Broadband Nanostructured Antireflection Coating on Glass for Photovoltaic Applications

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Abstract — **Ultra-high, omnidirectional transmittance through a coated glass window is demonstrated over the entire accessible portion of the solar spectrum. The average broadband transmittance has been increased to greater than 98.5% at normal incidence, and exceeds 97.8% at all wavelengths between 440 nm and 1800 nm, significantly outperforming conventional MgF_2 coated glass. The measured improvement in transmittance results from coating the window with a new class of materials consisting of porous SiO_2 nanorods. The step-graded antireflection structure also exhibits excellent omnidirectional performance, enabling average broadband transmittance in excess of 96% at incident angles as high as 70°.**

Index Terms — **antireflection coating, nanostructures, silicon dioxide, broadband, Omni-directional.**

I. INTRODUCTION

Optical transmittance through photovoltaic cover glass or other transparent encapsulants is typically limited by reflection losses. In particular, Fresnel reflections from optical windows arise because of the difference in index of refraction between air (n ~ 1) and the window material (n ~ 1.5). Although Fresnel reflection losses are relatively low at normal incidence, they can become quite substantial for off-angle light incidence. For example, Fresnel reflection at an uncoated glass – air interface generally varies from over 4% at normal incidence to more than 40% at a 75° incident angle.

Theoretically, it has been known for some time that Fresnel reflection losses can be minimized between two media by grading the refractive index across the interface. However, the unavailability of materials with the desired refractive indices, particularly materials with very low refractive indices, has prevented the implementation of graded and step-graded refractive index designs. Recently, however, a new class of optical thin-film materials consisting of porous nanorods has enabled the realization of ultra-low refractive index materials [1]. In particular, oblique-angle deposition is a simple physical vapor deposition process that can be used to tailor the refractive index of a wide variety of thin-film materials [2].

Oblique-angle deposition has been used to tailor the refractive index of SiO_2 materials, and to build high-performance step-graded refractive index structures on glass substrates [3-4]. Step-grade designs enable the formation of antireflection structures that combine broadband and omnidirectional characteristics. In this work, we report on the results of a step-graded antireflection coating on glass that has been designed for photovoltaic applications. This new, optimized nanostructured antireflection coating is shown to outperform an ideal quarter-wavelength MgF_2 coating over all wavelengths and incident angles.

II. EXPERIMENT

Oblique-angle deposition is a method of growing porous thin-films, and hence thin-films with low-refractive index, enabled by surface diffusion and self-shadowing effects during the deposition process. Random growth fluctuations on the substrate produce a shadow region that incident vapor flux cannot reach, and a non-shadow region where incident flux deposits preferentially, thereby creating an oriented rod-like structure with high porosity, as illustrated in Figure 1. The deposition angle, defined as the angle between the normal to the sample surface and the incident vapor flux, results in the formation of nanorod structures that are tilted relative to the sample surface. Because the gaps between the nanorods can be much smaller than the wavelength of visible and infrared light, the nanostructured layers act as a single homogenous film with a refractive index intermediate between air and the nanorod material, decreasing in refractive index with increasing porosity.

SiO_2 coatings are well known for their long-term stability and high transmittance over a wide spectral range. However, conventional, dense SiO_2 has a refractive index around 1.46, and thus is not an effective antireflection material for optical windows with a refractive index near 1.5. On the other hand, the refractive index of porous SiO_2 can be reduced to values of

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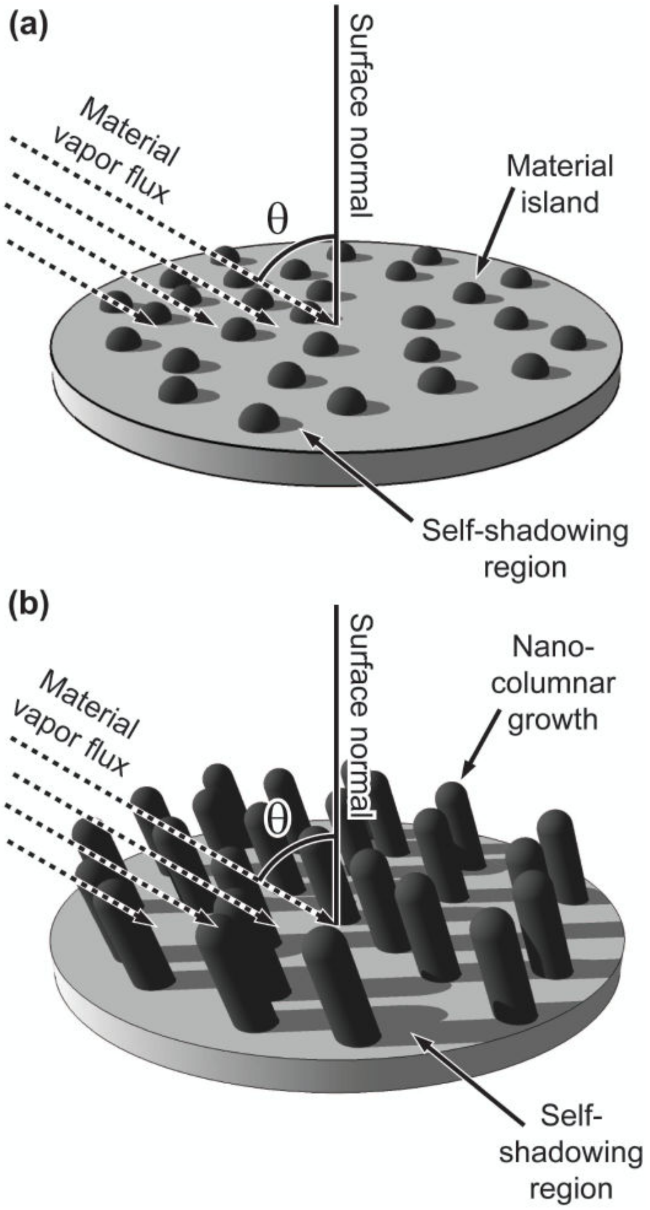

Fig. 1. Simplified schematic of the oblique-angle deposition process for synthesizing porous, nanostructured films, showing (a) the initial formation of material islands at random locations across the substrate, followed by (b) the formation of self-shadowed regions and nano-columnar growth when material vapor flux arrives at a non-normal deposition angle (θ) to the substrate.

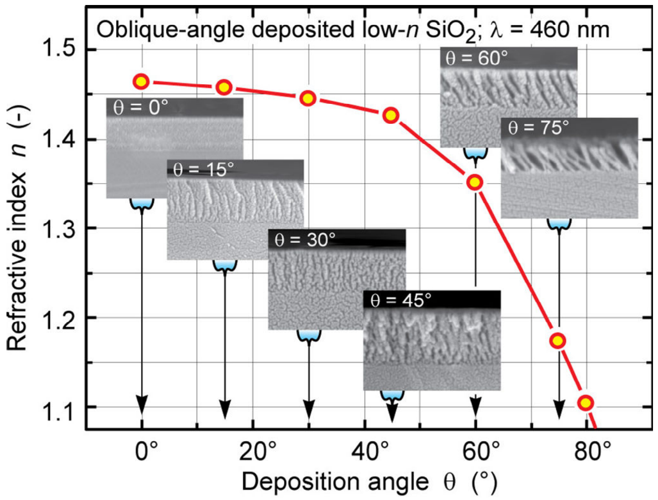

Fig. 2. Measured refractive index of SiO_2 films on silicon substrates as a function of deposition angle. The scanning electron micrographs reveal a gradual increase in porosity of SiO_2 starting from a dense film at 0^o deposition angle to a highly nanoporous film at 75^o deposition angle.

1.1 or lower by increasing the porosity [1]. Figure 2 depicts experimentally measured refractive index values of SiO_2 films deposited at increasing deposition angles in an electron beam evaporator. The refractive indices of these SiO_2 films deposited on silicon substrates were measured with an ellipsometry-based measurement system, and have been shown to follow a formula developed by Poxson *et al.* [2]. Figure 2 highlights the tunability of the refractive index of SiO_2 material to virtually any value between its bulk value and a value close to that of air. The scanning electron micrographs in Figure 2 also reveal the gradual increase in the porosity of SiO_2 films with increasing deposition angle, starting from a dense bulk film deposited at an angle of 0° to a highly nanoporous film deposited at 75°. Unlike any other method, the use of porous nano-materials fabricated by oblique-angle deposition offers advantages such as tunability of refractive index, flexibility in choice of material, simplicity of a physical vapor deposition process, and the ability to optimize the coating for any substrate-ambient material system.

In this work, antireflection coatings with specular surfaces comprised of multiple layers of porous SiO_2 layers have been deposited on glass slide substrates. The specific target thickness and refractive index values for the step-graded structure described in this work are shown below in Table I. These target thickness and refractive index values were chosen to minimize an unwanted dip in transmittance near 550 nm due to interference effects observed in our earlier work [4]. Both single-sided and double-sided structures were prepared in an electron-beam evaporator using a multiple-step process that included three different deposition angles. Three distinct layers of nanostructured SiO_2 on a glass slide are clearly visible in the cross-sectional scanning electron micrograph of the fabricated antireflection coating shown in Figure 3. The transmittance properties of both the single- and double-sided

Layer position	Air	Layer 1	Layer 2	Layer 3	Substrate
Refractive Index	1.0	1.09	1.22	1.33	1.46
Thickness	∞	209 nm	140 nm	116 nm	∞

Table I. Target nanostructured SiO_2 refractive index and thickness values for the three-layer, step-graded, broadband antireflection structure characterized in this work.

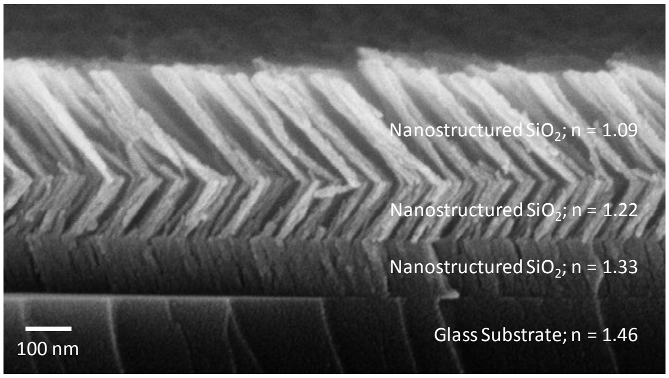

Fig. 3. Scanning electron micrograph of a three-layered, nanostructured SiO_2 anti-reflection structure fabricated by oblique-angle deposition on a glass substrate.

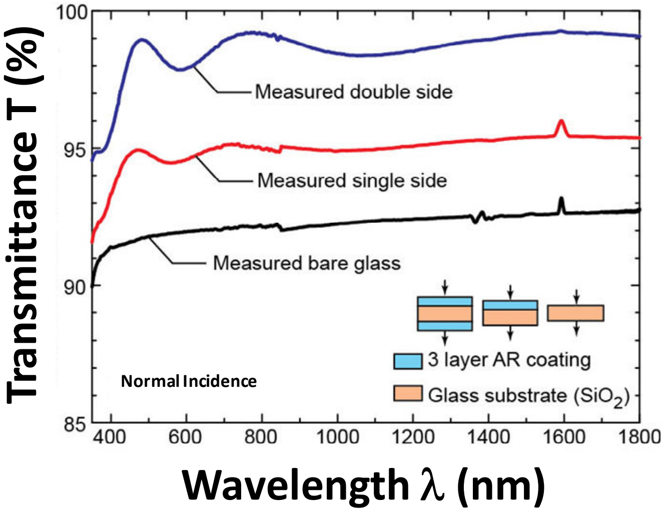

Fig. 4. Measured wavelength dependent transmittance of nanostructured SiO_2 coated glass compared to uncoated glass. The transmittance measurements were made at normal incidence using a JASCO V-570 spectrophotometer.

nanostructured samples as a function of wavelength have been compared to an uncoated glass slide at normal incidence. The measured transmittance spectrum of the double-sided structure has been well fit using generalized Airy's formulas [5]. The simulated performance of nanostructured SiO_2 coated glass has then been compared to the ideal performance of both uncoated glass and glass coated with a quarter-wavelength of MgF_2 over a wide range of incident angles.

III. RESULTS AND DISCUSSION

Figure 4 compares the measured transmittance of an uncoated glass slide to a glass slide coated on a single side and on both sides with the three-layered nanostructured SiO_2 coating summarized in Table I and imaged in Figure 3. The measured transmittance through the glass slide is dramatically improved over the entire spectrum by the application of the step-graded, nanostructured SiO_2 antireflection coating. In particular, the average measured broadband transmittance between 350 nm and 1800 nm increases from 92.2% for the uncoated glass, to 95.0% for the single-sided coated glass, to 98.6% for the double-sided coated glass. Moreover, the transmittance through the glass coated on both sides with a

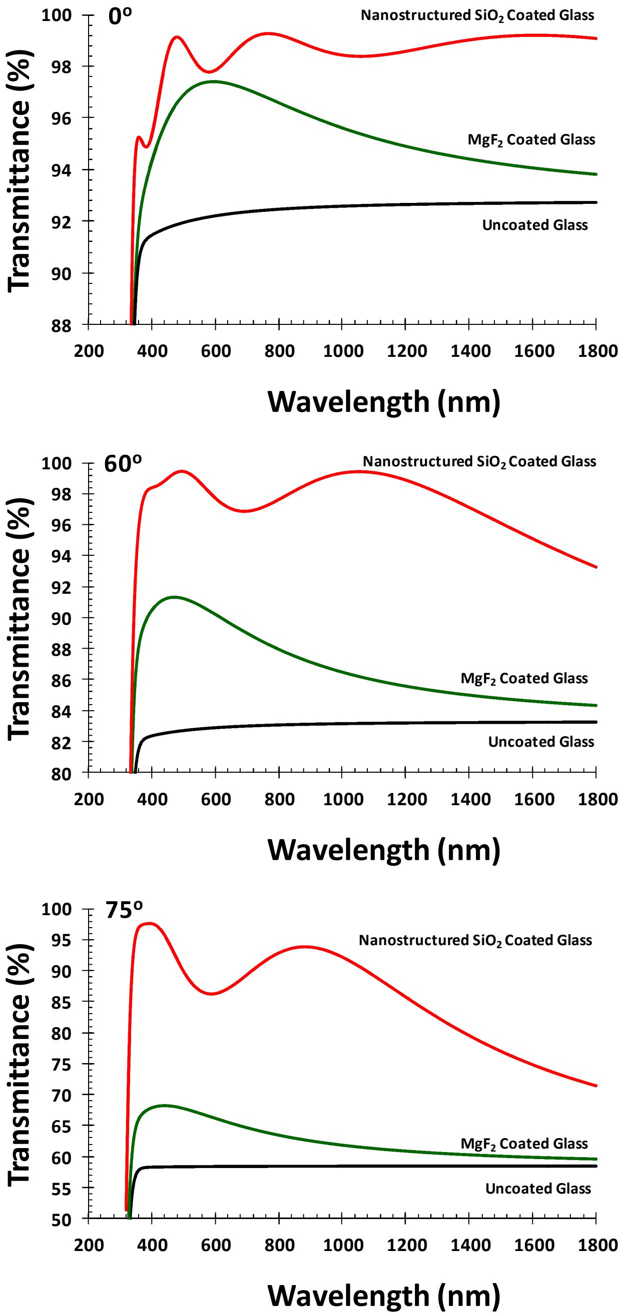

Fig. 5. Simulated wavelength dependent transmittance of nanostructured SiO_2 coated glass compared to uncoated glass at incident angles of 0^o (normal), 60^o, and 75^o. Also shown is the calculated transmittance of a glass side coated on both sides with an ideal quarter-wavelength MgF_2 layer.

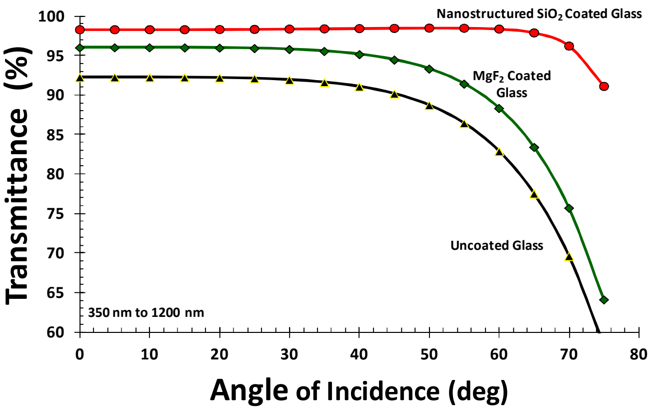

Fig. 6. Calculated average broadband transmittance (350 nm – 1200 nm) as a function of incident angle for of the double-sided, step-graded coating summarized in Table I compared to glass coated on both sides with an ideal quarter-wavelength MgF_2 film. Also shown is the calculated angle-of-incidence dependent broadband transmittance through a glass slide substrate with no antireflection coating.

nanostructured SiO_2 coating exceeds 97.8% at all wavelengths between and 440 nm and 1800 nm, implying a glass-air interface reflectivity below 1.1%.

Figure 5 compares the calculated performance of a glass side coated on two sides with a conventional quarter-wavelength MgF_2 layer to uncoated glass and to double-sided, nanostructured SiO_2 coated glass. At normal incidence, the nanostructured SiO_2 coating significantly outperforms conventional MgF_2 coated glass at all wavelengths, particularly in the longer wavelength band of 900 nm to 1800 nm (98.8% vs. 94.5%). While the maximum transmittance of MgF_2 coated glass can reach nearly 97.5% near its design wavelength (600 nm in Figure 5), the nanostructured SiO_2 coating exceeds this peak value over a very broad spectrum relevant for photovoltaic devices. The nanostructured SiO_2 coating also yields an average transmittance of 98.2% over the narrower 350 nm to 900 nm band, compared to 96.4% for conventional MgF_2 coatings.

Previous angle-of-incidence dependent transmittance measurements on a thicker step-graded structure indicate that the ultra-high broadband transmittance of the SiO_2 nanostructured coated glass can be maintained over a very wide range of incident angles [4]. Optical modeling indicates that the thinner three-layered structure summarized in Table I has similar omnidirectional characteristics. As seen in Figure 5, the peak transmittance of MgF_2 coated glass is below 91.4% at an incident angle of 60°, while the transmittance through the nanostructured SiO_2 coated glass exceeds 96.8% at all wavelengths between 365 nm and 1430 nm. At an incident angle of 75°, the transmittance through the nanostructured SiO_2 coated glass still exceeds 86.2% for all wavelengths between 335 nm and 1185 nm, while the peak transmittance of MgF_2 coated glass has dropped below 68.2%. Figure 6 summarizes the average broadband (350 nm to 1200 nm) transmittance as a function of incident angle calculated for an ideal double-sided, quarter-wavelength MgF_2 coated glass compared with both uncoated glass and nanostructured SiO_2 coated glass. Whereas the transmittance through both MgF_2 coated glass and uncoated glass falls below 76% at an incident angle of 70°, the broadband transmittance through the nanostructured SiO_2 coated glass remains above 96%. Moreover, broadband transmittance exceeding 98%, corresponding to a reflectivity of less than 1% at each glass-air interface, can be maintained for off-angle illumination out to incident angles exceeding 60°.

VI. CONCLUSION

In summary, antireflection coatings comprised of step-graded, nanostructured SiO_2 have been shown to significantly increase the transmittance through optical glass windows. Double-sided, nanostructured SiO_2 coatings outperform conventional MgF_2 coatings, achieving average transmittance values in excess of 98% over a broad spectrum and wide range of incident angles. The demonstrated ultra-high broadband performance of nanostructured SiO_2 anti-reflection coatings could benefit high performance single- and multi-junction solar cells, as well as other photonic devices sensitive to broadband and omnidirectional optical radiation.

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