mentioned earlier, that, with light shining on the sample, no maximum in diode current is observed under the conditions of Fig. 3(a).

CONCLUSION

It appears that the qualitative relationship between surface recombination velocity and surface potential for *n*-type germanium is as predicted by trap theory. Some features of the experiments appear at first to contradict this conclusion; on careful examination they turn out to be consistent, and in addition they lend credence to current theories of surface controlled noise.

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Photoelectromagnetic Effect in Insulating CdS

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The short-circuit photoelectromagnetic current in insulating crystals of cadmium sulfide has been measured in a batch of electroluminescent crystals. The product $(\text{mobility})^3\times(\text{lifetime})$ is found to be 1 $\text{cm}^6/\text{volt}^3\ \text{sec}^2$. The sensitivity of the equipment is sufficient to detect the photoelectromagnetic effect for crystals whose product is as low as 10^{-5} $\text{cm}^6/\text{volt}^3\ \text{sec}^2$.

THE minority carrier properties of insulators are difficult to measure because of the high resistance coupled with the small value of the carrier lifetime and the complications of induced space charge effects due to trapping. Measurements of the transient response due to alpha-particle, optical, or electron beam bombardment of single crystals give the product $\mu\tau$, mobility times lifetime, for either sign of carrier depending on the electrode polarity.[1] It is possible to get μ and τ separately if the response time of the measuring equipment is faster than the lifetime, but as the latter is usually millimicroseconds or less, this condition is seldom reached. Hall measurements on insulators, though they are also difficult because of the high resistance of the crystal and electroding problems, will yield the mobility of the majority carrier,[2] but unfortunately few insulators exist as both *n* and *p* type.

The photoelectromagnetic effect gives the product $\mu^3\tau$. It has been successfully used in the study of minority carriers in semiconductors.[3] For some insulators, where the mobility is reasonably high and the lifetime not excessively short, the effect should also be observable.

We wish to report positive evidence for significant minority carrier drift in insulating crystals of CdS from measurements of the short-circuit photoelectromagnetic (PEM) current. Single crystals of pure CdS approximately $2\times2\times0.05$ mm, grown by vapor phase reaction,[4] were provided with ohmic electrodes of gallium[5] on the two ends of the front surface. These crystals had no impurities intentionally added. Their dark resistivities were greater than 10^{10} ohm cm. Light from a Bausch and Lomb 250-mm replica grating monochrometer was focused on the electroded surface in such a way as to give a roughly uniform illumination over the entire face. To prevent the shadows of the electrodes from maintaining a high-resistance region in the path of the PEM current, the light actually struck the contact between electrode and insulator. The effect of the small photovoltage was nullified by reversing the magnetic field at a low frequency.

The light flux onto the crystal was measured with a 929 photocell calibrated against an Eppely thermopile. The short-circuit PEM current, which was at largest about 10^{-9} amp, was measured with a Liston-Becker chopper amplifier of 50-ohm input impedance, which is low compared to the megohm resistance of the illuminated crystal.

Figure 1 shows the gain of the crystal (the external current per incident photon per sec), against wavelength. It is apparent that the PEM gain (solid curve) has the same wavelength dependence[6] as does the normal photoconductive gain measured by inserting a battery in the external circuit. The rapid drop in gain with wavelength above 5000 A is associated with crossing the edge of the fundamental absorption band.

The majority carrier lifetime τ_m comes from the

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[5] R. W. Smith, Phys. Rev. **97**, 1525 (1955).

[6] The droop in PEM gain at short wavelength is not felt to be significant. The relative accuracy of the measurements is poorer in this region because of the low emissivity of the tungsten lamp light source.

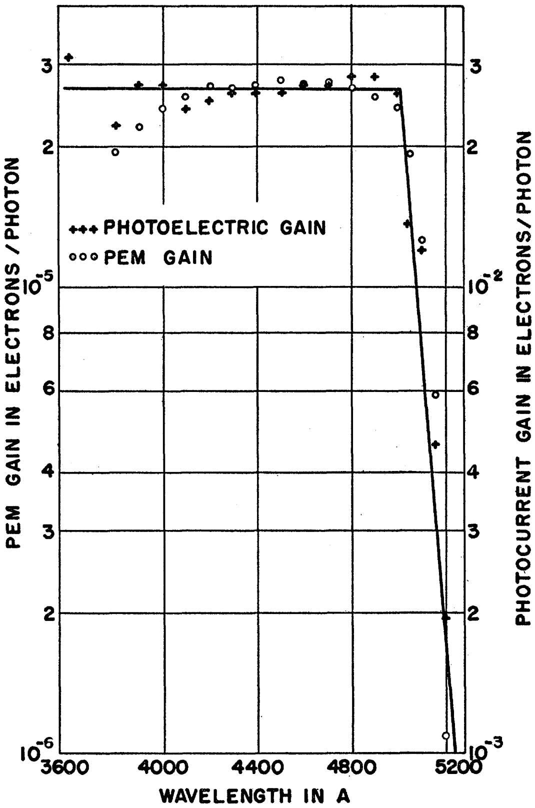

FIG. 1. Spectral response. The photocurrent gain is measured with 10 volts across the electrode spacing of 2 mm.

photocurrent gain through the relation[7]

$$\tau_m = (L^2/\mu V)(\text{gain}).^8 \qquad (1)$$

L is the crystal length, V the applied voltage and μ the majority carrier (electron) mobility. If we take μ as 200 cm^2/volt sec,[9] we find $\tau_m = 1.3\times10^{-6}$ sec, a short lifetime corresponding to the fact that these particular crystals are photoconductively insensitive.

As shown by Moss,[3] the PEM current is given by

$$I_s = (feB/L)([\mu^*]^3\tau_a KT/e)^{\frac{1}{2}}, \qquad (2)$$

where I_s is the short-circuit PEM current produced by absorption of f photons per second, e is the charge of an electron, B the applied magnetic field, L the crystal length, k the Boltzmann constant, and T the absolute temperature. τ_a is the ambipolar diffusion lifetime and μ^* the ambipolar or group mobility defined by van Roosebroek.[10] For this level of illumination, the free electrons are probably far more numerous than the free holes, and μ^* will then be the hole mobility. The equation assumes surface recombination is small compared to that in the volume, which seems to be satisfied in our crystals because the photo sensitivity is independent of the depth of absorption of the photons (Fig. 1).

Our measurements give the result

$$(\mu^*)^3\tau_a = 1 \text{ cm}^6/\text{volt}^3 \text{ sec}^2. \qquad (3)$$

Without an additional relation, no further information about the minority carriers can be rigorously deduced. However, it is instructive to speculate somewhat about the lifetime. If one takes for the minority carrier the same mobility as that of the electron, 200 cm^2/volt sec,[9] the hole lifetime is $\tau_a = 10^{-7}$ sec.

This is a much longer hole lifetime than is generally expected in insulators, but it is consistent with the expectation expressed by Smith[11] that the emission of edge luminescence from the body of these crystals under low dc fields indicated the presence of hole conductivity.[12] In fact, the interpretation of Smith's data on this basis required a hole lifetime of about 10^{-7} sec.

From a study of the noise level of our amplifiers and the random drift in the output voltage, we estimated that with a light beam giving 10^{14} photons/sec and a period of one minute for the reversing magnetic field, we could detect the PEM effect in crystals for which $(\mu^*)^3\tau_a \geqslant 10^{-5}$ cm^6/volt^3 sec^2.

We wish to thank Dr. A. Rose for many fruitful discussions in connection with this work, and Dr. H. B. DeVore and Dr. R. W. Engstrom for assistance in the absolute calibration of the light flux.

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[8] Strictly speaking, this gain is not equivalent to the one defined in the preceding paragraph; however, for strongly absorbed light and unit quantum efficiency the two differ only by the amount of light reflected by the crystal. This difference is neglected in the following arguments.

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[11] R. W. Smith, Phys. Rev. **93**, 347 (1954); **98**, 1169 (1955); and private communications.

[12] Prior to this, both R. Bube and A. D. Cope of this laboratory had evidence of hole conduction in CdS from their studies of photoconductivity (private communication).