THEORY OF THE FORMATION OF A LATENT ELECTROPHOTOGRAPHIC IMAGE AND THE LAW OF RECIPROCITY

1958

SovietRxiv

Abstract

Full Text

PHYSICS

V. M. Fridkin

THEORY OF THE FORMATION OF A LATENT ELECTROPHOTOGRAPHIC IMAGE AND THE LAW OF RECIPROCITY

(Presented by Academician A. V. Shubnikov, 25 III 1958)

The kinetics of the processes of formation of the photoelectret state in single crystals and of the depolarization of photoelectrets under illumination can be investigated on the basis of the concepts of the band theory of crystals ([1]). In turn, the indicated processes underlie electrophotography on photoelectrets ([2,3]), and, with them taken into account, a general theory can be constructed for the formation of a latent electrophotographic image, extending also to such processes as classical xerography and classical electrophotography. The basis of such an investigation is the solution of a system of differential equations describing electronic transitions in the band model corresponding to the scheme of the electron energy levels of a given crystal. Our calculation is based on the scheme of electron energy levels in a single crystal of sulfur proposed by P. S. Tartakovskii and G. Rekalova ([4]).

Let d_1 be the number of electrons passing, under the action of light, per unit volume per unit time from the valence band into the conduction band; kN the number of electrons passing, under the action of light, into the conduction band from filled trapping levels, where $d_1 = s_1 E$ and $k = s_2 E$. Here E is the light intensity (illumination); s_1 and s_2 are coefficients depending on the absorption of light and the quantum yield.

The kinetic equations describing the process of filling the trapping levels with electrons and corresponding to the scheme shown in Fig. 1 have the following form:

$$dn/dt = d_1 + kN - \alpha nP - \beta(M - N)n; \quad (1)$$

$$dN/dt = -kN + \beta(M - N)n + Q; \quad (2)$$

$$dP/dt = d_1 + Q - \alpha nP; \quad (3)$$

Fig. 1. Energy band diagram for a sulfur single crystal

Figure 1: Fig. 1. Energy band diagram for a sulfur single crystal

$$P = N + n, \tag{4}$$

where M is the concentration of trapping levels; N is the concentration of electrons on the trapping levels; n is the concentration of electrons in the conduction band; P is the concentration of holes in the valence band; Q is the number of electrons passing per unit volume per unit time, under the action of thermal motion, from the valence band to the trapping levels; α and β are recombination coefficients, the meaning of which is clear from the scheme shown in Fig. 1.

The problem reduces to determining the dependence of N on time, since the concentration of electrons on the trapping levels should be regarded as proportional to the charge of the photoelectret. In this connection, the orienting action of the polarizing field is not taken into account.

The system of equations (1), (2), (3), under the assumption $d_1 = Q = 0$, was studied in detail by É. I. Adirovich as applied to the problem of investigating ele-

elementary law of decay of the luminescence of ideal crystallophosphors ([5]). In this case the quantity P had the direct physical meaning of the light sum stored in the crystallophosphor, while the intensity of the luminescent afterglow was proportional to dP/dt.

E. I. Adirovich, in particular, proposed a solution of the system of equations (1), (2), (3) under the assumption $d_1 = Q = 0$ in a quasistationary approximation, which was determined by the conditions $n \ll N$ and $dn/dt \ll dN/dt$.

In the same work ([5]) it was shown that, for the quasistationary solution, the ratio of the effective capture cross sections $\gamma = \beta/\alpha$ is the only parameter determining the form of the elementary decay law.

Fig. 1. Energy band diagram for a sulfur single crystal

It can be shown that the quasistationary solution of the system of equations (1), (2), (3) ($n \ll N,\ dn/dt \ll dN/dt$) satisfactorily describes the kinetics of formation of the photoelectret state in a single crystal and can be taken as the basis for a theory of the formation of a latent electrophotographic image. It will be shown below that the necessary and sufficient condition for the validity of the quasistationary solution of the system of equations (1), (2), (3) is fulfillment of the reciprocity law, which, as applied to the electrophotographic process, acquires a direct physical meaning. The question of the analogy between the dark depolarization of a photoelectret, which determines the regression of a latent electrophotographic image, and the luminescent afterglow of crystallophosphors is not considered in the present work.

The reciprocity law for the process of formation of the photoelectret state in single crystals may be formulated as follows. The magnitude of the polarization, or the magnitude of the surface charge density of the photoelectret, proportional to the density of electrons at the trapping levels N, depends only on the product Et of the intensity of the light E, used in the polarization, and the polarization time t. As will be shown below, the reciprocity law, which is confirmed experimentally, can be given a clear physical interpretation.

Suppose that the reciprocity law is fulfilled. According to the definition given above, this means that $N = N(z)$, where $z = Et$. Substituting $N = N(z)$ into equation (2):

$$E\, dN/dz = -s_2 EN'(z) + \beta[M - N(z)]\, n_i^* + Q. \tag{5}$$

In expression (5), Q by definition does not depend on E. It follows from (5) that, if the reciprocity law is fulfilled, then $Q = 0$ and $n = n_0(z)E$. Consequently, for the reciprocity law to be fulfilled it is necessary and sufficient that, on the one hand, the effect of the transition of electrons under the action of thermal energy from the normal band to the trapping levels can be neglected and, on the other hand, that the following relation hold for the density of conduction electrons:

$$n = n_0(z)E. \tag{6}$$

Substituting relation (6) into equation (1):

$$\begin{aligned} E^2 dn_0(z)/dz = s_1 E + s_2 EN(z) - \alpha n_0(z) EN(z) - \alpha n_0^2(z) E^2 \\ -\beta[M - N(z)]\, En_0(z). \end{aligned} \tag{7}$$

From (7) it is seen that the reciprocity law can be fulfilled only in the case when the terms containing E^2 can be neglected; whence it follows that at least two conditions are fulfilled:

$$E^2 dn_0/dz \ll s_2 EN(z) - \beta[M - N(z)]En_0, \qquad \alpha n_0^2 E^2 \ll \alpha n_0 EN(z). \tag{8}$$

But when conditions (8) are satisfied, the conditions of the quasi-stationary approximation are always simultaneously satisfied: $n \ll N$, $dn/dt \ll dN/dt$.

Let us show that the presence of a small quasi-stationary concentration of conduction electrons, i.e., fulfillment of the conditions $n \ll N$, $dn/dt \ll dN/dt$, is a sufficient condition for fulfillment of the reciprocity law. From the inequality $dn/dt \ll dN/dt$ and relation (4) it follows that $dP/dt \simeq dN/dt$. Using the latter relation and equating the right-hand sides of equations (2) and (3), we obtain, assuming $Q = 0$,

$$n = \frac{d_1 + kN}{\alpha[P + \gamma(M - N)]}, \quad \text{where } \gamma = \frac{\beta}{\alpha}. \tag{9}$$

Substituting (9) into (2) and taking into account that, from the conditions of the quasi-stationary approximation, $P \simeq N$, we obtain

$$\frac{1}{E}\frac{dN}{dt} = \frac{dN}{dz} = -\left\{ s_2 N + \gamma(M - N)\frac{s_1 + s_2 N}{N + \gamma(M - N)} \right\}. \tag{10}$$

The solution of equation (10) can be represented in the form $N = N(z)$, which by definition means fulfillment of the reciprocity law.

The results obtained lead to the conclusion that every quasi-stationary solution of the system of equations (1), (2), (3) satisfies the reciprocity law and, conversely, every solution of the system of equations (1), (2), (3) that satisfies the reciprocity law is quasi-stationary.

On the other hand, the process of formation of the photoelectret state in a single crystal, as well as the process of depolarization of a photoelectret under illumination, underlies the formation of a latent electrophotographic image on photoelectrets ([2,3]).

When some positive image is projected onto the surface of a corresponding dielectric and the dielectric is simultaneously polarized, a latent electrophotographic image is created in it, caused by a nonuniform distribution of polarization. Upon development by one of the known methods ([3]) of the latent electrophotographic image, in this case we obtain a negative image corresponding to the positive original. Thus, the process of creating the photoelectret state in a single crystal, or the process of polarization, corresponds to the electrophotographic scheme positive—negative. It is easy to see that the process of depolarization of a photoelectret under its illumination, which also underlies the formation of a latent electrophotographic image, corresponds to the electrophotographic scheme positive—positive.

From this point of view, the reciprocity law should be understood as the dependence of the optical density of the developed electrophotographic image only on the product Et of the illumination intensity E and the exposure time t. The reciprocity law thereby acquires a concrete physical meaning and makes it possible to draw at least an external analogy between the process of formation of a latent electrophotographic image and photochemical processes in silver halides. Analysis of the quasi-stationary solution in general form appears cumbersome. Good agreement with experiment is given by the stationary solution, which is obtained under the assumption $dn/dz = 0$ and which may be regarded as a special case of the quasi-stationary approximation. Differentiating (9) and assuming $dN/dt \neq 0$, we have

$$d_1 = k\gamma M/(1-\gamma). \tag{11}$$

Substituting (11) into (9), we obtain an expression for the stationary concentration of conduction electrons

$$n = n_s = k/(1-\gamma)\alpha. \tag{12}$$

Substituting expression (12) into equation (2), we obtain the equation

$$\frac{dN}{dt} + N\frac{k}{1-\gamma} - \frac{\gamma M k}{1-\gamma} = 0, \tag{13}$$

whose solution gives the dependence of the density of electrons at the trapping levels N, or of the charge of the photoelectret, proportional to N, on the polarization time:

$$N = N_s\left[1 - e^{-\frac{k}{1-\gamma}t}\right], \qquad N_s = \gamma M. \tag{14}$$

The solution (14), which may be called stationary, has been obtained under the assumption

$$0 < \gamma < 1. \tag{15}$$

An arbitrary value of γ corresponds to a quasi-stationary solution, the study of which is an independent problem.

The solution (14), in full agreement with what was said above, satisfies the reciprocity law, since $k = s_2 E$. From the solution obtained (14) it is also evident that, in the formation of a photoelectret, a saturation effect takes place, and the electron concentration at the trapping levels corresponding to saturation is $N_s = \gamma M$.

Comparison of (14) and (15) shows that the saturation effect is due to the filling by electrons of only part of the trapping levels, the percentage of this filling being determined only by the ratio of the corresponding effective electron-capture cross sections.

From the conditions to which the stationary solution obtained above is subject, it follows in particular that $n_s \ll N_s$, or, taking into account (12) and (14),

$$k/\beta M \ll 1, \tag{16}$$

which must hold for all illuminations, since $k = s_2 E$. Relation (16) may be regarded as a necessary condition for the applicability of the stationary solution.

We note that this condition, in the form of inequality (16), coincides exactly with the expression obtained earlier by E. I. Adirovich as a necessary and sufficient condition for the applicability of the quasi-stationary solution of the system of equations (1), (2), (3), under the assumption $d_1 = Q = 0$, as applied to the problem of investigating the luminescent afterglow of ideal crystal phosphors. In view of this circumstance it is of interest to investigate the possibility of simultaneous observation of luminescent afterglow and the photoelectret state in crystal phosphors, taking into account that dark depolarization of the photoelectret may be partially or completely due to radiationless electronic transitions.

It should be noted that, because of the neutrality condition $P = N+n$, the initial equations (1), (2), (3) and the solution obtained do not contain the electric effect proper. A rigorous solution must take into account the field and the distribution of conduction electrons with respect to the coordinate.

The author expresses deep gratitude to Academician A. V. Shubnikov and I. S. Zheludev for guidance of the work, and to Prof. E. I. Adirovich for a number of valuable comments.

Institute of Crystallography
Academy of Sciences of the USSR

Received
20 III 1958

CITED LITERATURE

1. V. M. Fridkin, N. T. Kashukeev, I. S. Zheludev, *DAN*, **117**, No. 5, 804 (1957).
2. V. M. Fridkin, *DAN*, **118**, No. 2, 273 (1958).
3. V. M. Fridkin, *Kristallografiya*, **2**, No. 1, 130 (1957).
4. P. S. Tartakovskii, G. Rekalova, *ZhETF*, **10**, 1025 (1940).
5. E. I. Adirovich, *Some Problems in the Theory of Luminescence of Crystals*, 1957.

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