Development of Package Structure for High-Temperature Operation

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1. Introduction

In recent years, power electronics that efficiently convert electric energy have been applied to an increasing number of sectors such as the consumer electronics, industrial, electric railway, automobile, PV power generation, and wind power generation sectors, aiming at environmental protection and an energy-saving society. Among such power electronics devices, power modules work an important role of controlling electric currents. Therefore, power loss during operation and the package size need to be reduced while achieving high power density. Accordingly, silicon carbide (SiC) is expected to be used for next-generation power devices. SiC devices can operate faster than conventional silicon (Si) devices and their power loss is smaller, so the properties of power modules can be remarkably improved. In addition, SiC devices can operate at high temperatures, so reducing the package size can reduce the size of the power modules and the units on which they are mounted.[1)]

We improved the heat resistance of various parts (e.g., bonding and sealing agents) and developed new processes in the course of developing the packages, which improved the reliability of bonding when applying high temperature cycling, in particular, and extended the bonding lifetime. These improvements have realized high-quality, highly reliable packages. We have used such technologies to develop high-temperature operation packages for which the chips' operation temperature (Tjop) is 175°C or higher.

2. Structure of High-Temperature Operation Packages

Figure 1 shows the main structure (diagram) of the newly developed power module. As the structure of the new package type that is expected to operate at high temperatures (175°C or higher), a heat-resistant substrate is bonded to the surface of a baseplate with heat-resistant solder. A chip is bonded to the surface of the heat-resistant substrate using Ag sintering. An electrode on top of the chip is connected to the pattern on the substrate with a wire (e.g., Al). Another electrode, which provides electric connection to the outside, is connected to the pattern on the heat-resistant substrate by ultrasonic (US) bonding. A case is fitted to the baseplate. The inside of the case is filled with a heat-resistant sealing material.[2)]

The Ag sinter bonding, heat-resistant substrate, heat-resistant solder material, and US bonding technology for electrodes as elemental technologies for packages that enable high-temperature operation are introduced next.

3. Elemental Technologies for Packages

3.1 Ag sinter bonding technology

Assuming that the chips will be operating at high temperatures, there is a limit due to the properties of the soldering material used as bonding under the chips. Therefore, a new bonding material and process for such material are required. We developed a sinter bonding

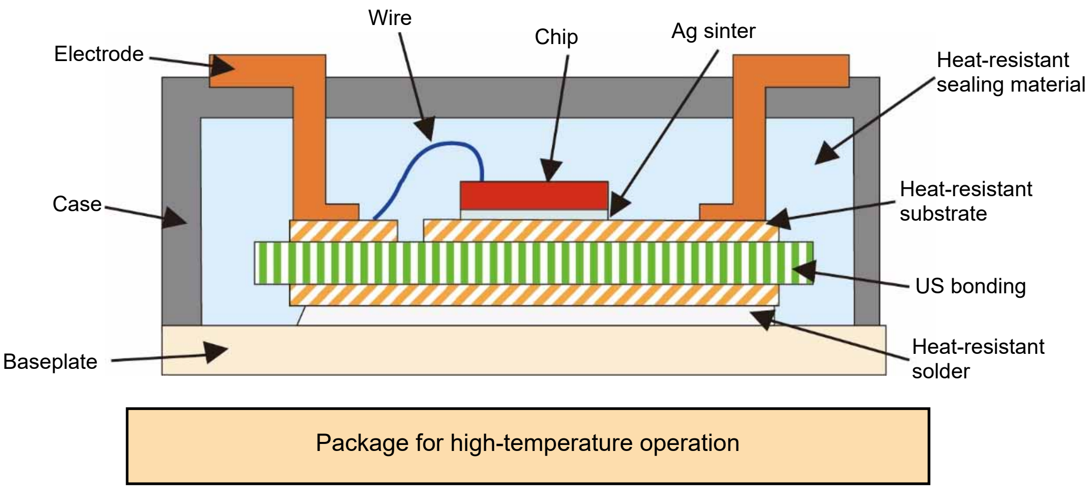

Fig. 1 Main structure of new package

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process using Ag particles, which ensures excellent heat resistance and high quality.[3] In the Ag sinter bonding process, multiple chips can be mounted and can be bonded at once. Therefore, the chips for the new package type can be made smaller than those of the conventional package type. We considered increasing the density in the arrangement of 4×3 chips by batch bonding. Figure 2 shows a scanning acoustic tomography (SAT) image after batch bonding by Ag sintering. Figure 3 shows the cross section of the bonding. The SAT image and the cross section show no voids or cracks at the bonding, so the bonding condition is good. As a result, for the new package type, the density of chips is increased by Ag sintering and the quality of bonding is high.

3.2 Heat-resistant substrates

Previously, aluminum nitride (AlN) ceramic was used for our substrates. We considered heat-resistant substrates to which silicon nitride (Si_3N_4) ceramic was applied as a new material. A thermal cycle test was carried out to evaluate the heat resistance. In the test, the temperature of AlN and Si_3N_4 substrates was changed from −40°C to 175°C (⊿T = 215 K) to see how cracks would progress at the ceramic sections and joints with the patterns on the substrates. As shown in Fig. 4, a crack progress to the ceramic section of the AlN substrate, but no cracks appeared on the Si_3N_4 substrate even after 600 cycles, so Si_3N_4 substrates have high reliability and excellent heat resistance.

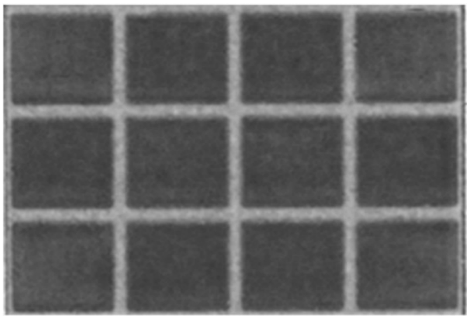


Fig. 2 SAT image of batch bonding using Ag sintering

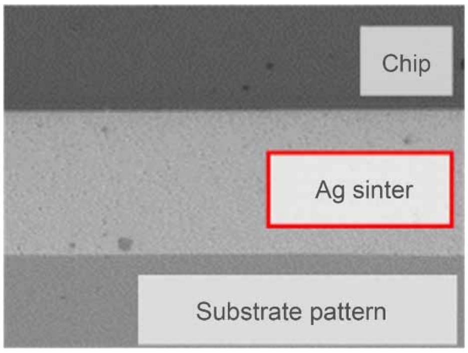
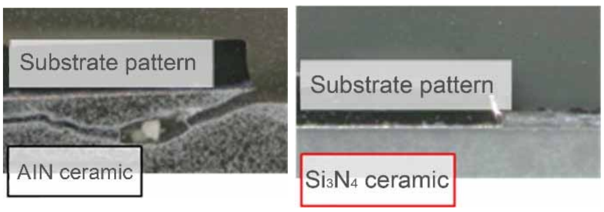


Fig. 3 Cross section of Ag sintering layer



(a) AlN substrate (b) Si_3N_4 substrate

Fig. 4 Cross section of substrate after temperature cycling test

3.3 Heat-resistant soldering material

The soldering material used to bond a substrate to a baseplate should remain free of cracks at the joint in order to continue dissipating the heat generated by the chip to the baseplate. Therefore, we considered using a highly durable and heat-resistant RoHS soldering material. Table 1 lists the basic elements of such heat-resistant solder. Multiple elements were added to the solder depending on the mechanical properties of substrates and baseplates to be bonded in order to extend the bonding lifetime. The selected soldering material was used to bond the Si_3N_4 substrate and baseplate mentioned in Section 3.2. A thermal cycle test in which the temperature was changed from −40°C to 175°C (⊿T = 215 K) was carried out to see if a crack would form at the solder joint. As a result, no cracks appeared at the joint after 600 cycles, which shows that the material can be used as heat-resistant solder (Fig. 5).

Table 1 Main materials of heat-resistant solder and their effects

Material	Melting temperature	Effect
Sn	231.9°C	-
Sb	630.5°C	Improved mechanical strength
Cu	1083.0°C	Improved creep property

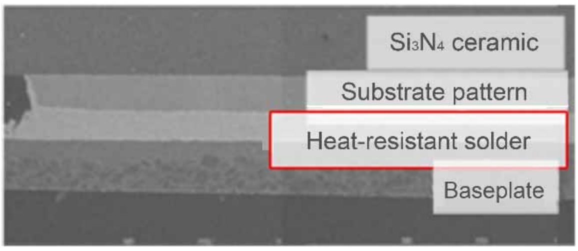


Fig. 5 Cross section of solder junction layer after thermal cycle test

3.4 US bonding technology for electrodes

In the past, the electrode used for electric connection with the outside was bonded with solder to the pattern on a heat-resistant substrate for energization. However, as the power density increases, heat generated due to the electrode's resistance also increases and so the temperature at the joint between the electrode and the pattern on the substrate increases. Therefore, the bonding lifetime at high-temperature cycles needs to be secured. We started using an ultrasonic (US) bonding technology to bond the electrodes and the substrate patterns to extend the bonding lifetime. Wiring by US bonding has eliminated the solder that existed between the electrodes and substrate patterns in the previous bonding; directly bonding the electrode and pattern can enhance the bonding strength. It has been confirmed that the bonding lifetime of the electrode and substrate can be extended for high-temperature cycling.

4. Conclusion

We have been developing elemental technologies for packages to allow high-temperature operation of power modules. Table 2 lists the new technologies introduced in the new package type to enable high-temperature operation. This paper described the technologies related to Ag sinter bonding, heat-resistant substrates, heat-resistant soldering material, and US bonding of electrodes. We believe that designing innovative packages and developing materials and production processes are important to commercialize power modules that operate at high temperatures in addition to the technologies introduced in the present report.

Table 2 Difference between new package and conventional one

Component	Conventional package	New package
Chip DB	Solder	Ag sinter
Substrate	AlN ceramic	Si_3N_4 ceramic
Substrate DB	Solder with Pb	Heat-resistant solder
Electrode-Substrate bonding	Solder	US (Ultrasonic)
Seal[3)	Conventional material	Heat-resistant material

Note: DB is die bonding.

To contribute to energy conservation and environmental protection, we will accelerate the development of next-generation high-quality power modules that operate at high temperatures and continue working to commercialize such modules based on our elemental technologies and mass production technologies for power module packages.

5. References

(1) Gourab Majumdar, et al.: New Technical Trend of Power Modules, Mitsubishi Denki Giho, 86, No. 5, 262–266 (2012)

(2) Hasegawa S., et al.: 1.7kV Hybrid SiC Power Module with Large Current Capacity, Mitsubishi Denki Giho, 86, No. 5, 287–290 (2012)

(3) Hino Y., et al.: Packaging Technologies for High Temperature Power Modules, Mitsubishi Denki Giho, 88, No. 5, 313–316 (2014)