# Zone-plate-array lithography using synchrotron radiation

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We present our results in the design and development of a multiple-beam x-ray pattern generator based on an array of Fresnel zone plates (FZPs). Exposures have been carried out using a synchrotron source at SuperACO (France), a PC-controlled piezoelectric scanning stage, and an array of FZPs fabricated by high resolution electron-beam lithography and reactive-ion etching of a tungsten absorber. In particular, we have implemented an array of apertures using a self-aligned process in order to minimize background intensity coming from diffraction orders other than the positive first order. We show that even with polychromatic synchrotron radiation and relatively low resolution FZPs, patterns of various geometries could be successfully written in poly(methylmethacrylate) resist and submicrometer resolution was obtained after metal liftoff. © *2000 American Vacuum Society.* [S0734-211X(00)11506-9]

## I. INTRODUCTION

In 1996, Smith proposed a novel form of x-ray projection lithography which would use an array of Fresnel zone plates (FZPs) coupled to multiplexed micromechanical shutters (and later, to deflecting micromirrors) to turn individual x-ray beamlets on or off in response to commands from a control computer.[1–4]

A circular FZP is basically a diffractive grating consisting of concentric zones in which the period decreases with radius so that positive first order diffraction from all zones will add constructively at the focal point. Much like an optical lens, a properly made FZP thus produces a diffraction-limited spot.

Compared to proximity x-ray lithography, and conventional electron beam lithography, this virtually maskless lithography could therefore allow fast parallel direct writing of arbitrary patterns with large area exposure capability, at large exposure gaps, and with sub-50 nm resolution as determined by the achievable FZP resolution.

Taking advantage of our experience in high resolution x-ray mask technology and synchrotron light source,[5,6] we have developed a multiple-beam x-ray pattern generator and started to study its lithography performances. In this article we describe the early stage effort on the implementation of x-ray zone-plate-array lithography (X-ZPAL).

## II. EXPERIMENTAL PROCEDURE

### A. X-ray source

We have used a synchrotron source at the SuperACO ring in Orsay, France. The high power density, high brightness, and parallel beam provided by a synchrotron source is particularly suited for high throughput lithography application. Beam focusing using a FZP depends on source bandwidth ($\Delta\lambda/\lambda < 1/N$, where $\lambda$ is the photon wavelength and $N$ is the number of zones in the FZP) and for this reason the use of an undulator is generally suggested. Monochromatic radiation can also be obtained with double crystal mirrors. While such a monochromator can be easily inserted on our experimental setup in order to select a $\lambda = 1.1$ nm wavelength, the obtained intensity is significantly reduced, therefore for this study we chose to investigate the feasibility of X-ZPAL using polychromatic radiation. The source characteristics are given in Fig. 1, which shows the power density distribution as a function of wavelength, before and after Be and SiC thin film filters. Figure 2 shows numerical calculations of the FZP focusing and lithography properties performed using the beam-propagation method for both the polychromatic and the monochromatic cases. Intensity distributions of the positive-first-order-diffraction focal plane $f$ and several planes close to $f$ for a FZP comprising 50 zones and 1 $\mu$m first zone radius are displayed. It can be observed that both polychromatic and monochromatic radiations provide a sharp focusing. The intensity at the focal point appears to be several thousand time stronger than the incident radiation intensity. However, the intensity in the polychromatic case is roughly half that obtained in the monochromatic case. Moreover, the polychromatic focusing exhibits a typical background intensity distribution. Nonetheless, the intensity contrast between the peak level and the background level remains large enough, allowing us to consider our polychromatic radiation as potentially useful for exposing patterns. Figure 2 also shows a clear dependence of the focusing properties on absorber thickness. Mask fabrication should take this effect into account. We also note that in the monochromatic case, the maximum intensity is not exactly at $f$, which could be attributed to absorber phase effects. It can also be observed from Fig. 2 that the depth-of-focus of this set of FZPs is on the order of 10 $\mu$m, which is comparable to the value obtained analytically with a monochromatic source.

### B. Zone-plate-mask fabrication

We have fabricated an array of circular Fresnel zone plates on a 2-$\mu$m-thick SiC membrane using high-resolution

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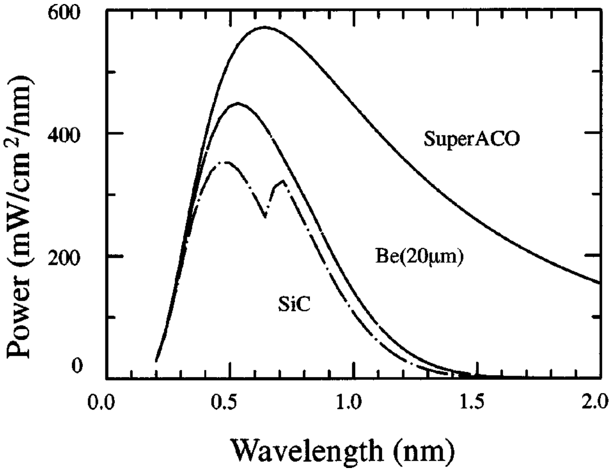

FIG. 1. Super ACO synchrotron radiation characteristics before and after Be and SiC thin film filters.

electron-beam lithography on poly(methylmethacrylate) (PMMA) resist followed by Ni liftoff and reactive-ion etching of the underlying 400-nm-thick W absorber. This technology was previously optimized for high-resolution proximity x-ray lithography.[5] Due to phase shifting with the chosen absorber, FZP efficiency is increased relative to pure-amplitude FZPs.

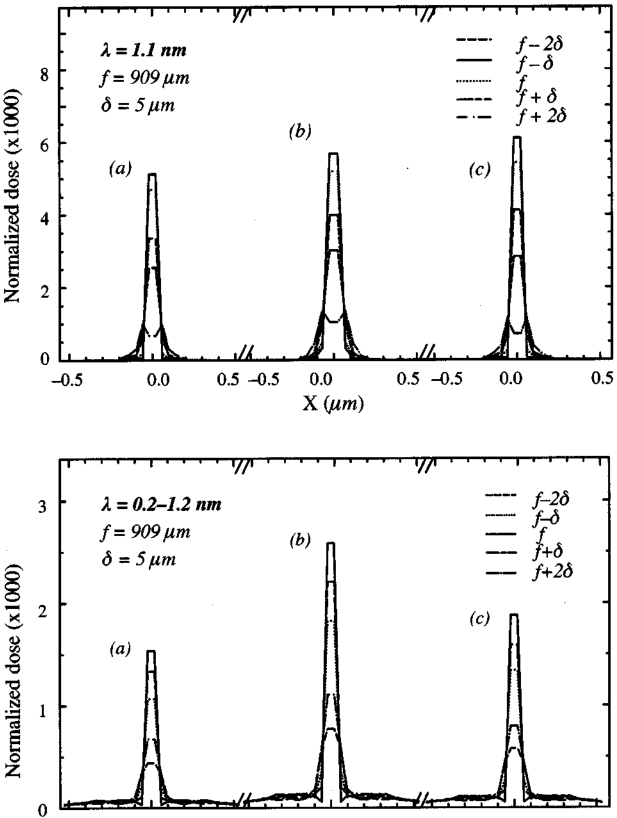

FIG. 2. Simulated intensity distribution at the first-order-diffraction focal plane $f$ and several planes close to $f$ for a FZP comprising 50 zones and 1 μm first zone radius for both the polychromatic (bottom) and the $\lambda = 1.1\,\mathrm{nm}$ monochromatic case (top), and for different W absorber thicknesses: (a) 150 nm, (b) 300 nm, and (c) 450 nm.

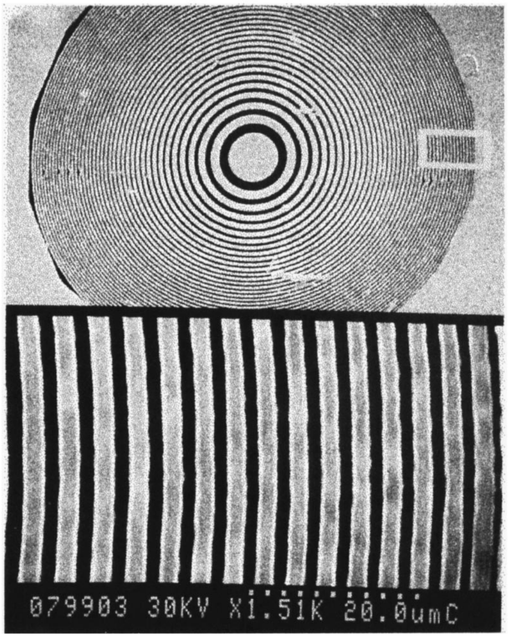

FIG. 3. Scanning electron micrograph of a 40 zone FZP of outer radius 25 μm, first inner radius 2.7 μm, and width of outermost zone 180 nm, fabricated by high-resolution electron-beam lithography and reactively ion etched W absorber.

Our FZPs all have 40 zones but different sizes, with the outer radius varying in the range from 4 μm to 34 μm. The space between zone plates was kept relatively large (300 μm) and was entirely covered with W absorber to block excess radiation. An example of a fabricated FZP of outer radius 25 μm, first inner radius 2.7 μm, and width of outermost zone 180 nm is shown in Fig. 3. For this FZP and a typical x-ray wavelength of $\lambda = 0.8\,\mathrm{nm}$, a focal length of 9.11 mm and a depth-of-focus close to 60 μm are expected from zone-plate optics calculation, thus providing significant process latitude at extremely large exposure gaps.

### C. Self-aligned stop-mask fabrication

In order to enhance exposure contrast by decreasing background intensity due to diffraction orders other than the positive first order, a stop mask was processed to serve as an array of apertures when placed and aligned between the FZP mask and the substrate. The effect of this stop mask is illustrated in Fig. 4(a).

A self-aligned fabrication process was developed to produce a stop mask perfectly aligned with the zone-plate mask: the stop mask is initially a SiC membrane covered with a CrAu plating base and spin coated with a layer of MMA/MAA copolymer resist. This blank mask and the FZP mask are then glued on opposite sides of a insulating Teflon ring of thickness corresponding to 80% of the focal length for a given FZP [see Fig. 4(b)]. X-ray exposure of the stop-mask blank is then carried out through the FZP mask in a self-

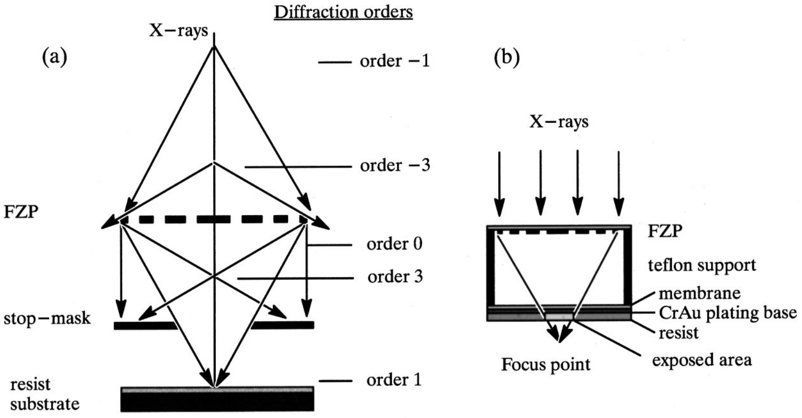

FIG. 4. (a) Schematic view of Fresnel zone plate diffractive focusing with a stop mask and (b) fabrication principle of a self-aligned stop mask.

aligned manner. An array of disks is therefore written in the resist due to defocused exposure. After development, local Au and Cr wet etching are performed to remove the plating base in the disk areas. The resist is then dissolved and electroplating of 400-nm-thick Au is carried out. The final result is the fabrication of a stop mask containing small apertures perfectly aligned to the matching FZP mask.

### D. Exposure system

Exposures are carried out under vacuum in a sealed chamber on our dedicated line at the SuperACO synchrotron in Orsay, France. The FZP/stop-mask unit described above is mounted on a piezoelectric stage which can be remotely controlled in *x*, *y*, and *z* directions. A maximum displacement of 100 $\mu$m is allowed in each direction. The PMMA-coated substrate is then fixed at focal length from the FZP mask.

The piezoelectric scanning stage is PC controlled to carry out exposures with the help of a homemade pattern generator based on a LABWINDOWS platform. The writing speed is automatically adjusted according to the synchrotron beam current available at the time of exposure.

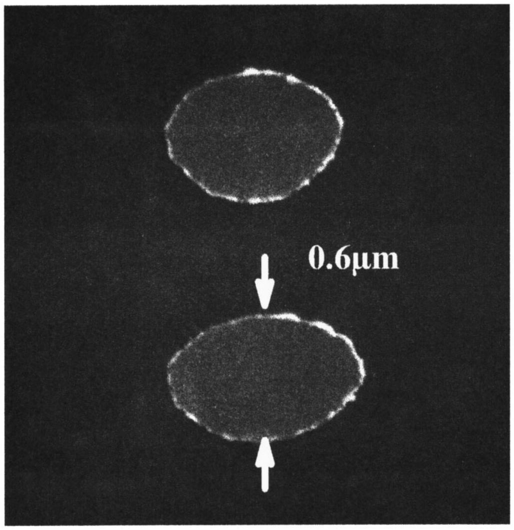

FIG. 5. Scanning-electron micrographs of TiAu liftoff patterns obtained via X-ZPAL without stop mask.

## III. RESULTS

For this set of experiments and for demonstration purposes, we chose to restrict ourselves to the use of one size of FZPs present on our mask, shown in Fig. 3. We worked at an exposure gap of roughly 9 mm. Examples of lithography results obtained without a stop mask are shown in Fig. 5. Exposure dose could be easily adjusted and contrast was good enough to allow successful liftoff of the submicron TiAu features. Patterns of 600 nm minimal feature were obtained.

For the fabrication of the stop mask, we first carried out several test exposures on wafers, at a fixed mask-to-substrate gap of 7 mm thus, purposedly out-of-focus. The exposure contrast was good enough and various sizes of apertures could be obtained only by adjusting the exposure dose. Figure 6 shows two examples of exposed spots observed after resist development, which show diameters of 2 and 10 $\mu$m, respectively. Aperture sizes of 10 $\mu$m diameter were selected for the actual stop-mask fabrication.

Examples of lithography results obtained with the full setup are presented in Fig. 7. Figure 7(a) shows a dot array after resist development and metal deposition, but prior to liftoff. TiAu liftoff could be successfully carried out on most of the patterned dot arrays, as illustrated in Figs. 7(b) and 7(c), where a minimal feature size of 500 nm can be measured. Arbitrary patterns were also written in PMMA during the same exposure, however liftoff of more complex patterns was more delicate due to insufficient dose adjustment. The

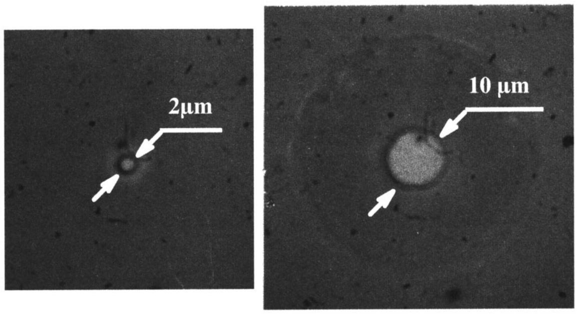

FIG. 6. Optical micrographs of two examples of apertures obtained after resist development via defocused stop-mask exposure.

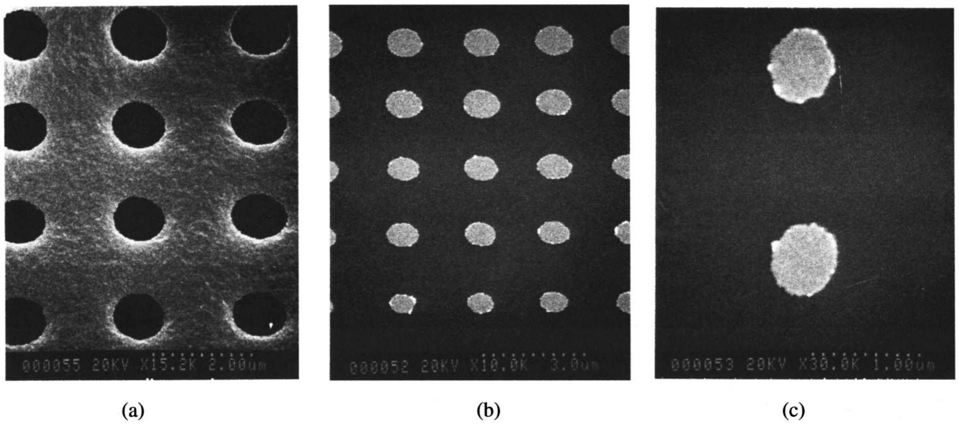

FIG. 7. Patterns obtained via X-ZPAL with use of the stop mask: (a) regular dot array after resist development and metal deposition, but prior to liftoff; (b) patterned dot array after TiAu liftoff; and (c) dots obtained after TiAu liftoff showing a minimal feature size of 0.5 $\mu$m.

180 nm resolution limit defined by the fabricated FZP was not reached in this work, which could be attributed to several factors: First, our FZP mask contains imperfections, for instance the outermost line-to-space ratio is larger than one. Second, the exposure contrast on the current setup may not be optimal due to insufficient electroplating, which leads to some background intensity passing through the stop mask. Also, we were not able to measure and set down the exact FZP mask-to-sample distance corresponding to the focal length. In the case where the actual distance is significantly far from the focal length, the 100 $\mu$m vertical displacement currently allowed by the piezoelectric scanner may not be sufficient for a sensitive adjustment. Finally, the use of a polychromatic light source will affect resolution and image contrast, although the latter is improved by the use of a stop mask.

## IV. DISCUSSION

One of the key issues in microfabrication is throughput. The parallel exposure scheme developed here with multiple focused x-ray beams is in itself a strong asset of this lithography technique. For each scan field, the exposure time of the whole patterned area depends on the FZP focusing characteristics and on the synchrotron power density. In our experiments, the exposing rate is typically 10–100 ms/pixel. Therefore, for a spot size of 1 $\mu$m and a unit cell area of $100\times 100\,\mu\text{m}^2$, the scan time required for a full area exposure is approximately 10 min. This exposure time is still long, but the fact that we are using an array of identical FZPs to expose many fields makes it a useful parallel writing tool for many applications. Ultimately, individual addressing of beamlets should be developed but this is out of the scope of this work. In order to shorten the exposure time, one can for instance consider increasing the number of Fresnel zones, to convert more incident energy into the focus spot. Of course, the use of an undulator would improve both the focusing properties and the exposure time. This option also remains to be demonstrated experimentally.

Increase of the signal-to-noise ratio can be achieved by decreasing the background intensity distribution. Our self-aligned mask fabrication process provides a way of controlling aperture size. The ideal stop mask would be a complementary stop, i.e., with an aperture size matching the FZP central stop radius, which would completely block zero order diffraction. Fabrication of such a stop mask is technologically feasible with the self-aligned process.

Although two x-ray masks are needed in our exposure system, we stress that: (a) the two membranes are placed far apart from each other (approximately 7 mm apart in this case), (b) the mask-to-substrate gap is also very large, and (c) extreme robustness of our setup to handling and changes of pressure during vacuum pumping was verified during the experiments. In addition, critical issues such as x-ray mask fabrication cost and defect-proof mask inspection are not relevant with this approach.

The resolution limit of ZPAL is defined by the outermost zone width but also depends on the source bandwidth. Minimal feature size achievable with our electron beam lithography tool (JEOL 5DIIU nanowriter) is 25 nm in PMMA and is therefore not a limiting factor. However, limitations do occur with the liftoff process on the smallest FZPs. Ultrasonic agitation cannot be used to facilitate liftoff on our membranes and narrow outer zones of smaller FZPs are often lost. We are currently preparing new masks where 450-nm-thick electroplated Au will be used as an absorber instead of sputtered W subsequently reactively ion etched. This mask fabrication approach was already developed in our group for proximity x-ray lithography purposes and led to masks containing 15 nm size Au absorber patterns.[6] Moreover, we have not carried out a systematic study of focal length and therefore cannot be sure it was working at the optimal distance. Significant improvement in resolution is therefore expected in the near future by improving on these two resolution-limiting factors.

Note that our approach departs from the scheme proposed by Smith who considered soft x rays of wavelength 4.5 nm emitted by an undulator as an ideal source. Although relatively narrow, wavelength dispersion of our polychromatic source is indeed a limiting factor for both resolution and image contrast due to corresponding dispersion in focal lengths. Source bandwidth limitations will need to be further investigated but we believe our preliminary results clearly demonstrate the feasibility of using synchrotron radiation to pattern large areas with a scan writing strategy.

## V. CONCLUSIONS

We have reported on our first steps in implementing X-ZPAL using synchrotron radiation. In particular, we have developed a self-aligned stop-mask fabrication procedure in order to improve image contrast. A minimal resolution of 500 nm after metal liftoff was achieved. Increase of pattern resolution should be possible using higher resolution FZP masks and accurate control of mask-to-wafer distance. We are currently fabricating new Au electroplated FZP masks for this purpose. The control of individual beamlets by specific multiplexing is a big challenge. Without dealing with this final goal, many critical issues of X-ZPAL can already be investigated.

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