The Modeling of Electromigration
A New Challenge for TCAD ?

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Abstract

It is argued that the modeling of electromigration at the microscopic level results into systems of equations which can be very well addressed by state-of-the-art TCAD methods.

1. Introduction

The problem of electromigration has been around in microelectronics from the early sixties, but so far a complete physical understanding is still lacking. Electromigration is the drift of atoms under the influence of strong electron winds. With the advent of the miniaturized integrated circuits, the current densities in the metal stripes on a chips can attain huge values (MA/cm^2). The usual way to obtain reliable circuits is to avoid such large current densities, by making stripe of sufficiently large widths. Unfortunately, the ever decreasing device sizes may ultimately prevent one from maintaining the design rules where a mininal stripe width is always present. In other words, the devices may become so small that the wires and vias are simply too crude for being attached to a single device terminal. Defects due to electromigration may show up in actual circuits after long operation times. In order to obtain predictions for product life times within the time-to-market constraints, accelerated tests are performed. However, in order to relate the outcomes of these tests to actual field performance, a good understanding of electromigration is a necessity. In this paper, we will argue that TCAD tools can contribute considerably to a better understanding of electromigration.

2. A TCAD model for electromigration

First of all it should be noted that electromigration can be modeled at several levels of sophistication. At the atomic level one may study the detailed interaction between vacancies, atoms and electrons [1]. A much cruder level of modeling, captures a large collection of experimental (statistical) data into semi-emperical relations. A famous example of the last type is Black's equation [2], which relates the median failure time to the current density according

$$t_{\frac{1}{2}} = \frac{A}{j^n}\exp(B/kT) \tag{1}$$

Explaining the inverse square dependence of the current density has been a major challenge for theorists. A few successful models were presented by Shatzkes and Lloyd [3], Korhonen [4] and Kirchheim [5]. In these models, vacancies were put forward as the key ingredient to explain the observed behaviour. The modeling is based on the idea that vacancies (like holes in an electron sea) are physical entities which obey balance laws possibly being modified with sources and sinks. As such they are subjected to the usual rules of statistical physics, i.e. vacancies can diffuse and drift.

A model which merely refers to vacancy behaviour is incomplete. The role of stress is not included, whereas it is known that stress plays an important role in the failure of metal stripes. Furthermore, vacancies are no stable objects. They annihilate at boundaries and make the volume of the grain smaller, they interact with dislocations, where vacancies may be created or annihilated. The models of electromigration which are of particular interest for submission to TCAD methods, are between the atomic modeling and the semi-emperical modeling, i.e. vacancy fluxes and stress migration is described in a set of coupled partial differential equations expressing the underlying balances of matter and force fields. For the vacancy fluxes, we have the following balance equation

$$\frac{\partial C}{\partial t} + \vec{\nabla}.\vec{J_v} = G \tag{2}$$

where $\vec{J_v}$ is the vacancy flux corresponding to the relative vacancy concentration and G is a source/sink describing the annihilation and creation of vacancies. The vacancy current is composed of a drift current and a diffusion

$$\vec{J_v} = -D_v\vec{\nabla}C - \mu Z^{*}eC\vec{E} \tag{3}$$

The Einstein relation $\mu = D_v/k_BT$ is assumed to be valid. The electric field, $\vec{E}$, is straightforwardly related to the electric current by Ohm's law, $\vec{j} = \sigma\vec{E}$ and σ is (here) the conductivity. The source and sink of vacancies are treated in a relaxation approximation, i.e. $G = -\left[C - C_{eq}\right]/\tau_c$, where the equilibrium vacancy concentration is related to the local hydrostatic stress

$$C_{eq} = C_0\exp\left(\frac{\Omega\sigma(\vec{x},t)}{k_BT}\right) \tag{4}$$

The time constant τ_c is much smaller (microseconds) than the time it takes for stripe failure (hours) to occur. Therefore, one may assume in general that $C = C_{eq}$, and the balance equation may be converted to an equation for the local stress. It should be noted that the limit $\tau_c \to 0$, should be taken with great care, since the stress and the concentration of lattice sites are related according to Hooke's law. The approximated modeling of electromigration suitable for the implementation into TCAD systems then becomes

$$\left[1 + \left(\frac{k_BT}{\beta\Omega^2}\right)\frac{1}{C_V}\right]\frac{\partial C_V}{\partial t} + \vec{\nabla}.\vec{J_V} = 0 \tag{5}$$

$$\vec{J_V} = -D_v\,\vec{\nabla}C_V - \left(\frac{D_v}{k_BT}\right)eZ^{*}\,C_V\,\vec{E}$$

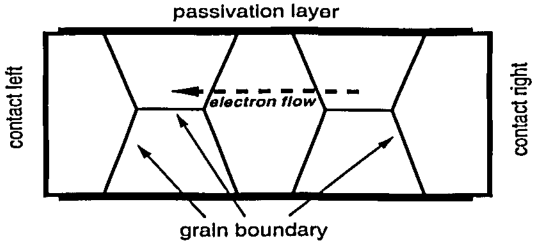

Figure 1: Selected grain structure.

Herein, β is Young's modules, Ω the atomic volume, Z^* the effective valence, which can be positive or negative, and D_v the vacancy diffusivity, which varies over orders of magnitude when passing from the grain bulk to the grain boundary. This model was evaluated in *one* dimension in [6].

3. Example

We have constructed a simulator for above equation in *two* dimensions, using the discretization techniques which are familiar for transient device simulators. In Fig. 1, a two-dimensional segment of a metal stripe is shown with grain boundaries. In Fig. 2, the stress distribution is shown after 1400 hours of stressing with a current of 10^6 A/cm^2. The stress distribution can be straightforwardly translated to the the distribution of the change in the resistivity and the latter one is correlated to the mean time to failure. Alternatively, one can record the time for reaching a critical stress and indentify this time interval with the time to failure. In Fig. 3, the relative change in resistance is shown for two single cluster lines with length of 16 μm and 75 μm. For the short line the simulations show a saturation of the resistance (stress) evolution, i.e. the stress difference between the stripe ends, being 785 MPa, balances the wind force. At this stage, we may identify the current as the critical current (10^6 A/cm^2) and the length, l, as the critical length (16 μm). From the Blech [7] product $(jl)_c = \Delta\sigma\Omega/(\rho Z^* e)$, we find $\Delta\sigma$ is 757 MPa. This value is in agreement with the result obtained by simulation.

4. Conclusion

We have demonstrated that TCAD method can be applied to the analysis of an electromigration phenomenon.

References

[1] H.B. Huntington and A.R. Grone, *J. Phys. Chem. Solids* vol. 20, pp. 76, 1961.

[2] J.R. Black, *Proc. 6th Ann. Reliab. Phys. Symp.* pp. 148, 1967.

[3] M. Shatzkes and J.R. Lloyd, *J. Appl. Phys.* vol. 59, pp. 3890, 1986.

[4] M.A. Korhonen, P. Borgesen, K.N. Tu and C.-Y. Li, *J. Appl. Phys.* vol. 73, pp. 3790, 1993.

[5] R. Kirchheim, *Acta Mettall. Mater.* vol. 40, pp. 309, 1992.
ibid. Mat. Res. Soc. Symp. Proc. vol.309, pp. 101, 1993.

[6] J.J. Clement and C.V. Thompson, *J. Appl. Phys.* vol. 78, pp. 900, 1995.

[7] I.A. Blech, *J. Appl. Phys.* vol. 4, pp. 1203, 1976.

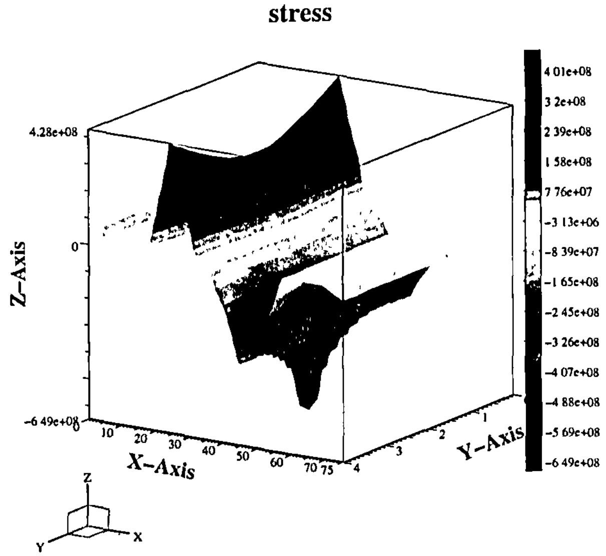

Figure 2: Stress distribution after 1400 hours.

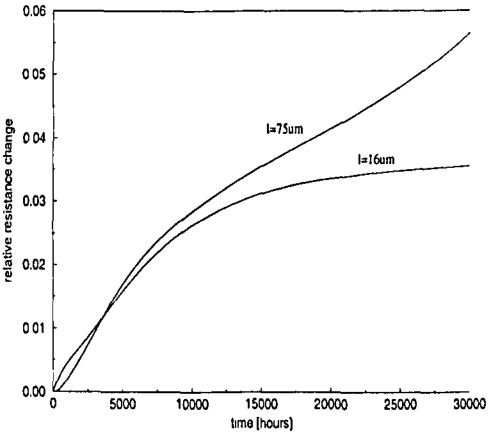

Figure 3: Relative resistance change for a short and long line.