Characterization of Intermetallic Compound (IMC) growth in Cu wire ball bonding on Al pad metallization

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Abstract
As one of the alternative materials in chip interconnection, copper wire has become popular because of its lower cost and higher electrical conductivity than gold wire. Moreover it is known that long term reliability performance at high temperature of copper wire is better than that of gold wire because of slower Cu/Al intermetallic compound (IMC) growth than that of Au/Al intermetallics.

However, majority of copper wire bonding development works has been focused on the material and/or process optimization and qualification so far, now it is time that we need to understand more on the Cu/Al IMC growth behavior to prevent IMC related failures in copper wire field application. So, in this paper, we aimed to generate Cu/Al IMC growth model based on the experimental result depends on high temperature storage (HTS) time and temperature and also tried to suggest Cu/Al IMC thickness guideline to minimize IMC degradation.

In this experiment, Al pad chips were bonded with 99.99% purity of copper wire and Pd coated copper wire and some of them were encapsulated with epoxy mold compound. The samples were stored at the temperature range from 150 C to 250 C upto 1000 hrs. IMC phase and thickness were analyzed by the help of SEM and EDX. In order to generate Cu/Al growth model, reaction rate (K) and activation energy (\(\Delta Q\)) were calculated with above experimental results by using Arrhenius diffusion equation. Also, in order to investigate the Cu/Al IMC effect on the bondability, ball shear strength was measured and its result was correlated with IMC thickness.

According to this paper, we could derive Cu/Al IMC thickness prediction model and suggest IMC thickness guideline that can minimize IMC failures.

Introduction
There are two major methods in chip interconnection such as wire bonding and flipchip technology. Currently flipchip technology has been highlighted as one of interconnection methods but wire bonding has been widely applied for many decades and still regarded as main technology due to its high stability and cost effectiveness in microelectronics.

In wire bonding, Au wire has been used as main stream in semiconductor packaging for many years. [1] However, recently the price of Au has greatly increased and this led the industry to begin to consider and develop Cu wire bonding as an alternative. Even though there are some disadvantages and barriers need to be overcome in Cu wire application such as oxidation and higher hardness, many researches have been performed on Cu wire bonding [2]-[5] and a number of papers have shown the expected benefits of Cu wire over Au wire bonding.[6]-[8] The advantages were lower material cost, higher electrical & thermal conductivity and lower reaction rates between Cu wire and Al pad which could improve the long term reliability performance compared to Au wire bond. Most of researches have been focused on the Cu wire bonding process optimization, manufacturing and reliability test so far, however, now it is time to give more attention to understand the Cu/Al intermetallics to prevent IMC failures for field application.

In this study, we investigated to generate Cu/Al IMC growth model based on the experimental result that can predict its IMC thickness depends on storage time and temperature. Also, we tried to give IMC thickness guideline to minimize IMC degradation.

![Fig. 1. Phase diagram of Cu/Al system](image_url)

The phase diagram of Cu/Al system shown in Fig. 1 indicates the possible IMC phases between Cu and Al interface. The reaction between Cu and Al is approximately 1/10th that of Au and Al in the temperature range 150C – 300C.[9]-[10] In the Cu/Al system, there are five IMC phases in the temperature range 150C - 300C [9] which are CuAl\(_2\), Cu\(_3\)Al\(_2\), Cu\(_4\)Al\(_3\), CuAl and CuAl\(_2\). Although there are five stable IMC phases in Cu/Al system, only three of these phases have been identified in the studies of Cu and Al diffusion, they are CuAl\(_2\), CuAl and CuAl\(_2\). [9]-[10] It is generally known that abnormal Cu/Al IMC growth can make bonding interface brittle and result in failure but moderate IMC growth increases the bonding strength by alloying between Cu wire and Al pads. In this paper, we investigated IMC thickness, Cu/Al IMC phase and ball shear strength were measured to see the characteristics between Cu and Al interfaces.
Experimental

A. Sample preparation – 20um wire diameter of 99.99% Cu wire and Pd coated Cu wires were bonded on the standard Amkor test wafer in a BGA package by using K&S Maxum Ultra wire bonder with Cu kit to minimize Cu wire oxidation. The bond pad composition was 99% Al and 1% Si and consisted of 6000Å of Al and 500Å of Ti. Bond pad pitch and pad opening size were 70um and 59um respectively. The bonding parameters were optimized to make target 50um bonded ball size. After completion of wire bonding, some of the parts were molded with commercialized G770SQ from Sumitomo and GE100LFCS from Nitto and then post mold cure at 175C for 4 hrs. Other used materials and processes were followed by Amkor standard condition.

The parts were exposed to high temperature storage at 150C, 200C and 250C for 100hrs, 250hrs, 500hrs and 1000hrs respectively in a oven with nitrogen environment to form Cu/Al intermetallics. No bake samples were also prepared for comparison. Table 1 shows the summary of used materials and high temperature storage condition.

Table 1. Summary of used materials and HTS condition

<table>
<thead>
<tr>
<th>Wire</th>
<th>Commercial 99.99% Cu wire and Pd coated Cu wire (99.99%), 20um wire diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Die</td>
<td>70um BPP/59um BPO 99% Al / 1%Si, 6000Å Al thickness, 500Å Ti thickness</td>
</tr>
<tr>
<td>Wire bonder &amp; Ball size</td>
<td>K&amp;S Maxum Ultra bonder with Cu kit and forming gas (95% Nitrogen with 5% Hydrogen) Bonded ball size target 50um diameter</td>
</tr>
<tr>
<td>Mold &amp; PMC</td>
<td>No molded sample Mold with G770SQ supplied from Sumitomo Mold with GE100LFCS supplied from Nitto Post mold cure at 175C for 4 hrs</td>
</tr>
<tr>
<td>HTS temperature</td>
<td>No bake, 150C, 200C and 250C</td>
</tr>
<tr>
<td>HTS time</td>
<td>No bake, 100hrs, 250hrs, 500hrs and 1000hrs</td>
</tr>
<tr>
<td>Substrate</td>
<td>Green substrate for BGA package</td>
</tr>
</tbody>
</table>

B. Cu/Al IMC observation – After completion of high temperature storage at each condition, samples were cross sectioned by CP (Cross-section Polisher, by JEOL) with ion cutting and IMC thickness and phases were analyzed under the help of SEM, FIB, EDX etc. For IMC thickness measurement, the thickest 10 data points/ball of Cu/Al inter-diffusion layers, 2 balls/test condition were measured by SEM as shown in Fig.2. IMC phase was analyzed by EDX. Point analysis, line scanning, element mapping were performed to understand the IMC phases.

C. Ball shear strength measurement – Ball shear test is a kind of destructive test that can measure the Cu/Al interface strength. Test was performed on the high temperature storage samples at each condition to investigate the effect of IMC growth on Cu wire bondability on Al pad. Dage 4000 series shear tester was used to measure the strength with the condition of shear speed 200um/sec and shear height 2.5um. Min 45 balls were tested at each storage condition so that test result could satisfy the standard normal distribution. To investigate the failure mode, fractured surface was observed through microscope.

Test result analysis & Discussion

A. Cu/Al IMC observation - Fig.3 shows the IMC thickness measurement result depends on high temperature storage time and temperature for 4N Cu wire with no molded parts. The IMC thickness was generally increased as proportional to time and temperature increase and followed a parabolic graph. The thickness of 250 C sample was much increased compared with those of other temperatures and it is believed the IMC growth significantly depended on storage temperature.

In Fig.4, IMC growth result depends on wire type was shown. JMP analysis result shows the thickness of Pd coated wire sample was thinner than that of 4N Cu wire sample and the difference was remarkable at longer storage time. In order to understand the reason of less IMC growth, ball was cross sectioned and EDX analysis was performed for the Pd coated wire sample. As shown in Fig. 5, Pd element was detected in the Cu/Al IMC area and it is assumed Pd in IMC layer may interrupt Cu diffusion to Al pad and this resulted thinner IMC growth than that of 4N Cu wire sample.
The effect of EMC on the Cu/Al IMC growth was investigated in Fig.6. Generally molded sample showed thicker IMC than that of no molded sample. This trend was observed in both 4N Cu wire and Pd coated Cu wire. It is assumed that mold temperature and additional thermal effect by post mold curing may make thicker IMC than that of no molded sample. In case IMC growth was compared by EMC type, G770SQ showed thinner IMC growth than that of GE100LFCS for both 4N Cu wire and Pd coated Cu wire. It is not sure but we can carefully assume the difference may come from thermal conductivity difference. According to supplier’s information, GE100LFCS has higher thermal conductivity than G770SQ by 10%. We need more study to verify the EMC effect on the Cu/Al IMC.

Fig. 4. IMC thickness growth per wire type at 200C storage temperature with no molded samples

Fig. 5. EDX analysis result of Pd coated wire sample. (a) EDX line scanning result. (b) EDX area mapping result for Pd, Cu and Al.

The IMC phases were investigated by EDX analysis. Two storage conditions were selected and compared whether there is any IMC phase difference or not. One is the mildest thermal storage condition, 150C for 100hrs and the other is severer condition, 200C for 1000hrs. Fig.7 shows that in the mildest condition, two kinds of IMC phases were observed at the upper and lower position of interdiffusion layer and they were CuAl and Cu$_9$Al$_4$ based on the element composition. However, the IMC phases were all changed to Cu$_9$Al$_4$ when the storage condition became severer as 200C for 1000hrs. This observation was an agreement with theoretical phase diagram in Fig.1.

Fig. 6. IMC growth comparison between molded and no molded samples at 200C storage (a) Mold vs no mold sample with 4N Cu wire, (b) By EMC type with 4N Cu wire sample, (c) Mold vs no mold sample with Pd coated wire, (d) By EMC type with Pd coated wire sample.

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Fig. 7. SEM/EDX image of 4N Cu wire sample storaged (a) at 150C for 100hrs, (b) at 200C for 1000hrs.
Table 2 shows the summary of EDX analysis result.

<table>
<thead>
<tr>
<th></th>
<th>HTS at 150C/100hrs</th>
<th>HTS at 200C/1000hrs</th>
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<tbody>
<tr>
<td></td>
<td>Upper position</td>
<td>Lower position</td>
</tr>
<tr>
<td>Al (atm%)</td>
<td>21.37</td>
<td>7.96</td>
</tr>
<tr>
<td>Cu (atm%)</td>
<td>78.63</td>
<td>92.04</td>
</tr>
<tr>
<td>IMC phase</td>
<td>Cu₈Al₄</td>
<td>Cu₈Al₄</td>
</tr>
</tbody>
</table>

B. Ball shear strength measurement – Fig.8 shows the ball shear test result as a function of storage time at 200C. In both 4N Cu wire and Pd coated wire, the shear strength was increased up to 250hrs but it was decreased at 500hrs and later. 4N Cu wire showed much decrease than Pd coated wire and it is assumed by thicker IMC growth as shown in Fig. 4. Faster IMC growth could make earlier ball shear strength decrease. Here we can assume that moderate Cu/Al IMC growth by thermal storage can increase the interface bonding strength by alloying Cu wire and Al pads but failure analysis was performed to analyze the changes of ball shear strength. The ball shear fractured surface and cross section view were shown in Fig 9. At 100hrs and 250 hrs, fracture occurred at the bulk Cu area but fracture was observed at the Cu/Al interface area at 500hrs and 1000hrs as shown in photos. This result is also correlated with cross section view. There was no abnormality up to 250hrs but IMC crack was observed at 500hrs and 1000hrs. Abnormal IMC was grown and this made interfaces brittle and resulted in shear strength decrease.

Growth model generation
Cu/Al IMC growth model was generated by diffusion equation and experimental data. The relationship between the IMC thickness (X) and the storage time (t) at a given temperature can be represented by

\[ X^2 = Kt \]

where X= IMC thickness(um), t=Storage time (s)

\[ K = K_0 \exp(-\Delta Q / RT) \]

Q=Activation energy (kcal/mol)
R=Gas constant, T=Storage temperature(°K)

The reaction rate K at each temperature was derived by the graph of Fig.10 and the activation energy \( \Delta Q \) were derived by the graph of Fig.11. The obtained activation energy was around 10.71Kcal/mol but it was different from that of other study, 26 Kcal/mol [11] and 29-34 Kcal/mol from Cu/Al bulk system. [9][12]

As a result, the IMC growth equation can be derived by storage temperature (T) and time (t) as follows.

\[ X^2 = t \times 1.641 \times 10^{-10} \times \exp(-53853/T) \]

Where, X= IMC thickness (um), R=Gas constant, 1.99Kcal/mol.
IMC thickness guideline

According to this study, we can predict no IMC failures until 445nm IMC thickness based on the growth equation and experimental data. This thickness guideline also can be correlated with similar condition as 150C for 960 hrs or 250C for 84hrs storage.

Conclusion

1. IMC growth model for Cu/Al interface was derived by using diffusion equation and experimental data and we could predict IMC thickness in a given storage time and temperature. Derived growth equation is

   \[ X^2 = t \times 1.641 \times 10^{-10} \times \exp(-5385.3/T) \]

2. Based on this evaluation, we can expect no IMC degradation until 445nm thickness at no mold.
3. The phase of initial IMC was CuAl at 150C for 100hrs and it was fully changed to Cu9Al4 phase at 200C for 1000hrs storage.
4. The IMC thickness of Pd coated wire is thinner than that of 4N Cu wire. The reason is assumed that Pd coated in Cu surface can interrupt Cu diffusion to Al pad and this resulted thinner IMC layers.
5. Molded sample showed thicker IMC than no molded sample. It is assumed molded temperature and post mold curing could make thicker IMC.

Acknowledgement

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References
