Title

AMPLITUDE FLUCTUATIONS OF JOHNSON NOISE IN SEMICONDUCTORS AND DISCONTINUOUS METAL FILMS: l/f NOISE IN AN EQUILIBRIUM SYSTEM

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MAY 1975

Amplitude Fluctuations of Johnson Noise in Semiconductors and Discontinuous Metal Films: 1/f Noise in an Equilibrium System[*]

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1/f noise is usually measured by passing a steady current through the sample and measuring the power spectrum of the noise generated. The fact that the spectrum remains 1/f down to very low frequencies implies that correlations in the voltage noise exist over time scales at least as long as the reciprocal of the lowest frequency of the spectrum. Some authors[1] have suggested that these very long correlation times require the presence of a long-term steady current, and that the noise is a result of turbulence in the current carriers. On this model, 1/f noise is inherently a non-equilibrium effect. However, measurements on metal films,[2,3] films at the superconducting transition,[4] and Josephson junctions[5] have indicated that 1/f noise in these systems is generated by equilibrium thermal fluctuations. On this model, 1/f noise is an equilibrium phenomenon, and the current flowing through the sample is simply a probe of the fluctuations. In this paper we report measurements on semiconductors and metals indicating that first, 1/f noise does not require a long-term steady current, and second, that the fluctuations in the mean-square Johnson noise voltage have a 1/f spectrum that arises from resistance fluctuations.

Our semiconductor samples consisted of strips of evaporated InSb about 1000Å thick with a resistivity of about 1 Ωcm. The films were cut transversely with a diamond knife while the resistance across the cut was monitored, until only a tiny bridge remained. In the sample reported here, the bridge had a resistance of about 20MΩ, and contained roughly 10^5 atoms.

The spectrum was first measured by passing a steady current through the sample. The voltage noise was amplified, digitized, and analyzed with a PDP-11 computer to determine the power spectrum. The measured relative power spectrum $S(f)=S_V(f)/\overline{V}^2$ is shown as the solid line in Fig. 1.

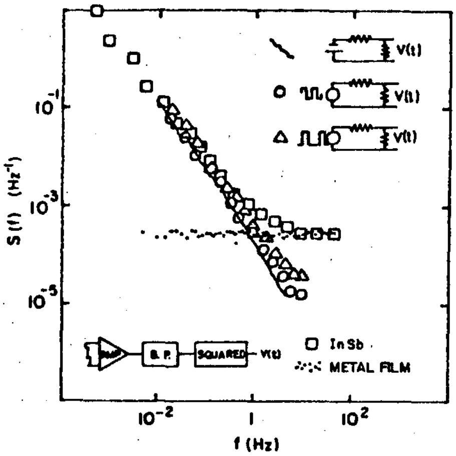

Fig. 1. S(f) versus f for an InSb film and a metal film resistor

The spectrum was remeasured with an ac technique in which a square wave current was applied to the sample. The PDP-11 was used as a digital lock-in to measure the amplitude fluctuations of the induced voltage. The relative spectrum plotted with open circles in Fig. 1, is identical with that produced by the steady current. The fact that the spectrum is 1/f-like down to frequencies very much less than the frequency of the square wave indicates that the long time correlations in the noise do not require a steady current.

In the two methods described, there was constant power dissipation in the sample. To investigate whether or not the constant power was the source of long-term correlation, we measured the spectrum using a technique in which a 10 msec pulse of current was applied with a period of 50msec. The noise voltage was measured during the pulse. The relative spectrum is plotted with open triangles in Fig. 1, and is consistent with the previous spectra.

The ac and pulse measurement indicate that the long-term correlations inherent in 1/f noise are not induced by a steady current or a steady dissipation of power. The measurements are consistent with equilibrium resistance fluctuations, whether or not these fluctuations arise from temperature fluctuations. The resistance of a sample in thermal equilibrium at temperature T may be determined by measuring the mean square Johnson noise voltage, $P=\overline{V^2}=4k_BTRB$, where $B=f_1-f_o$ is the bandwidth $(f_o \ll f_1)$. If we assume for the moment that temperature fluctuations have a negligible effect on P compared with resistance fluctuations, as appears to be the case with semiconductors, for fluctuations at frequencies $f \ll f_o$ we have

$$\frac{\Delta P}{\overline{P}} = \frac{\Delta R}{R} + \pi(t). \qquad (1)$$

Here, $\pi(t)$ represents the fluctuations in P (which are white) when R is constant. Hence, the relative power spectrum for fluctuations in P has the form

$$\frac{S_P(f)}{\overline{P}^2} = \frac{S_R(f)}{R^2} + \text{constant.} \qquad (2)$$

The constant background term decreases as B is increased. Low frequency fluctuations in R show up as an amplitude modulation of the mean square Johnson noise voltage.

Johnson noise from the InSb film was amplified, passed through a bandpass filter (10kHz to 300kHz), squared with an analog multiplier, and passed through a low pass filter. The output from this filter, P(t), had an instantaneous value that was proportional to the square of the Johnson noise voltage. The relative noise power spectrum of this signal, $S(f)=S_P(f)/\overline{P}^2$ is plotted as open squares in Fig. 1. The white spectrum at low frequencies above 1Hz arises from the term $\pi(t)$. The 1/f spectrum at low frequencies matches the spectra obtained by the other techniques. To ensure that the 1/f spectrum arose from sample fluctuations rather than noise inherent in our electronics, we replaced the InSb with a metal film resistor (in which no 1/f noise could be detected in the presence of a large steady current). The spectrum is shown dotted in Fig. 1, and is white down to the lowest frequency measured.

We have made similar measurements on metal films. For continuous metal[2,3] films in the presence of a current, 1/f noise arises from temperature fluctuations that modulate the resistance. We have been able to show that dc, ac, and pulsed measurements produce identical spectra. We have attempted to observe fluctuations in the mean square Johnson noise developed by continuous metal films. Unfortunately, we have been unable to observe these fluctuations, which are below $\pi(t)$ for samples large enough to be metallic. However, we have succeeded in measuring Johnson noise fluctuations in very thin (~100Å) metal bridges in which current is most likely transported by a hopping process rather than by metallic conduction. Such films are known to be relatively much noiser than continuous films.[6] At frequencies below about 10^{-2}Hz, the power spectrum of the Johnson noise fluctuations was in good agreement with the power spectrum obtained using the ac technique.

References and Footnotes

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