Influence of the cathode region preionization on the operating parameters of the eptron

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Abstract. Investigations of the operating parameters of a plasma-cathode switch based on a capillary discharge in helium and neon in the burst mode are presented. An increase in the efficiency of the switch is demonstrated when an additional preionization pulse is applied at a low pulse repetition frequency (5 kHz). The compression ratio of voltage pulses more than 300 is achieved at a pulse repetition frequencies less than 40 kHz.

1. Introduction

High-voltage nano- and subnanosecond switches have a wide range of applications including biology [1], plasma technologies [2], lasers excitation [3], accelerator physics [4] etc. Recently, the promise of using a capillary discharge with a plasma cathode for switching high-voltage pulses at high pulse repetition frequencies (tens of kHz) was demonstrated [5-7], proposed device was named eptron. In the initial works [5, 8] to create a plasma in the cathode region of the switch part of the energy stored in the operating capacitor was used. However, such a solution has some limitations. In the present work, for the preionization of the cathode region, a separate adjustable generator is implemented and the influence of the pulse energy of the cathode region preionization on the operating characteristics of the switch is investigated.

2. Experimental setup

The cathode region of the switch (figure 1 (a)) consists of two flat rectangular SiC cathodes with a total area of 22 cm² and two additional grid electrodes remote from the cathodes by a distance of 3 mm each and forming a 6 mm region between each other. A capillary of rectangular cross section with dimensions of 10×0.3 mm in the narrowest parts and a length of 35 mm is located at one side of the cathode region. The inner surface of the capillary has a meander shape with a period of 2 mm, which avoids surface breakdowns along the walls of the capillary. Two copper plates connected to the cathodes of the device are attached to the outer surface of the capillary through an additional insulator. Such a configuration allows to reduce the inductance of the switch and has a great influence on providing a large breakdown development time $t_d$ at high pulse repetition frequency (PRF) [7].

The positive voltage pulses from the generator were applied to the anode of the switch, the cathodes of the device were grounded (figure 2 (a)). The charging time of the operating capacitance $C$ was $\sim 100$ ns. The value of load resistance $R_L$ varied from 24.5 to 98 Ohm. Parameters were measured in the burst operation mode at a PRF in the burst $f = 5$ to 50 kHz. A positive pulse with an amplitude
of up to 8 kV was applied between the grids and cathodes to preionize the cathode region 1 μs before each of the pulses in the burst. Current measurements were carried out using two low-inductance shunts assembled from chip resistors. Resistive voltage dividers were used to measure the voltage across the electron. All waveforms were observed on a Tektronix MDO3104 oscilloscope (1-GHz bandwidth).

Figure 1. (a) - drawing of a switch based on a capillary with rectangular cross-section, (b) - electrical circuit for measuring parameters of the switch operation.

Figure 2. Oscillograms of the current $I$ through the load and the voltage $U$ on the switch. He, $P = 10$ Torr, $f = 20$ kHz, $R_L = 98$ Ohm. $U_{rev}$ (b) is the voltage across the switch when it is connected with reverse polarity.

3. Results and discussion
In figure 2 the oscillograms of the voltage $U$ on the switch and the current through the load $I$ (the sum of the currents through two shunts) are demonstrated. The typical voltage switching time is ~ 1.5 ns (figure 2 (b)). Voltage oscillogram for the case of applying reverse polarity to the switch is also presented. In this mode, under similar operating conditions, the starting losses in the switch and the conduction losses during the entire pulse are significantly larger. At low PRF (units of kHz and less) the starting losses in the switch significantly depend on the degree of prepulse ionization of the cathode region, which, in particular, can be seen in the current oscillograms (figure 3 (a)).

The energy deposited into the load in the first 10 ns after the start of switching is taken as a value characterizing the starting losses in the switch. The preionization pulse was applied to the cathode-grid gap 1 μs before the main pulse, while the oscillograms changed slightly with increasing time lag up to
5 μs. The value of the additional capacitance on the grid, $C_{\text{pre}}$, has little effect on the value of the starting losses (figure 3 (b)). With an increase in the pre-ionization pulse energy over ~ 10 mJ, the starting losses almost do not change. In addition, the preionization pulse does not significantly affect the total efficiency of energy transfer from the capacitor to the load, except for an increase in starting losses. The breakdown development time of the switch $t_d$ decreases insignificantly (less than 5%) with an increase in the preionization pulse.

![Figure 3](image1.png)

**Figure 3.** (a) - oscillograms of current $I$ through the load at different values of the preionization pulse energy of the switch $W_{\text{pre}}$ (He, $P = 10$ Torr, $U_A = 16$ kV, $f = 5$ kHz, $R_L = 24.5$ Ohm, $C_{\text{pre}} = 0.46$ nF); (b) - dependences of the energy $W_{10\text{ns}}$ deposited into the load during the first 10 ns on $W_{\text{pre}}$ ($U_A = 16$ kV, $R_L = 24.5$ Ohm).

![Figure 4](image2.png)

**Figure 4.** (a) - oscillograms of current $I$ through the load at different values of helium pressure ($U_A = 16$ kV, $f = 20$ kHz, $R_L = 24.5$ Ohm, $W_{\text{pre}} = 9.4$ mJ). Dependences of the efficiency $\eta$ (b) and the delay in the development of breakdown $t_d$ (c) on the gas pressure $P$ in the switch ($U_A = 16$ kV, $f = 20$ kHz, $R_L = 24.5$ Ohm, $W_{\text{pre}} = 9.4$ mJ).

The conductivity of the switch is significantly influenced by the gas pressure inside it (figure 4). On the one hand, with decreasing pressure, the conductivity of the switch and the delay in the development of breakdown $t_d$ (c) on the gas pressure $P$ in the switch ($U_A = 16$ kV, $f = 20$ kHz, $R_L = 24.5$ Ohm, $W_{\text{pre}} = 9.4$ mJ).
voltage pulse) increase, providing favorable conditions for the operation of the switch. But on the other hand, when a certain pressure value is reached (for helium $\sim 10$ Torr, for neon $\sim 3$ Torr at $U_A = 16$ kV, $W_{\text{pre}} = 9.4$ mJ), voltage oscillations begin to develop between the switch electrodes, which negatively affects the shape of the signal on the active load (figure 4 (a)). With an increase in the load, the efficiency of the switch, defined as ratio between the energy dissipated in the load and the energy stored in the capacitor $C$, increases (figure 4 (b)), reaching 0.8 at an amplitude value of the voltage $U_A = 16$ kV and a load of 98 Ohm in helium at a pressure of 5 Torr. At similar values of the efficiency in helium, larger values of the delay in the development of breakdown at which the oscillations do not yet occur are attainable than in neon (figure 4 (c)).

![Figure 5](image1.png)

**Figure 5.** Dependences of the efficiency $\eta$ (a), the breakdown development delay $t_d$, and the switching time $t_{sw}$ (b) on the $U_A$ voltage across the switch ($f = 20$ kHz, $R_L = 24.5$ Ohm, $C_{\text{pre}} = 0.46$ nF, $W_{\text{pre}} = 7.1$ mJ).

![Figure 6](image2.png)

**Figure 6.** Dependences of the of the efficiency $\eta$ (a) and the breakdown development delay $t_d$ (b) on the PRF $f$ ($U_A = 16$ kV, $R_L = 24.5$ Ohm, $C_{\text{pre}} = 0.46$ nF).
An increase in the amplitude of the charging voltage $U_A$ leads to an increase in the efficiency of the switch $\eta$ (figure 5 (a)). With a low active resistance - 24.5 Ohm, the efficiency increases from 0.45 to 0.54 with an increase in voltage from 10 to 16 kV in helium. The maximum amplitude value of the voltage in the experiments was 16 kV and was limited by the surface breakdown of the air gap between the conducting plates outside the capillary and its anode. With the organization of additional insulation, it is possible to further increase the operating voltage and, accordingly, the efficiency of the device. The breakdown delay decreases significantly with increasing voltage, reaching $\sim 0.5 \mu s$ for 10 Torr helium at 16 kV (figure 5 (b)). The frequency characteristics of the switch are investigated up to $f = 40$ kHz. The efficiency of the switch increases slightly with an increase in PRF, which is primarily associated with a decrease in starting losses (figure 6 (a)). In helium, after 10 kHz, an insignificant reduction in the breakdown development delay $t_d$ is observed; its value at 10 Torr is $\sim 0.5 \mu s$ (figure 6 (b)). Thus, up to a PRF of 40 kHz, at a switching time $t_{sw} \sim 1.5$ ns, the compression ratio of the leading edge of the voltage pulse exceeds $S = t_d/t_{sw} = 300$ at $U_A = 16$ kV.

4. Conclusion

The results of measuring the efficiency, breakdown time delay for various values of switching voltage, operating pressure of the electron and preionization pulse energy are presented. The maximum achieved efficiency reached 0.8. Further increase of the efficiency is possible with improvement of the external insulation of the switch in order to increase the maximum operating voltage. It has been demonstrated that at pulse repetition frequencies above 20 kHz the preionization pulse does not significantly affect the switch characteristics. Voltage pulse compression value of $\sim 300$ is achieved at a pulse repetition frequency up to 40 kHz.

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