

Onset of long-range diffusion and exponent of $1/f^\alpha$ noise in metal films with electromigration damage

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Investigations of low-frequency conductance fluctuations have been done on silver films which have been made to undergo electromigration damage. The system shows a clear increase in noise magnitude after electromigration damage. The noise spectral power shows a distinct presence of $1/f^{3/2}$ component arising out of long-range diffusion. The temperature dependence of noise ($150\text{ K} < T < 350\text{ K}$) shows a marked deviation from the Dutta–Horn type behavior with the $1/f^{3/2}$ term showing a strong dominance at higher temperatures. We propose that the increase of noise in metal films after electromigration damage arise predominantly from this spectral component.

Electromigration (em) induced failure in metallic interconnects is a major issue in reliability of electronic devices. Low frequency conductivity noise with spectral power $S_V(f) \propto 1/f^\alpha$ ($\alpha \sim 1$) has been investigated as a tool to detect early em failure.^{1–5} $1/f$ noise in metal films are known to arise from equilibrium defect fluctuations.^{6–8} Since at least a part of these defects are also involved in the process of mass transport arising from electromigration, noise measurement turns out to be a useful probe to investigate the process of em failure as well. In general, the increase in $S_V(f)$ at the onset of electromigration and its correlation with certain material parameters are taken as early indicators of damage in em stressed films. In this letter we address a specific issue of the value of the exponent α in $S_V(f) \sim 1/f^\alpha$ in metal films with em damage.

Our work is motivated by the following consideration: Generally, a defect model like Dutta–Horn (DH) model⁶ gives a $1/f^\alpha$ ($\alpha \sim 1$) power spectra. In this model the defect fluctuation is due to “localized” motion with time scale τ which itself has a distribution as well as an activated dependence on temperature. No long-range diffusion is associated with this defect motion. However, during electromigration, the atomic motion leads to long-range diffusion. The underlying atomic process is distinct from the type of localized motion envisaged in a DH type model. Hence, there is no reason to expect that the localized equilibrium defect fluctuations as envisaged in the DH model should also describe the dynamics of defects that give rise to long-range atomic transport caused by electromigration. In fact, it is natural to expect that the power spectrum should contain some signature of long-range diffusion in the form of resistance fluctuations with spectral power⁹ $S_V(f) \propto 1/f^{3/2}$. Such long-range diffusion has been seen in metals with H impurity.^{10,11} We argue that such a $1/f^{3/2}$ spectral power should be present in films with electromigration damage because the em damage opens up pathways that would support long-range diffusion of atoms. Determination of such a component from the spectral power during the em process itself (i.e., when the dc em stressing current is on) can lead to ambiguity due to the finite resistance drift that takes place during the em process. Often the contribution could be masked by the normal $1/f$ spec-

trum. At higher temperatures and with a high measuring current the sample resistance may drift substantially during the measurement. If the drift is not taken into account this may show up as a $1/f^2$ contribution in $S_V(f)$. However, if the noise is measured in a film which has already undergone an em damage process (and no em stressing current is flowing through it during measurement of noise spectra) it will be possible to measure the exponent α unambiguously.

Our investigations were done on Ag films on which noise was measured before and after they were made to undergo electromigration damage. Doing the experiment as a function of temperature T , we could identify a clear component of $1/f^{3/2}$ noise in films with electromigration damage. We also show that the enhancement of noise in films with em damage can predominantly arise from this particular component of power spectrum. We clearly distinguish our experiment from the $1/f^2$ noise observed in certain electromigration studies. Electromigration damage was induced separately using a high dc stressing current and noise was measured intermittently while the dc was switched off. The calculation of power spectrum is done after subtracting the effect of long term drifts. The experiment were done on silver films (length $\approx 140\ \mu\text{m}$ and width $\approx 12.5\ \mu\text{m}$) evaporated on sapphire substrates. Two types of films were grown (see Table I). The control film (film 1, thickness=150nm) deposited at 150°C had a room temperature resistivity ($\rho_{300\text{ K}}$) of $1.6\ \mu\Omega\text{ cm}$ and a residual resistivity ratio (RRR = $\rho_{300\text{ K}}/\rho_{4.2\text{ K}}$) ≈ 5 . Electromigration damages were done on 35 nm films grown on unheated substrates. These films with relatively high ρ could be damaged easily. Noise was measured using a five-probe ac technique^{12,13} with a measuring current density $j_{ac} < 5 \times 10^4\ \text{A cm}^{-2}$ \ll em stressing current, for $0.1\ \text{Hz} < f < 10\ \text{Hz}$ and within a temperature range $150\text{--}350\ \text{K}$ which was controlled within 4 mK.

In Fig. 1 we show the temperature dependence of noise of the control film between 150 and 350 K. The inset shows a typical power spectrum and the back ground noise which is $\approx 4k_B TR$. The noise is represented as $\gamma(f)$, where $\gamma = (NS_V(f) \cdot f^\alpha) / \langle V^2 \rangle$. Here, N =number of carriers in the volume of the sample, the spectral power $S_V(f)$ at a frequency f has a local frequency dependence $\sim 1/f^\alpha$ and $\langle V^2 \rangle$

TABLE I. Film properties and parameters.

Film	t (nm)	Dep. temp.	$\rho_{300\text{ K}}$ ($\mu\Omega\text{ cm}$)	RRR	$\gamma_{280\text{ K}}$ ($\times 10^{-3}$)	E_γ (meV)	E_B (meV)	T^* (K)
1	150	450 K	1.6	5	6	100	...	310
2	35	Rm. temp	2.72	3.47	8.8	150	43	270
3	35	Rm. temp	2.78	2.48	56	250	233	220
4	35	Rm. temp	2.79	2.45	58	250	370	220

is the mean square ac bias across the sample. [The local value of α is defined as $-\partial \ln S(f)/\partial \ln f$]. The noise passes through a shallow maxima at around 250–300 K and then increases again following an activated temperature dependence $\gamma(T) = \gamma_0 e^{[-E_\gamma/k_B T]}$. We designate the temperature at which the onset of activated behavior occurs as T^* (see Fig. 1 and Table I). Activation energy $E_\gamma \approx 100$ meV. The α in the complete range 150–350 K is close to 1–1.2 (see inset). DH model allows us to calculate $\alpha(T)$ as a function of T from the temperature dependence of $S_v(f)$ using the relation

$$\alpha(T) = \left[1 - \frac{1}{\ln(\omega\tau_0)} \left(\frac{\partial \ln S}{\partial \ln T} - 1 \right) \right]. \quad (1)$$

The α obtained from Eq. (1), however, deviates from the experimentally observed α in the temperature range $T > 220$ K and at higher T the observed trend in temperature dependence is different from the calculated one.

In Fig. 2 we show γ ($f=0.5$ Hz) in films 2, 3, and 4. Film 2, which is a pristine film of thickness 35 nm, has $\gamma(f=0.5\text{ Hz}) \approx 8.8 \times 10^{-3}$ at $T=280$ K which is about 1.5 times more than the control film 1. It has a shallow maxima around 230 K and α is ~ 1.2 – 1.3 , similar to that of the control film, and $E_\gamma \approx 150$ meV.

Film 3 is obtained by subjecting film 2 to an em stressing current ($J=0.35 \times 10^6$ A cm $^{-2}$) at 373 K for 15 h. This

enhances $\rho_{300\text{ K}}$ by $\sim 2\%$ and reduces of RRR by nearly 30%. The noise is enhanced at all temperatures, particularly very significantly for $T > T^* \approx 220$ K. This film with only 2% resistance change at 300 K has a noise which is nearly one order of magnitude more than that in the undamaged film 2 at ~ 280 K. E_γ in film 3 is ~ 250 meV. A further em stressing for 15 h using a higher current stressing of $J=5 \times 10^6$ A cm $^{-2}$ (film 4) does not cause any significant change in $\rho_{300\text{ K}}$, RRR and $\gamma(f=0.5\text{ Hz})$.

In Fig. 3 we show α as measured from the power spectrum $S_v(f)$ in films 2–4. In the undamaged film 2, α is typically in the range 1.2–1.3 for all T . The em damaged films 3 and 4 show similar α for $T < T^*$. However, in these films α increases noticeably in the temperature region $T \geq T^*$. In film 3 $\alpha \approx 1.36$ at $T=280$ K while in film 4 $\alpha \approx 1.41$ (we did not take data for $T \geq 300$ K to avoid significant drift R at higher T during measurement). In the same graph, we show the α obtained from Eq. (1). We find significant deviation from the prediction of the DH model, indicating that the noise in these materials have additional components which lead to deviations from the model.

We propose that the noise in these films arise from a combination of two processes which take place independently. The first one arises from processes with $S_v(f) \propto 1/f^\beta$ ($\beta \sim 1$). This can arise from relaxation of localized defects.^{6,7} In addition there is a second contribution from long-range diffusion with $S_v(f) \propto 1/f^{3/2}$, whose contribution is expected to be low in undamaged films or at low temperatures. But in em damaged films and at higher T it will increase. Eventu-

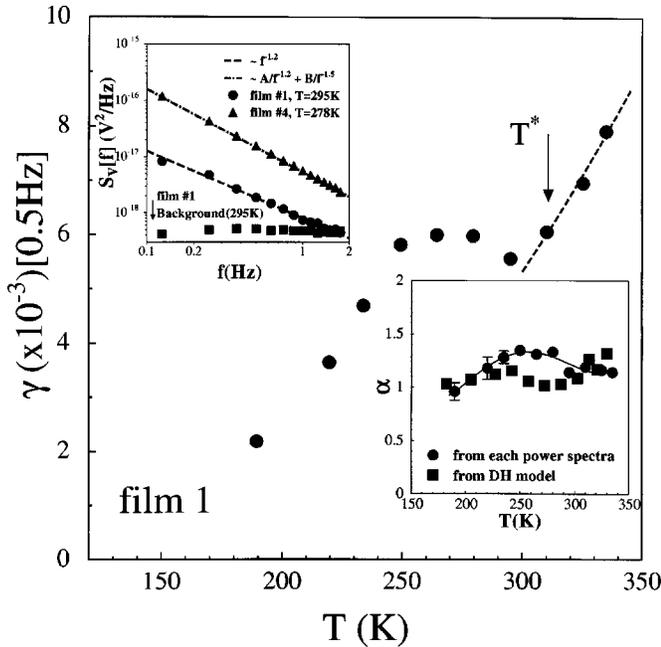


FIG. 1. Temperature dependence of noise in film 1 (thickness 150 nm). The insets show the typical power spectrum with background and temperature dependence of the exponent α in $1/f^\alpha$ for the control film 1. Also shown in the upper inset is a spectrum from an electromigration damaged film (film 4) which has a finite $f^{-3/2}$ component.

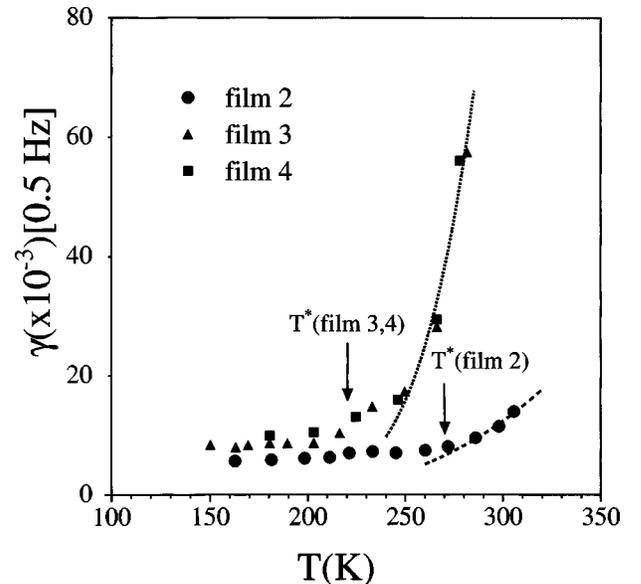


FIG. 2. Temperature dependence of noise in films with (film 3 and 4) and without (film 2) em damage.

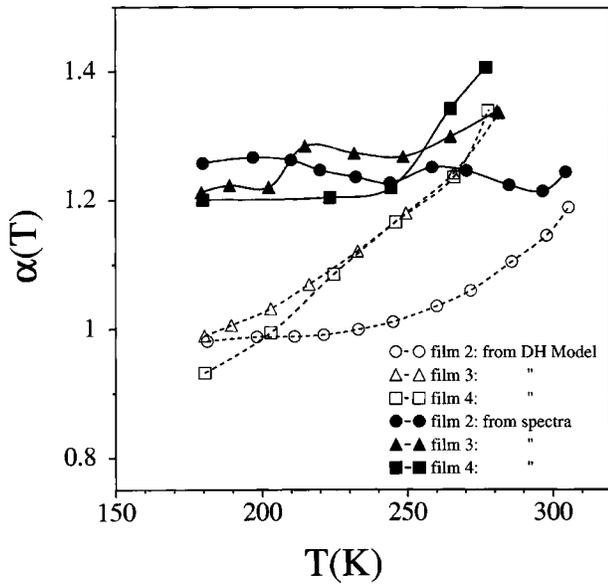


FIG. 3. The temperature dependence of the exponent α in films with (film 3 and 4) and without (film 2) em damage. The expected α from Dutta–Horn model is also shown.

ally, this process will become the dominant mechanism beyond a crossover temperature ($\approx T^*$). The observed $S_V(f)$ can thus be expressed as a combination of the two processes and can be written as

$$\frac{f \cdot NS_V(f, T)}{\langle V^2 \rangle} = \frac{A(T)}{f^{\beta-1}} + \frac{B(T)}{f^{1/2}}. \quad (2)$$

$A(T)$ and $B(T)$ are the relative weights of the two processes. We did the fitting of the spectrum by varying β from 1 to 1.2 and the best fitting was obtained for a value of $\beta = 1.2 \pm 0.03$. This is shown in the inset of Fig. 1.

Figure 4 shows the temperature variation of the ratio B/A . Film 2 with no em damage has a low B/A ratio for all T . However, in films 3 and 4 with em damage there is a significant rise in the ratio for $T \geq T^*$. In the inset we show the A and B individually for sample 4. As the temperature increases, the $B(T)$ term increases following an activated temperature dependence with $E_B \approx 370$ meV. Eventually beyond the cross over temperature T^* it wins over. The em damaged films have relatively higher contribution of the $B(T)$ term over all temperature range compared to the undamaged films which can often be subdued by the $A(T)$ term and may not always be visible. The enhancement of the noise in em damaged films may be caused predominantly by this diffusion contribution with $1/f^{3/2}$. Tracking the changes of this particular frequency component with the em process parameters could help us to establish a close correlation between the two.

To summarize, films with em damage show an enhanced contribution to noise spectral density from processes involv-

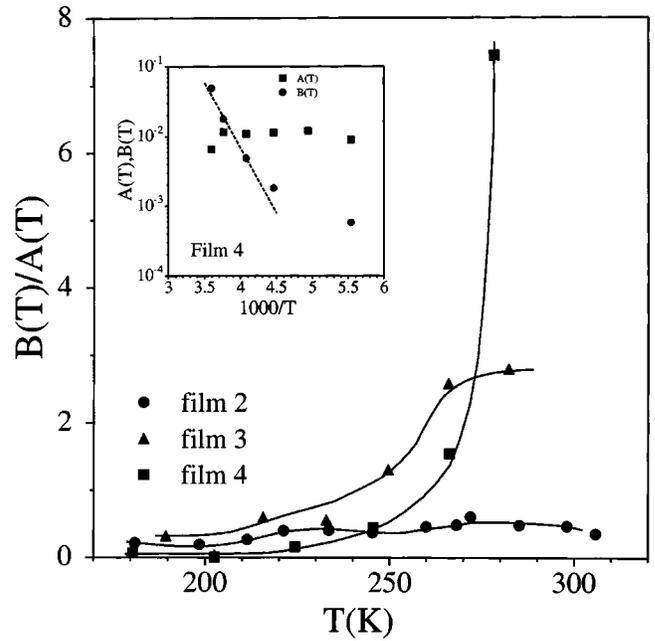


FIG. 4. Temperature dependence of the ratio B/A in the films with and without em damage. The inset shows the temperature dependence of $A(T)$ and $B(T)$ for film 4. Note the rapid rise of $B(T)$ with temperature.

ing long-range diffusion. The observed exponent α of the spectral power density is significantly affected by the $1/f^{3/2}$ type power spectrum arising from such processes. We propose that the $f^{-3/2}$ component in the power spectrum will have stronger correlation with em parameters.

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