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# VERY HIGH SPEED HIGH POWER SEMICONDUCTOR SWITCH OFF CIRCUIT

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*Summary: High speed high power semiconductor switch off circuits (SOS) attract an increasing interest due to their perspective application in various high power switching circuits in control, feeding or VHF systems. In this paper we concentrate on a short pulse generator for electronic equipment EMC resistance testing against a short but a high energy pulse overloading. The generator circuit design is described and an analysis of a high voltage diode in the off switching regime and related problems are described.*

*Key words: High speed switching, SOS, semiconductor diode modeling, circuit simulation, nanosecond pulse generation, electromagnetic impulse, electromagnetic compatibility, EMC, EMI.*

## INTRODUCTION

Generators of high speed high energy pulses are used in many applications like radar transmitter modulators, laser exciter generators, accelerator modulators or EMC testing devices. While the laser exciters should supply high energy pulses several nanoseconds long, the pulse generators for radar transmitter applications in the air traffic control deliver sub-microsecond pulses with a power of several MW (1). The last category of generators has been extensively studied in the recent years. A great amount of circuit architectures based on various technologies have been published ((2), (3), (4)…). The highest peak powers of TeraWats in subnanosecond pulses has been reached till now only with special valves. However such generators are able to deliver only a limited number of pulses to date. Further on generators driven by semiconductor switching devices has been introduced, which enables a repetitive operation. The first generation of those generators used special spark gaps in the role of the final pulse sharpener, enabling to reach high energy pulses of a subnanosecond length. However, the application of spark gaps leads to a high time jitter and to a great fluctuation of pulse amplitudes. Also a lifetime of such devices was limited to some tens millions pulses, which spans only several hours of active operation.. A true steady operation is possible using exclusively semiconductor devices. This paper presents such a fully semiconductor high power short pulse generator design and semiconductor SOS device modeling and simulation.

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## 1. SEMICONDUCTOR HIGH ENERGY SHORT PULSE GENERATOR

The generator block diagram is shown in the figure Fig.1. The semiconductor pulse generator consits of three sections:

- the driver section
- the SOS pulse generator section
- the avalanche pulse sharpener section.

The driver with IGBT transistors supplies a 0.1 microsecond long pulse of 1 kV/100 A.

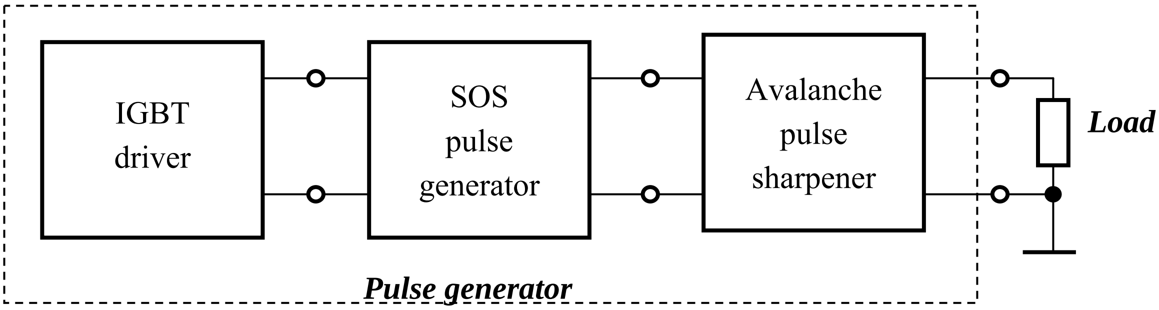


Fig. 1 - Pulse generator block diagram

The SOS pulse generator generates a short high voltage pulse using switch off semiconductor (SOS) diode. The principal circuit diagram of this section is displayed in the Fig. 2.

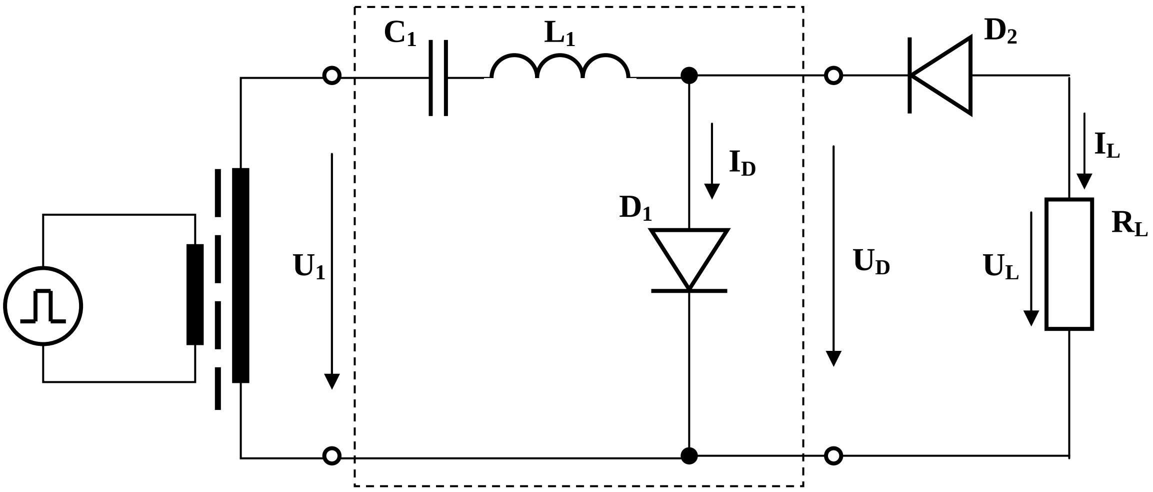


Fig. 2 - Principal SOS pulse generator diagram

The high voltage positive pulse $U_1$ (Fig. 3) induces current $I_D$ through the capacitance $C_1$, inductance $L_1$ and diode $D_1$. The diode $D_2$ prevents a pulse current leakage through the loading resistance $R_L$. At the end of the exciting voltage pulse the voltage $U_D$ across the diode $D_1$ gradually drops becoming negative. The diode current $I_D$ at first follows the voltage in the reverse direction due to an accumulated charge of carriers in the diode junction. After the carriers are exhausted, the current $I_D$ suddenly breaks inducing a steep negative voltage grows caused by inductance $L_1$ keeping the total current $I_D + I_L$ approximately constant. The current now flows through the high loading resistance $R_L$ until the energy, stored in the inductance $L_1$ and the capacitance $C_1$ is spended. The currents and voltages in the circuit are solutions of a set of highly nonlinear differential equations comprising complex non-linear diode models. This set is solved using SPICE/ORCAD programming tools:

$$
\begin{aligned}
& U_1 = U_{C_1} + L_1 \frac{d(I_D + I_L)}{dt} + U_D \\
& I_D + I_L = \frac{dU_{C_1}}{dt} \\
& U_D = Z_{D_1}(U_D, I_D) I_D \\
& Z_{D_1}(U_D, I_D) I_D + Z_{D_2}(U_D - R_L I_L, I_L) I_D + R_L I_L
\end{aligned}
\tag{1}
$$

Where:

$U_{C1}$ is the capacitor $C_1$ voltage

$Z_{D1}(U_D, I_D)$, $Z_{D2}(U_D - R_L I_L, I_L)$ are nonlinear differential operators of diodes $D_1$ and $D_2$ models respectively.

During the positive voltage pulse across the diode $D_1$ the charge $Q_{j0}$ is first accumulated in the junction area depending on the lifetime of the carriers $\tau_L$ and on the positive current $I_{F0}$ through the diode: $Q_{j0} = \tau_L . I_{F0}$. The current and voltage time responses ín the circuit are shown in the Fig. 3. At the exciting pulse trailing edge the charge is pumped out of the diode and simultaneously decimated by the carrier recombination. The current magnitude at the moment of the diode junction step recovery is limited by the negative current slope $dI_D/dt$ imposed by the outer circuit in relation to the carrier lifetime. The time interval necessary for diode current reversation should be less or equal to the carrier lifetime. If for instance diode with the carrier lifetime of 10 ns and a pulse current $I_{F0} =$ 10 A are available, the negative slope of the diode current drop should be of the order of 1 000 A/µs. It poses great requirements on the driver parameters.

The maximum reverse diode voltage $U_{Rmax}$ depends on the diode current $I_{Rmax}$ at the moment of the junction charge depletion, which in turn rely on the maximum forward current $I_{F0}$, on the carrier lifetime $\tau_L$ and on the maximum current slope $|dI_D/dt|$:

$$
\begin{aligned}
& U_{Rmax} = I_{Rmax} . R_L \\
& I_{Rmax} \cong I_{F0} . \tau_L / t_a \\
& |dI_D/dt| \cong I_{Rmax} / t_a
\end{aligned}
\tag{2}
$$

Where $t_a$ is the duration of the leading edge of the negative diode current pulse. In the above relations it is considered that the two mechanisma of the charge exhaustion i.e. the carrier recombination and the charge pumping out have approximately the same effect.

The leading edge of the consecutive negative voltage pulse practically coincides with the diode step recovery (cutoff) with duration time $t_b$. Recent investigations by authors of the ref. (5) showed that the subnanosecond cutoff time could be reached only using a short exciting pulse of tens of nanosecond long but with a very high current density up to 60 kA/cm$^2$. During this short high current density exciting pulse the plasma at the junction can not reach its stable space distribution remaining high electric field areas in the junction. These areas then accelerate the plasma charge exhausting during the current cutoff process. Hence the most of the energy, accumulated in the inductance $L_1$ and capacitance $C_1$ is transferred to the load.

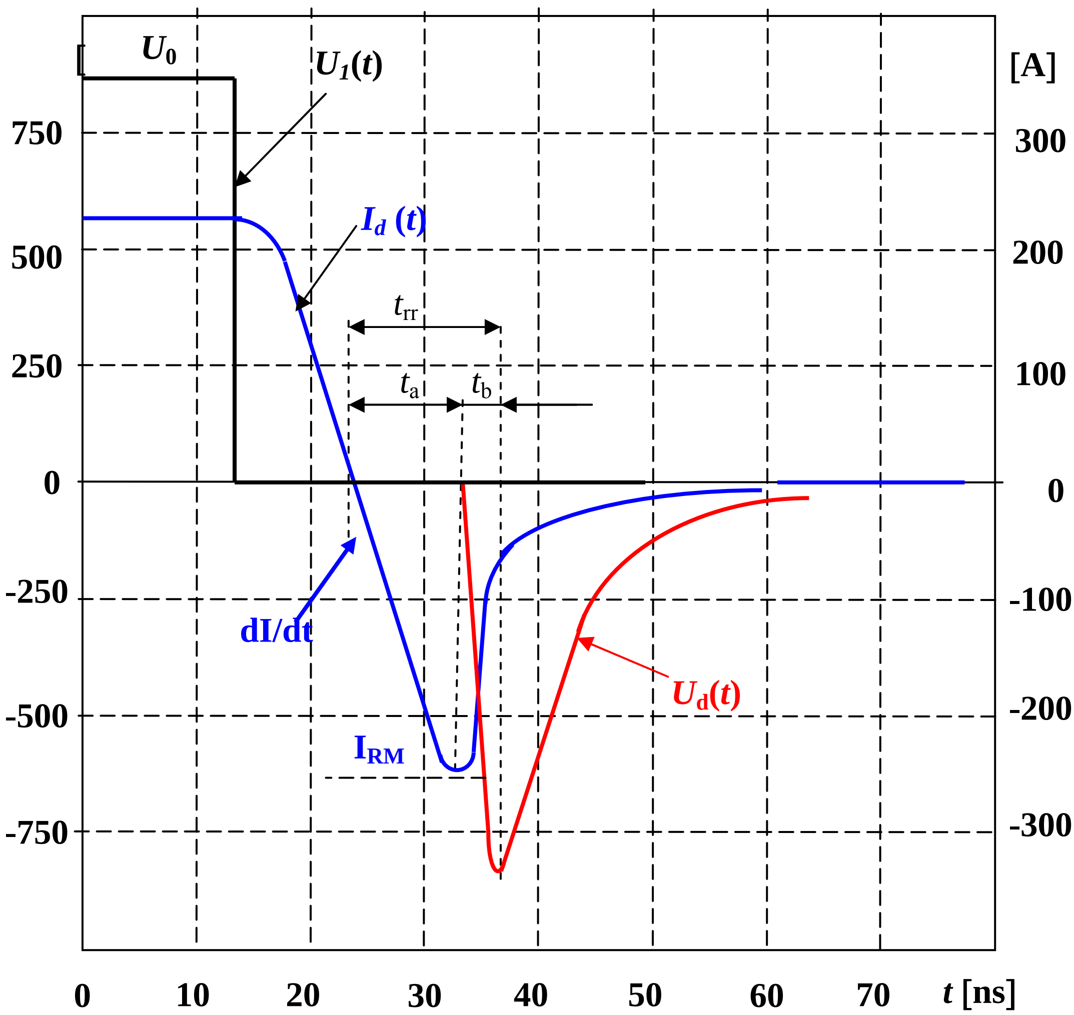


Fig. 3 - Current and voltage responses in the SOS pulse generator circuit of the Fig. 2.

The diode negative voltage pulse has a sharp leading edge and a long trailing edge due to the large time constant of the circuit loaded by the load resistor $R_L$. The avalanche pulse sharpener shown in the figure Fig. 4 cuts the pulse tail concentrating the whole stored energy into a very short high power pulse. Due to the two inversely oriented diodes in series no current flows through the load until the diode voltage $U_d$ reaches the reverse breakdown voltage $U_{BR}$ of the diode D3. Then the current $I_L$ rapidly increases while the differential load impedance falls down enabling all the accumulated energy to transfer into the load in a very short time. Contrary to the circuit in the Fig. 3, the loading resistor $R_L$ may now be of a fairly low value which facilitates a high current and a short discharge pulse.

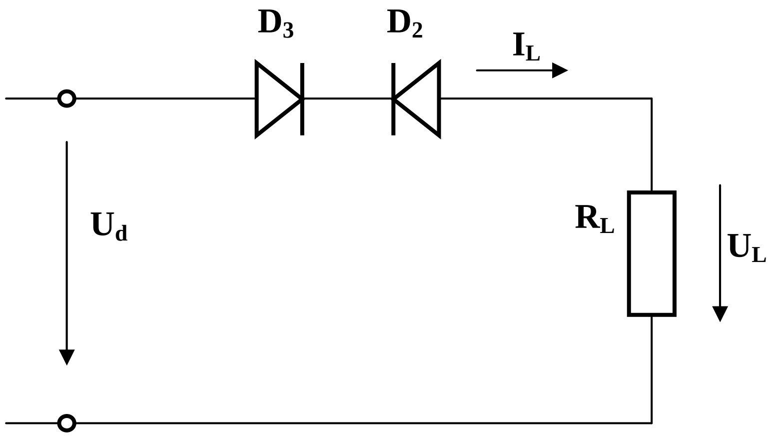


Fig. 4 - Circuit diagram of the avalanche breakdown pulse sharpener.

## 2. SWITCHIG DIODE MODELING AND SIMULATION

For circuit simulation and experimental verification of the SOS pulse generator the HV switching diode HFA25TB60 of Vishay manufacturer was chosen. The main parameters of this diode are as follows:

Saturation current $I_s = 2.272071.10^{-15}$ A
Junction capacitance $C_{j0} = 1.478010^{-9}$ F at $U_j = 0$ V
Breakdown voltage BV = 684.14
Carrier lifetime $\tau_L = 10$ ns

As a first step, the original ORCAD diode model (6) in the regime of diode recovery parameters measurement was tested in a standard measurement circuit (see Fig. 5).

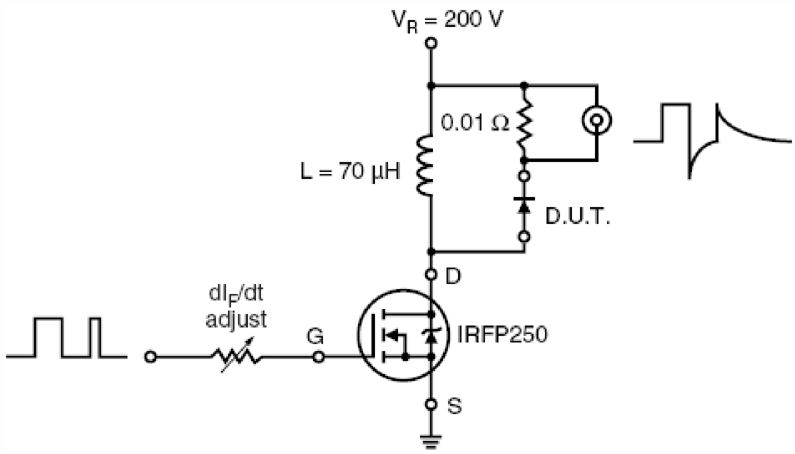


Fig. 5 - Reverse recovery diode parameters test circuit

The simulated current responses under various conditions are displayed in the Fig. 6. The Model slightly decline from the parameters, measured on real diodes. If we set the proclamative diode and circuit parameters for inst. the carrier lifetime 10,3 ns and the negative current slope of 200 A/μs in the model the reverse recovery time $t_{rr}$ of only 14 ns was achieved against 35 ns officially presented (6). Increasing the carrier lifetime $\tau_L$ to 60 ns and simultaneously the negative current slope to 600 A/μs lead to the really measured $t_{rr}$ values. This disagreement should be explained conducting the further simulations.

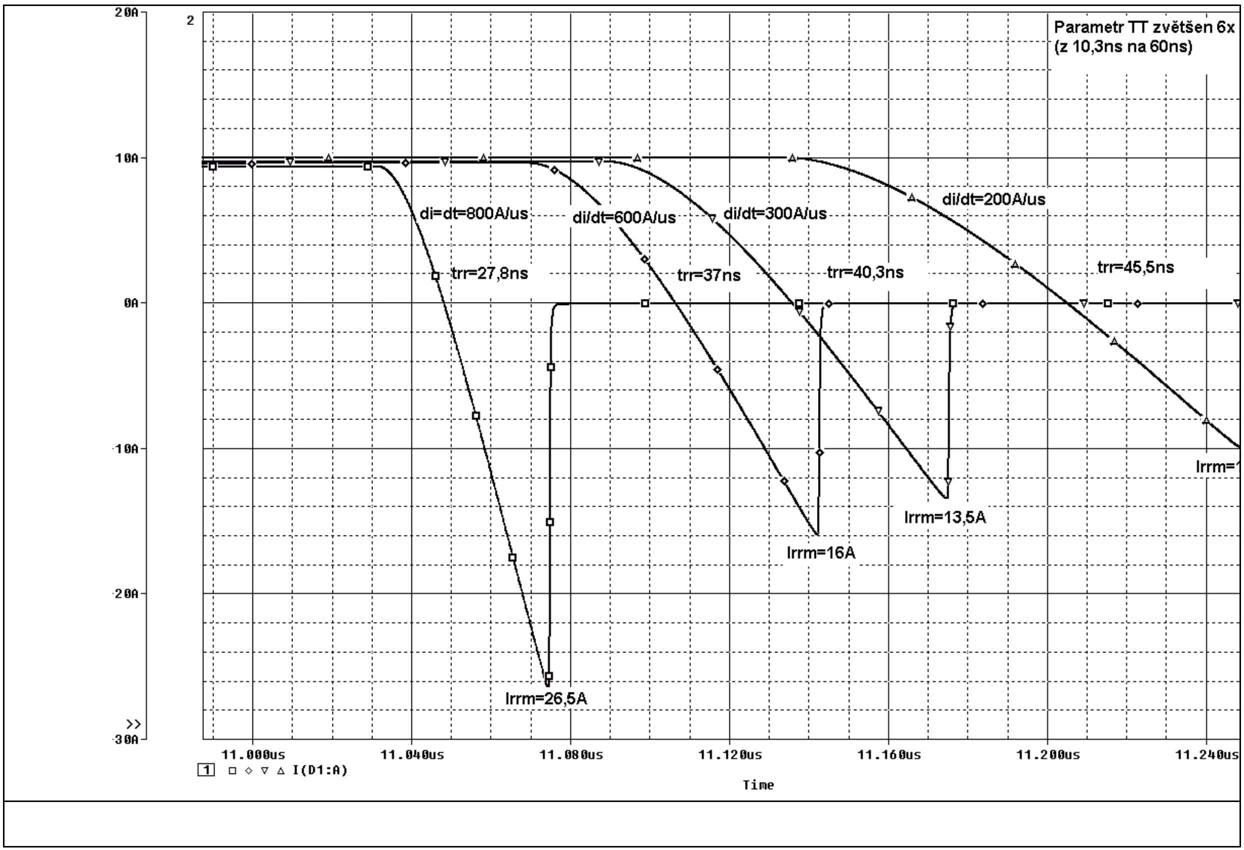


Fig. 6 - Diode current response during the reverse recovery at: $I_{F0}$=10A, $\tau_L$ = 60 ns

## CONCLUSION

Generators of nanosecond, high energy pulses based on various technologies for electronic devices testing has been extensively studied in the recent years. In this paper the high power short pulse generator based on SOS pulsed generator and avalanche pulse sharpener was described. The presented circuit is particularly highly suitable for a short pulse high power generator with stable long term operation for electronic equipment testing against the Electromagnetic Impulse (EMI) threat realization. The high voltage diode HFA25TB60 reverse recovery simulations show a good qualitative conformance with the presented theory. Certain disagreement in details will be cleared in the future research.

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