Contact Resistance Measurement of Bonded Copper Interconnects for Three-Dimensional Integration Technology

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Abstract: A novel test structure for contact resistance measurement of bonded copper interconnects in three-dimensional (3-D) integration technology is proposed and fabricated. This test structure requires a simple fabrication process and eliminates the possibility of measurement errors due to misalignment during bonding. Specific contact resistances of bonding interfaces with different interconnect sizes of approximately 10^{-8} Ω-cm^2 are measured. 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 interconnect sizes.

Copper wafer bonding is attractive for applications in three-dimensional integrated circuits (3-D ICs) because of its low electrical resistivity and high electromigration resistance [1,2]. To achieve a reliable Cu-Cu bonding interface, both the electrical and structural properties of the bonded layer need to be taken into account [3]. The bond strength, quality and interfacial morphologies under different bonding temperatures and durations have been reported previously [3-5]. This work focuses on the electrical performance after bonding since the contact resistance of the bonded layer will directly affect 3-D circuit performance.

To measure the contact resistance of 3-D bonded interconnects, a circuit placement on each wafer would be required. However, bonding misalignment makes it difficult to accurately estimate the contact area [6], and complicates the measurement of the Cu bonded layer contact resistance. In this letter, a novel and simple method to measure the contact resistance of the bonded layer is proposed. This new approach simplifies the fabrication process of the test structure and eliminates errors due to possible misalignments. The experimental results show reasonable specific contact resistances after bonding. The specific contact resistance can be effectively reduced with a longer anneal time. At this bonding condition, it is observed that specific contact

resistances of smaller size interconnects do not show higher value than larger size interconnects.

The schematic diagrams for the contact resistance measurement test structure are shown in Figures 1(a), 1(b) and 2(a). This test structure is similar to a Kelvin contact resistance test structure [7]. The contact resistance can be obtained from:

$$R_C = \frac{V_{MH} - V_{ML}}{I} \qquad (1)$$

where V_{MH} (pad 1) and V_{ML} (pad 2) are measured while a constant current from 1 mA to 100 mA is stressed from pad 3 to pad 4. The specific contact resistance ρ_c can be obtained from:

$$\rho_C = R_C \times A_C \qquad (2)$$

where A_C is the bonded area. Note that the upper and lower metal layers belong to different wafers and the bonded area is constant as designed. In Figure 2(b) for the Kelvin test structure, two L-shape metal lines, one belonging to the upper wafer and one to the bottom wafer, would only be contacted in the center area. The resistance of the contact area could be calculated from stressing the current between contact pads 1 and 2 and measuring voltage between pads 3 and 4. However, because of possible misalignment during the bonding process, the contact area A_C may give rise to measurement errors [6], and a reasonably accurate value of specific contact resistance may be difficult to obtain.

In our test structure, the bonding (contact) area does not change with the bonding misalignment. Consequently, a more accurate specific contact resistance can be expected.

Figure 1(b) shows a side view schematic diagram of the test structure. The bottom wafer was covered with 300 nm of thermal oxide, 50 nm of Ta and 300 nm of Cu. The upper wafer preparation was essentially 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. 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 [4]. Then the substrate of the upper wafer was 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 [8], 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 and were ready for measurement. For the case of 60 min of N_2 annealing, line widths of 5, 7, 10 and 15 μm were patterned on the upper and bottom wafers. The corresponding bonded areas are 25, 49, 100 and 225 μm^2, respectively. For the case of 30 min of N_2 annealing, line widths of 7, 10 and 15 μm were patterned on the upper and bottom wafers. The total bonded area was 30% of the whole wafer area and the remaining area was air.

Figure 3 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. Table I shows our measured data for Cu-Cu contacts bonded at 400 ^{o}C for 30 min followed by 400 ^{o}C N_2 anneal for 60 min, and data from the literature for metal-metal and metal-Si contact resistances and specific contact resistances [9-10]. By comparing these three systems, the specific contact resistance of Cu-Cu bonding is smaller than that of the Metal-Si system and is one order of magnitude smaller than that of the Metal-Metal system. A higher value of specific contact resistance in the Metal-Si system is due to the higher barrier height between metal and Si.

For bonded Cu interconnects annealed for 30 min, and for contact areas of 100 μm^2 or larger, the specific contact resistance is approximately 10^{-8} Ω-cm^2. Bonded Cu interconnects with a width of 7 μm shows a higher specific contact resistance. It may be due to an incomplete bonding process and/or due to the presence of a thicker bonded interface with porosities and impurities at the interface. Both of them represent a poorer bonding quality [4]. 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 100 μm^2 after 30 min anneal. This trend is identical to that of the bonding morphology evolution reported elsewhere [5].

Previous microstructure examination of Cu wafer bonding showed that the disappearance of Cu-Cu interface after bonding indicated excellent bonding [4]. The existence of the bonding interface results in higher contact resistance. Thus, the low specific contact resistance of the bonded interconnects after 60 min anneal is the result of a better bond quality. This is because the longer heat cycle provides the energy required for the bonded interconnect to refine their interfacial structure.

In conclusion, a novel and simple test structure for contact resistance measurements of Cu interconnect bonding interface was developed. This approach eliminates the measurement error due to misalignment during wafer bonding. Contact resistances under different bonding conditions were investigated. A reduction of contact resistance is obtained by longer anneal time since the bonded interconnects have more energy to refine the interfacial structure. In addition, the specific contact resistances of bonded interconnects with longer anneal time do not change with interconnect sizes.

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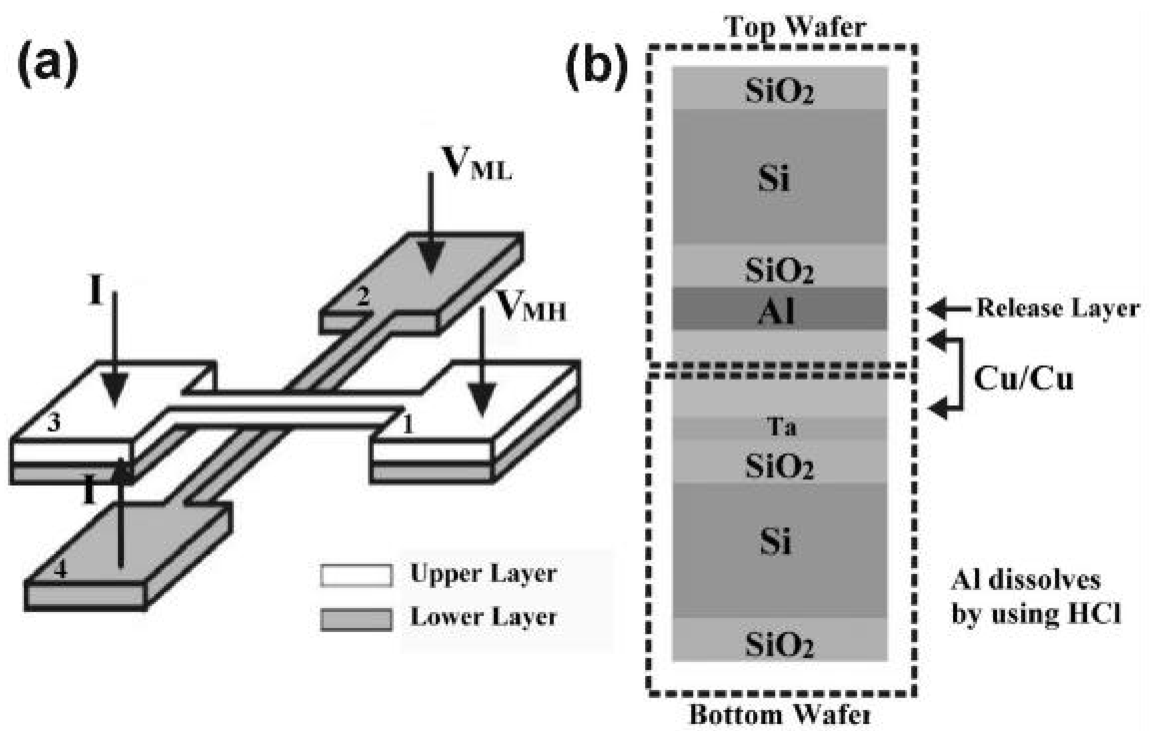
Figure and Table Captions

Figures 1 Schematic diagram of the contact resistance test structure

Figure 2(a) and (b) Top view of (a) our contact resistance and (b) Kelvin test structure

Figure 3 Average Cu-Cu bonded specific contact resistances as a function of interconnect size for different bonding conditions

Table I Comparison of contact resistance and specific contact resistance for Cu-Cu bonding at 400 ^{o}C bonding for 30 min followed by 400 ^{o}C N_2 anneal for 60 min (this work), metal-metal and metal-Si interconnects



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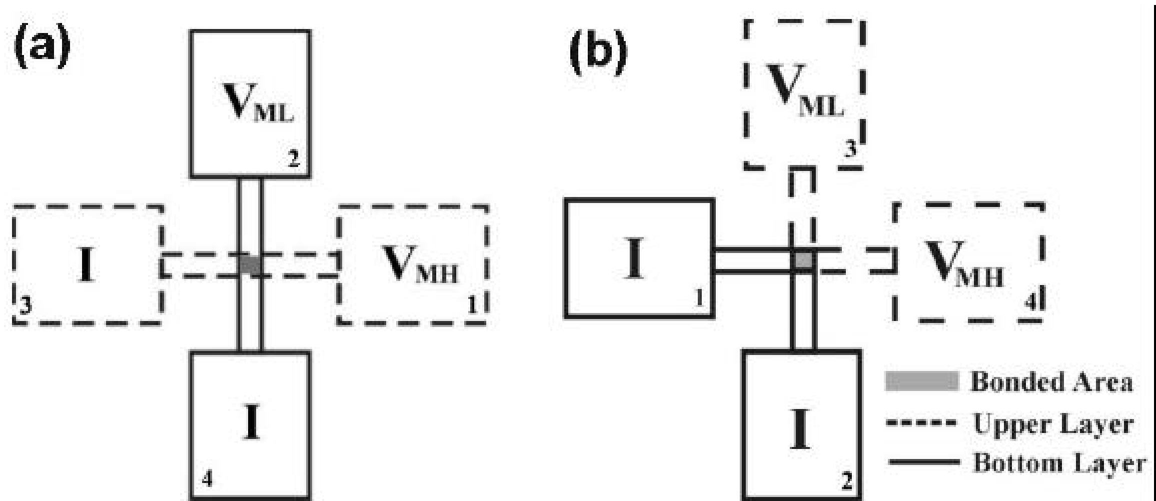
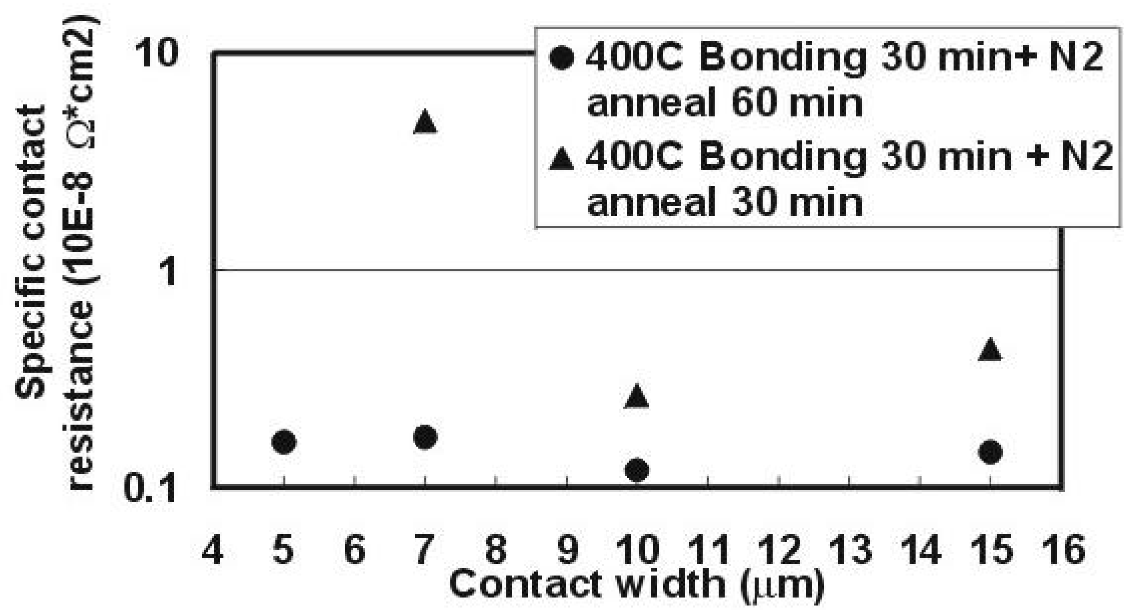


Figure 2(a) and (b)   Top view of (a) our contact resistance and (b) Kelvin test structure



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	Interconnect size (μm)	Specific contact resistance ρ_c (Ω-cm^2)	Average measured contact resistance R_C (Ω)
Metal-Si	1	$1\text{-}3*10^{-7}$	10-30
Cu-Cu	5	$0.16*10^{-8}$	$6.40*10^{-3}$
	7	$0.17*10^{-8}$	$3.47*10^{-3}$
	10	$0.12*10^{-8}$	$1.20*10^{-3}$
	15	$0.15*10^{-8}$	$6.67*10^{-4}$
Metal-Metal	1	$2*10^{-8}$	2