3-D Physically-Based Electromigration Simulation in Copper - Low-K Interconnect

Valeriy Sukharev, Ratan Choudhury, and Chong W. Park

LSI Logic Corporation, Advanced Development
1501 McCarthy Blvd.
Milpitas, CA 95035 USA
vsukhare@lsil.com

Abstract

We have developed a novel physical model and a simulation algorithm capable of predicting electromigration (EM) induced void nucleation and growth in an arbitrary interconnect segment. Incorporation of all important atom migration causes into the mass balance equation and its coupled solution with the corresponding electromagnetics, heat transfer and elasticity problems has provided a capability for the EM design rules generation/optimization with the physically based simulations. Simulations have been done on the realistic interconnect structures. Simulation results have been found to fit well to available experimental data regarding the location of void nucleation sites and growth kinetics.

Introduction

Implementation of copper and low-K materials as major components of interconnect structures has resulted in the necessity to create new physical and electrical current design rules to ensure chip immunity to EM-induced failures. Implementation of reliability simulations at the design rules generation step can help avoid unnecessary conservative approach, which reduces possible chip performance. To be able to reach this target a comprehensive simulation model of metal migration-induced failure should be employed. In the general case detailed 3-D modeling should be applied. This is especially true for copper metallization characterized by a complicated geometry of the dual damascene (DD) interconnect segments and by much lower critical stress for void nucleation than aluminum. In this study we have developed and solved a transient, fully linked EM model.

Model

The developed model targets void nucleation and its growth kinetics as a function of the segment geometry, interconnect architecture and electrical loading. We took into consideration all important atom migration causes: electron induced momentum transfer, time-dependent stress gradient, thermal diffusion, and concentration gradient [1,2]. Implementation of a vacancy based diffusion mechanism has provided us with the capability to accurately implement stress dependent atom diffusivity, which is different in different regions of the interconnect segment (Fig. 1). Coupling of the electromagnetics, heat transfer, structural mechanics and atom migration models,

based on a direct solution of a system of partial differential equations using the finite element method, has allowed us to simulate stress-induced void nucleation and

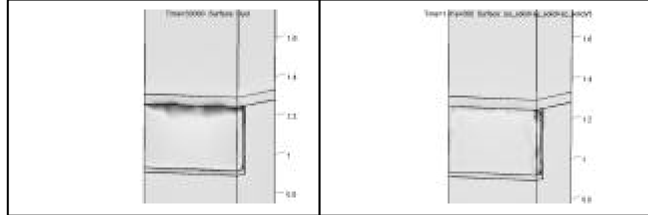

Fig.1. Evolution in the hydrostatic stress in Cu line caused by the atom migration.

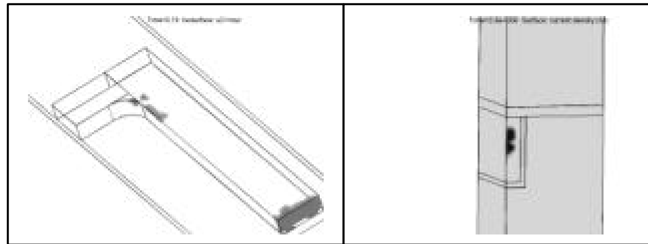

Fig. 2. Void distribution in the meander segment and Cu line (cathode edge).

growth in different interconnect segments (Fig. 2).

A governing equation, which describes the atom density evolution caused by an applied current, is the traditional mass balance (continuity) equation, which relates the rate of local atom density change with the divergence of the total atomic flux at this location, which is a combination of the fluxes caused by all above mentioned forces: namely by the electric current, and by the gradients of temperature, mechanical stress and concentration [3]. To obtain the kinetics of the atom density evolution in an arbitrary interconnect segment, stressed by the electric current, the mass balance equation should be solved in the coupled manner with the corresponding electromagnetics, heat transfer, and structural mechanics problems. The complete system of equations for all-important variables is formed by Laplace's, Fourier's, Navier's and mass balance equations. The solution of this system of equations describes the evolution of all variables of interest for the initial time interval, while voids have not nucleated. Void nucleation should modify the kinetics of all these variables. For the sake of model simplification we have introduced the threshold vacancy concentration, above which a void should be nucleated. In other words, all parts of the conductor characterized by the vacancy density higher than N_c will be occupied by the extending void. This condition occurs through relations between atomic concentration, hydrostatic stress and the vacancy concentration. Indeed, if the atom density inside some part of the metal segment is reduced by EM, then a tensile stress is developed in this area. The stress intensity depends on how rigid the confinement is. The generated tensile stress results in an exponential growth of the vacancy concentration. This vacancy concentration growth should increase the rate of reaction of coagulation of vacancies, leading to void nucleation.

Results and Discussion

The developed model was applied for the simulation of a material edge displacement in the Blech short strip test structure of electromigration. Fig. 3 shows simulated void growth taking place when all atom migration causes are taken into consideration. This picture fits well the experimental data, which demonstrate that voids initially nucleate at the upper left corner and, propagating to the right and down, deplete the cathode completely [4].

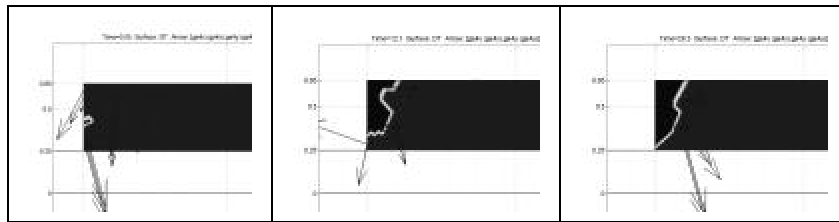

Fig. 3. Simulated void growth in the Blech structure.

The complicated geometry of the interconnect segments created by the DD copper technology demands implementation of the fully linked model for the simulation of EM-induced failure. The presence of a “weak” interface between Cu and an etch stop layer such as silicon nitride or silicon carbide should also be taken into account. Considering these interfaces as major channels for atom migration we assumed that dilation, associated with the Cu atoms deposition on these interfaces, is a primary cause for the hydrostatic stress development (in addition to the originally developed hydrostatic stress by the cooling a sample down from the highest process temperature). Implementation of this model into our simulation scheme provides the following picture for void evolution in the case of DD via segment (Fig. 4). It can be seen that void is nucleated initially, in accordance

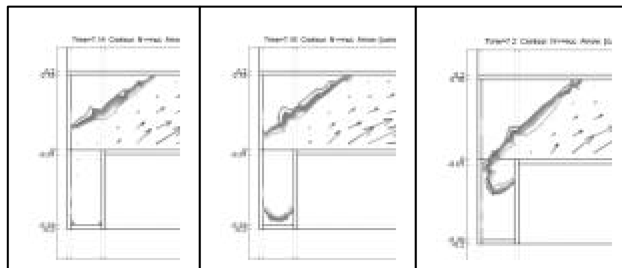

Fig. 4. Void evolution in the DD Cu via segment. Arrows show the electrical current direction and relative value.

with the available experimental data [2,5], at the top left corner of the segment and grows along the Cu line and down toward the via. New void is nucleated much later at via bottom and grows upward through via bulk. Later, these two voids coalesce, forming one big void, which depletes this via completely and extends further toward the anode end of the line. It should be noted that a continuous void extension takes

place even when via was depleted. This is possible if the current can pass through the conductive tantalum liners. Simulation results demonstrate that the character of void evolution strongly depends on the liner conductivity. If this conductivity is very low, then the void nucleates first at via bottom. The lower the liner conductivity the faster void nucleation happens. Simulation shows that the bottom void, which was nucleated very quickly upon applying an electrical load , was reduced and finally disappeared with the duration of time. Concentration gradient induced atomic flux has resulted in this void recovery. Such type of void evolution is possible when liners are characterized by small but non-zero conductivity. In the opposite case, the void evolution will stop when it occupies all via bottom interface, undercutting the current inlet. In the case of high conductive liners voids do not nucleate at via bottom at all. Increase in copper resistivity, taking place with the depletion in the Cu concentration, that we have incorporated in our model through the vacancy-induced scattering, results in redirection of the electrical current through the via liners. This reduction in the electrical current density passing through via bottom prevents void nucleation. These results can explain a nature of experimentally observed the early and long-term failures, taking place in the via-containing interconnect segments.

Fig. 5 is an example demonstrating a fit between the simulation results and available experimental data.

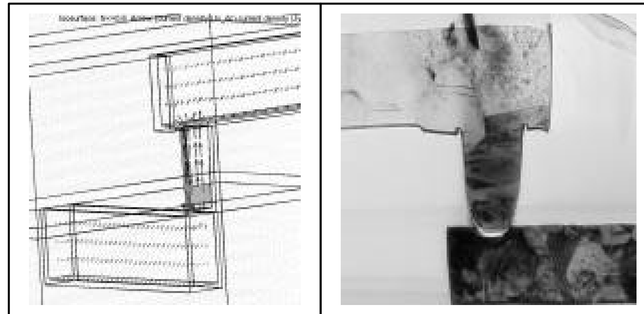

Fig. 5. Void in the DD structure with the upward electron flow.

Conclusion

We have developed a novel physical model and a simulation algorithm capable of predicting electromigration induced void nucleation and growth in an arbitrary interconnect segment. The model capability for optimization of physical and electrical design rules is stressed. Varying the feature geometry, segment architecture and material properties users are in a position to generate interconnect with high immunity to EM-induced failures.

References

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