Technology

NL1: Aluminum Bonding Wire with High Bondability and Corrosion Resistance

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Abstract

Aluminum bonding wire is conventionally used as an interconnect for power semiconductors as represented by the power module. In recent years, the application of aluminum wire to the lithium-ion battery module is also increasing due to the rapid proliferation of e-mobility such as electric vehicles. Our aluminum wire, NL1 is characterized by a large process window and high corrosion resistance, and suitable for both power semiconductors and battery connection. In this paper, we introduce our NL1 wire with the focus on its process window and corrosion resistance.

1. Introduction

Bonding wires are widely used as interconnecting materials to electrically connect the semiconductor devices of semiconductor packages with external terminals. As wire bonding enables highly flexible wiring and it is cost effective, the method has been used for more than fifty years as a main semiconductor package wiring method. Semiconductor packages involving wire bonding are expected to continue to increase in the future as well.[1] Although Au was exclusively used up to around 2010 as a bonding wire material for semiconductor packages, Nippon Micrometal Corporation developed Pd-coated Cu bonding wires (EX wires) before anyone else in the world. The rise of this material has changed the bonding wire market dramatically over the last ten years or so and the material has been steadily leading the way to the disuse of Au, which used to be considered impossible.[2]

Meanwhile, bonding wires are also used in the sector of power semiconductors, represented by power modules, in addition to the aforementioned semiconductor packages. Power semiconductor devices to be used to control and convert high voltage and large currents play an important role in reducing electric power loss. Accordingly, they are gaining attention as a key device in the approaching low-carbon society. As the bonding material, Al bonding wires are generally used. Because power semiconductors involve large currents, the diameters of wires for power semiconductors are 100 to 500 μm and thus much larger than the diameters of wires for semiconductor packages. In addition, as the bonding method of bonding wires for power semiconductors, ultrasonic wedge bonding is usually used; in this method, bonding is performed at room temperatures without forming free air balls. **Figure 1** illustrates a standard power semiconductor device.

The prices of Al wires are lower than those of other bonding wires manufactured from other materials and Al wires have excellent electrical and mechanical characteristics. Therefore, Al wires have been used as interconnecting materials for power semiconductor devices for an extended period of time. In recent years, there has also been growing demand for Al wires as bonding materials for lithium-ion battery modules. This is mainly because of the rapidly expanding E-mobility market including EVs in recent years. Lithium-ion batteries for EV battery modules are broadly divided into three types: Cylindrical, prismatic, and pouch types.[3] Among the three types, Al wires are increasingly being used as wiring materials for cylindrical-battery modules.[3–7] For battery modules, wires are used to connect the batteries and bus bars and also work as fuses in the case of abnormality (e.g., overcurrent).[7,8] **Figure 2** shows an example of the connection of battery cells by wire bonding.[9]

For battery modules, Ni is used for the outermost surface of bat-

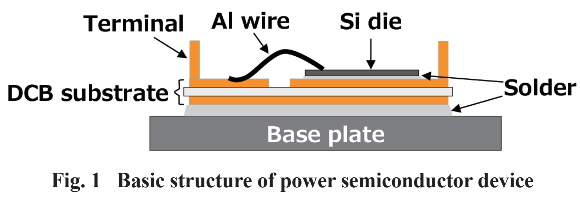

Fig. 1 Basic structure of power semiconductor device

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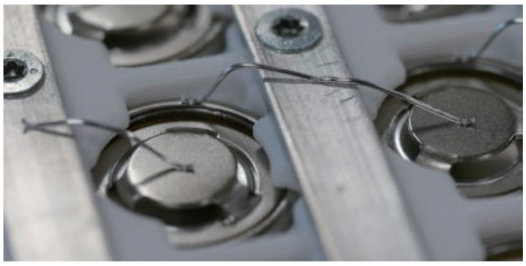

Fig. 2 Example of connection of battery cell using wire bonding

tery caps to which bonding wires are connected while Cu and Al are used as bus bars to which bonding wires are also connected.[3–5] Because the hardness of Ni and Cu is high and they are easily affected by oxidation, bonding wires to these materials is difficult compared to Al electrode pads, which are generally used in semiconductor devices. In addition, it has been reported that compared to semiconductor devices for which contamination is thoroughly managed in clean rooms, contaminants tend to remain on the surfaces of the battery caps and bus bars of battery modules.[7, 10, 11] Variation in the bond strength at sections at which wires are bonded and improper adhesion of bonds directly result in decrease of the productive capacity (e.g., yield rate). Accordingly, the bondability is a very important parameter in the selection of wires also for battery modules as is the case with semiconductor devices. In addition, battery modules are exposed to high-temperature and high-humidity environments in the air when they are actually used and thereby the corrosion resistance performance is also important when wires are selected.[7, 8]

Al bonding wire NL1 developed by Nippon Micrometal is a general-purpose wire characterized by having excellent bondability (large process window (range of operation conditions where bonding is possible)) and corrosion resistance. NL1 is suitable for both power semiconductors and battery modules. This report introduces NL1 focusing on the process window and corrosion resistance.

2. Evaluation of the Process Window

2.1 Evaluation procedure

We evaluated the process window in cooperation with an independent organization (Bond-IQ GmbH in Germany).[12] For the evaluation, in addition to an NL1 wire with a diameter of 300 μm, three types of Al wires having mechanical characteristics similar to those of NL1 were used as comparative materials. **Table 1** lists the breaking load (BL) and elongation (EL) of the wires. The three wires used for comparison are generally used in the market as bonding wires. As a wire bonder, Bondtec 5850 manufactured by F&S Bondtec was used and pure Cu plates (OF Cu: purity > 99.96%, thickness: 0.8 mm) without coating, etc., were used as base plates. Cu is generally used for bus bars in battery modules[3] and as a material of power semiconductors on the base plate side.[13, 14] To reduce variation in the surface properties between the base plates, the Cu plates were pickled before being subject to wire bonding so as to remove stains and oxide films on the surfaces. **Figure 3** is a photograph showing the Cu plate after wire bonding.

Table 1 Breaking load (BL) and elongation (EL) of tested wire

Wire	NL1	Wire A	Wire B	Wire C
BL (cN)	355.6	361.3	326.3	372.0
EL (%)	21.8	18.3	18.5	24.0

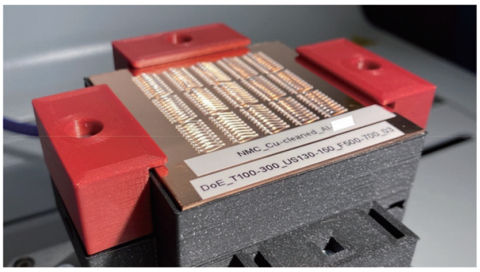

Fig. 3 Cu plate after wire bonding

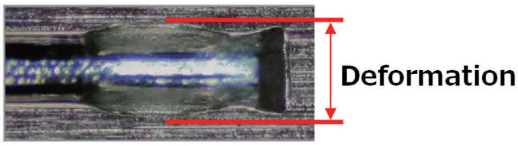

Fig. 4 Deformation width of wedge bond

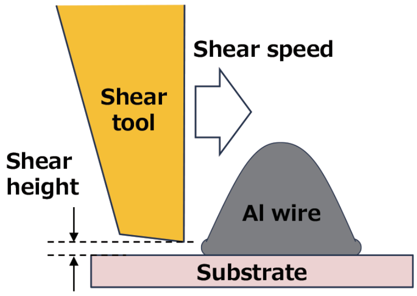

Fig. 5 Shear test condition
Shear speed = 300 μm/s. Shear height ≈ 30 μm (10% of wire diameter).

To evaluate the process window, the Box-Behnken design of DoE was adopted. Bonding was performed based on a matrix including three main parameters of force, ultrasonic power, and bond time. The deformation width (**Fig. 4**) at the bond and the shear strength were measured under each condition. In the shear test, a bond tester (Bondtec 5600) was used and as the conditions, the shear height was set to approximately 30 μm (10% of the wire diameter) and the shear speed was set to 300 μm/s (**Fig. 5**). Only the second bonds were used for the evaluation. Special software (Minitab) was used to measure the process window of each wire based on the obtained data on the deformation width and shear strength.

2.2 Definition of process window

The bondability of the Al wires was evaluated according to DVS-2811 determined by the German Welding Society.[15] The standards recommend that the average shear strength value when the wire diameter is 300 μm be larger than 950 cN and the minimum value be larger than 750 cN; that the deformation width be less than 1.6 times the wire diameter. On the contrary, in this test, to clarify the differences in the potential performance between the wires, the average shear strength value was determined to be larger than 1 250 cN and the minimum value was determined to be larger than 1 000 cN so as to exceed the values specified in DVS-2811. In addition, regarding the deformation width, considering the risk that excessive deformation may result in a decrease in the strength at the heel sections of bonds and the fact that bonding in a short time (small deformation width) would enhance the productivity, the deformation width was determined to be 1.3 times smaller than the wire diameter. This value is smaller than the value specified in DVS-2811. This evaluation adopted these harsher standards so as to compare the process windows between the wires.

2.3 Results

Figure 6 shows the evaluation results of the process windows of the wires. The figure shows the results when the load was fixed at 700 cN as an example. The horizontal axes in the graphs indicate the bond time (ms) and the vertical axes indicate the ultrasonic power (no unit). The red lines in the graphs indicate the boundaries on the right of which the shear strength is larger than 1 250 cN. The blue dotted lines indicate the boundaries on the left of which the deformation width is smaller than the value obtained by multiplying the wire diameter by 1.3. In other words, the white areas in the graphs are the process windows that satisfy the standards determined for this test: Shear strength larger than 1 250 cN and the deformation width smaller than the value obtained by multiplying the wire diameter by 1.3. The lines of 1 000 cN, which was the value determined as the minimum shear strength value, extend outside these graphs. Comparing the process windows of the four wires shows that the window of NL1 is the largest. Although wire C is in a rather inferior position compared to NL1, it has a relatively large window. The graphs show that the windows of wires A and B are significantly smaller than those of the other two types. These results indicate that NL1 can achieve a higher bond strength in weaker bonding conditions or shorter bond time compared to the other wires. NL1 is expected to exert its superiority also in environments where bond targets may get damaged (e.g., vulnerable semiconductor device structure), in addition to contributing to an increase of the productivity.

3. Corrosion Resistance Test

3.1 Evaluation procedure

The corrosion resistance of NL1 was evaluated in a pressure cooker test (PCT). For the evaluation, NL1 wires with a diameter of 300 μm were used as is the case with the process window test. For comparison, pure Al wires (purity ≥ 99.99%), which are generally used for power semiconductors, were used. The wires were exposed to an environment where the temperature was 121°C and the relative humidity was 100% for 20, 100, or 1 000 hours. Samples of the wires after the exposure for 20, 100, or 1 000 hours were subject to section processing using argon ion beams (Cross Section Polisher manufactured by JEOL). The cross sections of the wires were observed with an SEM (JSM-7800 manufactured by JEOL) to compare the progress of corrosion.

3.2 Results

Figure 7 shows the SEM images of the cross sections of the wires after the PCT. The image of the pure Al wire shows that the corrosion has advanced to several tens of μm deep from the surface along the grain boundary only after 20 hours. After 100 hours had passed, it was found that the corrosion had proceeded considerably and the wire had deformed and lost its original form. Accordingly, observing the sample tested for 1 000 hours was stopped. Meanwhile, the observation results of the cross sections of the NL1 greatly differed from those of the pure Al wires. No obvious corrosion had proceeded inside the NL1 samples tested for 20, 100, and even 1 000 hours and no remarkable changes were observed on the crystal structure. There results demonstrate that the corrosion resistance of NL1 is significantly higher than that of the pure Al wires.

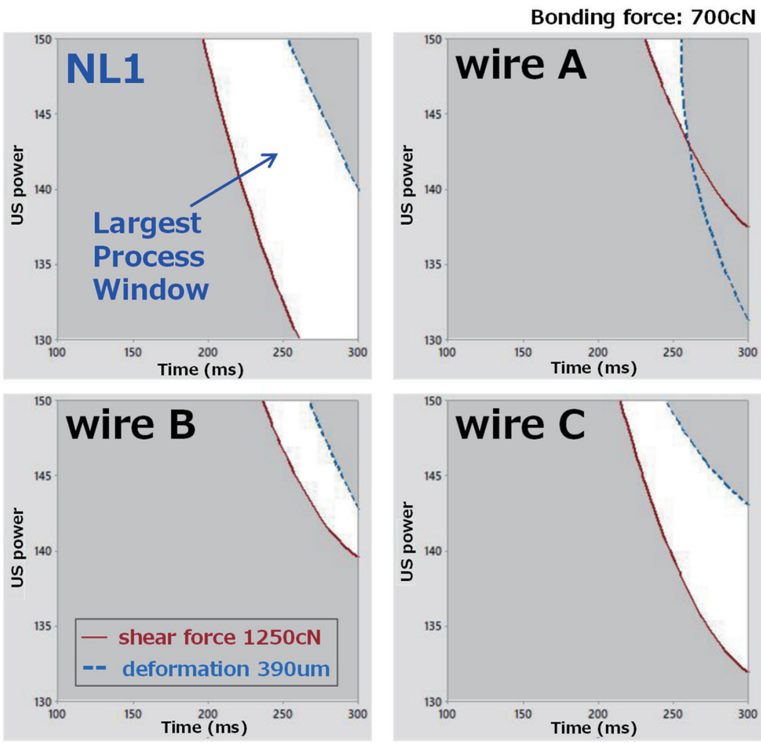

Fig. 6 Process window (white area) for each wire
Red line: shear force = 1 250 cN. Dashed blue line: deformation = 1.3 × wire diameter.

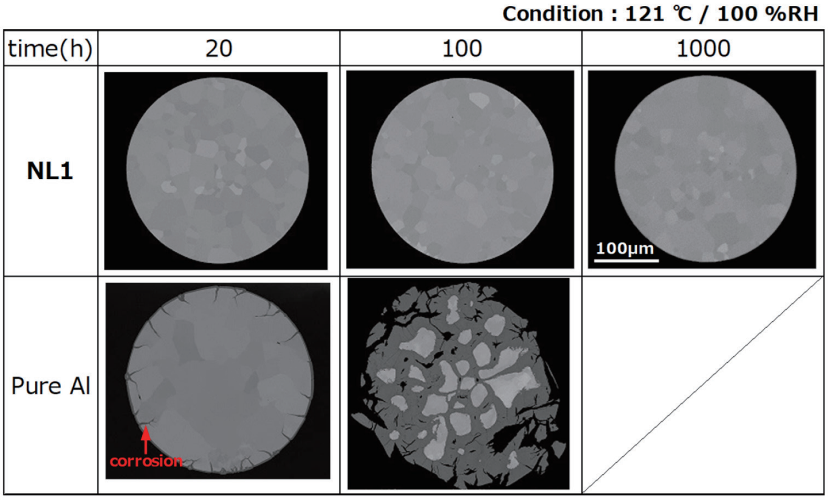

Fig. 7 SEM images of wire cross-section after pressure cooker test

4. Conclusion

This paper introduced our Al bonding wire NL1 that is suitable for both power semiconductors and battery modules. NL1 is a general-purpose bonding wire characterized by having a large process window and high corrosion resistance. NL1 can contribute to increasing the productivity thanks to its excellent bondability and can also contribute to extending the service life of devices thanks to the high corrosion resistance. NL1 is expected to be adopted in a wide range of applications in the future as well.

Nippon Micrometal has been developing various new materials that satisfy new needs in the power semiconductor market one after another, in addition to NL1. Examples of such materials are high-reliability Al alloy wire LX1 having high thermal fatigue resistance for SiC devices, soft Cu wire BX1V for power semiconductors for which there is an increasing demand as an alternative material for Al wires, and Cu bonding ribbons that have much larger current capacity compared to wires. Nippon Micrometal will continue to contribute to innovation toward the next-generation semiconductors through the development of new materials.

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