Defect Interactions and Noise in Metallic Nanoconstrictions

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Two-level resistance fluctuations have been observed in clean metallic constrictions of sizes 40–8000 nm^3. At low temperatures the measured values for the activation energies, attempt frequencies, and scattering cross-section changes of such two-level fluctuations suggest that we are observing defects moving between metastable configurations. The strength of observed interactions between fluctuations has been estimated. At high temperatures interactions dominate the noise dynamics, causing complex fluctuations that evolve slowly in time to produce a $1/f$ noise spectrum.

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Many models of the excess low-frequency or $1/f$ noise in conducting systems rely on the superposition of independent Lorentzian-spectrum noise sources with a broad range of characteristic times.[1] Although the source of the Lorentzian spectra varies from model to model, evidence that thermally activated defect motion is the predominant microscopic mechanism in metal films has been accumulating.[2–6] In this Letter we report on observations of discrete resistance fluctuations in small (< 8000 nm^3) clean copper nanobridges between three-dimensional electrodes. These fluctuations provide a direct test of the standard Lorentzian model and allow detailed study of the microscopic mechanism. We propose that these fluctuations are the resistive effect of individual defects fluctuating between metastable configurations.

Samples are fabricated by electron-beam lithography and reactive ion etching to pattern a hole in a 50-nm-thick suspended Si_3N_4 membrane. The device region is then formed in a single processing step by our rotating the sample in high vacuum while evaporating copper, so that a 200-nm coating of metal is deposited on all exposed surfaces. The low-temperature elastic-scattering length of electrons in bulk films formed in such an evaporation is $\lambda_e \simeq 180$ nm, on the basis of residual resistivity. Scanning electron microscope studies of arrays of these holes show that each opening on the patterned side of the membrane is about 40 nm, while the openings on the other side are much smaller. The largest-resistance nanobridges are so resistive (3–200 Ω) that the opening on the far side of the membrane must be small compared to the patterned-side opening, so that it dominates the resistance. A schematic of the device region is shown inset in Fig. 1.

We approximate our sample geometry by a lengthless constriction between massive electrodes. The resistance R of a small constriction of radius a between massive electrodes can be approximated by

$$R = \rho/2a + 4\rho\lambda/3\pi a^2, \quad (1)$$

where ρ is the resistivity and λ is the electron mean free path.[7,8] Note that since $\rho \propto 1/\lambda$ there is a resistivity-dependent term and a resistivity-independent, geometrical term. If the geometrical term dominates the resistance (equivalently, if $\lambda \gg a$), an applied voltage is dropped almost entirely within a distance a around the orifice, and at low temperatures the derivative of the resistance with respect to voltage is an angular average of the phonon density of states times the electron-phonon interaction strength, a measurement known as point-contact spectroscopy.[7,8] Figure 1 shows a typical phonon spectrum for a 15-Ω device. Good point-contact spectroscopy confirms the validity of our sample geometry approximation and shows that the effective device dimensions are small compared to the electron mean free path.

Figure 2(a) shows an example of the simplest type of low-frequency resistance noise observed for temperatures

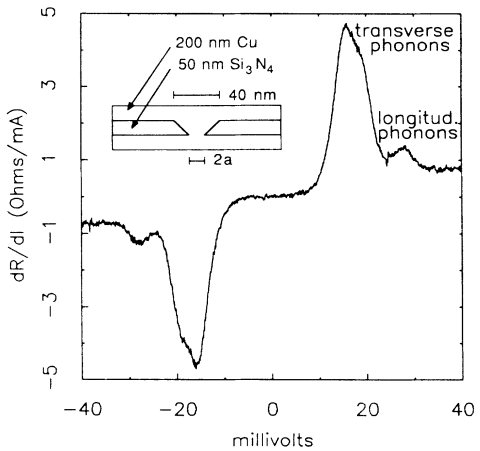

FIG. 1. Typical phonon spectrum for a 15-Ω nanobridge at 4.2 K. Inset: Schematic of the device region (not to scale), where a is the radius of the smallest constriction. Because of the high quality of the spectrum we can estimate $a \simeq 5$ nm for this sample.

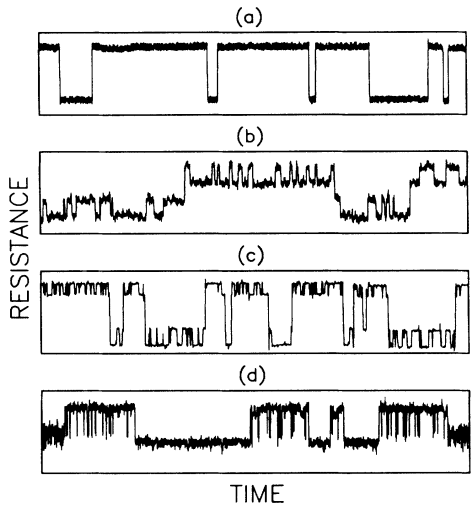

FIG. 2. Resistance vs time in copper nanobridges for $T < 150$ K showing several types of behavior. Fluctuations studied range from 0.005% to 0.2% of the total resistance. Time scales are somewhat arbitrary, as they depend on the temperature at which the fluctuation is observed. (a) A single TLF. (b) Two independent TLF's. (c) Amplitude modulation. Notice that the amplitude of the small TLF is larger when the large TLF is down than when it is up. (d) Frequency modulation of one TLF by another.

$T < 150$ K and for moderate dc device biases (< 50 mV). While voltage or current effects on the noise dynamics have been observed, all of the data presented here were taken in a bias range in which the noise dynamics are bias independent and the nanobridge resistance is stable in time, even though current densities are quite high ($\sim 10^9$ A/cm^2).[9] The sample resistance noise is dominated by random switching between two values. The distribution of times spent in the two states is found to be exponential resulting in a Lorentzian noise spectrum.[10] Above 20 K and for dc bias voltages below 5 mV, the two characteristic times $\tau_{\mathrm{up,down}}$ of each two-level resistance state have been measured over three to four decades, and are well described by thermally activated behavior $\tau \sim \tau_0 e^{E/kT}$. Attempt times τ_0 range from 10^{-11} to 10^{-15} s, clustering around 10^{-13} s, a time characteristic of vibration of weakly bound atoms, and activation energies E range from 70 to 300 meV. The fact that we observe a range of activation energies tells us that these samples are disordered. The measured values for E are somewhat lower than those expected on the basis of the temperature dependence of the $1/f$ noise magnitude in bulk copper films, $E \simeq 1$ eV.[3] However, note that at these low temperatures ($T < 150$ K) we are sampling only the low-energy tails of the distribution of noise sources, as τ_0 fixes the activation energy that will cause the noise to fall within the experimental bandwidth for a given temperature. In general, the higher the temperature range in which an active state is found, the higher the value of the two activation energies measured.

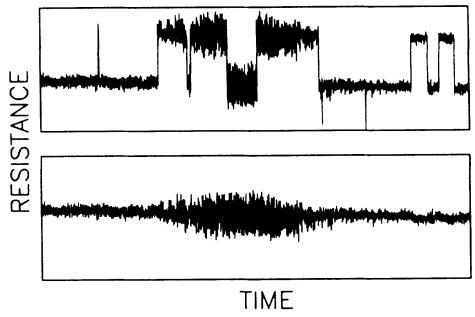

FIG. 3. Resistance noise due to a noise source diffusing through the sample volume, superimposed on a normal TLF (above) and with the TLF signal subtracted (below). The size of the resistance fluctuation caused by the diffusing defect grows from zero as the defect enters the device region and is a maximum when the defect is in the center of the device. Total transit time is about 30 s.

The number of active states increases with the temperature, and this fact, combined with the measured values of τ_0 and E, supports the view that we are observing the effect of defects fluctuating between two metastable configurations.

This view is also strongly supported by the change in scattering cross section, $\Delta\sigma$, that can be estimated from the magnitude of the resistance change due to the two-level fluctuation, and the resistivity-dependent part of the resistance which is estimated from the total sample resistance [Eq. (1)]. Assuming that the largest two-level fluctuators (TLF's) observed in a given device are in the center of the device, for noise from eight devices ranging from 5 to 180 Ω, we find $30\ \text{Å}^2 > \Delta\sigma > 1\ \text{Å}^2$. Thus the observed cross-section changes are on the order of atomic dimensions, which is reasonable for defect motion. Smaller cross-section changes may exist, but are indistinguishable from larger changes of scatterers near the edge of the device, because of the three-dimensional nature of the device.

Because this is a three-dimensional device, with the current density highest in the center of the device, we can readily distinguish between a localized defect fluctuating between metastable configurations and a defect diffusing through the metal. This is because any long-range defect motion will result in a change in the size of the resistance fluctuation as the defect moves toward or away from the device center. We have quite rarely seen signals characteristic of a defect diffusion through the sample, as shown in Fig. 3. The square switching in the upper figure is a stable TLF such as we have been discussing and has been subtracted out in the lower figure. The remaining noise signal slowly grows in amplitude and then slowly diminishes, as the noise source apparently enters the device region, passes through the center, and then leaves. Again, this behavior is quite rare, and is not a significant source of noise in these nanobridges. Since the noise in the nanobridges is dominated by

TLF's which below 150 K are quite stable in time, exhibiting the same behavior over days of data taking, we conclude that these fluctuations are not due to the diffusion of independent localized defects.

Figure 2(b) shows an example of noise where several independent TLF's are simultaneously active in the experimental bandwidth. However, we also observe interacting noise sources, where one TLF modulates the time, the amplitude, or both, of the other. Examples of amplitude modulation and frequency modulation are shown in Figs. 2(c) and 2(d). Large amplitude modulation such as that of Fig. 2(c) requires the defects to be within a few lattice spacings of each other because of electron screening effects, and is fairly rare. For a particular TLF (not shown in the figures) being modulated by another, we find

$$\tau_{0,\mathrm{up}} = 10^{-11.1 \pm 0.1}\ \mathrm{s}, \quad \tau_{0,\mathrm{down}} = 10^{-11.4 \pm 0.1}\ \mathrm{s},$$

$$E_{\mathrm{up}} = 70.5 \pm 0.8\ \mathrm{meV}, \quad E_{\mathrm{down}} = 72.3 \pm 0.6\ \mathrm{meV}$$

when the modulating defect is in one configuration, and

$$\tau_{0,\mathrm{up}} = 10^{-11.5 \pm 0.1}\ \mathrm{s}, \quad \tau_{0,\mathrm{down}} = 10^{-11.93 \pm 0.02}\ \mathrm{s},$$

$$E_{\mathrm{up}} = 72.5 \pm 1.0\ \mathrm{meV}, \quad E_{\mathrm{down}} = 82.0 \pm 0.2\ \mathrm{meV}$$

when the modulating defect is in its other configuration. Frequently, as in Fig. 2(d), the fluctuation moves completely out of the experimental bandwidth, and, assuming that the change in activation energy dominates, we can only place a lower bound on the change in activation energy due to the interaction, $\Delta E/E > 0.2$. The observed shift in both E and τ_0 clearly points to the interaction mechanism's being a shift in the detailed potential of the affected defect. The nature of this defect interaction mechanism is, of course, open to discussion, but it seems reasonable to propose that, as proposed for tunnel junctions,[11] when one defect changes its configuration, the change in its strain field at another defect is responsible for the observed changes of the second defect's attempt times and activation energies.

As the temperature is raised above 150 K the density of defects active in the experimental bandwidth increases, and only a generic $1/f$ noise spectrum can be observed. Standard models of $1/f$ noise use a superposition of many independent Lorentzians to produce a $1/f$ spectrum, but the $1/f$ noise that we observe is not simply due to an increase density of stable noninteracting TLF's. This is seen by our looking at the smallest (highest resistance) devices where, for $T > 150$ K, at any given instant the noise is composed of one or only a few TLF's, but where the characteristic time, amplitude, and number of these states change randomly with time. Figure 4 shows various snapshots of the resistance fluctuations of a 90-Ω sample at 300 K, which illustrate this behavior. The period between changes can range from much less than a second to much greater than an hour. We stress that the noise shown in Fig. 4 typically has a smooth $1/f$ spectrum when averaged over several minutes, even though only a few TLF's are active at any given instant.

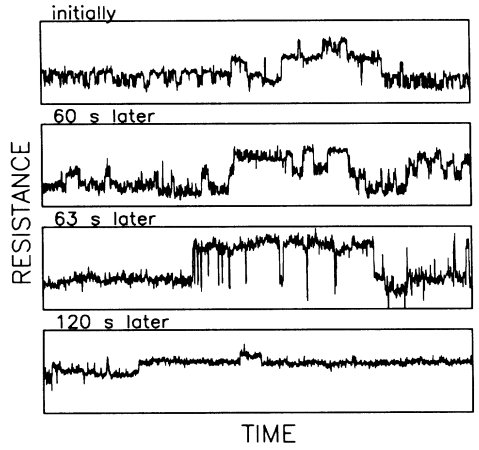

FIG. 4. Resistance vs time for a 90-Ω nanobridge at $T = 300$ K displaying the wandering nature of the low-frequency noise, which is still composed of discrete resistance fluctuations. Each noise snapshot is about 0.2 s long.

As is apparent from the comparison of the diffusion noise shown in Fig. 3 to the high-temperature behavior shown in Fig. 4, the high-temperature behavior is still not simple diffusion of localized defects. Indeed, its behavior suggests a random walk in a very complicated potential with many accessible local minima. At low temperatures we have proposed that we have a "local defect-induced potential" causing the observed interactions between defects. Consequently some of the randomness of the complicated potential sampled at high temperatures is caused by the defects themselves, and if a substantial fraction of these defects are moving, the potential seen by any one defect will itself by fluctuating with time. The noise-producing defects in the sample seem to comprise a "glassy defect system" which effectively melts above 150 K for our experimental bandwidth, sampling alternative configurations in an attempt to anneal to equilibrium, while below 150 K it is frozen into one or another configuration of a few two-level defects. This view is supported by the fact that once a sample is taken above about 150 K and then recooled, the nature of the TLF noise that is found is, in general, completely different from that which was observed before the sample was heated.

In summary we have made a detailed study of discrete two-level resistance fluctuations in metallic nanoconstrictions. The amplitude and thermally activated dynamics of independent TLF's is fully consistent with their origin's being the random transition of defects between two metastable configurations. These fluctuations, which cannot be ascribed to the simple diffusion of localized defects, have been observed to interact quite strongly. At low temperatures the active TLF's are determined by the

particular configuration that is frozen into the "defect glass" upon cooling, while above the effective defect-glass melting point the slowly evolving defect configuration results in very complex fluctuations with a $1/f$ spectrum, even in devices that are so small that only a few defects are active in the experimental bandwidth at any given instant. Since strong interactions between two-level defect states have been identified both in insulating tunnel barriers[11] and now in metallic structures, it seems reasonable to suggest that such interactions are an attribute of most, if not all, two-level defect systems.

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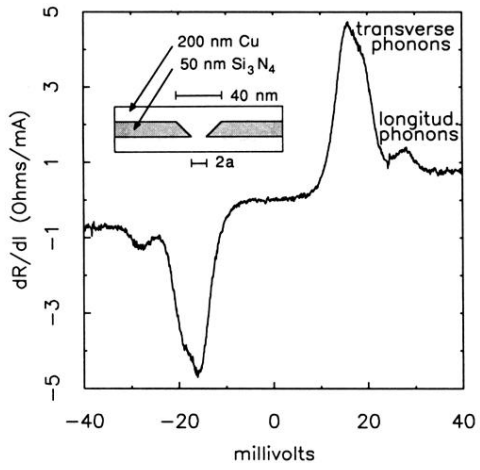

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