EXPERIMENTAL STUDY ON LASER AND HOT AIR REFLOW SOLDERING OF PBGA SOLDER BALL

by Yanhong.Tian and Chunqing Wang

National Key Laboratory of Advanced Welding Production Technology,
P.O. Box 436, Harbin Institute of Technology, Harbin 150001, China, tianyh@hope.hit.edu.cn

ABSTRACT

Laser and hot air reflow soldering of PBGA solder ball was investigated. Experimental results showed that surface quality and shear strength of solder bumps reflowed by laser was superior than the solder bumps reflowed by hot air, and the microstructure inside the solder bumps reflowed by laser was much finer. Analysis on interfacial reaction showed that eutectic solder reacted with Au/Ni/Cu pad shortly after the solder was melted. Interface of solder bump reflowed by laser consists of a continuous $AuSn_4$ layer and remnant Au element. Needle-like $AuSn_4$ grew sidewise from interface, and then spread out to the entire interface region. A thin layer of Ni_3Sn_4 intermetallic compound was found at the interface of solder bump reflowed by hot air, $AuSn_4$ particles distributed inside the whole solder bump randomly. It is the combination effect of the continuous $AuSn_4$ layer and finer eutectic microstructure inside the solder bump reflowed by laser that resulted in higher shear strength.

KEYWORDS

Eutectic solder ball，Laser reflow，Hot air reflow，Interfacial reaction

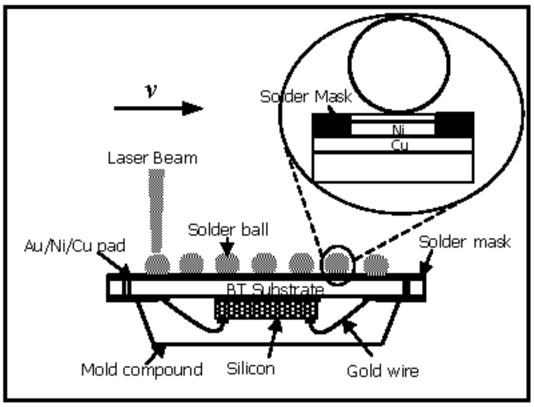
1.Introduction

Ball Grid Array (BGA) package has been in wide use in large scale integrated circuit due to its higher density, higher reliability and excellent electric performance[1,2]. The solder bumps arrayed like grids on the surface of substrate are I/O leads of BGA package. The process of melting eutectic solder ball and connecting it with Au/Ni/Cu pad to form solder bump is called reflow soldering. In recent application of heat source of reflow soldering, infrared, hot air and laser are in common use. Infrared and hot air reflow soldering methods are mature in technology and suitable for mass production. However, the disadvantages of long heating period, heat shock of sensitive material and oxidation of solder ball surface are unavoidable[3]. Laser reflow soldering is a relatively new process in electronics manufacturing, but one with tremendous potential, especially in solder bumping of BGA solder balls[4-7]. Precise beam placement and energy control means that even the finest pitched solder balls can be heated without exposing nearby heat-sensitive component material to the beam. With the Nd:YAG process, selective absorption of the beam energy by materials(due to the specific wavelength) allows continuous scanning of the beam across the solder balls without damaging component material. Accurate control of the laser beam energy and scan rate provide the means for controlling heating/cooling rate and the peak temperature of solder bump formation and so enables adjustment and control of the microstructure.

In this paper, laser and hot air reflow soldering BGA solder ball was investigated, shear test of solder bump was performed. Experimental results showed that surface quality and shear strength of solder bump formed by laser was superior than that of solder bump reflowed by hot air. In order to explain this phenomenon, interfacial reactions of 63Sn/37Pb eutectic solder and Au/Ni/Cu were analyzed, effect of laser input energy on morphology and distribution of intermetallic compounds was discussed.

2.Experimental Materials and Method

The pad used in this study has three layer structure as Au/Ni/Cu, the Au and Ni layers were deposited by electroplating and were 2 μm and 7 μm thick respectively. The composition of solder balls is eutectic 63Sn37Pb with a diameter of 0.76mm. BT substrate surface of BGA package was ultrasonic-cleaned before planting the solder balls on the pads, then solder balls were dipped into soluble flux and then planted on the pads manually. The laser used to reflow soldering is a continuous wave type Nd: YAG laser with a diameter of laser beam 0.6mm. Laser heating time and laser power is computer-controlled. The BGA package with planted solder balls was placed on a computer controlled x-y table. Fig.1 illustrates laser reflow soldering process of BGA solder balls. A 5-zone hot air reflow oven (BTU VIP-70N) was used to reflow the BGA solder balls. The measured peak temperature is 207℃, and dwell time beyond the melting point of eutectic solder is 53s. After the reflow soldering, ball shear test was carried out on the DAGE4000 microtester. The schematic drawing of ball shear test was shown in Fig.2. The distance between shear blade and substrate surface is 150μm.The bump was pushed horizontally at a constant velocity of 100μm, until 50 percent of solder bump was pushed off from the pad. Philips-XL40 scanning electron microscopy (SEM) was employed to study the surface and microstructural morphology of intermetallic compounds of solder bump. EDX was used to determine the chemical composition.



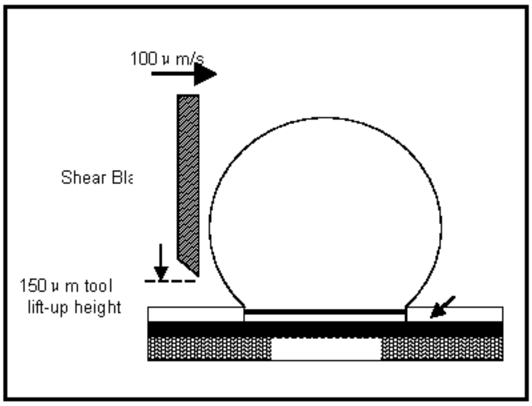


Fig.1 Scheme of laser reflow soldering of BGA solder ball **Fig.2** Scheme of shear test of solder bump

3.Results and Discussion

Experimental results showed that formation of solder bump was controlled by laser input energy. When laser power is small, chanciness existed although solder bump can be formed by increasing laser heating time. On the contrary, when laser power is much larger, solder balls would be easy to be burned out, especially when laser beam is not placed exactly on the top surface of solder ball, BT substrate would be burned out. So precise control for laser input energy is most important during laser reflow soldering. Fig.3 shows surface morphology of solder bump reflowed by laser and hot air. It can be seen that solder bump with smooth surface can be formed with appropriate laser power within short laser heating time. Moreover, solder ball has strong self-centering effect under laser heating due to the surface tension of molten solder, which avoids the offset of solder ball during hot air reflow soldering. The offset was caused by the inappropriate direction of gas jet in hot air reflow oven, as shown in Fig.3b. For a 0.76mm diameter of solder ball, solder bump can be formed within 0.05s with laser reflow soldering method, however, hot air reflow soldering would take at least 4 minutes to finish the preheating, soaking and reflow soldering process. So laser reflow soldering is hopeful to increase package efficiency and promote package quality.

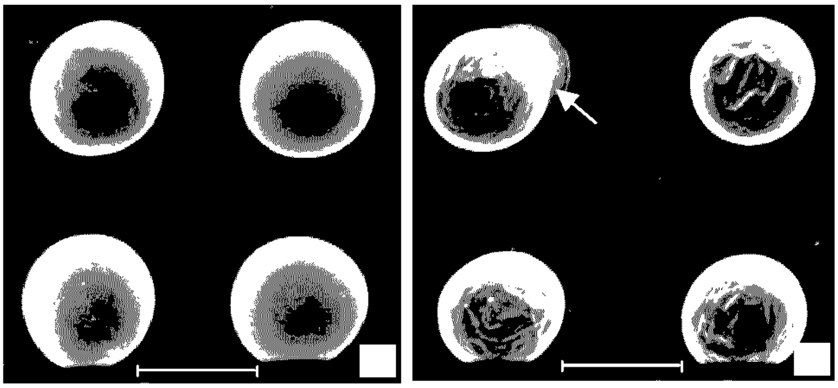


Fig.3 Surface appearance of solder bump formed by (a) laser reflow soldering (b) hot air reflow soldering

The shear test results showed that the shear strength of solder bumps reflowed by different laser input energy was stable, and was higher than the solder bumps reflowed by hot air. A typical load-displacement curve is shown in Fig.4. Fracture surface of solder bumps show that no soldering defects were found on fracture surface no matter what reflow method was used. EDX analysis on any point of fracture surface showed that fracture occurred at the solder side.

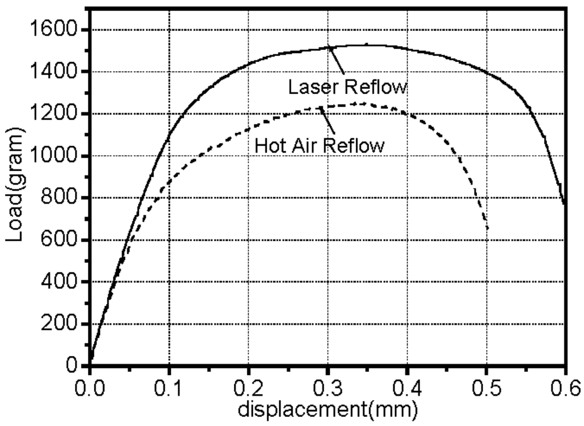


Fig.4 Typical load-displacement curve for ball shear test

Above experimental results reveal that surface quality and shear strength of solder bump reflowed by laser are superior than the solder bump reflowed by hot air. In order to explain this phenomenon, interfacial reaction of eutectic solder and Au/Ni/Cu pad was analyzed further.

Fig.5 shows backscattered scanning electron micrograph of solder bump interface reflowed by laser and hot air. The laser power is 18W, and laser heating time is 0.2s. From Fig.5a, it can be seen that solder reacted with Au/Ni/Cu pad within short laser heating time. The reaction zone includes need-like microstructure, continuous intermetallic layer and the remaining Au element. Some needle-like phases grew perpendicularly or sidewisely from the continuous intermetallic layer at the solder/pad interface into the solder, and then spread out to the entire interface region. EDX analysis on the continuous layer, needle-like phases shows that their chemical compositions are all close to $AuSn_4$. The growth of acicular $AuSn_4$ phase from the continuous layer and perpendicularly distribution to the interface suggests a steep temperature gradient in the molten solder. As shown in Fig.5b, a thin layer of intermetallic compound was found at the interface of solder bump reflowed by hot air. EDX analysis on the continuous layer after magnification reveals that its composition is near to Ni_3Sn_4. $AuSn_4$ particles distribute inside the solder bulk randomly, and some coarse Pb-rich phases were found near the interface. It indicates that Au element has dissolved into the solder completely during hot air reflow soldering. The formation mechanism of $AuSn_4$ particles will be discussed later in this paper. Fig.5c and d show the microstructure inside the solder. It can be seen that eutectic microstructure of solder bump reflowed by laser is much finer than the solder bump reflowed by hot air. The finer eutectic microstructure is caused by rapid cooling rate of molten solder which could reach to 10^4℃/s during laser reflow soldering. The rapid cooling rate promotes nucleation, but inhibits growing. So it can be concluded that it is the combination effect of continuous $AuSn_4$ layer and finer eutectic microstructure that resulted in higher shear strength of solder bump reflowed by laser. On the one hand, "wedge" function of the sidewise $AuSn_4$ phases at the interface strengthened the solder bump formed by laser reflow soldering. The previous study indicated that the shear strength of solder joint increases with the thickness of intermetallic compound layer increasing, until it reaches the critical value[7]. It indicated that the thin intermetallic compound layer of solder bump interface reflowed by hot air resulted in the lower shear strength. On the other hand, as the fracture occurred at solder side, the finer crystal grain of solder inside solder bump reflowed by laser would contribute to higher shear strength.

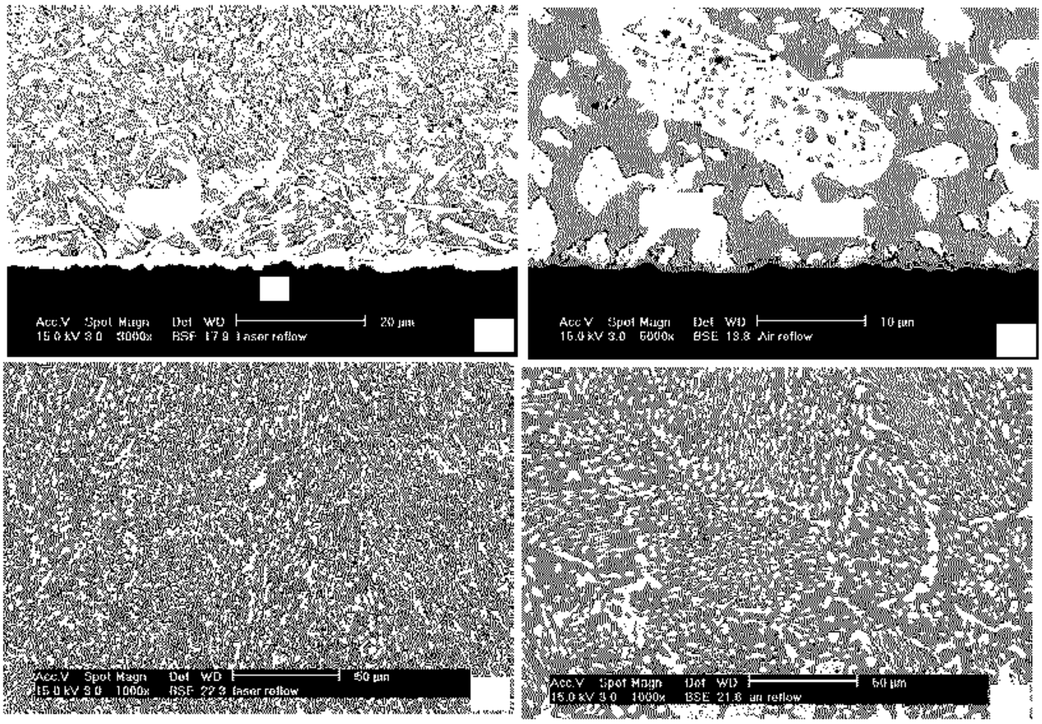


Fig.5 SEM image of solder /pad interface and microstructure inside solder bump

(a), (c) interface and microstructure inside the solder bump formed by laser reflow soldering;

(b), (d) interface and microstructure inside the solder bump formed by hot air reflow soldering

It is quite amazing that eutectic solder reacted with Au/Ni/Cu pad at a very short time. Even with the short heating duration such as 0.2s by the laser beam, the reaction layer grew up to 4 μm. Moreover, the morphology and distribution of $AuSn_4$ is quite different inside the solder bump reflowed by two soldering methods. So the effect of laser heating time on the morphology of intermetallic compound was discussed further.

Fig.6a shows the interfacial microstructure of solder bump reflowed for 0.2s by laser under 20W. The reaction zone includes continuous $AuSn_4$ layer, the remaining Au element and needle-like $AuSn_4$. A crack was found at the root of $AuSn_4$ phase, some $AuSn_4$ phases were broken off from the interface and fell into the solder. The formation of crack suggests that $AuSn_4$ leaves the interface under certain force. During laser heating, steep temperature gradient exists inside molten solder, which results in strong molten metal flow. It could be considered that $AuSn_4$ was broken off under molten solder flow. Furthermore, higher stresses built at the interface under the fast cooling condition of laser reflow soldering might also lead to cracking . Fig.6b shows interfacial microstructure of solder bump reflowed for 0.4s by laser under 20W. It can be seen that $AuSn_4$ intermetallic compounds disappear at the interface, and the eutectic microstructure of solder is fine and uniform, no Au-Sn intermetallics can be found inside the solder.

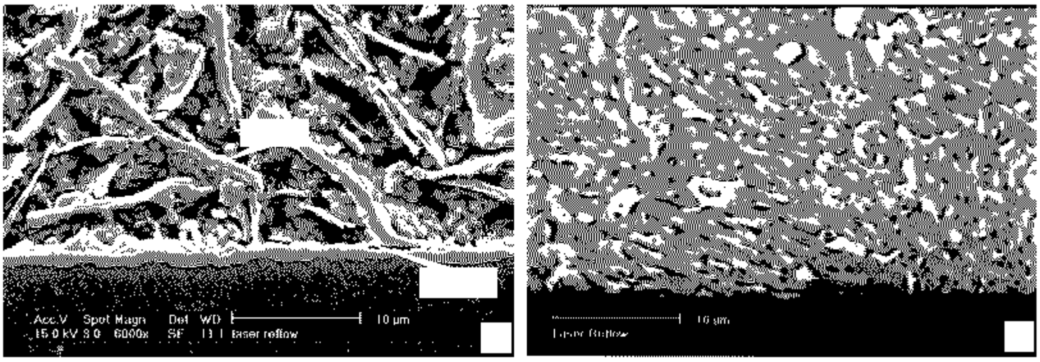


Fig.6 SEM image of the solder bump interface reflowed by different laser heating time

(a) 0.2s, 20W, (b) 0.4s, 20W

From above analysis, it can be concluded that when the liquid solder is in contact with Au, two reactions should complete with each other: one is the dissolution reaction of Au into the solder and the other is the formation reaction of Au-Sn intermetallics. It was widely known that the dissolution rate of Au into the molten solder is extremely rapid and increases with the temperature increasing. Previous investigators established that the dissolution rate of Au in eutectic PbSn solder follow an Arrhenius relationship[8].

$$Ln(R)=-98.48-14.49*Ln(1/T)$$

where R is dissolution rate, T is temperature.

So Au dissolves into the solder at the initial stage of the laser soldering. As the dissolution continues, the Au concentration near the interface should reach the solubility limit at the soldering temperature. Upon reaching the limit, the reaction of the $AuSn_4$ intermetallics formation at the interface should be followed. Then the $AuSn_4$ broke off from the interface and fell into the solder due to combination of molten solder flow and brittle nature of $AuSn_4$, and $AuSn_4$ has a tendency of dissolution into the solder, so it is possible that $AuSn_4$ dissolved into the solder partially.

It was generally believed that during hot air reflow, Au in the Au/Ni/Cu pad dissolved into the molten solder very quickly and the Ni layer was exposed. The exposed Ni then reacted with the solder to form Ni_3Sn_4 at the interface. During the solidification of the solder joint, the dissolved Au reacted with Sn to form $AuSn_4$[9,10]. This assumption seems to be reasonable. However, there is not any direct evidence to support this view. This study indicates that eutectic solder reacted with Au in the pad soon after the solder was melted. So the randomly distribution of $AuSn_4$ particles inside the solder bulk reflowed by hot air could be considered as the result of dissolution of $AuSn_4$ layer. When the continuous $AuSn_4$ layer fell into the solder, exposed Ni reacted with the Sn to form Ni_3Sn_4.

4.Conclusions

1. Formation of solder bump is controlled by laser input energy. Good quality solder bump with smooth surface could be achieved with appropriate laser reflow soldering parameters， and shear strength of solder bump reflowed by laser is higher than that of solder bump reflowed by hot air
2. Sn reacts with Au/Ni/Cu pad soon after the solder is melted to form a continuous $AuSn_4$ layer. At the same time, eutectic microstructure of the solder is much finer than that of the solder reflowed by hot air.

3. Morphology and distribution of interfacial intermetallics is related with laser input energy. With the increase of laser input energy, the continuous $AuSn_4$ layer converts into needle-like $AuSn_4$, then into the small particles, distributing evenly inside the solder.
4. During hot air reflow soldering, Au reacts with Sn first to form continuous $AuSn_4$ layer first, then $AuSn_4$ intermetallics dissolve into the solder as small particles. Finally, the exposed Ni layer reacts with Sn to form Ni_3Sn_4.

Acknowledgements

The authors are grateful to Professor Y.C. Chen of City University of Hong Kong for providing the equipment. The research was initiated and supported by a grant from ASMPT of Hong Kong Appreciation is also extended to Dr. P. L. Tu of City University of Hong Kong for his voluble comments.

References

[1] Lau,J.H., and S.Erasmus.. *Electronic Packaging & Production*, 6(1993),p51.
[2] H. L. Lau. *Ball Grid Array Technology*. New York: McGraw Hill,(1995), p23.
[3] Sandeep Mittal, Glenn Y. Masada. *IEEE Transaction on Components, Packaging, and Manufacturing Technology*. 19(1996),p127-132
[4] Wenge Yang, Robert W. *Journal of Electronic Materials*. 23(1994), p765
[5] Laertis Economikos. *Journal of Vacuum Science and Technology*. 12(1994), p2394.
[6] Jong-Hyun Lee, Yong-Ho Lee, and Yong-Seog Kim.. *Scripta Materialia*. 42(2000), p789.
[7] Jong-Hyun Lee, Daejin Park, and Yong-Seog Kim. *Journal of Electronic Materials*. 29(2000),p1153.
[8] W.G. Bader. *Welding Journal. Res. Suppl.* 48(1969),p551s.
[9] C.E. HO, Y.M. Chen. *Journal of Electronic Materials*. 28(1999),p1231
[10] A.Zribi, R.R. Chromik, R. Persthus, K. Teed, and L.Zavalij. *IEEE Trans. Comp. Manufact. Technol*. 23(2000),p383.