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$1/f$ Noise in Platinum Films and Ultrathin Platinum Wires: Evidence for a Common, Bulk Origin

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The $1/f$ noise of platinum films and ultrathin platinum wires has been found to scale inversely with the number of atoms in the sample, N, for N in the range 10^7 to 10^{14}. This strongly reinforces the idea that the $1/f$ noise of continuous metal films is of bulk origin, and demonstrates that the dominant form of excess low-frequency noise in the very small structures investigated here is the bulk $1/f$ noise.

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Recently there has been much interest in the physics of very small structures. Progress in the fabrication of these structures has contributed greatly to the understanding of a wide variety of phenomena.[1] For example, the study of ultrathin wires ($d \lesssim 500$ Å, where d is the diameter) has provided new insight into the effects of impurities on electrical conduction in metals.[2,3] Another potentially fruitful area of research involving very small structures is the study of fluctuation processes. In most cases, the relative magnitude of a fluctuation is inversely proportional to the volume of the system,[4] so that one might expect that previously unobservable fluctuations could be extremely important in very small structures. One type of fluctuation whose effects may be readily measured is the electrical noise of a resistor. If the voltage across a resistor is sampled as a function of time, the noise-power spectral density, $S_v(f)$, may be obtained. When there is no current flow, we expect $S_v = 4\,kTR$, which is the well-known Johnson (Nyquist) noise.[5] When a direct current is passed through the resistor, however, noise in excess of the Johnson noise is commonly observed. The excess noise-power spectral density is often found to be proportional to $1/f^{\alpha}$, with $\alpha \approx 1$, and it is therefore referred to as "$1/f$ noise." Although $1/f$ noise has been investigated extensively in recent years, its origin is not known.[6,7] Indeed, it is not yet even clear whether the $1/f$ noise of semiconductors is a surface effect, a bulk effect, or some combination of the two.[6,8,9] For metals, on the other hand, the general intuition is that the $1/f$ noise is of bulk origin.[6,7] However, there is actually very little experimental evidence to directly substantiate such an assertion, and what evidence there is remains somewhat open to interpretation.[10,11] This uncertainty is due to the limited range of sample sizes in which the noise has been studied previously[10,12,13] and to the large sample-to-sample variations of the noise magnitude which are commonly reported, even in nominally identical samples.[10,12-14] We have investigated the low-frequency excess noise of platinum films ($10^{11} < N < 10^{14}$, where N is the number of atoms in the sample) which were prepared similarly to the metal films studied by previous workers,[12,13] and of ultrathin platinum wires ($10^7 < N < 10^{11}$) which were prepared lithographically.[3,15-17] We find that the dominant form of excess noise for both the films and wires is $1/f$ noise, and that the noise magnitude is inversely proportional to N over the entire range of samples studied. This strongly suggests that the dominant low-frequency fluctuation process in the wires is the same as that which causes the bulk $1/f$ noise in platinum.

The platinum films were deposited by ion-beam sputtering onto glass and sapphire substrates, and ranged in thickness from 80 to 200 Å. The films were cut with a tungsten needle to form strips 50–700 μm long and 10–70 μm wide. Electrical contact to the films was made with indium-tin solder and/or evaporated gold contact pads. Using the technique of "step-edge lithography," which is described in detail elsewhere,[3,15-17] we fabricated platinum wires of lengths 0.3–250 μm and cross-sectional areas of 2.3×10^{-12}–3.9×10^{-11} cm^2 (150 Å $< d <$ 650 Å) on glass substrates. Since these wires are made starting from sputtered platinum films, they are essentially films which are much thinner and narrower than they are long.[3,15-17] We use the term "wire" to emphasize the very different length-to-width ratios of the two different types of samples. Electrical contact to the wires was made with platinum films in conjunction with silver paint and indium-tin solder pads.[3] Both the films and the wires had resistivities, ρ, in the range 40–60 $\mu\Omega$ cm,[18] and temperature coefficients of resistivity $[(1/\rho)(d\rho/dT)]$ of $(5-7)\times10^{-4}$ K^{-1}. Transmission electron microscope studies showed that the grain size of the platinum was $\lesssim$ 75 Å with any holes < 10 Å; hence, the samples studied here were continuous.[19]

Noise measurements were performed at room temperature; the apparatus used was the same as that described elsewhere.[20] In all cases the excess noise, $S_v(f)$, was proportional to $1/f^{\alpha}$ with $\alpha \approx 1.15$, over the frequency range measured ($0.2 < f < 100$ Hz), which is characteristic of "$1/f$" noise. For the platinum films we have studied (100 $\Omega < R <$ 500 Ω), and in previous studies[10,12,13] of the $1/f$ noise in metal films (1.0 $\Omega \lesssim R \lesssim$ 1.0 kΩ), it was not possible to perform measurements of the noise power below about 0.1 Hz. This is due to the impaired low-frequency response of available amplifiers and/or the high level of the amplifier noise. However, because of the relatively high impedance of the wires we have studied (8.0 k$\Omega \leq R \leq$ 140 kΩ), it was possible to extend the measurements to considerably lower frequencies. The results for a typical wire are shown in Fig. 1, where the noise-power spectral density is plotted as a function of frequency. The noise power is seen to be proportional to $1/f^{1.15}$ over the entire frequency range. Thus, any characteristic time scale of the fluctuation process must lie outside the range implied by the high- and low-frequency limits in

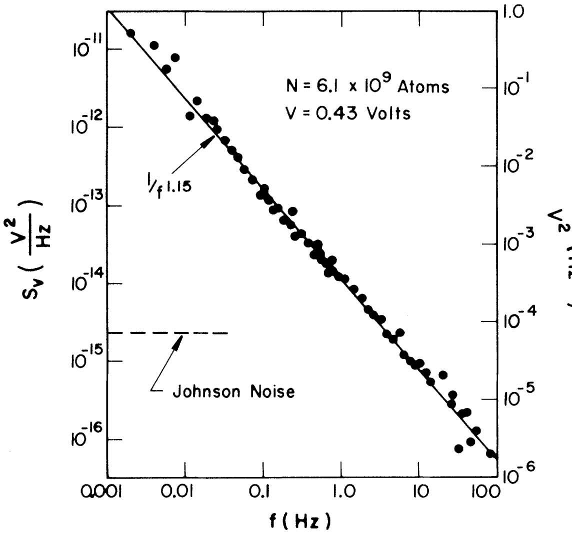

FIG. 1. S_v as a function of f for a platinum wire. The solid line is proportional to $1/f^{1.15}$, and the dashed line indicates the Johnson-noise level (although the Johnson noise has been subtracted in order to obtain the excess noise). The normalized noise power, SN/V^2, is given on the right-hand scale.

Fig. 1; i.e., it must be less than 0.01 s or greater than 500 s. We should remark that the overall noise magnitude of this wire is described fairly well by the semiempirical formula developed by Hooge and co-workers[6,21]:

$$S_v(f) = (\mu/\mu_{\rm ph})^2 \gamma V^2/N_c f. \qquad (1)$$

Here μ is the total mobility, $\mu_{\rm ph}$ is the mobility due to electron-phonon scattering, N_c is the number of free carriers[22] in the sample, and $\gamma \approx 2 \times 10^{-3}$. For this sample $\mu/\mu_{\rm ph} \approx \frac{1}{4}$, and so (1) predicts that $S_v(10\ \text{Hz}) \approx 4\times10^{-16}\ \text{V}^2/\text{Hz}$, while we find $S_v(10\ \text{Hz}) \approx 8\times10^{-16}\ \text{V}^2/\text{Hz}$. Since the value of N has an experimental uncertainty of nearly a factor of 2, the agreement is satisfactory. However, in work which is reported elsewhere,[14] we have shown that (1) does not provide an accurate description of the mobility dependence of the $1/f$ noise in metals. Thus, the agreement with the prediction of (1) appears to be fortuitous.

In Fig. 2 we show the "normalized" noise power ($S_v f/V^2$) as a function of the number of atoms in the sample, N, for a number of films and wires. Normalizing the noise power in this way removes the effect of the different measuring currents used (since for each sample it was found that $S_v \sim I^\beta \sim V^\beta$, with $\beta = 2.0 \pm 0.1$, as expected[6,7]), and allows a direct comparison of the noise levels of different samples.[10,13,14] If the noise in the wires and films is due to a purely bulk fluctuation, one would expect the normalized noise power to be proportional to $1/N$. It can be seen from Fig. 2 that our results are quite consistent with this prediction. To give a feeling for the uncertainties involved, Fig. 2 also shows lines proportional to $1/N^{0.8}$ and $1/N^{1.2}$. It can be seen that our results are not really consistent with either of these, and we therefore conclude that the normalized noise power is proportional to $1/N^\delta$, with $\delta = 1.0 \pm 0.2$. This implies that the noise of the films and wires has a common cause. If the noise of the wires were caused by a different mechanism than the noise of the films (as one might have easily imagined since the wires are of much smaller volume, and have a typically threefold greater surface-to-volume ratio, than the films), then there should be some change in scaling between the noise of the wires and the films.[23] Clearly, there is no such change[14,24] to within the ≈ 20% uncertainty due to the "scatter." Further, the "fully" normalized noise power ($S_v Nf/V^2$) was found not to depend upon any of the measured parameters[25]; in particular, it did not depend upon the cross-sectional area of the sample. This strongly suggests that, while surface effects (or other "nonintrinsic" sources of noise) may contribute to the sample-to-sample variations of the noise, $1/f$ noise of bulk origin is the dominant source of excess noise in both the films and the wires. It is interesting to note that the persistence of the $1/N$ dependence to the smallest wires fabricated implies[26] that (at least for platinum) any characteristic length scale of the fluctuation process is ≲ 3000 Å along the direction of current flow, and ≲ 150 Å in both transverse dimensions.

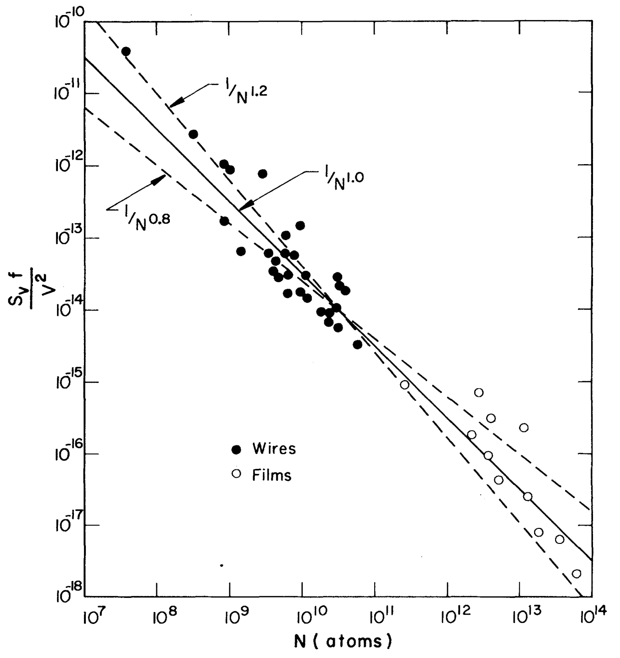

FIG. 2. $S_v f/V^2$ at $f = 10$ Hz as a function of N for platinum films and wires. The solid line is proportional to $1/N^{1.0}$. The dashed lines are proportional to $1/N^{1.2}$, and to $1/N^{0.8}$, as discussed in the text.

In summary, we find that the dominant source of low-frequency excess noise in platinum films and ultrathin platinum wires is $1/f$ noise. The noise scales inversely with the number of atoms, N, in the sample for more than six orders of magnitude variation in N, which is compelling evidence that the $1/f$ noise of both the films and the wires is of bulk origin.

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[18] The resistivity was nearly four times the bulk value, due to the increased impurity scattering commonly found in sputtered films. Some boundary scattering was also evident in the thinner ($t < 150$ Å) films.

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[22] In most metals $N_c \approx N$; we use the latter to normalize the noise power, for simplicity.

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[24] It is noted in Ref. 14 that the best measure of the noise in metal films seem to be the "minimum" noise shown. There is a well-defined minimum level of $1/f$ noise for platinum, which is evident in Fig. 2. The minimum noise scales almost exactly as $1/N$, and is in good agreement with the results reported in Ref. 14. Thus, while there is about a factor of 10 "scatter" from sample to sample, the minimum noise scales continuously with N at the transition between the films and wires. This indicates that the noise is independent of the specific sample geometry.

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