Relation of electric conditions between a source of Ar plasma jet and a substrate with a configuration of a plasma sheet on a target

Yu S Akishev¹,², A A Balakirev¹, V B Karalnik¹, A V Petryakov¹, N I Trushkin¹

¹SRC RF TRINITI, 108840, Russia, Moscow, Troitsk, Pushkovykh Str., vladenie 12
²National Research Nuclear University MEPhI, 115409, Russia, Moscow, Kashirskoe sh. 32

Abstract. The paper presents the experimental results relevant to the external electrical influence on the structure of a thin plasma sheet formed atop a substrate surface by Ar plasma jet that is being generated by a coaxial sinusoidal barrier discharge (BD) in an argon flow. The electrical influence on the target is being created due to connecting of a high-voltage or grounded electrode of the BD to the metal plate on which the dielectric or metallic substrate to be treated is located. Such an approach ensures a synchronism of the interaction of the external auxiliary electric field with the own electric field of the ionization wave (plasma bullet) propagating along the argon plasma jet toward the substrate during each period of the BD alternating voltage. An image of the structure of the plasma sheet on the substrate surface averaged over many periods of sinusoidal voltage was recorded in the experiments.

1. Introduction

Both the flow-type barrier discharge (BD) generating a plasma jet and the substrate (target) to be processed by the plasma jet are always bound electrically to each other by a capacitive coupling providing between them a displacement current. In some cases, the electrical coupling can be provided by the conduction currents (when metallic materials to be treated by plasma jet are grounded). This issue was considered in detail in [1] by the example of the interaction of a helium plasma jet with dielectric and metallic targets. The intensity of the electrical coupling depends on both the BD electrodes configuration, the frequency and amplitude of the applied voltage, the type of plasma forming gas, as well as on the electrical properties of the substrate processed (metallic or dielectric), the geometry and dimensions of the substrate, its distance from the plasma generator and its electrical coupling with the ground (capacitive and / or ohmic). The equivalent electrical schemes of the “generator - plasma jet - substrate - ground” circuit are shown in Fig.1.

The electrical coupling between the BD and the substrate is enhanced in the presence of a plasma jet striking the substrate, as follows from Fig. 1. In this case, some fraction of the electric current from the generator flows through the plasma jet and the substrate, and this fraction of the current for the case (d) in Figure 1 can be quite significant and even can exceed the current of the BD. The existence of a electric current flowing through the “generator-plasma jet-substrate-ground “ circuit can lead to a strong change in the properties of the plasma jet striking the substrate, as compared with the jet in free space. In addition, the properties and configuration of the plasma sheet formed by a plasma jet striking a target is also dependent strongly on the magnitude of the electrical coupling in the generator-jet-
substrate-ground circuit. This circumstance may affect the effectiveness and quality of plasma treatment of various targets.

![Figure 1](image)

**Figure 1.** The equivalent electrical schemes of a barrier discharge and a plasma jet with a substrate are depicted on the left and right sides of each figure. a) jet enters a free space; b) jet striking a dielectric substrate placed on a grounded metallic plate; c) jet striking an ungrounded metallic plate; d) jet striking a grounded metallic plate; R1 and R2 define the effective resistances of the BD and the plasma jet; C1 and C2 define the capacity of the BD and the plasma jet together with the substrate.

Argon plasma is a more sensitive subject to the development of ionization instabilities compared to helium plasma. For this reason, the argon plasma jet will be more sensitive to changes in the electrical coupling in the generator-jet-substrate-ground circuit. The relationship of the electrical conditions between the BD source of an argon plasma jet and the substrate with the configuration of the jet and the plasma sheet on a dielectric and metallic target is considered in this paper. The experiments were supplemented with a study of the gas-dynamic effect on the dimension and configuration of the plasma sheet on the target. The gas-dynamic effect is created due to close overlapping of a quartz disk over the target, which limits the thickness h of the gas-plasma jet radially diverging over the target. A plasma jet is introduced through a narrow hole in the quartz disk. In the case of small h, the gas-dynamic effect allows to significantly increase the radius of the plasma spot on the target.

### 2. The experiment and the results obtained.

The barrier discharge forming the plasma jet was generated inside the quartz tube in an argon flow at atmospheric pressure. The gas flow velocity was varied up to 120 m/s. The inner and outer tube diameters were 2.5 and 4 mm, respectively. The internal electrode of the BD was a stainless steel wire with a diameter of 1 mm and was located on the tube axis. The outer electrode was a strip of copper foil of 20 mm wide glued to the outer surface of a quartz tube. The downstream edges of the electrodes were in the same plane, located in 8 mm from the outlet of the quartz tube. The BD was excited by a sinusoidal voltage of 100 kHz frequency and an amplitude from 1 kV to 5 kV. High voltage was applied either to the internal electrode or to the external one. The time-averaged images of the plasma jet and the plasma spot on the target were made using a Canon EOS 550 D digital camera. Ceramic and aluminum plates were used as targets in the experiment which were located at different distances from the exit of the quartz tube. The dimensions of the ceramic plate were 70x70x1.6mm. The copper foil with dimensions of 50x50 mm was glued on the back side of the ceramic plate. The experiments were carried out at different potentials of copper foil and a metal plate: a) they were under floating potential, b) they were grounded, c) they were connected to the high-voltage electrode of the BD.
Figure 2. The dependence of the length of the plasma jet incident on a dielectric plate with a copper foil on the back side, versus the amplitude of the applied voltage.  
1 - high potential is applied to the internal electrode, the foil is under a high synchronous potential;  
2 - high potential is applied to the external electrode, the foil is grounded, like the internal electrode of BD.  
The dielectric target is located at a distance of 18 mm from the discharge exit. f = 100 kHz, V = 25 m / s.

The results of experimental studies of a plasma jet impacts a ceramic plate with a copper foil glued on the back side are presented below. In this case, the potential of the copper foil has a strong influence on the length of the plasma jet. In figure 2 show the dependences of the plasma jet length on the amplitude of the applied voltage for the cases when a zero-electric field space is created between the discharge output and the target, i.e. when the internal electrode of BD and the target are at the same potential. The experiment showed that in this case the development of ionization waves is significantly suppressed in comparison with the jet in free space, which leads to a significant decrease in the plasma jet length at same amplitudes of the BD voltage.  

Figure 3 shows the images of a plasma jet in an argon flow propagating in a zero-electric field space. Only a thin plasma channel formed by ionization waves (“plasma bullets”) is visible in the jet on the photos with a short time exposure.

Figure 3. The images of the plasma jets propagating in a zero-electric field space and striking a dielectric target at different amplitudes of the applied voltage. a-U_0 = 3.0 kV, t_e =50 ms; b -U_0 = 5 kV, t_e =20 ms. High potential is applied to the internal electrode, the target (foil) is under high synchronous potential. The dielectric target is located at a distance of 18 mm from the discharge output; f = 100 kHz, V = 25 m / s.
Figure 4. The dependence of the diameter of the plasma spot on the ceramic plate surface versus the amplitude of the applied voltage. 1-High potential is applied to the internal electrode, the target (foil) is under zero potential (grounded); 2- High potential is applied to the external electrode, the target (foil) is under high potential. The dielectric target is located at a distance of 18 mm from the discharge output; f = 100 kHz, V =25 m/s.

Figure 5. The images of plasma jet colliding with a ceramic plate at different amplitudes of the applied voltage. High potential is applied to the internal electrode, the target (foil) is grounded. The dielectric target is located at a distance of 23 mm from the discharge output; f = 100 kHz, V=25 m/s. a) $U_0 = 2.8 \text{kV}, t_e = 2 \text{mc}$, b) $U_0 = 3.5 \text{kV}, t_e = 1 \text{mc}$, c) $U_0 = 4.4 \text{kV}, t_e = 0.5 \text{mc}$, d) $U_0 = 4.4 \text{kV}, t_e = 0.25 \text{mc}$, e) $U_0 = 5 \text{kV}, t_e = 0.25 \text{mc}$.

Figure 6. The images of plasma jet colliding with a metallic disc (a) and ceramic plate (b, c) at different amplitudes of the applied voltage: a) $U_0 = 4 \text{kV}, t_e = 0.25 \text{ms}$; b) $U_0 = 3.2 \text{kV}, t_e = 0.25 \text{ms}$; c) $U_0 = 5 \text{kV}, t_e = 0.25 \text{ms}$. High potential is applied to the internal electrode, the target (foil) is grounded. The target is located at a distance of 23 mm (a) and 18 mm (b, c) from the discharge output; f = 100 kHz, V = 25 m / s.
The dependence of the diameter of the plasma sheet formed by the plasma jet colliding with a ceramic plate on the amplitude of the applied voltage for cases when the target potential is opposite to the internal BD electrode potential is presented in figure 4. This combination of electric potentials leads to the appearance of an additional barrier discharge between the internal electrode of the coaxial BD and the dielectric target when the amplitude of the applied voltage exceeds the threshold value (Figure 5).

A very intense spark channels between the inner electrode of the coaxial BD and the target occur when a plasma jet hits a metallic target. A screw instability of the spark plasma channel arises in this case. The plasma channel twists into a spiral with a step equal to the displacement of the gas flow in one period of the applied voltage as a result of the development of this instability. The screw instability of the spark plasma channel arises in the case of a dielectric target also, but its intensity (degree of twist of the spark channel) is less pronounced than with a metallic target (Figure 6).

3. Conclusion
The paper presents the results of experimental studies on the active electrical effect on the structure of a plasma jet, generated by a barrier discharge in an argon flow, and a thin plasma sheet formed on the target surface when a plasma jet striking it. It has been established that an electrical effect on a target can lead to significant changes in the parameters and structure of both the plasma jet and the plasma sheet on the target surface, which is formed when a plasma jet incident on substrate. It is shown that the gas-dynamic effect due to the close overlapping of a flat quartz disk above the target surface, limiting the thickness of the gas-plasma jet radially diverging across the target, allows to increase significantly the radius of the plasma spot on the target. In this case the plasma jet falls on the target through a narrow hole in the quartz disk.

4. References
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