Experimental studies of the electrical and radiative characteristics of a channel surface discharge

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Abstract Channel surface discharge (CSD) is a type of surface (sliding) discharges or dielectric barrier discharges in the incomplete stage. Experimental results of both incomplete (low-current) and high-current complete stages of the CSD are presented. The waveform of current pulse in the discharge incomplete stage as well as the influence of the voltage growth rate $dU/dt$ on the discharge electrodes on waveform are studied. Experimental dependence of the CSD current pulse amplitude on the $dU/dt$ rate is obtained in the incomplete stage over a wide range of variation of the $dU/dt$. For the CSD complete stage, the relation between the intensity of the discharge radiation in the UV region and the amplitude of the current pulse has been received. The dependence of the maximum electron concentration on the UV radiation intensity of the high-current stage CSD was obtained for the case when UV radiation from the CSD was used for ionization of atmospheric pressure nitrogen.

1. Introduction

The interest in channel surface discharge (CSD) is due to the fact that in the complete stage it is a source of powerful UV radiation, and in the incomplete stage it is a directed, extended discharge, convenient to study the properties of discharges of this type (sliding, dielectric barrier). The first detailed study of the properties of channel surface discharges was carried out in [1]. As a source of high-power UV radiation, the CSD was used to preionize a working mixture of a high-pressure CO$_2$ laser operating at a pressure of 3 atm [2]. In this role the CSD was also used to study the mechanisms of atmospheric pressure molecular nitrogen ionization [3-6]. The incomplete stage of the channel surface discharge was the subject of research in [7], which considered the possibility to optimize the length of such discharges with the same amplitude of high-voltage pulses of the power circuit.

In this work, experimental research of both the incomplete (low-current) and high-current complete stages of the channel surface discharge is carried out to study the influence of the voltage growth rate $dU/dt$ at the discharge electrodes on the waveform of current pulse of the incomplete stage and the current amplitude. For the current of the complete discharge stage, the experimental dependence of the radiation intensity of the CSD on the current amplitude is obtained. For the process of atmospheric pressure molecular nitrogen ionization by UV radiation of the CSD, the dependence of the electron concentration on the intensity of the CSD radiation in the UV region is obtained.

2. Experimental device

Figure 1 schematically shows an experimental device to produce channel surface discharges (CSD) and a CSD power supply circuit (the device and power supply circuit are described in detail in [1]).
When a high-voltage pulse is applied to the electrodes of the device in the channel bounded by the walls of the dielectric, a discharge develops from electrode 2 to electrode 3 (Figure 1). Initially, it develops in a low-current form of the incomplete stage of the discharge; when reaching electrode 3, the discharge becomes complete and high-current. Figure 2 shows typical waveforms of the CSD for the incomplete and complete stages of the discharge [1].

![Figure 1](image1.png)

**Figure 1.** Device for the organization of the channel surface discharge (CSD). (1) is the power supply circuit; (2,3) are the electrodes; (4) is the dielectric [1].

![Figure 2](image2.png)

**Figure 2.** Waveforms of the current (bottom) and voltage (top) of the CSD. (a) the incomplete discharge, (b) the complete discharge [1].

The experiments on channel surface discharges were carried out in air and nitrogen at atmospheric pressure with the use of various dielectric materials (ceramics, $\varepsilon \sim 100$, fiberglass, $\varepsilon \sim 4$). The discharge was powered by a capacitor bank assembled according to the doubling scheme (the capacitance in each arm is 10-30 nF), Figure 1.

3. **The incomplete stage of the CSD. The study of the waveform and amplitude of the electric current pulse of the incomplete stage of the CSD.**

The study of the waveform of current pulse and amplitude of the electric current pulse of the incomplete stage of the CSD was carried out on a device with a ceramic substrate with a length of 11.5 cm (Figure 1) according to the method described in [1, 7]. To measure the current of the incomplete stage $I_{in}$, a low-resistance, low-inductance electric shunt was used, which made it possible to measure the total charging current of the distributed capacitance of the dielectric substrate. During the
experiment, voltage pulses of the same amplitude, near 11.6 kV, were applied to the electrodes of the device each time, and the voltage growth rate on the electrodes was varied by the change in the inductance L (Figure 1) in the thyratron circuit.

The experiments showed that depending on the voltage growth rate \( \frac{dU}{dt} \) applied to the electrodes of the discharge, the incomplete stage current pulses \( I_{nz} \) had a different waveform of current pulse.

Figure 3 shows the waveforms of current and voltage at different \( \frac{dU}{dt} \) values on the discharge electrodes. The discharge length of the incomplete stage \( L_{nz} \) was visually monitored each time.

**Figure 3.** Waveforms of the current (bottom) and voltage (top) of the incomplete stage of the channel surface discharge (CSD) on a device with a ceramic substrate for experiments with different values of \( \frac{dU}{dt} \).

- **a)** \( \frac{dU}{dt} \approx 10.76 \times 10^9 \) V/s., \( I_{\text{max}}=1.14 \) A, \( L_{nz}=10.5 \) cm, oscilloscope sweep time \( \tau=2 \) μs;
- **b)** \( \frac{dU}{dt} \approx 4.8 \times 10^9 \) V/s., \( I_{\text{max}}=0.68 \) A, \( L_{nz}=8.5 \) cm, oscilloscope sweep time \( \tau=2 \) μs;
- **c)** \( \frac{dU}{dt} \approx 2.9 \times 10^9 \) V/s., \( I_{\text{max}}=0.63 \) A, \( L_{nz}=8.5 \) cm, oscilloscope sweep time \( \tau=4 \) μs.

It can be seen that at the same amplitude of the high-voltage pulse applied to the CSD electrodes (11.6 kV), the amplitude of the current pulse \( I_{nz} \) and the nature of the change in the waveform of the current pulse depend defining way on the voltage growth rate \( \frac{dU}{dt} \) pulse applied to the electrodes. The amplitude of the current pulse \( I_{nz} \), shown in Fig. 3, directly depends on \( \frac{dU}{dt} \), gradually decreasing with the decrease in \( \frac{dU}{dt} \). It should also be noted that, at a high growth rate of voltage rise, the amplitude of the current pulse \( I_{nz} \) increases in time (Figure 3a). When \( I_{nz} \) decreases, it becomes almost constant (Figure 3b), with the further decrease in \( \frac{dU}{dt} \) the amplitude of the current pulse decreases in time (Figure 3c). These results show the possibility of controlling the waveform and amplitude of the current pulse \( I_{nz} \) by the change in the \( \frac{dU}{dt} \) value at the discharge electrodes. With a decrease in \( \frac{dU}{dt} \), the amplitude of the current pulse \( I_{nz} \) also decreases from 1.14 A down to 0.63 A. These results are important because they indicate the possibility to control the behavior of the CSD current in the incomplete stage in time. On the same device for the CSD, the dependence of the current pulse amplitude \( I_{nz} \), CSD was experimentally studied as a function of the voltage growth rate of the applied voltage on the CSD device with a channel length of 11.5 cm on a ceramic substrate. The experimental results are shown in Figure 4. It can be seen that the current amplitude \( I_{nz} \), CSD increases with the growth of \( \frac{dU}{dt} \) and the dependence of the current amplitude on \( \frac{dU}{dt} \) is approximately linear.

The experimental results show that, along with the linear capacitance of the CSD substrate, the parameter \( \frac{dU}{dt} \), i.e., voltage growth rate on the discharge electrodes, determines the amplitude and waveform of the current pulse of the incomplete CSD stage. Thus, it is possible to control not only the amplitude of the current pulse of the incomplete stage of the CSD, but also its waveform of current pulse (Figure 3, 4).
Figure 4. Experimental dependence of the amplitude of the current pulses $I_{nz}$ (A) depending on the voltage growth rate $dU/dt$ applied to the electrodes of the discharge. Device for CSD is with a channel length of 11.5 cm (ceramic).

The experimental results show that, along with the linear capacitance of the CSD substrate, the parameter $dU/dt$, i.e., voltage growth rate on the discharge electrodes, determines the amplitude and waveform of the current pulse of the incomplete CSD stage. Thus, it is possible to control not only the amplitude of the current pulse of the incomplete stage of the CSD, but also its waveform of current pulse (Figure 3,4).

4. Investigation of the dependence of the radiation intensity in the completed stage of the channel surface discharge (CSD) within the UV region on the amplitude of the current pulse.

The experiment was carried out in a fiberglass chamber pumped down to a pressure of $10^{-1}$ Torr and filled with technical nitrogen up to a pressure of ~1 atm. The device for organizing the CSD was made of fiberglass and had a discharge length of 10 cm, the width and depth of the groove along which the discharge developed were 1 mm. The intensity of the CSD UV radiation was recorded in the spectral range of 300-360 nm with the use of a coaxial photocell 22SPU, which was placed 8 cm from the CSD. The experimental results of measuring the intensity of UV radiation of the CSD are presented in Figure 5.
Figure 5 shows experimental points for $W_{\text{rad}}$, according to the measurements with the coaxial photocell, and the dashed curve is the dependence $I_m^{16/11}$ in relative units for the corresponding amplitude values of current pulses of the CSD complete stage. According to the results of [1], the conductivity of the CSD in its complete stage is determined by electron-ion collisions and depends only on temperature. The energy input to the discharge is spent on the heating of the gas, and the heated gas emits as a completely black body in accordance with the Stefan-Boltzmann formula. The temperature maximum and the current maximum are related by the ratio: $T_m \approx 2.6 S^{-3/11} I_m^{4/11}$ [1]. $S$ - discharge cross-section, this leads to the following dependence $W_{\text{rad}} \approx I_m^{16/11}$ (in relative units). As shown in Figure 5, a good agreement is observed between this dependence and the experimental points.

5. Investigation of the dependence of the level of molecular nitrogen ionization on CSD emission intensities in the UV region.

The CSD in the completed stage is a powerful source of radiation in the UV region. This property was used in the works for preionization of a superatmospheric pressure CO$_2$ laser and in the study of mechanisms of atmospheric pressure molecular nitrogen ionization [2-6]. In this work, we have experimentally studied the dependence of the obtained electron concentration $n_e$ in atmospheric pressure nitrogen on the radiation intensity in the UV region of the complete CSD. The experiment was also carried out in a fiberglass chamber at a nitrogen pressure of ~1 atm. To measure the electron concentration, an electrostatic electron sensor was used. The sensor was placed with in 8 cm from the CSD and oriented so that its long side was located along the CSD. For this arrangement the illumination of the sensor space did not differ much from uniform. At the same time, the intensity of the CSD radiation in the UV region was measured with the use of a coaxial photocell 22SPU which was placed from the CSD as far as the electrostatic electron sensor.

The electrostatic electron sensor used to measure the electron concentration and the concentration measurement technics were described in detail in [3-6]. Electron concentration measurements were executed for two different CSD devices made of fiberglass with a discharge length of 10 cm. In device No. 1, the width and depth of the groove along which the discharge developed was 1 mm. In device No. 2, the corresponding parameters were 1 and 3 mm. The CSD power supply circuit generated high-voltage pulses applied to the CSD for the following values of charging voltages: 16, 18, 20 and 22 kV. The voltage pulses formed by the power circuit were applied to the CSD electrodes, Figure 1.

Figure 6 shows waveforms characterizing the electron concentration $n_e$ for various values of the discharge radiation intensity, which corresponded to the charging voltages on the CSD power supply circuit of 16, 18, 20 and 22 kV.
Figure 6. Device No. 1. Waveforms of signals of the electrostatic electron sensor for various values of the charging voltages on the capacitive storage of the power supply circuit of the CSD (16, 18, 20, 22 kV).

Figure 7 shows waveforms of the currents and signals of the coaxial photocell 22SPU in the UV region for the same values of charging voltages.

Figure 7. Device No. 1. Waveforms of currents (top) and coaxial photocell signals (bottom). Charging voltages in the power supply circuit of the CSD are 16, 18, 20, 22 kV, respectively. Amplitudes of currents are $I_m=1270$ A (frame 1), $I_m=2780$ A (frame 4).

Figures 8 and 9 show waveforms characterizing the concentration of $n_e$ electrons and coaxial photocell signals for a series of similar experiments with device No. 2 with the same values of charging voltages in the power supply circuit of the CSD.

Figure 8. Device No. 2. Waveforms of the signals of the electrostatic electron sensor for various values of charging voltages on the capacitive storage of the power supply circuit of the CSD (16, 18, 20, 22 kV).
Figure 9 shows the waveforms of the currents (top) and signals of the coaxial photocell 22SPU in the UV region (bottom) obtained on device No. 2 for the same values of charging voltages.

**Figure 9.** Device No. 2. Waveforms of currents (top) and coaxial photocell 22SPU signals (bottom). Charging voltages in the power supply circuit of the CSD are 16, 18, 20, 22 kV, respectively. Amplitudes of currents are $I_m=1085$ A (frame 1) and $I_m=2325$ A (frame 4).

The experimental results presented show that the amplitudes of the current pulses $I_m$ of the complete CSD for devices No. 1 and No. 2 are close in their values (Figs. 7, 9), while the values of the corresponding discharge radiation intensities and electron concentrations (Figs. 6, 8) differ considerably.

Figure 10 shows the obtained dependences of electron concentrations $n_e$ ($\text{cm}^{-3}$) on the radiation intensity of the CSD in the UV region (rel. units) for two devices.

**Figure 10.** Dependences of electron concentrations $n_e$ ($\text{cm}^{-3}$) on the radiation intensity of the CSD in the UV region for devices No. 1 and No. 2.

### 6. Conclusions

Experimental studies of the channel surface discharge (CSD) were carried out for low-current, (incomplete) and high-current (completed) stages. The effect of the voltage growth rate $dU/dt$ at the discharge electrodes on the amplitude and waveform of current pulse of the CSD incomplete stage was studied. It was found that the waveform of the current pulse $I_{nz}(t)$ could be controlled by the change in the voltage growth rate $dU/dt$. An experimental dependence of the amplitude of the current pulses $I_{nz}(A)$ on the rate $dU/dt$ was obtained, which was close to linear within a wide range of $dU/dt$.

For the completed stage of the CSD, a relation was obtained between the intensity of the discharge radiation in the UV region and the amplitude of the current pulse $W_{\text{rad}} \approx I_{nx}^{16/11}$, according to the results in [1]. A noticeable difference in the intensities of the UV radiation of the CSD discharge for devices No. 1 and No. 2 (Figures 7 and 9) can be explained by the geometry of the CSD channel. In device No. 2, the channel is deeper, therefore the UV radiation is partially limited by the channel walls. As a result (Figures 6, 8), the UV radiation intensity decreases as well as the resulting electron concentration. The dependence of the electron concentration $n_e$ on the radiation intensity $W_{\text{rad}}$ is close to linear in the UV region for both devices.
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