Compact Model for Solder Bump Electromigration Failure

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Abstract

The mechanical and electrical properties of solder bumps influence the overall reliability of 3D ICs. In this paper we present a compact model for prediction of the mean-time-to-failure of solder bumps under the influence of electromigration.

INTRODUCTION

In the last decade some attempts have been made to investigate whether Black's equation can be used for the prediction of the mean-time-to-failure of solder bumps. For these investigations the standard form of Black's equation has been used [1]. While some authors have obtained a reasonable prediction of the experimental mean-time-to-failure [2], others were forced to adapt the original equation in order to obtain a good agreement [3]. Both, the original work of Black [1] as well as the model of Shatzkes and Lloyd [4], which provides an explanation for Black's equation and its current density exponent, are considering only the one-dimensional problem of a straight aluminum strip. Besides the fact that they do not consider 3D geometries of modern interconnect structures, they also do not take into account the mechanical stress and its interaction with electromigration (EM), grain boundaries, and interfaces. These restrictions make the application of Black's equation for studying solder bump EM failures highly questionable.

ANALYTICAL SOLUTION OF KORHONEN

The model by Korhonen *et al.* [5] has already been successfully utilized for a derivation of EM compact models [6]. Compared to the above mentioned models [1, 4], Korhonen's model has a clear advantage, since it includes an influence of the microstructure and an effect of the mechanical stress. The central equation of Korhonen's model is

$$\frac{\partial\sigma}{\partial t} = \frac{\partial}{\partial x}\Big(\frac{D_a B\Omega}{kT}\Big(\frac{\partial\sigma}{\partial x} + \frac{|Z^*|e\rho j}{\Omega}\Big)\Big). \tag{1}$$

For a finite interconnect line of a length L with blocking boundary conditions on both ends of the line

$$J_v(0,t) = J_v(-L,0) = 0, \tag{2}$$

and for a constant diffusion coefficient D_a, the solution of (1) is given by

$$\sigma(x,t) = \frac{|Z^*|e\rho jL}{\Omega}\Big(\frac{1}{2} - \frac{x}{L} - S(x,t)\Big), \tag{3}$$

where

$$S(x,t) = 4\sum_{n=0}^{\infty}\frac{1}{\lambda_n^2}\exp\Big(-\lambda_n^2\frac{\kappa t}{L^2}\Big)\cos\Big(\lambda_n\frac{x}{L}\Big) \tag{4}$$

with $\lambda_n = (2n+1)\pi$ and $\kappa = D_a B\Omega/kT$. The function $S(x,t)$ has two important properties. First, for a large t it converges to zero, which enables to obtain the equilibrium stress distribution from (3)

$$\sigma(x,t) = \frac{|Z^*|e\rho j}{\Omega}\Big(\frac{1}{2} - \frac{x}{L}\Big) \tag{5}$$

and secondly, for sufficiently large L and $x = 0$, it behaves like a simple function of time

$$S(0,t) \approx \frac{1}{2} - \frac{2}{L}\sqrt{\frac{\kappa t}{\pi}}. \tag{6}$$

By combining (3) and (6) we obtain an expression for the stress development at the end ($x = 0$) of a one-dimensional interconnect line

$$\sigma(x,t) = 2\frac{|Z^*|e\rho j\pi}{\Omega}\sqrt{\frac{\kappa t}{\pi}}. \tag{7}$$

Equation (7) is a convenient reference for an initial guess in designing of a compact model because of two reasons:

- It analytically describes a stress behavior in time. Reaching of certain stress threshold is a usual condition for EM void nucleation [7].
- It implicitly considers large size interconnects.

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Modeling of Vacancy Electromigration

Vacancy EM has been well investigated and successfully modeled by different authors starting with the work of Sarychev *et al.* [8]. Today we have comprehensive and sophisticated EM models which include the gradients of the vacancy concentration, mechanical stress, and temperature as driving forces with tensorial diffusivity for modeling the material anisotropy. One such model, systematically presented in [9], is applied here for the development of a compact model of EM failure in solder bumps.

Simulations have been carried out for three solder bumps with the same geometric features but different diameters of $2R = 50\mu$m, 70μm, and 90μm. The top and the bottom of the spherical bump structure contacts the under-bump metalization (UBM) layer and the Cu layer, respectively, with a circular interface with a radius $r = 3R/4$.

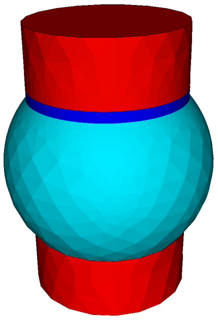

Fig. 1: Solder bump geometry used for the simulation. On the top of the Sn bump, a Ni UBM layer is placed.

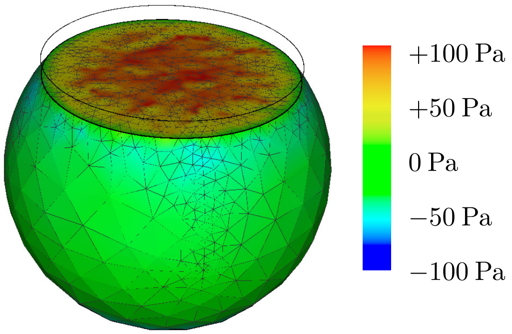

Fig. 2: Stress distribution at the top of solder bump beneath the UBM.

In all simulated cases a characteristic stress distribution at the top of the solder bump is obtained as can be seen in Fig. 2. The mechanical stress increases from the periphery towards the center of the bump/UBM interface, which leads us to the conclusion that a void most probably nucleates in the center of the interface. From the simulation results we see that for the larger bump (2R=70μm, Fig. 3), a shorter time is needed to reach the given stress threshold (70Pa) than for the smaller bump (2R=50μm, Fig. 4). This implies that for the larger bump EM induced material transport is more efficient, since it has more vacancies available in a cross section of the bump. The observed behavior is more pronounced for smaller current densities.

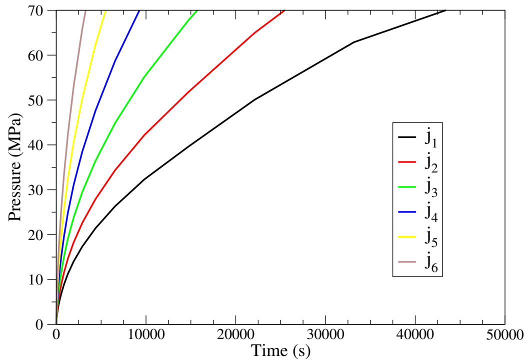

Fig. 3: Stress development in the 70μm bump for 6 different current densities $j_1 < j_2 < j_3 < j_4 < j_5 < j_6$.

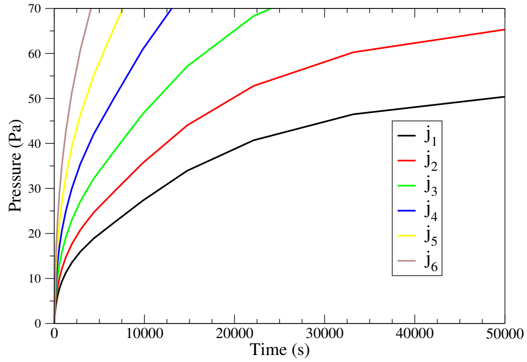

Fig. 4: Stress development in the 50μm bump for 6 different current densities $j_1 < j_2 < j_3 < j_4 < j_5 < j_6$.

Extension of Korhonen's Model

For deriving an expression for the mean-time-to-failure t_f it is important to define a failure condition. While the ultimate failure condition of any interconnect is an increase of its resistance, the question is which physical condition must be fulfilled for an initialization of the rapid phase of failure development, the void nucleation phase. According to our previous work [10], in the case of solder bumps, we have to consider two effects:

- Stress voiding [7]
- Kirkendall voiding [11]

It is plausible to assume that mechanical stress will either alone initialize void nucleation or enhance Kirkendall voiding. In this study we confine ourselves to the condition of stress voiding. The stress threshold σ_c in Korhonen's model is attained by a stress build-up along the one-dimensional interconnect. In the case of a 3D geometry we have more vacancies available in the cross section of the bump so, $\sigma \sim jR^2\sqrt{t}$. From (7) and by setting $A = kT\pi\Omega/((e|Z^*|\rho)^2 BD_a)$ we obtain

$$t_f = \left(\frac{A}{j^2}\left(\frac{\sigma_c}{\alpha R^2 + \beta}\right)^2 + \frac{B}{j}\right)\exp\left(\frac{E_a}{kT}\right). \qquad (8)$$

The parameters α and β are obtained by fitting to the results of the full physical simulations (cf. Fig. 3 and Fig. 4). While the first term on the right side gives a mean-time-to-failure contribution prior to void nucleation, the second term represents the time of void evolution characterized by the parameter B. In Fig. 5 we show the comparison between the mean-time-to-failure obtained by (8) and the full physical model [9] for three different bump radii. For all three different bump sizes a good agreement is obtained. In the studied cases, the void evolution time is assumed much smaller than the void nucleation time (the first summand), e.g. the void development leading to complete failure is very rapid.

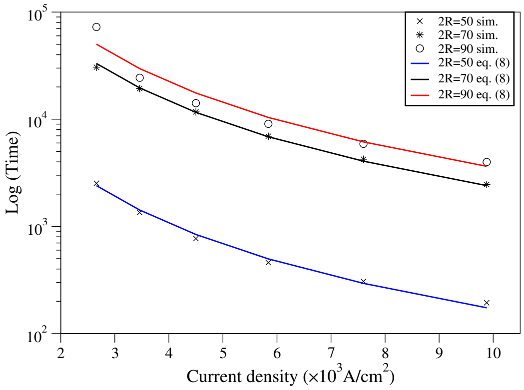

Fig. 5: Time to failure dependence on current density for three different bump sizes.

CONCLUSION

In this work we have presented an analytical compact expression for the estimation of a mean-time-to-failure of the solder bump. Our compact model for the mean-time-to-failure is designed by an adaptation of Korhonen's model and it is verified and calibrated through comparison with current density/mean-time-to-failure curves obtained by simulation based on a full physical model. It has been shown that the EM failure of the solder bump can be accurately predicted by a simple extension of Korhonen's model.

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