Free Air Ball Consistency of Palladium Coated Copper Wire

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Abstract

The formation of good free air ball (FAB) in palladium coated copper wire depends on many factors including the type of protection gas used, flow rate, Electric Flame Off (EFO) current, firing time and gap between the tip of wire and EFO wand. These factors can individually or, in combination of which, affect how good a ball can be formed prior to bonding onto the bond pad of a device. It is therefore important to find an optimum condition in forming good FAB so as to avoid poor bonded ball quality, or worse, non-uniform ball hardness that could lead to damage of the bond pad upon impact. The microstructure of the free air ball from palladium coated copper is unlike that of pure copper wire. It consists of palladium or palladium rich phase that can either exist partially or majority on surface of the ball making the structure non-uniform and inconsistency from one condition of EFO firing to the either. The hardness of the ball is also complicated by the non-uniform microstructure in such a way that determining the microhardness of the ball is never a straight forward characterisation. This paper covers the effect of process condition on the FAB size and quality of the wire. Microstructure and hardness of the FAB processed with different conditions are also presented and discussed.

Keywords: palladium coated copper, free air ball, microhardness

Introduction

The interest of using palladium (Pd) coated copper wire has been growing since early 2009 when gold price exceed US$ 1000 per troy ounce and pressure to reduce IC package cost increased. While switching from gold wire to bare copper wire provides significant cost reduction, especially on high pin count devices, the challenges with the use of copper wire in terms of handling, material properties, surface oxidation that impact bonding consistence and performance, shorter floor life and bonding tool life are a concern to many bonding engineers. Pd coated wire has the advantage over bare copper wire in terms of surface protection of wire surface to prevent or minimize oxidation due to mishandling and storage that renders it less susceptible to bonding issues, especially on 2nd bond.

As Pd coated copper wire is not homogeneous like bare copper [1-3], the melting of the wire to form a free air ball prior to bonding on bond pad of an IC chip need to be understood as it would allow bonding engineers to properly develop the process in order to prevent or minimize pad damage due to different free air ball (FAB) characteristics compared with pure copper or gold wire. This paper covers the understanding of process gas effect on the FAB quality. The parameter setting used in forming the ball also has an impact on the ball consistency. Most interestingly is the very different microstructure and respective hardness of the ball compared with pure metal wire can be a challenge in developing bonding process.

Experimental

Pd coated copper wires of mainly 0.8 mil (20 µm) in diameter were being processed with K&S's ball bonders fitted with copper kits. The models used in this study varied from fairly new model like iConn to older models like Maxum Ultra and 8028PPS. Free air balls were prepared using K&S bonders and in forming gas that consists of 95%

nitrogen and 5% hydrogen (95%N_2/5%H_2) and inspected with either Nikon high power microscope or Zeiss's LeoVP 1450 Scanning Electron Microscope (SEM). Cross-sections of the FABs were first cold mounted with epoxy followed by progressive grinding with 500 grid sand paper to at least 1200 grid fine sand paper followed by progressive polishing using diamond polish paste down from 6 micron to 1/4 micron size. Microstructure was revealed by chemical etching with special prepared nitric acid solution while images were taken with Leica DMRM high power microscope and SEM. Microhardness measurement was carried out using Fisher H100CXYp microhardness tester with a load of 0.05gm at duration of 5 seconds.

Results and Discussion

The quality and consistency of the FAB depends on a number of parameters such as Electric-flame-off (EFO) current, time, gap dimension between the tip of wire and tip of EFO wand, and protection gas flow rate, etc. Figure 1 shows the SEM images of surface quality of a Pd coated copper FAB formed with and without protection gas. It is clear that at least an inert gas like nitrogen is needed to prevent oxidation of the wire during FAB formation to achieve a smooth and spherical ball. Otherwise, the surface will oxidize and appear orange-skin-like effect. A good quality ball can only be formed if the environment and parameter settings are optimized to achieve high percentage of good FAB.

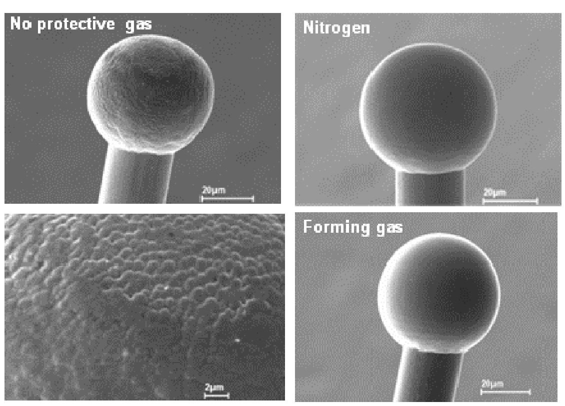

Fig. 1 Surface quality of Pd coated copper FAB. Protection gas is need when melting the wire before it forms a ball to prevent oxidation that lead to rough surface.

Effect of Gas on FAB Diameter

In the FAB formation, the size of the ball is targeted depends on wire diameter and application. Usually the size is 1.8 to 2 times the diameter of the wire. For a 0.8 mil (20 µm), for example, the targeted FAB size is usually set to 40 µm. When EFO current was applied and an electric spark is generated to melt the wire at the tip, how the quality of the resultant FAB is formed depends on how well the tip of the wire was protected from oxidation due to presence of oxygen within the vicinity. Figure 2 shows the effect of gas and flow rate on the FAB size of an 0.8 mil Pd coated wire processed in K&S's 8028PPS bonder. The gas flow rate used range from a low rate of 0.8 standard cubic feet per hour (scfh), or approximately 0.34 litre per minute, to double the rate of 1.6 scfh. When nitrogen was used to form the ball, the size of the ball decreased as the gas flow rate increased. Similarly for forming gas, the ball size also decrease with increasing flow rate. However, for forming gas, the resulting size of the ball was always bigger than the one formed under nitrogen. At low gas flow rate, the difference in average FAB size between the 2 gases was around 2 µm while at high flow rate of 1.6 scfh, the difference increased slightly to about 3 µm. Such difference between gas and flow rate is believed to be due to thermal process during EFO process. Forming gas is expected to cool faster because hydrogen provides 7 times higher thermal conductivity compared to nitrogen. Despite this, some thermal effects like reaction with oxygen and different behavior of plasma seem to provide more energy for FAB formation. In the case of nitrogen, there is no interaction and simply an inert environment protection on the wire. With higher flow rate, the cooling effect increases and lead to smaller balls.

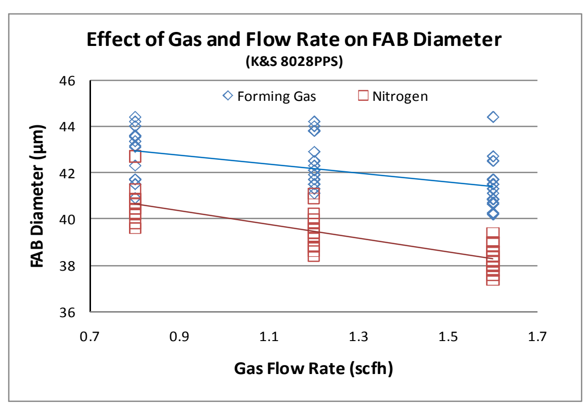

Fig. 2 Effect of processing gas on the FAB diameter of a 0.8 mil Pd coated copper wire. The higher the flow rate (1 scfh ≈ 0.42 l/min), the smaller are the balls.

Similar effect on FAB size can also be seen with another K&S bonder model, iConn. Figure 3 shows the effect of FAB diameter with different flow rate of nitrogen. The decreasing ball diameter with increasing flow rate is evident.

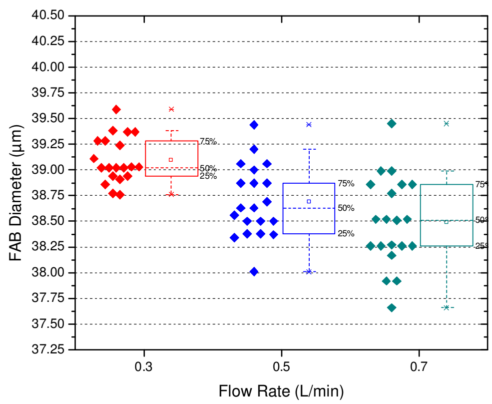

Fig 3. Effect of nitrogen flow rate on FAB diameter of Pd coated copper processed in iConn. The higher the flow rate, the smaller is the ball.

For a constant gas flow rate, the size of the FAB also varies with duration of EFO firing. Figure 4 shows the FAB size growth trend of a 0.8 mil Pd coated wire processed using K&S iConn bonder at 65 mA EFO current. The gas used was nitrogen and the flow rate was set to 0.3 l/m, which resulted in almost 100% good FAB. It can be seen that the increase in ball size over firing time appears to be linear with a growth rate of about 0.1 µm/µs. Longer firing time allows more energy to be supplied to the wire and maintain continuous melting of the wire to form FAB.

Effect of Gas on FAB Quality

A complete good spherical ball is expected for good bonding but not every time the ball is formed regularly. In some circumstances, the ball may appear pointed, or, strawberry shape, others may appear to have a deep dimple or sink mark. Figure 5 shows typical example of good and defective balls seen in SEM. Such defective balls could be the result of insufficient melting or other factors resulted in poor ball formation.

Similar to FAB diameter, gas flow rate has an impact on the ball quality. Table 1 shows the percentage of good FAB obtained for a 1 mil Pd coated wire processed in K&S Maxum Ultra bonder. Perfect good FABs can be obtained with sufficient gas coverage related to the gas flow, irrespective of the type of gas used. When gas flow is too low, no good FAB can be obtained for this bonder.

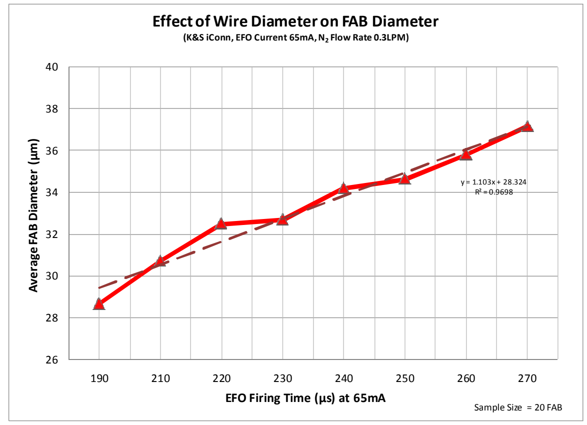

Fig. 4 Change of FAB size with different firing time at fixed EFO current. The longer the firing time, the larger is the ball.

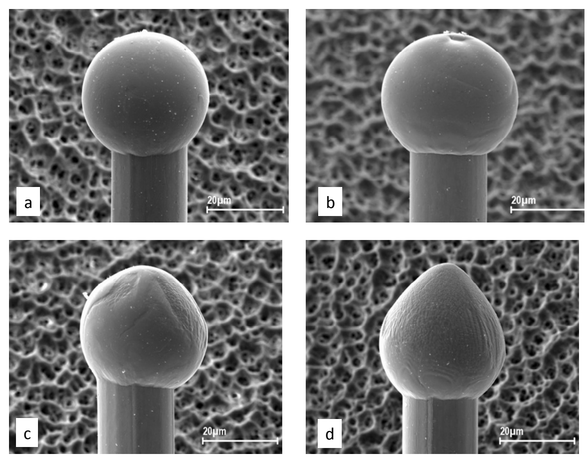

Fig. 5 SEM images of good and bad FAB. (a) good (round and smooth), (b) slight dimple at tip, (c) deformed, (d) pointed (strawberry shape)

Table 1

Percentage of good FAB under different gas and flow rate (typical for a 1 mil wire) in K&S Maxum Ultra bonder

Percentage Good FAB – Pd Coated Cu					
Flow Rate (l/min)	0	0.3	0.5	0.7	0.9
Nitrogen	0%	0%	100%	98%	98%
Forming Gas	0%	12%	100%	96%	100%

For a different bonder, the effect of gas flow rate and type of gas yielded a different result. Figure 6 shows the percentage of good FAB obtained from screening 400 FABs of a corresponding 0.8 mil wire at each flow rate condition. Across the flow rate between 0.3 to 0.7 litre per minute, almost 100% good FAB can be obtained if forming gas is used. However, the amount of good FABs processed in nitrogen is limited to low flow rate. The reason for the poorer FAB quality at high flow rate of nitrogen is probably due to no aided burning and faster cooling at high rate for a finer diameter wire. The other reason is probably due to different design of the glass or ceramic tubes in the two K&S bonders that render different results.

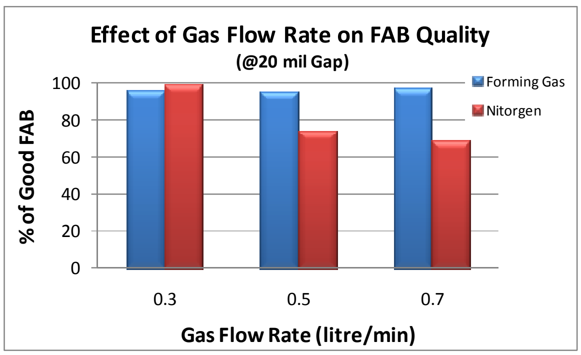

Fig. 6. Percentage of good FAB formed for a 0.8 mil Pd coated copper wire in forming gas and nitrogen using K&S's iConn showed different results.

The quality of FAB is also being studied with different EFO gap settings. Figure 7 shows the effect of EFO gap on the FAB quality of 0.8 mil wire diameter processed with nitrogen in iConn bonder. It can be seen that at low flow rate, all FAB are consistently good with close to 100% good balls obtained. However at higher flow rate, the percentage of good balls drops significantly, especially for short gap setting. The effect was not so severe with 20 mil gap. This indicated that an optimum gap must be set to achieve 100% good FAB.

Pd Distribution in FAB

In the course of melting, the core material, copper, will tend to melt first before palladium which has a melting temperature of 1550°C vs 1083°C for copper. As EFO sparks onto the wire, heat is build up at the tip to cause the copper core to melt but whether the palladium layer surrounding the wire also melt during the short micro-second timeframe difficult to confirm. At the end of the process, some Pd is believed to have dissolved into the copper but the majority of which remains un-dissolved and remain on the surface of the FAB or form a layer of silverish metal [1] consist of palladium.

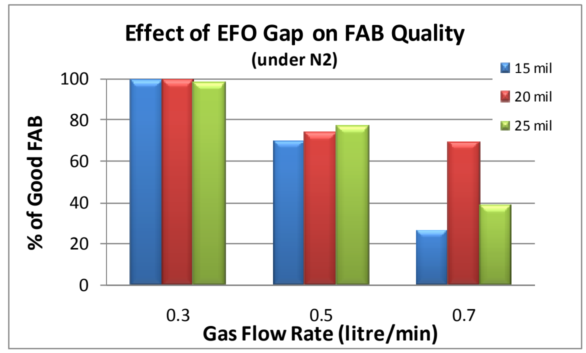

Fig. 7 Effect of EFO gap on FAB quality. At low nitrogen flow rate, FAB is consistently good for all gap width but deteriorates as higher flow rate was used.

From the binary phase diagram of Cu-Pd (Figure 8), it shows that the two metals can form solid solution in most composition upon equilibrium cooling. In Pd coated copper wire, the amount of Pd is only a few percent by weight of total wire. Therefore, from the binary phase diagram, one would expect to see the FAB of the Pd coated wire to have a complete Cu-Pd solid solution. However, in the FAB formation process, the solidification of the Pd coated wire will be fast as if it goes through quenching in air due to the micro-second duration of melting with the high energy EFO spark and cooling in the presence of protection gas and surrounding environment temperature in the bonder.

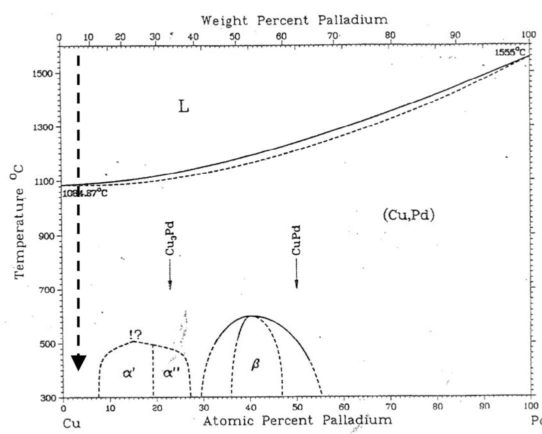

Fig. 8 Cu-Pd phase diagram showing the two metals will form solid solution upon equilibrium cooling at below 10% Pd (arrowed) or higher than 55% Pd.

From the cross-section of the FAB, it revealed that the grain structure in the bulk of the ball is a mixture of large, pure copper grain with separate grain or phases of Pd or Pd rich phase on the outer layer of the ball. The existence of the Pd layer depends on many factors such as bonder design, EFO parameters (current and time), BSR and EFO gap distance. One or all of the factors will affect the uniformity of the Pd layer in the ball.

Figure 9 shows the cross-sectional image of 0.8 mil Pd coated FAB processed in Maxum Ultra bonder at different EFO current and time. It has been observed that at low EFO current, much of the Pd remained behind the ball close to the wire portion. As EFO current increased, more heat was generated to melt the wire and that allowed Pd at the outer surface to flow, if not melt, around the surface of the ball towards the tip. Due to the vast difference of melting temperature between the two metals, there is probably insufficient energy to cause the molten copper to increase in temperature and allow Pd to melt and dissolve completely into the copper to form a homogeneous solid. At higher EFO current, there was enough heat to allow the flow of Pd on the surface of the wire to interact more readily and flowed into the bulk of the FAB. However, it is obvious that the Pd layer did not managed to melt completely even at very high EFO current of 120 mA in order to form a solid solution with copper in the core of the wire. In the optical images, Pd can be reflected in the bluish region and it resisted the etchant during the etching process to reveal microstructure of the wire. Apart from the bluish region, the adjacent area around the Pd also resists the etchant attack and this indicates that the lighter area next to the Pd is not pure copper but perhaps a low Pd content Cu-Pd mixture. EDAX analysis by Binghai Zhang et el [4] confirmed Pd content is not uniform on the FAB but it was not clear if the detection of high content of Pd was a result of thicker layer underneath the ball that allowed better detection through EDAX.

FAB Hardness

As the grain structure of Pd coated copper's FAB is not homogeneous as in pure copper wire, the hardness of the FAB is also discovered to vary from point to point. Indeed, microhardness measurement done FAB from different EFO currents showed high variation of hardness as been reported elsewhere [1]. Figure 10 shows typical example of the hardness value obtained in different positions in the FAB. Measurement was done using a low load of 0.05gm (5 mN) over a period of 5 seconds. Unlike similar study by others [5] which used a much higher load of 3 gf, the low load minimize error in measurement due deeper indentation mark at high load onto the softer support by the cold mount epoxy.

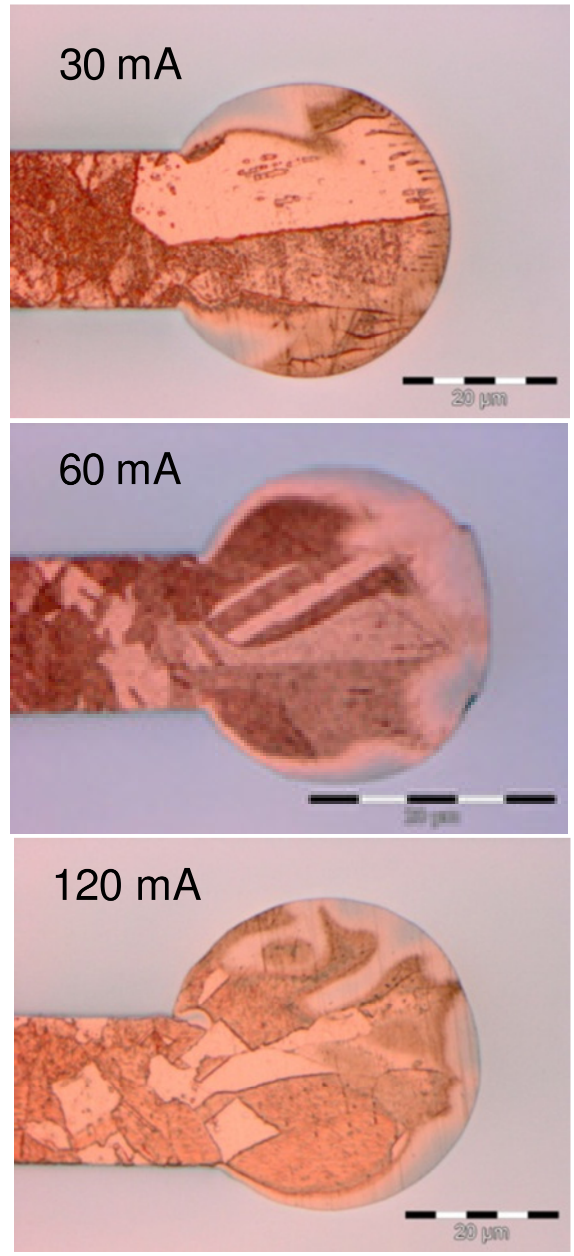

Fig 9. Pd distribution on FAB at different EFO currents. Pd or Pd rich phase moved from behind the FAB at low EFO current to the tip and form a continuous layer around the ball at high EFO setting.

Figure 10 shows typical example of a FAB formed with 60 mA EFO current. It can be seen that the hardness at the area where Pd is presence, it reflected highest hardness as compared with the area within the ball or in the region next to Pd. The hardness of this FAB varies from Hv of 89 to more than 105, a range far higher than normally recorded on pure copper. At different EFO current, the FAB hardness also changed, as seen in Figure 11.

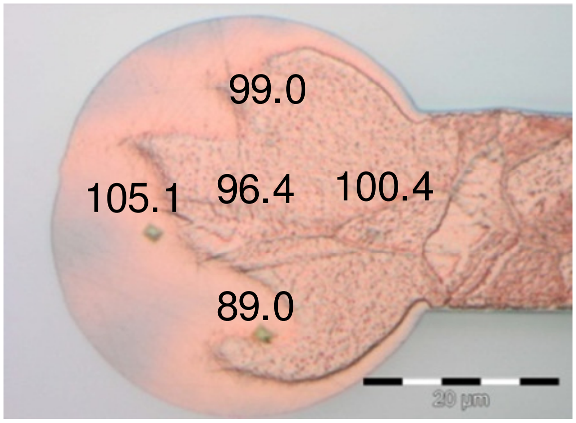

Fig. 10. Typical microstructure of Pd coated copper FAB. A large area of the ball consists of Pd or Pd rich phase that is resistant to acid attach during metallurgical etching. The values represent the measured microhardness at the location indicated.

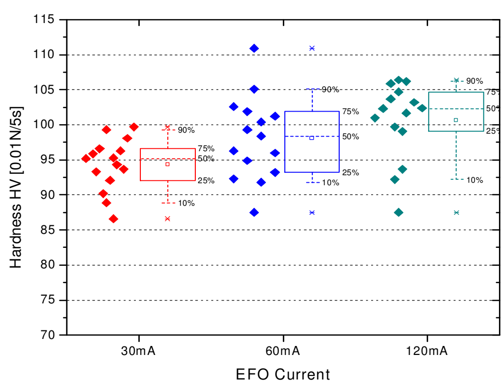

Fig. 11 FAB hardness of Pd coated copper processed with different EFO current shows increasing hardness of the ball as current increases.

Figure 11 shows the hardness value of a 0.8 mil Pd coated copper wire formed in K&S bonder using different EFO current with same targeted ball size of 40 µm. From the previously shown FAB microstructure at different EFO current, the upward trend of hardness with increasing EFO current can be explained by the higher tendency of larger Pd or Pd rich phase existed in the FAB that renders higher hardness being recorded. This observation is to be confirmed on other bonder models to see if there would be differences due to different melting characteristics with different bonders.

Conclusions

The FAB formation of Pd coated copper wire can be made possible with the use of nitrogen at suitably low flow rate, unlike bare copper that has to have forming gas for good FAB formation. In forming gas environment, Pd coated copper has a wider process window to form good FAB. The microstructure and hardness of the Pd coated copper is rather complicated with no consistent and uniform grain structure and hardness guaranteed. There is a trend on the Pd layer moving from the back of the FAB to the front and partially mixed into the copper core as EFO current increases. Hardness of the FAB has wide variation and increase with increasing current. Such hardness variation will post a challenge in bonding onto sensitive bond pad whereby pad crack and cratering will have a higher chance to occur.

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