Conf-9406116--3
SAND94-0236C

Illuminators for Extreme Ultraviolet Lithography Cameras with Ring Fields

William C. Sweatt
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0980
Telephone No. (505) 845-8566
Fax No. (505) 844-2057

RECEIVED
MAR 2 1 1994
OSTI

Abstract

Scanning, ring-field lithographic cameras designed for 14-nm radiation can print 100-nm features on large chips. Mating high-efficiency illuminators are described.

This work was supported by the United States Department of Energy under Contract DE-AC04-94AL85000.

Introduction

Mass production of large microchips with feature sizes as small as 100 nm should be possible using EUVL, extreme ultraviolet ($\lambda = 14\ nm$) lithography[1,2]. From an optics perspective, these systems are composed of a condenser that illuminates a reflective mask and a scanning, ring-field camera that images the mask onto a wafer with a 5:1 reduction. A diffraction-limited, F/5 camera at 14 nm can be designed because near-normal, multilayer reflective coatings[3] with reflectivities of $R_{SiMo} \approx 63\%$ are now available.

Ring-field cameras can be designed to be aberration-free at a given radius, i.e., $R_{image} = 25\ mm \pm \sim 1\ mm$. A 60° arc at this radius gives a 25-mm chord length. Large chips (25-mm square) can be printed with such a camera if the mask and wafer are scanned perpendicular to this chord. An example design[4] is shown in Figure 1. Note that the mask is reflective, so the entrance pupil has to be virtual.

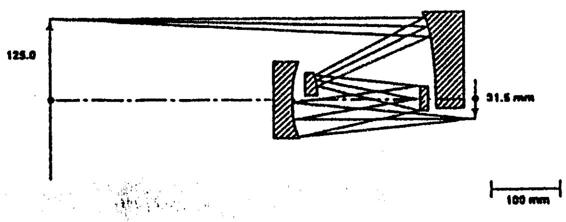

Figure 1. T. E. Jewell's ring-field lithography camera[4].

A condenser design is presented that couples extreme ultraviolet (UV) light from a laser plasma source (LPS) into a scanning, ring-field camera. A second design for use with a synchrotron is presented. Both designs produce Köhler illumination so the intensity is uniform and some degree of partial coherence can be introduced. The LPS condenser can collect half of the EUV radiation from a 200-μm-diameter LPS if, at the wafer, the ring-field width is $\Delta r \approx 3.5\ mm$. The synchrotron condenser collects ~70% of the light radiated from a 22° bend of the particle beam regardless of camera parameters.

Sources

Sandia National Laboratories and AT&T/Bell Labs, Holmdel and Murray Hill, NJ, are working together to develop an EUV lithography tool. We are considering two sources of EUV light: LPSs and synchrotrons. The LPS seems to be the better choice because of its efficiency, size, and cost. However, its debris problem must be overcome before the LPS can be used in a commercial tool. The plasma is produced by a high power, pulsed-laser that is focused on a metal surface (Au, Sn, W...). The plasma melts and shocks the metal, producing high-velocity ejecta debris that can damage or coat the collecting mirror. Some new debris mitigation schemes look quite promising.

Because a synchrotron produces no mirror-damaging ejecta, we have an alternate source of photons for EUVL with no potential "show stoppers." However, as stated above, synchrotrons are far more expensive and much larger than LPSs, and seem to experience much "down time." Such a system may well be too expensive for commercial lithography.

Illuminators in General

A condenser system for a lithography camera must uniformly illuminate the mask ($\pm 1\%$) with partially coherent light. Both requirements can be satisfied with a Köhler illumination geometry. In Köhler illumination, an incoherent source is imaged into the entrance pupil. The illumination is partially coherent if the source image is smaller than the entrance pupil; $50\% \leq D_{source}/D_{pupil} \leq 60\%$ is typical.

Both of our condenser designs give Köhler illumination in the circumferential direction and what is known as critical illumination in the radial direction. This means that the source is imaged in the slit in the radial direction and crudely imaged into the entrance pupil in the sagittal direction. Thus the intensity along the slit is uniform and fortunately, the scanning smooths out any radial intensity fluctuations.

In the LPS condenser design, the entrance pupil is illuminated with five images of the plasma ball arranged in a pentagon. We center this pentagon in the pupil so the partial coherence is almost radially symmetric. We have designed a similar beam arrangement for the synchrotron condenser.

Condenser for the Laser Plasma Source

The condenser for injecting EUV light from the LPS into a ring-field camera has five parallel channels, each composed of three parts: a collector mirror, a beam-rotating roof-mirror pair, and a pupil reimaging mirror. We begin this section by describing the collector mirrors.

A sketch of the rotationally symmetric "parent" collector mirror is shown in Figure 2. The parent, which might be described as an elliptical axicon, images the "point-source" LPS into a ring. As shown in the figure, five 60° segments are cut from the parent mirror. Each of these segments creates a 60° arc image of the LPS. These arc images have the same shape as the 60° ring field of the camera.

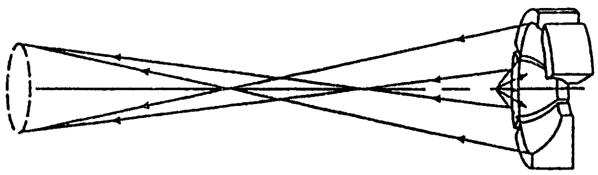

Figure 2. Parent mirror imaging LPS into a ring.

The rest of the condenser system has to do three things: 1) The arc images have to be individually rotated so they can all be superimposed in the ring field, 2) All five beams have to be squeezed into a real pupil, and 3) this real pupil has to be imaged into the virtual entrance pupil of the camera.

Figure 3 is a sketch of the journey of one beam through the whole system. After departing from the collector mirror, the beam encounters an off-axis, roof-mirror pair. This unit rotates the beam so the arc image fits into the ring field. Five of the roof-mirror pairs, the near-normal mirrors, are arranged in a minimum-sized, quasi-symmetrical array (Figure 3). This is the "real pupil," imaged into the virtual entrance pupil of the camera by the diagonal mirror located just below the reflective mask. This mirror will have an elliptical surface and will be about F/15.

The system efficiency is maximized by locating the real pupil where the beam segments are smallest; hence, they can be packed into the smallest array. Figure 2 shows this location to be where the middle ray in the bowtie-shaped, beam segment crosses the axis.

We see in Figure 2 that the beams are overlapped, so the five mirror segments must be tilted outward. We tilt them until the central rays in the five beams are parallel. These segment center lines form a pentagon, and we want to translate them into another pentagon in the real pupil.

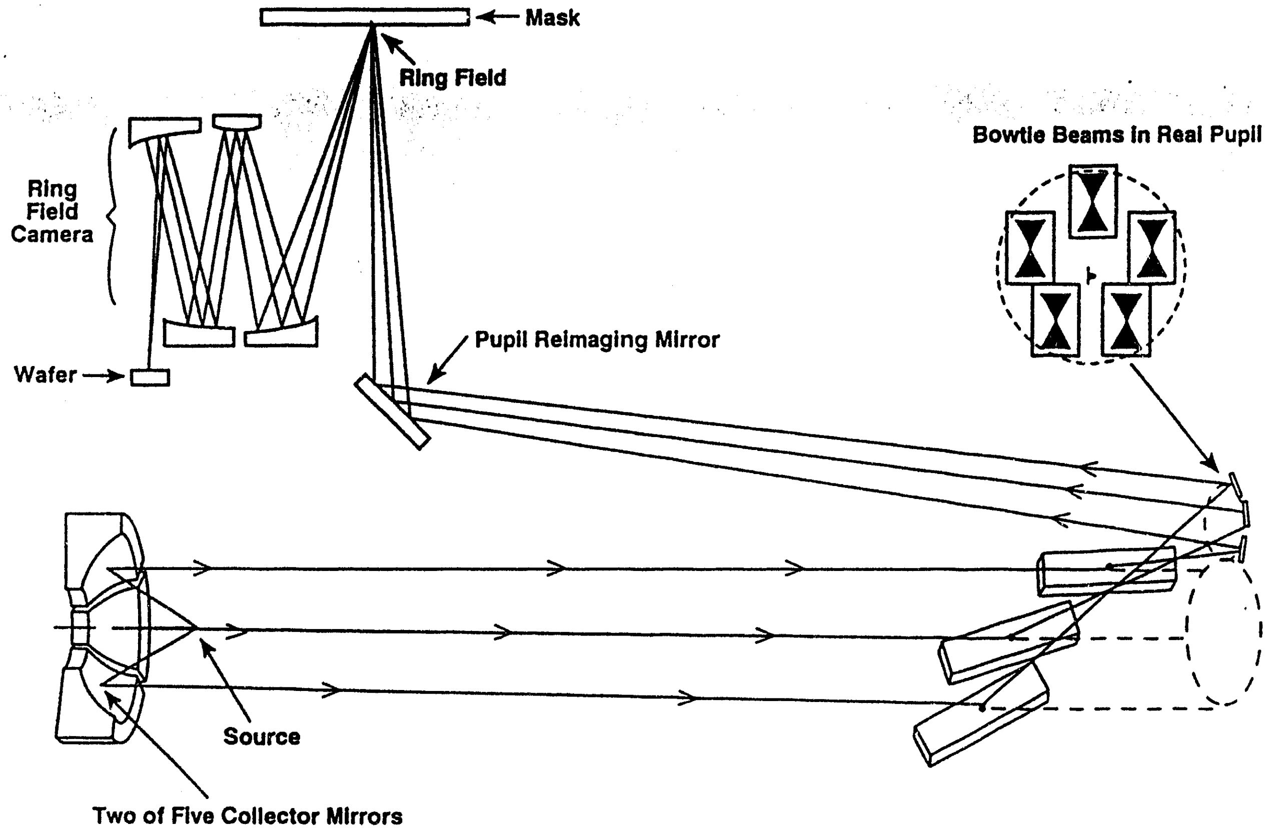

Figure 3. Schematic of LPS condenser system.

Serendipity is not unknown in engineering—it is just rare. Here is our lifetime allotment. Figure 4 shows a mapping of the input pentagon into the real-pupil pentagon that incidentally gives the desired rotation of the arc images, sketched for both the input and output beams. Note that the desired rotation angle for each beam is exactly twice that of the connecting ray, which is the precise function of a roof mirror.

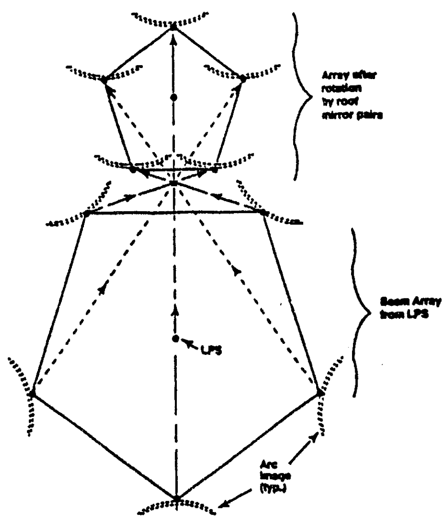

Figure 4. Beam rotation and translation geometry.

The simple geometry just described succeeds when the input and output beams are parallel. As shown in Figure 3, the output beam has a small upward tilt that was added so two of the output beams would not run into the upper collector mirrors. This deviation from parallelism requires that all of the mirrors be slightly tipped and tilted from the orientations that would be used for the "simple geometry." The grazing mirrors also need to be translated slightly.

In the roof-mirror pair, the first mirror is used at grazing incidence and the second one is near normal. This placement allows the beams to be tightly packed in the real pupil. A rhodium-coated, grazing-incidence mirror also happens to have higher reflectivity than would a near-normal multilayer. For an angle of incidence of 80°, the reflectivity is $R_{Rh@80} = 85\%$.

Modeling of the Laser Plasma Source Condenser and its Implications

Physical optics modeling is under way to validate the design concept of the LPS condenser. The mask shown in Figure 5a is well imaged using a source composed of five-point sources[5]. Figure 5b shows good imagery with only modest ringing[6]. Figure 5c is an image of the same mask using partially coherent, disk illumination. Note that Figures 5b and 5c are quite similar. We will soon model the five bowties to see if the array should be symmetric or slightly elliptical. We also need to know the size of the pentagon in the entrance pupil. This size affects the condenser efficiency, which will be addressed in the next discussion.

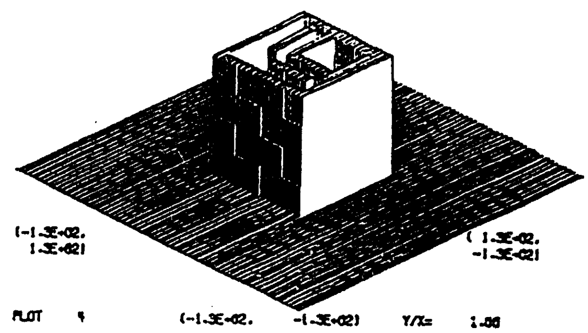

Figure 5a. Image using disk illumination ($\sigma = 0.5$).

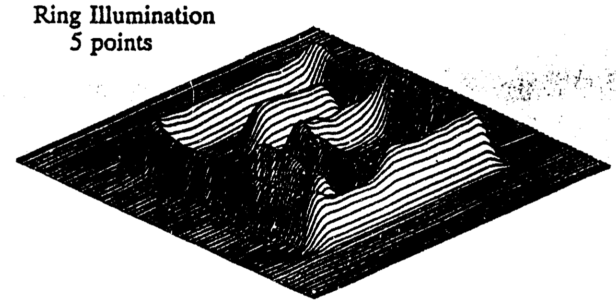

Figure 5b. Image with five-point sources arranged in a pentagon.

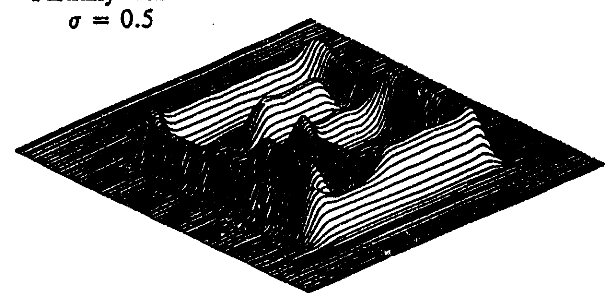

Figure 5c. Image with partially coherent illumination ($\sigma = 0.5$).

The etendue or Lagrange invariant of the camera limits the etendue of the condenser, and hence its efficiency. The etendue of the camera in the radial direction is the product of the numerical aperture, $n.a. = 0.10$, and the slit width, Δr_{image}. The etendue of the condenser is further reduced by the pupil fill factor, $\sigma = 0.5$. Furthermore, five segments must fit in the array so the beam segments must be 44% smaller. The etendue of one beam is

$$E_{condenser} \leq 44\% * \sigma * n.a._{image} * \Delta r_{image} = 0.022 * \Delta r_{image}.$$

At the source, the etendue is approximately $E_{LPS} \approx D_{LPS} * \Delta\phi$, where D_{LPS} is the diameter of the plasma ball and $\Delta\phi = \phi_{max} - \phi_{min}$ is the collection angle. This can be set equal to the etendue of the condenser, so the collection angle is limited by the function

$$\Delta\phi \leq 0.22 * (\Delta r_{image} / D_{LPS}).$$

The condenser efficiency increases with $\Delta\phi$, so it also increases with the slit width and decreases as the plasma ball grows.

The etendue is a first-order property and the collection angles are large, so the last equation is only an approximation. Figure 6 is the output of a more accurate calculation of the efficiency. It includes the effects of aberrations in the collector mirror, vignetting at the slit, reflectivity losses, and an experimentally determined[7], non-Lambertian source radiance. The three curves are for different maximum collection angles, ϕ_{max}. A spherical LPS with $D_{LPS} = 200\ \mu m$ has been assumed.

Because of these calculations, the brightness of the LPS is now being optimized, in addition to its efficiency. Also, since it is evident that a wider camera slit would be better, we are striving to increase it from $\Delta r_{present} = 1\ mm$ to $\Delta r_{goal} \geq 2.5\ mm$.

Condenser for the Synchrotron

Our condenser design that couples synchrotron radiation into a ring-field camera (Figure 7) is similar to the LPS design. Six long, narrow beams are collected, bent into 60° arcs, and directed into a "real pupil." The real pupil is once again imaged into the virtual entrance pupil of the camera. As seen with the LPS condenser, this system delivers very uniform flux and has uniform partial-coherence properties. In this design there is almost no angular dependence of the coherence properties.

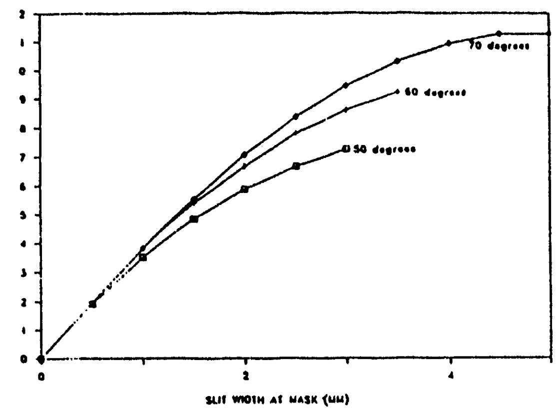

Figure 6. LPS condensor efficiency vs. slit width, Δr_{image}, with $D_{LPS} = 200\ \mu m$.

The system to be described was designed for an existing synchrotron—the National Synchrotron Light Source at Brookhaven National Laboratory. The radius of their particle-beam path is $R_{synchrotron} = 1.5\ m$ and its cross section is a small fraction of a millimeter. The high average-power EUV beam must be allowed to diverge so its flux will not damage the collector mirrors. Consequently, the collector mirrors are quite a distance from the particle beam, which makes the system quite large.

The first two mirrors in each beam are spherical. Their curvatures, separation, and tilt angles were chosen so that a 3° segment of the particle beam would be distorted into a 60° arc for imaging into the ring field. (Note that the image tilt is negligible.) The third mirror in the chain is flat. It directs the beam into the real pupil, which is the array of "fourth" mirrors. The fifth mirror images the real pupil into the entrance pupil of the camera.

The synchrotron's EUV beam has low divergence, so a camera with a narrow slit ($\Delta r \approx 0.5\ mm$?) that produces high-image quality can be used. Unfortunately, this system has many mirrors, causing the through-put to be abysmal; $\eta \approx 3\%$ at the mask. Other more efficient synchrotron condensers have been proposed that are multifaceted along the length of the ring field[7]. However, it is an open question whether uniform, image quality and intensity can be maintained across the facet boundaries.

Summary

A condenser design has been presented that couples a laser plasma source to a ring-field lithography camera. The system is designed for operation at

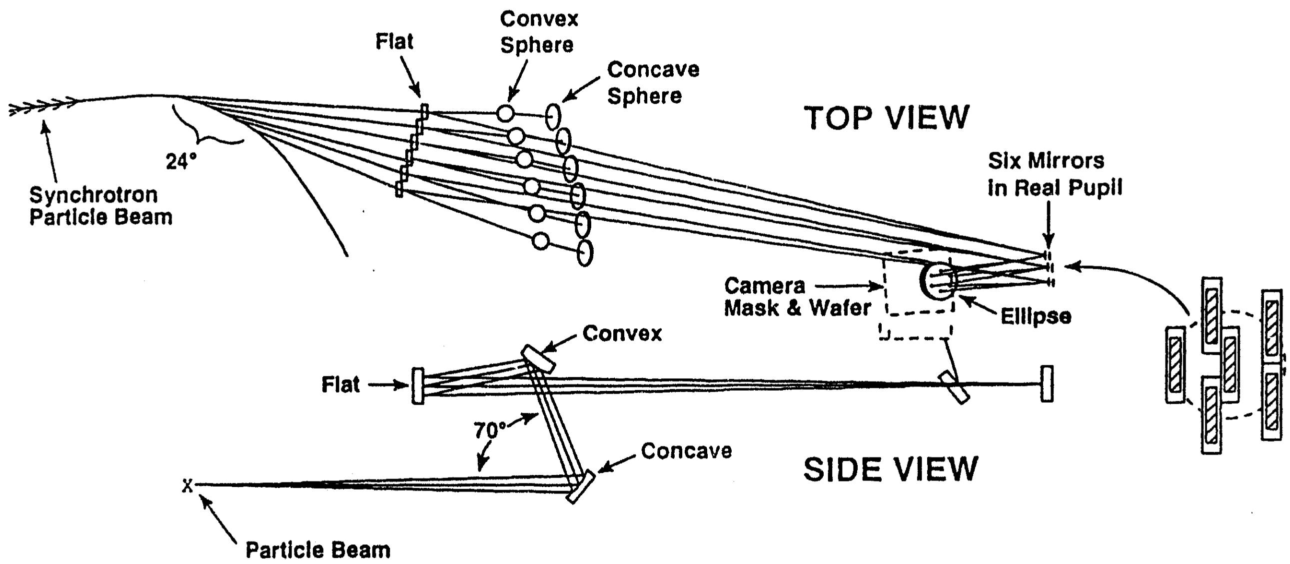

Figure 7. Condenser for synchrotron.

extreme ultraviolet wavelengths. This system can deliver 10% to 12% of the flux to the mask with properties of very good intensity uniformity and reasonable partial coherence. A second system is also presented for use with a synchrotron EUV source. Its imaging qualities are excellent, but the efficiency is poor.

References

[1]H. Kinoshita, et al., "Soft X-Ray Reduction Lithography-Using Multilayer Mirrors," *J. Vac. Soc. Technol. B* 7:1648 (1989).

[2]J. E. Bjorkholm, et al., "Reduction Imaging at 14 mm Using Multilayer-Coated Optics: Printing of Features Smaller than O.1 μm," *J. Vac. Soc. Technol. B* 8: 1509-1513 (1990).

[3]T. Barbee Jr., "Multilayers for X-Ray Optics," *SPIE 563*, 2-28 (1985).

[4]T. E. Jewell, "Reflective Systems Design Study for Soft X-Ray Projection Lithography," *J. Vac. Soc. Technol. B* 8:1519-1523 (1990).

[5]W. C. Sweatt and G. N. Lawrence, "Image Degradation in an SXPL System Due to Diffraction Phenomena," *OSA An. Mtg.*, Albuquerque, NM (1992).

[6]P. D. Rockett, SNL, Private Communication, Dec. 7, 1993.

[7]D. L. White, "High-Efficiency Condenser for LPS and Ring-Field Masks," *OSA's SXPL Conf.*, May 10, 1993.

DATE

FILMED

5/5/94

END