Distributed Bragg Reflectors Fabricated by Plasma-Enhanced Chemical Vapor Deposition

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Primary CNF Tools Used: Oxford PECVD, PT Takachi HDP-CVD, Woollam Ellipsometer, FilMetrics F40-UV, SC-4500

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Abstract:

Distributed Bragg Reflectors (DBRs) are mirrors composed of alternating layers of two different transparent materials with different refractive indices (n). When two parallel DBRs are separated by a transparent spacer layer, a Fabry-Pérot microcavity is formed. In such a cavity, the Q-factor of the cavity's resonant mode increases with the reflectivity of the DBRs. Thus, in order to create microcavities with high Q-factors, we tested several designs and compared the reflectance spectra of the resulting DBRs to determine which design produces the highest reflectance at the desired wavelengths.

Summary of Research:

Unlike metal mirrors that reflect light across a broad range of wavelengths, the high-reflectance of a DBR is limited to range of wavelengths known as a stopband. These are the wavelengths of light that are strongly reflected (e. g. reflectance R ≥ 0.99) by a DBR due to the constructive interference of the light scattered from the interfaces between the high- and low-index materials [1]. To make a DBR that reflects strongly at a certain wavelength, λ_{center}, at normal incidence, the layers are fabricated with thickness d = λ_{center}/4n (Figure 1). With a sufficient number of layers (roughly 15 or more), a DBR thus fabricated will exhibit high reflectance at normal incidence over a range of wavelengths around λ_{center}. For example, a 31-layer DBR made with λ_{center} = 500 nm reflects light strongly (with R ≥ 0.95) from about 450 to 550 nm. Outside of this stopband region, the reflectance of the DBR is low and varies sinusoidally with wavelength, as shown in Figure 2(a).

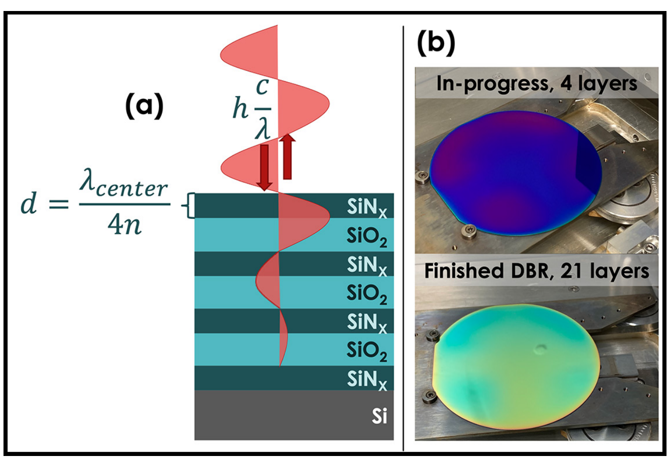
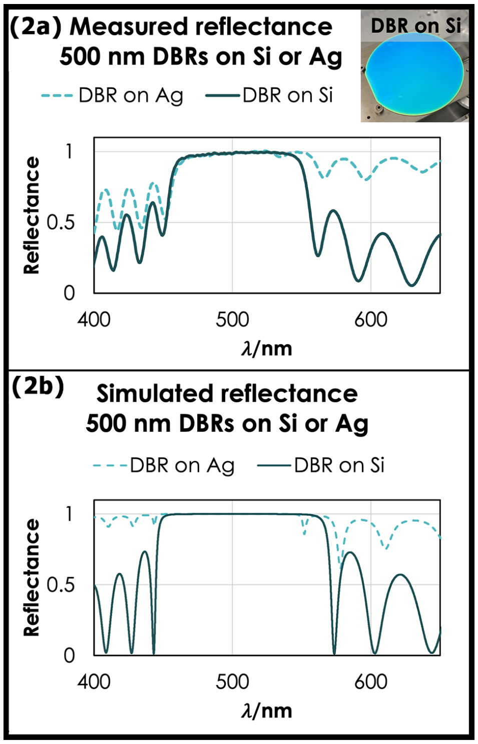


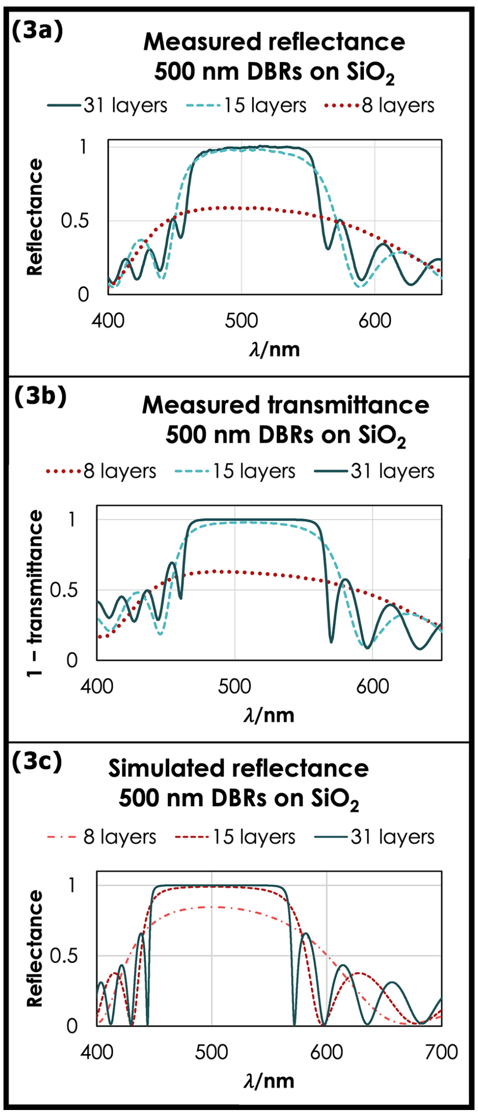
Figure 1: (a) DBR reflection at normal incidence. The impinging light wave is reflected due to the constructive interference of the individual reflections from each SiN_x/SiO_2 interface. (b) The reflection spectrum and color of the SiN_x/SiO_2 film stack on an Si wafer changes radically as layers are added during the deposition of a 21-layer DBR on Si with λ_{center} = 580 nm.

We tested several DBR designs and compared the resulting spectra. DBRs made of alternating layers of silicon nitride (SiN_x) and silicon oxide (SiO_2) were deposited using the Oxford plasma-enhanced chemical vapor deposition (PECVD) instrument. These DBRs were deposited onto 4-inch wafers of SiO_2, Si, or Si that had been coated with 200 nm of Ag in the SC4500 electron-beam evaporator.

We compared of Si- to Ag-backed DBRs (Figure 2) to determine if Ag-backed DBRs would exhibit greater reflectivity than the Si-backed DBRs, as was reported in the literature for 20-layer DBRs [2]. However, we found that, for 31-layer DBRs, the Ag-backed DBRs were not significantly more reflective than the Si-backed DBRs (Figure 2(a)). The simulated reflection spectra calculated using the transfer matrix method (TMM) likewise indicates that the Ag-backed DBR is not expected to reflect more strongly than the Si-backed DBRs for 31-layer DBRs (Figure 2(b)).

In other words, since the reflectivity of a 31-layer DBR is essentially "saturated" within the stopband region due to the constructive interference of the reflections from





each SiO_2/SiN_x interface, no significant increase in the reflection from the underlying Ag film could be observed. Additionally, the simulated spectrum shows a distinct dip in the reflectance in the DBR stopband for the Ag-backed DBRs due absorption of light into the Tamm plasmon mode [3]. This dip is also present in the experimental reflection spectrum of the Ag-backed DBR, but the absorption peak is much less distinct in the measured spectrum than in the simulated data. This might also be due to the "saturation" of the DBR reflectance for these materials at 31 layers, such most of the impinging light in the stopband region does not reach the Ag film underneath the DBR.

We also compared the spectra of DBRs having various numbers of SiN_x and SiO_2 layers deposited on SiO_2 wafers (Figure 3). Since these samples were deposited on transparent substrates, both their reflection and their transmission spectra were measured and compared (Figure 3). The spectra show that 8 layers is too few to make a highly reflective ($R > 0.95$) DBR; that 15 layers makes a DBR with low, but non-zero, transmittance in the stopband region; and that, for 31 layers, the transmittance in the stopband region is at or below the background noise level of the spectrometer (Woollam RC2 Ellipsometer, operated in the transmission configuration). Note that these conclusions are essentially qualitative. To precisely quantify the DBRs' transmittance in the stopband region would require measurement of the reflected and transmitted light using lasers or supercontinuum white light sources.

Acknowledgements:

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References:

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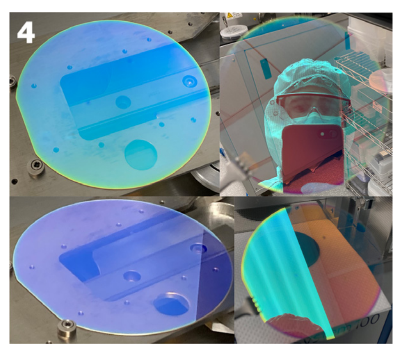

Figure 2, top left: *λ_{center} = 500 nm DBRs on Si or Ag. (a) DBR reflection spectra measured on the Filmetrics F40-UV. Inset: a photo of the 500 nm DBR on Si. (b) Simulated DBR reflection spectra calculated by TMM.* **Figure 3, bottom left:** *(a) Reflection and (b) transmission spectra of 500 nm DBRs with various layer numbers on SiO_2 wafers, measured using the Filmetrics F40-UV and Woollam RC2 Ellipsometer, respectively. (c) Simulated DBR reflection spectra calculated by TMM.* **Figure 4, above:** *31-layer 500 nm DBR on SiO_2. The transparent substrate allows the DBR's opalescence to be observed, as shown by the photos on the right, in which reflected light is cyan and transmitted light is orange or rose-colored.*