Fabrication and properties of visible-light subwavelength amorphous silicon transmission gratings*

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We present the first fabrication and investigation of visible-light subwavelength transmission gratings in high refractive index materials (e.g., amorphous silicon) on silica substrates. The gratings have periods ranging from 100 to 800 nm in 50 nm increments, a thickness of 180 nm (very thin), and they were fabricated using electron-beam lithography and reactive ion etching. Because of the high index, we have observed, for the first time, strong polarization dependence in light transmittance. The polarization effect was found to greatly depend on the ratio of grating period to wavelength, having the largest variation when the period is near half of the wavelength. The largest transmission difference for the polarization parallel and perpendicular to the grating fingers was found to be 12 dB. This observation contradicts the behavior manifested in subwavelength transmission gratings in low index materials, where the transmittance is essentially independent of the light polarization and the grating period. Rigorous electromagnetic theory has been used to model the gratings and agrees with experiments. © *1995 American Vacuum Society.*

I. INTRODUCTION

Subwavelength (period less than wavelength) dielectric transmission gratings are very attractive to future integrated optics for two reasons. First, they can serve as antireflection devices, wave plates, narrow band filters, and other optical elements. Second, they can be used to produce large arrays of different optical elements at different locations on a substrate by using a single fabrication step. However, due to the fine period required, previous investigations on subwavelength dielectric gratings in the visible-light range were primarily theoretical;[1] the experimental studies were not only few, but they were limited to a small number of grating periods and materials with low refractive index such as photoresist,[2] quartz,[3] polymethylmethacrylate (PMMA), and silicon nitride.[4] Furthermore, all previous experiments showed consistency with simple form birefringence theory or effective medium theory (EMT),[5] which predict that for normal-incidence light the transmission for the TE wave (the electric vector parallel to the grating fingers) should be almost the same as that for the TM wave (the electric vector perpendicular to the grating fingers), and that birefringence should be independent of grating period as long as the period is less than the wavelength.

In this article, we report the fabrication and investigation of thin subwavelength transmission gratings made of high refractive index material (i.e., amorphous silicon) on silica substrates. For normal-incidence light ($\lambda = 633$ nm), in addition to a large birefringence, we observed a strong polarization effect: significantly different transmittance for the TE and TM waves. Furthermore, we found that the polarization and the birefringence strongly depend on the ratio of grating period to wavelength. This strong polarization effect in dielectric gratings was not observed previously and cannot be described by simple form birefringence and effective medium theory.

II. FABRICATION

As shown in Fig. 1, the subwavelength gratings consist of thin amorphous Si (α-Si) grating with nanoscale finger width and spacing on fused silica. In fabrication, 180-nm-thick α-Si was first evaporated on a 1-mm-thick fused silica substrate. Then 950 000 molecular weight PMMA of 70 nm thickness was spun, followed by the exposure of grating structures of periods from 100 to 800 nm and nearly equal finger spacing and width using electron-beam nanolithography. A very thin layer (8 nm) of Al was coated before electron-beam writing to prevent electron charging, and was removed in diluted potassium hydroxide before development of the resist. After development, a 35-nm-thick layer of Cr was evaporated and lifted off, which served as a mask for reactive ion etching (RIE) of α-Si. In the RIE, Cl_2, $SiCl_4$, and Ar with flow rates of 20, 7.5, and 40 sccm, respectively, a pressure of 50 mTorr, and a power density of 0.32 W/cm^2 were used. The Cr mask was removed after the RIE. After fabrication, the α-Si thickness was measured to be 180 nm using a Dektak surface profiler. The refractive index was

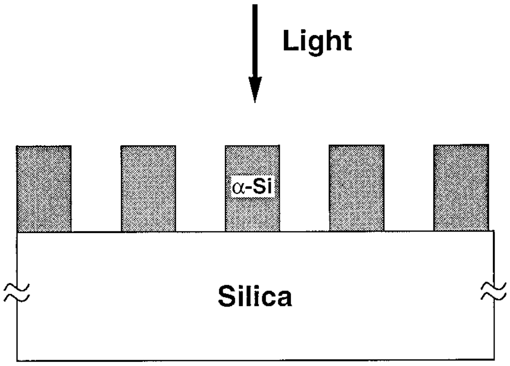

FIG. 1. Schematic of amorphous silicon transmission gratings on silica.

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measured by fitting the thickness dependence of the transmittance of α-Si films deposited on the same silica substrate and was $2.9+i0.08$.

Figure 2(a) shows a scanning electron microscopy (SEM) picture of a grating with a period of 150 nm. The grating sidewall is slightly sloped, making the profile more sinusoidal than rectangular. A grating with larger period (600 nm) is shown in Fig. 2(b). The area of the Si gratings is typically 26 by 34 μm.

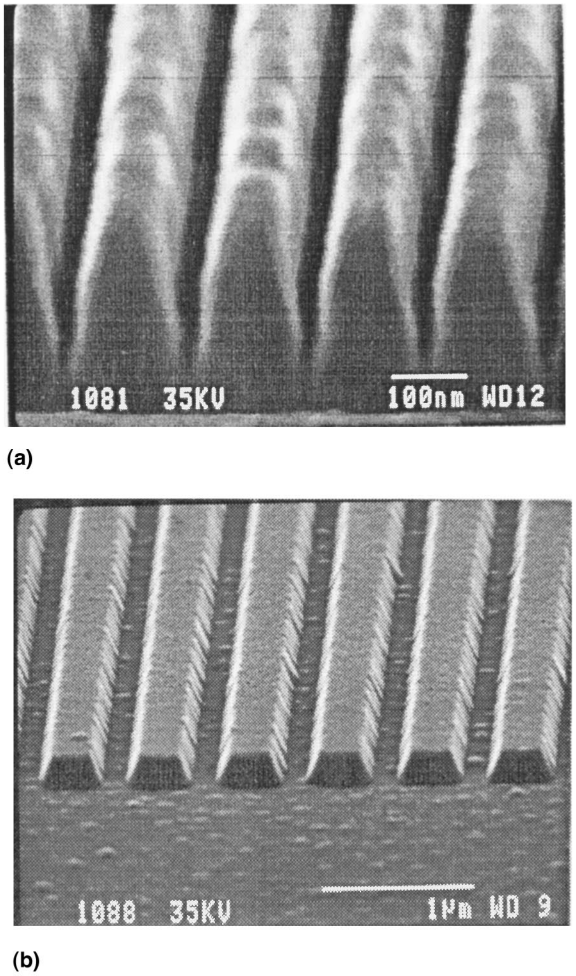

FIG. 2. Scanning electron micrograph of amorphous silicon gratings with thickness of 180 nm. (a) Period=150 nm; (b) period=600 nm.

III. CHARACTERIZATION

The experimental setup is shown in Fig. 3. This setup is basically an ellipsometer working in transmission mode.[6] A normal-incidence He–Ne laser (wavelength of 633 nm) is used as probe light source. The sample is mounted in such a way that the grating fingers are in the horizontal direction. The quarter-wave plate has its optical axis at 45° with respect to the horizontal direction. After passing through the polarizer and the quarter-wave plate, the light becomes elliptically polarized, with horizontal and vertical electrical components (corresponding to the TE and TM incident waves to the grating sample) of the sample amplitude. The phase between these two electrical components can be changed continuously by rotating the polarizer. When this phase difference is exactly compensated by the phase-delay difference introduced by the gratings, the transmitted light is linearly polarized. This linearly polarized light can be easily detected by an analyzer (another polarizer). Thus the phase difference between TE and TM waves can be derived from the rotation angle of the polarizer, and their transmittance ratio can be obtained from the polarization direction of the transmitted light.

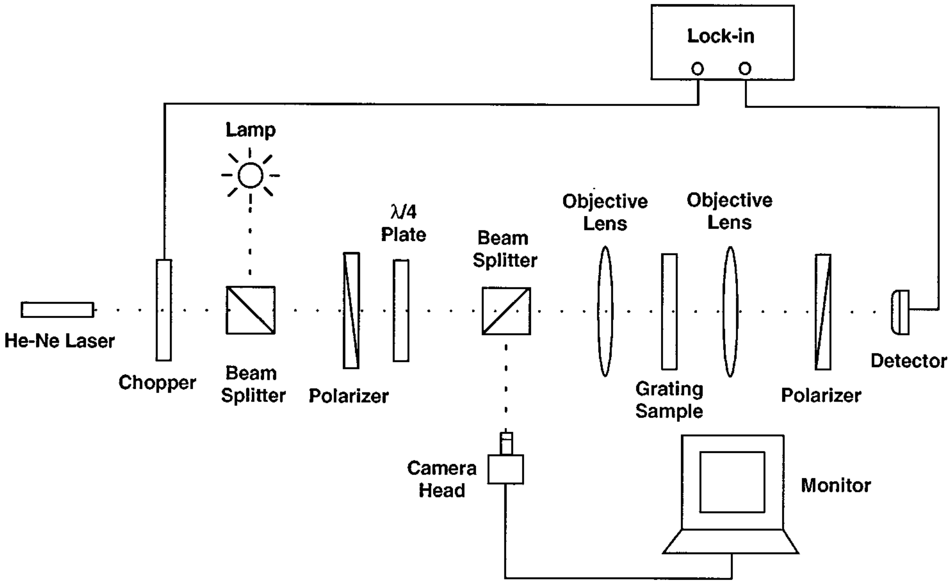

FIG. 3. Experimental setup for the grating characterization.

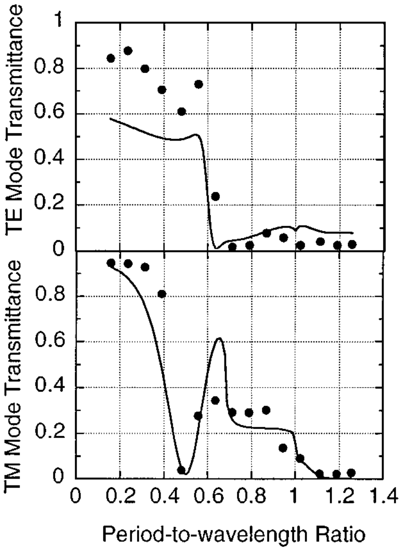

FIG. 4. Transmittance of TM and TE waves (zeroth order) for λ=633 nm. The dots are experimental results and the lines are the simulation from RME theory.

The transmittance of TE and TM waves through the α-silicon gratings for normal-incidence light was directly measured using the same He–Ne laser, the linear polarizer, and the Si photodetector (without the quarter-wave plate and the analyzer in the setup). The ratio of these two transmittances agrees very well with that from the ellipsometry measurement.

Because the grating area is small, one objective lens was used to focus the laser beam to a spot of diameter 5–10 μm. The other objective lens collects the light onto the Si photodetector. The gratings and the laser spot were monitored by an optical microscope and a camera. The polarization and birefringence of the lenses and silica substrate were measured and were negligible. All the above measurements are for zero-order diffraction, since for periods less than the wavelength the transmission only consists of zeroth order, and for periods larger than the wavelength the diffraction angles of higher orders are too large to be collected by the photodetector.

IV. RESULTS AND ANALYSIS

The transmittance of TM and TE waves through the α-silicon gratings is given in Fig. 4. The results clearly show that the transmittance strongly depends on the grating period, or more precisely the ratio of period to wavelength. For the TE wave, the transmittance is large for periods less than 0.45 μm (~2λ/3), but it is less than 5% for the periods between 0.45 and 0.8 μm. For the TM wave, the transmittance is large for periods less than 0.3 μm (~λ/2), moderate for periods between 0.45 and 0.7 μm, and less than 2% for periods between 0.7 and 0.8 μm. Furthermore, there is a transmittance minimum of 0.3 μm.

To further compare the transmittance difference of the TE and TM waves, the transmittance ratio is given in Fig. 5. We can see that the ratio is essentially equal for periods that are either less than 0.25 μm (~λ/4) or larger than 0.7 μm (~λ). Between the two periods, the ratio has an S shape. For grating periods between 0.25 (~λ/4) and 0.38 μm (λ/2), the TE wave transmits better than the TM wave. However, for periods between 0.38 (~λ/2) and 0.7 μm (~λ), the TM wave transmits better. The largest transmittance difference is 12 dB, which is remarkable for a dielectric grating that is only 180 nm (<λ/3) thick and is large enough for some polarization applications.

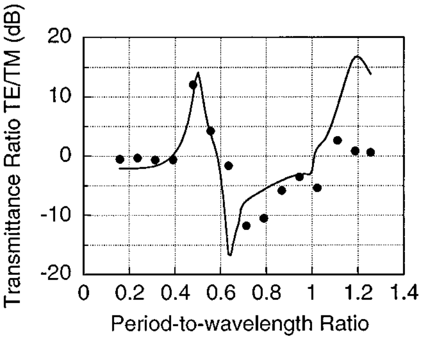

FIG. 5. Transmittance ratio of TM and TE waves (zeroth order) for λ=633 nm. The dots are experimental results and the lines are the simulation from RME theory.

The measured phase difference of TE and TM waves is shown in Fig. 6, which also strongly depends on the ratio of period to wavelength and has an S shape. Depending upon the period-to-wavelength ratio, the TE wave varies from 170° ahead of to 170° behind the TM wave. The phase difference is extremely large for a transmission grating with a thickness of only 180 nm (<λ/3). The middle point of the S shape is at the period of 0.38 μm (~λ/2), the same middle point for the S shape in the transmittance ratio. This means that at that period the subwavelength grating acts like an isotropic material. The physical significance of this observation is still under study. It should be pointed out that when the phase difference is the largest, the transmittances of TE and TM are almost equal.

Clearly, our observation is fundamentally different from previous experimental studies of dielectric transmission gratings[1–4] and from the simple form birefringence or the effective medium theory which have shown that the phase difference is almost independent of the period, and TE and TM waves have similar transmittances.

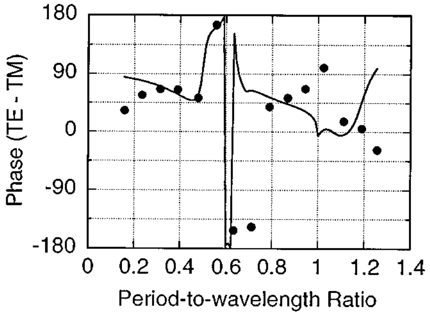

FIG. 6. Phase retardation between TE and TM waves (zeroth order) for λ=633 nm. The dots are experimental results and the lines are the simulation from RME theory.

To understand the physics of our observation, we have used a rigorous modal expansion (RME) theory[7] to simulate the gratings behavior. The results of our simulation are plotted in Figs. 4–6, along with the experimental data. As shown, except for a few discrepancies, our simulation generally agrees with the experiments. The agreement is better for smaller grating periods. Although the details of our simulation will be published elsewhere,[8] here we briefly discuss the physics.

Inside the grating region, due to the periodic structure, only electromagnetic waves with discrete characteristic wave vectors (eigenmodes) can exist. They are similar to the Bloch waves in a crystal. When a light wave enters the grating, it is decomposed into these grating eigenmodes. At the two boundaries of the grating with the air and the substrate, each eigenmode can be reflected, coupled to other eigenmodes, and coupled out to form the reflected and transmitted diffraction waves. If there is only one eigenmode inside the grating, then the transmittance of TE and TM waves and birefringence is determined by a single parameter, which is the effective refractive index associated with this eigenmode, and is almost independent of the period. This is the case observed by all previous experimental studies and predicted by simple form birefringence theory and EMT. However, if there are two or more eigenmodes propagating inside the grating region, each mode has a different effective index, and the interaction between these eigenmodes produces complex diffraction characteristics. Since TE and TM waves have different eigenmodes in the grating, their phase retardation and transmittance would be very different and would change drastically with the grating period. This is the case in our α-Si gratings. In previous experiments, either the period is small[4] or the refractive index is small.[2,3] Both result in only one grating eigenmode. Therefore, no drastic polarization effects were observed.

It is conceivable that these subwavelength gratings will have tremendous applications in future integrated optics. One obvious application is wave plates. The refractive index difference for TE and TM waves in the α-Si subwavelength grating waveplates is 0.83, which is three orders of magnitude higher than that of quartz and over 20 times larger than potassium dihydrogen phosphate (KDP) crystal. This means that the α-Si subwavelength grating wave plates not only can be integrated on a wafer, but also can be three orders of magnitude thinner than quartz and 20 times thinner than KDP crystal.

V. SUMMARY

We have fabricated the investigation subwavelength amorphous silicon transmission gratings with periods from 100 to 800 nm and a thickness of 180 nm on silica substrates. For normal-incidence light ($\lambda = 633$ nm), in addition to large birefringence, strong polarization effects were observed. Both polarization and birefringence effects were found to greatly depend on the ratio of grating period to wavelength, having the largest variation when the period is near half of the wavelength. The largest transmission difference for the polarization parallel and perpendicular to the grating fingers is 12 dB; the largest phase difference is 170°. The behavior of the gratings deviates significantly from previous experiments and simple form birefringence theory and effective medium theory, but it seems consistent with rigorous modal expansion theory. The subwavelength gratings have many important applications in the integrated optics, such as wave plates and polarization-selection mirrors for vertical cavity lasers.

ACKNOWLEDGMENTS

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