

Relationship between $1/f$ noise and nonlinearity effects in metal films

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A relationship has been found between the $1/f$ noise and the cubic nonlinearity of the current-voltage characteristic in unbroken metal films. In films with a high concentration of mobile defects, the $1/f$ noise and the nonlinearity effects arise from a conductivity modulation due to the creation and annihilation of vacancies.

The electrical fluctuations with a $1/f$ spectrum in metal films have attracted increased interest in recent years.^{1–3} The nature of this noise is still not clear. Several authors link the $1/f$ noise in films with mobile defects,^{2,4,5} in particular, vacancies.^{6,7} However, the literature reveals no direct experiments which confirm a vacancy mechanism for the $1/f$ noise. Our purpose in the present study was to identify the mechanism for the onset of the $1/f$ noise in solid metal films.

The test samples were molybdenum, tantalum, and chromium films deposited on glass and oxidized silicon substrates. The film thickness was varied from 50 nm to 1 μm . The spectral power density of the $1/f$ noise was measured by a direct method over the frequency range from $f = 2$ Hz to 10 kHz, at a direct current density $j \leq 10^5$ A/cm². The nonlinearity of the current-voltage characteristic of a film was determined by the third-harmonic method,⁸ by applying a sinusoidal test signal with a frequency $f_1 = 10$ kHz and a power $P \leq 10^{-5}$ W to the film. In the case of the chromium and molybdenum films, the measurements of the $1/f$ noise and the nonlinearity were supplemented with measurements of the internal stress, by a method involving the bending of a cantilevered substrate.⁹ The test samples for these stress measurements were long, narrow strips with dimensions of 40×2 mm. As a measure of the deformation we used the displacement of the free end of the substrate, whose position was determined before and after the condensation of the film (in the case of chromium) or before and after the film was etched off (in the case of molybdenum). The deflection of the free end of the substrate was measured with an MBS-2 horizontal microscope with an MOV-1-15 \times U4.2 micrometer attachment. The stress was calculated from the Stony formula with allowance for the Poisson ratio.¹⁰ The error of these stress measurements was less than $\pm 5\%$ at $|\sigma| > 2 \times 10^8$ Pa, $\pm 10\%$ at 10^8 Pa $< |\sigma| < 2 \times 10^8$ Pa, and $\pm 25\%$ at $|\sigma| \leq 10^8$ Pa. Films with different properties were produced by varying the conditions. The film samples for the stress and electrical measurements were deposited on the substrate in the same batch.

It was found that the dependence of the $1/f$ noise and that of the third-harmonic voltage U_3 on the various technological factors (the condensation rate, the condensation temperature, the voltage applied to the substrate during the growth of films by ion

sputtering, the film thickness, and so forth) were of the same nature. For the films with an elevated $1/f$ noise, the temperature dependence of the spectral power density of the noise and that of the voltage U_3 were both of an activation-law type, with identical activation energies E_a . For the molybdenum and tantalum films with a uniform microstructure, for example, these energies were $E_a = 0.35$ and 0.45 eV, respectively. The activation energies were found from the slope of a plot of the third-harmonic voltage U_3 and the spectral power density of the $1/f$ noise at a frequency of 300 Hz, S_u versus the reciprocal of the temperature T , in the coordinates $\{\ln U_3, 1/T\}$ and $\{\ln S_u, 1/T\}$, respectively. These plots are straight lines with a slope $-E_a/k$, where k is the Boltzmann constant. The measurements were carried out over the temperature range 295–540 K. These results suggest that the $1/f$ noise and the nonlinearity effects in the metal films result from the same physical mechanism. An activation-law temperature dependence of the spectral power density of the $1/f$ noise should be observed if a vacancy mechanism is responsible for the $1/f$ noise.⁷ The spectral power density of the fluctuations in the voltage on the film sample, U_3 , in the corresponding frequency range is proportional to the quasiequilibrium vacancy concentration in the film,⁷ n_v , and can be written¹¹

$$S_u \sim n_v = A_v \exp[-(U_v - \sigma V_v)/kT], \quad (1)$$

where A_v is an entropy factor, U_v is the internal vacancy formation energy, σ is the stress, and V_v is the vacancy formation volume. The preexponential factor A_v in (1) is determined by the concentration of sinks (or sources) of vacancies and by surface effects.⁷

The vacancy formation energy $E_v = U_v - \sigma V_v$ depends on the internal stress. A tensile stress ($\sigma > 0$) reduces this energy and increases the vacancy concentration. It thus also increases the level of the $1/f$ noise. As an estimate of the minimum value of the internal vacancy formation energy in the film we might use the energy per bond in the crystal lattice. For metals, we would have¹² $U_v \approx 0.1$ – 0.5 eV. The activation energies found in these experiments for the spectral power density of the $1/f$ noise for the Al, Mo, Ta, W, and Cr films do indeed correspond to these values.

Figure 1a shows the relative spectral power density of the $1/f$ noise, $S = S_u/U^2$ (U is the constant voltage applied to the film sample), versus the internal stress for Cr and Mo films in semilogarithmic scale. The experimental points conform well to straight lines, from whose slopes we can find the activation volume $V_a = 2.3kT \times (\Delta \log S / \Delta \sigma)$. For the Cr films we find $V_a = (1.4 \pm 0.4) \times 10^{-29} \text{ m}^3$, and for Mo $V_a = (1.1 \pm 0.3) \times 10^{-29} \text{ m}^3$. These values are close to the atomic volumes of bulk metals¹² and point to a vacancy mechanism for the $1/f$ noise in these films.

During the generation of the $1/f$ noise, the activation of the defects stems from the thermal energy of the crystal. The processes by which the vacancies are created and annihilated in the film obey statistical laws and are associated with temperature fluctuations.

During the application of a sinusoidal test signal $I = I_1 \sin(\omega_1 t)$ to a film (I_1 is the amplitude of the first-harmonic current, with $\omega_1 = 2\pi f_1$), the film temperature varies in time in accordance with $\sin^2(\omega_1 t)$ (the thermal relaxation time of the film-

substrate system satisfies $\tau_{rel} \ll \omega_1^{-1}$). According to (1), there will thus be a periodic change in the vacancy concentration in the film. The extent (Δt) to which the film temperature exceeds the equilibrium value T_0 is given in terms of the thermal resistance of the film, R_t , and the power dissipation of the test signal:

$$\Delta T = T - T_0 = R_t P = R_t K \rho_f I_1^2 \sin^2 \omega_1 t, \quad (2)$$

where T is the film temperature when the effect of the test signal is taken into account ($\Delta t \ll T_0$), $K = L / Wh$, L and W are the length and width of the film, respectively, h is the thickness, and ρ_f is the film resistivity. The temperature dependence of ρ_f can be written

$$\rho_f(T) = \rho_{01}(1 + \beta \Delta T) + A \exp[-E_v/k(T_0 + \Delta T)]. \quad (3)$$

Here ρ_{01} is the resistivity due to scattering by phonons at the working temperature T_0 , by stable defects, and by the surface boundaries of the film; β is the temperature coefficient of the resistivity ($\beta > 0$); and the coefficient A gives the component of ρ_f due to scattering by vacancies. The voltage drop of the test signal across the film is

$$U_1 = \rho_f K I_1 \sin \omega_1 t. \quad (4)$$

Substituting (3) and (2) into (4), and expanding in powers of ΔT ($E_v \Delta T / kT_0^2 \ll 1$), we find the following expression for the amplitude of the third-harmonic voltage:

$$U_3 = \frac{R_t K^2 \rho_{01} \rho_f^2 I_1^3}{4} [\beta + A E_v / kT_0^2 \rho_{01} \exp(-E_v/kT_0)]. \quad (5)$$

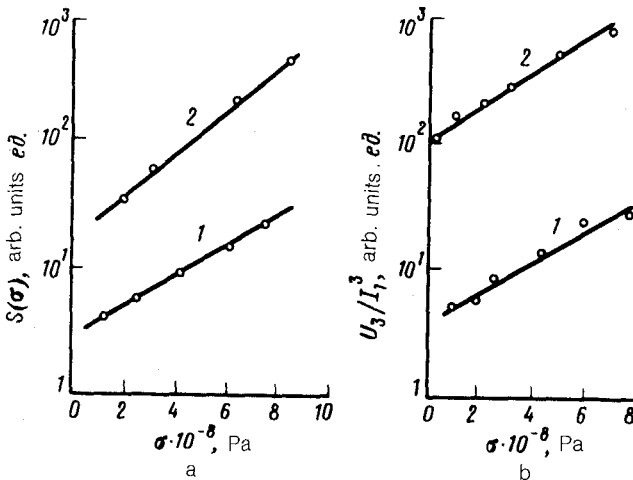


FIG. 1. Relative spectral power density of the noise (a) and amplitude of the third-harmonic voltage (b) versus the internal stress for films of molybdenum (1) and chromium (2).

The first term in (5) is related to the mechanism of phonon scattering of carriers. The second stems from an activation of vacancies by the test signal. Since the latter term is predominant for films with an elevated vacancy concentration, U_3 is an exponential function of the temperature and the stress. This case holds in the Cr and Mo films studied. Figure 1b shows experimental results on U_3/I_1^3 versus σ in semilogarithmic scale for Cr and Mo films. The activation volumes $V_a = 2.3kT\Delta \log(U_3/I_1^3)/\Delta\sigma$ found from these curves are $(1.3 \pm 0.4) \times 10^{-29} \text{ m}^3$ for chromium and $(1.1 \pm 0.3) \times 10^{-29} \text{ m}^3$ for molybdenum. These values are close to the atomic volumes of the metals. They agree with the activation volumes found from the $S(\sigma)$ curves in Fig. 1a. We can bring the calculated and experimental values of U_3 into agreement by taking the atomic fraction of vacancies in (1) to be $n_v \approx 10^{-3} - 10^{-4}$. This figure is quite reasonable for thin films.¹³

These results confirm that a vacancy mechanism is responsible for the $1/f$ noise and the nonlinearity effects in metal films with an elevated concentration of mobile defects. This mechanism involves the creation and annihilation of vacancies at various types of sinks.

The primary vacancy sinks (or sources) in the interior of a film are grain boundaries and the surfaces of microscopic voids. The vacancies are created predominantly at steps, through the rupture of one or two bonds in the crystal lattice of the metal. For high-quality films with a low concentration of mobile defects (the resistivity of such films approaches that of bulk metals) we observe a low level of the third-harmonic voltage and a linear dependence of this voltage on the temperature. This dependence stems from the temperature dependence $\rho_f(T)$, itself a consequence of the scattering of carriers by the lattice, according to (5). The $1/f$ noise in these films is also low⁷ and is given by the Hooge formula¹⁻³ with a constant $\alpha_H \approx 2.0 \times 10^{-3}$.

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