line may often be accounted for by a slight misorientation of the specimen, as a 5° misorientation can remove the degeneracy of one of the electron resonance lines in the (110) plane by a splitting of as much as 200 to 300 oersteds for some directions. There are several mechanisms which one might invoke for the production of extra lines, including (a) the possibility of resonance on excited bands or near higher local minima on the usual band; (b) partial breakdown of the selection rule $\Delta n = \pm 1$ on the fluted surfaces, as suggested privately by Dexter, Lax, and Zeiger; (c) nonclassical effects at low temperatures, as hinted at by Kohn and Luttinger[45]; (d) distortion of the form of the energy surfaces in the valence band at small k as a result of the Zeeman splitting of the band edge states; and (e) if the plot of m^* *vs* k_H should be horizontal at several separated k_H values, extra lines should appear.

We have recently observed cyclotron resonance of electrons and holes in InSb, and we have a preliminary indication of cyclotron resonance in InAs. Details of this work will be published separately.

[45] W. Kohn and J. M. Luttinger, Phys. Rev. **96**, 529 (1954).

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Measurement of Shot Noise in CdS Crystals

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The noise power spectrum associated with photoconduction current in CdS crystals with indium electrodes is found to flatten off at low frequencies at a value that corresponds closely to the noise inherent in the photon absorption process itself plus that associated with the random nature of the carrier recombination process. It is found that the noise power is not a unique function of the photoconduction current, but varies as the square of the applied voltage, and linearly with light intensity, as suggested by a simple model not unlike that of the photomultiplier.

MEASUREMENTS of noise associated with the passage of current through semiconducting materials have led to a variety of theories,[1–4] most of which center about boundary layer phenomena. The essential observations that these models seek to derive are (1), the large excess of noise relative to thermal and (2) a $1/f$ spectrum down to extremely low frequencies. Most of the models are complicated and have the flexibility to account for a wide range of spectra and often do, in fact, give a fairly good fit with observation. There are simple models[5,6] involving processes within the body of the semiconductor itself which yield spectra that flatten off at low frequencies and give noise levels much lower than those reported by most observers. These models are rather straightforward and simple, and represent a possible reference for the study of inner processes in semiconductors, for if the strong fluctuations associated with boundary layer phenomena could be eliminated, one would gain a useful tool for the study of current flow in solids. It is the purpose of this note to describe work wherein it was found possible to make noiseless ohmic contact to CdS crystals such that the noise associated with the passage of current through the crystal could be interpreted in terms of processes within the CdS crystal itself.[7]

In the study of the electrical properties of crystals there is always the important general question of separating out the effects of contact electrodes and their interaction with the material under study. Such interactions often cause nonlinear volt-ampere characteristics and nonlinear potential distributions within the body of crystals. The use of gallium[8] or indium as

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[6] J. H. Gisolf, Physica **15**, 825 (1949).
[7] Shulman, Smith, and Rose, Phys. Rev. **92**, 857(A) (1953).
[8] R. W. Smith, Phys. Rev. **92**, 857 (1953).

electrodes for CdS crystal studies changed the picture considerably, for not only was it found possible to obtain linear volt-ampere characteristics down to the smallest measurable voltages, but linear potential distributions within the body of the crystal were also observed. It was further found that noise arising from current flow through such crystals was considerably less than that observed in crystals with gold or silver contacts of various types. In fact, some CdS crystals showed noise that was closely attributable to the random absorption of photons within the body of the crystal.

To develop the simplest of models for fluctuations in photoconduction, we begin with a very simple description of the photoconduction process which involves one mobile carrier, no traps, and need not refer to a model for the material at all. Quantum gain, time constant, frequency response, and noise spectrum are all interrelated in a simple way, independent of crystal model, as follows. From the assumption of unity quantum efficiency in the excitation process, and space charge neutrality in the materials, one can immediately write the quantum gain[9] as

$$G_0=\tau/T, \tag{1}$$

where G_0 is the ratio of the number of electrons passing through the crystal to the number of photons absorbed by the crystal, τ is the carrier lifetime, and T is the transit time through the crystal. The frequency response of such a model is given by

$$1/(1+\omega^2\tau^2)^{\frac{1}{2}}, \tag{2}$$

while the mean square noise current per unit band width is given by[10]

$$\langle i_n{}^2\rangle_{\text{Av}}=4eI_0G_0/(1+\omega^2\tau^2) \tag{3}$$

where I_0 is the crystal photocurrent.

This noise spectrum can be derived, except for a factor of 2, in a simple way by thinking of the random absorption of photons as being a source of shot noise with a uniform spectrum which is modified by the crystal response given by Eq. (2). We would then have

$$\langle i_n{}^2\rangle_{\text{Av}}=2eFeG_0{}^2/(1+\omega^2\tau^2), \tag{4}$$

where F = average rate of absorption of photons. But $FeG_0=I_0$, so (4) reduces to (3), with a factor 2 instead of 4. Since the spectrum associated with fluctuations in gain is in this case identical with that due to random arrival of photons, gain fluctuation can be taken into account by the simple factor of 2.

[9] A. Rose, R.C.A. Rev. **12**, 362 (1951).

[10] This expression for noise current is derived by considering random passage of square pulses of current of height e/T, and duration S with probability distribution $(1/\tau)e^{-S/\tau}$. The usual derivations give Eq. (3) with a factor 2 instead of 4. The addition factor 2 comes from fluctuations in S as pointed out by D. O. North in a private communication. Davydov and Gurevich obtained Eq. (3) with the factor 4 for small lifetimes, and would have obtained the same result for all lifetimes if they had taken into account the correlation between carriers entering at the cathode and those leaving at the anode.

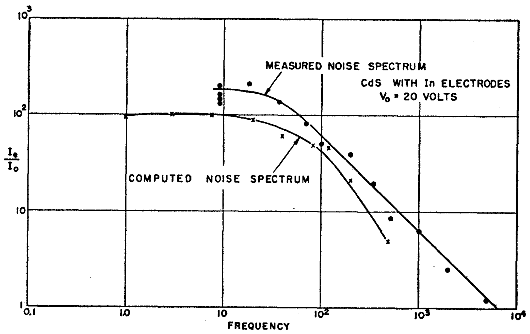

FIG. 1. Comparison of observed noise spectrum with noise spectrum computed from photon shot noise, crystal gain, and frequency response.

It is most convenient to refer this noise spectrum to that of an ordinary temperature limited diode in which

$$\langle i_n{}^2\rangle_{\text{Av}}=2eI_e(f),$$

where I_e is the current in the temperature limited diode to give the same noise as is observed in the crystal. Hence we can write

$$I_e(f)=2G_0I_0/(1+\omega^2\tau^2).$$

For a uniform potential distribution in the crystal

$$G_0=\tau/T=\mu V_0\tau/L^2,$$

where μ = carrier mobility, L = crystal length, and V_0 = voltage across the crystal length. Then

$$I_e(f)=2\frac{\mu\tau}{L^2}V_0I_0\frac{1}{1+\omega^2\tau^2}. \tag{5}$$

The essential features of this spectrum are (1) that it flattens off at low frequencies to a limiting value given by $2G_0I_0$, (2) its shape corresponds to the square of the crystal response characteristic, (3) for a given light intensity, $I_e(f)$ is proportional to $V_0{}^2$ and (4) for a given V_0, $I_e(f)$ is proportional to I_0. The last two follow from the observed linear dependence of I_0 on V_0, and of conductivity on light intensity. Experimental establishment of the relationships between these observables represents a good foundation from which photoconductors can be studied and on which to build models for the cases where departures from these relations are observed.

Measurements on CdS crystals with indium pellet electrodes show some of the features of the simple spectrum described above. Figure 1 shows a comparison between measured noise spectrum and the noise spectrum computed from photon shot noise, measured crystal gain, and measured frequency response of the crystal. Although there is scatter at the low end of the spectrum, it does flatten off at a value approximately twice that predicted by the simplest of theories. If one were to insert effect due to surface reflection the computed curve would move up toward the measured curve by 20 to 30 percent. This value should be compared with Butler's[4] measurements of the noise inte-

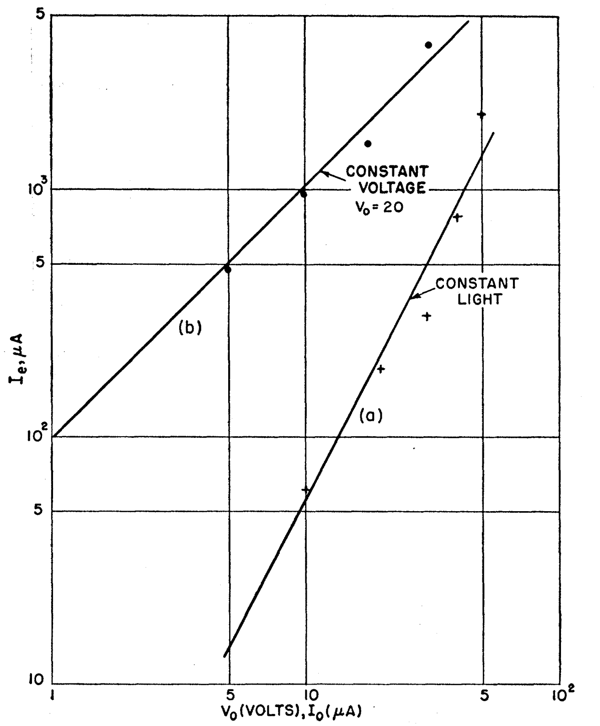

FIG. 2. Dependence of I_e on V_0 and I_0, measured at 40 cps.

grated over the entire spectrum in which he obtains noise powers six to eight powers of ten greater than that corresponding to the integrated noise derived from the simple theory. This suggests that he was dealing with complicated processes probably associated with electrode contacts. The dashed line which is the spectrum computed from measured gain and frequency response, represents the minimum possible noise power for it is due to the randomness of the photon absorption process and fluctuations in gain. The degree to which the measured noise approaches the minimum possible value represents the degree to which all other processes are eliminated. Considering uncertainties in measurements of crystal gain because of uncertainties in surface reflectivities, the closeness with which the leveling off noise power approaches minimum represents a strong argument for the simplest of models for there is not much room for complicated internal processes to add to the noise already inherent in the photon process.

There is however only a weak correspondence between the shapes of the measured noise spectrum and the spectrum derived from the simple model, for the half-power points disagree by a factor two, and the high-frequency end shows $1/f$ law for the noise spectrum and $1/f^2$ for the response characteristic. Although this difference is not understood, it is probably due to trapping processes and close study here may indeed be a fruitful source of information.

Figure 2 shows the dependence of noise power on V_0 and I_0, measured at 40 cps. Square-law dependence on V_0 and linear dependence on I_0 is indicated and

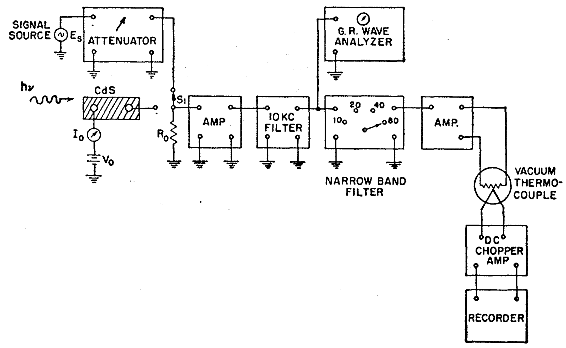

FIG. 3. Schematic arrangement for noise measurements.

corresponds to the simple picture. Curve (a) shows the variation in I_e with V_0 for constant illumination intensity, while curve (b) shows the variation in I_e with I_0, for constant V_0. I_0 is varied by varying the light intensity. Although other experiments give square-law dependence on voltage, the combination of square-law dependence on voltage and linear dependence on current is new,[11] and represents support for the simple model.

The general picture is that although these observations do not rigorously establish this simplest of models, it is believed to have sufficient merit to be useful as a guide in one's thinking on fluctuation processes in photoconductors. It should be pointed out however that not all crystals have shown this behavior. For instance CdS crystals with evaporated indium electrodes which were macroscopically ohmic showed large variations in noise power and in general gave more noise than those with indium pellet electrodes. There were also crystals with indium pellet electrodes which gave high noise.

The measurements were made with the arrangement shown in Fig. 3. The signal source E_s and the attenuator were adjusted to give the same reading on the output meter. The General Radio wave analyzer was used for readings from 100 cps on up. It has a noise band width of about 5 cps over its entire range. At low frequencies the small drift inherent in beat frequency instruments made it necessary to build narrow band filters for making the noise measurement. Twin T feed-back filters were built for 10, 20, 40, and 80 cps with noise bandwidths of 1 cps or less. To integrate out the slow fluctuation, a recorder was used to average each reading over several minutes. The crystal response was taken with a sinusoidally modulated kinescope light source, while the dc gain was measured with a calibrated photocell.

[11] A. Slocum and J. N. Shive [J. Appl. Phys. **25**, 406 (1954)] report measurements in which photocurrent noise in *p-n* junctions can be attributed to random arrival of photons and is proportional to photocurrent. However, their measurements correspond to unity gain and voltage saturated photocurrents, in contradistinction to the measurements described herein which involve high gains and photocurrents proportional to the applied voltage. Under this condition it is possible to observe two noise powers for a given photocurrent, depending on whether the condition is that of low light and high voltage, or high light and low voltage.