

be proven below, is that this requirement will be satisfied if and only if the first-class constraints form a system of involutions.

The integrability conditions for Eq. (1) on the hypersurface  $C^a=0$  are that a small loop whose tangent vector is everywhere a linear combination of null vectors  $U^{m(r)}$  can be closed,

$$U^{m(r)|n} U^{n(s)} - U^{m(s)|n} U^{n(r)} = c_{rs}{}^t U^m(t). \quad (2)$$

In the previous paper,<sup>1</sup> it was shown that

$$\begin{aligned} U^{m(r)} &= (C_r, x^m), & C_r &= U_{(r)a} C^a, \\ U_{(r)a} &= \epsilon_{ma} U^{m(r)}, & U_{(r)a}(C^a, C^b) &= 0. \end{aligned} \quad (3)$$

Clearly  $C_r$  are the first-class constraints,  $(n_0 - 2n^*)$  in number. If we substitute the expression (3) in (2), we obtain:

$$(C_r, x^m)_{, \nu} \xi^\nu|_n (C_s, x^n) - (C_s, x^m)_{, \nu} \xi^\nu|_n (C_r, x^n) = c_{rs}{}^t (C_t, x^m) \quad (4)$$

as our condition of consistency. Working on the left-hand side, we have further:

$$\begin{aligned} U^{m(r)|n} U^{n(s)} - U^{m(s)|n} U^{n(r)} &= (C_r, x^m)_{, \nu} [(C_s, \xi^\nu) - (C_s, C^a) \xi^\nu|_a] \\ &\quad - (C_s, x^m)_{, \nu} [(C_r, \xi^\nu) - (C_r, C^a) \xi^\nu|_a] \\ &= (C_s, (C_r, x^m)) - (C_r, (C_s, x^m)) = (x^m, (C_r, C_s)). \end{aligned} \quad (5)$$

The terms  $(C_s, C^a) \xi^\nu|_a$  and  $(C_r, C^a) \xi^\nu|_a$  inside the square brackets of Eq. (5) vanish because the  $C_s$  are first-class constraints. Condition (4) will be satisfied if and only if the Poisson bracket between any two first-class constraints is a linear combination of first-class constraints (i.e., free of second-class constraints); in that case, the right-hand side of Eq. (5) will equal a linear combination of null vectors  $U^{m(t)}$ .

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<sup>1</sup> P. G. Bergmann, and I. Goldberg, Phys. Rev. **98**, 531 (1955).

## Localized Photoeffect in PbS Photocells

E. S. RITTNER AND S. FINE

Philips Laboratories, Irvington-on-Hudson, New York

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SEVERAL years ago an ingenious experiment was proposed by Müser<sup>1</sup> to determine the degree of localization of the photoeffect in semiconductor photocells. It consisted simply in illuminating the photocell with a narrow slit image of high intensity, first parallel and then perpendicular to and overlapping the electrodes. If the photoeffect were confined exclusively to the illuminated region, then for a sufficiently high intensity of illumination the decrease in resistance of the cell would be limited for the parallel orientation by the series resistance of the unilluminated portions,

TABLE I. Photocell resistance vs slit orientation and applied field.

Cell No.	$R_d$ , megohms	$R_l$ , megohms illumination $\perp$	$R_l$ , megohms illumination $\parallel$		$E$ , volts/cm
			Observed	Computed <sup>a</sup>	
1	8.29	4.11	6.90	6.90	72.5
	8.31	4.19	6.98	6.93	145
	8.25	4.32	7.03	6.88	290
	8.08	4.36	6.83	6.73	485
2	3.48	1.80	2.36	2.32	145
	3.56	1.83	2.47	2.38	727

<sup>a</sup> The drift of the carriers and the resistance of the illuminated region are neglected. In principle, the actual magnitude of this resistance can be computed from the value of  $R_{l\perp}$ , if the response is uniform over the photocell. This is hardly the case; however, for the purposes of a rough estimate this procedure indicates the resistance of the illuminated strip to be about 1/12 of the corresponding dark value for cell No. 1 and about 1/5 for cell No. 2.

whereas for the antiparallel orientation a much more extensive decrease would occur. On carrying out this experiment on a PbS layer of his own construction (interelectrode distance 1 cm), Müser found substantially the same photoresponse for both orientations of the slit image (width  $\frac{1}{3}$  mm), thus implying that the photocarriers produced by the light drifted surprisingly large distances in the field direction.

We have repeated this experiment on two PbS photocells obtained from U. S. manufacturers and have obtained results differing from those of Müser. It is believed that this difference has its origin in a lower illumination level and/or a lower sensitivity of the cell studied by Müser.<sup>2</sup> It is a consequence of Ohm's law that for small resistance changes, the response for the two orientations of the light image should be the same. The cogent details of our experiment and the results obtained are presented below.

The photocell was illuminated with a slit image 1 mm in width and of length equal to that of the electrodes. In order to vary the applied field over a wide range without introducing heating difficulties, the cell was placed in series with a pulsed voltage supply of low duty cycle. The currents were measured by varying the resistance of a decade box, also in series with the cell, until the voltage drop across the box, determined oscillographically, attained a predetermined value. In this manner, the dark current and photocurrent were measured with the same field applied to the cell.

Of the two photocells studied, cell No. 1 had an electrode separation of 6 mm and an electrode length of 11 mm; cell No. 2 had an electrode separation of 3 mm and an electrode length of 4.5 mm. Hence, if the photoeffect were localized, we would expect a maximum lowering of the resistance for the parallel orientation of the slit image to a value  $\frac{5}{6}$  that of the dark resistance for cell No. 1 and to  $\frac{2}{3}$  of the dark value for cell No. 2. The data obtained are presented in Table I. Note that the resistance for the perpendicular orientation of the slit image is appreciably lower than for the parallel orientation and that the observed resistance for the latter case closely approaches the computed limiting value, independent of the magnitude of the applied field. This

implies a highly localized photoeffect, i.e., a drift length for the photocarriers in the field direction small compared to the image width (0.1 cm).

In the case of cell No. 2, the time constant for the decay of the photoresponse is stated by the manufacturer to be  $2 \times 10^{-4}$  second. If it is assumed that this time constant represents the lifetime  $\tau$  of the free photocarriers, then the expected drift length  $w$  for the higher-field case (taking the mobility  $\mu$  to be of the order of  $1 \text{ cm}^2/\text{volt sec}$ )<sup>3</sup> would be

$$w = \mu E \tau = 0.15 \text{ cm},$$

a distance large compared to the drift length implied by Table I. The most likely explanation of this discrepancy is that the time constant is very much longer than the free lifetime owing to the phenomenon of trapping<sup>4</sup> in these layers. The importance of trapping has heretofore not received recognition in theoretical treatments of this subject (summarized in reference 3) and complicates greatly the task of deriving an adequate theory.

We are indebted to H. Müser and to J. R. Haynes for helpful exchanges of correspondence relative to this experiment.

<sup>1</sup> H. Müser, *Z. physik. Chem.* **198**, 52 (1951).

<sup>2</sup> In private correspondence Dr. Müser has expressed his agreement with this explanation.

<sup>3</sup> R. A. Smith, *Advances in Physics* **2**, 321 (1953).

<sup>4</sup> A. Rose, *RCA Rev.* **12**, 362 (1951); J. R. Haynes and J. A. Hornbeck, *Phys. Rev.* **90**, 152 (1953); H. Y. Fan, *Phys. Rev.* **92**, 1424 (1953); **93**, 1434 (1954).

## New Class of Ferroelectrics

A. N. HOLDEN, B. T. MATTHIAS, W. J. MERZ, AND J. P. REMEIKA

*Bell Telephone Laboratories, Murray Hill, New Jersey*

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WE find that guanidine aluminum sulfate hexahydrate,<sup>1</sup>  $(\text{CN}_3\text{H}_6)\text{Al}(\text{SO}_4)_2 \cdot 6\text{H}_2\text{O}$ , is ferroelectric from as high a temperature as it will stand for a short time (about  $200^\circ\text{C}$ ) down to the temperature of liquid  $\text{N}_2$ , the lowest we have employed. The material is trigonal, with perfect cleavage in the basal plane; the direction of spontaneous polarization is along the trigonal axis. Ferroelectricity is not usually observed when electrodes are applied to naturally grown faces; the effect can be seen when new faces are generated by abrasion or better by cleavage.

At room temperature the saturation polarization is about 0.35 microcoulombs per sq cm, and the coercive force is between 1200 and 1500 volts per cm measured at 60 cps. These quantities increase with decreasing temperature. The small-signal dielectric constant is about 15 along the axis and about 5 perpendicular to the axis. Of isomorphous substances, we have so far

examined those in which  $\text{D}_2\text{O}$  replaces  $\text{H}_2\text{O}$ , in which  $\text{Ga}^{3+}$  and  $\text{Cr}^{3+}$  replace  $\text{Al}^{3+}$ , and in which  $(\text{SeO}_4)^{2-}$  replaces  $(\text{SO}_4)^{2-}$ . These substances show essentially the same properties. Dr. S. Geller and Dr. E. A. Wood have in progress a determination of the crystal structure of the material; they inform us that the space group is  $C_{3v}(2) - P31m$ , and the unit cell contains three molecules. The material bears no obvious structural relation to previously known ferroelectrics.

<sup>1</sup> F. Ferraboschi, *Proc. Cambridge Phil. Soc.* **14**, V, 473 (1908).

## Radiation-Controlled Electroluminescence and Light Amplification in Phosphor Films

D. A. CUSANO

*General Electric Research Laboratory, Schenectady, New York*

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THIS is a preliminary report of a new phenomenon observed when voltage is applied to a layer of  $\text{ZnS:Mn,Cl}$  phosphor during excitation by uv or x-rays. The luminescent layer (about 10 microns thick) is deposited by vapor reaction.<sup>1,2</sup> As contrasted with the granular phosphor commonly used for electrolumines-

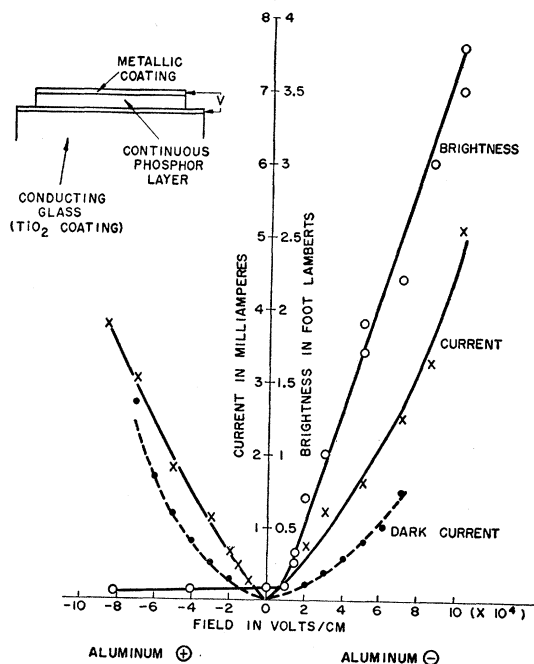


Fig. 1. Dependence of cell brightness and current on the average dc field (for constant 3650 A excitation intensity).

cent sources, this phosphor consists of a solid structureless sheet which makes unbroken contact with the electrodes. (See Fig. 1, upper left.) Such a cell exhibits negligible emission when a dc or ac potential is applied