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A statistical mechanics model to predict electromigration induced damage and void growth in solder interconnects

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HIGHLIGHTS

- The characteristic of electromigration induced cotton type void growth is studied a statistically.
- A new damage accumulation model is developed for solder under high current density.
- The proposed model takes into account the void initiation and growth.
- The theoretical predictions are in good agreement with the experimental observations.

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ABSTRACT

Electromigration is an irreversible mass diffusion process with damage accumulation in microelectronic materials and components under high current density. Based on experimental observations, cotton type voids dominate the electromigration damage accumulation prior to cracking in the solder interconnect. To clarify the damage evolution process corresponding to cotton type void growth, a statistical model is proposed to predict the stochastic characteristic of void growth under high current density. An analytical solution of the cotton type void volume growth over time is obtained. The synchronous electromigration induced damage accumulation is predicted by combining the statistical void growth and the entropy increment. The electromigration induced damage evolution in solder joints is developed and applied to verify the tensile strength deterioration of solder joints due to electromigration. The predictions agree well with the experimental results.

1. Introduction

Electromigration is caused by the gradual movement of ions in a conductor due to the momentum transfer between conducting electrons and diffusing atoms. With the reduction of microelectronic product size, the working current densities are increasing rapidly, and electromigration becomes a key reliability issue in solder interconnects [1]. Different from the traditional electromigration issues in the Al/Cu interconnects, when electromigration occurs in the solder joints, damage, which will accumulate over time and cause deterioration of the mechanical strength and service life [2,3], becomes the critical issue. According to continuum damage mechanics, damage is defined as the progressive deterioration of materials before final failure. Electromigration induced damage is irreversible and could be divided into two processes. Atoms diffusing into the solder interconnects will induce disorder of the system. The material microstructure is changing synchronously,

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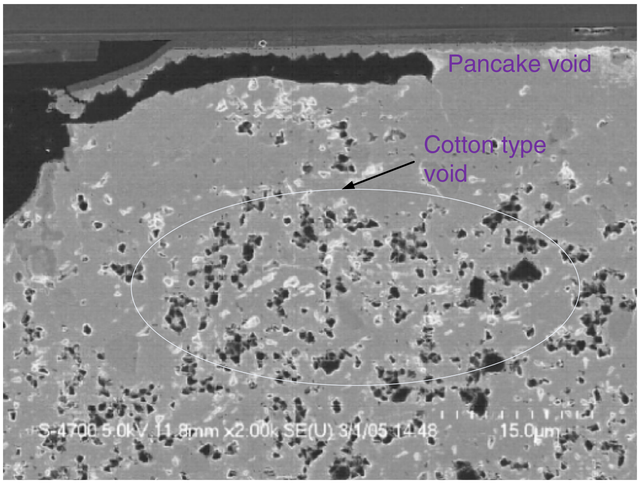

Fig. 1. The pancake and cotton type voids in the solder joints under electromigration [7].

such as the change of dislocation density and the vacancy concentration [4]. The system disorder is directly related to damage accumulation and has been verified by electromigration experiments of interconnects [5,6]. On the other hand, similar to the Al/Cu interconnects, voids will nucleate, propagate and even collapse to a crack in the solder joint under high current density [7]. The existence of the voids will cause a reduction of the material mechanical properties. However, these two processes are usually not coupled in previous analysis because the void growth is mainly affected by the grain boundry diffusion, while the first process is mainly controlled by the atom lattice diffusion in the solder joint. Thus, it is essential to incorporate the void effect into the damage analysis. As a multi-physics and multi-scale problem, the intrinsic mechanism for electromigration induced damage evolution is still not clear and requires further study.

Compared with the electromigration induced voids in the Al/Cu interconnects, the voids in the solder joints are more complex. Experimental analysis shows two type of electromigration induced failure modes in solder joints under high current density [8]: cotton or pancake type voids, as shown in Fig. 1. Initially, the voids are mainly cotton type, remain circular and are distributed randomly in the solder joint. As time passes or the current density increases, the circular void will collapse into a pancake void and cause interconnect failure. This failure process is instantaneous and has been studied by researchers [9,10]. However, until now little attention has been paid to the cotton type void due to its stochasticity. Compared with the pancake type void, more cotton type voids are observed at a lower current density level. On the other hand, the damage evolution during the failure process of the solder joint is directly related to the cotton type void growth. Due to the existence of cotton type voids, it is observed that the solder interconnect will transform from ductile to brittle failure with an obvious decrease of tensile strength [11]. However, the stochastic nature of cotton type voids makes it difficult to predict when and where the void will nucleate in the solder joint. Thus, clarifying the distribution law of the cotton type void is essential to understanding electromigration induced damage evolution.

Basaran et al. [12,13] have performed fundamental research on electromigration-induced damage evolution. They proposed that entropy can be employed as a damage metric for electromigration-induced damage evolution, which connects atomic scale to macro scale behavior. The irreversible thermodynamic damage model has been applied to analyze thermo-mechanical fatigue and predict the Mean Time to Failure (MTF) of the solder interconnects. However, it is difficult to correlate the entropy increment with void growth due to its inherent stochastic nature. Further study is still required to clarify the fundamental mechanisms of void initiation and growth. On the other hand, Montemayor et al. [14] have developed a non-equilibrium statistical theory to predict electromigration caused damage, however, the void nucleation and growth is neglected in their model.

In the present study, based on the mass diffusion theory, an individual void growth model under high current density is proposed and verified with experiments. The stochasticity characteristic of cotton type voids is predicted and the volume growth over time is solved by using statistical methods. A damage model is developed to study the tensile strength deterioration of the solder interconnect under high current density.

2. An individual void growth model based on mass diffusion theory

In general, there are three forms of diffusions in the solid materials: lattice diffusion, surface diffusion and grain boundary diffusion. As observed in the electromigration experiments, voids are mainly observed at the edges of interconnect lines or at the grain boundary of triple junctions. Since the lattice diffusion speed is relatively slow, the growth of void is dominated by the surface diffusion and the grain boundary diffusion, as shown in Fig. 2. It should be noted that surface diffusion alone can hardly cause the void volume change because lacking of the atoms sink or source. The surface diffusion can only induce the