Magnetic effects on $1/f$ noise in n-InSb

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$1/f$ noise has been observed in resistors fabricated from high-purity single-crystal n-InSb at 75 K. Noise levels which are much smaller than predicted by the Hooge relation are routinely observed. The $1/f$ noise is extremely sensitive to an applied magnetic field which is perpendicular to the current. A field of 24 kG increases the fractional noise, S_V/V^2, by a factor of 10^2 to 10^4. These large effects nearly vanish when the magnetic field is parallel to the current. Similar effects are observed for $1/f$ noise present in the Hall voltage. The data display a lack of reproducibility from sample to sample and with surface treatment within the same sample.

I. INTRODUCTION

For many years $1/f$ noise has been observed in semiconductors. Hooge[1] argues that $1/f$ noise is an intrinsic bulk effect. He postulates an empirical expression for homogeneous materials,

$$\frac{S_V}{V^2}=\frac{\alpha}{Nf} \quad , \tag{1}$$

S_V is the spectral density of the voltage fluctuations, V is the applied voltage, N is the number of charge carriers in the sample, and $\alpha \approx 2\times 10^{-3}$ is a constant. Hooge[2] and others[3] have performed experiments that are consistent with the equation.

Hooge and Vandamme[4] have measured $1/f$ noise in highly doped p-Ge and n-GaAs where phonon scattering and ionized impurity scattering are both significant. Their data suggest that $1/f$ noise has its origins in mobility fluctuations and that phonon scattering rather than ionized impurity scattering is the basic cause of $1/f$ noise in these materials.

There is also evidence that surface effects often play a dominant role in the $1/f$ noise of semiconductors.[5] For example, surface preparation techniques may greatly affect the observed $1/f$ noise.[6] McWhorter[7] explains $1/f$ noise related to surface effects by considering deep traps located in the oxide layer.

Van der Ziel[8] has pointed out that good-quality silicon JFET's (junction field-effect transistors) display much less $1/f$ noise than suggested by Eq. (1). The JFET is one of the few electronic components to have no semi-conductor-to-oxide interface in the active region.

Vaes and Kleinpenning[9] (VK) have investigated the effects of an external magnetic field B on $1/f$ noise. They insert fluctuations in mobility and charge carrier number into classical two-dimensional charge-transport equations for an n-type nondegenerate isotropic semiconductor assuming acoustic-phonon scattering to be the dominant conduction mechanism. The magnetic field is directed perpendicular (transverse) to the current flow. The applied voltage is assumed to be held constant for all values of the magnetic field. VK make assumptions concerning the form of the cross-correlation spectrum of the mobility and number fluctuations. Weissman[10] has questioned the validity of these assumptions. VK calculate the ratio γ of $1/f$ noise power with an applied magnetic field to the $1/f$ noise power without the magnetic field:

$$\gamma=\frac{S_V(f,B)}{S_V(f,0)} \quad .$$

The integrals that result from this analysis can not be evaluated analytically. However asymptotic forms are available.[11] For mobility fluctuations

$$\gamma_\mu=\begin{cases} 1+\left[1+\dfrac{8}{3\pi}\right]\mu_H^2B^2 & \text{for } \mu_H B << 1 \\ 1+\dfrac{315}{256}\mu_H^2B^2 & \text{for } \mu_H B >> 1 \end{cases} \quad . \tag{2a}$$

For fluctuations in the number of charge carriers

$$\gamma_\mu=\begin{cases} 1+2\mu_H^2B^2 & \text{for } \mu_H B << 1 \\ 1+\dfrac{81}{256}\mu_H^4B^4 & \text{for } \mu_H B >> 1 \ . \end{cases} \tag{2b}$$

The most interesting feature of these results is the role of the Hall mobility, μ_H. It is clear that the presence of a magnetic field should produce larger effects in materials with higher mobility.

VK measured the magnetic field dependence of $1/f$ noise in n-Ge and found reasonably good agreement with the predictions for mobility fluctuations. The effect was fairly small resulting in a doubling of $1/f$ noise power with a field of approximately 30 kG.

n-type indium antimonide has several properties that make it interesting for $1/f$ noise studies. The small effective mass ($m_e/80$) and small coupling constant for optical-phonon scattering yields very large mobilities. The mobility may approach 100 $m^2/V\,s$ in very pure material at 75 K. n-InSb is commercially available with donor concentration of 5×10^{13} cm^{-3}. The high purity and high mobility allow the preparation of conveniently shaped samples where both the number of charge carriers and the resistance are small. According to Eq. (1) this should yield $1/f$ noise that is large compared to the Nyquist noise which is proportional to the resistance.

n-InSb displays large magnetoresistance effects. At 75 K the resistivity increases by approximately a factor of 18 in a transverse magnetic field of 20 kG.

The increase in resistivity is proportional to the magnetic field above about 200 G. A magnetic field parallel to the current produces a much smaller increase in resistivity. These magnetoresistance properties make n-InSb a logical material to look for strong magnetic-field effects on $1/f$ noise.

II. EXPERIMENTAL

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. R_1 and C_1 filter out any current fluctuations originating in the battery. A blocking capacitor C_2 eliminates the dc voltage across the sample from the input of the low-noise amplifier. The sensitive electronics are shielded both electrostatically and electromagnetically. An optical isolation amplifier is used to break ground loops to the data-acquisition system. All electronics "in front of" the optical isolator are battery operated and on a separate grounding system. The data acquisition system consists of an A-to-D converter and a mini-computer programmed to compute the power spectrum of the digitized noise signal.

Samples were prepared from high-purity single-crystal n-InSb. The donor concentration is 7×10^{13} cm^{-3} and the mobility is 70 $m^2/V\,s$. The sample shapes are shown in Fig. 2. Electrical contacts were made in two ways. In the first technique the leads were soldered directly to the InSb. The soldering was performed in air using a fine-tipped soldering iron and resin solder. In the second method copper was immersion plated onto the contact areas. This plating technique was developed by Kunze *et al.*[12] Leads were then soldered to the copper-plated areas. The copper-plating technique gives better control over the size and position of the contacts and yields Ohmic contacts more reproducibly. In both methods tellurium-doped indium solder was used.

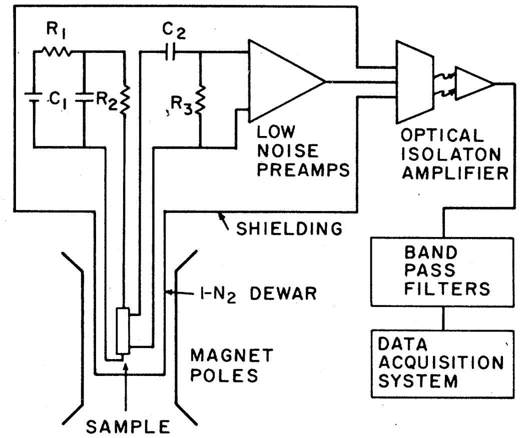

FIG. 1. Schematic diagram of the noise detection system.

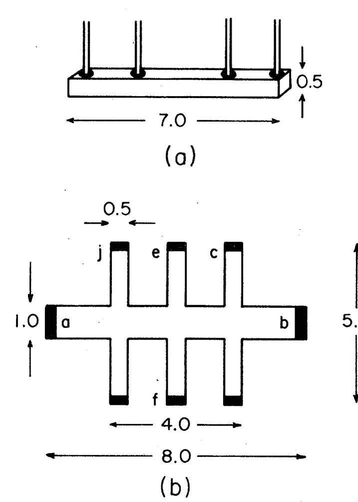

FIG. 2. InSb samples. (a) Bar-shaped samples, (b) bridge-shaped samples (0.2 mm thick). The shaded areas are soldered contacts. All dimensions are in mm.

Each sample was lightly etched in CP-4 and then immersed in a mixture of organic fluids (EPA). (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. EPA consists of six parts 2-methylbutane, five parts ether, and two parts ethyl alcohol). The sample and EPA are then cooled to 75 K. The EPA freezes close to the temperature of liquid nitrogen and thus rigidly clamps the sample in place without applying much stress due to differential contraction. This procedure separates the sample from the boiling liquid-nitrogen bath and greatly reduces temperature fluctuations due to bubbling.

Four probe measurements were made on several samples at 75 K in the absence of magnetic fields. The power spectra of the observed voltage fluctuations are given in Fig. 3. In all cases the noise background with no current has been subtracted. The dotted line represents the $1/f$ noise predicted by Eq. (1). Figure 3 demonstrates the difficulty in getting reproducible results from sample to sample. Some of the power spectra are reminiscent of earlier results in samples cut from a different ingot of n-InSb.[13]

We have observed that surface conditions affect the $1/f$ noise. A light surface etch usually reduces the $1/f$ noise significantly. The low noise levels reported in Fig. 3 appeared only in samples that were chemically etched immediately before cooling. We have also observed that the current contacts can sometimes create a large amount of $1/f$ noise even though they act like low-resistance Ohmic contacts.[14]

The important feature of the data in Fig. 3 is that noise levels well below Eq. (1) are possible in this material. We have found no evidence for a lowest level to the observed noise that would correspond to an inherent bulk effect.

The $1/f$ noise in n-InSb is consistently observed to be very sensitive to an external magnetic field. The magnetic field is applied perpendicular to the current flow and the voltage fluctuations are measured across potential leads that are separate from the current leads. Figure 4 shows the spectral density of $1/f$ noise in several samples for a field of 10 kG. Slight deviations from a strictly $f^{-\gamma}$ power law are fairly common. However, samples $G4$ and $G5$ demonstrate a rather large deviation that is sometimes observed. The noise spectra behave as $1/f$ noise at low frequencies but level off and then decrease more rapidly than f^{-1}.

Figure 5 shows the magnetic field dependence of the noise power spectra of several samples as measured at a fixed frequency. The quantity that is plotted is

$$\frac{S_V(f,B)/V_B^2 - S_V(f,0)/V_0^2}{S_V(f,0)/V_0^2} = \frac{\Delta S}{S_0} \ .$$

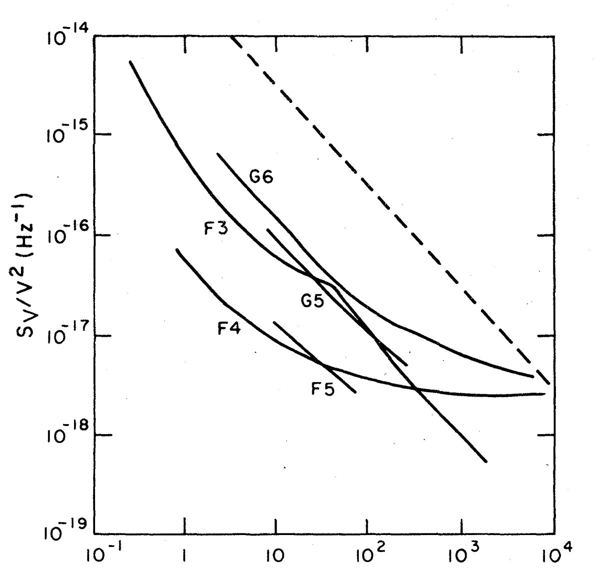

FIG. 3. Spectral density of fractional voltage fluctuations in several bar-shaped samples. The dotted line represents Eq. (1).

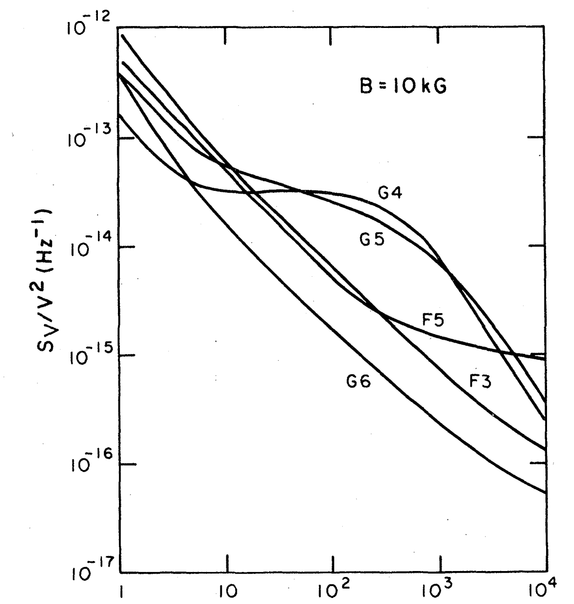

FIG. 4. Spectral density of fractional voltage fluctuations in several bar-shaped samples in a transverse magnetic field of 10 kG.

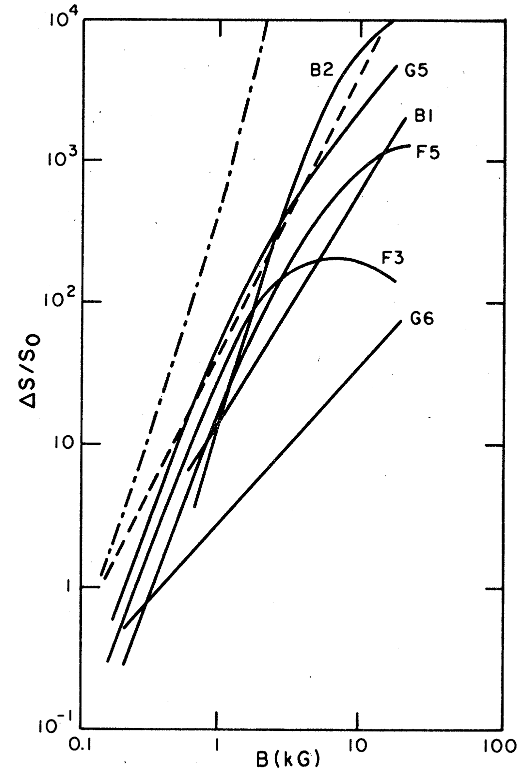

FIG. 5. Fractional change in the spectral density of $1/f$ noise for several samples due to an applied transverse magnetic field at a fixed frequency. *F* and *G* samples are bar-shaped samples measured at 200 Hz, *B* samples are bridge-shaped samples. *B* 1 was observed at 500 Hz and *B* 2 at 250 Hz. --- prediction for mobility fluctuations [Eq. 2(a)]; ... prediction for number fluctuations [Eq. 2(b)].

This is the increase in the spectrum of fractional voltage fluctuations due to a magnetic field *B* divided by the spectrum of fractional voltage fluctuations with zero magnetic field. This quantity is equivalent to $\gamma - 1$ where γ is given in Eq. (2). Usually the applied voltage was held constant for measurements at all magnetic-field strengths.

A fairly common feature of the data in Fig. 5 is that ΔS increases rapidly at low fields and more slowly at higher fields. All samples except one agree qualitatively in their behavior. Sample *G*6 is quite different from the others. It demonstrates a B^1 dependence on all field strengths. This behavior has not been reproduced in any other sample. However, we know of no reason to exclude the data from this sample.

One important feature of the data in Fig. 5 is that the effect of a magnetic field is much larger in *n*-InSb than in *n*-Ge as measured by VK. This supports their predictions concerning the role of the Hall mobility in the sensitivity of the $1/f$ noise to magnetic fields. The dashed lines in Fig. 5 are the predictions of Eq. (2) for mobility and number fluctuations.

We have attempted to measure the $1/f$ noise power with the magnetic field parallel (longitudinal) to the current flow. This experiment is difficult due to alignment and vibration problems. We have consistently observed that the $1/f$ noise is much less sensitive to longitudinal magnetic fields than to transverse magnetic fields. In some samples the noise power increased less than a factor of 2 in a field of 20 kG. Thus the large field dependence shown in Fig. 5 definitely requires a magnetic field perpendicular to the current. This behavior is similar to that of the magnetoresistance, which is large when the current and magnetic field are perpendicular but is quite small when they are parallel. This suggests that the same physical parameters are involved in the magnetic field dependence of both the resistance and the $1/f$ noise.

The dependence of the $1/f$ noise on the applied electric field has been measured in the range 0.4 – 3.0 V/cm. We have observed that the noise power behaves as V^{β} where $1.8 \le \beta \le 2.5$ depending on the sample. The value of β seems to have little dependence on the applied magnetic field. The bridge-shaped samples shown in Fig. 2 allow one to observe voltage fluctuations in the Hall voltage. A typical power spectrum of this noise is shown in Fig. 6 and clearly displays a $1/f$ character. Figure 7 shows the magnetic field dependence of the noise power in the Hall voltage. The quantity plotted is

$$\frac{S_V(f,B)-S_V(f,0)}{S_V(f,0)}=\frac{\Delta S}{S_0} .$$

The electric field parallel to the current is held constant for all measurements at different magnetic strengths. It is evident that ΔS increases as B^2 to at least 20 kG. This is significantly different from the data in Fig. 5. Again the dotted lines are predictions of Kleinpenning, Eq. (2). As before the large magnetic field effects disappear when the magnetic field is directed parallel to the current.

In *n*-InSb at 75 K the tangent of the Hall angle increases with increasing magnetic field to a value of about four and then stops increasing. This is due to the fact that the resistivity is nearly proportional to the magnetic field above a few kilogauss. Thus the data in Fig. 6 indicate that noise in the Hall voltage increases even when the Hall voltage does not.

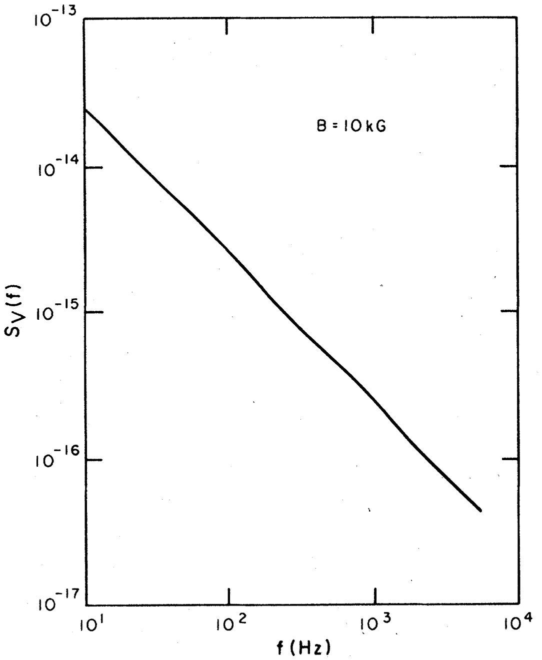

FIG. 6. Spectral density of voltage fluctuations in the Hall voltage of a bridge-shaped sample ($B2$) with a transverse magnetic field of 10 kG. The longitudinal electric field was about 2 V/cm, yielding a Hall voltage of about 0.8 V.

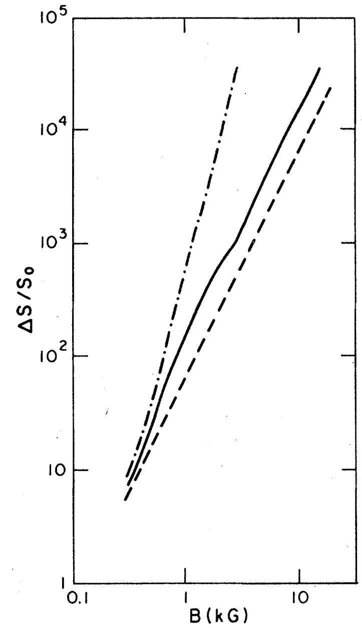

FIG. 7. Fractional change in the spectral density of $1/f$ noise in the Hall voltage of a bridge-shaped sample ($B2$) due to a transverse magnetic field at a fixed frequency of 250 Hz. The longitudinal electric field is held constant at 1 V/cm for all values of magnetic field. ---prediction for mobility fluctuations [Eq. 2(a)]; —·— prediction for number fluctuations [Eq. 2(b)].

One observation is worthy of note. According to VK the origins of $1/f$ noise are distributed throughout the bulk of a sample in a spatially uncorrelated manner. This has the consequence that the spectral density of electric field fluctuations is the same whether measured parallel or perpendicular to the current flow. This effect has been confirmed for thick film resistors by Hawkins and Bloodworth.[15] In sample $B2$ the ratio of longitudinal to transverse noise power was approximately 0.02 without an applied magnetic field. The VK theory predicts a ratio of 0.2 for this sample geometry. For magnetic fields greater than 1 kG this ratio increased to 0.1 in fair agreement with VK. This suggests that the noise present in a magnetic field is a bulk phenomenon.

III. DISCUSSION

It would be tempting to conclude, as did Vaes and Kleinpenning (VK) with respect to germanium, that Figs. 5 and 7 give evidence for mobility rather than number fluctuations in n-InSb. However, we feel that the fairly good agreement with the VK theory is fortuitous. The reason is that quantum effects play a dominant role in this experiment whereas the VK theory is basically a classical transport theory. For example, above several hundred gauss the transverse magnetoresistance in n-InSb varies linearly with magnetic field whereas the classical theory predicts a quadratic dependence. In order that a classical theory applies, the parameter $\eta = h\omega_C/k_B T$ must be much less than one. Here $\omega_C = eB/m^*$ is the cyclotron frequency. In other words, the splitting of the Landau levels must be small compared to $k_B T$. Owing to the low effective mass in n-InSb η has the value 2.8 at 75 K for $B = 20$ kG. Also optical-phonon scattering is dominant in n-InSb at 75 K, while VK assume acoustic-phonon scattering in their calculations. Thus, until the appropriate quantum modifications of the VK theory are calculated for optical-phonon scattering, it is premature to compare these experimental results with theory.

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