LBL-30068
Preprint

Lawrence Berkeley Laboratory
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Accelerator & Fusion Research Division

Submitted to Applied Optics

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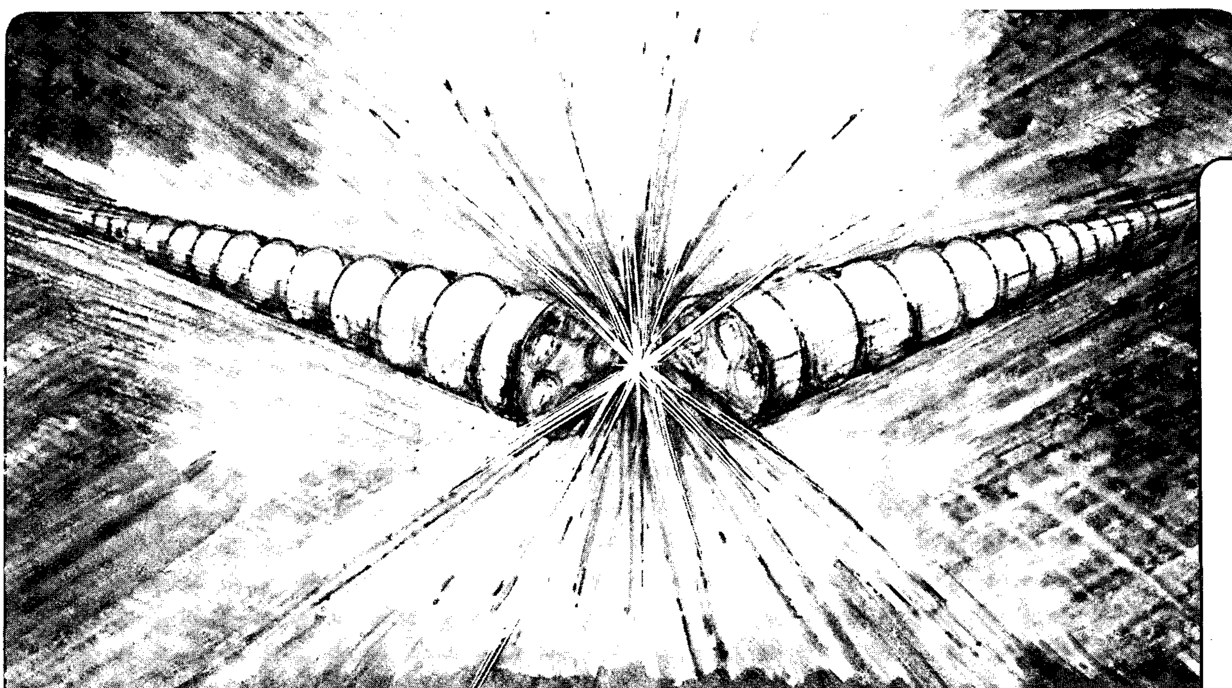
December 1990



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

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LBL-30068

Possibilities for Projection X-Ray Lithography Using Holographic Optical Elements*

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Paper to be Submitted for Publication to Applied Optics.

*This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Materials Sciences Division of the U.S. Department of Energy, under Contract No. DE-AC03-76SF00098

It has long been known that soft x-ray lithography provides a possible approach to microcircuit fabrication [1] at feature sizes below those that can be made with visible and ultraviolet radiation. There is a considerable literature on proximity x-ray lithography [1,2], and interest in projection x-ray techniques is beginning to rise [3]. The advantages of the projection approach would be the elimination of transmission masks and the contamination and penumbra problems associated with close proximity, the opportunity to demagnify a mask of a coarser spatial scale, and, assuming a rigid, reflection mask, the possibility of cooling. The assumption behind the pursuit of these advantages is that the technical challenges of making the optical system that would perform the projection and the x-ray source that would illuminate it are tractable on some timescale. The optical fabrication tolerances and other design issues involved in carrying out projection using a conventional reflection system have been investigated by Rogers and Jewell [4]. These authors find that the needed tolerances are well beyond the present state of the art [5] even for spherical surfaces and the required surfaces in these schemes are aspheric. In this paper we present an alternative form of projection which, of course, has its own, different challenges. Our proposal is to use a computer-generated hologram as the image-forming element and sole optical component. The use of holographic optical elements (Fresnel zone plates) is already standard in soft x-ray optics but our proposal for a hologram written on a rigid substrate and projecting a complex image represents a new type of x-ray optical device. It is a matter of one's judgement and technological starting point to decide whether this provides the easiest path to a working projection x-ray lithography.

The following advantages can be adduced for holographic x-ray projection:

1. The holographic image is aberration-free provided the hologram is illuminated by the reference beam that was used to form (or compute) it. This is exact within diffraction limits.
2. This means that one can achieve aberrationless imaging using only a single optical component, a computer generated hologram which serves as both imaging optics and mask.
3. Only one optical surface is needed (good for stray light) and it can be a flat (good for fabrication).

4. The above arguments do not require that the hologram be used at normal incidence and there are many advantages to using grazing incidence. (i) the power load of the x-ray beam is spread over a larger area, (ii) the use of multilayer coatings is avoided and (iii) the tolerances for surface figure and finish are relaxed compared to normal incidence. Furthermore the holographic geometry needs to be off-axis in order to avoid "twin-image" corruption [6] of the projected image. Ordinarily, such geometry requires a hologram recording resolution in the off-axis direction considerably greater than the image resolution [6]. The use of grazing incidence in that direction provides a way to avoid the requirement for extra resolution.
5. The advantages of a rigid, coolable "mask" are applicable here, as in other projection methods.
6. The technology for making the holograms would be something one would have to have anyway for advanced lithography, namely, electron-beam writing. Although the holograms are larger (see later) than the final image, the writing difficulty in terms of resolution and distortion tolerances would be similar to that in mask making for proximity printing at the same feature size.
7. No special effort is required to illuminate the hologram uniformly. Slowly varying nonuniformities of illumination have only a slight effect (on the shape of the resolution function) and in any case can be corrected in writing the hologram if their form is known.

We must also consider the following disadvantages and challenges posed by this method:

1. The opportunity to fabricate a mask on a coarser spatial scale and demagnify it is lost.
2. There are some questions which should be the subject of further study concerning unwanted signals due to the intermodulation term in the reconstructed image and to higher diffracted orders. Both these tend to be negligible in "normal" x-ray holography because the samples are weak scatterers whereas here we would be reluctant to deliberately make the hologram *as if* it were recorded with a weak-scattering object because of the low diffraction efficiency that would result. The twin-image is assumed to be eliminated by the use of off-axis geometry.
3. There is a need for a highly monochromatic, single-mode x-ray beam to illuminate the hologram. The value of $\lambda/\Delta\lambda$ needs to be on the order of the number of resolvable features

within the image width. Use of grazing incidence in positive diffracted order reduces the requirement somewhat but further study is needed to try to reduce it still further.

We consider now some specific design details based on Fig 1. Consider a feature size δ, wavelength λ, numerical aperture NA, hologram width L and a square image field of side w. We then have $NA = \sin\beta = k\lambda/\delta$, where k is an empirical constant which we will take to be unity [7]. α is the grazing angle of incidence. α and β are thus to be chosen on reflectance and resolution grounds respectively. We are interested in the monochromaticity so we need to adopt a criterion for satisfactory imaging when temporal coherence is the limit. This issue has been investigated by Thieme [8] for the case of zone plates (the archetypal holographic optical element) from which we can say that satisfactory imaging is obtained if $\Delta\lambda/\lambda = 2/n$ where n is the number of *half period* zones. It follows that our criterion for satisfactory imaging is that the coherence length of the light ($\lambda^2/\Delta\lambda$) must exactly equal the maximum path difference.

We must be careful not to limit the hologram area so that the rays at the maximum angle β only just fill the image plane. This would result in the outer edge of the image plane receiving rays *only* at angle β and thus only at one spatial frequency. This is obviously not enough to encode an image. We have therefore enlarged the hologram so that the outer point (D) receives frequencies (angles) from approximately half-maximum to maximum whilst the inner point (E) receives frequencies from zero to maximum. Similar arguments apply in the sagittal direction and lead one to choose a hologram width about three times that of the image.

From the geometry we find $w = L \sin(\alpha+\beta)/2$ and $p = BE = L \sin\alpha/\sin\beta$. The maximum path difference is for rays arriving at E and is $HBE\text{-}AE = BE\text{-}GE = (L \sin\alpha)^2/2p$. Setting this equal to the the coherence length we finally obtain

$$\lambda/\Delta\lambda = kw \sin\alpha/(\delta \sin(\alpha+\beta))$$

To penetrate at least 0.2 μm into typical resist materials the wavelength should be shorter than 135 Å. As the wavelength decreases, however, the monochromator technology becomes more difficult and the coherent output of x-ray sources decreases. For grazing incidence angles of 0.15 rad or less both gold and carbon reflect with 60% or greater efficiency for all wavelengths over 95 Å. A gold reflector at this angle should therefore offer good performance even with some of the contamination build-up which is common at synchrotron light sources. If we choose k=1, δ = 0.1 μm and w = 1 cm, we obtain the following example configurations:

λ(Å)	α(°)	β (°)	L(cm)	p(cm)	$\lambda/\Delta\lambda$	beam width (cm)
100	8.59	5.74	8.1	12.1	60000	1.2
130	8.59	7.47	7.2	8.3	54000	1.1

Thus we arrive at a compact system with hologram area of about 8x3 cm^2 and reasonable other values except those of $\lambda/\Delta\lambda$ which are rather challenging. Synchrotron-radiation, grazing-incidence monochromators have not yet demonstrated these levels of performance. However, similar levels have been adopted as goals by the Advanced Light Source [9] (ALS) group and resolution of 2.5 x10^5 has been demonstrated [10] at 794 Å and 0.35x10^5 at 200 Å [11] using spectrographs. Since a lithography facility would probably work at *fixed wavelength* , one could imagine that it would not be too difficult to equal or even exceed the spectrograph values. With an undulator source one could easily make a diffraction-limited-(i.e., adequate)-resolution *design*. The problem would then, come down to grating fabrication tolerances.

By means of the grating equation (including conical diffraction for the sagittal direction) we can obtain values of the resolution with which the hologram needs to be written (the fringe period) to obtain 0.1 μm feature sizes in the final image. They are 0.50μm in the tangential and 0.10μm in the sagittal direction for λ = 100 Å and 0.47μm tangential and 0.10μm sagittal for λ = 130 Å.

Contrary to the cases of direct projection imaging by an optical system or of proximity lithography, we require to operate a very high resolution monochromator. This will require an x-ray source of low emittance and high brightness. This means that the ideal synchrotron source would be about a 6cm-period undulator on a high-brightness storage ring like the ALS. Such a source would be essentially single-mode and with reasonable assumptions one can project exposure times on the order of several minutes. Another interesting possibility is an x-ray laser. These devices already have the needed monochromaticity and although they do not yet have enough flux per mode at 100 Å to expose

1cm^2 of resist, one could argue that they probably would do on the timescale of a projection lithography program.

The authors' work in this area is supported by the US Department of Energy, Office of Energy Research, Office of Health and Environmental Research under grant number DE-FG02-89ER60858 to the Research Foundation of the State University of New York, subcontract No. 431-3378A (MRH) and National Science Foundation grant number BBS8618066 (CJJ).

FIGURE CAPTION

1. Optical layout and notation for discussion of the holographic scheme.

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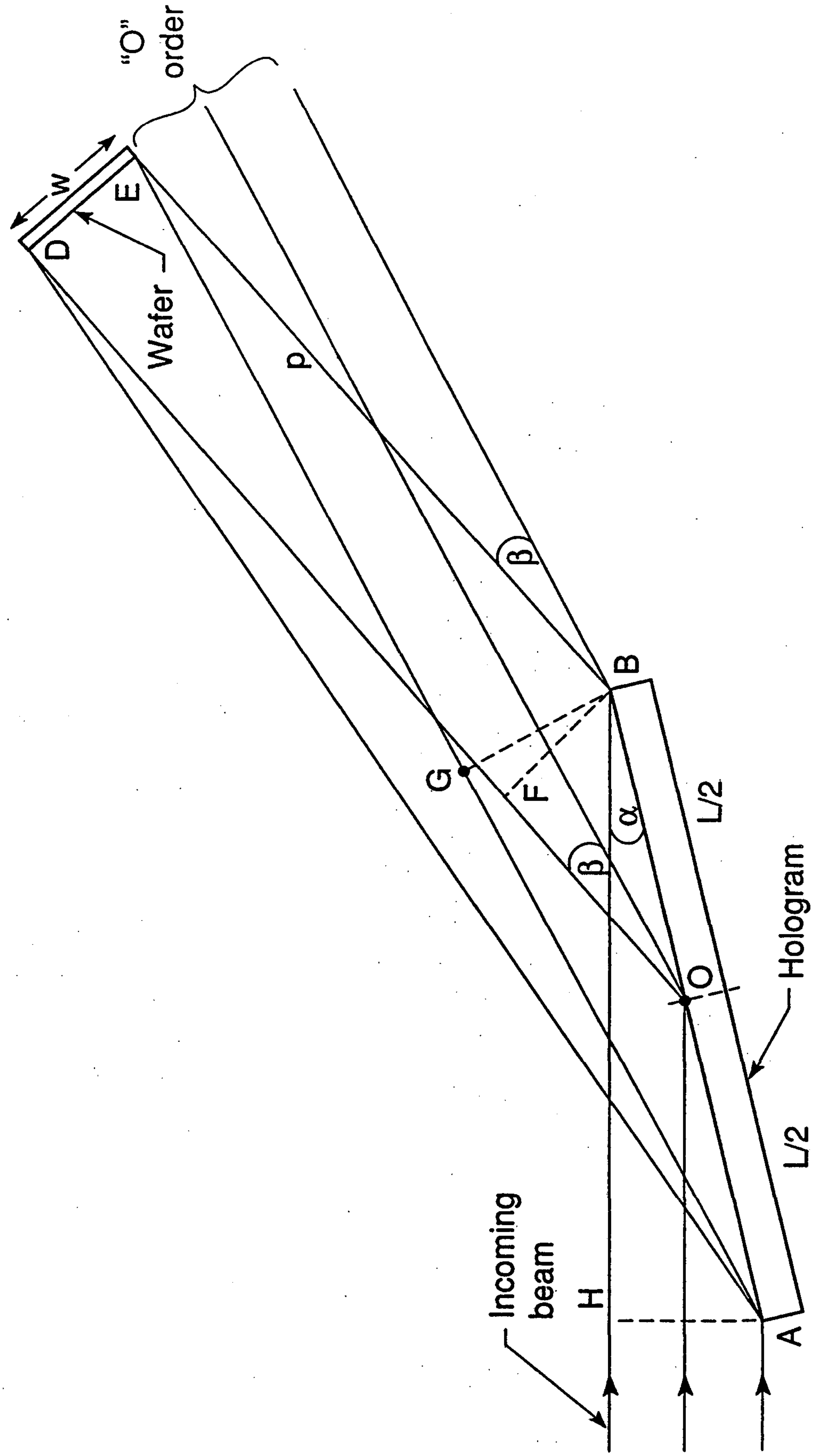

XBL 9012-5987

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