Temperature and Duration Effects on Microstructure Evolution During Copper Wafer Bonding

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Interfacial morphologies during Cu wafer bonding at bonding temperatures of 300°C to 400°C for 30 min followed by an optional 30 or 60 min nitrogen anneal were investigated by means of transmission electron microscopy. Results showed that increased bonding temperature or increased annealing duration improved the bonding quality. Wafers bonded at 400°C for 30 min followed by nitrogen annealing at 400°C for 30 min, and wafers bonded at 350°C for 30 min followed by nitrogen annealing at 350°C for 60 min achieve the same excellent bonding quality.

INTRODUCTION

While dimensional scaling has consistently improved device gate switching delay, it has a reverse effect on global interconnects[1]. Global interconnects RC delay has increasingly become a circuit performance limiting factor, especially in the deep sub micron regime. Even though the introduction of Cu/low-K materials has been improved this RC delay, this is not a long-term solution due to the need of a higher-resistivity diffusion barrier material of finite thickness in Cu metallization as well as surface electron scattering effects[2]. In seeking a long-term solution, the ITRS (International Technology Roadmap for Semiconductors) has outlined 3-D interconnects as a promising option that allows shorter global interconnects and hence improved RC delay[3]. High density device packaging and heterogeneous systems integration are among other potential advantages offered by 3-D integration.

Possible technology options to realize a 3-D structure include Si recrystallisation[4,5] and wafer bonding[6,7]. Wafer bonding can be carried out using a dielectric or a conductive layer as the bonding interface. Several research results on Cu wafer bonding have been reported.[8-11] This paper presents a complete picture of the effects of bonding temperature and duration on the microstructure evolution during Cu wafer bonding.

OVERVIEW OF PREVIOUS RESULTS

Wafers coated with Cu exhibit good bond properties when contact occurs at 400°C/4000 mbar for 30 min, followed by an anneal at 400°C for 30 min in N_2 ambient atmosphere. The microstructure morphologies of bonded copper wafers were examined by means of transmission electron microscopy (TEM). The distribution of different defects show that the bonded layer became a homogeneous layer under this bonding condition. An energy dispersion spectrometer (EDS) study indicated that oxygen distribution in the bonded layer is uniform and sparse from.[9]

For Cu wafers bonded at 400°C for 30 minutes followed by nitrogen anneal at 400°C for 30 minutes, morphologies of non-distinct, zigzag and distinct interfaces in the bonded layer were observed. A strong relationship between the roughness of surfaces prior to bonding and bonding initiation was found. Possible mechanisms were proposed to explain the observed morphologies. In addition, the role of atomic diffusion and that of annealing effects during bonding was discussed.[10]

Evolution of grain orientations of Cu-Cu bonded wafers during bonding and annealing were studied by means of electron diffraction and X-ray diffraction. An abnormal (220) grain growth was observed during the initial bonding process. Upon annealing, the preferred grain orientation of the whole film shifts from (111) to (220). The effects of yielding stress and energy minimization are possible reasons for the evolution of the preferred grain orientation.[11]

Although we have explored several material properties and issues during Cu wafer bonding in previous studies, those results were based on the same bonding condition: the wafer pair was bonded at 400°C for 30 minutes followed by nitrogen anneal at 400°C for 30 minutes. In order to get a more complete picture of microstructure evolution during Cu wafer bonding, experiments based on different bonding temperatures and bonding/annealing duration are necessary. This paper introduces the experimental method, and presents and discusses the results.

EXPERIMENTAL PROCEDURE

Fifty nm Ta and 30 nm Cu layered structures were electron beam deposited on N-type (100) 4” Si wafers. Before bonding, wafers were dipped in 1:1 (by volume) H_2O:HCl for 30 seconds to remove the native oxide on the Cu surface. The Ta layer acts as a Cu diffusion barrier.

After HCl treatment, wafers were ready to be bonded in the Electronic Vision EV 450 Aligner and AB1-PV bonder. The detailed bonding procedures are the same as in Reference 9. A 4000-mbar force was applied for 30 min at the bonding temperature. Afterward, it required 2 hours to cool the wafers to room temperature. Some bonded wafers were then annealed at the bonding temperature in a diffusion furnace in N_2 ambient for 30 or 60 min. The bonding temperatures were 400°C, 350°C, and 300°C.

A JEOL-200CX scanning transmission electron microscope (STEM) and a JEOL-2010 transmission electron microscope were used to examine the interfacial morphologies of the Cu-Cu bonded wafer. During the TEM sample preparation, the samples were kept below 120 °C to avoid grain growth.

RESULTS

Figures 1 and 2 show typical bonded interfacial morphologies. Figure 1 shows a well-bonded layer. The original interface has disappeared and only a homogeneous grain structure can be observed. In Figure 2, however, the original interface is still clearly observed on the left side while no interface can be observed on the right side. Table I summarizes the TEM results of the interfacial morphologies on Cu bonded wafers under different bonding conditions. The bonding temperature ranges from 300°C to 400°C. A well-bonded wafer pair is achieved at 400°C. In order to minimize manufacturing cost and possible damage to device structures during bonding, lower bonding and anneal temperature are desirable. Three different bonding and anneal time were examined: 30 min bonding without further annealing, 30 min bonding followed by 30 min annealing, and 30 min bonding followed by 60 min annealing. In previous work, a 30 min bonding and 30 min annealing was found necessary to remove the bonding interface for wafers bonded at 400°C.[9]

Two major bonding morphologies have been observed in the bonded layer[9-11]. In one, the original bonding interface still exists after bonding. In the other one is the bonding interface disappears and a whole grain structure appears after bonding. Therefore, TEM morphologies can be sorted into three categories: (1) No interface but grain structure (identified as "Grain" in Table I), (2) Interface structure (identified as "Interface" in Table I), and (3) Failure of TEM sample (identified as "TEM failed" in Table I). Figures 3(a), (b), and (c) show the corresponding schematic diagrams. The bonded morphology showing a whole grain structure without the original bonding interface is expected to exhibit a high bonding strength. In the case where the bonding interface still exists in the layer, however, it suggests that the structure has acquired sufficient but not maximum bonding strength. In other words, the grain structures of the two bonded layers did not have enough energy to completely remove the bonding interface. Finally, if the TEM sample fails during preparation, it is treated here as poor bonding strength.

For each bonding condition, several bonded wafer pairs were prepared in order to access the reliability/reproducibility of these results. Samples cut from different areas of each bonded wafer pair were used for TEM observation. Results gathered from different areas of different wafers are qualitatively classified into three categories: 1. “Most” means more than 66% of observed bonded area belong to this morphology, 2. “Some” means 33%-66% of observed bonded area belong to this morphology, 3. “Few” means less than 33% of observed bonded area belong to this morphology. Not only can this method easily distinguish the bonding quality of an individual bonding condition, but also show the bonding quality trend as a function of temperature and process duration.

As indicated in Table I, the bonding interface still exists in the wafer pair bonded at 400°C for 30 min. Whole grain structure morphology and TEM sample failure are rare. After 30 min annealing, however, the major morphology in the bonded layer becomes that of a whole grain structure and most of the original interface has disappeared. In addition, there are only very few failed TEM samples during sample preparation. This suggests that the bonding quality is strong and relatively uniform under this condition, which is consistent with previous observations[9,11]. When the annealing time is increased to 60 min, the morphology composition is almost the same as that corresponding to 30 minutes annealing. This suggests that the bonding strength does not further increase.

When the bonding temperature is decreased to 350°C and 300°C, the number of failed TEM samples increases for all bonding conditions. At the same time, the possibility of a whole grain structure in the bonded layer is low. For example, at 300°C, the morphology of bonded layer corresponding to 30 min bonding followed by 30 min annealing only shows a relatively small fraction of the no-interface "grain" structure, while this is the major morphology at 400°C under the same bonding condition. These results suggest that the bonding strength decreases when the bonding temperature decreases.

Furthermore, at all bonding temperatures explored here, the fraction of no-interface "grain" structure morphology increases, while the fraction of TEM samples failure decreases, when there is a post-bonding anneal in nitrogen. This suggests that post-bonding anneals are important for a successful bonding, consistent with our previous results at 400°C[9]. At 300°C and 350°C, increasing annealing duration also showed improvements in bond strength.

It is interesting to note that the interfacial morphologies at 350°C and 300°C, unlike those at 400°C, still changed with annealing time up to 60 min. This suggests that the bonding strength at 300°C and 350°C can still be improved by increasing the annealing duration further.

DISCUSSIONS

Several important observations can be made from Table I. When the bonding temperature is increased, the bonding quality improves. At higher temperature, diffusion and grain growth during bonding are enhanced. Strong inter-diffusion of the atoms from two originally distinct Cu layers probably increases the bonding strength. Further grain growth also helps remove the bonding interface, thus creating a whole grain structure. Finally, at a temperature of 400°C, the bonding quality becomes excellent.

Further anneals after bonding also improve the bonding quality. After bonding at a temperature higher than room temperature, the bonded wafer cools down to room temperature. When the bonded wafer is undergoing annealing, the temperature of the microstructure in the bonded layer is increased again. Consequently, the grains grow again during annealing and this will further remove the bonding interface. This explains no-interface "grain" structure observed as the main morphology in wafers further annealed at 400°C for 30 min. The microstructure appears to be stable stage and most of the grains seem to have stopped growing. Therefore, further annealing will not change the major morphology, which is why the interfacial morphology corresponding to 60 min annealing is the same as that corresponding to 30 min annealing.

At lower temperatures such as 300°C and 350°C, annealing still improves the bonding quality, but it takes longer to reach a stable state. Unlike at 400°C, it is interesting that the major morphologies still change when the annealing time is increased from 30 min to 60 min at 300°C and 350°C. This is also understandable. Compared with

400°C, in the 300°C and 350°C samples, the bonded layers may not have enough energy to allow grains growth to the stable state after 30 min of annealing. The major morphologies will continue to change with anneal time until the stable state is reached (i.e., until the interface is removed).

We have shown that wafers bonded at 400°C for 30 min followed by nitrogen annealing at 400°C for 30 min will reach a strong bond quality. From the manufacturing viewpoint, the bonding and annealing temperature should be kept as low as possible, but it is also desirable to reduce bonding and annealing time. One advantage of lower bonding temperature is cost savings. Another advantage is to avoid destroying device components. An alternative bonding condition that achieves the same bonding quality is 350°C for 30 min followed by nitrogen annealing at 350°C for 60 min.

CONCLUSIONS

Copper bonded morphologies were investigated by means of transmission electron microscope at different bonding conditions. The bonding temperature range was examined 300°C to 400°C. The bonding time was kept of 30 min and some wafers were annealed in nitrogen for 30 min or 60 min. The results show that the bonding quality improves when either bonding temperature increases or post-bonding annealing is used. The increase of the annealing time beyond 30 min improved the bonding quality when the wafers were bonded at 300°C or 350°C. Wafers bonded at 400°C for 30 min followed by nitrogen annealing at 400°C for 30 min, and wafers bonded at 350°C for 30 min followed by nitrogen annealing at 350°C for 60 min achieved the same excellent bonding quality.

ACKNOWLEDGMENTS

This paper acknowledges support from the MARCO Focused Research Center on Interconnects which is funded at the Massachusetts Institute of Technology, through a subcontract from the Georgia Institute of Technology.

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Figure and Table Captions

Figure 1 TEM image of a well-bonded Cu-Cu layer bonded at 400°C for 30 min followed by nitrogen annealing at 400°C for 30 min

Figure 2 TEM image of Cu-Cu layer bonded 400°C for 30 min

Figures 3 Schematic diagrams of three catalogues for possible TEM observation results of Cu bonded layer (a) No interface but grain structure (identified as "Grain" in Table I), (b) Interface structure (identified as "Interface"), and (c) Failure of TEM sample (identified as "TEM failed")

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

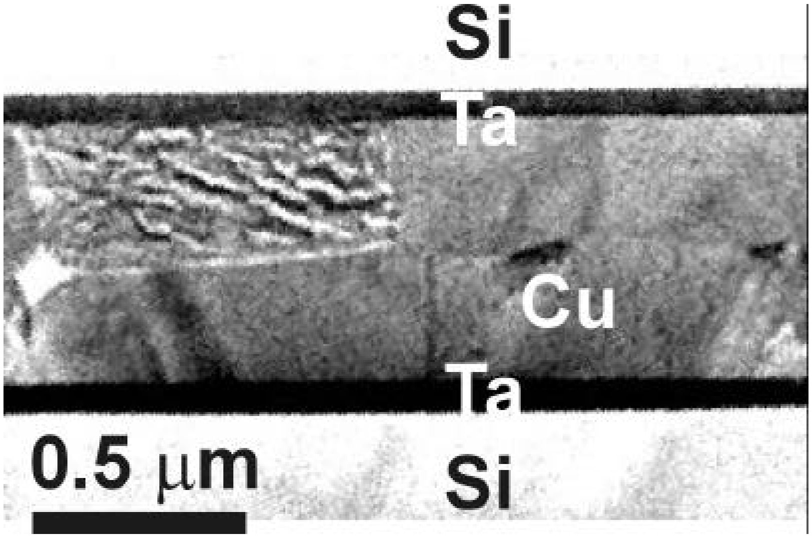


Figure 1 TEM image of a well-bonded Cu-Cu layer bonded at 400°C for 30 min followed by nitrogen annealing at 400°C for 30 min

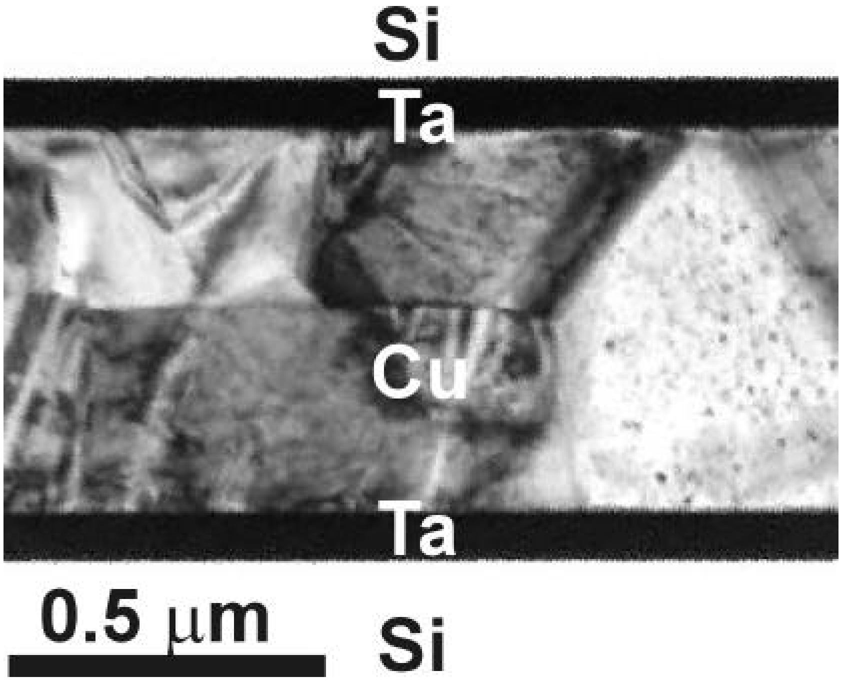
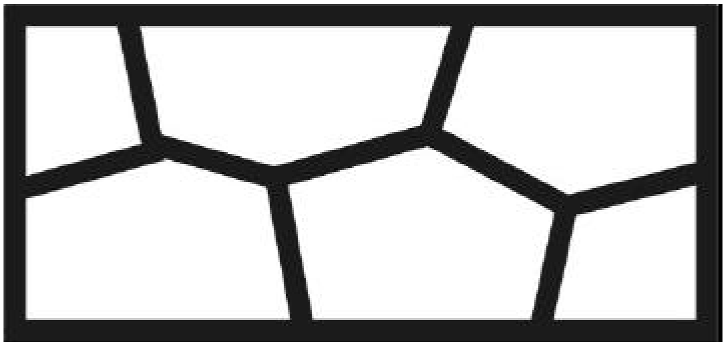


Figure 2 TEM image of Cu-Cu layer bonded 400°C for 30 min



Figures 3 Schematic diagrams of three catalogues for possible TEM observation results of Cu bonded layer (a) No interface but grain structure (identified as “Grain” in Table I), (b) Interface structure (identified as “Interface”), and (c) Failure of TEM sample (identified as “TEM failed”)

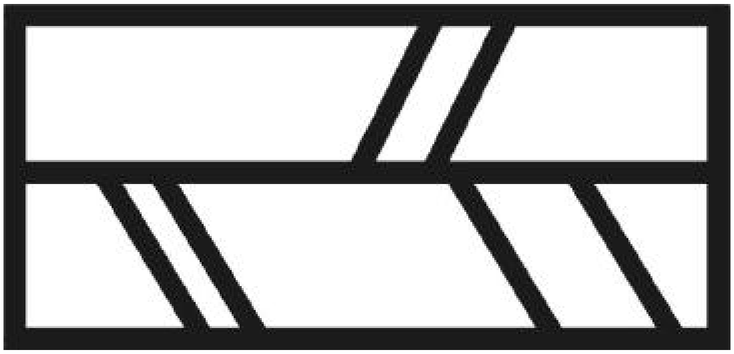


Figure 3(b)

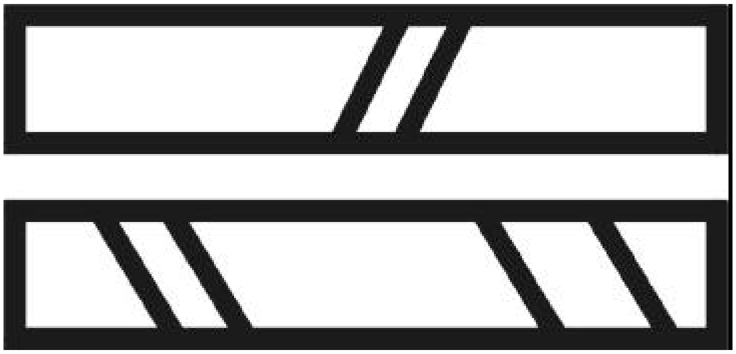


Figure 3(c)

Bonding Duration Bonding Temperature	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

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