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$1/f$ noise of metals: A case for extrinsic origin

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Small multiprobe resistors have been fabricated from continuous metal films of Ag, Al, Au, Cr, Cu, Mo, Nb, Ni, Pt, and W deposited under various conditions. Each shows some reproducible level of flicker ($1/f$) noise. This study implicates carrier scattering by extrinsic defects or impurities as the source of the resistivity fluctuations. The noise level appears to be determined by the number of defects introduced in the film during deposition. We introduce a new quantity, $\rho_*^2 = fS_\rho(f)N_a$, as an appropriate measure of the level of noise and relate it to the residual resistivity ratio $\rho(300\text{ K})/\rho(4.2\text{ K})$, a measure of the extrinsic defect and impurity density. [Here f is the frequency in Hz, $S_\rho(f)$ is the power spectral density of the resistivity fluctuations, and N_a is the number of atoms in the sample.]

I. INTRODUCTION

The power spectral density $S_V(f)$ of fluctuations in the voltage (V) across a physically small resistor (r) carrying a constant current (I) is generally found, at low frequencies (f), to exceed the intrinsic thermal noise ($4kTr$). When the excess noise, $S_V(f) - 4kTr$, is proportional to I^2, the fluctuations are interpreted in terms of resistance fluctuations having spectra

$$S_r(f) = [S_V(f) - 4kTr]/I^2 \ .$$

For homogeneous conductors of resistivity ρ it is convenient to define a resistivity fluctuation spectrum

$$S_\rho(f) = (\rho/r)^2 S_r(f) \ .$$

Such is the case for the low-frequency ($1\text{ mHz} \leq f \leq 1\text{ kHz}$) excess noise of metal films whose spectra are frequently described by a power law,

$$S_\rho(f) \simeq \rho_*^2/(N_a f^\alpha) \ ,$$

where N_a is the number of atoms in the conductor and $\alpha \simeq 1$. Though the frequency exponent α is seldom exactly equal to one, it is convenient to define a noise level

$$\rho_*^2 = [fN_a S_\rho(f)]_{f=1\text{ Hz}}$$

with units of resistivity squared. The normalization by N_a scales out an assumed inverse dependence of $S_\rho(f)$ on conductor size, consistent with observed trends.[1] The literature frequently uses a relative noise level, $C = \rho_*^2/\rho^2$, which typically ranges $10^{-4} \leq C \leq 10^{-1}$. (See the reviews by Nelkin[2] and Dutta and Horn.[3]) These fluctuations, designated $1/f$ noise since $\alpha \simeq 1$, are commonly observed in small conductors with, say, $N_a \leq 10^{14}$. Neither the physical origin of this $1/f$ noise nor the parameters responsible for variations in the values of C and α is yet understood despite extensive recent research. This paper reports results of a series of measurements on continuous metal films that implicate carrier scattering by extrinsic defects and impurities and suggest that $1/f$ noise is not intrinsic, at least at observed levels.

A notable analysis of resistance fluctuations due to local temperature fluctuations aimed to account for the $1/f$ noise of metal films.[4] Temperature fluctuation models, however, fail to account for either the observed temperature dependence[5] or the absence of spatial correlation.[6,7] Intrinsic temperature fluctuations are ordinarily too small to generate observable resistance fluctuations[8] with an interesting low-temperature exception near a superconducting transition.[9]

The temperature and frequency dependence of low-frequency resistance fluctuations can be represented by an *ad hoc* superposition of thermally activated processes[3,10] with a distribution of activation energies suggestive of defect relaxation processes in metals.[11] Typical defect concentrations, which are far above equilibrium levels in metal films, could account for the observed noise levels through fluctuations in the scattering of conduction electrons, rather than carrier trapping.[12] Evidence is mounting in support of such a picture in nonmetals through the observation of spectral features and temperature dependence attributable to particular thermally activated fluctuations.[13,14] Two level systems of scatterers, which are similar to tunneling systems in glasses at low temperatures[15] and related to "Snoek-like" internal friction mechanisms at high temperatures,[16,17] have been invoked to explain the $1/f$ noise of metals. Thermally activated features and local-symmetry properties of the $1/f$ noise of Bi films are consistent with such a model.[17]

Recent experiments on $1/f$ noise in metals are difficult to interpret. On the one hand, changes in the noise of Pt and Au films with time and applied stress suggest a possible connection with defect motion.[18] On the other hand, the noise of Sn and In films apparently depends on their thermal coupling to the substrate.[19] Fleetwood and Giordano[20] report a minimum level in the $1/f$ noise of other

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metals that would seem to support an intrinsic noise mechanism.

There is one metallic film system for which the origins of the observed excess noise have been fully understood because the spectrum is not featureless $1/f$ noise. The dominant excess noise of Nb films is associated with scattering of conduction electrons by hydrogen impurities, introduced into the film during sputter or chemical etching.[21,22] Resistivity fluctuations occur as hydrogen ions diffuse randomly in and out of the monitored film segment. The dependence of $S_\rho(f)$ on frequency (f), segment length (L), hydrogen concentration (c_0), and temperature (T) are all consistent with calculations based on a simple one-dimensional diffusion model:

$$S_\rho(f)=4\rho_0^2/(3\pi N_0) \quad \text{for } f \ll f_c$$

and

$$S_\rho(f)=3\rho_0^2/(2\pi N_0)(f/f_c)^{-3/2} \quad \text{for } f \gg f_c \ ,$$

where $f_c(T)\propto D(T)/L^2$ is a temperature-dependent characteristic frequency, D is the diffusion coefficient for hydrogen in Nb, $N_0=c_0N_a$ is the number of hydrogen impurities in the segment, and $\rho_0=(\partial\rho/\partial c)c_0$ is their mean contribution to the resistivity (ρ). Activated dynamics enter through a diffusion coefficient $D(T)=D_0e^{-E/kT}$.

In this paper we present the results of an experimental study of the low-frequency excess noise of a broad selection of metal films; noise measurements are analyzed as a function of film residual resistivity ratio, $\mathcal{R}\equiv\rho(300\text{ K})/\rho(4.2\text{ K})$. Our results show that lower noise can be obtained as $\mathcal{R}$ increases in value. These results lend support to the proposition that $1/f$ noise arises from extrinsic carrier scattering by defects or impurities. We find similar noise levels (ρ_*^2) for Pt, Au, and Al films of comparable quality, as measured by the effect of defect and impurity scattering on $\mathcal{R}$. The measured noise due to scattering by hydrogen impurities in Nb produces an analogous proportionality. The customary relative noise levels (C) of carefully prepared Pt and Nb films are found to be 1–2 orders of magnitude lower than any previously reported for other metals simply because they have higher resistivities.

II. EXPERIMENTAL METHODS

Thin-film strip resistors with multiple branches for terminals were shaped by photolithography from films deposited by evaporation or sputtering onto unused sapphire substrates with preformed contact pads. Gold contact patterns were formed on highly polished sapphire substrates by depositing a 300-nm-thick Au film (with a 20-nm-thick Cr underlayer) through a thin foil evaporation mask. The mask was held 0.003 in. away from the substrate to achieve a sloped edge profile. Four or five large rectangles of specimen metal were deposited through a second mask so as to overlap the Au contacts. The rectangles were subsequently patterned into multiprobe resistors (see Fig. 1) using photolithography followed by chemical etching or ion milling. Resistor dimensions ranged $40\le h\le 500$ nm, $0.5\le w\le 80$ μm, and 40 $\mu\text{m}\le L\le 2.2$ mm. Finished substrates were mounted on 24-pin gold-plated, hybrid packages with Apiezon N-grease; 0.7-mil Au wires were ultrasonically bonded between the package pins and the Au specimen contacts. For thicker ($h>100$ nm) films of Al, Cr, Nb, and Pt, adhesion was adequate to ultrasonically bond 1.3-mil Al wires directly to the specimen metal without the use of an Au contact layer. Table I summarizes the various deposition parameters and properties of each film. The deposition parameters tabulated are the background pressure p (in μT), the deposition rate (in Å/s), the substrate temperature T_s (in °C), and the deposition method (DM). Also included in the table are the measured thickness h (in nm), sheet resistance $\rho_\square$ (in Ω), residual resistivity ratio $\mathcal{R}$, and calculated resistivity ρ (in $\mu\Omega$ cm). Residual resistivity ratios enclosed in parentheses were not measured, but rather were calculated from measured room-temperature resistivities, $\rho=\rho(300$ K), and literature values of the intrinsic resistivity due to lattice scattering, $\rho_L=\rho_L(300\text{ K})$. Assuming that $\rho(T)=\rho_d+\rho_L(T)$, where ρ_d is the temperature-independent component due to defect and impurity scattering, then the residual resistivity ratio $\mathcal{R}\simeq\rho/(\rho-\rho_L)$.

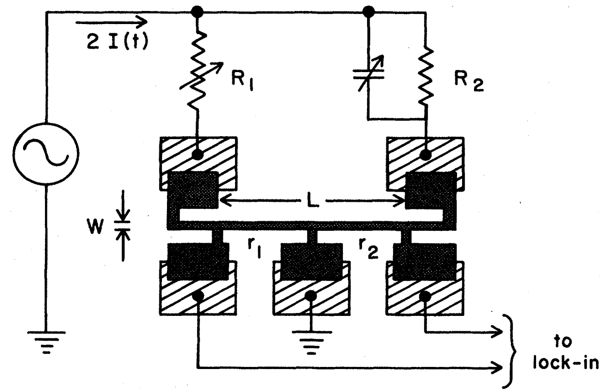

FIG. 1. Circuit diagram for the ac-noise measurement with the five-probe specimen geometry. The distance between either voltage probe and the center contact is $L/2$. In practice, $r_1\simeq r_2$ and $R_1\simeq R_2$; the specimen resistance $r=r_1+r_2$.

Excess noise was measured with the circuit shown in Fig. 1. The specimen was placed in an ac-resistance bridge, otherwise composed of 2 ppm/°C stable, 5-W wire-wound resistors R_1 and R_2 ($R_1\simeq R_2$) attached to large metal heat sinks. With a bridge current

$$I(t)=i_0\sin(2\pi f_0 t)$$

fluctuations in the resistances r_1 and r_2 of either specimen half produce a bridge imbalance that is detected by a Princeton Applied Research (PAR) 124A lock-in amplifier, operated in its $Q=1$ bandpass mode. The output of the lock-in amplifier is

$$\delta V(t)\simeq G_0 i_{\text{rms}}[\delta r_2(t)-\delta r_1(t)] \ ,$$

where $i_{\text{rms}}^2=i_0^2/2$ and the lock-in gain (G_0) is the ratio of the (dc) voltage at its output to the rms voltage at its input. For the PAR 124A lock-in, G_0 is 10.0 divided by the

TABLE I. Summary of film-deposition parameters and properties: device, background pressure (p), deposition rate, substrate temperature (T_s), deposition method (DM), thickness (h) and its relative uncertainty ($\Delta h/h$), sheet resistance ($\rho_\Box$), resistivity (ρ), residual resistivity ratio ($\mathscr{R}$), noise level (ρ_*^2), relative noise level (C) and its relative uncertainty ($\Delta C/C$), and frequency exponent (α) and its uncertainty ($\Delta\alpha$).

Film		Device[a]	p (μT)	Rate (Å/s)	T_s (°C)	DM[b]	h (nm)	$\Delta h/h$ (%)	$\rho_\Box$ (Ω)	ρ ($\mu\Omega$ cm)	$\mathscr{R}$	ρ_*^2 ($\mu\Omega$ cm)^2	10^3C	$\Delta C/C$ (%)	α	$\Delta\alpha$	Notes
Ag	$S1$	123	0.2	6	25	3	85	10	0.50	4.3	2.6	0.7	40	50	1.20	0.10	
	$S2$	34	0.5	50	25	3	66	10	0.42	2.8	2.9	0.16	20	30	1.16	0.05	c
	$S4$	24	0.08	50	300	2	250	10	0.098	2.5	6.0	0.04	6	50	1.15	0.05	
	$S5$	23	0.3	8	390	3	165	10	0.152	2.5	8.0	0.05	8	30	1.07	0.05	
Al	$A1$	25	5.0	60	25	1	95	10	0.370	3.5	5.0	0.018	1.5	30	1.01	0.03	
	$A2$	23	0.03	15	215	2	180	10	0.184	3.3	6.8	0.011	1.0	30	1.03	0.05	
	$A3$	4	0.2	45	300	3	450	10	0.063	2.8	44.0	0.004	0.5	40	1.10	0.15	d
Au	$G1$	1234	0.5	4	25	1	40	50	0.52	2.1		0.009	2.0	50	1.20	0.02	
	$G2$	3	2.0	20	25	1	83	10	0.43	3.6	(2.6)	0.03	2.5	40	1.13	0.02	
	$G3$	3	2.0	7	25	1	86	10	0.41	3.5	(2.7)	0.04	3.0	30	1.15	0.05	e
	$G5$	1	0.6	12	25	2	50	10	0.76	3.8	(2.4)	0.05	3.6	20	1.07	0.05	
	$G6$	1	0.6	70	375	2	490	20	0.044	2.2		0.003	0.6	30	1.04	0.05	d
	$G7$	123	0.4	18	380	2	202	10	0.10	2.0	15.3	0.003	0.7	30	1.05	0.03	
Cr	$C1$	12345	2.0	50	25	1	120	10	9.6	115	1.05	50	4.0	20	1.11	0.02	
	$C2$	3	0.3	100	25	3	84	10	11.4	96	(1.2)	10	1.1	30	1.09	0.02	
	$C3$	1234	0.6	40	406	3	123	10	1.96	24.1	1.7	1.0	1.7	30	1.02	0.02	
	$C4$	234	0.07	15	429	3	250	20	0.73	18.3	2.2	0.7	2	50	1.00	0.06	
	$C5$	234	0.02	15	25	2	135	10	4.8	65	1.16	7	1.6	40	1.20	0.10	
Cu	$U1$	145	0.02	40	25	2	187	10	0.13	2.4	4.2	0.03	5	20	1.13	0.04	
	$U1$	145	0.02	40	25	2	187	10	0.12	2.2	4.4	0.007	1.5	30	1.16	0.05	f
Mo	$M2$	145	0.04	13	25	2	115	10	1.4	16.1	1.58	0.04	0.15	30	1.10	0.04	
Nb	$N3$		0.9	7	25	4	240	10	0.87	20.9	(3.3)						
	$N3$	3	0.9	7	25	4	240	10	0.74	17.8	(5.4)	0.013	0.04	30	1.10	0.20	g
	$N3$	2	0.9	7	25	4	240	10	1.00	24.0	(2.5)	0.09	0.16	30	1.36	0.05	h
	$N6$	1	0.9	7	25	4	240	10	1.08	25.9	(2.3)	0.03	0.04	50	1.18	0.04	
	$N7$	4	0.03	12	25	2	120	10	2.34	28.1	2.02	0.05	0.06	30	1.05	0.05	
	$N8$	23	0.7	12	25	4	190	10	1.11	21.1	4.5	0.013	0.03	60	1.35	0.10	
	$N9$	1	0.9	9	25	2	244	15	1.05	25.6	2.6	0.03	0.05	40	1.30	0.10	
	NA	3	0.03	12	25	2	120	10	1.75	21.0	2.2	0.018	0.04	50	1.40	0.10	
Ni	$K1$	234	1.0	7	25	1	105	20	1.63	17.1	2.0	0.35	1.2	30	1.15	0.02	
	$K2$	1234	0.07	10	25	2	120	20	1.02	12.2	(2.4)	2.0	15	40	1.18	0.05	i
	$K2$	123	0.07	10	25	2	120	20	0.73	8.8	4.4	0.10	1.5	40	1.00	0.05	f,i
	$K3$	2	1.0	7	25	1	105	20	1.64	17.2	(1.7)	0.38	1.3	30	1.16	0.04	

TABLE I. (*Continued*).

Film		Device[a]	p (μT)	Rate (Å/s)	T_s (°C)	DM[b]	h (nm)	$\Delta h/h$ (%)	$\rho_\square$ (Ω)	ρ ($\mu\Omega$ cm)	$\mathscr{R}$	ρ_*^2 ($\mu\Omega$ cm)^2	10^3C	$\Delta C/C$ (%)	α	$\Delta\alpha$	Notes
	$K3$	12	1.0	7	25	1	105	20	1.05	11.0	3.8	0.085	0.7	40	1.17	0.05	f,i
	$K4$	1	0.07	10	25	2	120	20	1.02	12.2	2.5	0.9	6	30	1.25	0.10	i
Pt	$P1$	234	0.4	10	400	3	142	10	0.842	12.0	9.2	0.003	0.02	20	1.10	0.10	
	$P2$	24	15	10	400	3	125	10	0.855	10.7	13.5	0.008	0.07	30	1.06	0.10	
	$P3$	24	0.4	10	50	3	164	10	0.825	13.5	5.4	0.022	0.12	30	1.18	0.10	
W	$W1$	12	0.02	7	25	2	105	10	3.6	38	1.25	0.6	0.4	50	1.17	0.04	

[a]Indicates which of the five devices have had their noise measured.
[b]Deposition method: 1, thermally evaporated; 2, dc sputtered; 3, electron-beam evaporated; 4, rf sputtered.
[c]Some indication that noise increased from initial level.
[d]Excess noise difficult to measure because film is so thick.
[e]Excess noise measured within hours of deposition.
[f]Annealed for 1 h at 300 °C in H_2 atmosphere.
[g]Measurements with large dc bias to remove hydrogen from specimen.
[h]Annealed for several hours at 400 °C in a vacuum better than 5×10^{-8} Torr.
[i]$S_V(f)$ deviates from a power law at high frequencies.

full-scale sensitivity in $V_{\rm rms}$. The lock-in output is fed into an Hewlett-Packard (HP) 5420A fast-Fourier-transform (FTT) spectrum analyzer and its power spectrum $S_V(f;i_0)$ calculated. Excess noise spectra,

$$S_V(f;i_0)-S_V(f;0)\ ,$$

were always proportional to i_0^2 and are conveniently represented by resistivity fluctuation spectra $S_\rho(f)$ defined by

$$S_\rho(f)/\rho^2=[S_V(f;i_0)-S_V(f;0)]/(G_0 i_{\rm rms} r)^2\ ,$$

where $r=r_1+r_2$ and $\rho=rhw/L$. A detailed discussion of the measurement technique is given elsewhere.[23]

III. EXPERIMENTAL RESULTS

Excess noise has been measured from more than 100 metal-film specimens on 43 substrates. The films were formed during 26 depositions of Ag, Al, Au, Cr, Cu, Mo, Nb, Ni, Pt, and W. Resistivity fluctuation spectra $S_\rho(f)$ and resistivities ρ of films deposited at room temperature have been observed to change for a few days following deposition; both reach time-independent values after this initial stage of resistance recovery. Significant changes in ρ and $S_\rho(f)$ were induced by annealing at elevated temperatures, while smaller changes sometimes occurred upon low-temperature cycling. With the exception of Nb (Refs. 21 and 22) excess noise spectra were "$1/f$-like," that is, their power spectral densities were nearly inversely proportional to frequency with no observed low-frequency rolloff. For specimens fabricated from the same film of uniform thickness, $S_\rho(f)\propto 1/(Lw)$ with about 30% reproducibility. Measured values of the noise parameters ρ_*^2, C, and α are tabulated in Table I.

The inverse scaling of $S_\rho(f)$ with specimen area (Lw) is illustrated by measurements from four Cr specimens fabricated from the same film $(C1)$. Figure 2(a) shows a log-log plot of $[fS_\rho(f)/\rho^2]_{f=1\,\rm Hz}$ versus N_a for these four specimens; tabulated lengths (L) and widths (w) are both in μm. Note that all four specimens have the same thickness and resistivity so that Fig. 2(a) displays the dependence of $S_\rho(f)$ on the specimen Lw. A least-squares fit to the four points gives a slope of -1.05, not significantly different from -1.0. The systematic w^{-1} dependence implies that the noise arises from fluctuations $\delta\rho_\square(x,y,t)$ in the local sheet resistivity, with a correlation length $\lambda\le w_{\rm min}\simeq 0.5\ \mu$m. We have always observed this $(Lw)^{-1}$ scaling for specimens fabricated on the same substrate, in data typically including a factor of 10 or more variation in Lw. The column headed "devices" in Table I indicates which of the five specimens on each substrate have had their noise measured.

These same data illustrate the reproducibility of $N_aS_\rho(f)$ for specimens fabricated from the same film. Multiplying $S_\rho(f)$ by the specimen size (N_a) conveniently scales out both the observed $(Lw)^{-1}$ dependence and an anticipated inverse thickness dependence that is generally consistent with the data. The relative excess noise spectra $N_aS_\rho(f)/\rho^2$ for the four specimens, plotted in Fig. 2(b), differ by no more than 50% at all frequencies while their areas Lw vary by a factor of 200. In contrast with Fleet-

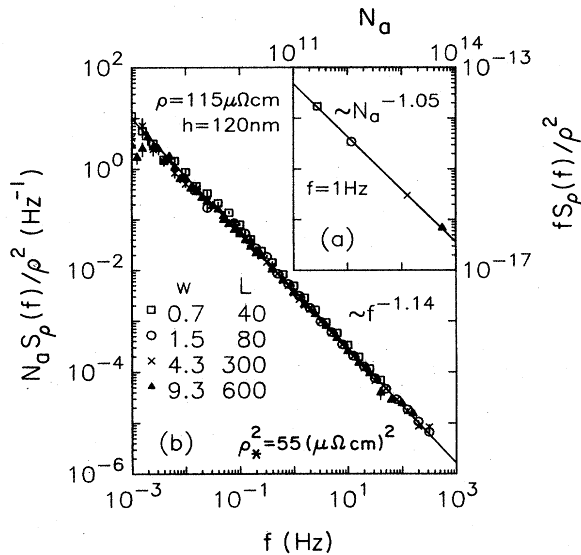

FIG. 2. Reproducibility and inverse size scaling of the $1/f$ noise of four Cr specimens ($C1$, $C2$, $C3$, $C4$) fabricated from the same film. The symbols, lengths L (in μm) and widths w (in μm), are tabulated in the figure. (a) Log-log plot of $[fS_\rho(f)/\rho^2]_{f=1\text{ Hz}}$ versus specimen size N_a. (b) Log-log plot of $N_a S_\rho(f)/\rho^2$ versus f for all four specimens.

wood and Giordano,[20] who found a factor-of-10 variation in the noise of nominally similar specimens, we find that $N_a S_\rho(f)$ is a closely reproducible property of a particular metal film.[24] Both ρ and ρ_*^2 are similar to those reported previously for Cr films.[7]

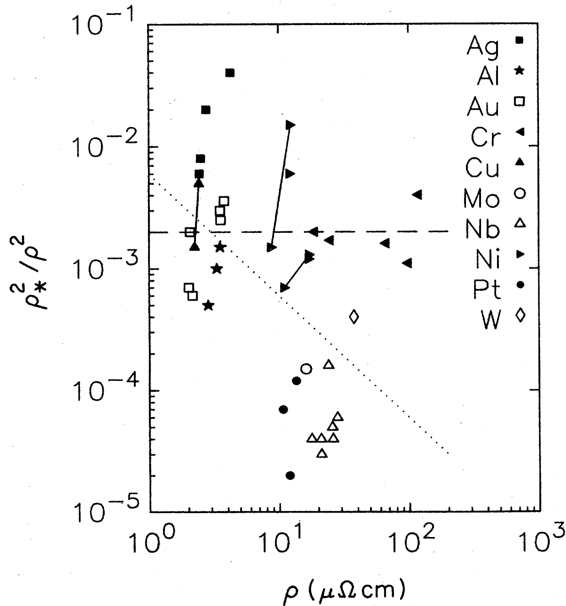

FIG. 3. Log-log plot of the relative noise level $C=\rho_*^2/\rho^2=[N_a fS_\rho(f)/\rho^2]_{f=1\text{ Hz}}$ versus film resistivity ρ for various metal films. The symbol corresponding to each metal is tabulated in the figure. Solid lines connect measurements before and after annealing. The dashed and dotted lines are discussed in the text.

The excess noise of films varied significantly with conditions of deposition. Following the example of Fleetwood and Giordano,[20] Fig. 3 represents a log-log plot of the relative noise level ($C=\rho_*^2/\rho^2$) versus resistivity (ρ) for the various metal films. Except for Cu, Nb, and Ni, each point in Fig. 3 represents a separate deposition. For Nb, $1/f$ noise was observed only in the smallest specimens with very low hydrogen concentrations $c_0 \leq 0.03$ at. %; the excess noise of most Nb specimens was dominated by resistance fluctuations associated with hydrogen diffusion and are not plotted. Thus the $S_\rho(f)$ for Nb films were not checked for scaling with film area. The solid lines connect measurements before and after annealing.

The effects of annealing were studied on Ni films. We have measured the resistivities (ρ) and noise levels (ρ_*^2) of both thermally evaporated ($K1$ and $K3$) and sputtered ($K2$ and $K4$) Ni films. One evaporated ($K3$) and one sputtered ($K2$) film were annealed for 1 h at 300 °C in a H_2 atmosphere[25] and their properties remeasured. The results are summarized in Table I but are most easily followed in Fig. 3. Before annealing, sputtered films had lower ρ, but higher ρ_*^2, then evaporated films. Annealing reduced both ρ_*^2 and ρ (increased $\mathscr{R}$). After annealing both films had similar ρ_*^2, but the sputtered film had lower ρ. Annealing reduced the noise of the sputtered film by a factor of 20.

IV. DISCUSSION

Our data are not consistent with the popular empirical formulas which have been proposed to describe the $1/f$ noise of metals. Hooge and Vandamme[26] asserted that $1/f$ noise is generated by lattice scattering in all conductors at a level given by

$$\rho_*^2/\rho^2=C_H(\rho_L/\rho)^2/Z ,$$

where Z is the effective valence (i.e., $N_c=ZN_a$ for a metal). When $Z=1$ and $\rho \simeq \rho_L$, this simplifies to $\rho_*^2/\rho^2=C_H \simeq 0.002$, which is plotted as the dashed line in Fig. 3. Lattice scattering dominates at room temperature for films with $\mathscr{R} \gg 1$. The lowest noise levels that we observe for high-$\mathscr{R}$ films of Nb and Pt are 1 to 2 orders of magnitude smaller than C_H. Failure of the Hooge formula has been discussed by Fleetwood and Giordano.[20] They found that $1/f$ noise levels were not reproducible, but that various measurements of ρ_*^2/ρ^2 were bounded by a "minimum,"

$$(\rho_*^2/\rho^2)_{\min} \simeq (0.006\ \mu\Omega\text{ cm})/\rho ,$$

which is plotted as the dotted line in Fig. 3. Our data do not support this formula either.

Several other trends, however, are suggested by our data. First, the noise of a given metal tends to be lower for films with lower defect and impurity scattering, ρ_d. Secondly, high-$\mathscr{R}$ films of high-resistivity metals (Pt, Nb, and Mo) tend to have lower relative noise levels, $C=\rho_*^2/\rho^2$, than do low-resistivity metals (Ag, Al, Au, Cu). These results show that $N_a S_\rho(f)$ does not generally scale with ρ and suggest instead a scaling with ρ_d.

The quantity ρ_d is difficult to determine experimentally whenever it is small. The residual resistivity ratio $\mathscr{R}$,

however, can be accurately measured; the two are related by $\rho_d \simeq \rho_L/(\mathscr{R}-1)$. Figure 4, a log-log plot of the noise levels (ρ_*^2) versus $(\mathscr{R}-1)^{-1}$, clearly indicates the trend that ρ_*^2 increases with $(\mathscr{R}-1)^{-1}$. That is, "better films" (i.e., lower ρ_d) have lower noise. Further, the highest-quality films of Pt, Al, and Au all have comparable ρ_*^2. The inference of relatively lowest noise for Pt, Nb, and Mo from Fig. 3 appears to be a misleading artifact of the popular ρ^2 normalization. We cannot expect an exact correlation between ρ_*^2 and ρ_d since ρ_d is determined by *many* scattering mechanism, whereas the noise may be associated with a *single* type of scatterer.

The above conclusions parallel those found for Nb films where the dominant excess noise is associated with fluctuations of scattering by hydrogen impurities.[21,22] The variance $\langle \delta\rho^2 \rangle$ of this noise spectrum is given by $\langle \delta\rho^2 \rangle = \rho_0^2/N_0$, where $N_0 = c_0 N_a$, c_0 is the mean hydrogen concentration, $\rho_0 = \beta c_0$ is the component of the resistivity due to scattering from hydrogen impurities, and $\beta \equiv \partial\rho/\partial c_0$. Note that we may write

$$N_a S_\rho(f) \propto N_a \langle \delta\rho^2 \rangle = \beta^2 c_0 \ .$$

This simple scaling generally applies to fluctuations of electron mobility that arise from scatterer-number fluctuations with two assumptions: (1) independent scatterers and (2) Matthiessen's rule.

We hypothesize that during formation of metal films impurities or defects are introduced that generate the $1/f$-resistivity fluctuations and contribute a component (ρ_0) to the mean resistivity. As with hydrogen in Nb, we might expect $N_a S_\rho(f) \propto \beta^2 c_0$. The scattering power (β) for various point defects and impurities in most metals is

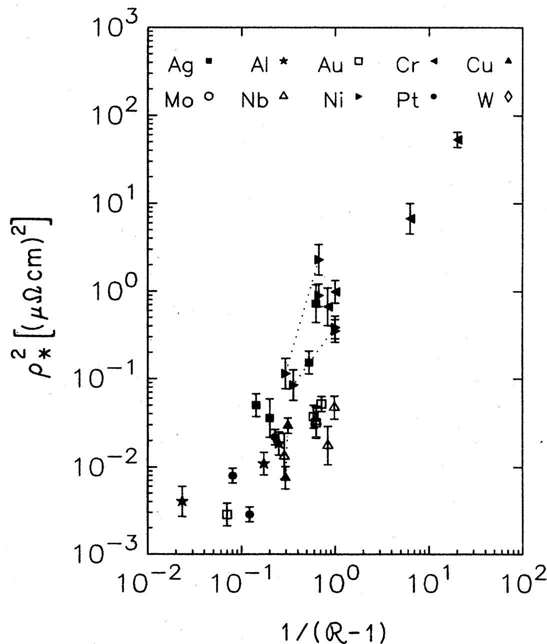

FIG. 4. Log-log plot of the noise levels $\rho_*^2 = [N_a f S_\rho(f)]_{f=1\ \mathrm{Hz}}$ versus $1/(\mathscr{R}-1)$, where $\mathscr{R}$ is the residual resistivity ratio.

$\beta \simeq 1\ \mu\Omega\,\mathrm{cm/at.}\,\%$ within a factor of 2, so that the ratio ρ_*^2/β^2 would generally reflect the concentration of the "noisy" defect. Scattering fluctuations, however, may involve either defect number changes, by entering and leaving the conductor, or transitions between two states with different scattering powers, β_1 and β_2.[16,17] In this case $\beta = \beta_2 - \beta_1$ would depend on the particular mechanism and might well be much smaller than $1\ \mu\Omega\,\mathrm{cm/at.}\,\%$.

Observations suggest that oxygen impurities may be responsible for the excess noise in several metals. The scaling of ρ_*^2 with ρ^2 in Cr films, over a factor of 25 change in ρ^2, suggests that $\delta\rho$ and ρ are dominated by the same mechanism. The high resistivity of Cr films is thought to be due to the presence of oxygen.[25] The factor-of-20 decrease in ρ_*^2 for sputtered Ni, affected by annealing in H_2, may be due to a reduction of nickel oxide.[25] Finally, consider the significantly higher ρ_*^2 and $\mathscr{R}$ of Pt film $P2$ (as compared to $P1$) deposited in an oxygen partial pressure of 1.5×10^{-5} Torr. In this case the higher $\mathscr{R}$ of the oxygen-annealed film $P2$ is expected due to the oxidation of dissolved metallic impurities which are thus removed from solution in the oxidation-resistant platinum. Together these results imply association of excess noise with particulate oxides.

There are, however, other interpretations for the above results involving grain (i.e., crystallite) size effects. The resistivities of Cr films may actually reflect the different grain sizes achieved by heating substrates during film deposition. Similarly, the grain size of the Pt films should vary with oxygen partial pressure in the deposition system. Though defect concentrations would be reduced by the annealing of Ni films to 300 °C, significant grain growth would not be expected.

One additional result on Au films suggests that impurities, not structural defects, are responsible for the $1/f$ noise. Two high-quality Au films ($G6$ and $G7$) had roughly the same noise level but different grain structure. One of these ($G6$) is an epitaxial Au film grown on a freshly cleaved LiF substrate, while the other ($G7$) is grown on a highly polished sapphire substrate. Both films may have similar point defect concentrations and grain sizes, but the epitaxial film has only low-angle grain boundaries whereas the sapphire-grown film is expected to have randomly oriented grains with many large-angle boundaries.

The precise defects or impurities responsible for the resistance fluctuations that generate $1/f$ noise in metal films remain to be identified for each case individually. Nevertheless, our pattern of results clearly eliminates intrinsic mechanisms and implicates extrinsic mechanisms that should be subject to control.

Our analysis of defect number fluctuations shows that the concentration (c_0) of the "noisy" defect is given by the variance, $N_a \langle \delta\rho^2 \rangle \simeq \beta^2 c_0$. The variance of the $1/f$ noise process may be estimated,

$$N_a \langle \delta\rho^2 \rangle = N_a \int_0^\infty S_\rho(f) df \simeq \rho_*^2 \int_{f_2}^{f_1} df/f^\alpha \simeq K\rho_*^2 \ , \qquad (1)$$

where K is the unknown integral over frequency. Identi-

fying this quantity with $\beta^2 c_0$ we see that the effective concentration is just $c_0 \simeq K\rho_*^2/\beta^2$. For example, taking $\alpha=1$, $f_2/f_1 \simeq 10^{40}$, and $\beta \simeq 1$ $\mu\Omega$ cm/at.% gives

$$c_0/(1 \text{ at. } \%) \simeq \rho_*^2/(\mu\Omega \text{ cm})^2 ;$$

the result only depends logarithmically on f_2/f_1. The noise levels of Fig. 4 imply effective concentrations from 0.001 at.% for high-quality Al, Au, and Pt to 100 at.% for poor-quality Cr films. Such defect concentrations are not unreasonable. While the above calculation should not be taken literally, it does provide a useful measure of excess low-frequency noise levels. The lowest noise level we have achieved may reflect nothing more fundamental than the limitations of our vacuum systems with $p > 10^{-8}$ Torr. A simple test of this viewpoint would consist of measurements of the excess noise of Cr, Al, or Au films with $\mathscr{R} \gg 1$ deposited in ultrahigh-vacuum (UHV) systems by molecular-beam epitaxy.

V. SUMMARY AND CONCLUSIONS

We have found that the $1/f$ noise of a metal film is a reproducible film property that arises from local fluctuations in the sheet resistance $\rho_\square(x,y,t)$ having a correlation length $\lambda \leq 0.5$ μm. Our data suggest that better quality films, i.e., those containing fewer defects and impurities, have lower noise. They do not support the concept of a "minimum" noise described by the formula of Fleetwood and Giordano.[20] Such a minimum may, of course, appear eventually as purity is improved and sensitivity is further increased by fabrication and testing of still smaller films. The data are not consistent with the empirical formula of Hooge and Vandamme[26] proposed to account for noise arising from lattice scattering. To the contrary, our results suggest that $1/f$ noise in metal films is associated with carrier scattering by extrinsic defects or impurities, as is known to be the case for the dominant excess noise of Nb films containing hydrogen impurities. For metal films of sufficiently high quality, the resistivity is dominated by lattice scattering, while resistivity fluctuations are dominated by fluctuations of impurity or defect scattering mechanisms. Thus normalization of $N_a S_\rho(f)$ by ρ^2 to form $N_a S_\rho(f)/\rho^2$ is inappropriate.

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