Variable-Width Pulse Generator

Eiji Sasamoto,
Toshihiro Osada,
Ikuo Azuma

Keywords Pulsed power, High-voltage switching technology, SiC-MOSFET, EUV, Film-forming

Abstract

The pulse generator is equipment made to generate momentary high power. It is being used especially for plasma-applied fields (film-forming and environmental (air-cleaning and water-processing) fields for example) by variable-width pulse generator. We focused on high-speed switching and low loss generation characteristics of Silicon Carbide (SiC) – Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET) which are recently actively being developed. We established our own approaches for the parallel connection of semiconductor devices, and realized outstanding characteristics of variable pulse width performance (pulse width: 0.1～2μs), high-frequency operation (repetitive frequency: 120kHz or below), high power (output voltage: Max. 6kV), and high-speed operation (rising and falling time: 30ns or less). This unique product is a pulse generator that cannot be found in our former product lineups. As an example of its application, it is now being used in the fields of Pockels cell drivers and plasma applications. We verified the presence of pulse voltage output in negative polarity or the operation of high-frequency at 400kHz by adjusting the equipment to meet requirements.

1 Preface

The pulse generator is an equipment to generate a high pulsed power to the unit for an extremely short amount of time of microseconds or nanoseconds. Such a pulse generator is used in the technical field of Pulsed Power[(1)] and its application is positively promoted. Formerly, the magnetic pulse compression method[(2)] was widely adopted for pulse generating circuits to deal with laser loads. This system, however, could not change the pulse width easily. For this reason, in many cases it was difficult for the system to be applied to the plasma-applied fields (such as film-forming and environmental "air-cleaning and water-processing" fields). In order to apply this technology easily to plasma-applied fields, we have recently developed a variable-width pulse generator that can generate high-speed and high-voltage power with variable pulse width capability. For the purpose of high-voltage switching, we used Silicon Carbide (SiC) Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs) for this product. Recently, the SiC MOSFETs are actively being developed recently worldwide. By the parallel connection of semiconductor devices, this product realized high dielectric strength. This paper introduces the operational principle and circuits of the variable-width pulse generator and some applications.

2 Operational Principle of the Variable-Width Pulse Generator

Fig. 1 shows an external appearance of the variable-width pulse generator and Fig. 2 shows

Fig. 1 Variable-Width Pulse Generator

An external appearance of the variable-width pulse generator is shown.

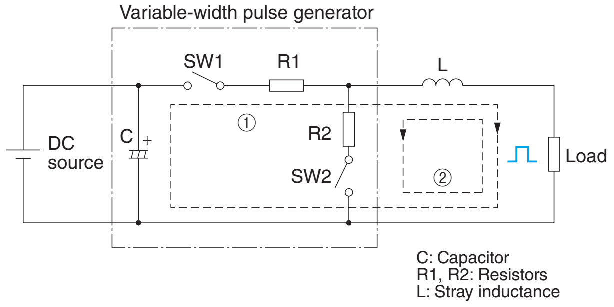

Fig. 2 **Circuit Configuration of the Variable-Width Pulse Generator**

A circuit configuration of the variable-width pulse generator is shown.

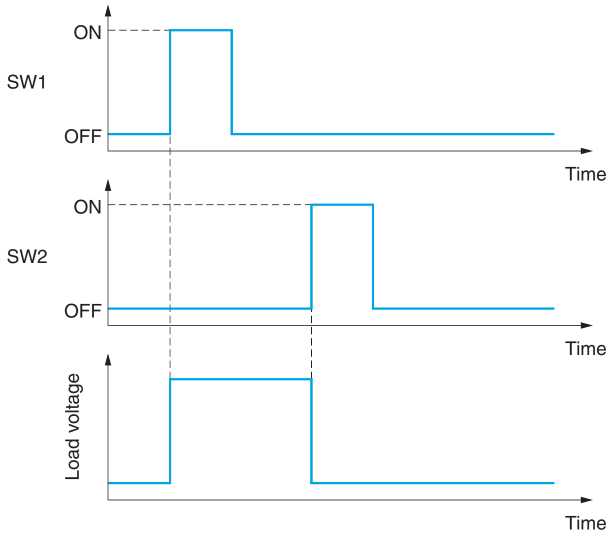

Fig. 3 **Timing Chart of Variable-Width Pulse Generator**

The timing chart of variable-width pulse generator operation is shown.

the circuit configuration. The variable-width pulse generator comes with two main switches (SW1 and SW2). Through the ON/OFF control of each switch, pulse-state voltages are applied to a load. The operating power is obtained from a DC power source that is supplied externally. A capacitor C is inserted where a voltage drop is anticipated due to a response characteristic of the DC power. Resistors R1 and R2 are inserted for the prevention of ringing phenomena that may be caused by the inductance L between the source and the load or by the load itself. In the case of a resistive load, R2 and SW2 need not be installed. In the case of a capacitive load, however, R2 and SW2 are required.

Fig. 3 shows a timing chart when a capacitive load is installed. When the load voltage is required to rise, SW1 is turned ON and SW2 is turned OFF. At that time, the current from the DC source runs toward the load along the route indicated by the dotted line ① in **Fig. 2** so that the load voltage can rise. When the load voltage must fall, SW1 is turned OFF and SW2 is turned ON. In this case, a current flows along the route indicated by the dotted line ② in **Fig. 2** and the load voltage falls as a result.

3 Configuration of the Switching Circuit

For the pulse generator used in plasma-applied fields, high-speed and high-voltage pulse output characteristics must be secured in addition to the capability of changing the pulse width. High speed in this contexture means the shortness of rising and falling time (in several tens of nanoseconds). High voltage means the height of a voltage peak (several to tens of kilovolts). When generating a pulse output in a circuiting system as shown in **Fig. 1**, the pulse output characteristics are greatly influenced by the characteristics of the switching circuit itself (of SW1 and SW2). A configuration of the switching circuit is introduced below for obtaining high-speed and high-voltage pulse outputs.

3.1 Selection of Power Devices

As a power device for generating a pulsed power, the thyristor, Insulated Gate Bipolar Transistor (IGBT) and MOSFET[(3)-(5)] are generally adopted. There is, however, no such switch that functions in several tens of nanoseconds and at several tens of kilovolts coming into a single device. When one wants to establish a high dielectric strength by connecting devices in series, it is inevitably necessary to choose power devices that work at some tens of nanoseconds. **Table 1** shows the characteristic comparison table of the power devices. Even the Silicon (Si)-MOSFET makes it possible to perform high-speed operation, but in this case, the ON-resistance is high and the resultant loss is substantial. Although the SiC-MOSFET by each supplier can perform high-speed operation, we adopted the SiC-MOSFET produced by Company “C” because its specifications on a catalog are outstanding.

3.2 Configuration of the Switching Circuit Block

Fig. 4 shows a configuration of the switching circuit block. For our switching circuit developed for this time, we established a high dielectric strength

Table 1 Characteristic Comparison Table of the Power Device

The table below shows comparison of characteristics of the power device that can be applied to the variable-width pulse generator.

Device material	Si-MOSFET	SiC-MOSFET	
Maker name	Company "A"	Company "B"	Company "C"
Rated current (peak current) (A)	12 (48)	14 (35)	12.5 (40)
Rising time (ns)	11	19	11
Falling time (ns)	18.5	29	10
ON resistance (Ω)	620	280	160

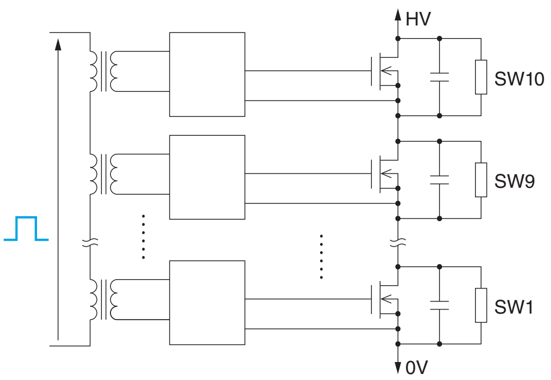

Fig. 4 Configuration of the Switching Circuit Block

A configuration of the switching circuit block is shown. The block is composed of 10 switching devices connected in series. A pulse transformer system is adopted for the gate driving circuit. In consideration of voltage sharing, each device is connected with a resistor and a capacitor.

by connecting ten devices of 1200V rating each in a series. When creating a high dielectric strength with devices in a series connection, a variety of device driving systems are available. Unless all the devices are switched simultaneously, there will be collapse of voltage sharing balance and devices may be broken. For a reasonable solution, we have adopted a system where devices are driven by a pulse transformer. In consideration of voltage sharing on each device in regular mode and transient mode, resistors and capacitors are connected in parallel to each device.

4 Examples of Applications

4.1 Pockels Cell Driver for Extreme Ultraviolet (EUV) Light Source

As the most powerful light source for photo lithography to be used for the next generation versions, there is an EUV equipment rated at the wavelength of 13.5nm. R&D activities on this equipment are promoted at Gigaphoton Inc. – an EUV light source equipment supplier in Japan. Our pulse generator is used as a Pockels cell driver at this company where the EUV light source is controlled. **Table 2** shows the major specifications of the Pockels cell driver for EUV. This pulse generator is used in positive polarity. It can frequently perform repeated generation of high-speed and high-voltage pulse output in pulse width variable mode. In addition, Jitter (deviation width in time-axial direction) is extremely small. Compared with conventional equipment made by other suppliers, power consumption in Pockels cell driver itself has been reduced by approximately 30%.

Table 2 Major Specifications of the Pockels Cell Driver for EUV

Major specifications of the Pockels cell driver for EUV are shown.

Output voltage	0～6kV (variable)
Repetitive frequency	0～120kHz (variable)
Load capacitance	10～40pF
Output pulse width	0.1～2.0μs (variable)
Rising/falling time	30ns or less
Jitter	Not more than 4ns
Cooling system	Water-cooled
Mass	16kg Max.
Dimensions	W270 × H290 × D210mm or less

4.2 Pulse Generator for Plasma-Applied Fields

The variable-width pulse generator is an equipment to generate a pulse-state voltage output by ON/OFF control of the main switches. If the switching technology with the use of main switches is established, it is possible to set up the frequency, polarity, output voltage, and other factors according to the user's demands. For example, the descriptions below are related to the modification of power source according to the user requirements.

We once developed a pulse generator of the magnetic pulse compression circuiting system to be used for empirical Diamond-Like Carbon (DLC) film-forming[4]. At this time, this power source has been modified according the user's request so that the variable-width pulse generator can be used in negative polarity for DLC film-forming experiments. **Fig. 5** shows the circuit configuration of the variable-width pulse generator in negative-polarity.

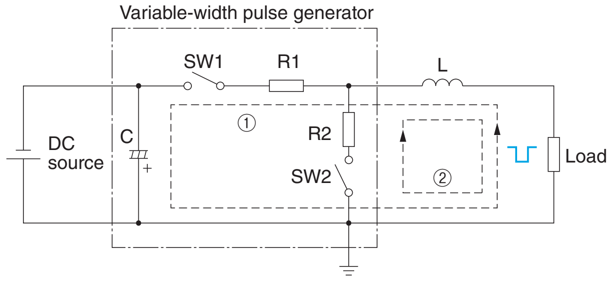

Fig. 5 **Circuit Configuration of the Variable-Width Pulse Generator in Negative-Polarity**

A circuit configuration of the variable-width pulse generator in negative-polarity is shown. Compared with **Fig. 1**, the circuit configuration may be slightly modified to enable voltage pulse output generation in negative polarity.

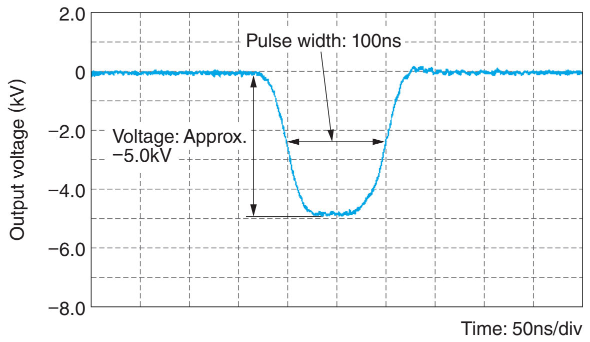

Fig. 6 **Example of Output Voltage Waveform for the Variable-Width Pulse Generator in Negative-Polarity**

An example of an output voltage waveform for the variable-width pulse generator in negative-polarity is shown. The output voltage is approximately −5.0kV and the pulse width is 100ns.

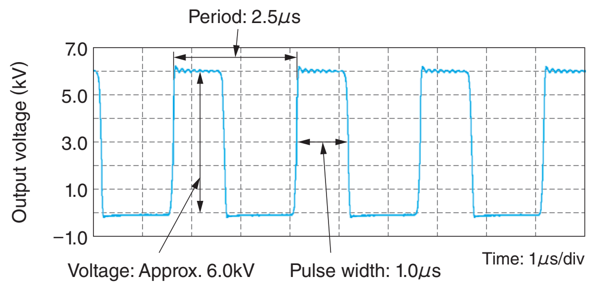

Fig. 7 **Example of Output Voltage Waveform Observed during Operation at 400kHz**

An example of output voltage waveform is shown, observed when the variable-width pulse generator is operated at 400kHz. The output voltage is approximately 6.0kV.

Compared with the positive-polarity circuit in **Fig. 1**, a DC power source in negative polarity can be provided separately making it possible to make a minimal wiring change inside the unit. **Fig. 6** shows an example of an observed output voltage waveform. We confirmed that a pulsed voltage output in negative polarity can be generated.

There is demand for more highly repetitive operation in regard to the variable-width pulse generator. For this time, we adjusted parts and circuits of the control circuit and confirmed that operation at a high frequency of 400kHz is possible. **Fig. 7** shows an example of output voltage waveform observed.

5 Postscript

This paper introduced the operational principle of our variable-width pulse generator and some examples of its applications. The pulse generator is used in a variety of industrial fields such as air purification and water processing in addition to applications introduced in this paper. Its application range is considered to expand further in the future. Going forward, we will work on improving our technologies so that we can expand our product line-ups and increase the fields of applications.

《References》

(1) Hara and Akiyama: High-Voltage Pulsed Power Engineering, Morikita Publishing Co., Ltd., 1991 (in Japanese)
(2) Sasamoto: "Pulsed Power Applied Technologies," Meiden Jiho Vol.323, 2009/No.2 (in Japanese)
(3) Ishii: "Future Prospect of Semiconductor Pulse Generator," Academic Journal on Plasma and Nuclear Fusion Engineering, Vol.81, 2005/No.5, p.375 (in Japanese)
(4) Sakugawa, Namihira, Katsuki, Akiyama, Nagata, and Koganezawa: "Application of Semiconductor Pulse Generator to Plasma-Applied Equipment," Academic Journal on Plasma and Nuclear Fusion Engineering, Vol.81, 2005/No.5, pp.350～354 (in Japanese)
(5) Koh and Takagi: "Roles of Power Semiconductor Devices," Academic Journal on Plasma and Nuclear Fusion Engineering, Vol.87, 2011/No.2, pp.106～111 (in Japanese)
(6) Sasamoto: "Pulsed Generator for DLC Film-Forming," Meiden Review Vol.161, 2014/No.2