# Thin films with tunable refractive indices for application of broadband, omni-directional anti-reflection coatings

by

David J. Poxson

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Approved:

Dr. E. Fred Schubert, Thesis Adviser

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## ABSTRACT

Anti-reflection (AR) coatings have been widely used in many optical devices and systems to reduce unwanted reflections. One particularly important application of these AR coatings is solar cells to minimize reflected sun light and obtain maximum photo current for a given solar spectrum. Single-layer AR coatings, for example $Si_3N_4$, are widely used for solar-cells. However, these conventional single-layer AR coatings show minimal reflectance only at a narrow range of wavelengths and angles of incidence. Since solar radiation is inherently broadband and has a wide range of incident angles during the course of a day, AR coatings with broadband and omni-directional characteristics are highly desirable and relevant for solar cell applications.

AR coatings with broadband and omni-directional characteristics require specific graded-refractive index multi-layer structures in which both, refractive index and thickness of each layer are optimized. Such optimized AR coatings have not, until recently, been realized due to the unavailability of materials with specific refractive indices, particularly materials with very low refractive indices < 1.4.

In this Master Thesis, multi-layer graded-refractive index (GRIN) AR coatings with broadband and omni-directional characteristics are demonstrated. The unavailability of materials problem can be overcome by two methods, i) co-sputtering of two oxides which allows deposition of composite films with any desired refractive index between that of the two oxides; ii) oblique-angle deposition which allows the growth of nano-porous materials with refractive indices tunable from its bulk value to a value close to that of air which is ~1.

The first quantitative analysis of the porosity and growth rate of obliquely deposited thin films in relation to incident flux angle θ has been performed. In this new analysis, excellent agreement between experimental data and theoretical prediction based on a single fitting parameter, *c*, and incident angle θ has been found. Our theory allows for the direct inference of refractive index of these obliquely deposited nano-porous thin films from theoretical predictions of porosity.

We have also applied a quantitative model to the deposition rate of co-sputtered films. In this model, for a desired index value, compositional percentage of each sputter

target material is calculated. Required deposition rates and corresponding power supplied to each sputter target is then predicted.

Finally, the methods of oblique-angle and co-sputtering depositions have been combined to create two unique multi-layer GRIN AR coatings with broadband and omni-directional characteristics. These multi-layer GRIN AR coatings show reduced average angular reflectance, i) from 31% to 10% utilizing a 7 layer GRIN AR coating, and ii) from 31% to 6% utilizing a 3 layer GRIN AR coating (for incident light between 40-80° and in the wavelength range 400-740 nm when compared to the traditional single layer quarter-wave coating.)