Evaluation of Bond Shear Strength of Heat Treated Cu-Al Bonding Interface

S. Shariza, T. Joseph Sahaya Anand, Chua Kok Yau, Lim Boon Huat, Lee Cher Chia

Abstract*: Ball shear strength of the thermosonic wire bond interconnection relates closely to the reliability of the microchip during performance of its function in any application. Concerns regarding the reliability of Cu wired electronic microchips are raised due to formation of void at the copper (Cu) wire-aluminium (Al) bond pad bonding interface, predominantly after high temperature storage (HTS) annealing conditions. The interfacial void formation is suspected originated from a volumetric shrinkage during the growth of the Cu-Al intermetallic compound (IMC) layer in the Cu–Al bonding interface. In this report, the ball shear strength and interfacial microstructure of the thermosonic Cu wire-Al bond pad system bonded at difference temperature (150 °C, 280 °C and 400 °C); and annealed at different HTS durations (as-synthesized, 500 hours and 1000 hours) were studied. It was observed no significant difference in the mean of the ball shear strength of bonds bonded at different temperature before HTS treatment. On the other hand, the ball shear strength increase with the HTS duration. This is due to the fact that higher bonding temperature and longer HTS promoted better growth of the Cu-Al IMC layer. A transmission electron microscopy - energy dispersive X-ray analysis (TEM-EDX) has also been carried out to observe the formation of the Cu-Al IMC layer in the sample.

Index Terms*: Wire bonding, Cu-Al intermetallic compound (IMC), High temperature storage (HTS), Wire pull test, Ball shear test

I. INTRODUCTION

Wire bonding has been used for its advantage of better-stability and cost effectiveness over other chip interconnection techniques in semiconductor industry. One of the most common methods for making interconnections in microelectronics packaging is via thermosonic ball bonding [1]-[4]. This technique combines heat, pressure and ultrasonic energy to weld a thin metal wire onto a metallic bond pad on microchips [3]. For bonding wires, gold and aluminium have been commonly used in the industry. Wire material such as Cu are being considered as an alternative to gold (Au) for wire bonding due to the increasing trend of the price of Au. Apart being three to ten times lower in cost compared to Au, Cu has been reported to possess better mechanical, thermal and electrical properties [2]-[4].

Furthermore, Cu-metallization and wire bond interconnection technology have received much attention due to their better electrical performances in comparison with aluminium [4]-[6].

Despite the benefits, Cu are easily oxidized, therefore the wire bonding process has to be performed in an inert environment [6]. The inert environment is commonly provided by 'Cu kit' tool which allows a continuous flow of forming gas (95% nitrogen and 5% hydrogen) [6].The high hardness of Cu wire as compared to Au wire results in a wire bonding process with higher levels of bonding force [3],[7]. This consequently lead to wire/pad damages such as pad metal splash, pad thinning and Cu wire ball defect [2],[8].

During the process of chip packaging and operations, temperature can reach up to a certain level that enhance the interdiffusion and cause IMCs growth at the Cu-Al bonding interface. Generally, moderate IMC growth increases the bonding strength by alloying copper wires with aluminium pads. However, an excessive IMC growth can make the bonding interface brittle and act as a major cause for bonding failure [9],[10]. For accelerating the growth of the IMCs, an annealing process called HTS is commonly used in the microelectronic industries [11]. HTS at 175 °C for 500 and 1000 hours are frequently carried out for reliability assessment at product levels [12]. IMC growth in Cu-Al system is generally in nanometre scale even after HTS treatment. Therefore, TEM is an appropriate tool for microstructural analysis [4],[6].

In this study, we evaluate the bond strength and microstructures of heat treated Cu wire-Al bond pad, under the influence of different bonding temperatures and different duration of high temperature storage (HTS). Mechanical strength examination of the bonding interface is carried out via the ball shear test, which is widely used in the electronics industry [13]. Microstructural and chemical characterization is done by transmission electron microscope (TEM) and line-scan Energy Dispersive X-ray (EDX) (equipped in TEM). Phase identification, thickness measurement and percentage weight (%wt) composition of the Cu-Al system calculation is done on the samples. This approach leads to better understanding on how the microstructure of the Cu-Al IMC system at the Cu-Al bonding interface affects the bond shear strength.

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II. MATERIALS AND METHODS

A die bonding process was carried out to transfer diode microchips with pure Al bond pad metallization from wafer to lead frame [5]. Then the wire bonding process on the samples were done on a commercially available Shinkawa® ACB-35 using Cu wire (purity of 99.999%). To ensure no Cu free air ball (FAB) oxidation on the wire bonds, the bonding parameters include forming gas flow rate were fine-tuned for the process. The wire bonding was carried out at the bonding temperatures of 150°C, 280°C and 400°C. Then, the samples were loaded into High Temperature Storage (HTS) annealing oven 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.

Sample labels with above mentioned bonding and HTS parameters are summarized in Table 1. A comparison study between the samples S1-S2-S3 was performed. This group provide an evaluation on how the HTS annealing duration affect the bond strengths. Another sample group S1-S4-S7 was evaluated to understand the effect of bonding temperature on the bond strengths without HTS treatment. Data analysis was performed using Minitab ® software.

Table. 1 Sample ID with corresponding bonding parameters

Sample ID	Bonding Temperature (°C)	HTS Duration (hours)
S1	150	0
S2	150	500
S3	150	1000
S4	280	0
S5	280	500
S6	280	1000
S7	400	0
S8	400	500
S9	400	1000

The samples with successful bonding were sent for ball bond shear test to measure the shear strength of Cu-Al bonding interface. To satisfy a standard normal distribution, 30 balls were sheared in each condition. Equipment used in this case is DAGE series 4000 ball shear tester.

Prior to mechanical cross-section analysis, samples were subjected to focus ion beam (FIB) sample preparation technique. In FIB, a thin lamella with dimension 10µm x 10µm x 0.1µm consisting of Si, Al bond pad and Cu ball bond was extracted from the peripheral bonding interface area. 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 carried out based on the Cu-Al equilibrium phase diagram. Figure 1 shows the Cu-Al equilibrium phase diagram for temperature below 548.2°C [14]. The Cu-Al phase identified from the phase diagram are α-Al, $CuAl_2$ (θ), CuAl (η2), Cu_4Al_3 (ζ2), Cu_3Al_2 (δ), Cu_9Al_4 (γ1) and FCC-Cu. Any of these phases are expected to be present in the IMC for the samples tested in the report.

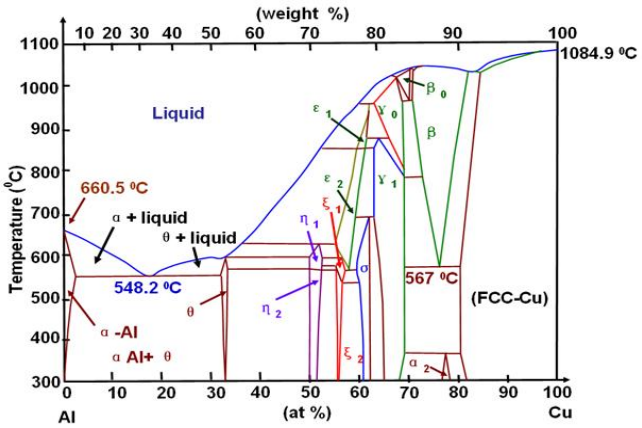

Fig. 1 The Cu-Al equilibrium phase diagram [14]

III. RESULTS AND DISCUSSION

In all samples tested through the ball shear test, the failure mode observed is identified as bond lift. Bond lift defined as a phenomenon whereby the ball bond is separated from the bond pad metallization upon shearing [15].

Table. 2 Mean ball shear strength for samples S1-S9

Sample ID	Bonding Temperature (°C)	HTS Duration (hours)	Mean Ball Shear Strength (g)
S1	150	0	57.43
S2	150	500	73.17
S3	150	1000	86.38
S4	280	0	59.83
S5	280	500	75.54
S6	280	1000	96.25
S7	400	0	59.35
S8	400	500	83.17
S9	400	1000	124.16

Two-Sample T-Test analysis was used to determine the effects of the bonding conditions in each of the sample groups. A box plot graph as a preliminary analysis to the test is plotted as shown in Figure 2.

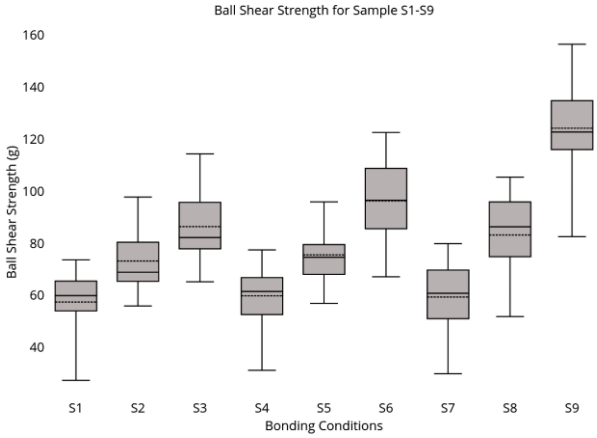

Fig. 2 Ball Shear Strength for Sample S1-S9

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Sample groups S1-S2-S3, S4-S5-S6 and S7-S8-S9 sample group provides an evaluation on how the HTS annealing duration affect the bond strengths. The test concluded that there is a significant difference in the mean ball shear strength of the samples. This can be seen clearly in Figure 2 through the box plot graph. It is seen that the ball shear strength shows an increasing trend over the HTS duration (for each sample group). A linear regression analysis resulted in an R^2 (R-square) value of > 0.97 for each sample group. This suggests that the ball shear strength is linearly proportional to the HTS duration (at HTS temperature of 175°C).

Moreover, bond shear strength of heat treated samples are observed to be higher than that of non-heat treated; due to an enhanced interdiffusion of the metals at a longer HTS duration. This observation agrees well with [16] and [17]. This is explained further by studying the microstructure of the interfacial IMC growth over the annealing process, as observed in the STEM analysis performed in Table 3**.**

Table. 4 Thickness measurements and phase identification of the Cu-Al system

Sample ID	Total IMC thickness (nm)	Phase Identification	Approximate %wt Cu	Mean Ball Shear Strength (g)
S1	380	**IMC 1:** α-Al + $CuAl_2$ (θ) **IMC 2:** α-Al + $CuAl_2$ (θ) **IMC 3:** α-Al + $CuAl_2$ (θ)	11% 35% 22%	57.43
S2	244	**IMC 1:** Cu_9Al_4 (γ1) + α2	86%	73.17
S3	1130	**IMC 1:** Cu_9Al_4 (γ1) + α2 **IMC 2:** $CuAl_2$ (θ) + CuAl (η2) **IMC 3:** α-Al + $CuAl_2$ (θ)	86% 63% 35%	86.38
S4	328	**IMC 1:** Cu_3Al_2 (δ) + Cu_9Al_4 (γ1)	80%	59.83
S6	582	**IMC 1:** $CuAl_2$ (θ) + CuAl (η2) **IMC 2:** α-Al + $CuAl_2$ (θ) **IMC 3:** $CuAl_2$ (θ) + CuAl (η2)	59% 5% 60%	96.25
S7	315	**IMC 1:** α-Al + $CuAl_2$ (θ) **IMC 2:** Cu_9Al_4 (γ1) + α2	19% 87%	59.35
S8	605	**IMC 1:** Cu_9Al_4 (γ1) **IMC 2:** $CuAl_2$ (θ) + CuAl (η2)	82% 68%	83.17

In addition, the ball shear strength comparison for the sample group S1-S4-S7 was analysed and box plot graph is shown in Figure 3. This set of sample group evaluates the effect of bonding temperature on the bond strengths. Two-Sample T-Test concluded that there is no significant difference between the ball shear strength of this group of samples. This indicated the bonding temperature has little influence on the ball shear strength when samples were not subjected to HTS treatment.

Table 3 shows STEM images of the lamella extracted from the samples and the results of line scan EDX performed along the measurement paths (as labelled in the micrographs) respectively. The STEM photograph shows the formation of the IMC layer in the Cu-Al wire bond system. The corresponding Cu-Al IMC phase identification and thickness measurement in presented in the table as well.

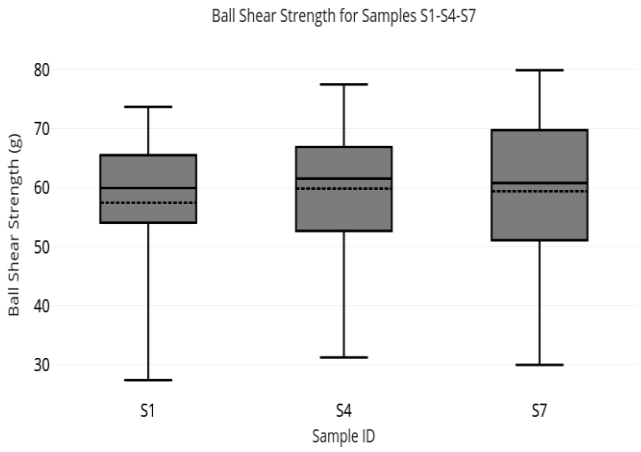

Fig. 3 Box plot for Samples S1-S4-S7

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Table 4 summarizes the total thickness measurement of the IMC, the Cu-Al phase identification of IMC formed in the samples based on the weight% composition profile and the mean ball shear strength measurements. In samples S1 and S7 which were not subjected to heat treatment, it is observed that Al-rich IMC forms. Meanwhile, samples that received heat treatment forms Cu-rich IMC phase and is seen to exist in layered structure at the bonding interface.

Figure 4 shows the correlation between the IMC thickness grown over HTS treatment. From Figure 4, with sample data S2 eliminated (refer to the following paragraph for in depth explanation of the removal of the data), it can be observed that for each sample group, the total IMC thickness increases upon longer HTS duration. Relating to its ball shear strength in Figure 2, this observation suggests that during heat treatment, the Cu-Al interfacial layer has undergone diffusion with the aid of annealing. This has also been reported by [18] and [19]. This is a strengthening effect as the thicker IMC layer that formed through longer HTS durations has higher ball shear strength as shown in Figure 5.

However, the IMC thickness for S2 as shown is 244 nm and this specific sample measurement does not fit into the pattern of the increasing thickness of IMC with increasing HTS duration as presented in Table 4. An unfavourable Cu-Al IMC formation can be clearly seen numerous voids in sample S2 (voids detected as oxygen in EDX) in the STEM image shown in Figure 6. This is due to the formation of Cu oxide layer (seen from the EDX line scan in Table 3) on the surface of free-air-ball during electroforming process, as it is suspected that there may be some localized areas in the bonding perimeter that is not protected well by the inert gas. This oxide layer at the bonding interface slow down the interdiffusion process and result in a relatively thinner IMC layer as observed in sample S2. [20] and [21] have also reported similar observations in their report.

In the STEM image of S3 as shown in Table 3, a layer of Al oxide with a thickness of approximately 500 nm is detected in the STEM-EDX analysis. This is due to the formation of Al oxide layer on the surface of the Al bond pad that is suspected to form before the wire bonding process. 1000 hours of HTS has enhanced the growth of this oxide layer as due to facility limitation, the oven is shared and oxygen may have entered at times the oven door was opened.

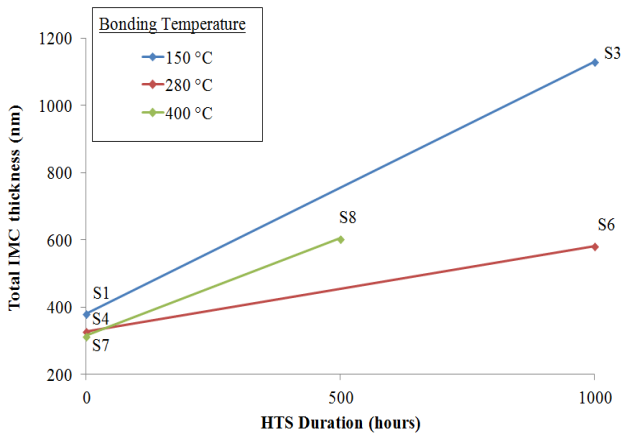


Fig. 4 Comparison of total IMC thickness vs HTS duration for samples S1-S3, S4-S6 and S7-S8

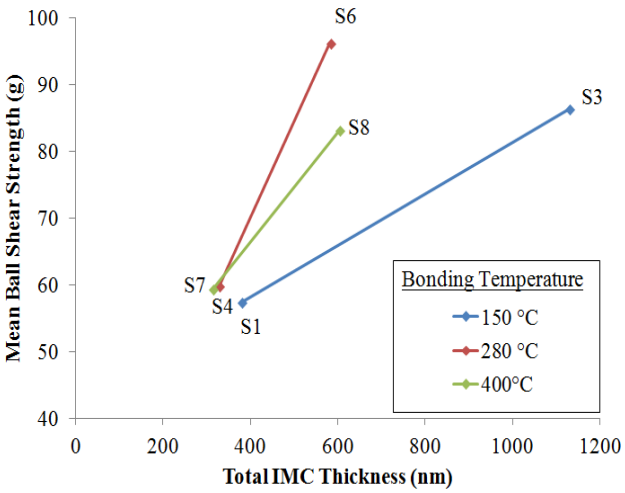


Fig. 5 Comparison of total IMC thickness vs ball shear strength for samples S1-S3, S4-S6 and S7-S8

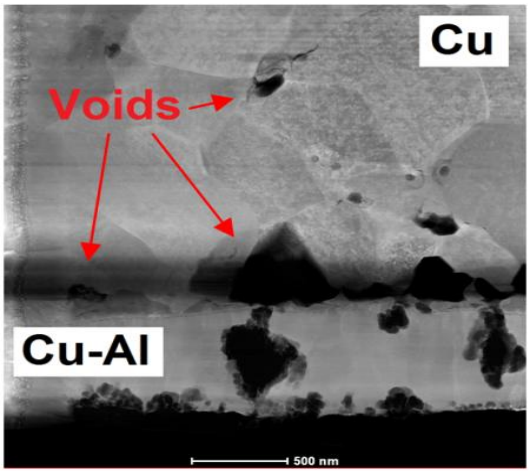
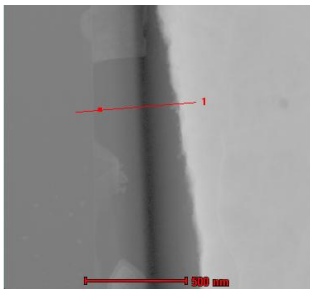
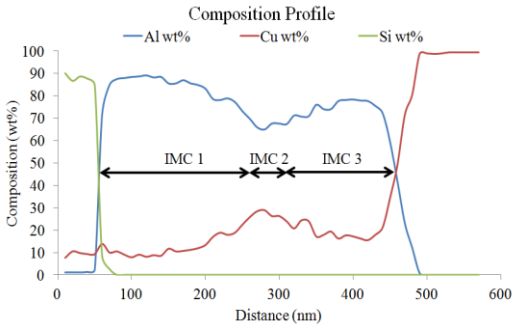
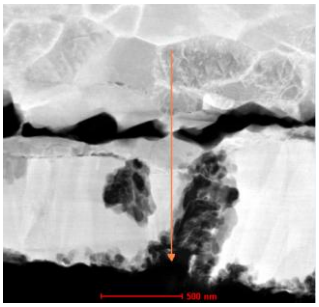
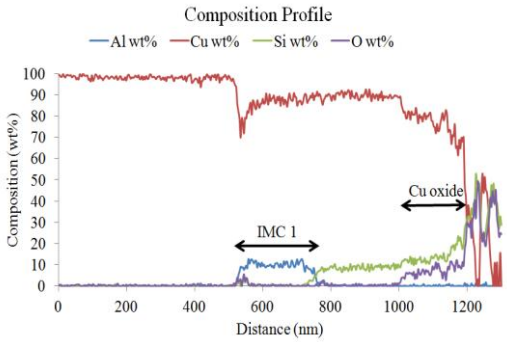
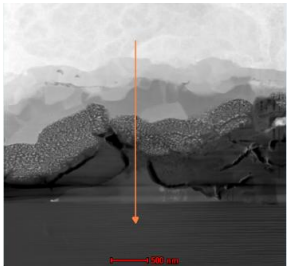
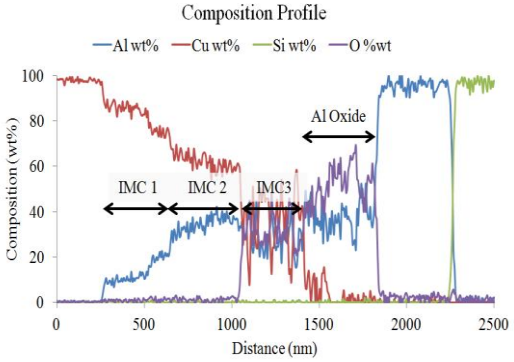
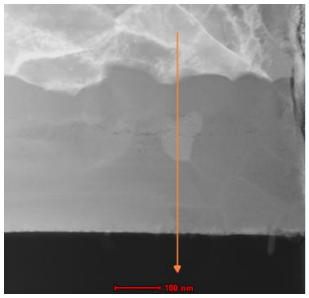
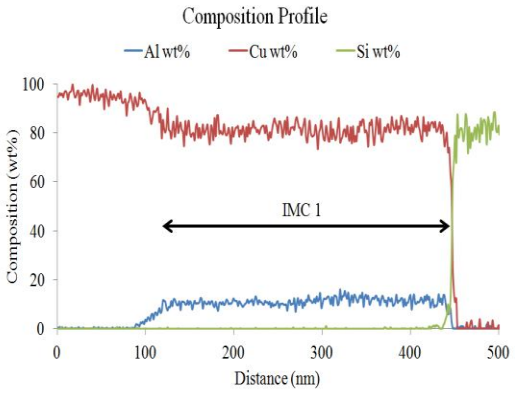
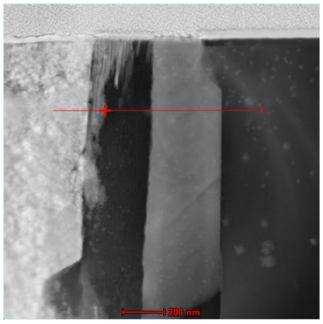
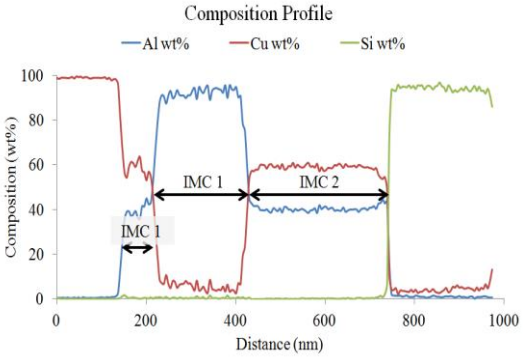
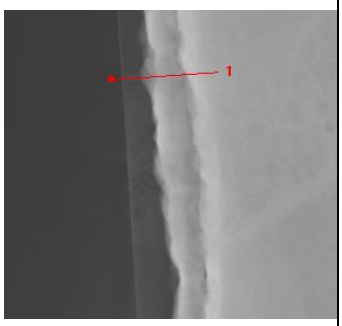
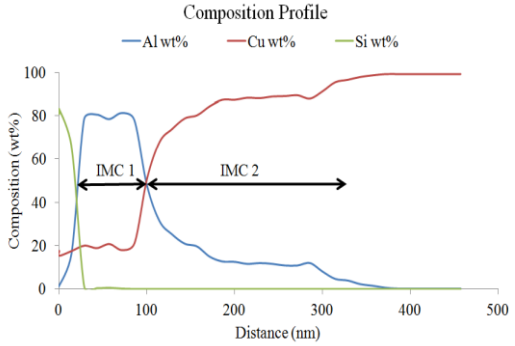
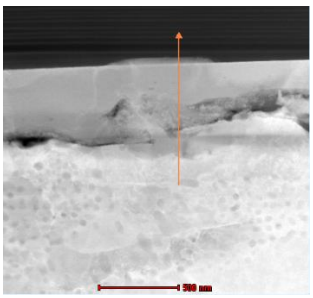
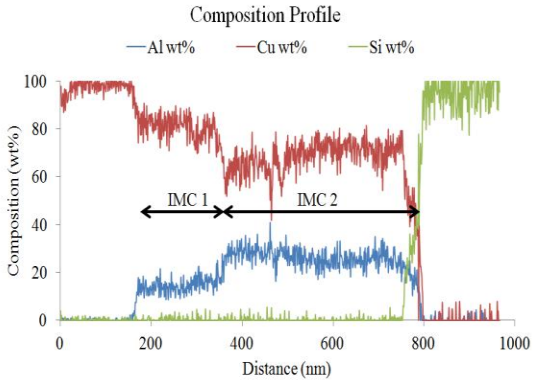


Fig. 6 STEM image of sample S2

Similar to [17], in S2 and S3, the population of voids and crack-like structure is due to the presence of oxide layers whereby the propagation of the oxide grains takes place upon longer HTS duration. However, Cu-Al interdiffusion is not hindered by the Cu oxide layer, thus IMC growth still proceed with a slower rate [22]. It is confirmed that a Cu-Al IMC layer was formed and identified to be of Cu-rich Cu-Al phase.

Table. 3 STEM Images, EDX Line Scan & Phase Identification of IMC Layers

Sample ID	STEM images	EDX Line Scan	Cu-Al IMC Phase Identification And Thickness
S1			**IMC 1:** α-Al + $CuAl_2$ (θ) Thickness: 210 nm **IMC 2:** α-Al + $CuAl_2$ (θ) Thickness: 50 nm **IMC 3:** α-Al + $CuAl_2$ (θ) Thickness: 120 nm Total IMC Thickness: 380 nm
S2			**IMC 1:** Cu_9Al_4 (γ1) + (α2) Thickness: 244 nm
S3			**IMC 1:** Cu_9Al_4 (γ1) + (α2) Thickness: 380 nm **IMC 2:** $CuAl_2$ (θ) + CuAl (η2) Thickness: 400 nm **IMC 3:** α-Al + $CuAl_2$ (θ) Thickness: 350 nm Total IMC Thickness: 1130 nm

S4			**IMC 1:** Cu_3Al_2 (δ) + Cu_9Al_4 (γ1) Thickness: 328 nm
S6			**IMC 1:** α-Al + $CuAl_2$ (θ) Thickness: 58 nm **IMC 2:** α-Al + $CuAl_2$ (θ) Thickness: 211 nm **IMC 3:** $CuAl_2$ (θ) + CuAl (η2) Thickness: 313 nm Total IMC Thickness: 582 nm
S7			**IMC 1:** Thickness: 86 nm **IMC 2:** Thickness: 229 nm Total IMC Thickness: 315 nm
S8			**IMC 1:** Cu_9Al_4 (γ1) Thickness: 195 nm **IMC 2:** $CuAl_2$ (θ) + CuAl (η2) Thickness: 410 nm Total IMC Thickness: 605 nm

IV. CONCLUSION

In this study, samples with Cu wire bonded on pure Al bond pad metallization are successfully synthesized at 150°C, 280°C and 400°C. The supply of forming gas has proved to control the oxidation of Cu FAB in the samples. Samples were then treated to HTS of durations 500 hours and 1000 hours. A longer HTS duration was found to enhance the diffusion of the Cu-Al IMC, hence, increasing the bond strength (ball shear) of the wire bond. Besides, it is observed that IMC thickness is higher in samples that were annealed for a longer period of time establish higher ball shear strength. Through line-scan EDX, the results reveals that the IMC consist of a distinctive thin layer of intermetallic phase, whereby increasing thickness of the IMC layer increased the shear strength of the bonds. This clear IMC layer is identified as the interdiffusion zone of the IMC. It is concluded that HTS promotes IMC formation from Al rich to Cu rich content.

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