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Abstract

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ON TWO MECHANISMS OF FORMATION OF A LATENT ELECTROPHOTOGRAPHIC IMAGE

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1. As is known (^{1}), the formation of a latent electrophotographic image occurs upon illumination of a photoconducting crystal (or electrophotographic layer), on whose surface ions of one sign are adsorbed. At present it is believed that there exist at least two mechanisms for the discharge of crystals or layers charged in this way under illumination. The equation describing the change in the surface charge density Q with illumination time t may be written in the form

$$\dot{Q} + \frac{1}{\tau} Q = 0. \tag{1}$$

The first of the mechanisms mentioned is associated with volume discharge due to photoconductivity, and the corresponding relaxation period coincides with the Maxwell time $\tau = \varepsilon/4\pi\sigma$, where σ is the conductivity ($^{1-3}$). In this case the decrease in the external field of the charged crystal occurs owing to the formation on its surface of an electric double layer consisting of the charges of adsorbed ions and charges of opposite sign in the screening layer. Since the development of an electrophotographic layer is determined by its external field, such a process is completely equivalent to a decay of the charge Q on the surface, although the density of the adsorbed ions does not change. In works ($^{1-3}$) it was shown that for this mechanism the kinetics of the process is uniquely determined by the dependence of the concentration of free carriers $n(I,t)$ on the time t and on the light intensity I. The corresponding dependences of the external-field strength (or charge Q) on the time t are monotonically decreasing curves, which in the general case have a point of inflection. The inflection occurs at the point where the function $N(t) = n^2 - dn/dt$ changes its sign. It is easy to see that in the case of a primary photocurrent (fast photoresponse) the point of inflection should practically not be observed, since it corresponds to a very small decay time. As was shown in (^{3}), the mechanism under consideration corresponds to an iso-opac of the electrophotographic process in the form of a monotonically increasing curve, provided only that the lux-ampere characteristic of the crystal is not superlinear.

The second possible mechanism of formation of a latent electrophotographic image, as applied to ZnO layers, was described by I. B. Levinson and I. Z. Plavina

Fig. 1. Depolarization curves for electrophotographic layers of amorphous selenium. Illumination I in lux: 1—140, 2—50, 3—7

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(^{4}) on the basis of a previously proposed model (^{5}). The authors believe that the decay of the surface charge is caused by tunneling leakage of electrons from the levels of adsorbed ions through a barrier at the surface into the bulk of the layer, where they recombine with holes. In this case the barrier width is assumed to be equal to the Debye screening radius, and the height V proportional to the charge Q on the layer surface. Illumination leads to a narrowing of the barrier and, consequently, to an increase in the probability of tunneling leakage. The kinetics of the process is determined by the geometry of the potential barrier. In the case of the rectangular barrier considered in (^{4}), the kinetics of the process is determined by equation (1) with the relaxation period

$$\tau = \tau_0 \exp\left(\frac{2}{\hbar}\sqrt{2mV}d\right),$$

where $d = (\varepsilon kT/e^2 n)^{1/2}$ is the Debye screening radius. As shown in (^{4}), in this case as well the dependences of the charge Q on the exposure time t are monotonically decreasing curves having an inflection point. The position of the inflection point depends on the light intensity I. As shown in (^{6}), this mechanism corresponds in the general case to an isoopacity in the form of a concave curve.

Fig. 1. Depolarization curves for electrophotographic layers of amorphous selenium. Illumination I in lux: 1—140, 2—50, 3—7

2. From the above it follows that analysis of the experimental curves $Q = Q(t, I)$, observation of the inflection points and of the dependence of their position on the illumination I, as well as investigation of the form of the corresponding isoopacities, cannot lead to an unambiguous decision regarding the role of one mechanism or the other separately. In the present work a method is described that makes it possible to separate unambiguously and investigate the two mechanisms indicated above. The essence of the method consists in creating, on the surface of the crystal or electrophotographic layer, an additional barrier opaque to electrons, the parameters of which do not depend on the light intensity.

Fig. 2. Isoopacity of an electrophotographic layer of amorphous selenium

Fig. 3. Depolarization curves for electrophotographic layers of ZnO.

Figure 3: Fig. 3. Depolarization curves for electrophotographic layers of ZnO.

For this purpose we deposited on the surface of electrophotographic layers of ZnO and amorphous selenium thin (several microns thick), optically transparent layers of an insulator having no photoconductivity. Polystyrene was used as the insulator. The magnitude of the resistance of the insulating films was monitored separately. For this purpose the films were deposited on metal, and the half-decay time of the charge of ions adsorbed on the film surface was measured. This time, amounting to hundreds of hours, exceeded by several orders of magnitude the dark-decay time for all the electrophotographic layers studied by us that were not covered with an insulating film. With respect to optical properties, the thin polystyrene films used by us were neutral light filters with a very small absorption coefficient in the visible region. Positive or negative ions from a corona discharge in air were adsorbed on the surface of the layer (more precisely, on the surface of the insulating film covering the electrophotographic layer). After this, by the dynamic-electrometer method (^{1}), the dependences $Q = Q(t, I)$ were recorded at different light intensities I.

Figure 1 presents the dependences $Q = Q(t, I)$ for an electrophotographic layer of amorphous selenium on whose surface positive ions were adsorbed. The dashed curves were obtained for an electrophotographic layer covered with an insulating film; the solid curves, for a layer without a film. From the results presented it is seen that, over the entire investigated range of illuminations I, the curves $Q = Q(t, I)$ obtained for the layer covered with the insulating film coincide, within the accuracy of the measurements, with the corresponding curves obtained for the layer without the film. This coincidence indicates that the only mechanism underlying

basis of the formation of a latent electrophotographic image in layers of amorphous selenium may be the formation of a double electric layer. This is also indicated by the form of the isopake (Fig. 2) obtained from the curves $Q = Q(t, I)$, some of which are presented in Fig. 1. As is seen from Fig. 2, the isopake of the amorphous selenium layer coincides in form with the theoretical isopake corresponding to the mechanism of bulk discharge of the layer (^{7}).

Fig. 3. Depolarization curves for electrophotographic layers of ZnO. Illumination I in lux: 1 and $1'$ -6850; 2 and $2'$ -2500; 3 and $3'$ -1000; 4 and $4'$ -350; 5 -140.

A completely different result was obtained by us for electrophotographic layers of ZnO. Figure 3 gives the dependence $Q = Q(t, I)$ for layers of zinc oxide, on whose surface negative ions from a corona discharge in air were adsorbed. As in Fig. 1, the dashed curves correspond to the electrophotographic layer covered with an insulating film, and the solid curves to the layer without the film. From Fig. 3 it is evident, first of all, that the kinetics of the two processes studied is entirely different and is characterized by half-decay times differing from one another by almost an order of magnitude. The dependences $Q = Q(t, I)$, obtained for a ZnO layer without an insulating film (curves 1—5), in accordance with (^{4}), have an inflection point which, as the light intensity I increases, shifts into the region of smaller values of t and larger values of Q. These dependences correspond to an isopake (not shown in the figure) in the form of a monotonically increasing curve. Apparently this curve represents the right-hand branch of the isopake; moreover, in accordance with (^{6}), in the region of sufficiently small values of I there must be a minimum separating the right-hand branch from the left-hand one. The dependences $Q = Q(t, I)$ obtained for a ZnO layer with an insulating film and corresponding to the mechanism of formation of a double electric layer (curves $1'$—$4'$) are exponentials, the relaxation period of which is directly proportional to the light intensity I; whence it follows, as was assumed in (^{6}), that $n = n_0/I$, and consequently the primary photocurrent in ZnO depends linearly on illumination. In accordance with this, the isopake constructed from curves 1—4 is a straight line parallel to the abscissa axis. The results obtained indicate that the mechanism of formation of a latent electrophotographic image in ZnO cannot be associated with bulk discharge of the layer and the formation on its surface of a double electric layer. These same results indicate that in the case of ZnO the mechanism under study must be associated with a decrease in the real surface charge, i.e., a decrease in the density of adsorbed ions, which testifies in favor of the variant of the mechanism proposed in (^{4}). This, however, does not exclude the possibility of the realization of other variants of this mechanism and, in particular, of ordinary photodesorption.

3. In conclusion, it is necessary to point out one general property of electrophotographic layers covered with an insulating film, due to the electrostatic nature of the latent image. If L_1 is the thickness of the insulating film; L_2 is the thickness of the electrophotographic layer; l is the distance from the measuring electrode to the layer; σ_1 is the charge density of adsorbed ions on the surface of the insulating film; σ_2 is the density of bulk shielding charges in the photoconductor; ε_1 and ε_2 are the di-

the dielectric constants of the insulator and the photoconductor, respectively, then the expressions for the strength of the external field E_e, measured by an electrometer, and of the internal field in the photoconductor E_i have the following form:

$$E_e = \frac{4\pi}{l}\left[\frac{L_1}{\varepsilon_1}\sigma_1 + \frac{L_2}{\varepsilon_2}(\sigma_1 - \sigma_2)\right]; \tag{2}$$

$$E_i = \frac{E_e}{\varepsilon_2} - \frac{4\pi}{\varepsilon_2}(\sigma_1 - \sigma_2), \tag{3}$$

provided only that $L_1/\varepsilon_1 \ll l$ and $L_2/\varepsilon_2 \ll l$.

If the dark conductivity of the photoconductor is neglected, then immediately before illumination of the layer $\sigma_2 = 0$, and, consequently,

$$E_e^0 = \frac{4\pi}{l}\sigma_1\left(\frac{L_1}{\varepsilon_1} + \frac{L_2}{\varepsilon_2}\right), \qquad E_i = \frac{E_e^0}{\varepsilon_2} - \frac{4\pi}{\varepsilon_2}\sigma_1.$$

Illumination leads to an increase in the density of the volume screening charges in the photoconductor, σ_2. Under complete screening, when $E_i = 0$,

$$\sigma_2 = \sigma_1 \bigg/ \left(1 + \frac{L_1}{l\varepsilon_1}\right). \tag{4}$$

This value of σ_2 corresponds to a value of E_e^1 that is not equal to zero:

$$E_e^1 = \frac{4\pi}{l}\frac{L_1}{\varepsilon_1}\sigma_1. \tag{5}$$

Thus, upon illumination of the layer, the magnitude of the screening charge density σ_2 increases from zero to a value close to σ_1, the field strength inside the photoconductor E_i falls to zero, and the experimentally measured value of the external field strength E_e correspondingly decreases from E_e^0 to E_e^1, with

$$\frac{E_e^1}{E_e^0} = \frac{L_1/\varepsilon_1}{L_1/\varepsilon_1 + L_2/\varepsilon_2}. \tag{6}$$

It is seen from (6) that the measured decrease in E_e in the general case does not go to zero, and the ratio E_e^1/E_e^0 depends on the relation between the parameters of the two layers. Recharging the layer in a corona discharge restores the initially measured value E_e^0, which is limited only by the breakdown strength of air at atmospheric pressure. However, the presence in the photoconductor of a volume screening charge leads to the fact that, upon repeated exposure, the measured decrease in the value of E_e is reduced. In general it can be shown that

$$E_e^n/E_e^0 = 1 - k^n, \tag{7}$$

where

$$k = \frac{L_2/\varepsilon_2}{L_1/\varepsilon_1 + L_2/\varepsilon_2},$$

and n is the ordinal number of the repeated exposure.

It follows from (7) that

$$\lim_{n\to\infty} \frac{E_e^n}{E_e^0} = 1,$$

i.e., under repeated exposure the layer as if loses sensitivity. The phenomenon described above was in fact observed by us; moreover, for selenium layers coated with an insulating film, formula (7) was in good agreement with experiment. It is possible that the often observed fatigue effect of electrophotographic selenium layers has the same nature and, consequently, is due to the appearance of a stable volume charge (photoelectric state).

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