Electromigration Induced Failure of Solder Bumps and the Role of IMC

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Abstract

Characteristic for solder bumps is that during technology processing and usage their material composition changes. We present a model for describing the growth of an intermetallic compound inside a solder bump under the influence of electromigration. Simulation results based on our model are discussed in conjunction with corresponding experimental findings.

Introduction

For the realization of modern three-dimensional (3D) integrated circuits new interconnect components such as through-silicon-vias (TSVs) and solder bumps, together with complex multi-level 3D interconnect structures are gaining importance. The application of new structures and materials inevitably introduces new reliability issues. The interconnect reliability is affected by degradation processes induced by thermal gradients, electromigration (EM), and stressmigration. Solder bumps are important components for 3D integration, because they enable vertical stacking of wafers. Pure Sn has been identified as the best Pb-free solder for ultra fine pitch solder bumps for advanced 3D interconnect applications due to its baseline advantages of being electrodeposited and exhibiting a low melting temperature. Failure analyses have shown that failures in Sn bumps occur by EM induced voiding at the interface between the intermetallic compound (IMC) and the solder. EM in Sn-based solder bumps is much more complicated than EM in copper due to the presence of impurities.

The development of a failure in a copper interconnect takes place in two distinctive phases: a void nucleation phase and a void evolution phase. During the first phase practically no resistance increase can be measured. The situation is quite different in the case of EM failure development in a Sn bump, where an IMC layer is also present [1]. From the beginning of EM stressing a continuous growth of the bump resistance (c.f. Fig. 1) is observed. After a certain period of EM stressing, the bump resistance starts to rise with a significantly steeper slope. Chen *et al.* [1] assume that the two slopes of the resistance growth represent two different stages of failure development: void nucleation combined with IMC growth and void propagation with IMC dissolution. The investigation of the physical mechanisms behind such a failure behavior is the main subject of this work.

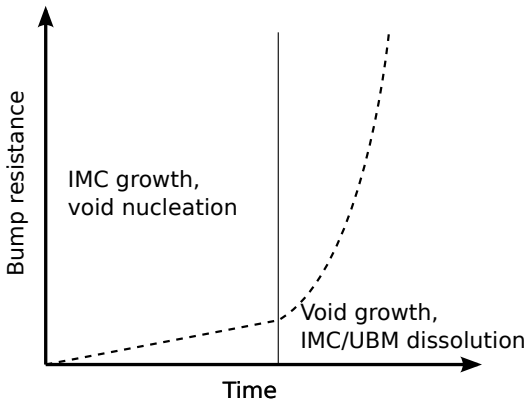

Fig. 1. Resistance change due to IMC growth and voiding with two different slopes.

Important for the layouts attached to the solder bumps is an under bump metallization (UBM), which separates the Sn bump from the surrounding metallization (c.f. Fig. 2). The solder bump with UBM has a lower maximum current density and peak temperature in the solder, which contributes to longer EM lifetimes [2].

Physics of Intermetallic Compound Growth

Until now several attempts have been published to model EM induced IMC development [3, 4], however, none of them is applicable for rigorous numerical simulation. The growth of the IMC is determined by atomic fluxes of different material components ($\vec{J}_{Sn}$, $\vec{J}_{Cu}$, and $\vec{J}_{Ni}$). The fluxes are driven by gradients of chemical po-

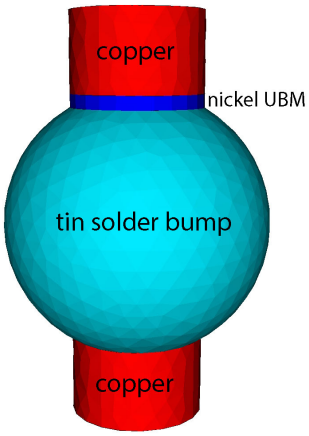

Fig. 2. Structure of the solder bump used for the study. On the top of the Sn bump a Ni UBM is placed.

tentials (μ_{Sn}, μ_{Cu}, and μ_{Ni}) and EM. In each of the chemical potentials an impact of the local mechanical stress and the local concentration of the corresponding atom type is contained [5]:

$$\vec{J}_{Sn} = -\frac{C_{Sn}}{k_B T}\mathbf{D}_{Sn}(\nabla\mu_{Sn} - |Z^*_{Sn}|e\nabla\varphi), \quad (1)$$

$$\vec{J}_{Cu} = -\frac{C_{Cu}}{k_B T}\mathbf{D}_{Cu}(\nabla\mu_{Cu} - |Z^*_{Cu}|e\nabla\varphi), \quad (2)$$

$$\vec{J}_{Ni} = -\frac{C_{Ni}}{k_B T}\mathbf{D}_{Ni}(\nabla\mu_{Ni} - |Z^*_{Ni}|e\nabla\varphi). \quad (3)$$

$\mathbf{D}_{Sn}$, $\mathbf{D}_{Cu}$, and $\mathbf{D}_{Ni}$ are the tensorial diffusivities. All other symbols are explained in [5]. After Cu and Ni atoms are injected in a Sn bump, the chemical reactions described by the following equations take place:

$$\frac{\partial C_{Sn}}{\partial t} = -\nabla\cdot\vec{J}_{Sn} - \kappa_1 C_{Sn}C_{Cu} - \kappa_2 C_{Sn}C_{Ni}, \quad (4)$$

$$\frac{\partial C_{Cu}}{\partial t} = -\nabla\cdot\vec{J}_{Cu} - \kappa_1 C_{Sn}C_{Cu}, \quad (5)$$

$$\frac{\partial C_{Ni}}{\partial t} = -\nabla\cdot\vec{J}_{Ni} - \kappa_2 C_{Sn}C_{Ni}, \quad (6)$$

$$\frac{\partial C_{\mathrm{IMC1}}}{\partial t} = \kappa_1 C_{Sn}C_{Cu}, \quad (7)$$

$$\frac{\partial C_{\mathrm{IMC2}}}{\partial t} = \kappa_2 C_{Sn}C_{Ni}. \quad (8)$$

(4)-(8) model a consummation of Sn, Cu, and Ni, respectively, and a production of two types of IMCs (IMC1 = Cu_6Sn_5 and IMC2 = Ni_3Sn_4). This process is schematically illustrated in Fig. 3. The rates of the chemical reactions κ_1 and κ_2 are thermally activated parameters according to an Arrhenius law.

Simulation Results and Discussion

The formation and growth of the IMC at the interface between the UBM and the Sn (c.f. Fig. 4) is caused by

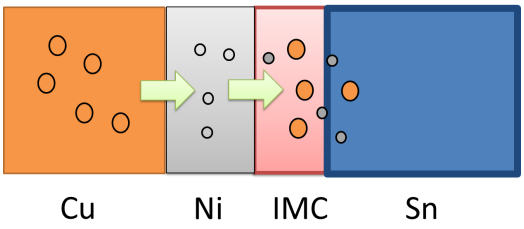

Fig. 3. EM of Cu and Ni atoms into Sn bump and the forming of IMC.

several physical mechanisms. In the initial phase both Cu and Ni penetrate into the Sn bump and segregate just below the UBM/bump contact surface.

The dynamics of subsequent IMC growth is determined by the chemical reactions which convert Cu, Ni, and Sn into IMCs (e.g. Cu_6Sn_5 and Ni_3Sn_4). The model assumes that all transport processes take place in Sn, i.e. Sn is the only transport medium in the model. However, when a thin layer of IMC is formed, impurities migrate through this layer in order to reach the Sn region, where the chemical reaction which produces the IMC occurs. Since our investigation focuses only on a very thin IMC layer, we consider that the model assumption regarding the transport is justified.

As we can see in Fig. 5, in the first hours of EM stressing the resistance increase at 100°C is higher than at 150°C and 200°C. Both migration and chemical reaction are enhanced at elevated temperatures, but it seems obvious that in the early phase, migration keeps the concentration of impurities below the threshold necessary for an IMC production which would cause an observable resistance increase. The delay in the IMC formation process can also be seen in Fig. 6.

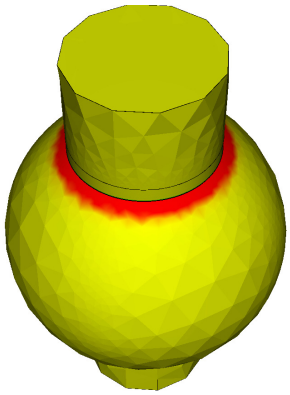

Fig. 4. IMC layer formed at the interface between a nickel UBM and a Sn solder bump.

EM of vacancies ultimately leads to void formation and failure of the bump, a scenario which is most commonly observed in EM experiments [1]. However, simu-

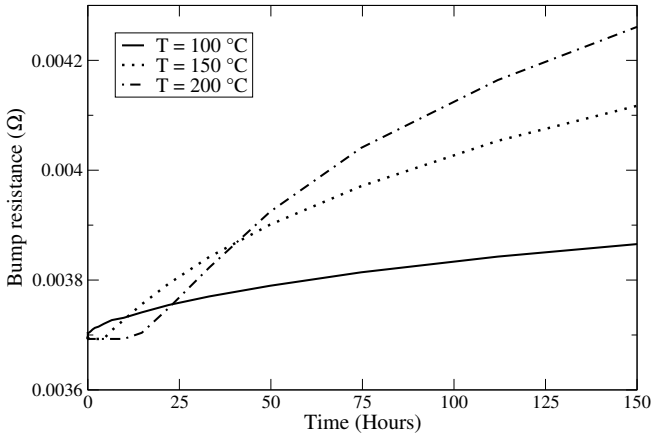

Fig. 5. Initial phase of solder bump resistance growth for three different temperatures.

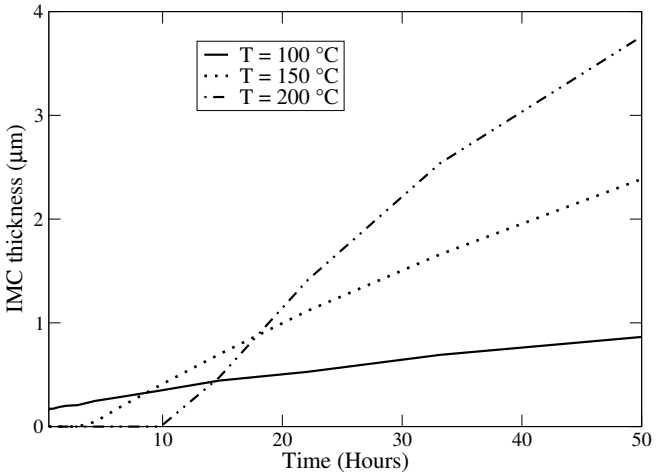

Fig. 6. Growth of IMC thickness in time. Fast migration of Cu and Ni at 150°C and 200°C prevents IMC emergence for several hours of stressing.

lation also permits to study a situation, where no void nucleation takes place but EM stressing proceeds, until the whole Sn of the solder bump is converted into an IMC. As we can see in Fig. 7 the bump resistance rises with a gradually increased slope, until the whole bump consists only of IMC (Ni_3Sn_4). From our simulation, we conclude that a much steeper second slope (c.f. Fig. 1) observed by Chen *et al.* [1], which appears abruptly after approximately 100h of stressing, can only be caused by an emergence of the new phase between the IMC and the Sn layer. We support the findings of Chen *et al.* [1] that this "second phase" is actually the beginning of void evolution.

Conclusion

The development of an IMC phase inside of Sn-based solder bumps represents a reliability risk for interconnect structures used for realization of 3D ICs. In this work we have presented a model for IMC growth in Sn solder

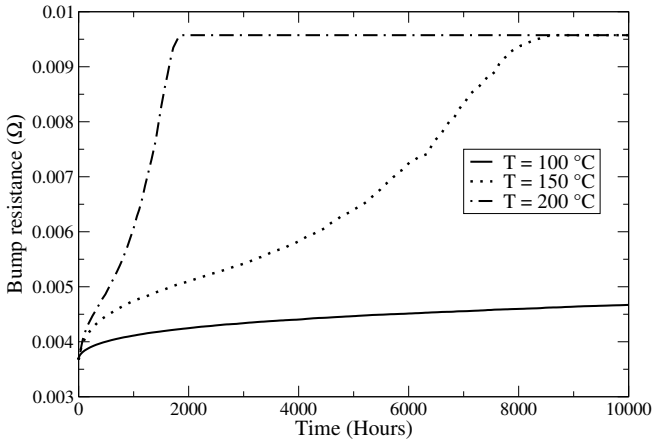

Fig. 7. Late phase of the resistance growth. The resistance of the solder bump increases, until the whole Sn is converted into IMC.

bumps. Our model includes a description of the Cu and Ni migration into the Sn bump and the chemical reaction which produces two different types of IMCs. Simulations based on our model predict 3D profiles of the IMC, the time-dependent resistance change, and time dependent change of the IMC thickness. The obtained results are compared and discussed with experimental observations and measurements. The model and simulations presented in our work explain the interplay between the mechanisms which participate in the degradation of solder bumps.

References

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