Plated Chip for Hybrid Vehicles

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1. Introduction

The automotive industry is implementing various efforts to reduce carbon dioxide emissions in order to help preventing global warming. As a result of the sudden rise in crude oil prices and the like, hybrid vehicles that use both a gasoline engine and an electric motor are becoming more popular in Japan and the USA. Systems having higher output power and a smaller size are needed to further popularize these hybrid vehicles.

Leveraging Fuji Electric's experience obtained with industrial-use IGBT (insulated gate bipolar transistor) modules, in May 2006, we realized an IGBT-IPM (intelligent power module) product which provides the guaranteed high reliability necessary for auto applications, and since then have supplied IGBT-IPMs for use in the boost converters of the LEXUS*1 GS450h and the like. Then we commercialized a power chip product for the PCU (power control unit) that is installed in the LEXUS LS600h and LEXUS LS600hL hybrid vehicles which came to market in May 2007.

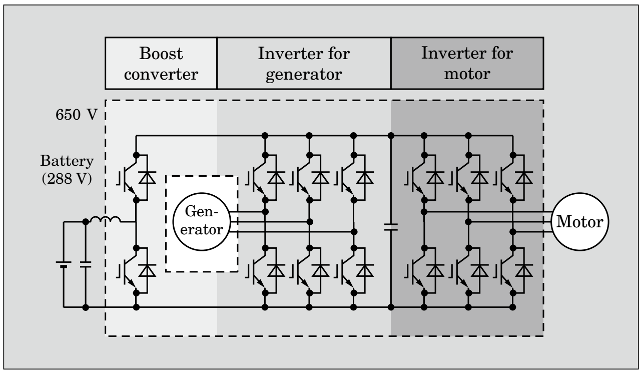
This paper describes, as IGBT chip technology for realizing the above products, a plated electrode structure for chips suitable for high current density and double-sided cooling, and Fuji Electric's efforts to increase the reliability of those chips.

2. Challenges

Toyota Motor Corporation's Hybrid System II (THS-II) is characterized by the combination of an inverter that controls two motors (a motor and a generator) and a converter that boosts the battery voltage, so that higher motor output can be realized without using a high-voltage battery. The THS-II circuitry, as shown in Fig. 1, is configured from 14 arms of semiconductor switches. The number of power chips arranged in parallel will differ according to the individual output capacities of the motor, generator and boost converter, but many power chips are used in the PCU system overall.

∗1: LEXUS is a registered trademark of Toyota Motor Corporation.

Fig.1 THS-II circuit diagram



However, with this type of conventional module structure in which many power chips are arranged in a planar state, the PCU will have a large footprint, and the requirement for smaller size cannot be satisfied. Thus, it is important to reduce the number of power chips, and challenges for achieving this goal include developing a power chip capable of withstanding a high current density and achieving a significant improvement in heat dissipation performance.

3. Development Overview

The IGBT chip used in the LEXUS LS600h and LEXUS LS600hL applies the technology of an industrial-use 1,200 V FS (field stop) type trench gate IGBT(1) that Fuji Electric has been mass-producing since 2002. This IGBT has a structure that reduces the on-state dissipation and switching dissipation during power conversion, and an improved unit cell design for automotive-use so as to increase current density.

An aluminum layer is typically formed on the chip surface, and in the case of double-sided cooling, soldering is also required on the surface side. This is made possible by a Ni film which is formed by plating technology on the upper surface of an aluminum electrode.

Moreover, to guarantee the high reliability necessary for automotive applications, we improved the processing before and after the gate oxidation process, and to improve the sensing technology we enhanced the accuracy of the temperature sensing element and current sensing element in the IGBT chip and developed a control IC.

4. Features

4.1 Improved chip characteristics

The IGBT chip is a voltage-driven switching semiconductor equipped with a MOS (metal-oxide-semiconductor) gate on its surface, and having voltage and current ratings higher than those of a bipolar transistor, exhibits highest performance as a 600 V or above high-voltage device. This device operates by repeating two states at high frequency, an ON mode that passes electric current and an OFF mode that maintains the voltage without passing electric current. The device was designed by improving the tradeoff relation between the different optimal structures for each of the variant operating states.

The FS-IGBT utilized herein employs a structure that achieves 1,200 V withstand voltage capability in an 140 µm thin chip, has a trench gate surface cell configuration, and maximally increases on-state characteristics to exhibit excellent performance. Figure 2 shows the unit cell cross-section of Fuji Electric's 1,200 V-IGBT.

The FS-IGBT requires a high level of manufacturing technology for grinding the semiconductor wafer thinly with high accuracy and for forming a diffusion layer on the wafer surface, and Fuji Electric, which has been involved in the development of thin wafer processing techniques from early on, is presently mass-producing wafer processed products with a 100 µm thickness.

Furthermore, with a total channel width increased to 1.5 times that of Fuji's prior chip, a reduction in saturation voltage and higher current density have been realized as shown in the I-V characteristic of Fig. 3. Moreover, a drive IC for sensing abnormal conditions in the FS-IGBT output and operating at high speed to protect the chip has been developed as a companion to the FS-IGBT, and enables the practical utilization of a system that employs this high current density device.

Reliability testing verified that, under the severe conditions required for automotive applications, there is no change in device characteristics for these devices having higher current densities than in the past.

4.2 Plating technology

Even if a power device is able to operate with a high current density, cooling technology is also needed in order to use the device at its guaranteed operating temperature of $T_j = 150\,°C$ or less. In the past, aluminum film was usually formed on the surface of the IGBT and diode chip in order to bond an aluminum wire, and in such a case, cooling could only be implemented from the rear surface of the chip. Double-sided cooling requires a structure that can also be soldering on its surface side. Moreover, by providing a cooling structure on the chip surface, an abnormal increase in device surface temperature due to a short-circuit can be suppressed, and as a result, reliability is increased.

Fig.2 IGBT unit cell cross-section

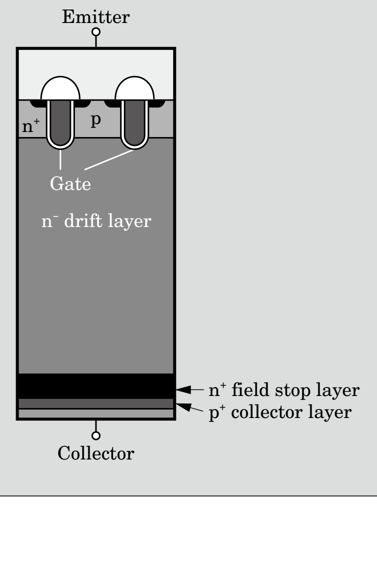


Fig.3 Comparison of IGBT output characteristics

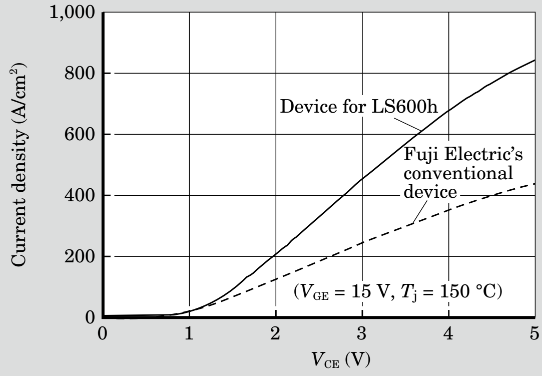


Fig.4 Comparison of cooling structures

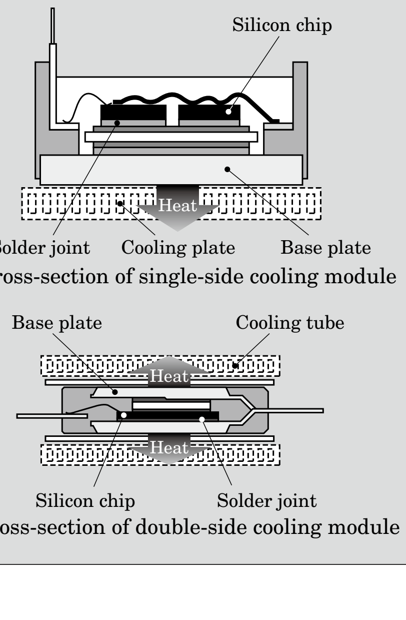


Fig.5 Chip comparison

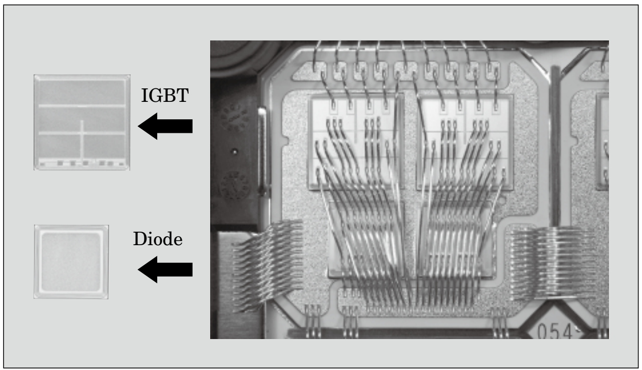
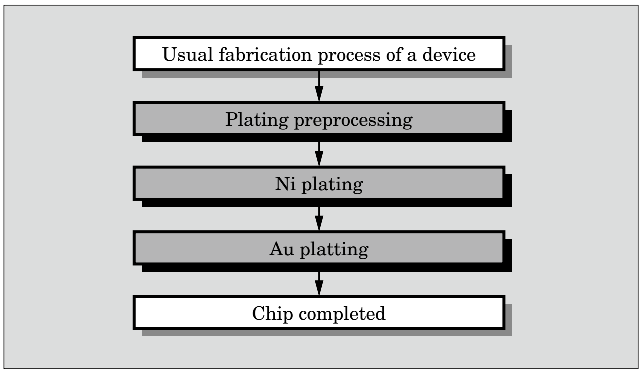


Fig.6 Process flowchart including the plating process



This technique is also an effective means for shrinking the chip size(2). Figure 4 shows a conventional module structure, and the internal structure of a double-sided cooling module made by Denso and for which IGBT and diode chip double-sided cooling is possible.

To enable the realization of this device, Ni film was plated over an aluminum electrode and Au film was plated on the surface to prevent oxidation. Figure 5 compares photographs of each chip. On the right side are an IGBT and a FWD chip in which wires have been attached to a conventional aluminum electrode, and on the left side is a chip whose surface has been plated with Ni and Au film.

The process flow of the plating process is shown in Fig. 6. After a device has been fabricated as usual, Ni plating and then Au plating are implemented consecutively to complete the chip.

The advantage of the plating method is that electrodes can be selectively attached only at locations where surface electrodes are exposed, differing for example from a method such as sputtering in which an electrode is attached to the entire surface, and hot etching and other processes can be eliminated. The technical challenges include preventing the plating material from wrapping around to the wafer rear surface and applying a plating film of uniform thickness to a wafer that may be warped due its thinness. Fuji Electric and Denso Corporation jointly developed technology to overcome these challenges and successfully commercialized the device.

4.3 Higher reliability

In contrast to industrial applications, since automotive applications have large load fluctuations and temperature fluctuations, and field accidents affect the human life, extremely high reliability and durability are required. In particular, the design and evaluation of this new device placed emphasis on the reliability of the gate oxidation film and the fluctuation of withstand voltage due to high temperature operation, which are important factors for IGBT chips. As a result, due to the improved processing before and after formation of the gate oxidation film and the reconsideration of the dimensions of the edge terminal structure, sufficient reliability for automotive applications was ensured.

Moreover, IGBT chips have been damaged when the temperature and current become excessive, and in order to utilize the maximum extent of the chip performance, protection techniques to prevent damage from occurring are important. Thus, a function for outputting the temperature and current is built into the IGBT chip, and measures were implemented to reduce the variances thereof. As a result, an abnormal state outputted from each sensing element can be sensed and protective measures implemented rapidly.

5. Postscript

A power semiconductor for use in the PCUs of hybrid vehicles has been developed. Aiming for the further popularization of hybrid vehicles in the future, efforts to reduce the costs of power semiconductors, batteries and motors will become increasingly important. Fuji Electric will continue to improve silicon devices, to develop devices that use new materials, and to contribute to the preservation of the global environment.

References

(1) Laska, T. et al. The Field Stop IGBT (FS IGBT) A new power device concept with a great improvement potential. Proc. 12th ISPSD. 2000, p.355-358.

(2) Otsuki, M. et al. Advanced thin wafer IGBTs with new thermal management solution. Proc. 15th ISPSD. 2003, p.144-147.

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