

# **Morphology and bond strength of copper wafer bonding**

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***Abstract:*** The morphology and bond strength of copper-bonded wafer pairs prepared under different bonding/annealing temperatures and durations are presented. The interfacial morphology was examined by transmission electron microscopy (TEM) while the bond strength was examined from a diesaw test. Physical mechanisms explaining the different roles of post-bonding anneals at temperatures above and below 300°C are discussed. A map summarizing these results provides a useful reference on process conditions suitable for actual microelectronics fabrication and three-dimensional integrated circuits based on Cu wafer bonding.

Copper wafer bonding is a promising option for future three-dimensional integrated circuits (3-D IC) application.<sup>1-2</sup> Consequently; investigation of its mechanical and electrical properties, as well as the bonding mechanism has become an important subject of research. The qualitative bond strength, interfacial bonding morphologies, possible bonding mechanisms and the parameters required for an excellent Cu wafer bonding have been reported.<sup>3-5</sup> These discussions focused on one particular bonding condition which results in excellent bonding quality, i.e. wafers bonded at 400°C for 30 min, followed by nitrogen anneal at 400°C for 30 min. We reported recently that wafers bonded at 350°C for 30 min, followed by nitrogen anneal at 350°C for 60 min exhibit the same bonding quality.<sup>6</sup> However, there are no complete experimental data for other process conditions. From the manufacturing standpoint, the bonding process should be performed at a temperature as low and within a duration as short as possible. Therefore, it is important to construct a complete map of the bonding characteristics for different bonding conditions. In this paper, TEM morphologies and the fraction of die failure during diesaw test are used to build a bond strength map under different bonding/annealing temperature and duration.

Layers of Ta and Cu, 50-nm and 300-nm of Cu thick respectively, were successively deposited on N-type (100) 4" Si wafers. The bonding procedure was the same as in ref. 4.

The bonding pressure is kept at 4000 mbar. The bonding temperature ranged from 150°C to 400°C, and the bonding time was 30 min. A subsequent optional nitrogen annealing was performed at the same bonding temperature for 30 or 60 min. The morphology of the bonded Cu-Cu layer was examined using a JEOL-2010 transmission electron microscope (TEM). During the TEM sample preparation, the samples were kept below 120 °C to avoid grain growth. For the diesaw test, bonded wafers were cut into 5mm x 5mm square dies at a speed of 0.69 mm/sec by a DAD-2H/6T Automatic Dicing Saw.

Table I summarizes the TEM interfacial morphologies of Cu bonded wafers under different bonding conditions. According to previous studies<sup>4-6</sup>, there are three types of TEM morphologies: (1) No interface but grain structure (identified as “Grain” in Table I), (2) Interface structure (identified as “Interface”), and (3) Failure of TEM sample (identified as “TEM failed”). Examples of TEM morphologies for types (1) and (2) are shown in Figs 1(a) and (b), respectively. In order to assess the reproducibility of these results, several bonded wafer pairs were prepared for each bonding condition. For each bonded wafer pair, samples were selected from different areas for TEM observation. Based on the definitions used in a previous study<sup>6</sup>, results from different areas of different wafers are qualitatively classified into three categories: (1) “Most” means more than 66%, (2) “Some” means 33%-66%, and (3) “Few” means less than 33% of observed bonded

area belongs to a given morphology.

Table I shows that the proportion of interface morphologies exhibiting “Grain” structure increases when the bonding/annealing temperature or annealing duration increases, while those with a “TEM failed” structure decreases. This suggests that better bonding strength can be achieved at higher bonding/annealing temperature or longer annealing duration since the “Grain” structure represents an excellent bonding quality, whereas the “TEM Failed” structure represents a poor bonding quality. In general, in order to obtain a “Grain” structure, wafer bonding conditions of 400°C for 30 min followed by nitrogen annealing at 400°C for 30 min, or 350°C for 30 min followed by nitrogen annealing at 350°C for 60 min, are required. Under the conditions investigated here, the minimum bonding temperature must be at or above 300°C to obtain a better “bonded” layer (i.e., a “grain” morphology). When the bonding temperature is 250°C, approximately half of the morphologies can be classified as “Interface” structure while the other half as “TEM failed”. On the other hand, almost all wafers bonded below 200°C failed during TEM preparation. In addition, further annealing at bonding temperatures at or below 250°C does not improve the bonding quality, while it does so at bonding temperatures of 300°C and higher.

The morphology observations summarized shown in Table I represent the quality of

the bonded layer. The “Grain” structure represents an excellent bonded layer. The “Interface” structure represents that the two layers that are not fully bonded and exhibit a bonding interface, but can withstand the TEM sample preparation. These are the two major morphologies observed at higher temperature. At lower bonding temperatures, part of the bonded layer cannot withstand the TEM sample preparation process. Therefore, another approach to characterize the bonding quality at low temperatures is necessary. A new method based on the diesaw technique was used in this study.

When the bonded wafer is sawed into 5mm x 5mm dies, the two bonded dies bond may stay bonded or the two dies may separate due to the applied stress during sawing. The later case is defined here as a “failed die”. This approach allows us to characterize the bonding quality when the wafers are bonded at lower temperatures. At the same time, it offers some interesting data relevant to subsequent packaging.

Table II shows the percentage of failed dies at different bonding conditions after sawing. For each data entry, the results are the average of failed dies from several wafers under the same bonding condition. As Table II indicates the dies bonded at 350°C and 400°C did not fail. The percentages of failed dies stay below 25% for the bonding temperatures of 250°C and 300°C. However, when the temperature is 200°C or lower, the percentage of failed dies is much higher. For wafers bonded below 200°C followed by

nitrogen anneal, the dies almost always failed.

Table II suggests that the bonding quality is better at higher bonding/annealing temperature and that it deteriorates below 250°C. When the two layers are bonded below 250°C, the thermal energy is not high enough for grain growth development during the bonding process. Therefore, as shown previously,<sup>5-6</sup> the bonded layer has not had sufficient time to develop a grain structure. In order to achieve a good bonded interface, the required bonding duration will be very long at lower temperature, and it would not be practical in manufacturing. On the other hand, when the temperature is higher, the layers will have more energy to reach a stable structure, thereby improving the bonding quality.

The data in both Tables I and II show an interesting behavior for wafers bonded below 250°C followed by nitrogen anneal. In Table I, for example, wafers bonded at 200°C for 30min without further anneal exhibit a mixed “Interface” and “TEM failed” structures while those that underwent further anneal all failed during TEM sample preparation. On the other hand, wafers bonded higher than 300°C tend improve their bonding quality after further anneal. Similarly, Table II shows that at low bonding/annealing temperatures, the percentage of failed dies increases if the wafer undergoes nitrogen anneal. This behavior is more striking when the temperature is below 200°C.

To explain this apparent discrepancy, the state of the bonding interface between two layers at “high” and “low” temperatures must be analyzed. As shown in previous results,<sup>5</sup> after bonding at high temperature, the two layers bond together though the original interface remains. At this stage, since the bonding temperature was high, both interdiffusion between the two layers and preliminary grain growth may have already occurred. Therefore, defects, impurities and voids in the bonding interface area have been effectively removed through this process. Consequently, during the further anneal, the grains will grow further until the whole structure reaches a stable stage.

However, when bonding occurs at “low” temperature for a relatively short time, the wafers do not achieve sufficient energy. Therefore, after bonding, although the two wafers are bonded together and can withstand the sawing process, the bonding strength may be insufficient, while defects, impurities, and voids may still remain at the bonding interface area. When these wafers undergo further nitrogen anneal, the weakly bonded interface with defects is subjected to thermal stress. If the bonding strength cannot tolerate the thermal stress and the stress field induced by the vacancies and defects, the bonded area may separate. We believe this qualitatively why the bonding quality and interfacial morphology become worse when further nitrogen anneal is carried out for wafers bonded at “low” bonding/annealing temperature.

A morphology and strength map summarizing the results of Table I and II for copper wafer bonding under the conditions examined here is shown in Fig. 2. Three lines are plotted. The first line distinguishes “Grain” structure and “Interface” structure regions. The second line represents “1% dies failure line”, and the third line represents “50% dies failure line”. The region above the first line yields a “Grain” structure as a major interfacial morphology with excellent bonding quality. The region between the first and second lines yields mostly an “Interface” structure that has sufficient bonding quality and that shows the original bonding interface. The region below “50% die failure line” represents a major result of “die failure”.

The map in Fig. 2 offers helpful information for future applications based on Cu wafer bonding. For example, for excellent bonding quality, the bonding condition can be either 400°C for 30min followed by annealing at 400°C for 30min or bonded at 350°C for 30min followed by annealing at 350°C for 60min. For sufficient bonding quality with an interface, bonding temperature above 300°C is necessary. In addition to the results from the map, researches focusing on grain growth, grain orientation, and oxide composition have been investigated.<sup>3-6</sup> A Cu wafer bonding model based on these accomplishments is being developed for future work.

In conclusion, a map summarizing the results of interfacial morphologies and

bonding quality for Cu wafer bonding under different bonding temperatures and durations was described in this paper. TEM morphology and the percentage of failed dies during sawing were used to illustrate the bonding quality. The results and physical mechanisms were also discussed.

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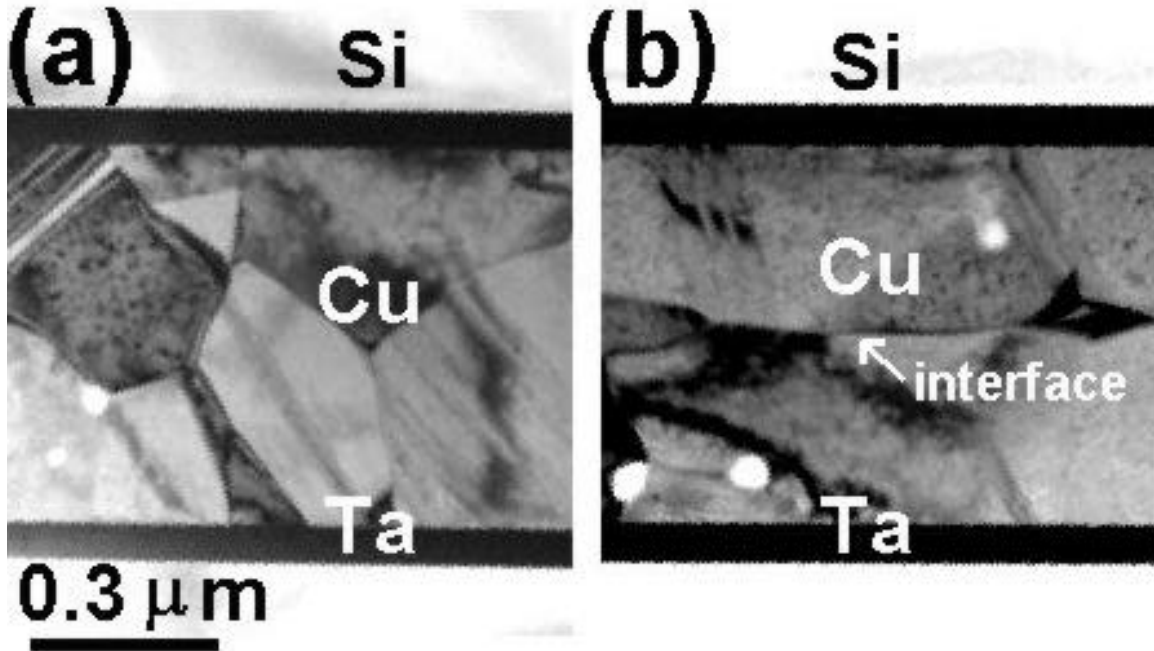
## **Figure and Table Captions**

Figures 1(a) and (b) TEM morphologies of (a) “Grain” (bonded at 350C for 30 min followed by N<sub>2</sub> annealing for 60 min), and (b) “Interface” (bonded at 350C for 30 min)

Figure 2 Morphology and strength map for copper wafer bonding under different bonding temperatures and conditions

Table I TEM results of the interfacial morphologies on Cu bonded wafers under different bonding conditions

Table II Percentage of failed dies at different bonding conditions after diesaw process



Figures 1(a) and (b) TEM morphologies of (a) "Grain" (bonded at 350C for 30 min followed by N<sub>2</sub> annealing for 60 min), and (b) "Interface" (bonded at 350C for 30 min)

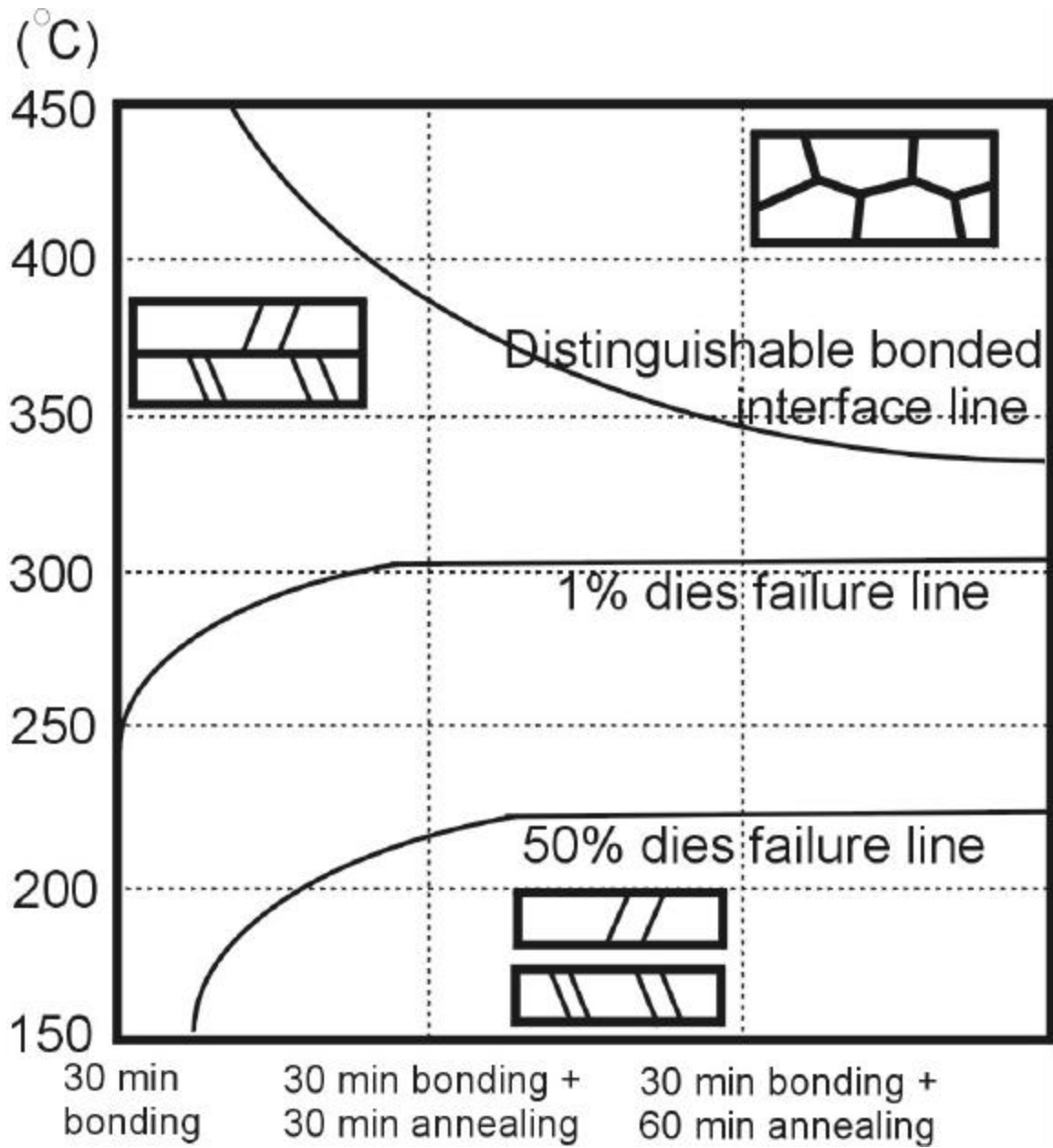


Figure 2 Morphology and strength map for copper wafer bonding under different bonding temperatures and conditions

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Table I TEM results of the interfacial morphologies on Cu bonded wafers under different bonding conditions.

Bonding Temperature \ Bonding Duration	30 min bonding	30 min bonding + 30 min annealing	30 min bonding + 60 min annealing
400°C	Grain: Few Interface: Most TEM failed: Few	Grain: Most Interface: Some TEM failed: Few	Grain: Most Interface: Some TEM failed: Few
350°C	Grain: Few Interface: Some TEM failed: Some	Grain: Some Interface: Some TEM failed: Few	Grain: Most Interface: Some TEM failed: Few
300°C	Grain: Few Interface: Some TEM failed: Some	Grain: Few Interface: Some TEM failed: Some	Grain: Some Interface: Some TEM failed: Some
250° C	Interface: Some TEM failed: Some	Interface: Some TEM failed: Some	Interface: Some TEM failed: Some
200° C	Interface: Some TEM failed: Some	TEM failed	TEM failed
150° C	TEM failed	TEM failed	TEM failed

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Table II Percentage of failed dies at different bonding conditions after diesaw process

Bonding Temperature \ Bonding Duration	30 min bonding	30 min bonding + 30 min annealing	30 min bonding + 60 min annealing
400 C	0 % dies failed	0 % dies failed	0 % dies failed
350 C	0 % dies failed	0 % dies failed	0 % dies failed
300 C	0 % dies failed	5 % dies failed	4 % dies failed
250 C	1 % dies failed	21 % dies failed	22 % dies failed
200 C	18 % dies failed	86 % dies failed	75 % dies failed
150 C	37 % dies failed	90 % dies failed	96 % dies failed

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