Design, Fabrication, and Characterization of Optical Coatings Made of Low- and Tunable-Refractive-Index Materials

by

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ABSTRACT

The refractive index, *n*, is the most fundamental material property in optical sciences. It determines the speed with which light travels inside a medium as well as its behavior at the interface between two media, e.g. reflection, transmittance, refraction or total internal reflection. Naturally, it is the most important material property when manipulating light. The refractive index is at the core of design of anti-reflective (AR) coatings, distributed Bragg reflectors (DBRs), optical resonators, optical lenses, optical filters, and photonic crystals. Performance of these optical components has been limited due to the lack of availability of optical materials with refractive index between 1.0 and 1.4, and the lack of tunability of the refractive index to a desired optimum value. However, recent advances in the field of low- and tunable-*n* materials deposited by using oblique-angle deposition have filled this void and allow for many new high-performance optical components to be realized. The following paragraphs will outline the key experimental results that validate the benefits of low- and tunable-*n* materials.

In this thesis, a broadband, omni-directional, graded-index multilayer anti-reflection coating for silicon substrates was designed, fabricated and characterized. The coating consisted of nanostructured low-*n* silica (n = 1.05 – 1.40) fabricated by oblique-angle deposition. The AR coating was optimized for a range of angles of incidence from 0° to 90° and a range of wavelengths from 400 nm to 1100 nm by using a genetic algorithm. Measurements showed dramatic reduction in reflection over wide range of angles of incidence as well as wavelengths in comparison with conventional single-layer quarter-wave (λ/4) AR coatings widely used for Si solar cells. The reflectance averaged over the range of angles of incidence and range of incident wavelengths, R_{avg}, of 5.9% was measured for the graded-index three-layer AR coating as compared to 17.3% for the conventional Si_3N_4 λ/4 AR coating. These values are in excellent agreement with the theoretical calculations which predict R_{avg} of 4.9% for the graded-index three-layer AR coating and 18.2% for the λ/4 AR coating.

Multilayer AR coatings were also designed for substrates other than Si and for different ranges of angles of incidence and wavelengths by using various different low-*n* materials. A two-layer AR coating on glass substrate was designed, fabricated and characterized by using nanostructured low-*n* silica (n = 1.05 – 1.40) fabricated by using

oblique-angle deposition. The AR coating is designed for the wavelength range of 400 nm to 2500 nm and 0° to 40° angle of incidence. The measured average optical transmittance of an uncoated glass substrate between 1000 nm and 2000 nm improved from 92.6% to 99.3% at normal incidence by using the designed two-layer AR coating deposited on both surfaces of the glass substrate.

Multilayer AR coatings, which consisted of low-*n* ZnSe and BaF_2 were designed and fabricated for ZnSe substrate and were optimized for angles of incidence between 77° and 87° and the wavelength range of 8 μm to 12 μm. The average reflectance for ZnSe substrate improved from 51.3% for ZnSe without any AR coating to 17.7% for ZnSe with two-layer AR coating.

Apart from being at the core of the design of many optical coatings and components, the refractive index also manifests itself as the governing material property when dealing with the light-extraction efficiency of semiconductor light-emitting diodes (LEDs). Light-extraction is an old problem in LEDs. It is well-known that due to the very high refractive index difference between semiconductor material and air the light-extraction from planar LEDs is seriously limited. Earlier, LEDs based on III-Arsenide and III-Phosphide material systems employed chip-shaping, resonant-cavity designs, and packaging techniques for improving light-extraction. The development of blue LEDs based on the III-Nitride material system in the early 1990s reignited the research interest in LEDs. The field of solid-state lighting has been expanding ever since. Once again, facing the challenge of light-extraction efficiency, researchers have employed various techniques such as surface roughening, photonic crystals, and patterned substrates. Tremendous progress has been made in improving the light-extraction efficiency of LEDs. The widely used method of surface roughening is limited by the fact that it does not have directionality and produces a Lambertian emission pattern. A vast variety of applications are possible by using LEDs and different applications demand different characteristics from the LEDs in terms of directionality and emission pattern. Therefore, development of novel methods for improving the light-extraction efficiency of LEDs is highly desirable.

In one such approach, a novel contact for III-Nitride blue LED was designed by using low-*n* indium tin oxide (ITO) for enhanced light-extraction efficiency. A single material, ITO, was used with varying refractive index values (by changing the porosity of the material). The contact consisted of six-layers of ITO with increasing porosity, thus decreasing n, going from the LED's semiconductor material to air. It was shown that GaInN LEDs with a graded-index ITO AR contact achieve a light-extraction efficiency enhancement of 24.3% compared to the LEDs with dense ITO coating due to strongly reduced Fresnel reflection at the ITO-air interface.

Apart from optical coatings, two other applications made possible by oblique-angle deposition are reported. In the first application, the oblique-angle deposition method was used to form direct electrical contacts to a GaN based nanorod LED. GaN based nanorod arrays with extremely low defect density have been demonstrated. LEDs and other optoelectronic devices fabricated by using these nanorod arrays, with typical diameter of 10 nm – 100 nm, can potentially have very high internal quantum efficiency. An ITO film was directly deposited on top of the GaN nanorods at a deposition angle of 80° by using oblique angle deposition. Uniform current injection into the LED was observed. In general, this contacting scheme can be used for making direct contacts to other kinds of nanoscale semiconductor devices.

In the second application, oblique-angle deposition method was used for nanopatterning a substrate. The feature size and density of the nanopattern can be controlled by varying the deposition angle during oblique-angle deposition, eliminating the need for photolithography and annealing. The *p*-type GaN surface of a GaInN LED was nanotextured and deposited with a semi-transparent Pd contact. The LED with nanotextured p-type GaN shows a 46% improvement in light-extraction efficiency over a standard GaN LED with a planar *p*-type surface.