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Sub-wavelength Diffractive Optics

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Sub-wavelength Diffractive Optics

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Abstract

This report represents the completion of a three-year Laboratory-Directed Research and Development (LDRD) program to investigate sub-wavelength surface relief structures fabricated by direct-write e-beam technology as unique and very high-efficiency optical elements. A semiconductor layer with sub-wavelength sized etched openings or features can be considered as a layer with an effective index of refraction determined by the fraction of the surface filled with semiconductor relative to the fraction filled with air or other material. Such a layer can be used to implement planar gradient-index lenses on a surface. Additionally, the nanometer-scale surface structures have diffractive properties that allow the direct manipulation of polarization and altering of the reflective properties of surfaces. With this technology a single direct-write mask and etch can be used to integrate a wide variety of optical functions into a device surface with high efficiencies; allowing for example, direct integration of polarizing optics into the surfaces of devices, forming anti-reflection surfaces or fabricating high-efficiency, high-numerical aperture lenses, including integration inside vertical semiconductor laser cavities.

Keywords: diffractive optics, diffraction gratings, e-beam lithography, fabrication of diffractive optical elements

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Introduction

Modern optoelectronic systems often require lenses and other micro-optics for modifying light signals. For practical, cost effective integration of these optical elements, it is desirable that the fabrication process be compatible with conventional microelectronic processing. One component of this compatibility is that the process be planar. For greatest applicability, it is desirable that the process yield optics of precision and broad functionality. Examples of the latter include off-axis lenses and multi-focal spot lenslet arrays. Figure 1 shows a segment of an arbitrary refractive optic along with four analogous diffractive optical elements. Refractive optics, Figure 1a, can provide ideal phase profiles but are non-planar and not easily fabricated on the micron scale. The Fresnel zone equivalent, Figure 1b, is planar, reducing the refractive phase profile to a modulo 2π stepped phase profile. Some progress has been made in demonstrating these structures¹ but the fabrication is challenging. Conventional, multi-level binary optics,² Figure 1c, are planar, but only approximate the smooth phase profile of the Fresnel zones and have the additional disadvantage of requiring multiple lithographic and etch steps with stringent alignment and etch depth tolerances. The gradient index structure, Figure 1d, is perfectly planar and provides the desired phase profile, but is practically unobtainable in this ideal form (on the micron scale).

Figure 1. Segment of an arbitrary refractive optical element and four analogous diffractive optical elements.

Recent work has suggested a way to create an arbitrary gradient index material using binary surface relief structures with features smaller than the wavelength of light in the material.^{3,4} Such a structure may be thought of as an artificial material with an effective index of refraction that can be tailored by varying the fill factor of the binary pattern. The change in fill factor may be accomplished by varying the duty cycle (pulse-width modulation), as represented in Figure 1e, or the period (pulse-position modulation) of the binary pattern. Subwavelength diffractive structures have significant advantages over conventional multi-level diffractive optics including fabrication using a single lithography and etch step, the ability to achieve very high efficiencies and arbitrary phase profiles, the formation of anti-reflection surfaces,⁵ and the incorporation of polarization dependent properties.⁶ The main challenge in fabrication is achieving the required small feature dimensions. We desire to integrate these optical elements into the surfaces of semiconductor optoelectronic materials with operating wavelengths on the order of 1 μm , requiring feature sizes on the order of 100 nm. Reported attempts at fabricating pulse-width modulated structures include a metallic reflection grating⁷ for operation at 10.6 μm and blazed transmission gratings in silicon⁸ for operation at 1.55 μm and in fused quartz⁹ for operation at 633 nm. Pulse-position modulation has been used to demonstrate a reflective binary Bragg-type multibeam splitter at 1.064 μm .¹⁰ In this previous work, the demonstrated efficiencies are not as high and/or the demonstrated diffractive optics are not as ambitious (in terms of equivalent lens speed) as that reported here.

A Subwavelength Blazed Grating

In this section, we demonstrate a blazed transmission grating whose dimensions closely match the design parameters and which exhibits very high efficiency. We designed a blazed transmission grating for operation at 975 nm. We chose a grating period of 3.285 microns to give a significant first order diffraction angle (17.3 degrees), corresponding to the outermost Fresnel zone of a moderately fast lens ($f/1.7$). The requirement that the line/space features making up one period of the blazed grating be subwavelength, constrained by practical fabrication limits, led to the choice of ten line/space pairs per period. Because the features are only slightly smaller than the wavelength

of light in the material, the design calculations are based on rigorous coupled wave analysis.¹¹ The technique allowed use of optimization algorithms to arrive at a structure based on maximizing the power in the first diffracted order.¹² A unique feature of our design procedure is that we did not limit ourselves solely to either pulse-width or pulse-position modulation but rather, allowed both the width and spacing of the grating ribs to vary in order to yield the most practically realizable design. Furthermore, the dimensions and aspect ratios of the etched grooves and ribs were constrained to lie within our fabrication capabilities. Specifically, the minimum rib dimension was set to 60 nm, the maximum rib aspect ratio was set to 10, the minimum groove width was set to 100 nm, and the maximum groove aspect ratio was set to 6. Without the flexible design and dimensional constraints, the most obvious design for a subwavelength blazed grating would be a linear variation in the duty cycle of a line/space pair resulting in vanishingly small rib widths at the low index end and vanishingly small grooves at the high index end (see Figure 1e). One period of the blazed grating design in this work is shown in Figure 2. Note the nonlinear variation in rib and groove width across the pattern, for example, the minimum groove width occurs between the 7th and 8th ribs, not between the 9th and 10th as would be expected in a linear design. This design has a theoretical diffraction efficiency into the first order of over 98% of the transmitted power compared to 41% for a conventional two-level diffractive optic.

Figure 2. Optimized line/space profile for one period of the blazed transmission grating. The narrowest line is 62.5 nm, the narrowest space is 115 nm, the etch depth is 642 nm, and the grating period is 3.285 μm .

Fabrication of the Grating

The stringent dimensional requirements of the above design were achieved using electron beam lithography and reactive-ion-beam etching (RIBE) with a Ni/SiO₂ mask. Fabrication was performed on a three-inch diameter bulk GaAs wafer. The backside of the wafer was coated with an anti-reflection coating consisting of SiO₂/Nb₂O₅ layers to minimize the effect of reflections from the backside GaAs-air interface on the transmission measurements. The frontside of the wafer was coated first with 110 nm of plasma-deposited SiO₂ and then spin-coated with 210 nm of poly(methylmethacrylate) (PMMA) electron beam resist. Following electron beam patterning of the PMMA, 5 nm of chrome (for adhesion) and 60 nm of nickel were evaporated onto the sample and the unwanted metal lifted-off. The Cr/Ni pattern was transferred first into the SiO₂ layer by reactive-ion etching (RIE) and then into the GaAs surface by RIBE. The fabrication steps are described in more detail below.

The electron beam lithography was performed on a JEOL JBX-5FE field emission system operating at 50 kV. A beam current of 500 pA, with a corresponding beam diameter of 6 nm, was used. The addressed pixel spacing was 5 nm in an 80 μm field. The PMMA thickness of 210 nm

was chosen to be as thin as possible for maximum resolution while still allowing for clean, reliable lift-off of the 65 nm evaporated Cr/Ni layer. The sub-tenth micron resolution required for the blazed grating is well within the capability of the JEOL instrument operated under the given conditions. The challenge of this work was to achieve the design dimensions etched in GaAs which required compensating for the proximity effect during exposure, resist deformation during metal evaporation, and any lateral dimension changes while transferring the Cr/Ni pattern to the SiO₂ and GaAs. Because the patterns are periodic on a scale less than the backscattered electron range ($\sim 4 \mu\text{m}$ at 50 kV), the proximity effect is expected to contribute a relatively uniform background dose across the pattern. This suggests that the proximity effect can be largely compensated using a single, optimized dose with an appropriately biased pattern. Pattern distortion was found to occur during the electron beam evaporation of the Cr/Ni etch mask and is attributed to deformation of the PMMA resist primarily caused by stress in the Cr/Ni film deposited on top of the PMMA. The PMMA pulls away at the top of the developed gap resulting in an increase in linewidth. It should be noted that this effect was minimized as much as possible by using a large source to sample distance of 27 inches and that the absolute magnitude of the effect is very small ($\leq 50 \text{ nm}$). Because the etch depths required in this work are relatively shallow, and the etch mask relatively robust, no appreciable lateral dimension change was observed during either the SiO₂ RIE or the GaAs RIBE, as measured near the tops of the etched features.

The blazed grating pattern was biased using a manual procedure. Since we did not believe that formal proximity effect correction was necessary and had no *a priori* knowledge of the magnitude of the resist deformation effect, the blazed pattern was initially exposed unbiased relative to the design dimensions with the exception of a standard one-half pixel spacing (2.5 nm) resize to compensate for the finite beam diameter. The pattern was exposed over a range of doses and developed for one minute in a 1:3 solution of methyl isobutyl ketone (MIBK) and isopropyl alcohol (IPA). At the best apparent dose for the pattern, a region of the developed PMMA pattern was inspected, uncoated, at low voltage in a scanning electron microscope (SEM) and the line/space dimensions were measured. The rest of the wafer underwent the Cr/Ni evaporation and

liftoff and the line/space dimensions again were measured. Relative to the design dimensions, the developed PMMA pattern exhibited from 20 to 55 nm of increased linewidth across the pattern, and the lifted-off Cr/Ni lines exhibited an additional increase of from 5 to 45 nm. Fortunately, the proximity effect is greatest where the blazed pattern is densest while the resist deformation effect is greatest where the pattern is least dense (and hence more area of PMMA to stress and deform) so that these two effects combined to produce an amazingly uniform increase in final linewidth of 65 ± 5 nm across the blazed grating. Of course, one cannot very well bias the smallest lines (e.g., 62.5 nm) downwards by 65 nm so a simple empirical rule was invented and employed. For linewidth design dimensions less than twice the average pattern increase (~ 130 nm), the pattern bias was one half the pattern design dimension. For the larger linewidth design dimensions, the pattern bias was simply the pattern increase for that line (~ 65 nm).

The biased pattern was then exposed over a new, higher dose range based on the results of the first exposure. The PMMA and Cr/Ni linewidths were again measured at the best apparent dose. The pattern accuracy showed significant improvement with the average magnitude error in the blazed grating linewidth being less than 10 nm, although covering an absolute range from +13 nm to -20 nm. A second, minor pattern bias was then performed to make the linewidth errors as small and uniform as possible. It should be noted that these changes were smaller (~ 10 nm) than the expected run-to-run process variations and did not result in significant changes in measured performance.

The overall blazed grating pattern was written as a strip 80 microns high and 960 microns long. The height corresponds to a single writing field of the JEOL instrument so that no field stitches are present in that direction across the pattern. The best dose range for the blazed grating was found to be $500\text{--}550 \mu\text{C}/\text{cm}^2$. After the Cr/Ni lift-off, the SiO_2 layer was etched using CHF_3/O_2 RIE. For the relatively shallow etch depths used in this work, the SiO_2 layer serves primarily to facilitate removal of the Cr/Ni layer at the end of the fabrication sequence. For deeper etches, the SiO_2 would serve to extend the robustness of the etch mask. The GaAs was etched in a custom-built RIBE system with an electron cyclotron resonance (ECR) ion source. The etch gas

was chlorine at a pressure of 2.5×10^{-4} torr. The typical acceleration voltage and beam current densities were 300 eV and 0.62 mA/cm², respectively. Etches were performed on a timed basis according to system calibration and accounting for etch lag effects.¹³ A scanning electron micrograph of the cross-section of a fabricated blazed grating is shown in Figure 3. The minimum feature size is 70 nm and the maximum aspect ratio is 10:1. As expected, there is etch depth variation across the pattern as a function of the etched groove width. The average etch depth is 705 nm, close to the design depth of 642 nm. The variation in etch depth is $\pm 17.7\%$ relative to the average etch depth. This is a significant variation but two things should be noted. One, because these are subwavelength structures where the effective index as a function of position is related to the integrated average of the index over a small volume of the structure at a given position, the exact geometry of the subwavelength features is not important so long as the effective index profile matches the design. Two, the etch depth variation could be parameterized and included in the design algorithm to compensate for the effect.

Figure 3. Scanning electron micrograph of the cross section of a single period of the fabricated blazed transmission grating.

Grating Performance

The diffraction efficiency of the blazed grating was measured by two techniques. In both techniques, the incident laser light polarization was parallel to the grating lines and a reference detector was used to normalize out laser fluctuations. Light transmission was limited to the grating region by depositing a chrome slit aperture aligned precisely to the grating area (the grating lines are perpendicular to the slit). The relative power in the different transmitted diffracted orders was measured by scanning a detector with a slit aperture in a 180 degree arc about the grating aperture. The resulting profile of the diffracted orders is shown in Figure 4. The integrated area under a given peak compared to the total integrated area for all peaks provides a measure of the diffraction efficiency of the grating into the given order. By this technique, the diffraction efficiency into the first order is 87% of the transmitted power. A second, more accurate measurement of diffraction efficiency into the first order was made using an integrating sphere. The total power in the first

order was measured by positioning the integrating sphere at the first order diffracted angle (17.3 degrees) and comparing that power to the total power transmitted through the grating as measured by positioning the integrating sphere as close to the grating aperture as possible. The diffraction efficiency into the first order measured by this technique is 85%, very close to the result determined above and consistent with the scattering of a few percent of the light out of the plane of the grating aperture. The 13% percent shortfall in measured efficiency compared to the predicted theoretical efficiency is attributed to deviations in the line/space dimensions and etch depths of the fabricated grating compared to the design values. This result demonstrates the potential for fast ($f/1.7$), high-efficiency diffractive optical elements in the one micron wavelength region suitable for integration with optoelectronic devices.

Figure 4. Angular scan of the transmitted diffracted orders of the blazed grating. The measured diffraction efficiency in the first order is 85% of the transmitted power.

An Antireflection Grating

Subwavelength, binary surface-relief structures act as artificial materials whose effective index of refraction depends on the fill factor of the binary pattern. The simplest subwavelength structure to analyze is that of a one-dimensional (1-D), rectangular-profile grating with periodicity less than the wavelength of light in the material, as shown in Fig. 4(a). This is a zero-order grating which transmits (and reflects) only the zeroth diffracted order, without change in the direction of propagation, analogous to light transmission through (and reflection from) a homogenous material. We use the general term 'structure,' instead of the more common term 'grating,' to refer to the subwavelength surface-relief pattern of this work to emphasize that it does not act as a conventional diffraction grating, but, rather, as an artificial material with a variety of interesting and useful properties. With the proper choice of fill factor and thickness, and for a given polarization, the 1-D structure exhibits antireflection (AR) behavior directly analogous to the quarterwave AR coating, as shown in Fig. 4(b). The antireflection property has broad application in micro-optics and in semiconductor-based optoelectronic systems, particularly at wavelengths where appropriate conventional AR coatings may not exist.

The polarization dependence of the antireflection property arises from the lack of rotational symmetry in the 1-D AR structure and has direct application to polarization control in vertical-cavity surface-emitting lasers (VCSEL) which consist of an optical gain region sandwiched between two mirrors, typically distributed Bragg reflectors. VCSELs have many desirable properties including the ability to have circular output beams and for fabrication in two-dimensional arrays. One potential problem for VCSELs with some type of symmetry in the shape of the output aperture (e.g., circular or square apertures) is that the axis of polarization of the output beam is random, although typically aligned to either of two orthogonal crystal directions.¹⁴ Another concern is that the axis of polarization is observed to switch between the two orthogonal orientations as a function of injection current.¹⁴ The ability to control the axis of polarization would be vital for any optical system containing polarization-sensitive elements or using the state of polarization to convey coded information. The integration of a subwavelength structure which

exhibits polarization-dependent reflectivity with a conventional VCSEL should lead to a device which lases with the axis of polarization aligned to the high-reflectivity axis of the 1-D subwavelength structure.

Another property of this 1-D AR structure is that of form birefringence¹⁵ which is the presence of polarization-dependent indices of refraction arising from the anisotropy of the subwavelength geometry of the 1-D AR structure (as opposed to simple birefringence arising from anisotropy in the electronic structure on a molecular scale in a crystalline material). The magnitude of the difference between the indices of refraction for the two orthogonal polarizations increases as the difference between the indices of the incident and substrate materials of Fig. 4 increases. The presence of form birefringence in these 1-D surfaces may be exploited to create waveplates which can be used to alter states or axes of polarization.

Various theoretical and experimental treatments of subwavelength AR surfaces have appeared in the literature.^{5, 16-21} Early experimental work by Flanders¹⁶ demonstrated birefringence in 1-D, rectangular-profile gratings in polymethylmethacrylate (PMMA) and silicon nitride, and its dependence on fill factor and thickness, at a wavelength of 633 nm. Enger and Case⁵ demonstrated antireflection behavior in 1-D, triangular-profile gratings in quartz at 633 nm. Gaylord,¹⁷ et. al., provided a rigorous theoretical treatment of 1-D, rectangular-profile gratings valid even for the regime where the grating period is of the same order as the incident wavelength. Ono,¹⁸ et al., reported a model for the observed AR behavior of 1-D, sinusoidal- and triangular-profile gratings in photoresist at 633 nm. Cescato,¹⁹ et al., studied birefringence in 1-D, sinusoidal-profile gratings in photoresist at 633 nm. Raguin and Morris²⁰ made an extensive theoretical investigation of 1-D, triangular-profile gratings and two-dimensional, pyramidal-profile gratings in GaAs at 10.6 μm . Finally, Deng and Chou²¹ have reported properties of 1-D, nominally trapezoidal-profile gratings as a function of grating period in amorphous silicon on silica at 633 nm.

In this section, we demonstrate a specifically-designed antireflection structure in a material system (GaAs) and at a wavelength (975 nm) directly integrable with GaAs-based VCSELs and

which exhibits strong polarization-dependent properties. To our knowledge, this AR surface is fabricated in the highest refractive index material ($n_{\text{GaAs}}=3.5$) and has the smallest feature sizes (~ 50 nm) yet reported. Fabrication is performed using electron beam lithography and reactive-ion-beam etching. The main challenge in fabrication is achieving the specific sub-tenth micron linewidths and controlling the etch profiles and depths. We observe excellent agreement between our theoretical calculations and our experimental measurements.

Design of the AR Grating

Our AR surface is designed for fabrication in GaAs and for operation at 975 nm with normal incidence. The period of the AR surface, $\Lambda = 260$ nm, is chosen to be just slightly less than the wavelength of 975 nm light in GaAs so that only the zero-diffracted order will propagate in the material. The goal of the design is to create an AR surface analogous to a conventional quarterwave AR thin film. For an air/GaAs interface, the AR layer would have a refractive index, $n_{\text{AR}} = (n_{\text{GaAs}})^{1/2} = 1.87$, and a thickness, $t = \lambda/(4n_{\text{AR}}) = 130$ nm. The AR surface designed for this work, then, is an artificial material whose effective index of refraction is 1.87. Since we are designing a periodic, rectangular-profile structure, the only parameter to be determined is the fill factor, f , of the binary pattern, or, alternatively, the width of the ribs which comprise the AR surface, indicated by $f\Lambda$ in Fig. 4. Because the period is only slightly smaller than the wavelength of light in the material, a more accurate calculation than the simple effective medium theory¹⁵ (EMT) should be used. We began by using a set of transcendental equations for the effective index of the fundamental eigenmode propagating parallel to the layers of an infinite periodic medium.²² The result of these equations was then used as the starting point for direct optimization using a full vector Fourier method. Further details of the design methodology are provided elsewhere.^{12, 23} The results of the design calculation are shown schematically in Fig. 5. The design rib width of 42 nm corresponds to a fill factor of 0.16 compared to a fill factor of 0.22 which is obtained from the simple EMT approximation. This design has a theoretical transmission of 100% for TE-polarized light (electric field parallel to the grating ribs), and 74% for TM-polarized light (electric field

perpendicular to grating ribs). For comparison, the transmission through an air/GaAs interface (for normal incidence at 975 nm wavelength) is ~71% and is polarization independent.

(a)

(b)

Figure 4. a) Schematic representation of a one-dimensional, rectangular-profile grating with pitch, Λ , depth, d , fill factor, f , and rib width, $f\Lambda$. b) Design for a standard quarterwave antireflection layer.

Figure 5. Design for the antireflection surface-relief structure. The pitch is 260 nm, the rib width is 42 nm, and the etch depth is 134 nm.

Fabrication of the AR Grating

The nanometer-scale dimensional requirements of the above design were achieved using electron beam lithography and reactive-ion-beam etching (RIBE) with a Ti/Ni/SiO₂ mask. The fabrication procedure used is a modified version of that which we described earlier for the fabrication of a subwavelength, blazed transmission grating. Several of the process parameters had to be optimized to achieve the ~50 nm feature sizes. The frontside of the bulk GaAs wafer was coated first with 100 nm of plasma-deposited SiO₂ and then spin-coated with 100 nm of PMMA electron beam resist. Following electron beam patterning of the PMMA, 5 nm of titanium (for adhesion) and 35 nm of nickel were evaporated onto the sample and the unwanted metal lifted-off. The Ti/Ni pattern was transferred first into the SiO₂ layer by reactive-ion etching (RIE) and then into the GaAs surface by RIBE. The fabrication steps are described in more detail below along with comments on the changes compared to the procedures for the blazed grating.

The electron beam lithography was performed on a JEOL JBX-5FE field emission system operating at 50 kV. A beam current of 500 pA, with a corresponding beam diameter of 6 nm, was used. The addressed pixel spacing was 5 nm in an 80 μ m field. The PMMA thickness was reduced to 100 nm for increased resolution and the Ti/Ni thickness was correspondingly reduced to a total of 40 nm to maintain reliable liftoff. The reduction in mask thickness was not an issue

because of the shallow etch depth (134 nm). The use of Ti instead of Cr arose from the observation of slightly better liftoff yield for Ti compared to Cr, but the difference was small. As with the blazed grating, the challenge of this work is to achieve the design dimensions etched in GaAs which requires compensation for the proximity effect during exposure, linewidth increase during post-development oxygen descum, resist deformation during metal evaporation, and any lateral dimension changes while transferring the Ti/Ni pattern to the SiO₂ and GaAs. Because the pattern is periodic, all of the above effects operate uniformly across the pattern. Compensation for these effects can thereby be accomplished with an appropriately biased pattern written at a single, optimized dose. The desired 42 nm-wide rib pattern was biased down to 15 nm for exposure.

The overall AR pattern was written as a square, 960 microns on a side, to provide a large area for measurement. One may note that this structure is relatively insensitive to field stitch errors which simply perturb the local fill factor over a one-period distance at the stitch boundary. For this structure, the period is 0.26 μm and the field size is 80 μm , so the affected area is only 0.3% of the total area and typical field stitch errors are less than 10% of the period. Because of the spatial averaging process which determines the effective index, subwavelength structures, in general, are relatively insensitive to all random fabrication errors whose magnitudes are small compared to the subwavelength geometry and whose means are near zero averaged over small areas. The best dose range for the AR pattern was found to be 1000-1050 $\mu\text{C}/\text{cm}^2$. Development was performed for 50 sec in a 1:3 solution of methyl isobutyl ketone (MIBK) and isopropyl alcohol (IPA). After the Ti/Ni lift-off, the SiO₂ layer was etched using CHF₃/O₂ RIE as described earlier. A scanning electron micrograph of the cross-section of three ribs of a fabricated AR surface is shown in Fig. 6. Typical measured rib widths are 55 ± 5 nm and etch depths are 140 ± 5 nm. Note the precise rectangular profiles achieved at this nanometer scale.

Figure 6. Scanning electron micrograph of the cross-section of a portion of the antireflection surface fabricated in GaAs.

AR Grating Results

Characterization of the behavior of the AR surface was performed using the experimental setup diagrammed in Fig. 7. The frontside of the wafer was coated with an opaque chrome layer everywhere except for the AR surface, forming a $960\text{ }\mu\text{m}$ square aperture. To further assure that transmission through only the AR surface was measured, the incident laser light was also passed through a $960\text{ }\mu\text{m}$ square aperture prior to incidence on the backside of the wafer. Transmission measurements were made for both TE and TM polarization, at normal incidence, over a wavelength range of 960-990 nm. The measurement used a Ti-Sapphire laser light source, a beam chopper, and lock-in detection. A small beam splitter was placed in close proximity to the sample to split off a reference beam for normalization of any power level fluctuations.

Figure 7. Diagram of the experimental setup used for measuring the transmission through the antireflection surface.

In order to determine the true performance of the AR surface, we need to separate the effects of the backside surface reflectivity and the optical absorption in the substrate. This can be accomplished by exploiting the information contained in the magnitude of the Fabry-Perot oscillations observed in the raw data. An asymmetric Fabry-Perot cavity is formed between the front and back air interfaces of the GaAs substrate. By assuming that the backside reflection and optical absorption are polarization independent, one may solve for the frontside reflection for both TE and TM polarizations. Details of this calculation are reported elsewhere.²³ The measured transmission data for both TE and TM polarizations is shown in Fig. 8 along with theoretical values for a typical AR surface with rib width of 50 nm and etch depth of 135 nm. The agreement between experiment and theory is seen to be excellent, with measured values for transmission of 98% and 77% for TE and TM polarizations, respectively. Note that the design of the AR surface is relatively

forgiving in that the significant percentage error ($\sim 30\%$) in the etched rib width compared to the design value results in only a two percent reduction in transmission from the theoretical maximum. In terms of reflectivity, the value observed for TE-polarized light is 2% versus 23% for TM-polarized light. This greater than a factor of ten polarization-dependent difference in reflectivity confirms the applicability of these AR surfaces to polarization control in VCSELs.

Figure 8. Measured transmission through the antireflection surface for TE and TM polarizations along with theoretical values for a structure with rib width of 50 nm and etch depth of 135 nm.

A Subwavelength Lens

Subwavelength, binary lenses are an emerging technology in the field of high-diffraction-efficiency micro-optics which exploit current capabilities in nanofabrication. The need for integrable micro-optics in the 1 μm -wavelength regime is driven by the success of vertical-cavity surface-emitting lasers (VCSEL) and applications such as high-speed optical interconnects in multichip modules. To create a given lens with subwavelength structures, one must create a subwavelength pattern whose spatial variation of effective index of refraction matches that of the desired, ideal Fresnel zone lens equivalent. In this section, we describe the nanofabrication of subwavelength, binary lenses in GaAs for operation in the infrared. The approach is based on the high efficiency blazed grating. There has been one report of an on-axis diffractive lens utilizing mostly subwavelength features but the lens design simply mimics a four-phase level binary optic. To our knowledge, our present work is the first report of the design and fabrication of a true, zeroth-order subwavelength lens. Certainly, this is the most ambitious subwavelength structure in terms of form and function reported to date.

Subwavelength Lens Design and Fabrication

We designed a fast off-axis subwavelength lens for fabrication in GaAs and for operation at 975 nm with normal incidence. The lens has a circular-aperture, with diameter of 80 μm , focal length of 110 μm , and deflection angle of 20° . Each Fresnel zone of the lens is generated by a single curved, subwavelength blazed grating element. For each zone the number of line/space pairs is chosen such that the features are less than the wavelength of 975 nm light in GaAs (~ 280 nm). The off-axis lens is comprised of 25 zones. The outermost zone has a width of 1.7 μm and four line/space pairs and the innermost zone has a width of 14.7 μm and 45 line/space pairs. Because the features are only slightly smaller than the wavelength of light in the material, the design calculations are based on rigorous coupled wave analysis.¹¹ The technique allowed use of optimization algorithms to arrive at a structure based on maximizing the power in the first diffracted order.¹² A unique feature of our design procedure is that we did not limit ourselves solely to

either pulse-width or pulse-position modulation but rather, allowed both the width and spacing of the grating lines to vary in order to yield the most practically realizable design. It should be noted that for the largest zone of the lens (the zone corresponding to the central zone of an on-axis lens), the simple effective medium theory¹⁵ was used because use of the optimization routine would have taken prohibitively long on the personal computer being used for the calculations. This approximation is not expected to affect the performance of the off-axis lens to a significant degree because the first zone is a small percentage of the overall lens area. The minimum dimensions of the lines and spaces were constrained to lie within our fabrication limits. Specifically, the minimum line dimension was set to 42 nm and the minimum space dimension was set to 100 nm. For the design etch depth of 540 nm, this results in a maximum aspect ratio of 12.8:1 for an etched line and 5.4:1 for an etched space. Without the flexible design and dimensional constraints, the most obvious design for a subwavelength blazed grating element would be a linear variation in the duty cycle of a line/space pair resulting in vanishingly small linewidths at the low index end and vanishingly small spaces at the high index end. The fact that subwavelength structures have polarization dependent properties complicates the design of a general lens for use with light of mixed polarization. In this case, the optimization algorithm was set to maximize the transmission efficiency (into the first order) of each zone for a 50/50 weighted average of TE and TM polarization. The resulting design for the off-axis lens has a theoretical diffraction efficiency into the first order of 92% of the transmitted power compared to a maximum of 41% for a conventional two phase-level diffractive optic. Eight-phase levels, requiring three lithography and etch steps, are necessary to achieve over 90% efficiency in a conventional binary optic. It may be noted that the same lens, designed solely for TE polarization, would have a theoretical efficiency greater than 92% while the same lens, designed solely for TM polarization, would have a theoretical efficiency less than 92%. For the lens design used in this work, the efficiency is expected to be greater for TE polarization than for TM polarization.

The stringent dimensional requirements of the above design were achieved using electron beam lithography and reactive-ion-beam etching (RIBE) with a Ni/SiO₂ mask. Fabrication was

performed on samples from a three-inch diameter bulk GaAs wafer. The frontside of the wafer was coated first with 120 nm of plasma-deposited SiO₂ and then spin-coated with 100 nm of polymethylmethacrylate (PMMA) electron beam resist. Following electron beam patterning of the PMMA, 5 nm of titanium (for adhesion) and 40 nm of nickel were evaporated onto the sample and the unwanted metal lifted-off. The Ti/Ni pattern was transferred first into the SiO₂ layer by reactive-ion etching (RIE) and then into the GaAs surface by RIBE. The fabrication steps are substantially the same as for the blazed grating.

A scanning electron micrograph of the cross section of four Fresnel zones of a fabricated subwavelength lens is shown in Figure 9(a). A scanning electron micrograph of the cross section of a single Fresnel zone showing the detailed structure of the line/space pairs is shown in Fig. 9(b). The minimum feature size is 50 nm and the maximum aspect ratio is 12.8:1. As expected, there is etch depth variation across the zone pattern as a function of the etched groove width. The average etch depth measured across all the spaces of the zone shown in Fig. 9(b) is 535 nm, extremely close to the design depth of 540 nm. The variation in etch depth is $\pm 20.5\%$ relative to the average etch depth. For the purposes of this work, the etch depth variation is not a significant enough problem to prevent demonstration of the functionality of the lens design.

(a)

(b)

Figure 9. Scanning electron micrograph of the cross section of (a) a portion of a fabricated subwavelength, binary lens in GaAs showing four Fresnel zones and (b) a single Fresnel zone of the lens showing the detail of the blazed grating element.

Subwavelength Lens Results

The diffraction efficiency of the lens was measured by the following technique. Light transmission was limited to the lens region by depositing a chrome aperture aligned precisely to the lens area. To measure the total transmitted power through the lens, an integrating sphere was aligned in close proximity to the lens to collect all transmitted light. To measure the transmitted power into the first diffracted order, the integrating sphere was aligned 20° off-normal and a pinhole with an effective diameter of $12\text{ }\mu\text{m}$ was aligned at the focal point of the lens. In each case, a reference detector was used to normalize out laser fluctuations. The diffraction efficiency for transmitted light into the first order measured by this technique is 72% for TE polarization and 59% for TM polarization, both respectable values but below the theoretical value of 92% for mixed polarization. The shortfall in measured efficiency compared to the predicted theoretical efficiency probably arises from the combination of several effects including deviations in the line/space dimensions and variation in etch depths across each of the blazed grating zone elements compared to the design values, the previously mentioned approximation used for the design of the first zone, and various random structural defects in the lens and deposited aperture. The beam spot profile at the focus point of the lens was measured for TE polarization by a CCD camera and is shown for two saturation levels in Fig. 10. The full-width, half-maximum (FWHM) as measured from the data shown in Fig. 10(a) is $4\text{ }\mu\text{m}$, within a factor of three of the diffraction limit for the lens which is $1.6\text{ }\mu\text{m}$. Fig. 10(b) shows the aberrations present at low levels in the focused beam. The aberrations can be attributed in part to an approximation used in the design of the lens. For each blazed zone of the lens, a linear phase profile was used instead of the ideal curved profile. This introduces higher order aberrations in the resulting lens. The aberrations may also arise in part from any optical misalignment present in the measurement setup. Because the fabricated lens is very fast ($f/1.3$), its performance is very sensitive to alignment of the incident beam.

(a)

(b)

Figure 10. Beam profile at the focal point for TE polarization for the off-axis lens as captured by a CCD camera (a) unsaturated, showing the 4 μm spot size and (b) saturated, showing the higher order aberrations present at low levels.

Summary

The nanofabrication of subwavelength, binary, high-efficiency diffractive optical elements has been demonstrated in GaAs utilizing electron beam lithography and reactive-ion-beam etching. A unique design procedure was used that employed both pulse-width and pulse-position modulation yielding a more practically realizable design. Successful fabrication of these structures was aided by constraining the design algorithm to dimensions and aspect ratios which were within the limits of our fabrication capabilities. The design dimensions were biased in the exposed pattern to result in final etched structures typically within 20 nm of the design values. The blazed transmission grating exhibited a diffraction efficiency into the first order of 85% of the transmitted power. This work demonstrates the potential for high-speed, high-efficiency lenses and other micro-optic elements fabricated in a single etch step and integrated with optoelectronic devices.^{12,24}

We have also demonstrated the design, fabrication, and characterization of a specific antireflection structure in GaAs and at a wavelength (975 nm) directly integrable with GaAs-based vertical cavity surface-emitting lasers.^{23,24} The design technique utilized an effective index approximation valid for the range where the grating pitch is only slightly less than the wavelength in the material, in conjunction with a full vector Fourier method. Characterization revealed a reflectivity of 2% for TE polarization and 23% for TM polarization, a difference in reflectivity of over a factor of ten for the two polarizations. The significant polarization-dependent difference in reflectivity confirms the applicability of these AR surfaces to polarization control in VCSELs. The nanofabrication of subwavelength, binary, high-efficiency diffractive lenses has been demonstrated in GaAs as well.²⁶ The design process was similar to that for the blazed grating, treating each zone of the lens as a single blazed grating profile. The fabricated off-axis lens exhibited a diffraction efficiency of into the first order of 72% and 59% of the transmitted power for TE and TM polarization, respectively. This work demonstrates the potential for high-speed, high-efficiency lenses and other micro-optic elements fabricated in a single etch step and integrated with optoelectronic devices.

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