NUMERICAL SIMULATION OF STRESSMIGRATION IN INTERCONNECTS WITH AIR-GAP STRUCTURES

E. S. Magro[1] and R. L. de Orio[1]
[1] School of Electrical and Computer Engineering (FEEC) – University of Campinas (UNICAMP)
e-mail: estevão.strini@gmail.com

1. Abstract

This paper presents a study of the impact of air-gaps on the stress development and stressmigration in Cu interconnect structures. We highlight the study for structures that incorporate the so-called air-gaps, a recent technological proposition that aims at reducing the effective dielectric constant associated with interconnections, and compare it to the results of a standard structure with low-k material.

2. Introduction

One of the major reliability problems for integrated circuits is the stressmigration (SM) [1]. During the fabrication process, the lines are subjected several cycles from a high temperature to room temperature. Large thermal mechanical stresses can develop during these successive cycles due to differences in the coefficient of thermal expansion (CTE) of the component materials. The region of the line that develops the greatest magnitude of mechanical traction is the most likely to occur the formation of voids [2]. Once a void is formed, the vacancy flow guided by SM causes the void to grow. This can cause a significant increase in the interconnect resistance, which can be considered as a fault.

In order to further reduce the dielectric constant associated to the interconnections, the so-called air-gaps (AG) structures, as shown in Fig. 1, should be introduced in the next technological nodes. These structures have empty regions that surround the metal lines. Thus, they are expected to have a significant impact on the distribution of mechanical stress and SM.

Thus, the objective of this work is to investigate the mechanical stress development and the SM behavior in copper interconnect structures with and without the air-gap technology. This is carried out by means of modeling and 3D numerical simulations.

3. Methodology

Fig. 2 shows the geometry of interconnects with the introduction of the air-gaps around the lower metal line. Here, three cases will be studied as a function of the air-gap volume around the line. In Fig. 2(b) the entire side volume is occupied by the air gap, whereas in Fig. 2(c) and (d) the air gap fills 75% and 50% of the volume, respectively. The dielectric material is SiCOH. The numerical simulations were carried out using the Comsol Multiphysics program [3].

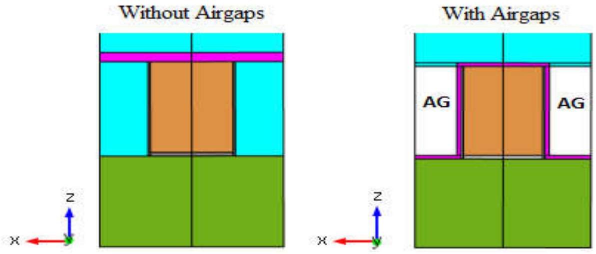

Fig. 1. *Sectional view of the structures. (a) Standard structure (without air-gaps). (b) Structure with air-gaps around the metal line. Blue-SiCOH, brown-Cu, green-silicon (Si), pink-silicon nitride layer (Si3N4), grey- barrier layer (Ta).*

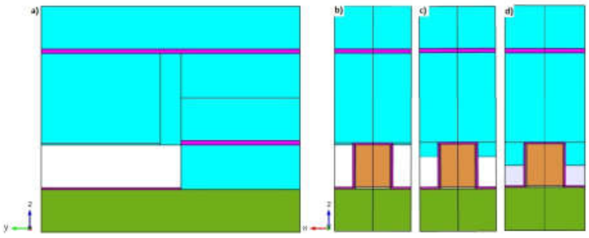

Fig. 2. *Interconnect structure with air-gaps. (a) Side view of the air-gap in the structure, occupying the entire length of the line. (b) Front view - air-gap occupies the entire lateral volume to the line. (c) Air-gap occupies 75% of original size. (d) Air-gap occupies 50% of the volume.*

There are two forces driving the vacancy transport in a metal line: 1) the diffusion of vacancies and 2) a hydrostatic stress gradient, i. e. the SM. Thus, the total transport of vacancies is modeled by a flux given by [4]

$$\vec{J_v} = -D_v\left(\nabla C_v + \frac{f\Omega}{kT} C_v \nabla\sigma\right), \tag{1}$$

where D_v is the diffusion coefficient of the vacancies, C_v is the vacancy concentration, $f\Omega$ is the vacancy volume, σ is the hydrostatic stress, k is the Boltzmann constant and T is the temperature. The variation of the vacancy concentration with time is given by

$$\frac{\partial C_v}{\partial t} = -\nabla \cdot \vec{J_v}. \tag{2}$$

This equation shows that in regions where the vacancy influx is larger than the outgoing one, the accumulation of vacancies occurs, therefore, increasing its concentration. Likewise, for a larger outgoing flux of vacancies than the influx, there is a reduction of the vacancy concentration. The regions of vacancy accumulation are those subject to formation and growth of voids that lead to the failure of the interconnection.

4. Results

Fig. 3 shows the mechanical stress generated by the manufacturing process considering a temperature variation of 400 ºC to the room temperature. At first, the introduction of the air-gap would open space for a relaxation of the structure and thus reduction of the magnitude of the stress. However, in Fig. 3 we observe that the tensile stress was higher than in the case without air-gap. A possible explanation for this is that in the air-gap structure the Cu line is surrounded by the Si_3N_4 layer, which has a large modulus of elasticity and a large difference of CTE with respect to Cu. Therefore, the studied air-gap interconnection structures do not reduce the magnitude of mechanical stress in the metal.

The concentration of vacancies follows the stress distribution, as shown in Fig. 4. From the point of view of SM, the air-gap structures behave quite similar to those typical with SiCOH. This can be seen from the graphs of the temporal variation of stress and the concentration of vacancies of Fig. 5 and 6, respectively.

In Fig. 3 and 4, the values of the 4 points mentioned above and their changes during the 24 hours are shown. As we can see, at points p1 and p2, for the structures with air-gaps, the stress was a little higher, consequently the concentration of vacancies as well. Therefore, the results indicate that the introduction of air-gap technology does not affect the reliability of metallization from the point of view of stressmigration.

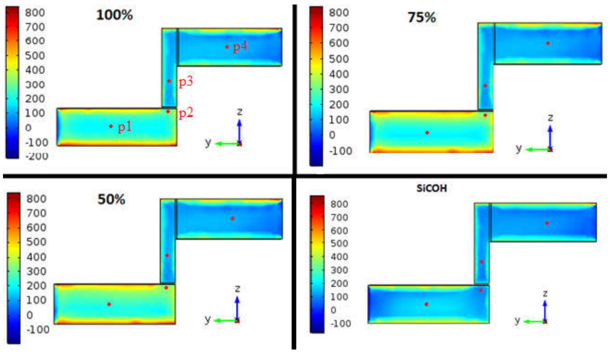

Fig. 3. *Distribution of the thermal tension in the interconnection of copper with air-gaps technology (t=0s).*

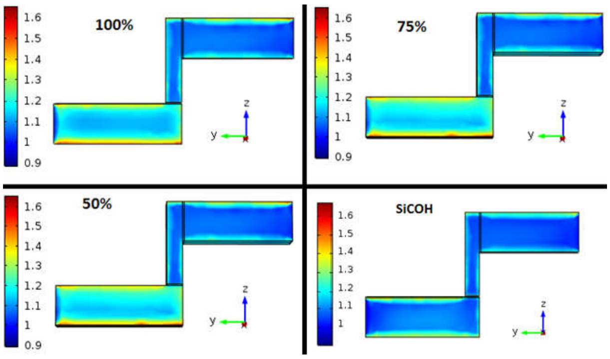

Fig. 4. *Distribution of the vacancy concentration at t=0s, corresponding to the thermal stress of Fig. 5.*

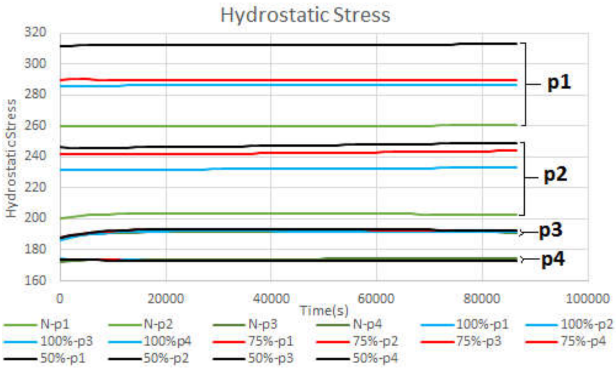

Fig. 5. *Concentration of stress within the copper structure at points p1, p2, p3 and p4.*

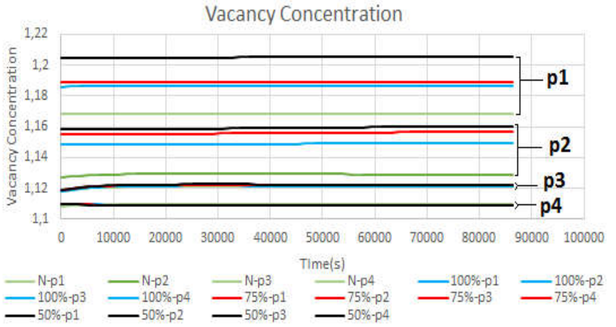

Fig. 6. *Concentration of vacancies within the copper structure at points p1, p2, p3 and p4 as a function of time.*

5. Conclusions

A SM model was implemented in a simulation tool and 3D simulations were performed. Our focus is the study of structures with air-gaps, a very current research topic from the point of view of BEOL technology. Our results indicate that the introduction of these structures does not significantly affect the problem of SM.

Acknowledgments

The authors would like to thank the Brazilian agency CAPES for the financial support.

References

[1] Webb, G. K. (1994). Integrated circuit (IC) pricing. The Journal of High Technology Management Research, 5(2).

[2] PAIK, Jong-min; PARK, Hyun; JOO, Young-chang. Effect of low-k dielectric on stress and stress-induced damage in cu interconnects . Microelectronic engineering, p. 348-357, 2004.

[3] COMSOL Multiphysics® v. 5.2. www.comsol.com. COMSOL AB, Estocolm, Sweden.

[4] M. A. Korhonen, S. Rzepka, R. G. Filippi, and C. -Y. Li, in Stress Induced Phenomena in Metallization, Third International Workshop, edited by Ho et al. (American Institute of Physics, New York, 1998), p. 303.