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Effect of strain on the $1/f$ noise of metal films

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The application of stress has been found to significantly affect the low-frequency excess noise of metal films. We find that in general the resulting noise is similar to the $1/f$ noise thought to be intrinsic to metals. Our results suggest that much of the noise observed in these systems may be caused by a process closely associated with strain relaxation.

Fluctuations with intensities proportional to $1/f^{\alpha}$, where f is the frequency and $\alpha \simeq 1$, occur in many physical systems. There is substantial interest[1] in this "$1/f$ noise" because of its unique statistical properties, and because in most cases its origin is unknown. Lately, much attention has been focused on the noise of continuous metal films; nevertheless, the physical process—or processes—which causes the noise has yet to be identified.[2,3] A perplexing finding of previous experiments[4-6] is that noise magnitudes of nominally identical samples can differ by more than a factor of 10, although the noise of a given sample generally does *not* show such variation. However, in recent studies of $1/f$ noise in a wide variety of metals we have found occasional samples for which the noise has decreased by one or two orders of magnitude over the course of several days.[7] This implies that the process which causes (at least some of) the $1/f$ noise in these samples is itself "relaxing" and/or disappearing with time. In an effort to learn more about this process, we have subjected several different types of metal films to stress. We find that the magnitude of the $1/f$ noise is significantly affected by the resulting strain within the film, and the strain-induced noise generally decreases with time. This suggests that there is a link between the $1/f$ noise of metal films and a process closely associated with strain relaxation.

The method of sample fabrication and the apparatus used to perform the noise measurements have been described previously.[6,8] All measurements were performed at room temperature. To apply stress, we mounted the substrate over a tapped hole in a metal block, with the edges of the substrate clamped to the block. A nylon screw was then raised from below to deform the substrate. In this manner, small strains could be induced in samples on glass substrates. To obtain large strains, it was necessary to use Mylar substrates, which have a larger elastic limit.[9] No significant contact noise resulted from the applied stress. Except for samples that showed burst noise (as discussed below), the excess voltage noise[10] power spectral density, S_V, was proportional to V^2, where V is the average voltage across the sample, for a given level of strain.[11]

In Fig. 1, S_V for a platinum film is plotted as a function of frequency. The normalized noise power, $S_V N/V^2$, where N is the number of atoms in the sample, is given on the right-hand scale. The quantity $\gamma(f) \equiv S_V Nf/V^2$, commonly used to compare the noise magnitudes of different samples,[2,3,6] may thus be obtained directly from the figure. Line A represents the noise before stress had been applied. Here S_V is proportional to $1/f^{\alpha}$ with $\alpha \simeq 1.35$. This value of α is somewhat higher than that normally observed for platinum, but it is well within the range reported for metal films.[4-6] As a convenient measure of the noise magnitude, we shall use $\gamma \equiv \gamma(10\ \mathrm{Hz})$. From Fig. 1 we find $\gamma \simeq 6.3 \times 10^{-4}$, which is typical for platinum.[6,12] When stress was applied, the noise (at the same measuring current) increased to the level of line B. That a sample on a deformed substrate would be noisier than a sample on an undeformed substrate is certainly not surprising. However, it is important to note that now $\alpha \simeq 1.15$; that is, the power spectral density still is of the form characteristic of $1/f$ noise. This strongly suggests that the increase in γ is not due to burst noise or some other "spurious" effect.[13] The time dependences of γ and α are shown in Fig. 2. It can be seen that, after its initial increase at B with the application of stress, γ decreases with time. During this interval the resistance of the sample, R, also decreased slightly, while α remained relatively constant. The decrease in R with time indicates that, after stress was applied, the sample began to relax in order to reduce the strain within the film. Both the amount of strain and the noise then decrease as the sample continues to relax, so the increased noise magnitude at B is evidently related to the increased strain. At C, the stress was removed from the substrate. Although the substrate is no longer under a stress here, the sample is strained since it had relaxed to accommodate the previously deformed substrate. Thus, the behavior resembles that seen when stress was applied at B. Note that R *decreased* at C; hence, the signs of the changes in R and γ are not correlated. At D stress was again applied to the substrate. While there are differences in detail, the previous behavior is qualitatively reproduced.

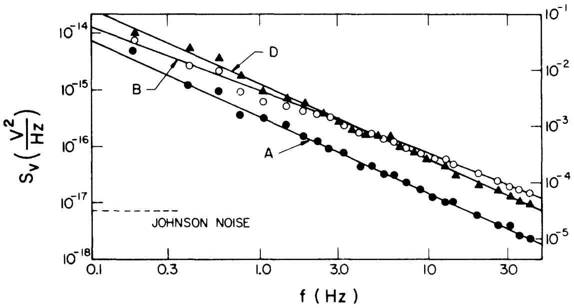

FIG. 1. S_V as a function of f for a platinum film at a current of 0.55 mA. The dashed line represents the Johnson noise level, although the Johnson noise has been subtracted to obtain S_V. The solid lines are discussed in the text.

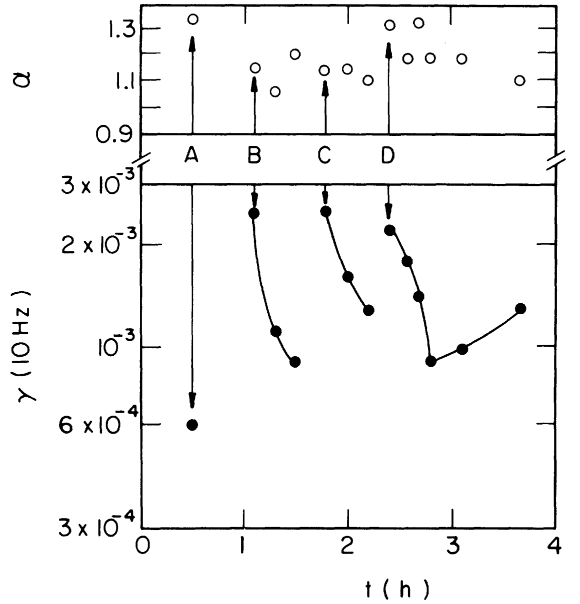

FIG. 2. Values of γ and α as function of time for a platinum film at a current of 0.55 mA. Power spectra of the measurements represented by points *A*, *B*, and *D* are given in Fig. 1. The conditions under which the measurements were made are given in the text. The curves are guides to the eye. The resistance at each point in Ω, and its value at the end of the interval shown, is as follows: *A*, 427.4; *B*, 428.7–428.3; *C*, 427.9–427.8; *D*, 428.6–428.1.

In Fig. 3 we show the results of a similar experiment performed with a gold film on a Mylar substrate. Again γ and α are shown as a function of time. Before the application of stress, samples on Mylar substrates were more likely to exhibit nonstationary (i.e., time dependent) behavior than samples on glass, presumably because of the ease in which strain may be induced in films on the relatively pliable Mylar substrates during the fabrication process. Such behavior is illustrated at *E*, which shows the values of γ and α for measurements performed on three successive days before stress was applied. The value of γ decreased systematically from the upper bound shown to the lower. (The "error bars" here are used to represent the spread in values obtained, not the uncertainty of a given measurement.[14]) Stress was applied to the substrate at *F*. There was initially a pronounced "burst noise," similar to that previously found in certain tin samples.[8,15,16] To indicate this, we enclose the first point at *F*, and other points at which burst noise was observed, in parentheses. Excluding these, it can be seen that γ exhibits a trend similar to that of Fig. 2; that is, the noise increased with applied stress, and then decreased with time. The strain was increased at *G*, and the behavior is repeated. Following the last measurement at *G*, the stress on the substrate was *not* relieved. The results of noise measurements performed over the two following weeks are summarized at *H*. At *J* the stress was removed. Again, there was substantial burst noise at first, after which γ returned to its value at *H*. Within four days the values of γ and α had stabilized at those given at *K*.[17] Thus, the trends of Fig. 2 are largely reproduced in Fig. 3.

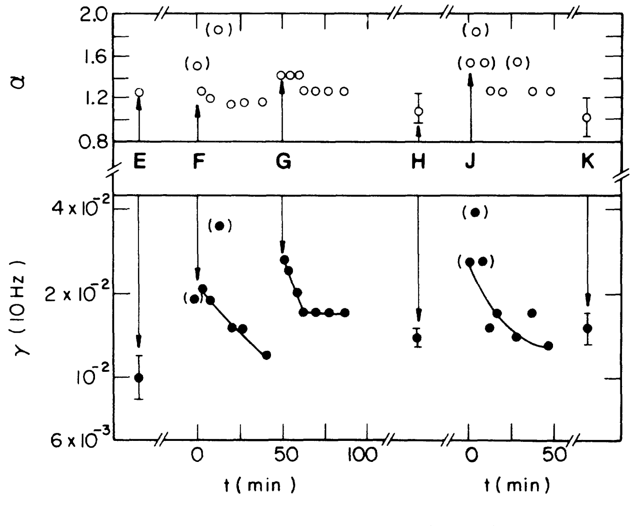

FIG. 3. Values of γ and α as a function of time for a gold film at a current of 2.0 mA. The conditions under which the measurements were made are given in the text. The curves are guides to the eye. Parentheses indicate that burst noise was observed during the measurement. The resistance at each point in Ω is as follows: *E*, 126.8; *F*, 128.9; *G*, 129.8; *H*, 129.4; *J*, 128.1; *K*, 127.5.

Results similar to those shown above were also obtained for silver, lead, and tin, implying that this behavior is quite general. We therefore feel that a link exists between the $1/f$ noise of metal films and a process closely associated with strain relaxation. It is well known[2] that for the case in which the noise results from a process having a single activation energy, corresponding to one characteristic time, the ensuing power spectrum has a Debye-Lorentzian profile; that is, S_V varies as $1/f^2$ at high frequencies and approaches a constant at low frequencies. Indeed, such noise has been observed in thick aluminum films by Bertotti *et al.*[15] However, Dutta and Horn[2,18] have shown that if, instead, the process were to involve a *distribution* of activation energies, having a width greater than k_BT and centered at an energy of about 1 eV, there would be an extended region of $1/f$ noise. Many processes associated with stress and/or strain relaxation have activation energies in this region[19]; therefore, the theory of Dutta and Horn may provide a natural explanation of our results. Moreover, the speculations of Eberhard and Horn[5] about the possible role of vacancy-interstitial diffusion in the noise process are quite consistent with the dependence of the noise on strain that we observe. To see if these results might explain the sample-to-sample variations of the noise, we have remeasured a number of samples used in a prior study.[6] We find that some of the samples, which initially had the largest noise, are now up to two orders of magnitude quieter[7,20]; indeed, their noise (six months to one year later) is near the minimum level exhibited in Ref. 6. That is, the behavior is similar to that shown in Figs. 2 and 3, but the time scale is much longer.[21] Hence, the sample-to-sample variations, at least in this case, may be a result of the differing amounts of strain within the samples. It is therefore worthwhile to consider two possibilities: (1) Strain within the film can lead to an increase of the noise above the level intrinsic to metals, or (2) a process intimately related to strain relaxation may be responsible for all $1/f$ noise seen in metal films. While the results of this study, and of previous experiments,[6] appear to be more consistent with the first interpretation, further work is needed to distinguish between these (and other) alternatives.

In conclusion, we have found that the magnitude of the $1/f$ noise of metal films is quite sensitive to strain within the film. This provides a natural explanation of the sample-to-sample variations of the noise commonly reported, and raises the possibility that much of the $1/f$ noise observed in metal films could be due to a process closely associated with strain relaxation.

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[1] See, for example, W. H. Press, Comments Astrophys. Space Phys. 7, 103 (1978).

[2] P. Dutta, and P. M. Horn, Rev. Mod. Phys. 53, 497 (1981).

[3] F. N. Hooge, T. G. M. Kleinpenning, and L. K. J. Vandamme, Rep. Prog. Phys. 44, 479 (1981).

[4] R. F. Voss and J. Clarke, Phys. Rev. B 13, 556 (1976).

[5] J. W. Eberhard and P. M. Horn, Phys. Rev. B 18, 6681 (1978).

[6] D. M. Fleetwood and N. Giordano, Phys. Rev. B 27, 667 (1983).

[7] D. M. Fleetwood and N. Giordano, in *Proceedings of the Joint 7th International Conference on Noise in Physical Systems and 3rd International Conference on 1/f Noise, Montpellier, France* (North-Holland, Amsterdam, in press).

[8] D. M. Fleetwood and N. Giordano, Phys. Rev. B 25, 1427 (1982).

[9] The strain-induced noise did not appear to depend on the type of substrate.

[10] The Johnson noise is subtracted from the total noise power to obtain the "excess noise."

[11] No detectable spatial correlations of the strain-induced noise were observed (on length scales greater than about 250 μm along the film, or between samples separated by 10–20 μm and not in electrical contact.)

[12] D. M. Fleetwood, J. T. Masden, and N. Giordano, Phys. Rev. Lett. 50, 450 (1983).

[13] It is well known that a slow monotonic resistance drift can mimic "noise" with a $1/f^2$ spectrum (Ref. 4). While the resistance of the samples we have studied decreased slightly during many of the measurements reported, it was not sufficient to affect the values of α or γ.

[14] The uncertainties in γ and α for an individual measurement depend, of course, on the number of power spectra averaged. These uncertainties are at most 20% for the data given, and are typically less than 10%.

[15] G. Bertotti, M. Celasco, F. Fiorillo, and P. Mazzetti, J. Appl. Phys. 50, 6948 (1979); see also M. Celasco, F. Fiorillo, and P. Mazzetti, Phys. Rev. Lett. 36, 38 (1976).

[16] This burst noise has also been found in previous studies (Ref. 15) in which the effect of dislocation motion on the noise of thick aluminum films was examined; however, no $1/f$ noise was observed in those studies.

[17] While α does not exhibit the striking strain-dependent behavior that γ does, we see in Figs. 2 and 3 that it, too, is sensitive to strain. This may account for the differences in α reported for gold films in previous studies (Refs. 5 and 6).

[18] P. Dutta, P. Dimon, and P. M. Horn, Phys. Rev. Lett. 43, 646 (1979).

[19] See, for example, A. S. Nowick and B. S. Berry, *Anelastic Relaxation in Crystalline Solids* (Academic, New York, 1972), pp. 91–112.

[20] The noise magnitudes of samples that were originally near the minimum level have not changed significantly.

[21] This is not surprising, owing to the very different manners in which the strains were induced.