Ultra-low-reflectance, high-uniformity, multilayer-antireflection coatings on large substrates deposited using an ion-beam sputtering system with a customized planetary rotation stage

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ABSTRACT

A customized planetary rotation stage has been fitted to a commercial ion beam sputter coater to enable the deposition of high uniformity, multilayer optical coatings on large substrates without the use of masks. Uniformity in this system achieved by sequentially depositing each layer in two fixed locations in the sputtered particle plume where the geometry of the natural thickness distributions on a rotating substrate in these locations are of complementary shape and add to produce an overall uniform layer. The modified planetary stage allows substrate rotation about its own axis at any fixed position of the substrate centre about the axis of the planetary system. The suitable locations in the plume of each material that allow maximum uniformity are found by trial and error refinement of locations obtained by modelling of the plume distribution and expected thickness distributions. Ellipsometric monitoring of the thickness of the layer in each fixed position is used to determine the precise ratio of thicknesses in each location needed to obtain the correct total layer thickness simultaneously with high uniformity. The system has thus far enabled single wavelength antireflection coatings of less than 0.001% reflectance to be fabricated over 270 mm diameter substrates. This requires the film thickness uniformity on all layers to be less than ± 0.2%. In addition, 4-layer, dual wavelength antireflection coatings have been fabricated with less than 0.01% reflectance on both wavelengths over similar substrate dimensions.

Keywords: Ion-beam sputtering, antireflection coating, planetary, high-uniformity, ultra-low-reflectance

1. INTRODUCTION

Almost all thin film scenarios require some degree of uniformity of the coating. For multilayer dielectric coatings for optical purposes this requirement can be quite severe as small errors in thickness or optical properties of the coatings can make significant differences to the optical performance. Most currently available versions of commercial optical multilayer design software1-3 can estimate these errors by a variety of techniques. In Fig. 1, the reflectance of a simple 2-layer antireflection (AR) coating designed for zero reflectance at 1064 nm, is modelled as a function of the uncertainty in the layer thickness and refractive index, using a commercial package1. Here it can be seen that to achieve less than 10 ppm reflectance (0.001%), the total layer thickness errors must be kept below ± 0.4%, assuming zero refractive index error, or the refractive index uncertainties must be below ± 0.2%, assuming no error in the layer thicknesses. Clearly, to produce such a coating the uniformity in optical thickness (refractive index × thickness) somewhat better than ± 0.4% would be required over the substrate, regardless of its size. Even in the case where the optical performance is quite tolerant to thickness or index variations, film thickness errors can contribute to the overall shape of a precision optical component and can contribute to wavefront errors.

While optical coatings can be produced using almost any thin film deposition technique, thermal and electron beam evaporation and sputtering are the most common for precision coatings. For the highest quality optical coatings - those requiring hard, dense material with very low absorption and scatter loss - ion beam sputtering is the preferred method.
Such optics as mirrors for ring-laser gyroscopes, gravity-wave interferometers and cavity ring-down spectroscopy are examples requiring ion beam sputtered coatings.

Figure 1. Predicted best-case reflectance obtainable as a function of the layer thickness and refractive index variation in a 2-layer AR coating designed for zero reflectance at 1064nm (calculations performed in TFCalc®).

Like most forms of physical vapor deposition, the sputtered material plume from an ion beam sputter coater (IBS) is highly spatially non-uniform. The non-uniformity causes variations in both deposition rate and optical constants of the sputtered coating. To obtain adequate uniformity in thickness and optical properties on large substrates, or a number of small substrates, usually requires either a planetary or similar motion stage to average the deposition rate, or fixed or movable masks to reduce high rate regions in the source plume\(^4\text{-}^7\). The best results usually require both methods. While source masks can be quite effective, they need careful design and fabrication and can be sensitive to small dimensional errors. Since the source plume geometry is generally different for each sputtered material, separate masks are required for each material to obtain the best results. The mask shape can be distorted by stress in the intercepted deposits and fracture of the coating near the sharp edges of the mask can be a source of particulate contamination.

Several descriptions of maskless methods of uniform deposition have been reported\(^8\text{-}^9\). These are typically applied to magnetron sputter sources and relatively small mass substrates and involve passing the substrate under the source plume using a predetermined velocity profile designed to integrate the deposition patterns at each point so that they sum to a constant value. Power modulation is also used to provide additional rate control. In previous work by the authors\(^1\text{0}\), a similar maskless method was applied to an ion beam sputter deposition system designed for coating large diameter, heavy optical components. Rather than move the substrate through the sputter plume in a specific time/power-dependent manner, the substrate was simply coated for specific times at two fixed locations in the sputter plume, while rotating about its center. The locations are chosen so that the thickness distributions are of a complementary shape and add to produce an overall uniform film. Since rapid lateral motion of the substrate is not used, the substrate stage and mount can be of relatively light construction. In this work, this method is applied to some specific examples of multilayer antireflection coatings requiring very high uniformity on large substrates.
2. EXPERIMENTAL

2.1 Modeling of the sputter-plume distribution

The sputter-plume distribution in an IBS system has a generally complex shape. The ion beam is usually incident on the sputter target at an angle close to 45°, with the resulting sputtered particle plume distribution centered at approximately 45°, the exact angle and shape being material dependent.

In Fig. 2a, a photograph of the white light optical interference pattern produced by a tantalum pentoxide film deposited onto a fixed glass plate in the present IBS system, is shown. The thickness of the film measured at selected points along the vertical and horizontal axes with an origin at the plume maximum is shown in Fig. 2b and can be seen to be approximately Gaussian and skewed Gaussian, respectively. This distribution has been modelled empirically (solid lines in Fig. 2b) by assuming that each interference fringe in Fig. 2a can be described as a ring formed by two half-ellipses with different minor axes, one on the left of the vertical axis of the distribution and the other on the right. The size of the axes and the position of the center of each ring in Fig. 2a can be measured and a mathematical description of these parameters, as a function of position, derived by curve fitting. This enables a model of the distribution to be obtained with arbitrary resolution.

![Figure 2a](image1.png)

![Figure 2b](image2.png)

Figure 2. (a) Photograph of the interference pattern produced by an ion beam sputtered tantalum pentoxide film (max 1µm thick) deposited on a 600 mm x 800 mm stationary glass plate. (b) Measured thickness (dots) of the film along the horizontal and vertical axes of the pattern together with the empirical model prediction (solid lines).

2.2 Modified planetary motion stage

A modified planetary motion stage was retrofitted to an existing commercial IBS system. The purpose of this stage was to enable more flexible motion options than the standard cycloidal motion produced by a conventional planetary stage. The design of the modified stage has been described in detail elsewhere. In summary, the normally fixed central or sun gear of the planetary stage is instead allowed to rotate independently and is driven by a different motor to that which drives the rotation of the planets (substrates). The system can perform standard planetary motion or the substrates can be
located at fixed positions about the sun gear axis and simply rotated about their own axes. The maximum substrate size allowed in this particular system is 400 mm diameter. The angular position of the planets around the stage axis can be fixed to within ~0.2°.

2.3 Obtaining uniform deposition

Figure 3 shows the radial thickness distributions of tantalum pentoxide thin films measured on a single rotating substrate located at various fixed angular positions around the sun gear axis. The horizontal axis of the system defines zero degrees and the center of the sputter plume is approximately equal to the center of the substrate at zero degrees. Also shown in the figure are the predicted distributions obtained by superimposing the substrate motion over the model of the plume (in Fig. 2) and integrating the thickness as the substrate rotates. The agreement between the model and experimental distributions are sufficient to enable the model to be used for predictive purposes. In addition, an important observation is that for an angle somewhere between 50° and 70°, the distributions change from being thicker in the center to thicker at the edge and are thus to some extent complementary. The model can be used to obtain two angles at which this complementarity is maximized and if two sequential depositions are performed for suitable times at these angles the uniformity of the resulting coating can be significantly improved. Figure 3b shows the modelled performance of such a sequential deposition, where the substrate is coated for a period T at 3° and 21\times T at 77°, the resulting distribution having a suggested thickness uniformity of ~0.2% peak-to-valley over a 400 mm diameter.

Experimentally, the optimum angles predicted from the model are quite close to those actually found to give the best uniformity. Figure 4 shows an actual deposition of tantalum pentoxide under the same conditions as those described in Fig. 3b for T = 150 sec. The film thicknesses were determined by fitting spectroscopic ellipsometry measurements to a model of the film using fixed values of the optical constants. Hence the thicknesses found are proportional to the optical thickness. The uniformity of the final film is ±0.3%, very close to the predicted value. The best value obtained by trial-and-error adjustment beyond this value was ±0.1% with a change of only 1° in the higher angle, although the stage
positioning accuracy and the degree of rotational wobble of the substrate planet may be limiting factors here. In addition, the precision of the model and the degree to which the thickness distributions at the two optimum angles complement each other are obvious limits to the process.

While the preceding description has been for tantalum pentoxide deposition in the present system, the same process has been applied to silicon dioxide films with similar results, although the angles for optimum uniformity are slightly different.

![Figure 4](image)

**Figure 4.** Measured radial thickness profiles of tantalum pentoxide films deposited on a rotating substrate at fixed angular positions to the horizontal axis, together with the profile of the sum of those depositions. Film thicknesses were determined by ellipsometric modeling of the film using fixed values of the optical constants. Hence the thicknesses shown are proportional to the optical thickness.

### 2.4 Deposition monitoring

Apart from determining the appropriate angles for each material, the practical application of this method involves determining the required ratio of the deposited thicknesses at the optimum angles. The deposition rate in a typical IBS system is relatively constant (~ 1%) so for coatings where the error tolerance is high, these thicknesses can be determined by deposition time and the thickness ratio becomes a time ratio (as in Fig. 3b). However, for the most demanding coatings, the thickness should be determined using accurate rate or thickness monitoring. The ultimate uniformity achievable will then be limited by the accuracy of this system. In the present case, a multiwavelength ellipsometer is used to determine the film thickness on a silica monitor positioned close to the sun gear axis. Although this does not directly monitor the thickness of the coatings on the actual substrate, the ratio between the monitor thickness and the thickness at the substrate center for the two angles and for each material can be measured quite accurately and the monitor thickness scaled to provide the required thickness on the sample substrate.

### 2.5 Thickness uniformity and optical properties

The determination of the various parameters needed to achieve high uniformity is strongly dependent on the precision of the methods used to determine the deposited film thickness or optical properties. Spectrophotometry, for example, is the standard technique for measuring the reflection or transmission of an optical coating. However, while able to determine wavelength quite accurately, the photometric accuracy of the best spectrophotometers is ~ 0.1% in transmission or
reflection and this may translate into quite large uncertainties in layer thickness, especially as the thickness must usually be extracted from a model that depends on equally accurate knowledge of the refractive index. For single layers, while the absolute thickness of the film may be uncertain at the 0.1% level, the relative thickness distribution measured over the same substrate can be much better. For multilayer films, however, the number of model parameters can be large and multiple solutions to the thicknesses of the layers can often be found, even on the same substrate. Spectroscopic ellipsometry is also limited in the same way because the prediction of transmission or reflection from ellipsometric measurements is model-dependent.

For the work reported here, the uniformity of AR coatings, has been inferred from accurate measurements of the reflectance using a specially constructed laser-based reflectometer. A laser signal reflected from the test optic is compared with that from a ~ 99.9% reflecting dielectric mirror. The absolute value of the reference mirror does not need to be known to a high accuracy since even quite large errors in this reference will translate to very small errors when the ratio against the small signal from the test optic is taken. The laser used is sufficiently powerful that signal intensities at the ~10^-6 level are still readily detectable using conventional lock-in amplification techniques. The optic under test is mounted on an XY stage with about a 270 mm diameter scanning capability, to enable a surface map of reflectance to be obtained. The overall uniformity of the optical thickness of the coating can then be estimated by using the technique described in Fig. 1.

3. RESULTS

3.1 2-layer antireflection coatings

Two-layer AR coatings designed for zero reflectance at 1064 nm were deposited on 300 mm diameter fused silica disks using ~ 50 nm of tantalum pentoxide as the base layer and ~ 240 nm of silicon dioxide as the top layer. The deposition was carried out in 4 steps, one at each of the two optimum angles for each material. Figure 5 shows a 3-D surface plot of the reflectance (in ppm) of one such deposition measured using the laser reflectometer at 1064 nm. The reflectance over a diameter of 270 mm is 4.5±1.5 ppm (~ 0.0004%). Analysis of the coating behavior with small changes in layer thicknesses suggests that a monitoring error of ~ 0.4 nm in the tantala layer can account for the minimum value of the reflectance of ~3 ppm. In addition, the variation of ± 1.5 ppm can only be accounted for if the uniformity of the physical layer thicknesses is at worst ± 0.1%, assuming zero refractive index variation. The physical thickness uniformity is therefore likely to be better than this. The slight tilt in the reflectance spectrum is most likely due to wobble in the plane of rotation of the substrate, which on this scale need only be ~ 0.2 mm.

Figure 5. 3-D surface plot of the reflectance at 1064 nm of a 2-layer AR coating (tantalum/silica) designed for zero reflectance at this wavelength. The reflectance is less than 6 ppm (0.0006%) over 270 mm diameter.
3.2 4-layer antireflection coatings

Four-layer AR coatings designed for zero reflectance at both 532 nm and 1064 nm were also deposited on 300 mm diameter fused silica disks. Figure 6 shows the 3-D surface plot of reflectance over a 270 mm diameter obtained at both 532 nm and 1064 nm in the laser reflectometer. The layer thickness error allowed on this more complex design is more severe than for the 2-layer, single wavelength design and hence the minimum reflectance obtained at both wavelengths was limited by monitoring errors to ~ 100 ppm. Nevertheless, the variation in the reflectance at both wavelengths is less than ± 20 ppm over the 270 mm diameter and analysis of this performance suggests a uniformity of all four layers better than ± 0.15% and allowing for ± 0.1% variation in the refractive index of all layers.

![Figure 6](image-url)
4. CONCLUSIONS AND FUTURE DEVELOPMENTS

A modified planetary stage has been fitted to a commercial ion beam sputter coater to achieve high uniformity on large substrates. Using a process whereby the coating of an individual layer takes place by sequential deposition on a rotating substrate at two fixed positions in the sputter plume, where the thickness profiles are largely complementary, uniformities at the ± 0.1% level can be achieved on 270 mm diameter substrates. At present, the uniform diameter is limited by measurement capability and greater uniform diameters can possibly be achieved. The process has been applied to single wavelength (2-layer) and dual wavelength (4-layer) AR coatings on 300 mm diameter silica substrates. Reflectances below 0.001% at a single wavelength and below 0.01% for dual wavelengths has been demonstrated over a diameter of 270 mm. The absolute reflectance is limited by the degree of thickness control afforded by the current optical monitoring setup.

Future developments of the process will include measurements over larger substrate diameters, up to the maximum 400 mm allowed in the current IBS system. Also, the possibility of direct thickness monitoring of the substrates at the two fixed positions will be investigated with a view to removing this source of error and improving the degree of absolute thickness control. Finally, the deposition of more complex multilayer coatings, where limits on uniformity due to the effects of accumulated error in the optical monitoring system, which is a common issue with this type of thickness control, will be investigated.

REFERENCES

[1] TFCalc®, Software Spectra Inc, 14025 N.W. Harvest Lane, Portland, OR 97229-3645, USA.