Plasma deposition of anti-reflective coatings on spherical lenses

O. Zabeida, A. Amassian, S. Larouche, C. Lavigne,
J. E. Klemberg-Sapieha, and L. Martinu
Groupe de Recherche en Physique et Technologie des Couches Minces (GCM) and
Department of Engineering Physics and Materials Engineering
École Polytechnique, Montreal, Quebec, H3C 3A7, Canada
lmartinu@mail.polymtl.ca

D. E. Morton, I. C. Stevenson, and F. Zimone
Denton Vacuum LLC, Moorestown, NJ

Abstract: Plasma-enhanced chemical vapor deposition (PECVD) was used to fabricate multilayer anti-reflective coatings (ARCs) on spherical fiber couplers. Two- and four-layer designs were applied for single- and double-band ARCs centered at 1300 nm and 1550 nm, respectively. The systems consist of SiO_2 as a low index material, and $SiN_{1.3}$ or TiO_2 as high index materials, obtained from different precursors (SiH_4, $SiCl_4$, and $TiCl_4$). The deposition was controlled *in-situ* by single wavelength (632.8 nm) reflection monitoring. The optical and mechanical performance of the lenses was evaluated and related to the deposition conditions and the film microstructure.

OCIS codes: (310.6860) Thin films, optical properties; (310.1620) Coatings

1. Introduction

Fiber-to-fiber coupling and fiber collimation in telecommunication applications has traditionally been accomplished using graded index (GRIN) lenses. The cylindrically shaped GRIN lenses are rather expensive and their performance is very sensitive to angular alignment [1]. Therefore, there is a growing interest in spherical lenses, which are more compact, less expensive, and easier to mount and align [2]. Despite these advantages, their wider acceptance has been limited due to considerable reflection losses. For the ball lenses with a refractive index $n = 1.5$, the total transmission through four surfaces is only about 85 % (see Fig. 1). A practical solution is, of course, to apply antireflective coatings (ARCs) with minimum reflection at common telecommunication wavelengths. In addition, these ARCs must also satisfy further requirements, mostly related to their stability, mechanical integrity, temperature excursions during mounting, and others. Deposition of ARCs on ball lenses using thermally activated low pressure chemical vapor deposition (LPCVD) has been described elsewhere [2, 3].

In the present work, we study the fabrication of two- and four-layer ARCs by plasma-enhanced CVD (PECVD), with the main emphasis on the optical performance, film microstructure, mechanical stability, and *in-situ* process monitoring. This follows our review of PECVD for optical coatings [4], and a successful demonstration of a high index PECVD material (TiO_2, $n = 2.40$) [5].

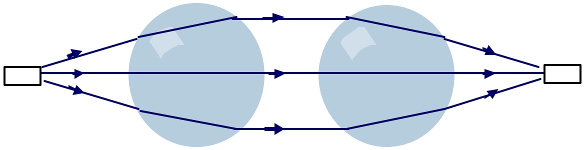

Fig. 1. Schematics of fiber-to-fiber coupling with two spherical lenses.

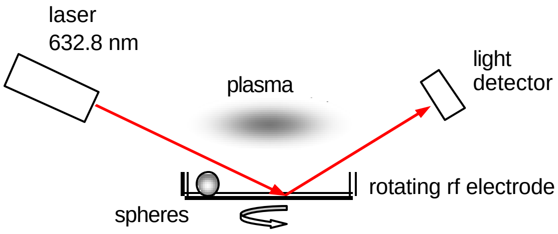

Fig. 2. Experimental setup.

2. Experimental methodology

The ARCs were fabricated using an experimental arrangement schematically illustrated in Figure 2. The ball lenses (2.5 mm or 3.5 mm diameter BK7 glass spheres) were placed on a radio frequency (RF, 13.56 MHz) powered electrode on which a negative substrate bias voltage develops. The electrode rotation at about 20 rpm assured a uniform coating. During deposition, we monitored the intensity of HeNe laser beam reflected from the flat witness at the center of the electrode. The angle of incidence was 70° with respect to normal.

Different amorphous low index (n_L) and high index (n_H) film materials from different precursors have been applied: (i) SiO_2 from $SiH_4/N_2O/Ar$ or $SiCl_4/O_2/Ar$ mixtures, (ii) $SiN_{1.3}$ from a $SiH_4/N_2O/Ar$ mixture, and (iii) TiO_2 from a $TiCl_4/O_2/Ar$ mixture. The total working pressure was typically between 20 and 100 mTorr, while the RF power was 100 - 300 W.

The film basic optical properties on flat reference substrates (glass, c-Si) were determined by variable angle spectroscopic ellipsometry (VASE, J. A. Woollam Co.) and spectrophotometry (Lambda 19, Perkin Elmer), using the WVASE32 software (J. A. Woollam Co.) and the Cauchy dispersion formula with Urbach tail extension for the extinction coefficient. Optical evaluation of the coated spheres was performed using different arrangements: (i) transmission of light from a 1286 nm laser coupled to a fiber; (ii) transmission (with no fiber confinement) in two ranges: 700 - 1100 nm and 925 - 1675 nm; (iii) reflectance using a Filmetrics F20 thin film measurement system in the 400 - 1000 nm range.

Surface morphology of the coated spheres was examined by optical microscopy and scanning electron microscopy (SEM).

3. Results and discussion

In the first set of experiments we determined and optimized the refractive index of all investigated materials. The *n* values of 1.80, 1.47, and 2.22 were obtained for $SiN_{1.3}$, SiO_2, and TiO_2 films, respectively, at 1300 nm, which was used as the reference wavelength in our designs. The corresponding extinction coefficient, *k*, remained systematically below 10^{-6} in the near infrared for all coatings.

We used the experimental dispersion data to generate optical designs, aiming at obtaining minimum reflection at 1300 nm (2-layer system) or at 1300 and 1550 nm (4-layer system). The corresponding design thicknesses and transmittance values are summarized in Table 1, and the desired performance is shown in Fig. 3.

In the second series of experiments we carried out calibration of the *in-situ* monitoring system. This experiment consisted of evaluating the thickness on the reference flat witness substrate in the middle of the RF electrode and the film thickness values obtained on the spheres. The ratio of the flat surface/ball surface thicknesses, *K*, was found to be typically 1.7. Using this parameter, we could then control the deposition process in real time.

Table 1. Designs for single- and double-band ARCs used in this work.

Filter design	Layers	QW @ 1.30 *m*m	Thickness (nm)	*T* @ 1.30 *m*m (%)	*T* @ 1.55 *m*m (%)
Single Band $SiN_{1.3}\|SiO_2$	1	1.000 H	180.8	99.9989	96.2
	2	1.000 L	221.2		
Single Band $TiO_2\|SiO_2$	1	2.260 H	331.2	99.9997	92.5
	2	1.310 L	293.3		
Double Band $TiO_2\|SiO_2$	1	0.485 H	69.8	99.9948	99.9952
	2	0.356 L	80.8		
	3	0.904 H	132.2		
	4	1.198 L	271.6		

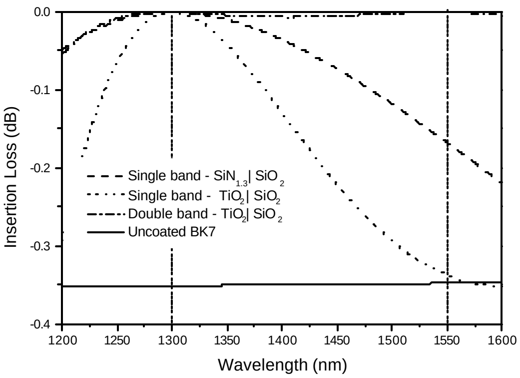

Fig. 3. Comparison of expected performance of AR coatings on BK7 spheres for different designs presented in Table 1.

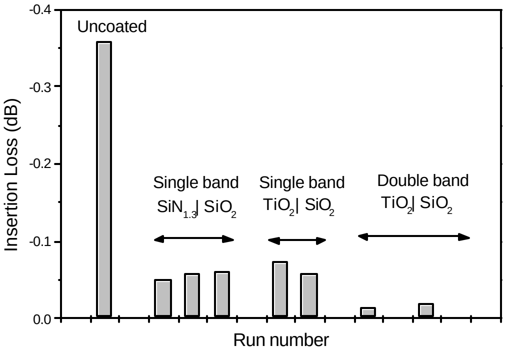

Fig. 4. Examples of performance measured on coated BK7 spheres at $\lambda = 1286$ nm.

In the third set of experiments we deposited the ARCs on the spheres following the designs shown in Table 1 and using *in-situ* monitoring. Figure 4 shows the insertion loss data at 1286 nm for the 4-layer and 2-layer stacks, as well as their comparison with the performance of an uncoated BK7 sphere. Relatively high losses for 2-layer filters are caused by the uncertainty in thickness of the deposited layers as a result of indirect thickness control. It is clear that 4-layer coatings perform better because of a much broader pass-band in the initial design. In this case, small errors in the thickness of each layer do not largely affect the coating performance.

During these experiments we have found that the ARCs can approach the design reasonably well; corresponding *T(1300 nm)* and *T(1550 nm)* values were above 98 %, indicating reflection losses of less than 1 % on each surface. In addition, we experienced a loading effect, i.e. the *K* parameter was found to depend on the number of spheres mounted on the holder-electrode. This clearly indicates that the deposition process has to be carefully calibrated regarding the movement control of the spherical lenses..

4. Conclusion

We have successfully applied antireflective coatings on 2.5 and 3.5 mm diameter lenses for fiber-to-fiber coupling, using PECVD of TiO_2/SiO_2 and $SiN_{1.3}/SiO_2$ systems and *in-situ* monitoring. The resulting measured reflectances were below 1 % on each surface at two desired telecommunication wavelengths, namely 1300 nm and 1550 nm. We noticed that the two-layer ARC design has a higher sensitivity to manufacturing errors compared to a four-layer design. Further optimization is needed to incorporate the loading effect, i.e. the number of spheres coated in one run, which is expected to improve the monitoring procedure.

References:

1. J. C. Palais, "Fiber coupling using graded-index rod lenses," Appl. Optics, **19,** 2011-2018, (1980).
2. D. Z. Rogers, "Ball lenses for coupling and collimation," Lightwave, **16**, 104-110 (1999).
3. M. A. George and D. Z. Rogers, "LPCVD of optical interference coatings for micro-optical applications," 43rd Ann. Tech. Conf., Society of Vacuum Coaters, Denver, April 2000, 193-196.
4. L. Martinu and D. Poitras, "Plasma deposition of optical films and coatings: A review," J. Vac. Sci. Technol. A **18,** 2619-2645 (2000).
5. L. Martinu, M. Latreche, V. Hajek, J. E. Klemberg-Sapieha, A. Argoitia, W. T. Beauchamp, "Search for high index PECVD optical coating materials: The case of titanium dioxide," 43rd Ann. Tech. Conf., Society of Vacuum Coaters, Denver, April 2000, 177-180.