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Abstract

Full Text

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PHYSICS

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ON THE MECHANISM OF FORMATION OF A LATENT ELECTROPHOTOGRAPHIC IMAGE IN ZINC OXIDE LAYERS

(Presented by Academician A. V. Shubnikov on 11 XII 1961)

The formation of a latent electrophotographic image has been considered from two points of view. In papers ([1],[2]) the authors relate the formation of an electrophotographic image to a potential barrier arising on the surface of zinc oxide when negative ions are deposited on it. Under illumination the charges of these ions recombine with holes, which are drawn to the surface by the electrostatic field of the surface charges. In papers ([3],[4]) the formation of the latent electrophotographic image is associated with the dissipation of surface charges as a result of recombination processes occurring in the bulk of the semiconductor. In this case the presence of a surface barrier is not taken into account.

Fig. 1. Experimental discharge curves of electrophotographic zinc oxide layers under illumination $E = 600$ lux

In zinc oxide, apparently, the surface barrier plays an essential role. This is indicated by the following facts: the more rapid discharge of positively charged layers as compared with negatively charged ones, the noticeable increase in the resistance of a charged layer as compared with an uncharged one, and also the possibility of attaining higher surface potentials with negative charging than with positive charging.

It is appropriate to point out here that, although in the mechanism considered in ([1],[2]) the presence of a barrier is assumed, it nevertheless has no substantial influence on the discharge process.

In the present work a discharge mechanism is proposed that is substantially connected with the potential barrier at the surface. The charges on the surface are in a potential well and are separated from the bulk by a Debye barrier, whose height V is determined by the surface charge Q, while its width is characterized by the Debye screening length

$$d = \left(\varepsilon kT/e^2 n\right)^{1/2}. \tag{1}$$

Here n is the concentration of free electrons in the bulk and ε is the dielectric permittivity.

The equation for surface discharge is

$$\frac{dQ}{dt} = -wQ, \tag{2}$$

where w is the probability for an electron to leave the potential well and pass through the bulk of the semiconductor. If the barrier is absent and the discharge is determined by bulk effects, then $w = 1/\tau$, where $\tau = \varepsilon/\sigma$ is the Maxwell relaxation time re-

relaxation; $\sigma = e\mu n$ is the volume conductivity; μ is the mobility of the carriers. The dependence of n on time is determined by recombination processes, and therefore the discharge is not, generally speaking, exponential. In the presence of a barrier, one must take into account the "resistance" of the barrier, which can be overcome as a result of a tunneling effect under the barrier or of thermal transport over the barrier. In fact, apparently several mechanisms act simultaneously; however, under certain conditions one of them may prove dominant. At the end of the discharge, when the barrier is already low, the decisive role is played by the bulk resistance and by the kinetics of recombination processes. The beginning of the discharge may, conversely, be determined by the barrier.

In what follows we shall consider zinc oxide, in which surface discharge occurs, as experiments show, over a time of the order of seconds (Fig. 1). During this time only the primary photocurrent is manifested ([1]), while the electron concentration n is established much more rapidly (over a time of the order of 0.01 sec. ([5])). This makes it possible to regard the concentration n as constant during the discharge and not to consider recombination processes. Therefore the end of the discharge must be exponential, with a Maxwell relaxation time which, of course, will decrease with increasing illumination. If the surface is positively charged and the barrier is absent, then the entire discharge curve must obey this same law with the same relaxation time.

Fig. 2. Discharge curves obtained with the aid of a model of tunneling leakage of charges from the surface of an electrophotographic layer

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Figure 2: Fig. 2. Discharge curves obtained by a model tunneling leakage of charges from the surface of an electrophotographic layer

To examine the beginning of the discharge, let us make a number of simplifying assumptions concerning the barrier: it will be considered rectangular, with width d and height proportional to the surface charge:

$$V = aQ. \tag{3}$$

By virtue of (3), instead of (2) we have

$$\frac{dV}{dt} = -wV. \tag{4}$$

Suppose that the overcoming of the barrier takes place as a result of the tunneling effect; then

$$w = w_0 \exp\left\{-\frac{2}{\hbar}\sqrt{2mV}\, d\right\}. \tag{5}$$

It is convenient to transform this expression to the form

$$w = \frac{1}{\tau_0} \exp\{-\sqrt{V/V^*}\}, \tag{6}$$

where the critical potential, after taking (1) into account, assumes the form

$$V^* = \frac{\hbar^2 e^2}{2m} \frac{n}{\varepsilon kT}. \tag{7}$$

Substituting (6) into (4), we integrate by separation of variables,

$$\overline{\mathrm{Ei}}(2\sqrt{v}) - \overline{\mathrm{Ei}}(2\sqrt{v_0}) = -\frac{1}{2}\frac{t}{\tau_0}, \tag{8}$$

where $v = V/V^*$ is the dimensionless potential, and $v_0 = V_0/V^*$ is its initial value—

change at the moment of exposure, and

$$\overline{\mathrm{Ei}}(x) = \ln x + \sum_{n=1}^{\infty} \frac{1}{n}\frac{x^n}{n!}. \tag{9}$$

Fig. 3. Experimentally obtained dependence between the potential at the inflection point V^* and the illumination of the layers

Figure 3: Fig. 3. Experimentally obtained dependence between the potential at the inflection point V^* and the illumination of the layers

the modified exponential integral function [6]. The dependence $V(t)$, following from (8), has a qualitatively different character for initial potentials V_0 greater or less than the critical V^*. For $V_0 > V^*$ the segment on which V decreases from V_0 to V^* is convex upward; at $V = V^*$ the curve has an inflection. A decrease in V_0 leads to a decrease in the duration of the convex segment, which for $V_0 \ll V^*$ disappears altogether (Fig. 2).

Experimental curves (Fig. 1), obtained for a negative charge of electrophotographic layers (zinc oxide dispersed in polyvinyl butyral), have precisely this character. The value of the critical potential, in accordance with (7), does not depend on the initial potential, but depends strongly on the illumination (Fig. 3). The experimental curves for positively charged layers in the region of the main potential drop are of a purely exponential character; the tail portions of the curves for negatively charged layers have the same character (for times at which the secondary photocurrent has not yet appeared), and the relaxation times at identical illuminations coincide. This confirms the considerations stated above concerning the role of volume discharge.

Fig. 3. Experimentally obtained dependence between the potential at the inflection point V^* and the illumination of the layers

Let us note in conclusion that if the onset of discharge is considered to be associated not with the tunneling effect, but with thermal transfer over the barrier, then

$$w = w_0' \exp\left\{-\frac{eV}{kT}\right\}. \tag{10}$$

In this case the discharge equation, by integration, is reduced to the form

$$\overline{\mathrm{Ei}}(v) - \overline{\mathrm{Ei}}(v_0) = -\frac{t}{\tau_0'} \tag{11}$$

with critical potential

$$V^* = \frac{kT}{e}. \tag{12}$$

The curves $V(t)$ in this case do not differ qualitatively from the curves for tunneling discharge; however, in this case the critical potential does not depend on the illumination, which contradicts the experiment.

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