Composition of $1/f$ Noise in Metal-Insulator-Metal Tunnel Junctions

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We have studied the low-frequency conductance fluctuations of very small-area metal-insulator-metal tunnel junctions. We find that the spectral power density at high temperature is typical of $1/f$ noise, but is resolved into a small number of Lorentzian spectra for $T \lesssim 80$ K. The thermally activated Lorentzians are described by a two-rate kinetics and a broad distribution of activation energies and attempt rates.

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The origin of excess low-frequency or $1/f$ noise in electronic devices has been an unsolved problem for many years.[1] Many theories explain such noise[1] in terms of an ensemble of microscopic fluctuators with a broad distribution of fluctuation rates, but no unambiguous demonstration of the validity of any particular theory has yet appeared. A fundamental problem is that the observed phenomenon, while ubiquitous, is also rather featureless. A voltage noise power spectrum which can be adequately described by $S_v(f)/V^2 = C/f^\alpha$, where α is of order unity, gives a severely limited number of characterizable quantities upon which to base definitive tests of microscopic theories. Thus, a logical experimental approach to the fundamental understanding of $1/f$ noise is to examine the phenomenon in such a manner as to resolve the behavior of the individual fluctuators, rather than to observe the featureless ensemble average. In this paper, we report the results of just such an examination.

Early work by Carruthers[2] on Schottky diodes suggested both the possibility of observing individual fluctuators and the value of low-temperature measurements in resolving the detailed character of $1/f$ noise. Ralls *et al.*[3] reported the observation of discrete resistance fluctuations in very small quasi-one-dimensional Si metal-oxide-semiconductor field-effect transistors (MOSFET's). The fluctuations were particularly prominent as a result of the small MOSFET channel dimensions. They suggested that such fluctuations are the source of $1/f$ noise in large MOSFET devices, but had insufficient statistics to demonstrate this claim conclusively. We have extensively studied the low-frequency noise properties of very-small-area metal-insulator-metal tunnel junctions from 2 to 300 K, combining the advantages of very-small-area devices and low temperatures to resolve clearly the behavior of the individual fluctuators and their combination into a $1/f$ noise spectrum.

Metal-insulator-metal junctions exhibit copious amounts of low-frequency conductance noise which we have attributed[4] to the slow filling and emptying of localized electron states in the tunneling barrier. Changes in the occupation of such states result in changes of the local tunneling barrier and thus in the conductance.[5] By studying junctions of very small cross-sectional area, $5\times10^{-10}\ \mathrm{cm}^2 < A < 10^{-8}\ \mathrm{cm}^2$, we have found that the measured voltage noise power spectrum S_v at $T \lesssim 80$ K for any of our devices can be uniquely resolved into a limited number (<5) of distinct Lorentzian conductance noise spectra of the form

$$I_b^2 S_1 \tau_{\mathrm{eff}}[1+(\omega\tau_{\mathrm{eff}})^2],$$

where the rate $1/\tau_{\mathrm{eff}}(V,T)$ determines the Lorentzian rolloff frequency, the magnitude $S_1(V,T)$ determines the total mean square conductance fluctuation contributed by that particular fluctuator, and I_b is the bias current.

The type of tunnel junctions which we have studied most extensively are Nb-$\mathrm{Nb_2O_5}$-PbBi devices with tunneling barriers formed by reactive ion beam oxidation[6]; they have been described in detail elsewhere.[4] We expect our barriers to be very similar to those formed by plasma oxidation in Nb-Pb alloy systems.[7,8]

We measured the tunnel junction voltage fluctuations with a four-point-probe arrangement and a low-noise field-effect transistor preamp while the junction was biased with a dc current I_b. The four-point probe allows us to check for contact noise by variation of the current ballast resistor. The measured voltage fluctuations were accumulated and fast Fourier transformed by a Hewlett Packard 5430A spectrum analyzer, resulting in a voltage noise power spectrum S_v over a bandwidth from 1 Hz to 25.6 kHz and accurate in magnitude to 3%.

Figure 1 shows the quantity f^*S_v for one particular junction at several values of T and I_b. These spectra demonstrate most of the important features typical of S_v for our junctions. Despite the rolling

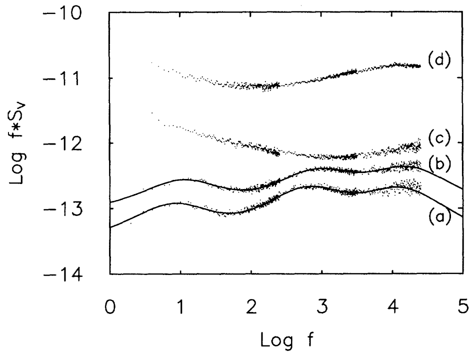

FIG. 1. f^*S_v for a metal-insulator-metal tunnel junction with $A = 10^{-9}$ cm^2 and $R = 110\ \Omega$. Traces a and b are at 24 K and 65 and 105 μA. The solid lines are fits described in the text. Traces c and d are at 85 μA and 170 and 26 K and cannot be accurately fitted with < 5 Lorentzians.

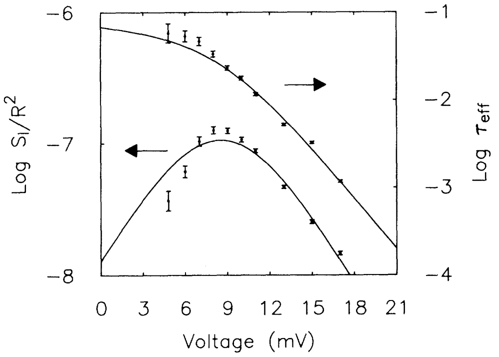

FIG. 2. τ_{eff} and S_1 vs V at $T = 4.2$ K. The fit is described in the text.

behavior of the spectra, they display a trend about a flat $1/f$ behavior. The magnitudes of the S_v at fixed T scale very well with I_b^2 as expected for conductance fluctuations. The spectra for different tunnel junctions biased at the same mean voltage scale well with $1/A$ as expected from any conductance fluctuation model where individual fluctuations affect only small regions of the barrier independent of total barrier area.

Our most striking observation is that for $A \sim 10^{-9}$ cm^2 and temperatures $T \lesssim 80$ K each of our spectra can be very accurately and uniquely fitted by a finite number (2–3) of distinct Lorentzian spectra plus a small [$\sim$(1–10)%] residual $1/f$ component. The solid lines in Fig. 1 are nonlinear least-squares fits using a three-Lorentzian function plus a small $1/f$ term. Every tunnel junction measured has its own particular collection of Lorentzians at a given T and V although the overall noise magnitude is remarkably consistent from device to device. Even junctions fabricated on the same substrate fail to exhibit in detail the same low-temperature spectrum. The spectra are reproducible over several months indicating a stationary noise process. The uniqueness of any particular fit is further validated by observing the changes in the spectra as a function of T and I_b. Each Lorentzian component is found to vary smoothly and continuously with these parameters in a manner similar to other Lorentzians in the bandwidth, but with a rate which is unique to each component.

Figure 2 shows typical behavior of $1/\tau_{\text{eff}}$ and S_1 for one particular Lorentzian at fixed T while V is varied. The rate $1/\tau_{\text{eff}}$ shows a knee at low voltage leading to a linear region on a semilog $1/\tau_{\text{eff}}$ vs V plot. At the same time, the power S_1 shows a peak on a semilog S_1 vs V plot. The peak in S_1 always occurs at the knee region of $1/\tau_{\text{eff}}$. In some cases $1/\tau_{\text{eff}}$ has only uniform linear behavior, in which case S_1 is either linearly increasing or linearly decreasing which indicates that we may be well to one side or the other of a peak in S_1. We find that a knee in $1/\tau_{\text{eff}}$ with a peaked S_1 is by far the most commonly observed behavior; this behavior strongly suggests that two separate rates combine to give the total $1/\tau_{\text{eff}}$.

Machlup[9] has presented a theory for noise processes characterized by two rates $1/\tau_1$ and $1/\tau_2$ (e.g., some time on and some time off) and found that the effective rate $1/\tau_{\text{eff}}$ and the power S_1 are given by

$$1/\tau_{\text{eff}} = 1/\tau_1 + 1/\tau_2,$$

$$S_1 = S_0\tau_{\text{eff}}/(\tau_1 + \tau_2),$$

where S_0 is determined by the physics of the particular system. We find that the rates $1/\tau_1$ and $1/\tau_2$ are given by

$$1/\tau_i(V,T) = 1/\tau_{0i}(T)\exp(eV/\gamma k_B T),$$

where γ is a constant always greater than 1 (usually ~ 5), independent of temperature and voltage but different for each of the τ_i. The solid lines in Fig. 2 are a simultaneous nonlinear least-squares fit to both $1/\tau_{\text{eff}}$ and S_1 using the Machlup equations and the exponential form for the $1/\tau_i$ above.

A key result is that at least two rates are required to characterize the microscopic kinetics which give rise to the peak in S_1 and the knee in $1/\tau_{\text{eff}}$. Many theories of $1/f$ noise[1] start with the assumption that the microscopic fluctuations are well described by single rate constants. Our data indicate that for this tunneling system, such an assumption is inadequate.

The peak power S_0 for any particular Lorentzian is a constant over the entire range of T in which that Lorentzian is visible in our bandwidth. Each Lorentzian is characterized by its own value of S_0, but all of our data fall in the range $5\times10^{-8} < S_0/R^2 < 5\times10^{-7}$ for junctions of area 1×10^{-9} cm^2, where R is the junction resistance. The rate $1/\tau_{\text{eff}}$ extrapolated to zero voltage is always a monotonically increasing function of T. For $T \gtrsim 15$ K, we find that $1/\tau_{\text{eff}}$ is always well characteized by the Machlup form with

$$1/\tau_i(V=0,T) = 1/\tau_0 \exp(E_a/k_{\text{B}}T).$$

Figure 3 shows a typical set of data showing thermally activated behavior of $1/\tau_{\text{eff}}$ for several Lorentzians visible for one junction at low voltage. We have measured apparent activation energies E_a of 10 to 150 meV in the temperature range from 4 to 70 K; in the same temperature range we find prefactors τ_0 in the range 10^{-9} to 10^{-13} sec, with $\tau_0 \sim 3\times10^{-13}$ sec being the median observed time. Typically, the higher the T at which a particular Lorentzian is first observed, the larger its E_a, but the spread in τ_0 makes this trend nonmonotonic.

Figure 1 also illustrates the behavior of S_v for high T. As T increases, we see a rapid increase in the number of distinct Lorentzians visible in our bandwidth until between 100 and 150 K the spectra become difficult to fit unambiguously. At this point, the known typical Lorentzian peak power and the measured total power indicate that roughly ten distinct Lorentzians are in the field of view. The total increase in S_v from roughly 100 to 300 K is nearly 2 orders of magnitude and is very similar to that seen by Dutta, Dimon, and Horn[10] in thin metal films. The spectra of most devices for $T \gtrsim 200$ K look very similar, with broad, shallow inflections in S_v which move to higher frequency with increasing temperature similar to those seen in silicon on sapphire.[11] Apart from the weak structure common to all the devices, in the high-temperature region the spectra are typical of $1/f$ noise. Thus, we observe a smooth transition for each particular device from nearly classic $1/f$ noise at high temperatures to a spectrum composed of a unique superposition of distinct Lorentzian components for $T \lesssim 80$ K.

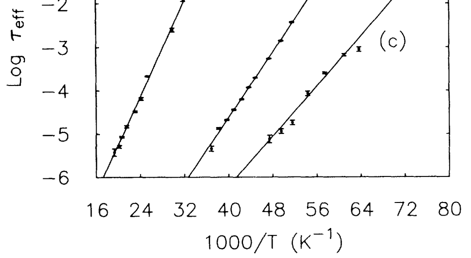

FIG. 3. Several activated rates for one junction at $A=10^{-9}$ cm^2 and $V=5$ mV. Lines are fits with $\tau_{\text{eff}}=\tau_0\exp(-E_a/k_{\text{B}}T)$: *a*, Log$\tau_0=-10.7$, $E_a=54.7$ meV; *b*, log$\tau_0=-12.1$, $E_a=37.3$ meV; *c*, log$\tau_0=-11.9$, $E_a=28.6$ meV.

Our full data set presents a self-consistent picture of how microscopic fluctuations give rise to $1/f$ noise and of how the microscopic fluctuations themselves behave. The noise up to ~ 100 K is clearly composed of a superposition of distinct Lorentzian spectra. Since each Lorentzian has an S_0 independent of T, then below 100 K increases in S_v are largely due to an increase in the total number of microscopic fluctuators active in our bandwidth. The rapid rise in S_v from ~ 100 to 300 K is completely consistent with a large increase in the total number of active Lorentzian contributions in our bandwidth, i.e., we have an activation-energy density of states which is relatively low for $E_a \lesssim 100$ meV and then increases rapidly. However, we do not expect that each Lorentzian power contributed to S_v remains T independent for all T since other conduction processes (e.g., thermionic emission) become important at high T.

The microscopic fluctuations themselves result in Lorentzian spectra characterized by $1/\tau_{\text{eff}}(V,T)$ and $S_1(V,T)$ which are well described by a two-rate model. The voltage dependence of the two rates is consistent with a barrier-lowering effect. We observe a wide range of temperatures over which $1/\tau_{\text{eff}}$ is thermally activated. Most theories of $1/f$ noise based on activated processes assume a single rate $1/\tau_0$ and a broad distribution of E_a. We find a broad distribution of both the activation energies and the attempt rates.

We now have the first direct and unambiguous link between observed low-frequency $1/f$-type noise spectra and individual Lorentzian spectra due to microscopic conductance fluctuations. The behavior of the Lorentzians in the activated region proves that a broad distribution of both attempt times and activation energies leads to the $1/f$ spectral behavior of tunnel junctions. Each microscopic fluctuation is characterized by at least two fundamental rates (e.g., escape rate and capture rate), thus requiring any successful theory to pay careful attention to the detailed kinetics of the fluctuation process. The data presented above represent a first step in the complete experimental characterization of the microscopic fluctuation kinetics.

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