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THERMALLY STIMULATED CURRENT UNDER PERSISTENT INTERNAL POLARIZATION CONDITIONS

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The photoelectret depolarization mechanism is considered in relation to the conventional thermally stimulated current method to show why the resolving power of this method is higher under persistent internal polarization conditions.

THE thermally stimulated current method is used widely to determine the energy positions and concentrations of carrier-trapping levels in semiconductors.[1-3] However, in some cases, the resolving power of the method is insufficient to separate discrete trapping levels which differ little in their energy.

In view of this, we have proposed a new method which has a higher resolution.[4] The physical basis of this method lies in the measurements of the thermally stimulated current due to the electric internal polarization field of a given sample. For this purpose, a sample is cooled first to a low temperature and then subjected to an external field and simultaneous illumination to establish the internal polarization, due to the spatial separation of carriers and their localization at trapping levels. Next, the electrodes of the sample are connected via a load resistance, and the sample is heated. A current appears in the circuit and the maxima of this current represent the liberation of carriers from the corresponding trapping levels.

We note that the persistent internal polarization can be established also by using a corona electrode,[5] by illumination of a sample using insulating electrodes,[6,7] or by nonuniform illumination.[8]

1. CALCULATION OF THE THERMALLY STIMULATED CURRENT CAUSED BY AN INTERNAL POLARIZATION FIELD

In the case of a barrier distribution of charge, we may assume that the photoelectret heterocharge is concentrated in thin layers which lie at certain effective distances l_1 and l_3 from the corresponding electrodes (Fig. 1). In this case, the intensity of the internal polarization field[7] is given by:

$$U(t) = 4\pi A q m(t)/\varepsilon, \qquad (1)$$

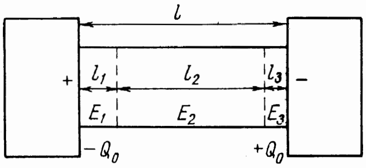

FIG. 1. Schematic representation of a photoelectret with a barrier type of charge distribution.

where m(t) are the densities of carriers at the trapping levels in the space-charge region at a given moment t; ϵ is the permittivity of the substance; A is a coefficient of proportionality which allows for the geometrical dimensions of the photoelectret charge; q is the elementary charge.

The heating of a sample (with a barrier distribution of the charge) results in the appearance of a current in the circuit, which, in the case $dT(t)/dt = v_T \equiv \text{const}$ (v_T is the rate of heating of the sample), can be determined from the following expression:

$$J(t) = \frac{d}{dt}\{q[m(t_0) - m(t)]\} = q\lambda m(t) n(t), \qquad (2)$$

where

$$m(t) = m(t_0)e^{-\lambda N}, \quad \lambda = \frac{4\pi q\mu}{\varepsilon}, \quad N = \int_{t_0}^{t} n(t)\,dt,$$

$$m(t_0) = m(0);$$

μ is the mobility of carriers in the quasi-neutral region; n(t) is the density of carriers in the conduction band in the same region.

If the rate of liberation of carriers from the trapping levels, which is governed by the rate of heating of a sample, is sufficiently slow compared with the rate of spreading of carriers, which is governed by the effective Maxwell relaxation time, no space charge is formed in the quasineutral part of the sample. In this case, the value of the current is governed by the density of carriers in the conduction band in the space-charge region. To determine this density, we shall solve the following system of equations:

$$dn(t)/dt - dm(t)/dt = -n(t)/\tau_M, \tag{3}$$

$$dm(t)\,/\,dt = \gamma M n(t) - \gamma N_c m(t) \exp\left[-E\,/\,kT(t)\right], \tag{4}$$

where γ is the capture coefficient; M is the concentration of trapping centers; N_C is the effective density of states in the conduction band; E is the thermal ionization energy of trapping centers; k is Boltzmann's constant; T(t) is the absolute temperature, which varies with time; τ_M is the effective diffusion-drift relaxation time.

In the quasi-equilibrium approximation,[4,9] when $dm(t)/dt \ll \gamma M n(t)$, we obtain from Eq. (4)

$$m(t) = \frac{M}{\alpha(t)} n(t), \qquad \alpha(t) = N_c \exp\left(-\frac{E}{kT(t)}\right). \tag{5}$$

Solving the system of equations (3), (4) within the framework of this approximation, we obtain the following expression for the determination of the carrier density in the conduction band:

$$\frac{dn(t)}{dt}\left(1 + \frac{M}{\alpha(t)}\right) = -n(t)\left[\frac{1}{\tau_M} + \frac{d}{dt}\left(\frac{M}{\alpha(t)}\right)\right]. \tag{6}$$

Since, under experimental conditions, we usually have $M/\alpha(t) \gg 1$, we obtain from Eq. (6) the following formula for the determination of n(t):

$$n(t) = n(t_0)\frac{\alpha(t)}{\alpha(t_0)} \exp\left\{-\int_{t_0}^{t} \frac{\alpha(t)\,dt}{M\tau_M}\right\}. \tag{7}$$

Thus, after substituting Eqs. (5) and (7) into Eq. (2), we find that the thermally stimulated current under photoelectret conditions has the form

$$J(t) = B\left[n(t_0)\frac{\alpha^{1/2}(t)}{\alpha(t_0)} \exp\left\{-\int_{t_0}^{t} \frac{\alpha(t)\,dt}{M\tau_M}\right\}\right]^2, \tag{8}$$

where B is some coefficient which depends weakly on temperature.

To determine experimentally the thermal activation energy of the trapping levels, it is usual to find the value of the thermally stimulated current J(t) at a maximum, where dJ(t)/dt = 0. Assuming that the heating of a sample is uniform, we replace the variables by $T \equiv T(t) = T(t_0) + v_T t$ and we find from Eq. (8) a relationship for the determination of the temperature of this maximum:

$$\left(\frac{kT}{E}\right)^{-7/2}\left(\frac{1}{2} + \frac{3}{4}\frac{kT}{E}\right)\exp\left(\frac{E}{kT}\right) = \frac{E^{5/2}N_0}{Mkv_T\tau_M}, \qquad N_0 = N_c(kT)^{-3/2}. \tag{9}$$

If measurements are carried out at two values of the rate of heating v_{T1} and v_{T2}, the substitution of these values into Eq. (9) and the separation, term by term, of the expressions so obtained yields a relationship for the determination of the energy position of a trapping level:

$$\left(\frac{T_2}{T_1}\right)^{7/2}\left(\frac{1}{2} + \frac{3}{4}\frac{k}{E}T_1\right)\left(\frac{1}{2} + \frac{3}{4}\frac{k}{E}T_2\right)^{-1} \times \exp\left\{\frac{E}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right\} = \frac{v_{T_2}\tau_{M_2}}{v_{T_1}\tau_{M_1}}, \tag{10}$$

where T_1 and T_2 are the temperatures of the thermally stimulated current maxima, and τ_{M1} and τ_{M2} are the effective Maxwell relaxation times, corresponding to the heating rates v_{T1} and v_{T2}.

Equation (10) is solved by two successive approximations:[2]

$$E = \frac{k}{\log e}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)^{-1}\left\{\log\left(\frac{v_{T_1}\tau_{M_1}}{v_{T_2}\tau_{M_2}}\right) - 3.5\log\frac{T_1}{T_2} + \left[\frac{3}{4}\frac{k}{E_0}(T_1 - T_2)\right] \Big/ \left[\frac{1}{2} + \frac{3}{4}\frac{k}{E_0}T_2\right]\right\}. \tag{11}$$

E_0 is obtained from Eq. (11) by dropping the third term in the numerator.

Since the values of τ_{M1} and τ_{M2} are, in this case, not measured directly in the experiments, when E is calculated using Eq. (11), the ratio of the relaxation times is defined as follows:

$$\tau_{M1}/\tau_{M2} = \sqrt{J_2/J_1}, \tag{12}$$

where J_1 and J_2 are the amplitudes of the current maxima, corresponding to the heating rates v_{T1} and v_{T2}.

2. EXPERIMENTAL RESULTS OF AN INVESTIGATION OF THE THERMALLY STIMULATED CURRENT UNDER PERSISTENT INTERNAL POLARIZATION CONDITIONS IN HgI_2 SINGLE CRYSTALS

The investigation was carried out on HgI_2 samples grown from a solution in acetone.[10] The dimensions of the samples were 5 × 5 × 2 mm and their resistivity was 10^{12}–10^{13} Ω-cm. A persistent internal polarization was established in the samples by the simultaneous application of a light flux and an external electric field for 10 sec. The field was 5×10^2 V/cm and the illumination of the sample was 10^3 lux.

The results of the investigation are shown in Fig. 2. Curve a was recorded using the conventional thermally stimulated current method, and curve b was recorded under photoelectret conditions. In both cases, the current was measured with an electrometer amplifier EK6-7. The rate

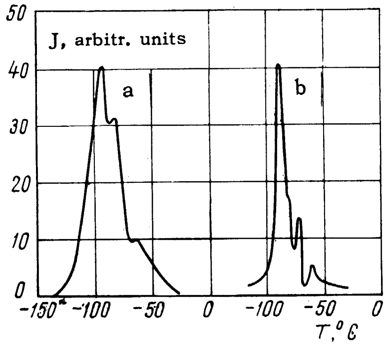

FIG. 2. Temperature dependence of the thermally stimulated current in HgI_2 single crystals: a) recorded by the conventional method; b) recorded under photoelectret conditions.

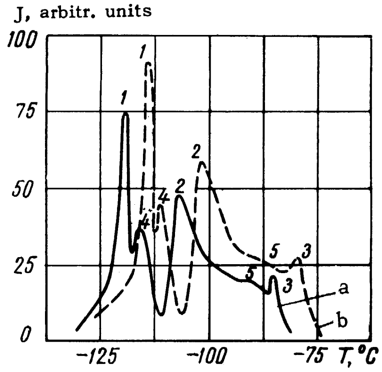

FIG. 3. Temperature dependence of the thermally stimulated current under photoelectret conditions for two different heating rates: a) 0.18 deg/sec; b) 0.45 deg/sec.

of heating was the same in both cases, 1.2 deg/sec.

Comparing curves a and b, we see that the number and positions of the maxima are the same in both cases. This means that all the carrier-trapping levels in a crystal are active under persistent internal polarization conditions. Moreover, examination of Fig. 2 shows that the thermally stimulated current under persistent internal polarization conditions (curve b) has much sharper peaks than the conventional thermally stimulated current (curve a), which is in agreement with Eq. (6).

Figure 3 shows the thermally stimulated current curves recorded under persistent internal polarization conditions at various heating rates. From these curves, we find that the maxima of curve a correspond to temperatures of 154.0, 166.0, and 187.3°K, while those in curve b correspond to 158.7, 170.1, and 192.2°K.

The ratios of the effective Maxwell relaxation times were determined using Eq. (12); they were found to be 1.09, 1.09, and 1.10.

The energy positions of the trapping levels corresponding to these maxima, found using Eq. (11), were, respectively, 0.344, 0.384, and 0.453 eV. These values were in agreement with the data obtained in[11] by the conventional thermally stimulated current method.

Figure 3 shows clearly a fourth maximum, which was not observed in the curves obtained by the conventional thermally stimulated current method because of the insufficient resolution of this method. The position of this maximum was 157.7°K in curve a and 162.1°K in curve b (Fig. 3). The corresponding energy position E was 0.356 eV.

Finally, we must mention that curve a in Fig. 3 also has a fifth maximum. However, because of the high rate of heating, it does not appear sufficiently clearly in curve b. Therefore, its exact energy position was not determined but it was estimated to be of the order of E = 0.440 eV.

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[1] R. H. Bube, Photoconductivity Conference, Atlantic City, 1954.

[2] V. E. Khartsiev, FTT, Supplement (Sbornik) I, 104 (1959).

[3] R. H. Bube, Photoconductivity of Solids, 1960 (Russ. Transl., IIL, 1962).

[4] D. G. Semak, D. V. Chepur, and V. F. Zolotarev, Tonkie poluprovodnikovye plenki (tezisy dokladov soveshcheniya) [Thin Semiconducting Films (abstracts of conference papers)], Naukova dumka, Kiev, 1966.

[5] V. M. Fridkin and I. S. Zheludev, Fotoelėktrety i ėlektrofotograficheskii protsess (Photoelectrets and the Electrophotographic Process), AN SSSR, 1960 [English translation publ. by Consultants Bureau, New York, 1961].

[6] V. M. Fridkin, Fizicheskie osnovy ėlektrofotograficheskogo protsessa (Physical Basis of the Electrophotographic Process), Ėnergiya, 1966.

[7] J. R. Freeman, H. P. Kallman, and M. Silver, Revs. Modern Phys., **33**, 553 (1961).

[8] M. Y. Ben-Sira, B. Pratt, E. Harnik, and A. Many, Phys. Rev., **115**, 554 (1959).

[9] S. M. Ryvkin, Fotoėlektricheskie yavleniya v poluprovodnikakh (Photoelectric Effects in Semiconductors) Fizmatgiz, 1963 [English translation publ. by Consultants Bureau, New York, 1964].

[10] D. V. Chepur, ZhTF, **25**, 2411 (1955).

[11] R. H. Bube, Phys. Rev., **106**, 703 (1957).

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