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Review article

High-temperature electro-ceramics and their application to SiC power modules

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ABSTRACT

This paper presents the research achievement in Japan to develop highly-refractive electro-ceramics for application to silicon carbide (SiC) power modules such as heat-resistive passive components (snubber capacitors and resistors), metalised substrates, ceramic circuit boards, and high-temperature packaging technologies. To enable the operation of SiC devices at high temperatures, the ability to withstand 250 °C and temperature cycle between −40 and 250 °C must be ensured for all the ceramic components and packaging technologies. For the passive components, the following properties were achieved, which would enable the operation of SiC devices at high switching speeds and high temperatures: low-resistance resistors which exhibit a resistance variation of less than 2% over a temperature range of −40 to 250 °C and with almost no variation at frequencies of less than 10 MHz; multi-layered ceramic capacitors (MLCCs) with a capacitance variation of less than ± 10% within the above-mentioned temperature range and with high self-resonant frequencies of about 10 MHz. In addition, Cu-metalised ceramic substrates using high thermal conductive Si_3N_4 (180 W /(m·K)) and ceramic circuit boards produced using a co-firing process were developed. It was shown that prototype SiC power modules (2-in-1 structure) fabricated using the developed ceramic components could be operated at 225 °C, while exhibiting a high switching speed, 10–20 times faster than that of conventional Si IGBT (150 °C operation).

1. Introduction – High-temperature electro-ceramics

One of the features of ceramics is their good heat resistance. As such, ceramics are used for a variety of high-temperature structural applications. We believe, however, that this property is also very important in the field of electro-ceramics. While there are several materials, in addition to ceramics, which exhibit electro-magnetic properties (including metals and polymers), it should be possible to enhance the performance of electro-ceramics and expand their range of applications by leveraging both the electro-magnetic properties of ceramics and their heat resistance. Based on this, we are proposing the material concept of “high-temperature electro-ceramics”, which exhibit useful and even unique electromagnetic properties at high temperatures. These high-temperature electro-ceramics are particularly promising for applications involving heat-resistant electronic devices and modules. Example applications include power modules for hybrid vehicles and electric vehicles, combustion-control modules, power generation, underground resource-excavation systems, and aerospace equipment [1–5]. To define this concept, we set a characteristic temperature of 125 °C as the lower limit of a “high-temperature electro-ceramic”. This temperature was selected for two reasons: (1) it is currently the designed upper limit temperature of p-n junctions in CPUs and other electronic components, and (2) it is the Curie temperature of barium titanate ($BaTiO_3$), a typical electro-ceramic material. The characteristic temperature of 125 °C can be used to divide electro-ceramics into two groups. One group consists of electro-ceramics that are conventionally used at temperatures below 125 °C but have been modified to enable operation above 125 °C. Specific examples of applications of this group of materials are capacitors, resistors, inductors, circuit boards, sensors, actuators, and magnets (Category I). The other group consists of electro-ceramics that begin to exhibit functions at temperatures of 125 °C or higher (Category II). Examples include solid-oxide fuel cells, oxygen pumps, and thermoelectric power generators. As an example of the application of Category I high-temperature electro-ceramics, this paper describes the status of the development of heat-resistant components and the packaging technology for SiC power modules.

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2. New SiC power module designs using high-temperature electro-ceramics

Currently, silicon (Si) is the most widely used semiconductor in power devices. However, it is thought that its performance approaches the limit in terms of electrical strength and switching speed. Silicon carbide (SiC) is a promising alternative; several practical SiC applications have already been created [6]. SiC exhibits less than one-hundredth of the power loss of Si, a high (kilovolt-order) voltage resistance, and other performance characteristics that make it ideal for application to power semiconductors [7–9]. As described below, SiC chips also offer the benefit of an overall module heat dissipation structure.

Although the maximum junction temperature possible with Si chips is currently approximately 150 °C, SiC chips are expected to be able to withstand temperatures of over 200 °C. Higher operating temperatures will enable benefits such as simpler cooling structures and smaller cooling parts. To enable the use of SiC chips at high temperatures, it will be important to ensure the heat resistance of components mounted near those SiC chips. However, currently, the potential uses of SiC chips have not been fully exploited, because there are no components or packaging technologies that are able to withstand temperatures exceeding 200 °C.

Extensive research has been conducted to develop highly-refractive electro-ceramic components as well as high-temperature packaging technologies. In Japan, the New Energy and Industrial Technology Development Organization (NEDO) had implemented a project entitled "New Material Power Semiconductor Project for Achieving a Low-Carbon Society: Developments of Heat-Resistive Components and Packaging Technology for Power Modules (2012–2014)". Based on the results of this project, research into next-generation SiC module technology, including the design and durability evaluation of the technologies needed to realize high chip current density (1 kA/cm^2 class) power modules have been the subject of an investigation since 2014 under the "Cross-ministerial Strategic Innovation Promotion Program (SIP) / Next-generation power electronics / Consistent R&D of next-generation SiC power electronics (funding agency: NEDO)". This paper focuses on the achievements of the previous study which involved the development of highly heat-resistant components that would enable SiC power devices to attain high-speed switching in a junction temperature range above that of the Si chip operation (200–250 °C), as well as the highly-reliable bonding technologies required to mount these heat-resistant components near SiC chips.

Fig. 1 illustrates the design concept of the power module. The module has the following characteristics: (1) Supports high-speed switching at the 1200V/50A class. (2) Passive components (snubber capacitors, resistors) are placed near the SiC chips to suppress transient oscillations. (3) Bonding wires are replaced by a circuit board to support high current densities. (4) To efficiently dissipate heat from the SiC chips and ensure high mechanical reliability, metalised heat-dissipating substrates made of silicon nitride with a high thermal conductivity and toughness have been developed. To support junction temperatures of up to 225 °C, a target heat resistance of 250 °C was set as a common specification for both the components and packaging technologies. In addition, the modules would be subjected to wide-range temperature changes between the upper limit of junction temperature and ambient temperature of cold districts (about −40 °C) during use. Therefore, both the heat-resistant components and the power modules were designed such that they could withstand at least 1000 temperature cycles of −40 to 250 °C. Although more than 1000 temperature cycles are favourable in order to guarantee high reliability of the modules, test of 1000 cycles was performed in this study due to a temporal restriction; it takes about one month to conduct 1000 temperature cycling test.

The following section describes the passive components (highly-heat-resistant snubber capacitors and resistors), metalised heat-dissipating substrates with high thermal conductivity and reliability, circuit boards capable of supporting high current densities, and packaging technologies developed as part of this project.

3. Development of highly-heat-resistant passive components for SiC power modules

As SiC devices can perform high-speed switching, unlike Si devices, snubber circuits play more important roles in SiC power modules in that they suppress voltage spikes and dampen the ringing surge caused by circuit inductance. Generally, snubber circuits consist of resistors and capacitors. To ensure the stable operation of power modules across the entire temperature range, it is crucial to suppress any variations in the resistance and capacitance with temperature as low as possible, in addition to increasing their heat resistance.

3.1. Development of highly-heat-resistant resistors

To create smaller components with a greater heat resistance, we focused on the development of a ceramic chip-type resistor. Fig. 2 shows the structure of a typical commercially-available chip-type resistor, in which a resistive element covered with a glass protective layer is formed on a ceramic substrate. Table 1 lists the technical levels of each of the component parts of commercially-available ceramic-chip resistors. Improvements in the heat resistance of the resistive element, external electrode, and protective film were required.

By controlling the structure and composition of RuO_2, a typical resistant material, and employing heat-resistant metal as the external electrode, while modifying the composition of the glass protective layer, highly-heat-resistant chip-type resistors have been developed. Fig. 3 shows the variation in the resistance of such a resistor over a temperature range of −40 to 250 °C. The change in the resistance was

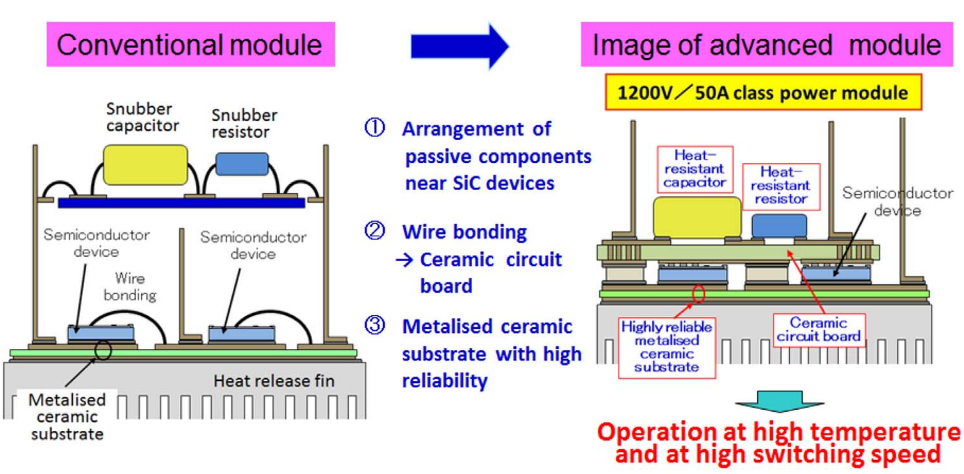

Fig. 1. Conventional power module (left) and advanced power module with proposed structure (right).