

Thickness effects of anti-reflection coating with graded refractive index structure

Ki-Chul Kim

Dept. of Advanced Chemical Eng., Mokwon University,
88 Doanbuk-ro, Seo-gu, Daejeon, 302-729, Republic of KOREA

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Abstract- The effective anti-reflection (AR) coating was designed a bi-layer graded refractive index structure with SiO₂ and MgF₂ thin films for polymer ophthalmic lens. The AR coatings were fabricated by electron beam vacuum evaporation process on polymer ophthalmic lenses. The AR effects have been investigated for different AR coating thickness. The mean reflectance of the AR coated polymer lens (25 nm MgF₂/ 94 nm SiO₂/blank polymer lens structure) was measured to 2.8% in the wavelength range of 400 nm to 800 nm, which was lower than that of the commercial five-layer AR coating (3.4%). The refractive index of blank polymer lens was 1.56. The average reflectance of the non-AR coated bare polymer lens was measured to 5.6% in the wavelength range of 400 nm to 800 nm. As decrease of the MgF₂ thickness, the mean transmittance is increased, and the photopic response is shifted from green spectrum band to violet spectrum band.

Keywords- Anti-reflection Coating, Graded Refractive Index, Polymer Lens, Thickness Effect, Ophthalmic Lens.

1. Introduction

Anti-reflection coatings are widely used to increase the transmittance of light through interfaces. Reduction of optical reflection is important for various applications such as photovoltaic devices [1, 2], display, camera lens, and ophthalmic lens [3]. Reflection from any given interface at normal incidence is related to the ratio of the refractive indices of the materials forming the interface. The reflection equals zero when $n_{AR} = \sqrt{n_0 n_m}$ where n_0 is the refractive index of the first layer (usually air), n_m is the refractive index of the second layer (window or glass or substrate), and n_{AR} is the refractive index of the AR coating layer. To minimize the reflection, the AR coating layer should be coated on the window.

To fulfill zero reflection, the various technologies have been extensively investigated such as vacuum deposition of AR coating [1, 2, 4], broadband moth-eye anti-reflective structure (ARS) [5], self-assembled colloidal monolayer AR coating [6]. The ARS of periodic nanostructures with sub-300 nm size is the most effective AR coating technology. But biomimetic ARS has a drawback such as lack of high throughput, large area patterning, and non-planar surface patterning. The most popular vacuum-based technologies for producing AR coatings include E-

beam evaporation, sputtering [1, 2], and plasma-enhanced chemical vapor deposition (PECVD) [4].

In this study, the effective graded-refractive-index (graded-RI) AR coating was designed and fabricated on blank polymer ophthalmic lenses by E-beam evaporation technology. The thickness effects of the effective graded-RI AR coating have been investigated for the various AR coating structures.

2. Experimental Details

The blank polymer ophthalmic lenses were manufactured with the lens monomer of Mitsui Chemicals Inc (Japan) & Shimizu Co Ltd (Japan) in KOREA OPTICAL Co Ltd (Korea). The bare 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 indices of the blank polymer lenses are 1.56, 1.60, and 1.67, respectively. The bi-layered effective graded-RI AR coating was deposited by E-beam evaporation system. The thickness of the coated films was controlled by thickness monitor. The refractive index and thickness of the deposited films were analyzed by Woollam M-200D spectroscopic ellipso meter. The microstructures and thickness of the coated films were characterized by JOEL JEM-200 TEM. The surface roughness and uniformity of the coated films were characterized by Park System XE-100 AFM. The samples for ellipso meter, AFM, and TEM analysis were prepared on Si substrate (SiO₂(300 nm)/Si(100)) with the same deposition conditions as for the blank ophthalmic polymer lenses. The sample of cross-section TEM analysis was prepared by GATAN 691 PIPS precision ion polishing system. The optical properties of the blank polymer lenses, commercial lenses, and effective graded-RI AR coated lenses were analyzed by UV-visible spectrometer.

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. The refractive index of thin films is affected by deposition conditions such as deposition rate, deposition power, degree of vacuum, and deposition system [1, 2]. To confirm the refractive index, uniformity, and surface roughness of the coated thin films, the SiO₂ and MgF₂ thin films were deposited on Si wafer substrate by E-beam evaporation system under the base vacuum of 5×10^{-5} Torr. The surface roughness and uniformity of the SiO₂ and MgF₂ thin films were

characterized by AFM. The refractive index of the SiO₂ and MgF₂ thin films were analyzed by ellipso meter. The surface morphology of the SiO₂ thin film by E-beam evaporation system was shown in Fig. 1 (a). The average surface roughness of the SiO₂ and MgF₂ thin films was 1.37 nm, and 0.73 nm, respectively. The SiO₂ and MgF₂ thin films have a quite smooth surface. The measured refractive index of SiO₂ thin film is 1.458 which is good agreed with the value of bulk SiO₂ (n₅₀₀ = 1.46). The refractive index of MgF₂ thin film (n₅₀₀=1.380, n₅₅₀=1.378) is coincided well with the literature value of bulk MgF₂ (n₅₀₀=1.38) [7]. It is inferred that SiO₂ and MgF₂ thin films have a dense microstructures.

The blank polymer ophthalmic lenses which are manufactured with Shimizu lens monomer typically have a refractive index of 1.56, therefore when light propagates from air to polymer lens, about 5% of light gets reflected from each air/lens 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 coating material is approximately 1.25. 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 110 nm for a film of RI=1.25. However for single layer AR coating, zero reflectance cannot be fulfilled 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 [1, 2]. Here, the effective graded-RI AR coating is designed a bi-layer structure using the measured refractive index values of the SiO₂ and MgF₂ thin films. The calculated thickness of the MgF₂ layer and SiO₂ layer for minimum reflectance at a green wavelength (550 nm) are 99 nm and 94 nm, respectively. To confirm the microstructure and thickness of the effective graded-RI AR coating, the SiO₂ and MgF₂ thin films were characterized by the cross-section TEM analysis as shown in Fig. 1 (b). The SiO₂ layer has a highly dense microstructure and an 88 nm thickness which is slightly thinner than that of the design. The MgF₂ layer has dense microstructure and a 99 nm thickness. The dense microstructures of the SiO₂ and MgF₂ thin films are supported the measured RI values of the SiO₂ and MgF₂ thin films.

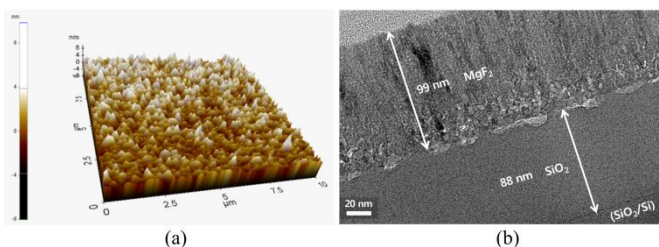


Fig 1. (a) AFM image of SiO₂ thin film surface deposited by E-beam evaporation system on Si wafer substrate (SiO₂(300 nm)/Si), (b) Cross-section TEM image of the graded refractive index AR coating on Si wafer substrate.

The effective graded-RI AR coatings are applied to blank polymer ophthalmic lenses. The thickness of the first SiO₂ layer is fixed to 94 nm, and the second layer MgF₂ is varied from 25 nm to 99 nm. The reflectance of the blank polymer lens (n=1.56) without AR coating, commercial lens with a five-layer AR coating, and the effective grade-RI AR coating lens with a bi-layer AR coating are shown in Fig. 2 (a). The mean reflectance of a blank polymer lens (n=1.56), commercial lens (Clex 1.56 Finished Lens), and the effective graded-RI AR coating lens with 25 nm MgF₂ layer are 5.6%, 3.4% and 2.8% in the wavelength range of 400 nm to 800 nm, respectively. The average reflectance of the graded-RI AR coating lens has lower than that of the commercial multi-layer AR coating lens.

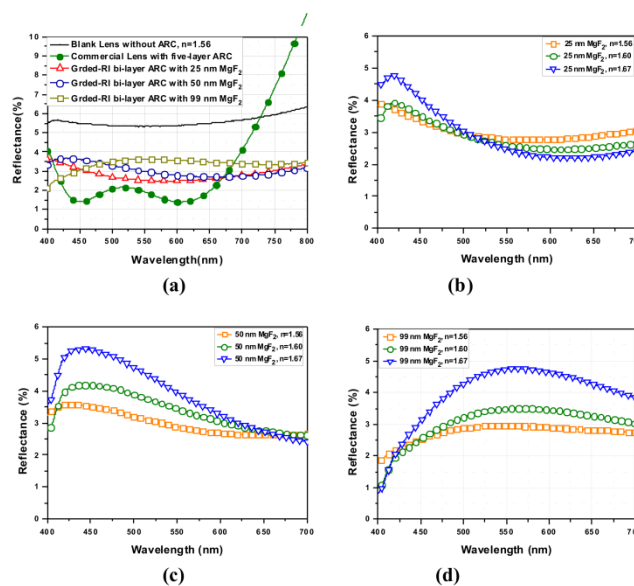


Fig 2. (a) Reflectance spectra of a blank polymer lens (n=1.56) without AR coating, commercial lens with five-layer AR coating, and bi-layer graded-RI AR coating lens, (b-d) reflectance spectra of the bi-layer graded-RI AR coating lenses for different AR coating thickness (SiO₂ : 94 nm, MgF₂: 25 nm to 99 nm) and different blank polymer lenses.

For ophthalmic lens and display applications, photopic response is used in order to represent the visual reaction of the human eye to a given light source [3]. Optical coatings are generally tuned for the spectral region of 460-660 nm. Human eye is the most responsive in this region. The reflectances of the effective graded-RI AR coatings for different blank polymer lenses with different second MgF₂ layer thickness are shown in Fig. 2 (b-d). The commercial AR coating has a maximum photopic response around 525 nm, which gives the residual reflection of green color. Excessive exposure to ultraviolet (UV) radiation can result in chronic harmful effects on the skin, eye, and immune system [8]. Thus recently functional AR coatings provide a block of UV and reducing the harmful UV-violet spectrum band [9, 10]. As the thickness of the second MgF₂ layer decrease, the mean transmittance is increased, and the photopic response is shifted from green region (99 nm MgF₂) to blue region

(50 nm MgF₂) and violet region (25 nm MgF₂). The maximum residual reflection of violet region reduces the harmful spectrum of the transmitted light through the ophthalmic lens.

4. Conclusions

The effective AR coating was designed a bi-layer graded refractive index structure with the SiO₂ and MgF₂ thin films for polymer ophthalmic lens. The AR coatings were fabricated by E-beam evaporation system. According to the cross-section TEM analysis, the deposited SiO₂ and MgF₂ thin films have a highly dense microstructures. The refractive indices of the SiO₂ and MgF₂ thin films are coincided with the values of the bulk phase. It is attributed the dense microstructures of the SiO₂ and MgF₂ thin films. The average reflectance of the effective graded-RI AR coating (25 nm MgF₂) was measured to 2.8% for blank polymer lens with n=1.56 in the wavelength range of 400 nm to 800 nm, which was lower than that of the commercial five-layer AR coating lens. The process time of the effective graded-RI AR coating is saved about 40% compare to the commercial multi-layer AR coating. In addition, the consuming amount of the raw materials is also reduced. As the thickness of the second MgF₂ layer decrease, the mean transmittance is increased, and the photopic response is shifted from green region to violet region.

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