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An iridium-coated Offner 1:1 ring field camera has been used to carry out projection lithography using 42 nm light from an undulator in the vacuum ultra violet storage ring at Brookhaven National Laboratory. Near-diffraction-limited resolution has been obtained showing features as small as 0.2 μm within a 2 mm $\times$ 0.25 mm image field. Images of both transmission and reflection masks have been obtained. The impact of source coherence on imagery has been investigated. Hydrocarbon contamination problems experienced in this photon energy range have been investigated and possible solutions are suggested.

I. INTRODUCTION

Soft x-ray projection lithography has been of interest for the last few years[1–3] because the imaging resolution improves with the use of shorter wavelength while still maintaining a reasonable depth of focus. First experimental results showing diffraction-limited imagery with soft x rays of wavelength 14 nm were obtained using the simple two-mirror Schwarzschild optical arrangement.[4] Lines and spaces of dimensions 0.05 μm were printed. The Schwarzschild optic has only a small image field and is not of use as a practical camera for integrated circuit (IC) manufacture.

A slightly more complicated design that is closer to a practical IC camera is the Offner ring field optic.[5] Wood *et al.*[6] calculated the optimal setup for this optic for a range of wavelengths (13–436 nm). These calculations provided the basis for this experimental work using this optic at 42 nm.

A. Ring field optic

The schematic layout of the Offner ring field optic is shown in Fig. 1. Offner[5] showed that with proper design, two opposite points on an annular ring could be nearly perfectly imaged as 3rd- and 5th-order aberrations cancel within this ring. The diameter of the primary mirror is 233.6 mm and with a numerical aperture (NA) = 0.135 the annular ring of good imagery has a radius of 55 mm and width of about 250 μm. The Raleigh criterion for the depth of focus and minimum feature size are $\pm$ 1.2 and 0.16 μm, respectively, at 42 nm wavelength. Figure 2 shows the modulation transfer function (MTF) of the optic for these parameters when illuminated with incoherent radiation of 42 nm wavelength.

Our choice of 42 nm wavelength was a compromise between our desire to use as short a wavelength as possible and the availability of suitable reflective coatings for the mirrors that could easily be deposited over the large area of active optical surfaces (150 cm^2). The preferred choice of reflective coatings would be multilayer coatings optimized for 14 nm, as these give the highest reflectivity in the soft x-ray range;[4] however, the technology for depositing these films over large areas with adequate control is still being developed. A thin film of iridium was chosen as the mirror coating due to its high normal incidence reflectance down to short wavelength. At 42 nm the normal incidence reflectivity is $\approx$13%.[7]

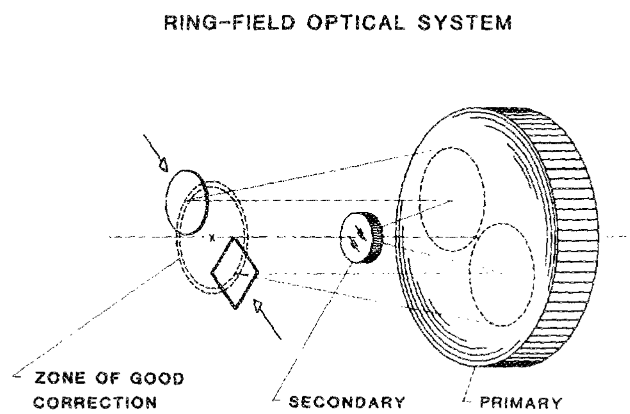


FIG. 1. Schematic layout of the Offner 1:1 ring field optic. Good imagery is obtained within the annular ring of radius 55 and width 0.25 mm. Scanning of the mask and wafer allows for imaging over a large area.

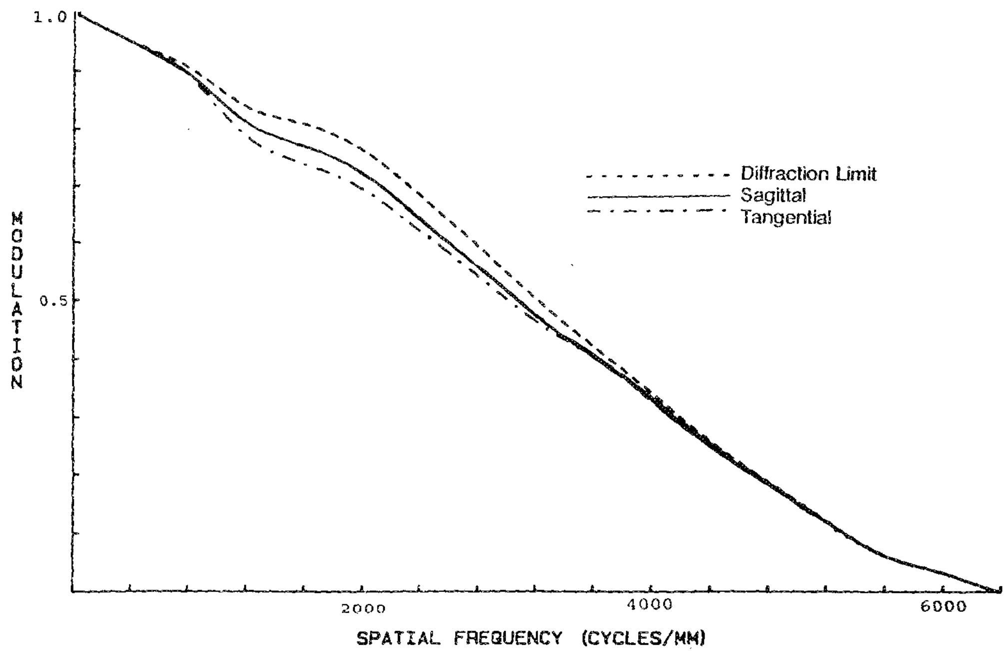


FIG. 2. Calculated diffraction based square-wave incoherent modulation transfer function (MTF) for the 1:1 ring field optic for $\lambda = 42$ nm, NA = 0.135. Features of size 0.16 μm have a MTF of 50%.

II. EXPERIMENTAL

The ring field optic was supplied by Perkin–Elmer as a modified version of the Micralign PE300 projection printer. The system was modified by removing all the scanning mechanism and peripheral optics leaving only the two main mirrors in their mounting assemblies. The mirrors were coated with 17 nm of iridium over 6 nm of chromium by Acton Research. The photon source was the first harmonic of the U13 undulator at the Brookhaven Vacuum Ultraviolet (VUV) Storage Ring.[8] This source provides a highly collimated beam of narrow-band radiation that can be tuned in wavelength by changing the magnet gap. The longitudinal coherence of this source is approximately 1 μm. All experiments were carried out in vacuum as photons of this wavelength (42 nm) are readily absorbed by all gasses. Figure 3 shows the calculated output of this source for flux passing through a 2-mm-diam aperture at a distance of 13 m.

The experimental layout for the reflection mask configuration is shown in Fig. 4. The undulator source is 12 m from the first optical component which is a 7.5° grazing incidence, water-cooled silicon mirror. This mirror acts as a low-pass filter and provides a horizontal deflection of the beam out of the path of the high-energy bremstrallung radiation which is absorbed by the lead radiation shield. The beam is filtered with an 8000-Å-thick aluminum foil which removes the stray visible and UV light from the source. Higher-energy photons are removed by the normal incidence reflections within the ring field optic itself. The beam then passes through a conduction limiter (a 2 mm internal diameter tube, 25 cm long) that separates the 10^{-6} Torr vacuum of the experiment from the ultrahigh vacuum of the beam line. Following the conduction limiter is a two-mirror device ("coherence buster") that rotates about the beam axis and produces a cone of radiation whose apex is a 2-mm-diam spot (defined by the conduction limiter) on the reflection mask. The mask is thus illuminated by light from all directions as defined by the surface of the cone and the radiation can then be considered to be incoherent. The cone angle is half that of the NA of the optic so the pupil of the ring field optic is filled with an annular ring of zero order light of diameter half that of the pupil diameter.

For operation with a transmission mask the ring field optic and vacuum chamber are rotated 120° in a clockwise direction such that the beam of radiation passes perpendicularly through the transmission mask into the optic.

The mask and imaging wafer are 5-cm-diam silicon wafers mounted vertically against three balls in the focal plane of the optic. The balls can be independently adjusted to an accuracy <0.1 μm with respect to their distance from the imaging mirrors. In this way both the mask and wafer can be adjusted for tilt, roll, and focus. The reflection mask is in-

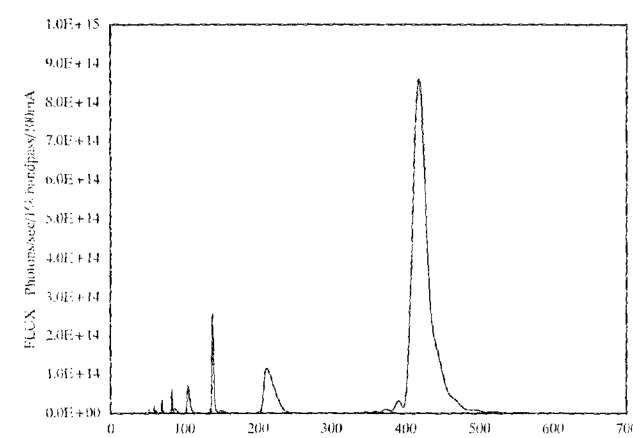


FIG. 3. Calculated total flux through a 2 mm aperture into the ring field experiment from the U13 undulator source at the VUV storage ring at Brookhaven National Laboratory. For these experiments we are using the 1st harmonic at ~42 nm. The storage ring current varied between 200–700 mA.

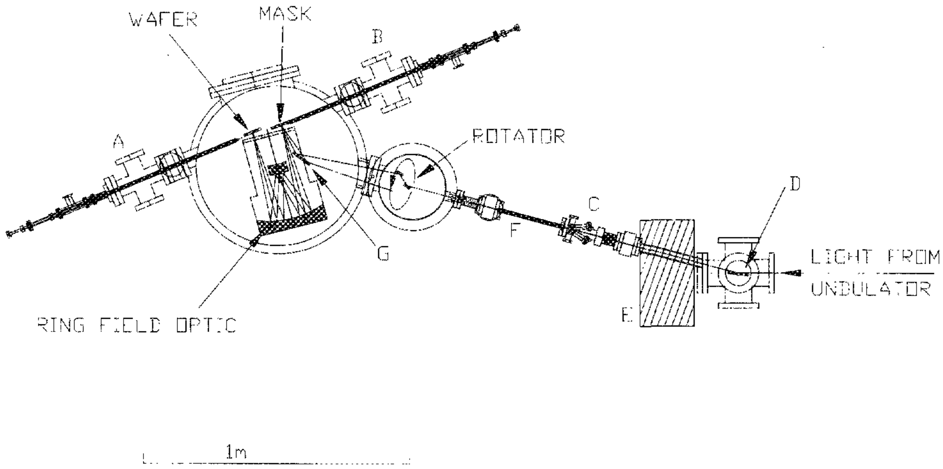
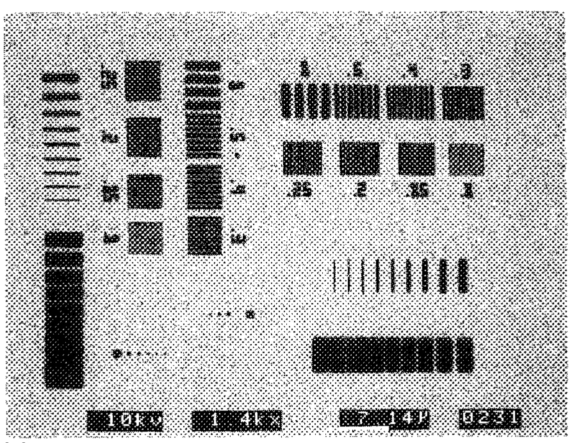


FIG. 4. Experimental arrangement for the soft x-ray projection experiment when using the reflection mask. (A) Load lock for wafer. (B) Load lock for mask. (C) Filter assembly. (D) Horizontally deflecting mirror. (E) Lead radiation shield. (F) Conduction limiter. (G) Fold mirror.

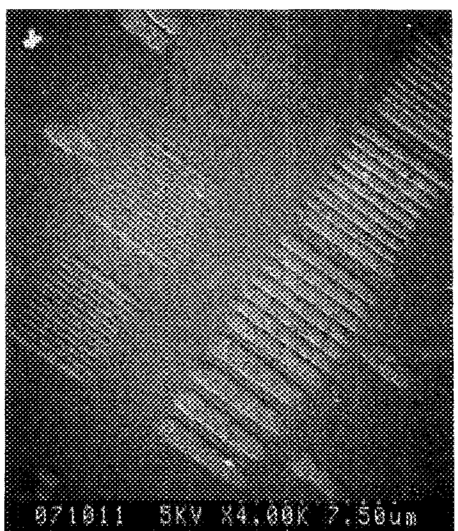
clined at 8° to the focal plane to allow for mask illumination and allow the reflected light to enter the optic. To maintain imaging symmetry the wafer is also inclined at 8°. Although the ring field optic lends itself to scanning of mask and wafer in order to increase the imaging field, such a scanning device was not incorporated in these early set of experiments.

III. RESULTS

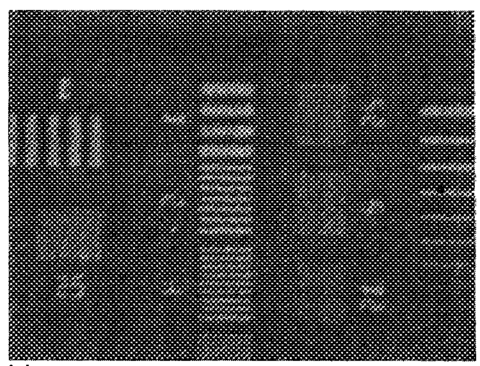
A scanning electron micrograph (SEM) of our transmission mask is shown in Fig. 5(a). It consists of various patterns etched through a 0.7-μm-thick silicon membrane. For our first set of experiments the coherence buster was not



(a)



(b)



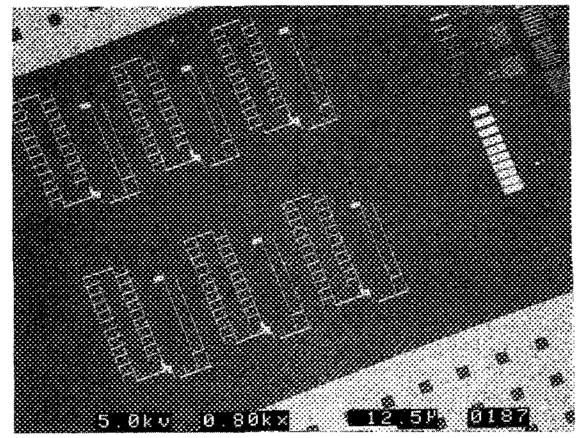
(c)

FIG. 5.(a) SEM of the open stencil transmission mask. It is etched through a 7000-Å-thick silicon film. The features range in size from 0.1 to 1.0 μm wide as indicated by the numerals which refer to the line-and-space dimensions in micron units. (b) SEM micrograph of the image of the transmission mask imaged by the ring field optic into 60 nm of PBS resist using coherent 42 nm x-rays. The 1.0, 0.5, 0.4, 0.3, 0.25, and 0.2 μm lines and spaces are printed. The 0.15 μm lines and spaces (to the upper right of the 0.2 μm lines) are not printed. The exposure time was 10 s. (c) Optical Nomarski micrograph of the image of the transmission mask imaged in 60 nm thick PBS resist with incoherent illumination. The numerals are clearly resolved compared to the image formed using coherent illumination (b). Exposure time was 50 s which was significantly longer than for (b). This was due to carbon contamination of mirrors in the coherence buster.

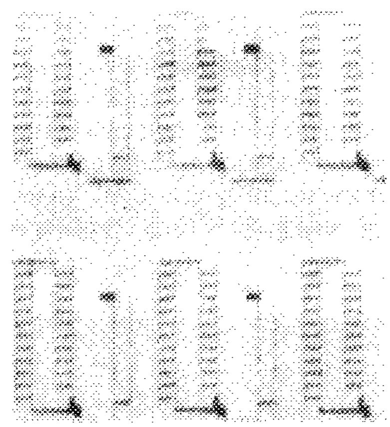
used so the illumination was highly coherent. The coherent illumination cutoff frequency for this system is 0.16 μm lines and spaces, so the 0.15 μm lines are not expected to be printed. Figure 5(b) shows an image of the transmission mask produced by the 1:1 ring field optic in a 60-nm-thick layer of polybutene-1 sulfone (PBS). The 0.2 μm lines and spaces are the smallest imaged. The 0.15 μm lines and spaces are not printed. The lowered contrast of the 0.2 μm lines and spaces compared to other lines and spaces indicate that the optic is very close to but probably not quite at the diffraction limit. The image of Fig. 5(b) is heavily overexposed as indicated by the unequal line-and-space dimensions. The overexposure was an attempt to clean out the spaces down to the silicon substrate. Scumming and granularity associated with PBS resist at these small line dimensions are readily visible. The absorption coefficient at 42 nm of most organic polymers is approximately 30 μm^{-1} (Ref. 9) so the flux intensity for the bottom of the resist next to the substrate is only 16% of the initial dose. This is an unfavorable situation for resist exposure and development and accounts for the gently sloping side walls.[10] Other resists tried at this wavelength were poly(methylmethacrylate) (PMMA), 2,2,2-trifluoroethyl α-chloroacrylate (EBR-9), and Shipley SAL-605. All showed image formation comparable to PBS. PBS was found to be the most sensitive so imaging experiments were performed with PBS.

Imaging of the numerals in Fig. 5(b) is very poor. We consider that this is due to fringing artifacts associated with the use of coherent illumination. Figure 5(c) shows an optical Nomarski micrograph of the image of the transmission mask produced by the ring field optic when illuminated with incoherent radiation. In this case the coherence buster was in use with the result that the numerals are clearly imaged better. The absence of the 0.2 μm features is due to vibration from the rotator. The use of the optical Nomarski microscope to record the images proved necessary as the exposure times became excessively long if the PBS was exposed to its full depth of 60 nm. With moderate exposure the images produce only a slight undulation on the surface of the resist. The optical Nomarski technique is well suited to imaging areas of small height differences with high contrast.

Figure 6(a) is a SEM of a reflection mask consisting of a gold reflecting pattern on an absorbing silicon substrate. Reflectivities at the wavelength of 45 nm used are 7% for gold[7] and 0.9% for silicon.[11] The reflectance contrast ratio is approximately 8:1. The pattern was formed by electron beam direct write in a PMMA bilayer followed by gold evaporation and lift off. The pattern is the gate level of a ring oscillator circuit. The smallest features are 0.35 μm. Figure 6(b) is a Nomarski optical micrograph of the developed image in PBS. The rotator was in operation and the pattern is imaged with high fidelity.



(a)



(b)

FIG. 6. (a) SEM of the reflection mask consisting of a gold pattern etched on the surface of a silicon wafer. The pattern is that of the gate level of a ring oscillator circuit. The smallest feature is 0.35 μm. (b) Nomarski optical micrograph of the image formed using the gold patterned reflection mask with incoherent 45 nm light. The image is printed in 600 Å of PBS resist. Imaging time was 10 min.

IV. CARBON CONTAMINATION

It became apparent early in the experiments that carbon contamination was a severe problem. The experiments were performed in a vacuum of $\sim 10^{-6}$ Torr. Soft x rays irradiating a surface contaminated with hydrocarbons result in their cracking and the deposition of a layer of carbon. Figure 7 shows a transmission mask after a few hours of exposure. The small features have essentially closed up with carbon deposits. The bent bars and the cracks that are visible in Fig. 7 were the result of damage caused by an earlier attempt to clean the contaminated mask with reactive ion etching in an oxygen plasma. For reflection masks the carbon contamination effect was apparent by a gradual degradation in the pattern contrast as the carbon plated out. By directing a local beam of oxygen ($\sim 10^{-3}$ Torr) at the mask the effect was reduced by more than a factor of 10. Future work involving soft x-ray projection lithography will necessitate the use of UHV cleaning and assembly procedures.

V. CONCLUSION AND DISCUSSION

We have demonstrated that this ring field optic has imaged features with 42 nm radiation near the diffraction limit. This implies a final wavefront error of less than $\lambda/4$. Operating at 42 nm with three reflections, this translates to a

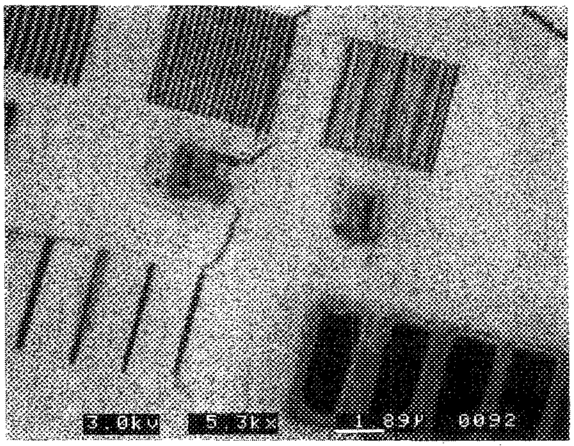


FIG. 7. SEM of the transmission mask after several hours of soft x-ray irradiation. The rather poor vacuum (10^{-6} Torr) results in the cracking of the residual hydrocarbons so that carbon is plated out and the holes fill up.

rms error of less than $\lambda/14$ (3 nm) for each mirror over the total active optical area of 150 cm^2. This large optical area demonstrates that it is possible to make mirrors that have close to the required figure for large optical areas. Future work will use shorter wavelengths and mirrors coated with multilayers optimized to reflect 14 nm radiation. Such an optic requires rms figure errors of less than 1 nm for each mirror. The fabrication of such large area high-quality mirrors has yet to be demonstrated. The carbon contamination problem necessitates the use of clean assembly and operating techniques. For continuous operation, as on a production line, it is likely that an in situ cleaning scheme will have to be employed to prevent the gradual degradation of the optical components. The work here has highlighted the difficulty using existing resists in this wavelength range. Future work will need to concentrate on shorter-wavelength radiation where there is less absorption which is more favorable for good exposure.

ACKNOWLEDGMENTS

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