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Evaluation of Partial Discharge Inception Voltage of Bonding-less Gas Insulation Packaging for High Temperature and High Voltage Power Module

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Abstract- The purpose of our work is to develop a power module using gas insulation and bonding-less interconnections to avoid the reliability issues known to current packaging technology. This paper deals with the temperature dependence of partial discharge inception voltage (PDIV) of a developed module up to 300 °C. In addition, an attempt is achieved to confirm half-wave rectifying operation up to 300°C using SiC Schottky barrier diodes (SiC-SBD). From these results, the PDs were not detected up to 1500 V and 300°C, proving its ability to be used in high temperature applications.

Keywords: Power module, Partial discharge, Gas insulation, Bonding-less structure, SiC semiconductor

I. INTRODUCTION

Wideband gap semiconductor devices (SiC, GaN, diamond) have attracted a lot of attention as the next generation power devices to replace conventional silicon-based semiconductors. This next-generation power device is expected to be used in high temperature and high voltage applications such as electric power facility, electric vehicles, and airplanes -in the all-electrical airplane approach- and space exploration. Despite many reports dealing with power module packaging for high temperature applications, the current packaging technologies, such as using silver nano paste instead of solder and using new solid insulating materials [1-3], is mainly based on solid insulation (epoxy resin, silicone gel), and they are not useable above 250°C.

We propose to develop a new packaging technology using gas as the insulation [4-7]. In recent reports, we confirmed the full-wave rectifying operation at AC 1 kV up to 250°C using gas insulation and the developed bonding-less power module [8]. Currently, we aim to increase the operating voltage of the packaged module. One of the key issues in the high voltage power module is the existence of partial discharges, which, once they exist, will impact its reliability. This paper deals in a first step with the temperature dependence of partial discharge inception voltage (PDIV) of the developed module up to 300°C. In addition, the module will be used in a half-wave rectifying operation up to 300°C using SiC-Schottky barrier diodes (SiC-SBD).

II. GAS INSULATION POWER MODULE

Fig. 1 shows a photograph of developed power module. This module consists of Al₂O₃ plates, copper plates and metallic spring electrodes. SiC power semiconductor devices are embedded in the ceramic bulk. The module developed module in this paper has a simple structure; it allows to perform half-wave rectifying operation by the diode. The device was connected to the copper plates thanks to the mechanical pressure applied to the metallic spring electrodes. Note that the developed module has no wire bonding or solder. The bonding-less structure excludes the possibility of aluminum wire crack and solder delamination, it is hence more adapted to high temperature environments and thermal cycling. Fig. 2 and 3 show this assembly placed inside a test chamber acting as the final hermetic case of the power module. C₄F₈ gas or nitrogen gas as insulating medium was introduced in the test chamber at the pressure P of 0.1 MPa. A squared shaped ceramic heater with 25 mm on a side (Sakaguchi E.H VOC Co.: MS-1000) used to heat the module was sandwiched within the module.

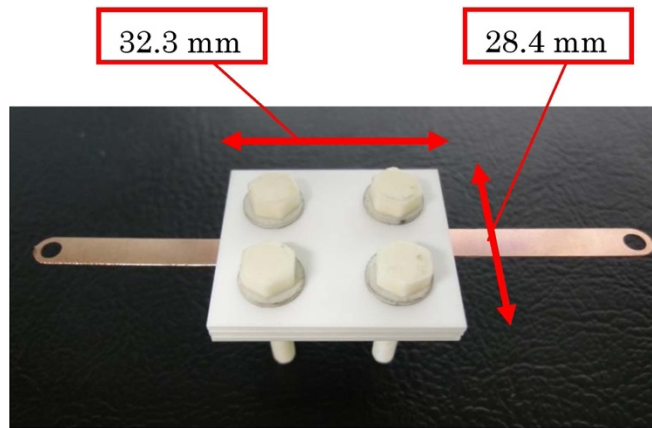


Figure 1. Photograph of the developed power module

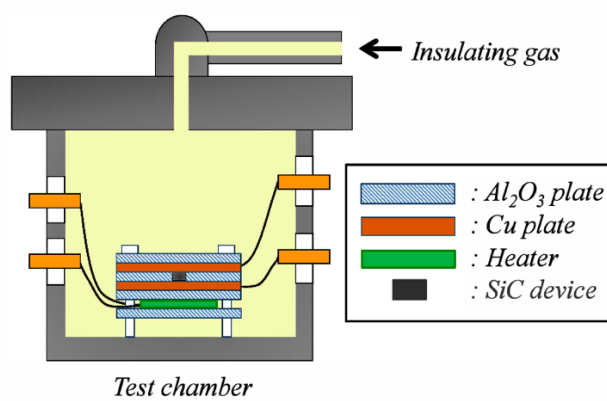


Figure 2. Structure of the power module and the test chamber

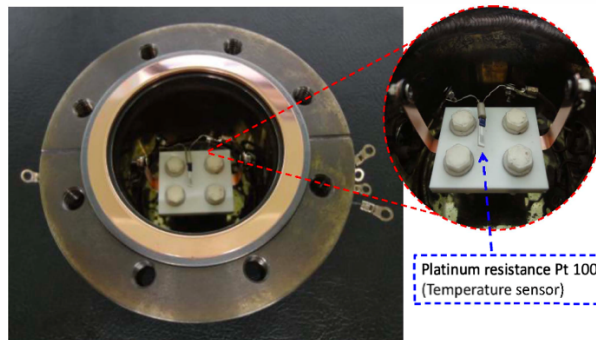


Figure 3. Photograph of the module placed in the test chamber

III. PDIV TEST OF DEVELOPED POWER MODULE

A. Experimental Method

Fig. 4 shows the experimental circuit of partial discharge inception voltage (PDIV) test. Si_3N_4 insulating chip, acting as a dummy device, was embedded inside the module instead of the SiC device for the PDIV measurements. The Si_3N_4 has a permittivity approximately equal to SiC. Signal generated with a function generator (NF Corporation: WF1974) was amplified with a power amplifier (NF Corporation: 4520A) and a transformer (YPAS3550: 200 V/30 kV). The amplified voltage was applied to the module up to PDIV at a rise rate of 150 Vrms/s. PD detection level was set at 10 pC. The applied voltage waveform and PD pulse waveform were observed and recorded with an

oscilloscope (LeCroy: WaveSurfer 104MXs-B, 1 GHz). This measurement was repeated 12 times at each temperature. The module was heated from room temperature up to 300 °C using the ceramic heater.

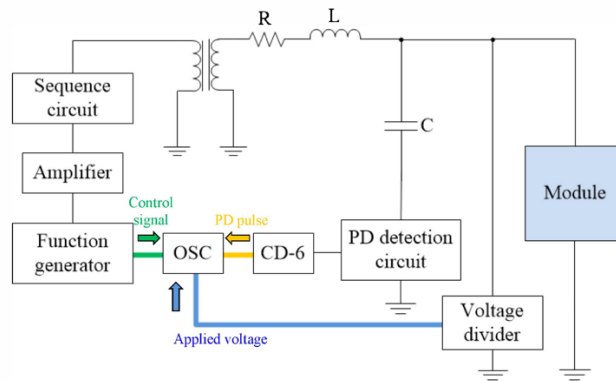


Figure 4. Experimental circuit of PDIV test

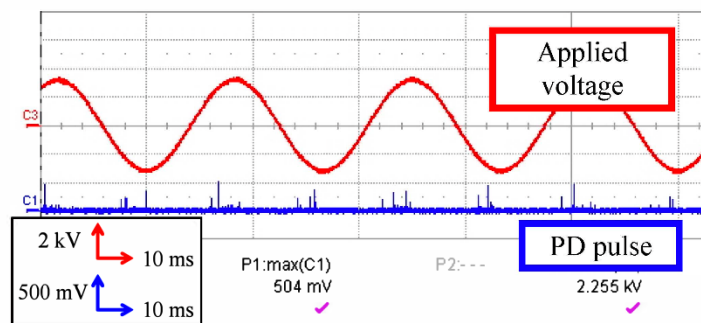


Figure 5. Obtained waveforms in PDIV test in C₄F₈ gas at room temperature

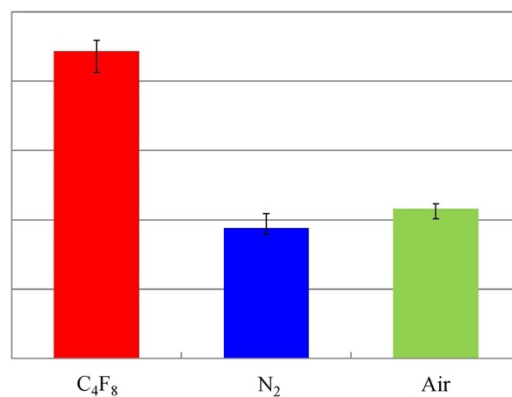


Figure 6. Comparison of PDIV in C₄F₈, Nitrogen and Air at room temperature

A. Results and Discussion

Fig. 5 shows an example of the obtained waveforms during PDIV test of the module. Blue and yellow lines in the figure represent the applied voltage waveform obtained by high voltage probe (Pulse Electronic Engineering: EP-50K, 1/2000) and PD pulse waveform obtained by PD measuring equipment (Nihon keisokuki: CD-6), respectively. Fig. 6 shows the comparison of PDIV when C₄F₈ gas, nitrogen gas or air was filled in the test chamber as insulating gas. From this figure, PDIVs of nitrogen gas and air are 940 Vrms and 1070 Vrms, respectively, and are found to have PDIV nearly equal. In contrast, the C₄F₈ gas has PDIV (2216 Vrms) two times as large as that in air and nitrogen. It is obvious from the figure that C₄F₈ gas has superior insulation characteristics compared to the other gases.

Based on this comparison results, we evaluated the temperature dependence of PDIV using two kinds of gases (C_4F_8 and N_2). Air with PDIV nearly equal to that in nitrogen was not employed in high temperature evaluation to avoid oxidation of copper. Fig. 7 shows temperature dependence of PDIV up to $300^\circ C$ when C_4F_8 gas or nitrogen gas filled the test chamber. From this result, it is confirmed that PDIV decreased with increasing temperature in both C_4F_8 and nitrogen gas. Nevertheless, the experimental results revealed that the developed power module has dielectric strength above rated voltage of SiC-SBD (1700 V) using C_4F_8 gas ($25^\circ C - 300^\circ C$).

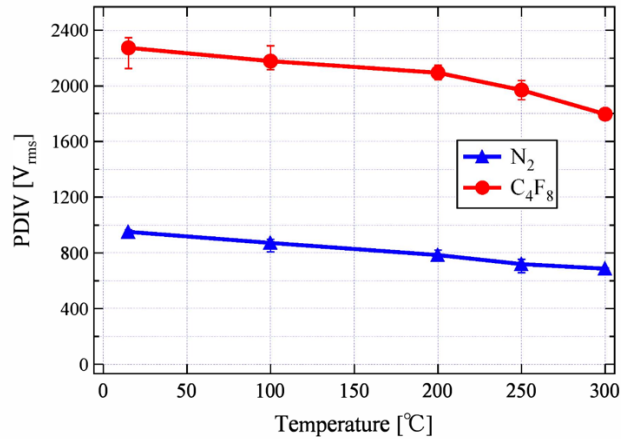


Figure 7. Temperature dependence of PDIV

IV. OPERATION OF SiC-SBD IN HIGH TEMPERATURE

A. Experimental Method

Fig. 8 shows the experimental circuit for the half-wave rectifying testing using a SiC-SBD (CREE, CPW3-1700-S025B, 1700 V, 25 A). Signal generated with a waveform generator (Kenwood, AG-204D) was amplified with a high voltage amplifier (Trek: model 20/20C). The maximum applied voltage to the module was set at 1500 V. The voltage and current waveforms were observed and recorded with an oscilloscope (Tektronix: DP04054, 500 MHz). Input voltage and current to the module were measured through the monitor channels of the high voltage amplifier. Output voltage from the module was detected by a differential probe (Yokogawa: 700924). The module was heated from room temperature up to $300^\circ C$ using an electrical oven (As One: HTO-450). Moreover, temperature dependence of reverse leakage current in the SiC-SBD was measured by a curve tracer (IWATSU, CS- 3200).

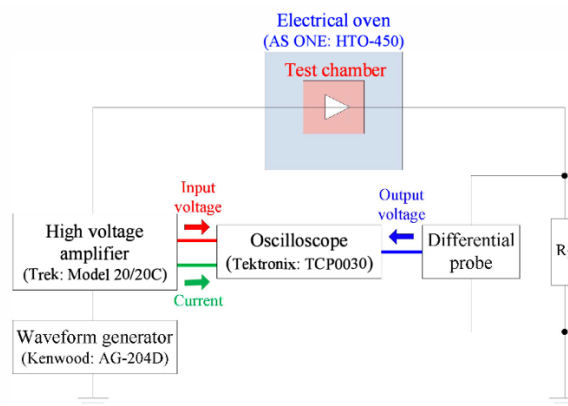


Figure 8. Experimental circuit of half-wave rectifying operation

B. Results and Discussion

Fig. 9 and 10 show the input and output voltage waveforms and current waveform at room temperature and at $T=300\text{ }^{\circ}\text{C}$, respectively. The applied voltage V_a in these measurements was 1500 V. From these results, it is obvious that the half-wave rectifying circuit integrated in the power module can operate normally at $300\text{ }^{\circ}\text{C}$ as well as at room temperature. Note that several nA of the reverse leakage current appears at $300\text{ }^{\circ}\text{C}$ although less nA appears below $250\text{ }^{\circ}\text{C}$. We have already reported about the increase of the reverse leakage current in the SiC-SBD with increasing temperature [9]. Fig. 11 shows the temperature dependence of reverse leakage current in the SiC-SBD. It is confirmed that several nA of the reverse leakage current appears under 1500 V at $300\text{ }^{\circ}\text{C}$.

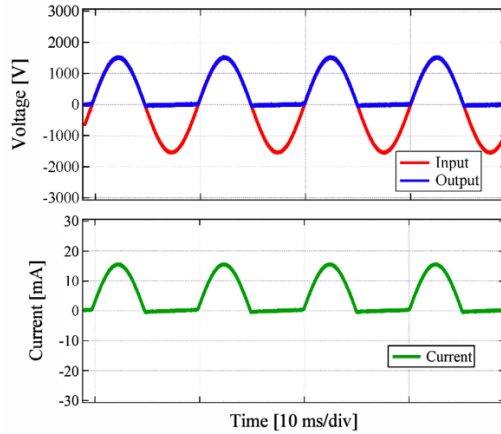


Figure 9. Voltage and current waveforms of half-wave rectifier at room temperature ($V_a = 1500\text{ V}$)

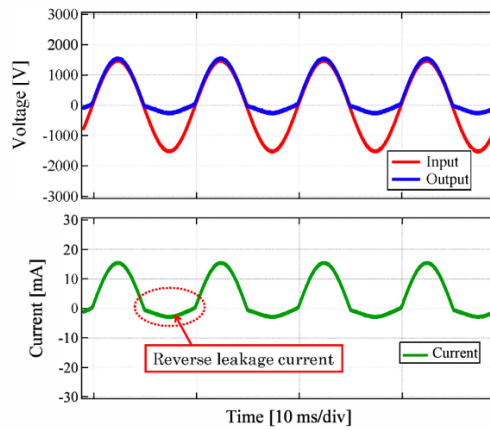


Figure 10. Voltage and current waveforms of half-wave rectifier at $300\text{ }^{\circ}\text{C}$ ($V_a=1500\text{ V}$)

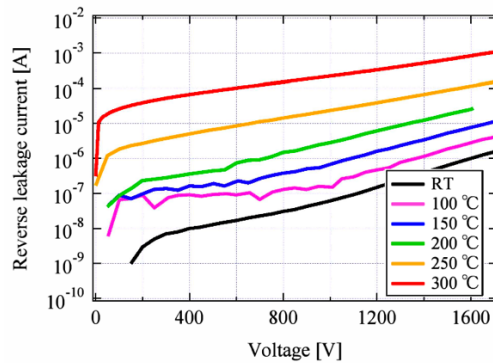


Figure 11. Temperature dependence of reverse leakage current in SiC-SBD

V. CONCLUSIONS

In this paper, we evaluated the temperature dependence of PDIV up to 300°C of a power module packaging with gas as insulating media. In addition, we also were able to demonstrate half-wave rectifying operation using SiC-SBD up to 300°C. From these results, the PDs are not detected up to 1500 V and 300°C using C₄F₈ gas, proving the packaging ability to be used in high temperature applications. In the future, the developed gas-insulated, solderless, bonding-less, package structure will be used for full inverters and DC-DC converters, in order to evaluate its potential as a packaging solution for high temperature and high voltage applications

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