Effects of Cu/Al Intermetallic Compound (IMC) on Copper Wire and Aluminum Pad Bondability

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***Abstract*—Copper wire bonding is an alternative interconnection technology that serves as a viable, and cost saving alternative to gold wire bonding. Its excellent mechanical and electrical characteristics attract the high-speed, power management devices and fine-pitch applications. Copper wire bonding can be a potentially alternative interconnection technology along with flip chip interconnection.**

However, the growth of Cu/Al intermetallic compound (IMC) at the copper wire and aluminum interface can induce a mechanical failure and increase a potential contact resistance. In this study, the copper wire bonded chip samples were annealed at the temperature range from 150 °C to 300 °C for 2 to 250 h, respectively. The formation of Cu/Al IMC was observed and the activation energy of Cu/Al IMC growth was obtained from an Arrhenius plot (ln (growth rate) versus 1/T). The obtained activation energy was 26 Kcal/mol and the behavior of IMC growth was very sensitive to the annealing temperature.

To investigate the effects of IMC formation on the copper wire bondability on Al pad, ball shear tests were performed on annealed samples. For as-bonded samples, ball shear strength ranged from 240–260 gf, and ball shear strength changed as a function of annealing times. For annealed samples, fracture mode changed from adhesive failure at Cu/Al interface to IMC layer or Cu wire itself. The IMC growth and the diffusion rate of aluminum and copper were closely related to failure mode changes. Micro-XRD was performed on fractured pads and balls to identify the phases of IMC and their effects on the ball bonding strength. From XRD results, it was confirmed that the major IMC was $\gamma-\mathrm{Cu_9Al_4}$ and it provided a strong bondability.

***Index Terms*—Aluminum pad, annealing, ball shear tests, bondability, copper wire, Cu/Al, diffusion rate, IMC, micro-XRD.**

I. INTRODUCTION

THERE are several chip interconnection techniques such as wire bonding, tape automated bonding (TAB), and flip chip technology. Wire bonding has been used for its advantage of better-stability and cost effectiveness over other chip interconnection techniques despite the current trend of flip chip interconnection. Wire bonding is still regarded as one of the most important cost effective chip interconnection technology even though flip chip technology has been highlighted on the use of high inputs/outputs (I/Os) and high-speed devices.

For bonding wires, gold and aluminum have been commonly used. Recently, instead of Al-metallization used in semiconductor industry, Cu-metallization and interconnection technology have received much attention due to their better electrical performances in comparison with aluminum. Therefore, many studies on the copper wire bonding are in progress [1]–[4]. There are several disadvantages and advantages. The disadvantages of copper wire are as follows:

First, the technology of copper wire bonding is not widely accepted yet in the industry because additional bonding parameters such as the forming gas need to be defined and optimized. Second, due to the easy oxidation of copper, copper wire bonder requires special tools to prevent copper oxidation. Copper wires need higher energy than gold wires when they are bonded to pads. However, copper wires also provide many advantages that are superior to gold wires. The advantages of copper wires are as follows.

1) First, copper wire is three to ten times lower in cost compared to gold wire.
2) Second, copper wire shows superior mechanical and electrical properties compared to gold and aluminum wires. Excellent electrical conductivity and low heat generation allow copper wire to be used not only for power management devices but also for thinner diameter wires to accommodate small pad sizes. The high rigidity of copper wires is considered more compatible to the fine pitch bonding than gold wires.
3) Third, slower intermetallic compound (IMC) growth between copper wires and aluminum pads results in lower contact resistance and better reliability in comparison to gold wires and aluminum pads. Applying copper wire bonding to copper pads on high-speed chip is ideal to make electrically and mechanically stable mono-metallic bonding interface. Because copper to copper mono-metallic interface does not form brittle IMC phases, it is expected to eliminate mechanical problems and to maintain stable electrical properties due to elimination of IMC formation. Copper pad technology as an alternative to pad system has not yet been accepted in the industry practically, because copper is easily oxidized and its oxidation layer acts as an obstacle to the bonding process. This is why the established aluminum pad has been used in this study instead of the copper pad.

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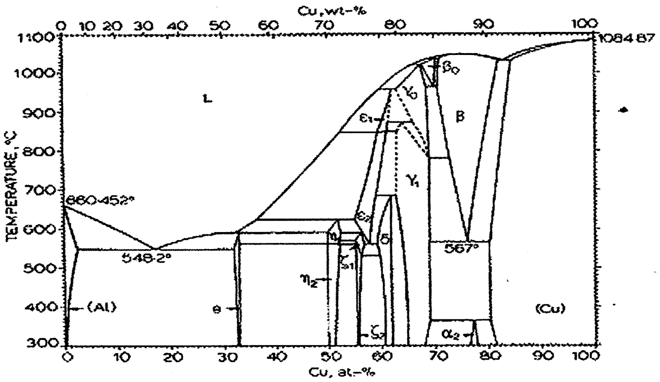


Fig. 1. Phase diagram of Cu-Al system.

Cu-Al IMC Phases: One of the most serious factors that leads to failure between gold wire and aluminum pad is the IMC formation, called "purple plague." Many researchers have established theories on the IMC formation in the Au/Al system and its effects on the bondability [5], [6]. In the case of Cu/Al system, some studies on IMC formation during annealing were reported using welded diffusion couple of bulky copper and aluminum [7], [8] or thin film Cu/Al diffusion couple [9], [10]. However, it was difficult to observe IMC formation in practical copper wire to aluminum pad bonding. Generally, the IMC formation in Cu/Al system is much slower compared to the Au/Al system. Therefore, copper wires on aluminum pads show higher mechanical reliability and smaller increase in the electrical resistance than that of gold wires on aluminum pads.

The phase diagram of Cu-Al system shown in Fig. 1 identifies the possible IMCs formed between copper and aluminum. Cu/Al IMC phases which formed at the temperature range between 150 °C to 300 °C are as follows [7]:

γ_2 phase ($\mathrm{Cu_9Al_4}$): 69.2 atm% Cu;
δ phase ($\mathrm{Cu_3Al_2}$): 60.0 atm% Cu;
ζ_2 phase ($\mathrm{Cu_4Al_3}$): 57.1 atm% Cu;
η_2 phase (CuAl): 50.0 atm% Cu;
θ phase ($\mathrm{CuAl_2}$): 33.3 atm% Cu.

During packaging processing and chip operation, temperature can reach up to a certain level that interdiffuses copper and aluminum at the bonding interface. The diffusion rate of aluminum into copper is faster than that of copper into aluminum. 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. However, moderate IMC growth increases the bonding strength by alloying between copper wires with aluminum pads.

In this study, we investigated the effects of IMC growth on the bondability of copper wires and aluminum pads.

II. EXPERIMENTS

Bonding Parameters of Copper Wire: The copper wire was bonded to the Al/1%Si/0.5%Cu pad of 2 $\mu\mathrm{m}$ thickness using the Shinkawa CUB-300BI machine. Tables I and II show the properties of a copper wire and bonding parameters for making samples.

TABLE I
PROPERTIES OF A COPPER WIRE

Composition	Cu (99.996%)
Diameter	2.0 mil
Specified Breaking Load (g)	40 ~ 45
Average Breaking Load (g)	47.5
Specified Elongation (%)	15 ~ 25
Average Elongation (%)	19.7

TABLE II
WIRE BONDING PARAMETERS

Bonding Time (ms)	30
Bonding Load (mN)	160
Ultrasonic Power (mW)	160

Specimen Preparation: Annealing was performed in the convection oven at 150 °C, 250 °C, and 300 °C (controlled within $\pm 5\,^\circ\mathrm{C}$) for 2 h up to 250 h, respectively. During the annealing, nitrogen gas was purged into the convection oven continuously to prevent copper oxidation, because copper can be easily oxidized at these high temperatures.

IMC Growth Evaluation: IMCs are different from copper and aluminum in colors. The presence of IMC could be checked using the change of colors under an optical microscope (OM) and a SEM, as a supplementary experiment, was also used to identify IMC. DI water and $\mathrm{HNO_3}$ mixed solution was used to etch copper selectively. IMC thickness, which grew as functions of annealing temperatures and times, was measured by OM and SEM. The least square method was employed for obtaining the reaction rate of Cu/Al IMC formation. Theoretical thickness of Cu/Al IMC by applying the obtained reaction rate was calculated, and compared with the observed thickness. Finally, bonding stability was confirmed through the comparison of the obtained reaction rate of Cu/Al IMC with that of Au/Al IMC.

Ball Shear Test (Fracture Analysis): Ball shear test is a kind of destructive test that measures the energy involved in the fracture of ball bonding. Tests were performed on annealed copper wire samples bonded on the aluminum pads to investigate the effects of IMC growth on copper wire bondability.

The ball bond shear data presented in this study were obtained using Dage series 4000, and the test conditions were as follows.

Ball shear height: 4 $\mu\mathrm{m}$ from chip surface.
Stylus moving speed: 300 $\mu\mathrm{m/s}$.
Overtravel length: 100 $\mu\mathrm{m}$.

More than 30 balls were sheared in each condition so that test results would satisfy a standard normal distribution. To investigate the failure mode at bonding interface, the fractured pads and balls were observed using OM and SEM.

Micro-XRD: Micro-XRD experiment was performed on the fractured pads and balls after the ball shear test to understand the effects of Cu/Al IMC formation at the interface. The identification of IMC phases was done by matching the micro-XRD results to the JCPDS cards, and the obtained results of phase identification were compared with those of EDS.

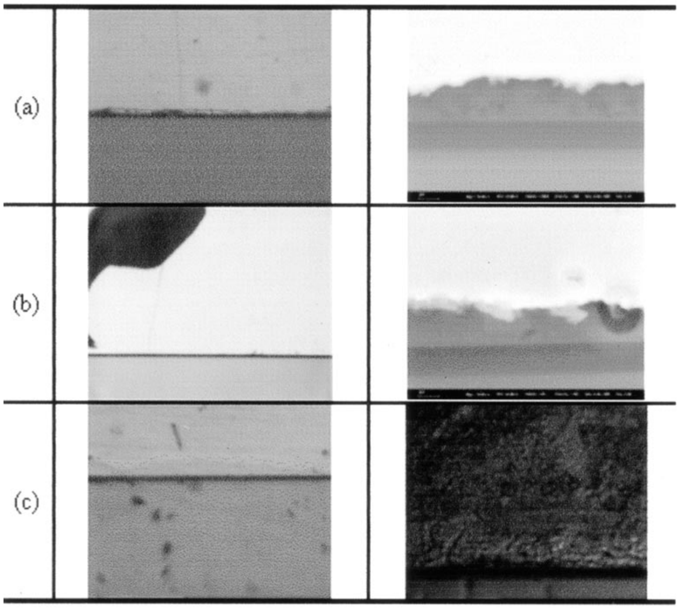


Fig. 2. Cross-sectional images of OM and SEM of Cu/Al interface after annealing treatment at (a) 150 °C, 25 h, (b) 250 °C, 25 h, and (c) 300 °C, 25 h.

The micro-XRD used a fine collimator of 50 μm in diameter to test on a small-sized specimen. It took a long time to obtain the XRD patterns because the X-ray beams were scattered inside the collimator resulting in weak intensity. The obtained diffraction patterns showed some differences from the diffraction patterns of powder samples, but identifying the IMC phases was not difficult.

III. Results and Discussion

A. Cu/Al IMC Observation

Fig. 2 shows the cross-sectional images of Cu/Al IMC which formed at the bonding interface. It was difficult to find out the formation of IMC in OM images at 150 °C for 25 h. However, light-colored images can be observed at the Cu/Al interface in SEM images. When annealing at 250 °C, light-colored images appeared at 150 °C, 50 h-annealed samples were quickly observed even in the 2 h-annealed samples at 250 °C. IMC thickness grew about 0.5 μm after 25 h of annealing at 250 °C. After 100 h of annealing, very clear IMC layer was formed at the Cu/Al interface because of significant growth of Cu/Al IMC at the bonding interface after annealing at high temperatures for a long time. Color of IMC layer was yellowish in OM images.

At 300 °C, the yellowish IMC layer was clearly observed even after 5 h of short annealing, and the bluish aluminum pad completely disappeared after 100 h. Aluminum was consumed very fast due to its rapid diffusion into the copper wire, and the high reaction rate of the formation of Cu/Al IMC at high annealing temperatures.

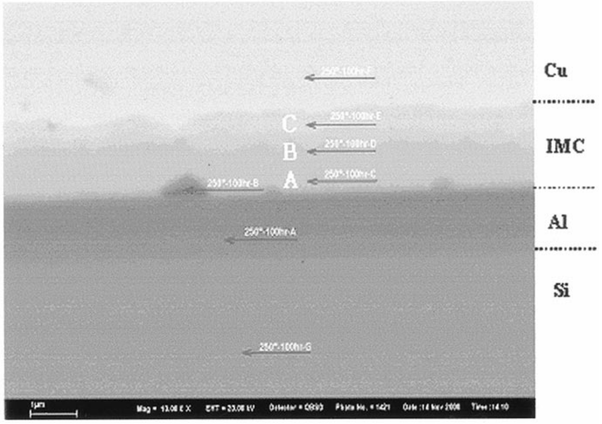


Fig. 3. SEM image of annealed Cu/Al sample at 250 °C for 100 h EDS analysis was performed at A, B, and C points.

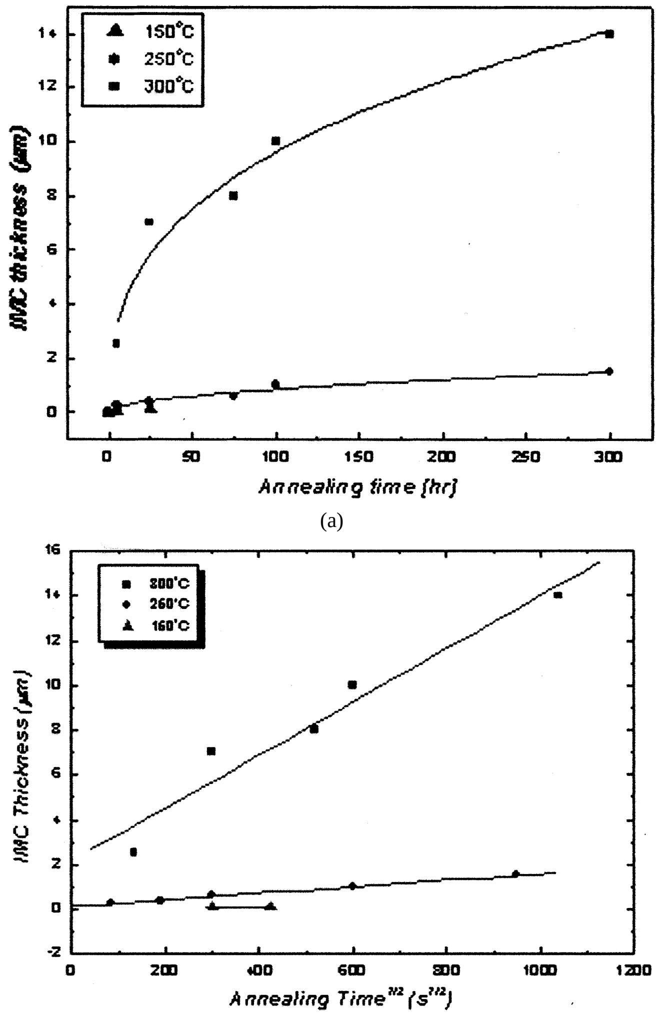
TABLE III
Result of EDS Analysis on the Sample Annealed at 250 °C for 100 h

	A point	B point	C point
Al (atm%)	34.97	59.08	55.29
Cu (atm%)	14.28	24.23	40.68
Si (atm%)	50.75	16.69	4.03
Cu:Al ratio	~ 1:2	~ 1:2	~ 1:1

EDS analysis was performed to investigate the composition ratio of each element at the yellowish IMC layer observed at annealed samples. Fig. 3 shows the cross-sectional SEM image of 100 h-annealed specimen at 250 °C, and the layers are distinguished as the change in colors becomes evident. EDS was carried out at A, B, and C points, and results are shown in Table III. According to results shown in Table III, Al rich phase was formed at the A point, close to aluminum pad, and Cu rich phase at C point, close to copper wire. Table III indicates that several different IMC phases can be formed at the bonding interface. In the case of a welded bulk Cu/Al diffusion couple, many former researchers reported that all possible IMC phases such as CuAl_2 (θ), CuAl (η_2), $\text{Cu}_4\text{Al}_3(\zeta_2)$, $\text{Cu}_3\text{Al}_2(\delta)$, and $\text{Cu}_9\text{Al}_4(\gamma_2)$ are formed layer by layer [7] from aluminum to copper. In the diffusion couple of thin film type, the reported IMC phases were CuAl_2, CuAl, and Cu_9Al_4 [9], [10], but many researchers had difficulty in distinguishing IMC layers clearly. Several variables such as the shape of specimen, annealing temperature, and time can affect the formation and the growth of IMC, and thereby change the possible IMC phases. In our experiment, it was also difficult to distinguish all IMC phases layer by layer.

B. Growth Behavior of Cu/AlIMC

The growth rate of Cu/Al IMC was determined by measuring the thickness of the inter-diffusion layers after annealing. Fig. 4(a) shows the parabolic growth behavior of IMC. At early stage of annealing, IMC thickness grew fast. However as annealing times increased, the IMC growth rate decreased. Moreover, the IMC growth significantly depended on annealing temperatures. Fig. 4(b) shows IMC thickness versus (annealing time) $^{1/2}$ to confirm whether IMC growth follows a parabolic law. The IMC growth follows the parabolic law, although there were slight deviations at the annealing temperature of 300 °C presumably due to the rapid IMC growth at the early stage. The reaction rate of IMC formation shown in Table IV, K, can be obtained from Fig. 4(b).



(a)

(b)

Fig. 4. (a) IMC thickness versus annealing time (h). (b) IMC thickness versus annealing $\mathrm{time}^{1/2}$.

TABLE IV
REACTION RATE OF CU/AL IMC GROWTH AT VARIOUS TEMPERATURES

Temperature(°C)	K, Reaction rate (cm^2/s)
150	1.878×10^{-16}
250	6.833×10^{-14}
300	6.027×10^{-13}

Within the experimental data, the relationship between the IMC thickness (X) and the annealing time (t) at a given temperature can be represented by

$$X^2 = Kt \quad X = IMC \text{ thickness } (\mu\text{m})$$

$$t = \text{annealing time } (s)$$

$$K = \text{Reaction rate of IMC formation } (\text{cm}^2/\text{s})$$

where K is characterized by the temperature and the activation energy. So it is given as

$$K = K_0 \exp\left(-\frac{\Delta Q}{RT}\right)$$

$$Q = \text{Activation energy (kcal/mol)}$$

$$R = \text{ Gas Constant}$$

$$T = \text{Annealing temperature } (^\circ K)$$

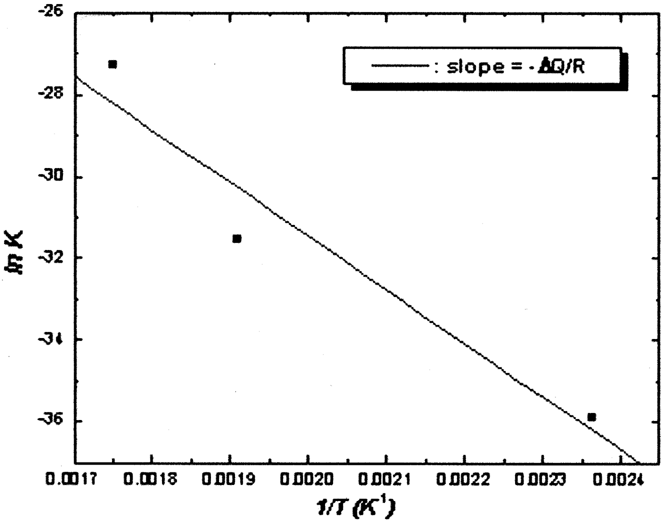


Fig. 5. Logarithm of the reaction rate in Cu/Al IMC formation as a function of inverse temperature.

TABLE V
COMPARISON OF THE REACTION RATE OF AU/AL IMC FORMATION WITH THAT OF CU/AL IMC FORMATION

Temperature (°C)	Au/Al, K (cm^2/s)	Cu/Al, K (cm^2/s)
150	1.1×10^{-14}	1.878×10^{-16}
280	2.4×10^{-11}	2.645×10^{-13}
350	3.9×10^{-10}	3.747×10^{-12}

and the reaction rate constant K and the activation energy ΔQ can be calculated from ln K versus $1/T$ curve shown in Fig. 5. The obtained activation energy was about 26 Kcal/mol, but this was slightly different from the reported activation energy, 29–34 Kcal/mol, obtained from the bulk Cu/Al diffusion couple [7], [8].

As a result, the IMC growth can be explained by annealing temperature (T) and time (t).

Derived IMC Growth Equation:

$$X^2 = t4.658 \times 10^{-3} \exp\left(\frac{-13\,046.179}{T}\right).$$

Theoretical thickness of IMC formation can be calculated by this formula.

Table V shows the comparison between calculated reaction rates of Cu/Al IMC formation and that of Au/Al IMC formation. At certain temperatures, the reaction rate of Cu/Al IMC is 100 times slower than that of Au/Al IMC. The IMC thickness is proportional to the square root of K so that the thickness of Cu/Al IMC is expected 10 times thinner than that of Au/Al IMC at the same annealing condition. Kirkendall voids, formed at gold wires on Al pads, were not observed at copper wire bonding interface. Consequently, the copper wire bonding can provide better mechanical and electrical reliability because of the slow growth rate of Cu/Al IMC and the absence of the Kirkendall voids.

C. Ball Shear Test and Failure Mode Analysis

Fig. 6. shows the results of ball shear test of annealed samples at 150 °C, 250 °C, and 300 °C. Ball shear strength increased gradually as annealing time increased in the cases of

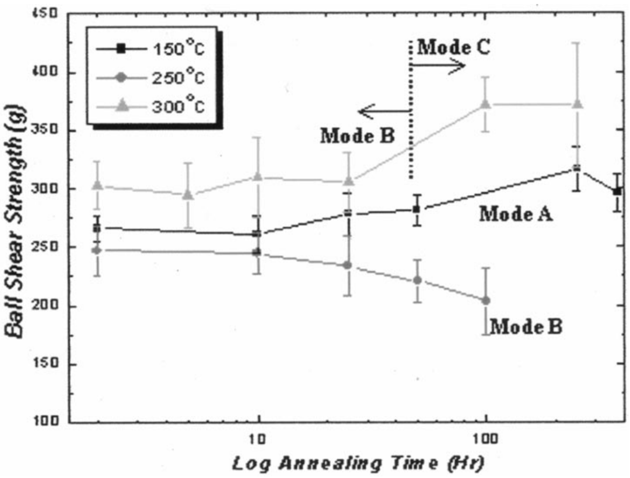


Fig. 6. Ball shear strength versus logarithm of annealing time at 150 °C, 250 °C, and 300 °C annealing temperature.

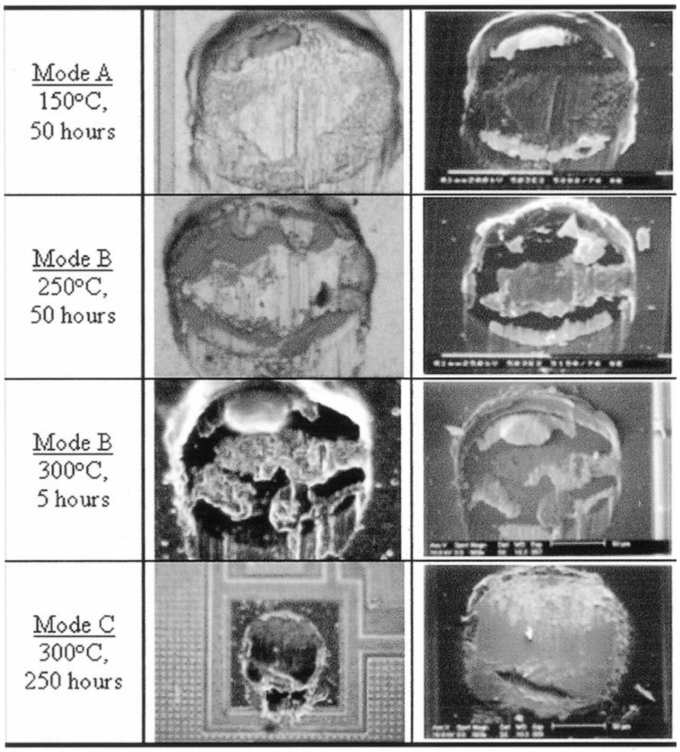


Fig. 7. OM and SEM images of fractured pads of annealed samples. Different failure modes were observed at each annealing conditions such as an adhesive interface failure (Mode A), the poor wetting failure (Mode B), and the cohesive failure inside Cu ball (Mode C).

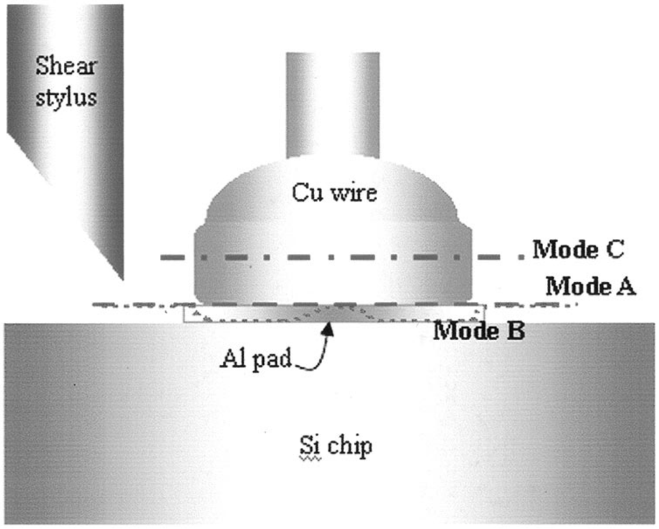


Fig. 8. A schematic diagram of the failure mode. [(- - - -)Mode A, (……) Mode B, and (-.-.-) Mode C].

annealing at 150 °C and 300 °C. However, ball shear strength decreased as the annealing time increased at 250 °C. Failure analysis was performed to analyze the changes of ball shear strength. Fig. 7. shows the OM and SEM images of fractured pads. Failure modes were different at each annealing temperatures. Types of failure mode were divided into Mode A, B, and C depending on annealing conditions.

150 °C Annealing: Silver-colored area in OM images was known as aluminum by EDS analysis. Al pad occupied the major portion of fractured pads. The amount of remaining copper wire at the edge of the fractured pad increased gradually as annealing time increased. It is considered that the effect of Cu/Al IMC during the ball shear test was very minimal because Cu/Al IMC formation was difficult at 150 °C. Therefore, fractures occurred at interface between copper wires and aluminum pads. The scratched marks of aluminum pads supported this analysis. The failure mode of 150 °C was "adhesive interface failure" (Mode A) and a schematic diagram of the Mode A failure is shown in Fig. 8. During longer annealing times, more copper and aluminum reacted, resulting in a stronger interface. As a result, more copper was observed at the fracture pad at longer annealing times.

250 °C Annealing: The images of fractured site annealed at 250 °C are different from those at 150 °C. Scratched aluminum pad, which covered most area of the fractured sites at 150 °C, remarkably disappeared, and the proportion of exposed $\mathrm{SiO_2}$ below aluminum pads increased at 250 °C. As annealing times increased, the area of $\mathrm{SiO_2}$ increased and occupied about 50% of fractured sites after 100 h annealing.

Due to the small quantity of the aluminum pad compared with the copper wire and the high diffusivity and reaction rate between copper and aluminum at 250 °C, only 2 μm thickness of aluminum pad could be easily consumed during longer annealing times at 250 °C. If aluminum is consumed entirely, Cu or Cu-rich IMC phase can meet $\mathrm{SiO_2}$ layer underneath. The adhesion of Cu or Cu-rich IMC to $\mathrm{SiO_2}$ may be weak resulting in delamination at this interface during a ball shear test. The increase of the exposed $\mathrm{SiO_2}$ area indicates that most aluminum was consumed by the Cu/Al IMC reaction, thereby increasing the portion of Cu-rich $\mathrm{IMC/SiO_2}$ interface. The change of fracture site from Cu/Al adhesive interface to Cu/Al $\mathrm{IMC/SiO_2}$ interface and low ball shear strength can be possibly explained by poor adhesion of Cu/Al $\mathrm{IMC/SiO_2}$ interface. Conclusively, at 250 °C the major failure mode is the Cu/Al $\mathrm{IMC/SiO_2}$ interface (Mode B, shown in Fig. 8) and the adhesive interface failure (Mode A) is observed as a minor failure mode.

300 °C Annealing: While annealing at 300 °C, until 25 h, fracture images were very similar to those at 250 °C, composed

TABLE VI
THEORETICAL IMC THICKNESS AFTER ANNEALING (A) AT 250 °C AND (B) AT 300 °C

(a) 250°C Annealing

Annealing time (hours)	IMC thickness (μm)
2	0.22
10	0.49
25	0.78
100	1.55
250	*2.48*

(a)

(b) 300°C Annealing

Annealing time (hours)	IMC thickness (μm)
5	1.00
25	*2.30*
75	4.00
100	4.65
250	7.36

(b)

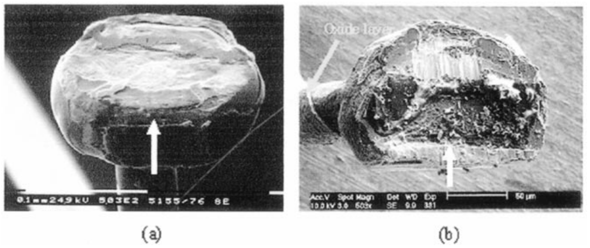


Fig. 9. SEM images of the bottom of sheared wire balls: (a) after annealing at 250 °C for 100 h and (b) at 300 °C for 250 h. The white arrow shows the direction of stylus moving.

of scratched aluminum pads, remaining copper wires and exposed SiO_2. After the samples were annealed for 100 h, ball fracture took place inside the balls (Mode C). SiO_2 was not exposed even after 250 h. As shown in Fig. 6, the fracture mode changed from Mode B to Mode C after 25 h.

The shape of fractured sites up to 25 h (Mode B) was similar to those of 250 °C of annealing (shown in Table VI) because theoretical thicknesses of annealed samples at 250 °C for 250 h and at 300 °C for 25 h were almost identical based upon a simple calculation using reaction rates at 250 °C and 300 °C. Therefore, it is understood that identical IMC thickness of about 2.3 μm results in similar fracture mode at different temperatures.

After 25 h of annealing at 300 °C, the fracture site moved inside the ball (Mode C) and the shear strength steeply increased. This is probably because the recrystallization changes the microstructure of copper wire balls resulting in softened balls. During a ball shear test, first, thick oxide layers formed at the wire surface broke, and the ball fracture occurred. Fig. 9 shows the difference of fractured balls at 250 °C and at 300 °C. The white arrow indicates where the stylus contacted a ball bond and a sheared direction. Samples, annealed at 250 °C, were a little flattened, but they maintained the original ball shape. However, 300 °C of annealing made balls significantly deformed, when they were sheared by stylus. Fig. 9(b) shows that about 1/4 of the ball was deformed and the contact surface was flattened.

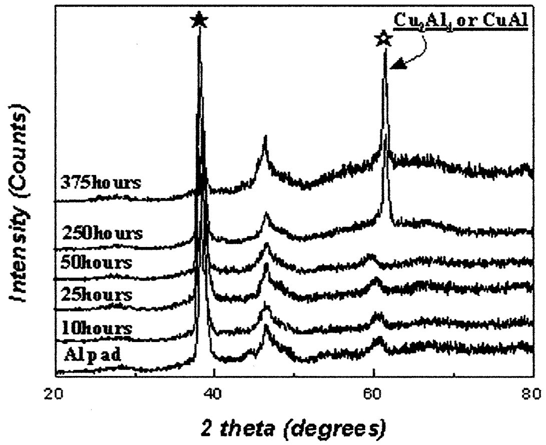


Fig. 10. Micro-XRD patterns of 150 °C annealed samples. Micro-XRD experiment was performed at fractured pad sites. (★: Al, Cu_9Al_4 or CuAl).

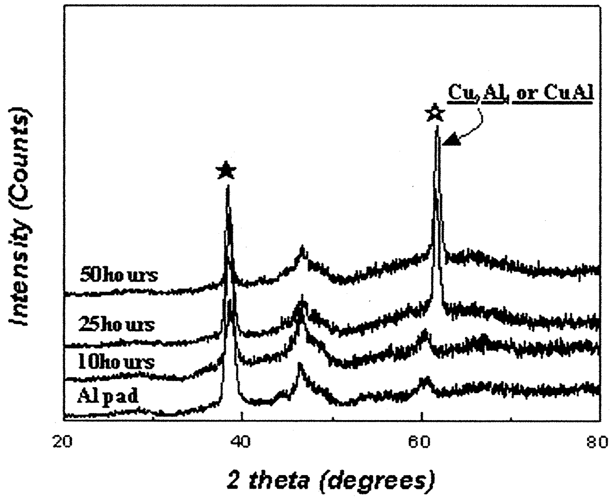


Fig. 11. Micro-XRD patterns of 250 °C annealed samples. Micro-XRD experiment was performed at fractured pad sites. (★: Al, Cu_9Al_4 or CuAl).

D. Micro-XRD Analysis

To identify IMC phases, a micro-XRD experiment was performed at the fractured sites after a ball shear test. First of all, micro-XRD was performed on the aluminum pad surface without bonding as a standard reference state. After the shear test of actual bonded samples, IMC phases could be identified by removing standard peaks on the XRD patterns of the fractured sites.

Fractured Pad: The XRD patterns of fractured pads after each annealing temperatures, compared with standard peaks, are shown in Figs. 10–12. At 150 °C, (111) Aluminum 1st peak appeared at about 38.5 ° and other minor peaks occurred from aluminum or SiO_2. IMC peaks were not observed until 50 h had passed, but after 250 h, a new peak appeared about 61.5 ° representing Cu_9Al_4 or CuAl.

Fig. 11. shows the XRD results of fractured pads after the wires were annealed at 250 °C. The Cu/Al IMC peak of 61.5 ° which appeared after 250 h of annealing at 150 °C could be observed even after about 25 h of annealing at 250 °C.

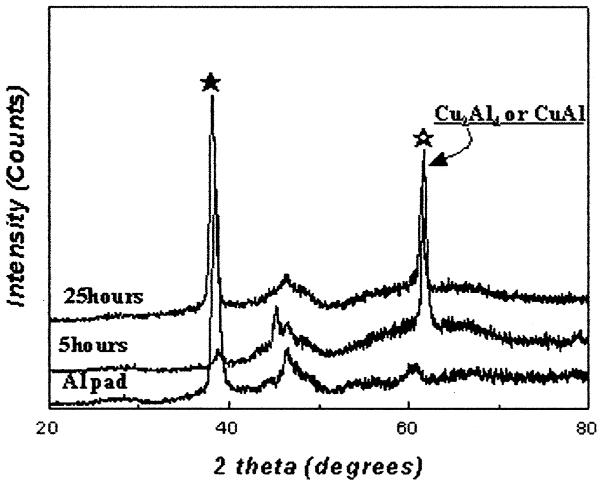


Fig. 12. Micro-XRD patterns of 300 °C annealed samples. Micro-XRD experiment was performed at fractured pad sites. (★: Al, Cu_9Al_4 or CuAl).

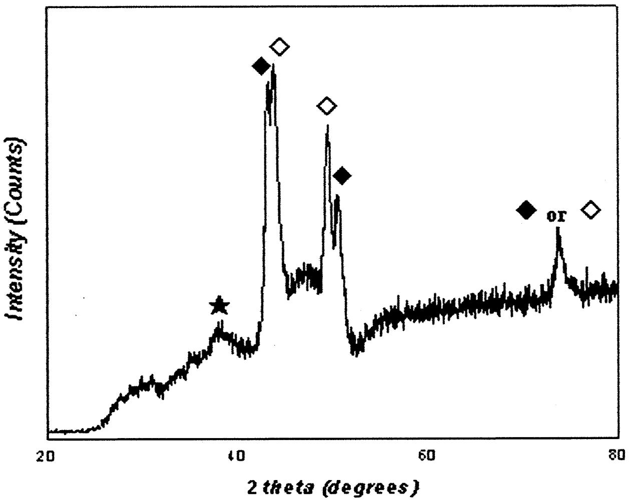


Fig. 13. Micro-XRD patterns of an annealed sample at 250 °C for 25 h. Micro-XRD experiment was performed at the fractured ball site. (★: Al, ◆: Cu, ◇: Cu_9Al_4).

Finally, Fig. 12 shows the XRD patterns of samples annealed at 300 °C. As shown in micro-XRD patterns, it took only 5 h to form Cu/Al IMC at the interface.

Fractured Ball: The XRD results obtained from the bottom of the fractured balls are shown in Figs. 13 and 14. From the XRD results of fractured pads, Cu/Al IMC phases were confirmed at 250 °C sample after 25 h of annealing. The XRD results of fractured balls are different from those of fractured pads, and the pattern is very complicated because of the overlapping of peaks and background effects. Three phases were identified from this pattern. Aluminum (111) peak is at 38.5 ° and copper (111) and (200) peaks are at 43.3° and 50.5 °. Cu_9Al_4 IMC peaks are at 43.9 ° and 49.6 °. This result agrees well with those of XRD results of fractured pads. Therefore, it can be concluded that Cu_9Al_4 is the major IMC phase formed after annealing at 250 °C for 25 h.

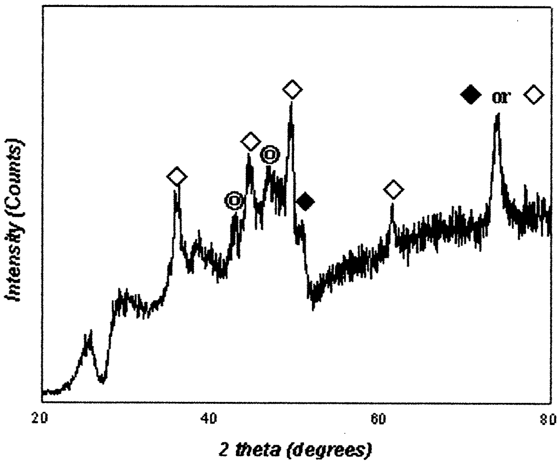


Fig. 14. Micro-XRD patterns of an annealed sample at 300 °C for 100 h. Micro-XRD experiments were performed at the fractured ball site. (◆: Cu, ◇: Cu_9Al_4, ◎: $CuAl_2$).

Similarly, XRD was performed on annealed samples at 300 °C for 100 h. As shown in Fig. 14, Cu_9Al_4 IMC formed at first as a major IMC. The pattern became more complicated as the annealing time increased because other IMCs such as a $CuAl_2$ formed after longer periods of annealing. Actually, it was difficult to identify the exact phases, due to peak split, peak overlapping, and background.

In summary, during 150 °C to 300 °C annealing, the major IMC phase was Cu_9Al_4 and other IMC phases formed as annealing times increased.

IV. CONCLUSION

1) Cu/Al IMC formation was confirmed using SEM and OM when samples were annealed at 150 °C to 300 °C for 2 h to 250 h. Furthermore, Cu/Al IMC growth followed the parabolic law as a function of annealing times at certain annealing temperatures.
2) Cu/Al IMC growth was more sensitive to the annealing temperature than the annealing time.
3) Reaction rate of Cu/Al IMC formation was obtained using the Arrhenius plot (lnK versus 1/T) and the universal IMC growth equation could be derived. Therefore, the theoretical IMC thickness can be calculated as functions of time and temperature. Moreover, the reaction rate of Cu/Al IMC formation is 100 times slower than that of Au/Al IMC formation.
4) Failure mode of ball fracture changed as a function of annealing time. The observed failure modes were adhesive interface failure (Mode A), the Cu/SiO_2 interface failure (Mode B), the mixed failure (Mode A + Mode B), and the ball inside failure (Mode C) depending on annealing times at 150 °C, 250 °C, and 300 °C, respectively.
5) Major forming Cu/Al IMC was Cu_9Al_4 at 150 to 300 °C annealing. However, more IMC phases appeared at 300 °C for longer annealing time.

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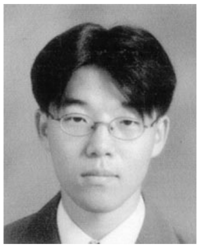

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