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High electric current density-induced interfacial reactions in micro ball grid array (μBGA) solder joints

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Abstract

The effect of a high electric current density on the interfacial reactions of micro ball grid array solder joints was studied at room temperature and at 150 °C. Four types of phenomena were reported. Along with electromigration-induced interfacial intermetallic compound (IMC) formation, dissolution at the Cu under bump metallization (UBM)/bond pad was also noticed. With a detailed investigation, it was found that the narrow and thin metallization at the component side produced "Joule heating" due to its higher resistance, which in turn was responsible for the rapid dissolution of the Cu UBM/bond pad near to the Cu trace. During an "electromigration test" of a solder joint, the heat generation due to Joule heating and the heat dissipation from the package should be considered carefully. When the heat dissipation fails to compete with the Joule heating, the solder joint melts and molten solder accelerates the interfacial reactions in the solder joint. The presence of a liquid phase was demonstrated from microstructural evidence of solder joints after different current stressing (ranging from 0.3 to 2 A) as well as an in situ observation. Electromigration-induced liquid state diffusion of Cu was found to be responsible for the higher growth rate of the IMC on the anode side.

Keywords: Joule heating; Heat dissipation; Electromigration; Solder joint; BGA

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1. Introduction

With the trend towards miniaturization and very-large-scale integration of circuits on Si devices, electronic packaging requires higher I/O density, smaller feature size, and better performance [1–3]. A common cause of failure at narrow electric conductors by high electric current densities is "electromigration" [3–10]. Electromigration is the enhanced diffusion of atoms in the current direction. Because of the higher current density in a fine–pitch solder joint, electromigration is a growing concern in electronic packaging that needs to be addressed. Without an electric current, the driving force of intermetallic compound (IMC) formation is the chemical potential difference between the two contact materials. At a high current density above 10^2 A/cm^2, electron flow can play a significant role in IMC formation. Chen and co-workers [11–18] have studied IMC formation in several diffusion couples such as Sn/Ni, Sn/Ag, Sn/Cu, and other solders, etc., with a DC current density of 10^2–10^3 A/cm^2. They observed a directional effect of electric current on the IMC thickness at the interfaces at a current density of 5×10^2 A/cm^2. Their samples were sandwich-type bars with a cross-section of 1 mm^2. Although the phenomena might not be directly comparable with a real package, they reported that the interactions at the cathode and anode are different due to a polarity effect. While electromigration enhances IMC formation at the anode, it enhances IMC dissolution at the cathode.

During current stressing, heat is also generated through Joule heating which may maintain a thermal gradient in the solder joint or may even melt the solder (solder alloy is a low melting point component among the interconnects

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used in an electronic package). However, melting of the solder joints during high current stressing has not been reported so far. Moreover, for an area array solder joint such as for a ball grid array (BGA) package, the way that electric current flows through a solder bump is not uniform. The origin of such a non-uniform current distribution is a high to low current density transition at the contact window between the conducting metal line and the solder ball. Thus, current crowding occurs at the contact interface between the solder ball and the metal pad/under bump metallization (UBM). It was found for a flip–chip solder joint that the high current density due to current crowding is about one order of magnitude higher than the average current density in the joint [4]. This current crowding exerts a much greater driving force for electromigration and also generates local Joule heating and/or enhances local dissolution of UBMs [3–5].

For a μBGA solder joint, current crowding could be much more intensive. This is because a very narrow Cu trace is connected to a relatively larger solder ball. Fig. 1 shows a typical solder ball arrangement on a μBGA package. When it is bonded on the printed circuit board (PCB), electric current flows through the Cu trace, of 60 μm × 15 μm cross-section, to the solder ball, of 300 μm diameter. A very large current crowding occurs at the interface of the Cu bond pad and the solder ball, where the narrow Cu trace meets. With a larger amount of current (e.g., a 1 A flow through the Cu trace when the current density in the Cu is 1.1×10^5 A/cm^2), the temperature rises by Joule heating. As this Cu trace is usually enclosed in a poor thermally conducting dielectric material (such as a solder mask), the temperature may rise to the melting point of the solder alloy. As a result, the solder alloy near the Cu traces may reach the liquid state and thus increase the dissolution of Cu and eventually lead to electrical failure. This work is intended to study interfacial phenomena of the solder joint of a real package under high current stressing. A dummy μBGA package with the same pair of solder joints was used to obtain reproducible results for a practical application. Detailed microstructural characterization was carried out to understand the changes under a range of current stressing.

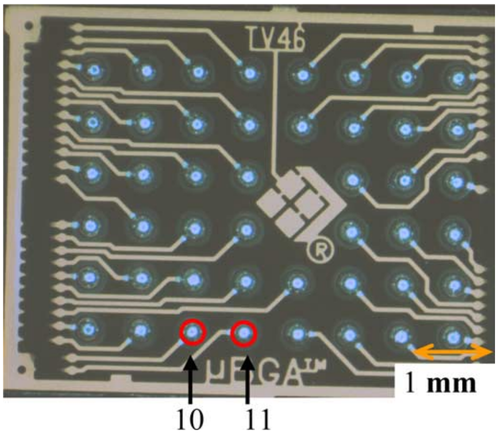

Fig. 1. Optical micrograph of the general view of a μBGA package from the bottom side showing the solder balls attached with the Cu traces on the μBGA substrate.

2. Experimental

The samples used in this study were the dummy version of Tessera's μBGA package (CSP46T75). The area of the package was 5.76 mm × 7.87 mm and the height including solder ball was 0.84 mm. The diameter of the solder balls was 0.3 mm. Solder balls were attached to the package with a 6 × 8 grid and a 0.75 mm pitch (see Fig. 1). The solder bump material was 63Sn–37Pb. The solder bumps were connected with a Cu trace 60 μm wide and 15 μm thick. The Au thickness on the Cu trace was 1 μm. The length of the Cu trace depended on the location of the bumps. Fig. 2(a) shows a schematic of the electrical connection between the solder bumps for the μBGA package (component side). The organic FR-4 substrate was chosen for the test board, since it is one of the most commonly used PCBs. The board size was 110 mm × 120 mm with a thickness of 1 mm. The width and thickness of the Cu trace were 100 and 15 μm, respectively. An electroless Ni–P layer 5 μm thick was deposited on the Cu trace followed by 1 μm of Au flash. A schematic of the PCB is shown in Fig. 2(b). The outside points are bump test pads with a diameter of 1 mm. The inside 6 × 8 array of pads with a diameter of 0.3 mm are to receive the solder bumps of the μBGA packages. The μBGA component was attached to the substrate using flip–chip bonding technology by a Karl Suss 9493 Mauren Flip–Chip bonder. The bonded samples were then reflowed using a five-zone air convection oven (BTU VIP – 70 N) in a compressed N_2 environment. In the temperature profile, the peak temperature was 225 °C and the time in the molten state was about 60 s. A completed daisy chain after bonding is shown in Fig. 2(c).

Two contiguous joints (nos. 10 and 11) were subjected to different currents ranging from 0.6 to 2 A DC at room temperature and from 0.3 to 1.2 A DC at 150 °C. The same pair of solder joints was used for the whole range of current stressing to make the results reproducible. For joint no. 10, the current flowed from the board side to the component side, whereas for joint no. 11, the current flowed from the component side to the board side. The daisy chain allowed one to find which joint failed. The real temperature of the solder interface has not yet been measured. However, the temperature was monitored by attaching a thermocouple to the backside of the component to correlate it with a variation in current stressing. It needs to be mentioned here that unlike other investigations, where a typical test module for an electromigration study was used [4,5,7], solder joints of a real package have been used for this study. Thus, the electrodes and