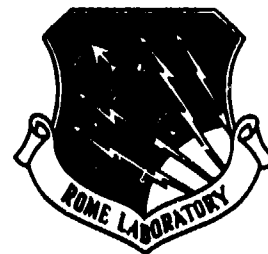


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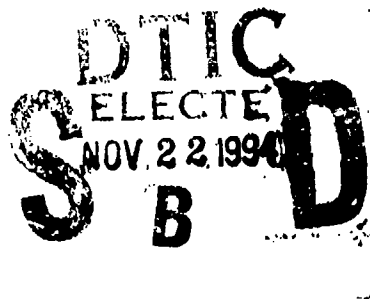


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DESIGN, FABRICATION, AND CHARACTERIZATION OF REFLECTIVE DIFFRACTIVE OPTICAL ELEMENTS IN Si FOR FREE-SPACE OPTICAL INTERCONNECTS

Cornell University

Steven M. Shank and Harold G. Craighead



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1. Introduction

The ability to fabricate integrated circuits with many densely packed devices that switch at high speeds, has produced the situation that the limitations in computing speeds are not due to on-chip processing effects, but are due to chip-to-chip and board-to-board interconnections. Fundamental limitations of electrical interconnections include cross-talk, energy radiation, clock skew, capacitive loading, and the difficulty of crossing wires without interference, all of which detrimentally effect the ability to transport high bandwidth data at high speeds using sophisticated, massively parallel and dense interconnect schemes, with highly precise clock signal distribution. These limitations are particularly severe for microwave signal communications where GHz clock rates limit electrical interconnects to a length range of mm to cm.¹ Multi-chip modules (MCMs), which have reduced interconnection length, reduced capacitive loading of the interconnects, smaller lead inductance, reduced size and weight, and reduced power consumption, compared to their printed circuit board (PCB) counterparts, have been developed for microprocessor rates in the 50-200MHz range where they outperform PCBs by over 100%.² MCMs also increase the number of possible interconnects which is essential for the efficient operation of advanced architecture CPU's such as RISC or CISC.² However, as the number of interconnections increase, the minimum pin spacing where acceptable signal cross coupling occurs will be reached and as clock rates increase to the GHz regime, an alternative to a purely electrical MCM technology will be required.^{3,4}

One such alternative is a hybrid architecture of planar electrical interconnects, and vertical, free-space optical interconnects for use in stacked MCMs.^{5,6} In previous final technical reports, the development of a free-space optical interconnect was described.^{7,8} Complete chip sets were fabricated, including light emitting diode (LED)

arrays⁶, diffractive optics⁹, and photodetector arrays. These chips were designed and fabricated to be compatible with current MCM technology. Work is currently in progress on incorporating the LED and photodetector chips in a MCM package manufactured by the General Electric Company.

In this report, further developments of the design, fabrication, and testing of the diffractive optics chip is discussed. This chip consists of a focusing, reflective, off-axis, diffractive optical element (DOE) that was designed to image a 4x4 array of GaAsP LEDs onto a 4x4 array of metal-semiconductor-metal silicon photodetectors.⁷ Although the design of transmissive architectures is more common^{10,11,12}, the use of a reflective geometry offers several advantages for both the MCM and DOE fabrication. Advantages for the MCM include patterned chips on a single side, the use of electrically active chips that face the same direction, and the use of semiconductor device substrates that are not required to be optically transparent. Advantages in the fabrication of reflective DOEs include buried diffractive and reflective surfaces¹³, shallower etched features, the ability to use the optic without an anti-reflection coating, and a decoupled substrate volume from the optic, which allows for the use of standard silicon processing techniques for the fabrication of the DOE.⁹ Section 2 of this report presents the design of the DOE using two different methods. The first method defines the phase contours of the DOE using equal path length modulo λ arguments. The second method uses the interference of two spherical waves to define the phase contours. This second method clearly points out that the DOEs that we are fabricating, are computer generated holograms. Section 2 also includes a discussion of the DOE design for maximizing the efficiency of the device by fabricating the surface relief for imaging using the first diffracted order. In section 3, the fabrication of 8-level DOEs using electron beam lithography and reactive ion etching (RIE) and the fabrication of continuously graded gratings using focused ion beam (FIB) milling is described. The characterization of these

devices by scanning electron microscopy (SEM) and atomic force microscopy (AFM) and an analysis of diffraction efficiency based on these characterization results is also presented. In section 4, preliminary results of the performances of linear test gratings are presented, and in section 5, conclusions and ongoing work are described.

2. Design of an off-axis, reflective, imaging diffractive optical element

2.1. DOE design using equal path length modulo λ arguments

The DOE consists of phase zones that are designed to image light by constructive interference. Each phase zone has a surface relief designed such that diffraction is maximized for the first order, thereby producing the potential for a highly efficient imaging device. The intersection of the plane of the optic with the family of confocal ellipsoids with foci at the desired object and image points, defines the phase zones of the DOE. The object and image points of the grating are taken to be the centers of the LED and photodetector arrays, respectively. The center of each phase zone is the point on the substrate where specular reflection connects the object and image points. This distance between object and image points through the specular point of the grating is defined as the specular distance. A schematic representation of the DOE is shown in figure 2.1a. The DOE is designed to be asymmetric in the x direction. This allows for off-axis operation which is necessary for reflective architectures which do not use beamsplitters. The DOE is symmetric in the y direction, which is sufficient for point to point imaging, and unoptimized imaging of object arrays⁷ A more sophisticated approach would average the aberrations across all detector elements and would require a more general design algorithm. Also shown in figure 2.1a are the parameters used to calculate the phase contours of the DOE. Figure 2.1b is a schematic of how the endpoint of a phase zone is calculated. The criteria for calculating these phase zones is that the sum of the distance from the object (0,0,0) to the endpoint (x,y,z) and the endpoint to the image (x₁,y₁,z₁) equals the distance through the specular point modulo λ . This is simply the criteria for constructive interference. This relation is given by,

$$\sqrt{x_s^2 + z^2} + \sqrt{(x_1 - x_s)^2 + (z_1 - z)^2} + m\lambda = \sqrt{x^2 + y^2 + z^2} + \sqrt{(x_1 - x)^2 + y^2 + (z_1 - z)^2} \quad (2.1)$$

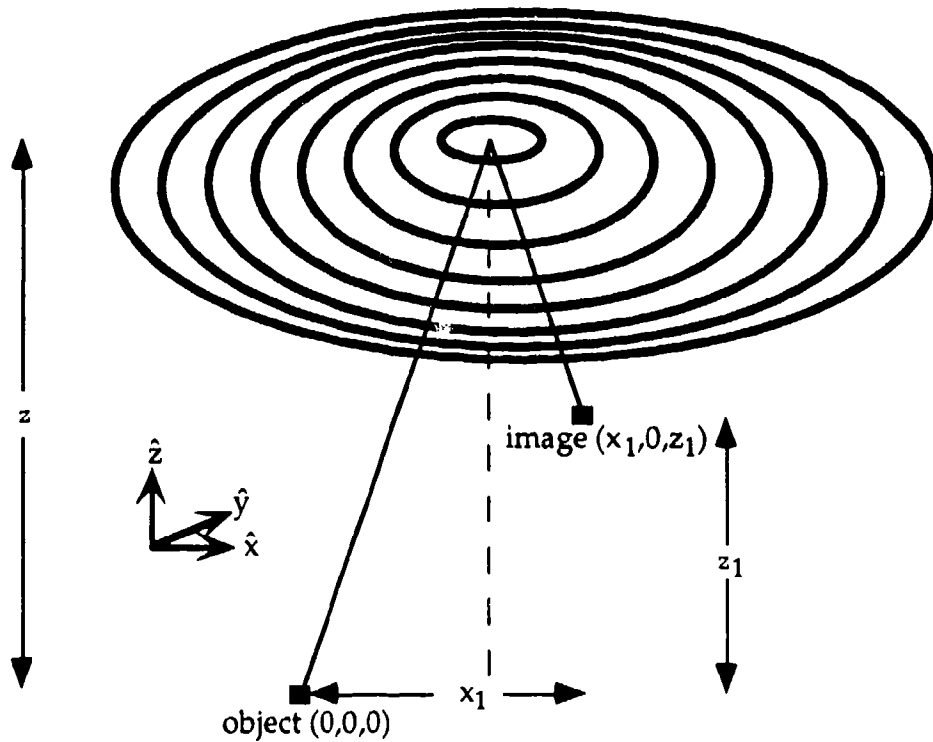


Figure 2.1a. Schematic representation of a DOE and the parameters used to calculate phase contours.

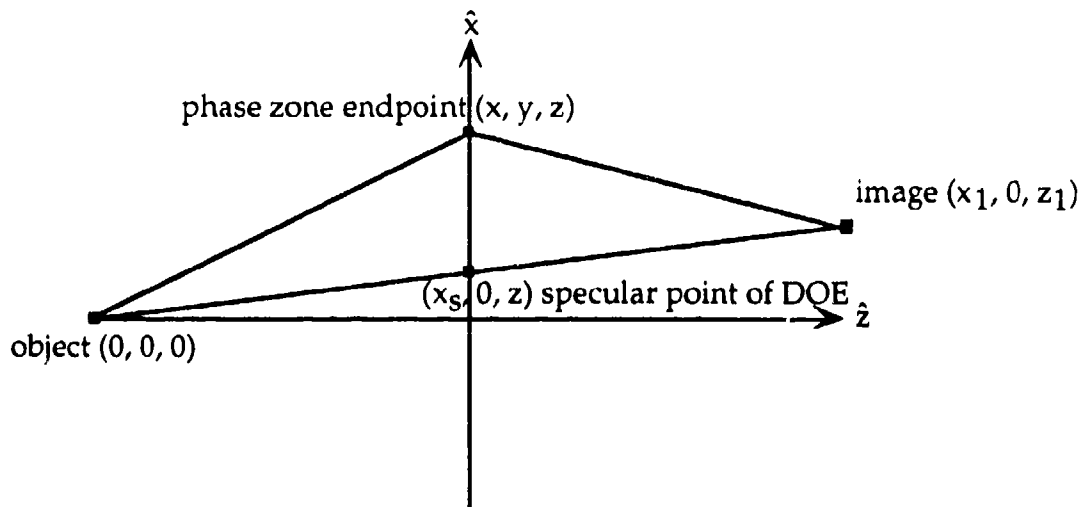


Figure 2.1b. Unfolded view of the diagram used to setup calculation of the phase zone endpoints of the focusing, reflective DOE. As discussed in the text, the endpoints are determined by solving for x and y using,

$$\sqrt{x_s^2 + z^2} + \sqrt{(x_1 - x_s)^2 + (z_1 - z)^2} + m\lambda = \sqrt{x^2 + y^2 + z^2} + \sqrt{(x_1 - x)^2 + y^2 + (z_1 - z)^2}$$

where x , y , z , x_1 , and z_1 are parameters given in figure 2.1, λ is the wavelength of the incident wave (center wavelength of the LED emitters), and m represents the particular phase zone. To define the surface relief, each phase zone is separated into subzones, where each subzone defines a surface relief step, with the total number of steps in each zone approximating a perfectly blazed relief which would image 100% of the incident intensity of a perfect point source into a point image. 2, 4, and 8 subzones are used to design 2-, 4-, and 8-level DOEs. These subzones are taken into account by replacing the $m\lambda$ term in equation (2.1) with $m\lambda/n$, where n is the number of binary levels of the DOE. Equation (2.1) can be solved for x to determine the endpoints of the phase zones. These endpoints are given by,

$$x_e = -\frac{(d^2 - x_1^2 - z_1^2 + 2zz_1)x_1}{2(x_1^2 - d^2)} \pm \frac{\sqrt{(d^2 - x_1^2 - z_1^2 + 2zz_1)^2 x_1^2 - 4(x_1^2 - d^2) \left[\frac{(d^2 - x_1^2 - z_1^2 + 2zz_1)}{4} - z^2 d \right]}}{2(x_1^2 - d^2)} \quad (2.2)$$

where x_e are the endpoints, and d is the specular distance modulo λ/n . Once the endpoints are determined, the phase contours are generated by solving equation (2.1) for y ,

$$y = \pm \sqrt{\frac{(d^2 - x_1^2 - z_1^2 + 2zz_1 + 2xx_1)^2}{4d^2} - x^2 - z^2} \quad (2.3)$$

where the x values in (2.3) are chosen to be evenly spaced between the endpoints x_e . Equation (2.3) can be further manipulated to be put in the form,

$$\frac{(x - h)^2}{a^2} + \frac{y^2}{b^2} = 1 \quad (2.4)$$

where,

$$h = \frac{-x_1(d^2 - x_1^2 - z_1^2 + 2zz_1)}{2(x_1^2 - d^2)} \quad (2.5)$$

$$a^2 = \frac{\left[\frac{x_1^2(d^2 - x_1^2 - z_1^2 + 2zz_1)^2}{4(x_1^2 - d^2)} - \frac{(d^2 - x_1^2 - z_1^2 + 2zz_1)^2}{4} + d^2z^2 \right]}{(x_1^2 - d^2)} \quad (2.6)$$

$$b^2 = \frac{\left[\frac{x_1^2(d^2 - x_1^2 - z_1^2 + 2zz_1)^2}{4(x_1^2 - d^2)} - \frac{(d^2 - x_1^2 - z_1^2 + 2zz_1)^2}{4} + d^2z^2 \right]}{d^2} \quad (2.7)$$

Since equation (2.4) is simply the equation of an ellipse, the phase contours of the DOE are ellipses centered about $(h, 0)$ with axis lengths of $2a$ and $2b$. The program FREDD (FREsnel Device Design), which has been previously described⁷, uses the algorithms in equations (2.2) and (2.3) to generate the phase contours of the desired DOE. Figure 2.2 compares several phase contours generated using FREDD with ellipses generated using equation (2.4). It is clear that from figure 2.2 that the ellipses generated using equation (2.4) are in agreement with the algorithms of FREDD.

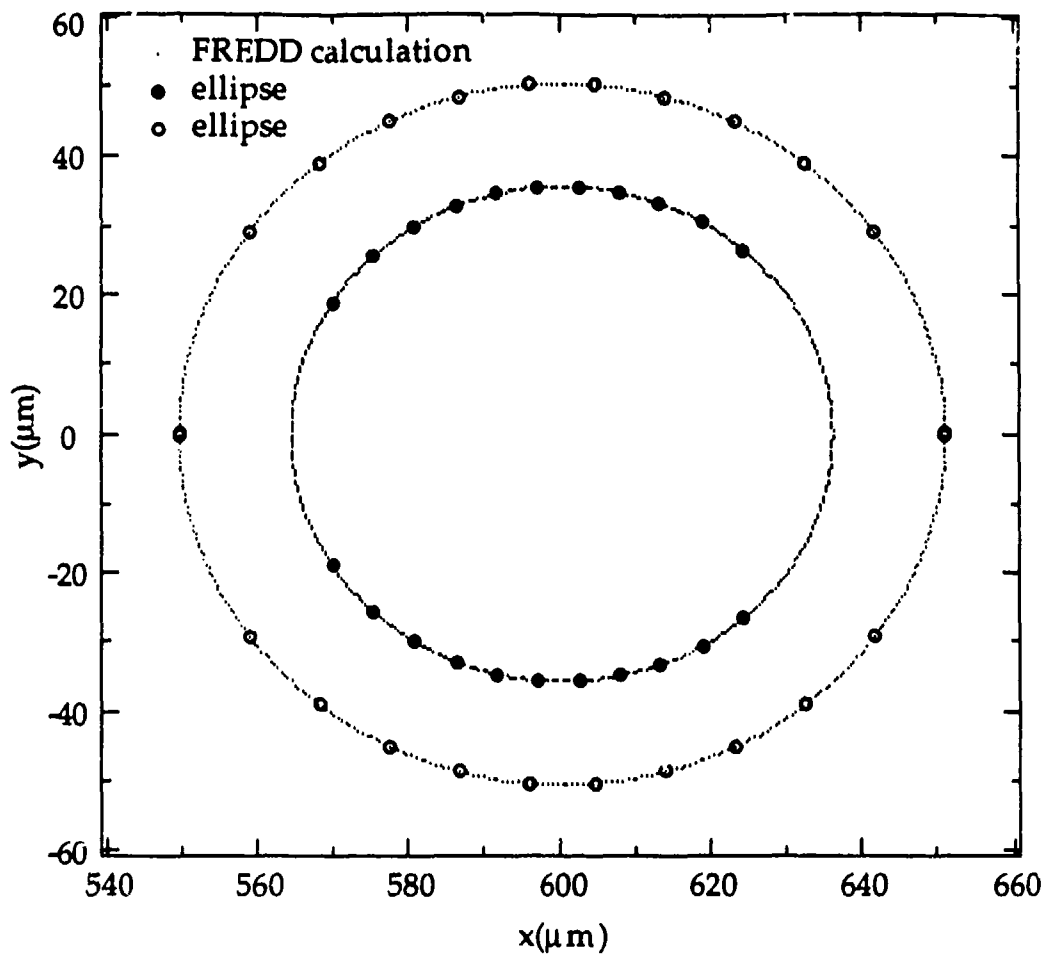


Figure 2.2. Phase contours generated using FREDD and equations (2.4) - (2.7).
 Parameters used to generate the contours are $x_1=0.9\text{mm}$, $z=6\text{mm}$, $z_1=3\text{mm}$,
 $\lambda=0.6328\mu\text{m}$, $m=1$, and $n=2$.

2.2. DOE design using the interference of two spherical waves generated by two point sources

An alternative to the method for generating phase contours described in section 2.1 is to determine the transmission function $t(x,y,z)$ that will convert a diverging spherical input wave, $E_{in}(x,y,z)$, that emanates from a point source at $(0,0,0)$ into a converging spherical wave, $E_{out}(x,y,z)$, that is imaged to the point $(x_1, 0, z_1)$. This relationship is given by,

$$E_{out}(x, y, z) = t(x, y)E_{in}(x, y, z) \quad (2.8)$$

where,

$$E_{in}(x, y, z) = \frac{A}{R_{in}} e^{i\phi_{in}} \quad (2.9)$$

$$E_{out}(x, y, z) = \frac{A}{R_{out}} e^{i\phi_{out}} \quad (2.10)$$

and,

$$\phi_{in} = \frac{-2\pi}{\lambda} \left(\sqrt{x^2 + y^2 + z^2} - \sqrt{x_0^2 + z^2} \right) \quad (2.11)$$

$$\phi_{out} = \frac{2\pi}{\lambda} \left[\sqrt{(x - x_1)^2 + y^2 + (z - z_1)^2} - \sqrt{(x_0 - x_1)^2 + (z - z_1)^2} \right] \quad (2.12)$$

where the convention has been chosen such that for a diverging spherical wave, the phase gets more negative farther from the specular point at the DOE plane and for a converging spherical wave, the phase gets more positive. The situation described in

equation (2.8) is analogous to the generation of a hologram where the reference beam is generated from the object point source and the picture beam is generated from the image point source. By interfering the reference and picture beams together at the (x,y,z) plane, $t(x,y,z)$ is generated. Upon subsequent illumination by E_{in} , E_{out} is generated and the point image at $(x_1, 0, z_1)$ is formed. Since for this work the case of purely phase objects are of interest, $t(x,y,z)$ is given by,

$$t(x, y, z) = \exp[i\phi_1] \quad (2.13)$$

where

$$\phi_1 = \phi_{out} - \phi_{in} \quad (2.14).$$

The phase function of the DOE, ϕ_f is equal to ϕ_1 modulo 2π so that the phase is always constrained between 0 and 2π , and across phase zone interfaces, the phase is reset from 2π to 0. The phase function of the DOE is therefore given by,

$$\phi_f(x, y, z) = \frac{2\pi}{\lambda} \left[\sqrt{(x - x_1)^2 + y^2 + (z - z_1)^2} - \sqrt{(x_s - x_1)^2 + (z - z_1)^2} + \sqrt{x^2 + y^2 + z^2} - \sqrt{x_s^2 + z^2} - m\lambda \right] \quad (2.15).$$

The phase zone boundaries are determined by setting $\phi_f = 0$, which produces an expression identical to equation (2.1). The DOE can therefore be thought of a fringe pattern or hologram that is generated by interfering two point sources. Since the fringe patterns, or phase contours are written using lithography, instead of being generated by the optical interference between two point sources, the DOEs can be classified as computer generated holograms. This formalism is useful for emitters with wave distributions other than spherical, such as vertical cavity surface emitting lasers, where

the wave distributions are Gaussian, and equations (2.9) and (2.10) can be modified accordingly.

2.3. DOE surface relief and effects on efficiency

The location of the phase zones in the plane of the DOE determines the image location for a given object location, while the surface profile within each zone determines the efficiency that light is diffracted into a given order. The efficiency of the DOE for a given relief profile can be determined by representing it as a Fourier series and solving for its Fourier coefficients. Ref The efficiency for a linear grating is given by,

$$\text{Efficiency} = \left| \frac{1}{L} \int_0^L e^{i\Phi(x)} e^{-i2\pi m f_0 x} dx \right|^2 \quad (2.16)$$

where $\Phi(x)$ is the phase profile of a phase zone, m is the diffracted order, f_0 is the grating spatial frequency, and L is the grating period. Equation (2.16) is also valid for radially symmetric DOEs by making a suitable change in variables for f_0 and replacing x with a radial coordinate. Ref For off-axis DOEs, equation (2.16) will most likely be more complicated. However, the effects of increasing the number of phase levels within a given period can be seen for all DOE types by evaluating equation 2.16 and in practice, each subzone defined by equations (2.2) and (2.3) is assigned a step height $\lambda/2n$. Figures 2.3a-c display one period of 2-, 4-, and 8-level approximations to a perfectly blazed linear grating. Since equation (2.16) is in the form of a finite Fourier transform, fast Fourier transform (FFT) routines can be used by noting that the frequency variable is equal to mf_0 . Diffraction efficiency versus order is also displayed in figures 2.3a-c. These diffraction efficiencies are generated by taking the two dimensional FFT of the corresponding phase profiles. A 64×64 point grid is used to assure that the contributions of efficiency to the orders displayed, due to aliasing from higher orders, is

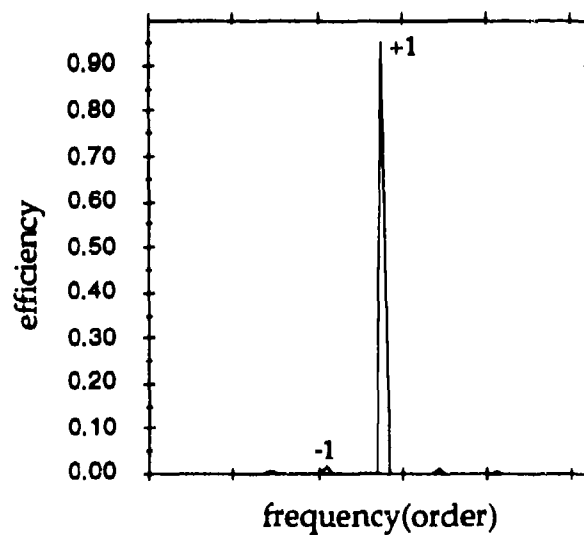
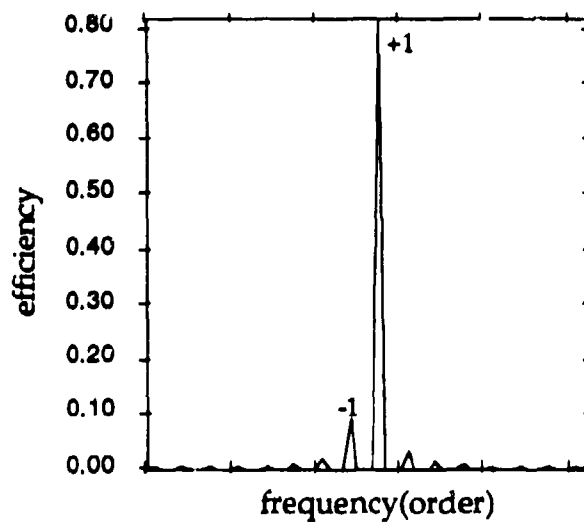
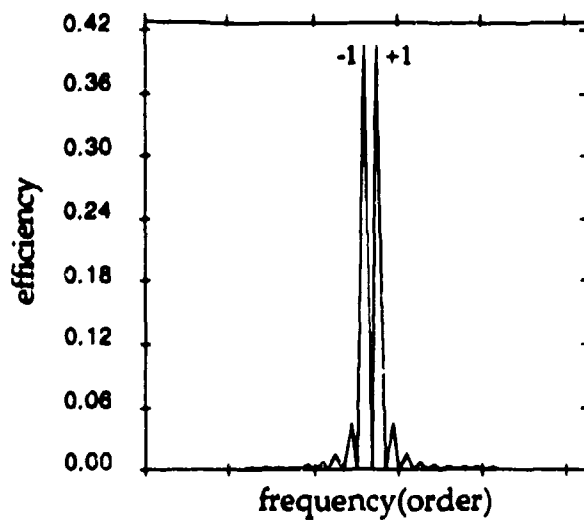


Figure 2.3. Efficiency versus diffraction order for (a) 2-, (b) 4-, and (c) 8-level binary surface relief profiles. Gray levels (left) indicate appropriate phase levels for a particular zone.

less than 0.1%. From figures 2.5b and 2.6b it is determined that very high efficiencies (>80%) in the first diffracted order can be achieved with 4- and 8-phase level approximations to a perfectly blazed surface relief. For the optical interconnect, both signal to noise at a particular detector and cross-talk between detectors must be considered. For a given emitter, the light not diffracted into the first order will be distributed over the other detectors leading to cross-talk. Since an 8-level relief has 5% of the light diffracted into higher orders while the 4-level has 20%, it is worthwhile to investigate 8-level DOEs despite the added complexity of their fabrication. If only signal to noise was of interest, a 4-level relief would most likely be sufficient.

2.4. Effects on surface relief due to off-axis operation

For off-axis rays incident on the grating at an angle θ_i with respect to the grating normal, the surface relief must be modified to account for the different optical path lengths. This effect is displayed in figure 2.4 for two rays at a zone interface. For a surface relief designed to operate in the first order, these two rays must have an optical path difference (OPD) of λ to interfere constructively. The surface relief h , is therefore given by,

$$h = \frac{\lambda}{\cos \theta_i + \cos \theta_d} \quad (2.17)$$

where θ_d is the angle of diffraction. The surface relief will therefore be larger compared to a relief designed for normal incidence.

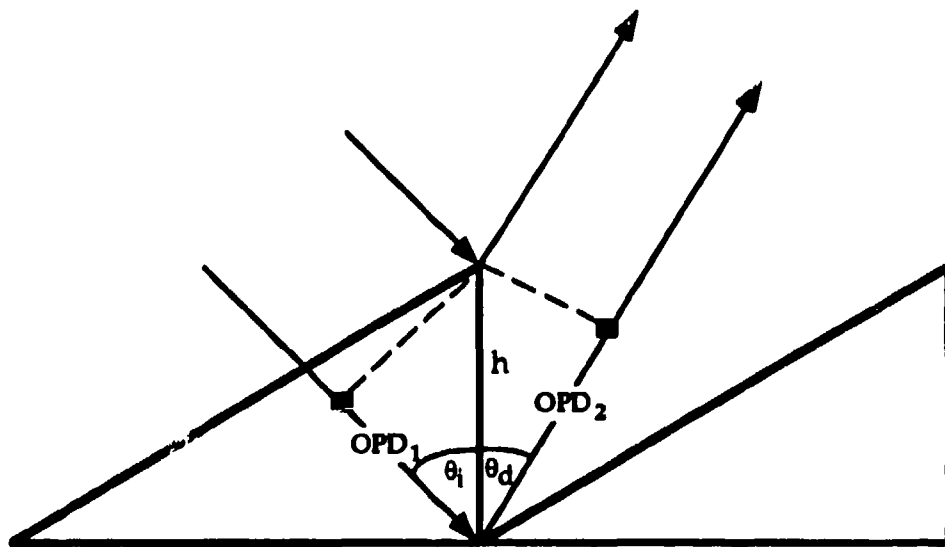


Figure 2.4. Surface relief for off-axis rays. The sum of the OPDs must equal λ for constructive interference to occur, thereby determining the surface relief.

3. Process development, fabrication, and characterization of DOEs using electron beam lithography and reactive ion etching, and focused ion beam milling.

3.1. Process development and characterization of fabrication of DOEs using electron beam lithography and reactive ion etching

3.1.1. Process overview

A schematic representation of the fabrication process is shown in figure 3.1. The wafer is first prepared with global and local alignment marks. Alignment marks consist of $4\mu\text{m}$ squares of lifted-off 1000\AA Pt and a 70\AA Cr adhesion layer. A 60nm film of thermally evaporated SiO_x is used to mask the wafer during the Si etch. Uniform SiO_x films with a minimum number of pinholes are generated by careful control of the input power to the SiO source material. A 90nm PMMA resist layer is spun on and baked. Phase contours are written by electron beam lithography at 20kV , a beam current of 2nA , a beam diameter of 100nm , and a field size of 0.8192mm^2 . The wafer is developed in a solution of 1:1 MIBK:IPA. The developed phase contours are etched into the wafer using a two step RIE process. The exposed pattern is transferred into the SiO_x using CHF_3 (30sccm) / O_2 (2sccm) at $0.25\text{W}/\text{cm}^2$ power and 30mT chamber pressure. The pattern is transferred from the SiO_x to the Si wafer using BCl_3 (10sccm) / Cl_2 (5sccm) at a sample bias of -100V and 20mT chamber pressure. The remaining oxide is stripped using a 6:1 solution of buffered HF. This process is repeated once to generate a 4-level DOE and twice to generate an 8-level DOE.

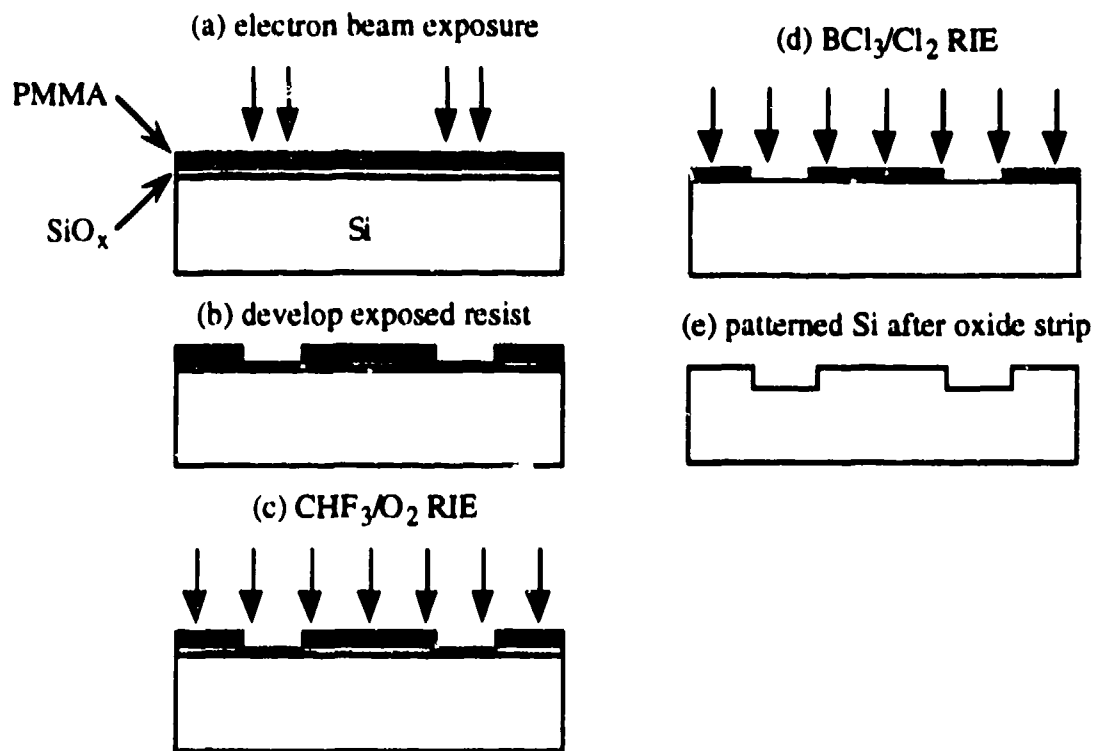


Figure 3.1. Overview of fabrication process for diffractive optical element in Si.

3.1.2. Alignment marks

The initial round of processing consists of the fabrication of global and local alignment marks on a 3" Si wafer. Global (wafer-level) alignment marks are used to correct for errors in rotation and translation by the insertion of the wafer into the electron beam lithography machine. Local alignment marks (field-level) are used to precisely locate, rotate, and scale the electron beam lithography field where the patterns are written.⁸ The layout and design of these marks are defined in the computer aided design (CAD) program SYMBAD. Global alignment marks are generated by the SYMBAD macro program GCA-KEY. A single global alignment mark is shown in figure 3.2. The $4\mu\text{m} \times 4\mu\text{m}$ square at the center of the arrows is the mark used by the electron beam lithography machine for alignment, while the arrows are guides for the operator to locate the center mark. $4\mu\text{m} \times 4\mu\text{m}$ squares are also used for local alignment marks. The patterns generated in SYMBAD are converted into an intermediate data format, Calma GDS-II using the SYMBGDS utility, and then converted into a binary pattern data (BPD) format which is the exposable format for the Cambridge Instruments EBMF 10.5/CS electron beam lithography system used in this work. GDS files are converted to BPD files using the Calma converter utility CALESF.¹⁴ As described previously⁸, the DOE patterns are exposed in four overlapping quadrants. 4-point local field alignment in each quadrant is used to align successive binary levels of the DOE. Three marks are used for global alignment.

The lift-off process used to fabricate alignment marks is schematically displayed in figure 3.3. The wafer is cleaned with a spin treatment of acetone and isopropyl alcohol (IPA) and then spun dry. The wafer is baked at 170°C for 10min. The wafer is then coated with a bi-layer resist. The first layer consists of a 6% P(MMA-MAA) copolymer dissolved in chlorobenzene. The copolymer solution is spun on at 1800rpm

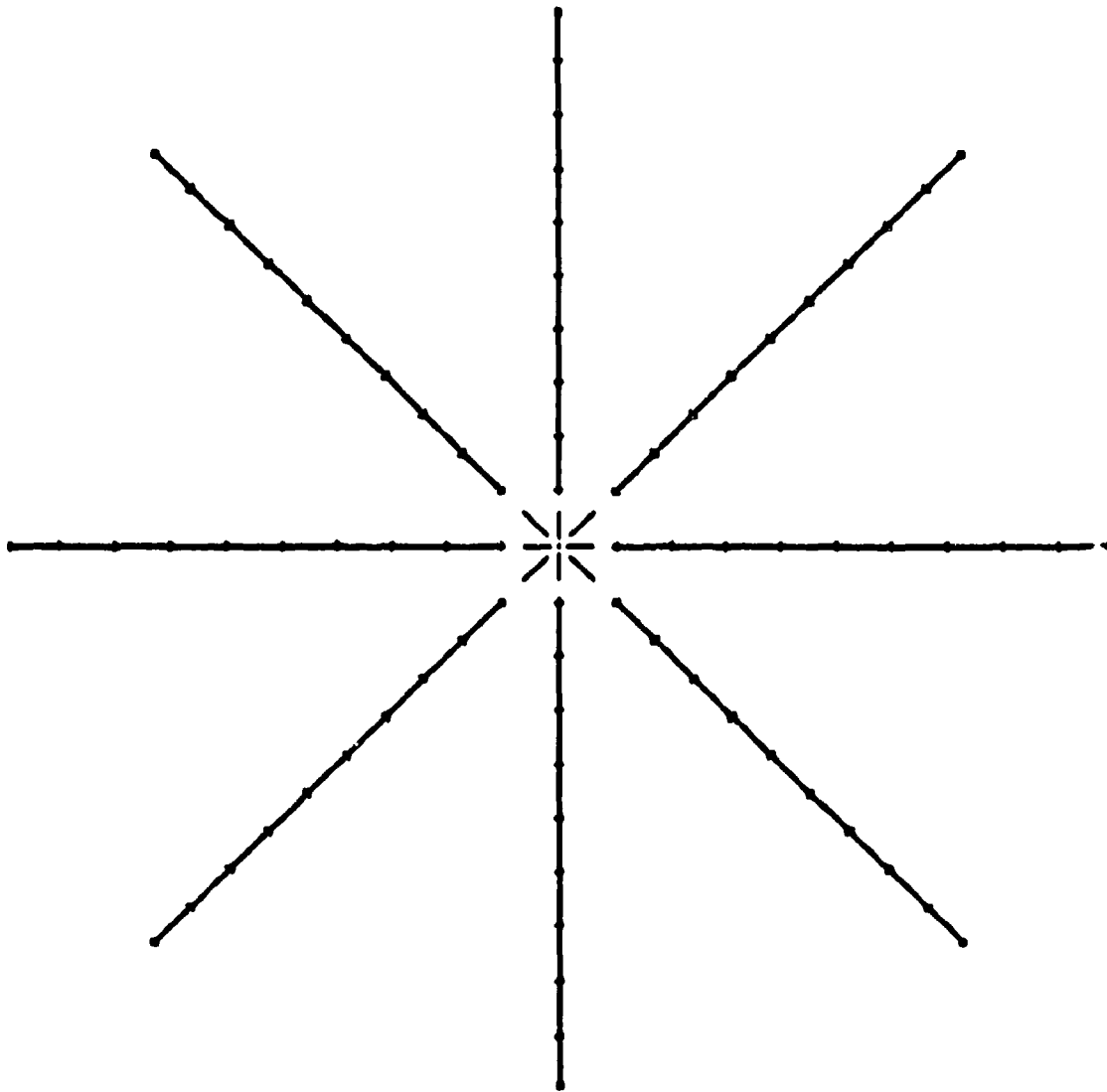


Figure 3.2. CAD pattern of a global alignment mark used to correct for rotation and translation errors at the wafer level.

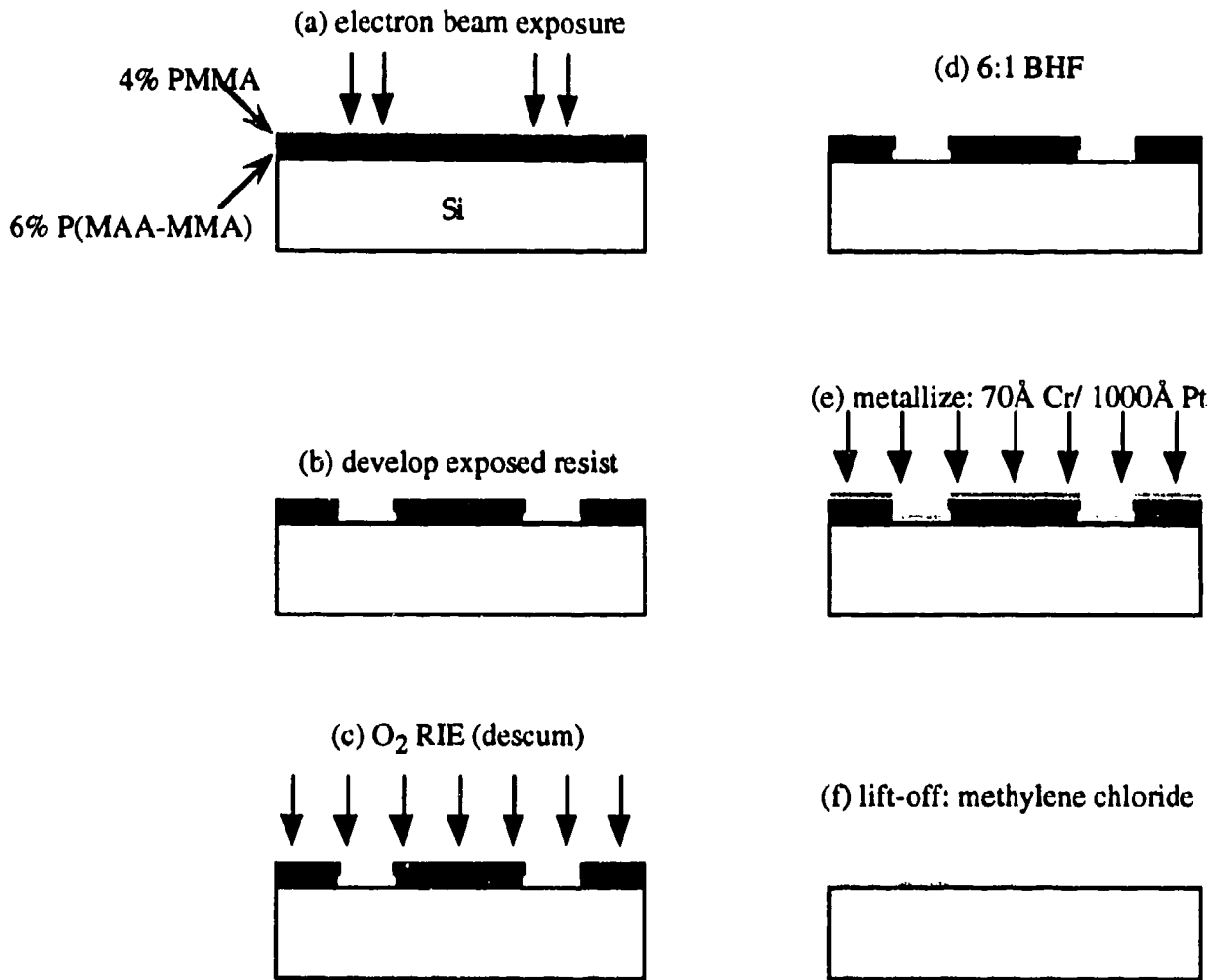


Figure 3.3. Process for fabricating alignment marks.

for 60sec and then baked at 170°C for 1hr. This produces a layer approximately 300nm thick. The second layer consists of 4% PMMA that is spun onto the wafer at 4000rpm for 60 seconds and then baked at 170°C for 1hr. This thickness of the second layer is approximately 240nm. Due to scattered electrons in the resist and backscattered electrons from the oxide and substrate during exposure, and the relative sensitivities of the two resists, an undercut profile occurs. This undercut profile is critical for lift-off. The wafer is then loaded into the EBMF where the alignment marks described in the previous paragraph are written into the bi-layer resist. EBMF parameters include a 20kV accelerating potential, 2nA beam current, 100 μ C/cm² dose, and 0.8192mm² field sizes. A single global alignment mark extends across 9, 0.8192mm² fields while a single set of local marks are centered in a single 0.8192mm² field. Automatic electron beam deflection, distortion, focus, and stigmation corrections are performed prior to the exposure. Typical beam diameters range from 100nm to 150nm and typical distortion errors across the field are less than 25nm or the linear dimension of one exposure element. After exposure, the wafer is developed for 90sec in a 1:1 solution of MIBK:IPA, rinsed in IPA, and blown dry. A 0.08min O₂ plasma descum is performed in the PT-72 reactive ion etcher. Prior to loading the wafer into the etcher, a 5min O₂ clean is performed to remove contamination left from previous users of the machine. PT-72 etching parameters include a 30% O₂ flow rate, a 20% RF power level, and a chamber pressure of 60mT. Up to two wafers have been descummed simultaneously with no evidence of detrimental loading effects. A wet etch using 6:1 buffered HF is performed for 5min to remove the native oxide on the wafer. The wafer is subsequently rinsed in de-ionized (DI) H₂O. Evidence that the etch behaved correctly is displayed if the H₂O does not wet the wafer surface. Native oxide formation should be prevented for approximately 1hr after this etch, so adequate time is available to perform the next processing step, metal deposition. For metal deposition, a special 'lift-off' chuck is used to hold the wafer. This chuck is radially symmetric about the electron beam source

material, thereby allowing metal atoms to strike the wafer normal to the surface. This is critical for preventing metal from bridging across the overhang profile of the developed resist, thereby preventing proper lift-off. 70Å of Cr is thermally evaporated onto the wafer for use as an adhesion layer for the 1000Å Pt that is subsequently evaporated using electron beam excitation. An evaporation rate of ~1Å/sec is used for the Cr and ~3Å/sec for the Pt. The CVC SC4500 evaporator is used so that both thermal and electron beam evaporations can be done in the same chamber, thereby maintaining a vacuum between evaporations. The sample is allowed to cool for 15min between evaporations. Once the wafer is unloaded from the evaporation chamber, it is placed in a methylene chloride bath. The majority of the metal on the wafer immediately lifts-off, leaving 1000Å Pt alignment marks. A second bath of methylene chloride is used to remove most of the remaining metal scum, and then the wafer is rinsed in an IPA bath and blown dry. Further removal of microscopic metal particles that were lifted-off and then reattached can be accomplished by a spin rinse of methylene chloride, acetone, and IPA.

3.1.3. Thin film SiO evaporation

The next step in the fabrication process is the evaporation of a 60nm film of SiO_x onto the Si wafer. The SiO_x is used as an intermediate masking layer for the selective etching of Si.^{Ref} Thermal evaporation is chosen over plasma enhanced chemical vapor deposition (PECVD), since less pinholes in the film are generated and the oxide is less conformal to previously patterned surface reliefs, thereby decreasing surface roughness profile irregularities. The source material for the evaporation is crystalline SiO. In previous reports⁸ a special chimney furnace was used to evaporate the SiO. The chimney furnace was used to prevent solid particles, that are outgassed from the source due to trapped water vapor, from embedding into the wafer, thereby ruining the quality

of the film. The power required to operate this furnace, however, is at the maximum power capacity of the evaporation system. Therefore, a standard tungsten source boat was tried, with the surprising result that high quality SiO_x films were deposited, at input powers well within the operating limits of the evaporation system. To deposit high quality films of SiO_x using this method, the source must be thoroughly outgassed before deposition can occur. The source current was increased at a rate of 10A/min until 150A was reached. The source was then stabilized at 150A for 7min and then deposition was initiated.

3.1.4. DOE pattern definition and electron beam lithography

DOE phase contours are generated using the algorithms given in equations (2.2) and (2.3) by FREDD. The conversion and subsequent data fracturing of these phase contours to BPD format has previously been described.⁸ Programs MODIFY⁸ and POLY.FOR⁸, which are used in the conversion process, have been modified according to the particular application. Figure 3.4 displays one quadrant of a phase subzone, after conversion and fracturing into BPD format. The primitive shapes shown in this figure are individually addressed by the Cambridge EEMF. 2 million primitive shapes are addressed for a 1mm diameter 2-level DOE, 6 million primitive shapes are addressed for a 4-level DOE, and 14 million primitive shapes for an 8-level DOE. Since 0.8192mm² field sizes are being used, the EBMF, using 15 bit digital-to-analog converters, has the ability to address these primitive shapes at 1.074×10^9 locations per quadrant, by using a 25nm pixel size. This makes pattern digitization unresolvable small, even for patterns with large curvatures. Linear 2-, 4-, and 8-level gratings have also been generated in SYMBAD and then written by electron beam lithography. These gratings are used as test structures to test the efficiency of a specific local spatial frequency region of the DOE, as well as monitor the ability to align successive multiple levels with submicron

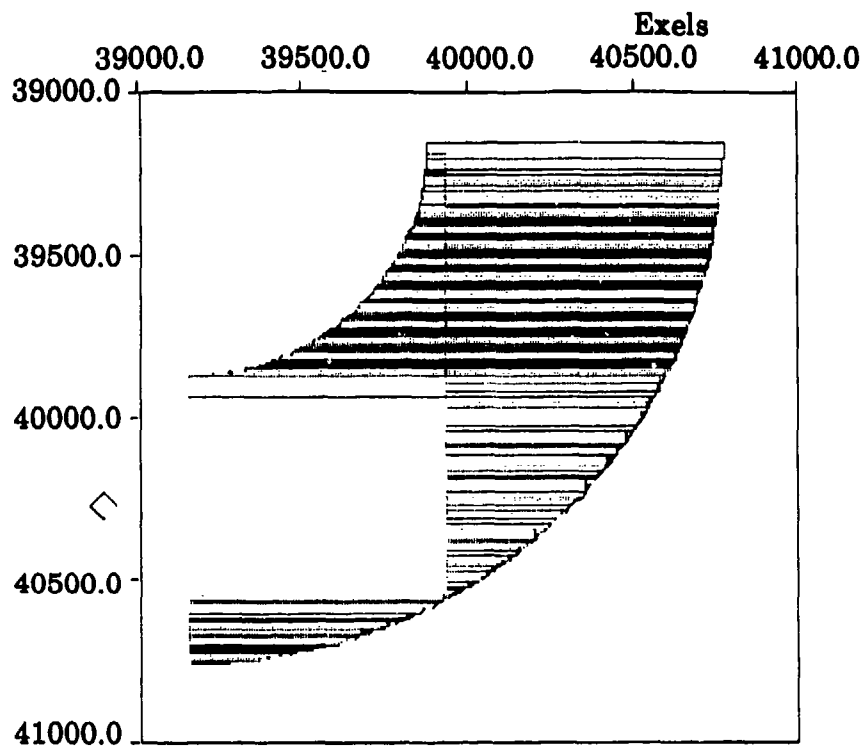


Figure 3.4. BPD data of a fractured subzone.

periods. All patterns are exposed at 2nA beam current.

3.1.5. Proximity effects on grating fabrication

To accurately align multiple levels of a DOE, not only must the alignment to metal marks be precisely defined (typical accuracies on the order of $0.1\mu\text{m}$), but the electron beam dose must be correct to define 50% duty cycle lines and spaces. Due to proximity effects caused by the scattering of secondary and backscattered electrons, overexposure or underexposure can occur for a given combination of resist thickness, oxide thickness, substrate type, and doping combination, if the electron beam dose is not correctly calibrated. The effects of overexposure and underexposure on an 8-level grating are displayed in figures 3.5a and 3.5b, respectively. To calibrate the dose, a series of 50% duty cycle lines and spaces were written using a range of doses ($40\text{-}110\mu\text{C}/\text{cm}^2$) while keeping other fabrication conditions the same as the actual DOE, including development and etching. Line and space widths were written in the range of $0.3\text{ - }4.0\mu\text{m}$, since this is the range of feature sizes used to fabricate the DOE. The cumulative results for proximity effects over a range of period sizes is displayed in figure 3.6. This data identifies $60\mu\text{C}/\text{cm}^2$ as the dose with the smallest pixel error (less than one pixel) over the range of feature sizes used to fabricate the DOE. 8-level linear gratings were fabricated at doses of 50, 60, 70, and $80\mu\text{C}/\text{cm}^2$. These linear gratings are displayed in figure 3.7. As expected, $60\mu\text{C}/\text{cm}^2$ produces the best results, while for $80\mu\text{C}/\text{cm}^2$ trenches at step interfaces clearly display overexposure characteristics (trenching) and similarly, underexposure effects are observed for a dose of $50\mu\text{C}/\text{cm}^2$. It should be noted that previously^{8,9}, an in depth analysis, taking into account proximity effects as well as the effects of transferring the developed pattern into the Si substrate using RIE, was used to determine the ideal dose. Using fabrication procedures identical to this work, a dose of $90\mu\text{C}/\text{cm}^2$ was determined. This is significantly different from

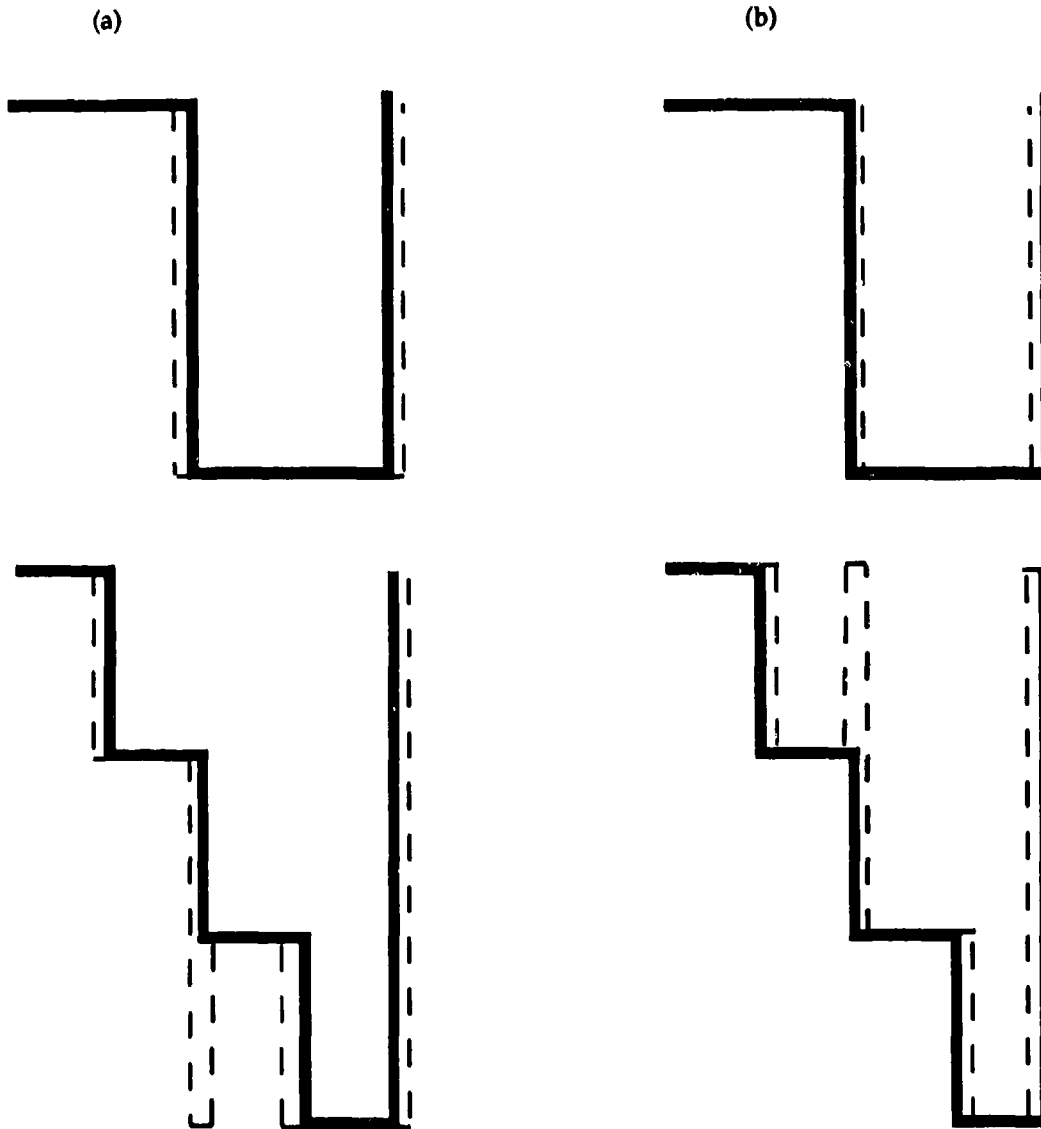


Figure 3.5. Schematic representation of the effects of (a) overexposure and (b) underexposure on the alignment of binary levels. The solid profiles are desired and the dashed profiles are the result of proximity effects. The top figures are the resulting profiles after one etch and the bottom profiles are the profiles after two etches. For overexposure, trenches develop at step interfaces and for underexposure, mesas develop at step interfaces.

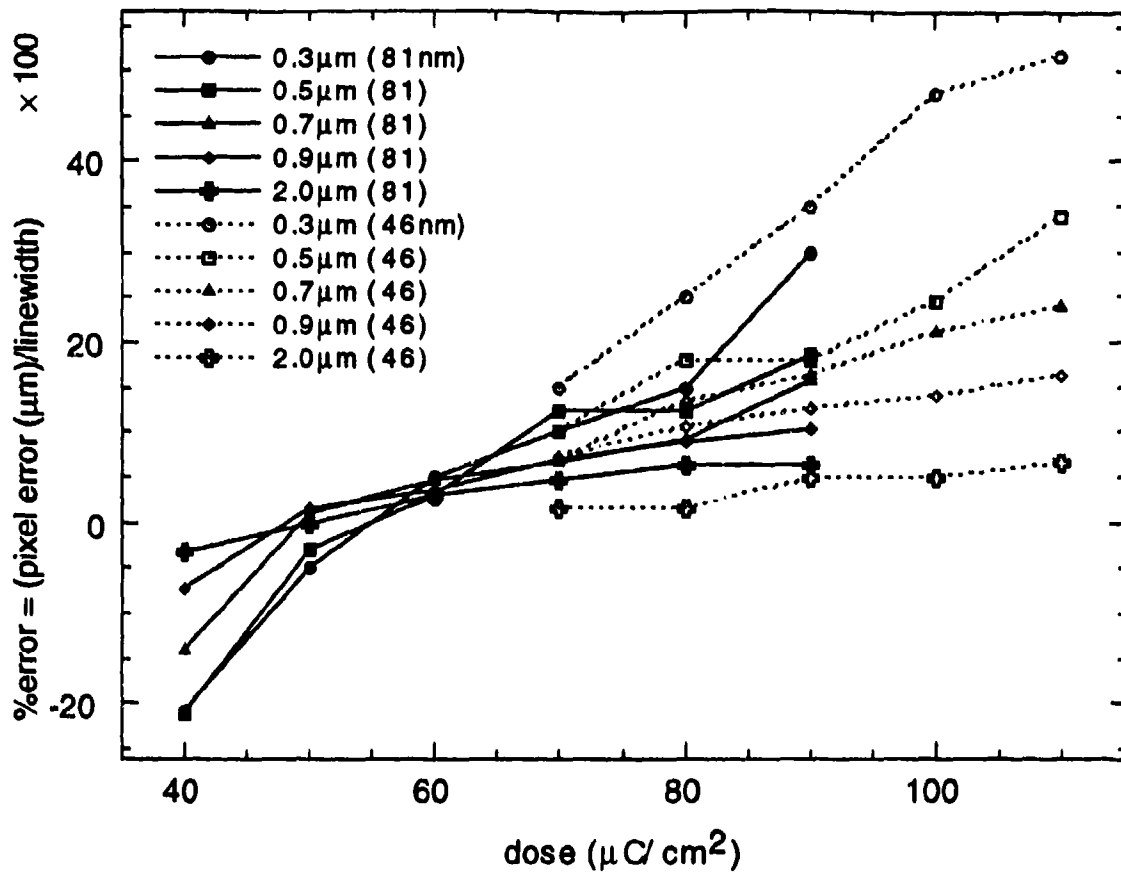


Figure 3.6. % pixel error versus dose for DOE feature sizes. $60\mu\text{C}/\text{cm}^2$ is identified as the optimum dose since errors less than one pixel are observed over the range of feature sizes.

the ideal dose determined in this work, which signifies that slightly different environmental conditions in the lab, as well as possibly different conditions of the electron beam lithography machine (new filament, different machine calibrations) can cause significantly different ideal exposure conditions. Therefore, dose calibrations for a given process must be performed regularly. Using a high-resolution (2nm) field emission SEM (Hitachi S800), a single period can be examined and is displayed in figure 3.8. This figure demonstrates the ability to align multiple levels to within 50nm worse case, and on the order of 2nm best case.¹⁵ Also displayed in figure 3.8 are several periods of this grating, demonstrating the uniformity of the fabrication. Such accurate alignment allows us to fabricate highly efficient DOEs.

3.1.6. Reactive ion etching

The transfer of the exposed pattern from the SiO_x to the Si wafer consists of a three step RIE process using a Plasma Therm PK1250 reactive ion etcher. In the first step, a 45sec etch using BCl_3 (40sccm)/ H_2 (20sccm) and a sample bias of -200V removes residual water contamination on the substrate and carrier. In the second step, a 45sec etch using Cl_2 (5sccm)/ BCl_3 (40sccm)/ H_2 (20sccm) and a sample bias of -300V removes the native oxide on the exposed Si surfaces. Both of these steps occur at a chamber pressure of 20mT. The Si is then patterned using BCl_3/Cl_2 . For DOEs to be tested at the wavelength of 632.8nm (HeNe laser wavelength) etch depths of 160nm, 80nm and 40nm are required for 2-, 4-, and 8-levels respectively. An extensive series of etch test runs were performed to determine flow rates, chamber pressures, and sample bias voltages required to achieve the desired etch depths. The results of these etch tests are displayed in figure 3.9. To determine the etch depth, after the sample is unloaded from the etcher, the remaining SiO is stripped using 6:1 BHF (2 minute bath), dunked in a DI H_2O bath, blown dry, and then measured using a Tencor alpha-step. It is clear from figure 3.9 that the conditions that

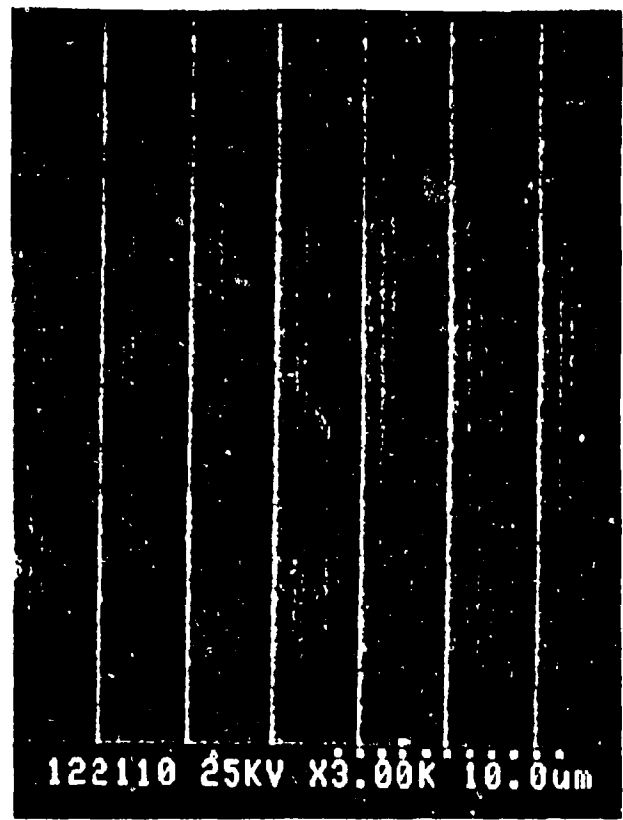
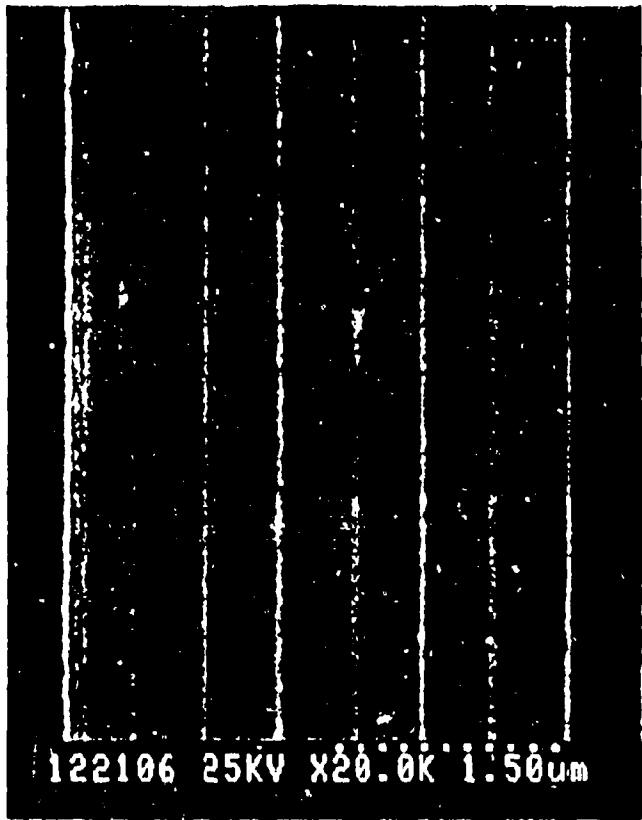


Figure 38 One (left) and several (right) periods of an 8 level linear grating

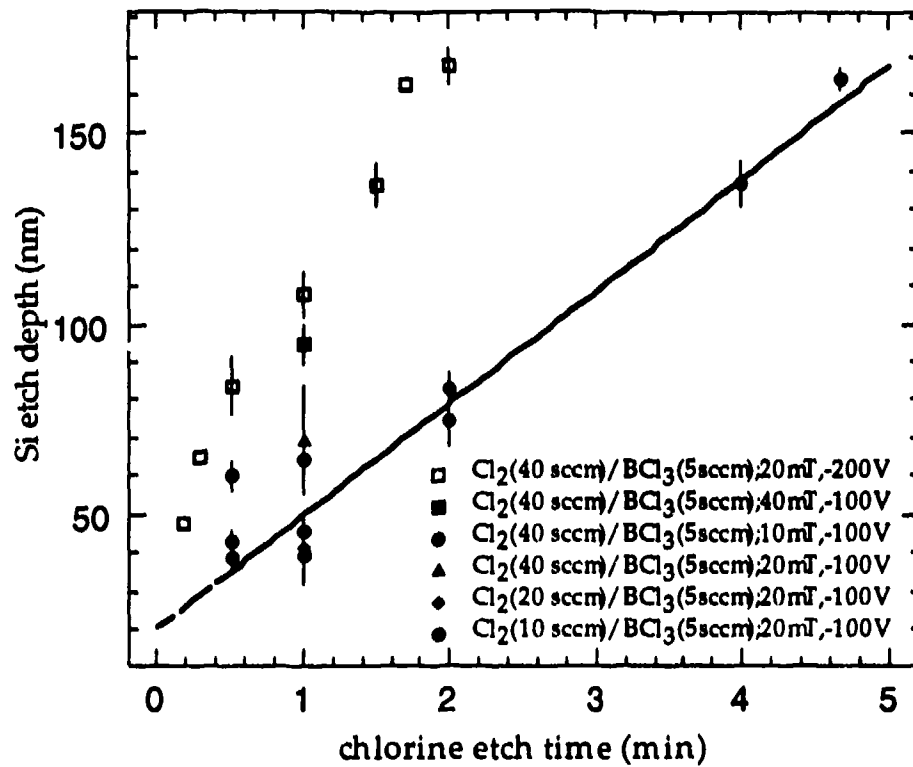


Figure 3.9. Si etch depth versus etch time for different flow rates, chamber pressures, and sample biases. The solid line is a linear fit to the data for the etching conditions most suitable for the 8-level DOE.

produce the desired etch depths in the most well controlled manner are BCl_3 (10sccm)/ Cl_2 (5sccm) at a sample bias of -100V and a chamber pressure of 20mT.

The data in figure 3.9 also indicates that the goal etch depths are repeatable to within +/- 10nm. To determine the effect of the etch error on efficiency, equation (2.16) is evaluated. Diffraction efficiency versus etch error is displayed in figure 3.10 for 4- and 8-level binary surface reliefs. In this plot, etch error refers to the error of each etch for 4- or 8-level DOEs. For an 8-level DOE, a +/- 10nm variation in etch depth produces efficiencies ranging from 95% to 77%, and for a 4-level DOE, 81% to 77%. This first order calculation demonstrates that tight tolerances are required to achieve near theoretical efficiencies for 8-level DOEs, with more relaxed requirements for 4-level DOEs. Since the shallowest etch produces the largest percent phase error, it should be performed first, so if necessary, subsequent etch depths can be adjusted to prevent the accumulation of phase errors.

3.1.7. Characterization of grating etch depths using atomic force microscopy

To characterize the etch depth and surface profile of the grating, AFM is used, since the alpha-step is not useful for submicron features. Area and line scans are displayed in figure 3.11, for several periods of an 8-level linear grating fabricated at near optimal conditions as described in sections 3.1.5 and 3.1.6. This grating was processed by etching deep features first, and then etching subsequently shallower features. For the third and shallowest etch, a large deviation (20nm) occurred in the etch depth producing significant errors in the step heights of the grating shown in figure 3.11. Using equation (2.16) a first order efficiency of 77.5% is expected and a non-zero zero'th order efficiency of 2.3% is expected. Since the PK1250 is a multi-purpose machine that is used for etching materials other than Si (i.e. GaAs), processes that use different gases than those used to

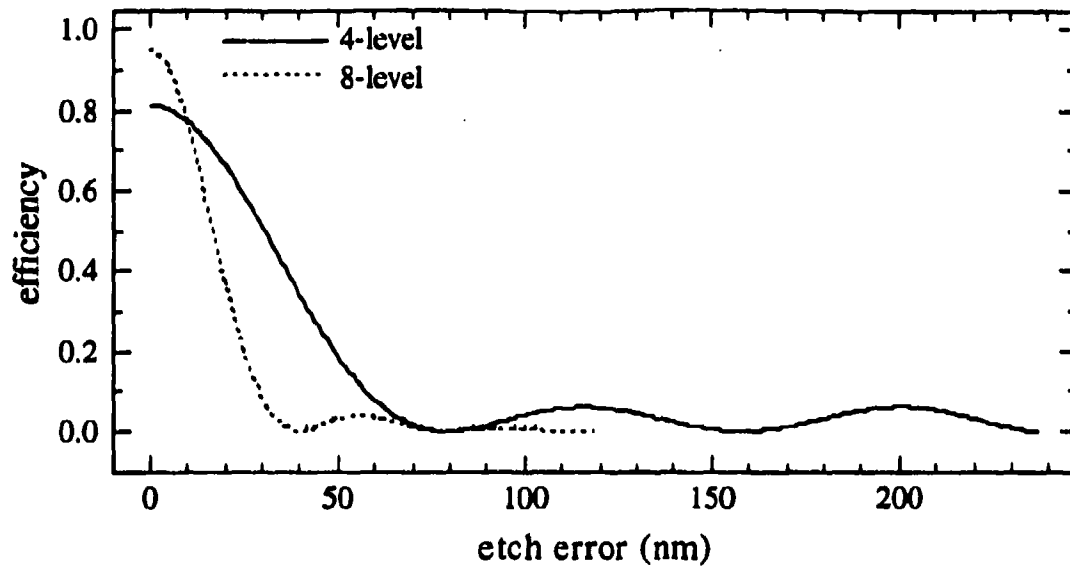


Figure 3.10. Diffraction efficiency versus etch error for 4- and 8-level binary surface reliefs. For a 9.7nm etch error at each etch, the efficiencies for 4- and 8-levels are equal.

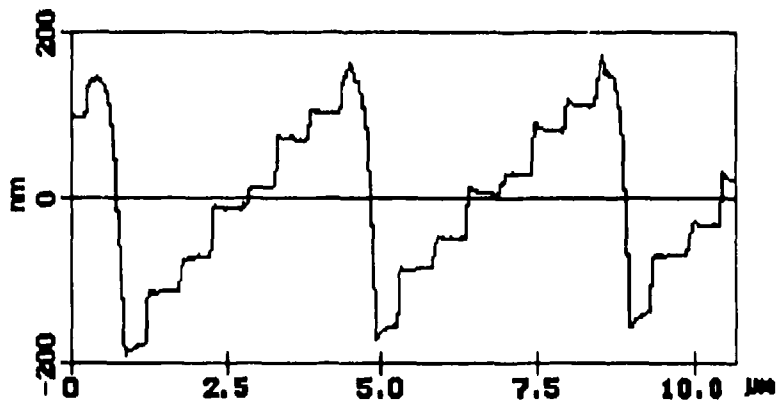
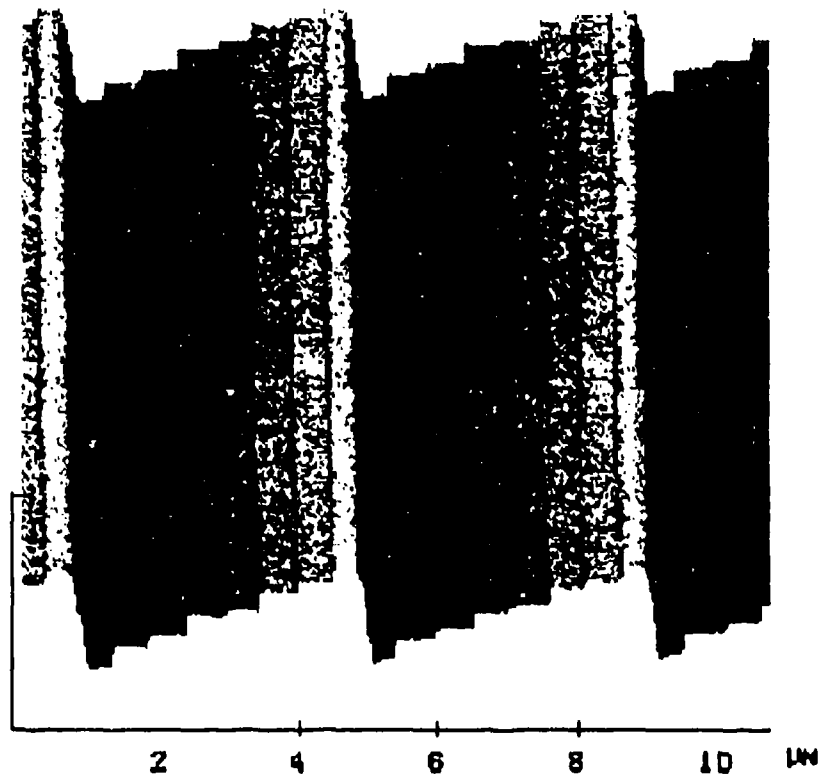


Figure 3.11. AFM surface profile (top) and line scan (bottom) of several periods of an 8-level linear grating fabricated at $60\mu\text{C}/\text{cm}^2$.

etch Si, (i.e. argon and methane) can produce contamination of the chamber, thereby changing the etch rate. A cleaning step should therefore be included in the process, possibly using the gas mixture of the first etch step, without the sample loaded into the chamber.

3.2. Process development and characterization of DOEs fabricated by focused ion beam milling

A $^{69}\text{Ga}^+$ focused ion beam is used to sputter continuously graded gratings.^{16,17} The linearly blazed surface relief is milled in a single lithography step by linearly varying the sputter yield across a given period. The linear variation in sputter yield is produced by a linear variation in area dose of the ion beam. For a reflection grating designed to operate at $\lambda=632.8\text{nm}$ with $4\mu\text{m}$ wide periods, the area doses used to produce surface reliefs of $\lambda/2$ range from 4×10^{16} to 6×10^{17} ions/cm². For a given area dose, the FIB is raster scanned the length of the grating using a 22.5nm square pixel size. The beam diameter is sub-tenth micron and the beam energy is 60keV. To account for the effects of redeposition of material and beam profile, a pattern scheme of 8 overlapping area doses within a given period is used. AFM is used to characterize the surface relief profile. AFM surface and line scans are shown in figure 3.12. Since binary surface relief profiles are only an approximation to a continuous blaze, FIB gratings can potentially produce superior diffraction efficiencies. The fabrication of a continuously graded surface relief by FIB milling, also suggests that diffractive optical elements with binary surface profiles or surface profiles with inaccuracies due to fabrication errors, such as the grating described in section 3.1.7 can be repaired and rendered continuous by FIB milling, thereby producing high-quality surface masters. For our particular FIB system, pattern write times can be prohibitive (a $48\mu\text{m}\times 48\mu\text{m}$ grating was written in 1.7hrs), thereby limiting the fabrication to very small areas, or the repair of slightly

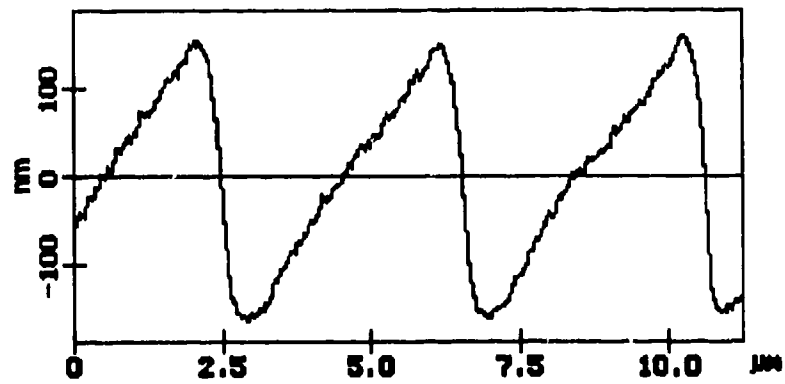
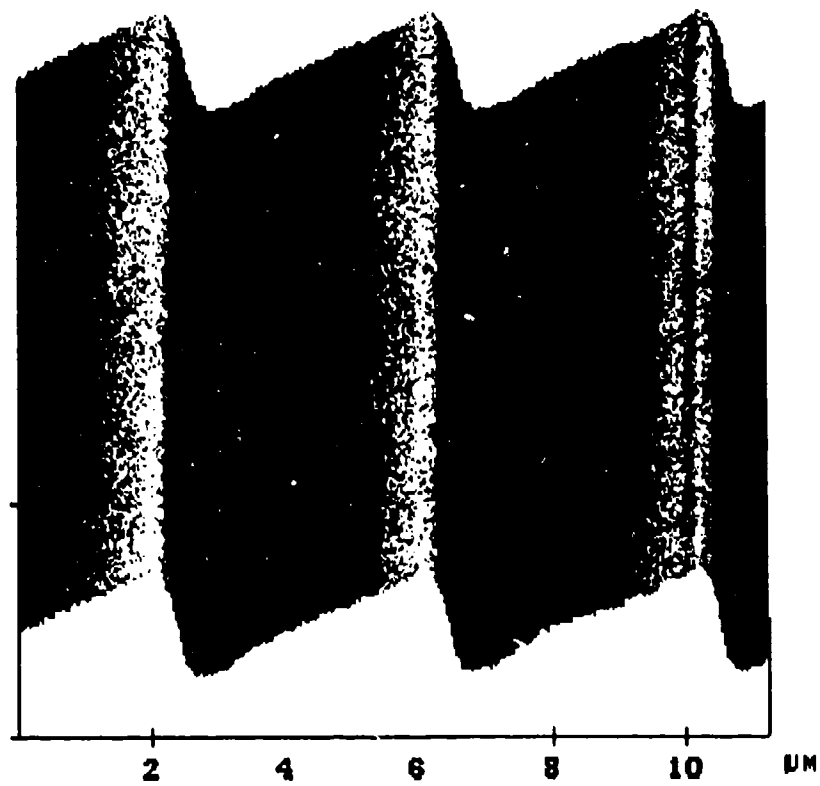


Figure 3.12. AFM surface profile (top) and line scan (bottom) of several periods of a continuously blazed grating fabricated using focused ion beam milling.

larger areas. Other FIB systems¹⁸, however, have write times that are faster by factors of 10, thereby potentially realizing the ability to fabricate high-quality diffractive optic masters.

4. Device performance

The zero'th and first order diffraction pattern for the 8-level linear grating ($60\mu\text{C}/\text{cm}^2$) is shown in figure 4.1. The relative efficiency (taking into account the reflectivity of the Si) of the first order is 75% and for the zero'th order, 6%. As expected from the analysis in section 3.1.7, the efficiency of the first order diffraction is less than theoretical (95%) and is slightly less than the calculated efficiency using the surface profile data (77.5%.) Additional losses in efficiency may be due to the overall roughness of the grating, non-uniformities in grating period across the grating area, and subwavelength feature sizes. Since etch depth errors dominate the reduction in efficiency, these additional effects are difficult to quantitatively analyze.

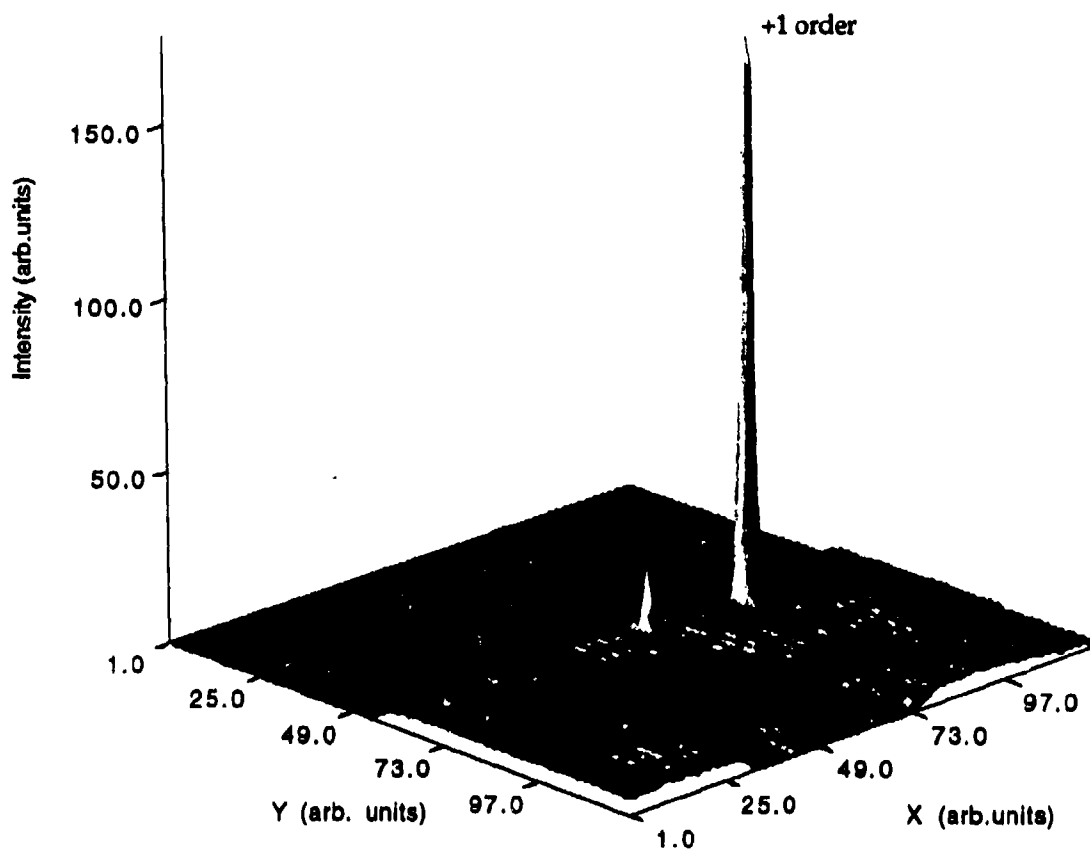


Figure 4.1. Rendered CCD image of diffraction pattern of the 8-level linear grating described in text.

5. Conclusions and ongoing work

2-, 4-, and 8-level off-axis DOEs and linear gratings have been designed and fabricated. Fabrication techniques include electron beam lithography and RIE. Continuously graded, blazed, linear gratings have been fabricated using FIB milling. The quality of the fabrication has been characterized using SEM and AFM. 8-level linear gratings have been tested with efficiencies of 75%. Although 8-level gratings have not been fabricated with near theoretical efficiencies (greater than 90%), procedures have been developed and discussed for fabricating highly-efficient devices.

Ongoing work includes fabricating higher efficiency devices, developing measurement techniques for measuring intensity profiles and efficiencies of the fabricated off-axis reflecting DOEs, and measuring system performances, including cross-talk, of a free-space optical interconnect.

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