Interfacial Microstructure between Copper Ribbon and Nickel-coated Copper Plate Formed by Ultrasonic Bonding*

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The present paper reports the bondability and the interfacial microstructure between copper ribbons and nickel-coated copper plates by ultrasonic bonding. The ultrasonic bondability of copper to nickel is significantly improved by heating up to 423 K. On the other hand, the bondability of copper to itself is deteriorated by surface oxidation. It is also shown that the nickel coating suppresses the deterioration. The nickel layer at the central part of the bond area shows S-curved morphology, whereas it is torn and/or folded in the peripheral part of the bond interface, indicating that a complicated deformation is induced during bonding. Although ultrasonic bonding at 423 K allows lowering of the ultrasonic power to one-third of that required for bonding at room temperature, it is difficult to avoid tearing of the Ni layer.

Key Words: Ultrasonic bonding, Electronics packaging, Interfacial microstructure, Cu, Ni, Oxidation protection coating, Surface oxide

1. Introduction

Major part of power cables, patterns on circuit boards and interconnections on integrated circuit chips of today is made of copper (Cu). High electrical and thermal conductivity and high strength makes Cu the irreplaceable material for electric power and signal transmission. However, gold and aluminum alloys are commonly used instead of Cu as bonding wires which connect semiconductor devices to outer circuits. Thus, Cu wire bonding technology has been strongly demanded for long time. One of the crucial reasons hindering Cu from the application to bonding wires is the difficulty in bonding at low temperatures¹⁻³⁾.

It is known that native surface oxides of Cu deteriorate the bondability^{2, 4)}. Cu forms oxide film on its surface by exposure to ambient air. To make things worse, Cu surface is not passivated by the formation of the oxide film, i.e., the film keeps growing by exposure to ambient air. To prevent the surface oxidation, the surface coating by tin (Sn) or nickel (Ni) is known to be effective. Although Ni is harder than Sn indicating that it is difficult to bond by solid-state bonding process⁵⁻⁷⁾, Ni has a great advantage to Sn. Ni does not form intermetallic compound with Cu, whereas Sn does⁸⁾. Thus, Ni/Cu interface does not deteriorate by formation of intermetallic compounds. To savor this advantage, ultrasonic bonding technology of Cu with Ni-coated Cu is needed.

The present study aims to clarify the following two points. One is the ultrasonic bondability between Cu and Ni including the effects of the bonding temperature and exposed time to air after surface cleaning. The other point to clarify is the interfacial

microstructure formed by ultrasonic bonding. Recently, Maeda et al. reported that interfacial microstructures formed by ultrasonic bonding of Cu ribbons to Sn-coated Cu plates reveal complicated deformation of the materials during bonding³⁾. Whether the same deformation occur with Ni-coated samples is to be clarified.

2. Experimental procedure

Three types of substrates were prepared, namely Cu, Ni and Ni/Cu substrates. Cu substrates were 0.6-mm-thick Cu plates of which nominal purity was 99.99%. Ni substrates were 0.1-mm-thick Ni plates of which nominal purity was 99%. Ni/Cu substrates were 2- μ m-thick Ni films electroplated on 0.3-mm-thick Cu plates. On the other hand, Cu ribbons were prepared by cold rolling of Cu substrates to a thickness of 0.1 mm and cutting into a 1.0-mm-wide 5.0-mm-long rectangular shape. Cu substrates, Ni substrates and Cu ribbons were annealed at 773, 1073 and 773 K, respectively, for 900 s in vacuum of 1.0×10^{-3} Pa. Then, they were immersed into diluted nitric acid for 180 s to remove surface oxide layers on them. Some of them were exposed to air for 864 ks after the acid cleaning, of which surface are expressed as “the exposed surface” in the following text. The other samples except the Ni/Cu substrates were subjected to bonding immediately after the acid cleaning (within 600 s), of which surface are expressed as “the fresh surface”. The Ni/Cu substrates were supplied by a manufacturer and thus they were inevitably exposed to air for a long time. Since the thickness of the electroplated Ni layer became ununiform by acid cleaning, the Ni/Cu substrates were subjected to bonding only in as-supplied state, i.e., without acid cleaning.

The substrates were fixed on the stage of the ultrasonic bonding apparatus. The Cu ribbon was laid on the substrate with its longitudinal direction parallel to the direction of ultrasonic

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vibration. The ribbon was pressed to the substrate with a wedge-tool and then vibrated parallel to the interface for 500 ms. The ultrasonic frequency of the apparatus was 75.0 kHz. The ultrasonic power (P) and the bonding force (F) were varied in the range of $10.0 \leq P / W \leq 40.0$ and $3.9 \leq F / N \leq 30.1$, respectively. The bonding temperature (T), represented by the temperature of the heater-embedded ultrasonic bonding stage, was set at room temperature or at 423 K. In both temperatures, bonding was carried out in ambient air without shielding gas.

The interfacial microstructures of the joints were analyzed by scanning electron microscopy. Back-scattered electron imaging mode was used to observe compositional change as the contrast.

3. Results and discussion

Fig. 1 shows the ultrasonic bondability diagram for fresh-surfaced Cu ribbons and exposed Ni/Cu substrates. The areas colored with dark and bright gray depict the ranges of ultrasonic power and bonding force in which bonds can be obtained by ultrasonic bonding at room temperature and at 423 K, respectively. Two important points are noticed in the figure. One is that the condition range of successful bonding is not sensitive to the bonding force, whereas it is very sensitive to the ultrasonic power. At ultrasonic power lower than the appropriate range, the bonding fails due to insufficient interfacial adhesion. On the other hand, ultrasonic power higher than the range results in failure due to the fracture of the Cu ribbon. The other point is that considerably high ultrasonic power and bonding force are required to bond Cu ribbons with Ni/Cu substrates at room temperature, whereas they are significantly reduced to one-third of that required at room temperature by heating the specimens up to 423 K. It is also noted that the condition range for successful bonding is narrow at room temperature, whereas it is broadened by heating up to 423 K.

Fig. 2 shows a cross-sectional bond interface between a Cu ribbon and a Ni substrate bonded under the condition of 26.5 N, 30.0 W at room temperature. Both surfaces of the Cu ribbon and the Ni substrate were fresh. The bonding condition was selected

Fig. 1 Bondability of fresh-surfaced Cu ribbons and exposed Ni/Cu substrates for ultrasonic bonding at room temperature and at 423 K.

as the optimum for bonding at room temperature on the basis of the bondability shown in Fig. 1. The micrograph of the entire bond shown in Fig. 2(a) indicates that a wide area of 600 μm is adhered firmly. No included particles are observed at the interface even by high-magnification observation shown in Fig. 2(b). The interface appears flat.

However, the interfacial microstructure becomes different by exposing the Ni substrate to air for 864 ks after the acid cleaning. Fig. 3 shows an interface of a fresh-surfaced Cu ribbon and an exposed Ni substrate bonded under the same condition with that shown in Fig. 2. The entire bond shown in Fig. 3(a) indicates that the length of the bonded area becomes 348 μm , which is only a half of that formed with fresh surfaces. This result indicates that the bondability is deteriorated by exposing the Ni substrate to air for long time. The peripheral part of the bond interface appears wavy, as depicted in Fig. 3(b). The microstructure suggests that both Cu and Ni have deformed locally under a non-uniform and complicated stress during bonding. The microstructure is considered that it is in a preliminary stage of that observed at the

Fig. 2 Interfacial microstructure of a Cu ribbon and a Ni substrate bonded under the condition of 26.5 N, 75.0 kHz, 30.0 W, 500 ms at room temperature. Both surfaces of the Cu ribbon and the Ni substrate were fresh. (a) Appearance of the entire bond; (b) magnified central bond area marked in Fig. 2(a).

Fig. 3 Interfacial microstructure of a fresh-surfaced Cu ribbon and an exposed Ni substrate bonded under the condition of 26.5 N, 75.0 kHz, 30.0 W, 500 ms at room temperature. (a) Appearance of the entire bond; (b) magnified peripheral bond area marked in Fig. 3(a).

ultrasonic bonded interfaces between Cu ribbons and Sn-coated Cu plates³⁾. On the other hand, Cu and Ni are adhered intimately showing no inclusion between them.

Although the bondability of exposed surfaces of Ni show a distinct deterioration, it is better than that of exposed surfaces of Cu. The exposure of Cu ribbons to air for 864 ks makes all bonding conditions employed in the present study fail to bond even if the Ni substrates just after acid cleaning are used. Thus, the deterioration of bondability by exposure to air is more significant with Cu surface than that with Ni surface. Ni-coating of Cu surface is effective for suppressing the deterioration.

Fig. 4 shows an interface of a fresh-surfaced Cu ribbon and an exposed Ni/Cu substrate bonded under the condition of 12.0 N, 30.0 W at room temperature. This condition is near the minimum bonding force for ultrasonic bonding at room temperature as shown in Fig. 1. The entire bond interface shown in Fig. 4(a) reveals that the length of the bond area is 199 μm, being one-third of that formed with fresh surfaces at the optimum condition shown in Fig. 2. Although the bondability of Ni is deteriorated by

exposure to air for considerably long time, it is demonstrated that Cu/Ni substrates can still form bonds. The Ni layer at the interface appears in S-curved shape. The layer is bent toward the substrate in the left side of the bond area and toward the ribbon in the right side. In addition, the Ni layer in the left side is torn as shown in Fig. 4(b), where the Cu ribbon is directly bonded to the Cu substrate under the Ni layer. On the other hand, the layer is folded in the right side of the interface.

The torn Ni layer suggests that a considerable stress is applied to the layer during ultrasonic bonding. In electronics packaging, such a high stress is not preferred, since it will damage the device structure under the electrode pad. Therefore, it is required to

Fig. 4 Interfacial microstructure of a fresh-surfaced Cu ribbon and an exposed Ni/Cu substrate bonded under the condition of 12.0 N, 75.0 kHz, 30.0 W, 500 ms at room temperature. (a) Appearance of the entire bond; (b) and (c) magnified peripheral bond areas marked in Fig. 4(a).

Fig. 5 Interfacial microstructure of a fresh-surfaced Cu ribbon and an exposed Ni/Cu substrate bonded under the condition of 5.7 N, 75.0 kHz, 10.0 W, 500 ms at 423 K. (a) Appearance of the entire bond; (b) enlarged left-half bond area of (a); (c) further enlargement showing an interface between bonded and non-bonded areas.

reduce the stress by lowering the ultrasonic power. As shown in Fig. 1, it is effective to preheat the substrate and the ribbon to achieve bonding under low ultrasonic power.

Fig. 5 shows an interface of a fresh-surfaced Cu ribbon and an exposed Ni/Cu substrate bonded under the condition of 5.7 N, 10.0 W at 423 K. By heating up to 423 K, the ribbon and the substrate can be bonded under a low ultrasonic power of 10 W. The length of the bond area is 369 μm , as shown in Fig. 5(a). It is wider than that shown in Fig. 4, even though some parts in the bond area are found non-bonded, as marked in Fig. 5(b) and depicted in Fig. 5(c). However, the Ni layer shown in Fig. 5(a) is torn at three points, suggesting that the ultrasonic power of 10 W is still high for the damage suppression.

Although it will be possible to lower the ultrasonic power by raising the temperature further, it is not appropriate for electronics packaging. A hint to avoid tearing and folding of the Ni layer is seen in Fig. 2 in which the interface remains flat even though the ultrasonic power is high. However, the mechanism and criteria to retain the interface flat is still unclear.

4. Conclusions

Ultrasonic bonding of Cu ribbons to Ni-coated Cu substrates were carried out to investigate the bondability and the interfacial microstructure. The following points are made clear.

1. A considerably high ultrasonic power is required to bond Cu ribbons with Ni/Cu substrates at room temperature. However, the required ultrasonic power is significantly lowered by heating the specimens up to 423 K. Heating to 423 K also broadens the condition range of ultrasonic power and bonding force for successful bonding.
2. The condition range of successful bonding is not sensitive to the bonding force, whereas it is very sensitive to the ultrasonic power.
3. Bonding of fresh surfaces forms a wide and flat interface free of inclusions. Exposed surface of Cu makes failure of bonding at all conditions employed in the present study, whereas

exposed surface of Ni allows bonding. However, the Ni layer is deformed anomalously (i.e., torn and/or folded) at the periphery of the bond area.

4. Lowering of the ultrasonic power by bonding at 423 K is still insufficient for prevention of the anomalous deformation.

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