Space-Time Evolution of the Pseudospark Discharge Plasma Emitting Near 13.5 nm [1]

Yu. D. Korolev, O. B. Frants, V. G. Geyman, R. V. Ivashov, N. V. Landl, I. A. Shemyakin

Institute of High Current Electronics 2/3 Akademichesky Ave., 634055 Tomsk, Russia
Phone: (3822) 491-544, fax: (3822) 492-410, e-mail: shemyakin@lnp.hcei.tsc.ru

Abstract – It is shown that generation of EUV radiation from pseudospark discharge plasma is accompanied by appearance of the bright channel at the discharge axis. Qualitative explanation of the radiating channel occurrence mechanism has been done. Size of the radiation region has been determined.

1. Introduction

Considerable interest has recently been generated in development of the sources of radiation in vicinity of 13.5 nm. The problem of generation of EUV radiation is traditionally solved by using a plasma focus method, a capillary discharge or a gas puff Z pinch in installations with high energy stored in primary capacitor bank (larger than 1 kJ) operating in the single pulse mode. In connection with EUV lithography, considerable interest has recently been displayed in installations capable to work with high pulse repetition rate. One of the new approaches is application of a high-current low-pressure glow discharge, initiated in hollow-cathode electrode geometry (pseudospark discharge) [1]. Results of investigation the radiating region dynamic are presented.

2. Experimental setup

The experimental setup is shown schematically in Fig. 1. The main gap was formed by a hollow cathode *2* and anode *3*. The gap between flat parts of electrodes *2* and *3*, diameter of the borehole and thickness of flat part of electrode *2* were D = 6 mm, d = 6 mm, h = 8 mm, respectively. The discharge was powered by means of a capacitor bank C_0 = 130 nF, charging for the time t = 2.5 μs to the voltage V_0 = 2 – 15 kV. The value of inductance was L_0 = 20 – 500 nH. The experiments were carried out in Xenon under working pressure $p = (1 - 7)\cdot 10^{-2}$ Torr. Discharge in the main gap was triggered externally by means of the trigger unit located in the cathode cavity. The main anode cavity *3* was intended for mounting different diagnostic equipment.

During the experiments registration of discharge burning voltage, discharge current and radiation in various spectral regions were carried out, as well as discharge image was observed. The discharge gap image was recorded by a CCD camera with minimal exposure time of 100 ns.

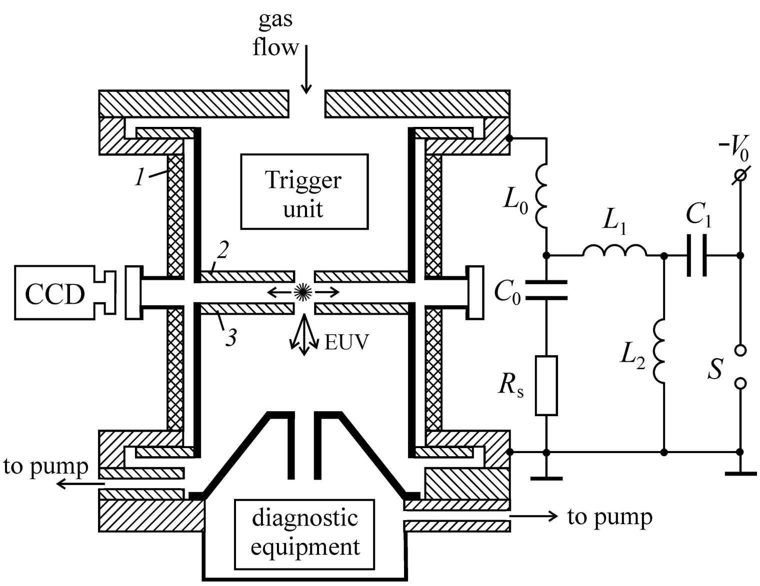

Fig. 1. Schematic of the experimental setup. *1* – ceramic chamber, *2* – main cathode, *3* – main anode.

[1] The work was supported by Russian Foundation for Basic Research under Project 05-02-16280-a

Registration of EUV radiation with temporal resolution 0.7 ns was provided by a photodiode AXUV-HS5. For radiation selection a multilayer Si/Zr filter was used. The installation design allowed observations both in axial (from anode) and side directions. Photodiode position could be changed in horizontal and vertical directions providing radiation region scanning. These methods allowed us to obtain information about development of the plasma radiating region. This experimental setup and methodic are described in more detail in [2] presented at this conference.

3. Results and discussion

The typical waveforms of discharge current i, voltage at the main gap V_d and photodiode current i_d are shown in Fig. 2. Radiation was recorded from a plasma region, limited by a cylinder with a diameter 0.8 mm and located at the discharge axis. Registration was carried out from the anode side in the spectral region $\Delta\lambda = (6 - 20)$ nm.

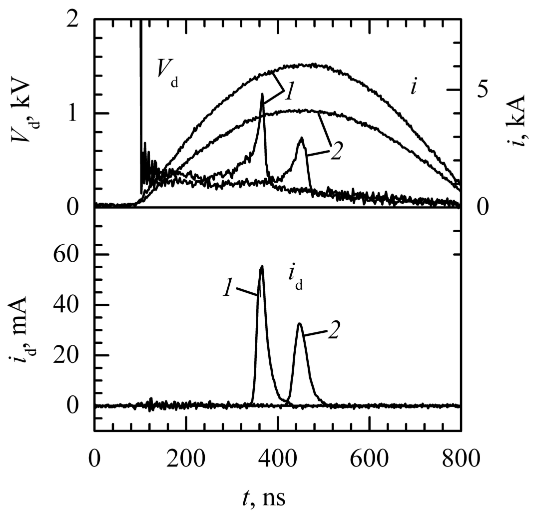

Fig. 2. Waveforms of discharge current, burning voltage and photodiode current; $p = 7{\cdot}10^{-2}$ Torr. V_0 = 12 kV (*1*), 8 kV (*2*), L_0 = 500 nH.

Let us consider the waveforms for the case of V_0 = 8 kV (*2*). It is seen that during a period of time after the breakdown, discharge burning voltage is almost constant, being about 300 V. Such mode of discharge burning corresponds to superdense glow discharge [3]. At t = 400 ns one can see an increase in burning voltage. At the same time the signal of EUV radiation is detecting on the photodiode. Then discharge burning voltage and radiation signal are decreasing. The same behavior of the burning voltage and the radiation intensity is typical for V_0 = 12 kV (1). But in all cases occurrence of EUV radiation is accompanied by burning voltage rise.

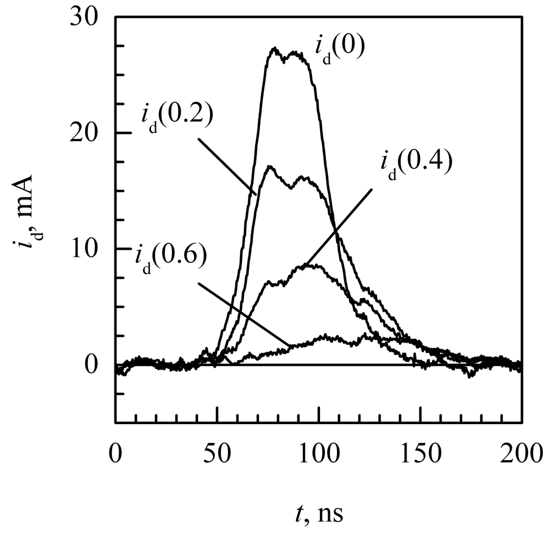

Fig. 3. Photodiode current waveforms at different positions of the detector with respect to the discharge axis (displacement value done in millimeters in brackets) L_0 = 500 nH, $p = 7{\cdot}10^{-2}$ Torr, V_0 = 8 kV.

In Fig. 3 the waveforms of photodiode current at different positions of detector with respect to discharge axis are presented. It is seen that maxim intensity is corresponding to the axial position of the detector. With increase of the distance between diode and discharge axis one can see radiation signal decrease, and at the distance of 0.6 mm EUV signal almost disappears. From above said we can conclude, that radiation is generating in the region at the discharge axis with the diameter less than 0.5 mm.

The waveforms of discharge burning voltage and photodiode current for the case, when radiation registration was made out from various plasma regions both along (i_{d1}) and across (i_{d2}) the discharge axis are shown in Fig. 4. Radiation was recorded from a plasma region, limited by a cylinder with a diameter of 1.5 mm. Figures in brackets point out location of recorded region in cathode-to-anode direction in millimeters. The obtained waveforms show that radiation is first generated at cathode hole output, further propagating from cathode to anode. It also can be seen that there is almost no radiation from region 3–4.5 mm. Thus, it follows that radiating region propagates from cathode to anode to the distance no more than 3 mm, and then disappears. The velocity of radiating region propagation can be estimated from the difference of radiation signals appearance from the first and the second regions (Fig. 4), being equal to $\upsilon \approx 10^7$ sm/s.

To achieve information about discharge dynamics, the experiments for the side and axial observation of the discharge images were carried out (Fig. 5). Time intervals $t_1 - t_6$ are corresponding to the exposure of the CCD camera (cathode is at the left side of the photograph). From the images it is seen, that on the initial stage the discharge luminosity in the main gap is nearly uniform, and on the inner surface of the cathode hole the numerous cathode spots are available. Such a discharge burning mode is a characteristic of the superdense glow discharge [3].

With an increase of burning voltage, a bright narrow channel about 0.5 mm in diameter appears on the discharge axis (time interval t_2). This channel is occurs inside the cathode hole, propagates to the anode, and at the time interval t_6 it crumbles. On the basis of these observations and results of scanning, presented above, we can conclude that EUV radiation is generating just in this channel.

Let's discuss the channel appearance mechanism. One of the conceptions, explaining the reason of such channel arising on the discharge axis is a conception of magnetic compression. The essence of this conception can be justified in the following way. Under the influence of self magnetic field plasma in the cathode hole and in the main gap is accelerating to the discharge axis. The kinetic energy of the compressing channel turns into plasma channels internal energy, and high temperature of plasma is achieved on the discharge axis. In this case the multicharged ions of Xe, which generate EUV radiation, can be available on the discharge axis. But in the framework of this conception it is not clear the way in which discharge current would be closed to the electrodes, because in this case plasma in the cathode hole will be isolated from the electrodes surface. On the other hand, it is seen from the discharge images (Fig. 5), that plasma in the main gap and between channel and inner surface of the cathode hole does not vanish during channel development. Moreover, at the inner surface of the cathode hole the cathode spots are attended. Hence, discharge current should be closed to these spots. Therefore, from our point of view, a mechanism of magnetic compression is not dominant in channel formation process.

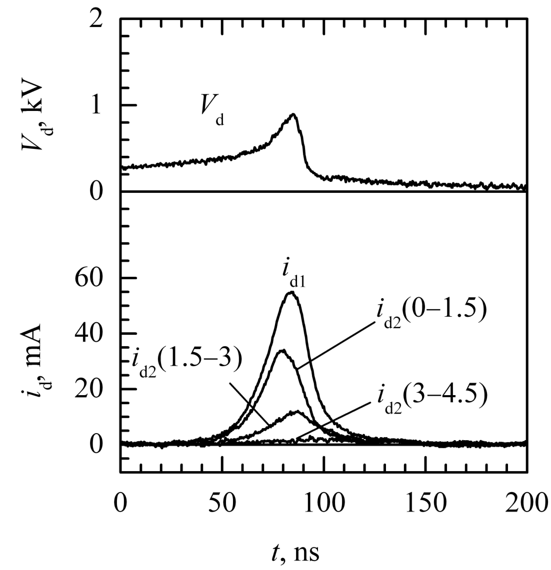

Fig. 4. Waveforms of discharge burning voltage and photodiode signals for the case of radiation registration from various plasma regions, L_0 = 500 nH.

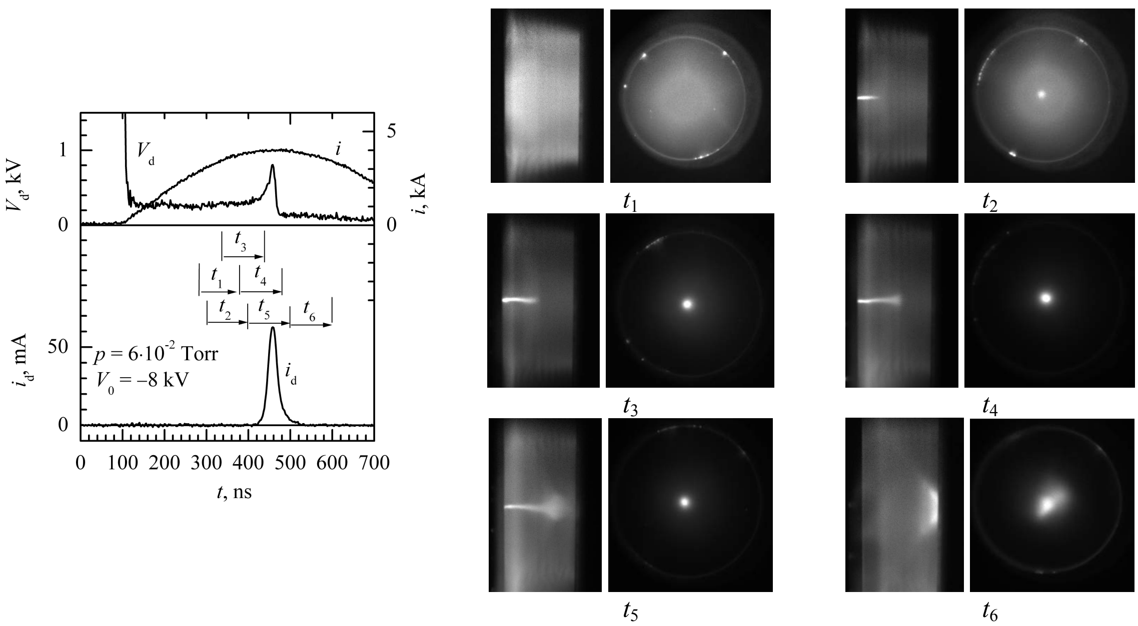

Fig. 5. Waveforms of current, voltage and radiation signals together with side and axial discharge images (cathode is at the left side of the image) for the case of L_0 = 500 nH

Based on the obtained experimental data, estimations proposing another mechanism of channel formation can be done. In the conditions of Fig. 5 concentration of neutral particles is $n_a = 2\cdot10^{15}$ cm^{-3}, and electron free path in reaction of ionization is $\lambda = 0.5$ cm. In such conditions, electron is capable to overcome the distance from one wall of the cathode hole to another without collisions. So, plasma in the cathode hole can be considered as collisionless plasma. However, in order to current could flow through the cathode hole, chaotic current density through the hole has to be much higher than discharge current density:

$$\frac{en_e\upsilon_e}{4} >> j_d \quad (1),$$

where n_e – concentration of electrons in plasma, υ_e – chaotic electron velocity [3].

From (1) it follows that concentration of electrons in plasma has to be much greater than $4j/e\upsilon_e$. In our conditions to the instant of current maximum $4j/e\upsilon_e = 5\cdot10^{15}$ cm^{-3} and thus $n_e >> 5\cdot10^{15}$ cm^{-3}. Therefore, in order that the cathode hole would be capable to conduct such a current, plasma inside this hole should be fully ionized. In these conditions multicharged ions are available. So we can consider that plasma in the cathode hole to current maximum instant of time from collisionless becomes collisional. In this case electron free path is decreased due to coulomb interaction and ionization rate on the discharge axis will be higher than for the fringe region. Thus, we can conclude that the reason for appearance of radiating channel is the high ionization rate on the discharge axis as compared to peripheral region.

Waveforms of the discharge current, burning voltage and diode current for the case of $L_0 = 20$ nH are shown in Fig. 6. In this case discharge current achieves its maximum value 15 kA within 100 ns, but behavior of voltage, current and diode current is the same, as for the conditions of Fig. 2. The main difference is that at the moment of burning voltage rise one can see the delay on the discharge current waveform, which can be treated as an incomplete current quenching. In [4] it was shown that in the case of the current quenching phenomenon the grown burning voltage is applied to the double electric layer, which arise between plasmas in the cathode hole and in the main gap. From the discharge image it is seen that at the discharge axis the narrow channel is also formed. But the brightness of the channel is comparable to the brightness of the discharge plasma in the whole gap. This is conditioned by the integral luminosity picture of the discharge in the main gap and by the fact that the minimal exposure of the CCD camera was 100 ns.

From the data, presented above, we can make the following conclusions. Appearance of EUV radiation is always accompanied by an increase in discharge burning voltage. This voltage is concentrated on the double electric layer between plasmas in the cathode hole and in the main gap both for the case of $L_0 = 20$ nH and for the case of $L_0 = 500$ nH [4]. At the stage of EUV generation the bright narrow channel is raised on the discharge axis. The mechanism of the channel appearance is related to high ionization rate on the discharge axis compared to the peripheral region. Magnetic compression in this case, possibly, promotes the channel formation, but not plays the dominant role.

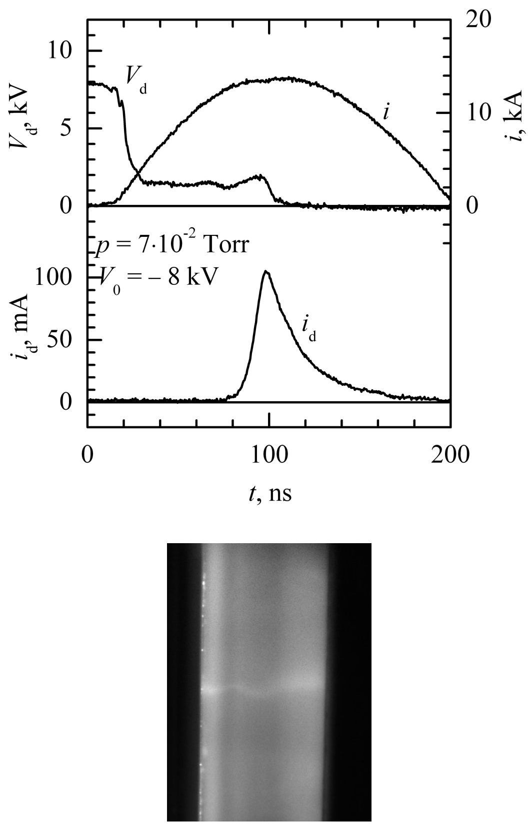

Fig. 5. Current, voltage and radiation signal waveforms together with a side discharge image (cathode is at the left side of the image) for the case of $L_0 = 20$ nH

References

[1] Yu. D. Korolev, O. B. Frants, N. V. Landl, et al, *in Proc 5th International Conference on Dense Z-Pinches, 2002, p. 157 – 160.*

[2] Yu. D. Korolev, O. B. Frants, N. V. Landl, et al, "Generation of EUV radiation in plasma of the high-current hollow-cathode glow discharge", presented at *14th Symposium on High Current Electronics*, Tomsk Russia, 2006.

[3] Yu. D. Korolev, K. Frank, IEEE Trans. Plasma Sci. **27**, 1525 (1999).

[4] Yu. D. Korolev, O. B. Frants, V. G. Geyman, et al, IEEE Trans. Plasma Sci, **33**, 1648 (2005)