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A Percolative Approach to Reliability of Thin Film Interconnects and Ultra-thin Dielectrics

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Degradation of thin film interconnects and ultra-thin dielectrics is studied within a stochastic approach based on a percolation technique. The thin film is modelled as a two-dimensional random resistor network at a given temperature and its degradation is characterized by a breaking probability of the single resistor. A recovery of the damage is also allowed so that a steady-state condition can be achieved. The main features of experiments are reproduced. This approach provides a unified description of degradation and failure processes in terms of physical parameters.

Keywords: Percolation; Failure; Healing; Electromigration; Dielectric breakdown

INTRODUCTION

Failure of metallic interconnects and dielectric degradation is a mandatory issue for reliability of electronic devices. Indeed, relevant research efforts exist on this subject concerning both the experimental characterization [1, 2], and the development of theoretical models [3]. The aim of this paper is to present a theoretical study of the degradation towards failure of metallic and/or insulating thin films. To this purpose we make use of a stochastic approach based on a biased percolation model recently developed [4].

MODEL AND RESULTS

We describe a thin film as a two-dimensional square-lattice network of resistors of resistance r_n, laying on an insulating substrate at temperature T_0 acting as a thermal reservoir. Initially all resistors are identical $r_n = r_0$. We take a square geometry $N \times N$ where N determines the linear sizes of the lattice and $N_{\mathrm{tot}} = 2N^2$ is the total number of resistors. Electrical contacts are realized by perfectly conducting bars at the left and right hand sides of the network. According to the choice of the operating conditions, the case of constant current I or constant voltage V is considered.

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The total network resistance R is related to the resistances r_n and to the currents i_n in each branch of the network by the relation:

$$R = \sum_{n=1}^{N_{\rm tot}} r_n \left(\frac{i_n}{I} \right)^2 \qquad (1)$$

We investigate two kinds of degradation processes associated with an increase or a decrease of the film resistance, respectively. In the former case, the degradation is attributed to the generation of open-circuit-like defects (local regions of very high resistivity) and therefore it corresponds to a conductor-insulator (CI) transition typical of metal interconnect degradations associated with electromigration phenomena [1]. In the latter case, the degradation is related to the presence of short-circuit-like defects (local regions of very low resistivity) and it corresponds to an insulator-conductor (IC) transition typical of the dielectric breakdown [3, 5, 6]. We assume that each elemental resistor can depend linearly on the local temperature according to: $r_n(T_n) = r_0[1 + \alpha\,(T_n - T_0)]$ where α is the temperature coefficient of resistance (TCR) and T_n is the actual temperature of the nth resistor. The thermal interaction among first neighbour resistors is accounted for by taking:

$$T_n = T_0 + A \left[r_n i_n^2 + \frac{B}{N_{\rm neig}} \sum_{m=1}^{N_{\rm neig}} (r_{m,n} i_{m,n}^2 - r_n i_n^2) \right], \qquad (2)$$

where $N_{\rm neig}$ is the number of first neighbours around the nth resistor and $B = 3/4$ provides a uniform heating of both horizontal and vertical resistors in the perfect network configuration. The parameter A, measured in (K/W), describes the heat coupling of each resistor to the substrate. The probability W_D (W_R) of creating (recovering) a defect at the nth resistor is taken as:

$$W_{D,(R)} = \exp(-E_{D,(R)}/k_B T_n) \qquad (3)$$

where E_D (E_R) is an activation energy characteristic of the defect creation (recovery) and k_B the Boltzmann constant.

Monte Carlo simulations are carried out using the following procedure. (i) Starting from the perfect lattice, we calculate the total network resistance and the local currents by solving Kirchhoff's loop equations by the Gauss elimination method. The local temperatures are then calculated and used for the successive update of the network. (ii) The defects are generated with probability W_D while the resistances of undefected resistors change accordingly to their TCR. The local currents and the local temperatures are then recalculated. (iii) The defects are recovered with probability W_R, and the total network resistance, the local currents, and the temperatures are finally calculated. This procedure is iterated from (ii) where each iteration step can be considered to be an elementary time step to be calibrated on an appropriate time scale. The iteration will proceed until the following two possibilities are achieved. In the first, the defect percolation threshold is reached; in the numerical calculations we stop the iteration when the resistance for CI (IC) type degradation increases (decreases) over (under) a factor of 10^3 (10^{-3}) with respect to the initial value. In the second, steady-state conditions are reached, and correlation and fluctuation analysis can be carried out.

The results of numerical simulations are summarized here in terms of the following two main features: damage pattern and resistance evolution. We validate the present approach by checking if it reproduces most of the features which are observed in experiments and is in agreement with the statistical properties typical of reliability analysis. To make computational times affordable, simulations are performed on networks with linear sizes determined by $N \simeq 10^2$. The square network is then taken to represent the dominant section of degradation of the film. For interconnects and dielectrics, constant current and constant voltage conditions are assumed, respectively. Current and voltages are then taken as the physical stresses which drive the film degradation. If not stated otherwise, for the simulations we used the following values for the parameters, where we report in parenthesis the values for dielectrics when they differ from those used for interconnects, $N = 75$, $r_0 = 1\Omega$ ($r_0 = 10^7\Omega$), $\alpha = 10^{-3}\mathrm{K}^{-1}$ ($\alpha = 0$), $B = 3/4$, $T_0 = 300\,\mathrm{K}$, $A = 5 \times 10^5\,\mathrm{K/W}$, $E_D = 0.17$ (0.19) eV, $E_R = 0.043$ (0.13) eV.

In order to evaluate the ability of our approach in reproducing the experimental damage patterns, we report in Figures 1 and 2 two typical damage patterns for the two cases considered in this paper, metallic interconnects and dielectric thin films. In Figure 1 we plot a network undergoing a CI transition which simulates the degrading region of a metal interconnect at a moment close to failure. Here the pattern shows several voides consisting of broken resistors (resistors with very high resistance). The voids exhibit the tendency to a transverse filamentation, *i.e.*, to clusterize along filaments perpendicular to the current flow. This filamentation of the damage pattern, characteristic of the biased percolation model, becomes more pronounced at increasing stress current values and it evolves into a multi-channel filamentation for high stress currents. Moreover, as a consequence of the generation and growth of voids, the current distribution becomes strongly non-homogeneous and high current densities are flowing in few resistors which act as bottlenecks for the current flow. Non-homogeneous heating effects, characterized by the presence of hot spots, because of the nonzero TCR implies the increase of the local resistor value shown in Figure 1 by different grey levels. In Figure 2 we plot the damage pattern in an IC type network at a few iteration steps before failure. Note that here the individual resistor values are taken to be temperature independent. The failure is caused by a longitudinal path of short-circuit-like defects (black resistors in Fig. 2), *i.e.*, the low-resistivity channel causing failure grows parallel to the applied electric field.

FIGURE 1 Damage pattern of a conductor-insulator degradation with the film close to failure under a constant current of 1 A. The substrate temperature is 300 K. The missing resistors are the broken ones and are associated with the voids. The different grey levels correspond to increasing resistance values due to Joule heating.

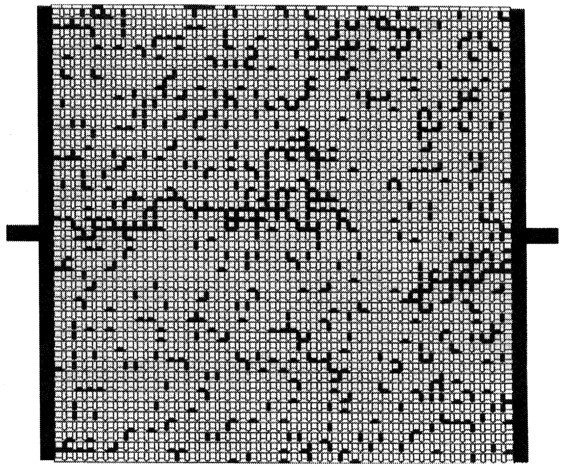

FIGURE 2 Damage pattern of an insulator-conductor degradation with the film close to breakdown for a network under a constant voltage of $V = 1.0$ V. The substrate temperature is 300 K. Fat segments indicate the short-circuit-like defects in the film.

The different kinds of filamentations in Figures 1 and 2 reproduce well the general features observed in experiments, where transversal voids perpendicular to the stressing current are typical damage patterns of electromigration in interconnects and longitudinal fused paths are present in the breakdown by leakage current in ultrathin dielectrics, respectively. We note that the filamentation pattern is enforced by the presence of nearest neighbour interaction while it tends to be suppressed by recovery effects. The most often used experimental way to obtain information on the level of degradation is to monitor a physical quantity which controls the degradation. In a CI transition this quantity is typically the resistance while in a degrading ultrathin insulator it is the leakage current (here we do not consider dielectric degradation through charge accumulation typical of thick film oxides).

Figure 3 reports the relative resistance evolutions for small, moderate and large stress currents in a network subjected to a CI type degradation as suggested by experiments. We suppose here that the length of the dominant region of degradation is 10^{-3} times the length of the film. Therefore, the relative resistance variations of the whole film are obtained by multiplying the relative resistance variations of the network by the same factor. The simulations show that for low currents a steady-state value of the resistance is reached. We note that the steady-state is achieved because of a balance between the two competing processes of defect generation and defect recovery. The steady-state simulates an experimental condition where damage can not be measured from the resistance evolution directly but only from indirect measurements such as excess resistance noise. When moderate stress currents are applied we can distinguish 3 phases in the resistance evolution. The initial phase, phase 1, shows a short growth in resistance which is followed by a long phase 2 featuring a slow steady growth of resistance accompanied by small resistance fluctuations. The evolution is terminated in phase 3 with violent bursts in resistance thus large resistance fluctuations due to healing events. The presence of bursts in the resistance evolution is thus a fingerprint of healing as typically observed in experiments [7]. We note that healing becomes more intense just before the breakdown. For large currents a sharp transition to failure is observed where healing effects become negligible; of course the failure occurs earlier than for moderate currents. The behaviours reported in Figure 3 are typical of degradation and failure due to electromigration of metallic interconnects where the degradation of a thin metal line is observed in accelerated aging experiments [1].

Figure 4 shows the leakage current evolutions for several values of the stress voltage, in a network undergoing an IC type degradation (here for the sake of convenience the direct resistance evolution was converted into current evolution by Ohm's law). The general behaviour of the current evolution parallels that of the resistance in Figure 3 with the voltage substituting the current as physical stress. An interesting pre-breakdown region is reproduced by the simulation in agreement with experimental evidences [3].

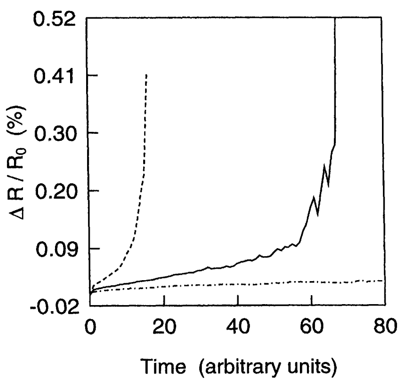

FIGURE 3 Relative resistance evolutions in a conductor-insulator type degradation for different values of the stress current I = 0.8, 1.0, 1.2 A. The higher is the applied current the steeper is the increase of the resistance.

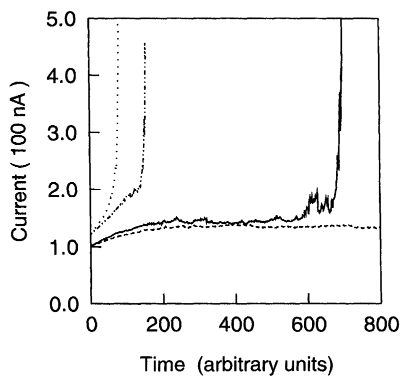

FIGURE 4 Evolutions of the leakage currents in an insulator-conductor type degradation for different values of the stress voltage V = 0.8, 1.0, 1.2, 1.4 V. The higher is the applied voltage the steeper is the increase of the current.

CONCLUSIONS

We have developed a percolative approach for the study of reliability of thin films made of metallic interconnects and/or dielectric insulators. In particular we found: (i) Filamentary damage patterns for both IC and CI degradations. (ii) The resistance evolutions show different behaviours depending on the importance of recovery effects. Accordingly, stationary conditions or failure can be obtained. In the latter case the presence of recovery manifests itself in resistance fluctuations which evolve into violent bursts just before the complete failure (pre-breakdown region in dielectrics and phase 3 in interconnects). (iii) We finally recall that our approach reproduces most of the main experimental features observed in the degradation of these films like the phenomenological Black's law together with the statistical properties of the time-to-failure distribution. The flexibility of the approach offers interesting possibilities of further improving the modelling by including compositional and structural effects which are often present in the early stages of thin film degradation [8].

Acknowledgements

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