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Bond strength evaluation of heat treated Cu-Al wire bonding

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ABSTRACT

Bond strength evaluation of wire bonding in microchips is the key study in any wire bonding mechanism. The quality of the wire bond interconnection relates very closely to the reliability of the microchip during performance of its function in any application. Concerns regarding the reliability of the microchip are raised due to formation of void at the wire-bond pad bonding interface, predominantly after high temperature storage (HTS) annealing conditions. In this paper, the quality of wire bonds prepared at different conditions, specifically annealed at different HTS durations are determined by measurements of the strength of the interface between the bond wire and the bond pad. The samples are tested in ball shear test and wire pull test. A transmission electron microscopy - energy dispersive X-ray analysis (TEM-EDX) has been carried out to observe the formation of the Cu-Al IMC layer in the sample. Results showed that longer duration of HTS increased the bond shear strength. Two-sample T-test analysis concluded that there is a significant difference in the mean ball shear strength of the samples. TEM photograph showed a distinctive thin layer of Cu-Al intermetallic compound whereby increasing thickness of the IMC layer increased the shear strength of the bonds.

Keywords: Wire bonding; Cu-Al intermetallic compound; high temperature storage; wire pull test; ball shear test.

INTRODUCTION

Thermosonic wire bonding technique has been a dominant interconnection technology in semiconductor industry [1-4]. This technique uses thermal and ultrasonic energies as well as mechanical pressure to achieve the interconnection between wire and bond pad on a microchip [2]. The welded wire enables a connection between circuitry embedded in the microchip and external circuit, for example, printed circuit board (PCB).

Figure shows the brief illustrations of the thermosonic wire bonding process [5]. Thermosonic wire usually has faster bonding speed (typically, about 10 wires/s) relative to that of ultrasonic wedge bonding (about 4 wires/s). This is due to the fact that there are only three axes of movement involved in ball bonding, compare to wedge bonding which move in four axes [3]. The faster bonding speed of thermosonic bonding technology is favour for mass production scenario.

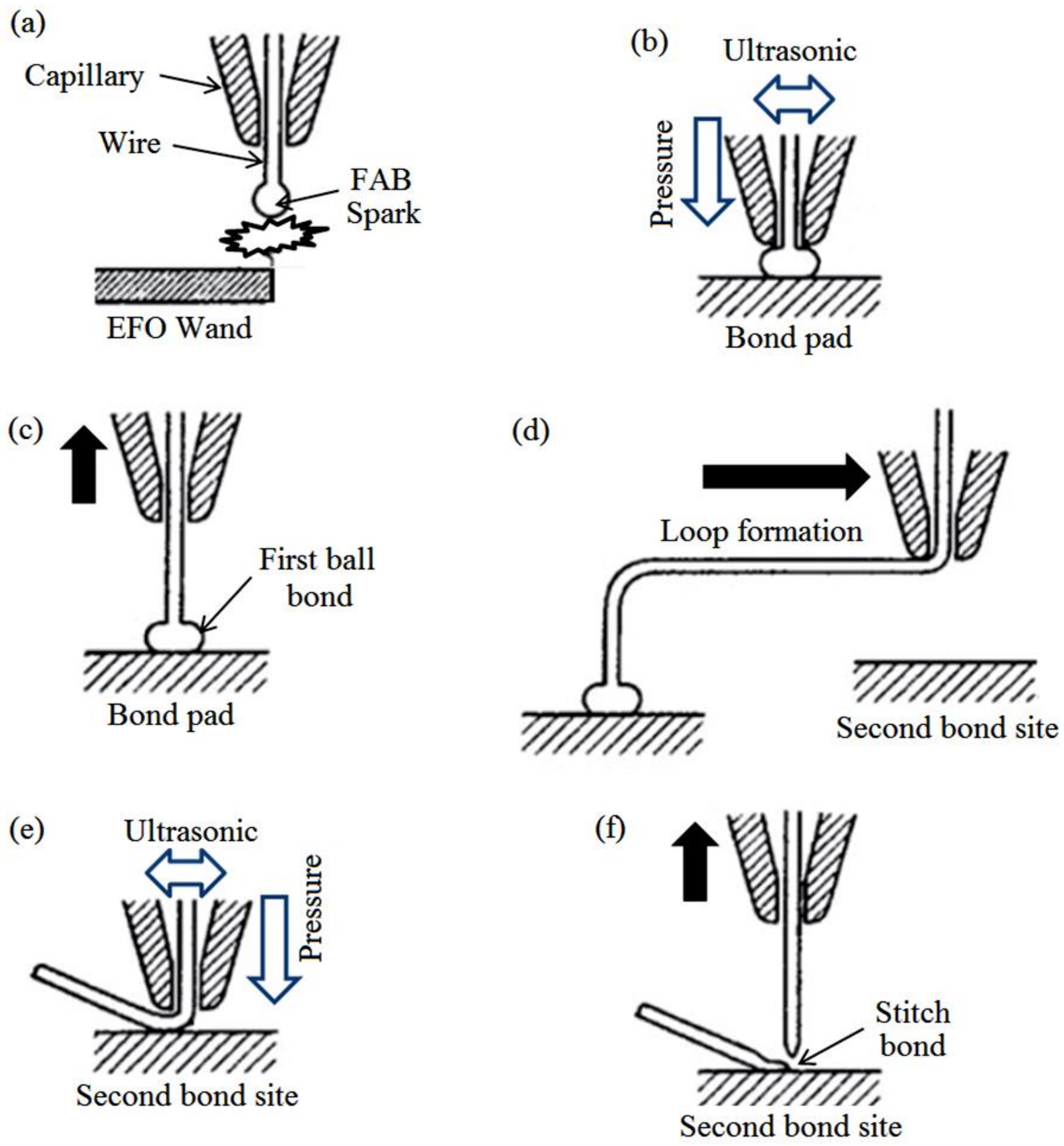

Figure 1. The process flow of thermosonic ball bonding [5].

Wire bonding has been used for its advantage of better-stability and cost effectiveness over other chip interconnection techniques. For bonding wires, gold and aluminium have been commonly used. Recently, instead of Au-metallization used in semiconductor industry, Cu-metallization and interconnection technology have received much attention due to their better electrical performances in comparison with aluminium.

One of the main methods for making interconnections in microelectronics packaging is via thermosonic ball bonding [4–7]. By combination of heat, pressure and ultrasonic energy, a thin metal wire loop is welded to a metallic bond pad. With the increasing trend of the price of Au, materials such as Cu are being considered for wire bonding as an alternative to the Au wire [8]. Cu possesses better electrical, thermal and mechanical properties and is three to ten times lower in cost compared to Au [5-8].

The combination of Cu wire and metal bond pad has been extensively studied. Among these researches, a high importance is given to morphological and chemical analyses on the intermetallic compound (IMC) developed at the bonding interface, after an annealing in high temperature storage (HTS) [9]. It is commonly believed that the IMC formation at the bonding interface is highly associated to the reliability of the bonding and thus that of the device [7-8].

However, using Cu wire has disadvantages [8–12]. One of the major shortcomings of Cu is that Cu oxidises easily compared to Au. Furthermore, the higher hardness of Cu wire compared to Au wire requires higher levels of bonding force [9]. This may consequently lead to wire/pad damage such as pad metal splash, pad thinning and Cu wire ball defect [3]. During the process of diode packaging and chip operations, temperature can reach up to a certain level that interdiffuses copper and aluminium at the bonding interface. Therefore, Cu/Al IMCs grow at the bonding interface.

Generally, significant IMC growth can make the bonding interface brittle and act as a major cause for bonding failure [6-7]. However, moderate IMC growth increases the bonding strength by alloying between copper wires with aluminium pads. Many factors such as wire composition, size, properties, free air ball formation, ultrasonic bonding process parameters, and post bond parameters affect the bond strength and reliability [4]. Nonetheless, the reliability of wire bonds depends primarily on the stable formation of the metal-metal interface between the wire and the bond pad. Essentially, the interface stability depends on the IMC layer at the interface. The IMC diffusion reaction is known to take place in a, elevated temperature environment but little reports have been found to study on this factor. Hence, high temperature storage (HTS) during post curing of the wire bonds is equally important to study the bond strength of the Cu-Al wire bond system. In this study, we investigated the effect of post bond high temperature storage on the bond strength, specifically copper wires bonded on aluminium pads and the effect of different duration of high temperature storage (HTS) on the Cu-Al wire bonding system.

EXPERIMENTAL PROCEDURES

Diode microchips with pure Al bond pad metallization were first transferred from wafer to lead frame by normal die bonding process. Then the samples were bonded with Cu wire (purity of 99.999%). The wire bonding process was carried out on a commercially available Shinkawa ACB-35 wire bonder at bonding temperature 280 °C. The bonding parameters include forming gas flow rate were fine-tuned to ensure no Cu free air ball (FAB) oxidation. Then, the samples were loaded into high temperature storage (annealing) at 175°C for 500 and 1000 hours. During the annealing, nitrogen gas was purged into the convection oven continuously to prevent copper oxidation at these high temperatures [13].

The samples with successful bonding were sent for ball bond shear test to measure the shear force of Cu/Al bonding as well as the wire pull test using the DAGE series 4000 ball shear tester. 30 balls were sheared and pulled in each condition so that test results would satisfy a standard normal distribution. Ball shear test and wire pull test are promising techniques to examine the mechanical strength of the bonding interface [14] and it is widely used by industry.

In the bond shear test, the shearing tool is positioned beside the ball bond to be tested as shown in Figure 3(b). The shearing arm then moves the tool horizontally against the ball, in effect pushing the ball off its bond pad. The force needed to shear a ball off its pad, known as the bond shear force, is then measured by the ball shear tester [15]. The pull tests on wire bonds are performed with a 90° hook that is positioned under the wire.

Wire pull testing applies an upward force under the wire, effectively pulling it away from the substrate. The hook moves up and the wire is pulled. The force at which the wire breaks of lifted off from its pad is measured to be the pull strength [16]. The schematic diagram of the wire pull test is shown in Figure 6.

Samples were further prepared for the mechanical cross-section which includes grinding and polishing the samples with alumina suspension prior to focus ion beam (FIB) process. In FIB, a thin lamella with dimension 10µm x 10µm x 0.1µm was extracted from the peripheral bonding interface consisting Si, Al bond pad and Cu ball bond. Lamellas were then inspected by FEI TECNAI G2F20 system which is capable for Transmission Electron Microscope (TEM) and line scan Energy Dispersive X-ray (EDX).

A Cu-Al phase identification is also carried out based on the Cu-Al equilibrium phase diagram. Figure 2 shows the Cu-Al equilibrium phase diagram for temperature below 548.2°C [17]. The Cu-Al phase identified from the phase diagram are $CuAl_2$ (θ), CuAl (η2), Cu_4Al_3 (ζ2), Cu_3Al_2 (δ) and Cu_9Al_4 (γ1). Any type of the phases is expected to exist in the samples reported in this paper.

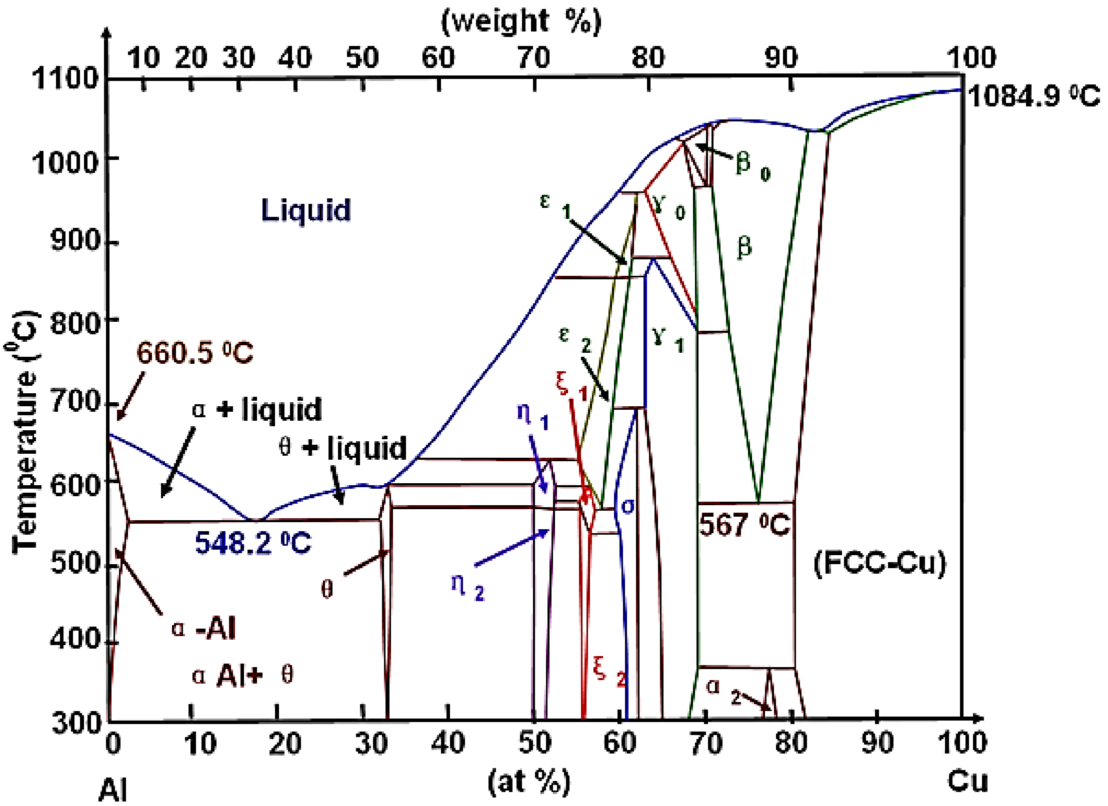

Figure 2. The Cu-Al equilibrium phase diagram [17].

RESULTS AND DISCUSSION

In all samples, ball shear test failure mode observed is ball bond lift. Ball bond lift failure mode in ball shear test is a phenomenon that ball bond is separated from bond pad metallization upon shearing [18]. Figures 3(a) and 3(b) shows the resulting bond lift observed under optical microscope and the schematic diagram of ball bond lift failure mode in ball shear test, respectively.

The results of the ball bond strength measurements of the Cu-Al IMC system are tabulated in Table 1.

Table 1: Results of ball strength measurements of the Cu-Al system.

Bonding Temperature (°C)	HTS duration (hours)	Mean Ball Shear Strength (gmf)	Mean Wire Pull Strength (gmf)
280	0	59.83	13.77
280	500	75.54	12.04
280	1000	96.25	12.40

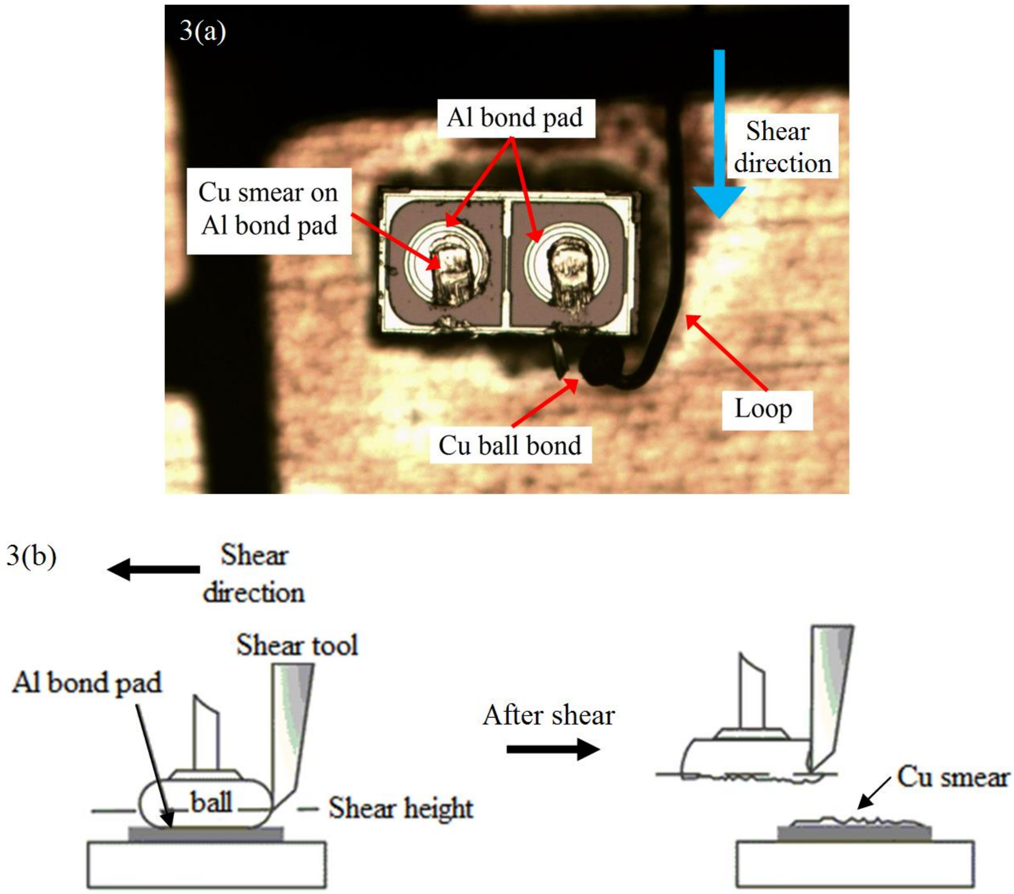

Figure 3. (a) Optical micrograph of ball bond lift after shearing and (b) Schematic diagram of ball bond lift failure mode in ball shear test.

Figure 4 shows the box plot of mean ball shear strength for Cu-Al bonded at 280°C with different HTS durations. Two-sample T-test analysis concluded that there is a significant difference in the mean ball shear strength of the samples. The mean ball shear strength increased due to an enhanced interdiffusion of the metals at a longer HTS duration. This observation suggests that with longer hours of HTS, the intermetallic Cu-Al compound layer undergoes an enhanced growth of the compound as reported by Xu et.al. [19]. The heat supplied to the system during the annealing period diffuses the Cu wire material with the Al bond pad material to promote the growth of Cu-Al IMC layer, resulting in higher bond strength of the wire bonds.

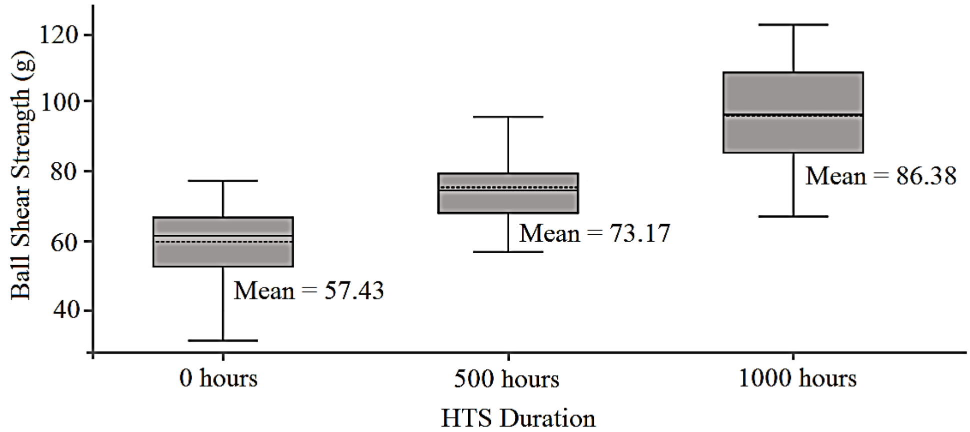

Figure 4. Box plot of mean ball shear strength for Cu-Al bonded at 280 °C.

Figure 5 shows the box plot of mean wire pull strength for Cu-Al bonded at 280°C with different HTS durations. Two-sample T-test analysis concluded that there is no significant difference in the mean wire pulls strength of the samples. The small variation between the values indicates that the duration of HTS does not have a significant effect onto the wire pull strengths of the Cu-Al wire bonds [20]. This is primarily due to the results obtained that failure modes in the wire pull test that has been identified as wire break at mid span and wire break at stitch bond. Any failure at mid span or stitch bond does not correlate to the Cu-Al IMC compound formation at the Cu ball bond area. The measurement of the wire pull test denotes the quantity of upward force applied under the Cu wire loop pulling it away from the substrate, termed as wire pull strength [21]. The schematic diagram of the positions of the wire break at mid span and wire break at stitch is presented Figure 6.

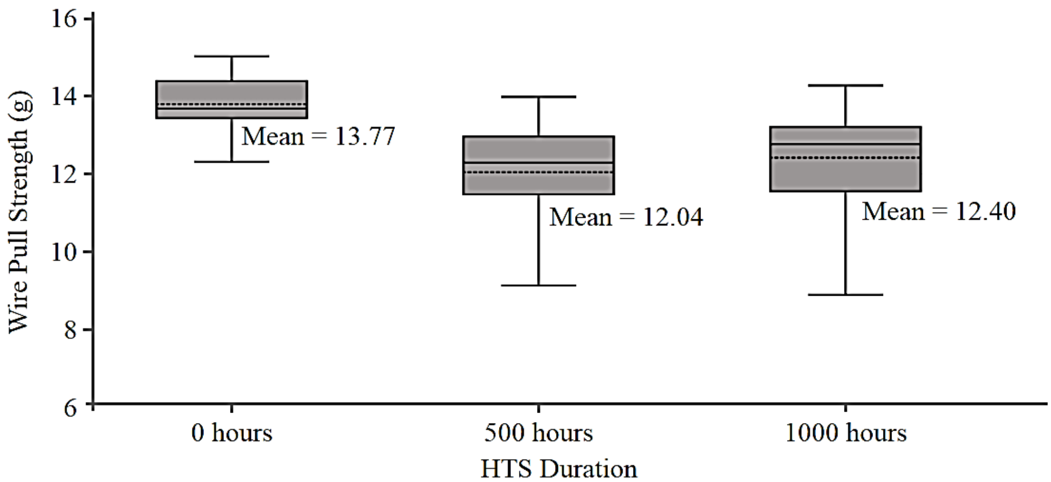

Figure 5. Box plot of mean wire pull strength for Cu-Al bonded at 280 °C.

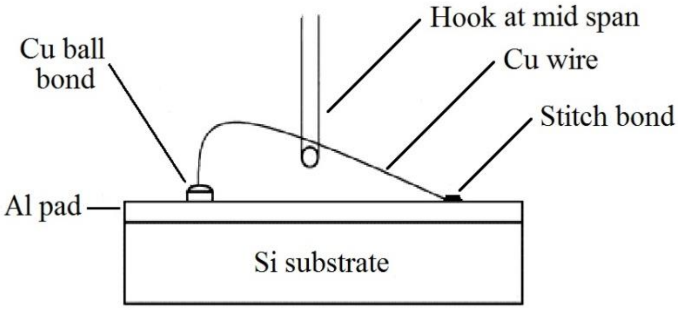

Figure 6. Schematic diagram of wire pull test.

Figure 7 shows TEM photograph of the lamella extracted from the sample for the Cu-Al wire bond system, bonded at 280 °C with no annealing duration (i.e. 0 hour HTS). The figure shows the formation of a distinctive layer in the Cu-Al wire bond system. The corresponding Cu-Al IMC phase identification and thickness measurement based on the results of line scan EDX performed along the measurement path is shown Figure 8. The thickness of the IMC is measured to be at 328 nm, as measured from the EDX line scan spectrum. The phase for Cu-Al IMC layer in this sample is identified to be Cu_3Al_2 (δ) + Cu_9Al_4 (γ1) phase with 80 wt% Cu – 20 wt% Al.

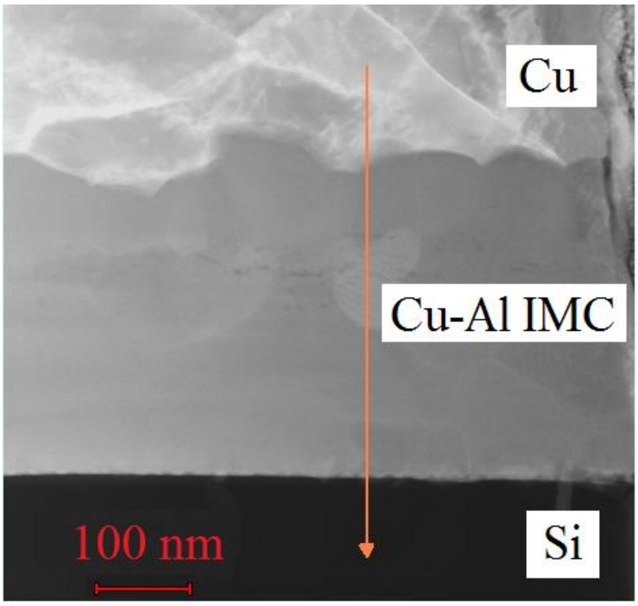

Figure 7. TEM image of wire bond cross section bonded at 280 °C, 0 hrs HTS.

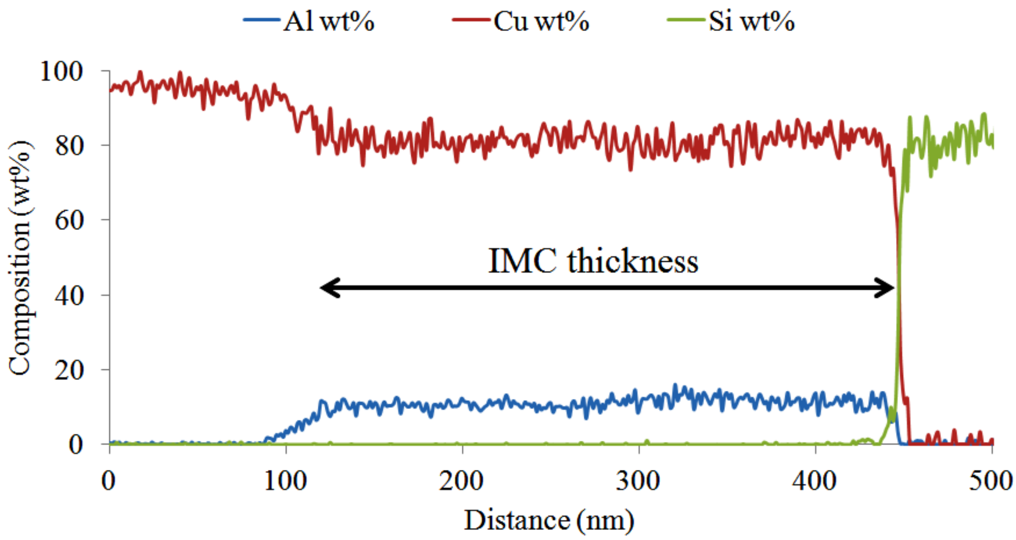

Figure 8. Composition profile of Cu-Al IMC system bonded at 280 °C, 0 hrs HTS.

CONCLUSION

In this study, samples with Cu wire bonded on pure Al bond pad metallization are synthesized at 280 °C with condition of forming gas to control the oxidation of Cu free air ball. Samples were subjected to heat treatment for 500 and 1000 hours. Ball shear test showed higher ball shear strength in samples that were heat treated for longer period of time. Ball shear test failure mode observed is ball bond lift. The small variation between the mean values of the wire pull tests indicates that the duration of HTS upon the samples does not play significant role in determining the wire pull strengths of the Cu-Al wire bonds. TEM studies at the bonding interface showed the IMC with thickness 328 nm is present in as-bonded (0 hour HTS) sample with the phase for Cu-Al IMC layer in this sample is identified to be Cu_3Al_2 (δ) + Cu_9Al_4 (γ1) phase with 80 wt% Cu – 20 wt% Al. Line-scan EDX reveals that the IMC actually consist of interdiffusion zone and a distinct thin layer of intermetallic phase.

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