Universal-Conductance-Fluctuation $1/f$ Noise in a Metal-Insulator Composite

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The dependences of the $1/f$ noise in CCu metal-insulator composites on temperature, frequency, magnetic field, and electric field and the noise symmetry properties were measured in the range 2 K $< T <$ 300 K, 0.1 Hz $< f <$ 3 kHz, $B <$ 80 kG, and $E <$ 500 V/cm. In the regime $T <$ 50 K all properties were consistent with a picture of noise from double-well systems coupled to the conductivity via the universal-conductance-fluctuation term.

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There is now a general consensus that most $1/f$ noise in metals arises from defect motions[1] which are generally thermally activated, although they can occur by tunneling at low temperatures. These motions show up in the conductivity because they change quantum interference terms which affect scattering rates. The first coupling terms proposed were essentially local interference (LI) terms resulting, for example, from the anisotropic effects of interstitials. Feng, Lee, and Stone[2] recently drew attention to the sensitivity to atomic motions of universal conductance fluctuations[3] (UCF), which result from high-order multiple-scattering events in highly disordered conductors. They proposed that UCF might be important in generation of $1/f$ noise even at room temperature. However, Pelz and Clarke[4] have pointed out that LI should be more prominent in even rather dirty metals except well below room temperature.

Conductance steps due to charge trapping in semiconductors[5] and probably due to atomic motions in Bi and Pt films[6] have been attributed to UCF on the basis of semiquantitative agreement between the step sizes and the UCF prediction. So far there have been no reports of UCF $1/f$ noise, of UCF effects above about 4 K, or of UCF noise under conditions allowing tests of predictions for average noise properties such as the temperature dependence of the spectral density. In this paper we describe measurements of $1/f$ noise in highly disordered metal-insulator composites,[7,8] in which the dependences of the spectral density on temperature and on composition can be used to distinguish the noise coupling mechanisms. The noise provides some information on the double-well systems[9] (DWS) which presumably account for most of the slow atomic motions in the cryogenic regime.

Metal-insulator composites have conductivity at low temperatures of, very roughly, $\sigma_0 + (e^2/h)L(T)^{-1}$ where $L(T)$ is a length scaling approximately as $T^{-0.5}$, although a full treatment of the conductivity has not been developed.[7,8] Near a critical concentration $\sigma_0 \approx 0$. Such materials should be well suited to measurement of UCF noise because they have approximately the minimum conductivity consistent with the applicability of the UCF theory, although precautions are required because a nonlinear conductance sets in at surprisingly low voltages.[7,8,10]

Our detailed results were obtained on samples of $C_{1-x}Cu_x$ with $x \approx 0.15$, prepared by sputtering a C target with Cu inserts onto sapphire and glass substrates, and lithographically patterned into (typically) six-probe bridges about 60 μm long, 3.0 μm wide, and 65 nm thick. Some similar results were obtained in preliminary work on $Ge_{1-x}Au_x$ samples, which have the drawback of being less stable in room-temperature storage. Some of the CCu films were examined by scanning transmission electron microscopy, including microprobe x-ray analysis, and by secondary neutral mass spectroscopy. They were almost entirely amorphous, although small ($\sim$2 nm) crystalline Cu inclusions occupied up to about 2% of the volume of some samples.

Noise with a nearly $1/f$ spectrum scaling as the square of the applied current for small currents was found in all samples at all temperatures. The noise spectral slope between 1 Hz and 1 kHz below 10 K varied from -0.95 to -0.99 showing that the distribution of logarithms of DWS relaxation rates is extremely close to flat, as expected. The spectral slope at room temperature ranged from -1.02 to -1.08, depending on the sample.

The magnitude of $1/f$ noise is usually characterized by a dimensionless parameter $\alpha_A \equiv f S_V(f) N_A / V^2$, where $S_V(f)$ is the noise voltage spectral density, V is voltage, and N_A is the number of atoms in the sample.[1] Figure 1(a) shows temperature-dependent conductances for five samples, for which α_A evaluated at $f \approx 100$ Hz in the linear conductance regime is shown in Fig. 1(b).

Several temperature-dependent factors enter into α_A. When the noise arises by LI mechanisms with the variance in the scattering cross section of each scatterer less than or equal to the square of the cross section, an approximate value of α_A can be calculated to be $\alpha_A \approx n_A \times n_S(T) S(\ln f, T)/n_k^2$, where n_A is the concentration of atoms, $n_S(T)$ is the concentration of scatterers whose effective cross sections fluctuate because of atomic displacements (presumably the concentration of thermodynamically active two-level systems at low tempera-

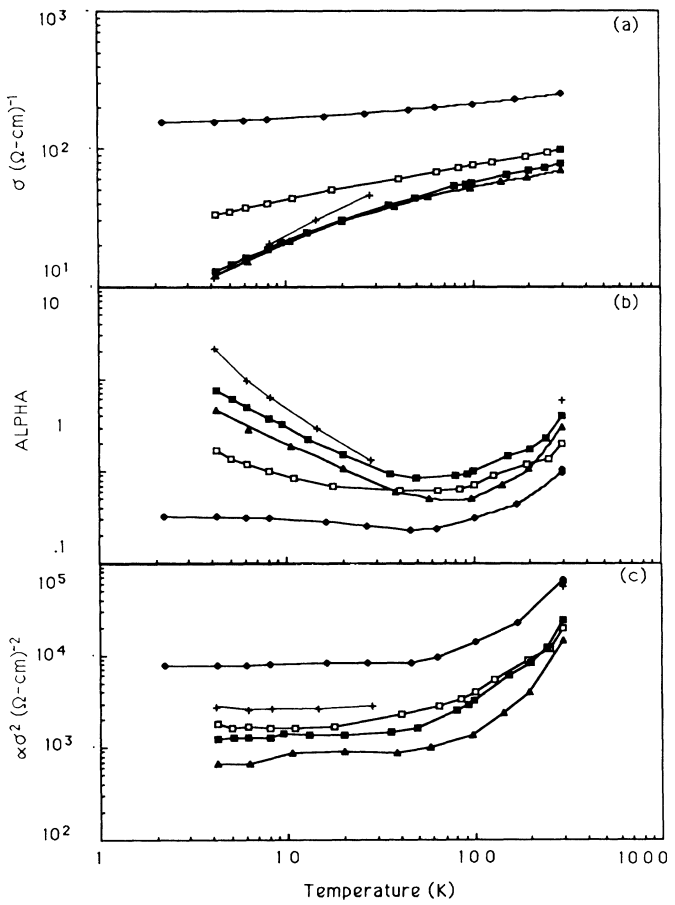

FIG. 1. (a) The conductivities of five different CCu samples as functions of temperature. The absolute normalization for each sample is uncertain to about 20%. (b) α_A, measured near 1 kHz, for each sample. (c) The product $\alpha_A\sigma^2$ for each of the samples.

tures), n_R is the total concentration of scatterers, and $S(\ln f,T)$ is a dimensionless kinetic parameter[1] which gives the fraction of the active states with relaxation rates within about an octave of f.

Typically, $n_S(T)$ scales as $T^{1.3\pm0.3}$ in the neighborhood of 1 K (Ref. 9), and the scaling should not be much different in the neighborhood of 4K. (Error bars here indicate slightly subjective 90% confidence limits.) If the states have thermally activated kinetics $S(\ln F,T)$ also has a temperature dependence, determined via the Dutta-Horn relation from the noise spectral slope,[1] since the distribution of characteristic times is compressed and shifted as the temperature is raised. For our typical sample below 20 K, this gives a slightly temperature-dependent $T^{0.4\pm0.4}$ factor, with very weak dependence of the exponent on the presumed attempt rate of 10^{12} s^{-1}. For tunneling kinetics one of course obtains T^0, which is fortunately within the error bars above, so that we need not treat that case separately. For LI mechanisms, regardless of the local details, the temperature dependences of L_i and L_T are irrelevant to the noise scaling, so that a net temperature dependence $\partial\ln\alpha_A/\partial\ln T=1.7\pm0.5$ should be found. A very similar estimate can be obtained by consideration of the temperature dependence of the internal friction in various amorphous materials.[11] Since $-1.1<\partial\ln\alpha_A/\partial\ln T<-0.1$ and since $\partial\ln\alpha_A/\partial\ln T$ varies strongly between samples, depending on $\partial\ln\sigma/\partial\ln T$, the results are in obvious disagreement with the LI prediction.

Order-of-magnitude calculations of α_A based on the UCF theory[2,3] can be easily done on the assumption that the typical atomic displacements involve only one strong scatterer moving a distance of the order of k_F^{-1}. Without claiming accuracy for the dimensionless prefactor, one finds that in three dimensions[12]

$$\alpha_A\sigma^2\approx n_A n_S(T)S(\ln f,T)L_i L_T^2 k_F^{-1}(e^2/h)^2,$$

where L_i is an inelastic-scattering length which should scale as $T^{-3/4}$ in the dirty Coulomb scattering limit,[7] L_T is an energy-average length[7] which scales as $T^{-1/2}$, and we can crudely estimate that the Fermi wave vector is $k_F\approx5\times10^7$ cm^{-1}. As Fig. 1(c) shows, $\alpha_A\sigma^2$ shows almost exactly the same temperature dependence below 10 K for all samples. By our previous argument, for UCF's we expect

$$\frac{\partial(\ln\alpha_A\sigma^2)}{\partial\ln T}=1.7+2\frac{\partial\ln L_T}{\partial\ln T}+\frac{\partial\ln L_i}{\partial\ln T}=-0.05\pm0.5,$$

in excellent agreement with the observations. Furthermore, the spread in $\alpha_A\sigma^2$ between samples is smaller than the spread in α_A, and correlates only weakly with σ.

Above 20 K we presume that activated kinetics dominate.[10,13] The deviation of the spectral slope from the Dutta-Horn value is essentially constant to $T=50$ K, suggesting that UCF noise dominates to at least that temperature. In the range 50 K $<T<$ 200 K, the deviation shrinks. Above 240 K, the deviation becomes positive, as expected for LI noise in which the deviation is due only to the increase in the density of thermodynamically allowed motions.[1] The most likely interpretation is that nonuniversal interference terms involving either low-order multiple scattering or LI (single scattering) dominate at these higher temperatures, in qualitative agreement with the prediction of Pelz and Clarke.[4]

When we applied ac currents (typically 500 kHz) and measured noise below 1 kHz we found $1/f$ noise—a familiar effect when the noise-making regions are rectifying.[14] At low fields the $1/f$ spectral density scaled as V^4, turning to about V^2 at higher fields, as shown in Fig. 2(a). In the saturation regime, the $1/f$ noise was about 10% as large as would be obtained with the same dc power, in all samples tested. The net rectification was less than one part per thousand, indicating random local rectification. Random mesoscopic nonlinearity due to UCF's has been predicted[15] to give $\langle[\delta G(E)]^2\rangle\approx(e^2/h)^2(E/E_c)^2$ for $E<E_c\approx kT/eL_T$, with $\langle[\delta G(E)]^2\rangle$

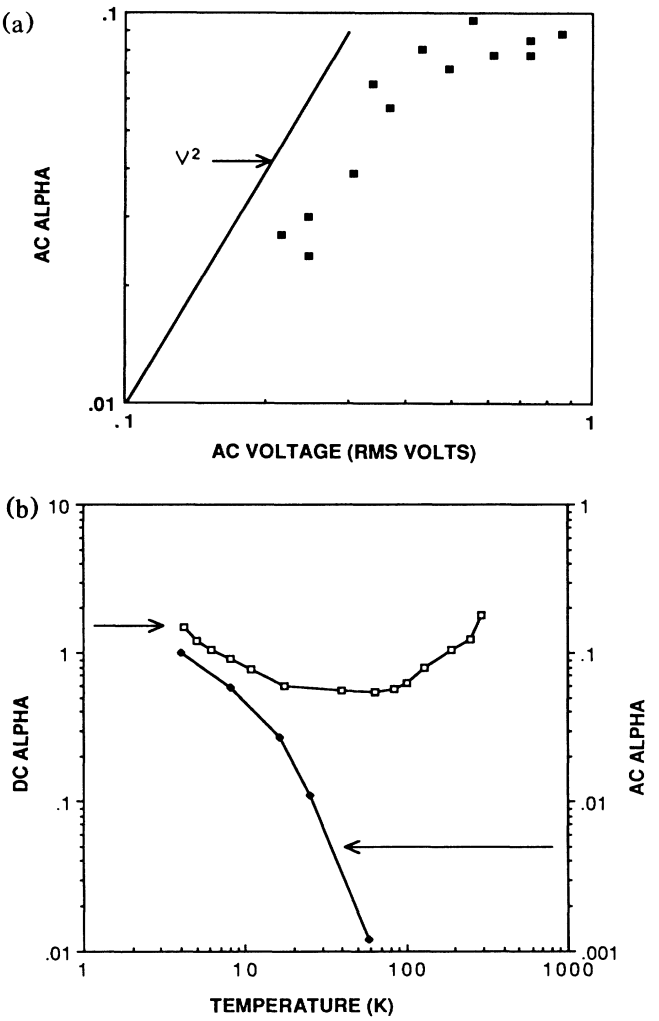

FIG. 2. (a) The apparent α_A determined as a function of applied ac voltage at 4.2 K for the sample represented by open squares in Fig. 1. Similar data were obtained on other samples. (b) The α_A measured with dc voltage (squares) compared with the apparent α_A (filled lozenges) measured with a fixed ac field of about 80 V/cm rms for the same sample.

$\approx (e^2/h)^2$ for $E > E_c$. This is precisely the scaling needed to obtain the V^4 regime and V^2 saturation. Direct conductance measurements at lower temperatures also find these nonlinearities,[16] although the change in scaling at E_c seems so far to be below the range of the direct measurements. From E_c we infer $L_T \approx 5$ nm at 4 K, a very reasonable value. The ratio of rectified noise to the ordinary noise was measured at fixed voltage sufficient to be in the V^2 regime at 4 K. Since E_c should scale as $T^{1.5}$, the higher-temperature measurements should be in the V^4 regime, with the relative size of the rectified noise falling about as T^{-3}, like the actual results shown in Fig. 2(b). Noise from regions not described by UCF theory (e.g., having activated hopping conductance[17]) would be quite unlikely to fit these detailed UCF predictions.

The clearest potential signature of UCF noise would be a factor of 2 reduction in noise power [18,19] in high magnetic fields ($B \sim hc/eL_i^2$). Unfortunately, our samples had significant positive magnetoresistance and also short L_i even at the lowest temperatures for which the noise measurement was feasible, so that several interpretations of our data are possible. However, data taken at about 2 K showing a $\sim 25\%$ reduction in $\alpha_A \sigma^2$ at $B = 6$ T are consistent with the UCF prediction if $L_i \approx 12 \pm 2$ nm, and data at 5 K showing a 10% reduction were consistent with the prediction if $L_i \approx 8.5 \pm 1.5$ nm, with both values being reasonable.

Using the approximate length scales obtained from the rectification and magnetic field effects, we can estimate the UCF noise level at 4 K, using typical values[1] $S(f,T) \approx \frac{1}{25}$ and[9] $n_S \approx 3 \times 10^{17}$ cm^{-3}, giving $\alpha_A \sigma^2 \approx 3 \times 10^3$ mho^2 cm^{-2}. The agreement of this crude estimate with the data is quite satisfactory. (Using the same parameters, we predict $\alpha_A \approx 3 \times 10^{-6}$ for LI noise.) The actual mean square conductance fluctuation per phase-coherent region per octave is only about 10^{-3} of the maximum UCF value of $(e^2/h)^2$, justifying the linear treatment of the noise. In the more insulating samples, the conductance per phase-coherent volume is slightly smaller than the predicted UCF ensemble standard deviation, indicating that we are near the lower limit of the conductance regime in which UCF theory can reasonably be applied.

The symmetry parameter[1] $S \equiv 2\langle \det(\delta\sigma)\rangle / \langle \mathrm{tr}[(\delta\sigma)^2]\rangle$ (where $\delta\sigma$ is the 2D conductivity fluctuation tensor) can be inferred from theoretical predictions[18] to be in the range $-\frac{1}{7}$ to 0 for UCF noise in three-dimensional samples. Unfortunately, these values do not serve to distinguish UCF noise from other common interference effects.[1] We found values of 0.0 ± 0.07 above 10 K and 0.15 ± 0.15 at 4 K in the one sample on which we made this measurement. The agreement is satisfactory, given the approximations involved in the theory (e.g., noninteracting electrons).

In summary, the properties of the $1/f$ noise in CCu near the metal-insulator transition below 50 K fit the predictions of the UCF theory. The detectability of DWS UCF noise well above 4 K may prove a useful tool in further studies of the DWS as well as UCF. For example, fluctuation statistics in very small samples may provide a test of the typical number of mobile scatterers per DWS. The DWS also provide a useful internal thermometer.[10] However, extrapolating our results to materials with σ typical for very dirty metals (10^4 mho/cm) suggests that UCF noise would rarely if ever be as large as LI noise above 77 K, in the regime where most $1/f$ noise observations have been made.

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