Simulation of failure time distributions of metal lines under electromigration

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Simulation of failure time distributions of metal lines under electromigration

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Abstract

Monte Carlo simulation of polycrystalline metal stripes under electromigration stress have been performed in order to obtain statistic information on failure modes. Several factors which can influence the phenomenon have been investigated, including stress current magnitude, line width and grain size. The resulting statistics exhibited a good agreement with the experimental data available in the literature, both on aluminum and more recent copper damascene lines.

1. Introduction

Electromigration damage still represents the major reliability concern of integrated-circuit interconnect lines. In recent times, the development of the new copper damascene technology, based on new and different methods of deposition, triggered a new series of theoretical and experimental studies of this phenomenon[1,2]. All these studies restated the primary role played by the polycrystalline structure of the interconnection lines, and especially showed the strong relationship between the grain size distribution and the reliability performances of the stripes.
Indeed, it is a well known fact that grain boundary electromigration has a lower activation energy than bulk electromigration and hence grain boundaries are a preferred way for electromigration-induced atom flux and a preferred location for void nucleation. Although the basics of electromigration are known, the reliability problems connected to it exhibit an extreme variability and the lifespans of similar interconnection lines stressed by the same current can differ by more than an order of magnitude. These differences can be ascribed to the random evolution of the current distribution inside the sample when the damage develops, which usually leads to current crowding and positive feedback effects.

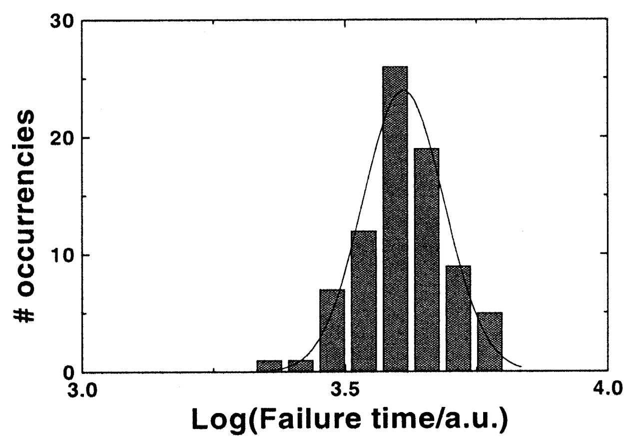

Fig. 1 Failure time distribution (for 80 runs, $I=2I_0$)

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To investigate the statistics of the interconnect line failures we have developed a Monte Carlo simulation code which takes into account both the polycrystalline nature of the metal line and the current crowding effects.

2. Monte Carlo simulator

The simulator consists of two tools: the random structure generator and the electromigration damage simulator. The random structure generator provides rectangular random resistor networks which model two-dimensional polycrystalline stripes[3].

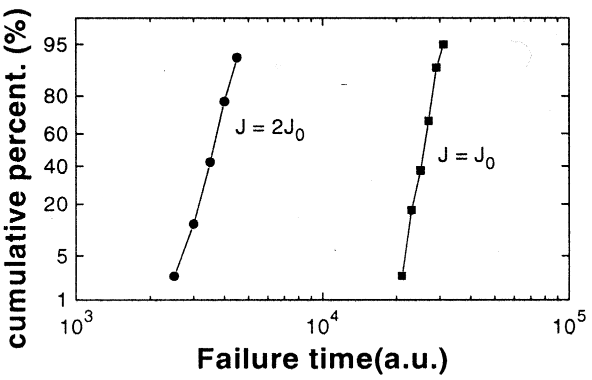

Fig. 2 Failure time cumulative distributions for two current density levels

The structure generator is able to generate rectangular stripe models of different length and width, and permits to dictate the total number of crystals grains, and thus to select the grain size of the stripe (since the grains are generic convex polygons, the grain size is defined as the diameter of the circle of the same area).

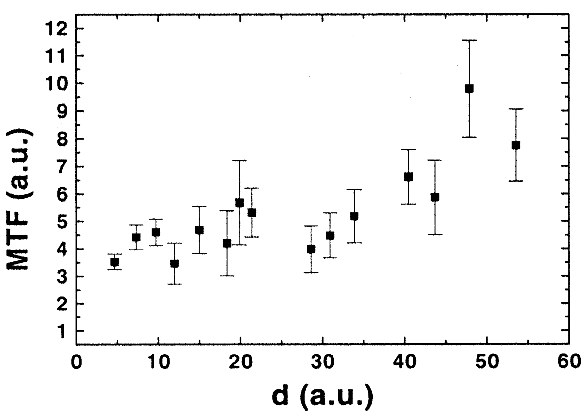

Fig. 3 MTF as a function of grain size. Error bars show DTTF

These resistor networks are then used by the damage simulator which calculates the time evolution of the damage induced by a user-selected constant current and provides the total electrical resistance of the stripe[4].

The electromigration damage is simulated by assuming that only the resistors which correspond to grain boundaries can be damaged (i.e. open circuited) by the current flow, and that the probability P_f of failure of each resistor is given by

$$P_f = A \exp(I / I_0)$$

where I is the current flowing in the resistor and A and I_0 are constant parameters of the simulation. As the damage develops, also resistors next to damaged ones are in turn subject to damage. In this way a void can be nucleated at grain boundaries and then build up.

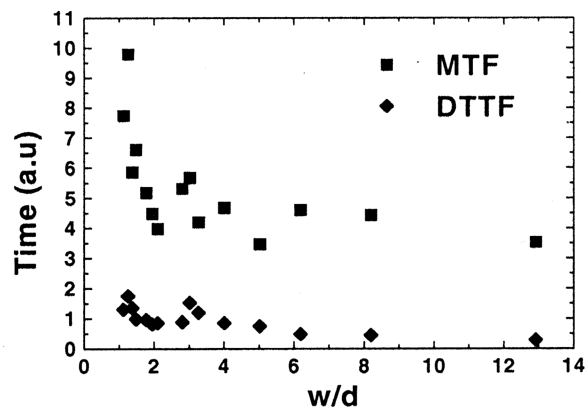

Fig. 4 MTF and DTTF as function of width to grain size ratio

Moreover, the interrupted resistors on void borders are subsequently considered and possibly repaired with a fixed probability P_r. Consequently, failures are activated by local current stress, while repair is due to atom thermal diffusion and consequently modeled with a constant probability as the stripe is almost isothermal[3].

The damage starts along grain boundaries and leads to a current increase in the neighborhood. This introduces a positive feedback which exponentially increases the resistor failure rate. The damaged region typically grows at an accelerated rate until complete failure of the stripe.

The simulator output provides, for every simulation step, the total stripe resistance and the number of failed and repaired resistors. We consider a tripe broken down only after a 20% resistance increase, as is typically assumed in experiments[1].

3. Results and discussion

The first set of 80 simulations was performed with a fixed current stimulus ($I=2I_0$) in a single stripe. Fig. 1 shows that the results are consistent with the commonly observed lognormal distribution of failure times[1,5].

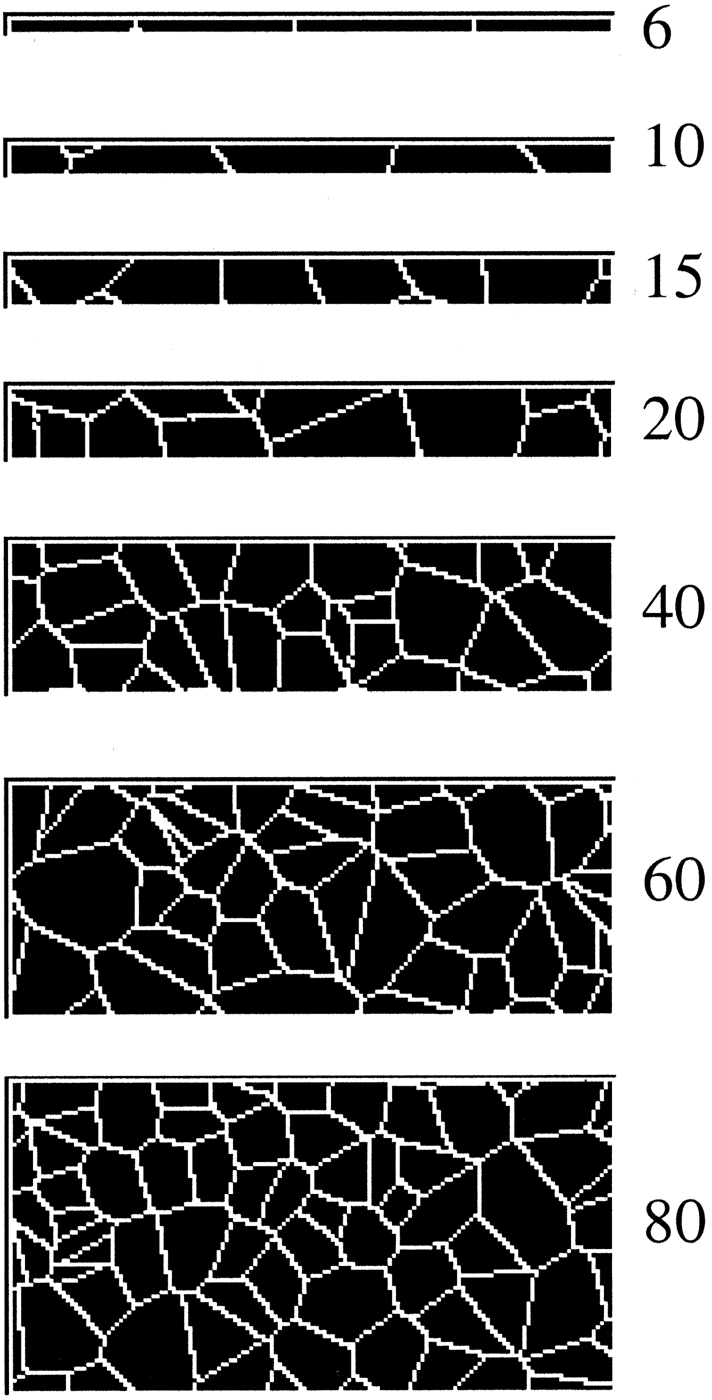

Fig. 5 Layout of stripes with different width and constant grain size

Currents, failure times and geometric dimensions are expressed in arbitrary units: indeed, we are interested in reproducing the functional dependence of failure time distributions upon geometry observed in experiments. Hard numbers depend on the material properties, and are beyond the scope of the present work. Fig. 2 shows the change of cumulative failure probability for different current levels, which is in very good agreement with experimental data obtained for copper damascene stripes[1].

Another set of experiments has been performed to obtain the behavior of the Mean Time to Failure (MTF) and the Distribution of Time To Failure (DTTF) as a function of grain size. Fifteen stripes, with the same width (60 resistors) and length (150 resistors) but with a number of grains ranging from 4 to 531 has been generated. Each of them underwent 10 simulation runs with the same current stress. The results are plotted, as a function of grain size, in Fig. 3. Unfortunately, as far as we know, experimental dependencies of MTF and DTTF on grain size are not available, as the control of deposition grain size is not a trivial task. However, [6] reports MTF and DTTF data as a function of the ratio of line width to grain diameter (*w/d*).

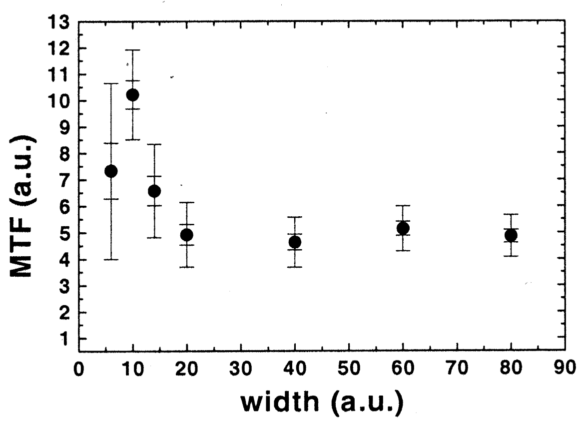

Fig. 6 MTF as a function of stripe width (Error bars show DTTF)

The simulated results, replotted as a function of *w/d*, are shown in Fig. 4, which exhibits a substantial agreement with the cited experimental data.

Another set of simulations has been performed at different line widths, with constant grain size and current. Seven stripe widths (from 6 to 80 resistors, displayed in Fig. 5) were used, obtaining the results of Fig. 6. Corresponding experimental results, in very good agreement, are reported in [1] for damascene copper lines.

4. Conclusions

In conclusion, our proposed Monte Carlo code captures the physics of the electromigration process in polycrystalline metal stripes, and provides distributions of failure times in good agreement with available experiments.

Furthermore, is suggests that the observed complexity of the failure behavior of metal interconnections could be ascribed to the developing of a basic phenomenon - the electromigration - with the constraints imposed by the polycrystalline geometry of the samples.

Another interesting conclusion that can be drawn is that the most valuable information can be extracted from the complete failure statistics (i.e. failure distribution) more than from single performance parameters (like MTF). This is true both from a theoretical point of view in a research environment, in which the comprehension of the physics is emphasized, and from a practical point of view where the accent is posed on the assessment of interconnection performances.

For that reason, experimental studies of line connection reliability and failure statistics would be quite useful, especially if oriented to the exploration of the effects of deposition methods variation which influence the size and distribution of grain size and other geometric aspects of the interconnections.

Acknowledgements

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