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A transition radiation source with a grazing angle optic for step and scan lithography

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Abstract

Using a grazing angle mirror, the collection and collimation of transition radiation into a slit pattern that can be scanned across an image plane for X-ray dose uniformity is demonstrated. An Au-coated grazing-angle optic was used to focus transition radiation into a rectangular or slit pattern (7 mm × 16 mm) in the image plane at 631 mm from the optic and 881 mm from the transition radiator. Intensity variation across the longitudinal direction (≈ 10 mm) of the slit was less than $\pm 5\%$. The grazing angle optic with a transition radiator can be used for step and scan lithography for obtaining circuit resolution patterns below 0.1 μm . © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

This work brings together a novel X-ray source and a simple X-ray optical technique to provide a source of collimated X rays for the uniform exposure of photoresist for the production of integrated circuits. Lithography is one of the key process steps in the fabrication of integrated circuits. The wafer is positioned and aligned by a mechanical device called the “stepper.” Having an

inexpensive dedicated source for each stepper is advantageous in that if there is failure of the source, it does not lead to the complete stoppage of the integrated circuit (IC) production line. Over the past quarter century the manufacture of denser integrated circuits has been a major driving influence of the lithography tool industry. Reduction of circuit pattern resolution has followed a 3 year cycle, known as Moore’s Law, through a combination of source wavelength reduction techniques. There has also been an increase in field size of the circuit pattern through scanning techniques. Both of these elements have increased the density and size of ICs (e.g., the number of bits of RAM has

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gone up by a factor of 4 every three years since 1983).

In the past, the wavelength reduction process has been realized through the use of low-cost, optical sources which expose only one wafer at a time. High-power mercury arc lamps and excimer lasers have provided inexpensive optical sources down to 248 nm wavelength. More wavelength reduction is forecast down to 193 and 13 nm (EUV), using more expensive optical sources with the excimer laser and the laser ablation of a high velocity gas, respectively. The lack of a competitive low-cost, single-stepper X-ray source has prevented wavelength reduction below 1 nm. Today's most practical X-ray source is the very expensive synchrotron ring, having several end-station steppers for source cost amortization. However, the downtime for this X-ray source includes the entire wafer fabrication facility. If the synchrotron fails, the entire IC production is halted.

Currently, the materials used in lenses and lasers at 193 nm wavelength have severe optical lifetime limits. Also, the entire infrastructure (masks, optics, laser source, and vacuum tool operation) at 13 nm (EUV) must yet be developed. Considering these issues, the limit for optical lithography is around 100 nm today. However, X-ray lithography already works above and below this optical limit, having both an infrastructure and funding. As a lower cost synchrotron equivalent for a single tool, a transition radiation source meets the wafer fabrication requirements. A system composed of a TR source, grazing-angle mirror, and a stepper would be less than \$6 million, approximately half the projected cost of an EUV system, but would have the option of going to much shorter wavelengths.

2. Transition radiation

Transition radiation (TR) shares with synchrotron radiation the advantage of being collimated [2–10]. The high degree of radiation parallelism decreases geometrical distortions such as run-out and blurring of the circuit elements. However, TR can be generated far less expensively than synchrotron radiation, since it is driven by small to

medium-energy (17–100 MeV) linacs rather than by large electron storage rings [5]. Although storage rings have higher average beam currents than linacs, TR is at least three orders of magnitude brighter on a per-electron basis than is synchrotron radiation [3]. Even with a 10^{-2} difference in average currents, TR can produce soft X-ray fluxes in the range of 3–10 mW/cm². Using a beryllium foil stack without collecting optics, we have produced total fluxes of 15.2 mW with power densities of 1 mW/cm² over 5 cm² area [8].

The low-divergence cone of transition radiation is ideally suited for grazing-angle optics. No other known X-ray source allows almost the entire emitted radiation pattern to be efficiently collected. Synchrotron radiators, conventional X-ray-tube bremsstrahlung, and laser-plasma sources cannot have their entire radiation patterns collected.

TR from an ideal point source emits a radially polarized, diverging cone of radiation that produces an annular image at the photoresist plane [3]. The cone half-angle, θ , is approximately $1/\gamma$, where γ is the relativistic gamma. There is radiation emitted out to a larger angle of $\theta_{\max} = \sqrt{1/\gamma^2 + (\omega_2/\omega)^2}$, where ω_2 is the plasma photon energy of the foil material and ω is the X-ray-photon energy. For large γ then $\theta_{\max} \approx \omega_2/\omega$. For Be foils $\omega_2 = 26.1$ eV, for $\omega = 1200$ eV, $\theta_{\max} \approx 22$ mr. Thus, we can benefit by collecting the radiation cone out to this angle. Although the radiation is spatially almost laser-like at moderate electron-beam energies, the radiation pattern is not uniform, having a hole in the center of the beam. In addition, much of the power lies outside the $1/\gamma$ cone and needs to be collected for efficient use of the radiation. For lithography the X-ray beam must have a uniform cross-sectional intensity at the mask/wafer for the exposure to be uniform. Since the radiation pattern from TR is an annulus, some method of collimation and radiation re-distribution must be achieved. In order to be useful for lithography, this variation must be reduced to levels of the order of 3% [11].

For TR to become useful, the power density must be increased by at least a factor of 10–20 over previously measured values [9]. One method to increase the power would be simply to increase the electron-beam current (the power scales linearly

with the current), although this would be ultimately limited by the linac capabilities and/or heating effects (i.e. damage) in the foil stack. A more effective method would be to collect the radiation in the long “tails” of the TR pattern which make up a significant percentage of the total power generated. Indeed, for the example described in [8], where a power density of 1 mW/cm² over an area of 5 cm² was measured, it is estimated that as much as 74% of the flux lies outside that 5 cm² area. Using a radiator with optimum thickness beryllium foils will also increase the flux by a factor of 2.5 [8].

3. Grazing angle optic

X-rays reflect with high efficiency when incident on smooth surfaces at low angles of incidence less than the critical angle: $\theta_c = \omega_p/\omega$, where ω_p is the plasma frequency of the reflecting surface. The plasma frequency for gold is 80 eV; thus the critical angle is 80 mr for 1000 eV soft X rays [12]. Design of a grazing-incidence X-ray optic is driven primarily by the reflectivity of the mirror surface. However, even for grazing angles below the critical angle, the reflectivities are very sensitive to changes in angle. Fig. 1 shows the variation of reflectivity for gold as a function of energy and grazing angle of incidence. The reflectivity rapidly drops below 50% for angles much greater than about 2° or 35 mr. Gold is typically used because it has a large plasma frequency, is chemically inert and may be sputtered and evaporated onto suitable substrates in very thin smooth films.

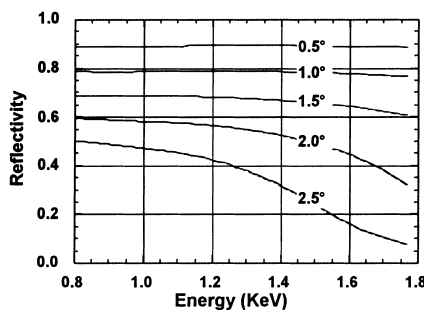


Fig. 1. Reflectivity for gold as a function of energy and grazing angle of incidence [1].

Table 1
Experimental parameters

<i>Cylindrical mirror</i>	
<i>R</i> major	10 m (292 mm width)
<i>R</i> minor	∞ (tapered: 8–13 mm width)
Angle of incidence	1.65° grazing
Source to mirror	250 mm
Mirror to image plane	631 mm
<i>Electron beam</i>	
Energy	72 MeV
Ave. Current	1 μA

As can also be seen from Fig. 1, if the angle of incidence is to be varied, as in a scanning system, the variation in angle must be kept below $\pm 0.5^\circ$ in order to maintain a loss of less than 50% in reflectivity in the 1–1.2 keV photon range. To cover a field of 33 mm, the minimum mirror-to-mask distance of 180 cm must be used. However, because of the limitations in space in which we performed the experiment, the distance was kept to 63.1 cm. The system parameters used for the experiment presented here using a simple parabolic mirror are given in Table 1. A simulation of a grazing-angle toroidal optic and some preliminary experimental results are given in [1].

4. Experimental results

We have developed an experimental beamline at the Naval Postgraduate School (NPS) Linac in Monterey, California. The NPS Linac is capable of delivering a 30–90 MeV, 1 μA electron beam to the TR target. To demonstrate feasibility, we utilized a TR stack composed of 60 mylar foils, each 2.0 μm thick (25 mm diameter foils separated by 0.5 mm). The expected spectrum is given in [1] and measured in [5]. The mylar stack generates X-ray from 800 to 4 keV, peaking at approximately 2.5 keV.

The experimental apparatus shown in Fig. 2 consisted of a transition radiator with an interchangeable phosphor screen, electron-beam bending magnet, a grazing-incidence optic with gymbal mount, and phosphor screen. To demonstrate that the X-ray annulus could be converted into a

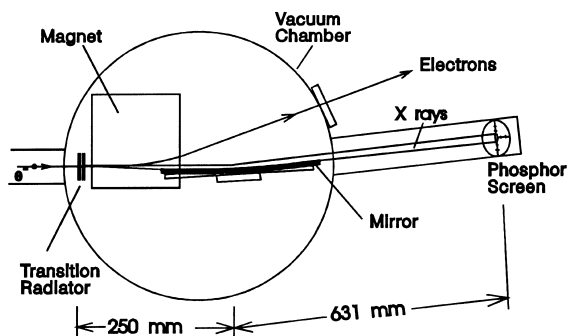


Fig. 2. Experimental apparatus for demonstrating the collection and collimation of transition X-radiation using a grazing-angle optic.

scannable line source, we utilized a simple cylindrical mirror, somewhat easier to manufacture than the toroid utilized in the computer simulation of [1]. A phosphor screen and the transition radiator could be alternately placed into the electron beam by remote control. The phosphor screen was used to locate, position and focus the electron beam. The TR radiator was then placed in the electron beam. After passing through the radiator, the electrons were bent away 30° from the trajectory of their original path and away from the X-rays that continued on to the grazing angle optic. The magnet (dump magnet) is unusual in that it was a permanent magnet and it was placed directly in the vacuum. A permanent magnet was used to minimize the distance from the radiator to the center of the optic. By having the optic extend into the magnet, a distance of 250 mm was achieved. The 292-mm-long mirror was tapered so that the end nearest the radiator was only 8 mm wide, permitting it to be easily placed inside the magnet gap of 11.5 mm.

The cylindrical mirror was made of standard float glass and coated with 50 \AA Cr (for better Au adhesion) and 600 \AA of Au. It was estimated that the thickness of the Au coating diminished to approximately 400 \AA at the end of the mirror due to a non-uniform coating process. The glass was held on a 6 mm thick aluminum bar at the center and bent by two screws at either end. The flat glass then formed an arc, estimated by measuring the sagitta to give a 10 m radius of curvature.

In the first experiment the mirror was removed and the X-rays imaged on the phosphor screen, at a distance of 508 mm from the transition radiator. The radiation produced a round spot on the ZnS screen and imaged using a video camera and frame grabber software. A cross section of the intensity was then obtained from this data. As can be seen from Fig. 3, the distribution appears to be Gaussian and does not contain the characteristic central hole of the toroidal distribution as was observed in [9]. This is because the distance between the radiator and the screen is such that the electron-beam emittance (angle divergence and finite electron-beam spot size) blurs the X-ray distribution and fills in the hole. Thus minimizing target-to-mirror distance assures us that the reflected radiation will not have a hole at the mirror or at the image plane. The latter was also checked using the computer simulation as given in [1].

With the mirror in place and the ZnS screen placed at a distance of 881 mm from the radiator, the X-rays were then reflected on to the screen. The mirror was rotated and tilted such that the X-ray intensity was maximized. A low-intensity TV monitor camera was then used to obtain the image of the visible photons converted from the X-rays striking the phosphor. Frame-grabber software was used to capture the image for analysis. Only the relative X-ray intensity was measured.

The measured FWHM slit was approximately 7 by 16 mm^2 . Cross sectional cuts were taken along

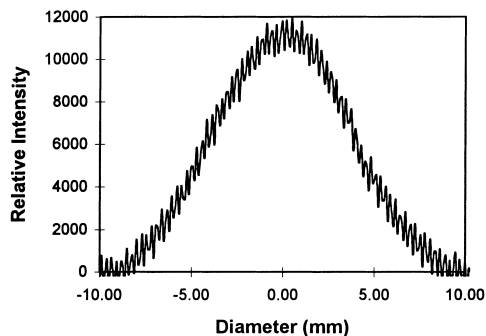


Fig. 3. The measured distribution of transition radiation from a mylar foil stack at a distance of 503 mm from the radiator. As can be seen from the figure, the distribution appears to be Gaussian. The electron beam energy was 77.2 MeV.

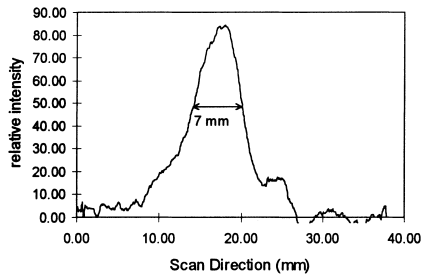


Fig. 4. The measured width of the slit distribution at the image plane [1].

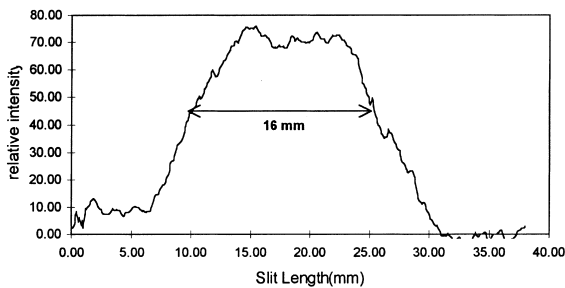


Fig. 5. The measured length of the slit distribution at the image plane [1].

the width (Fig. 4) and length (Fig. 5) of the X-ray image. The cut along the length of the slit (Fig. 5) shows that the relative intensity does not vary more than $\pm 5\%$ over 10 mm. The ray tracing computer simulation was used to predict a similar 5 mm by 18 mm distribution. Adjustment of the mirror radius of curvature should give a tighter focus in the scan direction.

To demonstrate how the X-ray power per unit area changes with angle, we changed the grazing angle, of the mirror and stepped the distribution across the phosphor screen, taking measurements at five angles. We obtained the relative average power and area of the distribution using the frame grabber software. We then plotted (Fig. 6) the relative power per unit area as a function of the grazing angle for the five data points taken. To see if the intensity of the radiation was decreasing due to mirror reflectivity, we also plotted the reflectivity as a function of grazing angle, normalizing it to be 1 at 20 mr. This gives us a rough comparison

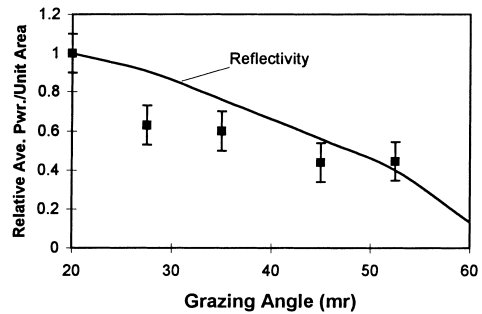


Fig. 6. The relative power per unit area as a function of grazing angle.

demonstrating that the flux was probably dropping due to the decreased mirror reflectivity. Some discrepancy in the measured values and theory can be attributed to electron beam instability occurring during these measurements. When applied to lithography, the effects of intensity variation with angle can be compensated by changing the angular velocity of the scan with angle.

5. Conclusion

In these results, we have demonstrated that the conical annular TR distribution can be collected and focused in one plane to achieve a scannable X-ray slit for a step and scan lithography tool. The annular cone of the transition radiation did not affect the uniformity of the X-ray distribution for these parameters. This is attributed to the fact that the optic was in the near field of the radiation pattern. The experiment results also demonstrate that uniformity transverse to the scan can be maintained. According to [11], a uniformity of 3% needs to be maintained over a larger slit width for lithography. We believe that if we had used a toroidal mirror and a more stable, higher current electron beam, we could have obtained better X-ray uniformity over a larger slit width (33 mm) [1].

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