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〈Research Article〉

Optimal pressure and temperature for Cu-Cu direct bonding in three-dimensional packaging of stacked integrated circuits

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Abstract

Scholars have proposed wafer-level bonding and three-dimensional (3D) stacked integrated circuit (IC) and have investigated Cu-Cu bonding to overcome the limitation of Moore's law. However, information about quantitative Cu-Cu direct-bonding conditions, such as temperature, pressure, and interfacial adhesion energy, is scant. This study determines the optimal temperature and pressure for Cu-Cu bonding by varying the bonding temperature to 100, 150, 200, 250, and 350 ℃ and pressure to 2,303 and 3,087 N/cm^2. Various conditions and methods for surface treatment were performed to prevent oxidation of the surface of the sample and remove organic compounds in Cu direct bonding as variables of temperature and pressure. EDX experiments were conducted to confirm chemical information on the bonding characteristics between the substrate and Cu to confirm the bonding mechanism between the substrate and Cu. In addition, after the combination with the change of temperature and pressure variables, UTM measurement was performed to investigate the bond force between the substrate and Cu, and it was confirmed that the bond force increased proportionally as the temperature and pressure increased.

Keywords : Cu-to-Cu bonding; 3D stacking; 3D package; C2C; C2W.

1. Introduction

The semiconductor industry has been downscaling transistors to improve the performance, and reduce the form factor and production costs of chipsets. Semiconductor integration technology, which avoids micro-stacking and functional lightening, has gained prominence in the industry with the development of three-dimensional (3D) stacked integrated circuits (ICs) [1,2]. These ICs can super-integrate more semiconductor chips within a limited package area and reduce power consumption by optimizing the wire length between transistors. However, concurring with Moore's law, transistor downscaling has reached its physical limit [3]. Given these difficulties in shrinking a transistor in two-dimensional space, engineers have attempted to develop chips in 3D space. Small form factor and high performance can be achieved by stacking chips vertically and shortening the interconnection length with through-silicon via [4]. chip-chip or chip-wafer interconnection is typically constituted by a solder bump as it is compatible with the existing semiconductor manufacturing process and equipment. To meet this requirement, researchers have developed several methods

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for wafer bonding that circumvent the use of a solder bump, e.g., direct wafer bonding, surface activated bonding, Cu–Cu thermoscompression bonding, solid liquid interdiffusion bonding, and metal/dielectric hybrid bonding. These applications require a low bonding temperature and pressure, with Cu as the main bonding material [5].

In this study, the optimal conditions of Cu–Cu direct bonding, i.e., bonding temperature and pressure, were determined. A technique to treat the oxide film on the Cu surface and corresponding cleaning solution was also demonstrated. The typical solder bump materials used for bonding microchips are Au, Sn, and Cu. Among these, Cu has a wide range of applications in electrical and electronics engineering owing to its electrical characteristics. In the case of the Cu junction, the 3D stacked IC junction characteristics are sustained by the effective activation of Cu atoms at elevated temperatures of above 400 ℃. However, for industrial processes, the temperature must be controlled to below 300 ℃ [6].

2. Experimental

A Cu substrate was used as the bonding material for Cu direct bonding. The surface, which contained organic and inorganic compounds and impurities, was cleaned using an ultrasonic washer with a diamond abrasive solution. The optimal sintering conditions were determined by considering five parameters: temperature, pressure, flatness, oxide film, and cleaning solvent. Firstly, to identify the Cu–Cu direct-bonding temperature, the surface of the as-prepared Cu substrate was treated with the abrasive solution for 10 min, removing the organic and inorganic compounds and oxide film and flattening the surface. Next, the Cu substrate was cleaned with distilled water and acetone, and the resulting specimen was dried at room temperature for 10 min.

Subsequently, the Cu substrate surface was characterized by field-emission scanning electron microscopy (FE-SEM, HITACHI, S-4300). A fixed pressure of 3,087 N/cm^2 was exerted on two washed Cu specimens by placing them between the bolt and nut of a torque wrench. The fixed Cu substrate was then placed in an oven for sintering. The samples were heated at a rate of 10 ℃/min and sintered for 4 h at sintering junction temperatures of 100, 150, 200, 250, and 350 ℃. In addition, the states of the Cu junctions at 100, 150, 200, and 350 ℃ and 2,303 and 3,087 N/cm^2 were observed under FE-SEM and EDX to confirm the bonding characteristics of the substrates. The Cu–Cu bonding interfacial adhesion energy and bonding quality were measured by a universal testing machine (UTM EZ Test, Shimadzu Corporation).

3. Results and discussion

The Cu substrates bonded with Cu atoms at a temperature of more than 200 ℃ and a pressure of 3,087 N/cm^2. Another important factor is the magnitude of pressure that must be reduced to make the substrate more mechanically reliable; in Table 1, the Cu specimens were pressurized to 2,303 at 200, 250, and 350 ℃. The sample de-bonded at a sintering temperature of 200 ℃. Hence, 200 ℃ is the marginal temperature for Cu–Cu direct bonding at the pressures of 3,087 and 2,303 N/cm^2.

According to previous studies by the authors [7], the Cu junction was underdeveloped at 200 ℃ and 2,303 N/cm^2, but it was well

Table 1. Characterization of Cu substrate junctions by temperature and pressure.

Pressure (N/cm^2)	100℃	150℃	200℃	250℃	350℃
3087	Non-bonded	Non-bonded	Bonded	Bonded	Bonded
2303	-	-	Non-bonded	Bonded	Bonded

Table 2. Cu substrate junction characterized by treatment condition at a pressure of 3,087 N/cm^2 and a sintering temperature of 200 ℃.

Treatment Condition	Pressure (N/cm^2)	Temperature (℃)	Polishing	Cleaning Solvent	Bonding result
POR	3087	200	Diamond abrasive	Acetone	Bonded
#1 (non-polishing)	3087	200	Non-polishing	Acetone	Non-bonded
#2 (water cleaning)	3087	200	Diamond abrasive	Water	Non-bonded

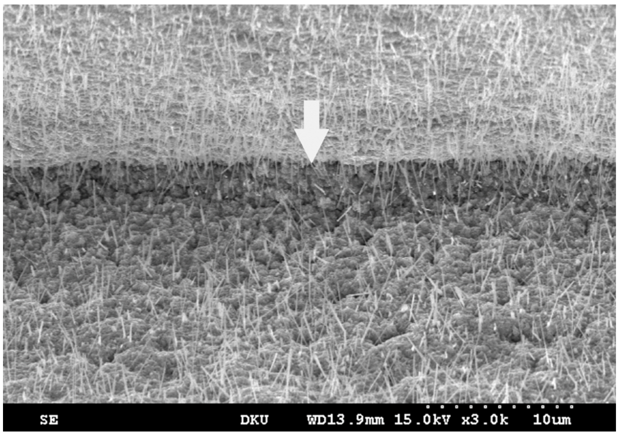
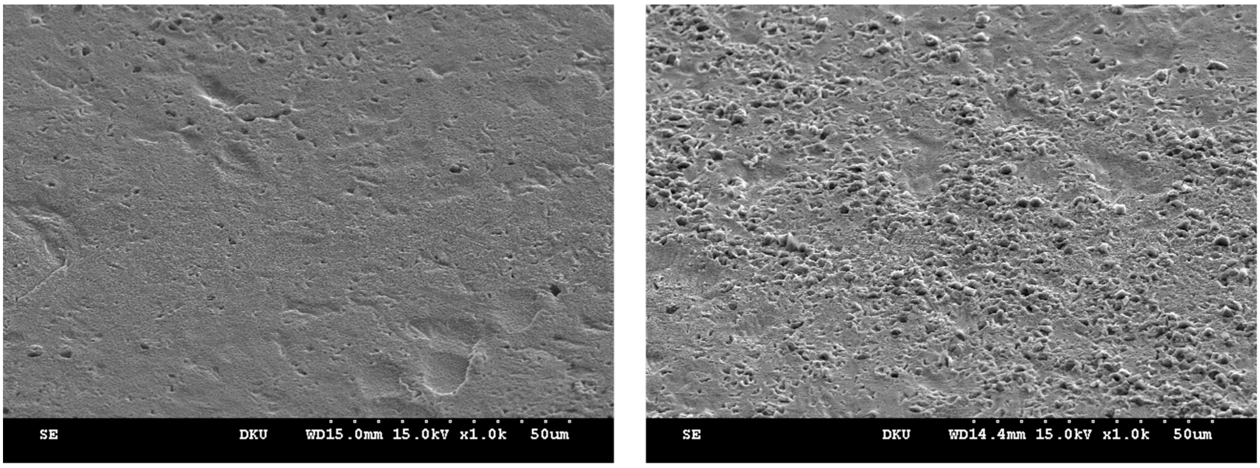


Fig. 1. Cross-section of the Cu substrate junction sintered at the pressure of 3,087 N/cm^2 and the temperature of 350 ℃.

formed at 200 ℃ and 3,087 N/cm^2. In other words, at the lower pressure, the surface of the individual Cu dopant does not bond with that of the Cu of the sample sintered at 200 ℃, and the dopant atoms do not diffuse smoothly on the surface. However, as the pressure increased, the formation of the Cu-Cu junction was confirmed by the activation of the Cu atoms. In Figure 1, the sintering interfaces (represented by the arrow) are tightly bonded to the junction owing to the increased activation as the temperature of Cu atoms increased under the pressure of 3,087 N/cm^2 and the sintering temperature of 350 ℃.

The surface treatment of the specimens ensures their stability by removing other component materials or oxide films that could have adverse effects on the junction surface characteristics. Table 2 summarizes information about the sintered junction state of Cu at a pressure of 3,087 N/cm^2 and a temperature of 200 ℃ after the implementation of different surface treatments. Surface roughness can affect the stability of specimens, and other component substances such as inorganic compounds and oxide films on their surface may react to the mechanical and electrical characteristics of the Cu junction interface [8].

Another factor considered in the Cu-Cu bonding experiment was the cleaning solvent used between the surface treating and sintering processes. Under the same temperature and pressure as with the surface treatments, the use of cleaning solvents, namely distilled water and acetone, produced different bonding results. Figure 2(a) illustrates acetone-cleaned Cu-Cu bonded surface after sintering. Figure 2(b)



(a) (b)

Fig. 2. The copper substrate surface after (a) POR treatment and (b) #2 treatment.

depicts the water-cleaned Cu de-bonded surface after sintering. The two images have significant difference, i.e., the number of blowholes on the surface. The surface of the water-cleaned specimen had numerous small blowholes, which were attributed to the moisture trapped between the Cu–Cu surface and evaporated. When the sintering temperature was increased, this evaporating water absorbed heat from the Cu atoms on the Cu surface and interrupted the Cu junction. In contrast, acetone is a high volatile chemical and did not remain on the surface after cleaning. Therefore, the acetone-cleaned specimen (POR) created stronger bonds.

In Table 3, EDX results show that the rate of oxygen saturation increases with increasing temperature, which shows that the oxide film can affect the bonding mechanism in Cu bonding. The oxidative saturation of the sample without polishing was 4.5~4.6% and the oxygen saturation of the sample with polishing was 3.6~3.8%. The polishing treatment decreased the oxygen saturation by about 0.9%. However, the change of pressure did not affect oxygen saturation. Finally, EDX result confirmed the oxygen saturation increases at over 150℃ and it grows as the temperature increases. Compare to non-polishing and after polishing sample, it affirms the polishing process is effective to raise the oxygen saturation in reduction. The Cu-Cu bonding interfacial adhesion energy and bonding quality was measured by UTM(Universal Test Machine) which is ez-test model from Shimadzu Corporation.

Table 4. summarizes the results of the bond-strength measurement of the Cu–Cu junction with respect to temperature and pressure. The bond strength increases at higher temperatures and pressures. In other words, the high temperatures and pressures cause the recrystallization of Cu atoms around the junction interface. Previous studies had shown that the inadequate activation energy of Cu atoms at sintering temperatures of less than 250 ℃ caused slow crystal growth of the Cu atoms. However, an excellent bond strength between Cu atoms and substrate was obtained in this study (Table III) by elevating the activation state of the Cu atoms by pretreating the surface with acetone and diamond abrasive solution and increasing the sintering temperature and applied pressure.

4. Conclusions

In this study, we evaluated the bonding characteristics between Cu atoms and Cu substrate through the Cu direct bonding method at high temperatures and pressures for a 3D stacked IC, which can be integrated by stacking more semiconductor chips within a limited package area. At low temperatures, the low activation energy of Cu atoms in the Cu–Cu junction process creates an environment that destabilizes the junction. The wet-surface pretreatment process can create an active environment at the interface between the

Table 3. EDX atomic% of every sintering condition.

Atomic%	Cu	O
Polishing, Solvent, 100 ℃, 3087 N/cm^2	96.52	3.48
Polishing, Solvent, 150 ℃, 3087 N/cm^2	97.74	8.41
Polishing, Solvent, 200 ℃, 3087 N/cm^2	77.24	22.76
Polishing, Solvent, 250 ℃, 3087 N/cm^2	59.07	40.93
Polishing, Solvent, 350 ℃, 3087 N/cm^2	55.56	44.44
Polishing, Solvent, 200 ℃, 2303 N/cm^2	76.07	23.93
Polishing, Solvent, 250 ℃, 2303 N/cm^2	60.54	39.46
Polishing, Solvent, 350 ℃, 2303 N/cm^2	46.98	53.02
Non-Polishing	95.34	4.66
After-Polishing	96.36	3.64
Polishing, Water, 200 ℃, 3087 N/cm^2	76.33	23.67

Table 4. Bond strength of the Cu junction vs. temperature and pressure.

Pressure (N/cm^2)	250 ℃	250 ℃	300 ℃
2303	476 ~ 599 gf	-	-
3087	-	640 ~ 865 gf	756 ~ 1003gf

Cu atoms and substrate, and consequently improve the bond strength at the Cu–Cu junctions through proper control of temperature and pressure. In addition, the bond strength increases at elevated temperatures and pressures [9,10]. The mechanism of integration is the surface diffusion of Cu atoms on Cu substrate. Higher temperatures and pressures provide the atoms with adequate energy to overcome the potential barrier that separates the adatoms at neighboring positions between Cu surfaces, stimulating recrystallization [11,12]. This study does not focus on the industrial application of Cu direct bonding for mass production. Thus, future research must be performed to determine the pressure that the Cu–Cu wafer can resist and the degree of bond strength required to prevent the junction from breaking under warpage.

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