Capillary discharge plasmas as a source of EUV and soft x-ray radiation

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ABSTRACT

A compact device, based on fast capillary discharge plasmas, is used as an intense EUV and soft x-ray source of radiation. The plasma is created by a discharge of low-inductance capacitors (30 nF) through a capillary (2 mm diameter, 20 mm length). Two types of capillary are used: a polyacetal (empty) and a gas-filled (Ar, Xe). All components are assembled in a coaxial geometry. The total size of the device including capacitors, switch and capillary is 30 cm long and 25 cm in diameter. Discharge current is monitored using a shunt circuit. The maximum current of 25 kA at applied voltage 40 kV, the pulse duration of 20–30 ns at FWHM, and the rise time of 1.5 ns are measured. The EUV spectra of multiply charged ions are investigated in a spectral range of 30–200 Å using a compact 1 meter grazing incidence spectrograph. Strong linear emission of OV-OVI ions from a polyacetal capillary and ArVII-ArX, XeXII-XeX from the gas-filled capillary is observed. The spectra are investigated for different capillary geometries and various gas pressures. The resulting electron temperature is equal to 60–100 eV. This compact fast discharge is promising for use as an intense compact source of EUV radiation for different practical applications (EUV lithography, soft x-ray microscopy, reflectometry, etc.).

Key words: capillary discharge plasma, EUV source, EUV lithography, soft x-ray microscopy

1. INTRODUCTION

In the past decade extraordinary progress was achieved in the development of soft x-ray and extreme ultraviolet (EUV) technology[1]. This progress was driven by advances in high-brightness soft x-ray and EUV sources, in new optical elements and in new types of detectors. Due to this technology a variety of novel practical applications has recently become feasible. One of the most prominent applications is EUV lithography that approaches the resolution goal of less than 100 nm for use in integrated circuit chip production for the next generation of semiconductor devices. A great deal of work was done on the development of laser-produced plasma EUV sources for EUV lithography, and the most advanced results were reported recently[2]. A clean, high-power EUV light source was developed based on a continuous jet of condensable gas irradiated with a diode-pumped solid state laser. However, it is now clear that in the future more efficient, more compact, less complicated and lower cost EUV sources will be required. This has led to recent activity in the development of gas-discharge plasmas as EUV sources based on capillary discharge plasmas[3-5] and Z-pinch plasmas[6,7].

It has been demonstrated that a capillary discharge plasma can be successfully used as a soft x-ray source and as an active medium for soft x-ray lasers. Probably the most advanced results have been achived by Professor Rocca's group (see, for example, review paper 8). In this group capillary discharges of various energetics, different designs, geometries and capillary walls were investigated; plasma diagnostics with temporal and spatial resolution were developed; and spectra of highly charged ions were investigated in a wide spectral range. As a result of these investigations, laser amplification at a wavelength of 469 Å in [Ne]-like ArIX ion was achieved. Applications of this laser in reflectometry and interferometry were demonstrated. However, the practical applications of this laser are restricted by the long wavelength—469 Å. In addition, the experimental setup is large as it has a high voltage (~700 kV) Marx generator and a 1 meter water transmission line.

From our point of view it will be more productive to pay attention to the development of a compact intense EUV source using spontaneous emission. The most important EUV practical applications are based on radiation with relatively short

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wavelengths (e.g., EUV lithography - 135 Å and 110 Å; soft x-ray microscopy - "water window" spectral range 23–44 Å). Laser generation in these spectral ranges is connected with great difficulty because the pump rate in a collisional scheme of excitation[9] is scaled as λ^{-4}. The use of spontaneous emission allows one to move to a short wavelength range, including the "water window" spectral region, without any difficulties[10,11]. This fact was recently demonstrated[3,4]. Compact capillary discharge plasma sources intended for EUV lithography show significant radiation yield at wavelengths 135 Å and 110 Å. The purpose of our investigation is to develop a compact and effective source of spontaneous soft x-ray and EUV radiation with wavelengths from the "water window" ~20 Å to several hundred Å. This source will have practical applications in microscopy and lithography and in fundamental research-spectroscopy, solid state physics. In this paper we describe a compact, fast capillary discharge plasma device developed for these purposes. The first results from spectra observations in a wide spectral range (40–200 Å) are presented.

2. EXPERIMENTAL SETUP

Usually, Marx generators[8] or inductive storage drivers[12] are used for capillary discharge drivers. However, large size, high applied voltage and high noise levels make these drivers inappropriate for power supplies.

To reduce the discharge circuit size, a simple high-current driver was developed. The scheme, based on full discharge of stored capacitors, is shown in Fig. 1. The use of a high-voltage, high-current switch RU-65 and low-inductance capacitors allowed us to get high rise times for voltage and current on the capillary discharge gap. Capacitors C_g were charged to voltage +(30–40) kV using a pulse generator. When the switch was turned on, the capillary spark gap broke down with current rise time of 1–1.5 ns and a current pulse duration at FWHM ~ 20 ns (see Fig. 3). The current was ended after a full discharge of the storage capacitors C_g. The stored electrical energy was equal to 16 J using capacitances C_g = 30 nF. Electrical measurements with a temporal resolution of ~1 ns have been made with a current shunt and a voltage divider. The current shunt was made from thin film conductors and had a resistance of ~0.01 Ω.

All components of the device (capacitors, switch and capillary) were assembled in a coaxial geometry. The device was 25 cm in diameter and 30 cm long. A grazing incidence spectrograph was connected on the exit flange of the capillary discharge chamber. The distance between the capillary end and entrance slit of the spectrograph was equal to 15 mm. Differential pumping was used on the device so that the pressure was 0.01 Torr in the spectrograph when the gas pressure was 0.5 Torr in the capillary. An electromagnetic fast valve was used to fill the capillary with gas.

Temporal measurements of current and voltage pulses were made at different Ar gas pressures (60–500 mTorr). As an example, the pulses at the Ar gas pressure of 100 mTorr are shown in Fig. 3. Two types of capillaries 2 mm in diameter and 20 mm long were used in the experiments: (1) a polyacetal $(CH_2O)_n$ and (2) a gas-filled ceramic. The axially emitted XUV radiation from the capillary discharges was studied using a 1 meter grazing incidence spectrograph. A W-coated grating with 600 G/mm was installed at a 4° grazing incidence angle. An off-Rowland geometry was used and the spectra were recorded in a plane perpendicular to the diffracted rays (see Fig. 2). In this method, the exact focusing takes place at only one wavelength λ_0, which corresponds to the intersection point of the registration plane with the Rowland circle. However, due to the small numerical aperture of the spectrograph, it is possible to record the spectrum in a wide spectral range $\lambda_0 \pm \Delta\lambda$. The value $\Delta\lambda$ is connected with the observed spectral resolution $\lambda/\delta\lambda$—the wider the $\Delta\lambda$ the lower the $\lambda/\delta\lambda$ because of defocusing. The alignment to different wavelengths λ_0 was produced by changing the distance between the plane of registration and the grating. A detailed description of the spectrograph will be published elsewhere. This type of spectrograph was used earlier for EUV spectroscopy of a KrF laser plasma source[13] intended for EUV lithography and capillary discharge plasmas[5].

The spectra were recorded on calibrated UF-4 photofilm[14]. The distance between the capillary exit and the entrance slit of the spectrograph was 15 mm. To record each spectrum it was necessary to produce 3–20 discharge shots.

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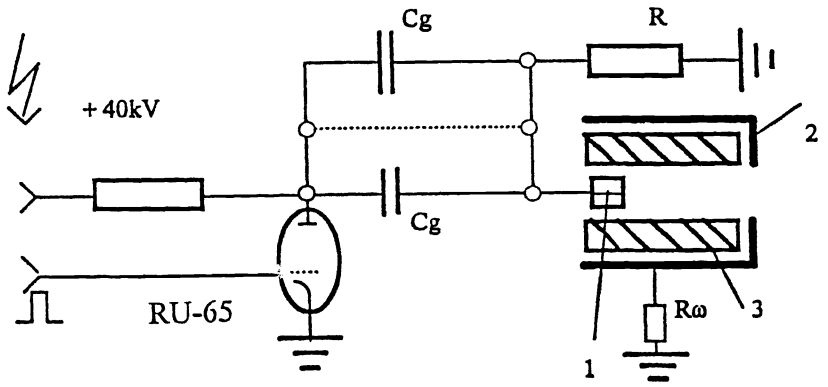


Fig. 1. Electrical scheme of the capillary discharge: 1 – negative electrode; 2 – positive, grounded, electrode; 3 – dielectric walls of the capillary; C_g – stored capacitors (30 nF); R_ω - shunt, RU-65 – switch.

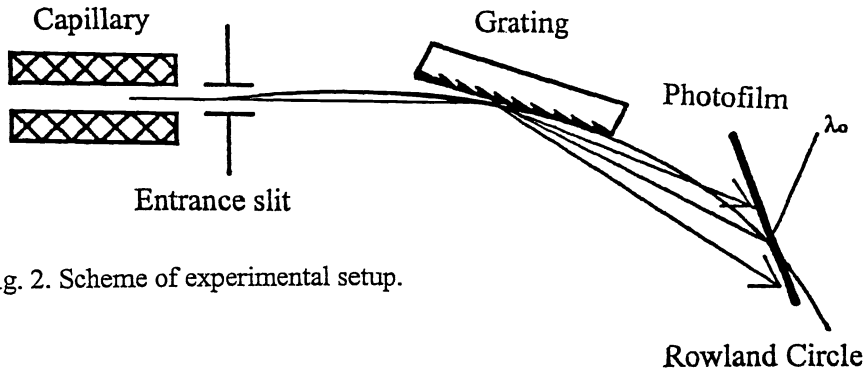


Fig. 2. Scheme of experimental setup.

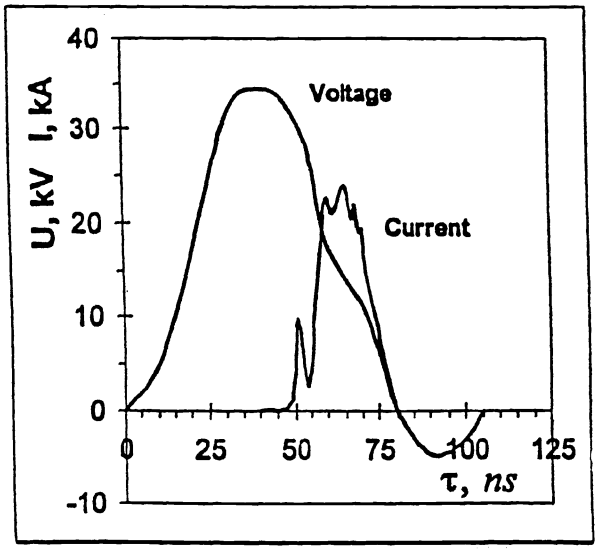


Fig. 3. Voltage and current pulses (Ar filled capillary at the gas pressure of 100 mTorr).

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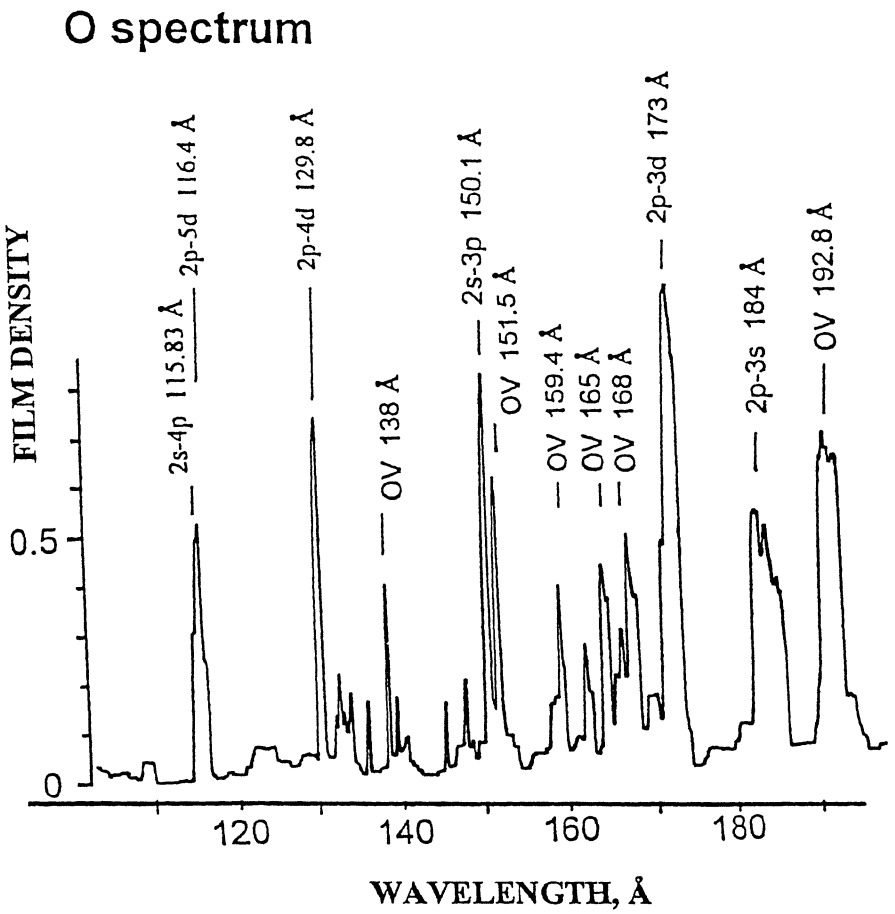


Fig. 4. Spectrum of O VI-O V ions in a polyacetal capillary.

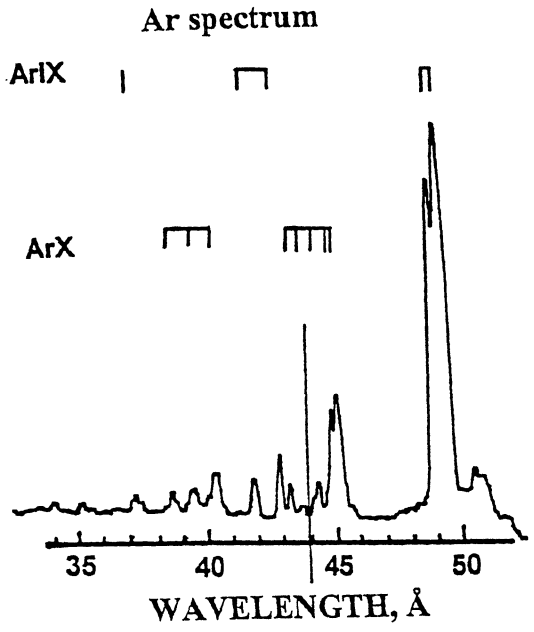


Fig. 5. Spectrum of Ar IX-Ar X ions in Ar filled capillary.

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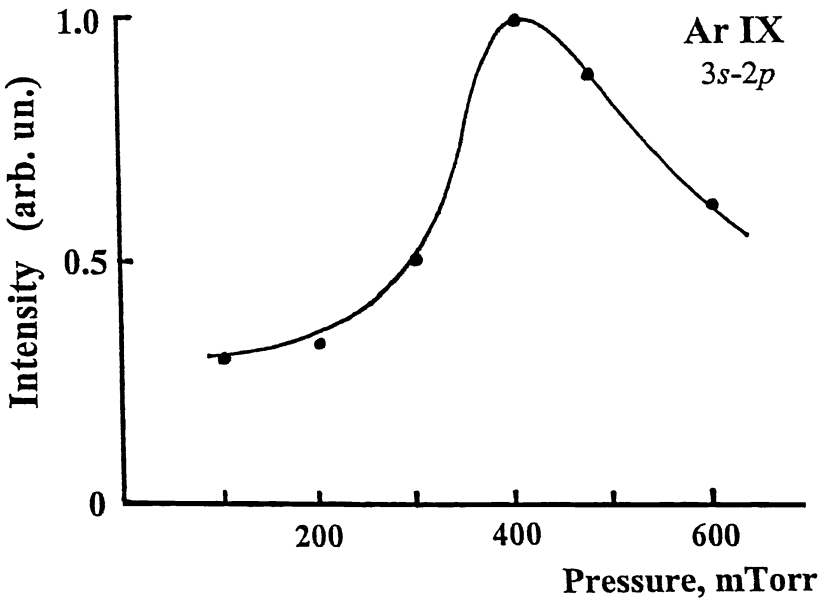


Fig. 6. Relative line intensity of the 3s-2p transition in Ar IX ion versus gas pressure.

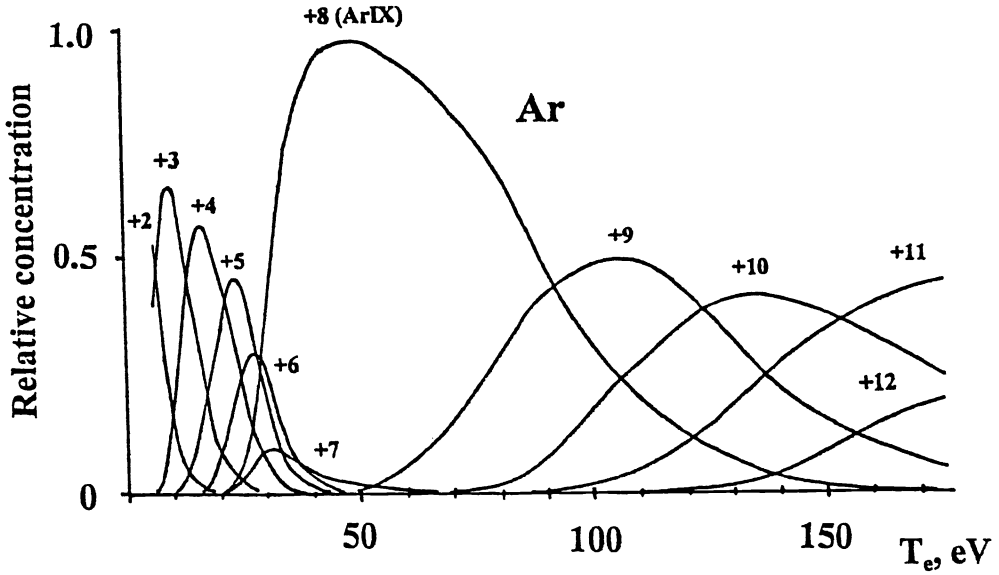


Fig. 7. Relative ionic concentrations according to coronal equilibrium.

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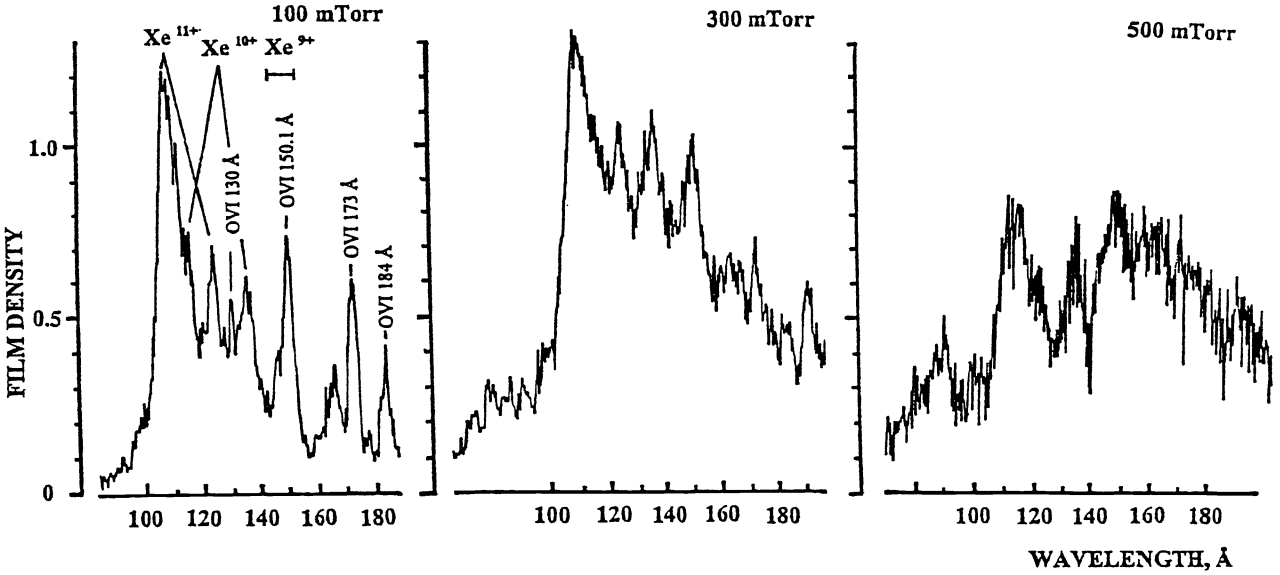


Fig. 8. Time-integrated axial emission spectra in Xe gas-filled capillary discharges at different gas pressures (100-500 mTorr). Xenon-ion stages contributing emission are indicated. Oxygen – contamination lines are also noted.

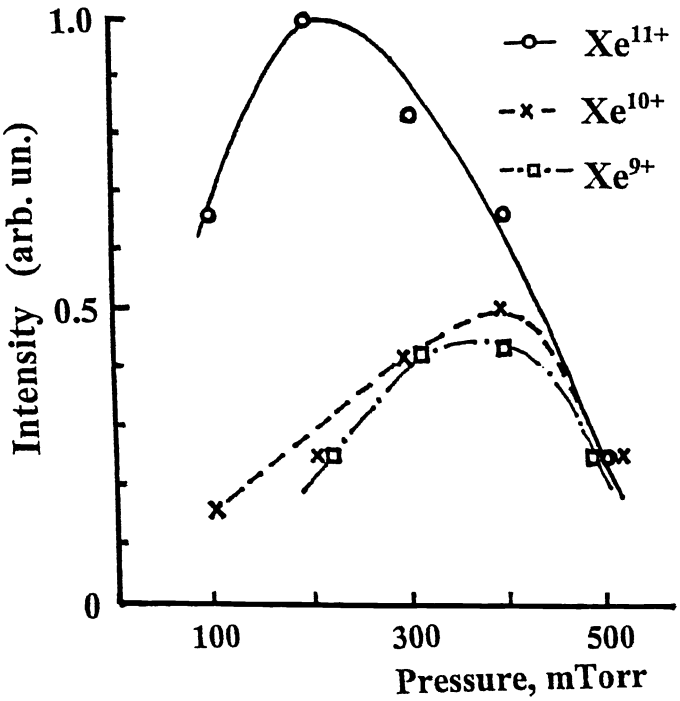


Fig. 9. Relative line intensities for Xe^{+11}, Xe^{+10}, Xe^{+9} ions (as indicated in Fig. 8) versus gas pressure.

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3. EXPERIMENTAL RESULTS

The short rise time of the current pulse ~1.5 ns (see Fig. 3) was achieved. The corresponding value dI/dt was in the range of 10^{12}–10^{13} A/sec. That is important for the debris problem because in this range evaporation of the walls does not play a significant role in capillary plasma compression and heating dynamics[15,12]. The appearance of highly charged ion spectra is correlated with dips on the current pulses, which can be explained by the increase of inductance of the collapsing plasma column.

Typical spectra of OVI-OV ions excited in a polyacetal capillary are shown in Fig. 4. Intense 2l-nl' transitions with n = 3–5 were observed. The spectrograph was aligned on the central line $\lambda_0 = 140$ Å. The spectral resolving power at this wavelength was equal to $\lambda/\delta\lambda = 500$ at the entrance slit width of 10 μm. Due to defocusing, the value $\lambda/\delta\lambda$ was reduced when the wavelength was increased and the value $\lambda/\delta\lambda = 80$ at wavelength $\lambda = 193$ Å.

The spectrum of the argon-filled capillary discharge at pressure 250 mTorr is shown in Fig. 5. References 16 and 17 were used for line identification. Intense transitions 2p-3s, 2p-3d in ions ArIX, ArX were observed. The relative intensity of the 2p-3s transition ($\lambda = 49$ Å) versus the gas pressure is shown in Fig. 6. The maximum intensity is observed at the pressure 400 mTorr. The observed stages of ionization (Ar^{8+}, Ar^{9+}) in argon-filled capillary discharges could be used for temperature estimation. The temperature dependence of relative concentrations of Ar ions correspondent to the coronal equilibrium[18] is presented in Fig. 7. It is seen that electron temperature T_e >60 eV corresponds to the ionization stages Ar^{8+}, Ar^{9+}.

For EUV lithography application, the broadband emission of xenon near 135 Å which was observed in gas discharges[4,6,7] and laser-produced plasmas[2] is of special interest. Time-integrated axial emission spectra in Xe-filled capillary discharges at different gas pressures (100–500 mTorr) are shown in Fig. 8. At low pressures (100–200 mTorr) three broadband emission peaks were observed in the spectral range 100–160 Å. The peaks were centered at ~110 Å, 135 Å and 150 Å, each having a bandwidth of ~10 Å. These peaks could be identified as transitions in Xe^{11+}, Xe^{10+} and Xe^{9+} ions[4,19,20] as indicated in Fig. 8. According to the collisional radiative model used for laser-produced plasmas[19], the observed ionization stage Xe^{11+} corresponds to an electron temperature of at least 45 eV. At the same time, the coronal model[18] gives the value of T_e ~100 eV.

Relative line intensities of different ionization stages of Xe ions (as indicated in Fig. 8) versus gas pressure are shown in Fig. 9. The highest temperature observed at small pressures (100–200 mTorr) where the relative intensity ratios Xe^{11+}/ Xe^{10+} and Xe^{11+}/Xe^{9+} was equal to 4. With increasing pressure these ratios were reduced up to a value of ~1 at the pressure of 500 mTorr. This means that the discharge temperature was reduced when the plasma density was increased. At high gas pressures (~500 mTorr) the Xe ion peaks were blured and observed spectra looked like a quasicontinuum. This could be caused by a high plasma optical thickness when the observed intensities were close to ones defined by the Planck radiation limit. We will investigate this question in more detail in the future.

4. CONCLUSIONS

An EUV and soft x-ray source of radiation based on a compact fast capillary discharge plasma device was developed and investigated. Short current pulse durations (20– 30 ns) at a rise time of 1.5 ns were formed using low-inductance capacitors and a fast switch. Intense line emission of OVI-OV ions and ArIX-ArX ions was observed in spectral ranges 120–170 Å and 40–50 Å, respectively. Spectra of XeXII-XeX in the vicinity of 135 Å, the wavelength used for EUV lithography, were observed at different gas pressures. The electron temperature of the plasmas was equal to 60–100 eV. This simple and compact source of radiation could be considered as a prototype of an experimental setup for different practical applications (EUV lithography, soft x-ray microscopy in a water window, reflectometry, etc.).

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