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S. Di Pascoli, G. Iannaccone, *Simulation of electromigration in polycrystalline metal stripes* , Microelectronics and Reliability, **40**, pp.1955-1958 (2000).

PERGAMON

Microelectronics Reliability 40 (2000) 1955–1958

MICROELECTRONICS RELIABILITY

www.elsevier.com/locate/microrel

Simulation of electromigration noise in polycrystalline metal stripes

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Received 11 November 1999; received in revised form 22 March 2000

Abstract

We have performed the Monte Carlo simulation of electromigration noise in polycrystalline metal stripes, based on a two-dimensional model which takes into account both the role of grain boundaries and the effect of current density redistribution in the stripe. The noise spectrum has the characteristic $1/f^{\gamma}$ ($\gamma \approx 2$) behavior, and the total noise power strongly increases with increasing damage of the stripe. The results of the simulation exhibit a substantial qualitative agreement with experiments, giving confidence in the capability of our model of including the relevant physics involved in the failure process. © 2000 Elsevier Science Ltd. All rights reserved.

1. Introduction

Electromigration in polycrystalline metal lines represents a major problem for the technology evolution of the microelectronics industry: as the widths of metal interconnects shrink and current densities increase, failures induced by electromigration can occur in relatively short times and reduce considerably the average circuit lifetime. It is therefore important to understand and control the electromigration process, by means of both experiments and theoretical modeling.

Experimental tests [1,2] have shown that electromigration is associated with an excess noise which has a typical $1/f^{\gamma}$ ($\gamma \approx 2$) spectrum, and a total power increasing with increasing damage of the stripe. For this reason, non-invasive techniques based on noise measurements have been proposed to identify damaged stripes and assess the presence of defects that might be responsible for anticipated failures [1].

In order to gain a better understanding of electromigration noise we have developed a Monte Carlo simulation code which takes into account both the polycrystalline nature of the metal line and the density current redistribution. It is particularly important to take into account the grain structure, as at low temperatures the electromigration in polycrystalline metal lines proceeds mainly by grain boundary diffusion driven by the "electron wind".

While similar models appeared in the literature [3–5] mainly focus on the mean time to failure, we are interested in the noise spectrum, therefore we have to simulate the time-dependent evolution of the resistance with a small time step.

2. Model

The simulations were performed on samples of polycrystalline metal films generated by means of a nucleation and growth algorithm [5] from which rectangular stripes of different dimensions were obtained.

These polycrystalline stripes are discretized into a square lattice of uniformly space nodes, connected with resistors (see Fig. 1).

Every crystal of the polycrystalline film is represented by a convex cluster of connected nodes. The resistors of the network have the same resistance and are divided into two classes: resistors connecting nodes in the same crystal grain ("bulk" resistors) and resistors crossing a grain boundary and connecting nodes from two adjacent grains ("boundary" resistors) which are represented with thin and thick lines in Fig. 1, respectively.

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PII: S0026-2714(00)00054-8

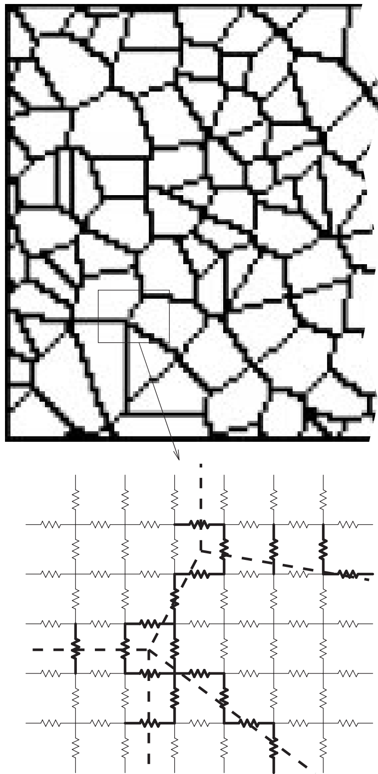

Fig. 1. Grain structure (above) and corresponding resistor network (below). Thick-line resistors are those traversing grain boundaries ("boundary" resistors).

The stripes are then stressed with a constant current stimulus. The flow chart of the simulation procedure is shown in Fig. 2: the main cycle consists of two phases: first, the total resistance of the network and the currents in each resistor are computed by solving the electrical problem with a Jacobi iteration.

In the second phase, all the boundary resistors of the network are sequentially examined: the ith boundary resistor, in which flows a current I_i, has a failure probability given by $A\ \exp(I_i/I_0)$, where A and I_0 are constant during the simulation. Then, each failed resistor is considered and possibly repaired with a fixed probability P_r. As can be seen, in this model failures are activated by current, while the repair is due to atom thermal diffusion and consequently modeled with a constant probability.

At the end of this phase, resistor properties are updated: failed resistors are removed from the network, resistors contacting a failed resistor become "boundary" resistors, repaired resistors are re-inserted in the network as "boundary" resistors.

At this point, as can be seen in Fig. 2, time is increased and the cycle is repeated until the total resistance of the network becomes greater than a certain value.

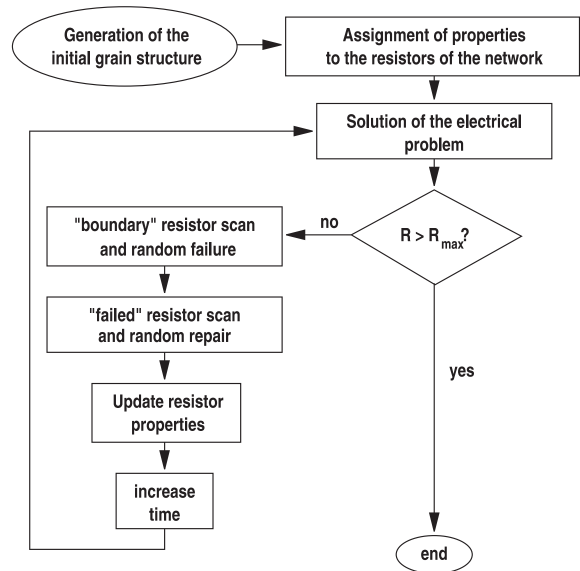

Fig. 2. Flow-chart of the simulation program.

As can be seen, the procedure described above forces damage to evolve along grain boundaries. It also introduces the positive feedback that leads to the observed abrupt failure of the stripe: as a small region of the stripe is damaged, resistors close to that region experience a current increase which exponentially raises their failure probability so that the damaged region typically grows at an accelerated rate until complete failure of the stripe.

Although in an electromigration test the temperature of the stripe can be quite higher than that of the substrate and of the environment, the temperature gradient in the stripe itself is very small and consequently we have not included in the model the temperature dependence of failure probability. The value of the parameter A is chosen in such a way that on an average there is less than one failure per simulation cycle.

3. Results

All the simulations have been carried out with $I_{AV}/I_0 = 2$, where I_{AV} is the average current per longitudinal resistor and corresponds to the ratio of the stimulus current to the stripe width. The output of the simulation program provides the time evolution of the resistance $R(t)$ along with the number of failed resistors per simulation cycle. As the resistance $R(t)$, on an average, increases linearly with time and we are interested only in the spectrum of fluctuations, we calculate $R_N(t)$ by subtracting from $R(t)$ the least square fitting line, and then calculate the power spectral density $S_{RN}(f)$ of R_N. Fig. 3 shows the spectra obtained from three different types of stripes with different widths: (a) is represented

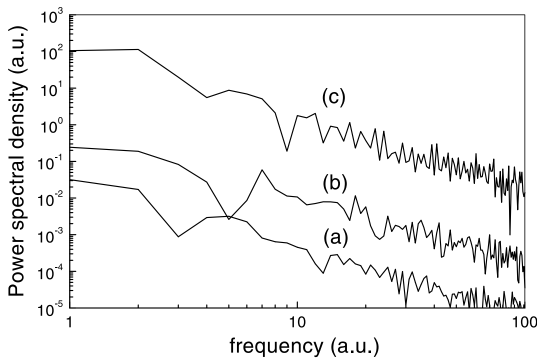

Fig. 3. Resistance noise spectra for stripes (a), (b), and (c) as described in the text.

by a network of 90×200 nodes, (b) by a network of 30×200, (c) by a network of 10×200 nodes. For all the three samples, the grain average area was set to 100 nodes, corresponding to an equivalent diameter of 11 nodes. The resistance noise spectra are averaged from three different Monte Carlo runs. The γ exponents obtained from a least square linear fit on the logarithmic scale are 2.13, 2.09 and 2.22 for stripe geometries (a), (b), and (c), respectively.

As expected, the total noise power is roughly proportional to the inverse cube of the stripe width: the product $P_N W^3$, where P_N is the noise power and W the stripe width, is equal 0.66, 0.25 and 1.16 for a width of 10, 30 and 90 nodes, respectively.

Fig. 4 shows the evolution of the total resistance until the complete failure for three Monte Carlo runs of a stripe of geometry (b). As can be seen all the three runs start with a very similar linear increase in which a total variation of about 3% of the resistance is observed. This regular and reproducible behavior is followed by a steeper and more irregular increase which leads to the complete failure and exhibits large differences from a run to another. This pattern can be frequently observed in experiments [1,2], where a regular increase of just a few percent is followed by an unpredictable catastrophic failure.

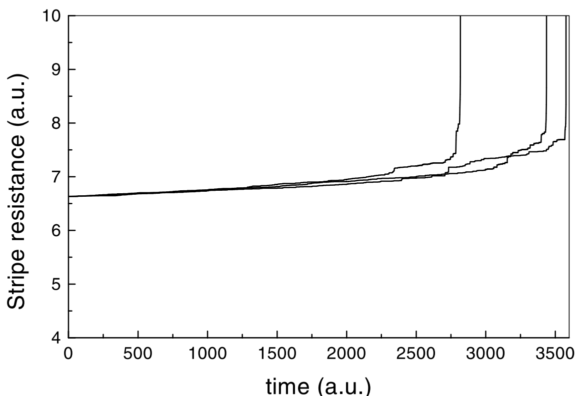

Fig. 4. Stripe resistance as a function of time until complete failure for three different Monte Carlo simulations on sample (b).

To better investigate the effects of increasing damage of the stripes on electromigration noise, a time-dependent analysis of γ and of the noise power has been carried out. At time t, the mean noise power and the γ exponent are extracted from a portion of $R(t)$ in the time interval $(t,\ t + \Delta t)$. In this case, the least square fitting line of $R(t)$ is computed for each considered time interval and subtracted from $R(t)$ before the spectrum S_{RN} is computed. As we are also interested in the behavior up to the complete failure, the calculation has been performed on a single simulation run (in particular the one shown in Fig. 4 associated with the smallest failure time).

As can be seen in Fig. 5, the exponent γ shows random fluctuations around 2 during the linear increase phase of the evolution of $R(t)$, while approaches the value of 2.3 near the complete failure. On the other hand, the noise power exhibits a small average increase with time even in the initial phase, while in the final phase, the increasing rate accelerates and leads to a noise power roughly three orders of magnitude larger than the initial one. As the calculation has been performed on a single simulation run, the behavior of γ and of P_N is very irregular, but qualitatively similar to what has been observed in experiments [6].

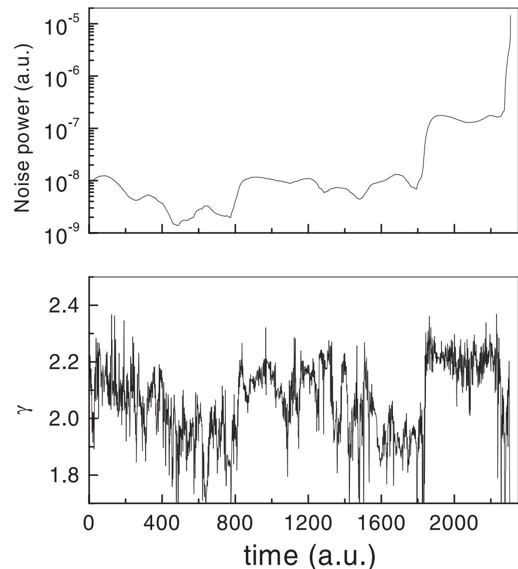

Fig. 5. Noise power (above) and γ (below) as a function of time for the Monte Carlo run of Fig. 4 associated to the smallest failure time.

4. Discussion

A very simple model can be used to derive the $1/f^2$ behavior of the spectrum. Let us consider the function $y(t) = \mathrm{d}R(t)/\mathrm{d}t$: it can be written as a series of delta functions

$$y(t) = \sum_i \Delta R_i \, \delta(t - t_i), \tag{1}$$

where t_i is the instant at which the ith event (failure or repair) occurs, and ΔR_i is the corresponding change in the total resistance. If the individual events are independent, $y(t)$ is the result of a poissonian process with probability per unit time λ [7], therefore the average of $y(t)$ is $\langle y \rangle = \lambda \langle \Delta R \rangle$ and its noise spectral density is

$$S_y(\omega) = 2\lambda \langle \Delta R^2 \rangle. \tag{2}$$

As $R_\mathrm{N}(t)$ is the time integral of the AC part of $y(t)$, its noise spectral density $S_\mathrm{RN}(f)$ is

$$S_\mathrm{RN}(\omega) = \frac{S_y(\omega)}{\omega^2} = \frac{2\lambda \langle \Delta R^2 \rangle}{\omega^2}, \tag{3}$$

i.e., exhibits the $1/f^2$ behavior.

If there is some weak positive correlation between successive failures, the spectrum of $y(t)$ should be somewhat enhanced with respect to that of Eq. (2), the failure process being super-poissonian. However, $S_y(\omega)$ would still be independent from frequency and therefore S_RN would still have a exponent γ equal to 2. The case of strong positive correlation, which is likely to occur near the complete failure, is different and needs deeper investigation.

In conclusion, the simulation model proposed allows to recover many of the characteristic features of the electromigration process and, in particular, of electromigration noise known from experiments [1,2]. This makes us confident in the fact that the model reproduces the relevant physics involved in the phenomenon. Simulations on statistically meaningful samples are required in order to extract information that can be compared with the large amount of experimental data available.

Acknowledgements

This work has been supported by the Italian National Research Council through the project MADESS II.

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