Fluctuations in CdS Due to Shallow Traps*

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The observed current noise of a lightly doped cadmium sulfide single crystal under uniform illumination is quantitatively explained by application of the generation-recombination theorem to retrapping effects. The results yield a frequency factor of 10^9 sec^{-1} for a discrete set of traps located 0.4 ev below the conduction band and 10^8 sec^{-1} for traps distributed between 0.3 to 0.5 ev. When the quasi-Fermi level is near the discrete states, the current noise spectra show a relaxation component characteristic of generation and recombination involving these levels.

ELECTRICAL noise in single crystal cadmium sulfide has been interpreted in terms of electronic transitions between the conduction band and recombination centers plus retrapping processes.[1] In particular, the high-frequency tail of the noise power density spectrum arises from transitions between shallow traps and the conduction band. We have found that by extending this analysis quantitative details about the kinetics of shallow trapping in CdS may be determined.

The current noise spectra of a lightly CuCl doped CdS single crystal having indium electrodes was examined under uniform 5200 A illumination using a conventional tunable amplifier-voltmeter system. The observed spectra at four different illumination levels shown in Fig. 1 are qualitatively similar to those of Van Vliet. The lower turnover frequency is below 10 cps and there is evidence of a single trapping transition for intermediate illumination levels at about 1300 cps. In Fig. 1 the curves are labeled with the position of the quasi-Fermi level below the conduction band as determined from the dc conductivity.

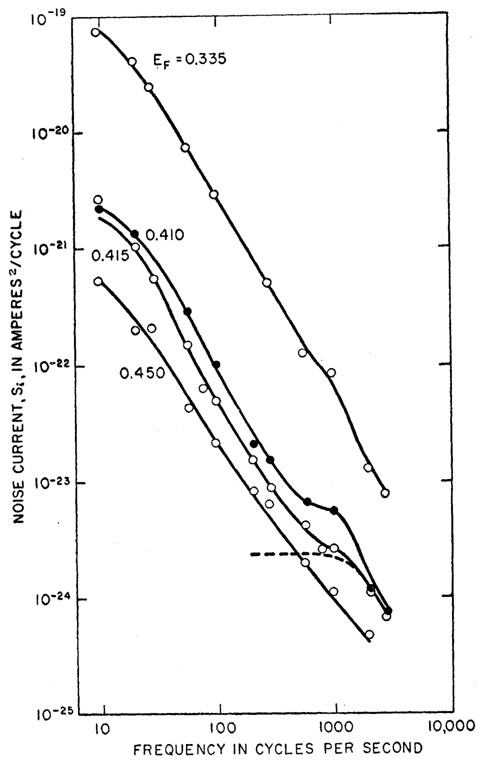

FIG. 1. Current noise spectra of a CdS single crystal at four 5200 A illumination levels. The quasi-Fermi level positions below the conduction band are determined from the conductivity. A relaxation process is evident at 1300 cps for $E_F \sim 0.41$ ev.

According to Van Vliet,[1] the current noise density, S_i, at low frequencies is given by

$$S_i = (4i^2\langle\Delta n^2\rangle\tau_0)/n_0^2 V, \tag{1}$$

where i is the current, τ_0 is the photoconductive decay constant, n_0 and $\langle\Delta n^2\rangle$ are the average and variance of the conduction band carrier density, and V is the crystal volume. The total noise, $\langle\Delta n^2\rangle/n_0 = F_n(E_F)$, computed from (1) varies with illumination intensity and is much greater than the value of unity expected for a Gaussian process; this is attributed to retrapping effects.

Assuming a Gaussian noise process, we write

$$\frac{\langle\Delta n^2\rangle}{n_0 + rh_0} = 1, \tag{2}$$

where h_0 is the total electron concentration in the traps and r is the number of times an electron is retrapped before recombining. Equation (2) may be derived from an application of the generation-recombination theorem taking retrapping into account. The trapped electron concentration is then

$$h_0 = (n_0/r)(F_n - 1) = \int_0^{E_g} N_t(E) f(E - E_F) dE, \tag{3}$$

where E_g is the forbidden bandwidth, E_F is the quasi-Fermi level, f is the Fermi function and $N_t(E)$ is the energy density of traps in thermal equilibrium with conduction band electrons. These equations may be solved for r and written in terms of the trap escape probability, P_t,

$$P_t = \frac{N_c}{N_t}\frac{F_n - 1}{2kT\tau_0} e^{-E/kT} = S e^{-E/kT}, \tag{4}$$

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[1] K. M. Van Vliet *et al.*, Physica 22, 723 (1956).

where N_c is the density of states in the conduction band, and E is the energy from the bottom of the band.

In applying Eq. (4), F_n is determined from Eq. (1) by low-frequency noise measurements over a range of illumination levels. The trap density is established by the usual photoconductivity techniques.[2] The noise, trap distribution, and frequency factor, S, are plotted as a function of the energy depth below the conduction band in Fig. 2. The trap distribution is nearly exponential but exhibits a discontinuity at about 0.42 ev showing a greater density at this depth. The frequency factor is of the expected order of magnitude and is markedly peaked at 0.40 ev. These two observations suggest the presence of a discrete set of traps at about 0.4 ev below the conduction band. The markedly different frequency factor and the increased density at this point appear to indicate these traps have a different origin than the others.

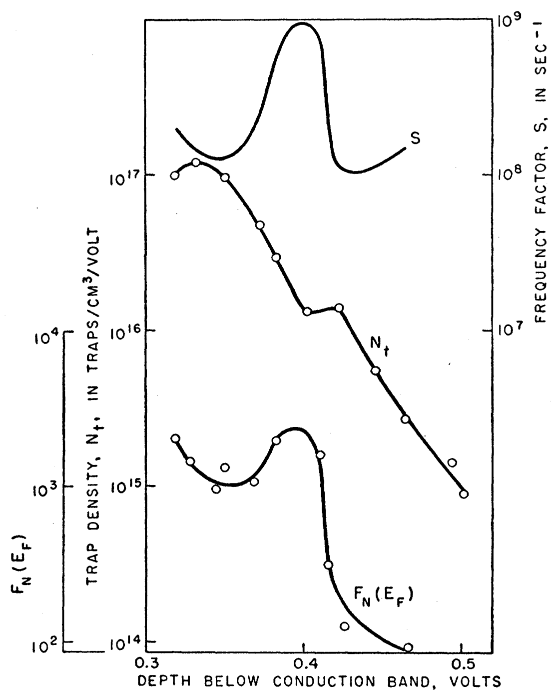

FIG. 2. Electrical noise, trap density, and trap frequency factor of a CdS crystal as a function of energy below the conduction band.

[2] H. B. DeVore, RCA Rev. **20**, 79 (1959).

When the quasi-Fermi level is in the energy region near these traps, they are expected to contribute to the fluctuations and this is the origin of the structure in the noise spectra of Fig. 1. The 1300 cps turnover frequency yields a time constant of 1.2×10^{-4} second, which is the retrapping time for these levels. Furthermore, the retrapping time multiplied by the number of times retrapped ($r=9$, at 0.41 ev) is 1.1×10^{-3} second, which is in agreement with the conduction band lifetime, 1.2×10^{-3} second, determined from photoconductivity. The magnitude of the extra retrapping noise, shown as the dotted line in Fig. 1, is accounted for quantitatively by the generation recombination theorem using the known conduction electron density and the retrapping time constant. In Fig. 2 the maximum of S is at 0.40 ev while N_t is a maximum at 0.42 ev. Possibly, traps slightly below the quasi-Fermi level are more effective in the photoconductivity measurements yielding N_t, while those slightly above are more important for noise; thus, a shift of the order of kT (0.025 ev) might be expected.

It should be noted that noise measurements as interpreted by Eq. (4) thus yield the frequency factor of traps in thermal equilibrium with the conduction band and the retrapping time. In the favorable case where one set of traps makes a major noise contribution, it is possible to determine the generation rate from the traps and demonstrate experimentally that electrons within a few kT of the Fermi level are the most important. Furthermore, low-frequency noise measurements alone are capable of predicting the high-frequency noise spectra which are due to retrapping effects and which can be explained entirely from the generation recombination theorem. We are currently attempting to identify the physical origin of the discrete traps and applying these techniques to other crystals.