Electrical Performance and Reliability Investigation of Cosputtered Cu/Ti Bonded Interconnects

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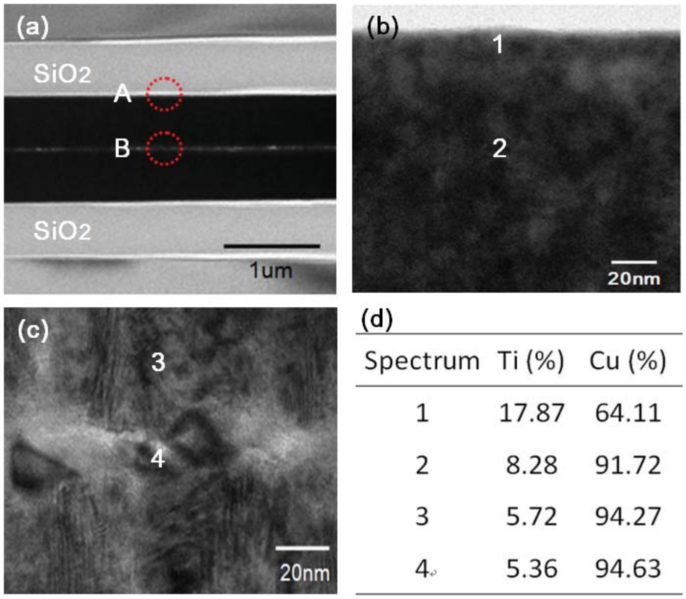
***Abstract*— Electrical evaluation along with the material analysis and reliability investigation of cosputtered Cu/Ti bonded interconnect in 3-D integration is presented in this paper. Diffusion behavior of cosputtered metals under different bonding ambient is evaluated as well. This paper shows that the bonded structure exhibits several interesting features under atmospheric bonding ambient, including self-formed adhesion layer, Cu–Cu bonding, and Ti oxide sidewall passivation. Electrical and reliability investigations of cosputtered Cu/Ti bonded interconnects show an excellent electrical performance and a high stability under a large variety of reliability tests, indicating the potential of using cosputtered Cu/Ti bonded interconnects for 3-D integration applications.**

***Index Terms*— 3-D integration, bonding technology, cosputtered.**

I. INTRODUCTION

DUE to the conventional semiconductor fabrication method is reaching its physical and lithography limitations, scaling of transistors will meet its bottleneck in the near future [1]–[3]. One of the most applicable solutions is 3-D integration, the vertical stacking of chips and wafers [4]–[6]. Among the key technologies of 3-D integration, bonding technology is one of the most important topics [7], [8]. Comparing different bonding methods, metal-to-metal bonding takes on the advantages of the direct electrical connection and the serving as an extra metal layer. For metal-to-metal bonding, copper has the most potential as the bonding medium with its outstanding electrical properties, and its high compatibility to current fabrication technology [9], [10]. Moreover, with the absent of intermetallic compounds, Cu bonding has a higher resistance toward electrical migration, mechanical forces, and thermal variation.

Although direct Cu-to-Cu bonding has been widely studied [11]–[13] cosputtered Cu-based metals as a bonding medium was first proposed in [14]. With the interdiffusion between the cosputtered metals at high temperature, interesting features can be generally observed on a varies substrate [14], [15]. Based on the previous studies, cosputtered Cu/Ti gives rise to a self-formed adhesive layer during thermal compression bonding, which makes it a promising candidate for 3-D integration [15]. However, detailed electrical properties, reliability performance, and bonding mechanism of this bond structure are still needed [16]. The results of these investigations reported in this paper provide an information for the application of this bond design in 3-D integration.



Spectrum	Ti (%)	Cu (%)
1	17.87	64.11
2	8.28	91.72
3	5.72	94.27
4	5.36	94.63

Fig. 1. TEM images of (a) bonded Cu/Ti sample, (b) circled region A, (c) circled region B, and (d) the corresponding Cu and Ti atomic ratio from (b) and (c).

II. EVALUATION OF Cu/Ti BONDED INTERCONNECTS

Cu/Ti samples were prepared by cosputtering Cu and Ti simultaneously in a multitarget chamber at 150 W for 90 min, under a working pressure of 7×10^{-3} torr with a base pressure of 1×10^{-6} torr. The approximate sputtering rates for Cu and Ti were 0.6 and 0.1 Å/s, respectively. Acetic acid cleaning for 60 s was applied to remove copper oxidation. The cosputtered samples were then bonded face-to-face at 400 °C for 100 min, in atmospheric ambient, and under the pressure of 145 psi. The quality and morphology of cosputtered thin films and bonded structure were analyzed through TEM, SEM, energy-dispersive X-ray spectroscopy (EDX) analysis, and electron probe microanalyzer (EPMA) mapping.

TEM images and EDX analysis of bonded interconnects are shown in Fig. 1(a)–(d). According to the EDX analysis, Ti has

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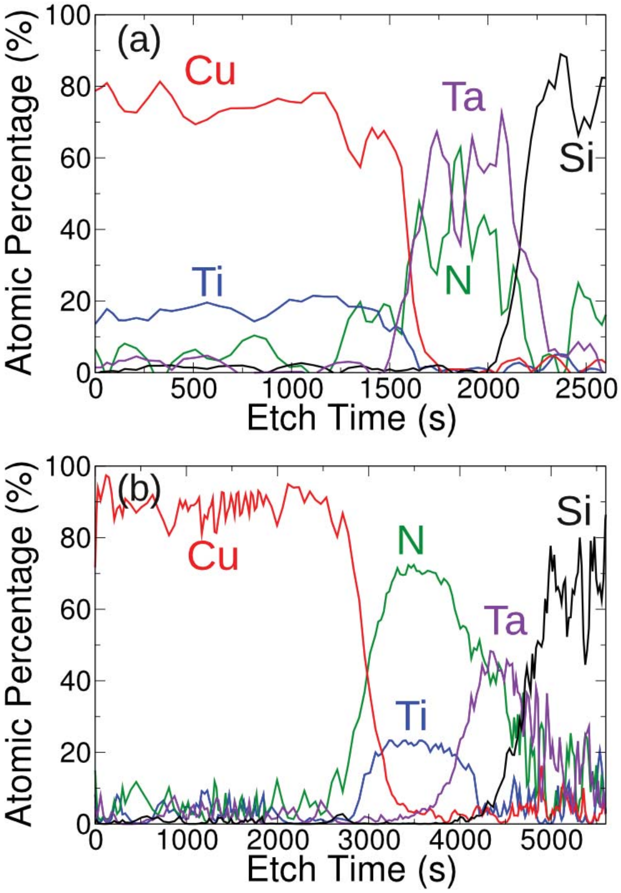


Fig. 2. Auger depth profile of cosputtered Cu/Ti (a) before annealing and (b) after annealing on TaN substrate.

a higher composition near the substrate [region 1 in Fig. 1(b)]. On the other hand, Cu composition gradually increases toward the bonding interface. The accumulation of Ti atoms close to the substrate leads to a self-formed adhesive layer during bonding, which not only improves the adhesion of the bond structure, but also reduces fabrication complexity. Moreover, a continuous Cu-rich layer is observed between the two samples [region 4 in Fig. 1(c)], which eliminates the original bonding interface, and thus indicates a good bonding quality. The segregation of the cosputtered metal implies that Ti atoms serve as adhesion between Cu and substrate, and Cu is the major bonding medium of the structure.

For Cu interconnect, diffusion barrier such as TaN layer is required to prevent the diffusion of Cu into isolated region or device substrate. Diffusion behavior on such substrates is evaluated by Auger depth profile analysis. A comparison between the distribution of metal atoms before and after annealing is shown in Fig. 2(a) and (b). After annealing in N_2 ambient for 60 min on TaN layer, the segregation that Cu accumulation at the surface and TiN layer formation close to the substrate is observed. Since TiN is a common diffusion barrier for Cu atoms, a clear decay of copper signal is observed at the presence of TiN layer in Fig. 2(b). Given that Cu does not react with the TaN diffusion barrier, the diffusion behavior of the cosputtered Cu/Ti is determined by the activation energy difference between two metals. In addition, activation energy is related to the physical and chemical properties of the metal, especially the melting point, and is regardless of the substrate [14]. Therefore, the segregation of Cu and Ti after bonding process is expected on different diffusion barriers and substrates.

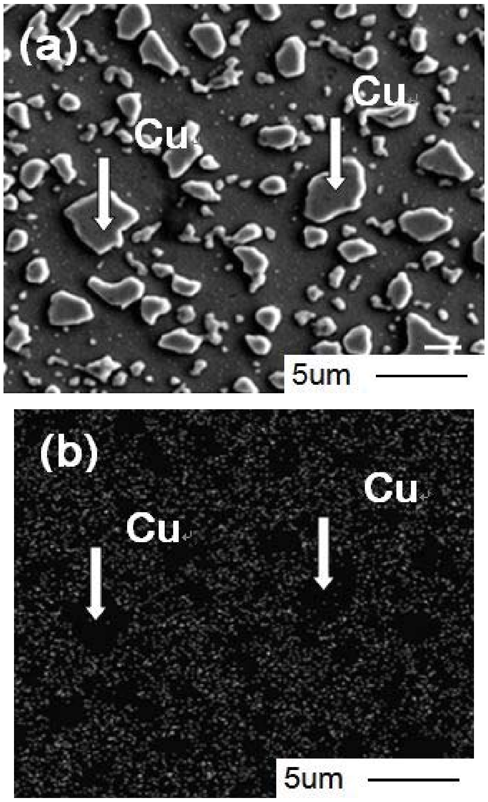


Fig. 3. (a) SEM image and (b) Ti EPMA mapping profile from the debonded surface of a partially bonded Cu/Ti sample.

III. EVIDENCE OF Cu–Cu BONDING

In addition to TEM analysis, one partially bonded sample in the middle stage of bond process (at 400 °C for 30 min) was intently debonded and then evaluated, as shown in Fig. 3(a) and (b). The bulges in Fig. 3(a) are the bonded area near the bonding interface of the sample. Comparing the existence of Ti signals outside the bulges at the debonded surface, Ti is not detected at the bonded area, where the dark area (the absence of Ti) of EPMA analysis in Fig. 3(b) matches the bulges in Fig. 3(a). Unlike Ti, Cu is detected all over the bulges of the debonded surface, indicating that Cu is the major bond material during bonding process.

Sheet resistance measurement of different bonding duration in Fig. 4 verifies the bonding mechanism of the proposed method. For Cu film of 3000 Å and Ti film of 500 Å, the sheet resistances are 350 m$\Omega/\square$ and 225 $\Omega/\square$, respectively. As the film is majorly composed of Cu, the starting sheet resistance of Cu/Ti film is 3 $\Omega/\square$. The value of sheet resistance of Cu/Ti film gradually reduces from 3 to below 1.5 $\Omega/\square$ after 60 min of bonding. The decrease of sheet resistance of Cu/Ti film implies that Ti atoms diffuse away and a Cu-rich layer starts to form at the bonding interface.

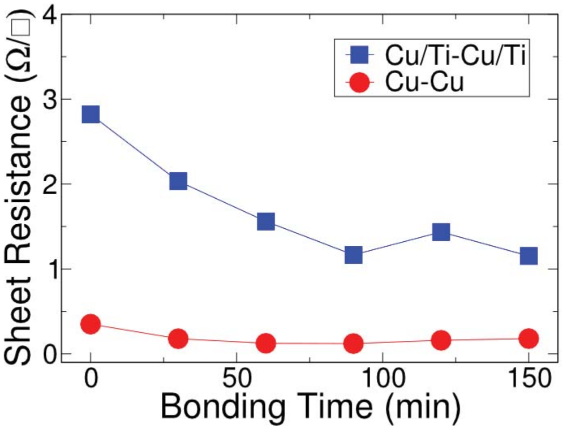


Fig. 4. Sheet resistance changes with respect to different bonding time.

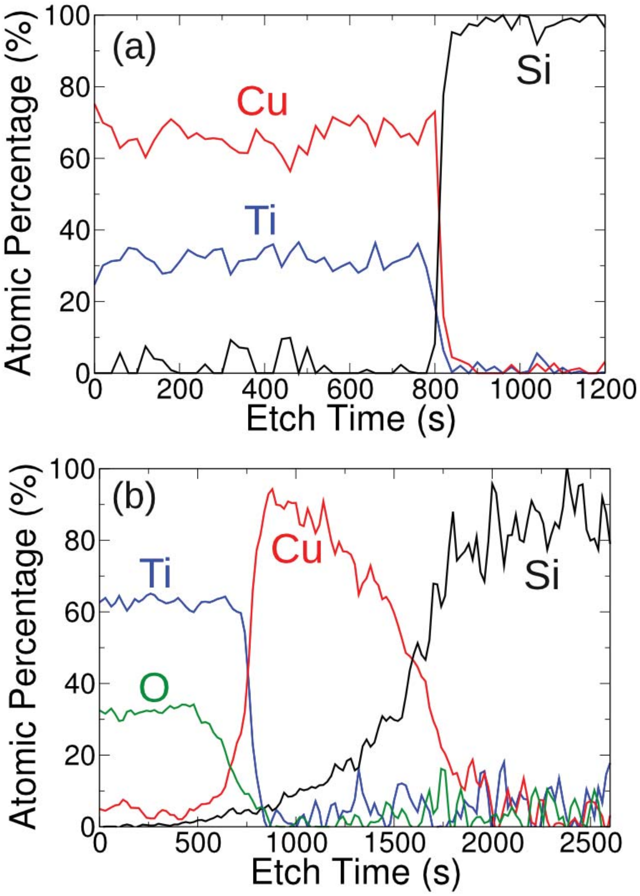
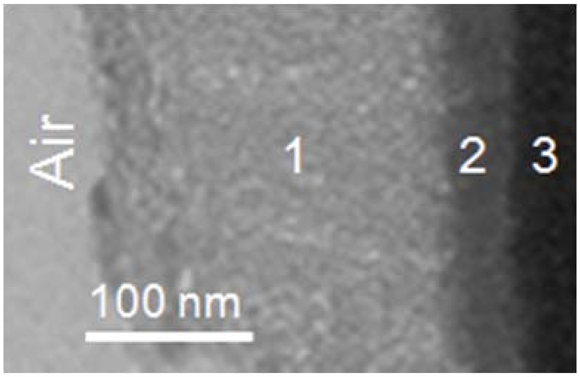


Fig. 5. Auger depth profiles of cosputtered Cu/Ti (a) before annealing and (b) after annealing in oxygen ambient at 400° for 60 min.

IV. POSSIBLE SIDEWALL PASSIVATION LAYER FOR COSPUTTERED Cu/Ti BONDED INTERCONNECT

Another interesting diffusion behavior of cosputtered Cu/Ti is observed after bonding in O_2 ambient. Fig. 5(a) and (b) are the Auger depth analysis of the cosputtered Cu/Ti sample before and after annealing in O_2 ambient at 400 °C for 60 min. Before annealing, Cu and Ti are uniformly distributed throughout the sample, as in Fig. 5(a). However, contrary to the previous case in N_2 ambient, instead of having a Cu layer at the surface, a layer of Ti oxide is formed at the surface, while Cu is capped in between the Ti oxide and substrate after annealing in O_2 ambient, as shown in Fig. 5(b).



Spectrum	Cu (%)	Ti (%)	O (%)
1	8.2	20.9	70.9
2	43.3	13.2	43.5
3	55.2	9.9	23.3

Fig. 6. TEM image and EDX analysis on the sidewall of one cosputtered Cu/Ti interconnect after annealed in oxygen ambient.

TEM and EDX analysis of the interconnect from surface after O_2 annealing are shown in Fig. 6. Region 1 in Fig. 6 is at the surface of the interconnect exposed to the air, where regions 2 and 3 are away from the surface and close to the substrate. Along with the EDX analysis, it is observed that region 1 is mainly composed of titanium and oxygen, and the composition of copper is relatively small. At region 2, a reduction of Ti composition is accompanied by the large increase in Cu composition.

As further toward the substrate at region 3, the composition of Ti drops more significantly and the composition of Cu rises to a higher percentage. On the other hand, the percentage of oxygen decreases with the increasing distance from the surface, for the oxygen is provided from the ambient. The result of the TEM/EDX analysis is consistent with the observation in Auger depth profile in Fig. 5(b), a layer of Ti oxide is formed at the surface and with copper layer sandwiched in between the substrate and Ti oxide. The discrepancy in the diffusion behavior of cosputtered Cu/Ti in different ambient is due to the highly interacting nature of Ti and O, where Ti tends to form Ti oxide at the presence of oxygen.

Considering cosputtered Cu/Ti as bond material in 3-D integration, in the case of atmospheric bonding ambient (with O_2 and N_2 ambient simultaneously), since cosputtered metals at the sidewall of the bond structure are exposed to oxygen and would lead to the diffusion behavior predicted in O_2 annealing ambient, it is possible to expect Ti atoms diffuse to sidewall surface and substrate of the bond structure, as shown in Fig. 7. Therefore, Ti atoms move toward the sidewall of the structure and form a Ti oxide layer. Away from the sidewall of the

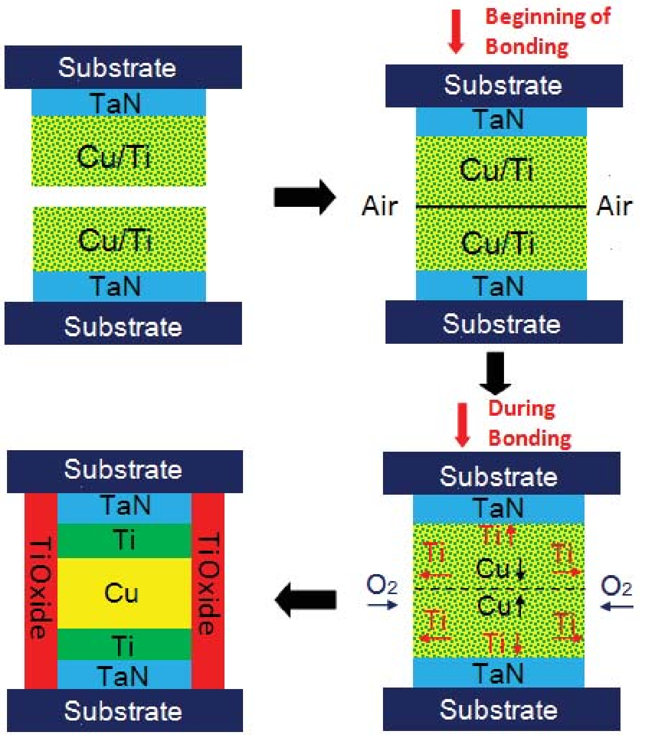


Fig. 7. Illustration of the diffusion behavior and the possible structure of cosputtered Cu/Ti bonded interconnected under thermal compression bonding in atmospheric bonding ambient.

structure, the diffusion behavior of Cu and Ti atoms can be treated as that in N_2 ambient where the diffusion is dominated by the activation energy difference between Cu and Ti. Hence, Ti atoms move toward the substrate and form a adhesion layer, while Cu atoms move toward the bonding interface and gradually form a continuous Cu layer that eventually eliminates the original bonding interface.

Ti oxide is known for its compact structure and high resistance toward deterioration. Therefore, with the protection of Ti oxide at sidewall, Cu atoms could be free from possible corrosion. Based on the previous discussion, an ideal possible structure of cosputtered Cu/Ti bonded interconnect is shown in Fig. 7. The structure should be composed of Ti oxide sidewall passivations, Ti self-formed adhesion layer, and Cu bonding medium. For the conventional metal bonding method, the major drawback is the air ambient exposure of bonded structure sidewall, which may lead to the corrosion and degradation. Based on the aforement results, this issue could be solved by cosputtered Cu/Ti bonding to form a Ti oxide as sidewall passivation. The degradation issue of the interconnect could be avoided, and the reliability of the bond structure could be greatly enhanced.

The diffusion behavior of Cu and Ti is independent of the deposition method of the metal. The composition of Cu and Ti can be specifically defined by the power/current applied to the two metal targets. Since Ti adhesion layer is generally much thinner compared with the thickness of Cu, Ti atoms still obey the diffusion rule as the case in cosputtered Cu/Ti. Along with a further investigation on the growth of Ti oxide, a precise control of the sidewall passivation layer can be achieved. Therefore, a Cu bonded interconnect with thickness controllable Ti adhesion layer and Ti oxide at sidewall could be expected.

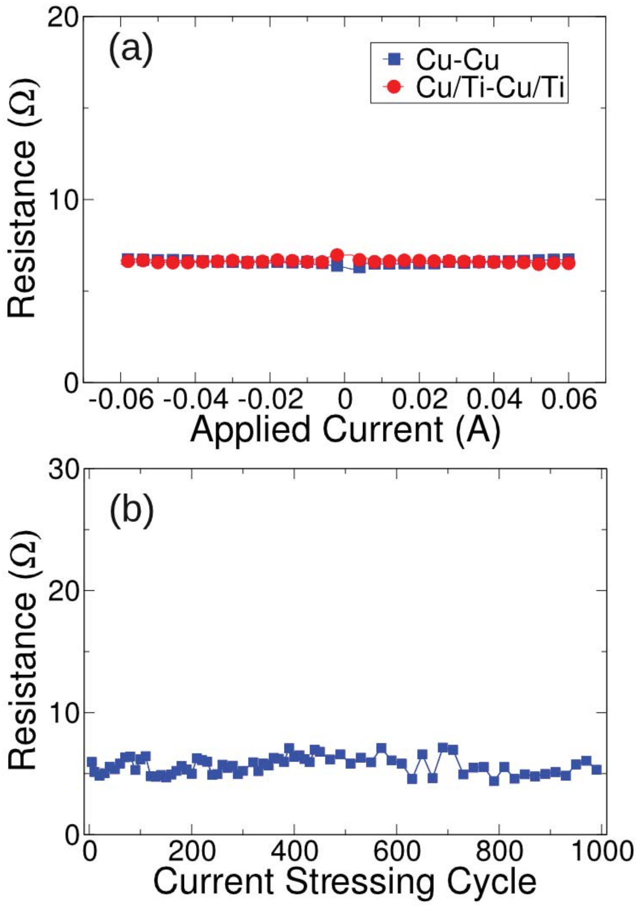


Fig. 8. (a) Contact resistance of Cu/Ti bonded interconnect. (b) Resistance variation during ac current stressing test.

V. ELECTRICAL PROPERTIES AND RELIABILITY OF THE BONDED INTERCONNECT

A. Resistance Measurement and Multiple Current Stressing Test

The bonded Cu/Ti interconnect investigated under current sweeping from −0.1 to 0.1 A shows stable values of resistance in Fig. 8(a). The resistance of cosputtered Cu/Ti is in good consistence with the value measured from direct Cu–Cu bonding. Therefore, the measurement once again implies that Cu is the major bonding/conducting material of the proposed structure, and the structure should have its electrical performance comparable with Cu bonded interconnect.

In addition, structure stability under current stressing is crucial for commercial applications A multiple ac current stressing cycling from −0.1 to 0.1 A was performed on the structure. In Fig. 8(b), evaluation results shows the bonded interconnect is stable up to 1000 cycles of current sweeping, similar to a well-bonded Cu–Cu structure.

B. Temperature Cycling Test

A temperature cycling test (TCT) ranging −40 °C to 125 °C was applied to multiple Cu/Ti bond structures. Fig. 9(a) shows

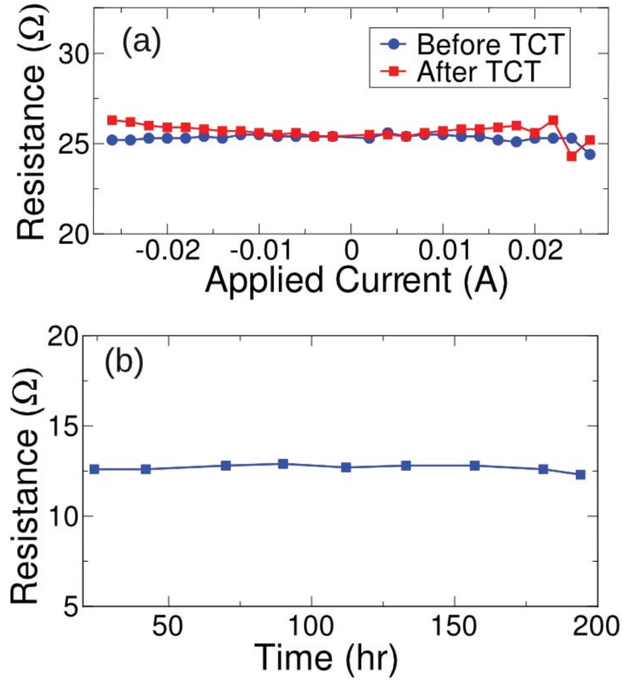


Fig. 9. (a) Resistance changes before and after 1000 cycles of TCT. (b) Resistance variation during humidity test.

the resistance behaviors of one Cu/Ti bond sample before and after a 1000 cycles of TCT. The results in Fig. 9(a) show that the resistance is almost the same after the TCT test. The stable and reliable behavior can be observed in multiple samples. Hence, it is suggested that the Cu/Ti bond structure can endure temperature variation from −40 °C to 125 °C without structural failure, such as wire break or bond separation.

C. Humidity Test

A humidity test of 55 °C/80% relative humidity was performed on the Cu/Ti bond structure for over 200 h, and the result is shown in Fig. 9(b). According to the result, the average resistance was stable within the whole test without deterioration and corrosion in the bond structure. Therefore, it is indicated that the Cu/Ti structure exhibits a good bonding quality and good resistance toward moisture and heated environment.

VI. CONCLUSION

A detailed study on cosputtered Cu/Ti as 3-D bonded interconnect is presented in this paper. The diffusion mechanism of cosputtered Cu/Ti under different annealing ambient gives rise to the prediction of a sidewall passivation layer and a self-formed adhesive layer of the bond structure. These interesting properties of cosputtered Cu/Ti bonded interconnect leads to an improvement of current metal bonding technology for the problems caused by the unprotected area in direct metal bonding. In addition, the bonded structure has a major conducting/bonding material of Cu, which is well known for its excellent electrical performance and high structural reliability. A series of electrical tests is also performed on the bonded structure. Results show that the proposed structure remains stable after current stressing, 1000 cycles of temperature cycling, and 200 h of humidity test. In summary, the proposed structure not only inherits the good electrical properties of direct Cu–Cu bonding, but also self-forms an adhesion/diffusion layer that improves bonding strength and simplifies the fabrication complexity. With the presence of Ti oxide sidewall passivation, an excellent stability and reliability of bonded interconnect could be possibly achieved.

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