1/F NOISE IN CONTINUOUS METAL FILMS IS NOT DUE TO TEMPERATURE FLUCTUATIONS[1]

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The possibility that 1/f conductance noise (also referred to as "excess", or "1/f" noise) in thin continuous metal films is caused by temperature fluctuations has been considered by several authors [1-6]. The power spectral density (PSD) of the voltage fluctuations $S_V(f)$, if generated by temperature fluctuations is supposed to be $S_V(f)=\beta^2\bar{V}^2S_T(f)$, where $S_T(f)$ is the PSD of the fluctuations of the average temperature of the film, $\bar{V}$ is the mean voltage across the film, and $\beta = (1/R)(dR/dT)$ is the film's temperature coefficient of resistance. Whatever the origin of temperature fluctuations, their propagation is governed by the diffusion equation so that the resulting excess noise would exhibit a frequency dependent correlation length characteristic of a diffusion process, $\lambda(f) = \{D/\pi f\}^{1/2}$, where D is the thermal diffusivity of the material. Spatial correlations of the excess noise along metal films have been observed [1,2].

Equilibrium temperature fluctuations do account for the magnitude and spectrum of measured conductance noise in freely suspended tin films near their superconducting transition temperature (where $\beta T>1000$) [3]. However, for substrate supported metal films various theoretical temperature fluctuation models predict spectra with a low frequency cut off, a limited 1/f range, if any, and a monotonic temperature dependence. In contrast, experiments reveal a wide range of 1/f spectrum and complex temperature dependence [1,4]. Thus, equilibrium temperature fluctuations do not appear to account for most observed 1/f noise in metal films. Voss and Clarke have proposed a thermal fluctuation model with a 1/f regime [1]. Such alternative temperature fluctuations of yet unrecognized origin might generate the observed 1/f noise [1,5]. Van Vliet, et al. have calculated that the spectrum of the fluctuations of the average temperature of a metal film on an insulating substrate with a uniform surface noise source having a white spectrum spatially coherent across the top of the substrate would yield a 1/f spectrum [6]. However, they find that the magnitude of the resulting temperature fluctuations would be negligible for thermal radiation fluctuations. Nevertheless, temperature fluctuations in conducting metal films near room temperature has remained in contention as a seductively simple mechanism to account for 1/f conductance noise.

We have designed an experiment to detect the possible existence of temperature fluctuations large enough to account for excess noise in thin metal films. Calculations and experiments showed that the temperatures of superimposed films separated by a thin electrically insulating layer are closely coupled over the relevant frequency range. Thus temperature fluctuations in one film will be correlated with the temperature fluctuations of the other. Therefore, if the 1/f noise in a film were due to temperature fluctuations this noise would be correlated with the 1/f noise in the neighboring film. We have fabricated suitable superimposed gold films, confirmed the calculated thermal coupling by modulated heat input experiments, and have looked for a correlation in their 1/f noise. Our experiments show that the coherence (defined below) between the excess noise of the two films is less than 1/100th the value anticipated were the measured 1/f noise in each film due to temperature fluctuations.

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The superimposed electrically insulated film bridges were prepared by evaporating a 600 Å layer of gold onto a 0.6 mm thick single crystal sapphire substrate and photo-etching it to a 1 mm long, 80 μm wide bridge. Next, a 6000 Å layer of SiO was evaporated on top of the gold bridge and surrounding sapphire substrate, and a second bridge similar to the first was evaporated and formed on top of the SiO layer. Finally, a thicker gold 4-probe electrical contact super-structure was evaporated onto the sample for electrical connections. Noise free contacts of negligible resistance were made using either pressed indium wire or gold wire soldered with indium. The substrate was then mounted onto a large copper heat sink. Bridge resistances ranged between 11Ω and 19Ω due to differences in geometry. Calculated resistivities were typically 6 μΩ·cm (about twice the bulk value) and the measured thermal coefficients of resistance were about $\beta = 0.003°C^{-1}$ (similar to the bulk value).

Conductance and Nyquist noise were measured with a constant current I < 40 mA derived from lead-acid batteries in series with a 1 KΩ wire wound ballast resistor. Due to the large thermal conductivity (K=0.1 cal/C s cm) of the single crystal sapphire substrate, the relatively large current densities (10^6 A·cm^{-2}) generated less than a 1°C film temperature rise as measured by I-V characteristics and confirmed by heat flow calculations.

Voltages across each sample were amplified with either an Ithaco 1201 or a PAR 113 low-noise preamplifier, impedance matched to the films with a PAR 190 low-noise transformer, and fed into an HP 5420A spectrum analyzer. The PSD of the excess noise for each film was obtained by measuring the PSD of its voltage fluctuations $S_E(f)$ and subtracting from this the PSD of the background (mostly Nyquist) noise $S_B(f)$, obtained by replacing the film with an equivalent wire-wound resistor. For frequencies between 1 Hz and 5 Hz it was necessary to correct up to 8 dB for the transfer characteristics of the instrumentation. Within the frequency range measured, 1 Hz <f< 100Hz, both films showed excess noise roughly consistent with Hooge's empirical formula, $S_v(f)/\bar{V}^2 = a/\{N_c f^b\}$, with 1.0 <b< 1.1 and 0.005 <a< 0.014, where N_c is the number of carriers [7].

We have modeled the three-dimensional thermal coupling problem by considering diffusion into the substrate. Our model calculations indicate that the average temperatures of those portions of each of the two films that are directly superimposed upon one another are virtually identical for frequencies $f \ll 1/\tau_{SiO}$, where $\tau_{SiO} = \pi s^2/D_{SiO}$, s is the thickness, and D_{SiO} the diffusivity of the SiO layer [8]. Since $\tau_{SiO} < 1$ μs this result holds true for all frequencies of interest. In order to confirm the validity of our model and to test for possible thermal barriers at the interfaces we have calculated the amplitude of the sin (2πft) component of the average temperature of the lower film that results when the top film dissipates a power P_1 sin(2πft). We measured this same quantity by passing a current i_1 sin(πft + θ) through the top film and a steady current I through the bottom film. The amplitude of the sin (2πft) component of the voltage across the bottom film is then a measure of its average temperature modulation amplitude. Measurements of the ratio of the modulation amplitude of the average temperature of the bottom film $\Delta T_2(f)$ to the amplitude of the power dissipated in the top film P_1, for frequencies 0.2 Hz <f< 24 KHz are plotted in figure 1. The modulation amplitude was proportional to Ii_1^2 as expected for thermal coupling. Measurements taken with the roles of the two bridges reversed gave identical results. The calculated values of $\Delta T_2(f)/P_1$ are plotted as the solid curve in figure 1. Theory and experiment agree at all frequencies within the factor of two uncertainty due to β, the temperature coefficient of resistance of the film, K, the thermal conductivity of the substrate, and the transfer function calibration at low frequency. The excellent agreement without adjustable parameters indicates that the model incorporates the important features of the system, and gives us confidence in its prediction for strong thermal coupling between the two films.

The correlation between fluctuations of the average temperatures of the two films can be expressed by the coherence function, $\gamma_T^2(f) = |S_{T12}(f)|^2/\{S_{T1}(f)\cdot S_{T2}(f)\}$, where S_{T12} is the cross-PSD between the average temperatures of the two films, and S_{T1} and S_{T2} are their individual PSD's [9]. The thermal coupling calculation indicates that if the two films were perfectly superimposed the coherence between fluctuations of their average temperatures would be unity for $f \ll 1/\tau_{SiO}$. However, since they are not perfectly aligned $\gamma_T^2(f)$ is slightly reduced by a factor that depends on the fraction of the area of one film which overlaps the other film. For our film geometry we expect $0.9 < \gamma_T^2(f) < 1.0$.

Consequently, if temperature fluctuations were the cause of the 1/f noise, essentially

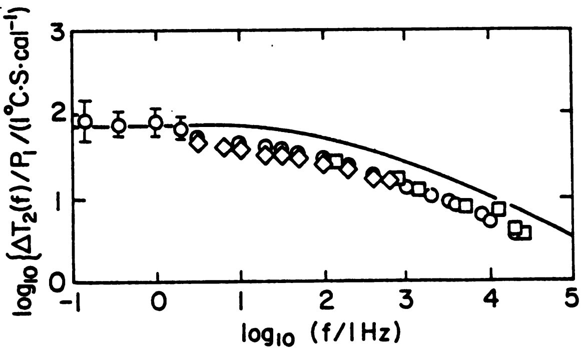

Fig. 1 Thermal response $\Delta T_2(f)/P_1$. Data points are representative of several different runs; omitted points superimpose; ○ and ◇ observed with power into top film, □ with power into bottom film. Error bars represent low frequency uncertainties in the transfer function. Solid line is the calculated value of the thermal response $\Delta T_2(f)/P_1$.

the same temperature fluctuations would appear in both films and the 1/f noise would be correlated. In this case we expect $\gamma_v^2(f) = \gamma_T^2(f)$, where $\gamma_v^2(f)$ is the coherence between the 1/f noise of the two films. Since the measured voltage fluctuations across a film include both the 1/f noise and (mostly incoherent) background noise, the coherence $\gamma_E^2(f)$ of the measured voltage fluctuations of the two films is not in general equal to $\gamma_v^2(f)$. Instead, $\gamma_v^2(f)$ and $\gamma_E^2(f)$ are related by

$$\gamma_E^2(f) = \gamma_v^2(f)/\{[1+S_{B1}(f)/S_{v1}(f)][1+S_{B2}(f)/S_{v2}(f)\},\qquad(1)$$

where S_{v1} and S_{v2} are the PSD's of the excess noise of each film and S_{B1} and S_{B2} are the PSD's of their background noise. Using measured values of S_{v1}, S_{v2}, S_{B1}, and S_{B2}, $\gamma_E^2(f)$ has been calculated and is plotted as curve a in figure 2 assuming that temperature fluctuations are completely responsible for the observed 1/f noise of a single film (i.e. $\gamma_v^2 = \gamma_T^2$).

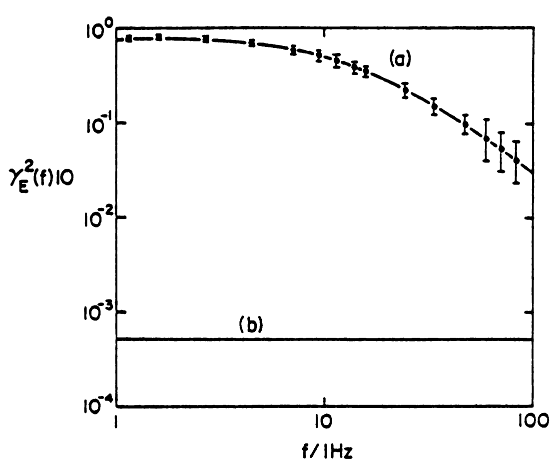

Fig. 2 (a) Calculated $\gamma_E^2(f)$ assuming $\gamma_v^2(f) = \gamma_T^2(f)$ from measured S_{v1}, S_{v2}. S_{B1}, and S_{B2}. (b) Upper limit of experimental coherence $\gamma_E^2(f)$.

Measurements of $\gamma_E^2(f)$ for frequencies 1 Hz $<f<$ 100 Hz discovered no coherence above the instrumental sensitivity indicated by curve b in figure 2. In this frequency range $0 < \gamma_E^2(f) < 5 \times 10^{-4}$. At the low frequency the coherence is more than a factor of 10^3 lower than would be expected if the 1/f noise were due to temperature fluctuations. At higher frequencies the Johnson noise reduces $\gamma_E^2(f)$, but the discrepancy is still large. Since the correlation length for temperature fluctuations $\lambda(f) = \{D/\pi f\}^{1/2}$ at 1Hz is already very much longer than the separation between the two films, and increases with decreasing frequency, this result should extend to lower frequencies. Therefore, we must conclude that the 1/f noise in these gold films is not due to temperature fluctuations.

Voss and Clarke [1] and Zhigal'skiy, et al. [2] have previously reported the observations of frequency dependent spacial correlations in the room temperature 1/f noise along metal films, as would be expected if the noise were due to thermal fluctuations. However, elsewhere in this conference Weissman reports similar experiments in which spacial correlations were not observed. Van Vliet and Chenette also report in private communication the lack of correlation of the 1/f noise between two thermally coupled semiconductor junctions.

In summary, we have measured the coherence between the 1/f conductance noise of two substrate mounted thin gold films that have been demonstrated to be in strong thermal contact, and have calculated the coherence between the 1/f noise that would be expected if temperature fluctuations were responsible for the observed 1/f noise. The measured coherence is several orders of magnitude lower than predicted for temperature fluctuations. Therefore, we conclude that the 1/f noise is not caused by temperature fluctuations.

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