collective effects. Again, the inclusion of H_{sr} should not materially influence the conclusions reached in Sec. 4 concerning the effective interaction between the dressed electrons, but a definite proof has not been carried through.

We may next consider the possible existence of other elementary excitations in solids. These correspond to excitations in which a few minority carriers undergo correlated motion. Such correlated motion is only possible if the direct correlations between minority carriers are stronger than the fluctuating correlations with the much more numerous majority carriers. This occurs only when the majority carriers fill a band completely, as in semiconductors or semimetals. The effective interaction between minority carriers is then given by (4.5). One may imagine two kinds of such correlated motion. First, two minority carriers may be found together, forming an exciton. Second, for long enough wavelengths, the minority carriers may undergo a collective motion, such as the conduction-electron plasmon in semiconductors. As we have mentioned, excitons and minority plasmons should be regarded as "complementary" excitations. When the density of minority carriers increases, the cutoff k_c increases. When k_c^{-1} reaches the size of an exciton, the latter is destroyed, and replaced by plasmon degrees of freedom.

If there exist two kinds of minority carriers with very different masses, there is the possibility of yet another collective degree of freedom, which we have called "acoustic plasmon." Such a mode corresponds to an electronic sound wave in which the heavy carriers are screened by the light ones, as the ions are screened by the electrons in the usual sound waves in metals. In fact, the conditions for the existence of such an excitation are probably encountered only infrequently in actual solids.

We should like to point out that our approach is, to our knowledge, the only one which enables one to describe the minority plasmons from first principles. In the scheme of Landau and Gell-Mann, the interaction between excited particles is neglected at the outset. Kohn's treatment is very close to ours, but is limited to the case of a single electron, and, therefore, cannot be used to describe collective effects in the conduction band.

To summarize, we expect plasmons in nearly all solids, with the exception of molecular crystals. "Effective electron" excitations are also present in all solids. Correlated minority excitations, such as excitons or minority plasmons, can only appear in solids with almost empty bands, i.e., in semimetals, semiconductors, or insulators.

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Quantum Efficiency of Photoconductive Lead Sulfide Films*

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By using photoconductivity measurements it is shown that the quantum efficiency of lead sulfide films is almost unity. Mobilities calculated from photoconductivity data agree with mobilities obtained from noise and Hall measurements. It is concluded that noise at room temperature is not photon noise.

RECENTLY two independent methods have been used to calculate the quantum efficiency of photoconductive lead sulfide films. From signal-to-noise ratio measurements Wolfe[1] concluded that 0.25% of the photons are effective. From Hall constant and photoconductivity measurements Petritz[2] concluded that 62% are effective. Since both values are for lead sulfide films manufactured by the Eastman Kodak Company, it is worth while estimating the quantum efficiency for similar films by using a third independent method involving only photoconductivity measurements. The method previously used by Rose[3] is employed.

Figure 1 shows the usual circuit for measuring photoconductivity in lead sulfide films.

When the conductance of the lead sulfide G_c equals the conductance of the load resistor G_r, it can be shown that the photovoltage ΔV developed across G_r, is

$$\Delta V = \tfrac{1}{4} E \Delta G_c / G_c, \tag{1}$$

where E is the bias voltage.

The number of electronic charges which flow through G_r per electron-hole pair liberated photoelectrically is $\Delta V G_r / Fe$, where e is the electronic charge and F is the number of excitations per second. This equals the ratio of the lifetime of the majority carriers τ (assumed

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[1] B. Wolfe, Rev. Sci. Instr. **27**, 60 (1956).

[2] R. L. Petritz, paper presented at the American Physical Society Meeting, Washington, D. C., April 26, 1956 [Bull. Am. Phys. Soc. Ser. II, **1**, 177 (1956)]. See F. L. Lummis and R. L. Petritz, Phys. Rev. **105**, 502 (1957).

[3] A. Rose, RCA Rev. **12**, 362 (1951).

equal to the measured lifetime of photoconduction) to the time taken by a majority carrier to traverse the lead sulfide film $2L^2/\mu E$. L is the distance between electrodes and μ is the mobility of the majority carriers (holes).[4] The expression for the mobility is then

$$\mu=2\Delta V G_r L^2/(eFE\tau). \quad (2)$$

Mobilities may be calculated from Eq. (2) provided F is known, for ΔV, G_r, τ, E, and L can be measured experimentally. The choice of F is the significant point of the argument. A quantum efficiency of almost 100% means that F is almost equal to the rate of absorption of photons. A quantum efficiency of 0.25% means that F is four hundred times smaller than the rate of absorption of photons.

When one uses a value of F equal to the rate of absorption of photons, mobilities calculated from Eq. (2) varied from 1 to 5 cm²/v-sec. Mobilities calculated from noise measurements by using the Petritz theory[2,5] varied from 2 to 6 cm²/v-sec. Petritz[2] has reported a mobility obtained from noise measurement of 5.7 cm²/v-sec and stated that the value agreed with the Hall mobility.

The fact that mobilities calculated from Eq. (2) agree with mobilities obtained by independent methods indicates that the photons are nearly 100% efficient and that the value of F used is the correct one. Using a value of F four hundred times smaller than the rate of absorption of photons would yield mobilities four hundred times larger than the values of 1 to 5 cm²/v-sec. Such large mobilities are unreasonably high for lead sulfide films.

Wolfe's conclusion is based on the assumption that noise in the lead sulfide originated from "fluctuations in the rate of arrival and emission of thermal quanta at the cell." [6] However, at room temperature the absorption of thermal quanta accounts for one percent or less of the conductance. Since noise is due to fluctuations in the conductance it seems unlikely that the fluctuations in one percent of the conductance would dominate the fluctuations in the other ninety-nine percent.

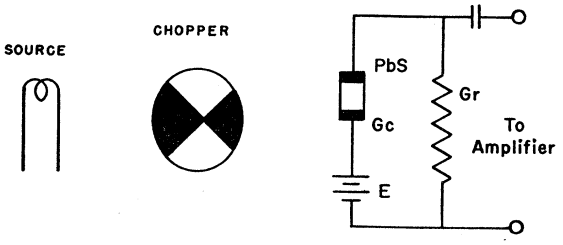

FIG. 1. Measuring circuit.

Wolfe made his assumption about the origin of noise because he found that the noise frequency spectrum paralleled the signal frequency spectrum. However, this does not necessarily mean that the noise is photon noise. It does indicate that the mechanisms of carrier generation, trapping, recombination, etc., are similar in the dark and under illumination. Lead sulfide is highly conducting in the dark, and the relative change in conductance caused by chopped radiation is small. The carriers generated by light are effectively lost in a sea of dark carriers. It appears possible that the mechanisms in the dark and under illumination are similar.

It is concluded that noise in a lead sulfide film whose noise frequency spectrum parallels the signal frequency spectrum is not primarily photon noise.[7]

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[4] In terms of R. L. Petritz, Phys. Rev. **104**, 1516 (1956), μ is the macroscopic mobility and E/L is the macroscopic electric field. The argument used here would apply equally well to the microscopic properties because Petritz shows that $\mu E/L$ equals $\mu_c E_c/l_c$, where μ_c is the mobility in a crystallite, E_c is the voltage drop across a crystallite, and l_c is the length of a crystallite. It is necessary to assume that the sum of the widths of the intercrystalline barriers is negligible compared to the length of the film.

[5] R. L. Petritz, in *Photoconductivity Conference*, edited by Breckenridge, Russell, and Hahn (John Wiley and Sons, Inc., New York, 1956), p. 49.

[6] B. Wolfe, Eastman Kodak Company, Navy Ordnance Division, Report No. 55-96-013, May 9, 1955 (unpublished).

[7] Petritz, using somewhat different reasoning, came to the same conclusion.[2]