New interconnection technologies based on Ni micro-plating bonding for high-temperature resistant power device packaging

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Abstract

This study proposes Ni Micro-Plating Bonding (NMPB) as a new bonding method for semiconductor packages for power devices with high heat resistance such as SiC. NMPB enables bonding at low temperatures (55°C) by using nickel plating, a high melting point metal. Bonding was conducted using newly developed Ni plating solution and lead frames with a chevron-shaped profile designed for NMPB, and the strength and microstructure of the bonded area were evaluated. As a result, it was found that bonding with NMPB exhibits stronger bonding strength compared to conventional lead-free solder. Furthermore, the electrical characteristics of power modules connected by NMPB were evaluated, confirming normal operation at both room temperature and high temperature (250°C). Thus, NMPB is suggested as a new high-temperature device-compatible bonding technology applicable to replace conventional bonding techniques.

Key words

Ni Micro-plating Bonding ; NMPB; SiC; Ni; MOS-FET; SBD; Cu lead; Power module; Chevron Shape ;

I. Introduction

Power semiconductors for automobiles and trains are increasingly being demanded to be smaller and more power-efficient. Consequently, the adoption of next-generation semiconductors such as SiC and GaN is advancing. These wide-bandgap semiconductors enable operation in high-temperature environments. Traditional semiconductor package joints involve Pb solder or aluminum bonding wires and lack sufficient heat resistance.

Fig.1(a) depicts a schematic diagram of the conventional semiconductor package, while Fig. 1(b) illustrates a schematic diagram of the new semiconductor package proposed by our research group. Our research group proposes a novel bonding technique using Ni, a high-melting-point metal with a melting point exceeding 1400°C, as a new joining method called Nickel Micro-Plating Bonding (NMPB) [1]-[5].

This technology allows bonding at approximately 55 °C, maintaining a constant growth rate of Ni plating crystals from opposing joined surfaces, ensuring a dense bond without voids. For NMPB, a newly developed copper lead frame with a Chevron shape is used for bonding, enabling void-free joints by supplying plating liquid to the tip of the Chevron shape. Examples of such bonding techniques include joining aluminum and copper using nickel plating, as well as joining aluminum or copper to aluminum or copper using copper plating[6-8]. This paper explores the optimization of plating conditions and additives for NMPB, along with a mechanical and microstructural study of the bonding using the Cu leads with a Chevron shape. Furthermore, the high-temperature operation of SiC-SBD and SiC-MOSFET implemented through NMPB is confirmed.

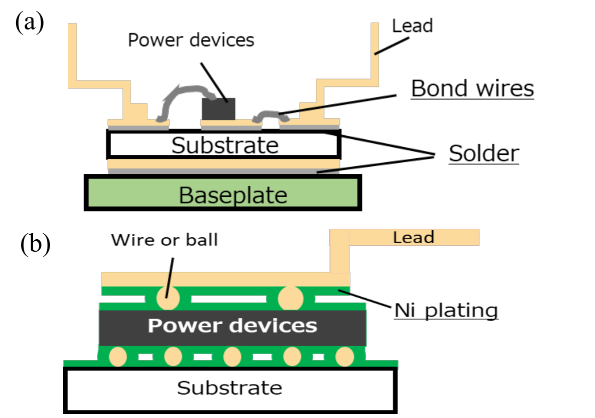

Fig. 1 A schematic diagram of (a) the conventional semiconductor package and (b) the new semiconductor package proposed by our research group.

II. Experimental method

The experiment involved fixing Cu wires or Cu leads with a Chevron shape to Cu plates and depositing Ni plating using a sulfamic acid bath. Electroplating prioritizes film growth in areas with concentrated current, such as the edge[9]. Therefore, Ni plating in this experiment used an additive (referred to as additive A) that prioritizes growth in narrow areas. We observed differences in the joint condition at the bonding interface depending on the presence or absence of additives by examining the cross-section of the bonded area. After bonding, heat treatment was performed at 300-500°C to enhance joint strength and stabilize the plating film. The joint strength was measured using a universal bond tester (Nordson Advanced Technology, Model 4000Plus) to determine the shear strength. Evaluation of the optimized plating conditions involved observing plating behavior and microstructures from the joint section using optical and scanning electron microscopes (Hitachi, Model SU5000). The SiC power module for automotive inverters, using SiC-MOSFET and SiC-SBD, was fabricated using NMPB with optimized plating conditions. Fig.2 shows the appearance of the SiC power module after plating and after resin encapsulation. The chips used were SiC-MOSFET(4.08mmx7.35mm) and SiC-SBD(6mmx6mm) . Fig. 3 illustrates the circuit diagram of the SiC power module. The connection section utilized mountain-shaped leads, and the I-V characteristics of the SiC high-temperature semiconductor power device module, equipped with SiC-SBD and SiC-MOSFET, were measured from room temperature to 250°C using a curve tracer (IWATSU, CS-3300).

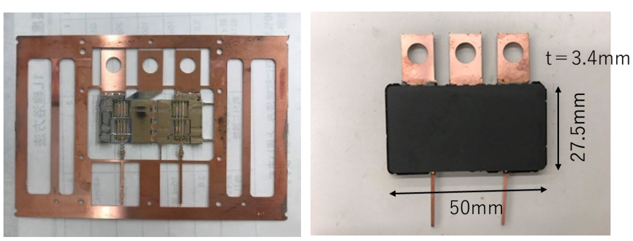

Fig.2 Appearance of SiC power module after plating and after resin encapsulation.

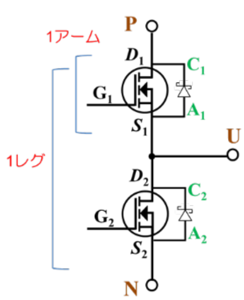

Fig. 3 Circuit diagram of the module.

III. Experimental results and Discussion

To investigate the effect of additive A, test samples were prepared by bonding Cu wire to Cu plate using NMPB with and without the addition of additive A, and the cross-sections were examined. Additive A is specifically designed for Ni plating to preferentially grow in narrow areas. Fig.4 shows optical microscope images of cross-sections of the test samples bonded by NMPB with Cu wire and Cu plate. Fig.4 (a) depicts the cross-section without the addition of additive A, while Fig.4 (b) shows the cross-section with the addition of additive A. The presence of plating at the base of the wire suggests potential enhancement in bonding strength. Furthermore, it is speculated that this could improve heat dissipation by ensuring a larger bonding area.

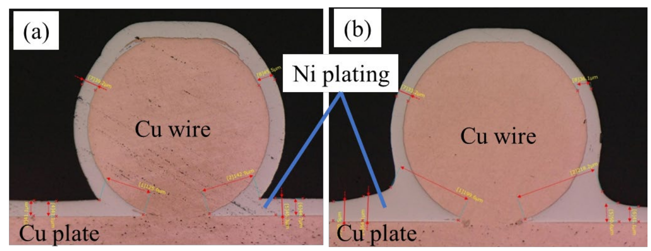

Fig. 4 Optical microscope images of the cross-sections of test specimens joined by NMPB with Cu wire and Cu plate: (a) without additive A, (b) with additive A.

To investigate the differences in bonding conditions based on current density, the cross-sections were observed when connecting the Chevron-shaped Cu lead and Cu plate using NMPB, with the Ni plating current density varied from 1.5 to 10 A/dm². Fig. 5 shows cross-sectional images of Cu leads with a Chevron shape joined by NMPB, with Ni plating current density varied from 1.5 to 10 A/dm2. In the low current density region, Ni plating growth extended to the narrow portion, forming a void-free interface. However, in the high current density region, preferential plating growth occurred at the edge, inhibiting growth in the narrow portion and resulting in void formation at the interface.

(a)
(b)
(c)

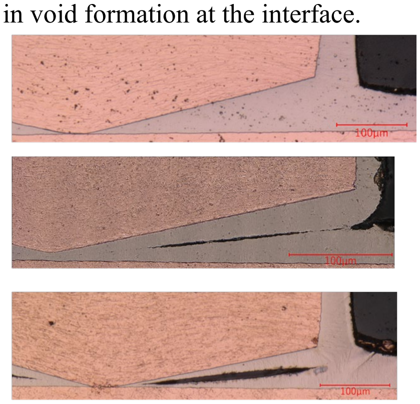

Fig.5 Cross-sectional images of Cu lead with a Chevron shape joined by NMPB, with Ni plating current

density varied from (a)1.5 A/dm2 (b) 5 A/dm2 (c)10 A/dm^2.

Adding additive A and stress-relief agent were confirmed to affect the microstructure of the plating. Fig. 6 presents EBSD maps taken from the Ni plating surface: Fig. 6(a) without adding additive A and stress-relief agent and Fig. 6(b) with additive A and stress-relief agent. The Ni plating film in Fig. 6(a) exhibits columnar crystal orientations and a textured structure, while Fig. 6(b) displays a fine equiaxed grain microstructure.

The plating additives added to the Ni plating solution are expected to be incorporated into the plating film at trace levels, on the order of several ppm. We examined the possibility of such trace elements being present on the surface of the Ni plating. Fig. 8 shows the AES analysis results of the Ni plating surface. To clean surface contamination caused by atmospheric exposure, a layer sputtered with Ar for 0.1 minutes is positioned as the outermost surface. Fig. 7(a) represents the case without additive A and stress relaxation agent, while Fig. 7(b) represents the case with additive A and stress relaxation agent. Sulfur (S) was detected at 0.8 at% and 2.8 at% on the surfaces of Ni plating, respectively. S on the surface of Ni plating without additives is believed to be derived from sulfamic acid. It was found that the amount of detected S in the Ni plating film with additives is higher than that in the Ni plating film without additives, indicating that S contained in the additives is incorporated into the plating film.

Using the above-mentioned Ni plating solutions, Cu wires and Cu plates were joined via NMPB, and the fracture surfaces of the specimens after shear testing were observed. Fig.8 shows typical SEM images of fracture surfaces after shear testing. Fig.8(a) corresponds to specimens without additive A and stress-relief agent, while Fig.8(b) represents specimens with additive A and stress-relief agent added. In the case of plating with a columnar -grained structure, the fracture surface exhibits some ductile features, while in structures with fine grains, fracture occurs at grain boundaries, indicating a grain-boundary fracture surface.

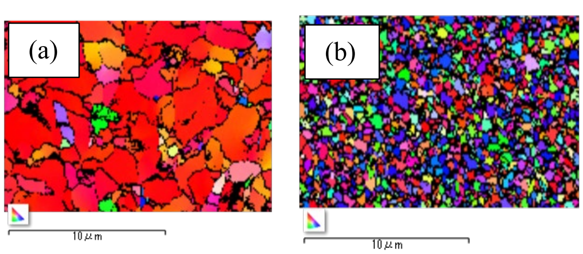

Fig. 6 Crystallographic orientation evaluation of the Ni plating surface: (a) Without additive A and stress relaxation agent (b) With additive A and stress relaxation agent.

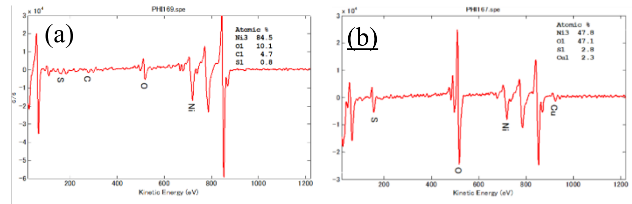

Fig. 7 AES analysis of the Ni plating surface:(a) Without additive A and stress relaxation agent (b) With additive A and stress relaxation agent.

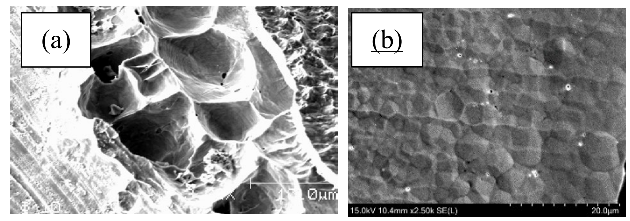

Fig.8 Typical fracture surfaces after shear testing: (a) without additive A and stress relaxation agent, (b) with additive A and stress relaxation agent.

Fig. 9 shows SEM images of the joined section. The crystal orientation of the Ni plating film remained unchanged with the addition of additive A, maintaining a columnar structure with preferred orientation. It is considered optimal for NMPB to form a void-free interface with a plating film having a textured structure of columnar grains.

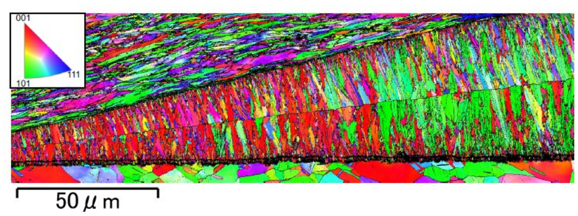

Fig. 9 Cross-sectional SEM-EBSD images of the junction.

Fig. 10 illustrates the bond strength when using conventional Pb-free soldering and when joining copper plates and wires, as well as copper plates and copper-shaped lead frames, using NMPB. Compared to the bond strength of conventional Pb-free soldering, NMPB bonding showed more than double the bond strength in all cases. Furthermore, NMPB bonding with copper plates and copper-shaped lead frames resulted in shear strengths of over 200 MPa after heat treatment at temperatures ranging from 200 to 500°C.

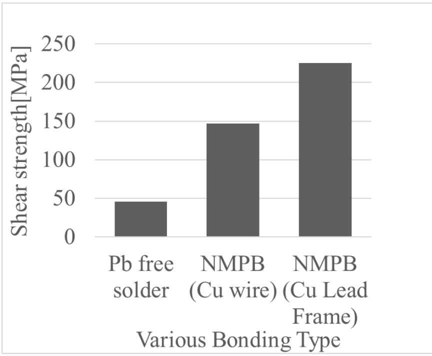

Fig. 10 The shear strength of each bonding type.

Fig.11 shows the shear strength after TCT testing. In TCT testing between 250°C and -45°C, no defects in interconnection due to NMPB were observed even after 1000 cycles. However, in some cases, chip leakage was observed. This suggests that the occurrence of leakage may be attributed to thermal stress within the chip, as robust joints do not experience rupture or deformation. The stress within the chip can potentially be alleviated by increasing the thickness of the Al layer in the electrode section or by depositing Fe-Ni Invar alloy between the electrode and the NMPB layer[10].

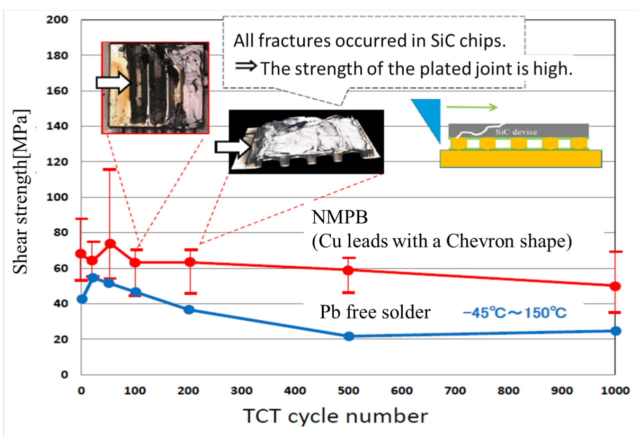

Fig. 11 Shear strength after TCT testing[2,11].

Based on the evaluation results of the plating conditions mentioned above, SiC power modules were manufactured under optimised plating conditions. Fig. 12 shows a cross-sectional image of the SiC power module. Fig. 13 shows the IV characteristics graph of the SiC-MOSFET in the SiC power module connected by NMPB at room temperature. The gate voltage was increased using a step generator, with increments of 2V from 6V, reaching a total of 6 steps (18V). Fig. 14shows the IV characteristics graph of the SiC-SBD when operated at temperatures ranging from room temperature to a maximum of 250°C. From these graphs, normal IV characteristic behavior was confirmed at both room temperature and high temperature.

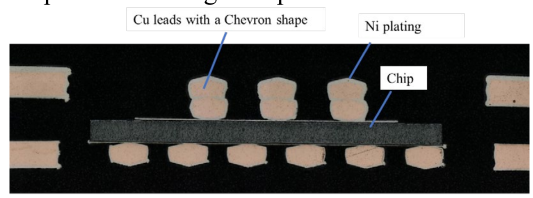

Fig.12 Cross-sectional image of the SiC power module.

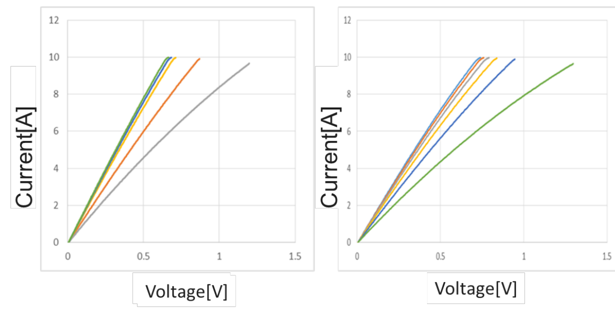

Fig.13□The IV characteristic graph of SiC-MOSFET (Left: Upper Arm, Right: Lower Arm).

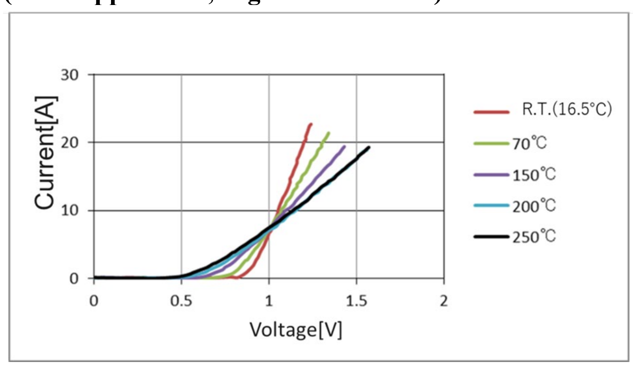

Fig.14 The IV characteristic graph of SiC-SBD.

IV. Conclusion

In this study, we proposed a new bonding technique called Ni Micro-Plating Bonding (NMPB) as an alternative to conventional Pb-free soldering methods, and evaluated its bonding conditions and mechanical properties. By controlling the plating conditions and microstructure during bonding, we were able to determine optimal NMPB conditions, resulting in higher strength bonding compared to conventional methods. Furthermore, we fabricated modules for SiC high-temperature semiconductor power devices using NMPB and confirmed their operation at room temperature and high temperatures. Moreover, even after more than 1000 cycles of TCT testing ranging from -45°C to 250°C, no defects were observed in the bond. Based on these results, NMPB shows promise as a new high-temperature bonding method for power devices.

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