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Energy Coupling Efficiency of Three Plasmas in Capillary Discharge at Different Pressures

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Abstract

Study on coupling source from three plasmas in capillary discharge opens up an alternative way for large-scale industrial production of extreme ultraviolet lithography. Based on the coupling mechanism of three plasmas in capillary tube, partial coupling parameters are calculated. It is found from experimental results that the average optical power of the coupling source is increased by ~1.2 times, and up to 1.7 times compared to that of the uncoupling source when the working pressure of N_2 is initially set at 30 Pa, this results in an average magnification factor of ~3.6 with the maximum of 5.1 and an average energy coupling efficiency of ~18% with the maximum of 41%. Further more, when the working pressure is adjusted at 90 Pa, the average optical power, magnification factor and energy coupling efficiency of the coupling source are improved by ~1.4 times, ~4.2 and ~28% respectively, corresponding to their maximums of 2.1 times, 6.3 and 52%. A higher working pressure (no more than the optimal breakdown pressure of N_2) produces a higher energy coupling efficiency, and this comes from the fact that more particles can absorb the energy of laser pulse in the coupling zone to intensify the ability of "expansion outward" at the higher pressure so that the annulus emitting plasma is expanded. In a word, the extreme ultraviolet coupling source from three plasmas in capillary discharge has been realized for the first time, and raising the working pressure is beneficial for the energy coupling efficiency.

Keywords

Plasma Sources; Z-pinches; Three Plasmas; Capillary Discharge.

1. Introduction

Extreme ultraviolet (EUV) ray with wavelength of 13.5 nm not only provides a minimum resolvable line width (LW) below the technological node of 10 nm for extreme ultraviolet lithography (EUVL), but also supplies a sufficient depth of focus (DoF)[1]. Moreover, the reflective reduction mask method is usually used in EUVL because a Mo-Si multilayer mirror has reflectivity of 30%~70% in band of 10~16 nm, especially around 13.5 nm (2% bandwidth of Ru-like Xe^{10+} system) up to 65%[2], so that it is recognized as the most suitable exposure source[3] and has already been employed in the industrial production of EUVL. Generally speaking, EUV source originates from the synchrotron radiation, laser produced plasma (LPP)[4,5], discharge produced plasma (DPP)[6] and laser assisted discharge plasma (LDP)[7]. The synchrotron radiation source has such disadvantageous features as the high cost of building and maintenance, complex configuration, hard operation, and inconvenient electron injection that it is difficult to be adapted to large-scale industrial production; The LPP source converts electric power into laser energy and then into plasma emission energy, which decreases the energy conversion efficiency. More importantly, the elements, e.g. the adjustment of laser parameters, controlling of shooting debris, stability of plasma emission state and etc., make it impossible to be utilized directly in EUVL production. In practical applications, more common way includes the DPP

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and LDP source, the former typically makes use of Xe gas while the later tends to be Sn target. The DPP source produces high-temperature and high-density plasma by gas discharging, and the electric power is directly translated into the plasma emission energy, giving a higher energy conversion efficiency. The LDP source transforms a Sn target into either liquid or gas state by laser pulse at first, and then into the discharged plasma, but it is worth noting that a large number of shooting debris, discharge debris and source impurities are accompanied during operation. Capillary discharge belongs to one of four types of gas discharge (hollow cathode plasma, plasma focusing, capillary discharge and Z-pinch)[8] which behaves some extraordinary characteristics such as small size, low cost, simple configuration, convenient operation, controllable discharge parameters, large energy conversion efficiency and etc., and this endows the plasma with good features of symmetry, axial homogeneity, stability and so on. Hence it is a good choice for EUVL source by generating high-temperature and high-density Xe plasma in capillary discharge.

The problems of emission power, collection efficiency, vacuum controlling, parameter adjustment, source impurities and spectral optimization have to be taken into consideration in application of the plasma sources. At present, the emission power of 13.5 nm per single operation of EUV source in the industrial production of EUVL is so weak that the repetition rate of shooting target or discharging has to be increased substantially to hundreds of even thousands of Hz as a simple and direct way so as to meet the threshold power for production. Unfortunately, the high repetition rate of operation releases a large amount of shooting debris or discharge debris on the one hand and on the other hand adds extra heat to the working system. Moreover, some debris can penetrate into the plasma to form source impurities. As all debris and impurities can absorb the photon of 13.5 nm and then emit photons of other wavelength, amplifying the “light noise” of EUV source. In brief, these factors not only seriously cut down the power of 13.5 nm, but also add difficulty to heat dissipation. In order to solve the problems, our research group intends to explore an EUV coupling source from three plasmas in capillary discharge based on the emission power of 13.5 nm[9-11] and to reduce the exposure times or the exposure period, and finally to improve the labor productivity & qualified product in EUVL production.

2. Coupling Mechanism of Three Plasmas in Capillary Discharge

2.1 Parallel Model of Three Plasmas

The parallel model of three plasmas in capillary discharge is shown in Fig. 1. Three high-voltage electrodes (with a gap of 6.8 mm between them) and three grounding electrodes (with a gap of 6.8 mm between them) are installed correspondingly and symmetrically around the capillary axis at the right and left end of capillary tube respectively with a discharging distance of 20 mm. When concurrently discharging between the high-voltage electrodes and the grounding electrodes in capillary tube filled with N_2 at an appropriate pressure, three parallel plasmas are emerged. In fact, three plasmas receive Lorentz force from the magnetic field themselves to produce the self Z-pinch effect, meanwhile they are also subjected to Lorentz force from the external magnetic field to generate the mutual pinch effect. For purpose of coupling, the laser beam is incident along the capillary axis from one end of the high-voltage electrode to center of three plasmas.

The configuration of three plasmas exhibits that they are close in the middle of capillary tube while slightly far away near two ends due to the mutual pinch effect. From the capillary parameters above, it can be calculated that the gap between any of three plasmas and the capillary axis is ~3.93 mm. In this circumstance, the plasma receives less Lorentz force from two other plasmas so that the mutual pinch effect seems negligible. Even though three plasmas in the middle of capillary tube approach to each other due to the mutual pinch effect by Lorentz force, the gap between any of them and the capillary axis still exceeds 3 mm so that they only have the self Z-pinch effect other than the mutual pinch effect because of the very weak Lorentz force from each other, not enough to make them merged, and there appears a vacuum zone along the capillary axis where the laser pulse passes through

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and has no chance to contact with three plasmas. It is clear to see that the parallel configuration of three plasmas can not form a coupling source.

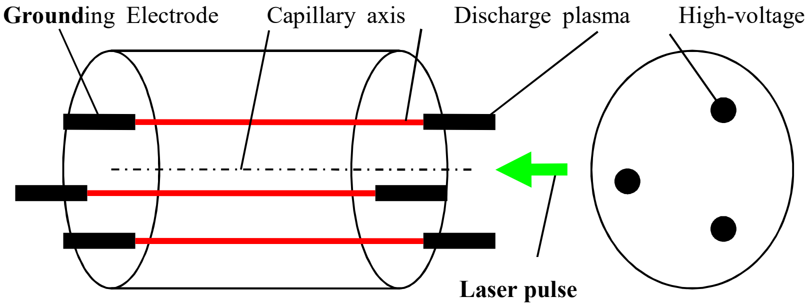

Figure 1. Parallel model of three plasmas

2.2 Gradient Model of Three Plasmas

The gradient model of three plasmas in capillary discharge as shown in Fig. 2 consists of three high-voltage electrodes (with a gap of 6.8 mm between them) and three grounding electrodes (with a gap of 0.5 mm between them), they are installed correspondingly and symmetrically around the capillary axis at the up and down end of capillary tube respectively with a discharging distance of 30 mm. under the condition of concurrently discharging from the high-voltage electrodes to the grounding electrodes in capillary tube, the working gas is broken down to yield three plasmas. Although the self Z-pinch effect and mutual pinch effect still exist, the reduction of the gap between the grounding electrodes creates a small angle between three plasmas and the capillary axis which is roughly cone-shaped distribution. Observing from the cone mouth to the cone top along the capillary axis, the mutual pinch effect of three plasmas at different section areas becomes larger and larger. Three plasmas near the cone mouth scatter more so that the mutual pinch effect is unobvious due to the weak Lorentz force, and moving gradually towards the cone top, the mutual pinch effect of three plasmas begins to strengthen, and up to the maximum when the gap between three plasmas become very small. Thanks to the mutual pinch effect by Lorentz force, three plasmas are merged into a whole annulus, and finally the gradient distribution of plasma density is formed. In fact, the current intensity passing through any section area of three plasmas is the same, but the section area of three plasmas decreases gradually from the cone mouth to the cone top so that the current density also displays a gradient distribution. As mentioned above, three plasmas can be coupled into a EUV source with suitable temperature and density by aid of the laser pulse. When the laser pulse enters into the coupling zone near the cone top, the formed LPP expands outward and squeezes the mutual pinch plasma, and an annulus coupling source is formed at last in section area (e), emitting intense EUV ray.

Three plasmas depend on concurrently discharging of three pairs of electrode to form a closed circuit. As a good conductor of electricity, the current mainly flows along the plasma surface owing to the skin effect, and three plasmas begin to self Z-pinch under the Lorentz force themselves meanwhile to mutually pinch under the weak Lorentz force from each other at section area (a) in Fig. 2. If three plasmas are far apart, the mutual pinch effect can be ignored. At section area (b), on the basis of the mutual pinch effect, three plasmas gradually approximate to the capillary axis, this makes the current density flowing through the plasma surface redistributed, showing a denser outside surface and sparser inside surface plasma current density. Since the outside surface is strongly pinched while the inside surface is weakly pinched, the plasma slowly changes its shape. At section area (c), the outside edges of three plasmas contact with each other, and their deformation increases continuously in the pinch process to merge into a whole annulus which permits the current mainly passing through the outside envelope surface other than the inside surface. At section area (d), three plasmas merge into a whole annulus. In the mutual pinch process, the uneven envelope current causes the protruding part above the outside surface of the plasma to pinch violently due to the concentrated distribution of current density while the flat part to pinch weakly, this brings about a smooth envelope surface. In essence, the inside surface is no longer pinched because of the absence of current distribution to form a hollow cavity. When the laser pulse propagating along the capillary axis from the cone mouth to the cone top sets up a LPP by ablating the protruding part to expand outward and extrude the discharge plasmas, its inside surface gradually becomes smooth. At section area (e), three plasmas perform a strong mutual pinch effect and merge into a whole annulus because of expansion and extrusion of the LPP. Under the action of "pinching inward and expansion outward", both the temperature and density of three plasmas increase, when the annulus plasma reaches the required high-temperature and high-density state, it emits intense EUV ray. From section areas (a)~(e) in Fig. 2, it can be seen that the gradient distribution of plasma density and current density is formed along the capillary axis, and it is impossible to make three plasmas coupled without the assistance of LPP. Therefore, the gradient model is not a hollow cavity, but a sandwich structure.

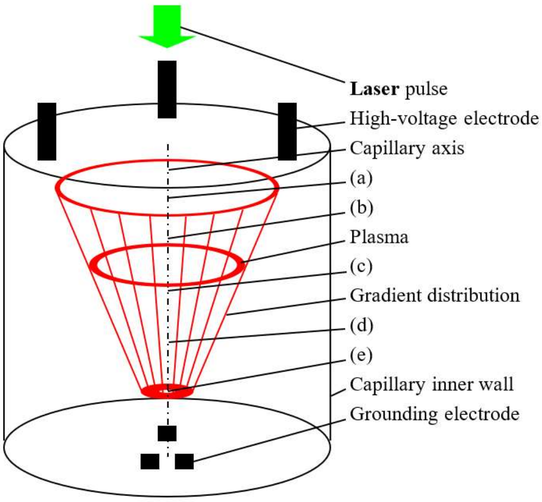

Figure 2. Gradient model of three plasmas

3. Coupling Parameters of Three Plasmas in Capillary Discharge

The force received by three plasmas in capillary tube is relatively simple, they are self Z-pinched by Lorentz force of the magnetic field from their own plasma current on the one hand, and on the other hand they are mutually pinched by Lorentz force of the magnetic field from other plasma currents. In the parallel model, three plasmas are almost parallel to the capillary axis, as like the current direction, but the circular magnetic field excited by the plasma current is perpendicular to the capillary axis which makes Lorentz force received by three plasmas perpendicular to and pointing to the capillary axis. Under the action of Lorentz force, three plasmas accelerate to move towards the capillary axis, the closer to the capillary axis, the larger the acceleration and velocity of three plasmas are. If there is no external intervention, three plasmas will eventually be pinched together. In reality, if the spacing between three plasmas becomes so larger that they only have the self Z-pinch effect due to very weak Lorentz force from each other, and the laser pulse can easily pass through them; If the spacing between three plasmas is small enough, the self Z-pinch and mutual pinch effect become strong, three plasmas are pinched into a whole piece before the laser pulse arrives, and finally the laser pulse cannot enter the coupling zone among three plasmas. In these two circumstances, the laser pulse is unable to play the role of "expansion outward". In the gradient model, there appears a small angle between three plasmas and the capillary axis, so does the plasma current, keeping the same small angle with the capillary axis. In this case, the plasma current should be decomposed into one component along the capillary axis and another perpendicular to the capillary axis, the former provides Lorentz force similar to the parallel model while the latter can not supply Lorentz force. Although the Lorentz force is weakened by the small angle, viewing along the capillary axis from the cone mouth to the cone top, three plasmas approximate closer to the capillary axis, both the density and current density of the

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plasma become larger and larger, and ultimately the gradient distribution of Lorentz force received by the plasma, density and current density of the plasma is good for timely and appropriately utilization of laser pulse. Therefore, it can be seen that the coupling of three plasmas only occurs near a certain section area perpendicular to the capillary axis other than any section area, so it is necessary to choose the feasible coupling location in accordance with the optimal coupled plasma state emitting photons at 13.5 nm.

On the basis of configuration and discharge parameters, force analysis of three plasmas, optimal state of the plasma emitting at 13.5 nm and so on, partial parameters of the coupled plasma are calculated. The result reflects that the magnification factor of three plasmas is $4.5 \leq n \leq 25$, but the experimental data may be far below that if both the optical shielding and the spectral absorption are taken into account. However, in actual applications, the collection efficiency of a EUVL source in capillary discharge is still lower because not all the photons towards every direction can be collected so that the measured value is not big yet. Since we mainly investigate the coupling emission of three plasmas with assistance of LPP other than the uncoupling emission, the measured magnification factor is lower than the theoretical value despite of the fact that the factors such as the optical shielding, spectral absorption, collection efficiency and etc. have no impact on relative measurement. As for how much below the theoretical value, it still needs waiting for practical verification.

4. Energy Coupling Efficiency of Three Plasmas in Capillary Discharge at Different Pressures

The experimental principle of EUVL source from three plasmas in capillary discharge is shown in Fig. 3, the laser pulse enters into the discharge chamber through window 1 and then is detected by a laser energy meter behind window 3, and the emission of three plasmas is checked by a photo detector following window 4. The pressure of N_2 in the discharge chamber is firstly set at 30 Pa, the average value by the photo detector is ~45.57 pA under the condition of discharging; and then triggering laser and discharge synchronously, the average (maximum) value is ~55.61 pA (77.54 pA) and is increased by ~1.2 (1.7) times compared to ~45.57 pA, this indicates that three plasmas have been coupled with the help of LPP, and the average (maximum) magnification factor is ~3.6 (5.1) corresponding to the average (maximum) energy coupling efficiency of ~18% (41%).

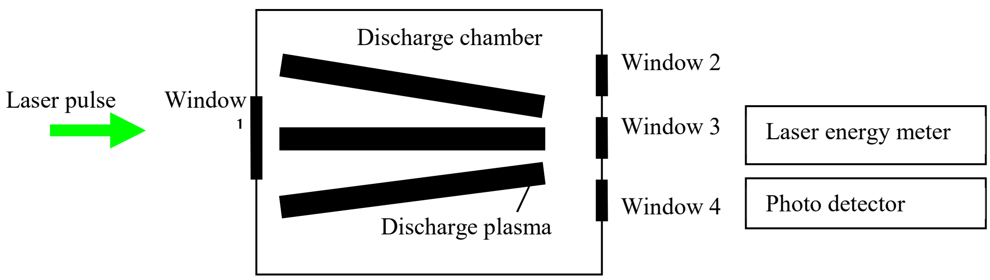

Figure 3. Experimental principle of EUVL source from three plasmas in capillary discharge

Raising working pressure to 90 Pa, the average value by the laser energy meter is ~0.25 mJ when the laser is triggered, but it changes to ~0.13 mJ if the laser and discharge are synchronously triggered and the average (maximum) value by the photo detector is ~78.05 pA (117.2 pA), while the average value by the photo detector is ~55.59 pA just by discharging. In terms of the average value by the laser energy meter, the laser energy of ~0.12 mJ has been involved in coupling process. Therefore, the average (maximum) value by the photo detector is increased by ~1.4 (2.1) times and the average (maximum) magnification factor is ~4.2 (6.3), leading to the average (maximum) energy coupling efficiency of ~28% (52%). Although the magnification factor is still small, the fact that it enters into the range of $4.5 \leq n \leq 25$ has proved that three plasmas have been coupled in capillary discharge.

After discharging, the residual plasma is promptly struck by the laser pulse, we can clearly hear the striking sound and the average value by the photo detector is ~44.37 pA. If the discharged plasma waits for a long time and after composition, the striking sound disappears completely and the photo detector has no response even if the laser pulse is harnessed. From interaction between the laser pulse and the plasma residue, it can be speculated that the laser pulse can also interact with three plasmas, which indirectly confirms the coupling facts.

Under the same experimental environment, when the working pressure rises from 30 Pa to 90 Pa, increase of the particle number density leads to improvement of the emitting ions density, and the optical power by the photo detector at 90 Pa is larger than that at 30 Pa whether with the laser or not. The reason originates from the fact that more particles enter into the coupling zone of three plasmas when the working pressure goes up (no more than the optimal breakdown pressure of N2) and absorb the laser energy to enhance the ability of “expansion outward”, and this yields an enlarged coupling zone and an improved energy coupling efficiency. Since both 30 Pa and 90 Pa are less than the optimal breakdown pressure of N2, increasing pressure means the boost of energy coupling efficiency. However, this is no longer true beyond the optimal breakdown pressure of N2, since the coupling zone of three plasmas is filled with high-density particles so that the laser pulse has been blocked and is difficult to enter into the coupling zone which can not play the role of "expansion outward". The specific data needs to be tested in depth, but the results obtained from above two pressures are still reliable.

5. Conclusion

The coupling parameters of EUVL source from three plasmas in capillary discharge are calculated and the experimental investigations are carried out on the corresponding setup. The results suggest that the average (maximum) optical power of the coupling plasmas is increased by ~1.2 (1.7) times at N2 pressure of 30 Pa compared with the uncoupling plasmas, and the average (maximum) magnification factor is ~3.6 (5.1) corresponding to the average (maximum) energy coupling efficiency of ~18% (41%). When the working pressure is adjusted to 90 Pa, the average (maximum) optical power is increased by ~1.4 (2.1) times and the average (maximum) magnification factor is ~4.2 (6.3) corresponding to the average (maximum) energy coupling efficiency of ~28% (52%). The energy coupling efficiency becomes larger and larger with growth of the working pressure, but no more than the optimal breakdown pressure of N2.

Acknowledgments

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