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Electrical Characteristics of Solder-Free SiC Die/Metal Foil/AlN Plate Junctions Fabricated Using Surface Activated Bonding

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SiC die/Al foil/AlN junctions are successfully fabricated by using surface activated bonding, i.e., without using solders. No structural defects are observed in Al/AlN interfaces. We measure current-voltage characteristics of Schottky diodes, which are fabricated on the SiC die before bonding, by applying bias voltages between Schottky contacts and the surface of Al foil that is connected to ohmic contacts. Schottky diodes normally operate at junction temperatures up to 300 °C. No change is observed in appearance of the SiC die/Al foil/AlN junction even after the measurement at 300 °C. Parasitic resistances get larger after the measurement at 300 °C, which is assumed to be due to the possible oxidation of surfaces of Al foil.

Introduction

Power electronics modules operating at high temperatures have been required in a variety of industrial applications such as automotive, aircraft, and resource exploration (1, 2). Widegap semiconductors such as SiC, GaN, and diamonds are likely to play a crucial role in realizing semiconductor devices for such applications because of their more excellent tolerance against high temperature environments in comparison with Si (3). Electron devices made of 4H-SiC have been eagerly developed and are going to be deployed into markets.

The maximum temperature of normal operation of modules is limited by the characteristics of packaging materials as well as those of semiconductor devices. As for solders that attach semiconductor dies, their melting temperature must be higher than the operating temperature of devices, which is ≈ 300 °C for SiC-based power devices (3). One approach for fulfilling this requirement is to use soldering materials with high melting temperatures such as Au/Ge (3). Usage of such solders might cause damage to dies during attaching since the processing temperatures are high. In another approach, the Ag paste that has been prepared by mixing Ag particles with organic binders has been used as die attach material (1, 2). The processing temperature can be lowered while the maximum temperature is retained by reducing the size of Ag particles. It is pointed out, however, that the uniformity in coverage of the paste might cause an issue for a large die area. Process without using solders or any other intermediate materials based on low-temperature direct bonding technologies should be explored so as to attach dies with low processing temperatures and high thermal tolerance in operation.

Joints of single crystals of metals (4) and those of deposited metal films (5) were made by low-temperature bonding after activating their surfaces, i.e., by employing surface activated bonding (SAB) technologies. We fabricated ultra-thick Schottky contacts (6) and low-loss coplanar waveguide circuits (7) by bonding several-ten-μm thick Al foils to SiC epi layers and sapphire substrates, respectively. In this work, we fabricated a ceramic plate/metal/ceramic plate junction and a SiC die/metal/ceramic plate junction using SAB. Note that intermediate solders were not used. As ceramics AlN was used since the coefficient of thermal expansion of AlN (4.6 ppm/K) (8) is close to that of SiC (5.12 ppm/K) (3) and the thermal conductivity of AlN (150 W/m·K) is higher than that of conventionally used ceramic materials such as SiN (54 W/m·K). An Al foil was used as metal layer. We examined the cross section of an AlN/Al/AlN junction and measured the current-voltage (I-V) characteristics of Schottky diodes fabricated on a SiC die/Al/AlN junction. It is noteworthy that the coefficient of thermal expansion of Al (23-26 ppm/K) (9) is largely different from those of AlN and SiC. Consequently, bonding interfaces might not withstand the thermal stress when the junction temperature is raised beyond the bonding temperature. The stability of junctions against such thermal stress was preliminarily discussed.

Experimental

A 635-μm-thick AlN ceramic plate and a 30-μm-thick rolled Al foil were used in this work. The surfaces of AlN plate and Al foil were observed using a scanning electron microscope (SEM). Both of mirror and matte surfaces of Al foil were also characterized using a laser microscope.

We prepared a SiC epi substrate by growing a 0.5-μm-thick n^+-SiC buffer layer and a 10-μm-thick n^--SiC epitaxial layer on an n^+-4H-SiC (0001) substrate. The nominal concentration of donors was 1×10^{18} and 5.4×10^{15} cm^{-3} for the buffer and epitaxial layers, respectively. We formed an ohmic contact on the backside of the epi substrate by evaporating an Al/Ni/Au multilayer and annealing at 1000 °C for 5 min. in a nitrogen ambient. Then we formed Ni/Au Schottky contacts with different diameters between 200 and 400 μm on the surface of the epi layer by evaporation and lift-off. An additional Al layer was evaporated on the backside after forming Schottky contacts so that 16 diodes were fabricated. No advanced structures for achieving better diode characteristics, such as surface passivation and guard ring (10), were not incorporated.

We bonded each surface of an Al foil to an AlN plate at 200 °C and fabricated an AlN/Al/AlN junction. We examined the structure of bonding interface by using SEM. For fabricating a SiC die/Al/AlN junction, we first bonded a matte surface of an Al foil to an AlN plate using a process similar to that applied for fabricating the AlN/Al/AlN junction. The SiC die was subsequently bonded to the exposed mirror surface of Al foil. The entire process flow for fabricating the SiC die/Al/AlN junction is schematically shown in Fig. 1. Note that the bonding between SiC die and Al foil was composed of a metal/metal (Al/Al) joint.

We measured I-V characteristics of SiC diodes by applying bias voltages between their Schottky contacts and the surface of Al foil. After measurements at room temperature, I-V characteristics of a diode with a 400-μm-ϕ Schottky contact were measured while the die was heated. All the measurements were performed using probes for the SiC die placed on a heating stage in the air. The highest temperature, which was limited by the specification of measurement facilities, was 300 °C. We extracted a parasitic series resistance of each I-

V curve and investigated the relationship between the parasitic resistance and die temperature.

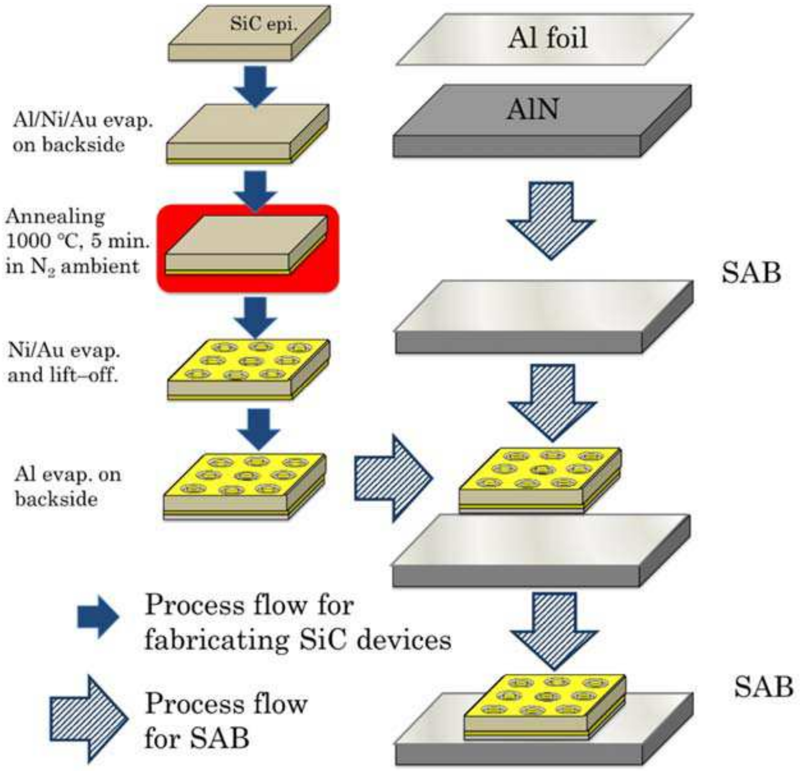

Figure 1. Process flow for fabricating a SiC die/Al/AlN junction.

Results and Discussion

AlN/Al/AlN junction

An SEM image of surface of an AlN plate is shown in Fig. 2(a), which indicated that the plate was composed of AlN grains. Their size, 1 or 2 µm, gave a measure for the roughness of AlN surface. SEM images of mirror and matte surfaces of an Al foil are shown in Figs. 2(b) and 2(c), respectively. Streaks are observed on both surfaces. The average roughness was found to be 0.06 and 0.19 µm for the mirror and matte surfaces, respectively, by characterization using a laser microscope.

An SEM image of the cross section of AlN/Al/AlN junction is shown in Fig. 2(d). As is shown in this figure, no structural defects were formed at AlN plate/Al foil interfaces, although the roughness of both surfaces was much larger than 1 nm, or an empirical measure of permissible roughness for successful bonding. The bonding strength of AlN/Al foil junctions, which is one of the important parameters from the practical viewpoints, is under investigation.

I-V Characteristics of SiC Schottky Diodes

I-V characteristics of all Schottky diodes on the SiC die at room temperature are shown in Fig. 3(a). The ideality factor of all diodes was found to be ≈ 1.05-1.07 by analyzing I-V characteristics for a current between 10^{-6} and 10^{-2} A/cm^2. As was typically found for the ideality factor, the I-V curves of diodes were close to one another, which demonstrated the uniformity of diode characteristics.

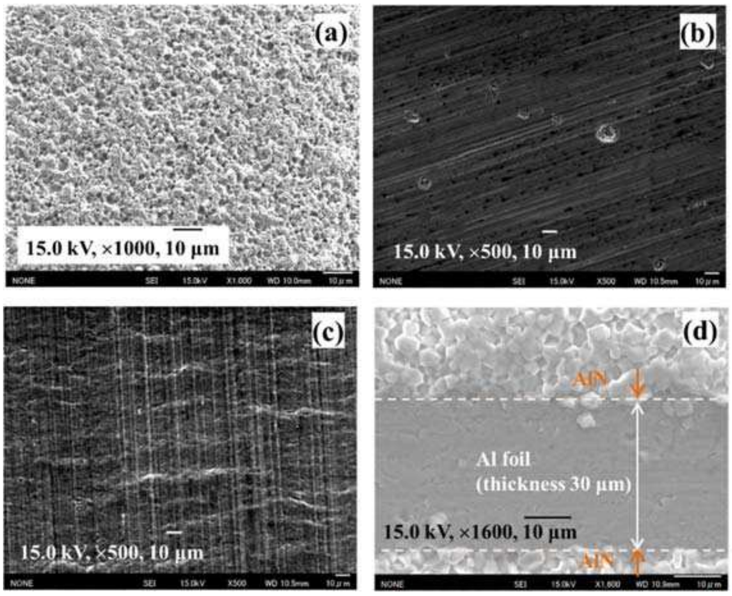

Figure 2. SEM images of (a) a surface of AlN plate, (b) a mirror surface of Al foil, (c) a matte surface of Al foil, and (d) a cross section of AlN/Al foil/AlN junction.

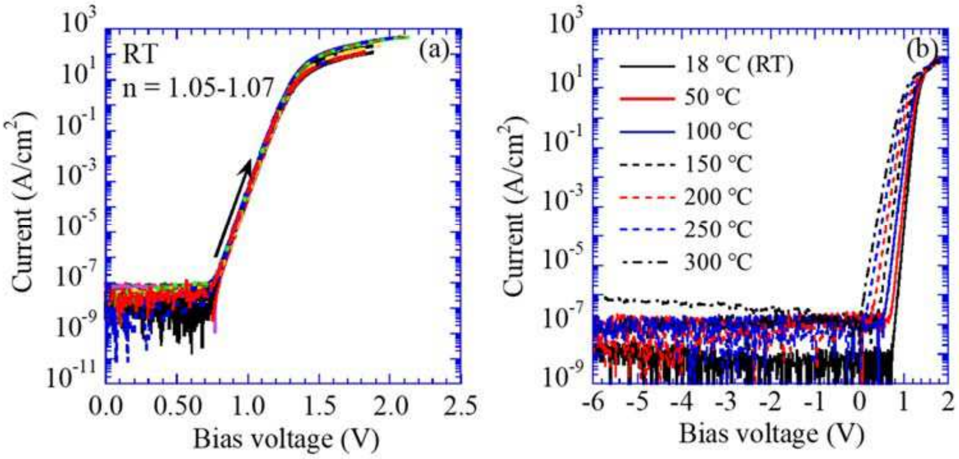

Figure 3. Current-voltage characteristics of (a) 16 Schottky diodes on a SiC die attached on Al foil/AlN junction using SAB, and (b) a heated diode with a 400-μm-ϕ Schottky contact.

I-V characteristics measured for a heated diode are shown in Fig. 3(b). A reverse current was ~10^{-7} A/cm^2 at a reverse-bias voltage up to 6 V for temperatures lower than

250 °C. A larger reverse-bias current (~10^{-6} A/cm^2) was observed in measurement at 300 °C. In the forward characteristics, lower turn-on voltages were observed for higher temperatures. The ideality factor was ≈ 1.07-1.13 irrespective of the temperature. It is notable that these features are typically observed for Schottky diodes. In addition, no change was observed in appearance of the SiC die/Al foil/AlN junction even after the measurement at 300 °C.

Estimation of Parasitic Resistance

The I-V characteristics of Schottky diodes under forward biases are approximately expressed as

$$I(V) = I_0\{\exp[q(V-I*R_p)/(nk_BT)]-1\} \approx I_0\exp[q(V-I*R_p)/(nk_BT)] \text{ for } I >> I_0, \qquad [1]$$

where q, k_B, and T are the elementary charge, Boltzmann's constant, and the junction temperature, respectively. I_0, R_p, and n stand for the saturation current, parasitic series resistance, and the ideality factor, respectively. Using this equation, we obtain

$$I*dV/dI \approx nk_BT/q + I*R_p \quad \text{for } I >> I_0. \qquad [2]$$

We extracted relationships between I and I*dV/dI from the experimentally obtained I-V curves. The relationships for forward biases at respective junction temperatures are shown in Fig. 4(a). We find that I*dV/dI almost linearly depends on I, which is in accordance with eq. [2]. Using this equation, we estimated R_p from the slope of relationship for I between 20 and 60 A/cm^2. Obtained R_p values are shown in Fig. 4(b). R_p increases from 2.7 to 6.5 Ω, or from 3.4×10^{-3} to 6.5×10^{-3} Ωcm^2 per unit area of Schottky contacts, as the junction temperature increases to 300 °C. I-V characteristics at room temperature was measured after measurements at 300 °C. Extracted R_p is also shown in Fig. 4(b). We find that R_p at room temperature after the 300-°C measurement, 4.7 Ω (5.9×10^{-3} Ωcm^2 per unit area of Schottky contacts), is larger than that its initial value (2.7 Ω, as mentioned above). A similar change in R_p was also observed for other diodes on the same SiC die.

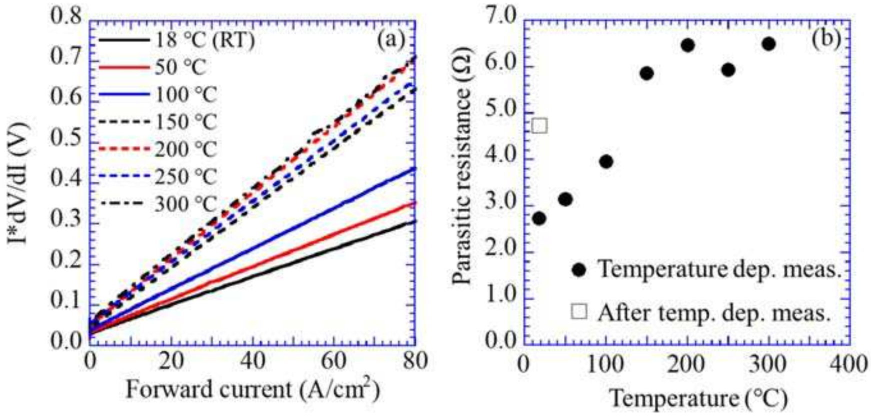

Figure 4. (a) A relationship between a forward current and a voltage drop due to parasitic resistance for a heated Schottky diode with a 400-μm-ϕ Schottky contact. (b) Dependency of parasitic resistance on junction temperature.

The larger R_p values observed for higher junction temperatures might be due to the increase of contact resistance. The difference in R_p between before and after the 300-°C measurement is assumed to be attributable to the possible oxidation on the surface of Al foil due to the heating in the air.

Conclusion

Using surface activated bonding technologies we fabricated AlN/Al foil/AlN and SiC die/Al foil/AlN junctions without intermediate solder layers. Schottky diodes were fabricated on the SiC die before bonding. We observed Al foil/AlN junctions using a scanning electron microscope and found that interfaces with no structural defects were obtained. We measured current-voltage characteristics of Schottky diodes on the SiC die by applying bias voltages between Ni/Au Schottky contacts formed on the top and the surface of Al foil that was bonded to the ohmic contact on the backside of die. The diodes showed normal performances even when they were heated up to 300 °C. In addition, no change was observed in the appearance of SiC die/Al foil/AlN junction after measurements at 300 °C. A slight increase in the parasitic resistance observed after measurements at 300 °C was assumed to be attributable to a possible oxidation on the surface of Al foil.

Acknowledgments

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