

Volume versus surface origin of $1/f$ noise in metals

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We have examined the question of whether excess low-frequency ($1/f$) noise in metal films arises in the bulk or at the sample surface. We measured the noise in continuous Cr films with $80 \text{ \AA} < t < 2600 \text{ \AA}$, where t is the film thickness. Establishing that the relative noise intensity $S_\rho(f)/\rho^2 \propto 1/t$ supports the hypothesis that the noise is produced throughout the bulk; here, f is the frequency, ρ is the resistivity, and $S_\rho(f)$ is the power spectral density of fluctuations in ρ . By considering a model of noise from the surface shunted by an underlying noise-free conductor volume, we devised a quantitative test which we used to refute the possibility that the noise arises only at the surface of our metal films.

I. INTRODUCTION

Excess low-frequency fluctuations, commonly known as “ $1/f$ noise,” are observed in many solid-state materials and devices.^{1,2} This ubiquitous phenomenon is typically measured as fluctuations of voltage across a small sample carrying a constant current. The voltage power spectral density $S_V(f) \propto I^2/f^\alpha$, where I is the applied current, and f is the frequency. The spectral exponent is typically $0.8 < \alpha < 1.2$, over the measured frequency range $1 \text{ mHz} < f < 1 \text{ kHz}$. This form for $S_V(f)$, along with other evidence, indicates that the voltage noise is produced by the applied current probing resistance fluctuations.

The difficult fundamental question about $1/f$ noise has proven to be identification of the mechanisms that generate it in various conductors. Associated with this is the question of the spatial distribution of the noise-producing process. In this paper, we consider whether $1/f$ noise in metal films is produced by a mechanism which is distributed throughout the volume Ω of the film (bulk effect) or is localized at the sample surface (surface effect). This problem is a question of longstanding controversy for both semiconductors (McWhorter³) and metals.⁴ Two examples in which the characteristic features of the excess low-frequency noise spectrum (not $1/f$ spectra) allowed determination of the noise mechanisms illustrate these two limiting cases. The resistance fluctuations due to hydrogen atom diffusion in niobium are distributed throughout the film volume.⁵ A surface effect is the noise produced by movement of adsorbed atoms on a metal surface.⁶

In order to distinguish between bulk and surface effect, we examined the dependence of the noise intensity on the sample size. For a bulk effect, the relative noise intensity $S_\rho/\rho_n^2 \propto 1/\Omega$, where ρ_n is the contribution to the resistivity ρ corresponding to the mechanism that produces the noise,⁴ and $S_\rho = (wt/l)^2 S_V/I^2$ is the power spectral density of fluctuations in the resistivity, where w , t , and l are the sample width, thickness, and length, respectively.

This relation is obtained from general statistical mechanical arguments by associating resistance fluctuations with individual independent fluctuators whose number is proportional to sample volume (i.e., the noise correlation length is smaller than all sample dimensions). In contrast, for a surface noise source we expect $S_\rho/\rho^4 \propto 1/\Omega t$ for a film of thickness t [see Appendix, Eq. (A4)]. This relation is derived from a model in which the voltage fluctuations produced at the surface are shunted by the conductance $A/\rho l$ of the noise-free bulk;⁷ for a nonplanar geometry, $1/t$ would be replaced by the ratio of the area of the noisy surface, A , to the volume. Thus, in this experiment we use the dependence of the noise intensity on t to distinguish between bulk and surface origin; we also confirm that the noise intensity is proportional to $1/A$.

We report measurements of the dependence of the $1/f$ noise intensity in chromium films on the sample area and thickness. We made a series of chromium films which ranged in thickness from 80 to 2600 Å (a factor of 32). Chromium was selected because it forms continuous metal films that generate $1/f$ noise over the entire thickness range. The reliability of our conclusions is ultimately limited by the possible variation with thickness of the film structure, resistivity, and noise mechanisms.

It is widely believed that the noise in metals has a bulk origin, in contrast to semiconductors.³ Various groups have measured the noise as a function of sample size, in gold⁴ and platinum films,⁸ and in point contact experiments.⁹ Each of these experiments has significant limitations. In one experiment,⁴ Au films with $500 \text{ \AA} < t < 5000 \text{ \AA}$ were doped with a few atomic percent In to reduce the mean free path λ , so that $t \gg \lambda$. The resistance R was reported as a function of t , and C as a function of R , to show $C \propto 1/t$, where $C = fS_V/V^2$. However, the noise exhibited large sample-to-sample variation, making the conclusion suspect. In addition, substantial Joule heating of the samples was probably occurring.¹⁰

In another experiment, using Pt films,⁸ it was shown that $C \propto 1/N_a^{1.0 \pm 0.2}$ for a range of N_a of more than 10^6 ,

where N_a is the number of atoms. However, these films had a range of only a factor of 4 in the surface to volume ratio, but a sample-to-sample variation of C by a factor of 10. As we previously indicated, it is only the dependence of C on the ratio A/Ω which allows a distinction between surface and bulk effect.

Hooge's point-contact measurements on ten different metals⁹ were intended to establish that $S_R/R^2 \propto R^3$ (confirming the presence of bulk noise). However, due to excessive scatter, the data does not adequately support the conclusion. Furthermore, Black *et al.* have shown that $S_R/R^2 \propto R^3$ can also be obtained if the surface near the point of contact is the source of the noise.¹¹

II. EXPERIMENTAL METHODS

Six chromium films were deposited on highly polished sapphire substrates bearing Au-Cr contact pads previously deposited by thermal evaporation. The Cr deposition was done by sputtering in a Varian Magnetron system, with an Ar gas pressure of 10^{-5} torr and a base pressure of 2.8×10^{-8} torr. Each substrate was placed under the continuously running sputtergun and had Cr sputtered onto it for a set time. The times ranged from 7 to 224 sec, with each substrate being exposed for twice the time of the one before it. The rate of deposition, estimated to be 12 Å/sec from a calibration run, produced films of nominal thicknesses 80, 160, 320, 640, 1300, and 2600 Å. We measured t for the two thickest films to within $\pm 5\%$ using an Alpha Step surface profiler, and found values that agreed with the nominal values. Calibration depositions in this system have confirmed that the film thickness is proportional to sputtering time. A small uncertainty in the effective metal film thickness caused by the passivated (exposed to air at room temperature) oxide layer [about 15 Å for Cr (Ref. 12)] is significant for the thinnest films; this is reflected in the horizontal error bars in Figs. 2 and 3.

The films were subtractively patterned into five-probe noise samples¹³ using standard photolithography and ion milling. Noise sample length l and widths w were measured with an electron microscope, as well as with a calibrated optical microscope. The samples were fairly close to rectangular, with nominal widths 1, 2, 4, 8, or 16 μm , and $l/w \cong 20$. The substrates were mounted with Apiezon N grease onto 24-pin gold-plated packages from Hermetite Corp., and 1.5-mil Al wires were ultrasonically bonded to the Au contact pads and to the package pins.

The noise measurements were performed using five-probe samples (standard four-probe sample plus a center tap) connected into a Wheatstone bridge configuration. A sine wave of frequency $f_0 = 700$ Hz was applied to the bridge, which included the two halves of the noise sample r_1 and r_2 ($r_1 \cong r_2$). Variable ballast resistors R_1 and R_2 in the Wheatstone bridge were typically set at 5–10 times the resistance of a sample half, and the bridge was balanced resistively and capacitively. The voltage error signal was demodulated by a PAR 124A lock-in amplifier, and then sent through low-pass (Unigon LP-120, set to cut off at 500 Hz with a 120 dB/octave rolloff) and high-pass (Krone-Hite 3220) filters. The noise level did not change when we removed these filters to check their

effect on the noise. This signal was analyzed with a Hewlett-Packard HP5420A spectrum analyzer. Details of the noise measurement and sample preparation techniques are described in Ref. 13.

Because of the wide range of film thicknesses used, the noise samples had resistances that varied from about 80 to 2500 Ω . Thus, the input impedance to the lock-in preamplifier ranged from 200 Ω to 10 k Ω . To avoid current flow in the voltage leads, we measured the noise in all samples using a PAR 116 preamplifier in the direct mode, which has an impedance of 100 M Ω .

To ensure that the noise did not arise from the contacts, the measured noise intensity was shown not to change when R_1 and R_2 were changed by a factor of 2, while the current was kept constant.¹³ For several samples, the noise was measured at different times over a period of many weeks, and showed no drift, within the uncertainty. The uncertainties in the quantity AS_p (see Figs. 2 and 3) for a single sample are due to uncertainty in the width, and in the measured noise intensity, which typically ranged from 10% to 25%. On each substrate, we measured between one and four noise samples. The uncertainty in the measured noise intensity was generally highest in the thickest samples.

III. RESULTS

In Fig. 1 we have plotted the average resistivity of all the noise samples on each substrate, weighted by their uncertainties. The error bars reflect the fact that different substrates had different numbers of samples for which the noise was measured. Notice that the Cr films are quite "dirty:" The bulk resistivity of pure Cr is 12.9 $\mu\Omega\text{cm}$, whereas these films have resistivities typically 5–7 times that. The variation of resistivity with thickness in the thinner films can be accounted for by the Fuchs size effect theory¹⁴ for boundary scattering, applicable when t is of the order of λ_∞ . Here, λ_∞ is the mean free path an in-

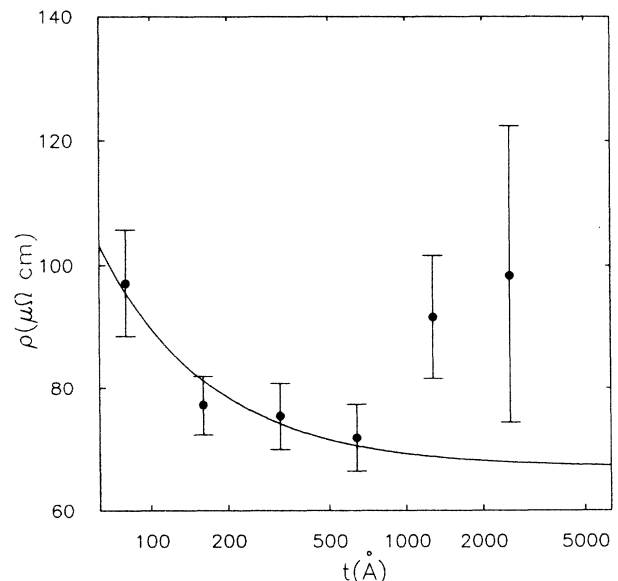


FIG. 1. Resistivity ρ versus thickness t . The line is the function $67[1 + 34/t \text{ \AA}]$ obtained from a fit of the Fuchs theory to the four thinnest samples.

finitely thick film with the same structure (density of defects, etc.) would have. This theory predicts the resistivity $\rho(t) = \rho_\infty(1 + 3\lambda_\infty/8t)$ for $t \geq \lambda_\infty$; ρ_∞ is defined similarly to λ_∞ . The best fit of this theory to the experimental data yields the function (shown in Fig. 1) ρ ($\mu\Omega\text{ cm}$) = $67[1 + 34/t(\text{\AA})]$, where $\lambda_\infty = 90 \text{ \AA}$, and $\rho_\infty = 67 \mu\Omega\text{ cm}$; these are typical values for dirty Cr films.^{15,16}

The two thickest films (1300 and 2600 \AA) have resistivities well above the values predicted by the Fuchs theory. A rise in ρ for thicker films cannot be explained by boundary scattering, since as λ_∞/t goes to zero, size effects should be diminished (ρ approaches a limiting value). We infer that the thicker films have additional extrinsic scattering of about 25% (relative to the thinner films). Possible causes include change in crystallite size or configuration, higher dislocation density, or additional impurities. Structural differences are implicated by scanning electron microscopy (SEM) examination, which shows elongated surface patterns (on the order of 1000 \AA in size) on the thicker films, but no discernible structure in the thinner films.

Voltage noise spectra were measured at room temperature. For all samples, the power spectral density $S_V(f) \propto I^2/f^\alpha$ with α constant (within the $\pm 10\%$ uncertainty) over at least two decades of frequency. The spectral exponent was $0.95 < \alpha < 1.2$, with an uncertainty of about 0.1. The measurement bandwidth was contained within the range 1 mHz–10 Hz.

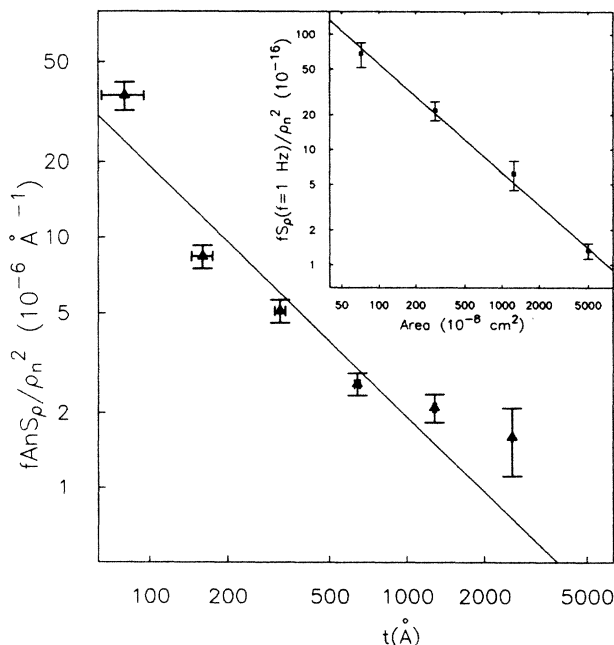


FIG. 2. Log-log plot of normalized noise versus thickness t to test for bulk noise. Each thickness is a consolidation of all the noise samples at that thickness. The line has slope -1 , which is the prediction of the bulk effect model. The vertical error bars represent statistical uncertainty; the horizontal error bars are due to the passivated oxide layer. Inset: log-log plot of relative noise versus area for the four samples with $t = 160 \text{ \AA}$. $\rho_n = 63.7 \mu\Omega\text{ cm}$ for all four data points. The straight line has a slope of -0.94 ± 0.04 , verifying the inverse area scaling.

For samples of a constant thickness, the noise intensity is predicted to be proportional to $1/A$, irregardless of surface or bulk origin (assuming the noise is uncorrelated over the width and length of the sample). We confirm this in the inset to Fig. 2, where we have plotted noise versus area for the four samples on the substrate with $t = 160 \text{ \AA}$. We saw the expected area scaling for all sample thicknesses.

A. Test for bulk noise

To test for bulk noise, we examine S_ρ/ρ_n^2 , where ρ_n is that part of ρ corresponding to the noise-producing mechanism(s). Presuming that the static enhancement of ρ due to the geometrical effect of a carrier scattering off the boundary of the sample (Fuchs size effect theory) does not produce resistance fluctuations, we normalize by $\rho_n = \rho/(1 + 34/t)$ to test for bulk noise. The frequency and applied current dependence of the noise intensity can be suppressed by calculating fS_ρ/ρ_n^2 ; this quantity contains information about the dependence of noise intensity on sample size. To suppress the inverse area proportionality and examine only the thickness dependence, we have plotted (Fig. 2) $AnfS_\rho/\rho_n^2$, where $A = lw$, and n is the number density of Cr atoms. As in the resistivity data, we have consolidated all of the noise samples on a substrate into a single data point for each thickness. The vertical error bars were calculated using statistical error analysis; the horizontal error bars are due to the oxide layer, discussed above.

Although there is some scatter in the data, there is a clear trend over the thickness range of a factor of 32. A linear least-squares fit to the data gives a slope of -0.95 ± 0.18 , in good agreement with the bulk effect prediction. This model predicts a slope of -1 for the log-log plot of noise versus thickness; a line with this slope is plotted in Fig. 2.

B. Test for surface noise

To test for surface noise, we have devised a model of two parallel resistors to derive the volume and resistivity scaling of the measured noise (see Appendix). A log-log plot of $AnfS_\rho/\rho^4$ versus thickness is shown in Fig. 3, to test for surface noise. A linear least-squares fit to this data yields a slope of -0.68 ± 0.04 . The straight line in the figure is a line with a slope of -2 ; this corresponds to the prediction of the surface effect (noise intensity proportional to $1/t^2$). The data clearly refute this possibility.

One might suppose that the measured noise is produced both in the conductor volume and at the surface. If the noise from these two sources is uncorrelated, then one would expect the total $1/f$ noise intensity to be proportional to $a/t + b/t^2$, with bulk and surface coefficients a and b . A fit of this function to the data (not shown in this paper), confirms that $(b/t^2)/(a/t)$ is less than 10^{-3} in the measured thickness range, showing that an insignificant amount (if any) of the total measured noise is produced at the surface.

IV. DISCUSSION

We have measured the $1/f$ noise in Cr metal films, to determine whether the noise is produced in the volume or

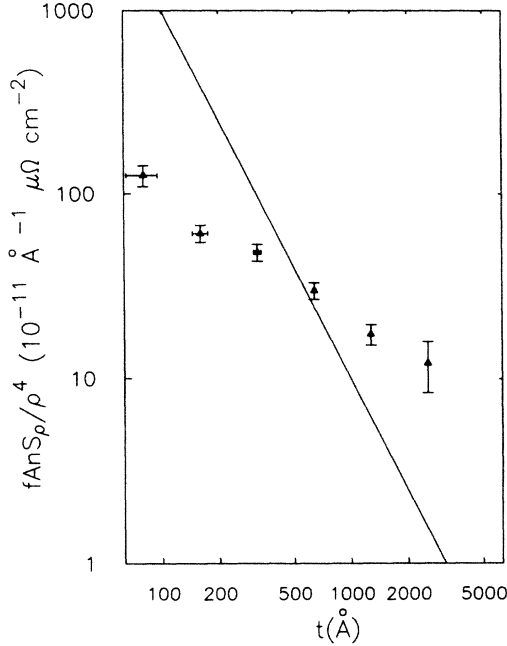


FIG. 3. Log-log plot of normalized noise versus thickness t to test for surface noise. Each thickness is a consolidation of all the noise samples at that thickness. The straight line has slope -2 , which is the prediction of the surface effect model. The vertical error bars represent statistical uncertainty; the horizontal error bars are due to the passivated oxide layer.

at the surface of the sample. By examining the dependence of noise intensity upon film thickness in the context of the two specific limiting models that we have considered, we have shown that the noise is of bulk origin, as opposed to surface origin. This experiment does not contradict the possibility that the $1/f$ noise is produced at grain boundaries, as long as the total area of the noise-producing grain boundaries scales linearly with the sample volume (for example, if the grain size is smaller than the sample dimensions, and does not change as the sample size is varied).

There are several ways in which this experiment could be improved, by significant additional experimental effort; however, anticipating diminishing returns, we have stopped with more modest results that clearly refute one possibility, and are in agreement with the other. We can make films with a larger spread in thickness, but we anticipate that it would be difficult to make a continuous metal film with $t < 80$ Å, and a film much thicker than 2600 Å would have a very low noise intensity, providing measurement difficulties. Uniform resistivity over the range of t would be desirable, for straightforward normalization of the noise, but this is difficult to realize experimentally. Although we have considerably diminished the substrate-to-substrate variation of the $1/f$ noise, there is room for further improvement. The most serious limitation of this experiment is the possibility of the systematic variation of the $1/f$ noise-producing mechanism with thickness; we attribute the discrepancies between the data and the bulk effect model at the two ends of the thickness range to this problem. This limitation is due to the fact

that the physical mechanism which produces $1/f$ noise in metals has not been identified. Totally conclusive determination of the spatial origin of $1/f$ noise must await this identification.

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APPENDIX

In this appendix, we derive the equation used to test for the presence of surface noise, $S_\rho/\rho^4 \propto 1/\Omega t$. We model the metal film conductor as a bulk resistor of resistivity ρ_b , width w , length l , thickness t , plus a surface layer of resistivity ρ_s , width w , length l , and thickness d . We assume $t \gg d$.

The two resistors are $R_b = \rho_b l/wt$ and $R_s = \rho_s l/wd$. With the two resistors in parallel, the measured resistance is

$$R = R_s R_b / (R_s + R_b). \quad (\text{A1})$$

The measured resistance fluctuation (assuming only the surface layer resistance fluctuates) is

$$\delta R = \delta R_s dR/dR_s = [R_b^2 / (R_s + R_b)^2] \delta R_s. \quad (\text{A2})$$

Now we assume that the surface resistance $R_s \gg R_b$; from Eq. (A1), this implies $R \cong R_b$, and thus the measured resistivity $\rho \cong \rho_b$. The measured resistivity noise $\delta\rho$ is

$$\delta\rho/\rho = \delta R/R \cong \delta R/R_b.$$

From Eq. (A2),

$$\delta\rho/\rho \cong (R_b/R_s) \delta R_s/R_s.$$

Converting to power spectral densities,

$$S_\rho/\rho^2 \cong (R_b/R_s)^2 S_{R_s}/R_s^2,$$

$$S_\rho/\rho^2 \cong (\rho d/\rho_s t)^2 S_{R_s}/R_s^2. \quad (\text{A3})$$

Assuming that the noise-producing mechanism is distributed throughout the plane of the surface layer, $S_{R_s}/R_s^2 = B/lw$, where the frequency dependence is suppressed; B is material dependent and may depend on d . From (A3),

$$S_\rho/\rho^2 \cong (\rho/t)^2 (1/lw) (Bd^2/\rho_s^2).$$

The final, crucial assumption is that the surface layer properties (thickness d , resistivity ρ_s , noise B) do not change as the sample thickness is changed. Then,

$$S_\rho/\rho^2 \propto \rho^2/lwt^2$$

or

$$S_\rho/\rho^4 \propto 1/\Omega t \quad (\text{A4})$$

as t is varied.

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