

Electric Field Distribution in Polarized Photoconductors*†

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Persistent internal polarization is shown to result from the accumulation of trapped charge near the surface layers of a photoconductor. At equilibrium it is predominantly of a bulk nature, rather than being localized in individual grains. The charge layers are found to be restricted to narrow regions from 5 to 10 microns from each surface. This distance is almost independent of sample thickness and polarizing voltage. While the external field is still applied, the equilibrium state of polarization is such that between the layers the field approaches zero. This is concluded from the fact that the buildup and release of polarization proceed at the same rate when equal exciting intensities are used.

I. INTRODUCTION

THIS paper deals with the electric field distribution in a photoconductor when polarization by charge displacements occurs. The distribution is determined from changes which occur in the persistent polarization¹ under various polarizing conditions.

Most photoconductive investigations attempt to avoid the creation of large polarization fields, and the majority of calculations are made under the assumption that dE/dx across the photoconductor is practically zero. Here, dE/dx is by no means zero and its distribution is investigated directly. Such a polarization will always occur, for instance, when the conductivity of a surface layer is different (larger or smaller) from that of the bulk of the material. This difference of conductivity may be intrinsic or may be due to contact potentials. Even a difference of 1:2 is sufficient to produce considerable polarization, which will persist when sufficient traps or lattice disturbances are available to store the charge accumulated near one electrode. Thus the essential conditions for the creation of persistent polarization are (1) a surface layer, usually of smaller conductivity than the bulk material, and (2) a sufficient number of traps.

II. POLARIZATION MODELS

If it is assumed that the polarization in the powder sample is due to discrete charge layers situated at distances d_1 and d_3 from the two electrodes (Fig. 1) then the polarization charge $(\sigma_0)_B$ at electrode *B* is

$$(\sigma_0)_B = \frac{\gamma \kappa V_0}{4\pi d_0} \left(\frac{d_2}{d_1 + d_3} \right), \quad (1)$$

which is the previous formula [see Eq. (5), Paper I] except that d_1 is not assumed equal to d_3 and a field factor γ is included which is defined by $E_2 = (1 - \gamma)E_0$.

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¹H. Kallmann and B. Rosenberg, Phys. Rev. 97, 1596 (1955), referred to as Paper I throughout.

E_0 is the external field in the absence of any space charge ($E_0 = V_0/d_0$) and E_2 is the actual internal field between the layers while E_0 is still applied. Previously we had assumed that $\gamma = 1$, which means that the polarization field exactly cancels the external field. It will be shown in Sec. IV that this assumption is a good approximation for equilibrium polarizations. The only significant simplification remaining in our formulation is the replacement of a charge layer of finite thickness by one of infinitesimal thickness placed at the position where the internal field changes its sign for a grounded out sample.

Another polarization model recognizes the fact that the sample is composed of many grains and that the separation of charge may be restricted to individual regions in the interior. If each grain is visualized as a small disk of thickness d_g , and if the above described model is applied to each grain, the expression for total sample polarization is (assuming n grains)

$$(\sigma_0)_B = \frac{\gamma \kappa V_0}{4\pi n d_g} \left(\frac{d_{2g}}{d_{1g} + d_{3g}} \right), \quad (2)$$

where the subscript *g* refers to single grain quantities, and the sample thickness d_0 is now $n d_g$. Thus similar formulas for bulk polarization (1) and grain polarization (2) are obtained, but there is a fundamental difference in their d_0 dependence. In (1), because of the size of the polarization observed, d_2/d_0 is practically independent of sample thickness for $d_2 \gg d_1$ and d_3 , and

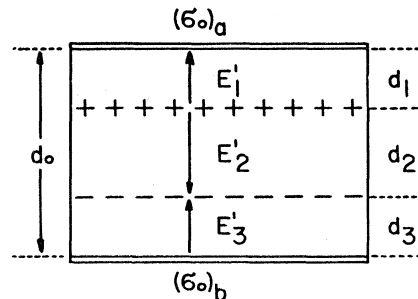


FIG. 1. The double charge layer model of polarization. E'_1 , E'_2 , and E'_3 refer to the internal fields upon removal of the polarizing field and grounding out of sample.

therefore the polarization should depend only upon the thickness of (d_1+d_3) . In (2), d_{2g}/d_0 is likewise insensitive to a change in d_0 , but the factor n means that the polarization should vary much more strongly with increasing thickness of sample when V_0 is kept constant. This is quite evident on physical grounds. The field strength decreases with increasing d_0 and hence so does the polarization. In order to determine whether formula (1) or (2) is the correct description, the thickness dependence of internal persistent polarization has been measured.

III. EXPERIMENTAL PROCEDURE

The persistent polarization was measured in detail with phosphor *K* as a typical photoconductor.² Equilibrium values of polarization were obtained by using the radiation discharge method of Paper I with the improvement that the discharge was performed into a large condenser in order to minimize the buildup of back voltages. The size of the condenser was chosen so that the ultimate released voltage was between 1 and 2 volts. Still smaller voltages decrease the accuracy of the method because of photovoltages created across the sample which are of the order of a tenth of a volt. The main difficulty which remained was to obtain reproducibility in two respects; (1) for one and the same sample the polarization must be the same under equivalent conditions regardless of previous sample treatment, and (2) different samples of the same thickness must yield the same polarization. Although rather good reproducibility is obtained with normal sample preparation methods, a better method has been developed which completely excludes moisture effects, guarantees better powder-to-electrode contact, and increases the magnitude of the polarization effect.³ In any one sample, the reproducibility is now approximately 1% while between comparable samples, the reproducibility is better than 5%.

Table I gives the measured polarization of four *K* samples differing in thickness but in each case polarized with 200 volts to equilibrium. It is seen from this table that although the sample thickness varied by a factor of 4, the polarization did not vary by more than 12%. Of course, one does not know how (d_1+d_3) or $(d_{1g}+d_{3g})$ change with d_0 . But if there is any change, it can only increase with increasing d_0 since the field strengths decrease. Since the decrease of polarization with in-

creasing d_0 is very small, formula (2) grain polarization is ruled out. This result further shows that (d_1+d_3) depends only slightly upon d_0 . From this it is clear that formula (1), bulk polarization, is the valid relation. It must be emphasized that these results have been found to be generally true not only in *K* samples but in a large number of other similar phosphors. The persistent polarization is, to a large extent, independent of sample thickness and is thus bulk polarization in the equilibrium case.

The factor γ is still undetermined. However, for any sample consisting of a high resistance layer near the surface, γ must decrease with increasing thickness d_0 if it is not close to 1. In Table I there is practically no dependence of polarization on thickness and therefore one may conclude that $\gamma \approx 1$.

Further, the results apparently mean that the resistance between grains is less important than that occurring near the powder surface; i.e., charge can be readily moved across these internal boundaries to the surface boundaries. Of course this is only true if the polarization is carried out until equilibrium conditions are reached. For shorter polarizing times, differences exist between samples of different thickness.

As a further check, another type of sample was investigated. Whereas the samples described above were prepared with very little Duco cement as binder, other samples were tested which contained in addition various waxes as binders.⁴ For these samples, a decrease in equilibrium polarization was observed with increasing thickness, but the decrease was weaker than one proportional to d_0 . This means that in these waxed samples, which displayed polarizations greater than 10^{-7} coul/cm², the contact resistance between grains becomes a more important factor. However, a considerable amount of charge must still have been shifted to the surface layers as evidenced by the weak d_0 dependence.

In Paper I experiments were described using a split-sample technique whereby the polarization distribution could be measured in each half after the sample had been polarized as a single unit. It was found that each half carried the proper sign of charge at its interface, implying local or grain polarization. In view of the present findings, these results may also be interpreted in terms of a high resistance separation layer in the split sample perhaps of the same order as the layers near the electrode contacts. Such a separation layer would impede the transfer of charge much more than that between grains, so that each half acted as a separate sample.

IV. EVALUATION OF γ

An entirely different approach can be used to show that γ is indeed of order one. If a sample is polarized under strong illumination, the initial buildup of polarization is determined by the intensity of excitation and the strength of the applied external field. Similarly

⁴ These experiments were performed by Mr. A. Segal of this Laboratory and will be described elsewhere.

TABLE I. Polarization^a as a function of sample thickness.

<i>K</i> powder sample	Thickness (mm)	σ_0 (coul/cm ²)
F-105	0.16	1.37×10^{-8}
F-106	0.31	1.15×10^{-8}
F-102	0.49	1.18×10^{-8}
F-103	0.65	1.20×10^{-8}

^a $V_0 = 200$ volts, visible excitation; radiation discharge after 1-min decay.

² H. Kallmann and G. M. Spruch, Phys. Rev. **103**, 94 (1956).

³ For details, refer to Progress Report No. 5 on "Persistent Internal Polarization," New York University in contract with U. S. Air Force, January, 1956.

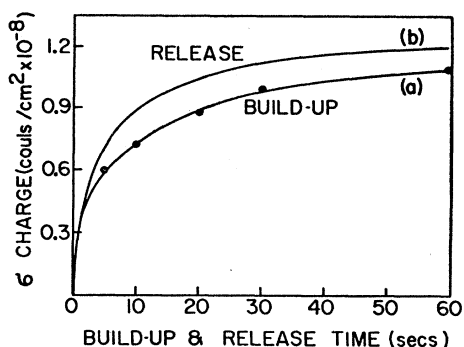


FIG. 2. The buildup and release of polarization in powder *K* as a function of polarizing and release time, respectively. The intensity of visible light in both cases is approximately 10 watts/cm². (Note: The release curve is given in terms of the voltage developed across the standard condenser.)

the release of polarization from equilibrium conditions (excluding that due to spontaneous dark decay) depends upon the excitation intensity and the internal or polarization field strength. By finding that external field which produces the same rate of polarization buildup as the discharge of a given polarization, using equivalent excitation in both cases, one can determine qualitatively the strength of the polarization field.

Figure 2 presents in curve (a) the observed buildup of polarization in a *K* sample when one uses a 200-volt polarizing field. Curve (b) gives the discharge of the equilibrium polarization using the same intensity of excitation. The almost uniform displacement of curve (a) below that of (b) can be accounted for by the spontaneous decay which occurs in the 1 or 2 seconds required to remove the external field and make a measurement. That is, curve (a) is derived point by point, whereas (b) is a standard radiation discharge measurement. When one takes this fact into account, Fig. 2 shows that the internal polarization field is approximately equal to the external field which produces this same polarization. Hence $\gamma \approx 1$. Beyond this result, the curves show that the decay of the polarization field is closely parallel to the decay of the polarizing field. In the buildup a displacement of charge occurs under the influence of the external field until the net field between opposite signs of charge approaches a small value. In the discharge a similar displacement takes place under the influence of the internal field until this vanishes. Similar conclusions have been drawn from ac impedance measurements of such samples under excitation⁵: The polarization field which persists after removal of the external field approaches the initial field in magnitude.

V. DISCUSSION

Using an external voltage of 200 volts and a polarization charge of 1.3×10^{-8} coul/cm², one obtains from Eq. (1) a value of $(d_1 + d_3)$ equal to 12 microns. This distance is not only independent of sample thickness but also of applied voltage since the polarization is

⁵ Kallmann, Kramer, and Mark, Phys. Rev. **109**, 721 (1958).

proportional to the polarizing voltage over a wide range. Thus 1.3×10^{-8} coulomb or 10^{11} charge carriers must be distributed over a distance of about 6×10^{-4} cm if d_1 and d_3 are assumed equal. Since it has previously been shown that the traps in this powder are filled to saturation throughout the whole sample, the polarization layer close to the positive electrode must consist of a layer several microns thick where all traps are filled but a large portion of the positive charges have disappeared because of an increased recombination rate with electrons during the polarizing process. At the other electrode, the picture is reversed and probably all the electrons are removed from traps and only the positive charge remains.

In a waxed sample, the density of polarization is still higher but the thickness of the respective layers is of the same order of magnitude as in unwaxed samples. Thus the number of positive charges is even more depleted and the limiting of polarization probably occurs when all these charges have disappeared from the neighborhood of the positive electrode. Such a description is in qualitative agreement with the number of traps per unit volume in this powder which is of the order of 10^{14} to 10^{15} .

These experiments were performed with powder materials since the reproducibility between samples can be made very exact. With crystals, this reproducibility is not so readily obtained. Nevertheless, it is noteworthy that with single crystals and crystal-like layers of quite different materials, similar polarization values greater than 10^{-8} coul/cm² are obtained.

The polarization distribution in such powders is therefore pictured as consisting of narrow charge layers of relatively high density, positive and negative, situated from 5 to 10 microns from the surfaces of the powder, with the remainder of the sample almost charge-free. In this region between layers there exists at equilibrium a field nearly equal to the original external field before polarization but in the opposite direction.

The conclusion that both layers are approximately of equal charge was derived from lifting electrode measurements. Since the samples used here were sealed, such measurements could not be performed and one could argue whether this conclusion is still valid. It may be remarked that our results about the field distribution and layer thickness are essentially independent of the assumption of equal charge layers. Formula (1) would still be valid with a slightly different meaning of d_3 . For instance, for zero charge at d_3 , formula (1) would be correct with $d_3 = 0$ and $d_0 = d_1 + d_2$. Besides, one can show experimentally, even for the case of sealed samples, that charge layers of both signs exist.

The internal field distributions as described above play an important role in photoconductivity, electroluminescence, and electrophotoluminescence processes. They are capable of explaining the small changes which occur when additional dc bias or ac is applied to the phosphor.⁶

⁶ H. Kallmann and P. Mark, Phys. Rev. **105**, 1445 (1957).