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Abstract

Full Text

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On the Isoopaque in Electrophotography

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Under the electrophotographic isoopaque of a crystal, by analogy with the isoopaque for photochemical processes in silver-halide crystals, one should understand the dependence of the logarithm of the exposure It (I is the light intensity, t the exposure time), corresponding to one and the same charge Q of the crystal during polarization (or during depolarization), on the logarithm of the light intensity I used in polarizing (or depolarizing) the crystal.

For a single-local-level energy-band scheme of a crystal with n-type conductivity (the case of p-type conductivity is analogous), shown in Fig. 1, expressions were obtained earlier (^{2}) for the dependence of the charge Q on time t and light intensity I during polarization and depolarization of the crystal; on this basis, the forms of the isoopaques and possible deviations from the reciprocity law were investigated ($^{3-5}$). In work (^{5}), in particular, it was shown that the form of the isoopaques in the general case satisfies the integro-differential equation

$$\frac{dz}{dI} = \frac{1}{In}\int_0^z \left[n - I\frac{dn}{dI}\right] dz, \tag{1}$$

where $z = It$ is the exposure, and n is the density of conduction electrons, determined for the quasineutral region of the crystal from the system of kinetic equations corresponding to the band scheme of Fig. 1:

Fig. 1. Single-local-level energy-band scheme of a crystal

$$\begin{aligned}
\frac{dn}{dt} &= K(M-P) + K_1N_1 - \beta_1 n(M_1 - N_1) - \alpha nP,\\
\frac{dN_1}{dt} &= -K_1N_1 + \beta_1 n(M_1 - N_1),\\
\frac{dP}{dt} &= K(M-P) - \alpha nP,\\
P &= N_1 + n.
\end{aligned} \tag{2}$$

Fig. 2. General form of the isopaque of the electrophotographic process ($K = 0$). Points 1, 2, 3, and 4 correspond to light intensities I_1, I_2, I_3, and I_4.

Figure 2: Fig. 2. General form of the isopaque of the electrophotographic process ($K = 0$). Points 1, 2, 3, and 4 correspond to light intensities I_1, I_2, I_3, and I_4.

Here N_1 and P are, respectively, the densities of electrons on trapping levels and of holes on activator levels; M_1 and M are the densities of trapping levels and activator levels; β_1 and α are the probabilities of trapping and recombination. In this case

$$K_1 = K_1^0 + K_1^{\mathrm{T}}; \qquad K = K^0 + K^{\mathrm{T}}; \tag{3}$$

$$K_1^0 = s_1 I; \qquad K^0 = sI; \tag{4}$$

$$K_1^{\mathrm{T}} = 2\beta_1 \left(\frac{2\pi mkT}{h^2} \right)^{3/2} e^{-\varepsilon_1/kT}; \tag{5}$$

$$K^{\mathrm{T}} = 2\alpha \left(\frac{2\pi mkT}{h^2} \right)^{3/2} e^{-\varepsilon/kT}. \tag{6}$$

Here K_1 and K are the probabilities of electron ejection into the band, respectively, from local levels and from activator levels, each representing the sum of the optical K^{o} and thermal K^{t} terms, while ε_1 and ε are the corresponding activation energies.

In Ref. (^{5}), the equation of the isopaque was determined for the non-quasi-stationary case from the condition $K_1^{\mathrm{t}} \gg \beta_1 M_1$, which contradicts the experimentally observed lifetime of photoelectrons and the time of dark decay of the charge of electrophotographic layers. Therefore, the results obtained in (^{5}) for the non-quasi-stationary case have physical meaning only as applied to the case of polarization of crystals with sufficiently low dark resistance. We shall show that even when the condition $K_1^{\mathrm{t}} \ll \beta_1 M_1$ is fulfilled, i.e., when only deep sticking levels are present in the crystal, the excitation of the crystal may be non-quasi-stationary and, from the system (1) and (2), an isopaque equation corresponding to the experimental data may be obtained. For definiteness, we shall consider here the case of depolarization of a crystal.

Fig. 2. General form of the isopaque of the electrophotographic process ($K = 0$). Points 1, 2, 3, and 4 correspond to light intensities I_1, I_2, I_3, and I_4.

1. In the region of sufficiently small values of the light intensity $0 < I < I_1$, the inequality holds

$$K_1^{\mathrm{o}} = s_1 I \ll K_1^{\mathrm{t}}. \tag{7}$$

Here, as indicated above, we always assume the condition

$$K^{\mathrm{t}} \ll K_1^{\mathrm{t}} \ll \beta_1 M_1. \tag{8}$$

In Ref. (^{5}) it was shown that condition (8) corresponds to quasi-stationarity of the excitation of the crystal (i.e., fulfillment of the conditions $n \ll N$, $dn/dt \ll dN/dt$), while condition (7) corresponds to deviations from the reciprocity law caused by thermal activation of electrons into the band. The corresponding isopaque equation has the form

$$\lg z = c + \lg I, \qquad 0 < I < I_1. \tag{9}$$

Indeed, for the case under consideration it follows from (1) that $dz/dI = z/I$. Thus, the isopaque on the interval $0 < I < I_1$ is a straight line parallel to the bisector of the coordinate angle (Fig. 2).

2. With a further increase in the light intensity, one may indicate a region of its values $I_1 < I < I_2$ for which the optical and thermal components of K_1 become comparable in order of magnitude,

$$K_1^{\mathrm{o}} = s_1 I \approx K_1^{\mathrm{t}}. \tag{10}$$

In view of the fact that in this region also the relation $K_1 \simeq 2K_1^{\mathrm{t}} \ll \beta_1 M_1$ holds, the excitation of the crystal, according to (^{5}), remains quasi-stationary. Deviations from reciprocity still occur; moreover, it follows from (1) that $0 < dz/dI < z/I$, i.e., the rise of the isopaque in this interval becomes more gradual (Fig. 2).

3. In a certain region of values $I > I_2$, the optical component may become much greater than the thermal component. Thus, in a certain region

for $I_2 < I < I_3$ the following conditions may be satisfied:

$$K_1^0 = s_1 I \gg K_1^{\mathrm{t}}, \qquad K_1 \simeq K_1^0 \ll \beta_1 M_1, \qquad I_2 < I < I_3. \tag{11}$$

As was shown in (5), inequalities (11) correspond both to the conditions of quasistationarity and to fulfillment of the reciprocity law. Indeed, from system (2), when inequalities (11) are satisfied, it follows that $n = n_0(z)I$. Substituting this expression for n into (1), we find that $dz/dI = 0$, and, consequently, the isopaque in the range of values of I under consideration is a straight line parallel to the abscissa axis, i.e., the reciprocity law is fulfilled in this region (Fig. 2).

4. If the probability of electron capture by the trapping level is sufficiently small, i.e. $\beta_1 \ll \frac{s_1}{M_1} I_3$, then for $I > I_3$ the conditions of quasistationary excitation of the crystal are violated. In this case

$$K_1 \simeq K_1^0 \simeq \beta_1 M_1, \qquad I_3 < I < I_4. \tag{12}$$

As was shown in (5), the conditions of quasistationarity, as well as reciprocity, begin to be violated in this case.

5. With a further increase in the light intensity, in the region $I > I_4$, the inequality

$$K_1 \simeq K_1^0 \gg \beta_1 M_1, \qquad I > I_4. \tag{13}$$

is satisfied. In (5) it was shown that inequality (13) corresponds to sharply nonquasistationary conditions of crystal excitation ($N_1 \ll n \simeq P$; $\partial N_1/\partial t \ll \partial n/\partial t \simeq \partial P/\partial t$). However, in contrast to (5), in the case under consideration the nonquasistationarity is due not to the magnitude of the thermal component of the probability of electron emission into the band (since $K_1^{\mathrm{t}} \ll \beta_1 M_1$), but to the corresponding magnitude of the optical component. The physical meaning of the observed nonquasistationarity is that, at sufficiently high light intensities $I > I_3$ and a sufficiently small capture cross section of the trapping levels, the emission of electrons into the band under the action of light significantly predominates over trapping.

As was shown in (5), in the region $I > I_4$ the equations of the isopaque have the form:

$$\lg z = c + \tfrac{1}{2} \lg I \quad (K \neq 0), \qquad I > I_4; \tag{14}$$

$$\lg z = c + \lg I \quad (K = 0), \qquad I > I_4. \tag{15}$$

Thus, in the region $I > I_4$, excitation of the crystal is nonquasistationary, which causes a deviation from the reciprocity law, the isopaque in this section being rectilinear. If $K = 0$, then the right branch of the isopaque in the section $I > I_4$ is parallel to its left branch in the section $0 < I < I_1$. If, during depolarization of the crystal, activator levels are excited ($K \neq 0$), then the right branch of the isopaque ($I > I_4$) makes with the abscissa axis an angle smaller than 45°, and, consequently, is not parallel to the left branch ($0 < I < I_1$).

As follows from (5), (10), and (12), the parameters β_1, s_1, and M_1 are related by simple relations:

$$\frac{\beta_1}{s_1} M_1 \simeq I^*, \qquad I_3 < I^* < I_4; \tag{16}$$

$$2\,\frac{\beta_1}{s_1}\left(\frac{2\pi mkT}{h^2}\right)^{3/2} e^{-\varepsilon_1/kT} \simeq I^{**}, \qquad I_1 < I^{**} < I_2. \tag{17}$$

If the values of I^* and I^{**} are determined from the isopaque to order of magnitude, then an estimate of the parameters β_1/s_1 and M_1 can be made directly from (16) and (17). It is assumed here that the magnitude of the activation energy

ε_1 is known, for example, from spectral measurements. If one conventionally characterizes the width of the reciprocity region by the ratio $\delta = I^*/I^{**}$, then (16) and (17) determine the relation between the width of the reciprocity region δ, the density of sticking levels M_1, and the activation energy ε_1:

$$\delta \approx \frac{M_1}{2\left(\frac{2\pi mkT}{h^2}\right)^{3/2}} e^{\varepsilon_1/kT}, \tag{18}$$

It follows from (18) that the width of the reciprocity region δ increases when the temperature of the crystal decreases and when the density of sticking levels and their corresponding activation energy increase.

If in a real crystal there is a system of l sticking levels ($l > 1$), characterized by the parameters ε_i, β_i, s_i, M_i ($1 \leq i \leq l$), then, as the light intensity I is increased in the reciprocity region $I_2 < I < I_3$, the conditions of non-quasistationary excitation ($N_i \ll n$; $dN_i/dt \ll dn/dt$) will be satisfied not simultaneously but successively for all N_i; and the point $I = I^*$, and consequently condition (16), will be determined by a single level, for example, with index l, having the maximum value $\beta = \beta_l$,

$$\frac{\beta_l}{s_l} M_l \approx I^*, \qquad I_3 < I^* < I_4. \tag{16'}$$

Since the point on the isopake curve $I = I^*$ is determined only by the level that has the largest value of β, the introduction into the crystal or electrophotographic layer of impurities that create levels with a large capture cross section must shift the point $I = I^*$ into the region of higher light intensities (to the right) and thereby increase the width of the reciprocity region.

As for condition (17), in the case under consideration of l levels it includes the parameters of all levels:

$$\frac{2(2\pi mkT/h^2)^{3/2}\sum\limits_{i=1}^{l}\beta_i e^{-\varepsilon_i/kT}}{\sum\limits_{i=1}^{l} s_i} \approx I^{**}, \qquad I_1 < I^{**} < I_2. \tag{17'}$$

Thus, in the general case, conditions (16′) and (17′) refer to different levels, and the expression for the width of the reciprocity region has the form

$$\delta \approx \frac{1}{2}\left(\frac{2\pi mkT}{h^2}\right)^{-3/2} M_l \frac{\beta_l}{s_l} \frac{\sum\limits_{i=1}^{l} s_i}{\sum\limits_{i=1}^{l}\beta_i e^{-\varepsilon_i/kT}}. \tag{18'}$$

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