Compact Plasma Focus EUV Source for Lithography

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Abstract – Compact, small energy plasma focus device (100J) has been developed as EUV radiation source for microlithography and micromachining. The spectrum of radiation in EUV band at 13.5 nm wavelength has been investigated by fast filtered photodiode. Various experimental conditions were employed to get high EUV spectral radiation. The pinch size and duration have been correlated to the duration of the EUV radiation emission at the top of the anode. The radiation emitted by the miniature PF device can be used for contact micromachining, producing structures with high aspect ratio. Due to smaller transference of load in pseudospark switch and between electrodes, the possibilities of small size repetitive plasma source are discussed.

1. Introduction

Modern semiconductor technology is strongly dependent on microlithography which uses optical projection technique, the wavelengths in the visible and UV part of the spectrum, to manufacture high-volume of integrated circuits. It is generally foreseen that around 2009, so-called Next-Generation Lithographies will be required. At this moment Extreme Ultraviolet Lithography (EUVL) is one of the most promising technologies to become the successor to optical lithography. Presently, one of the main obstacles towards the realization of EUV lithography is the lack of an adequate source of EUV radiation. Several source concepts, all based on hot plasmas, are under development. Gas discharge based sources for EUV radiation are expected to offer lower cost of ownership in comparison to synchrotron radiation sources and laser produced plasmas.

To achieve high production throughput at the wavelength 13.5nm, the EUV source or pinch plasma should be almost spherical, having a diameter about 1mm. Bowering *et a.l* [1] have obtained Xenon EUV spectra from 10 J PF device operated at repetition rates of 20 Hz. They calculated that the strongest EUV emission in the 13.5 nm band occurs at the electron temperature of about 30 eV. Stamm [2] reported that the current necessary to generate the plasma temperature of 20 eV in pinch device is to be about 20 kA for EUV lithography. The requirement for EUV production is thus very different as compared to x-ray, electron, ion or neutron production as the temperatures required for those radiations are almost two orders of magnitude higher. Fomenkov *et al.* [3] have chosen a dense plasma focus (PF) configuration for development of discharge-produced plasma (DPP) source targeted for EUV technology using reliable all-solid-state pulsed power drivers and advanced thermal management of water-cooled electrodes. However, for any application of the small PF device, the basic requirements are the same i.e. the device should be reliable with a high repetition rate, portable, long life time and should produce about the similar dose in each run.

In this article, we report about the development of miniature Plasma Focus device of 100J (MPF3) as EUV source for next generation lithography. The size of the device, which includes the capacitor bank, pseudospark gap switch and the focus chamber, is of the order of 22 cm × 22 cm × 38 cm.

2. Experimental arrangements

The optimum size of miniature plasma focus (MPF3) device was obtained by using the various theoretical models and experimental data from several large PF devices [4-6]. Yousefi *et al.* [4] determined the modification factor for the axial velocity for different PF devices and observed that whenever the ratio of insulator length to inner radius cathode (L_{ins}/b) is deviated from the unit value the neutron yield is decreased. Using simple dynamical model, Lee *et al.* [5] related the linear dimensions and time scales of the gross plasma focus pinch to the anode radius 'a' of the plasma focus device. It is known that the plasma energy density (E_d) at the pinch moment is proportional to $E/Vp \sim 28E/a^3$, and its value is of the order of $(1–10)\ \times 10^{10}\ J\ m^{-3}$ [6] for most of the PF devices. This plasma energy density E_d and the drive parameter S $(=1/aP^{1/2})$ can be used to find the anode radius 'a' for a particular device, whereas P is the pressure of the gas. Similarly, to determine the effective anode length, z_a, it is necessary to consider that the peak current must be coincident with the moment of the pinch, and so the $(z_a/v_a) + (a/v_r) = (T/4)$ relation can be used. Considering from other PF devices, $v_a = 1 \times 10^5\ ms^{-1}$, the axial velocity, and $v_r = 2.5 \times 10^5\ ms^{-1}$, the radial velocity of the current sheath and the expected time period of discharge current, $T \sim 1\mu s$ for 100 J machine. Then the effective anode length should be $z_a \sim$ 23 mm. The anode shape is considered as most important factor in order to enhance the radiation yield. It is well known that the pinch lifetime, pinch volume, the plasma energy density parameter E_d $(= 28E/a^3)$ and drive parameter S $(= I/aP^{1/2})$ are all dependent on the anode radius a [5]. The most important factor is the drive parameter S which can be increased by using the composite anode instead of flat cylindrical anode in efforts to increase the neutron, x-rays and EUV radiation yields. Zakaullah *et al.* [7] used three different anode shapes: cone-shaped anode, tapered anode and cylindrical at-end anode to investigate their effects on PF dynamics. They found that an appropriate tapering of the anode end enhanced the emission threefold for both x-rays and ions. Furthermore, the stepped-down composite anode with a step reduction in diameter toward the open end was reported to result in higher speeds of current sheath, which enhanced the temperature of the pinch column [5,8]. The speed is higher as the magnetic field pressure increases with decreasing radius. Similarly, D. Wong *et al.* [8] observed that flat-top hollow anode gives better soft x-rays (SXR) yield than the flat-top solid anode and the hemispherical-top anode with a small hole. On the basis of all these facts, we decided to use tapered flat-top hollow anode, cylindrical stainless steel cathode and Pyrex insulator sleeve in our miniature plasma focus as shown in figure 1 and its dimension is given elsewhere [9].

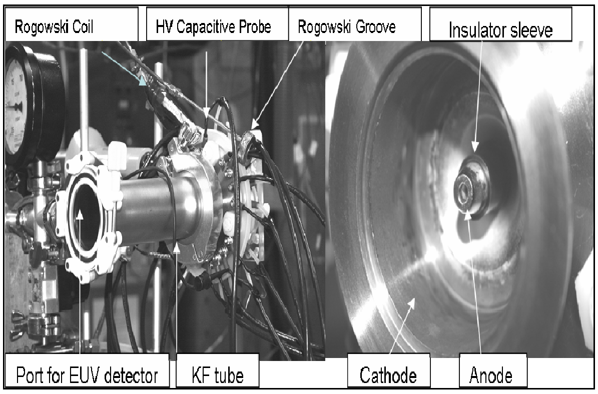

Figure 1: MPF3 electrode system.

The capacitor bank of MPF3 device has four capacitors (0.8 μF, 30 kV each) connected in parallel to obtain final capacitance of 2.4 μF with maximum operational voltage of 30 kV. A single pseudospark switch TDI1-150k/25 of having less than 4 ns jitter time is used in a compact layout which transfers the energy stored in all four capacitors of the capacitor bank to PF electrode system. Sixteen coaxial cables, having a length of 0.5 m, are used to connect the conducting plates from pseudospark switch to the input flanges of the focus assembly. The most important characteristics of the TDI1-150k/25 type of PSSs are their reliability of operation – practically 100%, a jitter time – less than 4ns, the repetitive mode of operation – 100 Hz and can produce commutation currents well above a hundred kiloamperes for more than one million shots The external inductance of the device is measured to be 50 nH. The device is operated with the Xenon gas in the pressure range of 0.1 mbar to 5 mbar. Different charging voltages from 6.5 to 9.1 kV at the rate of 2 Hz are used to operate the device in the range of energies less than 100J.

For the detection of EUV radiation in the range of 11 to 16 nm IRD SXUV-100 photodiodes with integrated thin film filters, Mo/Si/Sic-250/200/50 nm, are placed in front of the anode in the axial direction. The advantages of these integrated detector-filter devices over other separate freestanding thin foil filters and detectors are compactness, higher reliability, ease in handling and more stable bandpass. To detect the EUV radiation from the pinch area, a brass disc is placed in front of the anode having a hole of a diameter ~ 5 mm.

3. Experimental Results

The time profile of voltage and current of the transient plasma producing device gives basic and important information about overall plasma conditions. Like the peak in the voltage signal and the dip in the current signal give the information about the successful pinching during the radial phase. The velocity of the current sheath during the acceleration phase can also be obtained form the voltage signal. Similarly, the short-circuit signal of the current probe can be used to calculate the peak current, inductance and impedance of the device.

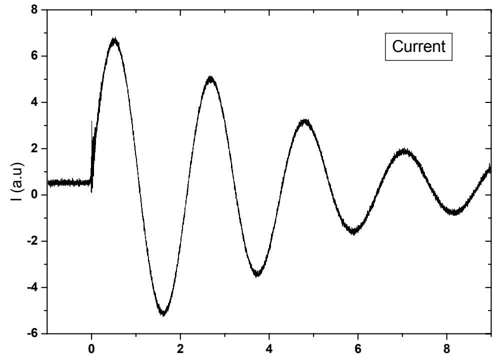

Figure 2: short-circuit discharge current.

We developed a fast current probe–Rogowski groove and a voltage probe–HV capacitive probe to find the characteristics of the device. The schematic of these devices are given in Ref. [9]. The peak current I flowing through the circuit was estimated in short-circuit configuration by using Lee formula [10]:

$$I_0 = \frac{\pi C_0 V_0 (1+f)}{T} \tag{1}$$

Where *f* is the current shedding factor and *T* is the period of ring-down signal. Figure 2 shows such type of signal of having time period T ≈ 2.2 μs, and is giving peak discharge current of 57 kA at 100 J energy of the device.

The typical electrical signals associated with the formation of a pinched plasma column on the axis in the gas Xe are shown in figure 3. The clear evidence of pinching, at gas pressure of 0.5 mbar, can be observed at around 770 ns after the breakdown of the gas. It may be interesting to note that the observed pinch time is 220 ns more than the expected time of pinch i.e. T/4 ~ 550 ns.

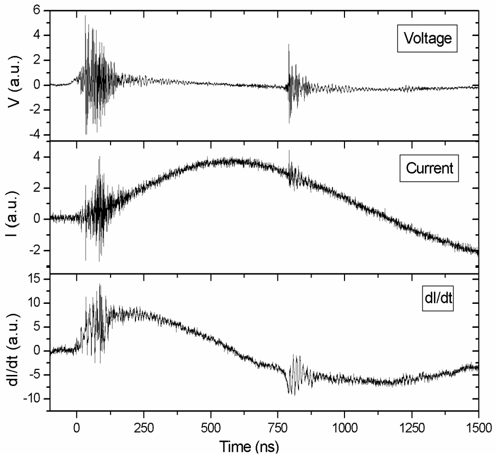

Figure 3: Typical electrical signals at 0.5 mbar gas pressure of Xe.

As described earlier, the IRD SXU-100 photodiode were used to detect the EUV radiation at the wavelength of 13.5 nm. Figure 4 shows the filtered quantum efficiency of the diode.

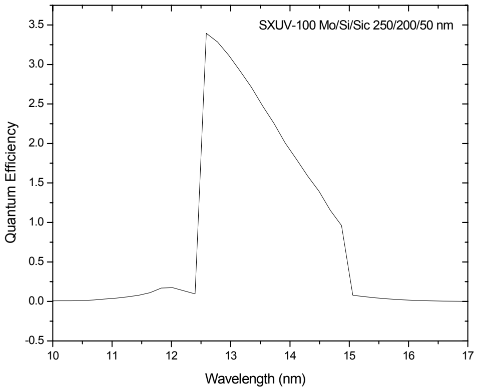

Figure 4: Quantum efficiency of EUV detector.

Time-resolved EUV radiation at different Xe gas pressure is shown in figure 5. At higher pressure multiple peaks are observed. The first peak is likely to follow the current sheath at the top of the anode and corresponds to the start of the radial phase. The second peak coincides with the occurrence of the maximum of the discharge current. The magnitude of this peak increases with the concentration of the gas. The duration of the pinch plasma or plasma existence has been calculated by using the [11]

$$\Delta t \approx \frac{d_{plasma}}{V_{ion}} \tag{2}$$

Where the ion velocity is

$$V_{ion} \cong 1.4\times10^{4}\sqrt{\frac{kT_i}{eV}}\cdot\sqrt{\frac{u}{M}}\ m/s \tag{3}$$

& d $_{plasma}$=plasma shortest extension=2*r$_{plasma}$(for PF) kT$_{ion}$=ion temperature and M=atomic mass of the element. With d$_{plasma}$=1mm, kT$_i$=20 eV and M=131 u for Xenon the typical lifetime of the plasma is estimated to 182 ns which is close to the observed duration. However, at low pressure the concentration of the Xe reduces and subsequently the duration as well as the intensity of the EUV radiation also decreases.

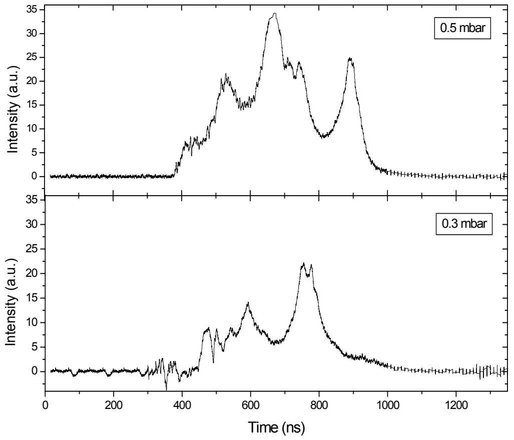

Figure 5: EUV emission in the wavelength range from 11 to 16 nm Vs time at different gas (Xe) pressures.

The third peak in the EUV radiation signals may correspond to the post collapse phase or due to the two successive pinch events occurring both on-axis at different distances in front of the central electrode. At higher pressures the pinch time is better matched to the peak current as well as to the voltage spike, resulting a better energy coupling to the pinch plasma. The change in the peak EUV amplitudes at different pressures and time gives the information about the effects of EUV radiation on the discharged current density and the average gas density within the electrode region.

4. Conclusion

A compact, low energy plasma focus device was constructed and tested for EUV radiation. The discharge current and voltage signals show the pinching phenomena at 100 J in Xe as the filling gas. The discharge current of this miniature PF device is more than the required current necessary to emit the radiation in the range of 13.5 eV. This gives the possibilities to produce intense EUV and other types of radiation for microlithography and spectroscopy. The MPF3 device can be operated in high repetition rate to increase the radiation fluence.

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References

[1] N.Bowering, M.Martins, W.N.Partlo and I.V.Fomenkov, J. Appl. Physics **95,** 16 (2004)

[2] U.Stamm, J. Phys. D: Appl. Phys. **37** 3244 (2004)

[3] I.V.Fomenkov, N.Bowering, C.L.Rettig, S.T. Melnychuk, I.R. Oliver, J.R. Hoffman, O.V. Khodykin, R.M.Ness and W.N.Partlo, Journal of Physics D: Applied Physics, **37,** 3266 (2004).

[4] H.R.Yousefi, G.R.Etaati, M.Ghorannevis 31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28** G, P-5.006 (2004)

[5] S.Lee and A.Serban, IEEE Trans. Plasma Sci. **24,** 1101 (1996)

[6] P.Silva, L.Soto, W.Kies and J.Moreno, Plasma Sources Sci. Technol. **13,** 329 (2004)

[7] M.Zakaullah, I.Ahmad, A.Omar, G.Murtaza and M.M.Beg, Plasma Sources Sci. Technol. **5,** 544 (1996)

[8] D.Wong, A.Patran, T.L. an, R.S.Rawat, and P.Lee, IEEE Tranc. Plasma Sci., **32** (6), 2227 (2004)

[9] S.M.Hassan, T.Zhang, A.Patran, R.S.Rawat, S.V.Springham, T.L.Tan, D.Wong, W.Wang, S.Lee, V.A.Gribkov, S.R.Mohanty and P.Lee, Plasma Sources Sci. Technol. **15,** 1 (2006)

[10] S.Lee, B.C.Tan, C.S.Wong and A.C.Chew, *Laser and Plasma Technology,* Singapore, World Scientific Publishing Co., 1985, pp.16

[11] R.Lebert, K.Bergmann, L.Juschkin, O.Rosier and W.Neff, *Proc. of SPIE* vol. 4343, 2001, pp.215-225