10.1117/2.1200704.0754

Thin film coatings that reflect virtually no light

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Attractive antireflection coatings made from nanostructured materials could open the door to more efficient solar cells, much brighter light-emitting diodes, and more.

Light reflects when it strikes the interface between two materials with different refractive indices. And the greater the difference between indices, the more light is reflected. Reflection-free surfaces might have many important uses. For example, they could make a solar cell almost perfectly absorbing to increase energy efficiency, or could make light-emitting diodes (LEDs) more transparent to deliver more light from the semiconductor to free space.

Scientists have long attempted to create reflection-free surfaces to safeguard the performance of various optical components and devices. However, fabrication has been hindered by the lack of optical thin-film materials with low refractive indices between 1.0 (air) and 1.46 (glass). Aerogels, highly porous materials that are spun onto surfaces, are one option that could fill the refractive index gap. But thickness is hard to control precisely when it is only around a quarter of the wavelength—i.e., ∼100nm—of visible light.

We have recently created a new class of materials by oblique angle deposition that have refractive indices varying between 1.05 and that of any thin-film material. The 1.05 value is not only extremely close to the index of air, but also the lowest ever reported. We have also demonstrated a virtually reflection-free surface on aluminum nitride (AlN) by multilayer coating of the low-index materials.

Oblique angle deposition is a vapor technique widely used to grow nanostructured thin-film materials with controllable porosity resulting from surface diffusion and a self-shadowing effect. Optical thin films consisting of nanorods grown this way have a lower refractive index than dense materials.[1] In addition, the approach provides very good control over the refractive index because the angle of incidence can be varied during the deposition process. The unique capabilities of oblique angle deposition enable fabrication of graded refractive index antireflection coatings with near-perfect properties, i.e., with extremely low reflection, broadband characteristics, and omnidirectionality.

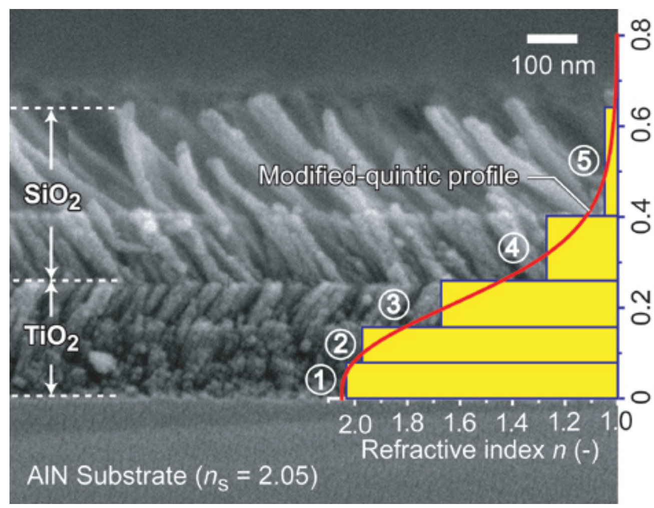

Figure 1. *Cross-sectional scanning-electron micrograph of a graded-index coating with modified quintic (i.e., graded) index profile. The coating consists of three TiO_2 and two SiO_2 nanorod layers made by oblique angle deposition.*

Conventional quarter-wavelength-thick antireflection coatings with single refractive index work only at one wavelength and at normal incidence. This is drawback with a broad spectral source such as the Sun. However, if the refractive index continuously varies from the substrate's index to that of the ambient medium, the result is a more versatile coating.[2]

Our experiments show that the refractive indices of TiO_2 and SiO_2 nanorod layers can be controllably varied from 2.7 to 1.3 and from 1.46 to 1.05, respectively, by changing the vapor incident angle. The combination of these layers can thus be used to achieve any refractive index value between 2.7 and 1.05. Figure 1 shows such a graded-index coating consisting of

Continued on next page

10.1117/2.1200704.0754 Page 2/2

three layers of TiO_2 and two layers of SiO_2 nanorods on a single-side polished AlN substrate (n_s = 2.05). It has ideal antireflection characteristics with a very low reflectivity of $R = 0.10\%$.[3] Our coatings were all found to be stable with no evidence of degradation.

The broadband properties of such antireflection coatings make them particularly attractive for solar cell applications because the solar spectrum is inherently broad, ranging from the ultraviolet to the infrared. The coatings can increase the amount of light that goes to the active region, with significant impact on energy-saving performance. Their omnidirectionality advantage is also particularly important for the light output efficiency of LEDs, usually limited by Fresnel reflection between the high-refractive-index semiconductor and surrounding medium, air or encapsulant. Low-index materials can also be used for the opposite purpose, i.e., for fabricating highly reflective mirrors such as omnidirectional reflectors or distributed Bragg reflectors (DBRs), entirely made of a single material with high-refractive-index contrast.

To summarize, we have created a new class of optical thin-film materials that fill the refractive index gap where no viable thin-film material existed before. Of interest is that these coatings only represent the tip of the iceberg: the next phase of our research effort is focused on several potential applications, including light-absorbing layers for energy-efficient solar cells, light-transmitting layers for highly efficient LEDs, and DBRs made of a single material.

The authors gratefully acknowledge support from the Samsung Advanced Institute of Technology (SAIT), Sandia National Laboratories, Crystal IS Corporation, the Army Research Office (ARO), the New York State Office of Science, Technology, and Academic Research (NYSTAR), the National Science Foundation (NSF), and the Department of Energy (DOE)

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