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Introductory invited paper

Numerical simulations of migration and coalescence behavior of microvoids driven by diffusion and electric field in solder interconnects

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ABSTRACT

A diffuse interface model is developed to simulate the effect of electric field on the morphological evolution and migration behavior of the microvoid in the solder interconnect consisting of the Sn based solder and Cu substrate (i.e., Sn/Cu system). The model takes into account the coupled effect of surface diffusion and electric field, and the validity of the model is confirmed by good agreement between the simulation and theoretical predictions in terms of evolution behavior of the noncircular microvoid driven by surface energy. The results show that the coalescence of microvoids driven only by surface energy occurs when the microvoids contact each other. The evolution and migration of the microvoid under electric field are governed by the magnitude of electric field and the initial size of the microvoid. The microvoid migrates at a constant velocity under a weak electric field, while the strong electric field results in the shape change of the microvoid from circular to narrow crack-like. In addition, the migration velocity of the microvoid increases linearly with the voltage and is inversely proportional to the size of the microvoid; a small microvoid can catch up with a large one, and finally they merge to form a larger microvoid, which may promote the open circuit failure near the solder/Cu interface in solder interconnects.

1. Introduction

With the rapid development of microelectronics technology, electronic devices and products have been moving toward miniaturization, intelligence, multifunction and wearable. This has led to a dramatic increase in packaging density and the scaling down of the solder interconnect (joint) dimension [1], and consequently the sharp increase of current density carried by the solder joints, which may have an average value up to 10^4A/cm^2 and even higher [2,3]. The high current density enhances atomic displacement and momentum exchange in the direction of electron flow (often referring to as electromigration), and drives vacancies from the anode to cathode where flux divergence occurs and vacancies will accumulate into voids at the current crowding region near the cathode [4–6]. Further, the unbalanced atomic diffusion in the most widely used interconnects consisting of the Sn-based solder and Cu substrate often induces Kirkendall voids that nucleate at the Cu/Cu_3Sn interface and in the Cu_3Sn layer [7–10]. Moreover, voids may also nucleate in the solder matrix caused by grain boundary sliding during cyclic creep fatigue owing to temperature or electrical load [11]. In addition, there is another type of voids with relatively large size formed by nonuniform solder shrinkage or gas during manufacturing or reflow process [12,13]. Previous studies have shown that the microvoids can reduce the reliability and durability of solder interconnects. In particular, the formation and existence of those microvoids at interfaces can promote the formation of cracks and increase the potential for brittle interfacial fracture [3–7]. Furthermore, the thermal conductivity [14], temperature distribution [15] and current density [5,16] are also affected by the microvoids. Thus, it is imperative to study the migration, coalescence and evolution of the microvoids in solder joints, in particular for the joints carrying high density current.

There have been extensive experimental observations aiming at deepening the understanding of the evolution and migration of microvoids. It has been shown that the formation and coalescence of microvoids are the dominant mechanism for degradation of solder joint strength and board level drop reliability [7,17,18]. The coalescence of microvoids can cause separation of intermetallic compound (IMC) from the Cu pad (substrate), especially when the microvoids coalesce into disk-like interfacial voids. Moreover, the microvoids located at the current crowding region in a flip chip solder joint may propagate quickly across the contact area in the direction of electron flow [5,19–21]. Growth and coalescence of microvoids at the contact area can reduce significantly the load

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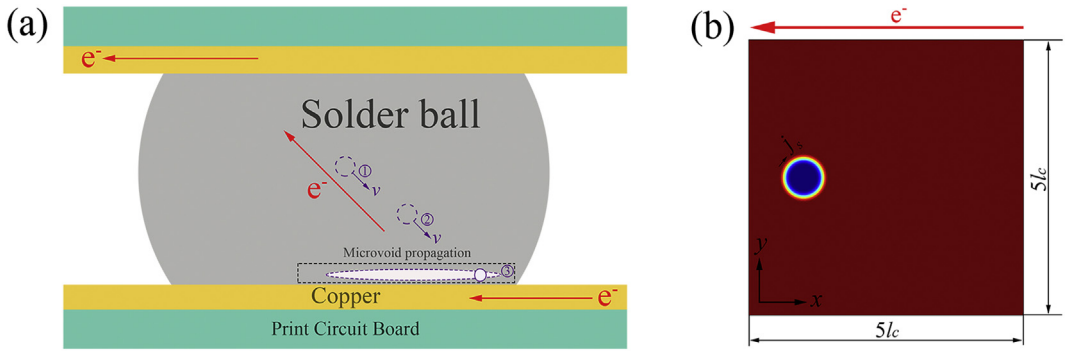

Fig. 1. Schematic configuration of numerical simulation in the present model: (a) Cross-section of a solder interconnect with a microvoid and its propagation; (b) representative two-dimensional computational domain with a microvoid and applied electric field (noting that the computational domain is a schematic drawing indicated by the dotted rectangle in (a)).

bearing cross-section of solder joints, and in turn further increase the local current density that may accelerate migration and coalescence of microvoids and eventually lead to an open failure of interconnects [22]. Thus, under the electric current stressing with a high density, the microvoid migration and evolution driven by atom diffusion and electric field make solder joints be more likely to fail, in particular when microvoids change their shape to form crack-like slits with sharp tips.

Although many experimental studies have been launched, it is still unclear how the microvoids migrate and evolve till failure of the interconnects and which factors affect the evolution of the microvoids. Numerical simulation may have the potential to resolve the above concerns, despite the existence of many challenges. Thus far, there have been some simulation studies on coalescence and migration behavior of microvoids in solder interconnects. Kim [23] used a three-dimensional computational model to simulate the interfacial failure near the cathode of solder joints due to the microvoid nucleation and propagation induced by electromigration and diffusion, but the work did not show the details of the microvoid evolution and propagation. Zhou et al. [24] developed a model to study the growth and coalescence of microvoids under both elastic stresses and electric current stresses without discussing the migration and coalescence kinetics of microvoids. Zhang et al. [25] proposed a kinetic model to describe the propagation of a pancake-type void in flip chip solder joints due to current crowding in electromigration, and the void growth velocity was also calculated. In addition, it is worth noting that there were many theoretical studies focusing on modeling and predicting the evolution and migration of voids in aluminum or copper interconnects, metallic thin films and interconnect lines [26–34]. Studies showed that the migration of voids is governed by the competition between the electric field and surface energy, and latter favors circular voids [26–29]; for example a rounded void collapses to a slit when the electric current prevails. It had been proved that the failure of metal thin films is originated from the evolution of microvoids due to microvoid electromigration [30,31], and the anisotropy of surface energy and surface diffusivity also affect the evolution of voids [32]. Indeed, these studies by using different models and simulations have made significant advances in understanding of the migration and evolution behavior of microvoids under electric fields. However, most of the existing models are based on sharp interface theories, requiring an explicit tracking of the constantly changing void surfaces during the course of the evolution and demanding remeshing with a mesh-based numerical scheme. Hence, the demand for computing resources is very high and the process is time-consuming.

In the present study, a two-dimensional phase field model is developed to study the evolution and migration of microvoids in the solder interconnect consisting of the Sn-based solder and Cu substrate (i.e., Sn/Cu system) under electric field. The model incorporates surface diffusion in addition to the electric field, and a diffuse interface approach is adopted to avoid explicit interface tracking. The focus of this study is to clarify the migration and coalescence process of the microvoid against time under surface diffusion and electric field, and reveal the effects of the electric potential on the evolution of the microvoid, as well as characterize the microvoid migration kinetics.

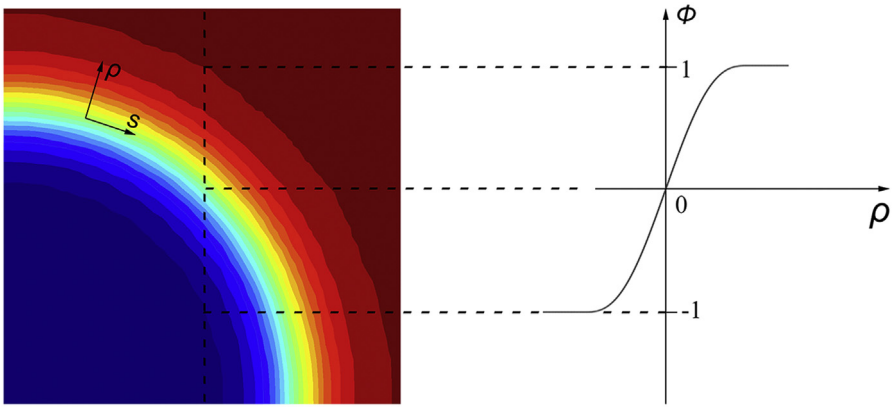

Fig. 2. Local view of the interfacial layer and distribution of the order parameter ϕ used in the phase field simulation.

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