1/f Noise in Cr Films from Spin-Density-Wave Polarization Rotation

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Measurements were made of the temperature dependence, strain dependence, defect dependence, symmetry properties, and small-sample statistical properties of the large $1/f$ noise in antiferromagnetic Cr films. The results are consistent with a model based on rotations of the polarization of spin-density-wave domains. Spontaneous electronic symmetry-breaking effects are proposed as a new source of $1/f$ noise in some metals.

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Recently Scofield *et al.*[1] found a rise of almost 2 orders of magnitude in the $1/f$ resistance noise spectral density, $S_R(f)$, on cooling a relatively clean Cr film from 300 to 250 K. Some connection with the antiferromagnetic transition was suggested,[1] since this sharp temperature dependence could not be explained simply by a conventional ensemble of fluctuators with weakly temperature-dependent variances.[1-3] We report here strong evidence that the noise arises from rotations of the linear polarization of domains in the transverse spin-density-wave (TSDW) structure.

Although little is known about magnetism in Cr films, because of the great difficulties of measuring effects (other than noise), the magnetic structure of bulk crystalline Cr is well known.[4] Below the Néel temperature, $T_N = 311$ K, and above the spin-flip temperature, $T_F = 122$ K, some of the conduction electrons are condensed into a linear TSDW.[5] Each TSDW domain has a single wave vector $\mathbf{Q}$ along a cubic axis, and a polarization vector $\boldsymbol{\eta}$ along one of the other two cubic axes. Below T_F in the longitudinal SDW the polarization degree of freedom is lost, with $\boldsymbol{\eta}$ parallel to $\mathbf{Q}$.

Thermally activated coherent rotations of $\boldsymbol{\eta}$ in polarization domains contained within $\mathbf{Q}$ domains[6] explain a variety of effects.[3] The coupling of the polarization to stress causes a stress and magnetic-field–dependent internal friction plateau between T_N and T_F, observed at frequencies as high[7] as 10^5 Hz, and as low[8] as 1 Hz. The internal friction plateau suggests that rotating TSDW polarization domains can generate $1/f$ noise, if an anisotropic resistivity tensor rotates with the polarization, just as more common noise and internal friction sources are linked.[9]

Figure 1 shows measurements versus temperature of the dimensionless $1/f$ noise parameter, $\alpha_H \equiv S_R(f) n_A V_s f / R^2$, where n_A is the atomic density and V_s is sample volume[2] for the six evaporated Cr films studied. In the films with the least residual resistance (largest residual resistance ratio, r) the noise rises rapidly beginning near 340 K. The onset region is broadened and pushed to lower temperatures in films with higher residual resistance. Initial attempts to find a clear noise plateau in commercial Cr masks, which are of low purity and not annealed, as well as in inadequately annealed high-purity films deposited on substrates heated only to 600 K, with $\rho \geq 45\ \mu\Omega$ cm, failed. Figure 2 shows the noise onset temperature T_n, at which $\partial \alpha_H / \partial T$ is maximized, versus $(r-1)^{-1}$ (roughly proportional to defect density) for the films.

Table I shows characteristics of the films, whose T_N's should differ from 311 K because of surface effects, defects, and planar strain produced on cooling from the deposition temperature by the different thermal expansion of Cr and the substrates.[10] The predicted strain

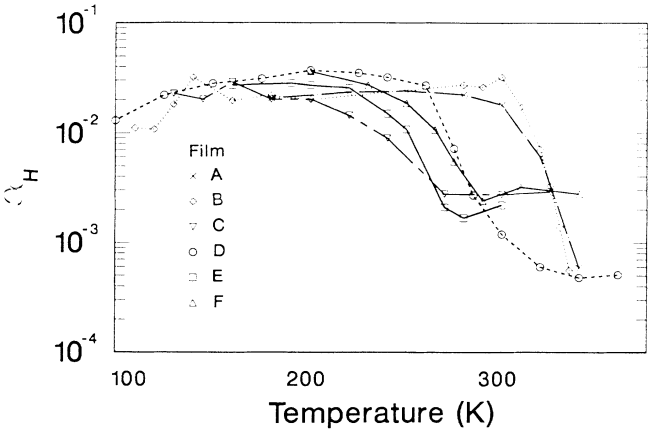

FIG. 1. Noise parameter α_H vs temperature for samples from the five films studied and a sixth (D) from Ref. 1. The absolute calibration of each curve is uncertain to a factor of 1.5.

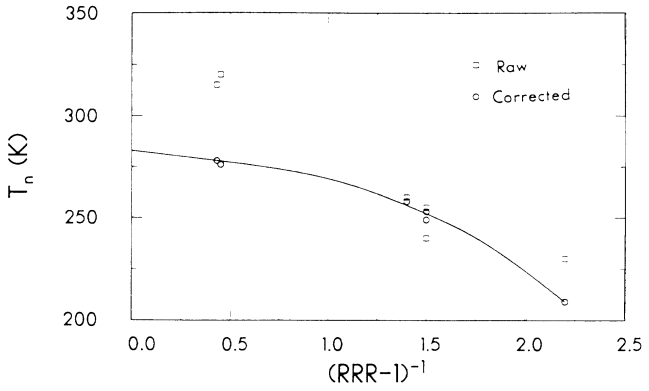

FIG. 2. Noise onset temperature T_n (defined in the text) vs $(r-1)^{-1}$. The points corrected by subtracting the predicted ΔT_N due to strain are connected with a hand-drawn curve.

effect on T_N is shown.[11] The $\alpha_H(T)$ curves for the simultaneously deposited films E and F are nearly the same except for a shift of $\simeq 13$ K, compared to the 11-K predicted T_N shift due to strain. After correcting by subtraction of the predicted T_N shift due to strain, the T_n points fit a smooth curve which extrapolates to somewhat below the bulk T_N for defect-free films, i.e., for $(r-1)^{-1}=0$.

Most of film F, which was deposited on a thin cover slide to minimize magnetic background, was sacrificed to measure magnetic susceptibility with a SQUID system, giving $T_N=245\pm 20$ K from the small susceptibility anomaly. Together, this approximate equality of T_n and T_N, the lowering and broadening of the noise onset in dirty films, the absence of the plateau in dirtier films, and the dependence of T_n on strain leave no doubt that the large noise is a property of the SDW phase.

The reduction in α_H found below about 100 K can be approximately explained by kinetic factors alone.[1] There is no strong evidence in these films for a spin-flip transition, which would be hard to detect unless the transition were sharp and involved a significant fraction of the domains. Impurities[12] and defects apparently can suppress the spin-flip transition, eliminating the phase transition friction peak sometimes found[13] at 122 K and leaving a tail of the polarization rotation friction extending to lower temperatures.[14]

The resistance noise from pure rotations gives a negative correlation between resistivity coefficients measured on orthogonal axes, since when an easy direction is aligned with one axis it is not aligned with another. A noise symmetry parameter[3,15,16] is defined for resistivity fluctuations $\delta\rho$ in 2D by $S\equiv 2\langle \mathrm{Det}(\delta\rho)\rangle/\langle \mathrm{Tr}[(\delta\rho)^2]\rangle$, with $-1\le S\le 1$. Rotations about a principal axis in the plane leave one component of ρ unchanged, giving $S=0$ since $\mathrm{Det}(\delta\rho)=0$. When the rotation occurs about an axis orthogonal to the plane, $S=-1$ results, while rotations of conductivity tensors whose principal axes are oriented isotropically in 3D yield $S=-\frac{5}{7}$. The prediction for TSDW rotation noise in Cr, assuming an isotropic distribution of **Q** orientation, is then $S=-\frac{5}{7}$. However, it is known that **Q** vectors align with tensile strain on cooling through T_N.[17] Hence, one would expect that in samples with large planar tensile strain (comparable to the random strain), **Q**'s in the plane dominate, so that S would be pulled toward zero. In a **Q**-

TABLE I. Film properties. All data on film D are from Ref. 1, in which it was named C3. All samples used high-purity (99.99+% pure metals) commercial Cr. AT&T and Cornell used electron-beam evaporators; Illinois used a thermal evaporator. Si substrates were wafers with thermally oxidized surfaces.

Designation	A	B	C	D	E	F
Source	AT&T	AT&T	AT&T	Cornell	Illinois	Illinois
Substrate	Si	Si	Si	Sapphire	EMC[a]	0211[b]
Temperature (K)	870	970	640	690	700	700
Pressure (10^{-8} Torr)	2	1.5	2	60	100[c]	100[c]
Thickness (nm)	90	90	220	123	140	140
ρ ($\mu\Omega$ cm)	14	14	33	24	28	28
r	3.3	3.2	1.43	1.7	1.65	1.65
T_n (± 5 K)	315	320	230	260	240	255
Strain at T_n (10^{-3})	3.1	3.7	1.8	0.2	−0.8	0.2
Predicted ΔT_N (K)	37	44	21	2	−9	2
					$E1$ $E2$	
S, 5–42 Hz, $T=190$ K		−0.27	−0.2		−0.47 −0.46	
90% confidence limits		± 0.06	± 0.1		± 0.08 ± 0.08	

[a]The substrate was a soda-lime glass from Electronic Materials Corporation.

[b]Corning glass number is indicated.

[c]Films E and F were simultaneously evaporated in 3×10^{-4} Torr Ar. The pressure given is the vacuum-system background.

fluctuation model, regardless of whether **Q** aligns parallel to or orthogonal to tensile strain, high-strain samples would have S closer to -1 than low-strain samples, since the changes in **Q** normal to the plane would be suppressed by planar strain.

Results for S, measured in two low-strain samples and two high-strain samples, are shown in Table I. The low-stress films have S near the isotropic Q prediction, with smaller $|S|$ in the high-stress films. Static conductivity anisotropies (e.g., due to grain structure) ordinarily lower the absolute value of S.[15] Judging from the resistivity and r, this latter effect would have been greater in film E than in film B, and thus cannot account for the sign of the large difference between their S values. The symmetry results support the TSDW polarization rotation model while contradicting a **Q** rotation model.

Although nearly all metallic $1/f$ noise sources show very smooth spectra and purely Gaussian statistical properties[3] for samples as small as 10^{-12} cm^3, random spectral features and slightly non-Gaussian statistics in Cr samples of that size should be expected because of the small number of fluctuating domains. Four such small samples were made and all showed spectral features which were stable, after equilibration, for long times at fixed temperature. Larger samples showed no spectral features. Different stable features were found at the same temperature after annealing 10–100 K above the measurement temperature, as expected given the ability of the domain structure to anneal[6] (see Fig. 3). Such features are incompatible with any model in which the noise comes from a smooth distribution of normal modes, e.g., phasons.[18] Temporal variance in the spectral density, measured carefully in one of the small samples, was about 8% above that expected for Gaussian noise, consistent with a small number of independent two-state systems.[19]

From the spectral features, using established techniques[19] (slightly adjusted for tensor noise), we estimate the average concentration n_D of two-state systems per factor of e in characteristic frequency per kT in level spacing to be 6×10^{11} cm^{-3}, within a factor of 2. Within the context of the model, the noise level is related to n_D by $\alpha_H \approx 0.4 n_D n_A \beta^2 V_D^2$, where V_D is domain volume and β is the fractional anisotropy between the resistivity along η and along $\eta\times\mathbf{Q}$. Thus $\beta V_D \approx 1.2\times10^{-18}$ cm^3.

It is quite unlikely that $\beta > 6\times10^{-2}$, which is the resistivity anisotropy between the **Q** direction and the average in the orthogonal plane,[20] since at most temperatures the SDW-induced strain anisotropy between the **Q** direction and the plane is much larger than the strain anisotropy within the plane.[21] Therefore it is quite likely that $V_D > 2\times10^{-17}$ cm^3. We may also estimate an upper bound to V_D and hence a lower bound to β. The S values and the weak dependence of the noise magnitude on strain indicate that the extent of polarization pinning by the mechanical strain, determined via the product of V_D and known magnetoelastic tensor elements,[22] is not large compared to random pinning effects, whose size in turn is limited by the overall noise magnitude. Without reproducing the detailed argument, we find $V_D \leq 6\times10^{-16}$ cm^3 and $\beta \geq 2\times10^{-3}$. Estimates for the polarization-domain size in bulk samples[6,23] have clustered within a factor of 3 of 5×10^{-16} cm^3.

In conclusion, our data on the temperature dependence, strain dependence, defect dependence, symmetry properties, and small-sample statistical properties and spectral shape effects of the large $1/f$ noise in antiferromagnetic Cr films are consistent with a model invoking the same rotations of the TSDW polarization which give the bulk internal friction plateau, and not with any other known model.

Unlike other methods, noise can be used to study the dynamics of a small number of polarization domains. The domains appear to be stable entities, but only at fixed temperature. The $1/f$ spectrum of the antiferromagnetic noise is not very different from the spectra of magnetization noise in spin-glasses,[24] and resistivity noise may provide a valuable probe for those metallic spin-glasses, such as CuMn, in which SDW's are suspected of playing a role.

This appears to be the first clearly demonstrated case of metallic $1/f$ noise with an electronic origin, as well as the first demonstrated case in which the mechanisms for electrical $1/f$ noise and mechanical friction are the same. The dramatic noise increase gives a very sensitive new method of detecting weak electronic symmetry-breaking effects. Such effects should be considered when one is analyzing noise in relatively clean systems, such as films of semimetallic Bi.[16]

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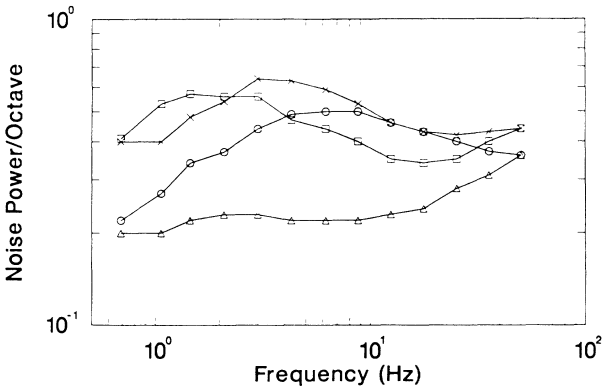

FIG. 3. Four spectra measured at 200 K from small-volume (10^{-12} cm^3) sample C-1. The measurements were separated by anneals to 215 K. $1/f$ noise would appear horizontal in this plot. Power units are arbitrary.

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