Influence of laser power on bonding strength for low purity copper wire bonding technology

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ABSTRACT

The drive for improving copper wire bonding has been more rampant with continued rise in gold prices. The global increase in gold price directly resulted the semiconductor packaging industry to rapidly replace gold as a medium of interconnection to copper wire. This is a cost effective solution for creating viable interconnections for integrated circuit packaging. However, through past research it is well known the hardness of copper wire is significantly higher compared to gold wire and the usage of copper poses various challenges in electronic packaging. These challenges, resulting from the usage of copper wire is primarily due to the high hardness of copper. Higher hardness of copper as compared to gold will require higher bonding force and ultrasonic energy to create bonding to the bond pads. The higher bonding force makes copper wire bonding unsuitable for fragile structures and possible damage to underlying circuitry. Past research has also exhibited the hardness of copper wire decreases as the purity levels increase, however the usage of higher purity copper wires in high volume manufacturing may significantly increase manufacturing cost. This research therefore investigates the application of laser assisted heating for enabling improved copper wire bonding strength and improved grain structures for low purity copper wires. Experimentations were conducted accordingly on three copper wire purity types, 99.99% purity (5N), 99.99% purity (4N) and 99.999% purity (5N) copper wires, so as to evaluate the impact of laser assisted heating on various copper purity levels. The result of this study shows laser assisted heating is able to improve the bonding strength and improve the grain structure by means of reduced columnar grains for copper wires with lower purity levels. It is shown, higher as-bonded ball shear strengths with fewer columnar grains were observed when the highest laser heating intensity was applied. The results of this study can be helpful for integrated circuit packaging especially to enable interconnections using copper wire materials with lower purity levels, enabling a more cost effective manufacturing.

1. Introduction

Thermosonic wire bonding technology is an essential process that is required for creating interconnections in integrated circuits (IC). Researchers have been pursuing methods with various materials to enable the usage of copper wire instead of gold. This shift comes as manufacturing using gold as a medium for interconnection is no longer viable economically. Copper as a raw material is significantly cheaper and more abundant than gold [1]. Besides the appealing cost of copper, better thermal conductivity and better electrical properties as compared to gold is the driver for this conversion. Higher electrical conductivity for copper wire leads to lesser heat generation and eventual higher conduction speed [2–5]. However, executing wire bond interconnections with copper instead of gold may pose some challenges. These may affect the quality of bonding and will need to be addressed to enable mass volume production. Copper wire requires a higher bonding force and higher levels of ultrasonic energy input which increase the likelihood of under pad damage [6].

Copper is also known to have higher work hardening characteristics which will require higher-intensity ultrasound setting to deform the copper free air ball (FAB). High stress from the applied contact force and ultrasonic energy are amongst the technical challenges of using copper which creates excessive bond pad damage as a result of wires for creating connectivity [7]. To achieve optimum bonding in terms of shear strength, copper bonding requires greater force and ultrasonic energy. These conditions when applied during wire bonding are the main causes of bond pad damage. Research has shown that copper wire bonding that needs more ultrasonic energy and higher bonding force, can damage the silicon substrate, initiate die cratering and induce cracking and peeling of the bonding pad [8]. It is also known through

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past research, the hardness of copper decreases as the copper purity increases, however the usage of higher purity copper wires significantly increases manufacturing cost [9].

With the outlined challenges of higher hardness and higher work hardening characteristics of copper, varied laser heating power intensities and its effects on bonding strengths for three types of copper wire purity levels are investigated in this work. It is known from the findings from Borisenko and Rudnitskii, that hardness of copper decreases as the temperature increases [10]. As research on the application of laser for wire bonding is gaining motion, recent research on laser heating of bond pad during wire bonding has been reported by Liu & Sun [11]. It has been concluded that bond strength increased with the increase of laser power which heated the bonding pad, leading to good bond quality. In addition, previous research on the application of laser using gold wires as a medium of interconnection has also concluded, the addition of heat during preheating brings the base materials to temperatures that makes them softer and with high potential to be plastic deformed during future pressure application specific to the hybrid ultrasonic laser welding process [12].

The effect of higher bonding temperature has been researched previously and it is known, at higher bonding temperatures the FAB is softer than a FAB at room temperature. This is mainly due to the fact that FAB cools more slowly over a heated metallization pad [13]. Previous research has also shown that higher bonding temperature for 20 μm 4 N copper wires has also resulted in an increase in ball shear strength [14]. Through the available past research, we have seen the advantages of applying higher bonding temperatures. However, other research has also shown that excessive bonding temperatures may pose a threat to plastic components of electronic device [15], hence indicating an opportunity to further address improvements in the wire bonding technology using lasers of various power intensities. In previous studies, lasers have shown to be effective in semiconductor processing. One such process is performing laser cutting ranging from the micrometer-scale cutting of thin semiconductor chips [16,17]. It has also been documented in recent reviews, the heating and cooling rate associated with laser processing is very high and results in very little or no thermal effects on surrounding components. This inherent quality of laser processing can mitigate some of the difficulties associated with small scale packaging as needed for packaging today’s electronic and MEMS devices [18].

Based on these highlighted challenges, it is therefore the objective of this paper to investigate the effect of varied laser-heating power intensities using different copper wire purity levels. This will enhance further understanding on the impact of different laser power intensities on interconnectivity using different copper wire materials. To date, the effects of varied laser heating power intensities on bonding strength for three copper wire purity types, 99.99% purity (3 N), 99.999% purity (4 N) and 99.9999% purity (5 N) has not appeared in the literature.

2. Experimental

A Shinkawa thermosonic wire bonder, model UTC3000 was used to prepare copper wire bond interconnections using 25.4 μm diameter wire with purity levels 99.9% (3 N), 99.99% purity (4 N) and 99.999% purity (5 N) copper wires. Wire bonding was performed on bond pads consisting of NiPdAu metallization. The automated wire bonder is operational with a copper tip to supply forming gas (95% N₂ + 5% H₂) so as to shield the area of the wire tip and torch electrode during FAB formation. Three different Nd: YVO₄ diode pumped solid state laser apparatus with a wavelength of 532 nm emitting 5 mW, 10 mW and 15 mW output power respectively was used to provide heating to the copper FAB. Laser heating was delivered after FAB formation and before contact to the bond pad surface. The weight of copper FAB in this study is estimated to be 4.6 × 10⁻⁷ g, based on the FAB diameter and copper density of 8.96 g/cm³. The FAB was heated for duration of 5 ms. The copper FAB is created as a result of the application of electronic flame off (EFO) sparking. The application of EFO current and EFO time enabled the copper wire tail to be melted. The molten copper then rolls up into a FAB. As the application of laser heating in this study is aimed on heating the FAB, the laser beam applied is focused on the FAB before it descends to the bond pad. Fig. 1 shows the laser assisted copper wire bonding setup for FAB laser heating.

As the application of laser assisted heating in this study is aimed on heating the FAB, the laser beam applied is focused on the FAB before it descends to the bond pad. Fig. 1 shows the laser assisted copper wire bonding setup for FAB laser heating. Wire bonding was performed with pedestal temperature ranging from 40 °C to 340 °C with a step of 20 °C. Other factors such as ultrasonic power, bond force and bond time were set to constant. The primary copper wire bonding parameters which were used include ultrasonic power 70 units, bond force 20 g, bond time 15 ms and pedestal temperature ranging 40 °C to 340 °C. For quantitative analysis of the bonding response, destructive ball shear testing using Dage 4000 bond tester to assess the adhesion strength. This testing method is compliant to standard provided by the Joint Electronic Device Engineering Councils [19].

In this study, in order to avoid the influence by uncontrolled variables, experimental run sequences were randomized in the design of experiment and replications were executed to precisely measure the responses. Cross sectioned samples using standard metallographic technique was performed to determine the overall thickness of meshed metal layers. Grain flows in cross sectioned samples examined for evidences of columnar grains using Scanning Electron Microscope (SEM). For qualitative analysis, microstructural examinations were conducted on cross sectional wire bonded samples in a scanning electron microscope.

3. Results and discussion

3.1. Effect of varied laser heating power intensity on bonding strength for copper wires with different purity levels

Fig. 2 shows the ball shear strength of copper wire bonding executed at pedestal temperature 40 °C. Shear strength results are shown for 3 N, 4 N and 5 N copper wire samples bonded with FAB laser heating power 5 mW, 10 mW and 15 mW respectively.

Results show the ball shear strength for 3 N, 4 N and 5 N copper wire, bonded at temperature 40 °C. The shear strength is shown to be increasing with the application of higher laser heating power intensities on the FAB. For wire bonding using 5 mW laser power, the average ball shear strength for all three purity level is 20 g. The shear strength using 15 mW laser power is improved by 10 g.

Fig. 3 shows the ball shear strength of copper wire bonding executed at pedestal temperature 120 °C. Results show the ball shear strength for 3 N, 4 N and 5 N copper wire bonded with FAB laser heating power 5 mW, 10 mW and 15 mW respectively. The shear strength is shown to be increasing with the application of higher laser heating power,
Fig. 2. Ball shear strength for three different copper wire materials purity wire bonded using pedestal temperature 40 °C, with laser power intensity of 5 mW, 10 mW and 15 mW.

Fig. 3. Ball shear strength for three different copper wire materials purity wire bonded using pedestal temperature 120 °C, with laser power intensity of 5 mW, 10 mW and 15 mW.

Fig. 4. Ball shear strength for three different copper wire materials purity wire bonded using pedestal temperature 200 °C, with laser power intensity of 5 mW, 10 mW and 15 mW.

intensities on the FAB. For wire bonding using 5 mW laser power, the average ball shear strength for all three purity level is 25 g. The shear strength using 15 mW laser power is improved by 5 g. Results show the margin of difference between shear strengths with 5 mW laser power and 15 mW laser power is narrower compared to the shear strength shown in Fig. 2.

In Fig. 4 shows the ball shear strength of copper wire bonding executed at pedestal temperature 200 °C. Results show the ball shear strength for 3N, 4N and 5N copper wire bonded with FAB laser heating power 5 mW, 10 mW and 15 mW respectively. The shear strength is shown to be increasing with the application of higher laser heating power intensities on the FAB. For wire bonding using 5 mW laser power, the average ball shear strength for all three purity level is

Fig. 5. SEM images of cross section on samples wire bonded using 3 N copper wire at pedestal temperature 40 °C. a) Wire bonded with 5 mW laser heating, b) wire bonded with 10 mW laser heating and c) wire bonded with 15 mW laser heating.

Fig. 6. SEM images of cross sectional samples of wire bonded using 3 N copper. a) Wire bonded at a pedestal temperature 40 °C with laser power intensity of 5 mW, b) 10 mW and c) 15 mW.
3.2. Effect of varied laser heating power intensity on grain structure for lower purity copper wire

Fig. 6a, b and c shows the SEM image of cross sectioned 3 N copper ball bonded at pedestal temperature 40 °C, with the application of laser heating with power intensity of 5 mW, 10 mW and 15 mW respectively. It is observed that; copper ball bonds applied with 10 mW laser heating has fewer columnar grain structures compared to heating with 5 mW laser power. In addition it is also shown; copper ball bonds applied with 15 mW laser heating has even fewer columnar grain structures as compared to heating with 10 mW and 5 mW laser power.

From previous research it is evident that columnar grains are present in the sample without the application of laser heating. Previous research by Hang, Wang, Tian, Mayer and Zhou also confirms that solidification of the FAB begins with epitaxial growth. It is also shown; FAB without sub grains and with fewer columnar grains reduces under pad stress during wire bonding [13]. It is shown in this study; these columnar grains grew from the wire-ball interface downwards to the bottom of the ball. The columnar grains were fewer with the increase in laser heating power.

Results from the bonded samples demonstrate the application of laser heating on FAB was sufficient to disrupt the directional solidification, thus reducing columnar grains. Columnar grains are reduced due to the disruption of temperature gradient which is preventing directional solidification. Directional solidification is prevented by minimizing the dissipated heat through the surface in contact. It is understood from prior research that, columnar grain growth observed in the copper FAB is due to the forced convective cooling [22]. The application of 15 mW laser power has resulted in smaller cooling rate as it has lengthen the duration of Cu FAB heating. Thus it is able to disrupt the directional solidification, thus reducing columnar grains. From past research, columnar grains not necessarily result in lower shear values.

When the columnar grain are many, these grain boundaries with high dislocation density will respond with higher hardness and thus resulting in higher shear values. It is shown that, lower shear values are attributed to shearing of specimen with fewer grain boundaries instead [23]. Previous research on Cu FAB cross sectioning has shown if cooling rate is higher, the resultant FAB is expected to have a higher residual stress, higher dislocation density and therefore higher hardness [24].

From this study it is shown, the effects of laser heating is most significant for lower pedestal temperatures and not at higher temperatures. Copper wires with lower purity levels and lowered pedestal temperatures can be considered as viable for creating interconnections with the application of higher laser heating power intensities.

4. Conclusion

It was demonstrated in this research, higher as-bonded ball shear strengths with fewer columnar grains were observed even on lower copper purity levels when the highest laser heating intensity was applied. The results of this study can be helpful for integrated circuit packaging especially to enable interconnections for copper wire materials with lower purity levels.

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