

Noise in Single-Crystal Tellurium from Thermal or Optical Excitation*†

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The electrical noise of carefully prepared single-crystal tellurium samples was measured in the extrinsic temperature range. The effect of temperature variations on the noise power spectrum is interpreted quantitatively as the result of transitions between the valence band and four species of traps lying ~ 0.045 eV above it. The additional noise due to steady optical excitation at 77°K is attributed to transverse carrier density gradients which result from nonuniform excitation.

INTRODUCTION

TELLURIUM crystallizes in a highly anisotropic, hexagonal lattice to form a semiconductor having a forbidden energy gap of 0.34 eV which is smaller than that of any elemental semiconductor except gray tin.¹ When conducting electric current, tellurium, like all semiconductors, exhibits random electrical fluctuations in excess of Nyquist-Johnson noise. It is of interest to investigate this excess noise because of its bearing on transport processes in tellurium and because such noise limits the performance of tellurium as a photoconductive detector. The present investigation was undertaken to measure the influence of optical or thermal excitation on excess noise in extrinsic tellurium and to interpret the results in terms of a model.

A study like the present one has become possible only rather recently with the advent of tellurium crystals having a high degree of perfection.^{2,3} Carrier lifetime is critically dependent upon imperfection density and, as many earlier workers failed to appreciate, dislocations are produced by comparatively mild mechanical stress. Noise measurements on adequately prepared single-crystal tellurium samples have previously been reported by van Vliet³ and by Pai³ who measured noise at various temperatures in the intrinsic range and by Edwards, Butter, and McGlauchlin⁴ who obtained noise spectra at a single temperature in the extrinsic range in a study directed primarily toward evaluating detector performance. Neither of these investigations attempted to provide a basis for the understanding of the electrical fluctuations in extrinsic tellurium and it is to fill this need that the present work was undertaken.

TECHNIQUE

The sample preparation method is described in detail elsewhere.⁵ A single-crystal boule, grown by the Czochralski process, was cut by a string saw into pieces about 2.5 cm long which were cleaved at 77°K into slabs about 2 mm thick. A bridge-shaped sample was then cut from a slab by a fine jet of gas bearing abrasive particles. Platinum leads were attached to the ends and sidearms by welding. After etching, the sample was supported by only one end in an evacuated double Dewar where a cooled shield surrounded it completely except for an aperture for external illumination. To control the temperature of the sample, the inner chamber of the Dewar was filled with liquid helium, nitrogen, or oxygen, or heated electrically.

A 0.25-mA direct current was supplied by a high-impedance source connected to the ends of the sample. The resulting voltage across the sidearms was led via a coupling capacitor and stepup transformer to a low noise, wide-band, three-stage preamplifier using 6CW4 tubes. The output from the preamplifier passed through a tunable, narrow-band amplifier, HP model 302A, the rectified output from which was coupled through a low-pass filter to a recorder. The gain of the system was frequently calibrated by injecting a sinusoidal signal in series with the sample. The effective bandwidth was determined by measuring the Nyquist-Johnson noise of a resistor which replaced the tellurium sample. The sample could be illuminated by light from a variable aperture 1125°K cavity through a 3.3- to 3.7- μ bandpass filter.

RESULTS AND INTERPRETATION

Two types of excess noise were measured; thermally excited noise (dark noise) and optically excited noise. To determine dark noise, external illumination was excluded and the average noise voltage measured with and without bias current. The difference in the squared voltages was taken as a measure of excess noise power. Similarly, to determine optically excited noise the bias current was left on and the difference taken between the squares of the voltages measured with and without illumination. In either case the difference was normal-

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¹ For a comprehensive discussion see J. S. Blakemore, G. D. Long, K. C. Nomura, and A. Nussbaum, *Progress in Semiconductors* (John Wiley & Sons, Inc., New York, 1962), Vol. 6.

² T. J. Davies, *J. Appl. Phys.* **28**, 1217 (1959).

³ F. M. Klaasen, K. M. van Vliet, and J. R. Fassett, *J. Phys. Chem. Solids* **22**, 397 (1961); M. D. Pai, Master of Science thesis, University of Minnesota (1961).

⁴ D. F. Edwards, C. D. Butter, and L. D. McGlauchlin, *Solid-State Electron.* **3**, 24 (1961).

⁵ V. A. Vis, *J. Appl. Phys.* **35**, 360 (1964) (the adjoining paper).

lized by dividing by the square of the dc voltage across the sample and by the effective bandwidth. A preliminary experiment showed that the excess dark noise power was proportional to the square of the bias current and thus attributable to fluctuations in conductivity.⁶

Thermally Excited Noise

Noise spectra at various temperatures in the absence of external illumination are shown in Fig. 1 where the measured points have been omitted from all but three curves to avoid confusion. It can be seen that noise power decreases as temperature is raised from 50°K up to the onset of intrinsic transitions at ~120°K. In the extrinsic range each spectrum becomes steeper with increasing frequency and approaches 1/f² above ~500 cps. The steepness of the high frequency slope and the strong dependence of amplitude upon temperature suggest that the noise is due to transitions between the valence band and acceptor centers, several species of such traps being required by the complex shape of the spectra.

The proposed trapping model consists of several species of traps of the type shown in Fig. 2 where the arrows symbolize electron transitions. The centers which provide the most of the holes in extrinsic tellurium are not shown. These centers, which are not frozen out even at 4°K, are assumed to be saturated in conformity to the observed fact that the hole density and Hall mobility are nearly independent of temperature in the range of interest here. Accordingly, we take the hole population to be the sum of a component p₀ which is independent

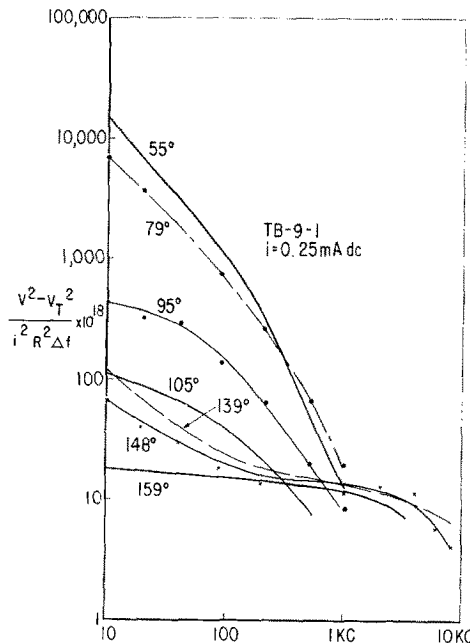


FIG. 1. Noise measured in the absence of external illumination.

⁶ A. Van der Ziel, *Fluctuation Phenomena in Semiconductors* (Academic Press Inc., London, 1959).

of temperature plus a component n₁+n₂⋯, which is equal to the number of electrons occupying traps of the type shown in Fig. 2. The only current carriers present are holes in the valence band and the noise is considered to be a result of fluctuation in their number. The continuity equation for electrons in the ith trap is

$$dn_i/dt = g_i - r_i = \epsilon_i p_0 (N_i - n_i) - k_i n_i (p_0 + n_1 + n_2 + \dots), \quad (1)$$

where N_i=number of type i traps/cm³, n_i=number of type i traps/cm³ occupied by electrons, k_i=hole trapping probability, and ε_i=electron excitation probability.

Here k_i is assumed to be independent of temperature but ε_i contains an exponential factor, thus⁷

$$\epsilon_i/k_i = N_v p_0^{-1} \exp[-E_i/KT],$$

where N_v=effective density of states in the valence band, E=trap energy level above valence band, K=Boltzmann's constant, and T=absolute temperature.

An equation like Eq. (1) can be written for each species of trap. The only coupling between such equations arises from the last term on the right and is negligible if, as we shall assume, p₀ ≫ n₁ + n₂ + ⋯. Under

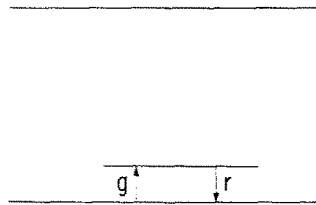


FIG. 2. A two-level system.

this assumption the equilibrium value of n_i is

$$n_{i0} = \epsilon_i N_i / (k_i + \epsilon_i) \quad (2)$$

and the corresponding generation and recombination rates are

$$g(n_{i0}) \equiv g_0 = r(n_{i0}) \equiv r_0 = k_i p_0 N_i \epsilon_i / (k_i + \epsilon_i). \quad (3)$$

In the absence of interaction among traps the difficult problem of noise in a multilevel system degenerates to the superposition of noise from several two-level systems for which the solution is well known. For each species of trap the fluctuation in the total number of carriers in a sample is⁶

$$S_n = 4g_0 \tau^2 / (1 + \omega^2 \tau^2) (\text{vol}), \quad (4)$$

where ω = 2πf, vol = sample volume—cm³,

$$1/\tau = \partial r / \partial n - \partial g / \partial n = p_0 (k_i + \epsilon_i). \quad (5)$$

S_n is related to the normalized voltage fluctuation S_v/V² plotted in Fig. 1 by

$$S_v/V^2 = S_n/p_0^2 \quad (6)$$

⁷ See, for instance, R. H. Bube, *Photoconductivity of Solids* (John Wiley & Sons, Inc., New York, 1960), p. 327.

whence

$$S_v/V^2 = [4Nk/p_0^3(\text{vol})][\epsilon/(k+\epsilon)^2][1/(1+\omega^2\tau^2)]. \quad (7)$$

From (5) and (7) we see that both the time constant and the low-frequency amplitude depend upon ϵ and hence upon temperature and trap energy level. The noise is to be represented by the sum of terms like the right number of Eq. (7), one for each species of trap. The sets of values of E , k , and N are chosen in such a way that the observed temperature dependence is reproduced. After some experimentation it is found that a set of four species of traps, characterized by the values given in Table I, agrees well with the measured noise spectra.

The curves in Fig. 3 were calculated according to Eqs. (5) and (7) and Table I while the points were obtained by interpolation from the measured values of Fig. 1. To avoid confusion in Fig. 3, the 60°K curve has been shifted upward by one decade and the 50°K curve by two decades. It is seen that the agreement between the model and the actual noise is good, the largest dif-

TABLE I. Characteristics of traps used in computing noise spectra.

Trap	E	k	N/p_0
1	0.050 eV	1.62×10^{-14} cm ³ /sec	1.75
2	0.050	1.50×10^{-13}	3.25
3	0.050	1.20×10^{-12}	4.45
4	0.045	1.56×10^{-12}	3.70
			13.15

ference occurring at the extremes of temperature where the measurements are least accurate due to difficulty in controlling the temperature.

We note in the last column of Table I that $p_0 < N_1 + N_2 + N_3 + N_4$ which contradicts the original "decoupling" assumption, $p_0 \gg n_1 + n_2 + \dots$, since at higher temperatures $n_1 \approx N_1$, etc. Inspection of Eq. (7) shows that a reduction in sample volume would reduce N by the same factor. The apparent volume of the sample was used in computing N/p_0 in Table I, but, if the sample were in fact composed of stochastically independent subvolumes,⁸ the appropriate value would be smaller. A sub-volume factor of 10 to 100 is required to justify the assumption of noninteracting trapping processes.

If we regard the hole trapping constant k as the product of a cross reaction and an average thermal velocity we have $S_p = k/v$. With $v = 5 \times 10^6$ cm/sec the values of k in Table I lead to trapping cross sections ranging from 0.3×10^{-18} to 0.3×10^{-20} cm² which are characteristic of centers having Coulomb repulsion for the carriers,⁹ i.e., positively charged centers. These traps, which have energy levels in the lower quarter of the

⁸ J. J. Brophy, J. Appl. Phys. 33, 117 (1962).

⁹ R. H. Bube, Ref. 7, p. 61.

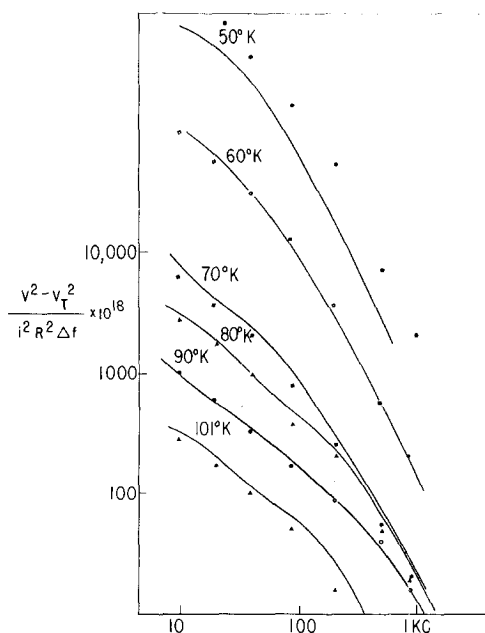


FIG. 3. A comparison of measured and calculated noise spectra.

gap, may be impurity atoms which have yielded one or more electrons to still lower lying states—possibly those which are responsible for p_0 .

Optically Excited Noise

Spectra of the noise at 77°K resulting from 3.5- μ excitation are shown in Fig. 4 for various intensities of illumination. It is seen that at a given frequency the noise power is approximately proportional to the increment in conductance produced by the illumination. Each spectrum has approximately a $1/f$ dependence at lower frequencies and approaches $1/f^2$ above 500 cps. If this noise were regarded as the result of several re-

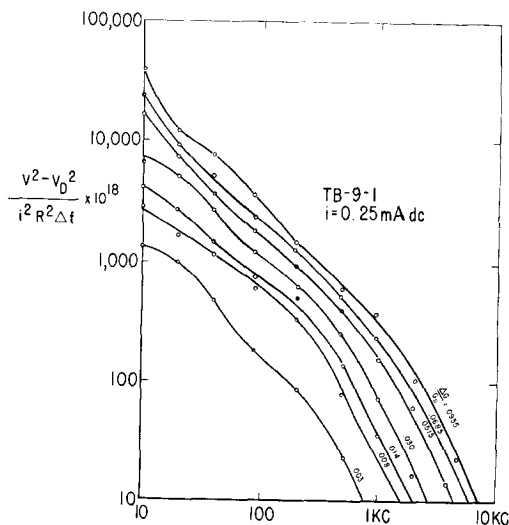


FIG. 4. Noise due to optical excitation at 77°K.

laxation processes, as the dark noise, the required time constants would fall in the range 16 000 to 1600 μsec to account for the nonzero slope between 10 and 100 cps. However, measurements of the small-signal, transient (nonfluctuating) response of this same sample revealed no time constants greater than 300 μsec at 77°K.⁵ Since the same time constants appear in both the fluctuating and the nonfluctuating processes if the same transitions are involved in both,¹⁰ we must seek an alternative source of the low-frequency, optically excited noise.

Optically excited noise might arise in the following way. Since the incident radiation is absorbed as it traverses the $\sim 1\text{mm}$ thickness of the sample, there exists a gradient in the density of optically excited carriers perpendicular to the original direction of the bias current. This leads to a transverse component of bias current, the magnitude of which increases with the intensity of optical excitation. Noise due to transverse current might arise from anisotropy of the tellurium lattice or it could be a "contact" noise produced as current crosses the boundaries of the subvolumes mentioned above. To get an idea of the magnitude of the latter effect we assume that all the current is flowing through a single contact and use.¹¹

$$S_v/V^2 = 0.5 \times 10^{-10} R/f$$

where R = contact resistance and f = frequency. If we take $R = 10 \Omega$ and $f = 10$ cps, we have $S_v/V^2 = 5 \times 10^{-11}$ which is 1000 times larger than the largest observed noise. This result would be reduced by a factor of $1/N$ if there were N contacts instead of a single one and would be further reduced by the square of the fraction of current flowing transversely. Thus it seems possible that contact noise could be of the same magnitude as the observed noise. The fact that the observed spectra

of optically excited noise turn down to a slope of approximately $1/f^2$ militates against a contact noise interpretation, but as Van der Ziel remarks¹¹ there is no strong theoretical basis for expecting the exponent of inverse frequency to be exactly unity, other values—some frequency dependent—having been reported. Van Vliet⁹ and Pai³ also found a similar spectrum for noise in single crystal tellurium when there was a transverse temperature gradient in the sample. They attributed such noise to modulation of surface recombination centers.

SUMMARY AND CONCLUSION

Thermally excited noise is attributed to carrier density fluctuations due to transitions between the valence band and traps with energy levels near the bottom of the gap. Little is known of the nature or location of such centers and further investigation of the effects of sample dimensions, gaseous environment, nonpenetrating optical excitation, etc. would be helpful. Optically excited noise is tentatively associated with a transverse component of bias current due to nonuniform excitation. The hypothesis that the transverse current generates more noise than current parallel to the c axis should be tested by measuring noise in perpendicularly cut samples. Although the present study by no means exhausts the subject of the electrical behavior of extrinsic tellurium, it does provide, in conjunction with the investigation of photoconductivity presented elsewhere,⁵ the means of making an optimum choice of the operating parameters of an infrared detector.

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¹⁰ K. M. van Vliet and J. Blok, *Physica* **22**, 534 (1956).

¹¹ A. Van der Ziel, *Noise* (Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1956), p. 212.