Growth Mechanism of the Cathode IMC Layer in Solder Bump Joints

Chun Yu and Hao Lu
School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, PR China

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1. Introduction

Dissimilar materials are usually joined by forming inter-phases, like intermeallic compound (IMC) and solid solution. IMC layer often forms at the interface of Sn based solder and copper. It is well known that, a thin IMC layer is necessary to keep a good joining between solder and subtract, while too thick IMC layer is sensitive to stress and sometimes induces crack initiation and propagation [1,2]. The IMC layer would keep growing up when subjected to current stressing or under thermal aging, that is not conducive to the properties of the solder joints. Most of the present references reported the electromigration (EM) behaviors of the solder joints under the conditions of current density greater than 1×10^4 A/cm^2 and holding temperature higher than 100 └ [3,4]. And the main conclusions are, in the EM process, IMC layer at the anode side grows up quickly, while that at the cathode side is suppressed to be thicker, even resolves to the solder and forms voids [5,6]. Some researchers also found that the growth of IMC layer at the cathode side obeys the parabolic rule under smaller current density, no voids would be formed at the interface. The miniaturization trend of the electronic products requires that the size of the solder bumps should become smaller and smaller, solder balls in 50 μm diameter will come in near future. If the solid reaction can not be controlled, the solder will be consumed totally in a short period when the electronic products are in service. Brittle IMC layer fills in the solder joints, and this will threaten the reliability, property and lifetime of the packages and electronic products.

It is inevitable for solder joints to subject to current. Therefore, how to control the growth of the IMC layer, and suppress the formation of voids, are of significant interesting. However, some basic knowledge is still short. In this paper, the relation between the growth behavior of the cathode IMC layer and current density was investigated from a diffusion dynamic view. In addition, finite element simulations were employed to verify this relation.

2. Methods

The mathematical model of the current density is

$$\vec{j}=\frac{1}{\rho}\vec{E}=-\frac{1}{\rho}\nabla\phi \qquad (1)$$

A BGA-like structure was designed, and the cross-sectional sketch of the structure on the *XY* plane was shown in Fig. 1. The *z*-axis is. The main structure includes Cu lines, Cu pads, Cu_6Sn_5 IMC layers, and the solder bump. A current stressing of 2.85 A was applied to the joint, and the direction of electron flux is shown in Fig. 1. Therefore, an average current density of 1_10^3 A/cm^2 to the contact opening at the cathode side was obtained.

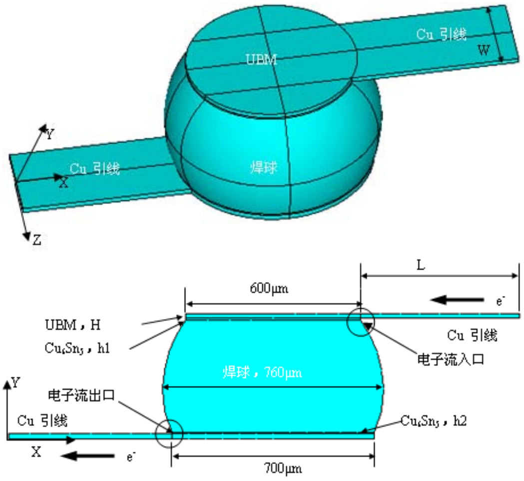

Fig. 1 sketch map of the trace to bump structure

3 growth dynamic of cathode IMC layer

Under current stressing, the atomic flux induced by chemical potential and electrical field intensity can be expressed as,

$$J_A=-D\frac{dC}{dx}+C\frac{D}{kT}Z^*eE \qquad (2)$$

So, the driving force accounted for the growth of the IMC mainly consists of the chemical potential and the wind force.the growth of IMC layer is controlled by two forces, chemical potential and electron wind force. Fig.2 depicts the diffusion model at the cathode side. We can see that, Sn atoms in the solder and Cu atoms in Cu subtract diffuse to the cathode Cu_3Sn/Cu_6Sn_5 or farther interface or a much farther interface (Cu_3Sn/Cu for Sn and Cu_6Sn_5/solder for Cu) along opposite directions due to the chemical potential. $J_{ch}(Sn)$ and $J_{ch}(Cu)$ respectively represent these two atomic flux. Obviously, they accelerate the IMC growth. Simultaneously, the wind force accelerates the diffusion of Cu toward the solder, but depresses or reverses the migration of Sn as determined by the magnitudes of the above two forces. Therefore, the relative quantity of Sn toward the reaction interface, which is defined as

$$\Delta J(Sn)=J_{ch}(Sn)-J_{em}(Sn) \qquad (3)$$

And for Cu,

$$\Delta J(Cu)=J_{ch}(Cu)+J_{em}(Cu) \qquad (4)$$

The above equations indicate that the Sn flux is a main factor determining the growth or dissolution of cathode IMC layer. As $\Delta J(Sn) > 0$, the IMC layers grow up and more Cu on the substrate could be consumed; otherwise, the IMC layers would dissolve greatly; in the meantime, both Cu and Sn migrate toward the anode side, leaving lots of vacancies at the interface. Therefore, the growth of IMCs can be accelerated under a lower current density and impeded by a higher current density. On the contrary, the higher current density would lead to a quick dissolution of IMCs and formation of voids. The formation of voids also blocks the effective diffusion path of Cu and Sn atoms.

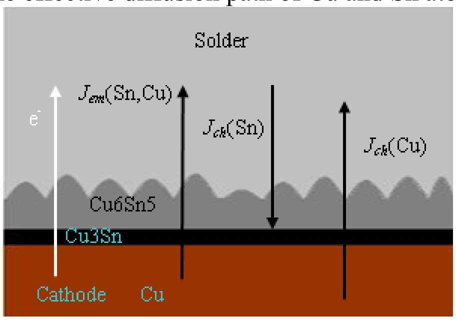

Fig.2 diffusion model at the cathode side

According to above analysis, the growth or dissolution of cathode IMC layer directly relates with the max. current density. Assuming that the growth rate of IMC layer equals to the dissolution rate, that means, the total atomic flux is 0, then,

$$J = J_{CH} + J_{EM} = D(-\frac{\partial C}{\partial x}) + C\frac{D}{kT}Z^*_{IMC}ej_{\max}\rho = 0 \qquad (5)$$

Since the thickness of the IMC layer is relative thin, $\frac{\partial C}{\partial x} \approx \frac{\Delta C}{\partial x}$, so,

$$(j_{\max}\Delta x)_{\text{Critical}} = \frac{kT}{C}\frac{\Delta C}{Z^*_{IMC}e\rho} \qquad (6)$$

Equation (6) indicates, the thickness of IMC layer is inverse to the critical current density. The lower the current density is in the solder, the thicker the IMC layer becomes. Similarly, if we increase the current density, the IMC layer would become thinner. With a given current density, we can determine the critical thickness of the IMC layer. And as the actual thickness of the IMC layer is bigger than this value, the max. current density would be bigger the critical current density induced EM-void, and voids would be formed at the cathode interface.

4 relation between IMC thickness and current density

Fig.3a and 3b reflect the cross-sectional views of the current density distributions of the solder joints with IMC layer in 10 μm and 2 μm thickness, respectively. It is seen that the IMC thickness affects greatly of the current density distribution at the corner. As the IMC is 10 μm, the max. current density is 7134.8A/cm^2, while as the IMC is 2 μm, the max. value becomes 9267.^{2} A/cm^2.

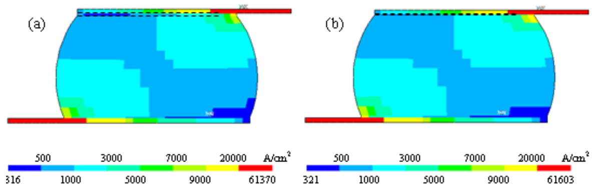

Fig.3 Effects of IMC thickness on current density in the trace-to-bump structure. (a) 10 μm; (b) 2μm

The relation between IMC layer and current density deduced by FEM is presented in Fig.4. It is seen that the result is in good agreement with the critical model, from a qualitative view.

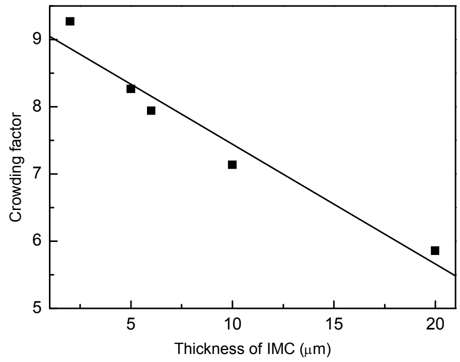

Fig.4 Relation between current crowding factor and thickness of IMC at cathode interface

5 Conclusion

The effect of current density on the growth of cathode IMC layer in solder bump joints was investigated. The thickness of the cathode IMC layer increases with the decrease of current density.

Acknowledgements

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