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NEW SOLID STATE OPENING SWITCHES FOR REPETITIVE PULSED POWER TECHNOLOGY

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Abstract

In 1991 we discovered a semiconductor opening switch (SOS) effect that occurs in p^+-p-n-n^+ silicon structures at a current density of up to 60 kA/cm^2. This effect was used to develop high-power semiconductor opening switches in intermediate inductive storage circuits. The breaking power of opening switches was as high as 5 GW with the interrupted current up to 45 kA, reverse voltage up to 1 MV and the current interruption time between 10 and 60 ns [1,2]. The opening switches were assembled from quantity-produced Russian-made rectifying diodes type SDL with hard recovery characteristic. On the basis of experimental and theoretical investigations of the SOS effect new SOS diodes were designed and manufactured by the Electrophysics Institute. The paper gives basic parameters of the SOS diodes. New diodes offer a greater value of the interrupted current and shorter time of current interruption accompanied by a considerable increase in the energy switching efficiency. The new SOS diodes were used to develop repetitive all-solid-state pulsed generators with an output voltage up to 250 kV, pulse repetition rate up to 5 kHz, and pulse duration between 10 and 30 ns.

SOS effect among other methods of current switching in semiconductors

The basic principles of current switching by semiconductor devices stem from the processes that take place in the low-doped base of the structure: either filling of the base with the electron-hole plasma (current switches) or removal of the electron-hole plasma from the base (current opening switches). For example, the process of current switching by a fast thyristor or a reverse switched dinistor (RSD) represents a slow (~10^{-6} s) diffusion filling of the base with excess plasma. Therewith a high density of the switched current vs a low switching speed dj/dt is realized (see Table 1). When current is interrupted, a maximum speed of carriers is achieved in the base of drift step recovery diodes (DSRD). The switching time is as short as ~10^{-9} s. However the density of the interrupted current is small, because there is no residual plasma in the base at the stage of current interruption. Still shorter switching time of ~10^{-10} s can be achieved at low current densities in silicon avalanche shapers (SAS) [3].

Table 1. Comparison of semiconductor switching technologies.

	j, kA/cm^2	dj/dt, A/cm$^2\cdot$s	t_c, s	U, V	P, GW	Ref
RSD	1 — 20	~10^{10}	10^{-6} — 10^{-5}	$2\cdot10^4$	~5	[3]
DSRD	0.1 — 0.2	~10^{11}	~10^{-9}	$2\cdot10^4$	~10^{-3}	[3]
SAS	0.6	$6\cdot10^{12}$	~10^{-10}	$5\cdot10^3$	~10^{-3}	[3]
SOS	1 — 60	$4\cdot10^{12}$	~10^{-8}	~10^6	~10	[1,2]

The aforementioned methods of switching provide either a high density of current and slow swithing (RSD) or fast switching and a low density of current (DSRD, SAS). A common drawback of the methods is a low working voltage, which in real devices does not exceed 10^4 V. The SOS-effect differs qualitatively from these switching methods in that current interruption is independent of the processes taking place in the base of the structure [4]. By the beginning of current interruption the base still has an electron-hole plasma whose concentration is approximately two orders of magnitude higher than the doping level of the base. The process of current interruption develops in a narrow high-doped region of the structure. The region of the structure covered by the electric field increases during current interruption to 15-25 μm in $\sim 10^{-8}$ s and the field is as high as 300-400 kV/cm. For these reasons the SOS-effect combines a high density of interrupted current and nanosecond interruption time.

One more distinctive feature of the SOS-effect is the mechanism of a uniform distribution of voltage in series-connected structures at the stage of current interruption. The mechanism is due to enhancement of the semiconductor ionization, which leads to additional generation of the electron-hole plasma and lowering of the field in the structures where it is higher than the average field. Then a large number of structures can be connected in series to obtain the working voltage at the megavolt level. There is no need for forced equalization of voltage across the structures. The parameters of the above-considered methods of switching are compared in Table 1 which lists both characteristic and maximum attainable parameters of developed devices.

Development of new SOS diodes

Experimental studies of the SOS-effect revealed that characteristics of the opening switches depend not only on the pumping regime (current density and time) but also on the initial doping profile of the p^+-p-n-n^+ structure. We have produced and tested more than 20 alternative structures with different combinations of the resistivity of the initial silicon, hole lifetime, base thickness, and doping profile of p^+, p and n^+ regions. Every version of the opening switch comprised 80 series-connected structures of the same type and its working voltage was up to 100 kV. The test parameters of the new SOS diodes proved to be much better than characteristics of the current interrupters employing standard high-voltage diodes. Fig. 1 shows the superposition of voltage pulses produced under the same conditions using an NTE 541 rectifier diode (soft recovery diode, USA), an SDL-0.4-800 diode (hard recovery diode, Russia), and the novel SOS diode.

Photographs of the novel SOS diodes are given in Fig. 2. By design a SOS diode is a stack of series-connected plates compressed with the help of insulation rods. Each plate is a copper heat-sink 30×30×2 mm or 20×20×2 mm in size with 4 structures soldered in series. The structures have a protective coating on the side and ground end contacts. The diode stack is provided with a device compensating for thermal linear expansion. The main technical characteristics of the SOS diodes are as follows:

Maximum peak reverse voltage -	120 kV
Interrupted current -	1 kA (S=0.25 cm^2), 4 kA (S=1 cm^2), 8 kA (S=2.2 cm^2)
Current interruption time -	6 - 8 ns
Maximum overvoltage (idle regime) -	7
Recovery time -	< 1 μs
Maximum dissipation power (in transformer oil/in air with force cooling) -	
continuously	50-100 W/25-50 W
burst mode	500-1000 W/250-500 W
Dimensions -	(80-120) x (50-70) x (30-45) mm
Mass -	0.2 - 0.3 kg.

The pulse repetition frequency of the SOS diodes is fully and solely determined by particular conditions of heat removal from the structures, because their self-recovery time does not exceed 1 μs. During the tests the devices operated at the pulse repetition frequency of 100 to 1000 Hz under the continuous mode and 1000 to 5000 Hz under the burst mode, the burst duration being 0.5 to 2 minutes.

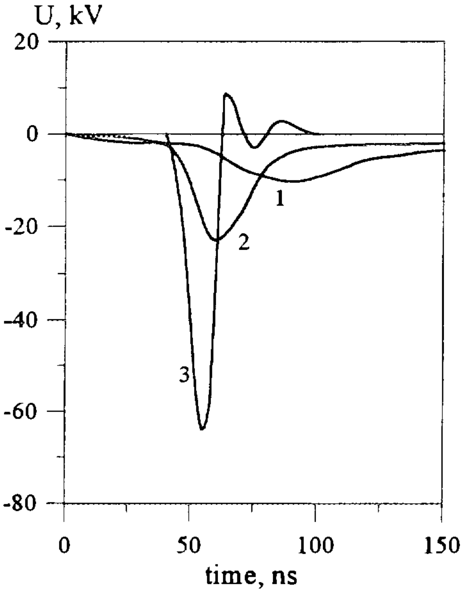

Fig.1. Oscillograms of voltage pulses at the interrupter when the voltage across the pumping capacitor is 9.5 kV: (1) NTE541; (2) SDL-0.4-800 diode; (3) new SOS diode.

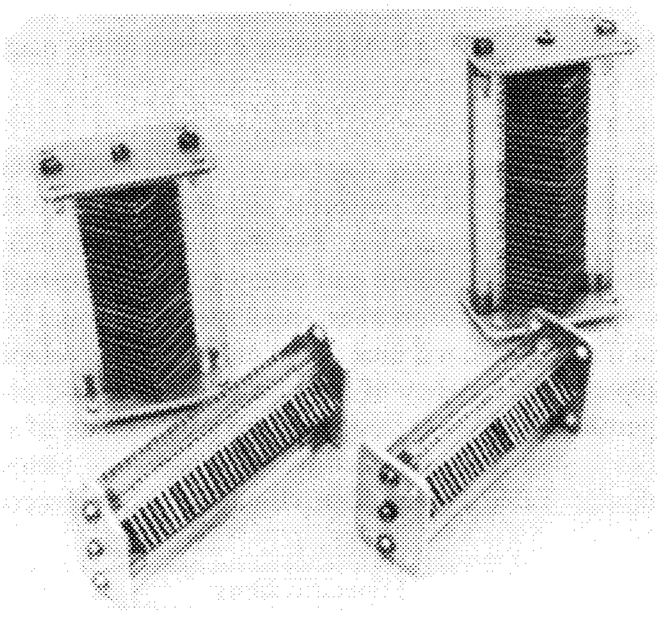

Fig.2. External appearance of new SOS diodes.

Application of new SOS diodes for repetitive pulsed power technology

The newly developed SOS-diodes can be used as the base of pulsed power technology with an all-solid-state switching system rated at the following output parameters:

voltage	10-1000 kV;
current	0.5-50 kA;
pulse duration	10-100 ns;
pulse repetition frequency	0.01-10 kHz;
pulse energy	0.1 J - 10 kJ;
average power	10 - 500 kW.

The required level of the output voltage is provided by simple series connection of the SOS-diodes, with voltage dividers being unnecessary. The required current is preset either by a proper selection of the surface area of the semiconductor structure or through parallel connection of smaller-area diodes. The pulse repetition frequency and the average power of the machine are fully determined by the heat removal conditions. Running-water cooling (also of SOS-diodes) provides an average power of hundreds of kW at the pulse repetition frequency from hundreds of herz to unities of kiloherz. In the pulse burst generation regime, where the machine runs under adiabatic thermal conditions, the pulse repetition frequency is limited only by the time of recovery of the thyristor switches in the charging device and can be as high as 10-20 kHz.

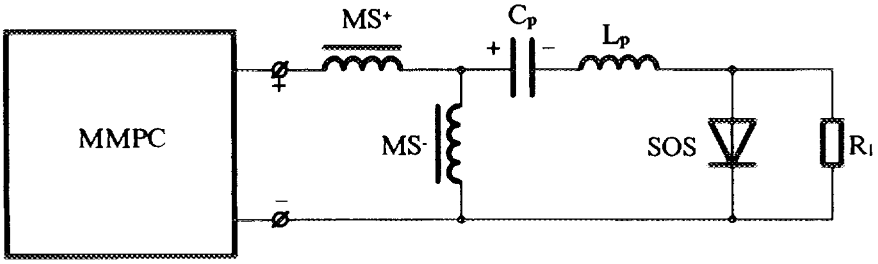

Fig.3. Matching diagram of the magnetic switches and the SOS.

The matching diagram of the magnetic switches and the SOS is shown in Fig. 3. In this approach, the SOS performs simultaneously the functions of a nanosecond pulse compressor and a voltage multiplier. For this reason, all other things being equal, SOS-based devices are simpler, more reliable and cheaper than traditional nanoseconds machines, imploing magnetic switches alone. Moreover, small specific thermal loads on the magnetic switches, which operate in the microsecond time range only, allow development of megavolt installations with the pulse repetition frequency of the kHz range. The microsecond compressor has cores made of cheap permalloy and capacitive storages are made up of standard commercial capacitors.

We have designed two all-solid-state nanosecond generators employing the new SOS diodes. Table 2 gives main parameters of the generators.

Table 2

Specifications	SM-1N	SM-2N
Voltage	250 kV	140 kV
Current	1.4 kA	0.4 kA
Pulse width	28 ns	25 ns
Pulse shape instability	<1%	<1%
Pulse repetition rate		
burst mode (30 s)	1000 Hz	5000 Hz
continiously	100 Hz	1000 Hz
Mass	~85 kg	~50 kg

References

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