Spectral purification and infrared light recycling in extreme ultraviolet lithography sources

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Abstract: We present the design of a novel collector mirror for laser produced plasma (LPP) light sources to be used in extreme ultraviolet (EUV) lithography. The design prevents undesired infrared (IR) drive laser light, reflected from the plasma, from reaching the exit of the light source. This results in a strong purification of the EUV light, while the reflected IR light becomes refocused into the plasma for enhancing the IR-to-EUV conversion. The dual advantage of EUV purification and conversion enhancement is achieved by incorporating an IR Fresnel zone plate pattern into the EUV reflective multilayer coating of the collector mirror.

Calculations using Fresnel-Kirchhoff’s diffraction theory for a typical collector design show that the IR light at the EUV exit is suppressed by four orders of magnitude. Simultaneously, 37% of the reflected IR light is refocused back the plasma.

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1. Introduction

Electronic devices are becoming more powerful and more energy efficient, the key to this progress being the ongoing miniaturization in the semiconductor industry. Integrated circuits (IC) fabricated with current lithography, using ultraviolet (UV) light at 193 nm wavelength, can have feature sizes as small as 32 nm [1]. On the other hand, this lithography technique is close to the physical limit to fabricate even smaller IC features. This is why the semiconductor industry is aiming to introduce extreme ultraviolet (EUV) lithography at a wavelength of 13.5 nm. Due to the extremely short wavelength it is possible to fabricate sub-22 nm features [1,2]. Consequently, the development of according EUV light sources with high power and clean, in-band radiation output [3,4] is one of the major challenges.

The currently most promising approaches for generating EUV radiation in the named range are based on discharge produced plasmas [1,3,4] and laser produced plasmas (LPP) [1,3–5]. The latter method is scalable to higher output powers and is therefore of interest for high volume production [6–9] in a lithographic tool. Figure 1(a) shows the standard schematic setup of an LPP source for generating EUV radiation at 13.5 nm wavelength with a hot tin (Sn) plasma. High-power, short laser pulses from an IR drive laser are focused to small tin droplets. The drive laser is typically a CO$_2$ laser with an IR wavelength of 10.6 μm and pulse duration around 100 ns [4]. The laser vaporizes and ionizes the tin to obtain a hot plasma which emits strong EUV radiation. In order to collect a maximum amount of the EUV radiation, a large-angle ellipsoidal mirror with a highly EUV reflective Mo/Si multilayer coating [3,4] is employed. The curvature and positioning of this so-called collector mirror is chosen to have its first focus located in the plasma. This setting directs the EUV into the secondary focus of the ellipsoid. In the secondary focus an aperture matching the size of the EUV beam forms the exit of the source towards the lithography optical system.

This standard collector approach can collect substantial EUV powers [3,4], however there are two clear disadvantages. These occur because the plasma reflects a considerable part of the incident drive laser. The first problem is that this reflected drive laser light is lost for the plasma heating process. The second problem is that the reflected drive laser radiation is directed into the most undesired location, the intermediate focus, from where it can exit close to the physical limit to fabricate even smaller IC features. This is why the lithography technique is close to the physical limit to fabricate even smaller IC features. This is why the semiconductor industry is aiming to introduce extreme ultraviolet (EUV) lithography at a wavelength of 13.5 nm. Due to the extremely short wavelength it is possible to fabricate sub-22 nm features [1,2]. Consequently, the development of according EUV light sources with high power and clean, in-band radiation output [3,4] is one of the major challenges.

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together with EUV radiation. This is highly undesired because the high power of the IR radiation causes heating of the photoresist materials used in lithography process.

Potential approaches for suppressing the IR radiation have been suggested, such as membrane [10,11] and gaseous filters [12]. However, these techniques may cause thermally induced optical distortions. Solutions based on interference techniques have been proposed as well [13–19] but these schemes do not recycle any reflected IR light. A recycling of the lost radiation has not been addressed so far.

Here we propose a new method that solves both problems simultaneously, via incorporating a Fresnel zone plate in the form of a diffractive pattern in the surface of the EUV reflective collector. The zone plate removes undesired IR light from the EUV exit of the source and diverts the removed IR light back into the plasma for further heating and increasing the IR-to-EUV conversion efficiency. In Fig. 1(b) we compare the IR and EUV beam paths obtained with the zone plate assisted collector to the standard situation shown in Fig. 1(a). It can be seen in Fig. 1(b) that the EUV radiation (shown in light blue) follows a completely different path than the IR light reflected by the plasma (shown as dark red stripes). Specifically, only the EUV radiation purified from the IR radiation leaves the exit while the reflected IR light is refocused into the plasma.

![Fig. 1. Schematic drawing of (a) a typical EUV source based on laser produce plasma (LPP). The reflected IR and generated EUV light both follow the same path through the exit (red-blue area). (b) The same source using a Fresnel zone plate on the collector mirror. Only the EUV passes through the exit aperture (blue), while reflected IR (red) is refocused into the plasma.](image)

**2. Calculation of Fresnel zone pattern**

In this section we present the physical action of our approach in more detail. The goal is to calculate the dimensions of a Fresnel pattern as required for refocusing the IR light reflected from the plasma back into the plasma. For the calculations we refer to Fig. 2 which shows the cross-section of an ellipsoidal collector, the surface of which is carrying a binary Fresnel zone pattern. The pattern is made of Fresnel zones of width \( w_n \), extending from a radius \( r_{n-1} \) to \( r_n \) \(( w_n = r_n - r_{n-1}) \). As we are considering a reflective Fresnel zone pattern, we chose the depth of the Fresnel zones as \( h = \lambda/4 \) to maximize the interference contrast where \( \lambda \) is the IR wavelength. The collector is positioned to overlap its first focus at point \( F \) with the plasma. In ordinary collectors without a Fresnel pattern, all the light from the plasma (both the reflected IR and generated EUV) is directed by the ellipsoidal surface to the intermediate focus. In contrast, when the collector is structured with a Fresnel zone pattern, the reflected IR light can be refocused into the plasma. For the determination of the required Fresnel zone dimensions we approximate the drive laser light reflected from the plasma as a point source located at point \( F \). In this case, refocusing of the radiation back to \( F \) is achieved when there is constructive interference of light from all Fresnel zones [20]. In Fig. 2 this corresponds to...
constructive interference of the on-axis path $\overline{FAF}$ with the off-axis paths $\overline{FBF}$, which can be written as:

$$2\left(\sqrt{d_n^2 + r_n^2}\right) - 2d_0 = n \lambda/2$$

(1)

where $d_n$ is the longitudinal and $r_n$ is the radial distance of point $B$ from point $F$, $d_0$ is the longitudinal distance between the center of the collector (point $A$) and the first focus (point $F$), $n = 1, 2, 3, \ldots$ is an integer representing the numbering of the Fresnel zones. Knowing that point $A$ lies on the elliptic contour of the mirror, as taken in this example, the distance $d_0$ can be written as $d_0 = a - \sqrt{a^2 - b^2}$ where $a$ and $b$ are the major and minor axes of the elliptical mirror contour, respectively. Inserting $d_0$ into Eq. (1) yields:

$$2\left(\sqrt{d_n^2 + r_n^2}\right) - 2\left(a - \sqrt{a^2 - b^2}\right) = n \lambda/2$$

(2)

Also point $B$ lies on the elliptical contour, therefore $d_n$ and $r_n$ in the Eq. (2) are mutually related via the equation for an ellipse:

$$\left(\frac{d_n + \sqrt{a^2 - b^2}}{a}\right)^2 + \left(\frac{r_n}{b}\right)^2 = 1$$

(3)

Inserting Eq. (3) into Eq. (2) and solving for $r_n$ yields the widths and radii of the Fresnel zone pattern required for refocusing:

$$w_n = r_n - r_{n-1} \quad \text{with} \quad r_n = b \sqrt{\frac{b^2 + t^2 - 2at}{a^2 - b^2}}$$

(4)

where $t = n \lambda/4 + a - \sqrt{a^2 - b^2}$.

Fig. 2. Fresnel zone pattern at the surface of an ellipsoidal collector with focus point $F$.

To this end we point to an important property of the Fresnel pattern determined by Eq. (4). If we insert for $\lambda$ the relatively long wavelength of the IR drive laser, typically 10.6 $\mu$m, the width of the Fresnel zones turn out to be several orders of magnitude larger than the Fresnel zone width required to focus the EUV light to the same point. As a result, diffractive focusing power of the Fresnel pattern for the EUV is several orders of magnitude weaker than for the IR. Therefore the change of the EUV spot size in the exit plane caused by the Fresnel pattern can be neglected compared to the original EUV spot size. We note that close to the edges of
the Fresnel zones the multilayer period may deviate from its intended value, which would cause some EUV loss. However, it shows that the surface fraction of these edges and therefore also the according loss is very small, in the range of 1% [21]. Improved deposition techniques are available that further reduce this fraction [22].

3. Numerical results

Now that the required dimensions of the Fresnel zones can be determined with Eq. (4), we turn to the quantification of purification and refocusing by calculating the transverse intensity distributions in the plasma plane and the exit plane. In order to obtain results that are relevant for applications, we do the calculations with typical parameters of current sources. Such sources often incorporate CO$_2$ lasers at 10.6 μm wavelength as drive lasers and a typical collector that have opening angles between 1.6 and 5 sr, and with collector diameters between 300 and 600 mm, respectively [23]. These numbers correspond to major and minor axes lengths, $a$ and $b$, of 1000 and 600 mm, respectively. From these numbers, the collector distance $d_0$ in Fig. 2 can be calculated as $d_0 = 200$ mm.

In the next step, we use the Fresnel-Kirchhoff diffraction theory [20] to calculate the intensity in the plasma plane and the exit plane. We use the parameters as given above and apply the point source approximation again. The latter is justified if the diameter of the source (i.e. the plasma diameter) can be neglected with regard to the distance to the collector. The plasma diameter in current sources (full width at half maximum, FWHM) lies in the range of 100 to 300 μm [4–10] which can be safely neglected with respect to the collector distance.

The calculation of the intensity distribution using the Fresnel-Kirchhoff diffraction theory is a computationally rather involved procedure, therefore we restrict ourselves to a maximum number of 200 Fresnel zones which corresponds to maximum patterned area of 44 mm diameter. This is much smaller than the typical 300 to 600 mm diameter used in a real source setup. If we would calculate the Fresnel-Kirchhoff diffraction for a fully patterned typical collector, the purified and refocused power would be higher due to the larger area. Also the focusing diameter would be smaller which is a well-known property of Fresnel zone plates [20]. This means that our limit of 44 mm yields a conservative calculation of the purification and recycling factors.

In Fig. 3 we present the calculated diameter (FWHM) of the intensity distribution generated by the Fresnel zone patterned collector in the plane of the plasma. In the calculations we have considered that the collector mirror is equipped with an opening for letting the drive laser beam enter. For simplicity we choose an opening with a diameter of 1.5 mm which is equal to the diameter of the first Fresnel zone. It can be seen in Fig. 3 that, indeed, the diameter of the IR focus decreases steadily with an increasing number of Fresnel zones included in the calculations. This decrease is of interest because it indicates how many Fresnel zones are required in order to obtain a focus smaller than the plasma diameter such that essentially all refocused light becomes recycled to the plasma for additional heating. For example, the diameter of the Fresnel focus becomes smaller than the plasma diameters of 300 μm and 100 μm if more than approximately 10 and 130 Fresnel zones are used respectively. In the rest of the intensity calculations we restrict ourselves to 130 Fresnel zones which correspond to 35 mm collector diameter.

Figure 4 shows the calculated transverse IR intensity distribution in the plasma plane. The two upper graphs compare the intensity distributions generated with (a) the zone plate assisted collector to the intensity with (b) a standard ellipsoidal collector without a Fresnel zone pattern. The two lower graphs show the corresponding cross-sections of the intensity distributions on a logarithmic scale. Comparing the Fig. 4(a) and Fig. 4(b) it can be seen that the IR laser intensity at the plasma location is enhanced by four orders of magnitude when the collector is patterned with Fresnel zones. Of more relevance is the fraction of the reflected IR light that is refocused to the plasma. To determine this fraction we take the ratio of the total power contained in Fig. 4(b) to the total power contained in a circle matching the plasma size for the intensity distribution in Fig. 4(a). We find a recycling factor of 37% and 31% for plasma diameters of 300 μm and 100 μm, respectively which compares well with the focusing...
efficiency of binary Fresnel zone plates. This suggests that the recycling factor can be further increased such as using a multilevel Fresnel zone plate [24].

Fig. 3. Decrease of the focus diameter (FWHM) generated by the Fresnel zone pattern in the plasma plane versus the number of contributing Fresnel zones. Currently used plasma sources have a diameter between 300 and 100 μm which is indicated by the light and dark shaded areas.

In the second step, in order to determine the intensity distribution in the exit plane, we repeat the Fresnel-Kirchhoff calculation for that plane. The calculated distributions are shown in Fig. 5 where (a) corresponds to the zone plate assisted collector whereas (b) corresponds to the standard collector with cross sections in logarithmic scale in the lower row. It can be seen that there is only very low IR intensity in the EUV exit plane. When looking at the centre of the distributions we find a four-orders-of-magnitude lower intensity.

In order to address to the intensity distribution a purification factor we select a relevant diameter for the exit aperture matching the image of the plasma. The diameter of the plasma
image can be determined by the collector magnification, $M$, and the diameter of the plasma. The collector magnification is given by $M = \frac{2a - d_o}{d_o}$. In our case we have $M = 9$ which means that the diameter of the plasma image is between 900 and 2700 μm. When an exit aperture of the image size is chosen we obtain an IR purification between $1.9 \times 10^4$ and $0.41 \times 10^4$ for plasma diameters between 100 and 300 μm, respectively.

![Intensity distribution at the intermediate focal plane of the collector](image)

**Fig. 5.** Intensity distribution at the intermediate focal plane of the collector which is also the exit of the source (a) with and (b) without the Fresnel zone plate on the collector. Exit apertures with 900 μm diameter are shown in the zoomed insets.

**4. Conclusion**

We present a novel collector design for EUV light sources using a laser produced plasma. The novel collector is based on a binary Fresnel zone pattern incorporated into the surface of a standard ellipsoidal collector. The design prevents undesired IR drive laser light, reflected from the plasma, from reaching to the exit of the light source. This results in a strong purification of the usable EUV light. The purification factor achieved is four orders of magnitude in the presented example. The fraction of the reflected IR light that is refocused to the plasma is 37%. This recycling factor might be further increased with multilevel Fresnel zone patterns, for example, above 95% with 16 levels [24]. This potential is highly attractive for recycling a substantial amount of the reflected IR drive laser light. This novel approach can also be used in other applications where selective suppression and refocusing of the light at two largely different wavelengths is required such as in pump-probe or Raman measurements.

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