Impact of a single defect on the conductance: Local interference and universal conductance fluctuations

K. S. Ralls
*School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853-2501 and Chemistry and Materials Science, Lawrence Livermore National Laboratory, Livermore, California 94550**

D. C. Ralph and R. A. Buhrman
School of Applied and Engineering Physics, Cornell University, Ithaca, New York 14853-2501
(Received 14 September 1992; revised manuscript received 8 January 1993)

By reversibly reconfiguring a single defect in a mesoscopic copper nanobridge < 10 nm wide, we have measured *both* the local interference and universal-conductance-fluctuation contributions to the impact of a single defect on the conductance. Both effects are in good agreement with the predictions of theory, despite the fact that the defects that reconfigure are more complicated than simple point defects.

In recent years, apparently random variations in the electrical conductance as a function of magnetic-field strength,[1] the Fermi energy,[2] or an applied voltage[3,4] have been observed in a large variety of disordered metallic samples whose size is of the order of the electron phase-coherence length λ_ϕ. The theory of universal conductance fluctuations[5,6] (UCF) successfully explains the aperiodic fluctuations in such mesoscopic samples as being due to quantum interference. Further predictions by Al'tshuler and Spivak[7] and by Feng, Lee, and Stone[8] assert that quantum interference effects in mesoscopic samples can enhance the impact of the motion of an individual defect to give a conductance change as large as the "universal" amount of e^2/h, with prefactors depending on the sample geometry and the strength of the scatterer. These predictions are supported by studies of the low-frequency $1/f$ noise in several types of disordered metallic samples at low temperature.[9] An alternative theory, the local interference (LI) mechanism,[10] describes conductance changes as due simply to changes in the local scattering cross section of defects as they move. This mechanism explains the noise observed in the regime of higher temperatures and/or less disorder, where the phase coherence length is comparable to the elastic mean free path λ_e.

A number of experimental groups have reported observations of reversible, discrete resistance changes in the UCF regime, presumably due to the movement of single defects, which are visible in the conductance because of the UCF enhancement. Of these studies, the observations of Gusev *et al.*[11] and Zimmerman, Golding, and Haemmerle[12] are noteworthy because their samples were stable enough that the magnetic-field dependence of the conductance change due to one moving defect could be measured over a range of fields much larger than the correlation field. An average over the magnetic field thus allowed a persuasive quantitative confirmation of the UCF theory. However, as their samples were too large to allow a direct measurement of the LI contribution to the defect reconfiguration, they could not establish that the defects they were studying actually had an atomic-sized change in the scattering cross section. We note that experiments examining low-temperature defect fluctuations in the disordered barrier layer of small tunnel junctions have found that interactions between atomic defects can be so strong that large tunnel-junction resistance fluctuations are often observed[13,14] that are due to the cooperative reconfiguration of many atomic-scale defects.

In this paper we report measurements of the impact on the sample conductance of the reversible motion of a single scatterer within a disordered metal sample which is much smaller than any studied previously. The small size and unique geometry of our samples allow separate measurement of both the LI and UCF contributions to the conductance changes at low temperature. This is achieved by using a sample bias to alter the phase-coherence length, thereby reversibly moving the sample between the UCF and LI regimes. From the direct measurement of the size of the LI contribution at high voltages we establish that we are indeed studying the impact of an atomic-sized defect reconfiguration on the UCF phenomena. At low voltages, we measure a UCF enhancement that is in good agreement with theory. Our measurements provide a direct view of a regime in which both LI and UCF effects are important and are a compelling demonstration of the qualitatively different effects of defect fluctuations inside and outside the UCF regime.

The samples we have studied, namely, nanobridges, are the thin-film equivalent of metal point contacts. They are fabricated[15] by first using electron-beam lithography to pattern a single 40–100-nm-wide dot in resist on top of a 50-nm-thick silicon nitride membrane. This hole is then transferred to the silicon nitride using a reactive ion etch that just breaks through the membrane, so that the far side opening is much smaller than that actually patterned lithographically. Finally, the wafer is rotated while copper is evaporated, filling the hole and coating both sides of the membrane in a single evaporation.

As fabricated, these metallic nanobridge samples are clean enough that electron transport through the nanobridge is predominantly ballistic. This fact is demonstrated by point-contact spectroscopy (PCS) (Refs. 16 and 17) studies. The idea behind PCS is that as the voltage across the device is increased, electrons may gain enough

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energy to emit a phonon and backscatter away from the constriction. This increases the differential resistance of the device for voltages corresponding to phonon energies, and in fact (for a ballistic constriction) the second derivative of the I-V characteristic yields the phonon density of states times an electron-phonon coupling strength. An example of such a PCS spectrum for an as-grown Cu nanobridge at 4.2 K is shown in Fig. 1(a). A short elastic mean free path in the constriction region would dramatically decrease the PCS amplitude in a well-characterized way[18] by randomizing the trajectories of electrons which are backscattered by phonon emission. The amplitude of the PCS signal in Fig. 1(a) is as large as expected for a ballistic Cu construction of this resistance, based on previous reports of PCS in ballistic Cu constrictions,[19–21] and is consistent with the amplitudes measured in all of our as-deposited Cu devices. This indicates that the probability for an electron to undergo elastic scattering while passing through the nanobridge is low. The resistance of a three-dimensional point contact may be approximate as the sum of diffusive and ballistic contributions,[17,18]

$$R = R_B + R_D = \frac{h}{e^2}\frac{8}{(k_F d)^2} + \frac{h}{e^2}\frac{3.2}{(k_F d)^2}\left[\frac{d}{\lambda}\right], \quad (1)$$

where d is the constriction diameter, k_F is the Fermi wave vector, and λ is the mean free path. Since an as-grown nanobridge is a ballistic device, its resistance is largely determined by R_B. From this we determine that typical diameters for these clean nanobridges range from 3–20 nm, for devices with resistances 100–3 Ω. These size estimates are in accord with plan view transmission electron microscopy (TEM) studies of our devices,[15] though TEM may not be used for routine characterization of the samples because the high-energy electron beam tends to alter or destroy our smallest, highest resistance devices. For comparison of the relevant length scales, the bulk Cu film has an impurity-limited low-temperature mean free path $\lambda_e \sim 180$ nm.

The low-voltage differential conductance of a ballistic Cu nanoconstriction, obtained by standard lock-in techniques, is shown in the upper curve of Fig. 2 as a function of applied bias. This conductance is featureless at the level of 0.02 e^2/h for voltages up to the bias point where inelastic scattering due to single-phonon emission begins to become detectable. (The asymmetry evident in the figure is often present for nanoconstrictions and is believed to be a thermoelectric effect unrelated to quantum interference). The featureless conductance behavior is a consequence of the ballistic transport though the nanobridge combined with the three-dimensional fan-out of the electrodes from the constriction region. These factors diminish the proportion of electron paths that undergo several elastic-scattering events and can thus contribute phase differences to quantum-mechanical interference effects. Because UCF effects are due to diffusive paths through the sample, when such paths make up a minority

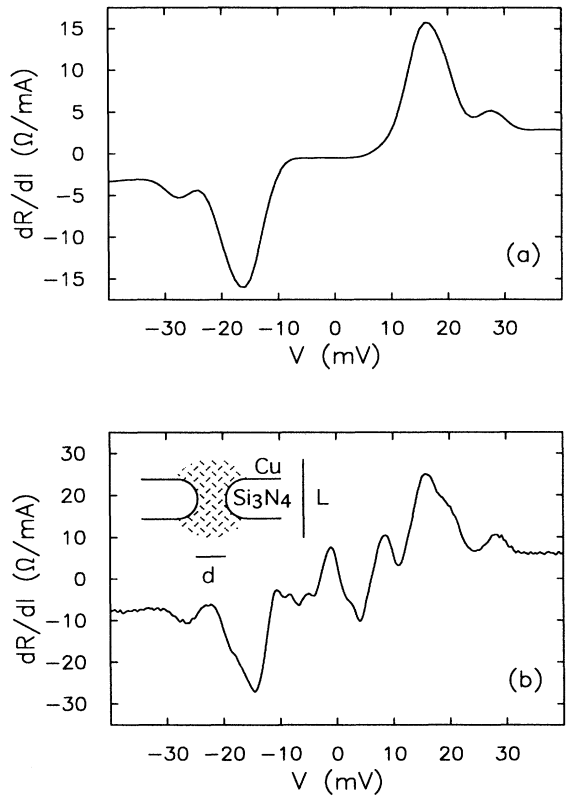


FIG. 1. (a) PCS signal for a clean 68-Ω copper nanobridge, measured at 4.2 K. The large amplitude of the PCS signal establishes that transport in the as-fabricated devices is ballistic. (b) PCS signal of the disordered 98-Ω nanobridge used for this study, measured at 4.2 K. From the height of the first phonon peak relative to that found for ballistic nanobridges of the same resistance, we can estimate the amount of elastic scattering in the constriction region. The inset shows a cross-sectional schematic of the disordered device, with a constriction diameter d and a disordered region of length L sandwiched between clean three-dimensional electrodes.

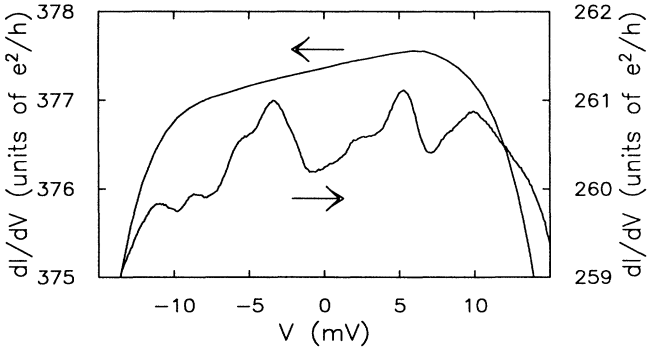


FIG. 2. Upper curve: The low-voltage differential conductance of a ballistic nanobridge at 4.2 K does not show any conductance fluctuations with amplitude close to the order of e^2/h, because UCF effects are suppressed in this geometry. 1 $e^2/h = (25\,813\ \Omega)^{-1}$. Lower curve: The low-voltage differential conductance of a disordered nanobridge at 4.2 K shows conductance fluctuations of order e^2/h, because in this device a significant fraction of paths involve diffuse transport.

of all possible paths, UCF effects are strongly suppressed.[19,22]

Because UCF effects are small in ballistic structures with three-dimensional electrodes, we add defects to an existing clean nanobridge before studying these effects. This is done by applying high voltage (100–500 mV, depending on the metal and the sample resistance) across the sample so that copper atoms are moved by electromigration. The resistance of the sample may go either down or up during migration, as atoms move into or away from the narrowest part of the constriction. The changes may be gradual and quasicontinuous or may occur in sudden jumps as large as 60% of the initial resistance. Electromigration in nanoconstrictions has been discussed at length previously.[15,23] The samples described in this paper were studied after the sample resistance dropped suddenly 10% or more below its initial value. Because these devices were originally ballistic, any decrease in resistance is an indication that new metal atoms are added to the narrowest part of the constriction region. It is conceivable that metal in the immediate vicinity of the constriction may actually melt and be quench frozen suddenly under high-bias conditions. The additional conducting material is not perfectly ordered, so this electromigration technique allows us to change λ_e within the nanobridge region. We will present data that show that this disordered region extends only a very short distance away from the constriction into the electrodes—to occupy a region less than 30 nm in extent. The remaining electrode material remains clean because electromigration is significant only where the current density is high. A probable cross section of the disordered nanobridge is shown schematically in the inset to Fig. 1(b).

This electromigration process introduces sufficient elastic scattering into the nanobridge region that UCF effects are quite significant, as discussed below. Nevertheless the disordered nanobridges still have a sizable PCS signal, as shown in Fig. 1(b). In this figure, the aperiodic structure at low voltages is due to conductance fluctuations, while the antisymmetric peaks beyond 10 mV are due to phonon emission. The height of the first phonon peak at 15 mV in Fig. 1(b), 26 Ω/mA, gives information about the mean free path within the constriction region. Predominantly ballistic nanobridges of this resistance have an average peak height of 40 Ω/mA.[19] Elastic scattering serves to reduce the PCS signal in a way that is calculable. From the paper of Yanson and Shklyarevskii,[18] we deduce that $\lambda/d \sim 2$ for this factor of 0.7 reduction. However, this estimate is complicated by the fact that after we use electromigration to add disorder to the devices, they may not exhibit the ideal point-contact geometry. For instance, if the constriction region took the shape of a tube of some finite length, the PCS signal would be enhanced relative to the case of a lengthless orifice. Our estimate $\lambda/d \sim 2$ is uncertain to perhaps a factor of 2.

In contrast to the results obtained with an as-grown ballistic nanobridge, the low-voltage behavior of an electromigrated sample, as shown in the lower curve of Fig. 2, has large aperiodic variations in the differential conductance as a function of bias, indicating that electromigration has indeed shortened λ_e and brought the sample to the UCF regime. A discussion of the voltage dependence of these fluctuations appears in a separate paper;[24] here we will concentrate our attention on the amplitude of these fluctuations and on their sensitivity to the change of an individual defect in the nanobridge. The overall root-mean-square (RMS) value of the time-independent conductance fluctuations for the data of the lower curve in Fig. 2, averaged between −10 mV and 10 mV, is 0.27 e^2/h. This is somewhat smaller than the value 0.78 e^2/h expected from UCF theory for a three-dimensional device,[25] but that theory is not strictly applicable to a constriction geometry such as that of the disordered nanobridges. In addition, there is still significant ballistic transport through the nanobridges, which tends to reduce the UCF signal observed.[19,22]

As a consequence of the clean, three-dimensional electrodes fanning out from a tiny disordered constriction, the UCF effects that we observe are generated only in the tiny disordered region, which is much shorter than the phase-coherence length.[24] This point is clearly demonstrated by the insensitivity of these conductance fluctuations to a magnetic field. As shown in Fig. 3, the conductance as a function of voltage for this nanobridge is largely insensitive to magnetic fields ranging from 0–2.6 T. Although some of the small amplitude, fine energy structure is influenced by the field, the larger scale structure remains unchanged; we clearly have not yet reached the correlation field for this sample. Samples with a larger disordered nanobridge region have shown greater sensitivity to an applied field, in accord with the conclusion that the significant UCF effects are generated only in the

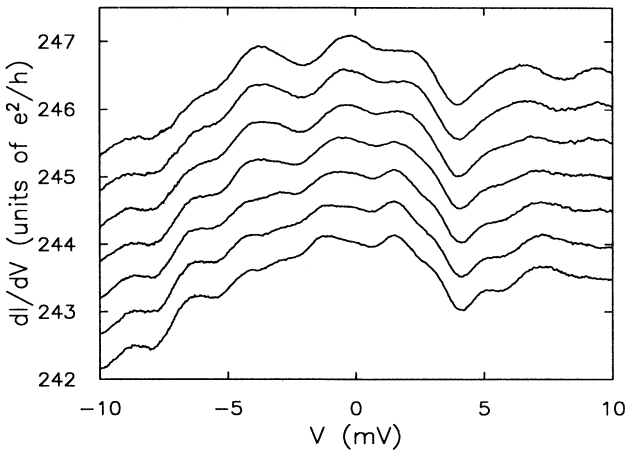


FIG. 3. Differential conductance as a function of voltage for the disordered nanobridge at 2 K for magnetic fields ranging from 0–2.6 T, with 0.43-T difference between each measurement. Beginning with the zero-field trace at the bottom, each data set has been offset from the previous one by 0.5 e^2/h for clarity. The magnetic-field dependence of the UCF is very weak, confirming that the UCF are generated within a very small sample region. The zero-field trace differs from the lower curve of Fig. 2 because defects in the device were reconfigured between the two measurements.

disordered region of these samples.

By calculating the area enclosing a flux quantum for the highest field studied, 2.6 T, we can place a stringent upper bound on the length scale L over which the fluctuations are generated. We conclude that L is considerably less than 30 nm, even at low voltages where λ_ϕ is 1 μm or longer.[24] If longer, extended paths into the electrodes were important in generating the UCF, we would expect the fluctuations to be extremely sensitive to much weaker magnetic fields. The fluctuations are slightly more sensitive to a magnetic field oriented parallel to the direction of current flow (shown in Fig. 3) than to perpendicular fields. Therefore the disordered region surrounding the constriction may be a bit wider than it is long. This is not surprising considering the means by which the disordered region is formed.

We have previously discussed observations of time-dependent two-level resistance fluctuations due to the reversible reconfiguration of individual defects in ballistic constrictions.[23,26] These observations were made only in the LI regime, and the amplitude of the resistance changes was due entirely to changes in the local scattering cross section of defects as they moved. The switching noise in the resistance was measurable only because of the extraordinary small size of the devices; as discussed above, the UCF enhancement could play no role. As a result, the amplitude of the discrete resistance changes due to fluctuating defects showed no dependence on magnetic field or voltage. In the disordered nanobridge samples similar two-level resistance fluctuations are also observed, but here, in the low-voltage regime, UCF contributions to the changes in sample conductance are readily observable and these contributions do show a dependence on voltage and magnetic field.

To quantify the effect of the reconfiguration of a single defect on the UCF signal we utilize the fact that the fluctuation rate of a metastable defect increases exponentially with sample bias.[23] Thus we are able to turn defect movement on and off controllably, in order to test the UCF predictions at a microscopic level. This is accomplished by taking the sample to a voltage where a large stable two-level resistance fluctuation is active (this occurs at 20–70 mV depending on the specific defect configuration of the device), allowing it to switch to its other configuration, and then returning to low voltage. The defect is then frozen in this configuration until the sample is once again taken to higher voltages.

To make direct comparisons with theoretical predictions we will discuss a single bistable defect in the sample of Figs. 1(b), 2 (lower curve), and 3, which produced two-level conductance noise of amplitude 0.15 e^2/h at 30 mV. At this high voltage the very short electron-phonon scattering time serves to dephase the electrons,[24] and the conductance signal is dominated by the LI contribution. Figure 4 shows four low-voltage differential conductance traces measured in between excursions to higher voltage, during which the defect discussed above was switched between its two positions. We took data only below 12.5 mV to ensure that the defect had no chance of reconfiguring during the measurement. The curve for each defect configuration is reproducible to ± 0.02 e^2/h,

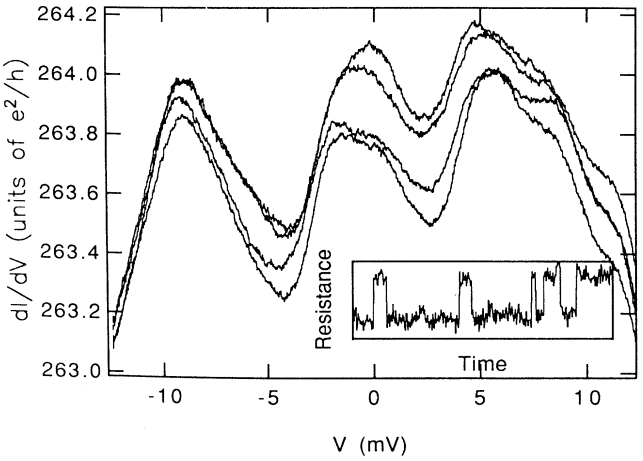


FIG. 4. Four different measurements at 4.2 K of the differential conductance as a function of voltage. In between measurements the sample bias was taken to about 30 mV in order to reconfigure a single influential scatterer; see inset. In order to demonstrate our reversible control of the defect, the conductance was measured first with the defect in its high conductance state, then in its low conductance state, then the high conductance state, and again in the low conductance state. Small deviations between the curves for the defect in the same configuration are presumably due to the random reconfiguration of less influential defects during the excursion to high voltages. The amplitude of the resistance changes in the inset is 0.055 Ω and the time scale extends 0.5 sec. The rate of switching may be varied over orders of magnitude by adjusting the bias.

demonstrating that indeed we could reversibly control this defect. The deviations are presumably due to less influential two-level fluctuations, which were also activated at high bias.

The difference between the curves shown in Fig. 4 is the conductance change Δg due to the movement of the defect. We display this difference in Fig. 5. The effect of the reconfiguration upon the sample conductance depends on voltage in a random manner, becoming as much as twice as large as its average value. The effect of the movement of a single scatterer therefore has a pronounced change in character, going from fluctuating with V in the UCF regime to being V independent in the LI regime. The average value of the change in Fig. 4, 0.148 e^2/h, is identical to the LI contribution measured at higher voltage, where UCF effects are reduced in size. Since the average of the fluctuations is the LI contribution, we identify the contributions due to quantum interference as the deviations from the average change.

As seen in Fig. 4, the characteristic voltage scale of the fluctuations is approximately 5 mV at 4.2 K, so we can readily average over a number of voltage correlation scales in determining the RMS average UCF contribution. The result is 0.074 e^2/h with a statistical error of roughly 0.033 e^2/h, as the average is taken over a range of approximately 5 correlation scales. The UCF fluctuations enhance the overall RMS conductance change above the LI value, demonstrating directly how quantum interference can amplify the impact of a scatterer. Of

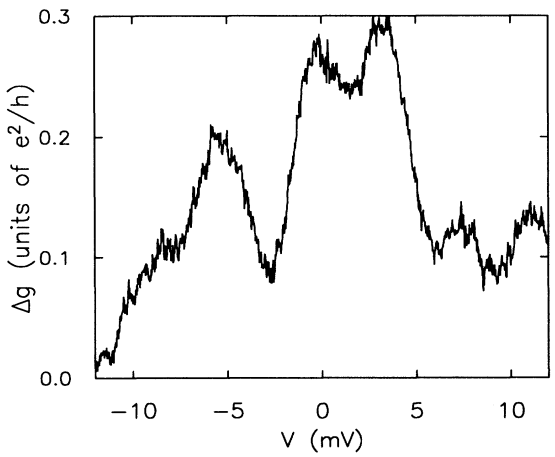


FIG. 5. Impact of the single scatterer on the conductance, given by the average difference between the high and low conductance states shown in Fig. 4, is strongly voltage dependent due to the UCF contribution. Notice that the impact of the defect over many correlation voltages does not average to zero, reflecting the fact that the local interference contribution to the conductance is quite large in this truly microscopic sample.

course, our samples are so small that the LI contribution is still larger than the RMS UCF enhancement. The LI contribution decreases rapidly with increasing sample volume, leaving the UCF enhancement as the dominant effect at low temperatures for large samples.

In order to compare our results with theory, estimates are required for the effective sample dimensions and the mean free path in the disordered nanobridge region. From Eq. (1) we see that it is difficult to obtain a large diffusive resistance in the point-contact geometry. For example, a diffusive point contact with $d=20$ nm and $\lambda_e=10$ nm has $R=3\ \Omega$. Even a 10-nm constriction with $\lambda_e=1$ nm would have a resistance of only 66 Ω. Our sample resistance of 98 Ω would only be found in a large device if it had an extraordinarily small mean free path. But the point-contact spectroscopy signal, as discussed above, demonstrates that this is not the case. From the sample resistance, we conclude that this nanobridge still contains quite a small constriction within the disordered region, with constriction diameter $d<10$ nm. Our best estimate for d, using in Eq. (1) the result from the point-contact spectrum that $\lambda/d\sim 2$, gives $d\sim 4$ nm. The smallest possible device dimensions for a given resistance are for a ballistic device; we conclude that for the 98-Ω sample for which the data of Figs. 3–5 were obtained, $d>3.4$ nm. Combining this result with the estimates made above from the magnetic-field dependence and PCS, we have the following bounds on the device parameters: $L<30$ nm, $10\text{ nm}>d\geq 3.4$ nm, and $\lambda/d\sim 2$.

The size of the LI contribution, 0.15 e^2/h, measured at high bias voltage, is consistent with changes expected by theory for the movement of an atomic-sized defect.[10] Because we specifically looked for the largest resistance change we could find in this sample, the scatterer cannot have been far from the center of the device, where it has a maximum impact on the resistance. In a ballistic sample, the resistance is inversely proportional to the cross-sectional area A of the constriction, see Eq. (1). A change in scattering cross section changes this area, so that we expect a relative conductance change

$$\frac{\Delta G}{G}\approx\frac{\Delta\sigma}{A}\ , \tag{2}$$

where $\Delta\sigma$ is the change in scattering cross section. This formula remains approximately correct even for samples that are not purely ballistic. For our range of constriction dimensions we find $4\ \text{Å}^2>\Delta\sigma>0.5\ \text{Å}^2$. This is a typical range for scattering cross-section changes calculated with the LI theory.[10]

This result, however, should not be taken as indicating that the defect responsible for this resistance change is a simple, isolated point defect. Previous studies of these two-state defects in metallic point contact[26] in the LI regime have shown that, in general even in quite clean metal films, interactions between such defects are so strong, stronger than can be accounted for by simple elastic dipole-dipole interactions, that these defects cannot be properly considered as isolated point defects. The available data clearly show that these defect reconfigurations are due to flexing of large defect complexes, even if the resultant change in the local scattering cross section is atomic sized. These direct observations are consistent with the suggestion that such defect interactions account for the distributions of defect activation energies seen in $1/f$ noise studies of metal films, and with the strong defect interactions necessary to account for the very large resistance fluctuations sometimes seen in tunnel-junction systems.

In the UCF regime, when comparing our data with theory, we can only compare to the UCF theory for a wire of uniform cross section,[8] as calculations have not yet been made for a constriction geometry. In addition, the theory assumes diffusive samples with $L\gg\lambda_e$. We therefore cannot claim any more rigor than a rough order of magnitude comparison between UCF theory and experiment. Nonetheless, the agreement is satisfactory. The UCF prediction for the RMS impact of the motion of one point scatterer within a device of length L_z and cross section L_x by L_y is

$$(\delta G)^2=\frac{e^4}{h^2}\frac{\sigma P L_z}{\lambda L_x L_y}\left[1-\left[\frac{\sin\frac{1}{2}k_F\delta r}{\frac{1}{2}k_F\delta r}\right]^2\right], \tag{3}$$

where δr is the distance the defect moves, P is a prefactor of order 1, and σ is the average scattering cross section for defects in the sample. A possible factor of 4 reduction in this quantity due to spin-orbit scattering in copper does not apply to our samples because the effective spin-orbit scattering length L_{so}^* is longer than our effective sample length.[27,28] We also do not include an energy-averaging factor to correct for nonzero temperatures because we measure our fluctuations at low enough temperatures that thermal broadening is not significant.

The maximum value of expression (3) occurs when $\delta r=2\pi/k_F$. A reasonable value for σ for a point defect is $4\pi/(k_F)^2$. We approximate $L_x=L_y=d$. For the two sets of values $L_z=30$ nm, $d=10$ nm, $\lambda/d\sim 2$ and $L_z=30$

nm, $d=3.4$ nm, $\lambda/d\sim 2$, we find that theory predicts a maximum of $(\delta G)^2=1\times10^{-3}$ $(e^2/h)^2$ and 3×10^{-2} $(e^2/h)^2$, respectively. These results comfortably bracket our measured value of 5.5×10^{-3} (e^2/h^2). The theoretical values are likely slight overestimates due to our use of $L_z=30$ nm, which is really an upper bound for the effective sample length, and our neglect of the fact that transport in the sample has some ballistic component, which reduced the amplitude of the time-independent UCF signal below that expected for a three-dimensional device. Our measurements are certainly fully consistent with the theoretical predictions.

It is, however, somewhat remarkable that the theory performs as well as it does in describing both our measurements and others.[9,11,12] In particular, the UCF theory assumes that the defect that is moving is an isolated point defect, yet as discussed above the previous studies of these bistable defects have shown that they are not simple point defects but an interacting defect complex.[26] One might expect that the reconfiguration of extended or strongly interacting defects would enhance the UCF effect somewhat. However, despite the fact that it appears to be overly simplistic to assume that in a real experimental system an isolated point defect can move or reorient in an otherwise rigid environment without the surrounding defect complex relaxing, the theory does appear to yield the correct order of magnitude of the observed effect.

In summary, we have produced nanobridge samples consisting of a very small region (diameter <10 nm, effective length $L\leq 30$ nm) of disordered material connecting two clean, three-dimensional electrodes. With such samples we have measured the conductance change caused by the reversible reconfiguration of a single defect. The disordered metal sample is so small that both the LI and UCF contributions to the conductance change can be measured directly as a function of voltage. Our data demonstrate clearly the features of both mechanisms from a microscopic viewpoint. We determine the RMS impact of quantum interference effects by averaging the UCF over a range of low voltages. The magnitudes of both the LI conductance change and the UCF enhancement are in good agreement with theory, despite the fact that the actual defects in thin metal films that reconfigure at low temperatures are substantially more complicated than the isolated point defect used in both theories.

We thank S. Hershfield and R. H. Silsbee for many useful conversations. We acknowledge the expert assistance of Richard Tiberio and other staff members of the National Nanofabrication Facility in fabricating the nanobridge samples. This research was supported in part by the National Science Foundation through the Cornell University Materials Science Center and by the Office of Naval Research. All of the data presented herein were taken at Cornell University. A significant part of the data analysis was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-ENG-48. Additional support was provided by the NSF through use of the National Nanofabrication Facility.

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