RB-122

CONSIDERATIONS OF SIGNAL TO NOISE RATIOS IN INFRARED PHOTOCONDUCTORS

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Considerations of Signal to Noise Ratios in Infrared Photoconductors

For photoconductors in which thermal generation-recombination noise predominates, the signal-to-noise ratio may in general be related to the threshold of response. For the case of impurity photoconductors, expressions are derived relating this ratio to the position of the impurity level and it is shown that at a given temperature of operation, the signal-to-noise ratio will decrease exponentially as the threshold of response is extended into the infrared. The dependence of signal-to-noise ratio on temperature, number of impurity centers, and degree of compensation is also given. The treatment is extended to intrinsic photoconductors and a qualitative comparison made between the ultimate signal-to-noise ratios which may be expected in intrinsic and impurity semiconductors.

Introduction

At present a concerted effort is being made to extend the response threshold of photoconductors farther and farther into the infrared. In view of this effort, it is interesting to estimate the way in which the limiting signal-to-noise ratio (and thus the ultimate sensitivity) of such photoconductors changes as the infrared threshold increases, and to compare the ratios obtained for several types of photoconductors.

The noise from a photoconductor can be subdivided into three classes: shot noise, Johnson noise, and 1/f noise. The Johnson noise is small enough to be neglected here. The 1/f noise appears to be associated with the contacts and the photoconductor surfaces and can be reduced by improving the quality of these contacts and the state of the surfaces. It also can be minimized by increasing the frequency at which the device is operated (i.e., the frequency at which the incident light is chopped). Thus, in principle, a range of operation may be found in which the shot noise predominates. This condition has been reached in a number of cases.[1,2,3] However, the shot noise, which is due to random generation and recombination of carriers, is basic to the device and, thus, in general will set the fundamental noise level.

The average value of the fluctuation in the number of free carriers in a semiconductor may be written as:[4]

$$(\langle (N - N_o)^2 \rangle)^{1/2} = \Delta N = 2(N\tau)^{1/2} \, \Delta f^{1/2} \qquad (1)$$

where τ is the carrier lifetime, N_o the average number of free carriers in the crystal, N the instantaneous number of carriers, and Δf the bandwidth of the amplifier used for the measurement.

The output from the photoconductor is measured as a voltage developed across a load resistor. The voltage produced in such a case due to any change in the number of carriers is given by:

$$V = \frac{E \, R_L R_C}{(R_C + R_L)^2} \, \frac{\Delta N \, \Delta f^{1/2}}{N(1 + \omega^2\tau^2)^{1/2}} \qquad (2)$$

Here E is the applied voltage, R_L the load resistance, R_C the sample resistance, ΔN the change in the number of carriers in the photoconductor, and ω the signal frequency.

Putting Eq. (1) into Eq. (2), we obtain for the noise voltage:

$$V_n = \frac{2E \, R_L R_C \, \tau^{1/2} \qquad \Delta f^{1/2}}{(R_C + R_L)^2 \, N^{1/2} \; (1 + \omega^2 f^2)^{1/2}} \qquad (3)$$

If the sample is exposed to a radiation signal, the change in number of carriers brought about is given by:

$$\Delta N_R = F\tau \qquad (4)$$

[1] J. Gittleman and M. L. Schultz, RCA Laboratories, private communication.

[2] F. L. Lummis and P. L. Petritz, *Phys. Rev.* **86**, 660(A) (1952).

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

[4] This would not hold for the case of an almost completely ionized impurity. However, in such a case, the dark conductivity would probably be too high for practical use.

where F is the rate of creation of carriers by the irradiation. Thus, the signal voltage would be:

$$V_s = \frac{E R_L R_C}{(R_C + R_L)^2} \frac{F\tau}{N} \frac{1}{(1 + \omega^2\tau^2)^{1/2}} \tag{5}$$

The bandwidth of the amplifier does not appear in Eq. (5) since the frequency spread of the signal is assumed to be less than the bandwidth of the amplifier. The signal-to-noise ratio is then given by:

$$\frac{V_s}{V_n} = \frac{F\tau^{1/2}}{2N^{1/2}\Delta f^{1/2}}$$

Since $n = N_C e^{-E_f/kt}$ and $N = nv$,

$$\frac{V_s}{V_n} = \frac{F\tau^{1/2}}{2v^{1/2} N_C^{1/2} \Delta f^{1/2}} e^{E_f/2kT} \tag{6}$$

Here v is the crystal volume, n the density of free carriers ($N = nv$), E_f the energy difference between the Fermi level and the nearest allowed band, and N_C the effective density of states in that allowed band. V_s/V_n is also independent of such parameters as mobility of the free carriers, applied voltage, and load resistance. However, it should be noted that in order to observe this condition it is necessary that the noise level of the samples be higher than that of the amplifying system following it; this places practical limits on the values of R_C and N for which the limiting noise is the sample noise.

Before treating specific cases, several general conclusions which may be drawn from Eq. (6) are worthy of discussion. As indicated by that equation, the signal-to-noise ratio at a given temperature and state of illumination will decrease exponentially as E_f decreases (provided the lifetimes and rates of excitation remain constant). Since the value of E_f can be expected to be roughly proportional to the photoconductive threshold energy, the signal-to-noise ratio at a given temperature can be expected to decrease exponentially as the threshold of response is extended. Thus, if materials with longer wavelength thresholds are to be useful, the signal gain obtained by extending the threshold must be greater than the reduction in signal-to-noise ratio accompanying this extension. Eq. (6) also indicates that the signal-to-noise ratio for any given material will increase exponentially with decreasing temperature; thus the ultimate sensitivity of a cell is dependent on the temperature of operation.

Impurity Photoconductors

One area of specific interest is the signal-to-noise ratio for impurity photoconductors in varying states of compensation. Here, for generality, no assumption is made as to whether the center is a donor or acceptor. The band in which the conduction takes place is termed the "allowed" band. The effect of traps is also neglected because the device would normally be operated in temperature ranges where only a small change in the total number of free carriers is brought about by the photo-excitation.

In evaluating Eq. (6), expressions are necessary for n, τ, and F. In deriving an expression for n in the case of an impurity semiconductor, it is usually sufficient to consider only the impurity level giving rise to photoconduction and the allowed band nearest this impurity level. If this is done, Eq. (7) is obtained:

$$n = 2N_C e^{-E_i/kT}\left(\frac{N_D - N_A}{N_A}\right)\left(1 + \sqrt{1 + \frac{4(N_D - N_A)}{N_A^2} N_C e^{-E_i/kT}}\right)^{-1} \tag{7}$$

where N_C is the effective density of states in the allowed band, N_D the density of impurity states, N_A the density of compensating states, and E_i the energy difference between the allowed band and the impurity level. Eq. (7) can be divided into two general regions according to whether the factor under the radical:

$$\frac{4(N_D - N_A)}{N_A^2} N_C e^{-E_i/kT} \tag{8}$$

is greater or smaller than unity. If Eq. (8) is less than unity, we have what is usually referred to as a "compensated semiconductor" and

$$n = N_C e^{-E_i/kT}\left(\frac{N_D - N_A}{N_A}\right) \tag{9}$$

On the other hand, if Eq. (8) is greater than unity, we get:

$$n = (N_C N_D)^{1/2} e^{-E_i/2kT} \tag{10}$$

Since the transition from the condition of Eq. (9) to that of Eq. (10) is quite swift, we will be sufficiently general if we treat only these two cases.

The lifetime τ will be given by:

$$\tau = \frac{1}{B(N_A + n)} \tag{11}$$

where $B = s\sigma$, s being the thermal velocity of a carrier in the allowed band and σ the recombination cross-section. In the compensated case (Eq. (9)), $N_A >> n$; therefore

$$\tau = \frac{1}{BN_A} \tag{12}$$

Whereas, in the uncompensated case, $n >> N_A$; therefore

$$\tau = \frac{1}{Bn} \tag{13}$$

The rate of excitation of carriers by the incident light may be written as:

$$F = L\,a(N_D - N_A - n)\,V \tag{14}$$

where L is the amount of incident flux per unit area on the sample, a the absorption cross-section for each impurity and V the volume of the sample. Here the assumption is made that the absorption is linear through the sample; this is usually well fulfilled since the concentration of centers is generally less than 10^{17} per cc. Since $N_D >> n$, for the compensated case, this reduces to:

$$F = L\,a(N_D - N_A)\,V\,; \tag{15}$$

and, for the uncompensated case, to:

$$F = L\,a\,N_D\,V \tag{16}$$

Putting these expressions into Eq. (6), the following expressions for the signal-to-noise ratios are obtained; for the uncompensated case,

$$\left(\frac{V_s}{V_n}\right) = \frac{L\,a\,N_D\,V^{1/2}}{2B^{1/2} n^{1/2} n^{1/2} \Delta f^{1/2}} = \left(\frac{L\,a\,V^{1/2}}{2B^{1/2}\Delta f^{1/2}}\right)\left(\frac{N_D}{N_C}\right)^{1/2} e^{E_i/2kT} \tag{17}$$

for the compensated case,

$$\left(\frac{V_s}{V_n}\right)' = \left(\frac{L\,a\,V^{1/2}}{2B^{1/2}}\right) \frac{(N_D - N_A)\,e^{E_i/2kT}}{N_A^{1/2} N_C^{1/2} \dfrac{(N_D - N_A)^{1/2}}{N_A^{1/2}} \Delta f^{1/2}}$$

$$= \left(\frac{L\,a\,V^{1/2}}{2B^{1/2}\Delta f^{1/2}}\right)\left(\frac{N_D - N_A}{N_C}\right)^{1/2} e^{E_i/2kT} \tag{18}$$

Note that in both cases the signal-to-noise ratio increases as the volume to the one-half power. However, the striking fact about these expressions is that they differ only by the factor $(1 - N_A/N_D)^{1/2}$; thus, as long as the sample is less than 10 percent compensated, the amount of compensation will affect the performance relatively little[5]; however, gains in signal-to-noise ratios might be realized by increasing N_D.

The values of a and B may not vary greatly from impurity to impurity as long as the compensated impurity is singly charged; whereas, at a given temperature, the signal-to-noise ratio decreases exponentially as the threshold ($h\nu = E_i$) is increased.

Intrinsic Photoconductors

In the case of intrinsic photoconductors, the lifetime is much harder to estimate. However, by considering the factors in Eq. (6) other than the lifetime, some comparisons may be made with the results obtained for impurity photoconductors. Because of the high intrinsic absorption coefficients (about 10^4 per cm), all of the incident light will be absorbed; whereas only a small percentage is usually absorbed in impurity materials. In addition, the thickness (and thus volume) of the sample may be reduced without reducing the absorption of the sample. Since the noise goes down as the square root of volume, it might be possible to gain in signal-to-noise ratio by reducing the size of the sample. The gain over an impurity photoconductor would be given by the square root of the ratio of the absorption coefficients for the two cases. Thus, gains of between 30 and 1000 might be realized if the carrier lifetime were unaffected. However, with such a small thickness, the lifetimes might be reduced greatly by sur-

[5] A measure of the amount of compensation may be obtained by observing the break in a curve of *log conductivity* (or, to be preferred, *log n*) *vs temperature* which occurs when $[4(N_D - N_A)/N_A^2] N_C e^{-E_i/kT}$ (8) in Eq. (7) becomes greater than one. In general, such a break should be observable if the compensation is 10 percent or less.

face recombination and thus the signal-to-noise ratio would be below the ideal value. Large surface-to-volume ratios would also tend to increase the $1/f$ noise due to surface recombination of dark carriers. It should also be noted that for relatively thick intrinsic photoconductors, the photoconductive lifetime will tend to be reduced by surface recombination whereas the bulk lifetime will not be reduced. This will lead to a decrease in signal-to-noise ratio as compared to impurity photoconductors. Therefore, until surface recombination rates are reduced below those of the bulk, the signal-to-noise ratios of intrinsic photoconductors will be less than ideal whatever the thickness of the material.

In an intrinsic photoconductor, the most favorable position for the Fermi level would probably be in the center of the band-gap. If such were the case, the intrinsic response would be reduced below that of the impurity photoconductor by the factor $(N_D/N_C)^{1/4}$, where N_D is the density of impurity states in the impurity photoconductor and N_C the "effective" density of states in the allowed bands of the intrinsic photoconductors. This factor will probably be of the order of ten. However, if the Fermi level in the intrinsic photoconductor is not in the center of the forbidden band, the case for the intrinsic material will be even less favorable than that given above. The lifetimes in impurity photoconductors are determined by the impurity centers giving rise to the photoconduction. However, in intrinsic materials where excitation from the valence band gives rise to the photoconductivity and the lifetimes are usually determined by impurity centers not connected with the excitation process, it should be possible to vary the lifetimes in intrinsic photoconductors to a much larger degree than is possible for impurity photoconductors.

This comparison of intrinsic and impurity materials has been qualitative in nature. However, it is possible to make some estimates from such considerations. If the surface recombination problem can be solved, the signal-to-noise ratio of intrinsic materials may be an order of magnitude larger than that for impurity materials with identical carrier lifetime and response threshold. In principle, it should also be possible to increase the lifetime in the intrinsic material and thus increase its advantage by a larger amount. However, it should be emphasized that the practical difficulties inherent in improvement of the performance of intrinsic materials are considerable.

Conclusions

It has been shown that the signal-to-noise ratio of photoconductors held at a given temperature[6] will tend to decrease exponentially as the threshold of response is increased into the infrared. For the case of impurity photoconductors, it has been shown that the signal-to-noise ratio varies with compensation only as $(1 - N_A/N_D)^{1/2}$, and that the signal-to-noise ratio can probably only be increased by increasing the density of the impurity centers. This increase will go as the square root of the number of impurities with a few times 10^{18} per cubic centimeter probably being the upper limit which can be expected in the impurity concentration.

In contrast to the relatively small amount of variability to be expected in the case of impurity photoconductors, intrinsic photoconductors can be modified more radically. Here a number of parameters such as bulk lifetime, surface recombination velocities, and position of the Fermi level might be varied. If the surface recombination of intrinsic photoconductors could be reduced sufficiently, such materials might have signal-to-noise ratios an order of magnitude higher than the maximum to be hoped for from impurity materials with identical bulk lifetimes. This would occur despite the fact that the signal-to-noise ratios of intrinsic photoconductors are reduced by the factor $(N_D/N_C)^{1/4}$ with respect to the impurity materials. In addition, it should also be possible to lengthen the lifetimes for intrinsic photoconductors appreciably. Thus, it should, in principle, be possible to push the signal-to-noise ratio of intrinsic semiconductors considerably above that of impurity materials; however, the practical difficulties involved in this are such that a very considerable effort would be required to develop intrinsic materials substantially superior to impurity semiconductors.

[6] However, the signal-to-noise ratio for a given photoconductor should increase exponentially with decreasing temperature.

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