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Effective graded refractive-index anti-reflection coating for high refractive-index polymer ophthalmic lenses

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ABSTRACT

The reduction of optical reflection is important for many applications such as solar cells and lenses. The effective graded refractive-index (graded-RI) anti-reflection (AR) coating is designed a tri-layer structure with SiO_2, MgF_2, and ITO thin films for high refractive-index polymer ophthalmic lenses. The effective graded-RI AR coating is fabricated using the E-beam evaporation system. The mean reflectance of the effective graded-RI AR coating lens was measured to 2.9% (400–800 nm), which was lower than that of the commercial multi-layer AR coating lens (3.9%) for high RI polymer lenses ($n=1.67$). Also, the blocking of the high energy visible light is more effective than the commercial multi-layer AR coating lens. It is known that the high energy visible light caused retinal damage. The ability to change the maximum reflectance band of an AR coating by simply changing the film thickness is advantageous for other potential applications.

1. Introduction

The anti-reflection coatings are widely used to increase the transmittance of light through interfaces and reduce the glare. Reduction of optical reflection is important for many applications including photovoltaic devices [1–4], displays, camera lens, superluminescent light emitting diodes [5,6], and ophthalmic lenses [7]. Reflection from any given interface at normal incidence is related to the ratio of the refractive indices of the materials consisting the interface and is given by $R\,(\%)=((n_0-n_m)^2/(n_0+n_m)^2)\times 100$ where R is % reflectance, n_0 is the refractive index of the first layer (usually air), and n_m is the refractive index of the second layer (window). To minimize the reflection, the AR coating layer, the refractive index is described as n_{AR}, should be coated on the window. The reflections from the air/coating and coating/window interfaces undergo destructive interference. Under the condition 4d $n_{AR}=\lambda_0$, the reflectance becomes $R\,(\%)=((n_0n_m-n_{AR}{}^2)^2/(n_0n_m+n_{AR}{}^2)^2)\times 100$ where λ_0 is the wavelength of incident light, and d is the coated film (AR coating layer) thickness. The reflection equals zero when $n_{AR}=\sqrt{n_0 n_m}$. The AR performance of conventional quarter-wavelength AR coatings depends on both the coating thickness and the refractive index of the material. Precise controlling both factors would result in lowering the amount of reflection from the surface. But zero reflectance cannot be achieved with a single layer coating due to the absence of suitable low refractive index materials.

To accomplish zero reflection, the various technologies have been extensively investigated including vacuum deposition of AR coating [1,3,4], self-assembled colloidal monolayer AR coating [8], broadband moth-eye anti-reflective structure (ARS) [9,10], and sol–gel AR coating [11]. The ARS of periodic nanostructures with sub-300 nm size is the most effective AR coating technology. In order to fabricate high performance artificial biomimetic ARS surfaces, various techniques have been intensively explored such as colloidal lithography [12], nanoimprint lithography [2], and multi-step anodization and etching process [10]. But biomimetic ARS has drawbacks such as lack of high throughput, large area patterning, and non-planar surface patterning. Colloidal self-assembly provides a simple and inexpensive approach in fabricating AR coating [8]. But the colloidal self-assembly technology is insufficient to apply mass production due to a lack of reliability. The most popular vacuum-based technologies for producing AR coatings include plasma-enhanced chemical vapor deposition [1], E-beam evaporation, and sputtering [3,4].

In this study, the effective graded-RI AR coating was designed and fabricated on blank polymer ophthalmic lenses using E-beam evaporation technology. The optical properties and microstructures of the effective graded-RI AR coating were characterized by spectroscopic ellipsometer, UV–visible spectrophotometer, transmission electron microscope (TEM), respectively.

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2. Experimental

The blank polymer lenses were manufactured with the lens monomer (MR series) of MITSUI CHEMICALS INC (Japan) in KOREA OPTICAL CO LTD (Korea). The blank polymer lenses were cleaned and corona treated before an AR coating. The blank polymer lenses have a siloxane hard coating which is coated in a bath by dipping method. The refractive index of the blank polymer lenses is 1.60 and 1.67. The blank polymer lenses are located in a rotating lens zig to AR coating. The lens zig is rotated with a constant speed for uniform film deposition. The effective graded-RI AR coating was performed by E-beam evaporation system under the base vacuum of 5×10^{-5} Torr. The deposition rate of SiO_2, MgF_2, and ITO films was 0.5 nm/s, 1.0 nm/s, 0.15 nm/s, respectively. The raw materials of E-beam evaporation (SiO_2 & MgF_2 granules, and ITO tablets) were purchased at DON CO LTD (Korea). The refractive index and thickness of the deposited films were analyzed by Woollam M-2000D spectroscopic ellipsometer. The porosity and thickness of the films were characterized by JOEL JEM-2100 TEM. The samples for ellipsometry and TEM analysis were deposited on Si substrates (SiO_2(300 nm)/Si(100)) with the same deposition conditions as for the blank polymer lenses. The sample of cross section TEM analysis was prepared by GATAN 691 PIPS precision ion polishing system.

3. Results and discussion

In general, the refractive indices of thin films are smaller than those of the bulk phase due to a lower density [3,4]. To identify the refractive index of SiO_2, MgF_2, and ITO films, the SiO_2, MgF_2, and ITO films were deposited on Si wafer substrate (SiO_2(300 nm)/Si (100)) by E-beam evaporation, respectively. The measured refractive index of SiO_2 thin film is 1.458 which is good agree with the value of bulk-SiO_2 ($n_{500}=1.46$). The measured refractive index of MgF_2 thin film ($n_{500}=1.380$, $n_{550}=1.378$) is coincided well with the literature values of bulk-MgF_2 ($n_{500}=1.38$) [11]. It is inferred that SiO_2 and MgF_2 film have a dense microstructures. The measured refractive index of ITO thin film of 4.5 nm thickness, which is a prevention layer of electrostatic charge, is 1.17.

Transparent polymer ophthalmic lenses which are manufactured with MR-7 lens monomer typically have a refractive index of 1.67, therefore when light propagates from air to polymer lens, about 6% of light gets reflected from each air/glass interface. In the case of a single layer AR coating, the refractive index of the material must satisfy the following criterion $n_{AR}=\sqrt{n_0 n_m}$. Hence, the ideal refractive index value of the AR material is approximately 1.29. The film thickness must be equal to $d=(\lambda_0/4n_{AR})$ for minimum reflection at a given wavelength λ_0. For green light of 550 nm this thickness is 107 nm for a film of RI = 1.29. However for single layer AR coating, zero reflectance cannot be achieved due to the lack of low refractive index materials. A way of further reducing the reflection is to assemble a multi-layer structure. This involves the deposition of a film with a high RI material onto the substrate followed by a low RI material coating [3,4]. The conventional multi-layer AR coating process is a time-consuming process, which leads to decrease of productivity. In the vacuum-based deposition technology, the precise control of deposition conditions can be controlled the material porosity of the thin films. The control of the material porosity can lead to a controllable refractive index of the thin films [3,4]. Here, the effective graded-RI AR coating is designed a tri-layer structure using the measured refractive index values of the thin films (ITO, MgF_2, SiO_2). A single layer of quarter-wave AR coating can give zero reflection at a specific wavelength [4]. The calculated thicknesses of the MgF_2 layer and SiO_2 layer by the single layer of quarter-wave AR coating for minimum

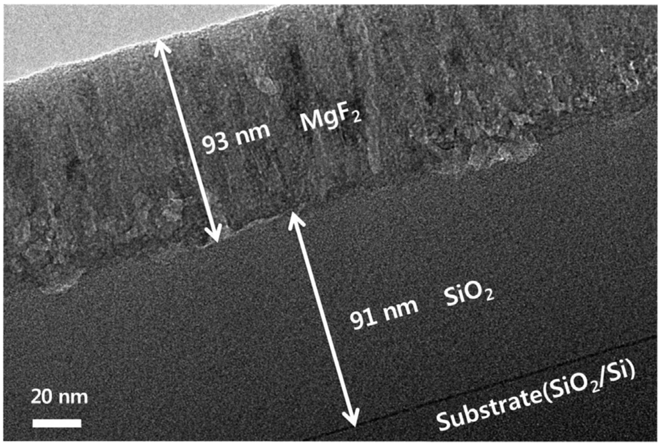

Fig. 1. Cross-section TEM image of the graded refractive index AR coating on Si wafer substrate (SiO_2 (300 nm)/Si(100)).

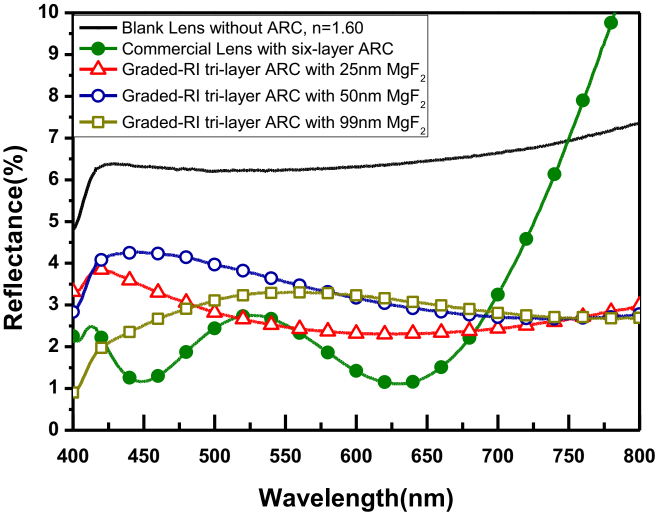

Fig. 2. Reflectance spectra of a blank polymer lens($n=1.60$) without ARC, commercial lens with a six-layer ARC by E-beam evaporation, and graded-RI ARC lens with a tri-layer ARC by E-beam evaporation.

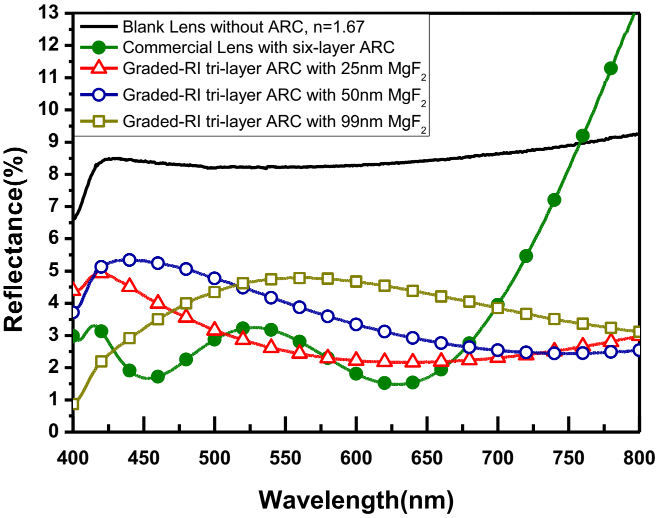

Fig. 3. Reflectance spectra of a blank polymer lens($n=1.67$) without ARC, commercial lens with a six-layer ARC by E-beam evaporation, and graded-RI ARC lens with a tri-layer ARC by E-beam evaporation.