

# Subwavelength amorphous silicon transmission gratings and applications in polarizers and waveplates

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Subwavelength amorphous silicon transmission gratings with a period from 100 to 800 nm and a thickness of 180 nm on silica substrates have been fabricated and studied. For a normal incident light ( $\lambda=633$  nm), in addition to strong birefringence (as large as  $170^\circ$  in phase difference), it was observed that the transmission of TE (the electric field parallel to the grating finger) wave is significantly different from that of TM (the electric field perpendicular to the grating fingers) wave (as large as 12 dB), and that both polarization and birefringence effects strongly depend on the ratio of grating period to wavelength, having the largest variations at the grating periods around a half of the wavelength. This observation deviates significantly from simple form birefringence theory and effective medium theory. Applications such as polarization selection mirrors for vertical cavity surface emitting lasers and waveplates are discussed. © 1995 American Institute of Physics.

Subwavelength dielectric transmission gratings can serve as antireflection devices, waveplates, narrow band filters, and other optical elements. They are very attractive to future integrated optics, because large arrays of different subwavelength optical elements can be made at different locations of a substrate using simple grating structures in a single fabrication step. However, due to the fine period required, most of the previous investigations were theoretical;<sup>1</sup> the experimental studies were few and limited. For example, the transmission gratings studied previously were fabricated in low dielectric constant materials such as photoresist,<sup>2</sup> quartz,<sup>3</sup> polymethylmethacrylate (PMMA), and silicon nitride,<sup>4</sup> giving small refractive index modulation. Furthermore, all previous experiments showed consistency with the simple form birefringence theory or effective medium theory,<sup>5</sup> which predict that for a normal incident light the transmission for the TE wave (the electric field parallel to the grating fingers) should be almost the same as that for the TM wave (the electric field perpendicular to the grating fingers), and that birefringence should be independent of the grating period as long as the period is less than the wavelength.

In this letter, 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 incident light ( $\lambda=633$  nm), in addition to large birefringence, we observed strong polarization effects: significantly different transmittance for the TE and TM waves. Furthermore, we found that the polarization and the birefringence effects strongly depend on the ratio of grating period to wavelength. This strong polarization effect was not observed previously and cannot be described by simple form birefringence and the effective medium theory. We will discuss possible applications of such gratings as polarizers and waveplates.

As shown in Fig. 1, the subwavelength gratings consists of a thin amorphous Si ( $\alpha$ -Si) grating with nanoscale finger

width and spacing on a fused silica. In fabrication, a 180 nm thick  $\alpha$ -Si was first evaporated on a 1 mm thick fused silica substrate. Then 950 K PMMA of 70 nm thickness was spun, followed by exposing grating structures of a period from 100 to 800 nm and nearly equal finger spacing and width using electron beam nanolithography. After development, a layer of Cr is evaporated and lifted off, and serves as the mask for reactive ion etching (RIE) of  $\alpha$ -Si. In the RIE,  $\text{Cl}_2$ ,  $\text{SiCl}_4$ , Ar with flow rates of 20, 7.5, and 40 sccm, respectively, a pressure of 50 MTorr, and a power density of  $0.32 \text{ W/cm}^2$  were used. The Cr mask was finally removed after the RIE. After fabrication, the  $\alpha$ -Si thickness was measured by Dektak surface profiler and was 180 nm. The refractive index was measured by fitting the thickness dependence of the transmittance of the plain  $\alpha$ -Si films deposited on the same silica substrate and was 2.9 in the real part and 0.08 in the imaginary part.

Figure 2 shows a scanning electron microscopy (SEM) micrograph of a grating with a period of 150 nm. The grating sidewall is lightly sloped and curved, making the profile more sinusoidal than rectangular. However, for the gratings with a period larger than 300 nm, the profile is almost rectangular and has equal spacing and width. The area of the Si gratings is typically  $26 \mu\text{m} \times 34 \mu\text{m}$ .

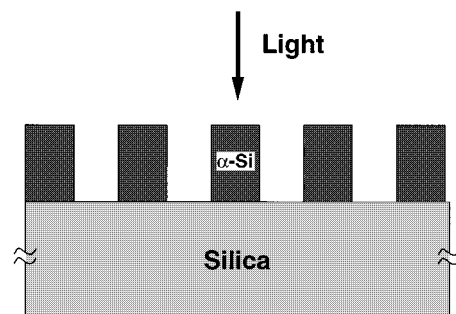


FIG. 1. Schematic amorphous silicon transmission gratings on silica.

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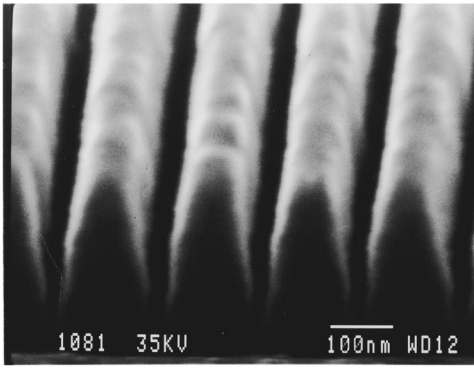


FIG. 2. SEM micrograph of an amorphous silicon grating with a 150 nm period and a 180 nm thickness.

The transmittance of the TE and TM waves through the  $\alpha$ -silicon gratings for normal incident light was measured using a He-Ne laser (wavelength 633 nm), a linear polarizer, and a Si photodetector. The transmittance ratio and the phase difference between the two waves were measured using a transmission ellipsometry method also with a normal incidence He-Ne laser.<sup>6</sup> Because the grating area is small, one objective lens was used to focus the laser beam to a spot having a diameter of  $\sim 5\text{--}10\ \mu\text{m}$ . The other objective lens collects the light into 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 the zero order diffraction, since for the periods less than the wavelength, the transmission only consists of zeroth order and for the periods larger than the wavelength, the diffraction angles of higher orders are too large to be collected by the photodetector.

The transmittance of TM and TE waves through the  $\alpha$ -silicon gratings is given in Fig. 3. It clearly shows 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 the periods less than 0.45

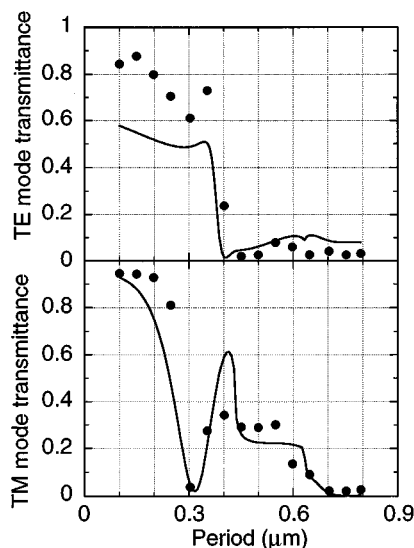


FIG. 3. Transmission of TM and TE waves (zeroth order). The dots are the measured values and the lines are a simulation from RME theory.

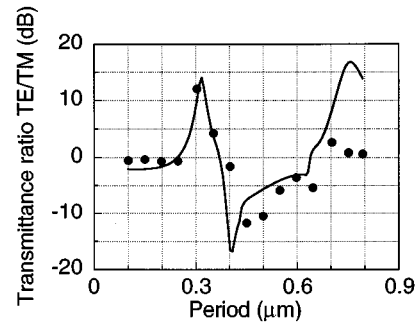


FIG. 4. Transmission of TM and TE waves (zeroth order). The dots are the measured values and the lines are a simulation from RME theory.

$\mu\text{m}$  ( $\sim 2\lambda/3$ ), but it is less than 5% for the periods between 0.45 to 0.8  $\mu\text{m}$ . For the TM wave, the transmittance is large for the periods less than 0.3  $\mu\text{m}$  ( $\sim \lambda/2$ ), moderate for the periods between 0.45 to 0.7  $\mu\text{m}$ , and less than 2% for the periods between 0.7 to 0.8  $\mu\text{m}$ . Furthermore, there is a transmittance minimum at 0.3  $\mu\text{m}$ .

To further compare the transmittance difference of the TE and TM waves, the transmittance ratio is given in Fig. 4. We can see that the ratio is essentially equal for the period that is either less than 0.25  $\mu\text{m}$  ( $\sim \lambda/4$ ) or larger than 0.7  $\mu\text{m}$  ( $\sim \lambda$ ). But between the two periods, the ratio has an S shape. For the grating period between 0.25  $\mu\text{m}$  ( $\lambda/4$ ) to 0.38  $\mu\text{m}$  ( $\sim \lambda/2$ ), the TE wave transmits better than the TM wave. However, for the period between 0.38  $\mu\text{m}$  ( $\sim \lambda/2$ ) to 0.7  $\mu\text{m}$  ( $\sim \lambda$ ), the TM wave transmits better. The largest transmittance difference is 12 dB, which is remarkable for a dielectric grating that is only 180 nm ( $\sim \lambda/3$ ) thick and is large enough for some polarization applications.

The measured phase difference of TE and TM waves is shown in Fig. 5, 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  $170^\circ$  ahead to  $170^\circ$  behind that of the TM wave. The phase difference is extremely large for a transmission grating with a thickness of only 180 nm ( $\sim \lambda/3$ ). The middle point of the S is at the period of 0.38  $\mu\text{m}$  ( $\sim \lambda/2$ )—the same middle point for the S in the transmittance ratio. This means that at that period, the subwavelength grating acts like an isotropy material. The physical significance of this observation is still being studied. It should be pointed out that when the phase difference is the largest, the transmittance of TE and TM are almost equal.

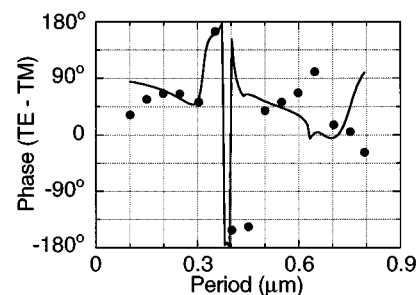


FIG. 5. The phase retardation between TE and TM waves (zeroth order). The dots are the measured values and the lines are a simulation from RME theory.

Clearly, our observation is fundamentally different from previous experimental studies of transmission gratings and from the simple form birefringence or the effective medium theory that have shown that the phase difference is almost independent of the period and TE and TM waves have similar transmittances.<sup>1-4</sup>

To understand the physics of our observation, we have used a rigorous modal expansion (RME) theory<sup>7</sup> to simulate the gratings behavior. The results of our simulation are plotted in Figs. 3, 4, and 5 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,<sup>8</sup> 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 crystal. When a lightwave 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 are determined by a single parameter which is the effective refractive index associated with this eigenmode, and are almost independent of the period. This phenomenon is 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  $\alpha$ -Si gratings. In previous experiments, either the period is small<sup>4</sup> or the refractive index is small:<sup>2,3</sup> 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 waveplates. The refractive index difference for TE and TM waves in the  $\alpha$ -Si subwavelength grating waveplates is 0.83, which is three orders of magnitude higher than that of quartz and over 20 times larger than KDP crystal. This means that the  $\alpha$ -Si subwavelength grating waveplates 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.

Another application that we are proposing here is to select the polarization direction of vertical cavity surface emitting lasers (VCSEL). The polarization in a VCSEL is generally random and changing with current injected due to the rotation symmetry of the cavity. Putting a subwavelength grating polarizer on one end of a VCSEL mirror, one polarization will have a reflectivity much greater than the orthogonal polarization. With a suitable lasing threshold, only one polarization is selected by the subwavelength grating polarizer to lase. The subwavelength grating polarizers also can make the polarization of a VCSEL different from that of its neighbors, opening up the possibility to have a two-dimensional array of VCSELs with a polarization pattern that varies from one VCSEL to another according to a function of the array.

In summary, we have fabricated and investigated subwavelength amorphous silicon transmission gratings with a period from 100 to 800 nm and a thickness 180 nm on silica substrates. For a normal incident 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, simple form birefringence theory, and effective medium theory, but it seems consistent with rigorous modal expansion theory. The subwavelength gratings have tremendous application possibilities for integrated optics such as waveplates and polarization selection mirrors for vertical cavity lasers.

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