Abstract – The paper deals with the investigations of high-pressure micro-spark gap in nitrogen in a regime of high pulse repetition rate. Typical voltage at the gap was about 1 kV and the gap distance was 0.1 – 0.2 mm. In this condition, it was demonstrated that the gap is capable of switching in sub-nanosecond time range with a pulse repetition rate up to 1 MHz. The studies on the processes of de-ionization in the gap in the pause between the pulses are presented.

1. Introduction

It is known that the spark gaps at a pressure of about 10 atm and higher are capable of switching with a time essentially less than 1 ns [1]. This property is widely used for development and construction of the high-voltage pulsed generators with a voltage level larger than 100 kV [2–4]. Typical interelectrode distance in such conditions is larger than several millimeters.

On the other hand, when the gap spacing decreases the switching time decreases as well [4] so that even with a pressure of 1 atm it becomes possible to obtain the subnanosecond current risetime. Beside that, the de-ionization time of the gap decreases in the microgaps, which forms the prerequisites for switch operation with high pulse repetition rate. It is obvious that for these condition we mean not the above mentioned high-voltage generators but the devices with a voltage level in a vicinity of 1 kV. The features of the switch operation for such devices are investigated in this paper.

2. Experimental arrangement

Schematic of experimental arrangement is shown in Fig. 1. This is the generator of nanosecond pulses base on the coaxial lines.

The electric circuit operates by the following way. Under the effect of power supplier $PS$ the pulse forming coaxial line $l_f$ is charged via charging resistor $R$ ($C_1$ is the intrinsic capacitance of the power supplier that maintains the constant value of the potential $V_{A}$). When the breakdown in high-pressure spark gap $G$ occurs an incident wave of amplitude $V_B/2$ propagates over the transmitting line $l_t$ to the matched load $Z = 50 \Omega$, where $V_B$ is the voltage value to which the pulse forming line is charged, i.e. the breakdown voltage for the gap $G$. In most experiments the length of the forming line $l_f$ was equal to 40 cm, that is the capacitance of the cable $C = 40 \mu F$. In some experiments, we used the line with a length of 90 cm. The spark gap $G$ with an interelectrode distance of 0.14 mm operates in nitrogen at a pressure $p = 2$ atm.

In generally used cases, the described system operates in so-called regime of $RC$ generator. When the voltage at the gap $G$ reaches the static breakdown value, the spark gap is switched and nanosecond pulse appears at the load $Z$. The characteristic time $RC$ is selected in such a manner that in the pause between the successive pulses the gap would be completely recovered its dielectric strength. However in this case, the high pulse repetition rate is not achievable, since typical time of the gap recovering falls on millisecond time scale. The regimes of operation under discussion are related to the case, as the gap is not completely recovered, i.e. residual plasma from preceding discharge is still available in the gap when a succeeding breakdown is ignited.

Example of the current and voltage waveforms for $R = 155 \text{k}\Omega$ and $C = 40 \mu F$ is shown in Fig. 2. In the experiments, we recorded the voltages $V_A$ and $V_B$ at the points $A$ and $B$ of electric circuit (see Fig. 1) and the current in the transmitting line $i_{t}$.

It is seen that the very first breakdown occurs at a voltage $V_{B} = 2.2 \text{kV}$, which corresponds to the static breakdown voltage of the gap $G$ (instant $t = 10 \mu s$). This breakdown results in a peak current in the load $i = V_{B}/2Z = 20 \text{ A}$. Demonstration of typical shape for

---

1 The work was supported by the Russian Foundation for Basic Research (Project 05-02-16477-a).
this current peak is presented in Fig. 3, where the length of pulse forming line \( l_f = 90 \text{ cm} \) and the breakdown voltage \( V_B = 2 \text{ kV} \). This figure illustrates that the circuit forms the single pulse at the matched load and the pulse duration is equal to twice the travel time of electromagnetic wave through the line \( l_f \).

Fig. 2. Voltage and current waveforms for regime of high pulse repetition rate (\( R = 155 \text{ k\Omega}, C = 40 \text{ pF} \)).

Fig. 3. Illustration of the current waveform for single current pulse. Charging voltage \( V_A = 2 \text{ kV} \), length of the charging cable \( L_i = 90 \text{ cm} \).

In order to clear up the reasons for instability we have measured a current via the switch in the pauses between the pulses. For this purpose, a special electric circuit had been used. The circuit cuts off the peaks of high current so that we have a possibility to send the voltage pulses to oscilloscope and to record the current in transmitting line at a level of 0.1 A and less.

The experimental data presented below had been obtained by this method.

3. Investigations of stability of the switch operation

Current and voltage waveforms containing information on discharge behavior after the high-current pulses for different \( V_A \) values are shown in Figs. 4 and 5.

When we increase the voltage \( V_A \) or decrease the ballast resistor \( R \) we increase the discharge current from power supplier, i.e. increase the current between the pulses. This fact is definitely seen from comparing the data in Fig. 4 and in Fig. 5. The less discharge current in the time interval between the pulses the larger breakdown voltage in the conditions under consideration and the larger duration of the pause between the spark discharges.

In terms of physical mechanism of the current passage in the pause between the pulses, the discharge at this temporal stage can be defined as a kind of glow. In general, this definition is correct and reflects the principal properties of the discharge. Nevertheless it would be more strictly to precise that we deal with the ignition of spark channel in the decayed plasma from preceding discharge. Actually, addressing to Fig. 5, we can see that the discharge current decreases while the voltage at the gap (because of charging the capacitance \( C \) from power supplier) increases. What this means is the gap resistance increases with time from extremely low value to approximately \( R_g = 100 \text{ k\Omega} \) just before the new spark ignition. In other words for the case under discussion the discharge in time interval between the pulses burns in a regime of decayed plasma where the processes of recombination in plasma column are prevailed over the process of ionization.

The transition to spark discharge occurs, as in any type of glow, due to development of instability in the near cathode region of glow discharge and appearing the cathode spot [1, 5–6]. For our case (Fig. 5) the energy for formation of the cathode spot and spark channel is delivered by the capacitance of the pulse forming line, \( C = 40 \text{ pF} \). The stored in this capacitance energy is rather low (\( w \approx 5 \mu\text{J} \)). However, this energy is sufficient to provide the glow-to-spark transition process and to form the micro-spark channel with a current about 5 A.

As a matter of fact the data in Fig. 5 represents an example of the optimal conditions of the switch operation. These conditions have achieved due to corre-
sponding selection of voltage $V_A$ and resistance $R$. In other words, the density of residuals discharge plasma in the time interval between the pulses turn out to be most suitable to provide a constant value of breakdown voltage in each pulse. The pulse repetition rate for the switch operation of about 2 MHz is achieved in these conditions.

![Figure 4](image)

**Fig. 4.** Illustration of the current behavior in the pause between the pulses of spark discharge (formation of the spark channel in the decayed plasma). $R = 89 \, \text{k}\Omega$, $V_A = 1.7 \, \text{kV}$.

![Figure 5](image)

**Fig. 5.** Illustration of the current behavior in the pause between the pulses of spark discharge (formation of the spark channel in the decayed plasma). $R = 89 \, \text{k}\Omega$, $V_A = 2.8 \, \text{kV}$.

When we further increase the current between the pulses, the spark breakdown process in the switch becomes unstable again. For such increased current a great variety of the non-steady state processes in the discharge is observed. One of the examples of the discharge behavior after the spark breakdowns for charging resistor $R = 20 \, \text{k}\Omega$ is shown in Fig. 6.

![Figure 6](image)

**Fig. 6.** Illustration of the current behavior in the pause between the pulses of spark discharge (temporal stages of the arc discharge with cathode spot and formation of spark in the decayed plasma). $R = 20 \, \text{k}\Omega$, $V_A = 2.25 \, \text{kV}$.

In Fig. 6 we can see the case when the stage of arc discharge with distinctively expressed cathode spot is available. This stage lasts from $t = 0$ to $t = 200$ ns. The discharge burning voltage is extremely low and the discharge current ($i = 0.1$ A) is determined by the charging resistor $R$. The arc with low current is not able to burn during a long time, as far as the lifetime of the cathode spot is limited [5, 6]. Then at the instant $t = 200$ ns the cathode spot is decayed, the conductivity sharply decreases, and the discharge current falls abruptly to a value of 15 mA. The discharge starts operating in a kind of glow mode. After that the voltage at the capacitance $C$ is increasing and when it reaches a value of 500 V new spark is ignited. It could be also noted that in terms of our preceding consideration the further stages in Fig. 6 (after $t = 200$ ns) are characterized as formation of the spark channel in the decayed plasma.

At the same conditions, the other version of the discharge behavior can be observed (Fig. 7). Here we see the glow-to-spark transition process in its “pure” form. Actually, from $t = 0$ to $t = 470$ ns the steady state glow discharge exists in the gap. As distinct to the regime of decayed plasma, this discharge with a current of 90 mA is characterized by constant burning voltage, $V_d \approx 400$ V. The glow-to-spark transition is accompanied by fast discharging of the capacitance $C$. When the capacitance is charged repeatedly, we observe that the glow discharge is established in the gap again (time interval from $t = 700$ ns to $t = 1000$ ns). It is evident that later on the glow discharge will transforms into the spark.
Here initially the glow discharge burns. At instant $t = 280$ ns the glow-to-spark transition occurs and when the voltage at the capacitance increases repeatedly, the discharge continue to burn in the glow mode. After the time $t = 670$ ns we observe the situation as the spark channel forms on background of decayed plasma.

4. Conclusion

In this paper, the investigations of high-pressure micro-spark gap in nitrogen in a regime of high pulse repetition rate with the purpose to form the nanosecond pulses at resistive active load had been carried out. The simplest electric circuit for charging the pulse forming line via the charging resistor had been used.

It is demonstrated that the pulse repetition rate in a range in a vicinity of 1 MHz is achievable. This regime of the switch operation is characterized by conditions when the residual plasma from preceding spark discharge is still available when the succeeding breakdown occurs in the gap. A great variety of the discharge burning modes in the gap in the pause between the pulses is observed. These are the arc of short duration with distinctively expressed cathode spot, the glow discharge at constant burning voltage and the regime of decayed plasma.

To achieve the stability of the switch operation it is necessary to select the discharge current in the gap in the pause between the successive pulses. The suitable current at a level from 5 mA to 10 mA corresponds to the regime of glow discharge in decayed plasma. Then the glow-to-spark transition process provides the stable operation of the switch.

References