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DEVELOPMENT OF A PULSED POWER SUPPLY UTILIZING 13 KV CLASS SIC-MOSFET

K. Okamura[†1], F. Naito[1], K. Takayama KEK, Tsukuba 305-0801, Japan
K. Fukuda, H. Kitai,H. Michikoshi, K. Sakamoto AIST, Tsukuba 305-8569, Japan
T. Kaito Chiba Institute of Technology, Narashino 275-0016 , Japan
D. Kumamoto, Nagaoka University of Technology, Nagaoka 940-2188, Japan
S. Lim, A. Tokuchi Pulsed Power Japan Ltd., Kusatsu 525-0058, Japan
[1] also at J-PARC Center, Japan

Abstract

To resolve the drawback of conventional thyratron switches, development of a semiconductor high voltage switch utilizing a 13 kV class SiC-MOSFET developed by Tsukuba Power Electronics Constellations (TPEC) is proceeding. At first, the device evaluation test was carried out with a resistive load circuit. With the conditions of drain voltage of 10 kV and load resistance of 1 kΩ, turn on loss Eon, turn off loss Eoff, rise time Tr and fall time Tf were 1.7 mJ, 1.1 mJ, 64 ns, and 75 ns, respectively. As to gate charge characteristics, required electric charge to increase gate source voltage from 0 V to 20 V was about 80 nC. Thereafter, the 2s-12p switch array was designed and assembled, where 12 MOSFETs are equally aligned on a circle shaped circuit board and two circuit boards are stacked in series. A 14 kV-490 A-5 us pulse with a rise time of 430 ns in the long pulse mode and a 18 kV-318 A-1 us pulse with a rise time of 289 ns in the short pulse mode were successfully demonstrated. This switch will be installed as a turn-off switch for the injection ES kicker in the KEK-DA.

INTRODUCTION

Various kinds of pulsed power supplies are used in an accelerator as well known. A thyratron has been long and widely used as a key element of the devices that generates high-voltage and large-current pulses. However, it has a drawback in life-time, reliability, and its handling. To replace a thyratron with a semiconductor switch, a number of devices must be connected in series [1,2] because of the limited withstand voltage of a conventional Si semiconductor device. The recently developed SiC-MOSFET is a promising candidate that can reduce the number of series connection because SiC inherently has a 10 times higher electrical breakdown strength compared with Si [3]. Actually a few kV class SiC-MOSFET is already commercially available [4,5]. Attempt replacing thyratrons by SiC-MOSFETs has started [6]. Moreover, SiC-MOSFET to allow an output voltage exceeding 10 kV has been developed recently [7]. The authors have evaluated basic properties of the newly developed 13 kV class SiC-MOSFET and then assembled the switch unit in 2s12p. This paper describes the first test results.

† katsuya.okamura@j-parc.jp

SIC-MOSFET

The device was developed by Tsukuba Power Electronics Constellation (TPEC). Figure 1 shows the external view of the device. The device package is similar to the standard TO-268-2L surface mount package.

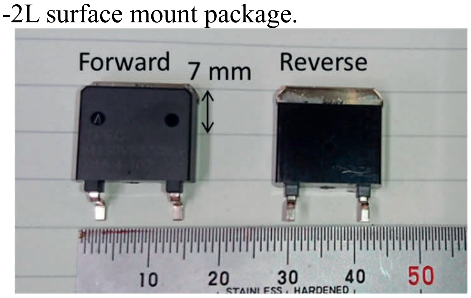

Figure 1: External view of the SiC-MOSFET.

Device Evaluation Test

Switching Test Switching test of the device was conducted with a resistive load. The switching test was carried out in a single-shot mode. Figure 2 shows switching waveforms and switching losses for various load resistance values with dc voltage of 10 kV. Maximum peak pulse current of 43.5 A was obtained with a load resistor of 200 Ω. However, high on-voltage was observed in that case. Figure 3 shows switching loss, turn on rise time (TR) and turn off fall time (TF) as a function of nominal drain current IDN, which is defined as (dc voltage)/(load resistance). Switching loss consists of turn-on loss EON, turn-off loss EOFF, and conduction loss ECOND, where EON is defined as the device loss generated from off state to the time point of drain voltage falling to 10 % of the dc value in the turn-on period, EOFF is defined as the device loss generated from the time point of drain voltage rising from 10% to 100 % of the recovery voltage in the turn-off period and Econ is the rest portion of the total loss in the switching period, respectively. The turn-on loss EON increases rapidly, whereas the turn-off loss EOFF increases gradually. Note that EOFF is a little bit underestimated because of a sag of the drain current and imperfect recovery voltage. However, this is not caused by the device characteristic but an insufficient capacitance of the storage capacitor. As to switching time, TR increases gradually, whereas TF decreases rapidly till IDN reaches 20 A. This is because TF depends on not only the device characteristics but on the time constant that is determined by the product of the output capacitance of the device and the load resistance.

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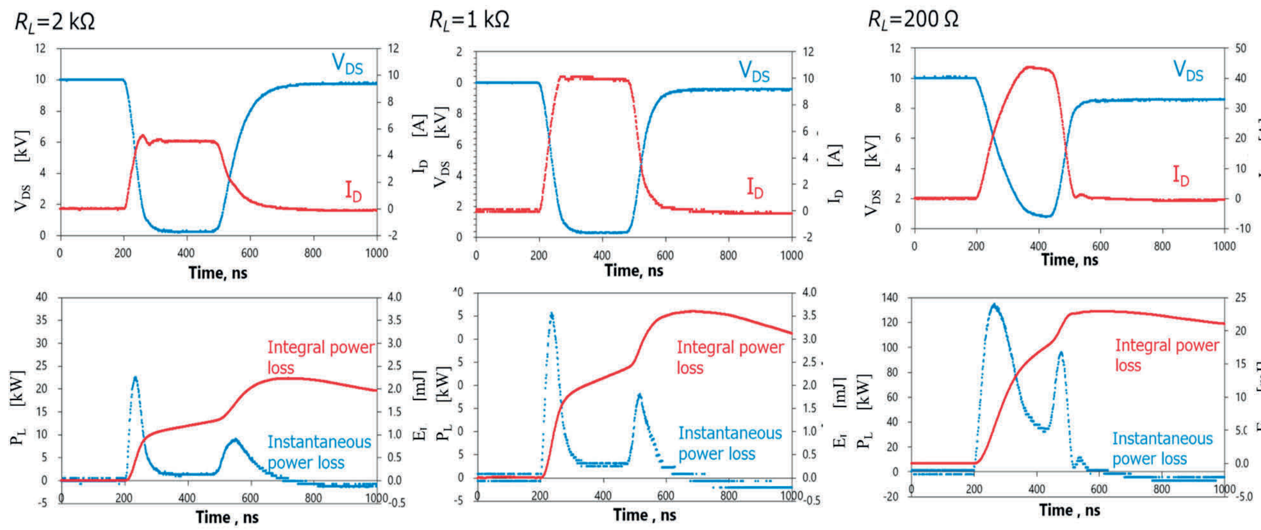

Figure 2: Switching waveforms and loss waveforms of a single SiC-MOSFET with a various value of load resistors. (Left: 2 k Ω, Center:1 kΩ, Right: 200 Ω)

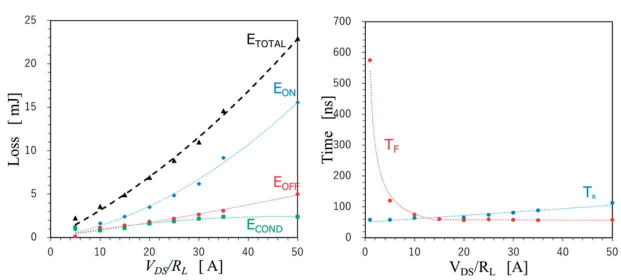

Figure 3: Switching loss and switching time as a function of nominal drain current.

Gate Charge Characteristics A gate charge characteristics is one of the important factor for designing a gate driver circuit. The gate charge can be calculated by integrating a gate current during the rising portion of the gate voltage. Figure 4 shows the gate charge characteristics in cases of V_{DS}=0 V and V_{DS}=5 kV.. Although some oscillation is observed in the case of VDS of 5 kV, a gate charge is required to drive increase gate voltage from 0 V to 20 V is estimated around 80 nC.

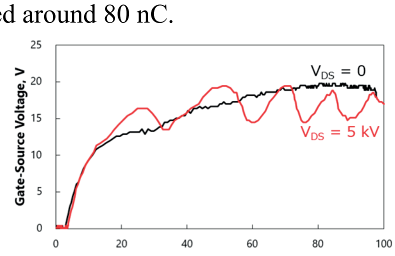

Figure 4: Gate charge characteristics.

Switch Unit

Encouraged by a successful result of a single device evaluation, we designed a high voltage switch unit. Limited number of available devices, the construction of the switch is decided as 2 series and 12 parallel. Figure 5 shows the top view of a single board that consists of 12 SiC-MOSFETs, their drivers and auxiliary circuits, where MOSFETs are placed surrounding around the center circle of the board. Also 12 connection plugs are set inside of the MOSFETs, which are used to connect between the boards electrically. Electrical power of control circuit is supplied from an external power board through the insulation transformer in the form of high frequency alternative current, whereas trigger signal is sent through fiber optics. The assembled switch unit is shown in Fig. 6.

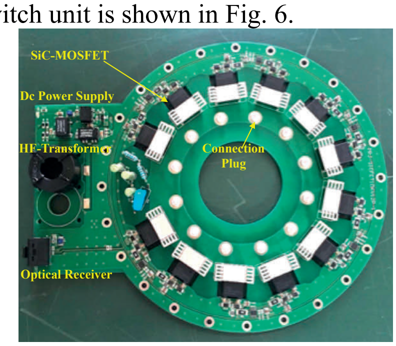

Figure 5: Single switch board of SiC-MOSFETs.

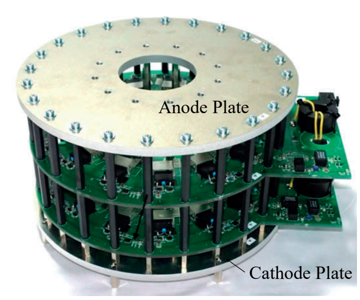

Figure 6: Assembled switch unit.

Switching Test

Long Pulse Test Long pulse test was conducted with a load resistance of 28 Ω. Figure 7 shows the test result. With

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dc voltage of 14 kV, 5 us-490 A pulse operation was successfully confirmed. However current rise time (10 % - 90 %) was 430 ns, the value of which was 4 times slower than the value of the intrinsic performance of the single device. Presumed one reason of this is a large gate resistance R_G of 10 Ω connected between the gate driver IC and the device gate and a shunt capacitance connected between the gate and the source of the device. Actually, R_G was 3.9 Ω and no shunt capacitance was used in the device test. However, decreasing the value of RG caused the unstable operation of the switch unit as shown in Fig. 8. Therefore, we haven't made modification to the gate circuit. The authors consider improvement can be attain by modifying gate pattern to shorten the length between the driver IC and the FET.

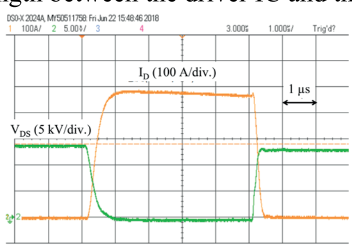

Figure 7: Long pulse switching waveform.

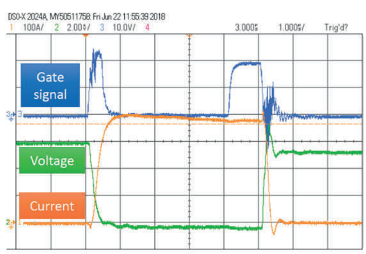

Figure 8: Unstable switching waveform with a low gate resistor. The gate signal is intermittent and the drain voltage is oscillating.

Short Pulse Test Short pulse test was conducted with a coaxial construction assembling an inner cylindrical return conductor and a capacitor bank with the body of the switch unit, which are shown in Fig. 9. Also, insulation cylinders made of Nomex® paper are inserted between the body of the switch unit and the center conductor to prevent an electrical discharge. Voltage and current waveforms with dc voltage of 18 kV and various load resistors are shown in Fig. 10. With the load resistance of 50 Ω, 1 us-318 A pulse operation was confirmed with the rise time of 289 ns. Fig. 10 shows a large droop in the case of small R_L because of insufficiency of the capacitor bank. Therefore, we are planning to increase capacitance.

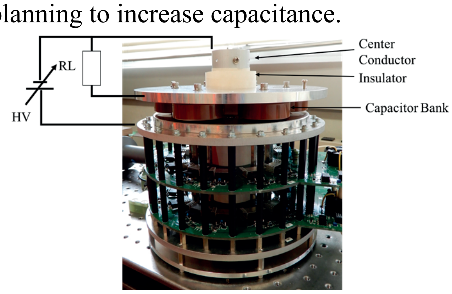

Figure 9: The switch unit assembled with the inner conductor and the capacitor bank for short pulse switching test.

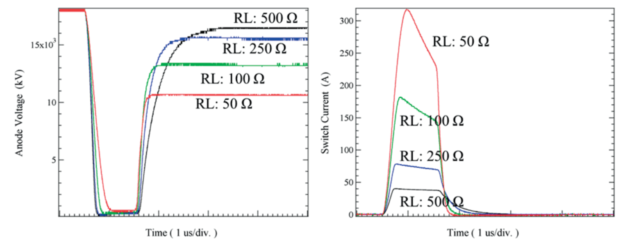

Figure 10: Short pulse switching waveforms for various value of load resistors.

SUMMARY AND FUTURE PLAN

- Device evaluation test of a 13 kV class SiC-MOSFET has been executed.
- With a resistive load switching test, 10 kV-43.5 A pulse switching was confirmed.
- After the device evaluation, high voltage switch unit consists of 2 series and 12 parallel MOSFET was designed and assembled.
- In the long pulse switching test, 14 kV-490 A-5 us pulse with a rise time of 430 ns was successfully generated.
- In the short pulse switching test, 18 kV-318 A-1 us pulse with a rise time of 289 ns was successfully generated.
- After reinforcing the capacitor bank, we will try 20 kV-500 A switching experiment. Then, the switch unit is installed in the KEK-DA [8] as the turn-off switch of the electro-static pulse generator of the ESS kicker, replacing the current SI thyristor switch [9].

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