tag{12}$$

4. If the leading edge of the rectangular light pulse cannot be regarded as infinitely sharp (i.e., shorter than all characteristic times), then experimentally—by the tail of the decay or rise curve—the largest of the relaxation times is determined. At large ohmic loads

Fig. 2. Relaxation curves of V_ϕ: 1–$R = 510$ kΩ; 2–$R = 1$ MΩ; 3–$R = 1.6$ MΩ; 4–$R = 3$ MΩ; 5–$R = 4.7$ MΩ.

$$(R \gg R_{\text{pl}})$$

this is either τ_0, or $R_{\text{pl}}(C_{\text{pl}} + C)$; at small loads

$$(R \ll R_{\text{pl}})$$

it is either τ_0, or $R(C_{\text{pl}} + C)$.

In order to establish which of the characteristic times determines the duration of the transient process and is measured in the experiment, one should study the dependence of τ_{exp} on the parameters of the external circuit, noting that τ^* depends on them, while τ_0 does not. Since the resistance of the afn films R_{pl} is very large, it is more convenient to carry out the experiment under conditions close to the short-circuit regime. In this case τ^* is an experimentally controllable quantity, since R can be varied over sufficiently wide limits. The possibility of making τ^* sufficiently small makes it possible either to reach a regime in which τ_0 becomes the largest, i.e., the characteristic time determining the relaxation process, and thus to measure τ_0 directly, or to give an upper estimate of this quantity if realization of such a regime proves experimentally impossible. Control of the regime is carried out from the dependence or independence of τ_{exp} on the load resistance R.

5. To measure the relaxation times, a mechanical modulator (9) was constructed with light-pulse fronts of $2 \div 3$ μsec and a pulse repetition frequency of 200 Hz. The intensity of the light beam was of the order of 300,000 lx. The measuring circuit consisted of a V3-3 tube voltmeter and an S1-15 oscilloscope.

The experiment was carried out on four afn films of cadmium telluride. We give some characteristics of these films ($V_{\phi 0}$–stationary

Fig. 3. Dependence of τ_{exp} on load resistance

Figure 2: Fig. 3. Dependence of τ_{exp} on load resistance

value of V_ϕ at 300,000 lx; R_t is the dark resistance of the film):

Film No.	3	5	6	7
$V_{\phi 0}$, V	220	200	350	380
R_t, ohm	$6 \cdot 10^{11}$	$1 \cdot 10^{12}$	$1.4 \cdot 10^{12}$	$1 \cdot 10^{12}$

The results obtained by us from the relaxation curves of the aph-effect in one of the films (film No. 7) at various load resistances are shown in Fig. 2 in the coordinates t, $\lg V$. The values of τ_{exp}, determined graphically from the slope of the straight lines, are shown in Fig. 3.

As can be seen from Fig. 3, the dependence of τ_{exp} on R is linear, as it should be in the case $\tau_{\text{exp}} = \tau^*$ in a regime close to short circuit. Consequently, even at the minimum load $R = 500$ kΩ the decay process is determined not by the intrinsic time of the photogenerator τ_0, but by the circuit time $\tau^* = R(C_{\text{pl}} + C)$. This means that the intrinsic relaxation time of the current photogenerator lies in the region of shorter times

$$\tau_0 < 5\ \mu\text{s}. \tag{13}$$

Fig. 3. Dependence of τ_{exp} on load resistance

From the slope of the straight line in Fig. 3 we determine the total capacitance of the circuit:

$$C_{\text{pl}} + C = 9\ \text{pF}. \tag{14}$$

Its value practically coincides with the magnitude of the parasitic mounting capacitance $C = 7$ pF, measured directly by applying -shaped current pulses from a GIP-2 generator to the input of a VÉ-3 tube voltmeter. Consequently, one can assert that the capacitance of the aph-film, in order of magnitude, does not exceed 1 pF.

Similar results were also obtained for the remaining films.

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Note: Figure translations are in progress. See original paper for figures.