Photonic-crystal near-ultraviolet reflectance filters fabricated by nanoreplica molding

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One-dimensional photonic-crystal reflectance filters operating in the near-ultraviolet wavelengths were fabricated using nanoreplica molding from a silicon surface structure "master" template, patterned using electron-beam lithography. The fabricated devices produce a narrow linewidth reflectance resonance at a wavelength of 411 nm for TM polarized illumination and a broadband reflectance characteristic between 402 and 439 nm for TE polarized illumination. The measured reflectance spectra are accurately predicted by Rigorous Coupled Wave Analysis computer simulations, which demonstrate the capability for designing similar filter performance for wavelengths <350 nm through minor adjustment of the photonic-crystal lattice period. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2173718]

Recently, there has been great interest in photonic crystals[1] (PCs) due to their ability to control and manipulate electromagnetic radiation, which has important consequences in designing waveguides,[2] filters,[3] and omnidirectional mirrors[4] that find use in communication systems. PCs may be designed for a wide range of operating wavelengths, from microwave to ultraviolet. However, decreasing wavelength requires reduced feature sizes and makes realization of the devices technologically challenging, as a high degree of control and accuracy is required in the fabrication process. The cost-effective fabrication of near-UV photonic crystals is an important step in the realization of PC-based near-UV lasers and filters used in high density optical data storage and optical memory applications.

Traditionally, one dimensional (1D) PCs have been manufactured by processes such as direct write electron-beam lithography,[5] focused ion-beam lithography,[6] and laser ablation.[3] Although these methods appear to work well for their intended applications, they all share the drawback of being expensive and having low throughput. High throughput replication of infrared PCs on continuous sheets of plastic film at a very low cost has been previously demonstrated.[7] Our aim in this work was to extend this process to the fabrication of 1D near-UV PCs operating at ~400–450 nm.

The structure for the 1D PC is shown in Fig. 1. A thin layer of high refractive index TiO_2 covers a low refractive index polymer substrate on which a linear surface structure is present. Structures similar to that presented in this work have been utilized as narrowband reflectance filters utilizing a guided mode resonance effect, in which a single film layer incorporates a subwavelength periodic dielectric constant modulation.[8] For the resonant wavelength, only the zero-order forward- and backward-diffracted waves are coupled to the structure, with all higher-order waves cut off, resulting in ~100% reflection efficiency. Through control of the magnitude of the dielectric constant modulation and the symmetry of the periodic profile, the spectral width of the resonance may be selected, and a variety of filter functions may be obtained.[9] Thus, the optical properties of the photonic crystal are primarily governed by the following five physical parameters: the grating period (Λ), the depth of the grooves (h), the index of refraction of the TiO_2 (n_{TiO_2}), the thickness (t) of the TiO_2, and the substrate refractive index ($n_{polymer}$).

Rigorous Coupled Wave Analysis (RCWA) software (RSoft) was used to model 1D PCs and to optimize their performance. Based on the model, the values $\Lambda=250$ nm, $h=100$ nm, and $t=100$ nm provided strong reflectance in the desired ~400–450 nm region. The index of refraction of the TiO_2 and polymer were fixed at $n_{TiO_2}=2.25$ and $n_{polymer}=1.464$, respectively. The reflection peak profiles and wavelengths are dependent on the polarization (TE or TM) of the incident light. For light polarized parallel to the linear surface structure, a resonance corresponding to the TE mode is obtained. When the incoming light is polarized at an angle of 90° to the linear surface structure, resonance corresponding to the TM mode is obtained. It was observed that the reflection in the TE mode had a broad peak (full width at half-maximum, FWHM=70 nm) and the reflection in the TM mode corresponded to a narrow and blueshifted peak (FWHM=11 nm), thus providing both narrow and broad reflectance resonance characteristics on the same device. Scaling Λ or t to lower values resulted in a blueshift of the resonance peak (regardless of incident light polarization), while increasing the value of h caused the resonance peaks to have a lower FWHM. Figure 2 shows the simulation results for the TE and TM resonances and the effect of varying the period (Λ) on the TE and TM resonant wavelengths.

To fabricate the required structure, the first step was to make a "master mold" from which a polymer structure could be replicated. This was done using direct write electron-

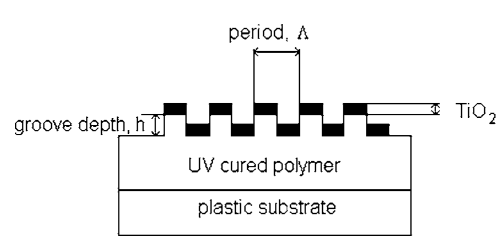

FIG. 1. Cross-sectional structure of the photonic-crystal device.

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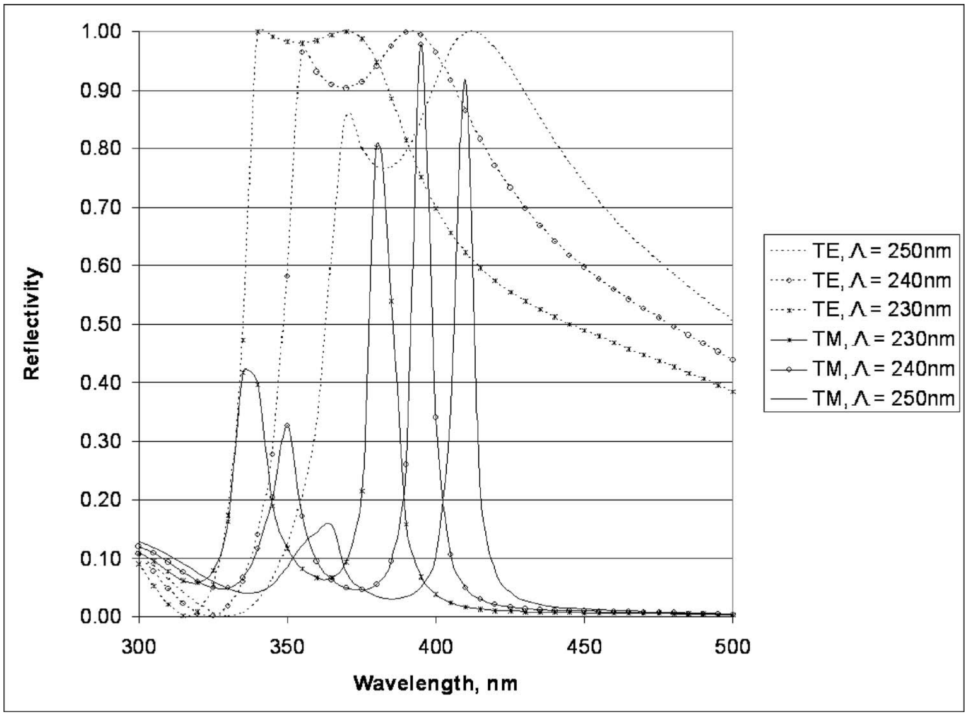

FIG. 2. Result of RCWA computer simulations predicting the shape and resonant wavelengths of the TE and TM spectra. The resonant wavelengths may be selected by varying the period (Λ).

beam lithography (Cambridge Instruments, EBMF 10.5) at a beam diameter of 80 nm, on a silicon substrate with a 200 nm thick SiO_2 layer. 950 K M.W. poly(methylmethacrylate) electron-beam resist (PMMA, Microchem) was used for the masking layer. Post writing, development of the resist in 1:3 methyl isobutyl ketone: isopropyl alcohol solution for 90 s was carried out to reveal the required structure in the PMMA. After a 5 s O_2 plasma descum operation, the SiO_2 was etched using reactive ion etching in a Freon 23 (CHF_3) plasma to a depth of 100 nm. Subsequent stripping of the masking PMMA with a 1:1 solution of methyl alcohol and methylene chloride in an ultrasonic bath revealed the desired structure of the silicon master mold.

Fabrication of the PC first required that the mold pattern be replicated onto a flexible plastic substrate. A UV curable polymer (UVCP) was used to form a replica of the mold and a flexible plastic (polyethylene terepthalate, PET) substrate provided support to this replica, by adhering to it. The mold was thoroughly cleaned using IPA and acetone, in an ultrasonic bath and treated in oxygen plasma for 3 min. Thereafter, it was silane treated (PlusOne Repel-silane ES, Amersham) to ensure easy release of the replicated structures. This was followed by dispensing a small amount of the UVCP into the mold and pressing it down by a uniform force to the PET substrate. Subsequent curing of this "sandwich" structure under a high power xenon UV lamp (RC-600, Xenon Corp.) resulted in hardening and adhesion of the UVCP through a crosslinking reaction onto the PET substrate, which was then peeled away from the mold. This resulted in a negative replica of the mold. Finally, a 100 nm thick layer of TiO_2 was deposited on the replicated structure using electron-beam evaporation (Denton Vacuum). To test stability and reusability of the mold over repeated replications, a number of replicas were made and tested for dimensional accuracy at five points on the surface, using a scanning electron microscope (SEM, Hitachi 4160). For ten replicated structures, the variation in period was ±0.1% indicating a high degree of dimensional stability and resilience in the mold. Figure 3 shows the SEM micrograph of the photonic-crystal mold and replica, at the center.

Reflection measurements on the fabricated PCs were carried out on a spectrometer (Ocean Optics USB 2000). First, a dark reference was taken for the spectrometer followed by measurement of the reflected spectrum of the PC, both in the TM and TE modes. The resulting spectrum was subtracted from the dark reference to yield a normalized result. The measurements obtained in the experiment are shown (Fig. 4). It can be seen that for the TM mode, the reflection maximum (or resonant wavelength) is obtained at 411.13 nm. For the TE mode, two broad overlapping peaks are obtained at 402.50 and 439.38 nm. For the fabricated structure, simulation predicted peaks at 366.90 and 409.17 nm for the TE mode, and 412.34 nm for the TM mode. Although the reflection behavior of the PC as predicted from simulation was accurate for the TM mode, the TE mode reflection is red-shifted. Possible causes could be slight variation of the period of the surface structure of the mold and/or variation in the thickness of the deposited TiO_2 in one direction.

An interesting feature of the device is its tunable nature, even in the completely fabricated state. When tested under normal conditions, the device is under an ambient atmosphere (air), whose refractive index (RI) can be approximated to be 1. When this ambient bulk is changed to water [i.e., RI is changed to a higher value (1.33)], a shift is observed in the resonant wavelength. In the case of these de-

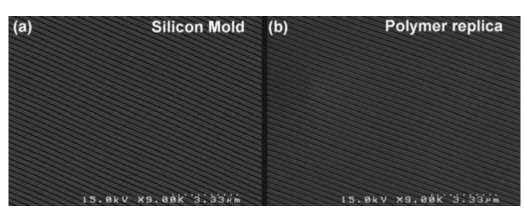

FIG. 3. SEM micrographs of (a) silicon mold and (b) polymer replica taken from the mold. The period (Λ) of the linear grating surface structure is 250 nm.

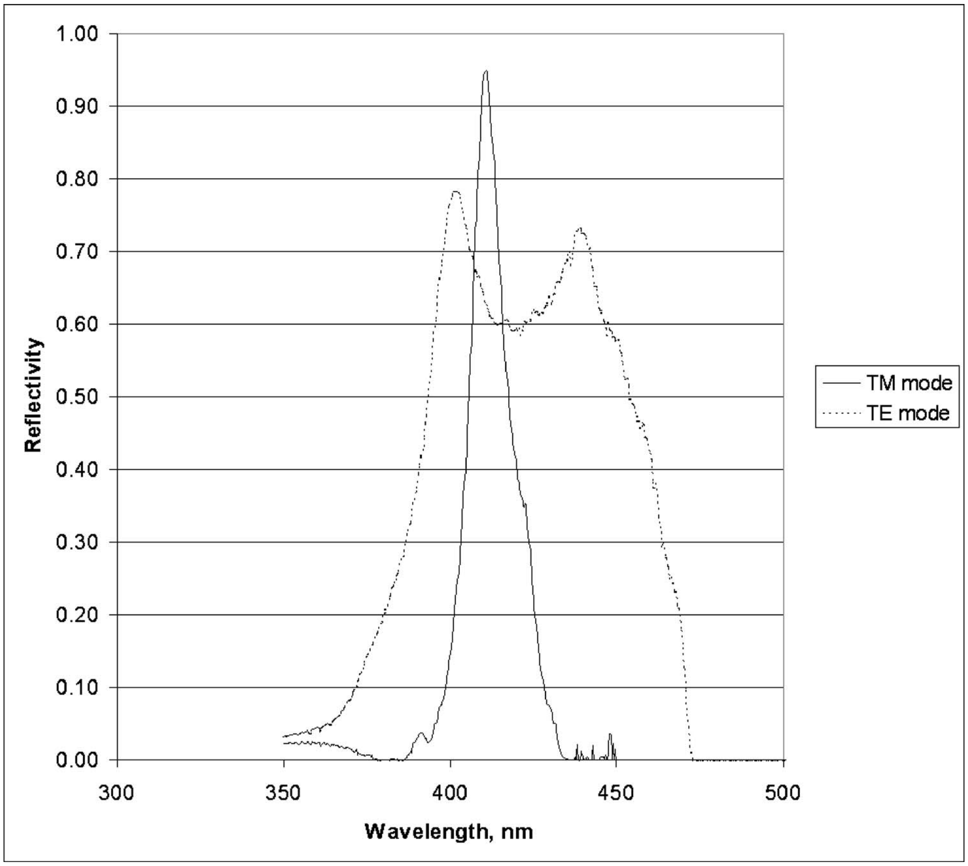

FIG. 4. Measured reflection spectrum for TM and TE modes.

vices, an increase of ~20–23 nm is observed both in the TM and TE modes. Thus, by coating the device surface with an appropriate "superstrate," one can tune its performance.

In conclusion, we have fabricated a photonic-crystal reflectance filter that is capable of operating in the near-UV wavelengths, both in a narrow reflectance mode (TM) and broad reflectance mode (TE). The device was fabricated in an inexpensive and repeatable manner through nanoreplica molding. The device also exhibits tunability after fabrication. The next steps will be to develop PC filters that operate at even lower wavelengths, extending into UV and deep UV wavelengths. An alternative approach based on two-dimensional PCs will also be explored.

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