

# The Evolution of the Resistance and Current Density During Electromigration

H. Ceric<sup>◦</sup>, R. Sabelka<sup>◦</sup>, S. Holzer\*, W. Wessner<sup>◦</sup>,  
S. Wagner\*, T. Grasser\*, S. Selberherr<sup>◦</sup>

\* Christian Doppler Laboratory for TCAD in Microelectronics  
at the Institute for Microelectronics

<sup>◦</sup> Institute for Microelectronics, TU Vienna  
Gußhausstraße 27–29, A-1040 Wien, Austria  
Email: Ceric@iue.tuwien.ac.at

## Abstract

We investigate the behavior of the resistance of a three-dimensional via during the evolution of an intrinsic void. The presented method is eligible for both copper and aluminum interconnects. An analysis of the mean current density over the void surface is also carried out.

## 1 Introduction

Electromigration is the main reliability issue in IC designs, which can trigger a system failure at some undefined future time [1]. The phenomenon is particularly likely to afflict thin, tightly spaced interconnect lines of deep-submicron designs. Electromigration is an atomic transport process which results from momentum transfer to the constituent metal atoms due to collisions with the current conduction electrons. As atoms electromigrate, there is a depletion of material “upstream” and an accumulation “downstream” at sites of flux divergence. This can lead to the formation and growth of voids at points of material depletion, causing a large increase in electrical resistance. On the other hand, accumulation of material may cause dielectric cracking and the formation of an extrusion, resulting in a short circuit between adjacent lines. The development of intrinsic voids, which leads to interconnect failure goes through two distinctive phases. These phases exhibit not only different influence on the operating ability of the interconnect but are also based on different physics. The first phase is the void nucleating phase. In this phase no electromigration generated voids are present and there is no significant resistance change. The second phase begins when a void is nucleated and visible in SEM pictures [2]. This is the rapid phase of the failure development. The void expands from its initial position (nucleation site) to a size which can significantly change the resistance or completely sever the connection.

## 2 Modelling Approach

An initial void with some small radius  $r_0$  is placed on some characteristic position inside the interconnect (Figure 1). Since most of the fatal voids are nucleated in the vicinity or in the area of interconnect vias we consider in particular these cases. The configurable

initial void volume is  $V_0$  which is smaller than  $4\pi r_0^3/3$  because the void area is confined by sphere and boundary of the interconnect (Figure 1). Starting from the initial void radius  $r_0$ , the void radius is gradually incremented  $r_0, r_1 = r_0 + \Delta r_1, r_2 = r_1 + \Delta r_2, \dots$ , with  $\Delta r_1 \geq \Delta r_2 \geq \dots \geq \Delta r_n$ . For each void radius the electrical field in the interconnect structure is calculated by means of the finite element method using a diffuse interface approach. To obtain the distribution of the electrical potential inside the interconnects the Poisson equation has to be solved

$$\nabla \cdot (\sigma_{Cu}(\phi)\nabla\varphi) = 0. \quad (1)$$

To imply correct boundary behavior of the electrical field on the spherical void surface a diffuse interface approach has been applied [3]. In this approach the electrical field in the metal and the void is calculated on the same mesh. The electrical conductivity depends on the scalar field  $\phi(x, y, z)$

$$\rho(\phi) = \frac{\sigma_{Cu}[1 + \phi(x, y, z, t)]}{2}. \quad (2)$$

In order to obtain sufficient accuracy the scalar field  $\phi(x, y, z, t)$  must be resolved on a locally refined mesh (Figure 2). For an electrical field calculated in such a way, the resistance of the interconnect via is also calculated [4, 5]. With growing void size the resistance increases. The whole process is stopped when a void radius is reached for which  $100 \times (R_{actual}/R_{initial} - 1) > 20\%$ .

## 2.1 Average Current Density Calculation

The primary driving force of material transport at the void surface is electromigration proportional to the tangent component of the vector current density. Since the diffuse interface approach for the calculation of the current density ensures physical behavior of the electrical field in the vicinity of the isolating void, the normal component of the current density on the void surface is always zero and we can apply the formula

$$J_{m,i} = 2 \frac{\int_V \|\mathbf{J}\| [1 - \phi_i^2(x, y, z)] dV}{\int_V [1 - \phi_i^2(x, y, z)] dV}, \quad (3)$$

for the average current density over a void with radius  $r_i$ . (3) expresses the averaging of the current density weighted with finite element volume inside the interconnect. Since  $\phi_i(x, y, z) = 1$  in metal and  $\phi_i(x, y, z) = -1$  in the void area, the term  $1 - \phi_i^2(x, y, z)$  is non-zero only in void-metal interface area.

## 2.2 Velocity of the Evolving Void Surface

The evolution of the void is caused by material transport on the void surface and in the vicinity of the void surface. The mass conservation law gives the mean propagation velocity  $v_i$  of the evolving void-metal interface

$$v_i = \frac{D_v}{kT\sigma} eZ^* J_{m,i}, \quad (4)$$

here  $D_v$  is the vacancy diffusivity and  $Z^*$  effective charge number of vacancies. The (4) is valid for all void shapes.

### 3 Simulation Results and Discussion

As we can see from Figure 4, the average current density on the void surface increases with the void size. Both, current density and resistance, exhibit a very similar dynamic behavior. The dynamical resistance increase is in accordance with the measurement results presented in [1]. Compared with the earlier result [6], which assumes cubical void shapes, our approach enables more realistic simulations.

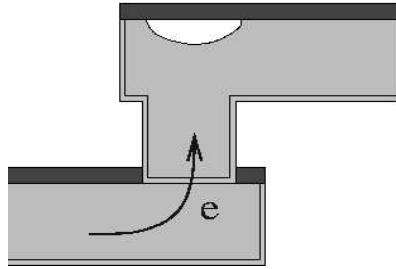


Figure 1: Position of the growing void. Initial position and volume are chosen on the basis of experimental results [7].

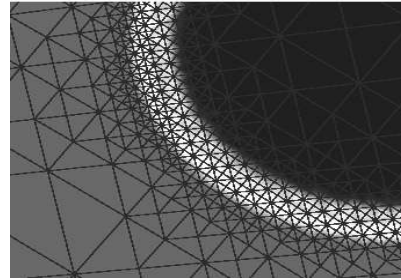


Figure 2: Detail of the used locally refined mesh.  $\phi = 1$  in the grey area and  $\phi = -1$  in the black area.

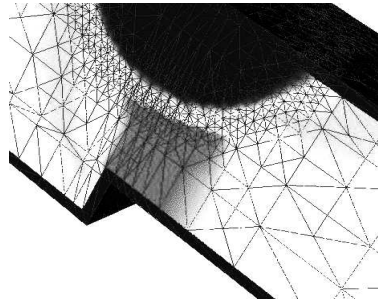


Figure 3: Typical current density distribution picture in the vicinity of the spherical void. The grey area marks peak values of the current density.

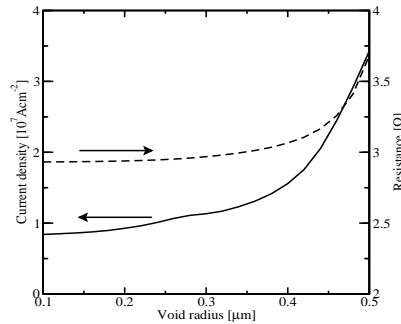


Figure 4: Change of the average current density and via resistance depending on the void radius.

An open question is how to use the obtained average current density (Figure 4) for the estimation of the void growing time ( $t_E$ ) up to the critical void size. In [6] a simple formula is applied

$$t_E = \frac{V_c - V_0}{v_m A_s}. \quad (5)$$

In this equation  $V_c$  is the critical void size,  $V_0$  is the initial void size,  $A_s$  is the cross section of the interconnect in the vicinity of the growing void, and  $v_m$  is the mean

velocity of the evolving void-metal interface. However, this formula is only valid in the case of the cubical void which is a very rough approximation of the real situation. According to the newer experimental results [7] the real void shape is significantly better approximated by a spherical sector. In this case  $t_E$  can be estimated as

$$t_E = \sum_i \frac{\Delta r_{i+1}}{v_i}, \quad (6)$$

assuming that for sufficiently small  $\Delta r_{i+1}$ , the void radius grows from  $r_i$  to  $r_{i+1}$  with a constant velocity  $v_i$ .

As we can see from (4), the velocity  $v_i$  depends on vacancy diffusivity  $D_v$  which itself has significantly varying values depending on the diffusion path. The electromigration assisted self-diffusion of copper is a complex process which includes simultaneous diffusion through the crystal bulk, along grain boundaries, along the copper/barrier interfaces, and along the copper/cap-layer interface. Therefore, the diffusivity applied in (4) must be a cumulative value as used in [2]

$$D_v = D_b + D_{gb} \left( \frac{\delta_{gb}}{d} \right) + D_{Cu/b} q_{Cu/b} + D_{Cu/N} q_{Cu/N}. \quad (7)$$

$D_b$ ,  $D_{gb}$ ,  $D_{Cu/b}$ , and  $D_{Cu/N}$ , represent the diffusivity through the bulk, along the grain boundaries, copper/barrier interfaces, and copper/caplayer interfaces, respectively.  $\delta_{gb}$  is the width of the grain boundary and  $d$  the average length of a grain boundary. Coefficients  $q_{Cu/b}$  and  $q_{Cu/N}$  depend only on the layout geometry. For the feasible estimation of  $t_E$ , reliable, experimentally determined values for all relevant diffusivities are needed and this is until now not the case [2, 7].

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