Power Electronics Equipment Applying SiC Devices

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ABSTRACT

To achieve innovative compactness, light weight, and low loss in power electronic equipment, it is beneficial to use power semiconductors that use wide bandgap materials such as SiC and GaN. By installing hybrid modules using Si-IGBT and SiC-SBD semiconductors into general-purpose inverters, Fuji Electric can reduce inverter loss by 25%. In addition, by installing all-SiC modules in power conditioners for solar power generation, we demonstrated that it can increase main circuit efficiency to 99% while also reducing the overall equipment volume to 1/4 of conventional models, which is a substantial size reduction.

1. Introduction

In order to achieve innovative miniaturization, weight reduction and lower power dissipation on power electronics equipment, the progress of power semiconductors including their packages is essential. We are now approaching the limits of what is possible for the performance of devices using Si, which is currently the mainstream material for power semiconductors. Product development is proceeding for power semiconductors using wide band gap materials such as SiC (silicon carbide) and GaN (gallium nitride), which have a high blocking voltage and low losses and can operate at high frequencies and elevated temperatures.

This article describes the characteristics of hybrid modules of SI-insulated gate bipolar transistors (IGBTs) and SiC-schottky barrier diodes (SBDs) and All-SiC modules of SiC-metal-oxide-semiconductor field-effect transistors (MOSFETs) and SiC-SBDs, and explains the characteristics of general-purpose inverters mounting these hybrid modules. Also the characteristics of prototype power conditioner equipment for solar power generation which mounts this All-SiC module are presented.

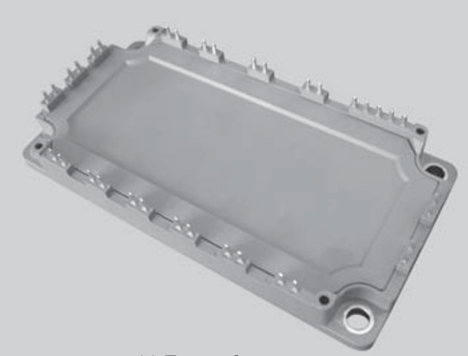
2. Characteristics of SiC Power Semiconductor Modules

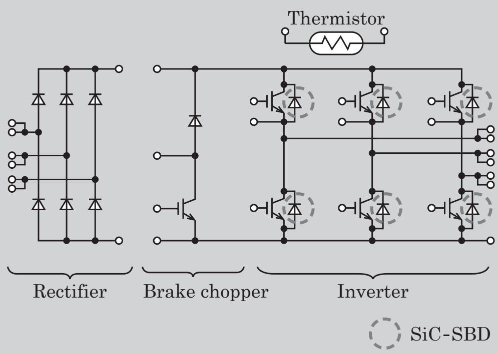
2.1 Hybrid Si-IGBT and SiC-SBD modules

Figure 1 shows the external appearance and internal circuits of a power integrated module (PIM) which is a hybrid of Si-IGBTs and SiC-SBDs.

For the SiC-SBDs, we used the chips[1] shown in Fig. 2, which were developed jointly with the National Institute of Advanced Industrial Science and Technology, and applied them to the free wheel diodes (FWDs). For the IGBTs, we used the 6th generation "V-Series" chips. There are a total of 6 types of the hybrid module: 3 types of 50 A, 75 and 100 A for 600 V, and 3 types of 25 A, 35 A and 50 A for 1,200 V[2]. The profile of the hybrid module product performance and characteristics given hereinafter will take the 1,200 V/50 A type as a representative example.

Figure 3 shows the forward characteristics of the


(a) External appearance



(b) Internal circuit

Fig.1 Si-IGBT and SiC-SBD hybrid PIM

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SiC-SBD and V-Series P-N junction diode (V-Series PND). They have almost identical characteristics within the range of currents for actual use. Also, the SiC-SBD shows a strong positive temperature coefficient such that the ON-state voltage rises with a rise in temperature, and the current can be easily balanced even in multi-parallel use.

Figure 4 shows the waveforms during reverse recovery of the hybrid module and V-Series module using V-Series PND as the FWD. Figure 5 shows the IGBT turn-on waveforms. Because the SiC-SBD is a unipolar device not injecting minority carriers, it is possible to suppress the generation of peak current at the FWD reverse recovery. Furthermore, by suppressing the peak current at the FWD reverse recovery, it is also possible to suppress the turn-on peak current of the IGBT. As a result of this, compared to the values for the V-Series PND, at rated current 50 A, the reverse

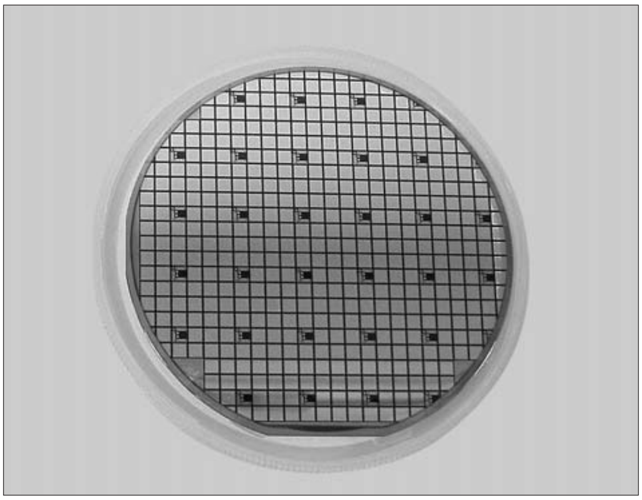

Fig.2 SiC-SBD chips

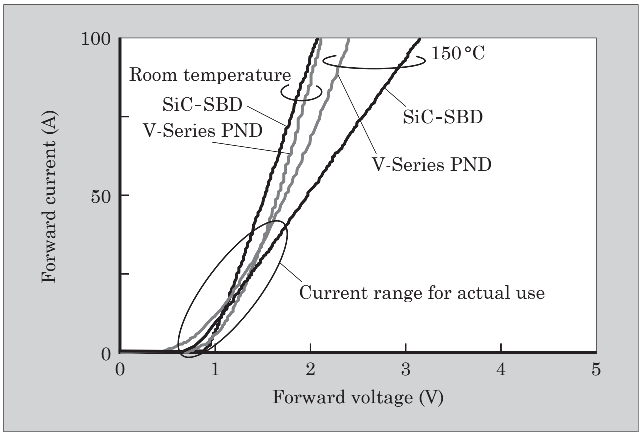

Fig.3 Comparison of forward characteristics

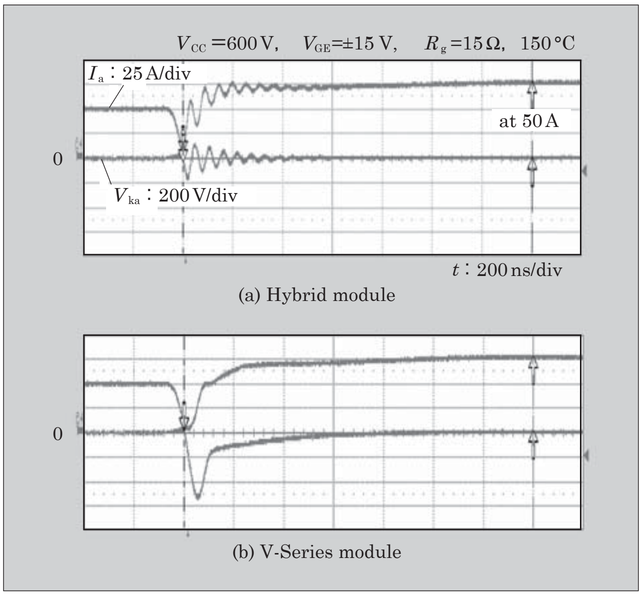

Fig.4 Comparison of FWD reverse recovery waveforms

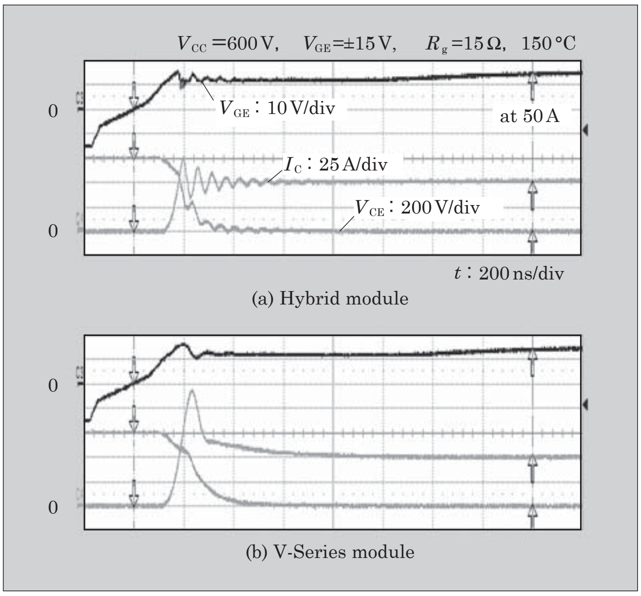

Fig.5 Comparison of IGBT turn-on waveforms

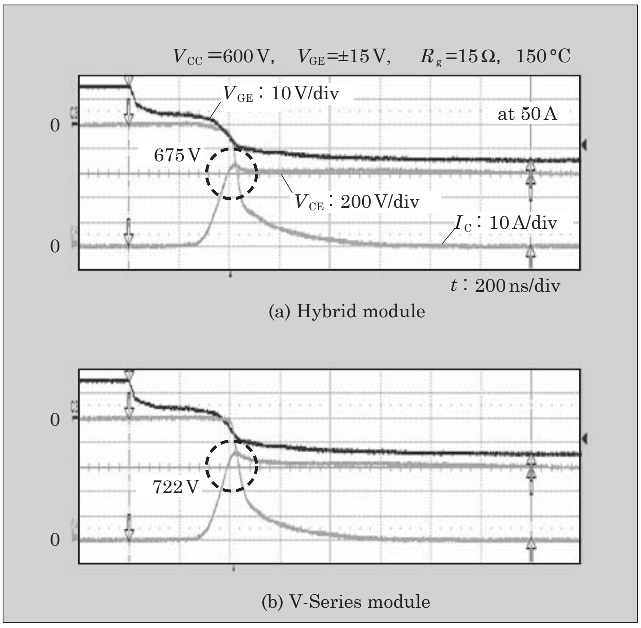

Fig.6 Comparison of IGBT turn-off waveforms

recovery loss is reduced significantly to 30% and the turn-on loss is reduced to 46% respectively.

Figure 6 shows the IGBT turn-off waveforms. As the turn-off surge voltage at a rated current of 50 A is kept to 47 V lower than that on the V-Series PND, the turn-off loss can also be reduced.

2.2 All-SiC module

For the SiC-MOSFETs, we used the implantation and epitaxial metal oxide semiconductor (IEMOS) chips[3] shown in Fig. 7, which was developed jointly with the National Institute of Advanced Industrial Science and Technology.

Figure 8 shows the forward characteristics of the chip and Fig. 9 shows the temperature characteristics of the on-resistance $R_{on} \cdot A$ and gate threshold voltage V_{th}. The SiC MOSFET also has a positive temperature coefficient, in the same way as the SiC-SBD, and balancing the current is easy even in multi-parallel use. Furthermore, it realizes a low on-resistance on a normally-off type, and the normally-off characteristics are maintained even at a high temperature state of 200 °C.

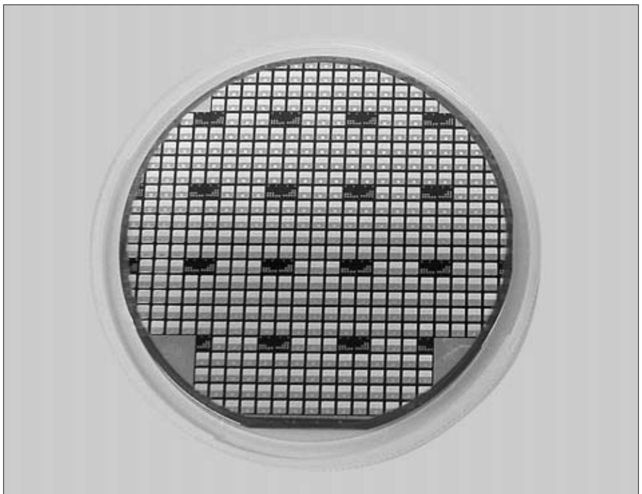

Fig.7 SiC-MOSFET chips

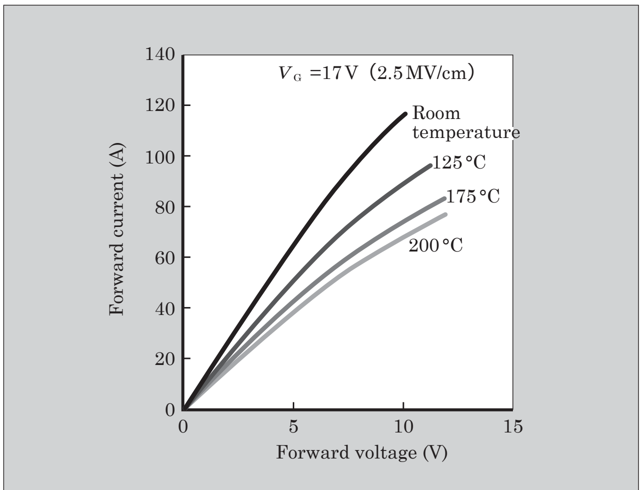

Fig.8 Comparison of forward characteristics

Figure 10 shows the SiC-MOSFET turn-off and turn-on waveforms at 200 °C. Both at the turn-off and turn-on, the time required for the switching is around 100 ns, which is greatly reduced to around 250 ns comparing Si-IGBT. Furthermore, the temperature causes little change in the switching characteristics, and the turn-off loss and turn-on loss show almost no dependence on the temperature. The turn-off loss and turn-on loss at 150 °C are 40% and 31% of those losses of Si-IGBT.

Figure 11 shows the module structure of SiC-

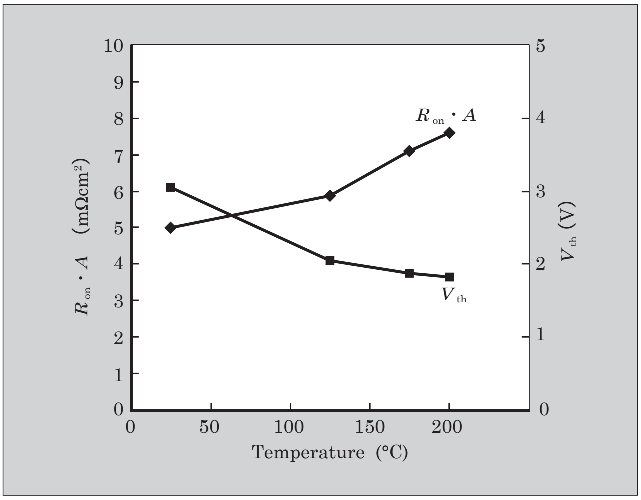

Fig.9 Temperature characteristics of the on-resistance and gate threshold voltage

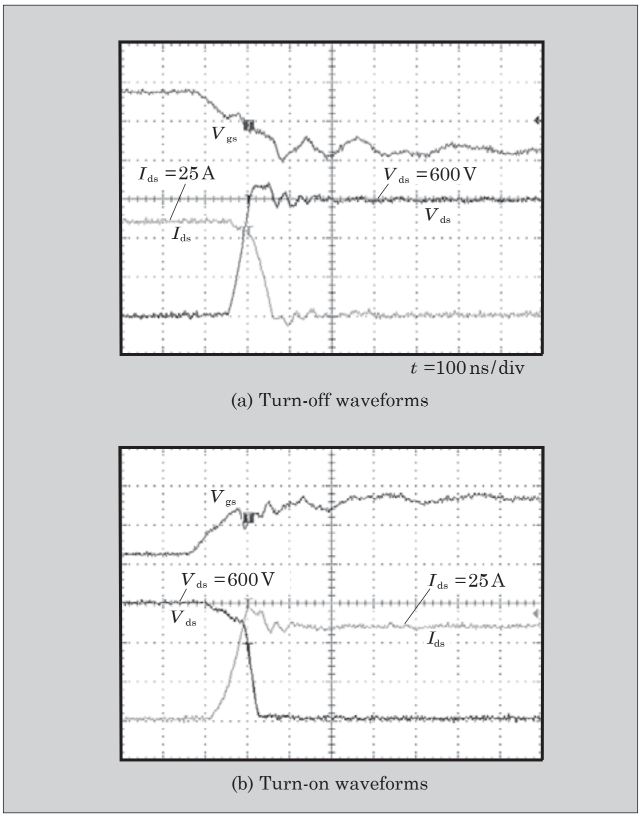

Fig.10 SiC-MOSFET turn-off and turn-on waveforms

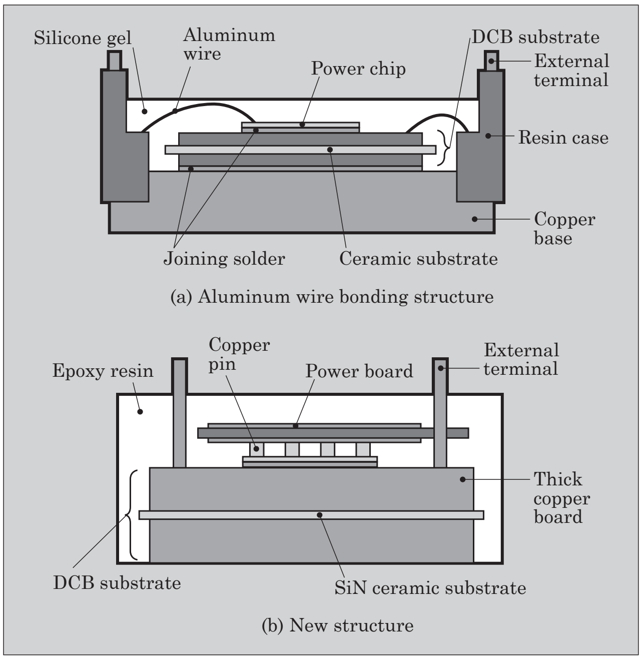

Fig.11 Comparison of the module structures

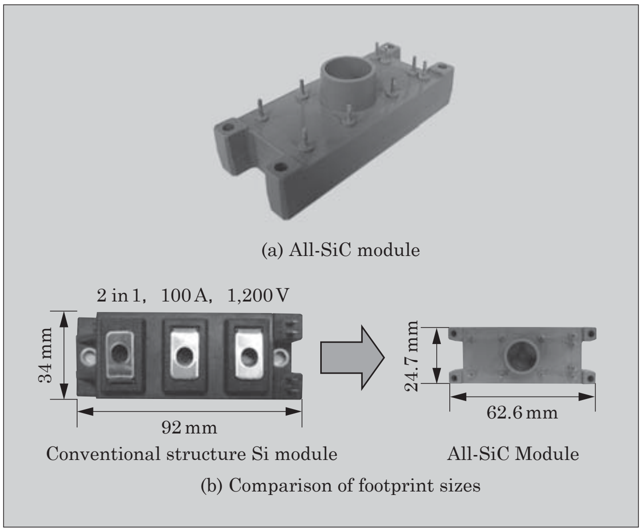

Fig.12 External appearance of All-SiC module and comparison of footprint sizes

MOSFETs and SiC-SBDs[(4)(5)] developed for All-SiC module. In the package developed, a Fuji Electric proprietary copper pin connection structure was used in place of the aluminum wire bonding structure used conventionally, and miniaturization and high power density were realized. Furthermore, by using a direct copper bonding (DCB) substrate made from copper plates and SiN ceramic substrate, the thermal resistance was reduced and the rise in the chip temperature T_j due to power density rise was suppressed. Also, by using an encapsulation structure using highly heat resistant epoxy resin in place of silicone gel, the warping which occurs at the points of connection around the chips has been eased and the reliability of the device has been improved. With this, it is possible to increase the capacity of modules with the parallel connection of multiple small SiC chips, and also to achieve miniaturization of the package. Figure 12 shows the external appearance of a 2 in 1 type All-SiC module rated 1,200 V/100 A and a comparison of footprint sizes (floor area). The footprint is half comparing that of a conventional structure Si module of the same rating.

3. Power Electronics Equipment Applying SiC

3.1 SiC-SBD mounted general-purpose inverters

The "FRENIC-MEGA GX-SiC" general-purpose inverter mounted Si-IGBT and SiC-SBD hybrid module was developed with the aim to raise further the efficiency of the inverters used for motor drives in air-conditioning systems and production equipment in factories. In the FRENIC-MEGA Series, this is a new GX Series specifically designed for synchronous motor drives. There are 6 models of three phase input devices, including 5.5, 7.5 and 11 kW for 200 V, and 5.5, 7.5 and 11 kW for 400 V. Figure 13 shows the external appearance of the 400 V/11 kW model and the external appearance of its major circuit part. The use of a hybrid model makes the switching losses such as turn-on

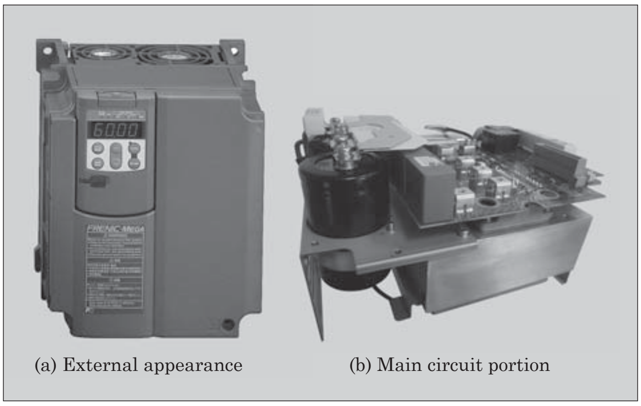

Fig.13 "FRENIC-MEGA GX-SiC"

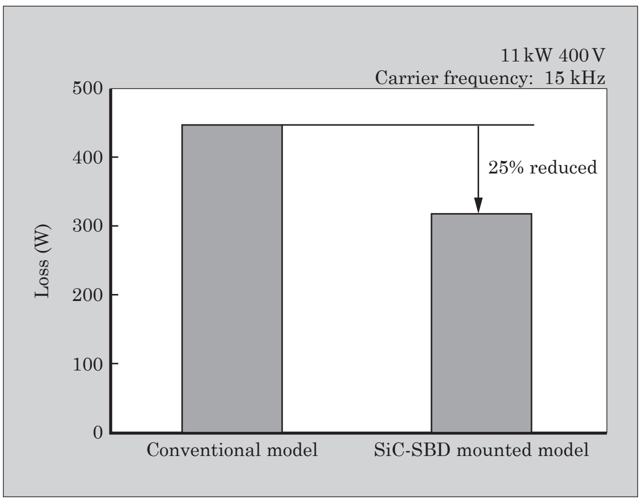

Fig.14 Comparison of generated loss of general-purpose inverters

& turn-off losses and the reverse recovery loss reduce. It was possible to reduce the generated loss in the general-purpose inverter by 25% compared to conventional models using Si devices (see Fig. 14). As a result, when used in combination with the highly efficient "GNS Series" and "GNP Series" of IPM motors, it was possible to achieve an even more efficient drive system.

3.2 All-SiC module mounted power conditioner

We produced a power conditioner for solar power generation which made miniaturization and improved efficiency possible with the use of the All-SiC module. The circuit structure chosen for the equipment was the AT-NPC 3-level circuit shown in Fig. 15. On consideration of the balance between the miniaturization of the filter and the switching losses, the switching frequency was set to 20 kHz. Figure 16 shows the external appearance of the 20 kW machine and the external appearance of its major circuit part. The use of All-SiC module made miniaturization of the filter and cooling fin possible, and it was possible to reduce the volume of the power conditioner equipment as a whole to a quarter of that of conventional models. Figure 17 shows the three phase output voltage waveform when the equipment is operated independently. Even with the switching frequency raised and the filter miniaturized, the waveform has little distortion or ripple. Furthermore, the efficiency of the main circuit part is 99%, and a great improvement in efficiency was realized.

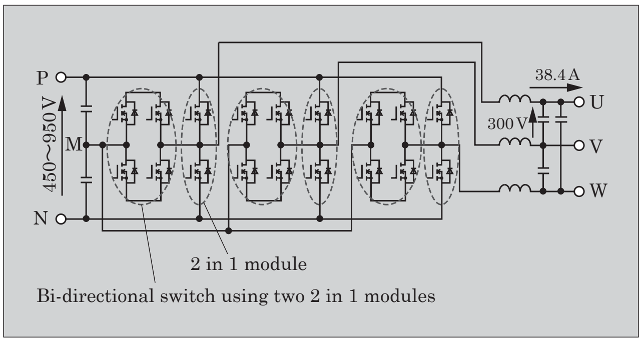

Fig.15 Circuit structure of All-SiC power conditioner

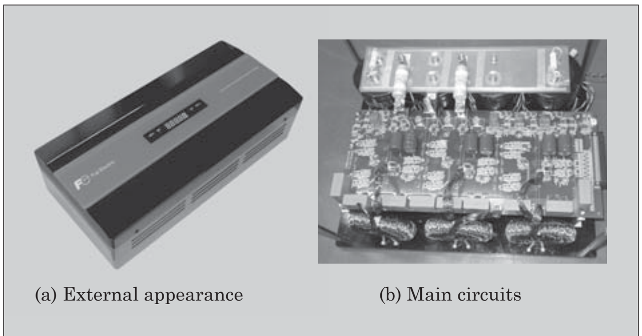

Fig.16 All-SiC power conditioner

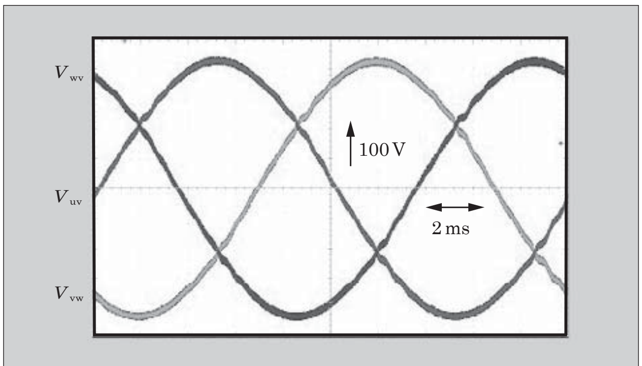

Fig.17 Power conditioner output waveform

4. Postscript

We developed a general-purpose inverter product using hybrid modules of Si-IGBT and SiC-SBD. We also produced a power conditioner for solar power generation using an All-SiC module. By mounting power semiconductor modules using SiC on power electronics equipment, it becomes possible to improve the efficiency of the equipment and to achieve miniaturization further. We will continue to contribute to the rapid progress of power electronics equipment by continuing the development of circuit technologies and package technologies which utilize the characteristics of SiC as much as possible.

We are very grateful to the members of the Advanced Power Electronics Research Center at the National Institute of Advanced Industrial Science and Technology for their cooperation in the development of the SiC chip. Some of this development was carried out as a part of "Experimental demonstration of the prototype mass production of SiC devices" in the National Institute of Advanced Industrial Science and Technology's Industrial Transformation Research Initiative.

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