RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 31, NUMBER 2 15 JANUARY 1985

Direct link between $1/f$ noise and defects in metal films

D. M. Fleetwood* and N. Giordano
Department of Physics, Purdue University, West Lafayette, Indiana 47907
(Received 30 July 1984)

We have found that gently annealing a AuPd film has a substantial effect on its $1/f$ noise. From the temperature dependence of the noise after various amounts of annealing, one can infer changes in the distribution of activation energies of the process responsible for the noise. These changes are consistent with general expectations concerning the effect of annealing on lattice defects. Our results strongly support the idea that at least some of the $1/f$ noise of metal films is associated with defect motion.

Several years ago Dutta, Dimon, and Horn[1] demonstrated that the temperature dependence of the $1/f$ noise of many different types of continuous metal films can be explained naturally, if it is assumed that the noise is due to a thermally activated process with a distribution of relaxation times. Central to their work was the realization that, contrary to a longstanding misconception,[2] a process having a nonuniform distribution of activation energies can produce noise with a power spectrum that is proportional to $f^{-\alpha}$, with $\alpha \simeq 1$, over a wide range of frequencies. According to their model, the temperature dependence of both the noise power spectral density, S_V, and the frequency dependence of the noise, $\alpha \equiv -(\partial \ln S_V/\partial \ln f)$, can be derived from the distribution of activation energies, $D(E_0)$. The behavior of $D(E_0)$ can be inferred directly from $S_V(\omega,T)$, via the relation

$$D(E_0) \sim \frac{\omega S_V(\omega,T)}{k_B T} . \tag{1}$$

Here $E_0 \equiv -k_B T \ln(\omega\tau_0)$, where T is the temperature, k_B is Boltzmann's constant, $\omega \equiv 2\pi f$, and τ_0 is the attempt time of the activated process.[1] Furthermore, $S_V(\omega,T)$ and $\alpha(\omega,T)$ are coupled through the expression[1]

$$\alpha(\omega,T) = 1 - \frac{1}{\ln(\omega\tau_0)} \left[\frac{\partial \ln [S_V(\omega,T)]}{\partial \ln T} - 1 \right] . \tag{2}$$

The prediction (2) is in good agreement with experimental results for metal films.[1] However, it does not provide any direct insight into the microscopic source of the noise, i.e., the specific thermally activated process. One possibility suggested by the inferred energy scale for the noise process, as noted by Horn and co-workers,[1,3] is that the noise is associated with defect motion. Recent experiments performed at room temperature[4-6] appear to be in good agreement with this interpretation. A natural experiment to test this idea is to study the effect of removing defects, via annealing, on the noise. Such an experiment was performed by Eberhard and Horn,[3] who found that the magnitude of the noise of a Ag film decreased significantly after it had been annealed, just as would be expected if the noise were caused by defects. However, the behavior they found for $\alpha(T)$ does not appear to be consistent with the measured $S_V(T)$ together with (2). We have performed a similar experiment with a highly disordered metal alloy. This system was chosen since it contains a large number of defects, and hence the effect of annealing should be much larger than in the relatively clean metals, such as Ag, which have been studied previously. We find that, in agreement with the prediction (2), the changes in $\alpha(T)$ that occur between successive stages of gentle annealing correlate well with the changes in $S_V(T)$. Further, the systematic changes in $D(E_0)$, inferred through (1), agree with one's expectations concerning the effect of annealing on a disordered system. This result strongly suggests that the observed noise is caused by the motions of defects.

For this study we selected a 530-Å-diameter AuPd ($Au_{60}Pd_{40}$) wire, fabricated from a sputtered film using the technique of step-edge lithography.[7] This material was chosen since it has a large resistivity (presumably due to a large defect density), and it readily anneals at temperatures only slightly above room temperature.[8] Our most detailed noise measurements were performed on a wire, as opposed to a film of typical dimensions,[3,4] because of its large impedance and length-to-width ratio, which facilitate an accurate measurement of the noise.[9] Similar results, although not as extensive, have been obtained with other AuPd films and wires,[10] and hence we believe that our results are characteristic of metal "films." Standard noise measurements[10] were made over the range $77 \leq T \leq 430$ K. No detectable Joule heating due to the measuring current, as determined by measurements[3] of $R(I)$ and $R(T)$, occurred during our experiments.

Figure 1 shows results for $\gamma \equiv S_V N f/V^2$, as a function of T. Normalizing the results for S_V in this way removes the dependences[1,9,11] on f, V, and N, the latter being the number of atoms in the sample. Before the sample was annealed (curve A), γ exhibited an abrupt increase in slope at approximately 200 K.[12] From (2), one expects that this increase in $(\partial \ln S_V/\partial \ln T)$ should be accompanied by a corresponding increase in the value of $\alpha(T)$ at the same temperature, and indeed, this is seen to be the case in Fig. 2. Moreover, the prediction of (2) is seen to be in excellent agreement with the experimental results for α

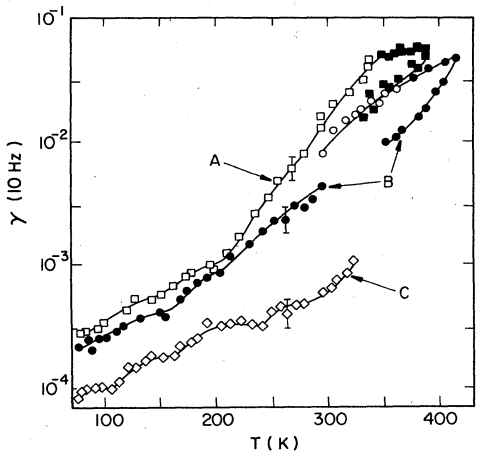

FIG. 1. γ at $f=10$ Hz as a function of T and annealing. The open squares represent the noise of the sample before it had been heated initially. For this range, $\rho(300\text{ K})=180\pm20\ \mu\Omega\,\text{cm}$ and $\beta\equiv(1/\rho)/(d\rho/dT)=(1.20\pm0.05)\times10^{-4}\ \text{K}^{-1}$. The solid squares denote the noise after the sample had begun to anneal. Similarly, the open circles [$\rho(300\text{ K})=160\pm18\ \mu\Omega\,\text{cm}$] and the solid circles [curve B, $\rho(300\text{ K})=145\pm16\ \mu\Omega\,\text{cm}$; $\beta=(1.38\pm0.05)\times10^{-4}\ \text{K}^{-1}$] denote the noise during the second series of measurements as described in the text. The diamonds [curve C, $\rho=125\pm14\ \mu\Omega\,\text{cm}$; $\beta=(1.24\pm0.05)\times10^{-4}\ \text{K}^{-1}$] represent the noise after the last annealing. Between the noise measurements shown in curves B and C, the sample was heated to $T\simeq470$ K in an oven outside the cryostat assembly for about an hour. Otherwise, all heating was accompanied by noise measurements. The curves are guides to the eye, and the error bars shown are representative uncertainties in the values of γ.

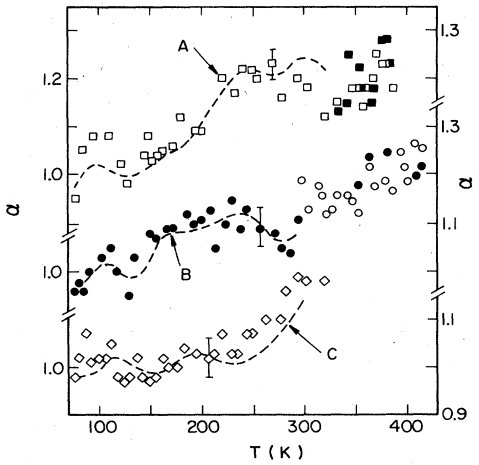

FIG. 2. α as a function of T. The symbols used are similar to those employed in Fig. 1. The only difference is that here (above 300 K) the solid symbols refer to noise measurements performed as the sample was cooled (after annealing), and the open symbols refer to measurements taken as the sample was heated. The dashed curves are the predictions of (2) as obtained from the results in Fig. 1, as discussed in the text.

over the entire range. Returning to Fig. 1, we now consider the noise above 350 K. In this region it was found (curve A) that the sample was actually annealing during the measurements.[14] Hence, the behavior shown above 350 K in curve A does not reflect the true, i. e., "equilibrium" behavior of S_V, and thus no meaningful comparison between the observed and predicted values of $\alpha(T)$ can be made in this case. However, the behavior in this range suggests that whatever is causing the noise (e.g., defects) was being removed from the sample at about the same rate as its influence was being enhanced by the increase in temperature. Once the sample was allowed to cool so that the annealing had stopped, the noise at a given temperature had decreased significantly,[15] although there is very little difference between the *slope* of $S_V(T)$ before and after annealing in the region 300—350 K. This behavior suggests through (2) that α should be unchanged (in this range), and this is seen to be the case in Fig. 2.

After this first annealing, another series of noise measurements was performed during which the sample was heated slowly from room temperature to 410 K and subsequently cooled to 340 K. This sequence is depicted by the circles in Fig. 1 (curve B). The noise below room temperature, represented by the lower portion of curve B, was then measured. Not only is the overall level of curve B below that of curve A at all temperatures, but the slope does not increase as rapidly above 200 K. This implies corresponding changes in the values of α above 200 K, and one can see from Fig. 2 that these changes are in excellent quantitative agreement with the measured values. After the wire had been annealed for a third time, by heating to approximately 470 K, the noise was measured again (curve C in Fig. 1). The decrease in the overall noise level, as well as the decrease in the slope of $S_V(T)$ above 200 K, relative to that found before annealing, are now even more pronounced. As found for the other sets of measurements, the values of α remained in excellent agreement with those expected from (2).

Since the model, in particular (2), provides a self-consistent description of our results, we feel it is justified to use (1) to obtain the distribution of activation energies. This distribution function can now be used to address the question of the microscopic origin of the noise. As has been noted above, an obvious interpretation of our results is that the decrease in the level of the $1/f$ noise was a consequence of the removal of defects. It is therefore important to examine the distribution of activation energies, $D(E_0)$, as a function of annealing. Recall from (1) that $D(E_0)$ is proportional to γ/T, and that E_0 is proportional to T, so a plot of γ/T as a function of T should reflect the shape of $D(E_0)$. Such results, taken from the data in Fig. 1, are shown in Fig. 3. At the lowest energies, $0.2\leq E_0\leq0.4$ eV, $D(E_0)$ decreases by about a factor of 3 over the course of the annealing. At higher energies, $E_0\gtrsim0.6$ eV, however, $D(E_0)$ decreases by a factor of 10 or more. One can perhaps understand these changes in $D(E_0)$ in the following way. The defects with the lowest activation energies are presumably also the defects which are removed by annealing at the lowest temperatures. These were evidently annealed out (at room temperature) after the film was prepared,[16] but before the initial noise

measurements were performed.[10,17] Thus, the number of low-energy defects would not be expected to change significantly with further annealing, as seen in Fig. 3. However, higher energy defects are more likely to still have been present in the sample when our measurements were begun, and thus are more likely to have been available for ready removal with annealing. We therefore expect $D(E_0)$ to exhibit a much larger decrease for large E_0, and this is precisely the behavior which is observed (Fig. 3). Hence, the changes in $D(E_0)$ inferred from the behavior of $S_V(T)$ are in good qualitative agreement with one's expectations concerning the effect of annealing on a disordered system.

In conclusion, we have found that the model of Dutta, Dimon, and Horn[1] provides a good framework with which to describe the $1/f$ noise of a disordered metal alloy.[18] We have used this model to infer the distribution of activation energies, and find that it changes with annealing in a manner which strongly suggests that defects are responsible for the noise. These results also suggest the possibility of using noise measurements to study defect energies, etc., in ways which might not be possible with other methods.

We thank R. H. Koch, J. H. Scofield, and M. B. Weissman for stimulating discussions, P. H. Keesom and R. W. Cline for the use of their screened room, M. D. Feuer and D. E. Prober for providing the mask from which the sample was made, and T. J. Postel for assisting with the construction of the experimental apparatus. One of us (D.M.F.) acknowledges partial financial support from the David Ross Foundation. This work was supported in part by the National Science Foundation-Materials Research Laboratory program through Grant No. DMR80-20249.

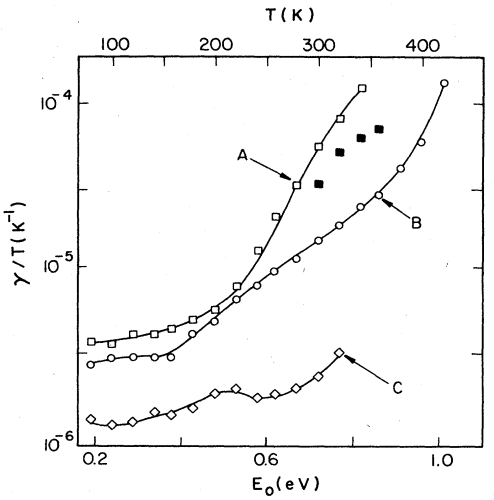

FIG. 3. γ/T as a function of E_0. The temperature scale [i.e., the temperature corresponding to the inferred value of E_0—see the discussion in connection with (1)] is also given. The symbols used correspond to those of Fig. 1. Only results in which the sample was not being annealed during the noise measurements are shown.

*Present address: Sandia National Laboratories, Division 2144, P. O. Box 5800, Albuquerque, New Mexico 87185.

[1]P. Dutta, P. Dimon, and P. M. Horn, Phys. Rev. Lett. **43**, 646 (1979); P. Dutta and P. M. Horn, Rev. Mod. Phys. **53**, 497 (1981).

[2]J. Bernamont, Ann. Phys. (Paris) **7**, 71 (1937); A. van der Ziel, Physica (Utrecht) **16**, 359 (1950); F. K. du Pre, Phys. Rev. B **78**, 615 (1950).

[3]J. W. Eberhard and P. M. Horn, Phys. Rev. Lett. **39**, 643 (1977); Phys. Rev. B **18**, 6681 (1978).

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

[5]D. M. Fleetwood and N. Giordano, Phys. Rev. B **28**, 3625 (1983).

[6]R. D. Black, P. J. Restle, and M. B. Weissman, Phys. Rev. Lett. **51**, 1476 (1983).

[7]D. E. Prober, M. D. Feuer, and N. Giordano, Appl. Phys. Lett. **37**, 94 (1980); **37**, 579 (1980).

[8]N. Giordano, Phys. Rev. B **22**, 5635 (1980).

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

[10]D. M. Fleetwood, Ph. D. thesis, Purdue University, 1984; D. M. Fleetwood and N. Giordano (unpublished).

[11]We note that since α was not precisely unity (see Fig. 2), γ is slightly frequency dependent. Figure 1 shows γ(10 Hz), but the precise reference frequency which is used does not significantly affect any of our results. Note also that S_V was found to scale accurately as V^2.

[12]The structure (i.e., "bumps") in $S_V(T)$ below 200 K is only slightly larger than the experimental uncertainties. We concentrate here on the relatively large change in slope which occurs near 200 K.

[13]The values of α, and also S_V, were obtained from noise measurements in the frequency range 0.2—100 Hz (see Refs. 5 and 10 for a detailed description of the apparatus and typical power spectra). In most cases, α was a constant to within the uncertainties (typically a few percent, see Fig. 2) over the entire frequency range studied. However, near the extrema of $\alpha(T)$ one would, based on (2), expect α to be slightly frequency dependent (see also Ref. 6). There were indications of this behavior, but our uncertainties in determining α preclude any definitive conclusions at this time.

[14]We emphasize that for *all* of the measurements below 350 K, the sample, its noise, etc., were all stable, so that these results reflect the "equilibrium" properties of the samples. The changes of S_V observed for $T < 350$ K in Fig. 1 after various amounts of annealing thus represent changes caused directly by the annealing. They are not due to long-term "drifts" of the sample or measuring apparatus. As noted in the text, for $T > 350$ K the sample was annealing during some of the measurements, so, as noted, these results cannot be used directly in the analysis, but they do yield useful information (see text). In addition, we note that our quantitative conclusions, see e.g. Fig. 3, are all based on measurements during which the sample was not annealing.

[15]This decrease in noise is not an artifact of the normalization. The decrease in S_V at a given current is really somewhat larger than the decrease in γ (since V is now smaller for the same current).

[16]It is also possible, of course, that it is not energetically favor-

able for such defects to form in as-prepared sputtered AuPd. We should, in addition, note that the values of $(1/\rho)(d\rho/dT)$ observed after various amounts of annealing do not scale as simply as expected from Matthiessen's rule. (See the caption of Fig. 1, and also the discussion in Ref. 8.) This would seem to indicate that annealing has a profound effect on the electron-phonon scattering, and this could conceivably be important for our experiments. It is also interesting, but perhaps coincidental, that two-level systems are mentioned as candidates to account for the inelastic scattering in thin wires at low temperatures (Ref. 8), and for the $1/f$ noise of disordered systems [see for example, R. D. Black, P. J. Restle, and M. B. Weissman, Phys. Rev. B **28**, 1935 (1983); and A. Ludviksson, R. Kree, and A. Schmid, Phys. Rev. Lett. **52**, 950 (1984)].

[17]This particular sample was fabricated several years before our experiments were begun. During this time, its resistance decreased by a factor of 2 from its initial value, while it was stored in a desiccator at room temperature. [Such an old sample was used to avoid the nonstationary behavior that is sometimes observed in freshly sputtered AuPd samples (Ref. 10).] We should also mention that the total (integrated) noise magnitude of this sample also seems to have decreased with annealing, an effect that is not considered in the model of Dutta, Dimon, and Horn. However, this point does not affect the comparison of the experimental values of α with the predictions of (2), nor does it enter the discussion of the *relative* changes in $D(E_0)$. A complete description of the changes in the noise induced by annealing would, of course, also have to be able to account for this behavior. It is worthwhile to note again that similar results were obtained on other samples (some of which were several years old, and some of which were freshly prepared), so that we believe our results are of general validity.

[18]It has recently been pointed out [W. W. Webb and J. H. Scofield, Bull. Am. Phys. Soc. **29**, 481 (1984); see also M. B. Weissman, in *Proceedings of the Sixth International Conference on Noise in Physical Systems,* edited by P. H. E. Meijer, R. D. Mountain, and R. J. Soulen, Jr., National Bureau of Standards Special Publication No. 614 (U.S. G.P.O., Washington, 1981), p. 133] that if, in contrast to the model of Dutta, Dimon, and Horn, one assumes that the activation energy of the noise-producing process is fixed and that the attempt time is distributed, one can produce results essentially identical to those discussed in Ref. 1. That is, available results for the $1/f$ noise in metal films [but not the (non-$1/f$) diffusion noise observed by Webb and Scofield for Nb containing H] are described equally well by the two different models. In this paper we have discussed our results in terms of the model in which the activation energy is distributed, but our conclusions would not be affected if the other model were assumed. This is true, in particular, since we would expect that defects which require higher temperatures for removal by annealing, would also have higher attempt frequencies, etc.