ON THE KINETICS AND RELAXATION TIME OF THE PHOTOCURRENT IN APhN FILMS OF CADMIUM TELLURIDE

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ON THE KINETICS AND RELAXATION TIME OF THE PHOTOCURRENT IN APhN FILMS OF CADMIUM TELLURIDE

1. The spectrum of relaxation times is the principal kinetic characteristic of a system, carrying extensive and important information both about its behavior under various macroscopic excitation conditions and about the microparameters of the elementary processes occurring in it ([1]). From the theory of the nonstationary APhN effect ([2]) it follows that, in the case of a barrier mechanism, the simplest model of an APhN film is characterized by the relaxation times*

$$\tau_0; \quad \tau^* = R_0 R(C_0 + C)/(R_0 + R), \tag{1}$$

the first of which is the characteristic relaxation time of the photocurrent

$$I_f = I_{f0} e^{-t/\tau_0}, \tag{2}$$

while the second is due to RC effects. The duration of the processes of establishment of the voltage $V_f(t)$ and current $I(t)$ in the transient regimes of the APhN effect (τ_{aphn}) is determined by the larger of the relaxation times τ_0 and τ^*. For $R \ll R_0$, which corresponds to real operating conditions of APhN films, $\tau^* = R(C_0 + C)$.

The most interesting physical characteristic of the APhN effect is the relaxation time of the photocurrent τ_0. In ([3]) it was shown that in cadmium telluride films $\tau_0 < 50$ μsec. The development of an experimental technique and the study of the dependence of τ_{aphn} on R showed ([2]) that, up to 5 μsec, the values of τ_{aphn} are proportional to R, i.e., τ^* is observed experimentally. Thus it was demonstrated that the upper limit of possible values of the relaxation time of the photocurrent in a CdTe APhN film does not exceed 5 μsec.

To measure τ_0 and to determine the factors on which τ_0 depends, it was necessary to solve two problems. First, to carry out optical excitation with a large amplitude intensity and with a front steepness of the order of, or less than, 1 μsec. Second, to increase the resolving power of the measuring system by

Fig. 1

Figure 1: Fig. 1

reducing the value of $R(C_0 + C)$, in order to make $\tau^* < \tau_0$. These tasks are correlated, since the higher the light intensity, the greater the photocurrent I_f generated by the light and the smaller R—the input resistance of the measuring circuit—can be.

2. The present article contains the results of an experimental investigation of transient processes in cadmium telluride APhN films down to times of the order of 0.1 μsec. Optical excitation of the films was carried out with the aid of ISSh-300 and ISSh-5 pulsed lamps, which produced powerful single triangular light pulses of durations, respectively, 1.5 and 0.2 μsec, with leading-edge steepnesses of ≈ 0.5 and ≈ 0.05 μsec. The amplitude light intensity was ~ 1 kW/cm^2 ([4],[5]).

The passband of the measuring channel made it possible to investigate relaxation times down to 50 nsec. The photocurrent $I_f(t)$ was measured from the voltage drop across the load resistance R, which shunted the input of a cascade cathode follower ([6]). Use of the cascade circuit ensured a reduction of the input capacitance C to $0.2 \div 0.3$ pF.

3. Investigations of relaxation processes were carried out on APhN films of three types: with a maximum of photosensitivity in the red regi—

* Here R_0 and C_0 are, respectively, the resistance and capacitance of the APhN film, R is the load resistance, and C is the mounting capacitance.

of the spectrum (Fig. 1, curve 1), with a maximum in the ultraviolet (Fig. 1, curve 2), and with inversion of the sign of $I_f(\lambda)$ (Fig. 1, curve 3). In terms of their time characteristics, samples with a maximum of $I_f(\lambda)$ in the red and ultraviolet regions of the spectrum practically do not differ. The experimental values of the relaxation time τ_{eff} for six such samples are shown by light points in Fig. 2 as a function of the value $R(C_0 + C)$. The variation of $R(C_0 + C)$ was carried out by changing R. The attainment by the curve $\tau_{\text{eff}} = \Phi[R(C_0 + C)]$ of a plateau means that in the experiment it was possible to realize conditions under which $\tau_{\text{eff}} = \tau_0$. In this case it turned out that τ_0 depends on the duration of the exciting light pulse t_0: for $t_0 = 1.5$ μs, $\tau_0 \approx 3$ μs (Fig. 2b); for $t_0 = 0.2$ μs, $\tau_0 \approx 0.6$ μs (Fig. 2a).

Fig. 1

Analogous dependences for two films with inversion of the sign of $I_f(\lambda)$ are shown in the same figures by black points. As is seen from a comparison of the data for films without inversion and with inversion, in the latter, both upon excitation by an ISSh-300 lamp and upon excitation by an ISSh-5 lamp, the values of τ_0 are greater than the values of τ_0 for films without inversion (for $t_0 = 1.5$ μs, $\tau_0 \approx 6$ μs (Fig. 2b); for $t_0 = 0.2$ μs, $\tau_0 \approx 1$ μs (Fig. 2a)).

Fig. 2

Figure 2: Fig. 2

Fig. 2

If a film possessing spectral inversion of $I_f(\lambda)$ is illuminated by a pulse of white light, then the photocurrent pulse $I_f(t)$ that arises in this case has an inversion in time. First a negative photoresponse arises, and then $I_f(t)$ changes sign. When the pulse of exciting light is passed through an SZ-22 light filter, which cuts off the red part of the spectrum, the amplitude of the negative part of the photoresponse increases. The use of a KS-11 light filter, which absorbs the short-wavelength portion of the spectrum, leads to an increase in the positive part of $I_f(t)$. In this case it turns out that the inertias of the negative and positive portions of the photocurrent are different. The negative pulse I_f, arising upon excitation by short-wavelength light, practically without inertia repeats the shape of the light signal, whereas that generated by long-wavelength ···

upon excitation, the positive pulse I_f has a noticeable aftereffect. This explains the kinetics of development and the fact of the sign inversion of $I_f(t)$ in time upon excitation by a pulse of white light. First a negative photocurrent pulse arises, caused by the "instantaneous" influence of the short-wavelength part of the spectrum, and then the inertial process of formation of the positive pulse I_f under the action of red light gradually develops and begins to predominate.

4. The solution of the equation

$$\partial p'/\partial t + p'/\tau - D\partial^2 p'/\partial x^2 = G(t) \tag{3}$$

for a single p–n junction shows that the relaxation of the photocurrent, produced by a light pulse $G(t)$, is described by the expressions

$$I_f(t) = \int_0^t G(t')g_f(t-t')\,dt', \qquad g_f(t) = \sqrt{\frac{D}{\pi t}}\,e^{-t/\tau}, \tag{4}$$

where $g_f(t)$ is the transient characteristic of the photodiode, corresponding to its response to a δ-pulse of light. Calculation of the Duhamel integral (4) for a rectangular pulse of light ($G = G_0$ for $0 < t < t_0$; $G = 0$ for $t > t_0$) leads to the following expression, describing the kinetics of decay of the photocurrent after the light pulse has ended:

$$I_f(t) = G_0 L_p \left[\operatorname{erf}\sqrt{\frac{t_0+t}{\tau}} - \operatorname{erf}\sqrt{\frac{t}{\tau}}\right] \approx \frac{G_0 L_p t_0}{\sqrt{\tau t}}\,e^{-t/\tau}. \tag{5}$$

Comparing the obtained solution with formula (2), we find that for $t > t_0$ and $t > t_0^2/\tau$ the exponential (2) approximates the kinetics of photocurrent decay, with

$$\frac{1}{\tau_0} = \frac{1}{\tau} + \frac{1}{2t_0}\,\frac{\ln t/t_0}{t/t_0}. \tag{6}$$

At late stages of decay $\tau_0 = \tau$; at shorter times the approximation of $I_f(t)$ by an exponential becomes worse, and τ_0 depends on the duration of the exciting light pulse, decreasing as t_0 decreases. This conclusion is in qualitative agreement with the experimental results.

5. To explain the range of phenomena associated with the sign inversion of I_f with respect to the excitation spectrum and in time, let us turn to the p–n-junction model of the aphn effect. As shown in works (7), an aphn film of cadmium telluride consists of an active near-surface layer, where an anomalously large photovoltage V_f develops, and of a passive "bulk" of the film shunting this layer. The active layer is formed by p–n- and n–p-junctions; moreover, owing to the dendritic structure of the film surface, junctions of one type are located closer to the surface, and the others farther from it.

According to this model, the p–n- and n–p-junctions are illuminated unequally, and the elementary photovoltaic phenomena arising in them do not compensate one another. When the film is illuminated by strongly absorbed short-wavelength light, only those electron–hole junctions located closer to the surface are active. As the wavelength increases, the depth of penetration of light into the film increases, and "deep" junctions begin to play an increasingly large role; at these junctions a photocurrent and photovoltage are generated whose signs are opposite to I_f and V_f produced by the "shallow" junctions. If, in their microcharacteristics, the deep junctions are more effective in the photoelectric sense, then a sign inversion of I_f or V_f appears in the spectrum of the aphn effect.

Considering in terms of this model the new kinetic phenomena described in Sec. 3 of the present paper, we see that the enhancement, by means of the SZS-22 light filter, of the negative branch of the photocurrent and the enhancement, by means of the KS-11 light filter, of the positive branch of the photocurrent when the film is illuminated by identical pulses of white light are caused by suppression in the spec-

···of the exciting light for those regions that create a photoeffect of the opposite sign. The inversion of I_f in time shows that τ is different for shallow and deep electron–hole transitions in the film; moreover, for deep transitions, to which $I_f > 0$ corresponds, τ is larger than for shallow ones, which generate $I_f < 0$.

Curve 1 in Fig. 3 shows the spectral dependence of the light-absorption coefficient in cadmium telluride ([7,8]). Comparing it with the photocurrent spectrum

Fig. 3

Figure 3: Fig. 3

(curve 2) and estimating the depth of occurrence of the electron-hole transitions from the quantity $1/k$ at the maxima of the negative and positive portions of $I_f(\lambda)$, we find that the shallow transitions are located at a depth $< 0.1\,\mu$ from the surface of the film, whereas the deep ones are at a depth of $0.3\,\mu$.

Fig. 3

An additional check experiment consists of illuminating the film from the other side (through the substrate). According to the model of a cadmium-telluride AFN film developed above, the light in this case passes through the thickness of the film, which plays the role of a light filter and of a photoconducting shunt. The spectrum $I_f(\lambda)$ under back illumination of the films (curve 3 in Fig. 3) shows that an appreciable photocurrent arises only at $\lambda \approx 800\,\mathrm{m}\mu$. Noting that the thickness of the film for which curves 2 and 3 in Fig. 3 are given is $0.8 \div 0.9\,\mu$, and that at the maximum of curve 3 $1/k = 0.5\,\mu$, we see that the maximum of $I_f(\lambda)$ under back illumination is well explained by excitation of the same transitions that give a positive photocurrent under front illumination. The small negative values of I_f in the shorter-wavelength region, where the light does not yet reach the electron-hole transitions, apparently have a photodiffusion nature.

Let us note further, in conclusion, that formulas (4), (5), and (6) were obtained under the simplifying assumption of generation of nonequilibrium carriers only in the n-regions of the AFN film. Taking account of excitation of the p-regions gives, additively, the same expressions for the nonequilibrium electrons, with $I_f(t)$ depending on two recombination times τ_p and τ_n. The difference in τ_0 for inverse and noninverse films, as well as, in part, the dependence of τ_0 on the duration t_0 of the exciting light pulse, may be connected with this.

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