Semiconductor Opening Switch Operation at Microsecond Forward Pumping Time[1]

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Abstract – Experimental and simulation results are presented on Semiconductor Opening Switch (SOS) operation at microsecond forward pumping time. Experimental generator contained primary capacitive store of 0.7 μF charged to initial voltage of 8 to 9 kV, step-up pulse transformer, high-voltage pumping capacitor, magnetic switch for reverse pumping, semiconductor opening switch based on SOS diodes, and external resistive load.

After switching the primary capacitive store, energy is transmitted to high-voltage pumping capacitor to a voltage level of around 120 kV. Current of this process passes via the SOS and insures its forward pumping. In experiments, forward pumping time was fixed at 2 and 5 μs. When magnetic switch is saturated, the reverse current in short-circuited mode reaches its maximum value of 3 to 5 kA in 50–80 ns.

The SOS structures having different surface area and position of the p-n junction were investigated. Optimized SOS cut off the reverse current of 1.4 to 2.7 kA in amplitude in 4–5 ns and formed output pulses across resistive load up to 500 MW in peak power, 25–30 ns FWHM with a peak voltage of 200–300 kV. Maximal efficiency of the generator that corresponds to the energy transmission from the primary store to the load reached 0.50–0.54.

The results of numerical simulations of the SOS operation at microsecond pumping time are presented.

1. Introduction

Thanks to the all-solid-state system of energy switching, high-current nanosecond generators equipped with a semiconductor opening switch comprising SOS diodes [1, 2] combine a high pulse repetition rate, stability of output parameters, and a long lifetime. The standard circuitry of a SOS generator includes primary energy storage with a thyristor switch, a magnetic compressor, and a semiconductor opening switch based on SOS diodes. The magnetic compressor is necessary for time compression of energy since the characteristic time of the energy transfer through the thyristor is 10 to 100 μs, while the pumping time of not longer than 300–400 ns is required for efficient operation of the SOS diode. The energy loss is the largest in the magnetic compressor that decreases total efficiency of the generator.

It was shown [3] that microsecond pumping regime could be realized by decreasing the current density through the SOS. The numbers of magnetic cells in the compressor were eliminated in this case. Fast IGBTs were used as a primary switch. After IGBT switched on the energy was transmitted to the pumping capacitor in about 1.5 μs that corresponded to the forward pumping time of the SOS. At pulse energy content of 0.5 J the generator had only one magnetic component, and generator efficiency was up to 70%.

It is of great interest to investigate possibility of the SOS operation at longer forward pumping time and higher level of energy and peak power of the output pulses. The SOS operation at forward pumping time up to 5 μs and pulse energy around 10 J is studied in this paper.

2. Experimental circuit

A simplified circuit diagram of the generator is shown in Fig. 1. The circuit includes the low-voltage section, which is exposed to air, and the high-voltage module, which is placed in a metal casing filled with transformer oil. The low-voltage section consists of the primary storage C_1 rated at 0.7 μF, and air spark gap as the primary switch S_1. Charging voltage U_1 across the primary storage was 8 to 9 kV. Inductor L_1 was used to adjust energy transmission time from C_1 to the high-voltage module.

The high-voltage module comprises the step-up pulse transformer PT, the pumping capacitors C_2–C_3, the magnetic switch for reverse pumping MS, and the opening switch SOS. The output pulse was transmitted from the oil tank to air through an insulator, across which the resistive load R_L was installed.

In experiments the energy transmission time from the C_1 to the pumping capacitors C_2–C_3 that corresponds to forward pumping time of the SOS was fixed by two versions, namely, 2 and 5 μs. The pulse transformer PT for the version $t^+ = 2$ μs was assembled on 3 permalloy rings K300 × 200 × 25, 20 μm and had one turn in the primary winding and 14 turns in the secondary winding. At $t^+ = 5$ μs the transformer con-

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tained two such rings, 4 turns in the primary winding, and 52 turns in the secondary winding.

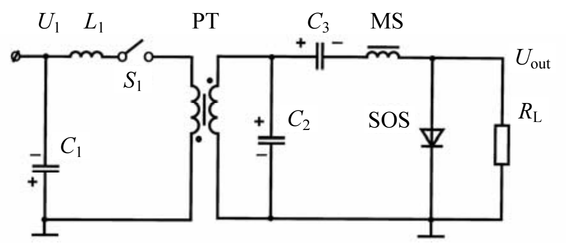

Fig. 1. Electrical circuit of the generator

The pumping capacitors C_2 and C_3 were assembled from KVI-3 capacitors and had equal capacitance of 1.64 nF. The magnetic switch for reverse pumping MS contained 3 permalloy rings K250 × 140 × 25, 10 μm and had 5 turns in $t^+ = 2$ μs version. In $t^+ = 5$ μs version it contained 5 such rings and 7 turns. Both pulsed transformer PT and magnetic switch MS contained additional windings for their cores reversal of magnetization from an external DC current source.

Semiconductor opening switch SOS was assembled from 4 SOS diodes – two parallel branches with 2 diodes in series in each branch. Each SOS diode was assembled from 240 semiconductor structures connected in series. Three versions of the SOS were investigated in experiments. The versions had different surface area S_{SOS} and position of the p-n junction X_p of the semiconductor structure: 4 cm^2 and 190 μm; 1 cm^2 and 190 μm; 4 cm^2 and 140 μm.

The circuit operates as follows. When the switch S_1 is turned on, the energy is transferred from the primary store C_1 to the pumping capacitors C_2–C_3 through PT to the voltage level of 115–120 kV. At $C_2 = C_3$ condition a half of the PT secondary winding current charges the C_3 capacitor and passes in the SOS in the forward direction and provides its forward pumping regime. After saturation of the PT magnetic core the C_2 capacitor is recharged via PT secondary winding to the opposite polarity of the voltage. During this time interval, the magnetic switch MS blocks the voltage increasing across it, and a current pause via the SOS sets in.

Reverse pumping of the SOS follows the saturation of the magnetic switch MS core when the voltage across MS is closed to its maximum value. The capacitors C_2–C_3 connected in series are discharged through the SOS in the reverse direction and ensure its reverse pumping regime. The output voltage pulse across external resistive load is formed when the SOS cuts off the reverse current.

3. Experimental results

3.1. Forward pumping time $t^+ = 2$ μs

At $t^+ = 2$ μs the circuit provided the following parameters. The amplitude of the C_1 discharge current was 4 kA, the PT secondary winding current was around 280 A, the current via the SOS in forward direction was 130–140 A and had duration of 1.9 μs, and duration of the current pause was 0.3 μs. After saturation of the magnetic switch MS core the discharge of the C_2–C_3 capacitors in reverse direction provided peak current of 4.6 kA with rise time of about 50 ns when the SOS was short circuited.

In this pumping regime the SOS having the following combinations of surface area S_{SOS} and position of the p-n junction X_p of the semiconductor structure were tested: 4 cm^2 and 190 μm; 1 cm^2 and 190 μm; 4 cm^2 and 140 μm. Typical waveforms of the reverse current via the SOS and the voltage across the SOS are given in Fig. 2.

Analysis of the waveforms obtained shows the following. In the version $S_{SOS} = 4$ cm^2 and $X_p = 190$ μm the SOS operates in the regime of the SOS effect. In this case, the reverse current cutoff time is significantly lower than the reverse pumping time. When the depth of the p-n junction is decreased (version $S_{SOS} = 4$ cm^2 and $X_p = 140$ μm) the SOS operates as usual rectifying diode, namely, sharp current cutoff stage is disappeared, and its duration becomes close to the reverse pumping time (Fig. 2, *b*, curve *1*). The same effect is observed at decreasing the SOS surface area that corresponds to increasing the current density. In the version $S_{SOS} = 1$ cm^2 and $X_p = 190$ μm the waveform of the reverse current via the SOS is similar to the curve *1* in Fig. 2, *b*.

The difference in the SOS operation regime leads to the following. In the version $S_{SOS} = 4$ cm^2 and $X_p = 190$ μm we observe increasing in the peak power of the output pulse, since the output pulse is formed by intermediate inductive store (inductance of the MS in saturated state) and the opening switch, having current cutoff time less than its pumping time (Fig. 2, *c*, curve *1*). In two other versions, the peak power is not increased due to less value of the reverse current amplitude and its smooth decay at the current cutoff stage. In last two versions the output pulse is formed by the discharge of the capacitors C_2–C_3 connected in series to the external load via magnetic switch MS that leads to decreasing the output pulse amplitude and increasing the pulse duration (Fig. 2, *c*, curves *2*).

The load characteristics of the generator were obtained also. Maximum of the peak power corresponded to resistive load value close to 74 Ω. The Table 1 summarizes the results obtained for the versions $S_{SOS} = 4$ cm^2 at $X_p = 190$ μm and $S_{SOS} = 4$ cm^2 at $X_p = 140$ μm.

In Table 1: U is the amplitude of the output pulse, P is the peak power, t_p is the pulse duration FWHM, I_{cut} is the amplitude of the reverse current via the SOS, t_0 is the current cutoff time.

We also tested the SOS having the surface area increased up to 6 cm^2 at $X_p = 190$ μm. But increasing in the reverse current amplitude and the output voltage was around 5% only.

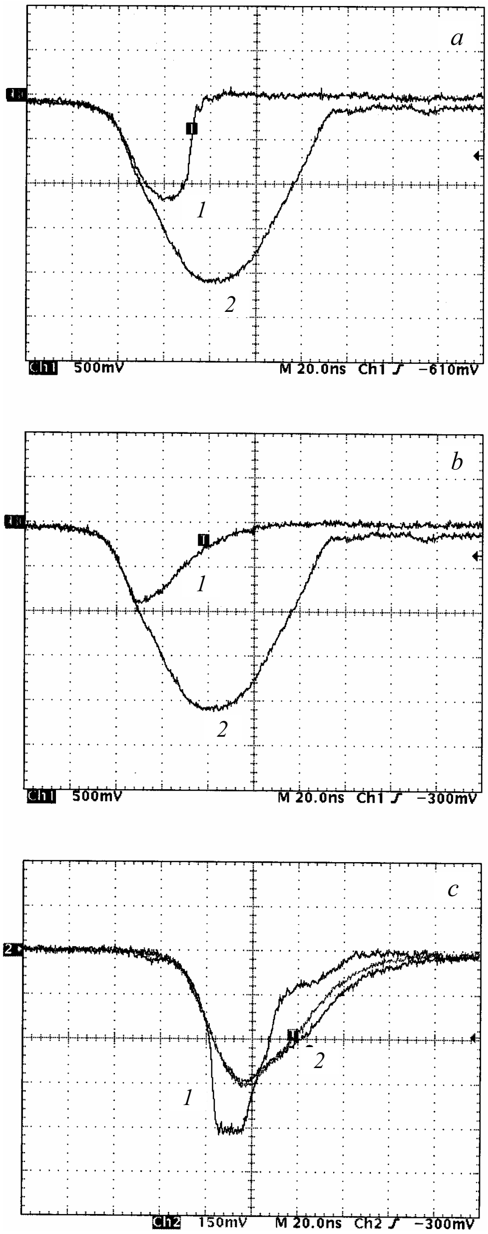

Fig. 2. Experimental waveforms at forward pumping time $t^+ = 2$ μs: (*a*) – reverse current via the SOS (curve *1*, amplitude 2.7 kA) and current via short circuited SOS (curve *2*, amplitude 4.6 kA) for the version $S_{SOS} = 4$ cm^2 at $X_p = 190$ μm; (*b*) – reverse current via the SOS (curve *1*, amplitude 2.0 kA) and current via short circuited SOS (curve *2*, amplitude 4.6 kA) for the version $S_{SOS} = 4$ cm^2 at $X_p = 140$ μm; (*c*) – voltage waveforms across $R_L = 74$ Ω for the version $S_{SOS} = 4$ cm^2 at $X_p = 190$ μm (curve *1*, amplitude 200 kV) and for the versions $S_{SOS} = 4$ cm^2 at $X_p = 140$ μm and $S_{SOS} = 1$ cm^2 at $X_p = 190$ μm (curves *2*, amplitude 145 kV)

Table 1. Specifications of the generator at $t^+ = 2$ μs, $S_{SOS} = 4$ cm^2, $R_L = 74$ Ω

SOS	U, kV	P, MW	t_p, ns	I_{cut}, kA	t_0, ns
$X_p = 190$ μm	200	540	26	2.7	4
$X_p = 140$ μm	145	280	50	2.0	40

3.2. Forward pumping time $t^+ = 5$ μs

At $t^+ = 5$ μs the circuit provided the following parameters. The amplitude of the C_1 discharge current was 1.5 kA, the PT secondary winding current was around 120 A, the current via the SOS in forward direction was 50–55 A and had duration of 4.8 μs, and duration of the current pause was 0.8 μs. After saturation of the magnetic switch MS core the discharge of the C_2–C_3 capacitors in reverse direction provided peak current of 3 kA with rise time of about 80 ns when the SOS was short circuited.

In this pumping regime the SOS having the same combinations of surface area S_{SOS} and position of the p-n junction X_p of the semiconductor structure were tested: 4 cm^2 and 190 μm; 1 cm^2 and 190 μm; 4 cm^2 and 140 μm. Waveforms obtained were similar to the waveforms given in Fig. 2. In the version $S_{SOS} = 4$ cm^2 and $X_p = 190$ μm the current cutoff time was around 4 ns. In two other versions, sharp current cutoff stage was disappeared. The duration of the cutoff stage was higher than the reverse pumping time.

The transition to the forward pumping time $t^+ = 5$ μs increased the inductance of the magnetic switch MS. Due to this factor optimal load resistance R_L corresponding to maximum peak power of the generator was increased to the value of around 150 Ω. Table 2 summarizes the results obtained for the forward pumping time $t^+ = 5$ μs (the same designations as in Table 1).

Table 2. Specifications of the generator at $t^+ = 5$ μs, $R_L = 150$ Ω

SOS	U, kV	P, MW	t_p, ns	I_{cut}, kA	t_0, ns
$S_{SOS} = 4$ cm^2 $X_p = 190$ μm	210	290	54	1.4	4
$S_{SOS} = 1$ cm^2 $X_p = 190$ μm	170	190	77	0.62	40
$S_{SOS} = 4$ cm^2 $X_p = 140$ μm	140	130	96	0.57	90

4. Numerical simulation of the SOS operation

For numerical simulation of the SOS operation, the theoretical model described in [4] was used. This model is based on a fundamental system of equations including continuity equations for electrons and holes and the Poisson equation for the electric field. This system is solved simultaneously with the Kirchhoff equations for electric circuits. The model also takes into account the real doping profile of semiconductor structures.

Calculations revealed that characteristic features of the SOS operation at microsecond forward pumping time are determined by the following two main factors: (*a*) quantity of the electron-hole plasma accumulated inside the structure during the forward pumping process; (*b*) distribution of the plasma concentration in the structure between p-region and n-base. To obtain the sharp reverse current cutoff process it is needed the most part of the accumulated plasma is concentrated in the high doped p-region of the structure. At short pumping time around hundreds of ns and high current density this ratio is determined by the ratio of electron and hole mobility that is close to ~ 3 [5]. At long pumping time, the fraction of the plasma accumulated in the p-region of the structure decreased.

Increasing the forward pumping time from 2 to 5 μs leads to the loss of accumulated charge increases also due to recombination process. Moreover, the diffusion process makes the distribution of the plasma concentration more uniform, reducing plasma concentration in the p-region, and increasing it in the n-base. Due to this reason when the reverse current is injected into the structure the high electric field regions appear in the structure in less time that restricts further increasing of the reverse current.

Comparison of the SOS structures having the same X_p and different surface area S_{SOS} shows that increasing the current density (reducing the S_{SOS} from 4 to 1 cm^2) causes increasing the concentration of the plasma in the p-region and its corresponding more intensive loss due to the recombination process.

The difference in the SOS operation at the same pumping time t^+ and current density (the same S_{SOS}) is determined by the position of the p-n junction X_p. Fig. 3 illustrates distributions of the accumulated plasma concentration across the structures having the same $S_{SOS} = 4$ cm^2 and pumping time $t^+ = 2$ μs but having different values of X_p. The ratio of the plasma accumulated in the p-region and n-base is around 1.5 for $X_p = 190$ μm, and around 1.0 for $X_p = 140$ μm. Different distributions of the accumulated plasma concentration determine the SOS operation during reverse pumping and cutoff stage. At $X_p = 140$ μm current cutoff process begins earlier, and high level of the residual plasma in the n-base impedes the current cutoff process making it longer and more smooth.

Thus, the study shows that at low current density the microsecond pumping regime of the SOS can be realized, and current cutoff stage is still sufficiently fast and takes a few nanoseconds. To realize this regime the structures having very deep position of the p-n junction have to be used.

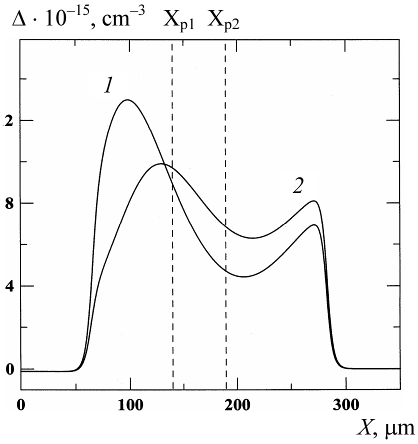

Fig. 3. Distributions of the accumulated plasma concentration at $t^+ = 2$ μs, $S_{SOS} = 4$ cm^2 across the structure having $X_p = 140$ μm (curve *1*) and $X_p = 190$ μm (curve *2*)

In technical point of view microsecond pumping regime allows to improve the SOS generators. Firstly, at longer pumping time it gives a possibility to reduce the peak power of the primary switch. IGBT switches having higher repetition rate capabilities in comparison with fast thyristors can be used as the primary switch. Secondly, it allows reducing a total number of the magnetic components in the compressor and thus increasing a total efficiency of the SOS generator. In conditions of this work the maximum value of the generator efficiency corresponding to energy transition from the primary capacitive store C_1 to external resistive load R_L was around 0.50–0.54.

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