Comment on $1/f$ noise and its temperature dependence in silver and copper

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Recent measurements taken by Eberhard and Horn of the temperature dependence of the excess noise in very thin continuous Ag and Cu films can be interpreted in terms of a surface effect. On the basis of experimental results on discontinuous metal films, we suggest that a substrate interface conduction mechanism (i.e., a shunting between a continuous and a discontinuous metal film) is responsible for that effect.

In a recent Letter Eberhard and Horn[1] (EH) report some experimental results on the temperature dependence of the current noise in Ag and Cu films evaporated on sapphire substrate, and claim that these are the first systematic measurements on the temperature dependence of the excess noise in metals.

According to these results, Ag and Cu films present a rather similar behavior: in both cases there is found a two decade increase on the magnitude of the noise spectral density when temperature increases between 100 and 500 K, with a maximum at 410 and 490 K for Ag and Cu, respectively. Above these temperatures, the noise decreases slowly in both films.

In that Letter, the authors state that none of the previous theories[2,3] on the current noise can explain the reported behavior of noise versus temperature. The model of a creation-diffusion vacancy process that they propose is recognized as merely speculative.

Actually, for temperatures below 500 K, the vacancy contribution to the noise is absolutely undetectable (at least in Al and Au films) with extremely high sensitivity (10^{-21} V^2/Hz), and at higher temperatures, where a vacancy activation process has already been detected,[4] the vacancy contribution should give an increasing noise with increasing temperature, and not a peaked behavior as reported by EH.

We suggest an alternative explanation of the above results. Because of the very small thickness of the films (400–1600 Å) evaporated by EH, a realistic explanation of the $1/f$ excess noise and its temperature dependence can be obtained by assuming a substrate interface conduction mechanism. Two alternatives are possible: (i) owing to the many irregularities (hills and hollows at microscopic level always present in the substrate surface) the continuous film behaves at the interface as a discontinuous one, and part of the electrical conduction takes place within the insulator;[5] (ii) the films employed are partially discontinuous, especially in the edge regions, on account of the adopted scribing technique.

In both cases we are in the presence of a discontinuous film having a characteristic temperature dependent noise.[6,7] shunted by a continuous homogeneous noise-free film responsible for the drop of the overall noise in the low-temperature range. If only the discontinuous film were present and a constant current flowing, a strong $1/f$ excess noise would be detected, whose relative voltage spectral density can be expressed in an obvious way:

$$\Phi_{vd}(f)/V^2 = \Phi_{gd}(f)/G_d^2(T) , \tag{1}$$

with V the average voltage at the film terminals, $G_d(T)$ the temperature-dependent conductance of the film, and $\Phi_{gd}(f)$ the spectral density of the conductance fluctuation.

The shunting of the discontinuous film by a continuous layer of conductance $G_c(T)$ leads to a drop of the detected noise, and the new relative voltage spectral density becomes

$$\Phi_{vc}(f)/V^2 = \frac{\Phi_{vd}(f)}{V^2}\frac{G_d^2(T)}{G_c^2(T)} = \frac{\Phi_{gd}(f)}{G_c^2(T)} , \tag{2}$$

having taken into account that it is always $G_c(T) \gg G_d(T)$.

The conductance spectral density $\Phi_{gd}(f)$ is a quantity whose temperature dependence is representative of a general temperature behavior of excess noise in discontinuous metal films,[7] with a maximum between 400 and 500 K.

In Fig. 1 we report the typical experimental behavior of $\Phi_{gd}(f)$ versus temperature at low frequencies for a discontinuous gold film evaporated

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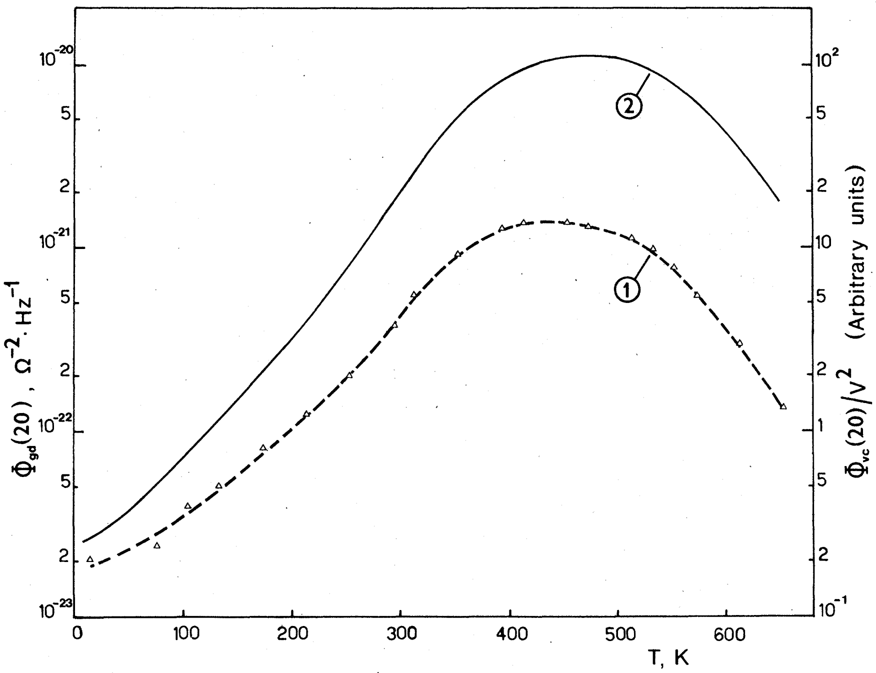

FIG. 1. Spectral density at 20 Hz of the conductance fluctuation vs temperature in a discontinuous gold film on a sapphire substrate (curve 1). The continuous line represents $\Phi_{vc}(f)/V^2$, the relative voltage noise spectral density upon the film when shunted by a continuous metal layer. Curve 2 is obtained by dividing curve 1 by $G_c^2(T)$.

on a sapphire substrate (curve 1). A very similar curve is obtained if a platinum film on a same substrate is considered. This fact suggests that the noise behavior in discontinuous films depends mainly on the substrate conduction mechanism and less on the nature of the deposited metal.

In the case of shunting by a continuous metal layer, it is easily seen from Eq. 2 that the relative noise voltage spectral density $\Phi_{vc}(f)/V^2$ can be simply obtained by dividing curve 1 by $G_c^2(T)$. One obtains curve 2, which represents, apart from a constant factor, the same quantity $S_v(f)/V^2$ of EH. This curve is quite similar to the experimental curves reported by the same authors for Ag and Cu films, and strongly suggests that the excess noise found by EH can be interpreted as due to a surface effect.

Further support to this interpretation is given by the fact that the slope of the $1/f$ noise spectra reported by EH increases with decreasing temperature, as in discontinuous films.

A theory that accounts for this effect and explains the excess noise and its temperature dependence in discontinuous metal films has been developed recently by Celasco, Masoero, Mazzetti, and Stepanescu.[8] This theory assumes that in the tunneling process between metal islands within the insulator substrate the electrons must overcome a temperature-dependent potential barrier. The current noise is generated as a result of the thermal fluctuation of the potential barrier, modulated by a corresponding fluctuation of the surface charges, due to the ionized donor states located in the insulator surface between metal islands.

The drop of the noise at higher temperature (i.e., the maximum in the curve 1 of Fig. 1) is attributed to the thermal injection effect of electrons from the metal to the conduction band of the insulating substrate.

Obviously our interpretation of the noise as a surface effect would require that noise intensity depends on film thickness according to an inverse square law. From the data reported by EH in Fig. 3 of Ref. 1, related to Ag films of different thicknesses (1400 and 800 Å), it is difficult to draw any conclusion because arbitrary scales were used and because the ratio of the noise intensities for films of different thickness depend upon temperature. Actually, if an inverse linear dependence on thickness is assumed at room temperature, an inverse square law dependence is found from the same data at lower temperatures. The conclusion is that more extended results about the thickness dependence of the noise are needed to make more conclusive remarks.

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