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A capillary discharge plasma source of intense VUV radiation

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***Abstract*. The results of investigation of a capillary discharge plasma, used as a source of intense VUV radiation and soft X-rays, are presented. The plasma was generated during the discharge of low-inductance capacitors in a gas-filled ceramic capillary. Intense line radiation was observed in a broad spectral range (30 – 400 Å) in various gases (CO_2, Ne, Ar, Kr, Xe). The absolute radiation yield for the xenon discharge was ~ 5 mJ $(2\pi$ sr$)^{-1}$ pulse^{-1} within a spectral band of width 9 Å at 135 Å. Such a radiation source can be used for various practical applications, such as EUV projection lithography, microscopy of biological objects in a 'water window', reflectometry, etc..**

Keywords: *VUV radiation, capillary discharge plasma, VUV spectroscopy, reflectometry.*

1. Introduction

Investigations in two very important directions of quantum electronics were started in 1970's at the Laboratory of Quantum Radiophysics at the P.N. Lebedev Physics Institute, headed by N.G. Basov. One of these directions, the development of the short-wavelength lasers, led to the advent of a family of lasers with different pumping schemes, generating radiation in the wavelength range from the 'water window' to the near UV. A review of the research activity in this field is presented in Ref. [1].

The second important field of research is associated with the use of spontaneous X-rays emitted by a laser plasma. The laser plasma produced by focusing high-intensity laser radiation on a solid or gaseous target is a powerful source of X-rays and VUV radiation, and is therefore used widely in basic and applied research. The advances made in the field of laser technology make it possible to focus radiation whose parameters vary over a wide range: the flux density on the target $10^{10} - 10^{20}$ W cm^{-2}, and the laser pulse duration varying between tens of femtoseconds and hundreds of nanoseconds. The electron temperature T_e of the plasma varies from 10 eV to several kiloelectronvolts, the electron density N_e varies from the density in solids $\sim 10^{23}$ cm^{-3} and below, while the ionic charge varies up to 30 – 50.

Significant progress has been made in recent years in the technology of using soft X-rays and VUV radiation (see, for example, review [2]). This has been made possible by the advances in designing new types of detectors and elements of X-ray optics (normal incidence multilayer mirrors, Fresnel lenses, etc), as well as very bright X-ray sources (synchrotron radiation sources, laser plasmas, micropinch plasmas, etc). Among the laboratory sources, the main attention was paid to various types of laser plasma X-ray sources. Their efficiency was demonstrated in many applications. The fabrication of an industrial unit for submicrometer EUV lithography using laser plasma as the source of radiation at 135 Å and an optical system for this wavelength with normal incidence multilayer mirrors [3] can be regarded as one of the most impressive achievements of recent years. At the same time, it became obvious that a whole range of applications require more efficient, compact and cheaper X-ray sources. Such radiation sources (plasma focus [5, 6], Z-pinch-plasma [7 – 10], and capillary discharge plasma [11 – 27]) use various types of a gas-discharge plasma [4].

A capillary discharge plasma as a radiation source has a number of advantages such as compactness, relative simplicity, high efficiency, etc. It has been the object of extensive research during recent years in a number of countries, including USA, Japan, Germany, France, Italy, Israel, Korea, Russia, etc. The capillary discharge plasma was used as a source of soft X-rays and VUV radiation [11 – 13, 20, 23, 24, 27], as well as the active medium for X-ray lasers [14 – 17, 21, 26]. A capillary discharge was used as an efficient radiation source for EUV lithography in Refs [4, 18, 19, 22, 25].

So far, the most significant achievements in this field have been reported by the group headed by J.J. Rocca at the University of Colorado (USA). They have investigated capillary discharges with various energy parameters and of different construction, carried out diagnostics of plasmas with spatial and temporal resolution, and also studied the spectra of multiply charged ions over a wide range of wavelengths (see review [16]). These investigations have led to record-high parameters [21] for the amplification of 469 Å radiation at the transition in the Ne-like ion Ar IX [17]: pulse energy between 0.1 and 1 mJ, pulse duration ~ 1 ns, peak power 0.1 – 0.6 MW, and monochromaticity $\lambda/\delta\lambda \sim 10^4$. At present, this laser is the brightest radiation source at this wavelength [1]. The application of this laser in reflectometry and interferometry of plasma, as well as in the

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investigations of ablation of matter from the surface of a solid has been demonstrated [1]. This laser is characterised by a relatively long wavelength (469 Å). However, it has a quite large size [it uses a high-voltage (~ 700 kV) Marx generator and a one-metre water line], which hampers its applications.

The development of compact high-intensity radiation sources using spontaneous emission is important for many applications. Indeed, the most interesting practical applications require radiation with a relatively small wavelength ($\lambda = 135$ Å for EUV projection lithography and $\lambda = 23 - 44$ Å for X-ray microscopy in a 'water window'). Lasing in such wavelength ranges is extremely complicated (in the case of the population inversion produced by collisions, the pump rate is proportional to λ^{-4} [28]), and is unlikely to be realised in the near future.

The use of spontaneous emission from the capillary discharge plasma makes it possible to advance to the short-wavelength spectral range right up to the 'water window' without any particular problems. Monochromatisation of the radiation from the source can be accomplished quite efficiently with the help of normal incidence multilayer mirrors. In this case, the capillary discharge plasma can serve as a source of high-intensity monochromatic spontaneous emission for various practical applications such as EUV projection lithography, microscopy, etc.

The aim of our study is to develop a compact efficient source of spontaneous emission using a gas-discharge plasma in a ceramic capillary. This source of soft X-rays and VUV radiation over a wide spectral range, from ~ 20 Å (water window) to several hundred angstroms, can find many practical applications.

2. Experimental

A gas-filled capillary of diameter 2 mm and length 10 mm was used in the experiments. The capillary was filled with gas with the help of a fast electromagnetic valve. The electric circuit employed conventionally for pumping excimer lasers and based on a complete discharge of storage capacitors over the capillary gap was used as a power supply [24, 27]. All components of the device (capacitors, switch and capillary) were assembled in a coaxial geometry. The diameter and length of the source did not exceed 25 and 30 cm respectively. A low-inductance current shunt and a voltage divider were used for electrical measurements with a time resolution ~ 1 ns.

The electrical parameters of the capillary discharge are as follows:

Capacitance of the storage capacitors/nF	30
Power supply voltage/kV	30 – 40
Discharge current/kA	25
Energy stored in the capacitors/J	16
Energy supplied in the discharge/J	6

This electric circuit made it possible to obtain short current and voltage pulses (tens of nanoseconds) in the capillary discharge. The rise time of the pulse did not exceed 1.5 ns. The rate $\mathrm{d}I/\mathrm{d}t$ of the rise of current in the discharge acheved $10^{12} - 10^{13}$ A s^{-1}. The high rate of the current rise, which plays a significant role in the processes of compression and heating dynamics of the plasma, is very important for lowering the capillary destruction rate and, hence, for increasing the service life of the source.

A grazing incidence spectrometer with a constant deflection angle $\alpha = \varphi + \psi = 166^\circ$ was used for spectral measurements [25]. The scheme of the spectrometer is shown in Fig. 1. Scanning over wavelengths is performed by a precise rotation of the spherical diffraction grating. The spectrometer parameters are such that defocusing due to the escape of radiation beyond the Rowland circle is small and does not deteriorate the spectral resolution. Three diffraction gratings (1200, 600 and 300 lines mm^{-1}, radius 1 m, blaze angle 2°, tungsten coating) used in the spectrometer cover the wavelength range $44.3 - 425.2$ Å. The spectrometer can be used as a monochromator, reflectometer, and a spectrograph. In the first case, an exit slit is used. The widths of the entrance and exit slits are set with the help of vacuum seals with an accuracy of 0.5 μm. In the second case, the monochromator is connected to a special chamber to measure the coefficient of reflection of the gratings and grazing incidence mirrors. In the third case, a photographic film is placed at the exit slit. In this case, the exact focusing is performed only for the central wavelength λ_0. However, the spectrum can be recorded over a fairly wide spectral range $\lambda_0 \pm \Delta\lambda$ owing to a small angular aperture of the grazing incidence spectrograph. The quantity $\Delta\lambda$ is related to the observed spectral resolution $\lambda/\delta\lambda$: the larger the quantity $\Delta\lambda$, the smaller the resolution $\lambda/\delta\lambda$ caused by defocusing. At the central wavelength λ_0, the spectral resolution $\lambda/\delta\lambda = 330$ for the entrance slit of width 15 μm. The spectrograph is tuned for different wavelengths by rotating the diffraction grating.

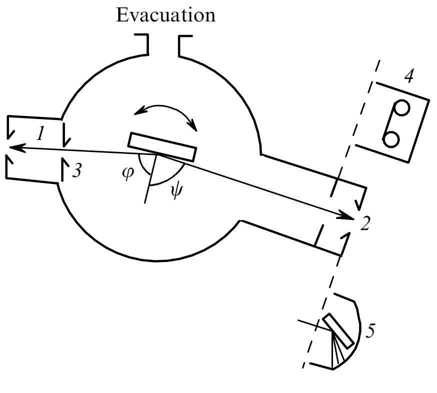

Figure 1. Scheme of a grazing incidence monochromator – spectrograph (GIMS) with a constant deflection angle: (*1*, *2*) entrance and exit slits; (*3*) diaphragm; (*4*) camera for recording spectra on the photographic film; (*5*) chamber for measuring reflection coefficients.

A detachable cassette was used for the photographic film in the spectrograph, for recording several spectra without violating the vacuum in the chamber. The spectra were recorded on a calibrated UV-4 photographic film [29]. Recording of each spectrum required between 1 and 10 discharges in the plasma.

The spectrometer was mounted at the output flange of the capillary source of VUV radiation. The distance between the output window of the capillary and the entrance slit of the spectrometer was 50 mm. The capillary source and the spectrometer were evacuated by differential pumping. The pressure in the spectrometer was maintained at 10 mTorr, while the pressure of the working gas in the capillary was 100 – 800 mTorr.

3. Experimental results

Examples of capillary discharge VUV spectra are shown in Figs 2–5 for various working gases. We used CO_2, Ne, Ar, Kr, Xe gases at a pressure of 100–800 mTorr. The spectral lines were identified on the basis of the data [30]. In light element gases (O, Ne), high-intensity *L*-spectra (2–3 and 2–4 transitions) were excited in Li- and Be-like ions at wavelengths $\lambda > 90$ Å (Fig. 2). Radiation with the shortest wavelength was recorded in the Ar discharge at the $2p - 3s$ and $2p - 3d$ transitions in Ar IX and Ar X ions (Fig. 3). The maximum intensity of the $2p - 3s$ transition at 49 Å was observed at a pressure of 400 mTorr. These spectra were used to estimate the electron temperature T_e in the discharge: the temperature corresponding to the observed stages of ionisation (Ar^{8+} and Ar^{9+}) at the coronal equilibrium [31] is $T_e > 60$ eV.

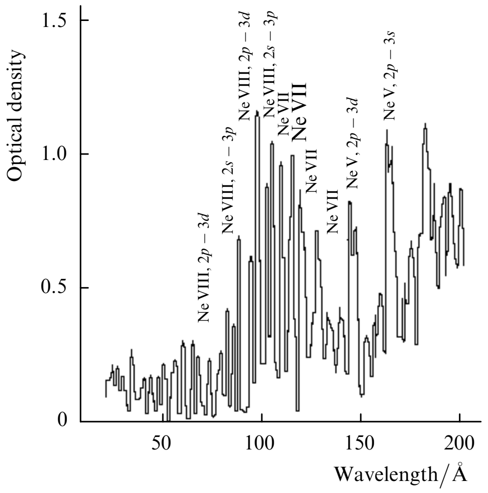

Figure 2. Spectrum of a capillary Ne discharge at a gas pressure of 400 mTorr; central wavelength of the VUV spectrometer is 90 Å.

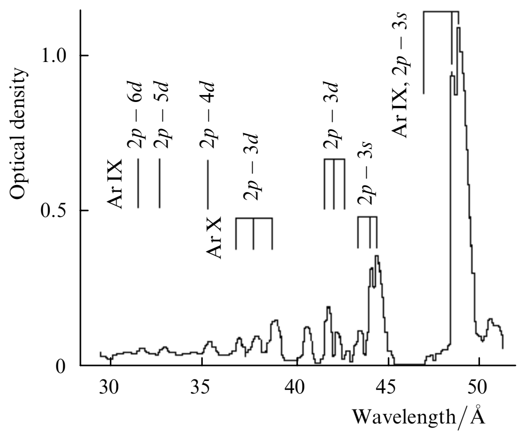

Figure 3. Spectrum of a capillary Ar discharge at a gas pressure of 250 mTorr; $\lambda_0 = 50$ Å.

As the atomic number of the working gas increases, the spectra of the next electron shells are excited with a larger number of spectral lines. Thus, the intense *M* spectrum (the 3–4 transitions in Kr VIII–Kr X ions) was excited in the Kr discharge with a large number of spectral lines at $\lambda > 100$ Å (Fig. 4). When the Xe discharge was excited, the spectral lines corresponding to various stages of ionisation merged into separate bands, and even coalesced to form a quasi-continuum. The integral spectra of a capillary Xe discharge at two gas pressures are shown in Fig. 5. Three emission peaks were observed in the spectral range 100 – 160 Å at low gas pressures (100 mTorr). The peaks were located at 110, 135 and 150 Å, and had widths of no more than 10 Å. These peaks can be assigned to transitions in Xe^{11+}, Xe^{10+} and Xe^{9+} ions. According to the collision-emission model used for describing a laser plasma [32], the observed stages of ionisation of Xe correspond to $T_e >$ 45 eV. At the same time, the coronal model [31] gives $T_e \sim$ 100 eV. The highest electron temperature was observed for low Xe pressures (100–200 mTorr). With increasing gas pressure in the capillary, T_e in the discharge decreased, the peaks in the Xe spectrum disappeared, and the emission spectra represented a quasi-continuum.

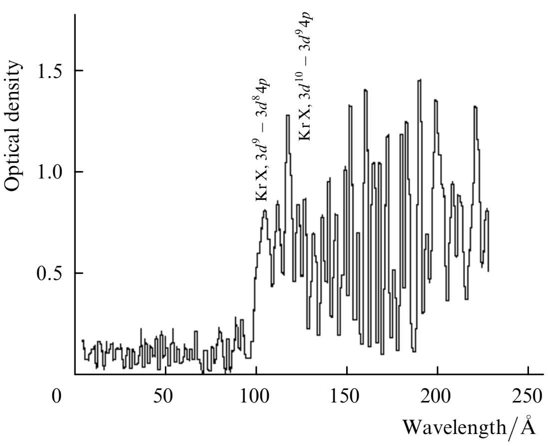

Figure 4. Spectrum of a capillary Kr discharge at a gas pressure of 300 mTorr; $\lambda_0 = 165$ Å.

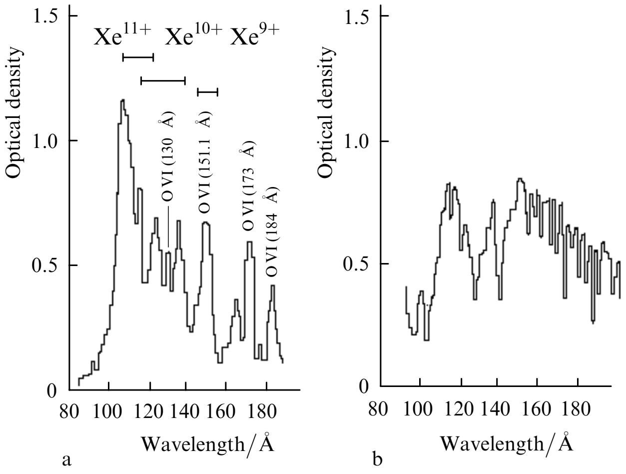

Figure 5. Spectrum of a capillary Xe discharge at a gas pressure of (a) 100 and (b) 500 mTorr; $\lambda_0 = 135$ Å.

For EUV projection lithography, capillary Xe-discharge plasma emission at 135 Å is of special interest. A VUV spectrometer with a calibrated diffraction grating (see below) and an absolutely calibrated photographic film [29] as a photodetector were used for absolute measurements of the emission intensity of this plasma. This made it possible to evaluate the absolute yield of the capillary Xe-discharge plasma emission at 135 Å. For a gas pressure of 400 mTorr, the emission yield was $W = 5$ mJ $(2\pi\ \mathrm{sr})^{-1} \times$ pulse^{-1} within a reflection bandwidth of 9 Å for a typical Mo/Si mirror with the maximum reflection at 135 Å. This value of W is very close to that obtained in Refs [18, 19].

Capillary Xe-discharge plasma radiation at 135 Å was also used for measuring the reflectance of grazing incidence gratings. A module with the grating to be tested was attached to the monochromator for the system to work as a reflectometer. The grating could be set at the required grazing angle (from 1 to 8°). The incident and diffracted radiation were recorded on a photographic film. By using different working gases, gratings can be calibrated over a wide spectral range (40 – 450 Å). First, the reflectance of a 600-lines mm^{-1} grating (grazing incidence angle 5°) was measured at 135 Å. The reflectance was found to be 7 %, 10 %, 1 % and 3 % – 4 % for zero, first, second and third reflection orders, respectively. This calibrated diffraction grating was subsequently used for absolute measurements of the radiation yield for a capillary Xe-discharge.

4. Conclusions

A high-intensity compact source of VUV radiation and soft X-rays has been developed on the basis of a capillary discharge plasma. A high-voltage power supply and the axial geometry of elements in the device ensured high current rise rates in the gas-discharge plasma: $\mathrm{d}I/\mathrm{d}t = 10^{12} - 10^{13}$ A s^{-1}. The service life of the source was increased by using a gas-filled ceramic capillary. The use of various working gases (CO_2, Ne, Ar, Kr, Xe) made it possible to create a high-intensity source of VUV radiation and soft X-rays in a wide spectral range (30 – 600 Å) where transitions in multiply charged ions were observed at the electron temperatures $T_e = 50 - 100$ eV. The absolute radiation yield for the capillary xenon discharge, which is of considerable significance for projection EUV lithography, was measured at 135 Å. At this wavelength, the radiation source was used for reflectometry (preliminary results have been obtained on the measurement of reflectivity of grazing incidence gratings).

We plan to use the capillary discharge for developing a modified compact VUV radiation source working at a pulse repetition rate of ~ 10 Hz. This will make it possible to perform the VUV reflectometry of optical elements in a broad spectral range.

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