Cosputtered Cu/Ti Bonded Interconnects With a Self-Formed Adhesion Layer for Three-Dimensional Integration Applications

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***Abstract*—A novel 3-D bonding technology with cosputtered copper and titanium as bonding material is proposed and investigated based on the diffusion mechanism of cosputtered metal during bonding. This technology features a self-formed adhesion layer for Cu metal layers and interconnects. In addition, cosputtered Cu/Ti bonding exhibits good electrical performance as well as high resistance to multiple current stressing. With the advantages of fabrication efficiency and reliable bond quality, cosputtered Cu/Ti bonding technology presents the potential to be applied in 3-D integration.**

***Index Terms*—Adhesion layer, metal bonding, 3-D integration.**

I. INTRODUCTION

DUE TO lithography and physical limitation, the development of conventional semiconductor fabrication will meet its bottleneck in the near future [1]–[3]. As a solution, the concept of 3-D integration technology has come into the picture [4], [5]. Bonding technology, for the vertical stacking of chips and wafers, is one of the main focuses in 3-D integration. Various types of bonding approaches have been proposed, including wafer-to-wafer, die-to-wafer, and die-to-die bonding. Each type is subjected to different throughputs and yields. Utilizing metal as the bonding medium is the mainstream for current bonding technology, for its higher tolerance to surface cleanliness and also serving as an additional metal layer.

Among all metal materials, copper is the preferred candidate for its outstanding electrical properties [6]. For 3-D metal bonding technology, Cu as bonding material provides numerous advantages over other metal and eutectic bonding technology. In addition, Cu bonding avoids the formation of intermetallic compound in many other metal alloy bonding, which, in turn, provides higher resistance toward electromigration, mechanical forces, and thermal stressing [7].

Although Cu bonding has been widely studied [8], [9], cosputtered Cu-based metals are not studied for bonding medium yet. The interdiffusion of cosputtered metals leads to segregation of the cosputtered metals at high temperature [10], [11], which provides a good foundation for metal-to-metal bonding. In this letter, cosputtered copper and titanium as bonding materials are investigated. Due to the segregation of cosputtered copper and titanium at thermal compression bonding condition, an automatically formed adhesion layer and a copper-to-copper bonding structure are demonstrated. With the excellent bonding result, it is suggested that cosputtered copper and titanium bonding is a promising approach for 3-D bonding technology.

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 and with a base pressure of 1×10^{-6} torr. The approximate sputtering rates for Cu and Ti are 0.6 and 0.1 $\text{Å}/\text{s}$, respectively. Prior to bonding, acetic acid cleaning was applied to the sample to remove copper oxidation [12]. The cosputtered samples (wafers or chips) were then bonded face to face at 400 °C. The quality and morphology of the cosputtered thin films and bonded structures were analyzed through Auger, TEM, EDX analysis, and EPMA mappings.

When cosputtered Cu/Ti is annealed in nitrogen ambient, since Cu has the lower activation energy at the surface and a comparable atom volume with respect to Ti vacancy [11], [12], Cu has a tendency to move toward the surface, while Ti tends to move toward the substrate side. This behavior is demonstrated in the Auger depth profile of a cosputtered Cu/Ti sample. Before annealing, as shown in Fig. 1(a), two metals are uniformly distributed in the thin film, while after annealing in nitrogen ambient at 400 °C for 100 min, the segregation of copper and titanium is observed, as shown in Fig. 1(b). Based on this phenomenon, cosputtered Cu/Ti as bonding material can be utilized for 3-D bonding technology.

The EPMA analyses of the bonded sample are shown in Fig. 2(a) and (b). Fig. 2(a) shows that most Ti atoms accumulated at the two sides close to Si substrates but almost no Ti signal is detected around the original bonding interface. On the other hand, Cu in Fig. 2(b) shows a completely different result, with strong Cu signal detected in the original bonding interface region but no Cu at the two sides close to Si substrates. This result demonstrates that the interdiffusion mechanism can be applied to the bonding process.

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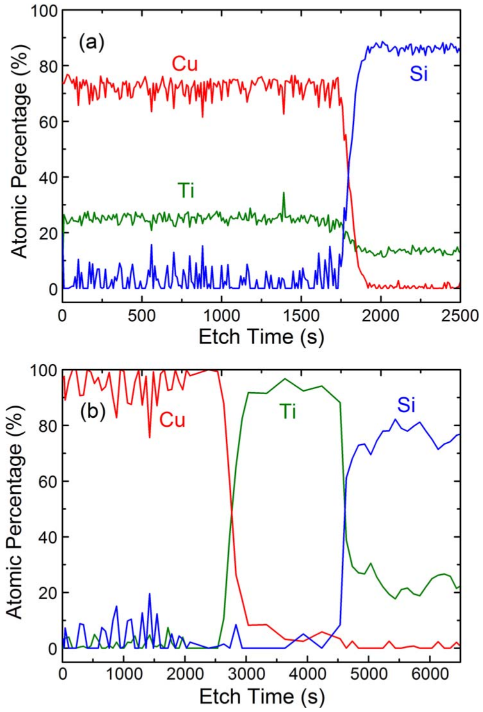
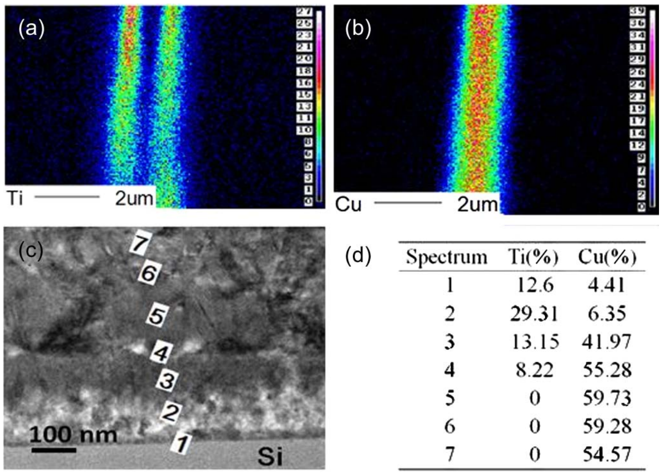


Fig. 1. Auger depth profiles of cosputtered Cu/Ti (a) before annealing and (b) after annealing at 400 °C for 100 min.



Spectrum	Ti(%)	Cu(%)
1	12.6	4.41
2	29.31	6.35
3	13.15	41.97
4	8.22	55.28
5	0	59.73
6	0	59.28
7	0	54.57

Fig. 2. EPMA mapping profiles of (a) Ti atoms and (b) Cu atoms of the bonded Cu/Ti sample. (c) XTEM image of bonded Cu/Ti sample near Si substrate. (d) Corresponding atomic ratio of Cu and Ti from (c).

The XTEM image of the region close to the Si substrate of a Cu/Ti bonded sample is shown in Fig. 2(c). The corresponding EDX analysis results in Fig. 2(d) show a similar result with the EMPA analysis. From the analysis, Ti atoms are only observed at spots 1–4, which corresponds to the layer close to the substrate, but not at spots 5–7. Copper atoms, in the total opposite, are found mostly in the region of the original bonding interface between the two bonded layers.

III. ELECTRICAL MEASUREMENT OF CONTACT RESISTANCE

The contact resistance of Cu/Ti bonded interconnects was evaluated by fabricating and measuring a Kelvin structure of a bonding area subjected to 625 $\mu m^2 (25\ \mu m \times 25\ \mu m)$. The result of contact resistance with respect to different applied currents is shown in Fig. 3. The deviation of resistance is small under different applied currents, indicating a stable bonded structure.

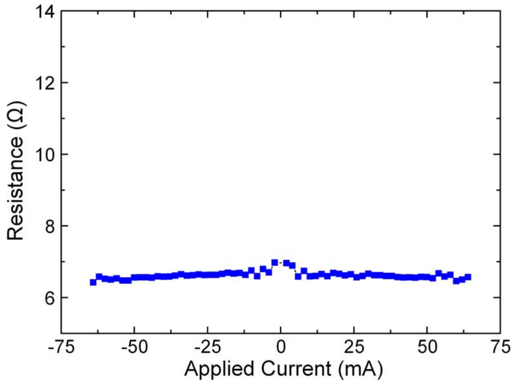


Fig. 3. Contact resistance measurement of Cu/Ti bonded structure under different applied currents.

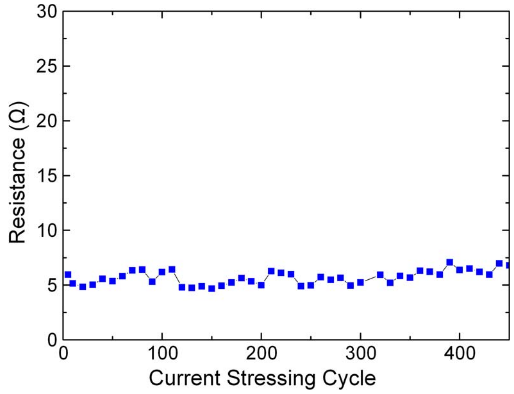


Fig. 4. Contact resistance measurement of Cu/Ti bonded structure under multiple current stressing cycles.

The stable electrical contact resistance measurement result under different applied currents suggests that Cu/Ti structure has completed the diffusion process of Cu and Ti atoms and formed a reliable bonded structure during bonding. Therefore, the atomic distribution is not changed across the bond structure, and the contact resistance remains in the same range of values.

IV. ELECTRICAL PERFORMANCE UNDER MULTIPLE CURRENT STRESSING

The stability of the bond structure is significant for 3-D integration applications, particularly its electrical performance after multiple operations. Therefore, the Cu/Ti bonded structures were evaluated for stability against current stressing, with each cycling consisting of a sweeping current from 100 to −100 mA. The contact resistance after multiple loops of current stressing was measured and is shown in Fig. 4. It is shown that the deviation of resistance is small within the entire range of 450 current stressing loops. This result implies that the bonded contact is stable and could also endure a long term of electrical current.

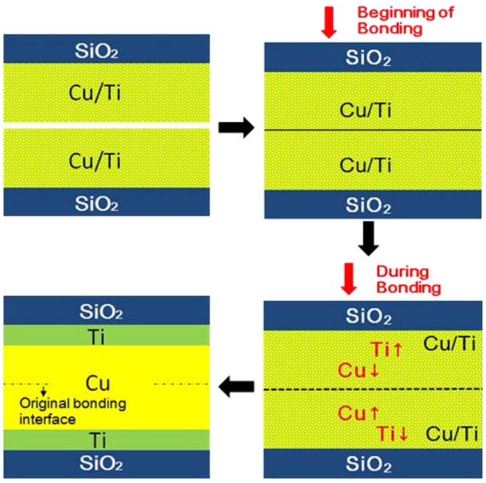


Fig. 5. Schematic diagram of the cosputtered Cu/Ti bonding procedure.

V. SCHEMATIC OF BONDING PROCEDURE AND THE SELF-FORMATION ADHESION LAYER

With stable electrical performances, Cu/Ti bonded structure is verified to be suitable for interconnects in 3-D integration. Fig. 5 shows the schematic diagram of the cosputtered Cu/Ti bonding procedure. At first, Cu and Ti atoms are uniformly distributed throughout the layer. When bonding process starts, copper atoms start to move toward the bonding interface of the two layers, while Ti atoms diffuse toward the substrate side. As the heating process goes on, Cu atoms at the bonding interface start to diffuse and form into a continuous layer. The diffusion occurs at the bonding interface, where Cu atoms from the top and bottom samples diffuse to the other sample and coalesce into grains connecting the two layers. At last, a continuous Cu layer is formed, and the interface is eliminated.

The separation of the Cu and Ti layer indicates one promising feature of cosputtered Cu/Ti as bonding material: an automatically formed self-adhesion layer. Due to the poor adhesion of copper on silicon substrates, an additional adhesion layer is required for copper deposition. Titanium is a typical candidate of adhesion layer in Cu metal layers and interconnects. In this letter, with the formation of the self-adhesion Ti layer during bonding, the deposition of the extra adhesion layer is no longer mandatory. In addition, due to the segre gation of the two metals, almost no Cu signal is detected at the substrate. Therefore, the Ti layer serves not only as an adhesion layer but also as a diffusion barrier in this bonding process.

VI. CONCLUSION

In this letter, a novel bonding technology utilizing cosputtered Cu/Ti as bonding material has been proposed for 3-D integration. The bonding method exhibits great features, including an automatically formed Ti self-adhesion layer which reduces fabrication complexity. The Cu/Ti bonding provides excellent electrical properties and reliability against current stressing, showing the potential as a candidate for 3-D integration.

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