Proceedings of the 3rd International Conference on the Frontiers of Plasma Physics and Technology (PC/5099)

Optimization of Parameters Required for EUV Radiation Based on UNU/ICTP Plasma Focus Device

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Extreme Ultravilolet (EUV) radiation sources are currently drawing many interests, as they are being developed to comply with the demands of the production of the next generation semiconductors chips. The wavelength for lithography of interest is around 13.5 nm. In this work, a plasma focus device which is known to be a powerful source of radiation is investigated. A plasma computational model of UNU/ICTP plasma focus device is used to determine important parameters for EUV radiation production. The computational model has been verified with experiments on 3 kJ UNU/ICTP plasma focus device and was found to be in good agreement. For the determination of EUV production, the physical parameters such as the configuration of the electrodes are fixed while the input energy and operating pressure under xenon gas are variable. From the calculation, it was found that discharges with input energy range of 184 J to 454 J and using xenon gas at pressure of 1 mbar can yield radiation that covers EUV region with total power in the range of $6x10^{10}$ W to $16x10^{10}$ W. This shows and confirms the possibility of developing a plasma focus as a powerful EUV radiation source for future semiconductor industry as well as a possibility of physical scaling of the plasma focus.

1. Introduction

Recently, extreme ultraviolet (EUV) radiation at a wavelength of 13.5 nm has drawn many interests as there are demands for the production of the next generation semiconductor chips [1]. Many plasma based EUV radiation sources such as the laser produced plasma and pulsed discharge sources such as the capillary discharge, vacuum spark and plasma focus are being considered by researchers worldwide [2]. These radiation sources, especially the pulsed discharge sources, could be the sources for Next Generation Lithography (NGL) because of their lower cost and simplicity compared to laser produced plasma and synchrotron sources. Various plasmas such as argon, xenon and tin have been investigated for generating EUV radiation around 13.5 nm [2-5]. The demands for high power EUV radiation lead to a requirement for optimization of these plasma discharge devices.

In this paper, we investigate a possibility of using the plasma focus as a EUV radiation source by simulating the plasma generation process using a computation model [6]. It is well known that the plasma focus device [7] is capable of producing dense transient high temperature plasmas since the 1960's. It is an inexpensive and compact source of intense X-rays [8-9], neutrons [10], and beams of ions [11] and electrons [12]. It also has potential applications as a high-brightness source for lithography and soft X-ray microscopy [8]. The X-ray energy produced in a plasma focus discharge can be as much as ~10% of the stored capacitor energy [13]. It is known that these X-ray emitted from the plasma focus may consist of Bremsstrahlung, recombination, and line radiation [14]. The detailed characteristics of the radiation emission from a plasma focus device may depend, in a rather complicated way, on the design and operating parameters of the plasma focus device such as the stored capacitor energy, the plasma discharge current, the physical configuration, as well as the materials of the electrodes and insulator, the gas pressure and its composition. A simulation based on the 5 phase dynamics of a plasma focus is used to calculate the radiation power that covers the EUV wavelength region by varying physical parameter of the plasma focus as well as its initial stored energy and the operating pressure. The calculation of the radiation power produced during the radiation phase would give a good indication of possible emission power as well as optimized values of plasma focus parameters when operating as EUV radiation source.

2. Radiative Computational Model

In order to calculate for emission power from a plasma focus device, the plasma temperature, in one of possible three processes, is related to the wavelengths at the peak of its continuum, from the Bremsstrahlung process by $\lambda_0 = 620/T_e$ (nm) [14] where, λ_0 is the wavelength in nanometer and T_e is the plasma temperature in eV. For the line radiation, certain plasma temperatures will allow some possible species of ions to exist based on Corona Equilibrium (CE) Model. This is shown in Figure 1a. Each species can radiate at certain wavelengths based on their transition of excited electrons. The species of xenon that may be of interest are Xe^{10+} and Xe^{25+}, where these two have line radiations around the wavelength of interest [15]. Considering these two radiation processes, the EUV radiation can be produced if the plasma temperature is ≅40 eV, where Xe^{10+} has prominent EUV lines as well as wavelength of the peak of continuum from the Bremsstrahlung process.

By using the computation model [6] of a typical UNU/ICTP plasma focus device, which simulates the dynamics of five phases of the plasma focus, the plasma temperature can be determined. In this simulation, the five phases are axial phase, radial inward shock phase, radial reflected shock phase, radiation phase and expanded column axial phase. The radiation phase bases on CE model, where it applies to atoms that have principal quantum number n ≤6. Where the electron density N_e is given by;

$$N_e^{\max} \approx 6.5\times10^{16}(z+1)^6 T_e^{1/2}\exp(0.1(z+1)^2/T_e)\,.$$

By using the CE model, the population of ions with charge z+1 and z can be related by;

$$N_{z+1}/N_z = 1.27\times10^8 \times \zeta T_e^{3/4}\exp(-\chi_z/T_e)/\chi_z^{11/4}$$

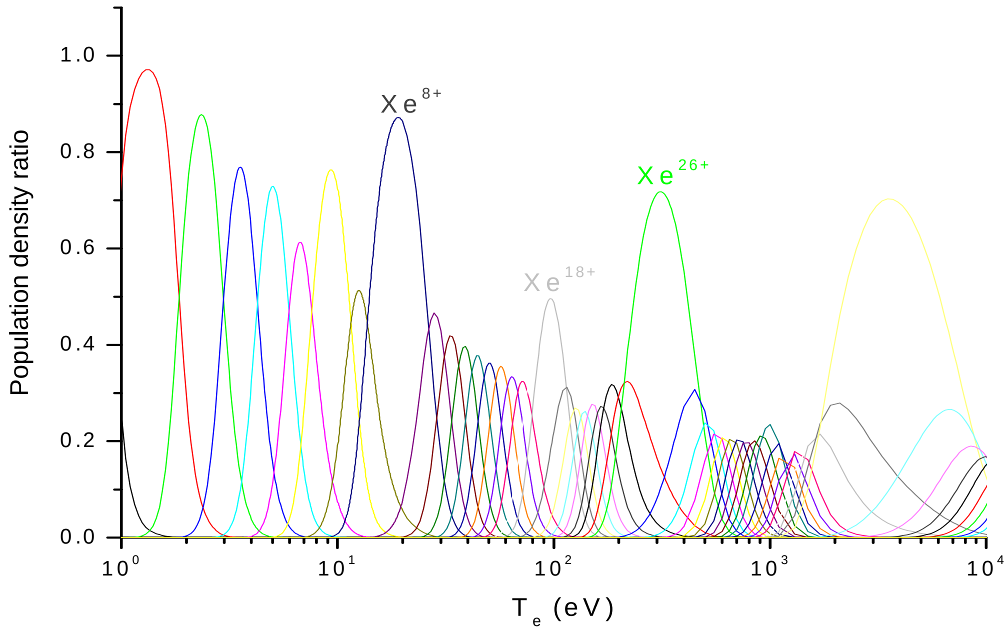

Figure 1a. The population density ratio α_z of xenon ionic species versus electron temperature T_e (0-10^4 eV) calculated from the Coronal Equilibrium Model.

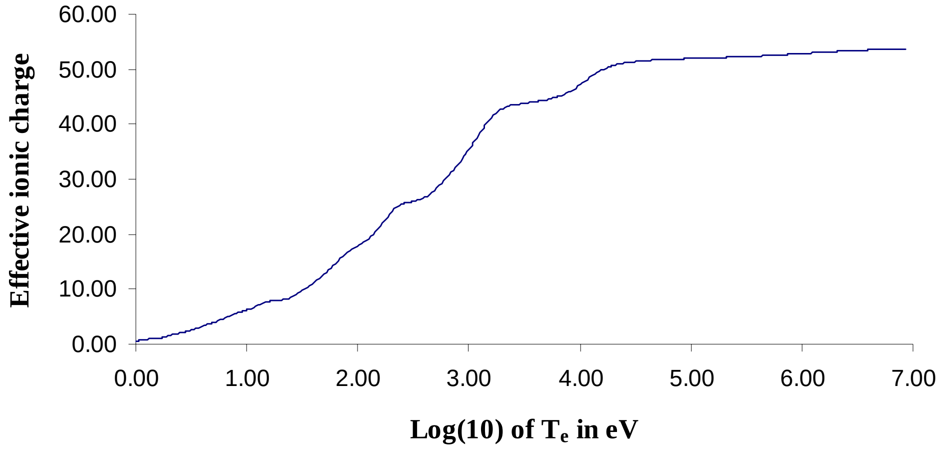

Figure 1b Effective ionic charge Z_{eff} of xenon versus electron temperature T_e based on the Coronal Equilibrium Model.

where N_{z+1} and N_z are the concentration of ions in z+1 at and z ionized state respectively, ζ is the number of electron in the outer shell and χ_z is the ionization potential of zth ion in eV.

The effective ionic charge, Z_{eff} is calculated by $Z_{eff} = N_e / N_i = \sum_{z=0}^{z_n} z \cdot N_z \Big/ \sum_{z=0}^{z_n} N_z$, where the fractional density α_z is defined by $\alpha_z = N_z / N_i$. From the above equations, the relationship between Z_{eff} and T_e, as well as α_z and T_e can be plotted and are shown in Figures 1a and 1b.

For calculating the power of radiation generated in the radiation phase, where the plasma has already compressed and released out radiation through instability process, one can consider the change of energy loss by radiation with time, that can be described as;

$$\frac{dQ_{rad}}{dt} = \int_{V_p} (P_b + P_l + P_r) dV ,$$

where P_b is the power density of Bremsstrahlung given by $1.69 \times 10^{-38} N_e T_e^{1/2} \sum_z N_z z^2$,

P_l is the power density of line radiation given by $3.95 \times 10^{-35} N_e N_i z^4{}_n / T_e$, and P_r is the power density of recombination given by $5.5 \times 10^{-37} N_e T_e^{-1/2} \sum_z N_z z^4$.

The plasma temperature during this phase can be determined by equating the magnetic pressure and the plasma pressure that is given by;

$$T_e = \mu f_c^{\,2} I^2 \big/ (8\pi^2 e (1 + Z_{eff}) N_i r_p^{\,2}) ,$$

which depends on the piston radius during the radiation phase r_p. Physical parameters of a UNU/ICTP plasma focus are shown in Figure 2. The change in piston radius is given as follow;

$$\frac{dr_p}{dt} = \frac{(-r_p / \gamma I) \frac{dI}{dt} - (r_p / (z_f (\gamma + 1))) \frac{dz_f}{dt} + (4\pi(\gamma - 1) r_p / (\mu \gamma z_f f_c^{\,2} I^2)) \frac{dQ}{dt}}{(r - 1)/\gamma} ,$$

where z_f is the length of the radius compression, γ is the specific heat ratio, I is the discharge current and $\frac{dQ}{dt}$ is the difference between the power from Joule's heating and the power of radiation (loss).

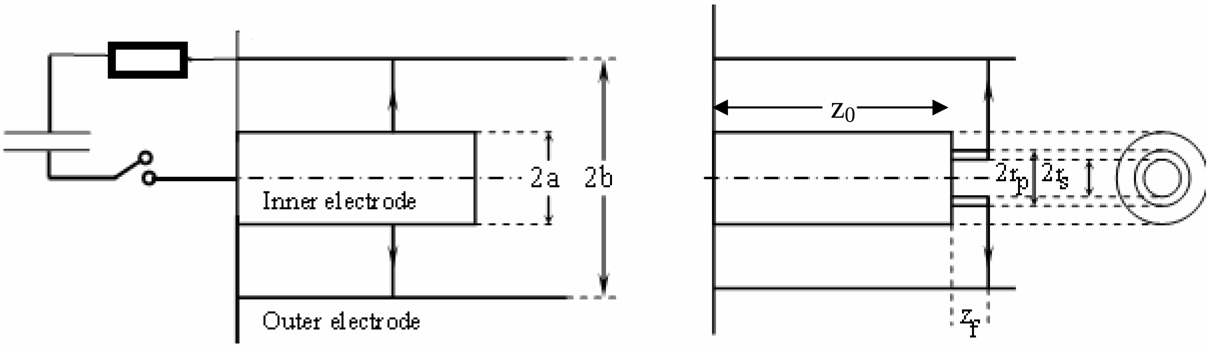

Figure 2 Schematic for a UNU/ICTP plasma focus device.

Based on this radiative computational model which takes into account the movement of the plasma and the electrical discharge of the plasma focus as well as the radiation process, we can investigate the relationship between the plasma temperature and the power of the radiation. As mentioned earlier, the radiation power obtained will be of radiation of all possible wavelengths. Photons with wavelength in the 13-14 nm range may only account for a small fraction of all the photons emitted by the plasma. Nevertheless, bearing in mind the prominent species from the line radiation and the Bremsstrahlung with appropriate plasma temperatures, the EUV radiation will correspond to this radiation power.

3. Experiment

In order to compute for the radiation power of from a plasma focus, we vary the potential between the electrodes of the plasma focus, V, and the length of the anode when operating at pressures between 0.5 mbar and 2.5 mbar by fixing the radial separation, that is shown in Figure 2. The separation between the electrodes at b = 3.2 cm and the cross section of the anode a = 0.95 cm. The potential was varied in a 0.5 kV step as well as the length of the anode by 0.5 cm step for a compilation of resulting radiation power at different operating pressures. These parameters are varied in such steps since they can be easily applied in real operation.

The calculation of the radiation power was carried out with the plasma temperature required for possible EUV radiation, which is around 40 eV. In this work, xenon gas was chosen as the operating gas since in previous work this gas is widely used as a source of EUV radiation by pulse plasma discharge device. The plasma focus device characteristic constants used in the computational model that define UNU/ICTP plasma focus type are 0.08 for mass factor (MASSF) which is the fraction of mass swept down the plasma focus tube in the axial direction, 0.7 for the fraction of the current flowing in the plasma shock piston (CURRF), 0.16 for the radial mass swept up factor (MASSFR). These factors are obtained from fitting the actual current and voltage signals of a UNU/ICTP plasma focus device that has an inductance L_0 = 110 nH, resistance r_0 = 0.012 Ω and the capacitance C_0 = 30 μF with the result from the computation model of the same physical and electrical parameters.

4. Results and Discussion

Figure 3 shows surface plots of radiation power that varies between various operating voltages, which can be calculated as the stored energy input of the device, and the length of the anode. In this case the range of input energy is 135 J to 1,215 J that relates to 3 kV and 9 kV respectively. It can be seen that there is a specific relationship between the input energy and the length of the anode. More input energy is required if the anode is lengthened which, in general, is in a ratio of 4 cm to 3 kV. Also by using higher operating gas pressure, the plots show that more total radiation power can be obtained even though the dynamics of the plasma sheath from the computation shows expected decrease in plasma sheath velocity. At the same length of anode when operating pressure is increased, the input energy must also be increased in order to obtain the targeted plasma temperature. The increase in operating voltage required can be estimated to be 1kV for every 0.5 mbar increase in operating pressure. A pressure of more than 1.5 mbar is required to yield a radiation power of more than 25×10^{10} W as well as 375 J with at least 2 cm long anode.

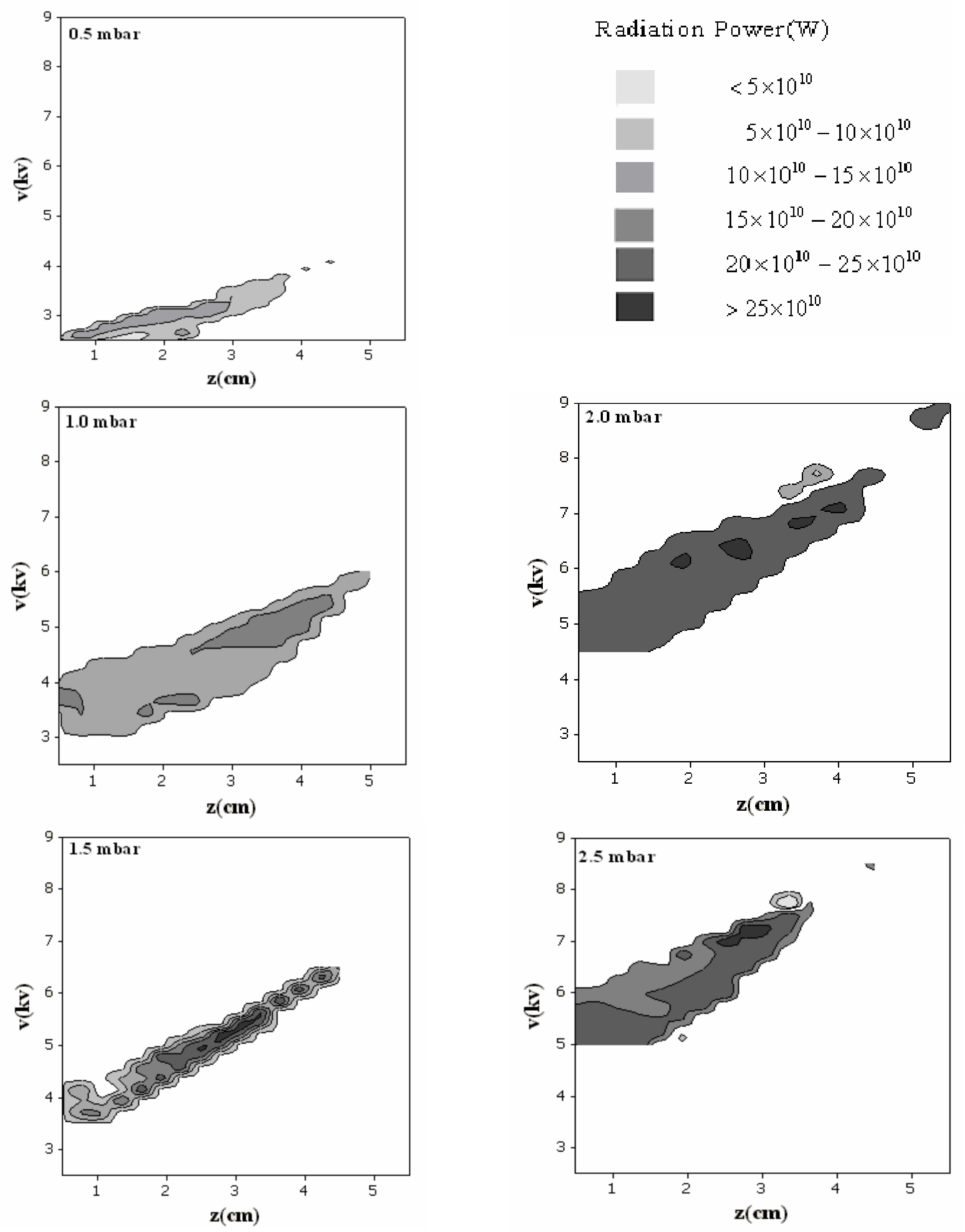

Figure 3 Surface plots showing total radiation power for different operating voltages, V, and lengths of anode, z, under different operating pressures.

By looking closely at the required plasma temperature of around 40 eV, that is possible to produce EUV radiation, combinations of parameters of V and z that allow UNU/ICTP plasma focus to give maximum radiation power, where a majority is expected to be contributed by the line radiation, is shown in Figure 4. The size of the bubble represents the radiation power obtained for each combination of mentioned parameters as well as the operating pressure. It can be seen that 1 mbar operating pressure gives the highest radiation power, which can be as much as 10.4×10^{10} W, when having longer anode of 4 cm and operating with stored input energy of 375 J. Other operating pressures are also possible to produce plasma with the required temperature but with less resulting radiation power. By selecting the length of the anode to be 2 cm, it can be seen from the result that this length can accommodate different operating pressures with their corresponding voltages to yield reasonable radiation power of approximately 7.7×10^{10} W.

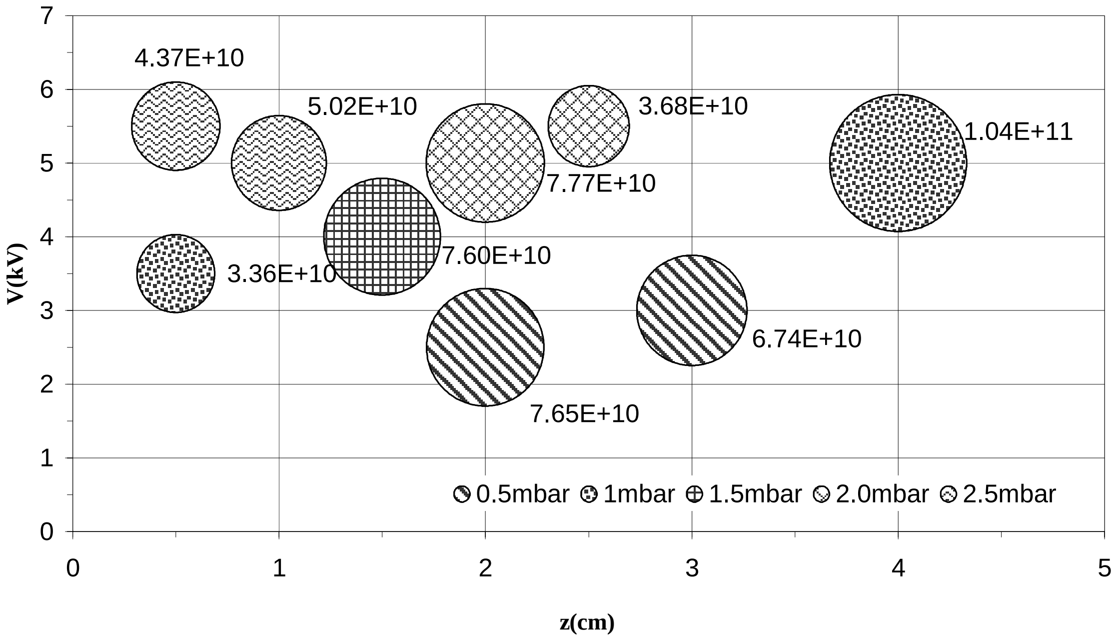

Figure 4 Bubble plot indicating possible combination of voltages, V, and length of the anode, z, at different operating pressures in producing radiation power that correspond to plasma temperature of 40 eV.

5. Conclusion

It has been demonstrated from the theoretical point of view that a UNU/ICTP plasma focus device can produce EUV radiation by its radiation mechanism with suitable operating parameters. From the calculation, it was found that input energy range of 184 J to 454 J under to the operation with xenon gas at pressure of 1 mbar can yield radiation with total power in the range of 6×10^{10} W to 16×10^{10} W which are possible for EUV production according to plasma temperature that the device generates. The optimum operating voltage is found to be 5 kV with the anode length of 4 cm for producing maximum radiation power of 10.4×10^{10} W associated with the required plasma temperature of 40 eV. This shows and confirms the possibility of developing a plasma focus as a powerful EUV radiation source for future semiconductor industry as well as a possibility of physical scaling of the plasma focus in the future. Further work that may be carried out is to experimentally verify this result and varying other parameters for future compact EUV generating plasma focus device. .

6. Acknowledgement

The authors would like to extend our great appreciation to Asian African Association for Plasma Training (AAAPT) for its support to initiate plasma focus research in this laboratory and Prof. S. Lee for his extensive work in the radiative computation model and useful discussion.

7. Reference

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