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CHALLENGE IN FREE AIR BALLS FORMATION OF COPPER DURING THERMOSONIC WIRE BONDING PROCESS

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ABSTRACT

Copper wire ball bonding has gained popularity recently due to its economic advantages and superior electrical and mechanical performances. Although it has great advantages compared to gold, however, it still not been widely used in industry because of some challenges that need to be addressed. One of the main challenges in this copper wire bonding process is to form a free air ball (FAB) without being oxidized. This paper reviews the difficulties and challenges that the semiconductor industries faced during copper wire bonding process in order to get the perfectly spherical and bright surface of FAB without signs of oxide scales.

INTRODUCTION

Wire bonding has remained as the most popular interconnection methods in semiconductor device packaging today instead of flip-chip and tape-automated bonding in the field of high-speed, power management devices and fine-pitch applications. Gold is still widely used as an interconnection material in wire bonding process. However, due to the increasing demand for enhancing the reliability of the devices and cost saving factor, attention has been focused on wire bonding using high strength and conductive copper wire [1]. The benefits of copper wire bonding as compared to gold wire bonding are shown in Table 1. Copper possesses greater conductivity than gold, allowing the use of a smaller diameter wire for equivalent conductivity or, in power limited devices, allowing for higher current-carrying capacity [2].

In spite of promising performance of copper, copper wire ball bonding has not been widely implemented in mass production in most semiconductor industries today. The major reason is copper readily oxidizes in a relatively high temperature environment. Copper oxide growth is not self-limiting and it is not breakable during bonding which can impedes the bonding process and leads to non-stick bonds and other reliability problems. Prevention of copper wire and copper ball oxidation during wire bonding is very important to have a reliable bond. Furthermore, copper wire bonder requires additional tools to prevent copper oxidation and the parameters about the forming gas need to be defined and optimized. Figure 1 shows the schematic illustration of the Electron Flame Off (EFO) setup of copper wire ball bonding. The EFO setup consists of EFO wand, capillary and inert gas tube. The

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wire ball bonder uses an EFO unit connected to high voltage to create a free air ball (FAB). During operation, the EFO gap was breached by a high current to create a high voltage spark that melt the tail of the metal wire in a glow discharge to form a spherical ball. Instead of that, the copper wire bonding must be sealed in an environment without oxygen and be enclosed in an inert gas environment to prevent the oxidization of the FAB during FAB formation [3,4].

Table 1: Copper's Advantages of Copper as Compared to Gold.

Features	Benefits
Lower cost	Package savings Competitive advantage
Electrical conductivity Gold $4.55\times10^7\ \Omega$–m Copper $5.88\times10^7\ \Omega$-m	Thinner wires for fine pitch packages Higher current capacity for power packages
Thermal conductivity Gold 31.1 kW/m^2K^0 Copper 39.5 kW/m^2K^0	Improved heat transfer efficiency
Mechanical Properties	Higher tensile strength Increased ductility Stronger heat Affected Zone (HAZ) Stiffer, improved looping Reduced molding sway
Slow Intermetallic Growth	High mechanical stability Long-term reliability Less resistance drift/time

Challenges in FAB Formation

The ball bonding process requires the formation of a ball on the tip of the wire. The ball is formed by a spark, discharged from the EFO wand. The spark melts the wire tip and the surface tension of the molten tip causes a spherical ball formation. However, to get standard FAB balls with consistent dimensions and unoxidised ball surfaces are crucial in copper wire ball bonding process because copper wire oxidizes quickly when exposed to elevated temperatures and slowly under ambient conditions. Oxidation during a ball formation significantly increases surface tension

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and results in distorted hard balls, unsuitable for bonding. The perfect ball is the ball that is perfectly spherical and has a clean, bright surface, without signs of oxide scales or blemishes [3, 4]. Constant ball and wedge dimensions are important for the connection quality in wire bonding process because any slight variations in the deformed ball size of the first bond would cause quality defects. Since the size deviation and the miss control of FAB are directly related to the defect modes of wire bonding such as off-centered bond and ball-lift, the FAB control of wire is considered to be very critical. Otherwise, the length of Heat Affected Zone (HAZ) has direct relationship with the ball neck damage of loop height control [3, 5]. Therefore this paper will review the challenges to obtain a good FAB formation without being oxidized from the researches and studies done by other researchers before.

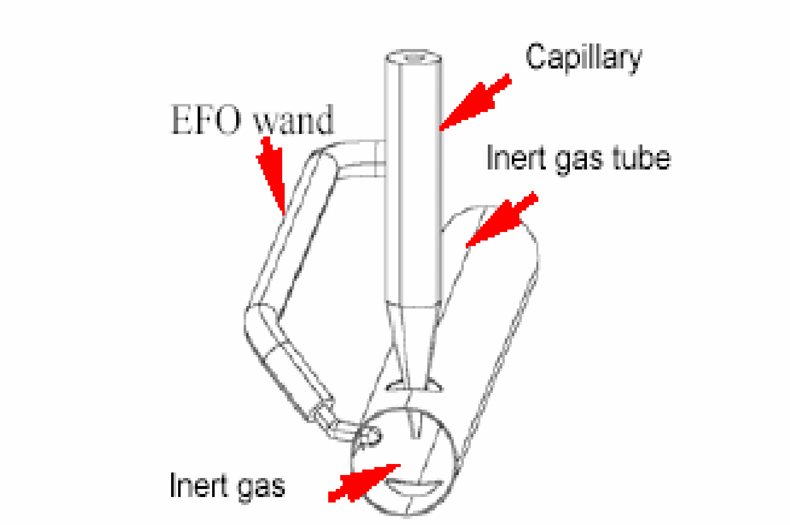

Figure 1: Schematic illustration of the EFO setup of copper wire ball bonding.

EFO Current Parameter Effects on FAB Formation

Due to the thermal properties of copper, more energy is needed during EFO process to form a standard FAB ball (the ball diameter is 2-2.5 times to the wire diameter in general). These studies showed that only the FAB ball with more than 120 mA EFO current would get symmetrical shapes and perfect surface [3]. It is reported that when the EFO current was 90 mA, the FAB ball was clearly off-center, un-round and there were some legible ripples in the ball surface. The FAB balls formed under less than 120 mA such as 110 mA and 90 mA could not meet the requirement due to the insufficient EFO current to possibly generate spark that can melt the end of the copper wire to form the tiny ball and contributed to the bad surface as shown in Figure 2 below. Basically, the surface conditions of FAB is also a critical requirement in the process because the FAB balls with bad surface conditions would cause defective bonds, failure to stick and craters. With the elevation of the EFO current, this condition is improved [5].

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Forming Gas and Flow Rate Effects on FAB Formation

It is generally accepted that the impact of the forming gas flow rate on the FAB formation was not very significant. However, Hang et al. (2005) studies indicated that the flow rate of forming gas had a significant impact. A low flow rate of forming gas would lead to FAB balls with top-ends and high flow rate would cause the tilted FAB balls. When the flow speed is too low, 0.4l/min in this study, the FAB ball would have an asymmetric shape with a top end and considered to be a bad FAB that could bring reliability problems. The cause of this phenomenon was unknown and it was assumed that the type of gas flow and the cooling-down method of FAB ball had some impacts on the FAB ball appearance. Further research about this phenomenon would be carried out in the next steps. If the flow rate is high, the forming gas would disturb the wire tail and make the FAB ball tilted during the EFO process. Therefore, too high flow rate had an adverse effect on the FAB formation with 50.8 µm copper wires.

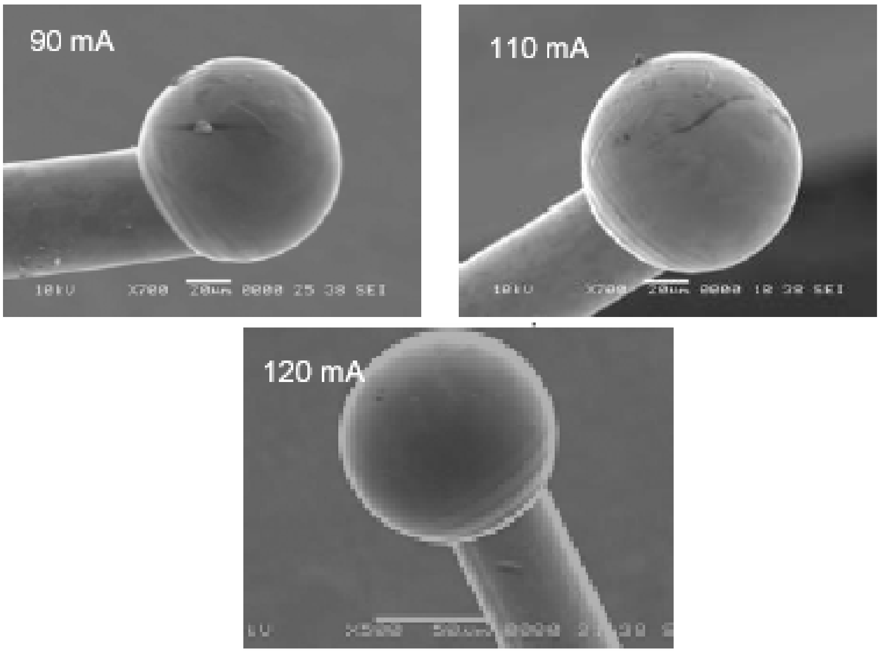
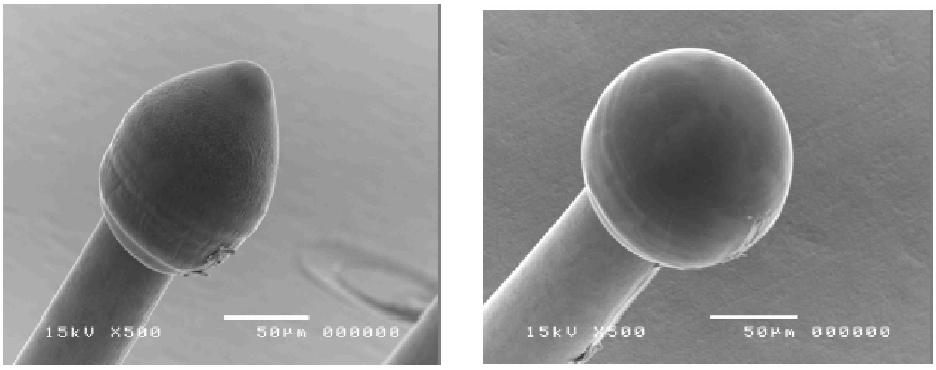


Figure 2: SEM of FAB under different EFO current.

Besides non-spherical FAB, the size and FAB formation is also affected by the forming gas type. Ho et al. (2005) had studied the mechanism of formation of copper FAB under different types of inert gas environment which is in 100% N_2, 5% H_2 + 95% N_2 and 10% H_2 + 90% N_2. It is seen that when forming gas (with small percentage of hydrogen in the cover gas) is used, besides serving the function as a reducing agent, the hydrogen is able to provide additional thermal energy for melting the copper wire during the FAB formation which is attributed to the ignition temperature of the hydrogen. Toyozawa et al. (1990) also deduced that FAB formation with the forming gas (95% N_2 + 5% H_2) will provide much better (oxidation free) surface quality that will result in better bonding.

In order to have a softer FAB, it is recommended to have higher flow rate and shorter EFO firing time. Basically, if the flow rate is not sufficiently high to provide a complete inert gas envelope during the melting of the copper FAB, the oxygen at the surrounding atmosphere might surge in and oxidization of the surface layer of the molten copper FAB would take place and results in pointed FAB. Hence, it is reasonable to assume that higher current could result in higher temperature during the melting of FAB. Figures 3 and 4 showed the enlarged views of the SEM pictures for the pointed FAB and that of the spherical FAB. It can be seen that there was some level of scaling at the region of the pointed ball but for spherical ball, it has a very smooth surface. This scaling is most likely due to oxidization of the surface layer of the molten copper FAB. In order to have all FAB in spherical form, one only needs to increase the flow rate as this will provide sufficient inert gas volumetric coverage during FAB formation.



(a) (b)

Figure 3: SEM picture of pointed FAB, (a) scaling surface, (b) smooth surface.

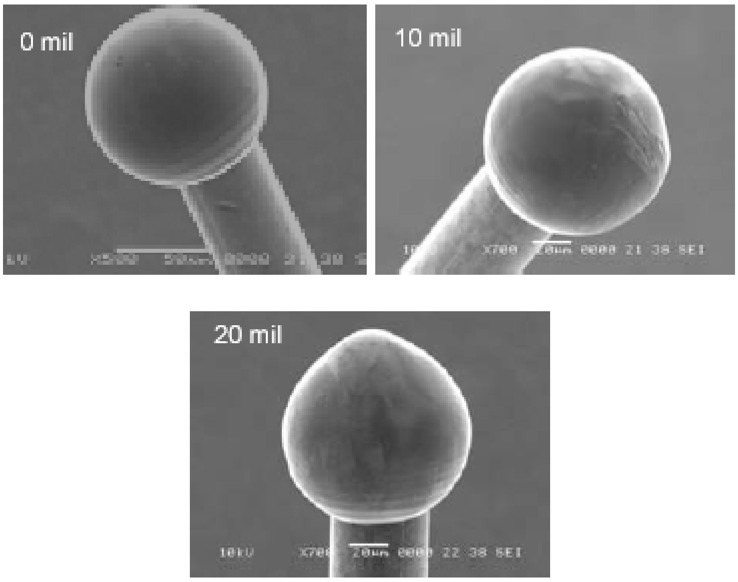


Figure 5: The SEM of the FAB under different gap length.

Gap Length Effects on FAB Formation

A high voltage is produced between the wire tail and EFO wand during EFO process. Under the effects of the high voltage, the air in the gap was ionized. Then an electric discharge channel that could transmit the EFO current was formed. During the EFO process, lots of heat was generated in the gap and then partially used to melt the wire tail to form a FAB. Moreover, the other heat was dissipated uselessly. Generally, the longer gap would cause more heat dissipation, so, the length of the gap would have some impacts on the FAB formation. These studies indicated that excessive gap length had an adverse effect on the FAB formation because of the more heat dissipation that would cause abnormal FAB balls with bad surface conditions [3]. They found that the FAB balls had similar dimensions but dissimilar appearance. Obviously from in Figure 5 below FAB balls with gap length 0 µm (0 mil) had a bright, clean surface compared to FAB balls with gap length 254 µm (10 mil) and 584 µm (20 mil). When the length of the gap increased, the heat dissipation also increased. Then the FAB balls became asymmetric and the surface became rough. This kind of the FAB balls would cause craters on the pad and other reliability problems during bonding process.

CONCLUSIONS

As copper ball bonding establishes a stronghold in fine-pitch packaging, it will grow and eventually reach a dominant position. In spite of having great advantages such as cost reduction, improved reliability and better electrical performance, there are still many challenges ahead before copper ball bonding becomes a fully qualified manufacturing process. The major challenges are to get the perfect FAB formation without being oxidized. Therefore, all the factors affecting the FAB formation such as EFO parameter, types of forming gas and flow rate and gap length need to be considered in order to implement it in mass production in semiconductor industries.

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