Low Temperature (<180°C) Wafer-level and Chip-level In-to-Cu and Cu-to-Cu Bonding for 3D Integration

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Abstract

Two bonded structures, Cu/In bonding and Cu-Cu bonding with Ti passivation, were investigated for the application of 3D interconnects. For Cu/In bonding, the bonds were achieved at 170°C due to the isothermal solidification. The intermetallic compounds formed in the joint was Cu_2In phase. For another case, Cu-Cu bonding with Ti passivation was successfully achieved at 180°C. Application of Ti passivation can protect inner Cu from oxidation; therefore, the required bonding temperature can be decreased. Compared to direct Cu-Cu bonding, Cu/In bonding and Cu-Cu bonding with Ti passivation can be performed at low temperature, which can meet low thermal budget requirement for most devices. Besides, with the good electrical performance and reliability, these two bonded interconnects can be applied for 3D IC interconnects.

Introduction

Copper, the mainstream interconnect material used in semiconductor industry with low resistivity and high electro-migration resistance, has been developed for 3D integration in order to fabricate devices with high function density, high performance, and small form factor for different applications [1-3]. Conventional Cu/Cu thermal-compression bonding can provide good electrical connection and sufficient bonding strength for follow-up processes. However, the high bonding pressure and the required bonding temperature is up to 350-400 °C to acquire high yield [4]. The high bonding pressure and temperature may lead to bonding misalignment, residual thermo-stress and thermal damages, which will degrade the device performances. Therefore, it is urgent to develop a low temperature bonding to meet the thermal budget.

Diffusion soldering, which is based on the principle of isothermal solidification, has a great potential for electronic applications. By applying the isothermal solidification reaction between a molten metal and a solid metal, formation of one or more intermetallic compounds (IMC) with melting temperature higher than the follow-up process temperature is possible. Cu/Sn, Ni/Sn, Au/Sn, and Ag/Sn have been successfully used as joint materials [5-7]. Indium, owing to its low melting temperature (156.6°C), can be an attractive option for low temperature bonding technology. However, In needs to be completely consumed to form IMC, or the remelting of bond structure during multiple operation [8].

Two bond structures, Cu/In bonding and Cu/Cu bonding with Ti passivation which can be performed at low temperature were investigated in our study. For Cu-to-In bonding, the evaluation of different kinds of materials for adhesion between In and Si substrate was developed; besides, this paper presents further evaluation on the electrical characteristics and reliability of bonded structures. Since there are only few previous studies on the electrical properties of Cu/In bond, these results may provide useful guidelines and information for 3D interconnects. For another case, a novel bonded structure of Cu/Cu bonding with Ti passivation was developed. Due to the interdiffusion behavior of Cu and Ti, Cu tends to move toward the bonding interface while Ti moves toward substrate side; hence, a continuous Cu to Cu bonding layer can be formed at the bonding interface region. With the good bonding results, it is recommended that Cu/Cu bonding with Ti passivation can be a promising solution for low temperature bonding. The detailed study on the diffusion behavior of Cu and Ti will be presented in this paper.

Adhesive Material Evaluation

For enhancing mechanical strength of the bonds, the evaluation of materials used for adhesion between In and Si substrate was firstly developed. Four different kinds of adhesive materials adopted in the study were SiO_2 (500 nm), Ti (30-40 nm), Ni/Ti (30-40 nm/30-40 nm), and Cu/Ti (100-120 nm/30-40 nm).

SiO_2 was chosen because it is usually acted as electrical insulator with high chemical stability, while Ti is a commonly used adhesion layer for less-adhesive metals and has good adhesion to Si and SiO_2. For the Ni/Ti and Cu/Ti structures, Ni and Cu are the wettable metals for In, and Ti is the conventional adhesion layer [9-10]. The thickness of metal layers was examined by the scanning electron microscopy. However, the thickness of In was difficult to determine because of its wettability on the adhesive materials, especially under nanometer scale [11-12]. Therefore, the coating thickness of In was determined by quartz oscillator and fixed at same value.

The evaporation rate of In was controlled at 1.5-1.8 Å/s. A large number of In atoms deposited on the substrates will become separate clusters, and then grow into separate grains in the final film. Figs. 1 (a)-(d) show the surface morphology of In coating on different adhesive materials. By using SiO_2, Ti, and Ni/Ti as adhesion layers, In atoms tend to form larger grains with more uniform structures, while form smaller grains and grow independently on Cu surface without coalescing to a larger one. Hence, it proves that the wettability of In on SiO_2, Ti, and Ni/Ti layers is better than Cu/Ti layers.

The adhesive materials were further evaluated by In/In bonding test. The sample were bonded at 173°C, 1MPa for 50 min. Figs. 2 (a)-(d) show the SEM images of In/In bonded interfaces, which demonstrates the good bonding results with uniform bonding integrity by using SiO_2, Ti, and Cu/Ti. In addition, the In/In bonded structures have great mechanical strength which can withstand the drop test and the polishing step of sample preparation for SEM analysis. However, the bonded structure with Ni/Ti shows the poor bonding result and cracks at the bonding interface, which cannot survive from the drop test. Even after a series of adjustment on coating thickness and bonding temperature, the bonding results of Ni/Ti did not improve. Therefore, the application of Ni/Ti as adhesion layer for bonding needs to be further qualified.

Shear test was used to evaluate the adhesion strength of the well bonded samples. As the results shown in Fig. 3, Ti required the maximum shear force; besides, the upper chip was broken which indicated that the adhesion strength should be larger than this value. Hence, Ti with the good bonding result is capable of serving as adhesive material for Cu/In bonding.

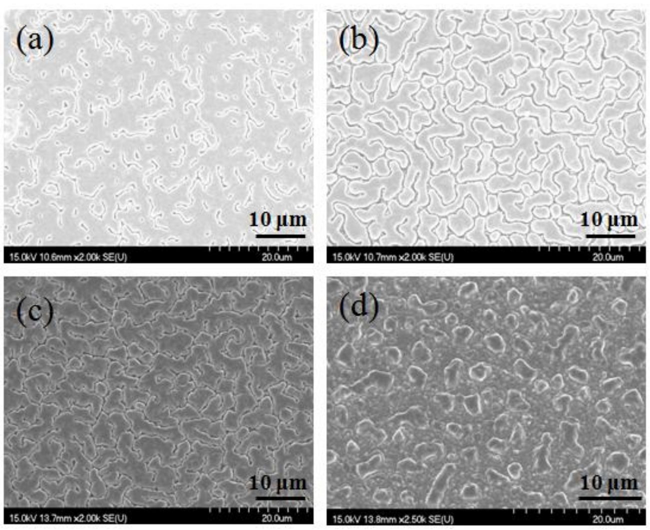

Figure 1. The surface morphology of In coating on (a) SiO_2, (b) Ti, (c) Ni/Ti, and (d) Cu/Ti.

Experimental and Investigation of Cu/In Bonded Structure

Standard RCA cleaning was applied to the wafers before 500nm TEOS deposition. Copper samples were prepared by sputtering Cu (300 nm) and Ti (30 nm) in a multi-target chamber under a working pressure of 7×10^{-3} torr and with a base pressure of 1×10^{-6} torr. The approximate sputtering rate for Cu and Ti were 0.6 Å/s and 0.1 Å/s. Indium samples were prepared by evaporating In and Ti (30 nm) under a base pressure of 2-4$\times10^{-6}$ torr with deposition rate at 1.5-1.8 Å/s and 1 Å/s, respectively.

Cu and In samples were bonded face-to-face with a bonding pressure of about 1.91 MPa, followed by a heating temperature of 170 °C for 50 min at atmosphere ambient. There is no surface treatment used in this case because it will contribute to high surface roughness which may hinder the bonding process.

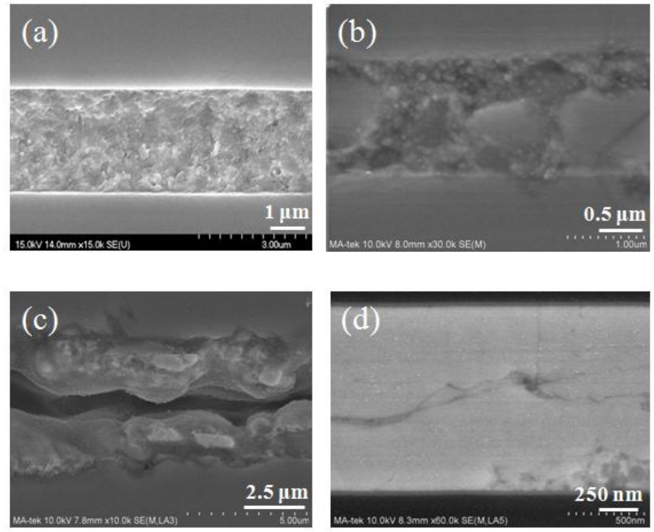

Figure 2. In/In bonding with different adhesive materials: (a) SiO_2, (b) Ti, (c) Ni/Ti, and (d) Cu/Ti.

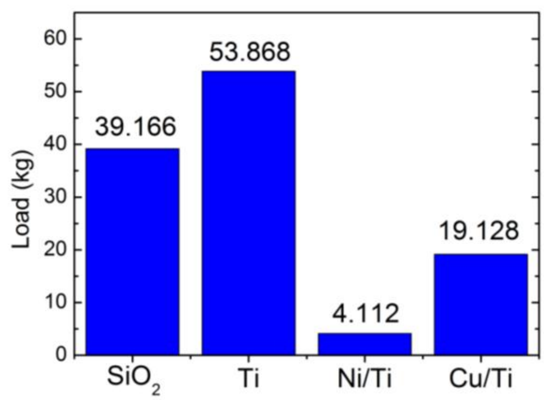

Figure 3. The shear test results of In/In bonding with different adhesive materials.

During the process, Cu/In intermetallics formed due to the isothermal reaction between Cu and In. Scanning and transmission electron microscope with an attachment of energy dispersive X-ray spectrometer were applied for the structural and chemical characteristics of intermetallics formed in Cu/In bonds. Finally, the Scanning Acoustic Tomograph (SAT) analysis was used to check the bonding result.

According to the phase diagram (Fig. 4), three intermetallic phases can form below 307 °C: $Cu_{11}In_9$, $\eta(Cu_2In)$, and $\delta(Cu_7In_3)$ [13]. Without facing difficulties in the nucleation, all the phases should appear and grow in the bonded structure initiating at the Cu/In interface. However, according to Sommadossi's observation [14], the sequence of intermetallic phases formed in the Cu/In bonds follows a function of reaction time. After liquid In has been completely consumed and transferred to the $Cu_{11}In_9$ phase, the $\eta(Cu_2In)$ and $\delta(Cu_7In_3)$ phases start to form by consumption of $Cu_{11}In_9$ and Cu.

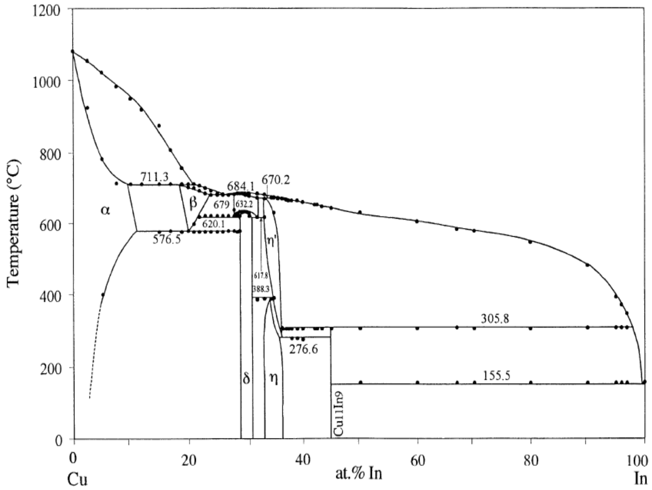

Figure 4. Cu-In system [13]

Fig. 5 shows the Cu/In wafer bonding result by the SAT analysis, demonstrating that the Cu/In bonded structure has uniform bonding integrity. The well-bonded sample possesses great bonding strength with no sample de-bonded after the dicing. A cross-sectional view of Cu/In bonded structure is shown in Fig. 6 (a) and the total bonding thickness is about 728 nm. The EDX line-scan of the bonded structure is given in Fig. 6 (b), which indicates that Cu_2In phase was formed in the structure. The detection of excessive oxygen in the joints is due to the oxidation of metal films during the manufacturing procedure.

After liquid In is saturated with Cu, the first IMC of $Cu_{11}In_9$ will be formed. As the heating process goes on, the second Cu-rich IMC of Cu_2In starts to form by the interdiffusion of Cu and solid $Cu_{11}In_9$. There is no apparent Cu_7In_3 detected in the structure which may due to the insufficient time for the growth of Cu_7In_3 [14]. The growth of Cu_2In and Cu_7In_3 at low temperature requires a larger incubation time, but in the bonding process, the reaction is stopped before the Cu_7In_3 appears. Besides, no $Cu_{11}In_9$ phase is detected, which implies it is completely consumed by the formation of Cu_2In. Therefore, there are only Cu_2In and unreacted Cu shown in the structure.

With the good bonding results, the bonded Cu/Cu_2In (m.p. 388.3 °C) interconnect without the presence of In becomes a strong candidate for the application of 3D integration.

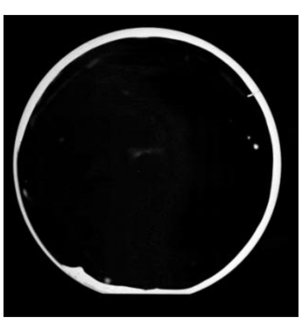

Figure 5. SAT image of 4” Cu/In wafer bonding result.

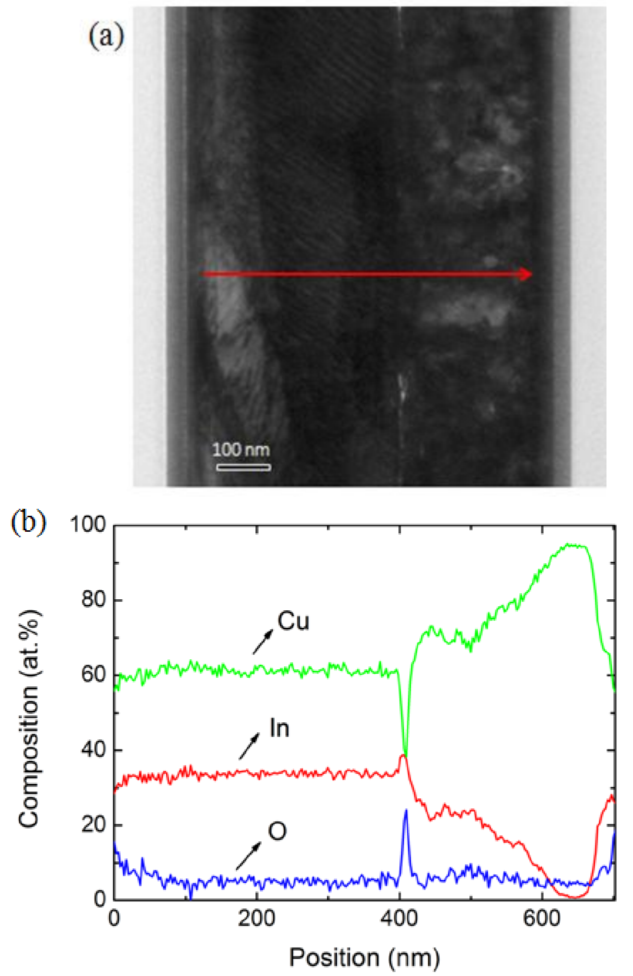

Figure 6. (a) TEM image of the Cu/In bonded interconnect and the EDX scanning direction; **(b)** composition profile obtained by EDX line-scan.

Electrical and Reliable Characterization of Cu/In Bonded Interconnect

The designed pattern of Kelvin structure was fabricated for the electrical characteristic and reliability tests. Fig. 7 shows the measured contact resistance after a few cycles of current sweeping between -0.1 and 0.1 A. The resistance is about 0.03 Ω and the deviation of resistance is small under different applied currents, suggesting a stable Cu/In bonded interconnect with good bonding quality. The specific contact resistance ρ_c is approximately 1.82×10^{-5} Ω-cm^2.

The resistance of bonded interconnects after multiple cycles of current sweeping was measured, as shown in Fig. 8. The deviation of resistance is also small after 1000 cycles of current sweeping, implying that the Cu/In bonded interconnect has good stability against current stressing. It is especially important for multiple operation and applications in 3D integration.

Temperature cycling from -55 °C to 125 °C was performed to evaluate the thermal reliability of Cu/In bonded interconnect. The requirements and conditions of the test were based on the JEDEC standard [15]. Fig. 9 shows the result after 1000 loops of temperature cycling test, indicating that the bonded interconnect could withstand large temperature variation without failure, such as wire break or bond failure.

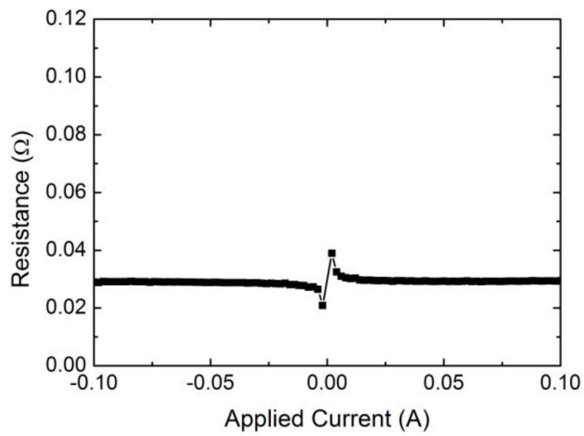

Figure 7. The measured resistance of Cu/In bonded interconnect.

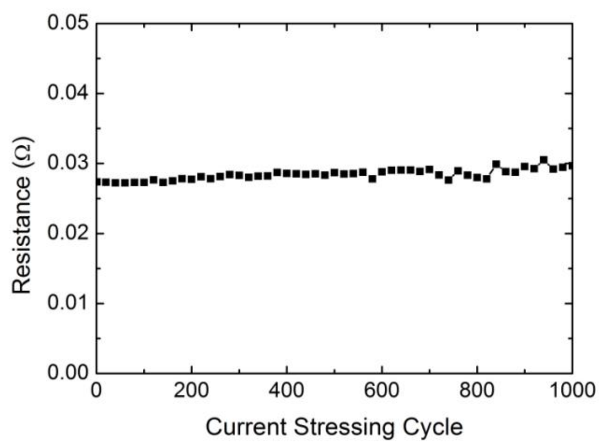

Figure 8. The measured resistance of Cu/In bonded interconnect under current cycling test.

To evaluate the reliability of Cu/In bonded interconnect in the humid environment, the humidity test of 85% at 130 °C were performed. The resistance measurement result of one bonded interconnect after 168 hours of humidity is shown in Fig. 10. The more stable and lower resistance is observed under current sweeping, which demonstrates that the bonded structure has good bonding quality against moisture and corrosion.

In addition, the reduction of resistance may due to the heat generated during the humidity test. Some voids may be appeared at the bonded interface after bonding because of high surface roughness or uneven bonding pressure. The heat could provide energy for the rearrangement of structures, which eliminates the defects and voids at the bonded interface [16]. Therefore, the Cu/In bonded structure shows good reliability against corrosion even under the tough environmental conditions. Again, these results appear that the Cu/In bonded interconnect possesses great electrical stability and reliability which can be a promising choice for 3D integration.

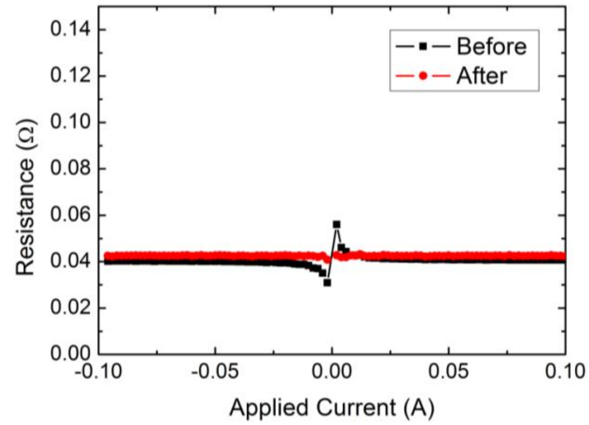

Figure 9. The measured resistance of Cu/In bonded interconnect under temperature cycling test.

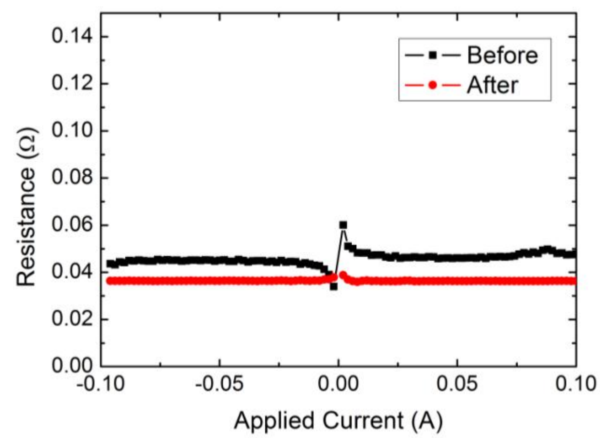

Figure 10. The measured resistance of Cu/In bonded interconnect under humidity test.

Experimental and Investigation of Cu/Cu Bonded Interconnect with Ti Passivation

For the bonded structure fabrication, Ti adhesion layer, Cu bonded layer, and Ti passivation with the thickness of 30, 300, and 10 nm were deposited on 4" Si wafer sequentially, under a working pressure of 7×10^{-3} torr and a base pressure of 1×10^{-6} torr. The samples were bonded face-to-face at 180°C, 1.91 MPa for 50 min. There is no need of surface treatment to remove copper oxidation due to Ti passivation.

The cross-sectional view of bonded structure is given in Figure 11. Although there is an apparent bonding interface, the bonded structure presents the good bonding morphology without voids and cracks. Figure 12 shows the TEM image and EDX line-scan across the bonded interface. During the bonding, Ti/TiO_X moved toward substrate side while Cu moved toward bonding interface, demonstrating the interdiffusion mechanism can be proposed to the bonding process.

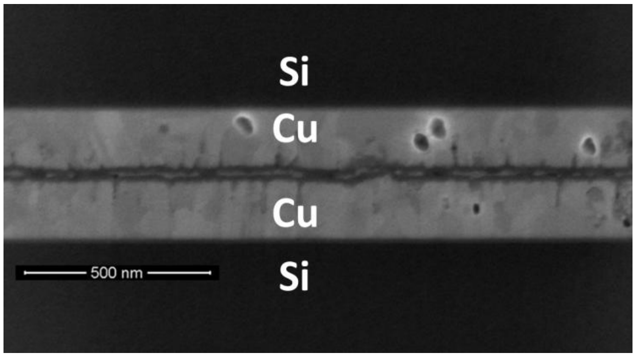

Figure 11. SEM image of Cu/Cu bonded interconnect with Ti passivation.

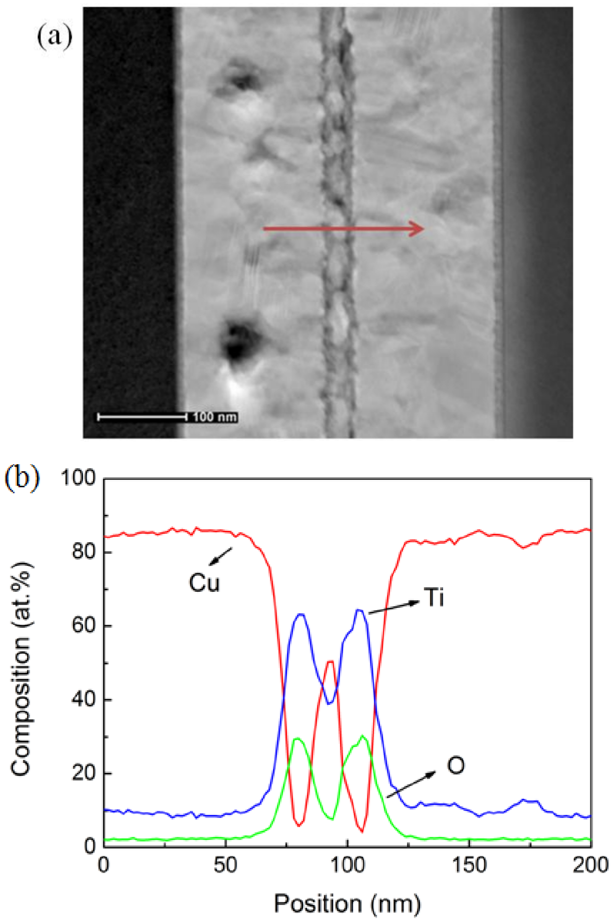

Figure 12. (a)TEM image of the Cu/Cu bonded interconnect with Ti passivation and the EDX scanning direction; **(b)** composition profile obtained by EDX line-scan.

Cu has lower activation energy at the surface and a smaller atom volume (72 $bohr^3$) than Ti vacancy volume (75.48 $bohr^3$) [17-19]. Hence, Cu has a tendency to diffuse toward the bonding interface through Ti vacancies, whereas Ti/TiO_X tends to diffuse toward the opposite direction. Auger depth profile of the structure annealed at a higher temperature can be applied to demonstrate this phenomenon. Before annealing, Ti passivation formed a thin layer of TiO_X to protect inner Cu from oxidation. As shown in Figure 13(a), the oxygen signal is only detected at surface. After annealing under nitrogen ambient at 400°C for 60 min, Cu diffused out of surface as shown in Figure 13(b). Therefore, as the diffusion keeps proceeding, it can form Cu to Cu bonded structure at interface.

According to the experimental observations above, Cu/Cu bonding with Ti passivation is confirmed to be an attractive option for interconnects in 3D integration. Figure 14 shows the schematic diagram of the bonding procedure. The designed bonded structure is compatible with current semiconductor industry.

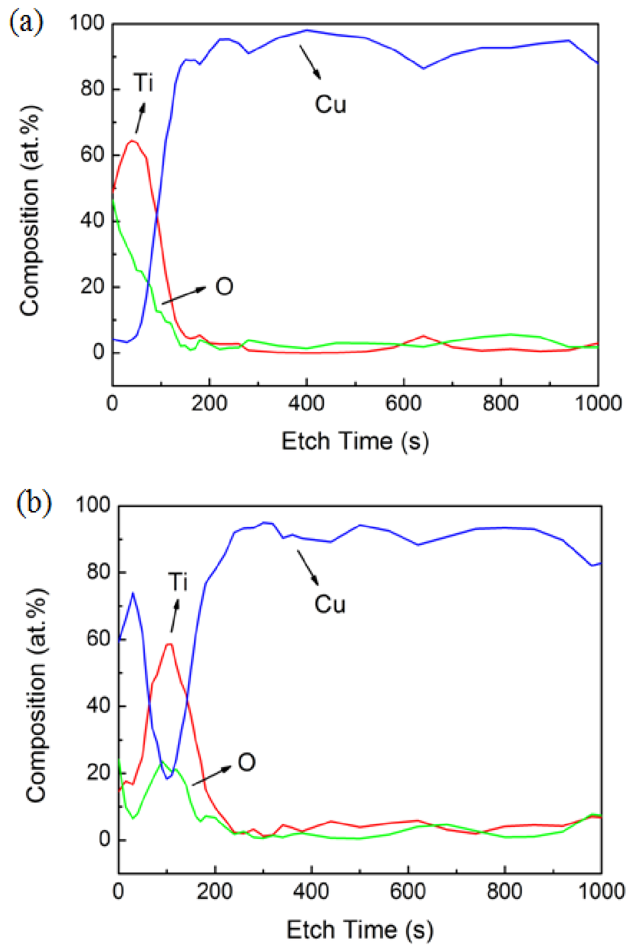

Figure 13. Auger depth profile of bonded structure **(a)** before annealing, and **(b)** after annealing at 400°C for 60 min.

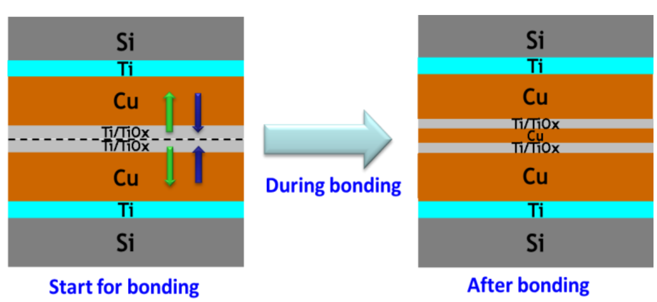

Figure 14. Schematic diagram of the Cu/Ti-Cu/Ti bonding procedure.

Reliability Investigation of Cu/Cu Bonded Structure with Ti Passivation

The Cu/Cu bonded interconnect with Ti passivation show similar resistances before and after 500 cycles of thermal cycling. The result implies that the Cu/Ti-Ti/Cu bonded interconnect has a good thermal stability (Fig. 15). Other reliability tests, including electrical migration and humidity test, are under investigation and will be reported in the future.

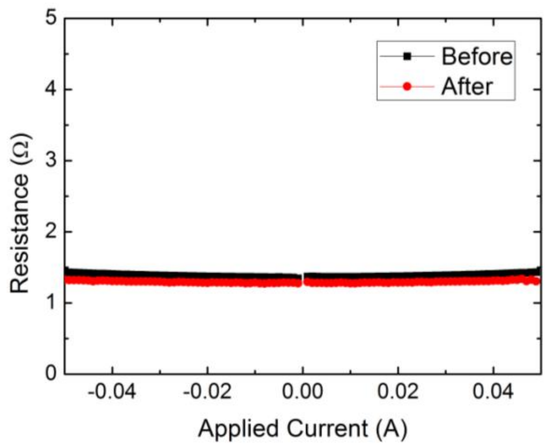

Figure 15. The measured resistance of Cu/Ti-Ti/Cu bonded interconnect under temperature cycling test.

Conclusions

Successful Cu/In and Cu/Ti-Ti/Cu bonded interconnect were achieved at low temperature (< 180 °C). The Cu/In bonded interconnect shows the good bonding quality with the completely consumption of In to form Cu_2In intermetallic. For another case, a novel Cu/Cu bonded interconnect with Ti passivation also shows good bonding results. Since Cu has lower activation energy at the surface and a smaller atom volume than Ti vacancy volume, Cu tends to diffuse toward the bonding interface while Ti/TiO_X diffuses toward the substrate side. Finally, Cu-to-Cu bonded structure can be formed at interface.

The reliability assessments demonstrate that the Cu/In and Cu/Ti-Ti/Cu bonded interconnects both have great electrical stability and reliability. In addition, the two bonding techniques can be performed at low temperature, which can meet low thermal budget requirement for most devices, and show the great potential for 3D integration.

Acknowledgments

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