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Low-frequency resistance fluctuations in metal films under current stressing at low temperature ($T < 0.3T_{melting}$)

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In this paper, we report a systematic study of low frequency $1/f^{\alpha}$ resistance fluctuation in thin metal films (Ag on Si) at different stages of damage process when the film is subjected to high current stressing. The resistance fluctuation (noise) measurement was carried out *in situ* using a small ac bias that has been mixed with the dc stressing current. The experiment has been carried out as a function of temperature in the range of 150–350 K. The experiment establishes that the current stressed film, as it undergoes damage due to various migration forces, develops an additional low-frequency noise spectral power that does not have the usual $1/f$ spectral shape. The magnitude of extra term has an activated temperature dependence (activation energy of $\approx$0.1 eV) and has a $1/f^{1.5}$ spectral dependence. The activation energy is the same as seen from the temperature dependence of the lifetime of the film. The extra $1/f^{1.5}$ spectral power changes the spectral shape of the noise power as the damage process progress. The extra term likely arising from diffusion starts in the early stage of the migration process during current stressing and is noticeable much before any change can be detected in simultaneous resistance measurements. The experiment carried out over a large temperature range establish a strong correlation between the evolution of the migration process in a current stressed film and the low-frequency noise component that is not a $1/f$ noise.

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I. INTRODUCTION

Metallic thin films when subjected to a dc current of high density for long time get substantially damaged. This happens due to migration of atom under the influence of combined effect of temperature, mechanical stress, and electromigration. This phenomena attracts tremendous technological interest since the time it was observed to be one of the major causes of failure of thin metallic film interconnects. It has become one of the most important issues related to the reliability of very large scale integration (VLSI) or ultra large scale integration (ULSI) circuits as the dimensions of the interconnects used there have been substantially reduced with the continuing advances in microelectronic technology. The phenomena have been reviewed extensively.[1–4] Over the last two decades, resistance fluctuation (noise) associated with metal films has been investigated as a tool to study such phenomena.[5–14] In a current carrying metal film, in addition to equilibrium white thermal noise (popularly known as the Nyquist noise), dominant contribution comes from the low-frequency $1/f$ noise [spectral power $S(f) \propto 1/f$]. The magnitude of the first kind of noise can be estimated from the spectral power $S_{th} \approx 4k_BTR$ for a film of resistance R at a temperature T. It depends only on the resistance R and the temperature T of the film and it does not depend on the quality of the material that makes the film. On the other hand, the $1/f$ noise cannot be predicted *a priori*. It depends on the material that makes the film. It is generally believed to arise from smeared out activated dynamics of two-level-type defects in the films and its spectral shape can be explained by such model as the Dutta-Horn model.[15] In this model, the $1/f$ noise resulted from the superposition of uncorrelated noise sources with a distributed relaxation time.[15,16] The spectral power of noise of many metallic films often follow an empirical formula (often referred to as the Hooge's formula),[17]

$$S_V(f) = \frac{\gamma_H V^2}{N f^{\alpha}}, \tag{1}$$

where α has a value between 0.8 and 1.2, N is the number of electrons in the sample, V is the bias for measurements, and γ_H is an empirical constant (known as Hooge's parameter) which takes a value in the range of $\simeq 10^{-3}$–10^{-5} in films of conventional metals.

In earlier studies, many investigators tried to correlate lifetime of metal film against electromigration to the magnitude of $1/f^{\alpha}$ noise at some particular frequency.[5,7,9,11] They found that, in general, samples with larger low-frequency noise spectra had smaller electromigration lifetime, although a clean correlation could not be obtained because $S_V(f)$ in metal film depends on different material parameters. Some investigators were interested in the study of spectral form of $1/f^{\alpha}$ of electromigrated film.[12,13] Most of these investigations, however, were done either by less sensitive dc four-probe method for noise measurement or by *ex situ* ac method and these experiments reports an frequency exponent α to have values ranging from 1 to 2. The noise power spectra were attempted to explain using Dutta-Horn model. None of these investigations were made to correlate the noise spectra with the evolution of the damage process by measuring the noise spectra *in situ* at different stages of damage in the current carrying film. These experiments were often carried out in accelerated condition, commonly at temperature close to the half of the material's melting temperature.

In practice, the damage process in a metal film subjected to high current stressing is due to atomic migration which is a result of the combined effects of stress migration, thermomigration, and electromigration. The details of the damage process closely depend on the mechanisms of atomic migration involved under influence of these driving forces. These migration leads to formation of hillocks and voids and lead to gross change in its topography. The presence of defects (in particular, extended defects and internal interfaces) play an important role in this process by providing low activation energy path ways for diffusion. The hypothesis that there may be a relation between the migration process leading to damage and the $1/f$ type noise power depends on the central role of "defects." This is because a broad spectrum of defects in principle can contribute to both these phenomena. However, there is no reason to believe that the defects that facilitate atomic diffusion and those which contribute to electrical noise (particularly $1/f$ noise) need be the same. There is no reason to assume that those defects that take part in atomic migration would also lead to the same noise spectra as that would result from the "localized" motion between equilibrium two-level-type defect states as envisaged in the Dutta-Horn model for $1/f$ noise. The migration process may or may not be initiated from these localized defects and there is no reason that these processes will be correlated. The observed absence of a tight correlation between the damage process and the magnitude of the $1/f$ noise probably owes its origin to this fundamental cause.

On the contrary, one can expect that since the process of damage involves mass migration and the diffusion of defects, this will lead to noise spectra which are very distinct from generic $1/f$ noise spectra and the spectral dependence will carry signature of long range diffusion.[18,19] In an earlier investigation from our group, we had shown that there indeed appears an additional noise component which has an $1/f^{1.5}$ dependence in case of films which are electromigrated prior to the noise measurement.[20] We have also shown in a preliminary report that in a current stressed film at room temperature, as the damage process evolves the spectral power of $S_V(f)$ acquire an increasing component of $1/f^{1.5}$ term.[21] These observations indicate that the noise spectra arising due to diffusion have a close correlation with the entire damage process. The effect of the observed extra term is not to affect the $1/f$ part of the spectral power but to add a frequency dependent part to the spectral power and thus change the spectral shape of the noise power.

Diffusion, and hence the damage process, is a thermally activated process. Thus, the temperature dependence of noise associated with damage of film during current stressing should have a close correlation to that of the damage process. We realize that this particular aspect has not been investigated experimentally. Being motivated by this, we have carried out an *in situ* noise measurements in thin metal films stressed with high current at different temperatures in the temperature range of 150–350 K. For $T < 150$ K, the damage process is very slow. We observed that the magnitude as well as the spectral shape of noise clearly carry the signature of onset of damage process and the various stages as it progresses. Since these experiments were done as a function of temperature, we could follow the temperature dependence of the relevant parameters. We note that while the temperature dependence of noise in metal film have been studied for decades, however, study of resistance noise during current stressing of film as a function of temperature has not been done before. We follow up the experimental result with a simple simulation procedure that captures the essential aspects of observation.

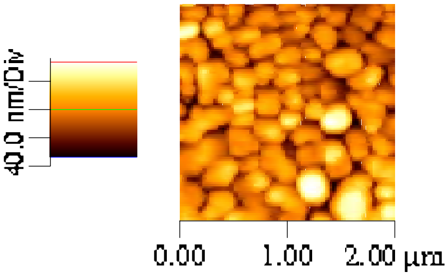

FIG. 1. (Color online) AFM image of a typical film used in this study.

II. EXPERIMENTAL TECHNIQUES

A. Sample preparation and characterization

The experiments on current stressing and *in situ* noise measurements were carried out in silver (Ag) films grown on silicon. While different metals will have details which are specific to them, it is reasonable to expect that the observations made here on Ag films will be sufficiently general to capture the basic phenomena and the underlying physics. We realize that Ag film is not used in any VLSI circuits. However, the purpose of this paper is to investigate the basic phenomena in a single component system as a model system.

Films were grown on silicon(100) in an ultrahigh vacuum (UHV) chamber using an effusion cell at vacuum better than 5×10^{-8} torr during deposition. The substrate were kept at 150 °C during deposition and the films were subsequently annealed at 200 °C for 6 h in the same vacuum. The purity of the Ag granules used for deposition was 99.9999%. Prior to deposition of the film the substrate was first cleaned with the well-known RCA cleaning method[22] and then was placed inside the load-lock chamber of the UHV deposition unit. There, it was cleaned by 5 keV ion beam of Ar at 1.5×10^{-5} torr and 40 μA of ion current for 10 min. A mask was used during deposition of the film to get a five probe linear pattern. The film thicknesses were typically around 0.155 μm. The dimension of the film between voltage probes was 12 μm $\times$ 12 μm^2. (Note that we used somewhat wider size because it allowed us to do *in situ* scanning thermal microscopy which allowed us to investigate the temperature inhomogeneity during current stressing. The result of this will be reported separately.[23])

For characterization of the films we studied them with x-Ray diffraction (XRD), scanning electron microscopy, and atomic force microscopy (AFM). The XRD of the films shows that the films were well textured and strongly oriented along the (111) direction. The average grain size for the films were found to be 0.250 μm from the AFM image (Fig. 1). We have measured resistance of the Ag films using a four-probe technique down to liquid He temperature. The temperature dependent resistivity of a typical film used for cur-

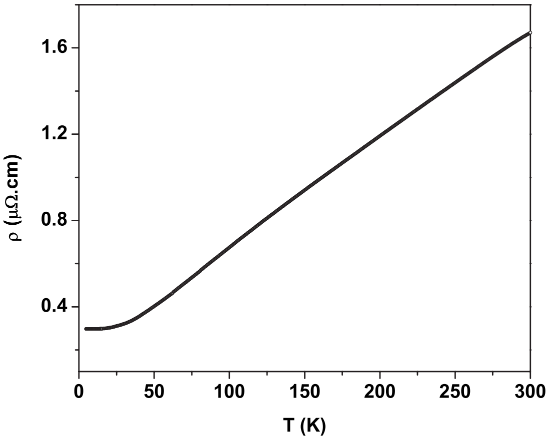

FIG. 2. Temperature dependence of the resistivity of a typical Ag film used.

rent stressing is shown in Fig. 2. The room temperature resistivity (ρ_{300}), residual resistivity ratio ($\mathrm{RRR}=\rho_{300}/\rho_{4.2}$), electronic mean free path at 4.2 K ($\lambda_{4.2}$), and temperature coefficient of resistivity at room temperature (TCR) for five different films used in this investigation are shown in Table I. The bulk values of RRR and TCR for pure Ag are 1.6 $\mu\Omega$ cm and 3.81×10^{-3} K^{-1}, respectively.[24] The resistivity measurement shows that the films are of good quality with mean free path of electrons comparable to that of bulk value at room temperature. Reproducibility of the room temperature resistivity value within 5% also shows a good control on the growth process. An important quantity that can be used as quality of a metal film is the magnitude of $1/f$ noise at room temperature. We have measured the $1/f$ noise of the films used in the experiments (to be described later on). The room temperature values of γ_H calculated from the noise using Eq. (1) lie in the range of 4×10^{-5}–35×10^{-5}. This is a low value signifying good quality of the films. In the same table, we give the values of γ_H for each film. These films were used in stressing at different temperature, as indicated in the last column of Table I.

B. Measurement of noise in presence of an applied dc stressing current

To perform the *in situ* noise measurement during current stressing process, we used a circuit which mixes a dc current with ac excitation through the sample. The dc serves the purpose of current stressing, while the noise measurement has been done using the ac excitation. The details are given elsewhere.[21] Here, we give a brief description. In our circuit, the dc source was decoupled from the ac with an inductor and the ac source was decoupled from the dc with a capacitor so that in this circuit, both of the signals can be controlled independently. The applied dc we used had a typical current density $J_{dc}=2\times10^{7}$ A/cm^2, whereas the amplitude of the ac excitation was chosen so that the current density J_{ac} was always lower than 1×10^{4} A/cm^2. This, being less than J_{dc} by more than three orders, does not contribute to stressing. We used a five-probe ac technique for noise measurement that allows for much higher sensitivity.[25] We recorded resistance of the film at regular time intervals until the film got damaged. The evolution of the damage process of the films was detected by the observation of change in resistance of the films. The experiments were carried out in liquid nitrogen cryostat, and throughout the experiment, the temperature of the sample was stabilized at some particular temperature with a stability better than 150 μK with a digital temperature controller.

To carry out the noise measurement, we used a digital signal processing based ac technique using a lock-in amplifier (model SR830) which allows simultaneous measurement of the background noise (bias independent) as well as the bias dependent noise from the sample.[25] The sample was ac coupled to the lock-in amplifier with a transformer preamplifier (model SR554). Thus, dc stressing current does not affect the process of noise measurement. The bridge was balanced to better than 10 nV. With an applied bias of 1 mV, this would imply a resistance balance of one part in 10^5. The resistance noise from the sample shows up as the out-of-balance signal of the bridge. This was recorded as a time series from the output of the lock-in amplifier. The noise signal appears as a side band on the main carrier frequency of the lock-in amplifier. The output of the lock-in amplifier was recorded by a 16 bit analog-to-digital card and stored in the computer. We recorded the time series at a sampling rate of 1024 data points/s for a fixed time slab (long enough to collect nearly 2×10^{6} data points) at a regular time interval until the film got damaged. Every data set collected at various stages of damage process was decimated to about 0.1×10^{6} points before the spectral power $S_V(f)$ is determined numerically. The lower-frequency limit of 1 mHz is determined by the quality of the temperature control which is within ±0.5 ppm. The output low-pass filter of the lock-in amplifier was set at 3 ms with a roll-off of 24 dB/octave which has a flat response for $f\leq10$ Hz. This determines the

TABLE I. Samples used in this work and their electrical properties.

Film	ρ_{300} ($\mu\Omega$ cm)	RRR	$\lambda_{4.2}$ (nm)	TCR (10^{-3} K^{-1})	γ_H at 300 K (10^{-5})	Temperature during stressing
Ag01115	1.61	8.30	435	3.353	4	150
Ag07016	1.67	5.63	285	3.055	35	200
Ag210206B	1.66	5.88	299	3.136	8	250
Ag13016	1.61	9.34	490	3.512	4	300
Ag20056	1.61	9.91	519	3.621	4	350

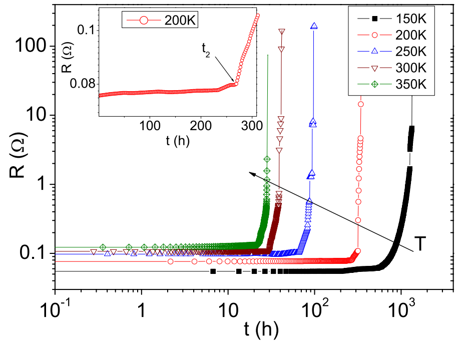

FIG. 3. (Color online) Resistance history of five different films subjected to the same high stressing current at different temperatures. Inset shows zoomed plot for the film stressed at 200 K as an example. The arrow indicates the sequence of curves with the increasing temperature. The lifetime increases significantly as temperature is decreased.

upper limit of our spectral range. To minimize the contribution of the transformer noise to the background noise, the carrier frequency was chosen to lie in the eye of the noise figure of the transformer preamplifier. Except the lock-in amplifier, all other instruments were kept inside a Faraday cage to shield them from any external electromagnetic noise. The apparatus can measure a spectral power down to 10^{-20} V^2 Hz^{-1}. The measured background noise was white and was contributed mainly by the $4k_BTR$ Nyquist noise. Before the actual measurement, we made it confirm that there were no cross coupling from the dc bias on the noise. Improved noise measurement procedure as well as temperature control during measurement allowed us to obtain reliable data from which we can derive definitive conclusion on the frequency dependence of the spectral power. [We note that if the resistance drifts during measurement, it can introduce a low-frequency component in the spectral power, generally resulting a $1/f^2$ dependence of the spectral power. We subtract a least square mean line from the time series to take care of this before we calculate $S_V(f)$].

III. RESULTS

The time evolutions of damage process at five different temperatures from 150 to 350 K are shown in Fig. 3 as evolution of resistance. It can be seen that as the stressing is done at lower temperature, there is a significant enhancement of the lifetime. At 150 K, the lifetime is enhanced to more than 1000 h from 20 h at 350 K. The evolution of resistance of the film as a function of time occurs in a nonmonotonous manner. There is distinct time when the resistance of the film rapidly increases with time as the onset of damage process. Such a stage is marked as t_2 ($\approx 265h$) in the inset of Fig. 3. The resistance follows a clear dependence on time like $\ln R \simeq mt$ with different values of m before and after the point t_2. At t_2, there is a substantial change in m. This can be seen in Fig. 3. We call m for $t < t_2$ as m_1 and for $t > t_2$ as m_2. We also observed that the values of m are higher for the films which were stressed at higher temperature. This is expected because the damage process is expected to become faster at high T. In Fig. 4, we show the dependence of m_1 and m_2 on the temperature at which the film was stressed at.

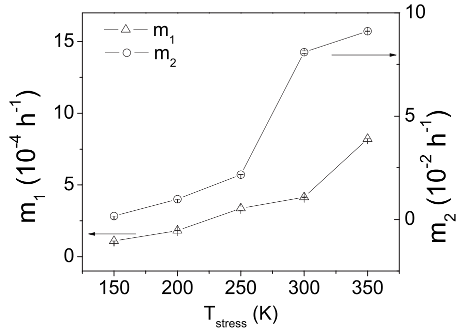

FIG. 4. Values of m before and after the onset of damage for the films stressed at different temperatures.

Noise measurement shows that the noise magnitude as well as the spectral power $S_V(f)$ change as the damage process proceeds. In Fig. 5, the noise magnitude at different stages are plotted in the form of relative resistance fluctuation $\langle(\Delta R)^2\rangle/\langle R^2\rangle$ [$=\frac{1}{\langle V\rangle^2}\int_{f_{min}}^{f_{max}} S_V(f)df$, where f_{min} and f_{max} are the minimum and maximum frequencies of the bandwidth and $\langle V\rangle$ is the mean ac bias across the sample] at various stages of the damage process for the film stressed at 200 K. The spectral power density in a scaled form $S_V(f)/\langle V\rangle^2$ [since $S_V(f)$ varies as $\langle V\rangle^2$] at some selected stages of the damage are plotted in Fig. 6. The data obtained for the films stressed at other temperatures also show similar behavior; hence, they are not shown to avoid repetition.

From Fig. 5, it can be clearly seen that the noise remains almost same for a long period of stressing until some time, marked as $t_1(\approx 165h)$, after which it starts increasing. We find that not only the magnitude but also the spectral shape changes at this point. These changes were seen to take place at much earlier time than any significant change in resistance occured. (The measured resistance is shown in the same figure.) The resistance starts changing significantly at t_2 $\approx 265h$, whereas the noise starts changing at t_1. Thus, the

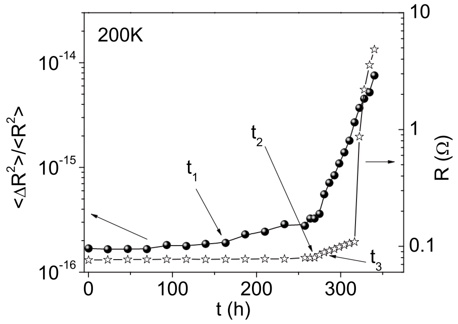

FIG. 5. Relative resistance fluctuation for the same film as the damage process progress. The resistance of the film also shown (right Y axis). t_1 is the time when the relative resistance fluctuation starts to increase, t_2 is the time when the rate of change in the resistance increases, and t_3 is the time when the resistance of the film increases by 10%.

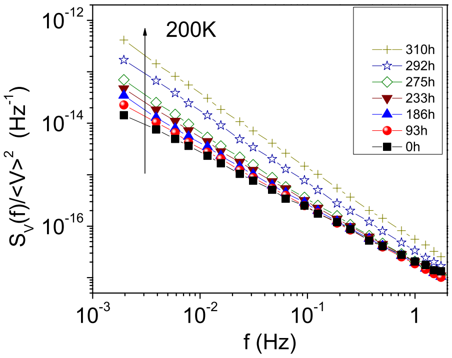

FIG. 6. (Color online) Scaled noise $S_V(f)/\langle V\rangle^2$ at different stages of the damage process for the film stressed at 200 K. The arrow shows the increase of stressing time.

onset of rapid change in noise, both in magnitude and spectral shape, is a clear precursor to the failure process. Superior sensitivity of the noise measurement allows the changes to be picked up much before the average resistance shows change. The spectral power dependence in Fig. 6 shows a very important observation that the damage process affects the spectral power and it enhances the low-frequency component significantly. A way to quantify the low-frequency component is to express spectral power as $S_V(f) \propto 1/f^{\alpha}$. We observe that the frequency exponent α evolves as a function of time during the stressing process. This is shown in Fig. 7 as a function of time for the same film. This is a representative data and is qualitatively similar for the all films stressed at other temperatures. We find that the unstressed film has α close to 1. However, α starts to change, although slowly, from the initial period of stressing. Significant rapid change starts to happen at time t_2 when R changes rapidly.

The enhancement of the low-frequency component during current stressing is an important feature because in metal film without current stressing such enhancement is not observed, at least within the temperature range, at which the films were stressed. It was observed based on large number of sample studied that for the films stressed with high current, the value of α enhances to values higher than 1 with the progress of the damage process, whereas for unstressed film, it was usually in between 0.8 and 1.2. In Fig. 8, we show α and γ_H as a function of temperature for an unstressed film. The dashed line in Fig. 8(a) shows α as calculated from Eq. (2) for Dutta-Horn model,[15]

$$\alpha_{DH}(f,T) = 1 - \frac{1}{\ln(f/f_0)}\left(\frac{\partial \ln S(f,T)}{\partial \ln T} - 1\right). \qquad (2)$$

where $f_0 = 10^{14}$ the attempt frequency. We observed that for $T < 350$ K, α roughly follows the values as obtained from Eq. (2), but above 350 K, a deviation from it can be seen. To accentuate deviation of α from 1 with the progress of the damage process, we plot the noise spectra of the stressed film in the form $fS_V(f)/\langle V\rangle^2$ at different times in Fig. 9.

From the comparison of noise spectral information for the film at stressed and unstressed condition, it is very clear that in the stressed film, we have additional noise sources which result in an additional noise component with a spectral power that varies more rapidly than $1/f$. The observed enhancement of noise occurs at low-frequency regime. It is also noted that this increase of the low-frequency component distinctly depends on the temperature at which it is stressed. To quantify these changes, we follow the procedure elaborated below.

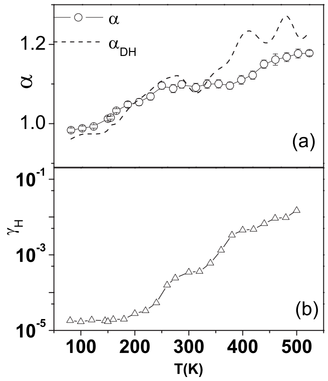

FIG. 8. (a) α and (b) γ_H of the same film without any current stressing for wide range of temperature. α was obtained from the slop of linear fits to a $\ln[S_V(f)]$ vs $\ln f$ plot (not shown here). The error bars are the fit errors. α_{DH} was calculated at $f = 0.5$ Hz using Eq. (2). γ_H was obtained at 0.5 Hz.

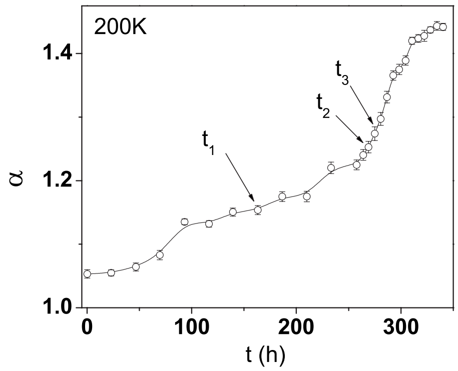

FIG. 7. Evolution of the frequency exponent α as a function of time during the damage process for the film stressed at 200 K.

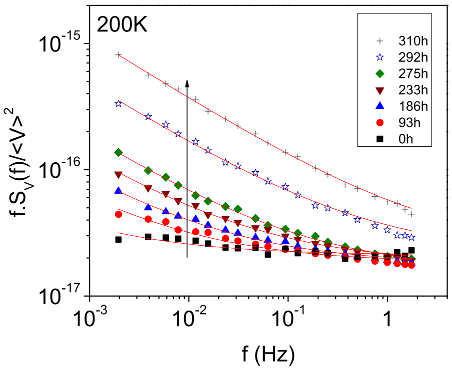

FIG. 9. (Color online) $fS_V(f)/\langle V\rangle^2$ of the film stressed at 200 K at different stages of damage process.

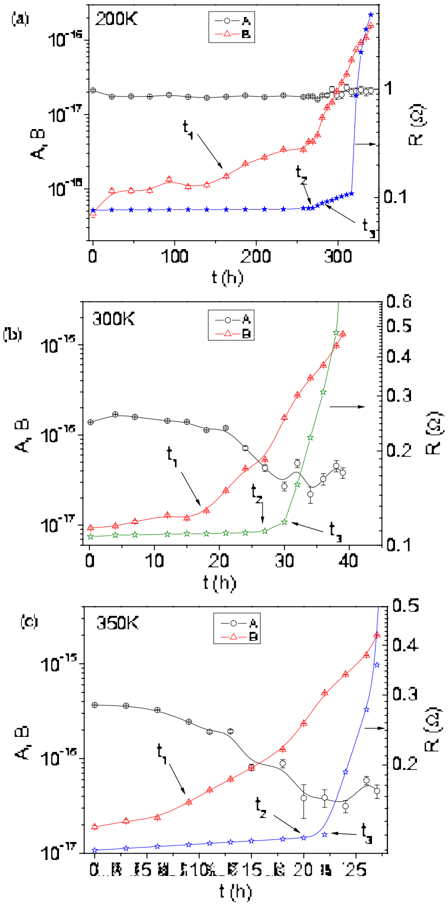

FIG. 10. (Color online) Values of A and B for the films stressed at (a) 200 K, (b) 300 K, and (c) 350 K, as obtained from the fits to Eq. (3) as the damage process proceeds. The evolution of resistance is also shown.

We argue that since the damage process involves diffusion and resistance noise due to diffusion has a spectral dependence like $1/f^{1.5}$,[19] it is likely that this additional component would have spectral shape varying as $1/f^{1.5}$. This particular aspect has been reported in previous publication from us where we addressed to the problem at room temperature only.[21] We fitted the noise spectra of the stressed film to the following equation:

$$\frac{S_V(f)}{\langle V\rangle^2} = \frac{A}{f} + \frac{B}{f^{3/2}}. \tag{3}$$

In this equation, the first term in the right hand side associates noise component for the normal $1/f$ component, whereas the second term is for the additional component. As the damage process evolves the change in spectral weight will be denoted mainly by change of A and B. In Fig. 9, we show the typical fitting as solid lines. We observe that this equation fits very well to the noise spectra taken at various stages of the damage process. The values of A and B obtained from the fits are plotted in Fig. 10 along with the resistance evolution as a function of stressing time for the films stressed at three different temperatures. From this plot, it can be clearly seen that for all the films, B (which measures the additional noise component) increases as the damage process progresses, whereas component A (which measures the $\frac{1}{f}$ component) remains almost the same throughout the damage process at lower temperature and it even decreases for higher stressing temperature. The increment of B become more significant after point t_1 and it enhances further and more rapidly after point t_2 when the resistance changes. This is a very important observation. Since B is associated with process involving diffusion, the strong change in B would mean that the principal changes are controlled by diffusion which shows strong temperature dependence. To investigate the nature of temperature dependence, we take the values of A and B when there are significant damage for the films stressed at all the stressing temperatures and plotted them as a function of stressing temperature. In Fig. 11, we plot the values of A and B for each film when its resistance increases by 10% of the resistance at unstressed conditions (we mark this point as t_3 in Fig. 10) as a function of temperature at which the film was stressed. (This choice of t_3 is justified because for all the films, this has been taken as a defined point of damage of ~10%.) While A shows a very shallow change with stressing temperature, B shows a strong temperature dependence. From the plot of $\log B$ vs $1/T_{stressing}$ (Fig. 11), activation behavior of B can be clearly observed with an activation energy of 0.09 ± 0.01 eV. Defining t_3 as the lifetime of the film, we also plot lifetimes of the films as a function of temperature at which they were stressed in Fig. 12. The lifetime of the film follows Arrhenius behavior with an activation energy of 0.1 ± 0.01 eV. The activation behavior seen in the noise parameter B (which is interpreted as a measure of the diffusive component) is thus similar to that seen for the lifetime. The two experiments though done simultaneously are distinct. It is indeed gratifying that they show activated behavior with the same activation energy. We note that this is a very important observation because we could clearly establish a close connection between the activation process of migration and that associated with the excess low-frequency components of noise by two separate measurements.

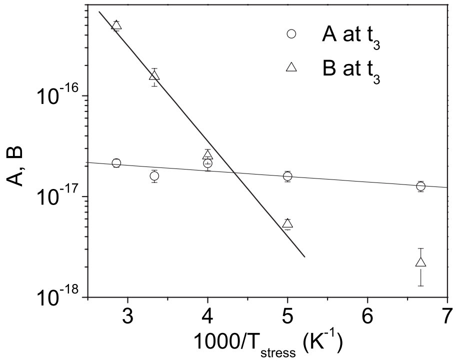

FIG. 11. Values of A and B at t_3 for each film as a function of temperature at which they were stressed to show the activation behavior.

IV. DISCUSSION

The experiments carried out in this paper established that due to the presence of an additional low-frequency compo-

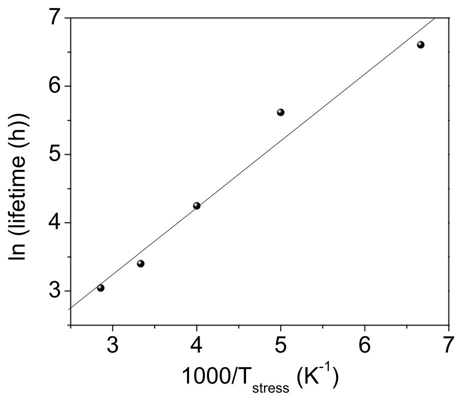

FIG. 12. Lifetime of the films stressed at different temperatures.

nent, the spectral shape of the noise power spectrum changes on current stressing. The current stressing leads to eventual damage of the film. We have also shown that the likely source of this extra noise component is diffusion which contributes $1/f^{1.5}$ to the spectral power. The results presented here establish a strong correlation between the damage process and the extra noise spectral power that is distinct from conventional $1/f$ noise. Our experiment also shows that the $1/f$ noise component may not have any correlation to the damage process. We mention here that the resistance drift as a function of time can modify the power spectra[10] and, in particular, contribute a $1/f^2$ contribution as stated before. We have checked this particular issue with care. First, we note that the resistance drift that we observe is a slow monotonous drift over long times. This allows us to subtract a background drift without really affecting the power spectrum. One can calculate the contribution of the resistance drift to the noise power following Koch.[10] We find that such a contribution (calculated from the experimentally observed resistance drift) is much larger by orders of magnitude than the noise power we observe. This ensures that the drift has been properly subtracted form the time series. We also find that the noise power within the bandwidth of our experiment does not depend on the length of the data set. If the drift has a contribution to the power spectrum, one would observe dependence of the calculated noise power on the length of the data set. Finally, we have checked the power spectrum by stopping the stressing current and find that the power spectrum does not depend on whether the stressing current is on or it is turned off during the collection of the time series (for power spectrum calculation).

To explain the spectral signature of damage process, we argue that the noise of the film under current stressing arises from two independent different processes. This is represented in Eq. (3). One of these involves the localized motion of defects between equilibrium defect states with a distribution of relaxation time and it results $1/f$ component of noise, observed even without any current stressing. On the other hand, a parallel process also exists which involves long range diffusion resulting an excess $1/f^{1.5}$ dependent component of noise. The diffusion is the process which is associated with actual damage process. This can be supported from the observation that the activation energy of lifetime of the films (as calculated from Fig. 12) matches closely with that associated with long range diffusion resulted noise (calculated from Fig. 11).

The change in noise magnitude during current stressing should be attributed to the both components. So, the total noise magnitude can be written as

$$\frac{\langle(\Delta R)^2\rangle}{\langle R^2\rangle} = \left(\frac{\langle(\Delta R)^2\rangle}{\langle R^2\rangle}\right)_A + \left(\frac{\langle(\Delta R)^2\rangle}{\langle R^2\rangle}\right)_B, \tag{4}$$

where

$$\left(\frac{\langle(\Delta R)^2\rangle}{\langle R^2\rangle}\right)_A = \int_{f_{min}}^{f_{max}} \frac{A}{f} df \tag{5}$$

and

$$\left(\frac{\langle(\Delta R)^2\rangle}{\langle R^2\rangle}\right)_B = \int_{f_{min}}^{f_{max}} \frac{B}{f^{3/2}} df. \tag{6}$$

We interpret the enhancement of relative contribution of $1/f^{3/2}$ component (with weightage B) during damage process as a result of the increase in the number of such defects which take part in long range diffusion. From the experimental results (refer to Fig. 11), we can conclude that the enhancement of total noise magnitude is almost entirely due to the increase in number of mobile defects which moves by long range diffusion.

One interesting observation to be noted here is that for the films stressed at higher temperature, the first component of noise ($1/f$ component) decreases also by some amount after long time of stressing. This observation suggests a decrease of number of localized defects that give rise to the $1/f$ noise. These defects existed in the films before the current stressing but get annealed out. Alternatively, they can be arrested in voids or take part in long range diffusion in later course of time as the damage process progresses. This is a very reproducible observation and shows clearly that such defects as localized two-level defects that give rise to the $1/f$ noise has an anticorrelation with the damage process if any. We note that in the earlier investigations,[7–11] which were carried out *ex situ*, the noise in current stressed film, were explained under the frame work of Dutta-Horn model (which applies to $\sim 1/f$ type of spectral behavior only), even though frequency exponent α was observed to lie in 2–2.5. We would like to point out that a clean distinction between these two types be made.

The temperature dependent study carried out in this experiment shows an interesting observation that strengthens the claim of using the low-frequency spectral component as an early indicator of atomic migration underlying the damage process. In Fig. 13, we plot the ratios t_2/t_1 and t_3/t_2 as a function of stressing temperature. While t_1 is obtained from the noise data, t_2 and t_3 are obtained from the time dependent resistance data and are related to the lifetimes of the film. Interestingly, irrespective of the actual values of t_2 and t_3 which change significantly as a function of stressing temperature, the ratio t_3/t_2 remains more or less constant at $\approx 1.1-1.2$. However, the ratio t_2/t_1 increases significantly as

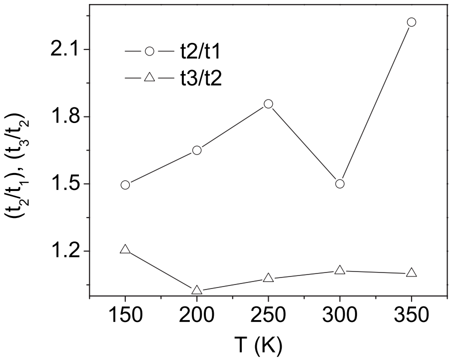

FIG. 13. $\frac{t_3}{t_2}$ and $\frac{t_2}{t_1}$ of the films as function of stressing temperatures.

the stressing temperature increases. Both t_1 and t_2 decrease as the stressing temperature increases; however, the enhancement of the ratio of the two occurs due to the shift of t_1 to smaller values. This signifies that as the films is stressed at higher temperature, the onset of diffusion related noise component occurs at earlier stage of the stressing.

The significance of the onset of the long range diffusion and the role of temperature associated with this process can be connected to the damage mechanism as follows. It is known that when a metal film is subjected to high current, in course of time the average temperature increases and there also develops temperature inhomogeneity over the film which results in development of spatial variation of mechanical stress over it. The mechanical stress field in combination of thermal gradient and electromigration force (due to the high dc current) acts as a net driving force for atomic migration in the film via some energetically favorable defect diffusion pathways. A simulation based on this scenario shows that this can lead to enhancement of resistance as well as eventual damage of the film.[23] The basic underlying process is atomic diffusion which has significant temperature dependence arising from the activated process described by an Arrhenius term. The highest temperature at which we carried out our current stressing experiments is less than one-third of the melting temperature of Ag. At this temperature, the activation energy will be decided by the low activation pathways such as surface, grain boundaries, and the presence of extended defects. In the case of polycrystalline Ag film, defect diffusion over surface has an activation energy very close to 0.1 eV for (111) surface.[26–28] The vacancy migration in grain boundary also has a wide range of activation energy depending on the structure and the mechanical stress inside it. The presence of mechanical stress field inside the grain boundary increases number of defects inside it as well as makes some sites unstable to accommodate defect which results in multiple jumps of migrating atom.[29,30] We observe that much before a significant change occurs in resistivity at an early stage of the damage process, the low-frequency spectral power (the $1/f^{1.5}$ component) starts to rise after time t_1. We interpret this as onset of diffusion through very low activation energy pathways. As the time proceeds, due to the enhanced in mechanical stress and thermal gradient field (both of which will rise as the time progress), more and more defects becomes mobile and diffuses over the film resulting in nucleation of void or hillock (at time t_2). At this point, the resistance of the film also starts increasing significantly. On further stressing, due to growth of voids or hillocks and enhanced defects diffusion, the film got damaged. Throughout the complete damage process, the changing spectral shape of the noise power carries signature of it.

V. CONCLUSION

In this investigation, we have carried out a systematic study of evolution of damage process in metal films stressed by high dc current at different temperatures using *in situ* resistance fluctuation measurement as a tool. We observed that both noise magnitude as well as spectral shape carry signature of the damage process. Besides the increase in the noise magnitude, we could clearly observe an existence of an additional noise component with $1/f^{1.5}$ spectral dependence, arising due to long range diffusion of defects, which are closely involved with the damage mechanism of the film. We could observed also that the lifetime of the films against the damage has a very close connection to this additional noise component.

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