2002

121.6 nm Radiation Source for Advanced Lithography

Jianxun Yan
Old Dominion University

Ashraf El-Dakrouri
Old Dominion University

Mounir Laroussi
mlarouss@odu.edu

Mool C. Gupta
Old Dominion University

Original Publication Citation

Jianxun, Y., El-Dakrouri, A., Laroussi, M., & Gupta, M. C. (2002). 121.6 nm radiation source for advanced lithography. *Journal of Vacuum Science & Technology B, 20*(6), 2574-2577. doi:10.1116/1.1515302

JVSTB Journal of Vacuum Science & Technology B

121.6 nm radiation source for advanced lithography

Jianxun Yan, Ashraf El-Dakrouri, Mounir Laroussi, and Mool C. Gupta

Citation: Journal of Vacuum Science & Technology B **20**, 2574 (2002); doi: 10.1116/1.1515302
View online: http://dx.doi.org/10.1116/1.1515302
View Table of Contents: http://scitation.aip.org/content/avs/journal/jvstb/20/6?ver=pdfcov
Published by the AVS: Science & Technology of Materials, Interfaces, and Processing

121.6 nm radiation source for advanced lithography

Jianxun Yan, Ashraf El-Dakrouri, Mounir Laroussi, and Mool C. Gupta[a)]
Applied Research Center, College of Engineering and Technology, Old Dominion University, Newport News, Virginia 23606

(Received 28 May 2002; accepted 26 August 2002)

A vacuum ultraviolet (VUV) light source based on a high-pressure cylindrical dielectric barrier discharge (DBD) has been developed. Intense and spectrally clean Lyman-α line at 121.6 nm was obtained by operating a DBD discharge in neon with a small admixture of hydrogen. The spectrum, optical power, stability, and efficiency of the source were measured. The influence of the gas mixture and total gas pressure on the VUV intensity has been investigated. Maximum optical power of 3.2 W and spectral width <0.03 nm was achieved. Power stability of $\pm 2\%$ for 100 h of operation has also been obtained. The newly developed Lyman-α line source at 121.6 nm appears very promising for advanced lithography and other applications. © *2002 American Vacuum Society.* [DOI: 10.1116/1.1515302]

I. INTRODUCTION

Lithography at 157 nm with fluorine lasers is widely considered to be the last generation of conventional photolithography methods for sub-100 nm device fabrication. 100 nm lithography and beyond will be performed with next-generation lithography technologies such as x-ray, extreme ultraviolet (UV) ($\sim$13 nm), electron beams, and ion beams. But these alternatives represent a more radical deviation from the present optical-based technology, and thus they encounter more engineering challenges.[1] It has become apparent that a more mainstream extension of optical lithography should be considered as well. One of the alternatives is 121.6 nm technology. Therefore, the development of an intensive 121.6 nm light source appears to be necessary.

121.6 nm, Lyman-α line ($2p\,^2P_0 \rightarrow 1s\,^2S$), is emitted from an atomic transition in hydrogen, and is sufficiently narrow for lithography. There are many plasma-based methods which can achieve 121.6 nm line emission. Examples are arc discharge,[2] microwave excited discharge,[3] glow discharge,[4] microhollow cathode discharge,[5] and laser induced plasma.[6] Here we explore a discharge lamp based on a variant of the dielectric barrier discharge (DBD).[7] The DBD configuration is characterized by the presence of at least one dielectric layer in the current path between the electrodes and discharge space.[8,9] The dielectric barrier serves two functions. It distributes the microdischarges evenly over the entire electrode area and it limits the amount of charge and energy that can be fed into an individual filament. The plasma conditions of these microdischarges are ideal for excimer formation, in which a major fraction of the energy gained by the electrons in the electric field can be deposited in excited atomic and molecular states. One important feature of the DBD is that the plasma parameters can be influenced and thus optimized by external means. The reduced electric field E/n (n is gas density), which mainly controls the mean electron energy, can be influenced by the pressure in the discharge, the electrode spacing, and voltage slope at breakdown. On the other hand, the electron density in a microdischarge can be controlled again by pressure and by the properties of the dielectric barrier. The simplicity, versatility, and low cost of the DBD make them attractive for generating the Lyman-α line.

Due to the high excitation energy of rare-gas ions or excited rare-gas atoms, the Lyman-α line can be obtained under various excitation conditions when trace amounts of hydrogen are added to rare gas. For example, intense Lyman-α was observed in He–H_2 mixture near atmospheric pressure.[10] Argon/hydrogen mixture in low pressure glow discharge has been investigated to generate vacuum ultraviolet (VUV) for the photochemical treatment of polymer surfaces.[4] Energy transfer from neon ions to hydrogen molecules has been studied by an e-beam induced light source to obtain a strong intense Lyman-α line.[11] Neon–hydrogen mixture in a high-pressure discharge was shown to be a very efficient and selective method for generating Lyman-α.[5] The process of neon excimer formation, the resonant energy transfer from neon excimer molecules to molecular hydrogen, and subsequent light emission are shown as follows:

$$\mathrm{Ne} + e^- \rightarrow \mathrm{Ne}^+ + 2e^-, \tag{1a}$$

$$\mathrm{Ne}^+ + 2\mathrm{Ne} \rightarrow \mathrm{Ne}_2^+ + \mathrm{Ne}, \tag{1b}$$

$$\mathrm{Ne}_2^+ + e^- \rightarrow \mathrm{Ne}^* + \mathrm{Ne}, \tag{1c}$$

where Ne* denotes a metastable neon atom. Alternatively, Ne* can be the product of direct electron impact:

$$\mathrm{Ne} + e^- \rightarrow \mathrm{Ne}^* + e^-. \tag{1d}$$

Neon excited molecular complexes without stable ground states, also called excimers, are formed by a three-body reaction of a metastable neon atom and two atoms in the ground state

$$\mathrm{Ne}^* + \mathrm{Ne} + \mathrm{Ne} \rightarrow \mathrm{Ne}_2^* + \mathrm{Ne}. \tag{2}$$

Resonant energy transfer from Ne_2^* (14.8 ± 0.8 eV) to molecular hydrogen leads to H_2 dissociation (4.48 eV) and excitation H* (10.2 eV),

a)Electronic mail: mgupta@odu.edu

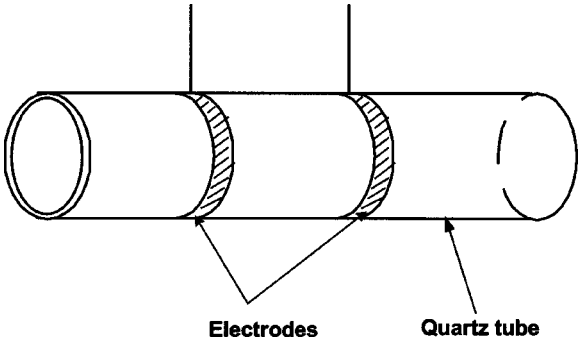

FIG. 1. Cylindrical DBD configuration with ring electrodes.

$$Ne_2^* + H_2 \rightarrow 2Ne + H + H^*(n=2). \quad (3)$$

Excited hydrogen atoms spontaneously emit the Lyman-α line

$$H^* \rightarrow H + h\nu(121.6 \text{ nm}). \quad (4)$$

II. EXPERIMENTS

The discharge geometry used in our experiments is cylindrical, featuring a hollow quartz (or alumina) tube and two copper-ring electrodes wrapped around the outer surface of the tube[7,12] (see Fig. 1). Since the electrodes are out of the discharge volume, electrode erosion and contamination of the plasma with metal vapor is avoided. The length, diameter, and thickness of the tube, and the distance between the ring electrodes are variable, thus the plasma can be optimized by adjusting external parameters.

The experimental setup consists of the discharge unit, monochromator, detector, gas inlet and outlet assembly, pump system, and rf power supply with impedance matching network. The system is schematically shown in Fig. 2. The discharge unit is a 115 mm$\times$8 mm o.d.$\times$4 mm i.d. quartz tube, which connects with two flanges by two O-rings to vacuum seal the tube. The whole discharge unit is fixed on an 8.5 cm six-way cross cube, on which a monochromator and photodetector can be easily mounted. The monochromator is connected with the cube chamber by a flange adapter, on which a window could be installed. The system can either have a window or be windowless. For the Lyman-α line, the LiF window was used to transmit the radiation, because its short-wavelength cutoff is at 105 nm. On the other side of the cube, the gas inlet flange and detector chamber, which contains a filter and a silicon photodiode, are mounted. The discharge is ignited with a rf power supply system, which consists of a 13.56 MHz rf generator and an impedance matching network.

Before generating the plasma, the discharge unit, monochromator, and detector were evacuated to 10^{-6} Torr. High vacuum was necessary before filling the neon and hydrogen gas, to avoid emission from impurities such as O, N,.... Two flow meters, one connecting with high purity neon and the other with 1% hydrogen/neon mixture (research grade), controlled the flow rate and ratio of hydrogen and neon. A needle valve and flow meters were adjusted together to control the flow rate and to maintain a constant pressure in the lamp. The lamp was operated in a dynamic mode, which had a gas flow rate of 600 sccm. The plasma was initially ignited at a relatively low pressure (less than 100 Torr). The discharge formation rf power depended on pressure p, electrode gap width d, and type of dielectric.

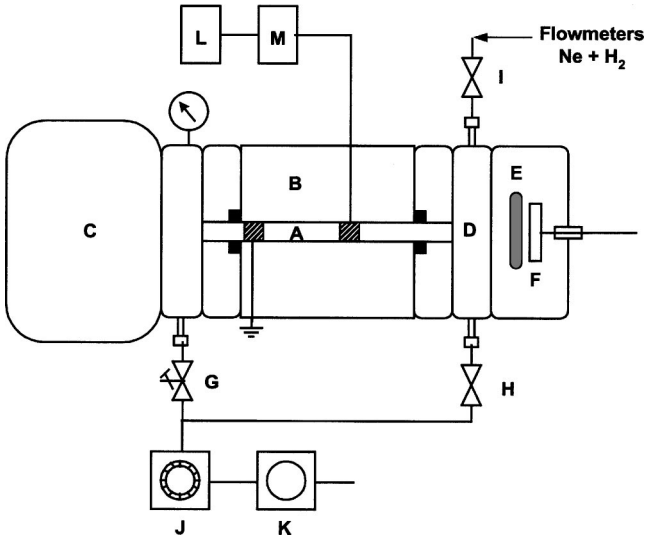

FIG. 2. Schematic drawing of the experiment setup. (A) Quartz tube, (B) chamber, (C) monochromator, (D) gas inlet and outlet flange, (E) filter, (F) semiconductor detector, (G) needle valve, (H and I) valves, (J) turbo pump, (K) roughing pump, (L) rf generator, and (K) matching network.

III. RESULTS AND DISCUSSION

Emission spectra were measured with a 0.2 m McPherson scanning monochromator (model 320). Intense Lyman-α radiation was observed as the only strong radiation in the entire VUV spectrum. Figure 3 shows the emission spectrum at a pressure of 500 Torr, with a neon gas containing 0.058% hydrogen and a flow rate of 600 sccm. The emission line has a bandwidth of less than 0.1 nm full width half maximum (FWHM) and was limited by the resolution of the monochromator, which has grating of 1200 G/mm. The range of hydrogen from 0.03% to 0.12% was found to be the ideal range to achieve a Lyman-α line dominated spectrum. Beyond this range, the intensity of the line would dramatically decrease, and other lines, 130 nm from oxygen, 156 and 165 nm from carbon, would relatively increase. According to our experimental results, the optimum ratio for intense Lyman-α line is about 0.06% hydrogen in neon. The pressure and electrode gap also influenced the intensity of Lyman-α. From our experiment, the optimum range of pd value was from 50–100 Torr cm. This represents a great advantage over many other discharge types, because of the relative simplicity in changing the pressure–electrode gap product. Thus in a fairly simple way one can adjust this important plasma parameter to optimize the yield of the excimer and Lyman-α emission.

The absolute intensity of the Lyman-α radiation was measured by a silicon photodiode[13] (IRD company, model SXUV-100), which has 1 cm$\times$1 cm active area and 0.01 A/W responsivity at 121.6 nm. A narrowband filter located

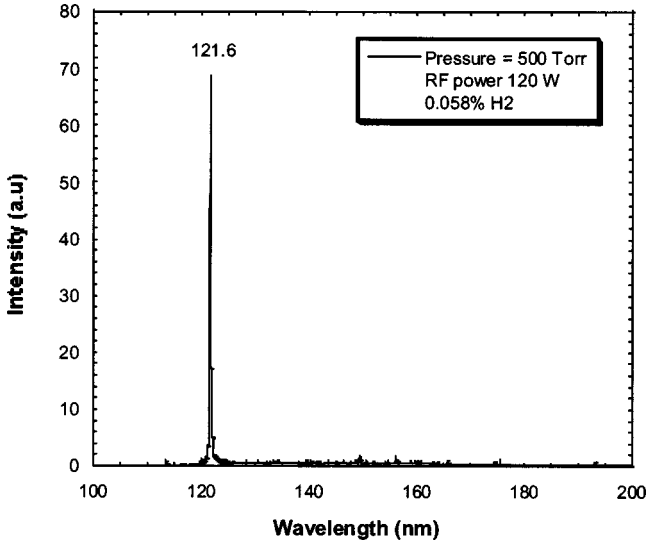

FIG. 3. Emission spectrum of neon/hydrogen mixture at a pressure of 500 Torr.

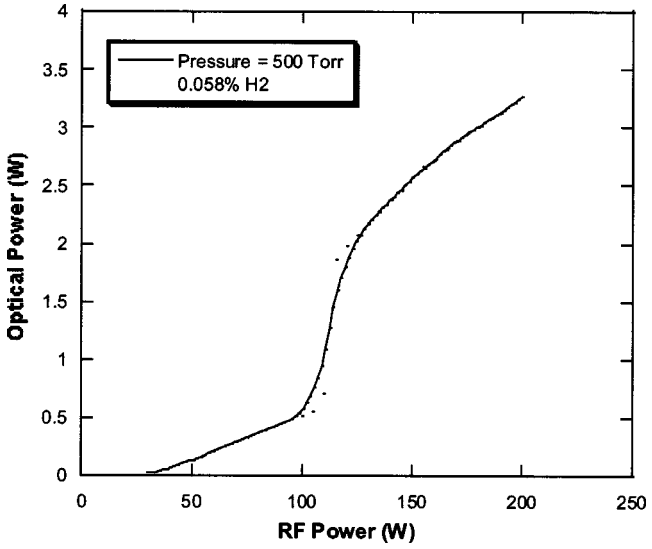

FIG. 4. Total optical power dependence on the input rf power at pressure of 500 Torr.

between the discharge unit and the detector was used. It has peak transmittance at 119.6 nm, FWHM of 13.5 nm, and a transmission efficiency of 15% at 121.6 nm. Although visible light in the red region was radiated with a low intensity compared to the Lyman-α nm radiation (1:30), it is necessary to block out this radiation with the filter. The intensity that the detector measured was that of 121.6 nm. The discharge is a filament source with 2 mm diameter and 3 cm length. The calculation of total power was based on a line source. Figure 4 shows the total optical power increased with rf input power. At a pressure of 500 Torr and rf input power of 200 W, we obtained emission intensity of 5.3 mW/cm^2 on detectors, which had a distance of 5 cm from the front edge of the source. The maximum total optical power of 3.2 W and with an efficiency of 1.6% was obtained. In order to generate more power, a stronger rf field should be applied to the discharge. For increased efficiency, the impedance of the discharge and that of the rf generator should match. Since the capacitance of the discharge was variable, a wide load-matching range network was specially designed to meet the impedance matching criterion.

Beam profile was measured to identify the emission intensity across the beam cross section. At low pressures the tube was filled with the discharge, and the whole section had a nearly uniform intensity. As the pressure increased, the discharge restricted toward the center and a filament between two electrodes was formed. The front view of the discharge appeared like a 2 mm diam disk, and the side view was a line source. Figure 5 shows the two-dimensional (2D) and three-dimensional (3D) beam profiles at 500 Torr. Since we could not image beam profile at 121.6 nm directly, these images were based on the visible light generated in the discharge.

Power stability is an important criterion for a lamp used in lithography applications. Preliminary tests showed that our source was capable of continuous operation over a 24 h period with rf input power of 120 W and total optical power of about 2.0 W (Fig. 6). The average emission intensity on the detector was 3.34 mW/cm^2 with a distance of 5 cm from the source. During the 24 h of operation the power fluctuation was less than $\pm 2\%$ and without power degradation.

IV. CONCLUSIONS

We have demonstrated a DBD-based VUV source that emits strong radiation at 121.6 nm. Using high-pressure neon

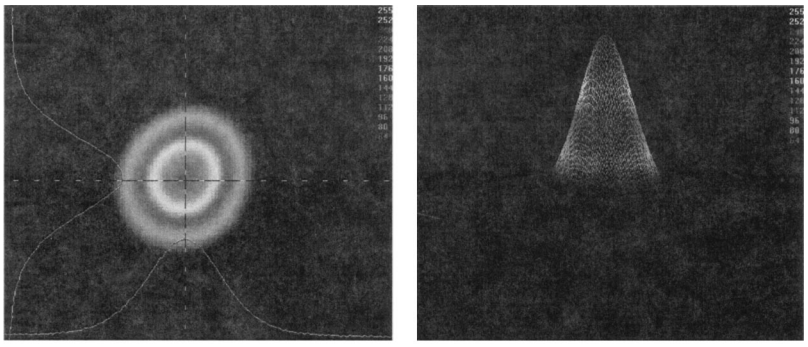

FIG. 5. 2D and 3D beam profile.

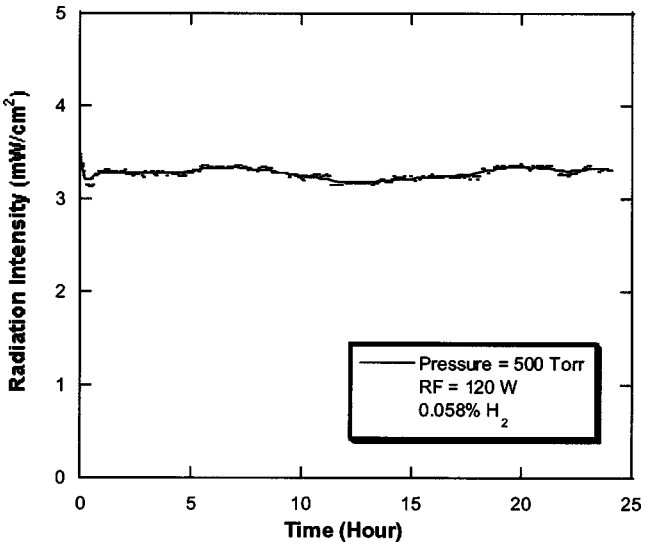

FIG. 6. Radiation intensity vs operating time: $P = 500$ Torr; rf $= 120$ W; 0.058% H_2.

with a small admixture of hydrogen, an intense and nearly monochromatic source at the Lyman-α line was built with FWHM less than 0.03 nm. The emission spectrum, optical power, efficiency, beam profile, and stability were investigated. High power emission up to 3.2 W at 121.6 nm was achieved. This study demonstrated that it is possible to achieve high power, spectrally narrow and stable 121.6 nm sources from a compact lamp for advanced lithography and other applications.

ACKNOWLEDGMENTS

This work was supported by the U.S. Defense Advanced Research Projects Agency (DARPA) under Contract No. DAAD 19-99-1-0277 and administered by Army Research Office. The author thanks Professor K. Becker and Dr. Akhmerov for helpful discussions.

[1]M. Rothschild *et al.*, J. Vac. Sci. Technol. B **17**, 3262 (1999).
[2]W. R. Ott, K. Behringer, and G. Gieres, Appl. Opt. **14**, 2121 (1975).
[3]A. Hollander and M. R. Wertheimer, J. Vac. Sci. Technol. A **12**, 879 (1994).
[4]A. C. Fozza, A. Kruse, A. Hollander, A. Ricard, and M. R. Wertheimer, J. Vac. Sci. Technol. A **16**, 72 (1998).
[5]P. Kurunczi, H. Shah, and K. Becker, J. Phys. B **32**, L651 (1999).
[6]M. Spaan, A. Goehlich, V. Schulz-von der Gathen, and H. F. Doele, Appl. Opt. **33**, 3865 (1994).
[7]M. Laroussi, Proceedings of the IEEE International Conference on Plasma Science, Monterey, CA, 1999, p. 203.
[8]B. Eliasson and U. Kogelschatz, IEEE Trans. Plasma Sci. **19**, 309 (1991).
[9]B. Gellert and U. Kogelschatz, Appl. Phys. B: Photophys. Laser Chem. **52**, 14 (1991).
[10]O. Motret, J. M. Pouvesle, and J. Stevefelt, J. Chem. Phys. **83**, 1095 (1985).
[11]J. Wieser, M. Salvermoser, L. H. Shaw, A. Ulrich, D. E. Murnick, and H. Dahi, J. Phys. B **31**, 4589 (1998).
[12]*Techniques and Applications of Plasma Chemistry*, edited by J. R. Hollahan and A. T. Bell (Wiley, New York, 1974).
[13]E. M. Gullikson, R. Korde, L. R. Canfield, and R. E. Vest, J. Electron Spectrosc. Relat. Phenom. **80**, 313 (1996).