Reliability Study of Two-Step Plasma-Activated Copper-Copper Direct Bonding in Ambient

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***Abstract*—Copper-copper direct bonding is a promising technology for various applications such as microelectronics, microelectromechanical systems, and power electronics. Plasma-activated copper-copper direct bonding is a two-step bonding process that has shown great potential for high-quality copper-copper bonding in ambient conditions. In this paper, we present reliability study of a two-step plasma-activated copper-copper direct bonding process by investigating the bonding strength and the long-term stability of the copper-copper bonds. The reliability of the bonding technique is investigated using various techniques such as shear test, aging test, and highly accelerated temperature and humidity stress test. The results show that the plasma-activated copper-copper direct bonding process can achieve a high bonding strength and good long-term stability, which makes it a promising technology for various applications.**

***Keywords*—copper-copper direct bonding, plasma activation, ambient conditions, highly accelerated temperature and humidity stress test, reliability of copper-copper bonds**

I. Introduction

With the growing trend of miniaturization (high density) in electronics and the demand for high-performance (low power consumption) devices, copper-copper (Cu-Cu) direct bonding has become a popular technology that has attracted much attention in semiconductor manufacturing due to its potential for high-quality bonding of heterogeneous components [1]. The Cu-Cu direct bonding has many applications, including microelectronics, power electronics, and microelectromechanical systems (MEMS) [2]. The conventional thermo-compression bonding (TCB) process is widely used for Cu-Cu bonding, but it has some limitations, such as high process temperature, high bonding pressure, and the need for a high-vacuum environment [3, 4]. Therefore, there is a need for a new technology that can overcome these limitations and achieve high-quality Cu-Cu bonding in ambient conditions.

Plasma-activated Cu-Cu direct bonding (PACDB) is a two-step bonding process that uses plasma treatment to activate and passivate the Cu surfaces before bonding. The PACDB process has been shown to achieve high-quality bonding of Cu substrates at low temperatures and low pressures, which makes it a promising technology for various applications [5-14]. However, the reliability of the PACDB process needs to be investigated to determine its suitability for practical applications.

In this paper, we present a reliability study of the PACDB process in ambient conditions by investigating the bonding strength and the long-term stability of the Cu-Cu bonds. The bonded samples are subjected to various reliability tests, including highly accelerated temperature and humidity stress test (HAST), aging test, and shear test. The results provide insights into the effectiveness and reliability of the PACDB process for microelectronics packaging applications [15-20].

II. Experimental Methods

A. Two-Step Plasma-Activated Copper-Copper Direct Bonding

1) Preparation of Cu surfaces: Top and bottom Cu dies, as shown in Fig. 1, were prepared by cleaning with a mixture of acetone and isopropanol (IPA) in an ultrasonic bath. The dies were then dried with nitrogen (N_2) gas flow.

2) Plasma activation: The cleaned Cu surfaces were subjected to plasma treatment using a plasma enhanced chemical vapour deposition (PECVD) system. The plasma treatment was carried out at a pressure of 20 Pa and a power of 200 W for ~5 minutes. The Ar plasma were first applied to the Cu surfaces (Step 1 in Fig. 2), followed by N_2 plasma (Step 2 in Fig. 2).

3) Two-step bonding processes: The plasma-activated Cu surfaces were placed in contact with each other under a force of 50 N for 10 seconds (Step 3 in Fig. 2). The bonding was then annealed at 300°C for 3 hours in an oven to enhance the bonding strength (Step 4 in Fig. 2).

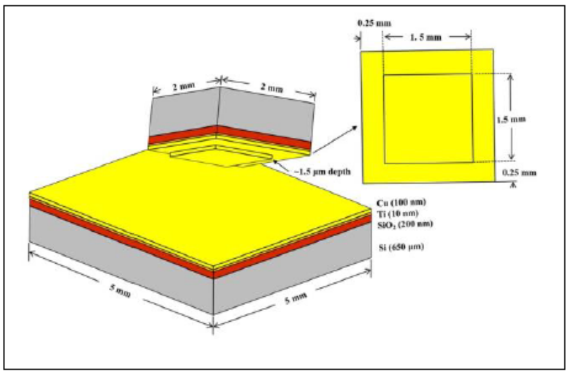

Fig. 1. The schematic diagram of a top Cu die bonded onto a bottom die.

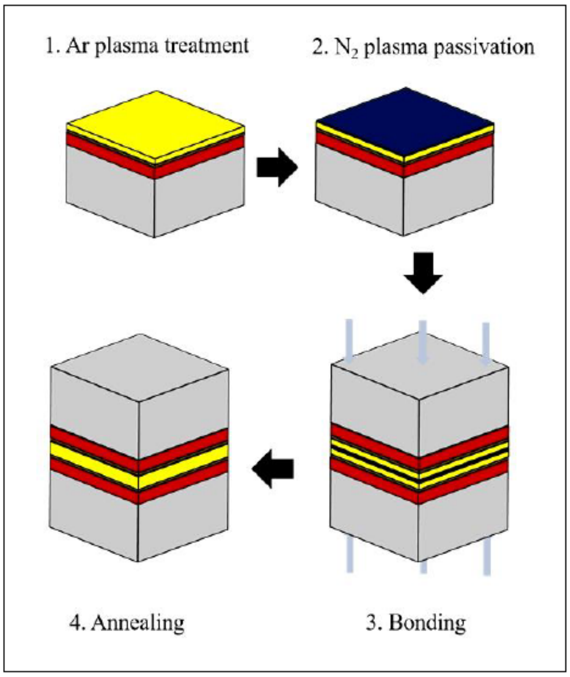

Fig. 2. The two-step plasma-activated Cu-Cu direct bonding processes.

B. Reliability Tests of Plasma-Activated Copper-Copper Direct Bonding

1) Highly accelerated temperature and humidity stress test: Some of the bonded dies were stored at 85°C and 85% relative humidity (RH) for 1000 hours.

2) Shear test: The bonded dies were subjected to shear strength test with a speed of 200 µm/s [21].

3) Aging test: The aging test was performed by exposing the bonded dies to ambient conditions for various durations, and the hermeticity was measured after each aging duration [22].

C. Characterization of Reliability of Plasma-Activated Copper-Copper Direct Bonding

The bonded dies were characterized using scanning acoustic microscopy (SAM), transmission electron microscopy (TEM) and energy dispersive X-ray spectroscopy (EDS). The shear strength of the bonded dies was measured using a mechanical tester. The hermeticty of the bonded dies was assessed using a fine tester.

III. Results and Discussion

To investigate the reliability of the two-step PACDB technique, we performed HAST test on the bonded dies. The bonded dies were subjected to store at 85°C and 85% RH for 1000 hours. The shear strength of the bonded dies was measured before and after 1000-h storage. The shear strength of the bonded dies was measured to be above 6 MPa, which is higher than the minimum accepted value ~6 MPa (Fig. 3). The results show that the shear strength of the bonded dies remained stable throughout the HAST test. No significant decrease in shear strength was observed even after 1000-h HAST test, indicating the high reliability of the two-step PACDB technique.

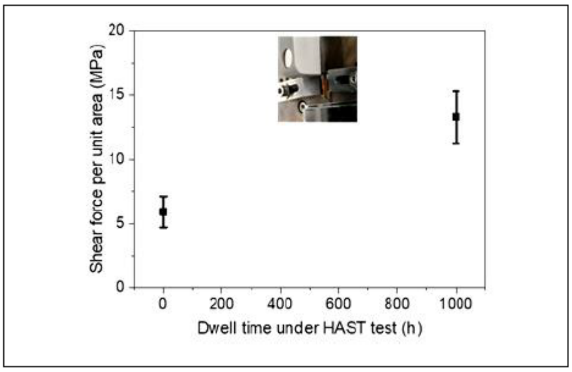

Fig. 3. The shear strength of the bonded Cu dies before and after 1000-h HAST test.

The SAM images (Fig. 4) show that there are no defects and interfacial voids observed even after 1000-h HAST test. The TEM images of the bonded Cu surfaces show a uniform and continuous bonding interface, indicating a good bonding quality (Fig. 5). The EDS elemental analysis confirms the presence of Cu-Cu bonding without any interfacial oxides and contamination at the bonding interface (Fig. 6).

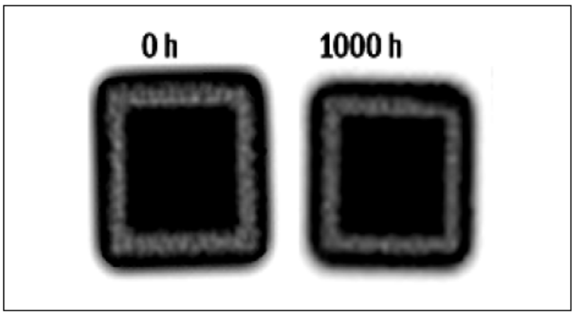

Fig. 4. SAM images before and after 1000-h HAST test.

The results of the aging test showed that the helium (He) leakage rate of the bonded dies decreased gradually after exposed to ambient conditions. The leakage rate was less than the maximum accepted value 5 × 10^{-8} atm-cc/s even after 12-month exposure time (Table I).

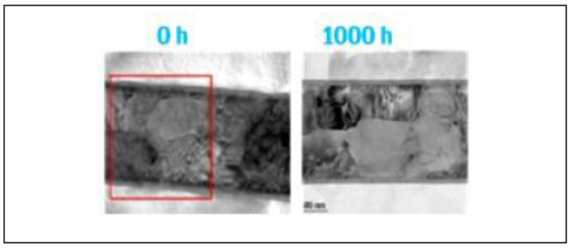

Fig. 5. TEM images before and after 1000-h HAST test.

TABLE I. HERMETICITY VARIATION OF BONDED CU DIES WITH TIME EVOLUTION

Ambient Exposure Time After Bonding (month)	0	3	6	9	12
He Leakage Rate (atm-cc/s)	6.5 × 10^{-10}	2.0 × 10^{-9}	6.3 × 10^{-9}	9.6 × 10^{-9}	1.6 × 10^{-8}

In summary, the HAST test showed that the bonded dies maintained their bonding strength, no defects and no interfacial oxides observed after 1000-h storage. The aging test showed that the leakage rate was less than the maximum accepted value 5 × 10^{-8} atm-cc/s even after 12-month exposure time. The results demonstrate the good reliability of the two-step PACDB bonding process.

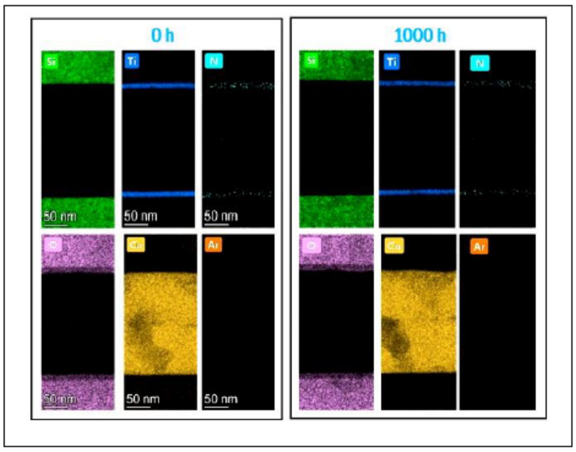

Fig. 6. EDS elemental analysis before and after 1000-h HAST test.

IV. CONCLUSION

In conclusion, the two-step PACDB bonding technique is a reliable method for bonding Cu substrates in ambient conditions. The bonding interface is uniform and continuous, and the shear strength of the bonded dies is high. The HAST tests show that the shear strength of the bonded dies remains stable even after 1000-h storage. The two-step PACDB technique offers a low-cost, high-throughput, and reliable solution for Cu-Cu bonding in microelectronics applications.

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