Thyristor Based Switches Triggered in Impact-Ionization Wave Mode

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***Abstract*—Commercial thyristors of tablet design with diameters of silicon wafers of 40 to 56 mm and an operating voltage of 2 to 2.4 kV DC were triggered by an external overvoltage pulse applied across the thyristor main electrodes. In experiments a voltage rise rate across the thyristor was changed from 0.5 to 6 kV/ns. Under such conditions the thyristor closing process occurred due to initiation and propagation of a fast ionization front across the semiconductor structure. The time of switching the thyristor from the blocking state to the conducting state was within 200 to 400 ps. The thyristor based switches operated in this mode were tested in two discharge circuits. In the first circuit, an assembly of nine 2-kV and 40-mm thyristors connected in series switched a 2-μF capacitor, which was charged to a voltage of 20 kV, to a resistive load of 0.17 Ω. The following results were obtained: discharge current amplitude of 45 kA, maximum current-rise rate of 134 kA/μs, current rise time (0.1-0.9 level) of ~0.4 μs, pulse duration (FWHM) of ~1 μs, and switching efficiency of 0.85. In the second circuit, the switch contained two 2.4-kV and 56-mm thyristors connected in series. A 1.1-mF capacitor, which was charged to a voltage of 5 kV, was switched to a resistive load of 0.018 Ω. The following discharge parameters were obtained: discharge current amplitude of 200 kA, maximum current-rise rate of 58 kA/μs, current rise time (0.1-0.9 level) of 5.5 μs, pulse duration (FWHM) of ~25 μs, and switching efficiency of 0.97. It was shown that the voltage rise rate at the triggering stage was the main factor affected on the thyristors switching characteristics.**

Keywords—commercial thyristors; fast ionization front; high current-rise rate; subnanosecond switching process

I. INTRODUCTION

In recent years, semiconductor switches on the basis of dynistor structures with a time of transition into a conducting state of <1 ns were developed at the Ioffe Physical Technical Institute [1], [2]. Such switches – deep-level dynistors (DLDs) – are able to switch a current of several kiloamperes of a capacitive energy storage at a current rise rate of up to 200 kA/μs; at present, this cannot be attained using any other semiconductor switches [2]. A DLD is switched into a conducting state upon application of an overvoltage pulse with a rise rate of >1 kV/ns. This allows the electric field in the plane of the reversely biased collector junction of the dynistor to be increased to values of 300–350 kV/cm, at which an intense ionization of deep levels in silicon is initiated, within a few nanoseconds.

The injection of electrons from these centers into the structure region with a high field initiates an impact-ionization wave, which passes through the structure of a device and uniformly fills its entire area with dense electron-hole plasma. The wave motion velocity is considerably higher than the saturated velocity of carriers in silicon; in connection with this, the structure of a device with a typical wafer thickness of several hundred microns and a carrier transit time of a few nanoseconds is filled with plasma with a time of several hundred picoseconds. The further current flow through the structure is maintained by the injection of carriers into the base regions through the injector junctions. Detailed descriptions of the physical principles of the DLD operation can be found, e.g., in [3] and [4].

Recently it was shown in [5] and [6] that ordinary thyristors, which, as dynistors, have a four-layer semiconductor structure, can operate in such a mode. A thyristor switch, which contained several series-connected commercial thyristors of tablet design with diameter of silicon wafer of 40 mm, was triggered by an external overvoltage pulse with a few nanosecond rise time [5]. The switch operated at current pulse amplitude of over 20 kA and a current rise rate dI/dt of over 100 kA/μs. Compared with the traditional mechanism for triggering the thyristor by a current pulse through the gate electrode the dI/dt value was increased about 250 times.

In [6] the impact-ionization switching of power thyristors, implemented by an overvoltage pulse with a nanosecond rise time, applied to main thyristor electrodes, was studied experimentally and by numerical simulation methods. It was shown that the voltage rise rate at the triggering stage was the main factor affected on the time of switching the thyristor from the blocking state to the conducting state.

This work continues the research started in [5] and [6]. We study the thyristor based switches triggered in impact-ionization wave mode and operated in different discharge circuits. The results of experiments on switching current pulses with amplitude of up to 200 kA during discharge capacitors with up to 15 kJ of stored energy are presented. Effect of the

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voltage rise rate at the triggering stage on the thyristors main switching characteristics is shown and discussed.

II. SWITCHING PROCESS

A. Experimental Circuitry and Tested Thyristors

Experimental electrical circuit for studying the process of switching a thyristor from the blocking state to conducting state is shown in Fig. 1. The circuit contains capacitor C1 = 0.1 µF charged to a bias voltage U_0 = 2 kV of negative polarity. The bias voltage is applied to tested thyristor T through the resistor R1 = 100 kΩ. For thyristor triggering a compact solid state generator is used. Output unit of the generator contains coaxial oil-filled 50-Ω line (item 1 in Fig. 1). Triggering pulse of negative polarity is delivered to thyristor T via isolating ceramic capacitor C2 (4.7 nF), and is registered by means of capacitive probe 2. The output pulse in the line has amplitude of ~40 kV and a rise time of ~0.9 ns measured at a level of 0.1–0.9 of the amplitude value.

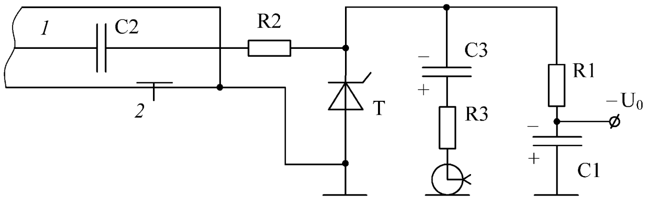

Fig. 1. Circuit diagram of the experimental setup.

Resistor R2 serves to change a triggering voltage rise rate across thyristor T. In experiments the value of resistance R2 was varied from zero (resistor is short circuited) up to ~500 Ω.

In experiments we used two types of commercial low-frequency tablet thyristors made in Russia (http://www.proton-electrotex.com). The thyristors are of common use and intended for operation in industrial frequency converters. The thyristors had the same DC operating voltage of 2 kV, but were different in wafer diameter and initial resistivity of the *n*-type silicon. The first thyristor of T343-500 type had the following main specifications: DC operating voltage was 2 kV, surge current amplitude was 8 kA, critical current rise rate was 400 A/µs, and diameter of silicon wafer was 40 mm. It was made from silicon with initial resistivity ρ = 80–85 Ω·cm. The second thyristor of T133-320 type had the same operating voltage of 2 kV, surge current amplitude of 6 kA, critical current rise rate of 100 A/µs, diameter of silicon wafer of 32 mm, and silicon initial resistivity of 110–120 Ω·cm. Visual appearance of T343-500 thyristor is given in Fig. 2.

The voltage across thyristor T was measured by means of resistive divider having elements C3 and R3 (Fig. 1). The divider contains high voltage arm – resistor R3, and low voltage arm – 50-Ω cable loaded on 50-Ω attenuator. Capacitor C3 is charged to the voltage U_0 and serves for the divider isolation from DC bias voltage. To reduce own inductance of the divider elements capacitor C3 rated at 680 pF was made of metallized Mylar film with 50-µm thickness, and resistor R3 rated at 500 Ω was shielded partly by registration cable braiding. Own transient response of the divider determined under calibration procedure was ~170 ps at a level of 0.1–0.9 of a signal amplitude value. To escape the influence of the inductance of the thyristor contacts located inside the casing, semiconductor wafer was extracted from the casing, and the divider was connected directly across the wafer. The measuring circuit included 18-GHz attenuators and a Tektronix DPO 70404C 4-GHz digital real-time oscilloscope.

Fig. 2. Visual appearance of T343-500 thyristor having a silicon wafer of 40 mm in diameter.

B. Experimental Results

Typical waveform of the voltage across the thyristor semiconductor wafer at the triggering stage is shown in Fig. 3. In each experiment at fixed resistance R2 the following parameters were determined (see Fig. 3): voltage rise time t_r from initial value of U_0 to the maximum voltage value, maximum voltage value U_m, switching time t_s (level of 0.1–0.9 of the amplitude value U_m), voltage increasing $\Delta U = U_m - U_0$, and voltage rise rate $dU/dt = \Delta U/t_r$. The value of the bias voltage U_0 was equal to 2 kV and was not changed during experiments.

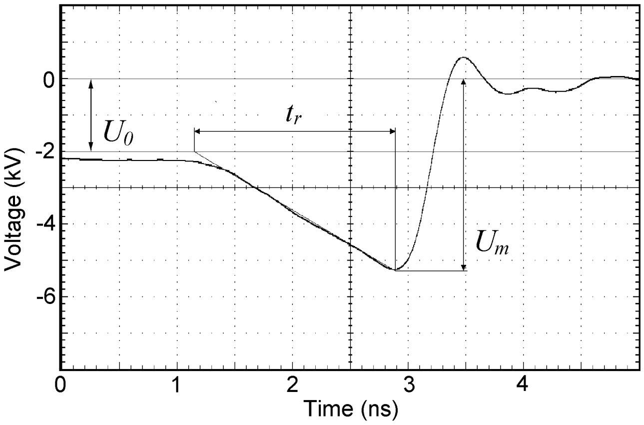

Fig. 3. Waveform of the voltage across 32-mm thyristor during switching process. U_0 = -2 kV, R2 = 140 Ω.

Experimental dependences were obtained by varying the resistance R2. Fig. 4 illustrates some of the waveforms obtained at different values of resistance R2, and experimental results are plotted in Figs. 5–7. Increasing in rise time t_r (Fig. 5) was due to increasing resistance R2 from zero (left experimental points) up to ~300 Ω for 40-mm thyristor and ~470 Ω for 32-mm thyristor (right experimental points).

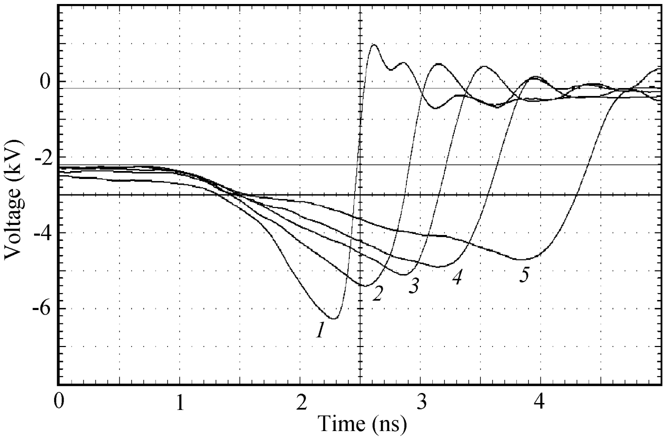

Fig. 4. Waveforms of the voltage across 32-mm thyristor during switching process. U_0 = -2 kV, R2 = 0 (*1*), 88 (*2*), 196 (*3*), 297 (*4*), and 467 Ω (*5*).

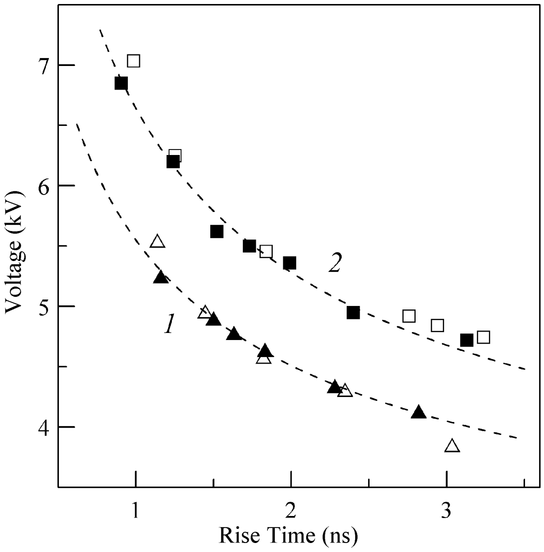

Fig. 5. Time dependences of the maximum voltage U_m across 40-mm thyristor (curve *1*) and 32-mm thyristor (curve *2*). Black symbols – experiment, white symbols – numerical simulation, dashed curves – equation (1).

Analytical treatment of experimental data showed that for all experimental points the product $(\varDelta U)^2 \cdot t_r$ was close to a constant. This allows writing the following empirical equation

$$U_m = U_0 + (a_{32,40} / t_r)^{1/2} \tag{1}$$

where the constant a_{32} = 21.54 $(\mathrm{kV})^2 \cdot$ns is for 32-mm thyristor, and a_{40} = 12.6 $(\mathrm{kV})^2 \cdot$ns is for 40-mm thyristor. Equations (1) are presented in Fig. 5 as dashed curves. Average deviation of experimental values U_m from the calculated ones in accordance with (1) is 0.3% for 40-mm thyristor and 1.2% for 32-mm thyristor. Figures 5 and 6 contain also the results of numerical simulations, which are presented in detail in [6].

Figure 6 shows the influence of the voltage rise rate *dU/dt* on the maximum voltage U_m. Assuming $dU/dt = \varDelta U/t_r$ and using (1) we receive the following equation

$$U_m = U_0 + (a_{32,40}\, dU/dt)^{1/3}. \tag{2}$$

Average deviation of experimental values U_m from the calculated ones in accordance with (2) is <1% for the both thyristors.

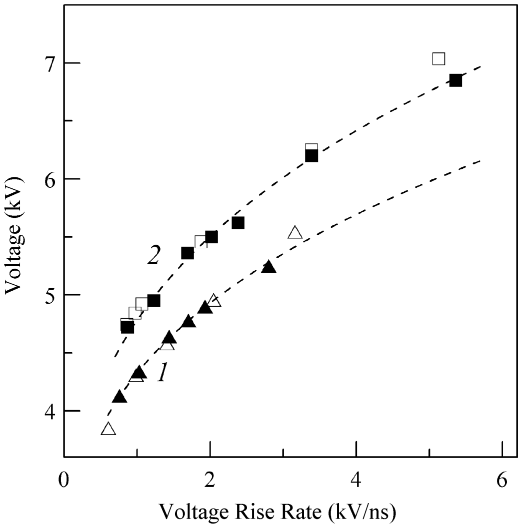

Fig. 6. Maximum voltage U_m as a function of the voltage rise rate for 40-mm thyristor (curve *1*) and 32-mm thyristor (curve *2*). Black symbols – experiment, white symbols – numerical simulation, dashed curves – equation (2).

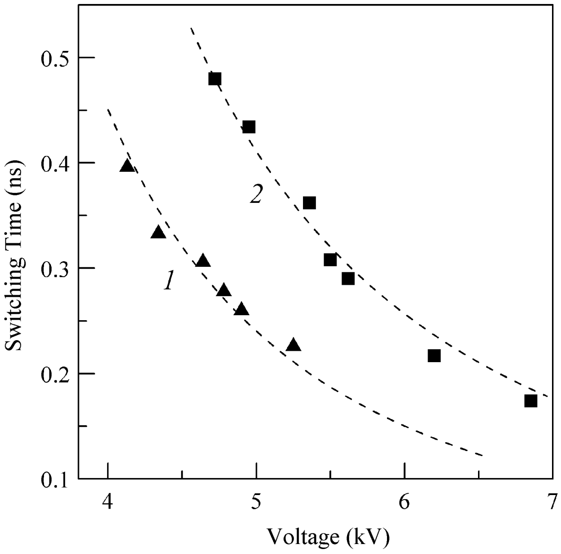

Fig. 7. Switching time t_s as a function of the maximum voltage U_m for 40-mm thyristor (curve *1*) and 32-mm thyristor (curve *2*). Symbols – experiment, dashed curves – equation (4).

In Fig.7 experimental data on the switching time t_s are presented. Switching time is reduced with increasing the voltage across the thyristor. Analytical treatment of these experimental data showed that parameter $\Delta U \cdot t_r \,/\, U_m \cdot t_s$ was close to a constant. This allows writing the following empirical equation

$$t_s = b_s\, \Delta U\, t_r \,/\, U_m \tag{3}$$

where $b_s = 0.286$ is a common constant for the thyristors of both types. Assuming (1) equation (3) can be written as

$$t_s = a_{32,40}\, b_s \,/\, (U_m - U_0)\, U_m\,. \tag{4}$$

Equations (4) are presented in Fig. 7 as dashed curves. Average deviation of experimental values t_s from the calculated ones in accordance with (4) is 4.7% for the thyristors of both types.

From empirical equation (4) describing the dependence of the switching time t_s on U_m (Fig. 7), it follows that, in the approximate form, $t_s \sim 1/(U_m - U_0)^2$ or $t_s \sim 1/(E_m - E_0)^2$. These relations confirm the conclusion that the voltage-drop process is caused by the propagation of impact-ionization waves in the thyristor structure, for which the front velocity is proportional to $(E_m - E_b)^2$, where E_b is the static breakdown field [6].

III. THYRISTOR BASED SWITCHES

Thyristor based switches operating in the impact ionization wave mode were tested in two discharge circuits. The first circuit had a capacitive storage with a charging voltage of 20 kV and a stored energy of 400 J, in the second one these parameters were equal to 5 kV and up to 15 kJ, respectively.

A. *20-kV Switch Operating at 45-kA Peak Current and 130-kA/µs Current Rise Rate*

Experimental electrical circuit is shown in Fig. 8. A capacitive storage C is charged to the voltage level U_0 of negative polarity from an external DC power supply. After the tested switch T is triggered, the storage is discharged through a resistive load R, whose value is chosen to be close to the characteristic impedance of the discharge circuit. The inductance L represents a stray inductance of the discharge circuit. The measured values of the discharge circuit elements were as follows: C was 2 µF, L was 0.1 µH, and R was 0.17 Ω.

The layout of the experimental circuit elements is shown in Fig. 9. The discharging loop had a coaxial design. Storage capacitors *1* were placed between round electrodes *2* and *3* having outer diameter of 400 mm. Along the central axis thyristors *4* and metal rods *5* were located. Rogowski coil *6* was fixed on one of the rods. Load resistors *7* were soldered on a radius in the central hole of electrode *3*. The construction had a total height of 300 mm.

In experiment the thyristors of T343-500 type with 40-mm wafer were connected in series in amount up to 9 pieces (Fig. 9 shows 6 thyristors) and compressed with recommended axial force of 14 kN. Charging voltage U_0 was uniformly distributed across the series connected thyristors with the help of chains made of resistors and varistors. The gate electrodes of the thyristors were in open state. The triggering pulse was applied across the whole stack of the series connected thyristors from the same generator described above. The arriving triggering pulse affected only the thyristors T, because the elements C and R were blocked by the circuit inductance L, and the power supply with the voltage U_0 was connected through a charging resistor.

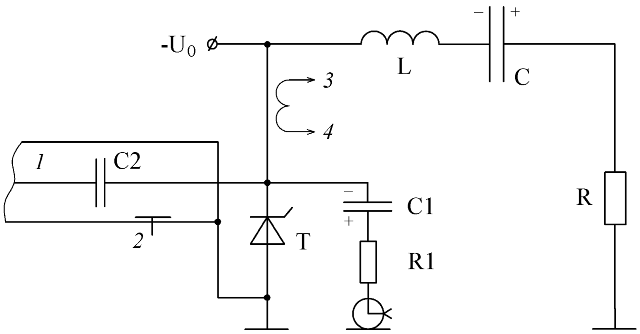

Fig. 8. Experimental discharge circuit.

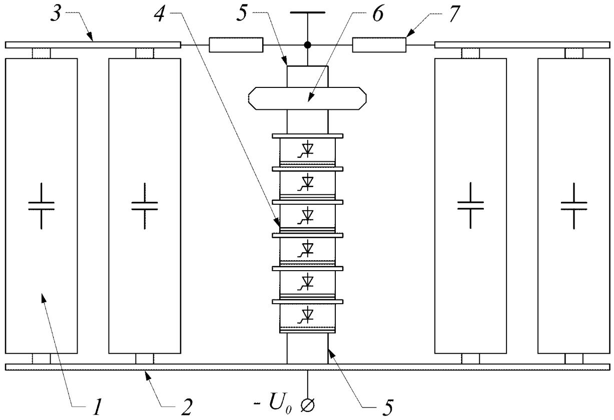

Fig. 9. Layout of the circuit elements.

The current was measured by Rogowski coil (outputs *3* and *4* in Fig. 8), and the resistive voltage divider was connected across only the first thyristor in the stack, which had a connection to a ground bar.

At high level of the current rise rate in the circuit, it becomes necessary to consider for the voltage drop across the thyristor own inductance. To determine the inductance in one of the thyristors in the stack, to which the voltage divider is connected, a semiconductor element was replaced by a copper plate with the corresponding thickness and diameter sizes. The thyristor inductance that was determined in this way using waveforms of the voltage and current through it was ~1.8 nH.

Figure 10 shows the waveforms obtained at the maximum charging voltage of 20 kV. The following results were obtained: discharge current amplitude was 45 kA, maximum current-rise rate was 134 kA/µs, current rise time (0.1-0.9

level) was ~0.4 μs, pulse duration (FWHM) was ~1 μs, and switching efficiency was 0.85.

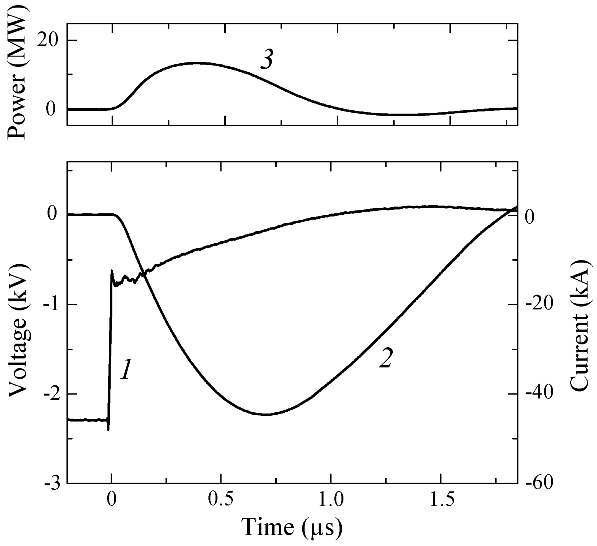

Fig. 10. Waveforms of the voltage (*1*), current (*2*), and power losses (*3*) for the thyristor T343-500 (40-mm wafer) during its operation in the stack of 9 thyristors at a charging voltage of 20 kV.

During the performed experiments, thyristors were enabled several thousand times. No malfunctions of thyristors or changes in their operating characteristics were observed. However the life time of the thyristors on that performance needs to be studied in more detail.

B. 5-kV Switch Operating at 200-kA Peak Current

In these experiments the thyristor switch contained two series connected thyristors of T453-800-24 type with DC operating voltage of 2.4 kV, surge current amplitude of 20 kA, critical current rise rate of 400 A/μs when triggered through the gate electrode , and diameter of silicon wafer of 56 mm.

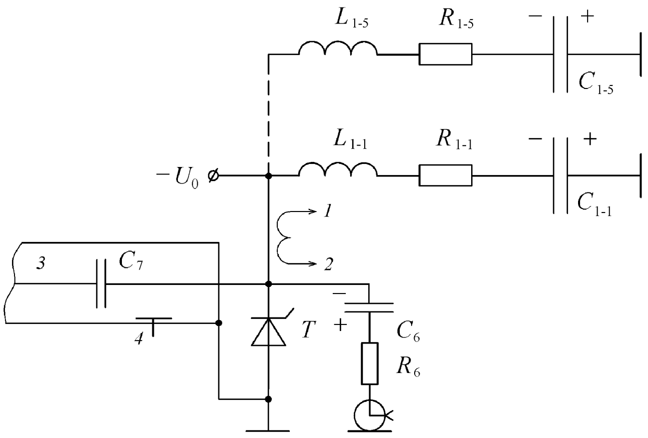

Fig. 11. Experimental discharge circuit.

The electrical circuit is shown in Fig. 11. The resistive voltage divider was connected across the whole switch of two thyristors. Capacitive store contained 5 identical modules connected in parallel. The measured values of the each module elements were as follows: C was ~220 μF, L was ~0.33 μH, and R was ~72 mΩ. In experiments charging voltage U_0 was equal to 5 kV. The value of the peak current through the thyristor switch was changed by changing the number of parallel modules included in the discharge circuit and by changing the total value of the load resistance. The maximum amplitude of the discharge current at 5 modules connected in parallel was ~230 kA. Pulse duration (FWHM) was ~25 μs. Equivalent values of capacitance and resistance of the total discharge circuit were 1.1 mF and 14.5 mΩ respectively.

It was found that the voltage rise rate *dU/dt* at the triggering stage was the main factor affected on the thyristors switching characteristics. In experiments we varied *dU/dt* value in the range of 0.5 to 2.1 kV/ns. Typical waveforms across the thyristor switch at different *dU/dt* are shown in Fig. 12.

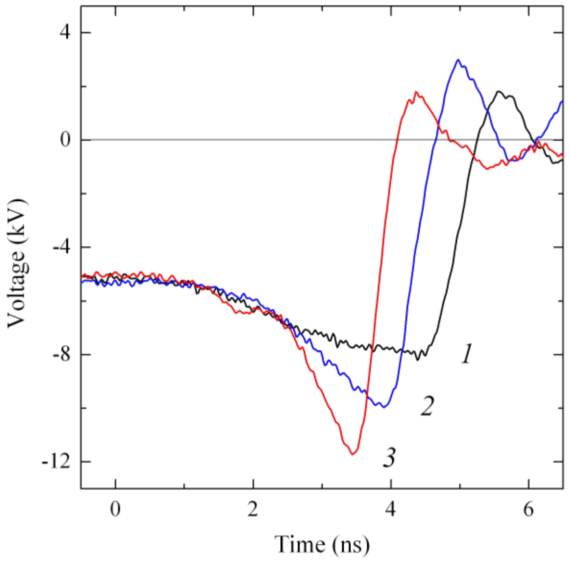

Fig. 12. Waveforms of the voltage across 56-mm thyristors during switching process: *dU/dt* is ~0.5 (curve *1*), ~1.1 (curve *2*), and ~2.1 kV/ns (curve *3*).

At each triggering mode shown in Fig 12 we increased the discharge current through the switch up to the failure of the tested thyristors occurred. The results of these tests are shown in Fig. 13. It is seen that increasing *dU/dt* value from ~0.5 to ~2.1 kV/ns allowed increasing the failure current from ~140 up to ~220 kA (curve *1* in Fig. 13).

To explain the experimental results obtained, we calculated temperature increasing of the silicon wafer during current pulse through the waveforms of the dissipated power for the failure current values shown in Fig. 13. Assuming that the wafer was heated uniformly on its surface area the following calculated results on the structure temperature were obtained: 95.3, 127.6, and 156.3 ^{0}C for *dU/dt* values of 0.5, 1.1, and 2.1 kV/ns respectively.

It is well known that the failure of the power silicon devices due to overheating occurs when the temperature of the structure reaches 400–600 ^{0}C. At this range of temperature due to a process of electron-hole plasma thermal generation the current flowing through the structure pinches to overheated spots of the structure that leads to the device failure.

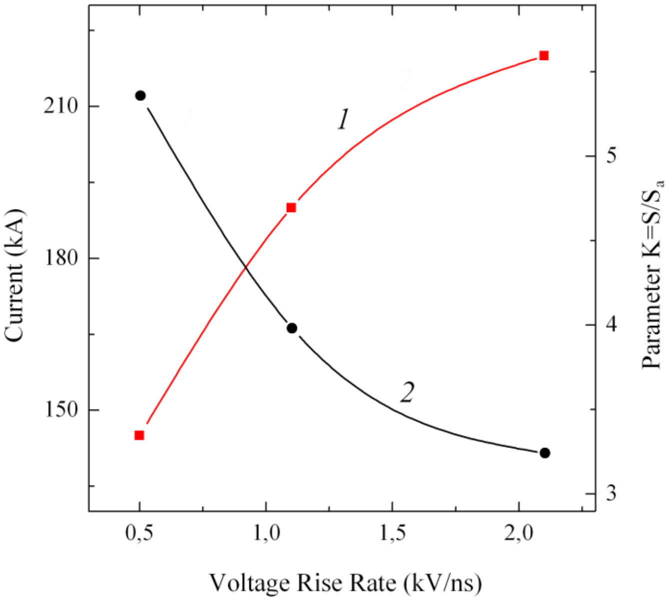

Fig. 13. Amplitude of the failure current (curve *1*) and coefficient of the structure active surface area K = S/Sa (curve *2*) as a function of the voltage rise rate at the triggering stage.

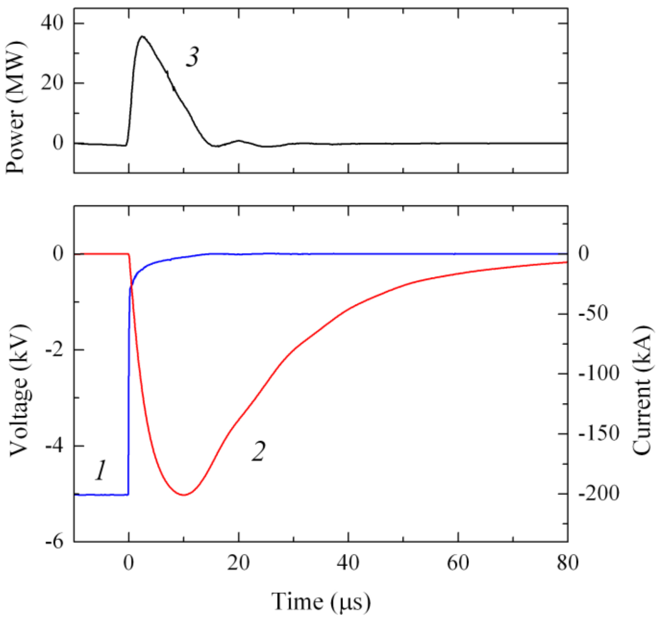

Fig. 14. Waveforms of the voltage (*1*), current (*2*), and power losses (*3*) for the 5-kV thyristor switch triggered by *dU/dt* of 2.1 kV/ns and operated at peak current of 200 kA.

The different temperature values of the structure obtained in our experiments could mean that the current flowed through a part of the total surface area of the structure. In this case increasing in *dU/dt* values at the triggering stage led to increasing an active surface area of the structure through which the current was flowed. This nonuniformity of the current distribution could be defined by coefficient $K = S/S_a$, where S is the total surface area of the structure, and S_a is its active part.

Assuming that in all experiments the failure temperature was equal to 500 ^{0}C we calculated the values of the coefficient K as a function of *dU/dt* (curve *2* in Fig. 13). It shows that the active area of the structure is increased from ~18 to ~31% of the total area when *dU/dt* is increased from ~0.5 to ~2.1 kV/ns. This question needs to be considered in an independent study.

Finally we tested the thyristor switch in no-failure operation regime. The waveforms are shown in Fig. 14. In the experiment *dU/dt* value was 2.1 kV/ns. A 1.1-mF capacitor, which was charged to a voltage of 5 kV, was switched to a resistive load of 18 mΩ. The following discharge parameters were realized: discharge current amplitude of 200 kA, maximum current-rise rate of 58 kA/µs, current rise time (0.1-0.9 level) of 5.5 µs, pulse duration (FWHM) of ~25 µs, and switching efficiency of 0.97. During the performed tests, thyristors were enabled over 100 times. After each 5 shots the leakage current through the thyristors was measured. At nominal DC voltage of 2.4 kV per thyristor it was around 4 µA and was not changed during the tests.

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