Static Induction Thyristors as a Fast High-Power Switch for Pulsed Power Applications

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Abstract

Semiconductor power devices are employed widely in pulsed power applications. A first goal of device development for the applications is to establish high di/dt characteristics similar to that of spark gap switches, namely, 10^{12} A/s. We examined turn-on characteristics of SI-thyristors for fast high-voltage pulse generators. The SI-thyristors have a buried gate structure in which the gate electrodes are placed in n-base region. Since they are normally on-state, gate electrodes must be negatively biased to hold off-state. The SI-thyristors at on-state behave similar to pin diodes. We characterized three kinds of SI-thyristors, two of which were for power electronics use with a rated voltage of 4000 V. The device named RT201 was designed for pulsed power applications. The difference among them is device structures at the vicinity of anode. The punch-through and anode shorted structures are commonly used to improve turn-off characteristics for power electronics. The RT201 device with a rated voltage of 5500 V has the punch-through structure and is not an anode-shorted device. The turn-on speed is mainly determined by carrier injection rate to the n-base region. Therefore performance of the gate driving circuit influences fast turn-on characteristics. When the newly developed high current gate driver was used, the fastest turn-on operation with T_f = 35 ns and di/dt = 9.5 10^{10} A/s was obtained in the RT201 device. We made a stacked SI-thyristor switching unit to characterize repetitive and higher voltage operation. The stacked unit comprised three SI-thyristors, and each of them had the gate driver. The switching unit was successfully operated with the repetition rate of 2 kHz at 10 kV.

INTRODUCTION

Pulsed power technology covers physics and engineering on fast high-power pulses that are employed in particle accelerators, plasma sources, pulsed gas lasers, short-wavelength light sources, and so on. The switching devices, which can control high voltages and high currents, give large effect in-performance of the pulsed power generators [1]. For high voltage and high current switching, discharge-type switches such as spark gaps or hydrogen thyratrons have been commonly used. The spark gap switch can close the circuits within nanoseconds. The pressurized spark gap is used for higher voltage switching. The lifetime of spark gap is limited because of electrode erosion by high current discharges. The high power switches are classified as a closing switch and an opening switch. Fast closing switches are necessary to generate fast or very short pulse-width pulses. Opening switches are required for inductive energy storage pulse generators in which discharge currents have to be transferred to another circuit. If the opening switch is employed, square pulses are easily generated. Although the discharge type switches have capability of fast closing action, it is rather difficult for them to open the circuits. Power semiconductor devices come into increasing use especially in industrial applications of pulsed power. Although the power devices for power electronics have been designed and developed to have superior turn-off performance, fast turn on characteristics is also required in pulsed power applications.

POWER SEMICONDUCTOR DEVICES FOR FAST HIGH-POWER SWITCHING

The power semiconductor devices have the advantage of compactness, long lifetime, and maintenance free nature in comparison with the discharge-type switches. High-power switching capability depends on the device characteristics, namely, peak currents, hold off voltages, switching time, and switching power losses. The power devices enable the high power pulse generator to work at a high repetition rate. Moreover, reliability and performance of the generator systems will be tremendously improved. The first goal of the device development for pulsed power applications is to establish a high rate of current rise being comparable to that of the spark gap switches, namely, 10^{12} A/s.

There are several candidates for the fast high power switch in the power semiconductor devices, which can be classified by turn-on mechanisms. Thyristors and GTOs are driven by current injection from the gates. Carriers in the depletion layers control SI-transistors and SI-thyristors. IGBTs, IEGTs (Injection Enhanced Gate Transistor), MOSFETs, and MAGTs (Mos Assisted Gate-triggered Thyristor) have MOS gate structures. The avalanche effect is applied in RSDs (Reversely Switched Dynistor) and FIDs (Fast Ionization Dynistor). Photon energy to create the carriers is employed in photo-triggered thyrisors and photo-conductive bulk semiconductor switches.

For the junction type power devices, the typical hold-off voltage ranges from 4000 to 6500 kV and the maximum peak current is less than 50 kA. Therefore, they are employed by connecting in series to achieve higher voltage operation and by connecting in parallel to obtain higher current pulses. The rated voltage of more than 10 kV is highly expected in the applications for gas lasers or plasma sources. To obtain higher hold-off voltages, the base layer must be thicker. Consequently, the turn-on time becomes longer. There exists trade-off between device specification and switching capability.

When the devices are used in the high power pulse generators, they are usually operated in extreme conditions. The device structure must be designed with special care in comparison with that for conventional power electronics apparatus. The data on device characteristics obtained in power electronics use are not sometimes helpful, because the operating conditions are not so critical as in the pulsed power systems. Reduction of switching power loss is always required that determines the efficiency of generators and the power for cooling systems. Degradation and its mechanism in the power devices, which are not well known, have to be understood under high electromagnetic field environment. Electrical breakdown is also a serious problem in designing and manufacturing the power device with high hold-off voltages. The steep high voltage pulse sometimes destroys power semiconductor devices. Mechanical stress in the devices cannot be ignored, especially in long pulse or extremely high current applications. Since misfiring of the devices will result in serious damage to themselves and the pulsed power systems, one must avoid electromagnetic noise in the gate circuits.

SI-THYRISTOR AS A FAST SWITCHING DEVICE

SI-thyristors are promising candidates for fast high-current and high-voltage switches capable of high repetition rate operation. The SI-thyristor was invented by Nishizawa in 1975 [2]. The on-state voltage is low in the Si-thyristor, which is due to thyristor action followed by carrier injection effect around the gate channel. The device has also high immunity for electromagnetic noise, which is established by its low gate resistance owing to the device structure. Fast and low loss switching characteristics are remarkable in comparison with other power semiconductor devices with hold-off voltage over the 3 kV. The SI-thyristors have buried gate structure in which the gate electrodes are located in the n-base region near the cathode. We believe that the buried gate structure is suitable for the high-current and high voltage fast SI-thyristor. Since they were normally on-state, the gate electrodes have to be negatively biased. The negative bias voltage to the gate forms a low-conductive depletion region around the gates, and the SI-thyristor holds off-state. When a positive voltage pulse is applied to the gates, the depletion region is filled with carriers and the device becomes on-state. The transition time of the turn-on process is largely dominated by the rate of the carrier injection time. Temporal and spatial behavior of holes and electrons in the SI-thyristor was numerically obtained using a device simulator. The current distribution was found to be uniform especially for hole-current. At the turn-on phase the SI-thyristor acts just like as a pin-diode. We examined on-state current characteristics of both the devices with the same chip-diameter experimentally. Pulse turn-off characteristic is carrying out the examination.

We tested turn-on characteristics of SI-thyristors for fast high-voltage pulse generators[3]. The characterization was carried out on three types of SI-thyristors, two of which, namely, Type-C and Type-D, were for power electronics use with a rated voltage of 4000 V. The device named RT201 was specially designed for pulsed power applications. The difference among them was device structure at the vicinity of anode. The punch-through and anode shorted structures are commonly used to improve turn-off characteristics for power electronics use. However, the RT201 with a rated voltage of 5500 V has the punch-through structure and is not an anode shorted device. They were all reverse-conducting type devices, which had diodes connected in antiparallel. The reverse-directional current that appears in LC discharge circuit would flow in the diode. A test circuit for characterization was composed of a 38 nF capacitor and a coaxially arranged return circuit with a residual inductance of 13 nH [4]. Temporal behavior of anode voltages and anode currents at the turn-on phase are shown in Fig. 1, where the charging voltage was 1 kV. The di/dt became larger as the charging voltage increased up to 3 kV for all the types of devices. The rate of current rise for the RT201 is always larger than that for the other devices.

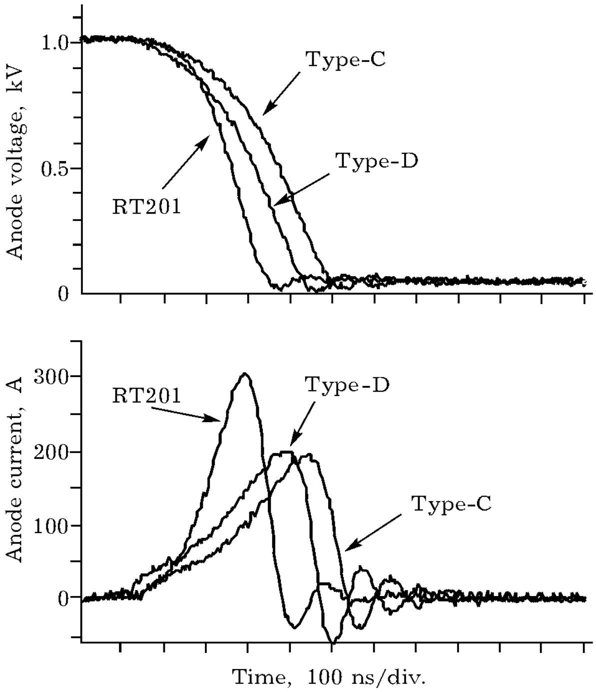

Fig. 1. Turn-on characteristics for three types of SI-thyristors.

The turn-on speed is mainly determined by the carrier injection rate to the n-base region in the SI-thyristors. Therefore performance of the gate driving circuit influences fast turn-on capability. We designed a high current gate driving circuit with the low inductance MOSFET module that could repetitively generate the gate currents more than 300 A. We referred to the high current driving circuit as circuit-4. The gate driving circuit was connected to the gate terminal of device as short as possible to minimize the residual inductance. We also employed two other gate drivers for power electronics use that included a low current one, circuit-1, and a medium current one, circuit-3. The turn-on characteristics for three drivers are summarized in Fig. 2, which shows the peak di/dt and the anode voltage fall time, T_f. When the circuit-4 was used for the RT201, the fastest turn-on capability with T_f = 35 ns and di/dt = 9.5 10^{10} A/s was accomplished. It was found that the turn-on characteristics were improved by carefully designing device structure of SI-thyristors.

We made a stacked SI-thyristor switching unit to test repetitive and higher voltage operation. The stacked unit comprised three SI-thy-

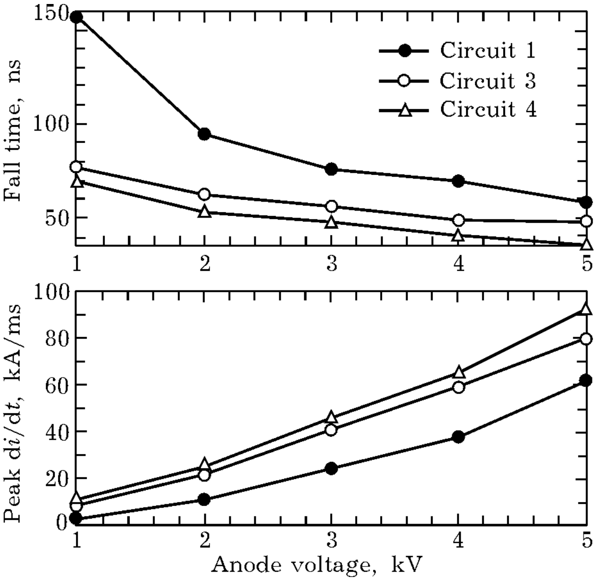

Fig. 2. Voltage dependence of turn-on characteristics for different gate driving circuits for RT201.

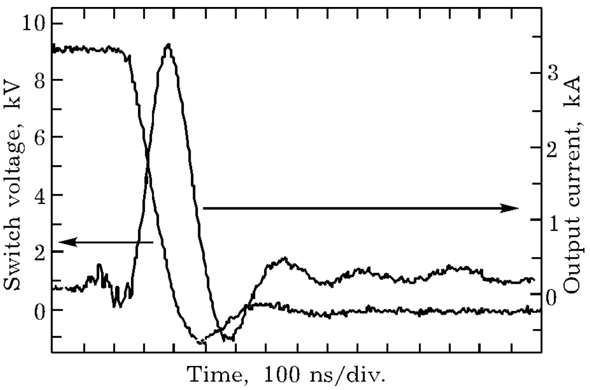

Fig. 3. Current and voltage waveforms of the pulse generator with the stacked switching unit.

ristors, each of which had the gate driver. In this experiment, the type of SI-thyristor employed was different from those mentioned above. An energy storage capacitor of 40 nF was connected to a load resistor of 1 W *via* the switching unit in the test circuit. A resistor of 2 MW was connected in parallel to each SI-thyristor to make the voltage distribution equal. However, in the case of high repetition rate operation, the voltage distribution became non-uniform because of stray capacitance when the unit was switched on. To compensate the stray capacitance, a capacitor of 120 pF was connected in parallel at the highest voltage arm. The circuit current and the anode voltage for each pulse are shown in Fig. 3, where the charging voltage was 9kV and the repetition rate was 2 kHz.

CONCLUSIONS

The power semiconductor devices are recognized as potential fast high power switches in pulsed power technology. Further development is necessary to establish faster turn-on and turn-off characteristics. The SI-thyristors show fast and high current switching capability that is almost comparable to that of the spark gap switches. A break through in the power semiconductor device design will be realized by accumulating the experimental data of the device property under extreme condition. Detailed carrier behavior in the device operated at fast high power switching have to be analyzed and examined theoretically and experimentally.

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