# Current Noise and Distributed Traps in Cadmium Sulfide*

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The high-frequency portion of the current noise spectrum observed in lightly doped CdS single crystals under uniform 5200 A illumination is characteristic of electron trapping transitions to shallow levels. In many crystals the noise spectra have a characteristic $1/f$ trend when the electron quasi-Fermi level is not located near a discrete trap. The $1/f$ trapping noise observed in one crystal at temperatures of 10, 27, and 52°C and for 20 different positions of the electron quasi-Fermi level between 0.5 and 0.3 ev below the conduction band can be represented by a single expression of the form $(1/\omega)\tan^{-1}\omega\tau$, where $\tau$ is determined by the low-frequency turnover of the $1/f$ trapping noise. From these experimental values of $\tau$, trap depths are calculated which are in good agreement with the positions of discrete trapping levels determined from other measurements. Since the low-frequency turnovers of the $1/f$ spectra are thus related to the discrete traps, rather than to the position of the electron quasi-Fermi level directly, it appears that the $1/f$ noise may not be associated with a postulated continuous distribution of traps in energy, but rather with a dispersion of capture and release times into the discrete traps.

## I. INTRODUCTION

It is well established that photoconductivity in single crystal cadmium sulfide is strongly influenced by the characteristics and energy distribution of shallow traps[1] and there exists experimental evidence for discrete levels as well as for traps having a continuous distribution in energy.[2,3] Many properties of the discrete traps have been derived from combined photoconductive and current noise measurements,[4–6] and it has been noted that the observed $1/f$ trapping noise may imply the existence of distributed levels. In the present work a more extensive study of these continuously distributed levels using current noise measurements is reported.

Photoelectrons excited to the conduction band may experience many trapping events before they disappear through recombination. These transitions cause fluctuations in the number of carriers in the conduction band which are observable as current noise. The measurements yield quantitative information concerning trap depths and transition probabilities and are obtained under steady state conditions. When the electron quasi-Fermi level is near a discrete trap, transitions to this trap dominate so that through variation of illumination intensity it is possible to move the quasi-Fermi level to different energy positions and thus examine each set of discrete levels in turn. It is assumed that the trapping levels are simple traps and that they are in thermal equilibrium with electrons in the conduction band.

Under many experimental conditions the trapping noise spectrum is observed to have a $1/f$ behavior, which formally may be accounted for by transitions to a trap population having an exponential distribution in energy,[7] after the traditional explanation of $1/f$ noise. Trap distributions derived from photoconductivity measurements,[2,4] often display an exponential variation

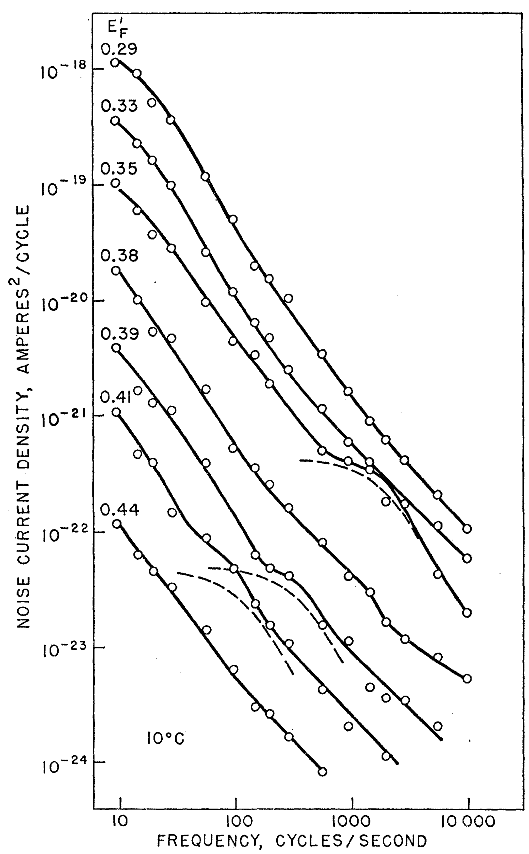


FIG. 1. Current noise spectra for different positions of the electron quasi-Fermi level below the conduction band at a temperature of 10°C.

* Supported by the Office of Naval Research.
[1] A. Rose, RCA Rev. **12**, 362 (1951). R. H. Bube, *Photoconductivity of Solids* (John Wiley & Sons, Inc., New York, 1960).
[2] H. B. DeVore, RCA Rev. **20**, 79 (1959).
[3] R. H. Bube, J. Chem. Phys. **23**, 18 (1955).
[4] J. J. Brophy and R. J. Robinson, Phys. Rev. **118**, 959 (1960).
[5] J. J. Brophy, Phys. Rev. **119**, 591 (1960).
[6] J. J. Brophy and R. J. Robinson, Paper V9, International Conference on Semiconductor Physics, Prague, September, 1960 (unpublished).
[7] A. van der Ziel, *Fluctuation Phenomena in Semiconductors* (Academic Press, Inc., New York, 1959), p. 59.

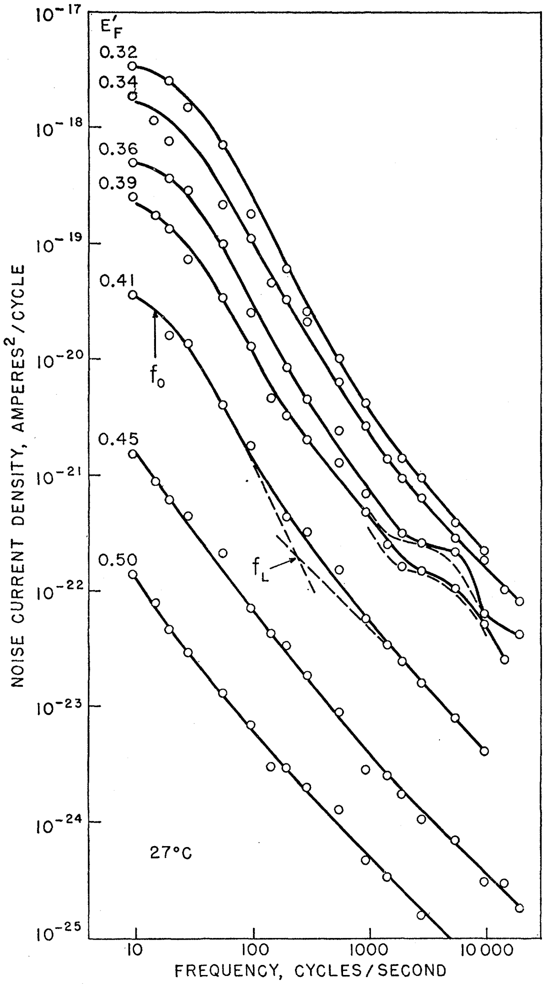


Fig. 2. Current noise spectra for different positions of the electron quasi-Fermi level below the conduction band at a temperature of 27°C.

with energy below the conduction band, so there is some expectation that more detailed noise measurements than previously obtained would lead to useful results. In particular, because of the strong temperature dependence of trapping transition rates, a study of trapping at other than room temperature is deemed most appropriate.

## II. EXPERIMENTAL TECHNIQUE AND RESULTS

The same experimental techniques previously described[4,5] were used in the present work. The sample studied was a single crystal 2.5 mm×2.5 mm×0.3 mm, lightly CuCl doped during growth from the vapor, and was provided with soldered indium electrodes. Illumination was from a calibrated dc tungsten lamp through a 5200 A interference filter and the potential applied to the crystal did not exceed 1.35 volts. The crystal was mounted on a copper heat sink which was cooled with ice or resistively heated. The temperature was measured with a copper constantan thermocouple. A standard tunable amplifier-voltmeter system was used to measure voltage fluctuations across a $1.25\times10^4$ wirewound load resistor.

The photoconductive time constant, $\tau_0$, was determined while partially chopping the incident radiation mechanically and the conduction band lifetime, $\tau_c$, was calculated using $\tau_c=N_0/G_L$, where $N_0$ is the number of conduction electrons determined from the conductivity and $G_L$ is the carrier generation rate due to photon absorption. The position of the electron quasi-Fermi level was calculated from the measured conductivity and temperature using appropriate values of electron mobility.

Several current noise spectra for different illumination intensities at each of three temperatures, 10, 27, and 52°C are shown in Figs. 1, 2, and 3, respectively. A total of 25 such spectra were obtained in all, some of them have been omitted from the figures for clarity. The range of electron quasi-Fermi level positions, between 0.3 and 0.5 ev below the conduction band, represented by this data is restricted by the sensitivity of the noise amplifier on the one hand and the maximum available illumination intensity on the other. The temperature range is similarity restricted since it is necessary to investigate the same quasi-Fermi level positions at all

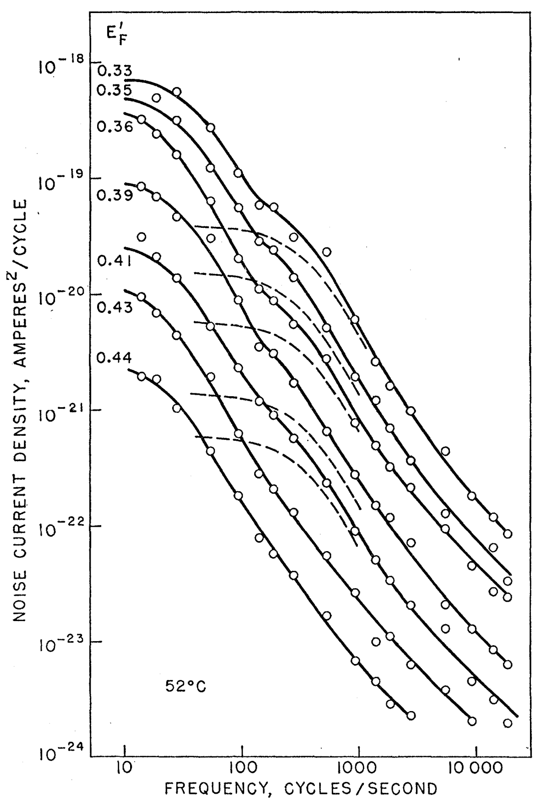


Fig. 3. Current noise spectra for different positions of the electron quasi-Fermi level below the conduction band at a temperature of 52°C.

temperatures. In addition, it seems desirable not to have too great a temperature variation in order to minimize the introduction of spurious phenomena. In this connection it is significant that the curves of Figs. 1, 2, and 3, all do have the same general features.

### III. INTERPRETATION OF NOISE SPECTRA

These noise spectra may be interpreted with the aid of an approximate expression due to van Vliet[8] for the case of a single trap level. The current noise density, $S_i(\omega)$, may be put in the form [Eq. (44) of reference 8 using the present notation]

$$S_i(\omega)=\frac{4i^2}{N_0}\left\{\frac{\langle\Delta N^2\rangle}{N_0}\frac{\tau_0}{1+\omega^2\tau_0^2}+\frac{1}{\tau_c}\left[1-\frac{\langle\Delta N^2\rangle}{N_0}\frac{\tau_c}{\tau_0}+\epsilon\frac{H_0}{G_L}\right]\frac{\tau_t^2}{1+\omega^2\tau_t^2}\right\}, \quad (1)$$

where $i$ is the photocurrent, $\langle\Delta N^2\rangle$ is the variance of the number of conduction electrons, $\epsilon$ is the transition probability out of the trap, $H_0$ is the number of trapped electrons, and $\tau_t$ is a relaxation time due to trapping. If it is assumed that each trapping transition is independent, the variance in Eq. (1) should be considered a total variance and written[9] in terms of the generation rate from the traps, or

$$\langle\Delta N^2\rangle=mG_L\tau_c, \quad (2)$$

where $m$ is the number of times an electron is trapped on the average. If $m$ is large ($m\gtrsim 10$), as is the case in CdS, introducing Eq. (2) into Eq. (1) results in the particularly simple form

$$S_i(\omega)=\frac{4i^2}{N_0}mG_L\left\{\frac{\tau_0\tau_c}{1+\omega^2\tau_0^2}+\frac{\tau_t^2}{1+\omega^2\tau_t^2}\right\}=S_R(\omega)+S_T(\omega), \quad (3)$$

where $S_R(\omega)$ and $S_T(\omega)$ are each simple relaxation expressions related to recombination transitions and trapping transitions, respectively.

Experimentally it is found that $\tau_0\tau_c\gg\tau_t^2$ so that $S_R(0)>S_T(0)$, which means at low frequencies the noise spectrum has a simple relaxation form with a turnover frequency associated with the photoconductive time constant. This is confirmed experimentally[4,10] and is seen again in the spectra of Figs. 1, 2, and 3. When the electron quasi-Fermi level is near the energy position of a discrete trap, a high-frequency relaxation effect attributable to $S_T(\omega)$ is visible, as shown by the dotted lines in Figs. 1 and 2. From these data $\tau_t$ may be determined and very satisfactory quantitative agreement is reached between the predictions of Eq. (3) and experimental results[6] as well as between the magnitudes of the various parameters $m$, $G_L$, $\tau_0$, $\tau_c$, and $\tau_t$.[11] The experimental behavior of both $S_R(\omega)$ and $S_T(\omega)$ predicts energy locations of discrete traps which are in good agreement with those detected in thermally stimulated current measurements.

The spectra of Fig. 3 show an additional relaxation effect, also indicated by dashed lines, which appears to be fundamentally different from trapping noise. The phenomena is visible and shows the same turnover frequency for all of the higher quasi-Fermi level positions. This behavior, as well as essentially the same turnover frequency (350 cps, $\tau\sim450\,\mu$sec), has been observed in samples which exhibit long-range photodiffusion under experimental conditions such that the electroded end of the crystal is dark.[12] If, as previously suggested, this characteristic time constant is associated with neutral energy transport effects, it is not clear why the phenomena should be apparent under the present experimental conditions in which the electrode end of the sample is illuminated, nor why it is seen only above room temperature. For present purposes the effect is tentatively identified with neutral diffusion and is not considered as part of trapping noise.

With the quantitative success of Eq. (3) in explaining trapping noise when a trapping relaxation is visible in an experimental spectrum, we turn to those spectra which show a $1/f$ high-frequency behavior. For these the electron quasi-Fermi level is presumably not located near a discrete trap level. In order to examine the trapping noise alone it is convenient to eliminate the effect of the strong variation in noise magnitude with

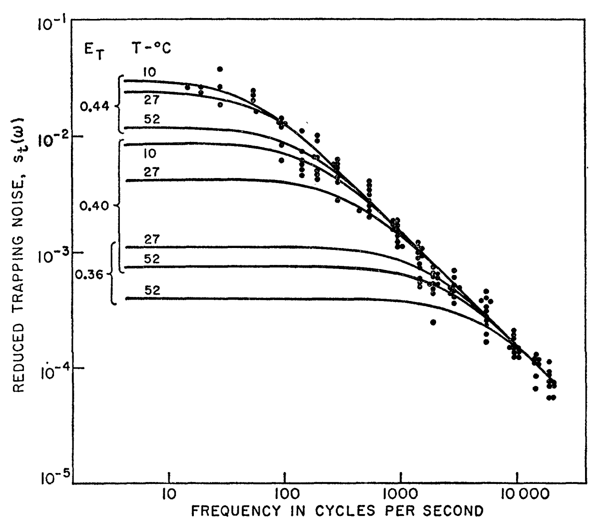


FIG. 4. Reduced trapping noise for 20 different positions of the quasi-Fermi level and the three temperatures of Figs. 1, 2, and 3. The curves represent Eq. (5) and are labeled in accordance with calculations in Part IV of the text.

[8] K. M. van Vliet and J. Blok, Physica **22**, 525 (1956).
[9] R. E. Burgess, Physica **20**, 1007 (1954); Proc. Phys. Soc. (London) **B69**, 1020 (1956).
[10] K. M. van Vliet, *et al.*, Physica **22**, 723 (1956).
[11] R. J. Robinson, thesis, Illinois Institute of Technology, June, 1960 (unpublished).
[12] R. J. Robinson and J. J. Brophy, Physica **26**, 440 (1960).

illumination intensity, which is essentially due to the variation of $m$ in Eq. (3). This can be done by defining a reduced trapping noise, $s_T(\omega)$, such that

$$s_T(\omega)=[S_i(\omega)-S_R(\omega)]/S_i(0). \tag{4}$$

When this procedure is applied to the experimental data of Figs. 1, 2, and 3, it is found that the high-frequency regions of the reduced trapping noise for all spectra fall on the same $1/f$ line within experimental error, as shown by the data points in Fig. 4. This seems to be a most remarkable regularity, considering the extremely wide range of total noise magnitudes observed under the different conditions of illumination and temperature. For display purposes the 20 individual sets of data are not separately indicated in Fig. 4 nor are those spectra included for which a discrete trapping relaxation is visible in the curves of Figs. 1, 2, and 3.

In most of the individual reduced trapping noise spectra of Fig. 4 there is definite indication of a low-frequency turnover and plateau. The general trend of the data suggests a behavior which can be represented by the familiar expression,[7] $(1/\omega)\tan^{-1}(\omega\tau)$, where $\tau$ is determined by the turnover frequency. An expression of this form was fitted to each curve to yield a value for $\tau$ and $s_T(0)$. These values so determined are such that the entire set of 20 spectra can be well represented by the single expression

$$s_T(\omega)=(7.0/\omega)\tan^{-1}(\omega\tau), \tag{5}$$

and the curves in Fig. 4 are plots of Eq. (5) using the experimental values of $\tau$.

## IV. EXPONENTIAL TRAP DISTRIBUTIONS

A familiar explanation for the origin of $1/f$ noise is a superposition of individual relaxation spectra of the form of $S_T(\omega)$ with a $1/\tau_t$ distribution of time constants. Furthermore, an exponential energy population of traps has the proper time constant distribution.[7,13] For example, starting with $S_T(\omega)$ of Eq. (3) for one trap level and summing the contributions from a presumed exponential distribution of levels, it is quite straightforward (using the approach of references 7 and 13) to develop an expression for $s_T(\omega)$ which is formally identical to Eq. (5) in its functional dependence on $\tau$ and $\omega$. The result is

$$s_T(\omega)=(1/S\omega)\tan^{-1}(\omega\tau_F), \tag{6}$$

and

$$1/\tau_F=S\exp(-E_F'/kT), \tag{7}$$

where $S$ is a frequency factor and $E_F'$ is the position of the electron quasi-Fermi level below the conduction band.

This result differs from Eq. (5) in two important respects. Taking a value of $S=10^{10}$ sec$^{-1}$, which is appropriate for discrete traps,[4,6] Eq. (6) predicts a noise intensity approximately six orders of magnitude smaller than observed experimentally. Of perhaps greater significance is that the time constant is a direct function of the electron quasi-Fermi level, which is illustrative of the fact that traps below this level do not contribute to the $1/f$ noise[13] and that the low-frequency turnover is therefore determined by the time constant of those traps at the quasi-Fermi level positions. The experimental data, in fact, do not show this dependence, as illustrated in Fig. 4. The spectra for several nearby positions of the quasi-Fermi level are quite coincident. Several such groups of coincident spectra can be distinguished. It appears that this behavior cannot be accounted for on the basis of an exponential trap distribution.

The observed grouping of noise spectra suggests that the phenomena may be related to discrete traps. The experimental values of $\tau$ derived from the reduced trapping noise data can be used to calculate trap depths with

$$1/\tau=S\exp(-E_T/kT), \tag{8}$$

where $E_T$ is the trap depth below the conduction band. All 20 different values of $\tau$ for the various temperature and illumination conditions yield only three different trap depths, 0.44, 0.40, and 0.36 ev. These are very nearly the locations of discrete traps as determined from the trapping noise relaxations and $S_R(0)$ as discussed above.[6]

These results are represented schematically in Fig. 5 where on the left are shown the energy depths of the discrete traps. On the right are the energy positions of the electron quasi-Fermi levels for which noise spectra

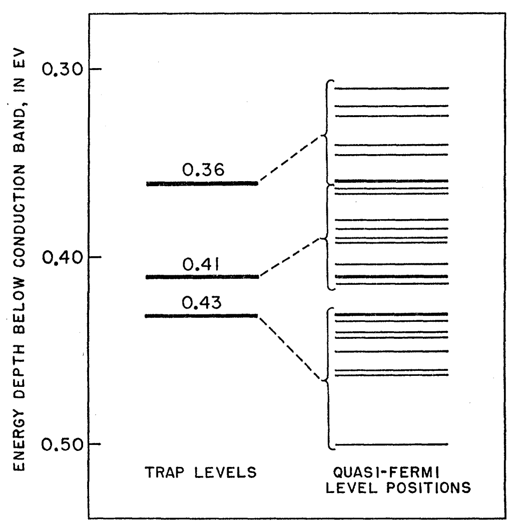


FIG. 5. Comparison of the energy depth of discrete traps as determined from low-frequency noise results with the quasi-Fermi level positions associated with these traps based on Part IV of the text. The heavier quasi-Fermi level positions are those for which discrete trapping noise relaxations are visible in the noise spectra.

[13] A. L. McWhorter, *Semiconductor Surface Physics* (University of Pennsylvania Press, Philadelphia, Pennsylvania, 1957), p. 213; also published as Lincoln Laboratory Technical Report No. 80, (Massachusetts Institute of Technology, Cambridge, Massachusetts, 1955).

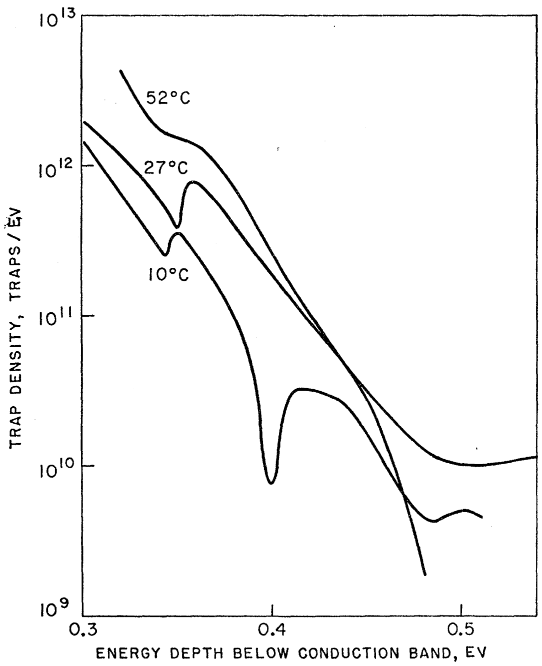


FIG. 6. Energy distribution of traps as determined from photoconductivity measurements.

are available. The brackets indicate the results of the above calculations and associate each trapping noise spectrum with a particular discrete level. From this picture, it is clear that each discrete level dominates when the quasi-Fermi level is in its energy vicinity. Some asymmetry exists in the diagram which possibly is due to the relative concentrations of the various traps.

Since it does not now seem desirable to require the existence of an exponential population of trapping states to explain the $1/f$ trapping noise, it is of interest to examine the distribution of states suggested by photoconductivity data for this crystal. Using the techniques previously developed,[4,5] trap distributions calculated for the three temperatures examined are shown in Fig. 6. It should be recalled that this method involves only the variation of the photoconductive time constant, $\tau_0$, and the conduction band lifetime, $\tau_c$, with the quasi-Fermi level position. These curves all yield approximately the same number of traps, but show rather wide variations in structure, particularly in view of the rather small temperature excursions.

It is significant that the 52°C curve shows the least structure, while the 10°C curve shows the most. The implication seems to be that at still lower temperatures only discrete traps would be predicted and that the high-temperature data are "smeared out" by the Boltzmann exponential factor giving trap occupancy near to the quasi-Fermi level. On this picture an exponential population is an artifact and is not unexpected. It has been realized that this photoconductive technique for determining trap distributions is an approximation at best, but the present data shows how erroneous it may be. On the other hand, it should be noted in Fig. 6 that the locations of discrete levels from the purely photoconductive data are in quite satisfactory agreement with those derived from the noise measurements. Levels at 0.36, 0.41, and 0.43 ev are evident although the latter two are not completely resolved.

### V. DISCUSSION

On the basis of both the noise data and the photoconductivity results it must be concluded that there is little, if any, evidence for a continuous distribution of traps in this crystal in the region 0.3 to 0.5 ev below the conduction band. Since most of the properties of this sample are very similar to many other specimens studied, it is expected that this conclusion must extend to them as well. If this is indeed so, the origin of the $1/f$ trapping noise must still be explained.

It is possible that transitions to the discrete traps alone can give an approximation to a $1/f$ spectrum. Through an ideal superposition of as little as three discrete relaxations a surprisingly near-$1/f$ behavior can be synthesized. However, it is felt that the present trapping noise data are sufficiently accurate to make this possibility unlikely. Furthermore, this idea still requires that the concentration of the various discrete levels be related exponentially to their energy depth (if the traps are similar) since this is really a "quasi-continuous" exponential distribution. Alternatively, the various discrete states must have time constants approximating a $1/\tau$ distribution. Both of these possibilities are too highly artificial to be likely.

The present results would seem to favor an explanation in terms of a suitable dispersion of time constants related to each discrete trap. The required dispersion must have the proper temperature behavior to permit the $1/f$ spectrum over at least such temperature excursions as investigated here. A trap-lattice interaction, perhaps influenced by gross effects such as mechanical strain, can be suggested. In this connection, the observation that the $1/f$ trapping noise can be reversibly altered by electrode phenomena not related to contact noise[14] may be significant. It is hoped that this approach may be further explored.

[14] J. J. Brophy and R. J. Robinson, J. Appl. Phys. **31**, 1343 (1960).