DEVELOPMENT OF AN INDUCTION ACCELERATOR CELL DRIVER UTILIZING 3.3 kV SIC-MOSFETS

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Abstract

Pulse switching characteristics of newly developed 3.3 kV SiC-MOSFET were investigated. With supply voltage of 2.5 kV and the load resistor of 100 Ω, rise time T_r and fall time T_f were 76 ns and 88 ns respectively. Thereafter, they were provided for a prototype switching power supply (SPS). In the SPS, drain to source voltage waveform exhibits a extremely spike-free switching waveform. From the switching loss evaluation, the maximum operation of the SPS is expected exceeding 100 kHz.

INTRODUCTION

A novel synchrotron called an induction synchrotron (IS) was developed at KEK in 2006 [1]. In the IS, charged particles are accelerated by pulse voltages driven by switching modulators employing high-power high – repetition –rate semiconductor switches. The switches are turned on and off by gate signals corresponding to the revolution frequency of the ion bunches. As the ion beam is accelerated to nearly light speed, maximum switching frequency reaches up to MHz order.

A switching pulse supply (SPS) that generates bipolar pulses is one of the key technologies for the IS. The rating of SPS is roughly 2.5kV-20A-1MHz. To accomplish these requirements, we adopted 7 series connected Si-MOSFET for the switches of the 1st generation SPS. However, it was too large and complicated for practical accelerators. Therefore we started to develop the next generation SPS utilizing silicon carbide (SiC) devices, because they have inherently excellent properties in high electric fields such as durability, high-speed switching and high-temperature resistance [2, 3].

In the early stage of this research, we had focused on JFET devices, which had been considered to be more practical in those days. Consequently we developed a high power discrete package [4] and succeeded to demonstrate a beam acceleration experiment [5] utilizing SiC-JFETs. However, development of MOSFET devices has been dramatically progressed recently. Thereby 3.3 kV class MOSFET has been already demonstrated [6, 7]. In this paper, we describe the pulse switching test results of a prototype SiC-MOSFET developed by Rohm Co., Ltd and test results of a prototype switching power supply utilizing them.

SWITCHING PERFORMANCE OF THE PROTOTYPE DEVICE

Firstly, we conducted the switching performance test of the prototype device. The device package utilizes general TO-247 package with a minor conversion so that it could ensure the higher voltage rating. The switching test was performed with resistive loads since the load is not inductive in the induction accelerator driver. Figure 1 and 2 shows the switching waveforms and switching losses with various values of load resistors at constant V_{DD} of 2.5 kV respectively. With load resistors of 220 Ω and 100 Ω, on voltages are extremely low, whereas on voltage exceeds 200 V with such a heavy load of 50 Ω. Moreover, switching losses also steeply increase. With the load resistor of 100 Ω, rise time T_r and fall time T_f were 76 ns and 88 ns respectively.

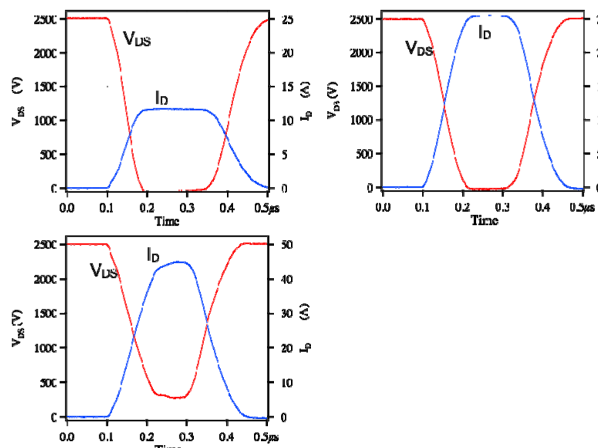

Figure 1: Switching waveforms of a prototype 3.3 kV MOSFET. Top left: R_L=220 Ω, top right: R_L=100 Ω, bottom : R_L=50 Ω.

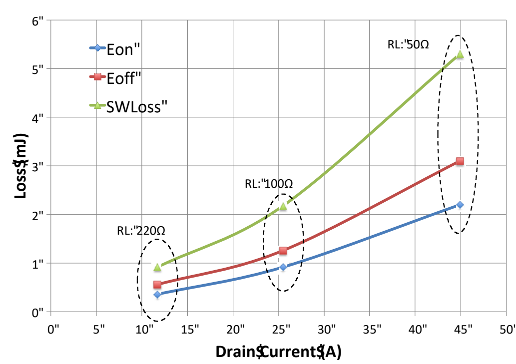

Figure 2: Switching losses (V_{DC}=2500 V).

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PROTOTYPE SWITCHING POWER SUPPLY

Design

A pulse generator that has a circuit topology of H bridge circuit was fabricated with this prototype MOSFET, the circuit diagram is shown in Fig. 3 and an actual view of the SPS is shown in Fig. 4, where MOSFETs are mounted on water-cooled heat sink and interconnection between devices are done with laminated copper plates insulated by Nomex® paper.

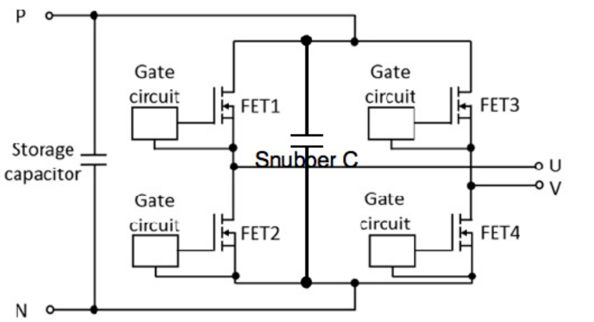

Figure 3: The circuit diagram of the switching power supply.

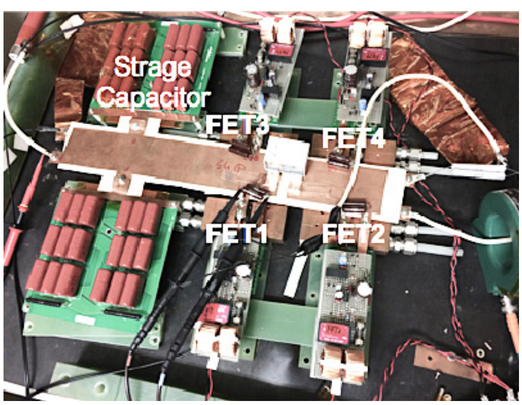

Figure 4: Actual view of the SPS.

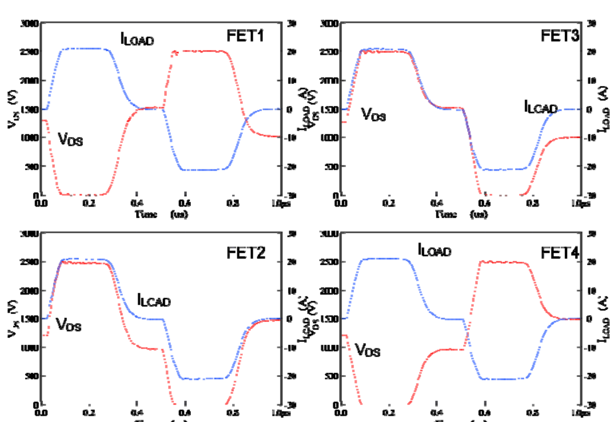

Figure 5: Drain-Source voltage of the FETs and output current waveforms in single shot mode with dc voltage of 2500 V and load resistance of 120 Ω.

Single Shot Performance

At first, the SPS was tested with single shot mode operation mode. In such a high speed switching circuit, switching surge voltage is one of the most crucial issues. Therefore spike voltage between drain and source of each FET was measured with the dc rating voltage of 2.5 kV. Figure 5 shows the waveforms of drain to source voltage and output current. As a consequence, even in the highest case, spike voltage was 2532 V corresponding to only 101.3 % of the dc voltage. Low stray inductance structure of laminated bus enables such a low spike voltage only with a simple snubber capacitor.

Continuous Operation

After the single shot mode operation, continuous mode operation, with load resistance of 80 Ω has been started with water cooling. Drain to source voltage, drain current, and case temperature of FET2 have been measured, also output current waveform, water inlet and outlet of SPS have been measured. Figure 6 and 7 shows the waveforms of the drain to source voltage and the drain current and the load current with dc voltage of 2500 V at 10 kHz operation, respectively.

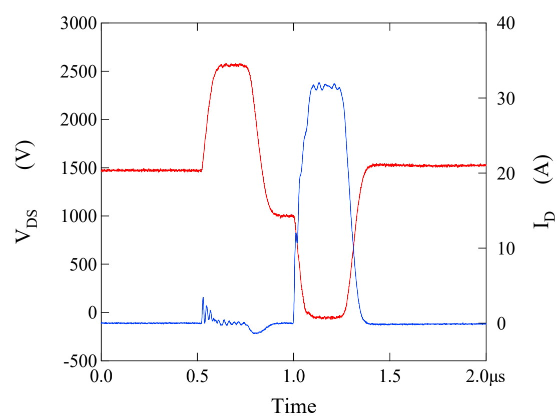

Figure 6: Waveforms of the drain to source voltage and the load current with dc voltage of 2500 V and load resistance of 80 Ω at 10 kHz operation.

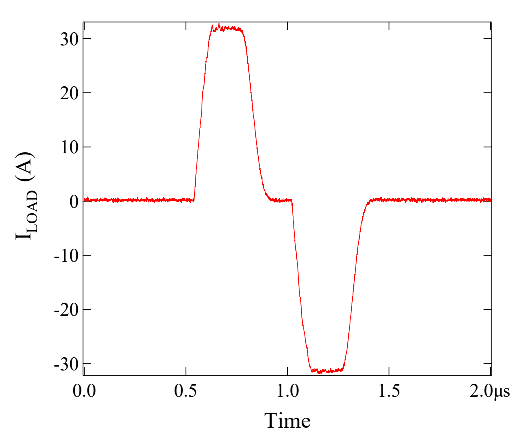

Figure 7: Load current with dc voltage of 2500 V and load resistance of 80 Ω at 10 kHz operation.

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From the switching waveforms switching loss was estimated as roughly 0.8 mJ/pulse. Assuming the maximum heat dissipation of the device is 100 W, maximum operating frequency is around 125 kHz. Of course this value does not reach the required maximum frequency. Therefore development of a high power dissipation package is necessary. However, circular frequency during the injection phase is much less than maximum frequency, hence it may be adoptable in a kind of intermittent mode operation. In such application, the period at which in highest frequency operation is quite limited. Therefore, burst mode operation was also tested. Figure 8 shows the output voltage and current wafeforms at 1 MHz burst mode operation with dc voltage of 2500 V and the load resistance of 120 Ω.

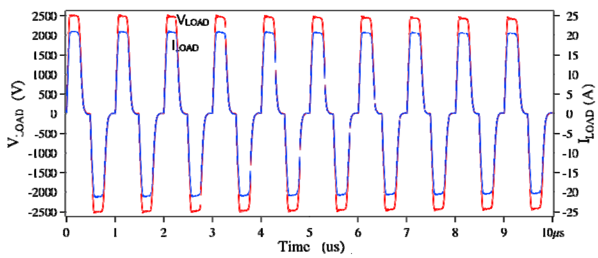

Figure 8: Output voltage and current waveforms at 1 MHz burst mode operation.

SUMMARY AND FUTURE PLAN

Pulse switching characteristics of newly developed 3.3 kV SiC-MOSFET were tested and they were provided for a prototype switching power supply (SPS). The SPS consists of only 1 device in its arm and can output 2.5 kV pulse. Ten kHz continuous mode operation was confirmed and maximum operation frequency is expected to be over 100 kHz from the switching loss evaluation. Furthermore, 1 MHz burst mode operation was also confirmed. These successful results encourage us to develop an ultra-compact pulsed power supply the induction acceleration system for future accelerators, such as the fast cycling hadron driver for cancer therapies [8], induction microtron for giant cluster ions [9], and giant cluster ion inertial fusion driver [10]. Moreover, custom high-power packages with bi-directional heat-exhaust technology will also enable MHz order continuous mode operation [11].

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