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A Study of a 5.2 kV/100 mm Thyristor Triggered in Impact-Ionization Mode toward Fast High-Current Applications

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Abstract—Microsecond range high-current pulses (hundreds of kA) with high dI/dt (100 kA/ μ s) are used to generate megagauss-range magnetic fields. Industrial applications of such technology require high average power, repeatability and a reliable high-current pulse generator with a long lifespan. Hence, the development of a fast solid-state switch operating in the range of several hundred kA is of great interest. The switching characteristics of semiconductor devices have been substantially enhanced due to an effect of delayed impact-ionization breakdown of high-voltage p-n junction. This leads to the subnanosecond switching time of high-voltage semiconductor devices and increase in their rate of current rise dI/dt capability. Nevertheless, the maximum current amplitude and dI/dt are limited by the area of semiconductor device. Therefore, to increase current switching parameters one can use a large area structure. However, a trigger generator becomes the main challenge, in this case, due to increased capacitance of the switch. In this paper, we study a possibility of triggering large area thyristors in impact-ionization wave mode using a Marx generator equipped with a peaking module. An experimental setup has been developed to investigate a switching process of the thyristors with a wafer diameter of 100 mm and a blocking voltage of 5.2 kV. A trigger circuit based on the Marx generator with the peaking module was developed. It can deliver pulses with dV/dt of several kV/ns into a few nF capacitive load which corresponds to the equivalent thyristor capacitance. Next, the transition of thyristor from the blocking state to the conducting state in impact-ionization mode without energy switching is presented. Finally, by adding an energy discharge circuit, the thyristor switching in impact-ionization mode is analyzed. By applying a trigger pulse with dV/dt of 1.7 kV/ns to the thyristor, the voltage across it reaches 10.7 kV that leads to the following switching parameters: thyristor switching time 420 ps, $dI/dt \sim 15$ kA/ μ s, current amplitude ~ 20 kA and current pulse duration ~ 3 μ s. To the best of our knowledge, impact-ionization switching of the standard thyristor (5.2 kV, 100 mm) was demonstrated for the first time.

Index Terms—Commercial thyristors, high dI/dt , impact-ionization switching, Marx generator, pulsed power systems, subnanosecond switching time.

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I. INTRODUCTION

APPLYING a steep overvoltage pulse with a rise rate dv/dt of more than 1 kV/ns to high-voltage diodes leads to a subnanosecond switching as it was first time demonstrated by Grekhov at Ioffe Institute in 1979 [1]. Based on this significant breakthrough in semiconductor physics, four-layer dynistor structures capable of switching kA currents with a rate of current rise dI/dt of up to 200 kA/ μ s were developed. The operating principles and detailed discussions on characteristics of such devices can be found in [2], [3]. In an attempt to extend this discovery to commercial semiconductors, triggering thyristors in impact-ionization switching mode has been successfully tested in [4], [5].

The major difference between impact-ionization switching and conventional switching of a thyristor is highlighted as follows. First, in a conventional thyristor switching mechanism, current carriers are injected through the gate electrode [6]. This process injects electron-hole plasma from n and p layers located on the opposite side of thyristors to depleted p-n junction of space charge region. Theoretically, nanosecond switching time can be obtained in standard thyristors with a conventional switching mechanism [7]. Carrier saturation velocity (10^7 cm/s for electrons in silicon) is a limiting factor in this switching process, which results in a switching time of several nanoseconds for high voltage thyristors (300-400 μ m base length). On the other hand, in impact-ionization switching mode, the gate electrode remains open and a steep triggering pulse is applied to the cathode and anode electrodes of thyristor. To meet the parameters of impact-ionization switching, the trigger pulse must have two characteristics: (i) rise rate of triggering pulse dV/dt of more than 1 kV/ns and (ii) maximum voltage of triggering pulse twice that of stationary breakdown voltage. With employing aforementioned conditions, electron-hole plasma is generated directly within space charge region leading to subnanosecond switching time. It is noteworthy that switching happens only on the particular part of the cross section. Hence, subnanosecond switching time can be explained as a result of superfast discharge of the non-avalanche part of device via conducting part [8].

Subnanosecond impact-ionization switching and reaching high current pulses can be employed in several research domains such as: inertial fusion [9], X-pinch [10], [11] and high-energy-density physics [12]. Moreover, a number of industrial applications such as magnetic pulse forming and welding, rock

fracturing [13] and mining require high current pulses in the range of hundreds of kA [14].

To address the abovementioned demand of pulsed power applications, several studies have been conducted to reach high current with high level of rise rate [15]–[22]. Reverse switching dynistors (RSD) have been demonstrated to reach ultra high currents of several hundred kA in [15]–[20]. The main drawback of these devices is RSDs limitation in terms of dI/dt which is up to $40 \text{ kA}/\mu\text{s}$ at current amplitude above 100 kA [20].

A low-frequency commercial thyristor with a wafer diameter of 40 mm triggered in impact-ionization wave mode is able to switch current pulses with an amplitude of 45 kA and dI/dt of $134 \text{ kA}/\mu\text{s}$ [22]. Further study in [23] reveals promising results for silicon wafers of 56 mm diameter as follows: the blocking voltage of 5 kV , the switching current of more than 200 kA , the rate of current rise more than $50 \text{ kA}/\mu\text{s}$ and the pulse duration of $25 \mu\text{s}$. These results show that a standard thyristor triggered in impact-ionization mode is a promising approach to build a high-current semiconductor switch for pulsed power systems. However, it reveals limitations in current amplitude, which can be overcome by higher dV/dt triggering pulse or using a thyristors with larger area.

The main contribution of this paper is to prove the possibility of switching 5.2 kV thyristors with a wafer diameter of 100 mm in impact-ionization mode. The preliminary results of subnanosecond switching time of this thyristor confirm impact-ionization mode of operation. Successful tests of switching current pulses with an amplitude of 20 kA and dI/dt of $15 \text{ kA}/\mu\text{s}$ make us believe that higher values are feasible. Indeed, these two parameters are currently limited not by thyristor itself but by the amount of stored energy and the connection inductance between the capacitor bank and the thyristor. The experimental setup and obtained results are presented in following sections.

II. TRIGGER GENERATOR OPTIMIZATION

A. Thyristor Equivalent Capacitance

Applying a triggering pulse with a rise rate of more than 1 kV/ns is crucial for the impact-ionization switching. To safely test thyristors, we were using an equivalent load to optimize the trigger generator. A forward-biased thyristor (positive anode-cathode voltage) can be considered as a capacitor. In this case, the capacitance of the thyristor is mostly due to the barrier capacitance of the intermediate p-n junction, which is in the reverse direction. In order to find the equivalent capacitance of the thyristor T193-2500-52 with 100 mm wafer diameter and 5.2 kV blocking voltage, we followed the procedure below for three thyristors of the same type.

- 1) The capacitance is measured at the bias voltage of up to 30 V as illustrated in Fig. 1(a); all thyristors show similar behavior.
- 2) Depending on a doping profile a p-n junction can be of two main categories: abrupt junction and linearly graded junction. In [24], capacitance-voltage relationship is stated as $C \propto V^{-n}$ and the value of n for

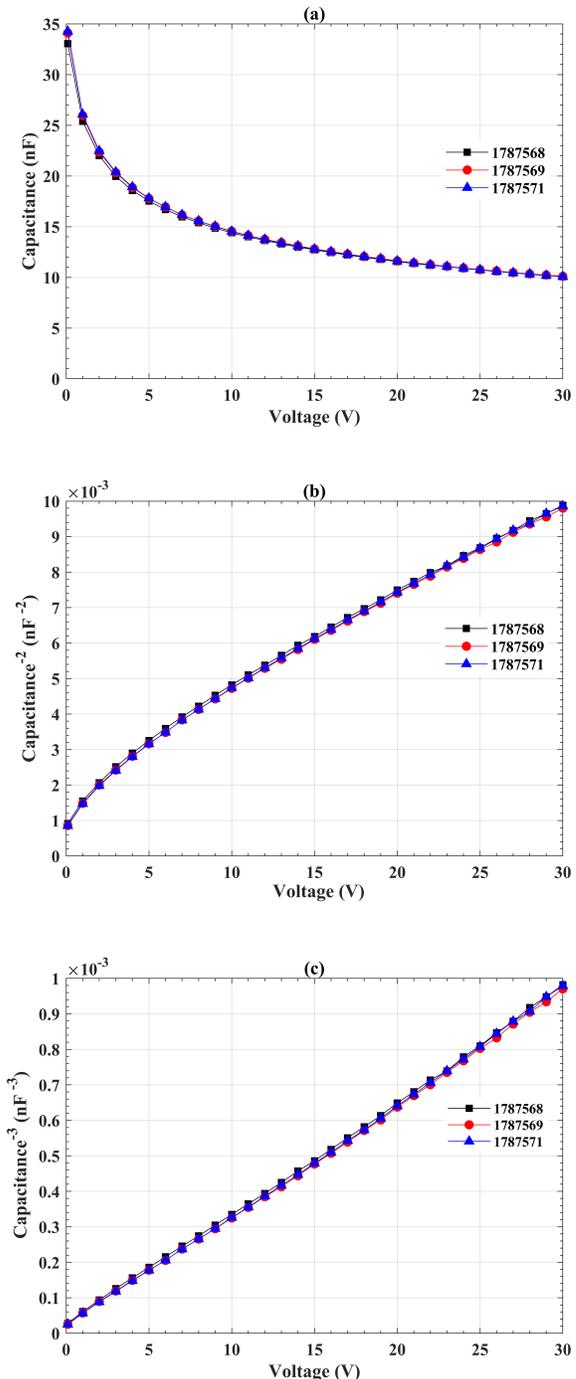


Fig. 1. The equivalent capacitance calculation of thyristor T193-2500-52: (a) the measurement of low voltage capacitance of thyristors, (b) the plot of negative second power capacitance versus voltage, (c) the plot of negative third power capacitance versus voltage.

abrupt or linearly graded junctions is 2 and 3 respectively. The plot of capacitance-voltage relationship for these two semiconductor doping profiles is illustrated in Fig. 1(b) and Fig. 1(c). The most linear relationship is achieved through calculation of negative third power of capacitance versus voltage as plotted in Fig. 1(c). This indicates the high voltage thyristor doping profile is based on linearly graded p-n junction.

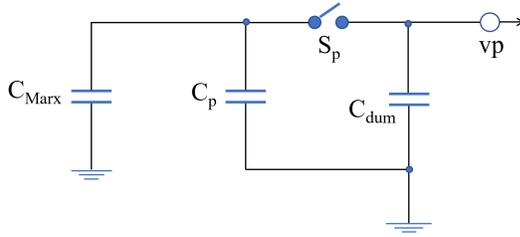


Fig. 2. An electrical diagram of the capacitive dummy load test.

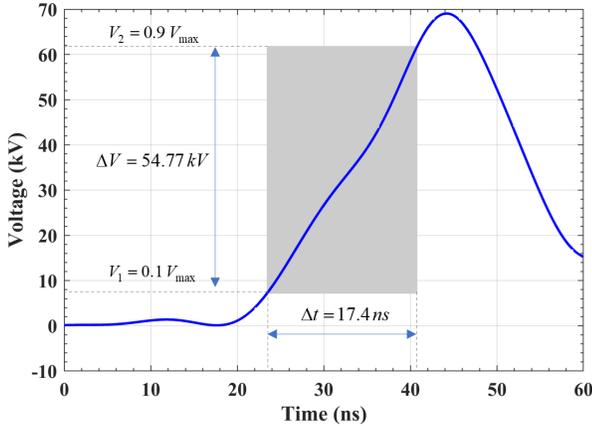


Fig. 3. The triggering pulse applied across the capacitive dummy load: calculation of rise rate.

- 3) Extrapolating the bias voltage up to the nominal value of 5.2 kV, we found the equivalent capacitance of 1.85 nF, which reduces to 1.46 nF at 10 kV. Assuming linear change, an average value of 1.6 nF was considered as the thyristor equivalent capacitance in the experiment. Therefore, the trigger requirement is defined as charging a capacitive load of 1.6 nF up to 10 kV in less than 10 ns.

B. Experimental Test of the Capacitive Dummy Load

A simplified schematic of experimental setup to test the dummy load is shown in Fig. 2. The Marx generator (MM4) is used to provide triggering pulses. MM4 has 4 stages with maximum output voltage of up to 40 kV per stage, and its total equivalent capacitance, C_{Marx} , is 500 pF. The charging and discharging resistances of MM4 are 47 k Ω and 10 k Ω , respectively. Self-breakdown spark gaps operated in air at atmospheric pressure are used as switches. This trigger theoretically can provide 160 kV and the energy of 6.4 J into a load.

To test the trigger generator, we use the capacitive dummy load, C_{dum} consisted of ceramic capacitor of 1.6 nF. A peaking module including an equivalent peaking capacitor C_p of 235 pF and a peaking spark gap switch is added to the output of the Marx generator. The equivalent peaking capacitor includes two stacks of capacitors in parallel, and each stack consists of four capacitors of 471 pF with an operational voltage of 15 kV. For measuring voltage across the capacitive dummy load, a

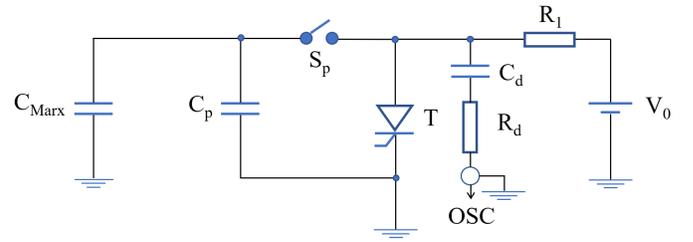


Fig. 4. An electrical diagram of experimental setup for triggering thyristor in impact-ionization mode with 5.2 kV bias voltage.

Northstar PVM-5 high-voltage probe is used, which is shown as vp in Fig. 2.

The peaking module connected to the output of the Marx generator plays a significant role to enhance the rise rate of triggering pulses. It sharpens the voltage waveform delivered to the device under test (DUT). The electrode distance of spark gap and pressure are calculated to selfbreak at around 100 kV. This compact energy storage, connected to the DUT with a minimized inductance of connection, increases the voltage rise rate across the load.

The triggering pulse across the capacitive dummy load is shown in Fig. 3. In order to calculate the rise rate, dV/dt is considered from 10 to 90 percent of maximum value of the voltage waveform across dummy load. As seen in Fig. 3, the triggering pulse reaches approximately 69 kV with dV/dt of 3.13 kV/ns. This result confirms an enhanced rise rate of triggering pulse using peaking module, allowing to continue the study by replacing the capacitive dummy load with a thyristor in the next stage.

III. THYRISTOR SWITCHING

A. Triggering Stage

After optimizing the trigger to reach a proper voltage rise rate, the 5.2 kV thyristor (T) with wafer diameter of 100 mm is implemented within the experimental setup, as illustrated in Fig. 4. In order to trigger the thyristor in impact-ionization mode without energy switching the procedure bellow is followed.

In the initial state, a dc voltage source supplies $V_0 = 5.2$ kV bias voltage across the thyristor. A 35 k Ω resistor (R_1) is used to decouple dc voltage source from triggering pulse. While the bias voltage is maintained, a triggering pulse produced by the Marx generator and enhanced by the peaking module in terms of rise rate is applied across the main electrodes of switch T.

In order to measure voltage across the thyristor, a wide bandwidth voltage probe described in [25] is used. This voltage probe is a resistive divider consisted of a ceramic resistor $R_d = 1$ k Ω as high voltage arm resistance and 50 Ω coaxial cable as a low voltage arm. Coupling capacitor $C_d = 1$ nF is employed in order to isolate the probe from bias voltage. Cable braiding is extended up to half of ceramic resistor in order to compensate parasitic inductance. The wide bandwidth voltage probe measurement is tested up to 10 kV with frequency response of around 1 GHz, with usable rise time of ~ 200 ps.

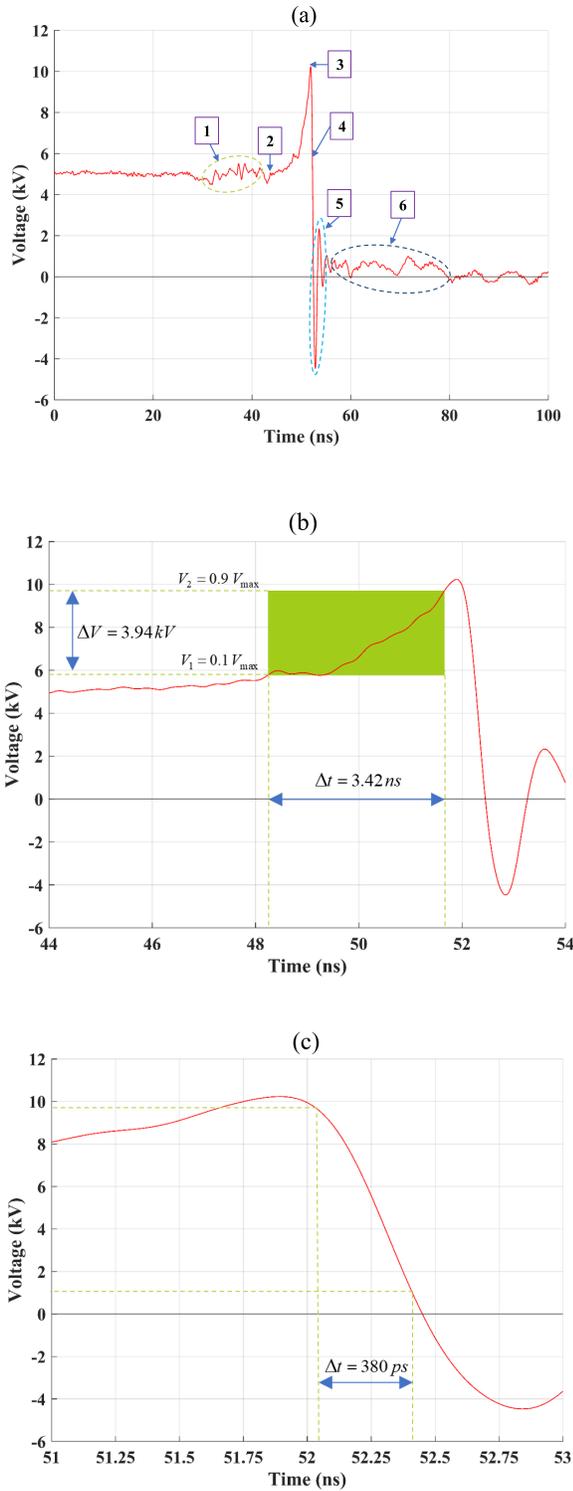


Fig. 5. The triggering pulse applied to the thyristor: (a) voltage waveform, (b) calculation of rise rate and (c) calculation of switching time.

The experimental result of applying triggering pulse to the switch T is illustrated in Fig. 5(a). The triggering pulse starts from bias voltage of 5.2 kV. Different stages of the pulse depicted in Fig. 5(a) can be explained as follows: (1) Marx generator commutation causes minor voltage disturbance of

measurement, (2) closure of peaking spark gap switch S_p leads to a steep triggering pulse, (3) maximum voltage across the switch T is about twice of the thyristor blocking voltage, (4) subnanosecond switching of thyristor, (5) transient oscillations occur due to parasitic components of the voltage probe measurement, and (6) finally, voltage drops to zero with negligible fluctuation of measurement.

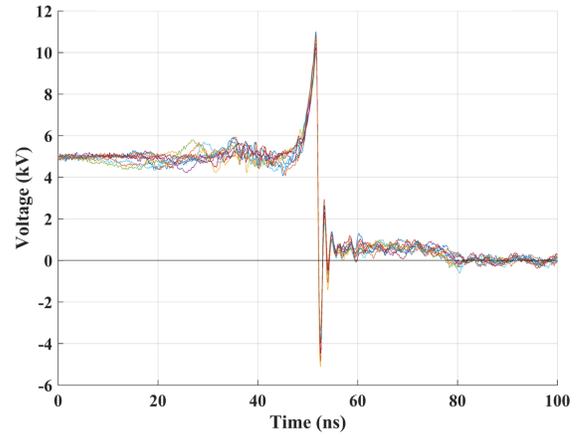


Fig. 6. Reproducibility of the experimental result over 10 shots.

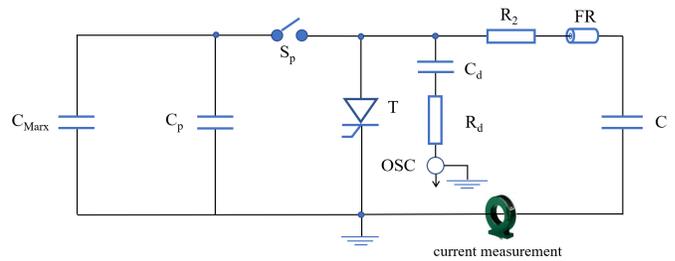


Fig. 7. A simplified electrical diagram of the experimental setup with energy switching.

Fig. 5(b) and Fig. 5(c) depict the calculation of dV/dt and switching time of the thyristor, respectively. The triggering pulse dV/dt equals to 1.15 kV/ns alongside with maximum voltage of 10.4 kV (twice of blocking voltage of the thyristor) guarantee superfast impact-ionization switching of the thyristor [26]. As a result, switching time of the thyristor is within subnanosecond range i.e. 380 ps, which indirectly confirms impact-ionization manner of switching. In this calculation, the switching time is considered from 90 to 10 percent of the pulse maximum value.

Hitherto, one of the most significant characteristics of impact-ionization mode, i.e. picosecond switching time, is proved for the standard 5.2 kV thyristor with a 100 mm wafer. It is worth mentioning that this is the first time such a thyristor is triggered in impact-ionization mode. However, one important practical aspect of this work for industrial application, which is the reproducibility of the experimental result, has not been addressed yet. That is why the same experiment is repeated for over 10 triggering pulses. The experimental results demonstrating the reproducibility of such tests are illustrated in Fig. 6.

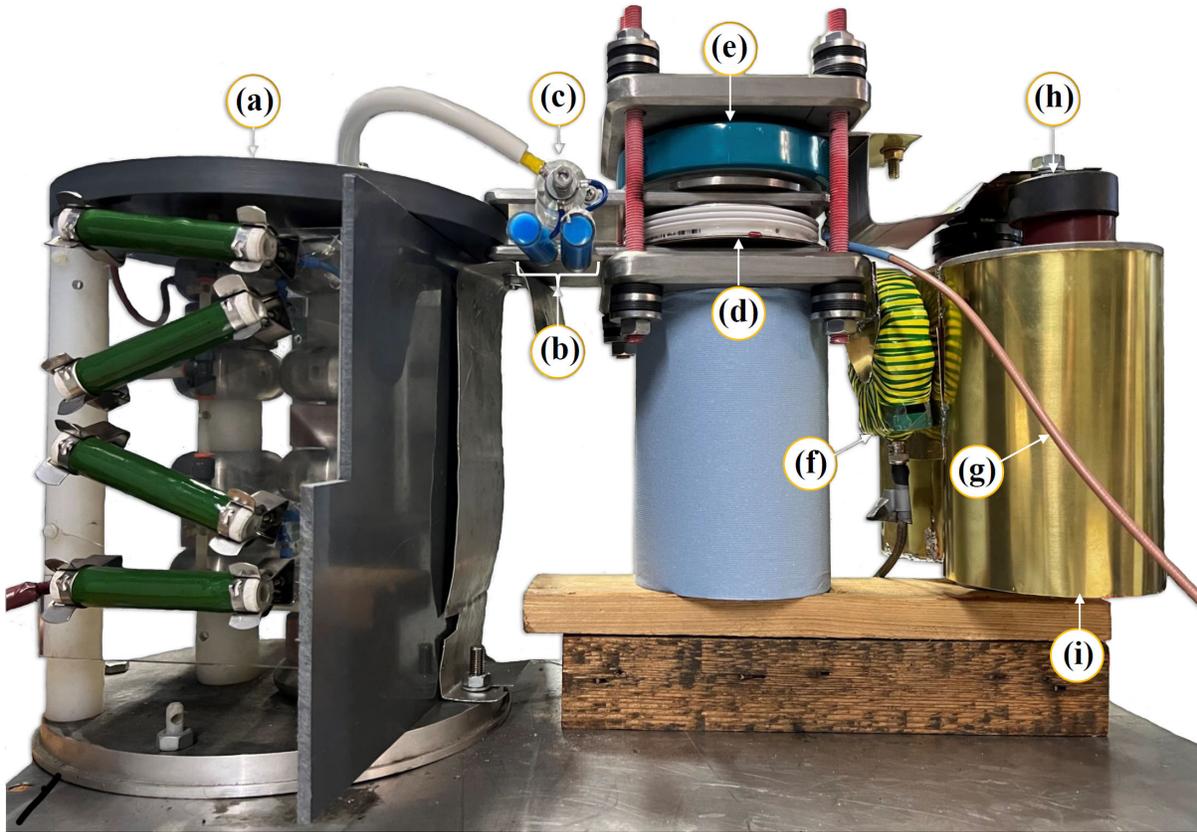


Fig. 8. Experimental setup for triggering thyristor in impact-ionization mode with energy switching.

After these experiments, no degradation of the thyristor has been observed since leakage current of the thyristor ($14 \mu\text{A}$) is exactly the same as its initial value. This indicates the experiment on the thyristor can be continued to the next stage which is adding a discharging circuit to the experimental setup.

B. Current Flow Stage

The main focus of this section is regarding the thyristor switching with the additional capacitor discharging circuit. The discharging circuit, added to experimental setup illustrated in Fig. 7, includes a capacitor bank (C), a resistor (R) and ferrite rings (FRs). In this experiment the external dc power supply in Section III.A is replaced by a capacitor bank of $C = 10 \mu\text{F}$, and $20 \mu\text{F}$ for two following conducted experiments, respectively. The capacitor bank in these experiments is shielded in order to minimize the series inductance. In addition, the decoupling resistor $R_1 = 35 \text{ k}\Omega$ is replaced by a resistor of $R_2 = 0.2 \Omega$ and 0.25Ω for two experiments in current flow stage. The value of resistor R_2 is optimized to minimize the reverse current on the thyristor and thus avoid damaging it. In addition, the FRs are used to isolate the triggering pulse over thyristor from other elements.

Fig. 8 shows the actual experimental setup in which different components can be seen as: (a) Marx generator (MM4), (b) peaking capacitor, (c) peaking spark gap, (d) thyristor, (e) resistor of discharging circuit ($R_2 = 0.25 \Omega$), (f) current

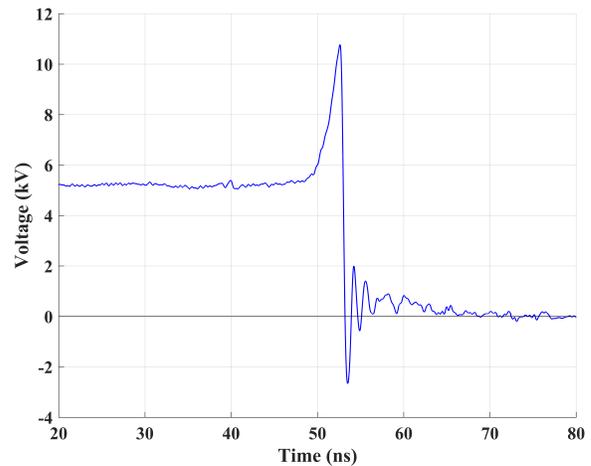


Fig. 9. The triggering pulse applied to the thyristor in energy switching circuit.

measurement, (g) wide bandwidth voltage probe measurement, (h) FRs and (i) capacitor bank.

In the first experiment, the $10 \mu\text{F}$ capacitor bank is charged by the external dc voltage source up to 5.2 kV . A bias voltage of $V_0 = 5.2 \text{ kV}$, which is equal to the thyristor nominal voltage, is directly applied over cathode and anode electrodes of the thyristor. Then a triggering pulse is applied and voltage

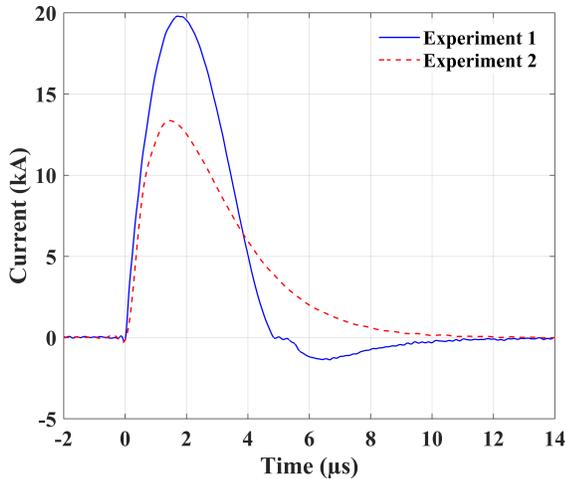


Fig. 10. The current pulse in energy switching circuit at $R_2 = 0.2 \Omega$ (solid curve) and $R_2 = 0.25 \Omega$ (dashed curve).

over thyristor is measured in similar manner of previous experiment. The measured pulse voltage over the thyristor is illustrated in Fig. 9. The bias voltage of 5.2 kV is followed by a steep voltage pulse with dV/dt of 1.7 kV/ns and amplitude of 10.7 kV. Eventually, picosecond switching happens with a switching time of 420 ps. Transient oscillations that one can see after the switching are probably caused by the parasitic parameters of the voltage probe measurement. Finally, voltage drops to zero with negligible fluctuations.

In addition to pulse voltage, microsecond range current is measured in energy switching mode as depicted in Fig. 10. A Pearson current monitor model 101 is used to measure current.

Two experiments have been carried out for this stage: First, a single capacitor of $10 \mu\text{F}$ is used alongside with a resistor of 0.2Ω within discharging circuit. In this experiment, the current waveform shows rise rate of $15 \text{ kA}/\mu\text{s}$ from 10 to 90 percent of maximum current and pulse duration (FWHM) of $3 \mu\text{s}$. In this particular discharging circuit maximum current of 20 kA is measured. The current wave form $4.9 \mu\text{s}$ to $5.3 \mu\text{s}$ illustrates the impact of FRs employed within discharging circuit. This flat part of the current waveform is the time duration of FRs saturation in reverse polarity. After the saturation of FRs, a reverse current appears over the thyristor. In this experiment, we obtained a higher peak current than expected in the simulation. This can be explained by the resistor flashover, which leads to lower resistance in comparison with the nominal value ($R_2 \ll 0.2 \Omega$ in Fig. 7). Thus, the resistor is replaced in the following experiment.

Second, two capacitors of $20 \mu\text{F}$ in total are used alongside with HVR ceramic disk resistor of 0.25Ω . With these new elements in discharging circuit, the reverse current is completely eliminated. However, increased resistance in discharging circuit leads to decrease in maximum current amplitude. The results of the second experiment are as follows: the rise rate of $12 \text{ kA}/\mu\text{s}$, FWHM of $3.4 \mu\text{s}$ and maximum current amplitude of 13.5 kA. The dI/dt value is mainly limited by the parasitic inductance of the discharging loop. According to

the Spice simulation, this parasitic inductance was estimated as 230 nH and 190 nH for the first and second experiments respectively.

A thyristor switching efficiency of 0.85 is calculated as $(1 - E_T/E_C)$, where $E_T = 40 \text{ J}$ is the thyristor energy loss and $E_C = 270.4 \text{ J}$ is the energy initially stored in the capacitor bank. This relatively good switching efficiency makes us believe that the thyristor is not a limiting factor to reach higher current values.

Degradation of the thyristor after aforementioned experiments in terms of leakage current has not been observed.

IV. CONCLUSION

In this paper, triggering of 5.2 kV/100 mm thyristor in impact-ionization wave mode has been demonstrated for the first time from the perspective of both the rated voltage and wafer diameter. Based on experimental results it can be concluded that thyristor is not a limiting component to reach higher currents with a high level of dI/dt .

Although the present study proves the concept of impact-ionization switching of large area thyristors, the switching limits will be revealed in future studies. The discharge loop parasitic inductance and limited energy stored in a capacitor bank prevent reaching the higher current and dI/dt values. Therefore, the circuit should be improved by reducing the parasitic inductance (e.g. by connecting more capacitors in parallel) and by increasing the charging voltage of the capacitor bank (stacking several thyristors in series). This seems a promising approach to reaching high currents in the range of a few hundred kA with high dI/dt .

To achieve this goal, which would be a game-changer in pulsed power, the trigger generator must be capable of charging each thyristor in the stack up to double the stationary breakdown voltage with dV/dt of more than 1 kV/ns, which is required for the impact-ionization switching mode.

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