EARLY RESISTANCE CHANGE AND STRESS/ELECTROMIGRATION EVOLUTION IN NEAR-BAMBOO INTERCONNECTS

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SUMMARY

A complete description for early resistance change and mechanical stress evolution in near-bamboo interconnects, related to the electromigration, is given in this paper. The proposed model, for the first time, combines the stress/vacancy concentration evolution with the early resistance change of the Al line with a near-bamboo microstructure, which has been proven [1] to be a fast technique for prediction of the MTF of a line compared to the conventional (accelerated) stress.

1. INTRODUCTION

A serious reliability concern in the last decade for IC manufacturers is electromigration, defined as mass transport resulting from the momentum transfer between the conducting electrons and lattice atoms. The measurement of small resistance changes in the early stages of electromigration has gained considerable interest in the last few years, a reasonable amount of data being available [2,3]. The contradictory behaviour of increase of resistance with time made very difficult to capture all effects in one model. The present paper extends and improves the existed models [4,5,6,7] correlating the mechanical stress/vacancy concentration with early resistance changes of the Al lines.

2. MODEL DESCRIPTION

It is generally assumed that there is a linear relation between a change in vacancy concentration and small resistance changes due to

electromigration. In our model electromigration is related with mechanical stressmigration that opposes to the electromigration flow. Consider a near-bamboo interconnect line, (the line consists of a successive alternation of polycrystalline regions and single crystal regions) at places where a flux divergence occurs. A depletion of atoms at the cathode end of a polycrystalline region (usually called cluster) and a mass accumulation at the anode end will give rise to a mechanical stress σ . Where a large tensile stress develops a void can be initiated to grow (nucleate) and a hillock can cause cracking of the passivation layer at places where compressive stresses are built up. In a real metallization line, grain boundaries and line imperfections such as dislocations provide suitable diffusion paths for atoms. The flux of atoms is modelled, using an opposite but equal flux of vacancies J_v , supposing that atoms diffuse via a

vacancy (c_v is the vacancy concentration) mechanism:

$$J_v = -D_v \nabla c_v + \frac{D_v c_v}{kT} Z_v^* e E \quad (1)$$

The diffusivity D_v of vacancies is

$$D_v = D_0 \exp\left(\frac{-E_a}{kT}\right) \quad (2)$$

where the activation energy E_a has different values in bulk and at grain boundaries. The conservation law for vacancies

$$\frac{\partial c_v}{\partial t} + \nabla J_v = G \quad (3)$$

introduces a sink/source term G that allows for the creation or annihilation of vacancies at sites as grain boundaries, dislocation lines, surfaces. The number of vacancies in a crystal at equilibrium is given by

$$c_{ve} = c_o \exp\left(\frac{\sigma \Omega}{kT}\right) \quad (4)$$

where Ω is the atomic volume. The creation/annihilation of vacancies at places as dislocation lines or grain boundaries, (which can be described in terms of a distribution of dislocations /8/), cause the dislocation to climb upwards (when vacancies are annihilated) or downwards (when vacancies are created). The climbing motion of an edge dislocation either inserts or removes a vertical plane of atoms in the metal lattice, changing the crystal volume. The change of the crystal volume due to the creation/annihilation of vacancies causes the built up of mechanical stresses (we are supposing that vacancies are not created or annihilated at the metal surface, the metal line is considered encapsulated in a strong dielectric). The change in the vacancy concentration from the equilibrium value can be related to the mechanical stress through Hooke's law:

$$\frac{\partial \sigma}{\partial t} = B \Omega \frac{c_v - c_{ve}}{\tau_s} \quad (5)$$

The resistivity of the line is also, related to the change in the vacancy concentration:

$$\rho = \rho_o [1 + \xi (c_v - c_o)] \quad (6)$$

where

$$\xi = \frac{1}{N_a - c_v} \quad (7)$$

and N_a is the atomic concentration.

3. SIMULATION RESULTS

Simulation results show the relative resistance change (fig. 1), the time evolution of mechanical stress (fig. 2) and vacancy distribution (fig. 3) for an Al line with a microstructure configuration, as indicated in the insert. The Al line is stressed for 590 hours with a current density of 1 MA/cm² at 200°C. The stress distribution (fig. 4) across the simulated lines proves the role of a 2D simulator tool for a complete characterisation of the metal line compared to 1D model /9/. If we define the time to failure of a line as the time required to reach a critical, or failure, stress a critical stress of 600 MPa will cause relatively rapid failure of the line having the microstructure as indicated in the insert in fig. 1. If critical stress is 800 MPa the line will last significantly longer. The simulated structure takes into account also the cluster interaction /9/. The effect of cluster length (L) and the distance between two clusters (d) are important factors on the behaviour of the stress distribution. Simulations have been performed on a very simple structure: two clusters parallel to the current stress, separated by a bamboo region (as indicated in the insert in fig. 5), in order to show the degree to which clusters interact and the results of this interaction. The lines have been stressed 180 hours

with a current density of 1 MA/cm^2 at 200°C . In fig. 5 the relative resistance change for two $20\text{ }\mu\text{m}$ clusters length but with different distances in between is shown. The relative resistance change of clusters which interact is significantly larger than for isolated one's. In fig. 6 the time evolution of mechanical stress for the above mentioned structures has been showed, the maximum value of the stress that has been obtained is for the clusters that interact. The differences in the behaviour of the relative resistance change and mechanical stress distribution can be explained taking into account clusters interaction. For a distance $d=2*L$ the simulation results show that the clusters act independently as isolated clusters as it is shown in fig. 7 and fig. 9. For a distance $d=L/2$ the stress

profiles of the two clusters can overlap and reinforce each other, as shown in fig. 8 and fig. 10. The discontinuity in the slope of the linear increase of the resistance in time can be correlated to different regimes in stress evolution. We can distinguish in cluster interactions: an initial, non interactive regime (fig. 8) and at longer times, the interaction regime (fig. 10), when the stress profiles of the clusters overlap.

4.CONCLUSIONS

The erratic behaviour of resistance change can be seen in measurement and it can be correlated to different regimes in cluster interaction. Cluster interaction plays a large role in determining line reliability.

Fig. 1: Relative resistance change in time

Fig. 2: The time evolution of mechanical stress

Fig. 3: The vacancy distribution [in cm^{-3}] at $t=590\text{h}$

Fig. 4: The mechanical stress distribution [Pa] at $t=590\text{h}$

Fig. 5: Relative resistance change in time

Fig. 6: Time evolution of mechanical stress

Fig. 7: Mechanical stress distribution [in Pa] at $t=2$ hours for two isolated clusters

Fig. 8: Mechanical stress distribution [in Pa] at $t=2$ hours for cluster interaction

Fig. 9: Mechanical stress distribution [in Pa] at $t=180$ hours for two isolated clusters

Fig. 10: Mechanical stress distribution [in Pa] at $t=180$ hours for cluster interaction

5. REFERENCES

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