Investigation of thyristor-based switches triggered in impact-ionization wave mode

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Abstract. An operation of the thyristor-based switches triggered in impact-ionization wave mode has been investigated. The thyristor switch contained two series connected tablet thyristors having a silicon wafer of 56 mm diameter. Applying across the switch a triggering pulse with a voltage rise rate *dU/dt* of over 1 kV/ns, the thyristors transition time to a conductive state was reduced to shorter than 1 ns. It is shown that the maximum amplitude of a no-failure current is increased with increasing *dU/dt* at the triggering stage. A possible mechanism of the *dU/dt* value effect on the thyristors breakdown current is discussed. Under a safety operation regime at *dU/dt* = 6 kV/ns (3 kV/ns per a single thyristor), the switch discharged 1-mF capacitor, which was charged to a voltage of 5 kV, to a resistive load of 18 mΩ. The following results were obtained: a peak current was 200 kA, an initial *dI/dt* was 58 kA/µs, a FWHM was 25 µs, and a switching efficiency was 0.97. It is shown also that a temperature of the silicon wafer is one of the main factors that affects on the thyristor switching process.

1. 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]. The DLD is switched into a conducting state upon an 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 a 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 a plasma in 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 a tablet design with a diameter of a silicon wafer of 40 mm, was triggered by an external overvoltage pulse with a few nanosecond rise time [5]. The switch operated at a 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 by 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 affecting the time of switching the thyristor from the blocking state to the conducting state.

This work continues the research started in [5] and [6]. The results of experiments on switching current pulses with an amplitude of up to 200 kA during discharge capacitors with over 10 kJ of stored energy are presented. An effect of the voltage rise rate at the triggering stage on the thyristors main switching characteristics is shown and discussed. Finally, we also show how a temperature of the silicon wafer affects on the thyristor switching process.

2. Experiments with thyristors operating at 200-kA peak current

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

The electrical circuit is shown in Figure 1. The capacitive store contained 5 identical modules connected in parallel. The measured values of every module elements were as follows: C was ~220 µF, L was ~0.33 µH, and R was ~72 mΩ. In the experiments, the 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 for 5 modules connected in parallel was ~230 kA. A pulse duration (the FWHM) was ~25 µs. Equivalent values of the capacitance and resistance of the total discharge circuit were 1.1 mF and 14.5 mΩ, respectively.

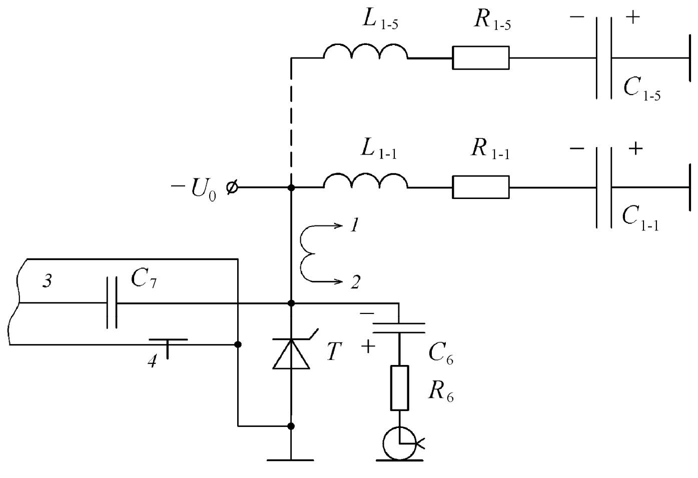

Figure 1. Experimental discharge circuit.

For the thyristor switch T triggering, a compact solid state generator is used. An output unit of the generator contains a coaxial oil-filled 50-Ω line (an item 3 in Figure 1). The triggering pulse of a negative polarity is delivered to the thyristor T via an isolating ceramic capacitor C7 (4.7 nF), and is registered by means of a capacitive probe 4. The output pulse in the line has a rise time of ~1 ns. The output pulse amplitude can be adjusted within 50 to 100 kV. The current was measured by Rogowski coil (outputs *1* and *2* in Figure 1). The resistive voltage divider (elements C6, R6, and 50-Ω measuring cable) was connected across the whole switch of two thyristors.

It was found that the voltage rise rate *dU/dt* at the triggering stage was the main factor affecting the thyristors switching characteristics. In the experiments, we varied *dU/dt* value in the range of 0.5 to 3.0 kV/ns. Typical waveforms across the thyristor switch at different *dU/dt* are shown in Figure 2.

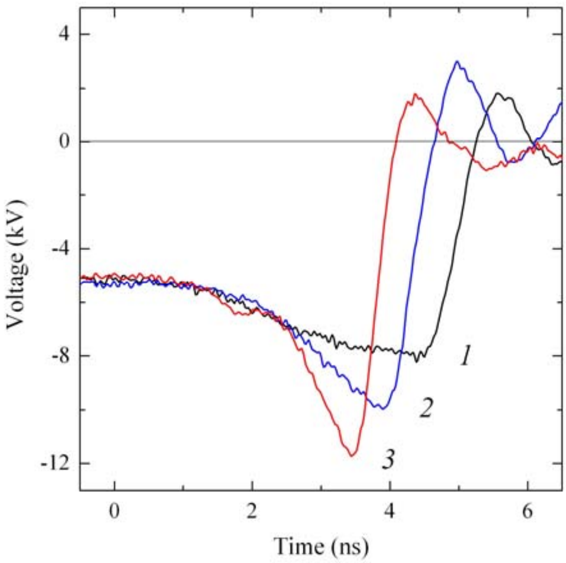

Figure 2. Waveforms of the voltage across 56-mm thyristors during switching process: *dU/dt* is ~0.5 (curve *1*), ~1.3 (curve *2*), and ~3.0 kV/ns (curve *3*).

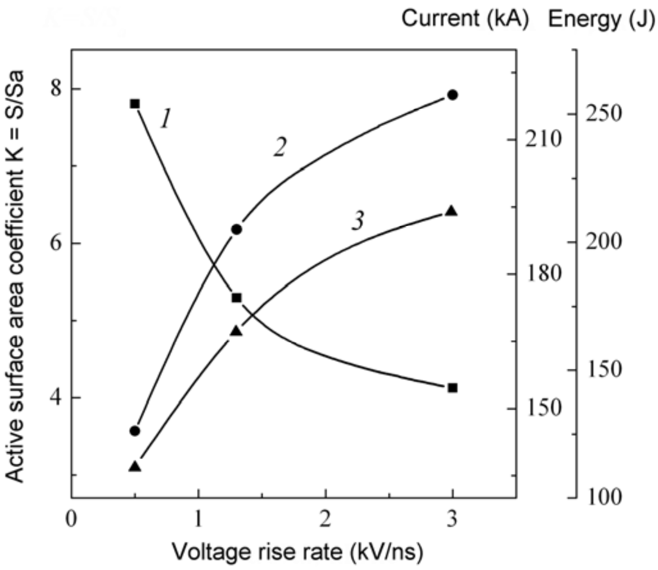

Figure 3. Coefficient of the structure active surface area K = S/Sa (curve *1*), amplitude of the failure current (curve *2*) and thyristor dissipated energy (curve *3*) as a function of the voltage rise rate at the triggering stage.

At each triggering mode shown in Figure 2, we increased the discharge current through the switch until the failure of the tested thyristors occurred. The results of these tests are shown in Figure 3. It is seen that increasing the *dU/dt* value from ~0.5 to ~3.0 kV/ns allowed us to increase the failure current from ~140 up to ~220 kA (the curve *2* in Figure 3).

To explain the experimental results obtained, we calculated a temperature increase of the silicon wafer during a current pulse through the waveforms of the dissipated power for the failure current values shown in Figure 3. Assuming that the surface area of wafer was heated uniformly, the following calculated results for the structure temperature increase were obtained: 61, 90, and 115 ^{0}C for *dU/dt* values of 0.5, 1.3, and 3.0 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 temperature range, due to a process of electron-hole plasma thermal generation, the current flowing through the structure pinches to the overheated spots of the structure that leads to the device failure.

The various 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, an increase of the *dU/dt* values at the triggering stage led to an increase of an active surface area of the structure through which the current flowed. This nonuniformity of the current distribution could be defined by a 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 the 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 *1* in Figure 3). It shows that the active area of the structure increases from ~13 to ~25% of the total area when *dU/dt* is increased from ~0.5 to ~3.0 kV/ns. This question needs to be considered in an independent study.

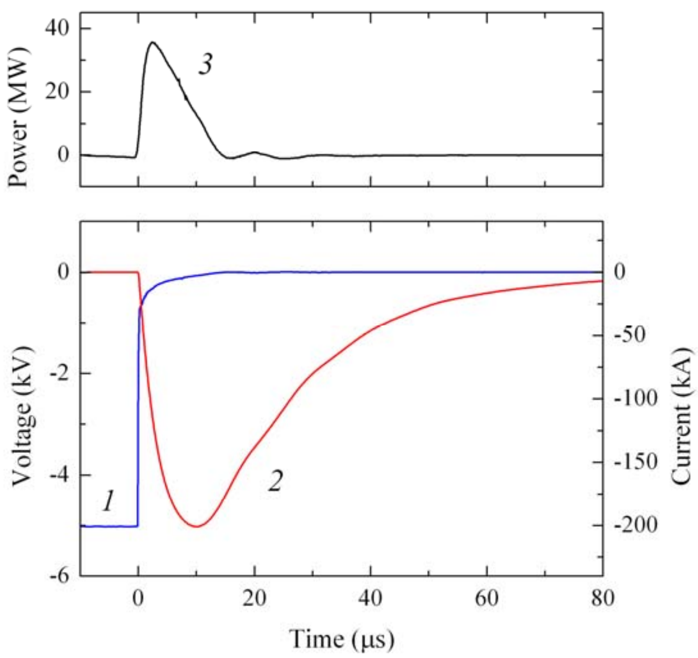

Figure 4. Waveforms of the voltage (*1*), current (*2*), and power losses (*3*) for the thyristor switch triggered by *dU/dt* of 3.0 kV/ns (curve *3* in Figure 2) and operated at peak current of 200 kA.

Finally, we tested the thyristor switch under the no-failure operation regime. The waveforms are shown in Figure 4. In the experiment, the switch was triggered by an overvoltage pulse, in accordance with curve *3* in Figure 2. 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: the discharge current amplitude of 200 kA, the maximum current-rise rate of 58 kA/μs, the current rise time (0.1-0.9 level) of 5.5 μs, the pulse duration (FWHM) of ~25 μs, and the 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 a nominal DC voltage of 2.4 kV per thyristor, it was around 4 μA and did not change during the tests.

3. Effect of temperature on the thyristor switching process

An experimental electrical circuit for studying the process of switching a thyristor from the blocking state to the conducting state at different temperatures is shown in Figure 5. In the experiments, we used a commercial low-frequency tablet thyristor of T133-320-22 type, made in Russia (http://www.proton-electrotex.com). The thyristor had the DC operating voltage of 2.2 kV and a silicon wafer of 32 mm diameter. The circuit contains a capacitor C1 = 0.1 μF charged to a bias voltage U_0 = 2.2 kV of a negative polarity. The bias voltage is applied under DC or pulse modes to the tested thyristor T through a resistor R1. For thyristor triggering, the same triggering generator was used. A resistor R2 served to change the triggering voltage rise rate *dU/dt* across the thyristor T.

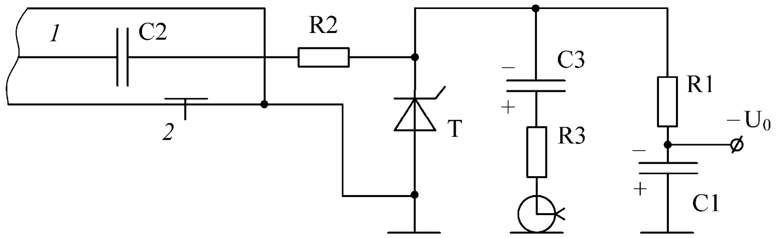

Figure 5. Circuit diagram of the experimental setup.

The voltage across the thyristor T was measured by means of a resistive divider having the elements C3 and R3. To avoid the influence of the inductance of the thyristor contacts located inside the casing, a semiconductor wafer was extracted from the casing, and the divider was connected directly across the wafer. In the experiments, the tested thyristor T was heated up from a room temperature of 25 °C up to 175 °C using an external heater. The temperature of the semiconductor wafer was measured by means of a thermocouple. The experimental results are shown in Figures 6 and 7.

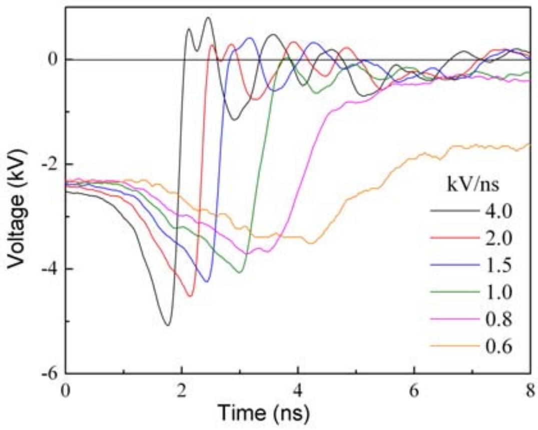

Figure 6. Waveforms of the voltage across the thyristor during switching process at room temperature (T = 25 °C) and different values of the voltage rise rate *dU/dt*.

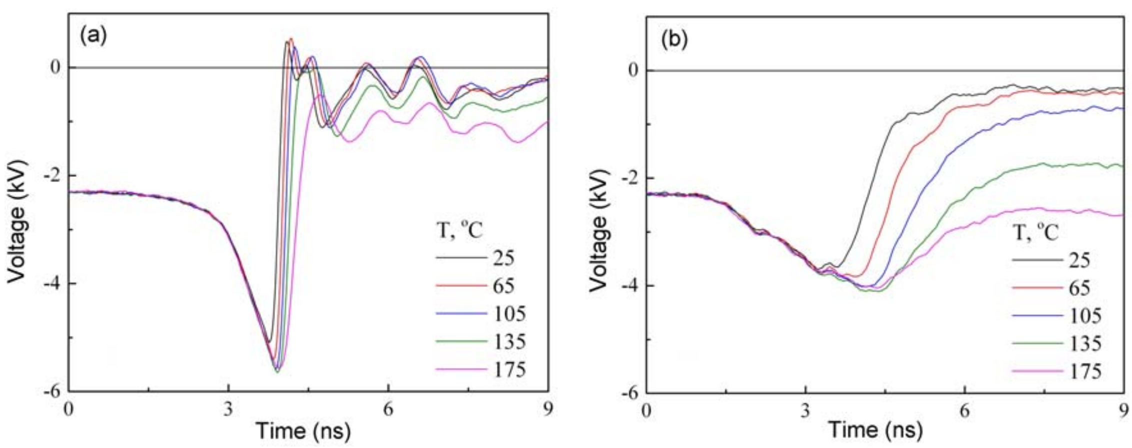

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Figure 7. Waveforms of the voltage across the thyristor during switching process at different temperatures: *dU/dt* = 4 kV/ns (a) and 0.8 kV/ns (b).

The obtained results show the existence of two main factors that affect the thyristors switching process – the voltage rise rate *dU/dt* at the triggering stage and the temperature of the semiconductor wafer. These two factors affect the switching process in an opposite manner. An increase of the *dU/dt* values leads to an increase of the voltage across the thyristor before its switching into the conductive state (Figure 6). For this reason, the impact-ionization front in the structure is formed at a higher electric field and has a higher velocity. Finally, the higher velocity of the impact-ionization front decreases the thyristor transition time to the conductive state (Figure 6).

And vice versa, the increase of the structure temperature has a negative effect on the switching process, since the temperature growth reduces the intensity of carrier avalanche multiplication processes. This factor leads to the decrease of the impact-ionization front velocity, the concentration of the electron-hole plasma, and as a result, to the increase of the residual voltage across the thyristor after the switching process (Figure 7).

At high values of *dU/dt*, the switching process depends weakly on the temperature up to T ~105 ^{o}C (Figure 7a, 4 kV/ns). At T > 105 ^{o}C, the increase of a transition time to the conductive state and the residual voltage is observed. At low values of *dU/dt*, the temperature growth makes the switching process dramatically worse (Figure 7b, 0.8 kV/ns), and at T > 105 ^{o}C, the switching process disappears.

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References
[1] Aristov Yu V, Voronkov V B, Grekhov I V, Kozlov A K, Korotkov S V and Lyublinskii A G 2007 *Instrum. Exp. Tech.* **50** pp 224–227.
[2] Korotkov S V, Aristov Yu V, Voronkov V B, Zhmodikov A L, Korotkov D A and Lyublinskii A G 2009 *Instrum. Exp. Tech.* **52** p 695.
[3] Grekhov I V, Korotkov S V and Rodin P B 2008 *IEEE Trans. on Plasma Science* **36** pp 378-382.
[4] Grekhov I V 2010 *IEEE Trans. on Plasma Science* **38** pp 1118-1123.
[5] Gusev A I, Lyubutin S K, Rukin S N and Tsyranov S N 2015 *Instrum. Exp. Tech.* **58** pp 376-380.
[6] Gusev A I, Lyubutin S K, Rukin S N and Tsyranov S N 2016 *Semiconductors* **50** pp 394-403.