RELATION OF CONTACT RESISTANCE REDUCTION AND PROCESS PARAMETERS OF BONDED COPPER INTERCONNECTS IN THREE-DIMENSIONAL INTEGRATION TECHNOLOGY

K. N. Chen, A. Fan, C. S. Tan and R. Reif
Microsystems Technology Laboratories,
Massachusetts Institute of Technology,
60 Vassar St., Room 39-623, Cambridge, MA 02139
E-mail: knchen@mit.edu

Contact resistances of bonded copper interconnects in three-dimensional integration technology under different bonding conditions are investigated by using a novel test structure. A reduction in specific contact resistance is obtained by longer anneal time. The specific contact resistance of bonded interconnects with longer anneal time does not change with the interconnect sizes. Underlying physical mechanism is discussed. The relationship between specific contact resistance and bonded wafer location is discussed as well. The specific contact resistance shows a lower value at the center of the wafer. Stability and reversibility tests show that the specific contact resistance does not change when the stress current is increased gradually or decreased after that. The excellent stability and reversibility of specific contact resistances shows that the microstructure of bonded Cu interconnects has reached a stable state.

INTRODUCTION

Three-dimensional integration using copper interconnect bonding is an attractive candidate for future IC technology [1]. In order to achieve the best circuit performance, the quality of bonded Cu interconnects is crucial. To achieve successful bonding, both structural strength and electrical performance are important. Cu wafer bonding morphology and material characterization have been previously reported [2-3]. Excellent bond strength has also been demonstrated [4]. The contact resistance of the bonded interconnects is studied in this work as it affects the circuit performance directly.

During the measurement of the contact resistance of the bonded Cu interconnects, several issues need to be taken into account. First, the misalignment during bonding makes it difficult to decide the accurate bonding area [4]. Therefore, an error may be included in the final specific contact resistance. Second, a complicate process flow is needed to fabricate 3-D structure to measure the contact resistance.

In previous work [5], we have demonstrated a novel test structure to measure the contact resistances of bonded Cu interconnects. This test structure can eliminate the misalignment during bonding, and is not complicate. Specific contact resistances of the bonding interfaces with different interconnect sizes of approximately 10^{-8} Ω-cm^2 was measured when the wafers were bonded at 400 ^{o}C for 30 min followed by nitrogen anneal at 400 ^{o}C for 30 min. The average specific contact resistance is higher for interconnect smaller than 10 μm due to larger local surface roughness fluctuation.

In this paper, different bonding conditions are explored. The specific contact resistance can be effectively reduced with a longer anneal time. It is observed that specific contact resistances of smaller size interconnects do not show higher value than larger size interconnects. This paper also presents contact resistance as a function of contact area and wafer location. The specific contact resistance does not change when the stress current is increased or decreased as the bonded structure has reached a stable state. This shows excellent stability and reversibility of the bonded interconnects.

EXPERIMENTAL

The process of the test structure for contact resistance measurement is explained in Ref. [5]. The bottom wafer was covered with 300 nm of thermal oxide, 50 nm of Ta and 300 nm of Cu successively, while the upper wafer preparation was the same as that of the bottom wafer, except that there was no Ta layer and a 1 μm Al layer was inserted between the thermal oxide and Cu layers. Detailed bonding procedure for the wafers is described in Ref. [4]. The upper and bottom wafers were bonded face-to-face at 400 ^{o}C for 30 min followed by 30 or 60 min of N_2 annealing. Then, the substrate of the upper wafer was ready to be released to reveal the test structure by soaking the bonded wafer in HCl for 2 hours. Since HCl dissolves Al preferentially over Cu, Ta and SiO_2, the substrate of the upper wafer separated from the bonded wafer pair due to the undercut in the Al layer created by the HCl solution. After releasing the upper substrate, the bonded test structures remained on the bottom substrate.

Line widths of 5, 7, 10 and 15 μm were patterned on the upper and bottom wafers. Therefore, the corresponding bonded areas are 25, 49, 100 and 225 μm^2, respectively. The total bonded area was 30% of the whole wafer area and the remaining area was air. An HP 4156 Semiconductor Parameters Analyzer was used to apply a constant current or ramp a current between 1 mA and 100 mA on the test structures.

RESUTLS AND DISCUSSION

Figure 1 shows the measured specific contact resistances of bonded interconnects under two bonding conditions: (1) 400 ^{o}C bonding for 30 min followed by 400 ^{o}C N_2 anneal for 30 min, and (2) 400 ^{o}C bonding for 30 min followed by 400 ^{o}C N_2 anneal for 60 min. For bonded Cu interconnects annealed for 30 min, and for contact areas of 10*10 μm^2 or larger, the specific contact resistance is approximately 10^{-8} Ω-cm^2 [5]. Bonded Cu interconnects with a width of 7 μm shows a higher specific contact resistance, and this is possibly due to the larger local surface roughness fluctuation. When the N_2 anneal duration is increased to 60 min, the specific contact resistance decreases significantly. In addition, the contact resistance is independent of contact area after 60 min anneal, while it increases for interconnects smaller than 10*10 μm^2 after 30 min anneal. This trend is identical to that of the bonding morphology evolution reported elsewhere [3].

From previous research, it was observed that both low contact resistance and the disappearance of bonding interface after bonding indicated an excellent bonding. Thus, the low specific contact resistances of the bonded interconnects after 60 min anneal indicates a better bond quality. This is due to the bonded interconnects has sufficient energy to refine the interfacial structure under longer duration of heat cycle.

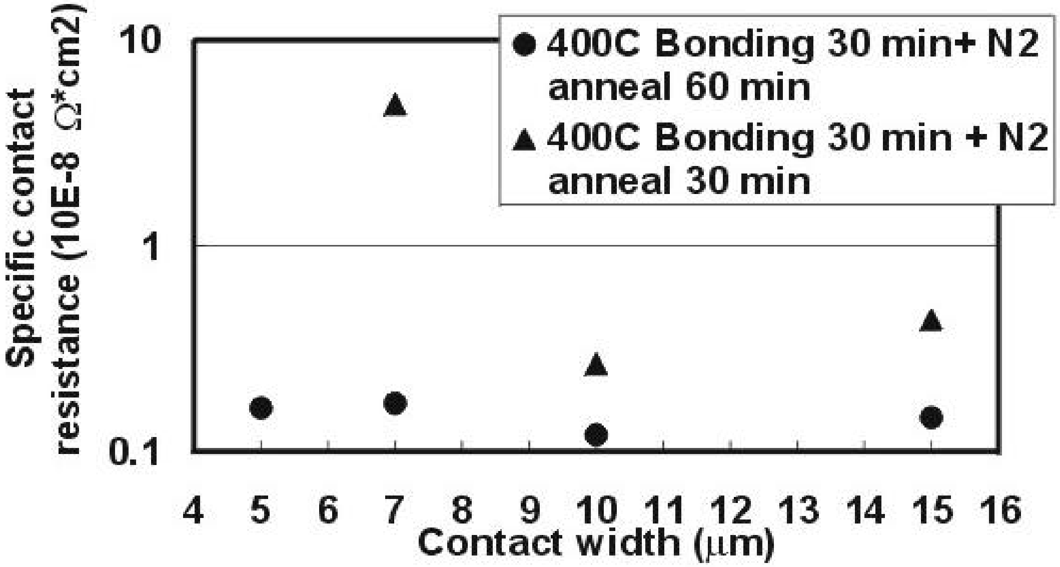

Figure 1 Specific contact resistances of bonded interconnects at two bonding conditions: 400 °C bonding for 30 min followed by 400 °C N_2 anneal for 30 min; and 400 °C bonding for 30 min followed by 400 °C N_2 anneal for 60 min. The contact area is a square in shape.

The dependence of specific contact resistance on the bonded interconnect location on the wafer is shown in Figure 2. The bonding condition is at 400 °C for 30 min followed by 400 °C N_2 anneal for 60 min. The bonded interconnect location is measured from the center of the wafer. It is clear that the center area has a lower contact resistance than the edge area. In addition, the contact resistances of different contact sizes show similar distribution on the wafer. This trend is similar to previous morphology observations [2]. We found from the TEM micrograph of the bonded interfacial morphology a larger fraction of bonding interface at the edge of wafer than that at the center of the wafer. For excellent bonding structure, the interface should be removed after bonding. During the bonding process, a high load is applied at the center of the wafer resulting in non-uniform pressure across the wafer. Therefore, a better bonding quality wafer is achieved at the center of the wafer.

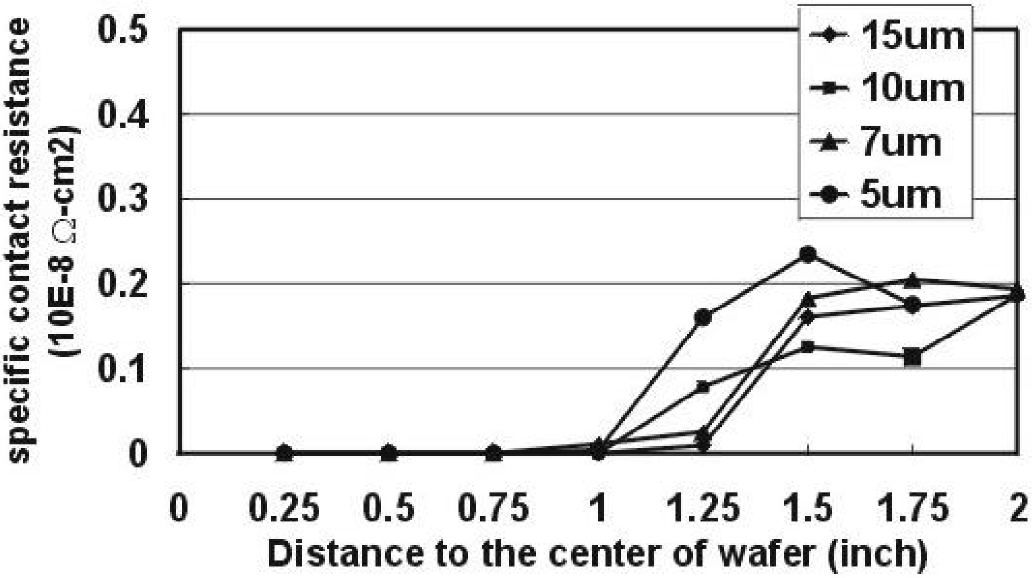

Figure 2: The relationship between the bonded interconnect location and specific contact resistance. The bonding condition was that 400 ^oC bonding for 30 min followed by 400 ^oC N_2 anneal for 60 min.

In order to examine the stability and reversibility of the specific contact resistance of bonded interconnects, stress current is ramped gradually from 1 mA to 100 mA at a rate of 1 mA/s. Figure 3 shows the corresponding specific contact resistance of bonded interconnects at this ramping rate for wafers with 5 μm-width interconnects bonded at 400 ^oC for 30 min followed by 400 ^oC N_2 anneal for 60 min. It shows that the specific contact resistance values are all in the range of 0.2 – 0.5 * 10^{-8} Ω-cm^2 during the testing period. This means the specific contact resistance is stable regardless of the applied current. In other words, the microstructure of bonded interconnects does not change after current stressing. This suggests that the state of the microstructure has reached a final stable state. As a result, a higher current does not affect the measurement results.

When the stress current is reversed from 1 mA to 100 mA at the rate of 1 mA/s, the corresponding specific contact resistance does not show obvious changes comparing to the value measured above. This observation further proves that the bonded interconnects has reached a steady state.

We had made a similar observation in previous research from the TEM micrograph of the interface microstructure with regards to the results from current stressing [3]. TEM micrograph of the interfacial morphology shows that the microstructures including grain sizes and grain orientations do not change by increasing the anneal time after bonding if the bonded structure has acquired enough energy from a shorter anneal duration. Therefore, combining all these results, we conclude that once the bonded interconnects has acquired enough energy to refine the microstructure, it reaches a final steady state and there is no need for further anneal.

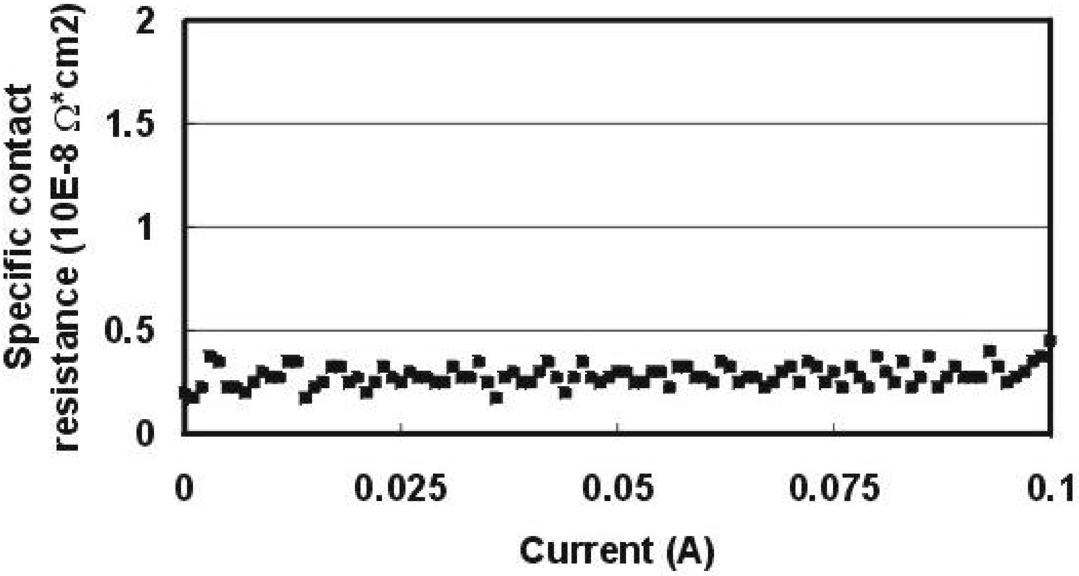

Figure 3 The corresponding specific contact resistance of bonded interconnects when stress current is ramped gradually from 1 mA to 100 mA at the rate of 1mA/s. The interconnect is 5 mm wide and was bonded at 400 °C for 30 min followed by 400 °C N_2 anneal for 60 min.

CONCLUSIONS

In conclusion, contact resistances under different bonding conditions were investigated. A reduction of contact resistance is obtained by longer anneal time since the bonded interconnects has more energy to refine the structure. In addition, the specific contact resistances of bonded interconnects with longer anneal time does not change with the interconnect sizes. Underlying physical mechanism is discussed. The relationship between specific contact resistance and bonded wafer location is discussed as well. The lower specific contact resistance is measured at the center of the wafer. Stability and reversibility testing shows that the specific contact resistance does not change when the stress current is change gradually. The excellent stability and reversibility of specific contact resistances also suggests that the microstructure of bonded Cu interconnects has reached a steady state.

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