New Generation of High – Power Semiconductor Closing Switches for Pulsed Power Applications

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New generation of semiconductor closing switches based on reverse switched dynistors (RSD) has been developed to switch high – power current pulses with microsecond duration. In this report the results of theoretical and experimental investigations of RSD at peak current more than 500 kA and pulse duration up to 500 μs (at 0.1 Imax) are observed. The criteria of extreme peak current for switch taking into consideration the longtime performance under pulse-periodical mode are gave. The design and test results for switch under single pulse mode at operating voltage up to 25 kV and peak current up to 300 kA are described. The possibility of using such a switch in the ISKRA-6 capacitor bank is estimated.

I. Introduction

Solid state semiconductor switches are very inviting to use at pulsed power systems because these switches have high reliability, long lifetime, low costs during using, and environmental safety due to mercury and lead are absent. Semiconductor switches are able to work in any position, so, it is possible to design systems as for stationary laboratory using, and for mobile using. Therefore these switches are frequently regarded as replacement of gas-discharge devices – ignitrons, thyratrons, spark gaps and vacuum switches that generally use now in high-power electrophysical systems including power lasers.

Traditional thyristors (SCR) are semiconductor switches mostly using for pulse devices. SCR has small value of forward voltage drop at switch-on state, it has high overload capacity for current, and at last it has relatively low cost value due to the simple bipolar technology. Disadvantage of SCR is observed at switching of current pulses with very high peak value and short duration. Reason of this disadvantage is sufficiently slow process of switch-on state expansion from triggering electrode to external border of p-n junction after triggering pulse applying. This SCR feature is defined SCR using into millisecond range of current switching. Improvement of SCR pulse characteristics can be reached by using of the distributed gate design. This is allowed to decrease the time of total switch-on and greatly improve SCR switching capacity. Thus, ABB company is expanded the semiconductor switch using up to microsecond range by design of special pulse asymmetric thyristors (ASCR) [1]. These devices have distributing gate structure like a GTO. This thyristor design and forced triggering mode are obtained the high switching capacity of thyristor (I_p=150kA, t_p=50μs, di/dt = 18kA/μs, single pulse). However, in this design gate structure is covered large active area of thyristor (more than 50%) that decrease the efficiency of Si using and increase cost of device.

Si-thyristors and IGBT have demonstrated high switching characteristics at repetitive mode [2,3]. However, such devices do not intend for switching of high pulse currents (tens of kiloamperes and more) because of well-known physical limits are existed such as low doping of emitters, short lifetime of minority carriers, small sizes of chips etc.

Our investigation have obtained that switches based on reverse – switched dinistors [4] are more perspective solid-state switches to switch super high powers at microsecond and submillisecond ranges. Reverse – switched dinistors (RSD) is two-electrode analogue of reverse conducting thyristor with monolithical integrated freewheeling diode in Si. This diode is connected in parallel and in the back direction to the thyristor part of RSD. Triggering of RSD is provided by short pulse of trigger current at brief applying of reversal voltage to RSD. Design of RSD is made thus that triggering current passes through diode areas of RSD quasiaxially and uniformly along the Si structure area. This current produces the oncoming injection of charge carriers from both emitter junctions to base regions and initiates the regenerative process of switch-on for RSD thyristor areas. Such method of triggering for this special design of Si plate is provided total and uniform switching of RSD along all active area in the very short time like as diode switch-on. The freewheeling diode integrated into the RSD structure could be used as damping diode at fault mode in the discharge circuit. This fault mode such as breakdown of cable lines can lead to oscillating current through switch.

It has been experimentally obtained in [5,6,7] that semiconductor switches based on RSD can work successfully in the pulsed power systems to drive flash lamps pumping high-power neodymium lasers. It was shown in [5] that RSD-switches based on RSD wafer diameter of 63 mm (switch type KRD-25-100) and RSD-switches based on RSD wafer diameter of 76 mm (switch type KRD-25-180) can switch the current pulses with submillisecond duration and peak value of 120 kA and 180 kA respectively. Three switches (switch type KRD – 25-180) connected in parallel were successfully tested under the following mode: operating voltage V_o = 25 kV, operating current I_p = 470 kA, and transferred charge Q = 145 Coulombs [6].

During 2000 – 2001, the capacitor bank for neodymium laser of facility LUCH was built at RFNC-VNIIEF [7]. This bank including 18 switches type KRD-25-100 operates successfully during 5 years without any failures of switches.

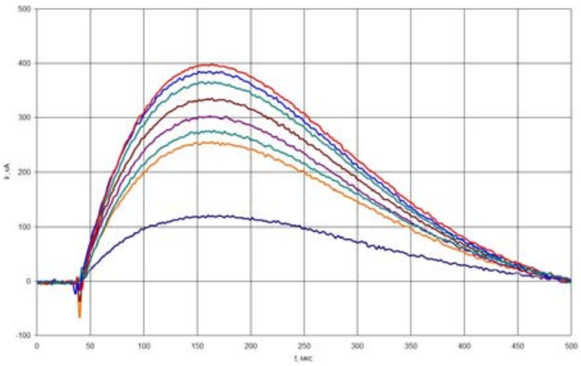
This report is submitted results of development of new generation of solid state switches having low losses of power and high-current switching capacity.

II. Development of RSD's next generation

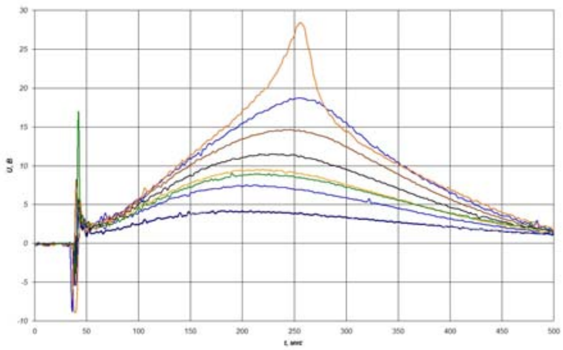
The technology of fabrication of new RSD structure has been developed to increase the switching capacity. This new structure is SPT (Soft Punch Through)-structure - with "soft" closing of space-charge region into buffer n'-layer. Firstly such RSD structures were described in [8].

Decreasing of n-base thickness and also improving of RSD switch-on uniformity by good spreading of charge carriers on the n'-layer at voltage inversion are provided decreasing of all components of losses energy such as losses at triggering, losses at transient process of switch-on, and losses at state-on. Our preliminary estimation was shown that such structure must provide the increasing of operating peak current through RSD approximately in 1.5 times.

Investigations were carried out for RSD with blocking voltage of 2.4 kV and Si wafer diameters of 63, 76, and 100 mm by special test station. The main goal of these investigations is definition of maximum permissible level of peak current passing through single RSD with given area. Current passing through RSD and voltage drop on RSD structure during current passing are measured at testing. In Fig.1 waveforms of peak currents and voltage drops is shown for RSD with size of 76 mm and blocking voltage of 2.4 kV.



a)



b)

Fig.1. Waveforms of pulse current (a) and voltage drop (b) for RSD with wafer size of 76 mm and blocking voltage of 2.4 kV

In according with study program current was slowly increased until maximum permissible level I_{pm}. When this level was reached the sharp rise of voltage and than the same sharp decay of voltage for curve U(t) was observed. Reason of voltage rise is strong decreasing of carrier mobility at high temperature, and reason of voltage decay is quick modulation of channel conductivity by thermal generated plasma that is appeared in accordance with sharp exponential dependence for own concentration of initial silicon into base areas of RSD at temperature of 400 – 600^{0}C.

Tests were shown that this sharp rise of voltage at maximum permissible current does not lead to immediate fault of RSD. RSD keeps its blocking characteristic. However, after passing of such current I_{pm} we can observe the appearance of erosion from cathode for aluminum metallization of

RSD contacts, and this fact is evidence of borderline state of device. The subsequent increasing of current (more than I_{pm}) leads to fusing of Si structure. Therefore, level I_{pm} is the reference position to define the value of operation peak current for RSD-switch under long and repeated many times operating mode.

We have determined that operating peak current I_{pw} must be less than 80% from level I_{pm}. This ratio was confirmed by calculations and results of tests under I_{pw} mode (several thousands of shots).

Data of test results for new generation of RSD with the various diameter of Si wafer are shown in Table 1. In this Table for comparing results of the same tests for the first generation of RSD with size of 63 and 76 mm are shown. These RSDs were used for RSD-switches which is described in [5,6,7]. As may be seen from data of Table 1, switching capacity of new generation of RSD greatly exceeds switching capacity for the first generation of RSD, and exceeds the switching capacity of thyristors with the same size in the several times.

Table 1

RSD diameter, mm	Maximum permissible current I_{pm}, kA	Operating current I_{pw}, kA
63 (new)	250	200
63 (first)	150	120
76 (new)	380	305
76 (first)	240	180
100 (new)	540*	500

* - limited ability of test station

III. Switches based on RSD of new generation

New reverse – switched dinistors is manufactured in two variants. RSD of the first variant is in the low-profile metal-ceramic housing. The second variant is RSD fabricated without housing and with additional protection of periphery area from external action (see Fig.2).

Dinistors placed into housing can be used for work under as mono - pulse mode and repeated - pulse mode. If repeated-pulsed mode using the forced cooling of semiconductor devices and using of heatsinks to both side of pellet must be made. Dinistors without housing connects in series, and such assembly could be placed into a single compact housing. However, such assembly can work under mono-pulse mode only.

Operating voltage for switch typically exceeds blocking voltage of single RSD (U_{BO} ≤2400V), thus switch is included several RSDs connected in series.

Fig.2. Reverse – switched dinistors for peak current from 200 kA to 500 kA and blocking voltage of 2400 V, encapsullated in hermetic metal – ceramic housing and without housing (RSD sizes of 64, 76, and 100 mm)

Number of RSDs included in assembly depends on operating voltage of switch. Therefore, technical problem of switch development is mainly optimization of design for assembly of several dinistors connected in series. A lot of special investigations have carried out such as choice of optimum materials to provide best contacts between RSDs, calculation of dynamic forces to clamp assembly, etc. These investigations are provided small and stable transition electrical and thermal resistances between RSDs that guarantees long and reliable performance of switch. Especial computer technique has developed to select RSDs for connection in series. At this RSD selection value of leakage current and stability of blocking volt-amps diagram are measured especially. This selection technique is allowed exclude the voltage dividers using for equalization of static voltage for each RSD at assembly. Thus, after such selection switch design can simplify, sizes of switch are increased approximately in 1.5 times, and cost of switch is increased too.

The switch type KRD-25-300 designed for long performance at mono-pulse mode is shown in Fig.3. This solid state switch has operating voltage of up to 25 kVdc, operating peak current of up to 300 kA at current pulse duration of up to 500 μs. RFNC-VNIIEF plans to use such switch at capacitor bank of laser facility “Iskra-6” [7]. This switch is included 15 RSDs with size of 76 mm and blocking voltage of 2.4 kV connected in series and encapsullated into dielectric housing. Very high level of switched power density per volume unit has reached by this switch design. This value is of 2.5 10^6 W/cm^3, and this value is exceeded in the several times the same switches based on pulse thyristors.

Triggering of all RSDs in switch is provided by the single trigger generator which connected to switch in parallel (see Fig.3). Triggering current passes simultaneously through all RSDs connected in series. Such triggering type is allowed to increase efficiency and reliability of triggering circuit for this switch, and this is one more advantage of RSD – switch compared to switch based on thyristors.

For new generation of RSD trigger current has peak value between 1-1.5 kA at pulse duration between 1.5 – 2 µs. These values are less in 2-3 times compared to values of trigger current for RSD of the first generation [5].

Fig.3. RSD-switch (switch type KRD-25-300) for operating current of up to 300 kA and operating voltage of up to 25 kV (left) with trigger generator (right) connected in parallel.

IV. Conclusion

Next generation of reverse-switched dinistors and RSD – switches has been developed Tests of these switches are shown that all – time high level of switched power density per volume unit has reached. The switches are able to work under as mono-pulse and pulse-repeated modes and suitable for many applications of pulsed power.

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