An intense XUV source of radiation, within the 4-45-nm-spectral range, based on capillary discharge plasmas

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ABSTRACT

A compact device, based on fast capillary discharge plasmas, is an intense EUV and soft x-ray source of radiation. The plasma is created by a discharge of low-inductance capacitors through a gas-filled ceramic capillary (2 mm diameter, 10 mm length). Parameters of the discharge are: maximum current of 25 kA at applied voltage 40 kV, a pulse duration of 20-30 ns at FWHM, and a rise time of 1.5 ns. The soft x-ray and EUV emission of multiply charged ions is investigated using a compact 1 meter grazing incidence spectrometer-monochromator with a constant angle of deviation. The use of various gases (CO_2, Ne, Ar, Kr, Xe) allows the observation of XUV spectra in a wide spectral range—4–45 nm. A Xe-filled capillary discharge shows intense radiation (~5 mJ/2π ster/pulse within a 0.9 nm bandwidth) near 13.5 nm—the region of interest for EUV lithography applications. A reflectometer is used for testing grazing incidence gratings.

Keywords: capillary discharge plasmas, EUV spectroscopy, reflectometry and lithography.

1. INTRODUCTION

A great deal of effort is now going into the development of compact intense soft x-ray and extreme ultraviolet (EUV) sources. These sources are needed for several practical applications—EUV lithography, soft x-ray microscopy, etc. Much of this work has focused on the development of laser-produced plasma EUV sources for EUV lithography.[1,2] There is now a new emphasis on the development of other EUV sources which will be more efficient, more compact, and less complicated at lower cost. These sources include different types of gas-discharge plasmas: plasma focus,[3] Z-pinch plasmas [4-6] and capillary discharge plasmas. [8-10]

A capillary discharge plasma, as a source of radiation, possesses several advantages. These included compactness, relative simplicity, high efficiency, etc. Capillary discharge plasmas have been successfully used as a soft x-ray source [11,12] and as active medium for soft x-ray lasers.[13,14] The discharge was demonstrated as an effective source for EUV lithography.[8-10, 15, 16]

The purpose of our investigation is to develop a compact, effective, and wide spectral range source of EVU and soft x-ray radiation based on the ceramic capillary, gas filled capillary discharge plasmas.[16] The wide spectral range source, from the "water window" ~20 Å to several hundred Å, will find several practical applications: EUV lithography, soft x-ray microscopy, spectroscopy, etc. In this paper we describe a compact fast capillary discharge plasma source of EVU and soft x-ray radiation. Preliminary results, using the source for reflectometry application, are presented.

2. EXPERIMENT

The scheme of the experimental set up is shown in Fig. 1. A ceramic gas filled capillary, 2-mm-diameter and 10-mm-long, was used in the experiments. The capillary was filled with gas using an electromagnetic fast valve. A simple high current driver, based on full discharge of stored capacitors, was applied to the capillary gap. The discharge concept is described in detail in an earlier paper.[16] All components of the device (capacitors, the switch and the capillary) were assembled in a coaxial geometry. The device was 25 cm in diameter and 30 cm long. Electrical measurements with a

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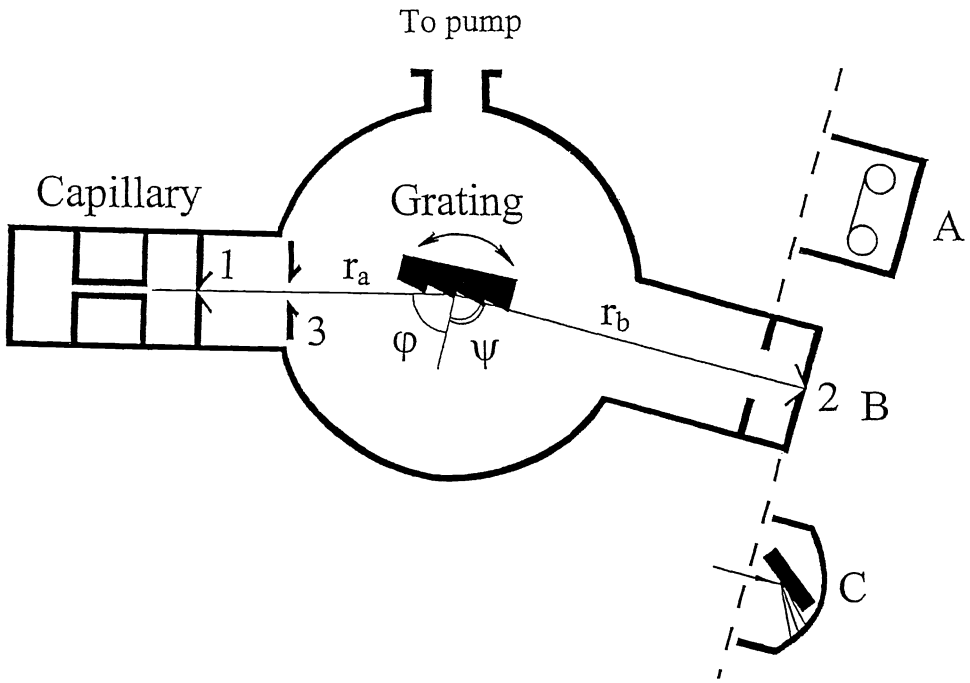


Fig. 1. The scheme of the experimental set up. Grazing incidence spectrometer: 1 - entrance slit; 2 – exit slit; 3 – diaphragm; φ – incidence angle; ψ – diffraction angle; φ+ψ=166°; r_a - distance between entrance slit and grating; r_b - distance between the grating and exit slit; A – spectrograph mode; B – monochromator mode; C – reflectometer mode.

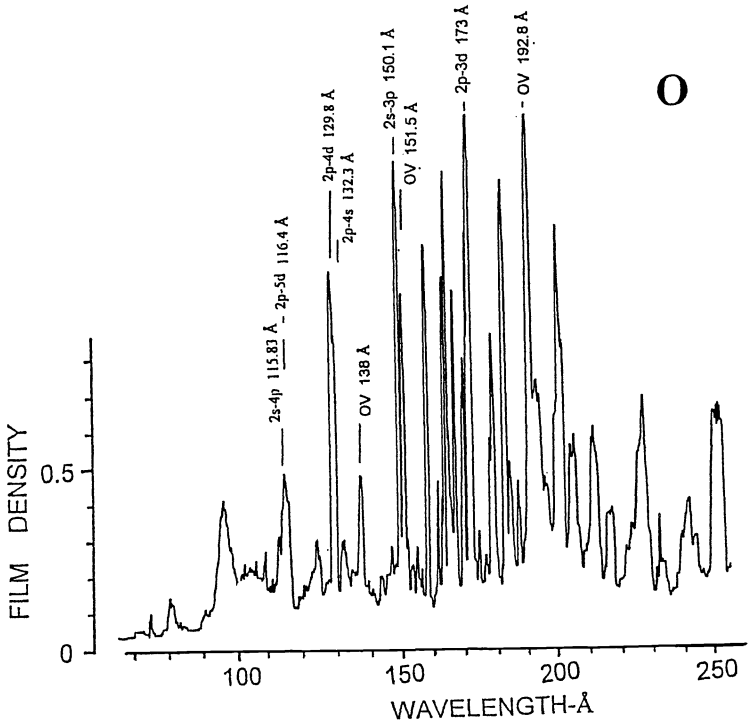


Fig. 2. Spectra of OVI-OV ions excited in a CO_2 filled capillary. Central line λ_0= 165 Å.

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temporal resolution of ~1 ns were made with a current shunt and a voltage divider. Electrical parameters of the capillary discharge are shown in Table 1. The use of a high voltage, high current switch and low inductance capacitors allowed fast rise times for voltage and current accross the capillary discharge gap. The current pulse had a rise time of ~1.5 ns. The corresponding value of dI/dt was in the range of 10^{12}-10^{13} A/sec. This is important with respect to the debris problem, because in this range evaporation of the walls does not play a significant role in capillary plasma compression and heating dynamics. The appearance of highly charged ion spectra is correlated with dips in the current pulses, which can be explained by the increase of inductance of the collapsing plasma column.

Table 1.
Parameters of the capillary discharge

Capillary	ceramic, gas filled, 2-mm-diameter and 10-mm-long
Capacitance	30 nF
Voltage U	30-40 kV
Current I	25 kA
Pulse duration	~ 20ns (FWHM)
Rise time	1-1.5 ns
dI/dt	10^{12}-10^{13} A/sec
Storage energy	16 J
Energy input to the capillary	~ 6 J

3. GRAZING INCIDENCE SPECTROMETER

An innovative grazing incidence spectrometer with constant angle of deviation, α, was developed (see Fig. 1) for use with the capillary discharge EUV source for reflectometry purposes. The angle of deviation is equal to $\alpha=\varphi+\psi=166°$. The angle of incidence, φ, and diffraction angle, ψ, can be changed as $\varphi = 85° \pm 1°$ and $\psi = 81° \pm 1°$. The angles are changed, and alignment on different central wavelengths λ_0 is achieved by using a precise grating rotation.

In the spectrometer three diffraction gratings are used: originally ruled, 1 meter radius, 1200, 600, 300 G/mm, blaze angle 2°, blank size 30(H)x25(W)x10 mm, ruled part 25(H)x15(W) mm, W coated. Each grating is mounted in its individual pre-aligned holder. The distance between the entrance slit and the grating is equal to r_a=86.7 mm, the distance between the grating and the exit slit is r_b=159 mm. The position of the exit slit can be changed with high precision (variable distance r_b). The spectral range, covered by the three gratings, is 44.3 – 425.2 Å. The spectral range can be extended in both sides with some losses in spectral resolution or realignment of the position r_b. The spectrometer has micrometer driven entrance and exit slit assemblies. The slit width can be varied from 0.5 μm to 0.2 mm with an accuracy of ~ 0.5 μm. The slit height is 20 mm. Some parameters of the spectrometer are listed in Table 2: recommended spectral range, dispersion D(Å/mm) in the exit slit plane, spectral resolution $\delta\lambda$ at the entrance slit width of 15 μm. The device has a port for differential pumping. The spectrometer is compact—spectrometer length ~ 250 mm.

Table 2.
Parameters of the grazing incidence spectrometer: recommended wavelength range, dispersion D(Å/mm) in the exit slit plane, spectral resolution $\delta\lambda$ at the entrance slit width of 15 μm.

Grating, G/mm	Wavelength range, Å	D(Å/mm)	$\delta\lambda$, Å
1200	44.3 – 106.3	7.3-9.1	0.5
600	88.6 – 212.6	14.6-18.2	1.0
300	177 – 425.2	29.2-36.4	2.0

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The spectrometer can be used in two modes: monochromator mode and spectrograph mode. In the spectrograph mode a removable cassette for photographic film is installed instead the exit slit. In this mode the exact focusing takes place at only one central wavelength λ_0 near the exit slit position. However due to the small numerical aperture of the spectrometer, it is possible to record the spectrum in a wide spectral range $\lambda_0 \pm \Delta\lambda$. The value $\Delta\lambda$ is related to the observed spectral resolution $\lambda/\delta\lambda$--the wider $\Delta\lambda$, the lower $\lambda/\delta\lambda$ because of defocusing. The alignment for different wavelengths, λ_0, is produced by a grating rotation.

In the reflectometer mode a special chamber with a test grating is installed behind the exit slit. The grating can be aligned at the needed grazing angle (from 1° to 8°). The incident intensity at the exit slit position and intensities reflected from the grating are recorded using photographic film or a luminescence detector.[17] The detector consists of a photomultiplier connected with a flexible fiber optic light guide. The end of the guide is covered by the luminescence layer (sodium salicilate). The calibration procedure for the detector is described in Ref. [17].

The grazing incidence spectrometer was connected to the exit flange of the capillary discharge chamber. The distance between the capillary end and entrance slit of the spectrometer was equal to 50 mm. The device required differential pumping of the discharge chamber and the spectrometer. The pressure in the spectrometer was 0.01 Torr when the gas pressure in the capillary was 0.5 Torr. The spectra were recorded on calibrated UF-4 photographic film.[17] To record each spectrum it was necessary to produce 1-10 discharge shots.

4. RESULTS

EUV spectra of gas filled capillary discharges are shown in Figs. 2-5. The following gases were used: CO_2, Ne, Ar, Kr, Xe at the gas pressure of 100-800 mTorr. Ref. [18] was used for line identification.

Typical spectra of OVI-OV ions excited in a CO_2 filled capillary is shown in Fig. 2. Intense 2l-nl' transitions with n=3-5 were observed. The spectrometer was aligned on the central line of λ_0= 165 Å. At the wavelength range near the central line, λ_0, the spectral resolving power was equal to $\lambda/\delta\lambda$=330 at the entrance slit width of 15 μm. Due to defocusing the value $\lambda/\delta\lambda$ was reduced when the wavelength was moved away from λ_0.

In the neon gas filled capillary discharge intense 2-3 transitions in NeV-NeVIII ions at wavelengths > 90 Å were observed (Fig. 3).

The spectrum of the argon filled capillary discharge at a pressure 250 mTorr is shown in Fig. 4. Intense transitions 2p-3s, 2p-3d in ions ArIX, ArX were observed. The maximum intensity of the 2p-3s transition (λ=49 Å) was observed at the pressure 400 mTorr. The observed stages of ionization (Ar^{8+}, Ar^{9+}) in an argon filled capillary discharge were used to estimate the electron temperature in the discharge [16]: T_e>60 eV.

In the krypton-filled capillary discharge intense 3-4 transitions in KrX-KrVIII ions at wavelengths > 100 Å were observed (Fig. 5).

For EUV lithography applications the broadband emission of xenon near 135 Å, which was observed in gas discharges [4-10, 16] and laser-produced plasmas,[1] is of special interest. Time-integrated axial emission spectrum in Xe filled (100 torr) capillary discharges is shown in Fig. 6. Three broadband emission peaks were observed in a 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 as indicated in Fig. 6. 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 of 45 eV. At the same time the coronal model [20] gives the value of T_e~100 eV. The highest temperature was observed at low pressures (100-200 mTorr). With increasing pressure the temperature in the discharge was reduced as the plasma density increased. At high gas pressures (~500 mTorr) the Xe ion peaks were blured, and observed spectra looked like a quasycontinuum.

The spectra excited in the discharge were used for measurements of grating reflections. The chamber with a test grating was installed after the exit slit. The grating was aligned at the needed incidence angle. The monochromator selected the

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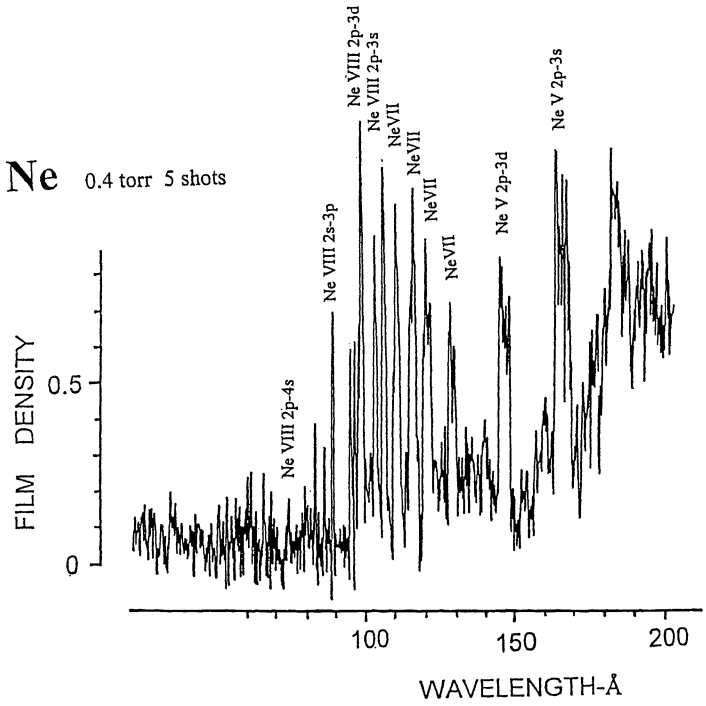


Fig. 3. Spectra of neon gas filled capillary discharge plasma. Central line λ_0= 90 Å.

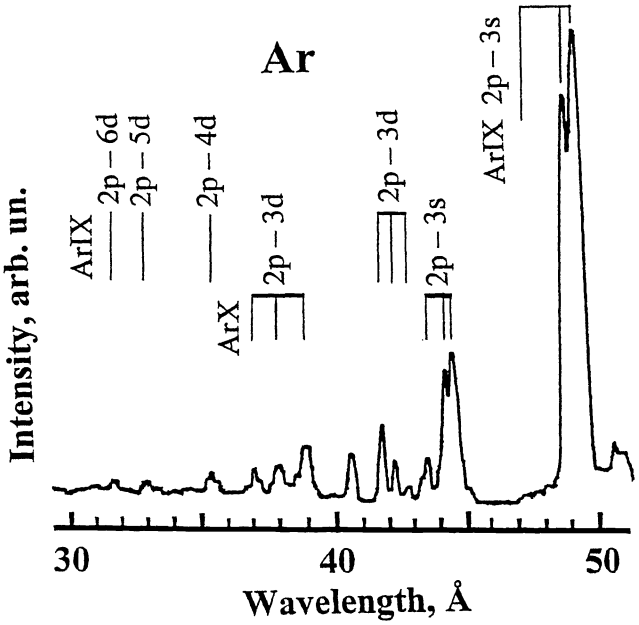


Fig. 4. Spectra of argon gas filled capillary discharge plasma. Central line λ_0= 50 Å.

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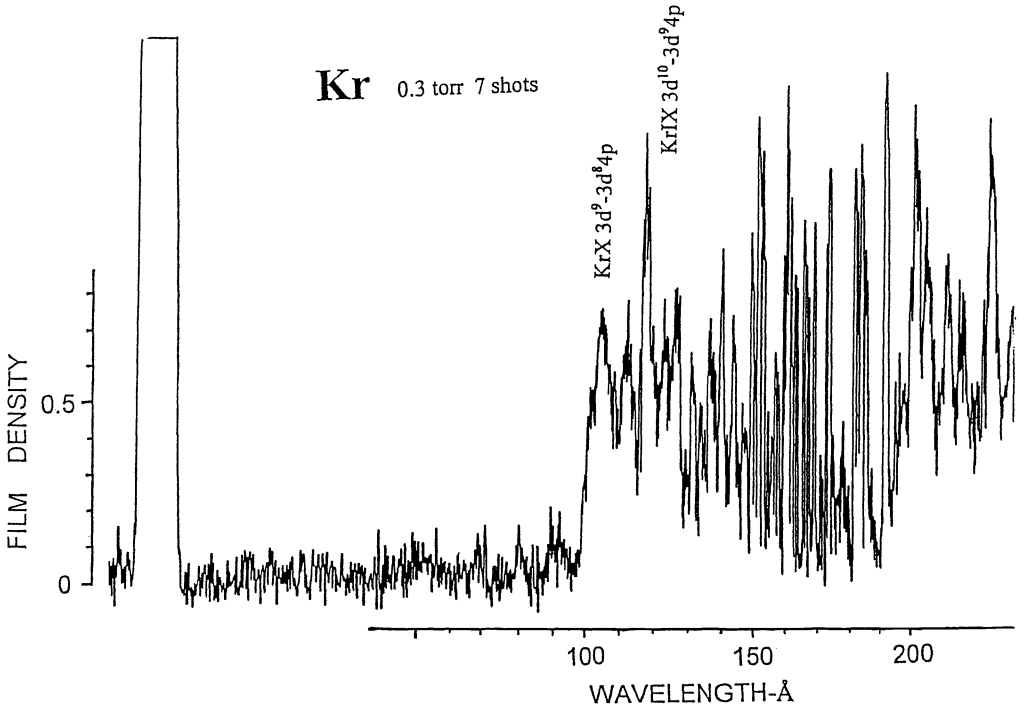


Fig. 5. Spectra of krypton gas filled capillary discharge plasma. Central line λ_0= 165 Å.

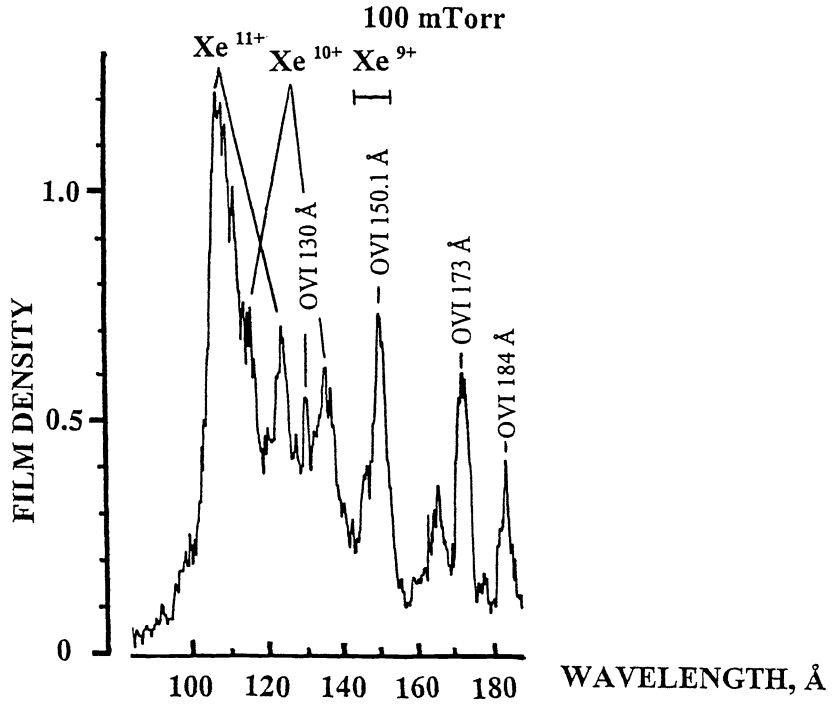


Fig. 6. Spectra of xenon gas filled capillary discharge plasma. Oxygen-contamination lines are also noted.

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needed wavelength. Using different gases it was possible to calibrate the gratings in a wide spectral range: 4-45 nm. As an example, the reflections for the grating with 600 G/mm (grazing incidence angle of 5°) were measured using a Xe gas filled capillary discharge. The radiation near wavelength 135 Å was selected. The measured reflections were equal to 7%, 10%, <1% and 3-4% for the zero, first, second and third reflection orders respectively.

With calibrated gratings the spectrometer can be used for absolute intensity measurements. Using the reflection data for the grating and calibration data for the photographic film,[17] the absolute yield Y from the Xe capillary discharge (gas pressure of 400 mTorr) was measured at a wavelength of 135 Å : Y=5 mJ/2π ster/pulse within a 9 Å bandwidth of a typical Mo/Si mirror with peak reflectivity at 135 Å. This value is very close to the one observed in [7, 8].

In the future the experimental set up will be equipped with a theta/2 theta device to characterize the multilayer mirrors.

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REFERENCES

1. G. Kubiak, L. J. Bernardez, K. Krenz, W. C. Replogle, W. C. Sweatt, D. W. Sweeney, R. M. Hudyma, and H. Shields, "High-power source and illumination system for extreme ultraviolet lithography," *SPIE* **3767**, pp. 136-142, 1999.
2. G. Schriever, M. Rahe, U. Rebhan, D. Basting, W. J. Walecki, H. Lauth, R.Lebert, K. Bergmann, D. Hoffmann, O. Rosier, W. Neff, R. Poprawe, S. Sauerbrey, H. Schwoerer, S. Dűsterer, C. Ziener, P. Nickles, H. Stiehl, I. Will, W. Sandner, G. Schmahl, D. Radolph, "Extreme ultraviolet source development: A comparison of different concepts," *SPIE* **4146**, pp. 113-120, 2000.
3. W. Partlo, I. Fomenkov, R. Oliver, and D. Birx, "Development of an EUV (13.5nm) Light Source Employing a Dense Plasma Focus in Lithium Vapor," *SPIE* **3997**, pp.136-156, 2000.
4. M. McGeoch, "Radio-frequency-preionized xenon z-pinch source for extreme ultraviolet lithography," *Appl. Opt.* **37**, pp.1651-1658, 1998.
5. K. Bergmann, G. Schriever, O. Rosier, M. Muller, W. Neff, and R. Lebert, "Highly repetitive, extreme-ultraviolet source based on a gas-discharge plasma," *Appl. Opt.* **38**, pp.5413-5417, 1999.
6. M. W. McGeoch, "Power Scaling of a Z-Pinch Extreme Ultraviolet Source," SPIE 3997, 861-866, 2000.
7. M.A. Krosner, H.A. Bender, W.T. Silfvast, and J.J. Rocca, "Intense plasma discharge source at 13.5 nm for extreme-ultraviolet lithography," *Opt.Lett.* **22**, pp.34-36, 1997.
8. M.A. Klosner and W.T. Silfvast, "Intense xenon capillary discharge extreme-ultraviolet source in the 10-16-nm-wavelength region," *Optics Letters* **23**, pp.1609-1611, 1998.
9. W. T. Silfvast, M. Klosner, G. Shimkaveg, H.Bender, G. Kubiak, and N. R. Fornaciari, "High-power plasma discharge source at 13.5 nm and 11.4 nm for EUV lithography," *SPIE* **3676**, pp. 272-275, 1999.
10. N. R. Fornaciari, J. J. Chang, D. R. Folk, S. Gianoulakis, J. E. M. Goldsmith, G. D. Kubiak, B. C. Long, D. J. O'Connell, G. Shimkaveg, W. T. Silfvast, and K. D. Stewart, "Development of an Electric Capillary Discharge Sorce," *SPIE* **3997**, pp. 120-125, 2000.
11. P. Bogen, H. Conrads, G. Gatti, and W. Kohlhaas, "Continuum Radiation Source of High Intensity," *JOSA* **58**, pp.203-206, 1968.
12. R.A. McCorkle, "The High-Power Sliding-Spark Capillary Discharge in Vacuum: Variations and Applications," *Appl. Phys.* **A 26**, pp.261-270, 1981.
13. J.J. Rocca, V. Shlyaptsev, F.G. Tomasel, O.D. Cortaszar, D. Hartshorn, and J.L.A. Chilla, "Demonstration of a Discharge Pumped Table-Top Soft-X-Ray Laser," *Phys.Rev.Lett.* **73**, pp.2192-2195, 1994.
14. J.J. Rocca, "Table-top soft x-ray lasers," *Rev.Sci.Instrum.* **70**, pp.3799-3827, 1999.
15. L. Knight, S. Turley, C. Crawford, D. Hullinger, A. Shevelko, O. Yakushev, R. Miller, "EUV spectroscopy of ultrafast capillary discharges," *SPIE* **3767**, pp.45-49, 1999.

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16. A. P.Shevelko, L. V. Knight, O. F. Yakushev, "Capillary discharge plasmas as a source of EUV and soft x-ray radiation," *SPIE* **4144**, pp. 68-75, 2000.
17. A. Shevelko, "Absolute measurements in the VUV spectral range with a luminescence detector," *Quantum Electronics* **26**, pp.729-731, 1996.
18. R.L.Kelly, "Atomic and ionic spectrum lines of hydrogen through krypton," *J.Phys.Chem.Ref.Data* **16**, Suppl.1, pp.105-109 and 401-402, 1987.
19. J.Blackburn, P.K.Carroll, J.Costello, and G.O'Sullivan, "Spectra of Xe VII, VIII, and IX in the extreme ultraviolet: 4*d*-*mp*, *nf* transitions," *J. Opt. Soc. Am.* **73**, pp.1325-1329, 1983.
20. M.Arnaud and R.Rothenflug, "Anupdate evaluation of recombination and ionization rates," *Astron.Astrophys.Suppl.Ser.***60**, pp.425-457, 1985.

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