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NIR High-Efficiency Subwavelength Diffractive Structures In Semiconductors.

R.E. Smith, M.E. Warren, J.R. Wendt and G.A. Vawter

Sandia National Laboratories
Albuquerque, NM 87185-0603

Abstract: We have fabricated sub-wavelength diffractive optical elements with binary phase profiles for operation at 975 nm. Blazed transmission gratings with minium features 63 nm wide were designed by using rigorous coupled-wave analysis and fabricated by direct-write e-beam lithography and reactive ion beam etching in gallium arsenide. Transmission measurements show 85% diffraction efficiency into the first order. Anti-reflection surfaces, with features 42 nm wide were also designed and fabricated.

I. Introduction

It was recently predicted that highly efficient diffractive optical elements could be realized by fabricating binary phase surface relief structures comprised of features with sizes smaller than the wavelength of light in the material.[1,2] These structures have groove widths and spacings that vary, but have uniform depth. The simplest example is that of a grating with a period less than the wavelength of light. Such a structure will have only evanescent diffracted orders, so that the only propagating transmitted and reflected orders are the zeroth orders. Such a structure has essentially the same properties as a homogeneous layer of material with an effective index of refraction determined by the duty cycle of the features at the grating surface. Such a subwavelength grating is utilized in the anti-reflection surface discussed below.

If this sub-wavelength grating is modulated to form a pattern with dimensions larger than a wavelength of light, a gradient effective index surface can be formed that can be used to form diffractive optics with very high diffraction efficiencies. These predictions were recently validated by devices designed for operation at 10.6 microns, where fabrication of sub-wavelength features is possible with conventional photolithography.[3] Another group has

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fabricated shallow grating structures for 1.5 microns.[4] There has also been recent success in fabricating subwavelength metallic grating structures that operate in reflection with high efficiency at 10.6 microns.[5]

We report here high-efficiency, dielectric, subwavelength surface relief blazed transmission gratings fabricated in GaAs substrates for operation at 975 nm. To our knowledge, this is the shortest wavelength for which structures of this type have been successfully demonstrated in a semiconductor. Our choice of wavelength and substrate material was motivated by interest in integrating diffractive optical elements with vertical-cavity surface-emitting laser diodes and other semiconductor optoelectronic devices.

II. Design and Fabrication

The design method used an implementation of the rigorous coupled wave analysis technique for calculating the diffraction efficiency of periodic structures.[7] The implementation allowed use of optimization routines[8] to optimize a structure for a specific purpose by systematically varying the width and position of individual grooves from an initial guess to values that best achieve that purpose. For the blazed grating the merit function for this optimization is total power in the first transmitted diffraction order.

The individual periods of the "blazed" grating contain numerous subwavelength grooves to produce a "blazed" phase profile to optimize the efficiency into the first diffracted order. A linear 2π phase shift within a single period is required. Design of the actual grating profile to be fabricated required careful consideration of the practical fabrication constraints. The grating period was chosen to be approximately 3.28 microns to give a significant first order deflection angle (17. 3 degrees) and to correspond to a moderately fast lens (F/1.7).

Fig 1. shows the predicted diffraction for the resulting structure, shown in Fig. 2. It is interesting to note that the grating design predicts modest antireflection properties. The percentage of the incident intensity predicted to be diffracted into the first order, 78%, is predicted to exceed the Fresnel transmission limit of 69%, as shown in Fig. 1. For this the theoretical limit of efficiency of total transmitted light into the first order was 98%.

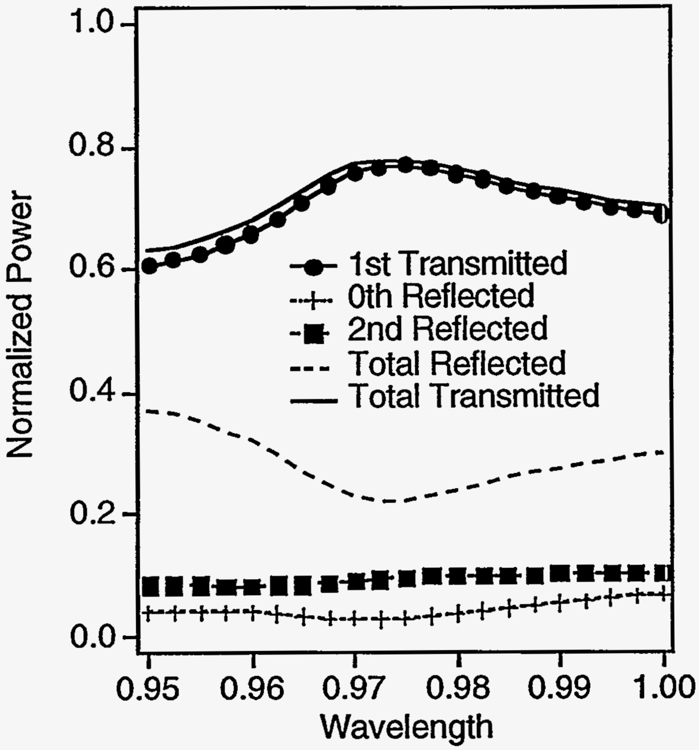

Fig. 1. Calculated values of the dominant transmitted and reflected orders of the optimized grating design in Fig. 1 as a function of wavelength.

The grating was fabricated in GaAs by a combination of e-beam lithography and reactive ion beam etching (RIBE). Polished, undoped GaAs substrates were anti-reflection coated on one side and the other side was coated with 100 nm of SiO_2 by plasma enhanced CVD. The SiO_2 side was then spin coated with PMMA resist, and the PMMA layer was patterned with a JEOL JBX-5FE electron beam pattern. After development of the pattern, 50 nm of nickel was evaporated onto the patterned surface and lifted off by dissolving the PMMA. The exposed SiO_2 areas were then etched away in a CHF_3 plasma. The resulting mask, consisting of Nickel on SiO_2, is used to pattern the GaAs surface in a RIBE system using chlorine. The RIBE system is an ECR source system that allows very anisotropic, uniform etching.[9] After etching the pattern, the remaining nickel and SiO_2 mask is removed in an HF dip. A scanning electron micrograph of a cross section of one of the subwavelength blazed gratings is shown in Fig. 3.

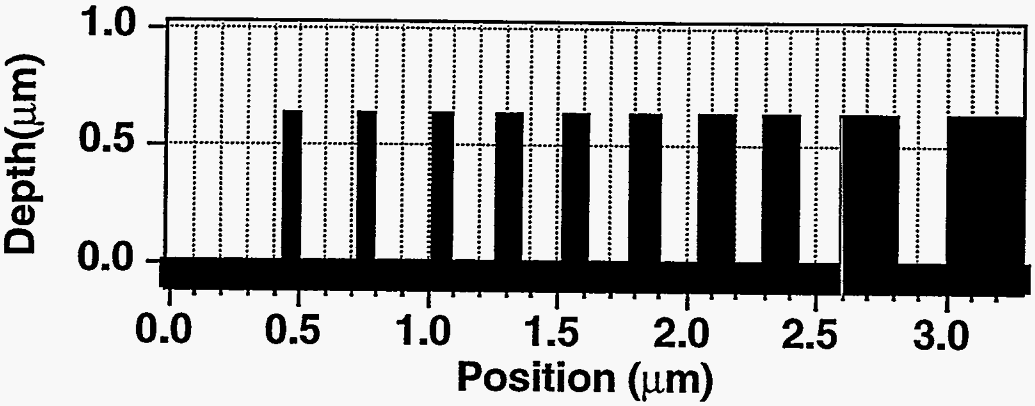

Fig. 2. Optimized groove profile for one period of the blazed transmission grating.

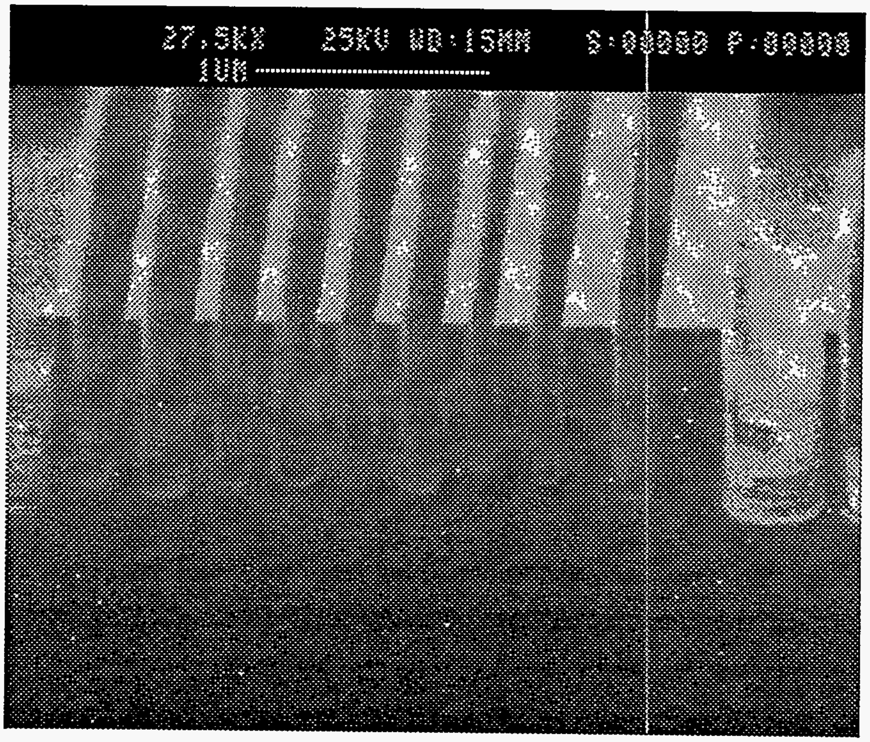

Fig. 3. Scanning electron micrograph of a cross section of a single period of a subwavelength blazed transmission grating.

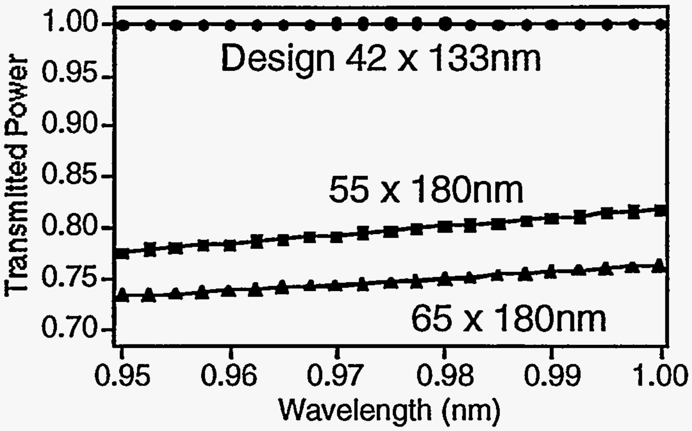

Fig. 5. Calculated values of the transmitted power as a function of wavelength for the design specifications and two estimates of the as grown structure.

For the design of the anti-reflection surface the period was fixed at 260 nm so that it was less than the wavelength of light in the substrate. Then the width and height of the tooth were allowed to vary and the zeroth order transmission was maximized. The result was a structure with 42 nm wide and 130 nm tall teeth predicted to increase transmission though the semiconductor interface to nearly 100% as shown in Fig. 5. In turns out that owing to over etching in the initial fabrication run, the structure in Fig. 6 has teeth that are 180 nm tall, in addition to the teeth being slightly too wide. The lower two traces in Fig. 5 show that over etching dramatically influences the anti-reflective properties.

III. Testing

The performance of the blazed grating was characterized by two methods. A detector with a slit aperture was scanned in a 180 degree arc in the plane of the grating aperture slit to profile the diffracted orders of the grating as shown in Fig. 7. Integration of the peaks in the scan allows comparison of the relative diffraction efficiency of the various orders. The diffraction efficiency into the first order was also determined by measuring it's power with an integrating sphere positioned at that lobe and comparing with the total power transmitted through the grating, measured by positioning the integrating sphere as close to

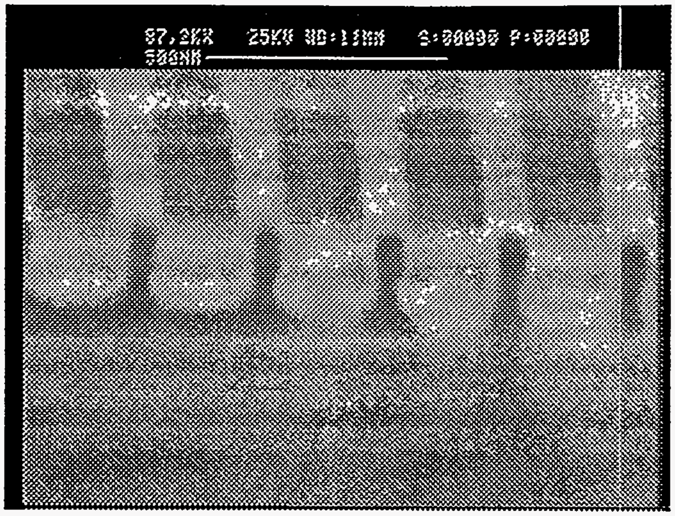

Fig. 6. Scanning electron micrograph of a cross section of five periods of a subwavelength blazed transmission grating.

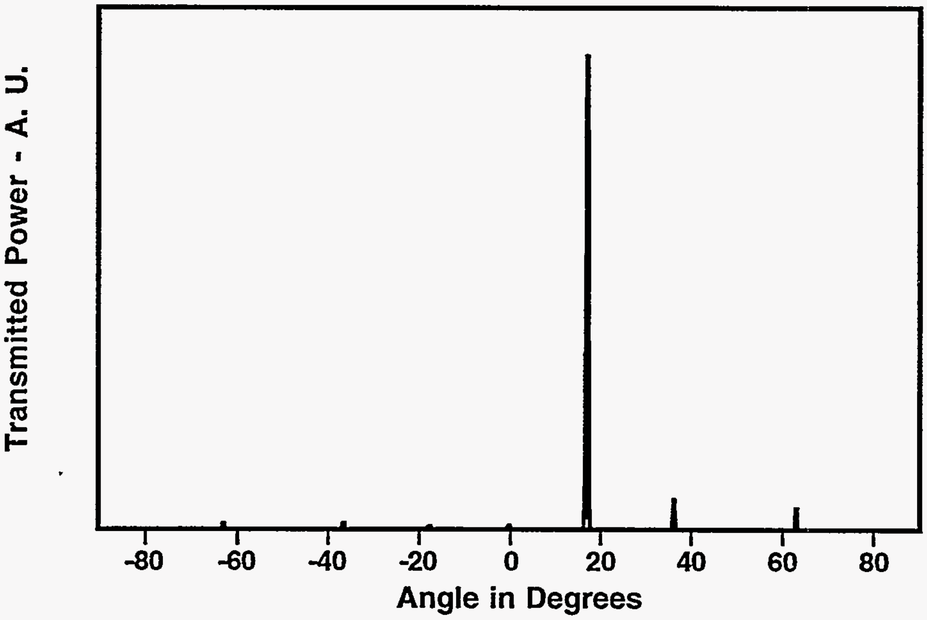

Fig. 7. Plot of the scan of the diffraction from the subwavelength grating showing the power in each order relative to the first order.

the grating surface as possible. The resulting two measurement were quite close, measuring the diffraction efficiency into the first order at 87% and 85% of transmitted light, respectively. This suggests less than 2% of the transmitted light was scattered out of the plane.

The measured efficiency is only 13% lower than the predicted theoretical limit. This may be explained by slight departures in the actual grating dimensions from the design as shown in Fig. 3. In addition, fabrication defects resulted in a few missing grating features. Additional factors are the finite aperture of the grating and scattering from sample surfaces. Although fabrication of this type of structure is demanding, the potential has been demonstrated for high efficiency optical elements for the NIR suitable for integration with optoelectronic devices and systems.

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