Generation of EUV Radiation in Plasma of the High-Current Hollow-Cathode Glow Discharge [1]

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Abstract –Experimental setup for obtaining EUV radiation from pseudospark discharge plasma is presented. Measuring method for discharge gap voltage drop is presented. Apparatus and method allowing to record the behavior of both EUV radiation and radiation in a visible light with spatial and temporal resolution are presented.

1. Introduction

It is known, that the high-current hollow-cathode pulsed glow discharge (pseudospark discharge) is an efficient source of EUV radiation in a wavelength region of about 13.5 nm [1, 2]. One of the applications of this radiation is photolithography. However in order to use the pseudospark discharge as a source of EUV radiation, it is necessary to know the discharge characteristics (such as burning voltage, current, energy entered in plasma and so on). Moreover, it is necessary to know the geometrical size of the radiating region. Experimental setup for obtaining of EUV radiation from the pseudospark discharge plasma is presented. Correct method of burning voltage measurement is offered. Apparatus and methodic for recording the discharge image and EUV radiation in various spectral regions are described.

2. Experimental setup

The experimental setup is shown schematically in Fig. 1. The hollow cathode *2* and anode *3* are fixed on the upper and lower flanges of ceramic chamber *1*, with 70-mm inner diameter and 95-mm height. The gap between the flat parts of the electrodes *2* and *3*, diameter of the borehole and thickness of the flat part of electrode *2* were D = 6 mm, d = 6 mm, h = 8 mm respectively. Size of the cathode cavity varied in a wide range. The discharge was powered by means of ceramic capacitor banks TDK, arranged around the chamber with a summary capacitance C_0 = 130 nF.

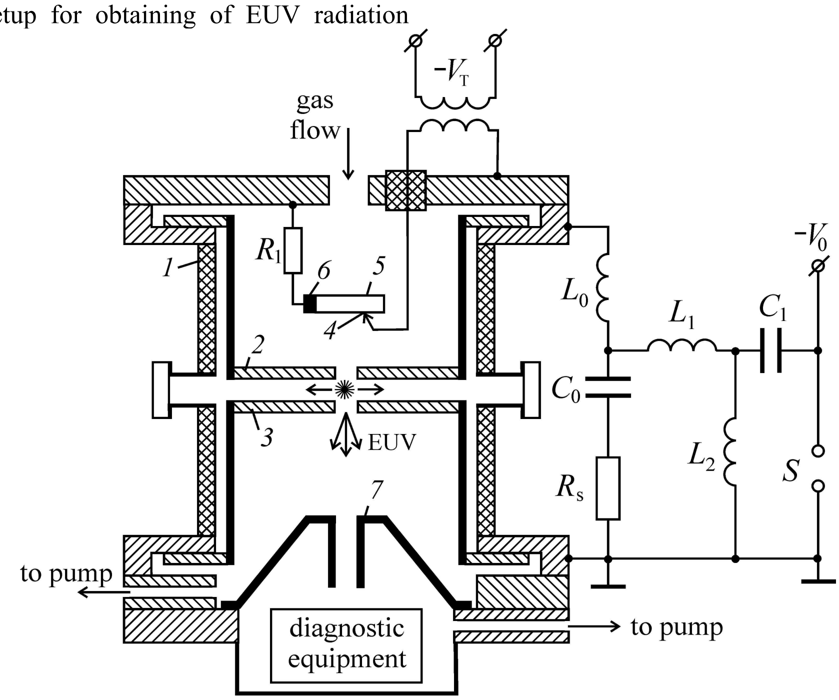

Fig. 1. Schematic of the experimental setup. *1* – ceramic chamber, *2* – main cathode, *3* – main anode, *4* – multipoint contact of the trigger unit, *5* – semiconductor cylinder, *6* – carbon contact of the trigger unit, *7* – bypass

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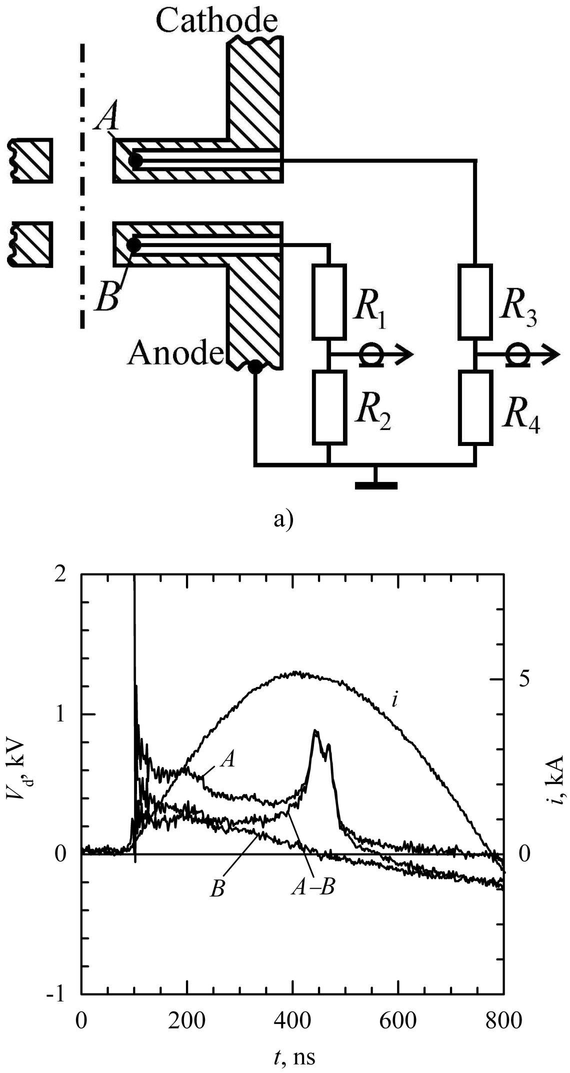
Pulsed voltage $V_0 = 2 - 15$ kV at the main gap results from resonant charging of the capacitor C_0. As a result of small voltage rise time ($\Delta t \approx 5$ μs), high overvoltage at the main gap is achieved. This fact allowed us to carry out the experiments in a wide range of the pressure $p = (1 - 7) \cdot 10^{-2}$ Torr. Working gas was Xenon. The value of inductance was $L_0 = 20$ nH. During some experiments the inductance was specially increased up to 500 nH.

Discharge in the main gap was triggered externally by means of the trigger unit, located in the cathode cavity. Principle of the triggering is based on a general idea, implying that at a prescribed instant of time it is necessary to generate trigger discharge plasma in the main cathode cavity [3]. As a role, in classical schemes of the pseudospark switch connection main anode is under the high voltage, and cathode cavity is grounded. Distinctive feature of our installation is that the main anode *2* is intended for mounting different diagnostic equipment. Thus electrode *2* has to be under the ground potential, and trigger unit has to be located in the cathode cavity under the high potential. Principle of operation of such trigger system is demonstrated schematically in Fig. 1. When the trigger pulse of a voltage $V_{tr} \approx 2.5$ kV arrives at the secondary coil of the pulsed transformer *PT* a surface discharge over semiconductor cylinder plate *5* arises. Initially the discharge current flows in a form of displacement current between multi-point contact *4* and electrode *6*. At a later stage the current is intercepted to the main cathode cavity *2*, the trigger discharge plasma appears in the cavity, and discharge in the main gap is triggered [4]. This process is accelerated by the resistor R_1.

On the bottom flange of the ceramic camera *1* EUV radiation diagnostics camera is mounted. To protect radiation registration system from discharge burning products and decrease radiation absorption of the differential vacuum pump, provided by the bypass *7* was used. Pressure in the diagnostic camera was $p_1 = 10^{-4}$ Torr. To avoid destruction of the recording equipment by the electron beam, the deflecting magnets, located in the main anode cavity were used. In some experiments diagnostic camera was replaced by quartz window, that allowed us to carry out observation of the discharge dap image in an axial direction from the anode side. For EUV radiation and discharge image registration in direction perpendicular to the discharge axis camera was equipped by side windows.

3. Equipment and method of measurement

In described experimental conditions there is a problem of correct measurement of the discharge burning voltage at the main gap. Usually to measure the voltage drop, an active divider connected to a potential electrode is used. In this case, the divider measures the voltage drop at the gap and the inductive voltage drop at the electrodes. In order to remove such an effect we used special registration circuit, based on two active dividers R_1/R_2 and R_3/R_4, $R_1 = R_3 = 1$ kΩ, $R_2 = R_4 = 50$ Ω, connected directly to the main gap (Fig. 2a).



b)

Fig. 2. Schematic of the method of measurement the discharge burning voltage (a) and the typical waveforms of discharge current *i*, voltage at points *A* and *B* and discharge burning voltage (*A* – *B*) (b)

Principle of operation of this circuit can be described in the following way. At point *B*, the anode voltage drop relatively earth is measured. At point *A*, voltage drop at the main gap is measured together with voltage drop at the anode. Consequently, the difference in the voltage signals from these dividers gives us the voltage drop directly at the main gap. The typical discharge current waveform in the main gap and voltage from dividers are shown in Fig. 2b. It is seen, that at the instant of time, when current waveform crosses zero line, discharge burning voltage is also equal to zero (curve *A* – *B*). From this we can conclude that burning voltage registration was done in correct way. It should also be noted that this method of voltage measuring allows to register the small change in voltage of about tens of volts with respect to the initial voltage up to 15 kV with high accuracy.

During the experiments, the discharge image observation, registration of EUV radiation with temporal and spatial resolution, and measurement of absolute energy values of EUV radiation were carried out. Discharge image observation was realized both in axial and in side direction. The main gap image was projected on the entering chip of the CCD camera SensiCam. Minimal exposure was 100 ns. In the frame mode, operation minimal time shift was 10 ns, that allowed us to obtain information about dynamic of the discharge development with temporal resolution 20 – 30 ns.

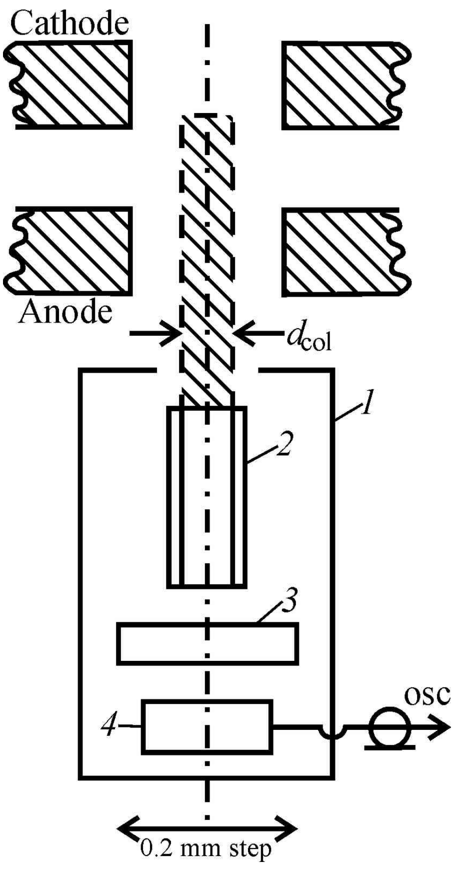


Fig. 3. Scheme of registration of radiation with temporal and spatial resolution. *1* – broadband spectrometer, *2* – collimator tube, *3* – filter, *4* – photodiode AXUV HS5

Registration of EUV radiation with temporal and spatial resolution was carried out by broadband spectrometer. The design of the spectrometer and the measuring method, implied for axial observation are demonstrated in Fig. 3. Plasma radiation entered collimator tube, and then passed through a filter, being registered by a photodiode. The tube length, its inner diameter d_{col} and location were chosen with respect to discharge gap and diode photocathode in such a way that the photocathode might catch radiation from plasma region, limited by a cylinder with a diameter $d_{col} = 0.8 – 2.5$ mm. Scanning of radiating region was carried out by shift of spectrometer across discharge axis with 0.2 mm step.

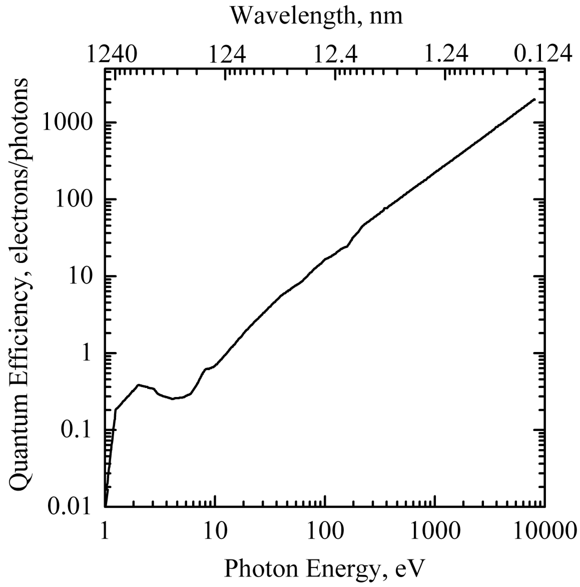


Fig. 4. Quantum efficiency of photocathode of diode AXUV HS5

In the described construction, the spectral range of detecting radiation was determined by spectral characteristic of photocathode and transmission factor of filter. As a radiation detector we chose a photodiode AXUV HS5, which has high sensitivity, wide dynamic range, and high resolution time $\Delta t \approx 0.7$ ns. Quantum efficiency of photocathode of diode is shown in Fig. 4. It is seen, that the diode registers radiation in wavelength region $\Delta\lambda = (0.1 – 1250)$ nm. For the radiation selection we used multilayer Si/Zr filter with thickness 200 nm, developed and manufactured at the Institute of Physics of Microstructure RAS (Fig. 5). The advantages of this filter are high selectivity and capacity, and stability of spectral characteristics during operation. With the use of such filter, spectral range of detecting radiation was $\Delta\lambda = (6 – 20)$ nm. In our experiments, we registered radiation both using the filter and without it.

One of the tasks, which arose during investigation of EUV radiation, related to measurement of geometrical size of radiating region. As a rule, for this purpose, pinhole cameras and expensive X-ray CCD cameras are used. We developed a method, which allowed us to solve this task without such expensive equipment. For that, registration of EUV radiation with spatial resolution was carried out simultaneously in two inter-perpendicular directions: along the discharge axis (Fig. 3) and across that. Analysis of obtained waveforms allowed us to recover profile of radiating region and its time evolution.

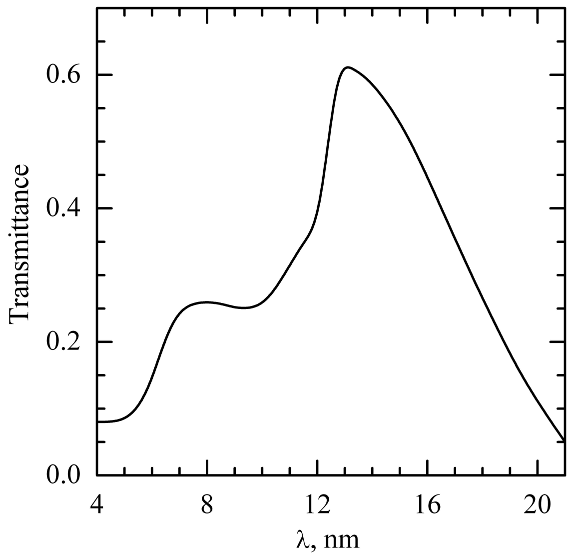


Fig. 5. Transmittance of Zr/Si filter

Measurement of absolute energy of EUV radiation was carried out in wavelength regions $\Delta\lambda = 6 - 20$ nm and $\Delta\lambda = 13.5 \pm 0.1$ nm. For the first case, measurements were done by a broadband spectrometer, described above. Inaccuracy of measurements was ± 100%.

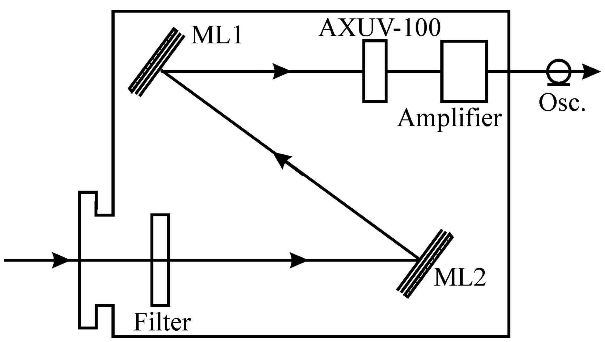


Fig. 6. Schematic of narrow-band spectrometer (ML1 and ML2 – multilayer mirrors)

For measurements in wavelength region $\Delta\lambda = 13.5 \pm 0.1$ nm we developed and produced narrow-band spectrometer, based on the method [5] (Fig. 6). The main element of this device is a monochromator, assembled on the basis of two multilayer Nb/Si mirrors. These mirrors have high selectivity (Fig. 7). In front of the mirrors a Si/Zr filter, suppressing radiation in visible wavelength region is located. EUV radiation is registered by high-precision diode AXUV-100. Later on radiation signal intensified with the help of amplifier PA-100. Described spectrometer allowed to carry out measurements with high accuracy (inaccuracy of measurements is about 20%) and without preliminary absolute calibration [5].

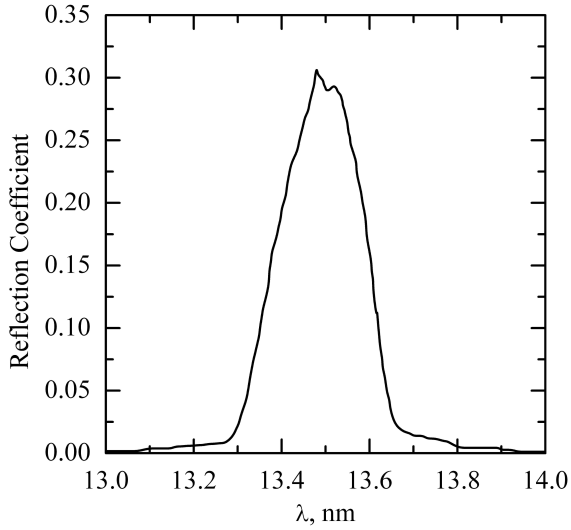


Fig. 7. Spectrum of reflection coefficient of double-optical Nb/Si system

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