Glancing-Angle–Deposited Silica Films for Ultraviolet Wave Plates

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Glancing-angle deposition (GLAD) is a coating process where the incident vapor condenses on a substrate oriented at a high incidence angle θ relative to the substrate normal, forming microscopic nuclei (experimental setup is shown in Fig. 1). Self-shadowing occurs at this high angle, shaping the nuclei into individual columns that tilt toward the vapor source.[1] These anisotropic structures create birefringence in the film, allowing for the creation of wave plates when depositing a film of the proper thickness.

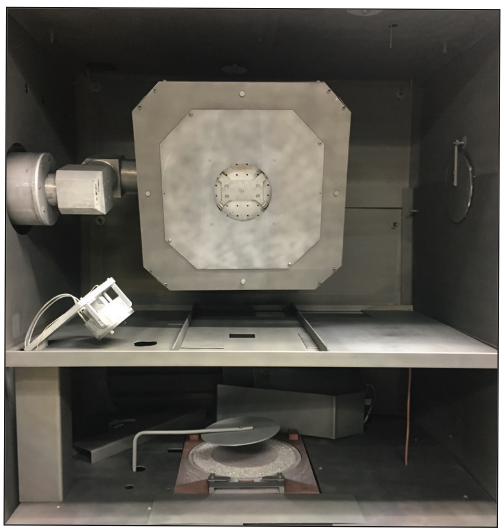

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Figure 1
Angstrom Engineering GLAD stage mounted in a 1.2-m vacuum chamber. Each coating deposition included a 100-mm-diam fused-silica substrate or two 50-mm-diam substrates: a silicon wafer and a fused-silica witness sample. Substrates remain in the center of the stage as it flips to the programmed $\pm\theta$. An electron-beam gun is mounted directly below the aperture, and an Inficon Crystal 12 sensor is mounted on the side to measure the deposition rate/thickness.

With a lack of shadowing in the substrate tilt-axis direction, there is a progressive fanning of the column cross section along with a chaining together of adjacent columns, which can lead to greater light scattering in the film. To reduce this column broadening and limit scatter, an all-silica, multilayer GLAD structure was implemented. Alternating layers of birefringent and dense SiO_2 were deposited during a single-coating deposition by alternating the substrate angle (0° for the dense layers and 73° for the birefringent layers). The number of birefringent and dense groupings was based on the desired retardance value for a quarter- or half-wave plate at a wavelength of 351 nm. Dense layers provide a base for the growth of a new birefringent layer and were inserted throughout the coating at intervals less than 400 nm since the width of individual silica columns was found to increase only beyond that thickness.[2] An antireflective coating was then added as a final layer in the design, which consisted of a single GLAD layer deposited at 82°.

The refractive indices and thickness of each layer in the design had to be precisely calibrated with a Woollam variable-angle spectroscopic ellipsometer (VASE®) since these values change with substrate deposition angle and deposition time.[3] Scanning electron microscope (SEM) and spectrophotometer measurements were also used to corroborate the index and thickness data.

Photometric performance was evaluated using a 351-nm laser and a 4-in. integrating sphere with a silicon detector. The quarter-wave plate exhibited a reflectance of 3.9% and a transmittance of 95.8%, yielding a loss of 0.3%, while the half-wave plate exhibited a reflectance of 4.2% and a transmittance of 95.3%, yielding a loss of 0.5%. Both reflectance measurements include the uncoated back surface of the substrate. This multilayer design helped to decrease scatter loss compared to previous SiO_2 single-layer coating runs (with an optical scatter loss of 10% to 15%) (Ref. 4). SEM and spectrophotometer measurements for a multilayer quarter-wave plate are shown in Fig. 2.

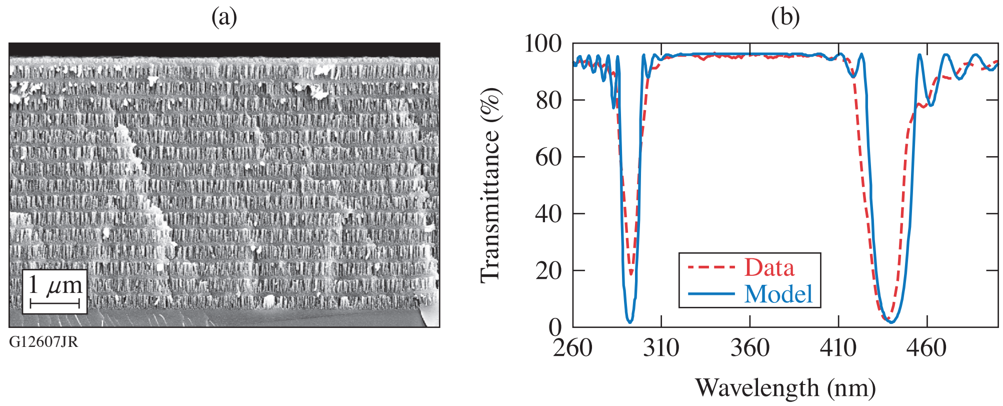

Figure 2
(a) SEM image of a 31-layer quarter-wave–plate coating. (b) Theoretical transmittance through the quarter-wave design with back-side reflection (solid blue curve) overlaid with spectrophotometer data (dashed red curve).

The multilayer design also helped to limit scatter loss over time. Eight months after deposition, the scatter detected in single-layer quarter- and half-wave–plate samples increased 16% and 48%, respectively, while the scatter increase in multilayer wave plates remained under 1% (as shown in Fig. 3).

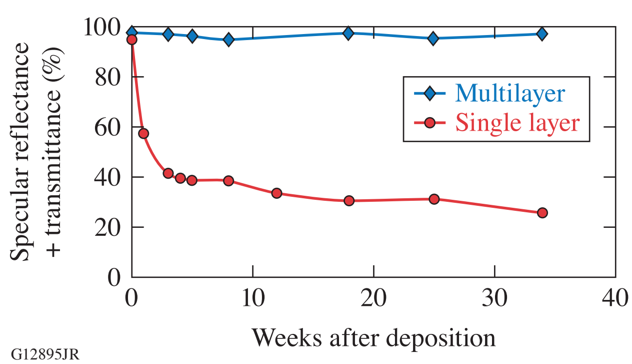

Figure 3
Scatter measurements for a single-layer and multilayer half-wave plate. Eight months after deposition, multilayer scatter has remained approximately the same and single-layer scatter has increased 48%.

Retardance was measured with a Hinds Instruments Exicor® 450XT Mueller Matrix Polarimeter and found to be uniform across all 50-mm and 100-mm samples. The wave plates also exhibited a high laser-induced–damage threshold (LIDT). The LIDT for a multilayer quarter-wave–plate coating, performed on polished fused silica processed with an "advanced mitigation process," was found to be 12.51 ± 0.51 J/cm^2 in a 1:1 testing protocol and 36.31 ± 3.74 J/cm^2 in an N:1 testing protocol. This is an improvement from previous silica single-layer LIDT measurements (~11 J/cm^2 in both a 1:1 and N:1 testing protocol).[4]

In the future, we hope to deposit these multilayer wave plates on larger substrates (up to ~400 mm in diameter), while maintaining the same low-loss, high-LIDT, wide-design bandwidth achieved with this current experiment.

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1. M. M. Hawkeye, M. T. Taschuk, and M. J. Brett, *Glancing Angle Deposition of Thin Films: Engineering the Nanoscale*, Wiley Series in Materials for Electronic & Optoelectronic Applications (Wiley, Chichester, United Kingdom, 2014), pp. 6,7, 53–60, 237–240.

2. L. Grinevičiūtė *et al*., Phys. Stat. Sol. A **214**, 1770175 (2017).

3. C. Smith, S. MacNally, and J. B. Oliver, "Modeling of Serially Bi-Deposited Glancing-Angle–Deposition Coatings," to be published in Applied Optics.

4. J. B. Oliver *et al*., Opt. Express **22**, 23,883 (2014).