Highly tolerant a-Si distributed Bragg reflector fabricated by oblique angle deposition

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Abstract: We demonstrate a highly tolerant and highly reflective broadband a-Si distributed Bragg reflector fabricated by oblique angle deposition. By tuning the refractive index of an a-Si film, a high index contrast material system was achieved. The highly tolerant and broadband reflective characteristics of the a-Si distributed Bragg reflector were investigated by calculation and fabrication. A broad stop band (Δλ/λ = 33.7%, R>99%) with only a five-pair a-Si distributed Bragg reflector was achieved experimentally. The size-, feature- and substrate-independent method for highly reflective Bragg reflectors was realized by simple oblique angle evaporation.

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References and links

1. Introduction

Broadband high reflective distributed Bragg reflectors (DBRs) are essential in optical devices, including telecommunication, semiconductor lasers, solar cells, optical sensors, and photo detectors [1–4]. For DBRs, the reflectivity and stop band width directly depend on the refractive index contrast between the high- and low-index material, i.e., a higher refractive index contrast contributes to a higher reflectivity and a wider stop band. Moreover, a higher index contrast guarantees higher tolerance during the fabrication process of DBRs in the cases of permissible deviation of stop band width. Because process parameters such as the deposition rate seriously affect the quality of thin film optical components, highly tolerant DBRs are prerequisite to low-cost fabrication. Thus far, various material systems or novel techniques have been used to realize broadband high-reflective DBRs; however, these have their own limitations, including, 1) the necessity for expensive equipment and a substrate-sensitive process, 2) a complicated and protracted process, 3) non-conductive and poor thermal properties, and 4) low refractive index contrast [5–8]. Moreover, these material systems are heterostructures, as DBRs generally consist of several pairs of different materials with different refractive indices. However, the refractive index and other properties of this type of material, such as conductivity and thermal expansion coefficient are in general inseparably coupled. Due to the limited number of available materials, the choice of the refractive index also dictates the remaining material characteristics. Although porous silicon multilayers were reported in the early 1990s for a homogeneous material system, it has been limited by process tolerances, e.g. etch rate and process temperature [9,10].

Recently, it was shown that oblique-angle deposition (OAD) of materials, e.g., SiO$_2$, TiO$_2$ and ITO, can be used to fabricate optical components with optical properties that can be
controlled by the oblique angle [11–13]. By controlling the angle of deposition and thereby
the layer porosity and refractive index, oblique-angle deposition allows the fabrication of thin
film optical components composed of a single material chosen for its optical properties in
which each layer has a different refractive index that is individually tuned to a specific desired
value. Schubert et al. reported experimental results involving a homogeneous DBR structure
by OAD but the index contrast was still low [14]. The capability of the use of a single-step
and single-material deposition for high-low or graded-index optical component is crucial
when a highly tolerant process is important [15].

This paper represents the first-demonstration of amorphous silicon (a-Si) DBRs fabricated
by OAD having high process tolerance and broadband high-reflective properties due to the
high index contrast. A five-period a-Si/a-Si DBR was fabricated by OAD via e-beam
evaporation on a two-inch silicon wafer (100). The reflectivity and wafer-scale uniformity
were analyzed by spectrophotometry measurements and reflectivity mapping. This a-Si/a-Si
DBR has advantages in that it offers the least complicated means of realizing a highly tolerant
and large-scale mirror fabrication process leading to high reflectivity with a wide stop band.

2. Design and Fabrication

To realize an a-Si/a-Si DBR, the low- and high-index layers of the a-Si should be prepared
with high refractive index contrast. The Si layers were deposited on Si substrate by an e-beam
evaporator using inclined sample holders for the tilted angle evaporation. A detail discussion
about the experimental setup was reported in a previous paper [16]. Generally, the refractive
index of the deposited film decreases as the oblique angle increases in the OAD process
[16,17]. This means that the most oblique angle is necessary for the highest index contrast.
However, excessively tilted evaporation creates a roughened surface on the deposited film
and porous structure that can be filled by subsequently arriving atoms for the high index layer
[14]. Therefore, a carefully chosen oblique angle and refractive index for the low index layer
are crucial to ensure a high index contrast DBR by OAD.

![Fig. 1. Schematic diagrams of the fabrication process steps and SEM images of a-Si DBR
structure based on OAD. Scale bars: 100 nm.](image)

A schematic of the fabrication procedure is shown in Fig. 1. Normally high reflective
DBRs consist of low-index layers alternatively with high-index layers. Initially, a low-index
layer was deposited by OAD with a tilted angle of 70°, which was carefully chosen from the
results of previous work [18]. As shown in a cross-sectional scanning electron microscopic

(SEM) image in Fig. 1, the nanocolumnar layer has the distinct pattern of a vacancy; hence, the refractive index of the layer was decreased by a controllable amount. The refractive index of a nanocolumnar material is determined by the volume fractions of the air and the material. For two parameters with volume fractions of $V_{\text{air}}$ and $V_{\text{a-Si}}$, where $V_{\text{air}} + V_{\text{a-Si}} = 1.0$, and refractive indices $n_{\text{air}}$ and $n_{\text{a-Si}}$, the Bruggemann effective medium approximation is

$$V_{\text{air}} \left( n_{\text{air}}^2 - n_{\text{eff}}^2 \right) / \left( n_{\text{air}}^2 + 2n_{\text{eff}}^2 \right) + \left( 1 - V_{\text{air}} \right) \left( n_{\text{a-Si}}^2 - n_{\text{eff}}^2 \right) / \left( n_{\text{a-Si}}^2 + 2n_{\text{eff}}^2 \right) = 0, \quad (1)$$

where $n_{\text{eff}}$ is the effective refractive index of the nanocolumnar a-Si film and $V_{\text{air}}$ is the volume fraction of air (or the porosity of the film) \[19\]. The porosity $V_{\text{air}}$ of the low-n a-Si layer was calculated to be 65.5\% using the following parameters: $n_{\text{eff}} = 1.639$, $n_{\text{a-Si}} = 3.291$, and $n_{\text{air}} = 1.0$. The characterization of the mechanical, electromechanical, thermal and other physical properties of nanostructured Si films has already been presented \[20\]. The porous Si films seem fragile, but even in the conventional semiconductor process it can stand without any physical or optical changes. Secondly, as a high refractive index layer, the a-Si film was deposited with normal incident e-beam flux. Because our first deposited low-index layer has a relatively flat surface, we could ignore the filling in of certain spaces between the nanocolumns. Figure 2 shows the results of cross-sectional SEM and transmission electron microscopic (TEM) measurements of the fabricated five-period a-Si/a-Si DBR. As shown in Fig. 2 (a), the fabricated five-period a-Si/a-Si DBR was precisely formed on a silicon substrate (100) by OAD. For the low-index layer and the high-index layer, the tilted e-beam flux was fixed respectively at 70° and 0°, as mentioned above. The gap between the nanocolumnar structures is less than 10 nm, i.e., much smaller than the wavelength of visible light, thereby limiting optical scattering \[21\]. In this case, the SEM is not well suited for analyzing such random and nanocolumnar structures, especially the interface between low and high refractive index layers. Hence, we used the TEM image in Fig. 2 (b). Normally, a film deposited at an oblique angle has significant porosity, leading to an uneven surface \[22,23\]. Nevertheless, the interface between the low- and high-index layers is relatively good to distinguish the interfaces in this work, as depicted in the TEM image. The estimated thicknesses of the low- and high-index layers are 220 ± 5 nm and 118 ± 2 nm, respectively. While the normal deposition was precisely controllable, the OAD had a thickness error of approximately 10 nm. The thickness error of the OAD a-Si film may result from the estimation error of the deposition rate of the OAD. Notwithstanding this, as the film was deposited by evaporation, the controllability of the film thickness was mostly suitable for quarter-wavelength optical films.

\[150.00 USD\]
3. Results and Discussion

The reflective property of the five-period a-Si/a-Si DBR structure was investigated both theoretically and experimentally. The calculated and measured reflective spectra are shown in Fig. 3 (a) and (b), respectively. For comparison, the reflectivity values of DBRs with other general material systems were calculated, with these results shown in Fig. 3 (a). The reflectance calculation was done using a method based on a rigorous coupled-wave analysis (RCWA), and each material property of the a-Si films was sourced from previous results [18,24,25]. The highest reflectivity, close to 100%, was observed in the wavelength range from 1400 nm to 1800 nm, and nearly perfect agreement between the calculated and measured results was observed. In addition, the stop band with high reflectivity ($\Delta \lambda/\lambda, R>99\%$) of the a-Si/a-Si DBR was comparable to the other material systems in both the experimental and calculated results, as shown in Table 1. The stop band from the measured result is comparable to that of subwavelength gratings designed with a high level precision [26]. This may be contributed by the large index contrast [27,28]. Figure 3 (b) shows the reflectivity spectra of fabricated a-Si/a-Si DBRs as a function of the number of periods. A three-period a-Si/a-Si DBR was sufficient to ensure high reflectivity that exceeded 97%.

![Fig. 3](image)

**Fig. 3.** (a) Calculated reflectivity spectra of GaAs/AlAs, SiO$_2$/TiO$_2$ and a-Si/a-Si DBRs as a function of wavelength. (b) Measured reflectivity spectra of 2, 3, 4 and 5 period a-Si/a-Si DBRs as a function of wavelength. The center wavelength of every DBR was 1550 nm.

**Table 1.** Refractive index, thickness, index contrast and stop bandwidth of GaAs/AlAs, SiO$_2$/TiO$_2$ and a-Si/a-Si DBRs. The center wavelength is 1550 nm.

<table>
<thead>
<tr>
<th>Material</th>
<th>$n_{\text{low}}$</th>
<th>$n_{\text{high}}$</th>
<th>$t_{\text{low}}$</th>
<th>$t_{\text{high}}$</th>
<th>$\Delta n$</th>
<th>$\Delta \lambda/\lambda_{c}$ (R&gt;99%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs/AlAs</td>
<td>2.894</td>
<td>3.374</td>
<td>134 nm</td>
<td>115 nm</td>
<td>0.480</td>
<td>0%</td>
</tr>
<tr>
<td>SiO$_2$/TiO$_2$</td>
<td>1.444</td>
<td>2.447</td>
<td>268 nm</td>
<td>158 nm</td>
<td>1.003</td>
<td>16.6%</td>
</tr>
<tr>
<td>a-Si/a-Si (Cal)</td>
<td>1.639</td>
<td>3.291</td>
<td>236 nm</td>
<td>118 nm</td>
<td>1.652</td>
<td>35.6%</td>
</tr>
<tr>
<td>a-Si/a-Si (Exp)</td>
<td>-</td>
<td>-</td>
<td>220 ± 5 nm</td>
<td>118 ± 2 nm</td>
<td>-</td>
<td>33.7%</td>
</tr>
</tbody>
</table>
To demonstrate the high process tolerance and potential for a large-scale process, we fabricated a 2” full-wafer a-Si/a-Si DBR with five periods. The result from the reflectivity mapping of the 2” full-wafer a-Si/a-Si DBR is shown in Fig. 4 (a). The relative reflectivity map was measured by reflectance mapping tool (RPM 2000, Nanometrics) at the center wavelength of 1550 nm. There is a slightly different color in the measured relative reflectivity, as the wafer was not rotated in the evaporating chamber. This indicates that the evaporating distance to one edge of the wafer is slightly different from the distance to the opposite edge. Nevertheless, relatively uniform reflectivity of the full-wafer DBR was achieved. To study the influence of the sample position on the reflectivity, we measured the reflectivity of each position marked in Fig. 4 (a) by spectrophotometry measurement. As shown in Fig. 4 (b), there was little difference in the measured reflectivity of each position. Furthermore, the calculated results shown in Fig. 5 show that a certain amount of thickness deviation does not have a serious effect on the reflectivity of the a-Si/a-Si DBR at the target wavelength. This is also true for the circumferential wavelength. In Fig. 4 (b), the largest difference exists between B and E. The wavelength difference of spectral band width between B and E was about 45 nm. We can define the thickness errors of position B and E from Fig. 5. They were $-5$ nm and $-1$ nm respectively, and the total deviation across the whole wafer was only 4 nm. Therefore, the DBRs oblique angle deposited on 2” wafer show relatively good uniformity. Therefore, we can indeed confirm that the highly tolerant and high reflective a-Si/a-Si DBR is useful, practical and innovative for cost-effective optical components capable of high levels of reflection.

![Reflectivity Mapping Image](image1)

**Fig. 4.** (a) The relative reflectance mapping image of 2” full-wafer DBR fabricated on Si substrate. The words, A-E, represent each measurement position for the reflectivity. (b) The measured reflectivity of all positions of DBR fabricated on 2” Si wafer as a function of wavelength.
Fig. 5. Calculated reflectivity spectra and thickness deviation dependency of the five-period a-Si/a-Si DBR as a function of wavelength.

Figure 6 (a) shows a digital photographic image of the deposited a-Si/a-Si DBR shaped as the media mark of an institute. Any size or any feature of a structure can be fabricated by a simple lift-off process for the realization of a highly reflective broadband DBR suitable for various optoelectronic devices. As shown in Fig. 6 (b), the relative reflectivity of the patterned structure at 1550 nm was plainly higher than that of a normal Si (100) substrate and the superiority of the tolerant a-Si/a-Si DBR and its fabrication process are clearly evident.

Fig. 6. (a) Photographic image of ‘GIST’-patterned a-Si/a-Si DBR on Si substrate. (b) Relative reflectance mapping image of ‘GIST’-patterned a-Si/a-Si DBR on Si substrate.

4. Conclusion

In summary, we proposed a novel class of DBRs based the OAD of a-Si. The reflective characteristics were investigated both theoretically and experimentally. Highly tolerant and highly reflective broadband a-Si/a-Si DBRs were demonstrated successfully for the first time. A broadband stop band (Δλ/λ = 33.7%, R>99%) with only a five-period a-Si/a-Si DBR was achieved experimentally. The size-, feature- and substrate-independent method to realize highly tolerant and broadband DBRs will provide an interesting new pathway that opens future practical applications such as resonant-cavity-light-emitting-diodes or vertical-cavity-surface-emitting-lasers or solar cells. In an addition, oblique-angle deposition is promising for the growth of homogeneous highly reflective DBR structures with a very high refractive index contrast.

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