Interface Reaction between Solder and Plated Nickel Film

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Ni plating is widely used as the metallization for solder joints in semiconductor devices. However, reliability degradation occurs in the joint interface, because numerous voids are formed during soldering, which leads to heat loss at the solder joints. This paper describes the void formation mechanism and the reaction mechanism between Ni plating and solder. The defective area of an oxide film on plated Ni film can be broken by Sn and H₂ before the Ni surface is cleaned. Sn reacts with Ni, resulting in the formation of intermetallic compounds. Voids form in the areas where oxide film is remains. When joining plated Ni film and solder, it is necessary to remove the oxide film from the Ni surface in order to decrease the number of voids.

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1. Introduction

Ni plating is widely used as the metallization for solder joints in semiconductor devices because of its low cost and high corrosion resistance. An insulated gate bipolar transistor (IGBT) module is shown schematically in Fig. 1.¹⁻³⁾ In this figure, large-area Ni plated metal and AlN substrates are joined by using a Pb–Sn soldering process.

Since IGBT modules are used for traction motor drives, their long-term reliability must be guaranteed. However, reliability degradation occurs in an IGBT module when voids form in the solder joint during soldering. These voids cause heat loss at the solder joint in proportion to the area of voids. However, reducing the number of voids in large-area solder joints has so far proven to be very difficult.

As shown in Fig. 1, IGBT modules are composed of various materials, each with a different thermal expansion coefficient, thus thermal stress is generated at the solder joints. Thermal stress increases its magnitude depending on the heat loss. Therefore, it is important to clarify the mechanism which creates these voids in order to develop a void-free soldering process.

It has been reported that an oxide film forms on the surface of plated Ni film when it is exposed to air and this firm oxide film prevents molten solder from wetting.⁴⁾ Therefore, surface oxides have become the subject of our current research. First, we investigated the structure and thickness of oxide on the Ni plating. Then, we clarified the influence of the surface oxide on the void at the solder joint. And finally, the reaction mechanism between Ni plating and solder was studied.

2. Experiment Procedure

2.1 Solder joining

30 × 30 mm² Cu plates were electroplated with a Ni film, and then a 15 × 15 mm², 200 μm thick piece of Pb50 mass%–Sn solder was superimposed on the Ni plated Cu. Each of these specimens were heated to a peak temperature from 458

Fig. 1 A schematic representation of the IGBT module.

to 623 K in H₂ atmosphere. The holding time at peak temperature was 5 min for each specimen.

2.2 Evaluation

The thickness of the oxide film on the plated Ni film was evaluated by using secondary ion mass spectroscopy (SIMS). The structure of the oxide on the surface of the plated Ni film was measured by electron spectroscopy for chemical analysis (ESCA).

After soldering, an ultrasonic inspection (UT) device was used to measure the area percentage of voids (abbreviated as V.A. hereafter) formed during the soldering process. Then, the specimen was dipped into a mercury bath to remove the Pb–Sn solder by amalgamation. The surface was inspected with a scanning electron microscope (SEM) and compared with the results obtained from UT. Since the intermetallic compounds are stable in mercury, the voids were confirmed as those areas where compounds were not formed.

The composition of the intermetallic compound was determined with X-ray diffraction (XRD). Auger electron spectroscopy (AES) was also used to measure the depth profiles of the oxygen concentration for both the plated Ni film on which the void was formed and the intermetallic compounds.

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3. Results and Discussions

3.1 Investigation of surface oxide films on plated Ni films

Figure 2 shows SIMS depth profiles of oxygen on the sur-

Fig. 2 SIMS depth profiles of oxygen for three kinds of plated Ni films.

Fig. 3 The ESCA measurement of the oxide film on Ni film.

face of several plated Ni films. The ion intensity of samples (A), (B), and (C) decreased with etching time up to the points marked by an asterisk (*), after which it became almost constant. The etching times associated with these points correspond to the thickness of the oxide film. It was found that the thickness of the oxide films differed among the plated Ni films. Figure 3 shows the Ni 2P spectrum of the surface of plated Ni film by ESCA. Both NiO and Ni₂O₃ were formed on the plated Ni film.

3.2 The relationship between the thickness of the surface oxide film on a plated Ni film and the V.A.

Figure 4(a) shows UT of the joining interface after soldering. In this figure, the black areas are the penetration-type voids and the gray areas are the interfacial voids. Figure 4(b) shows a SEM image of the joining interface after removing the Pb-Sn solder by amalgamation. The voids shown by UT are virtually identical to the voids revealed by SEM. Therefore, it is possible to measure V.A. using UT.

Figure 5 shows the V.A. as a function of the thickness of the oxide film on the surface of a plated Ni film when joined

Fig. 5 The area percentage of voids as a function of the thickness of surface oxide films on plated Ni films.

Fig. 4 Voids at the solder joints. (a) ultrasonic inspection, (b) SEM image.

with 50Pb–50Sn solder at 503 K for 5 min in H_2 atmosphere. Here, the etching times correspond to the thickness of the oxide films as shown in Fig. 2. When the surface oxide film is thin, both the V.A. and the deviation are small. However, the V.A. and the deviation increase with the thickness of the oxide film.

3.3 Investigation of the joining interface

The relationship between the thickness of the oxide film on a plated Ni film and V.A. was described in the previous section. Next, we investigated the reaction process between the plated Ni film and the solder by changing the soldering temperature and the thickness of the surface oxides on plated Ni films.

3.3.1 V.A. as a function of soldering temperature, and the thickness of surface oxides of plated Ni film

Figure 6 shows the SEM images of the interface as a function of heating at temperatures from 458 to 623 K. The void

areas are very large and the size of the intermetallic compounds are very small for the samples with peak soldering temperatures of 458 and 473 K. This indicates a partial interaction between Ni and solder. At 503 K the void areas become small. However, the intermetallic compound sizes are also small. At higher temperatures (from 543 to 623 K), the compound size increases with the soldering temperature.

Figure 7 shows the XRD results for the intermetallic com-

Fig. 7 X-ray diffraction result of the intermetallic compound.

Fig. 6 SEM images of intermetallic compound on Ni film and voids as a function of heating temperature.

Fig. 8 AES line profiles of intermetallic compound on Ni film and surface of void area.

pounds formed on plated Ni films by soldering. The composition of the intermetallic compound was found to be Ni_3Sn_4 .

Figure 8 shows the oxygen concentration depth profiles for the void area surface and the intermetallic compound on plated Ni film with AES. Figure 8(a) shows that Ni and Sn both exist in the compound layer. Oxygen can not be detected from the interface between the Ni and Ni–Sn intermetallic

(a) Without Oxidation

(b) After Oxidation at 473K for 30min in air

Fig. 9 SEM images of the solder interface after removing the Pb–Sn solder.

Fig. 10 Graphic chart of the standard free energy of the reducing reaction toward NiO of Sn and H_2 .

compounds. However, Ni oxides can be detected in the area just below the void, as shown in Fig. 8(b). These results suggest that voids were formed on the surface oxides of plated Ni films.

3.3.2 The influence of the thickness of the surface oxide film on the reaction between solder and plated Ni film

Figures 9(a) and (b) show the joining interfaces of the same plated Ni film after the removal of the solder both before and after heating at 473 K for 0.5 h in air. It was originally joined with Pb–Sn solder at 473 K for 5 min in H_2 . In the case of the Ni plating without oxidation (Fig. 9(a)), a result similar to Fig. 6 (473 K) was obtained. While, the interface was quite different for Ni plating after oxidation (Fig. 9(b)). In Fig. 9(b), the point marked with an arrow shows Sn as a result of EDX analysis.

This result shows that Sn initially interacts with Ni in some areas before other and that their reaction rate is significantly lower without oxidation.

(a) Plane View

(b) cross-sectional

Fig. 11 The process of joining plated Ni film and solder.

3.4 The joining mechanism between solder and plated Ni film

It has been reported that defective areas form in the oxide film and the thickness of the defective areas is thinner in certain places.⁵⁾ Therefore, when solder joins with Ni plating, it begins at the defective area. Figure 10 is a graphic chart of the standard free energy of the reducing reaction toward NiO of Sn and H₂.⁶⁾ Sn has a stronger reducing power for NiO than H₂. Hence the influence of Sn is very strong in the reducing reaction of NiO during soldering.

We suggest the following mechanism for the joining process between the plated Ni film and the solder based on the above results. The process is shown schematically in Fig. 11. First, Sn and H₂ begin to reduce the oxide film on plated Ni film during heating. The defective areas in the oxide film are easily destroyed, and the Ni surface appears. Sn begins to react with Ni, and an intermetallic compound is formed at the interface. The area of the intermetallic compound layers spreads as temperatures increased and voids form in the areas where the oxide film remains.

4. Conclusion

When the oxide film is thin, the V.A. and deviation of the

V.A. are small. However, the V.A. and deviation increases with the thickness of the oxide film. Hence, the difference in the surface oxide film thickness is the key factor for the deviation of void areas.

The reaction mechanism between Ni plating and solder proceeds as follows. First, the defective area of the oxide film is broken by Sn and H₂, then the Ni surface is cleaned. Next, Sn reacts with Ni, and an intermetallic compound is formed. Finally, voids are formed on the areas where oxide films remain.

Thus, when joining a plated Ni film and solder, it is necessary to remove the oxide film on the plated Ni film surface before soldering.

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