UV optical filters based in magnesium

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Abstract. This article presents the fabrication of magnesium fluoride (MgF_2) and magnesium oxide (MgO) thin film-based ultraviolet (UV) optical filters and compares their optical transmission. The MgF_2 thin-films were deposited by electron beam (e-beam) technique and their optical properties were characterized by ellipsometry. The effects of substrate temperature on the optical properties were studied. The MgF_2 optimum refractive indices were obtained with high substrate temperatures, 200 °C and 300 °C. Optical simulations were performed to compare the performance of MgF_2 and MgO in the fabrication of near UV narrow bandpass optical filters. While MgO based optical filters result in a higher transmittance peak intensity, especially at 350 nm, the MgF_2 optical filters are narrower, *i. e.*, present lower values of full width at half maximum (FWHM), mean value of 21 nm. The MgF_2/TiO_2 UV optical filters show a peak transmittance approximately of 70 % close to 400 nm as expected. The results were discussed with a focus on applications in fluorescent optical sensors for the peaks at 350, 370, 380 and 400 nm respectively.

1. Introduction

The use of magnesium oxide (MgO) as low-refractive index material for the near ultraviolet (UV) optical filters is already reported on literature [1]. The use of magnesium fluoride (MgF_2) as low refractive index material for UV optical filters is only reported for the visible range (central wavelength of 511 nm) [2]. The MgF_2 presents a wide transparency range from 120 nm to 8 μm, good mechanical properties, low optical absorption and low optical refraction index [3, 4]. MgF_2 thin-films are widely used in antireflection coatings and in dielectric interference filters [5]. Also, the MgF_2 thin-films suffer from high tensile stress and for reasonable durability must be deposited on heated substrates [6]. Dumas *et al.* deposited MgF_2 by electron beam (e-beam) technique at substrate temperatures from the room temperature to 300 °C and at a pressure of 1×10^{-7} mbar [7]. The work of Ristau *et al.* present a deposited MgF_2 by thermal e-beam with a substrate temperature of 300 °C at a pressure of 6×10^{-6} mbar [8]. Yang *et al.* conclude that the characteristics of the MgF_2 thin-films obtained at a substrate temperature of 200 °C were the best for an antireflection film for solar cells [9]. This work presents the study of MgF_2 as low-refractive index material for UV optical filters. The MgF_2 thin-films were deposited by e-beam technique and optical characterized. Also, optical simulations were performed on TFCalc™ software to compare the performance of MgF_2 and MgO in the fabrication of narrow bandpass UV optical filters, between 350 nm and 400 nm. Additionally, a Fabry-Perot based MgF_2/TiO_2 UV optical filter was fabricated using e-beam and a reactive Radio Frequency (RF) sputtering technique. The fabricated UV optical filter was optically characterized. The obtained results were discussed taking into account specific applications on fluorescent optical sensors.

2. Simulation and methods

2.1. MgF_2/TiO_2 UV optical filters

The performance of the MgF_2/TiO_2 UV optical filters (considering the experimental refractive indices presented on Figure 3, at 200 °C) was evaluated. Moreover, for the simulation of MgF_2/TiO_2 UV optical filters, the refractive indices of TiO_2 thin-films (deposited by a reactive RF-sputtering) were used, since they are reported by the authors in [10]. Table 1 shows the thickness of each thin-film that forms each optical filter centered at 350, 370, 380 and 400 nm. The optimization function in continuous approach and interval of 10 nm for each peak was used. By this way, the precise thickness for each layer is obtained and results in a sharper and thin peak (high intensity and low full width at half maximum (FWHM)).

Table 1. Layer thicknesses for the simulated narrow bandpass UV optical filters with MgF_2/TiO_2.

Material	**Filter transmittance peak (nm)**			
	350	370	380	400
	Layer thickness (nm)			
TiO_2	30			
MgF_2	110			
TiO_2	10			
MgF_2	259	287	300	330
TiO_2	10			
MgF_2	110			
TiO_2	30			

Figure 1 shows the simulation results extracted from TFCalc™ software of the near UV optical filters based in MgF_2/TiO_2 thin-films.

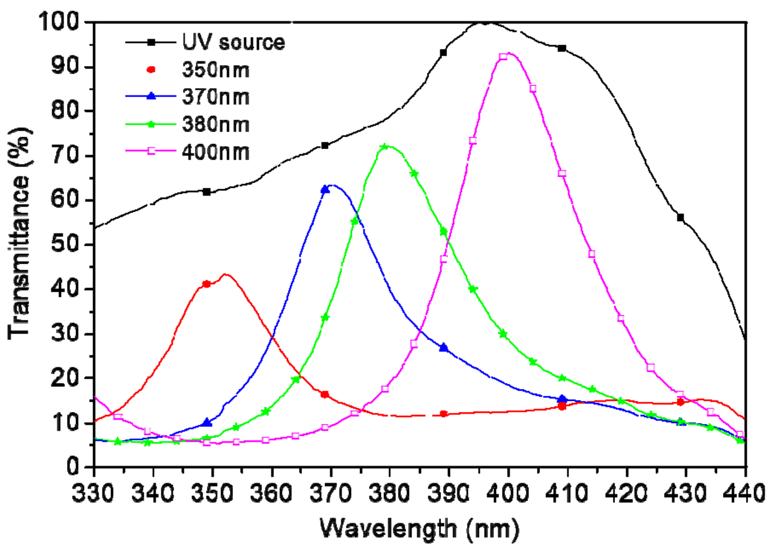

Figure 1. Transmittance of the MgF_2/TiO_2 simulated UV optical filters.

2.2. MgO/TiO_2 UV optical filters

Replacing the MgF_2 by MgO as the low-refractive index layer of the optical filter for near UV filters applied to optical sensors, the authors already reported the fabrication of narrow band pass optical filters between 350 nm and 400 nm using the MgO material [1]. The work of Pimenta *et al.* reported using MgO as low-refractive index material and TiO_2 as high-refractive index material. Both MgO and TiO_2 thin-films were deposited by Ion Beam Deposition (IBD) technique and their refractive indices were also obtained by ellipsometry [1]. Considering the MgO and TiO_2 refractive indices reported in [1], the performance of four optical filters, centered at 350, 370, 380 and 400 nm, was also simulated on TFCalc^{TM} software. Table 2 shows the thickness of each thin-film that forms each UV optical filter.

Table 2. Layer thicknesses for the simulated narrow bandpass UV optical filters with MgO/TiO_2.

	Filter transmittance peak (nm)			
Material	350	370	380	400
	Layer thickness (nm)			
TiO_2	30			
MgO	80			
TiO_2	10			
MgO	215	237	248	275
TiO_2	10			
MgO	80			
TiO_2	30			

Figure 2 shows the simulation results extracted from TFCalc^{TM} software of the near UV optical filters based in MgO/TiO_2 thin-films.

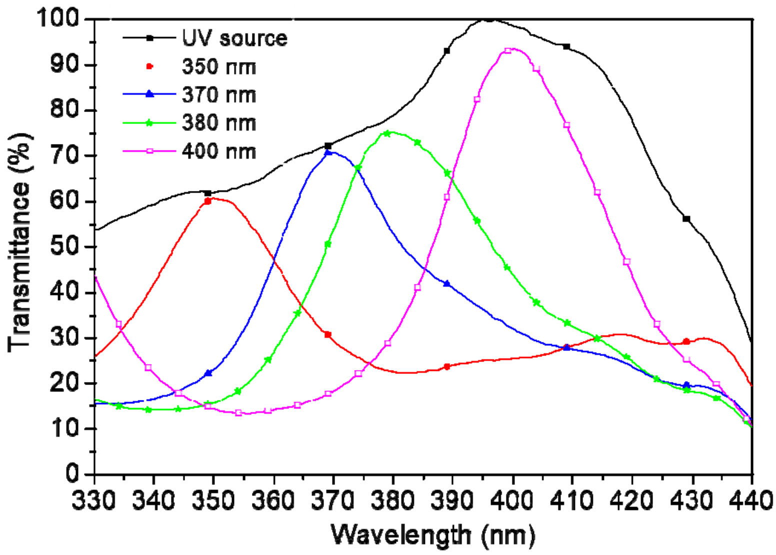

Figure 2. Transmittance of the MgO/TiO_2 simulated UV optical filters.

2.3. MgF_2/TiO_2 UV optical filters fabrication

The MgF_2 thin-films were deposited by e-beam technique at several substrate temperatures (100 ºC, 200 ºC and 300 ºC). The distance between the MgF_2 pellets to substrate is approximately 150 mm. The different substrate temperatures were obtained by irradiance with 150 W halogen heating lamps. The heating lamps are connected to a controller and to a temperature sensor installed near the substrates. This simple and reliable technique insures a controlled temperature of the substrates. For each temperature step, an MgF_2 thin film with thickness of 300 nm was deposited, on a polished silicon (100) substrate for optical characterization by ellipsometry. Initially, the deposition chamber was evacuated to 7×10^{-6} mbar. Typically, the increase of temperature inside of the deposition chamber induces the increase of the total pressure. Therefore, the optimum conditions to deposit the MgF_2 thin-films were archive with the e-beam power of 7 kV set at 10 mA and a deposition rate of 45 Å/s was obtained. A shutter was activated to ensure the precise thickness of 300 nm.

The TiO_2 thin-films were deposited by a reactive RF sputtering using a Titanium sputtering target. The optimum conditions were obtained at a deposition pressure of 2×10^{-3} mbar, 10 sccm of Ar, 2 sccm of O_2 and a power of 200 W with a deposition rate of 0.3 Å/s. The UV optical filter was deposited on borosilicate glass substrates and on polished silicon (100) substrates.

3. Characterization

3.1. MgF_2 thin-films ellipsometry

The refractive indices were obtained using an ellipsometer (J. A. Woollam). Figure 3 shows the refractive indices from 300 nm to 500 nm light spectrum of the 300 nm thick deposited MgF_2 thin-films. Also, is presented the refractive indices for MgF_2 thin-films reference reported by E. Palik [3]. The obtained refractive indices showed good agreement with the literature results, especially at high substrate temperatures (200 °C and 300 °C).

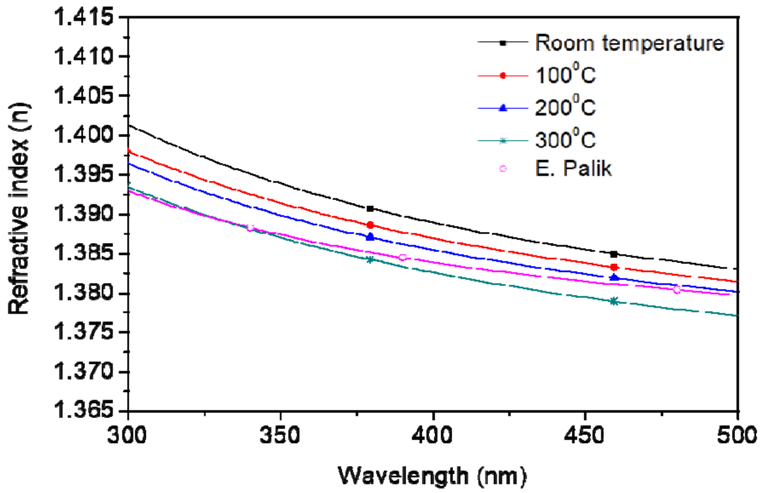

Figure 3. Refractive indices of MgF_2 thin-films.

4. Results and discussion

The MgF_2/TiO_2 UV optical filter programmed to be centered at 400 nm was fabricated, as described on section 2.1 and according to the thin-films thicknesses presented on Table 1. Figure 4 shows the optical transmittance obtained for the borosilicate glass substrates.

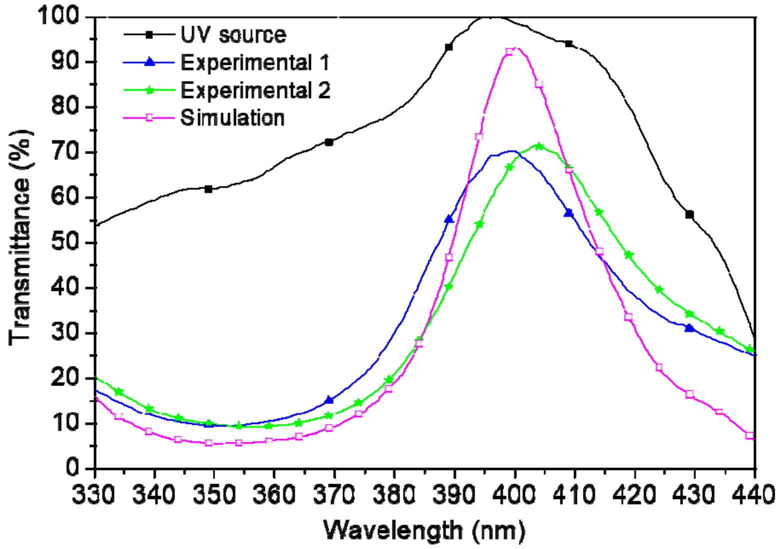

Figure 4. Experimental transmittance of the MgF_2/TiO_2 fabricated UV optical filter.

The peak transmittance of the UV optical filters is approximately 70 % and the peaks are slightly deviated from the 400 nm, 399 nm (for experimental 1) and 404 nm (for experimental 2). The difference between the two samples is due to the different position of the substrates in the deposition chamber. Moreover, the FWHM increase slightly, comparing with the simulation result. However, this increase could not be critical for some applications, for example, the extraction of fluorescent emission from Fluoresbrite® BB Carboxylate Microspheres, since the filter transmittance at 360 nm is very low when comparing to the transmittance at 407 nm. The total thickness is 619.5 nm (measured by ellipsometer), which is close to the expected result (630 nm). Table 4 shows the peak intensity and the FWHM for each optical filter.

Table 4. Comparison between the MgO/TiO_2 and MgF_2/TiO_2 UV optical filters.

Materials	Filter transmittance peak (nm)							
	350		370		380		400	
	Intensity (%)	FWHM (nm)	Intensity (%)	FWHM (nm)	Intensity (%)	FWHM (nm)	Intensity (%)	FWHM (nm)
MgO/TiO_2	60.75	32	70.74	28	75.23	30	93.72	28
MgF_2/TiO_2	41.29	20	63.53	22	72.17	20	93.07	22

With the combination MgO/TiO_2 is possible to obtain UV optical filters with a higher transmittance peak intensity, especially at 350 nm. However, combining MgF_2/TiO_2 the UV optical filters are narrower. This could be especially important for fluorescent optical sensors when part of the fluorescent molecule emission spectrum overlaps the molecule excitation spectrum. The FluoSpheres™ Carboxylate-Modified Microspheres blue fluorescent [11] and the Fluoresbrite® BB Carboxylate Microspheres [12] are such examples, considering the spectral range of interest (near UV). When there is a spectrum overlapping, narrow optical filters are crucial for: (1) a correct excitation of the molecule, narrow optical filter centered at its excitation peak; (2) a correct extraction of the molecule emission with low interferences from the excitation light, narrow optical filter centered at its emission peak. As an example, for the Fluoresbrite® BB Carboxylate Microspheres, the optical filter to extract its fluorescent emission should have a high transmittance at 407 nm (peak emission) and the minimum transmittance at 360 nm (peak excitation). According to the simulations results, this compromise is better achieved with a MgF_2/TiO_2 based UV optical filter.

5. Conclusions

The fabrication and characterization of MgF_2 thin-films deposited on silicon substrates at different temperatures were presented. The MgF_2 thin-films were deposited by e-beam technique and optical characterized by ellipsometry. The measured refractive indices showed good agreement with the literature results, especially for higher substrates temperatures (200 °C and 300 °C). Also, the optical simulations compared the performance of near UV optical filters when using the materials combinations MgO/TiO_2 and MgF_2/TiO_2. With the first combination, optical filters with higher peak transmittance were obtained, especially at 350 nm. Finally, with the second combination, narrower optical filters were achieved, which can be important to specific applications on fluorescent optical sensors. Those specific applications include using narrow optical filters for extraction of the fluorescent emission of a molecule without interferences from the excitation light, when the excitation and emission spectra of the molecule overlap. Additionally, an MgF_2/TiO_2 UV optical filter was fabricated based on e-beam and reactive RF-sputtering. The optical filter transmittance was measured, with a peak transmittance of approximately 70 % and close to 400 nm. The optical filter total thickness was also measured by ellipsometer, with a value of 619.5 nm, which is close to the expected value (630 nm).

Acknowledgements

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