Structure in the flicker-noise power spectrum of n-InSb

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We have measured the power spectrum of flicker noise in high-purity, single-crystal n-InSb at 76 K in the frequency range 0.1 Hz–10 kHz. The power spectrum can be interpreted as a superposition of two noise spectra. One of them is $1/f$ like at frequencies above a cutoff frequency f_0 which is on the order of a few hundred Hz, while at frequencies below f_0 it appears to level off to a constant value. The second spectrum is dominant at frequencies well below f_0 and behaves as $1/f$. Noise power much smaller than that predicted by the Hooge relation, $S_{\delta V} = \alpha V^2/NF$, is observed. Also it is found that chemical treatments of the surface have a strong influence on the magnitude of the measured flicker noise.

I. INTRODUCTION

For many years flicker noise has been observed in semiconductors. This noise generally possesses a power spectrum with frequency dependence given by $f^{-\gamma}$, $\gamma \cong 1$. The origin of flicker noise is generally believed to be due to resistivity fluctuations. Since these fluctuations are generally measured with a probing current passed through the sample, some people have used the terms "current noise" or "excess noise" to describe the resulting noise spectrum. In this paper the term "flicker noise" will be used to describe the observed resistivity fluctuations even though the power spectrum deviates from $1/f$-like behavior in a limited frequency range; see Figs. 2 and 3.

Hooge[1] has proposed a semiempirical expression for bulk $1/f$ noise:

$$S_{\delta V} = \alpha V^2/Nf \,, \tag{1}$$

where $S_{\delta V}$ is the spectral density of voltage fluctuations, V is the average voltage across the sample, $\alpha \cong 2\times 10^{-3}$ is a constant, N is the number of charge carriers in the sample, and f is the frequency.

It was found[1] that the observed $1/f$ noise in InSb was usually larger than that predicted by Eq. (1). In 1974 Vandamme[2] measured $1/f$ noise in InSb down to 10 Hz and found values for α of about 1.3×10^{-3} at 77 K. This is in agreement with Eq. (1). However, more recent measurements[3] of $1/f$ noise in InSb have yielded values for α as large as 10^{-1}. No experimenter to our knowledge has reported any strong deviation from a $f^{-\gamma}$ frequency dependence of the power spectrum of flicker noise in semiconductors.

In this paper we report new measurements of the flicker noise in high-purity single-crystal n-InSb at 76 K. The magnitude and frequency dependence of the noise power spectrum are found to depend on the methods of sample preparation. The exact nature of the important parameters in sample preparation has not yet been established except that surface cleanliness is of great importance. However, we have obtained reproducible power spectra which show that the flicker noise in InSb deviates strongly from Eq. (1) and seems to consist of two superposed noise processes.

II. EXPERIMENTAL TECHNIQUES

A. Detection system

Figure 1 shows a schematic diagram of the noise detection system. A 45-V battery in series with a large wire wound resistor drives a dc current through the sample. A blocking capacitor eliminates the dc voltage across the sample from the input of the low-noise preamplifier. By choosing C and R_2 large enough we are able to measure spectra down to at least 0.1 Hz.

The preamplifier used depends on the frequency range. A Brookdeal 9431 Nanovolt Preamplifier is used in the range 10 Hz–10 kHz and a battery powered low-noise amplifier designed by Andressen[4] for low-frequency stability is used in the range 0.1–10 Hz. The background noise level of the system is approximately 10^{-18} V^2/Hz down to 80 Hz where it begins to increase roughly as $1/f$.

The sensitive electronics are shielded both electrostatically and electromagnetically. An optical isolation amplifier is used to break ground loops to the data acquisition system. After amplification the noise signal is filtered, digitized, windowed, and Fourier analyzed by a Nova 800 computer using the fast Fourier transform. A separate run with appropriate filtering is made for each decade of frequency in the reported spectra. The number of spectra averaged varied from about 100 at the

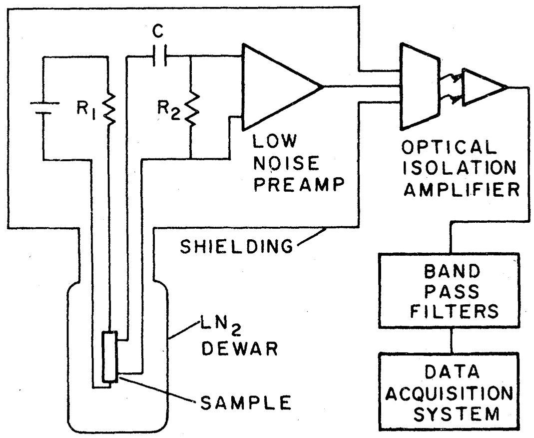

FIG. 1. Schematic diagram of the noise measurement system.

low frequencies to about 250 at high frequencies. The Nyquist noise and amplifier noise background is subtracted whenever necessary.

B. Sample preparation

All specimens are single crystal n-InSb with a resistivity of 0.18 Ω cm and a carrier concentration of 1.0×10^{14} cm^{-3} at 76 K yielding a Hall mobility of 3.5×10^5 cm^2/V sec. A four probe method was selected to eliminate any contact noise.

Two types of samples have been investigated. Type A is a wafer with approximate dimensions of $2\times0.7\times0.15$ mm mounted on a Vespel[9] insulating material and held in place by its current leads. The sample was etched in CP-4,[5] and rinsed in water, alcohol, and acetone. Then four leads were soldered on in a forming gas atmosphere (90% N_2, 10% H_2) at 200 °C for about 5 min. without the use of any flux. Fairly massive current leads made from 0.4-mm phosphor bronze were attached perpendicularly to the large area face of the crystal at either end. Small voltage leads were attached opposite to the current leads on the back face of the crystal using 0.125-mm gold wire.

The type-B sample is a bar with approximate dimensions $7\times0.4\times0.4$ mm. Current and voltage leads were soldered along the bar in air at room temperature using a fine copper tipped soldering iron, 0.125-mm gold wire, and Kester 1544 flux. The bar was freely suspended by its leads and then etched in CP-4,[5] and rinsed in water, alcohol, and acetone immediately prior to measurement. For both sample types tellurium-doped indium solder was used to make low-resistance Ohmic contacts.

After preparation the sample was immersed in a mixture of organic fluids[6] which freezes just above the temperature of liquid nitrogen. Since it freezes close to the temperature of measurement where the thermal expansivities are small, there is little strain applied to the sample. This procedure eliminates temperature fluctuations due to bubbling that occur if the sample is placed in direct contact with the liquid-nitrogen bath. Also it has proven superior to surrounding the sample with a gaseous atmosphere, since the solid medium allows no convection currents that could cause temperature fluctuations. In addition it has eliminated any problems with microphonics since the solid medium rigidly clamps the sample in place.

III. EXPERIMENTAL RESULTS

Figures 2 and 3 show typical results for type-A and type-B samples, respectively. For Fig. 2 the applied voltage and sample resistance between the voltage probes were 0.29 V and 34 Ω, and for Fig. 3, 0.58 V and 30 Ω. In each figure the dots are the experimental data. The dashed line represents Eq. (1) for each sample, where N is taken to be the number of charge carriers located between the voltage contacts. The triangles are the result of subtracting line (a) from the data.

It is clear that in both spectra the noise levels at low frequencies are much smaller than that predicted by Eq. (1). Line (a) in Figs. 2 and 3 lies at a factor of 16 and 120, respectively, below the dashed line. These numbers have been found

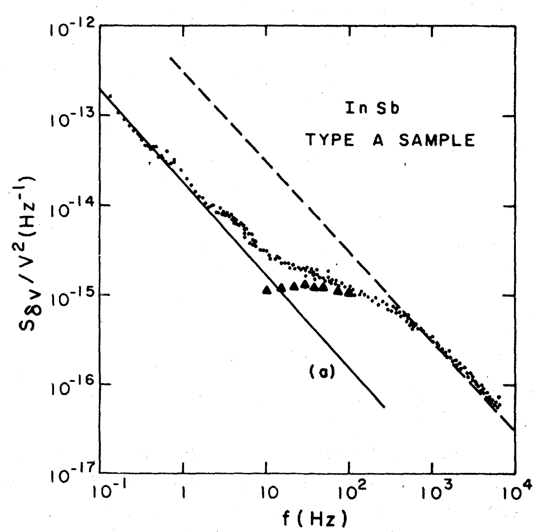

FIG. 2. InSb type-A sample; measured flicker noise power spectrum (dotted line); Eq. (1) for this sample (dashed line); subtraction of line (a) from the spectrum (triangles).

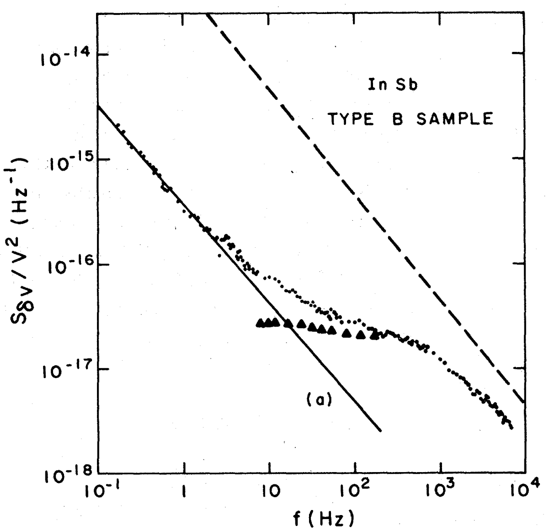

FIG. 3. InSb type-B sample; measured flicker noise power spectrum (dotted line); Eq. (1) for this sample (dashed line); subtraction of line (a) from the spectrum (triangles).

to vary by approximately a factor of 2 in different samples. In Fig. 2 the power spectrum approaches Eq. (1) at frequencies above about 200 Hz. In Fig. 3 the spectrum is below Eq. (1) by a factor of 4 even at 1000 Hz. These low noise levels plus the reproducibility of the spectra lead us to hope that they represent truly bulk effects in our samples. However, it should be noted that the noise level is significantly lower in type-B samples than in type-A ones. At the present time we do not understand the reasons for this.

The power spectra shown in Figs. 2 and 3 can be interpreted as a superposition of two separate noise spectra. At frequencies below 5 Hz the spectra are dominated by a $1/f$ noise process represented by line (a). Subtracting line (a) from the data leaves one with a second spectrum that is $1/f$-like above about 1000 Hz but then begins to roll off to a constant value as indicated by the triangles in Figs. 2 and 3. The data in both Figs. 2 and 3 can be fit reasonably well to a function of the form

$$S_{\delta V}/V^2 = C_1/f + C_2/(f+f_0),$$

where $f_0 \approx 230$ Hz for Fig. 2 and $f_0 \approx 630$ Hz for Fig. 3.

As mentioned before, sample preparation techniques and surface conditions can affect the magnitude of the observed noise. An example of this is shown in Fig. 4. A type-B sample was prepared in the usual manner except that a different flux[7] was used. The sample was not etched after soldering and yielded the upper curve. Etching in CP-4,[5] reduced the noise to the lower curve, which gives

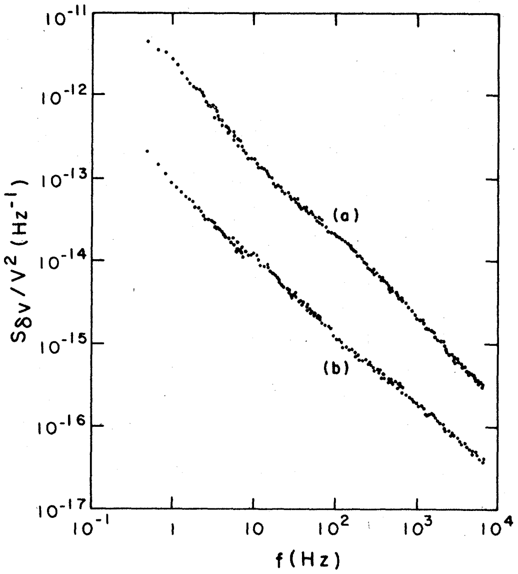

FIG. 4. Effect of surface treatment on the flicker noise power spectrum of InSb type-B sample; (a) before etching; (b) after etching.

a value of α of 2.3×10^{-3} in good agreement with Eq. (1). It is clear that the upper noise spectrum was caused by surface rather than bulk affects. But even the lower curve in Fig. 4 lies above the noise level of Fig. 3 and does not show the two $1/f$ regions. This leads us to suspect that surface or contamination effects are still dominant in the lower spectrum of Fig. 4 even though it agrees with Eq. (1).

Another problem is that type-B samples show a divergence in the power spectrum at frequencies below about 1 Hz. This has been attributed to nonequilibrium temperature fluctuations as reported by Clark and Hsiang.[8] Large copper heat sinks surrounding the sample significantly reduced this divergence. A power spectrum of the noise caused by these temperature fluctuations has been obtained by measuring the noise in a copper wire wound resistor at 76 K. The copper resistor used was wound from 0.025-mm wire. It was similar in size and resistance to our type-B InSb samples and had a temperature coefficient of resistance about three times larger than InSb at 76 K. It was immersed in our mixture of organic fluids[6] to duplicate the thermal environment of our InSb samples. The resulting noise power spectrum showed no detectable $1/f$ noise but did show a low-frequency divergence below about 1 Hz. This divergence had the same frequency dependence and a slightly larger magnitude than that present in our type-B InSb samples. We then scaled this divergence to fit exactly the low-frequency divergence observed in the power spectra of the type-B

samples. It was then treated as part of the background and subtracted from the measured power spectra in a limited frequency range. In Fig. 3, for example, the points in the region 0.1–0.4 Hz have been corrected to remove the effects of the low-frequency divergence. These corrections are small; however, below 0.1 Hz the noise diverges rapidly and effectively sets a low-frequency limit on the measurement of flicker noise in these samples.

IV. CONCLUSION

The data presented in this paper have some important implications: (i) If one is careful with surface cleanliness, noise levels well below that predicted by Eq. (1) are possible to attain in *n*-InSb. (ii) Flicker noise spectra in *n*-InSb deviate strongly from an $f^{-\gamma}$ frequency dependence. (iii) Since the observed noise spectra may be interpreted as the superposition of two simpler spectra, it is suggested that flicker noise in *n*-InSb may be the result of more than one physical process.

ACKNOWLEDGMENTS

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[2]L. K. J. Vandamme, Phys. Lett. A 49 (1974) 233.
[3]J. Sikula, B. Kaktavy, and P. Vasina, Fifth International Conference on Noise in Physical Systems, 1978, p. 88 (unpublished).
[4]S. Andressen and J. Nesheim, IEEE Trans. Instrum. 22, 185 (1973).
[5]CP-4 is a mixture of one part hydrofluoric acid, one part glacial acetic acid, 1.5 parts concentrated nitric acid, and a few drops of liquid bromine per 50 cm^3.
[6]This mixture consists of six parts 2-methylbutane, five parts ether, and two parts ethyl alcohol.
[7]Eutectic Corp. Eutectic Flux 157.
[8]J. Clarke and T. Hsiang, Phys. Rev. B 13, 4790 (1976); see especially Sec. III C.
[9]Vespel is a thermal setting plastic produced by Du Pont, E. I. de Nemours & Co., Inc., Wilmington, Del. 19898.