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Freeform Optics and The Ideal Antireflection Surface

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ABSTRACT

Freeform optical surfaces have recently become practical to produce in quantity. Such surfaces can be viewed as the same coating problem as for the antireflection (AR) coating a hemisphere. The hemisphere has areas that are at all possible angles of incidence (AOI) from 0° to 90° and in all azimuths. A helpful partial solution to the freeform surface AR requirement can be provided by atomic layer deposition (ALD). ALD provides a conformal coating which is the same thickness on all exposed surfaces, independent of the surface orientation. In certain classes of freeform surface AR requirements, this may be all that is needed. If the ALD stack could further have the ideal index of refraction profile versus thickness, this would solve almost all AR problems. However, obtaining very low indices approaching that of the air medium has only recently become within the realm of possibility.

INTRODUCTION

Prior to the turn of the century, Willey[1] showed empirically that the ideal AR coating had a Gaussian index of refraction profile from the substrate index to that of the medium in which the substrate is immersed. Such a profile is illustrated in Fig. 1, where the index ranges from index 1.52 at the substrate (crown glass) to near 1.00 at the medium of air or vacuum. The application of this principle is discussed below with respect to "Moth Eye" type AR coatings and also with respect to ALD AR coatings for freeform optical surfaces.

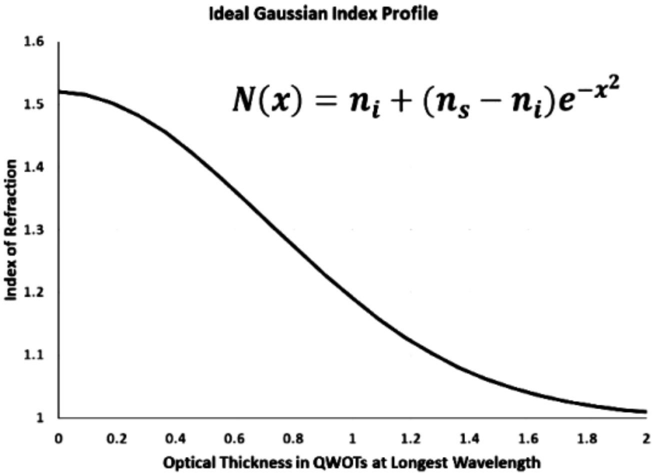

Figure 1. Index refraction profile versus optical thickness for an ideal antireflection coating on a substrate of index 1.52.

GRADED INDEX MATERIALS

The principle shown in Fig. 1 could be approximated by a stack of thin homogeneous layers whose indices decreased from the substrate to the medium (air) in a step-down fashion to present an index profile as close as practical to that of Fig. 1. It is further possible to create an approximation of each of these thin layers of various indices by three even thinner layers per each previously individual single layer by using only a single high and single low index material in all of the three-layer combinations. This would be called a Herpin[2] or Epstein[3] approximation which would create the whole step-down coating by using only the two high and low index materials in a combination of relatively thin layers with a variety of thicknesses. (The details of these Herpin or Epstein approximations are beyond the scope of this discussion.) Figure 2 shows such an index profile and Fig. 3 shows the very broad spectral curve (from 2 to 20 microns) resulting from this profile.

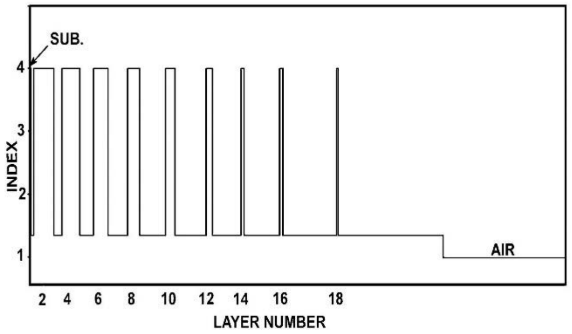

Figure 2. Herpin equivalent index profile approximation of the profile in Fig. 1

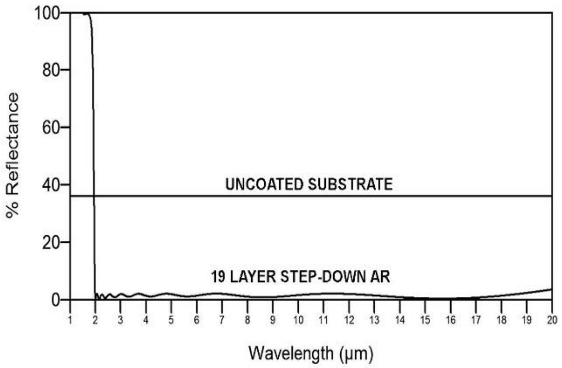

Figure 3. Spectral reflectance resulting from the index profile in Fig. 2.

Yet another approach to realizing the principles of Fig. 1 is what the industry calls a “Moth Eye” surface treatment. This can be accomplished by etching away a layer of the substrate surface in such a way as to create cones, pyramids, or more random shapes which taper from the substrate to the medium in the required manner. The ability to lithographically etch many materials on a “nano-scale” has advanced rapidly in the last 20 years. The effective index in any thin section of such coating parallel to the surface of the substrate would be the average of the area of the voids (of index 1.0) between the cones, pyramids, etc., and the area (of index n) of that section of the substrate within those shapes. If that effective index has the same profile as Figure 1, as long as its details are sufficiently smaller than the wavelengths of interest to the AR coating, it will create the same AR effects. Figure 4 illustrates on a microscopic scale the ideal profile of such an etched surface. In this figure, pyramids are illustrated whose side view, as shown in this figure, is the square root of the curve in Figure 1 so that the area of the pyramid at any section plus its surrounding air/vacuum would have the needed effective index of refraction for that section as a function of height.

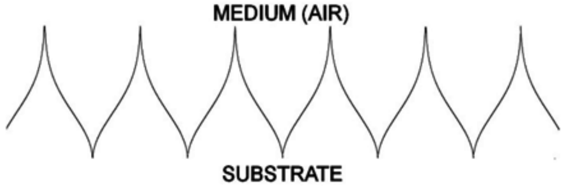

Figure 4. Microscopic section of a “Moth Eye” etched structure to produce a perfect AR surface/coating.

The recent decades have seen widespread use of consumer electronics with cameras having polymer or plastic optics. AR coatings for plastic optics are limited to processes that will not exceed temperatures which will harm the polymer optics, such as 100°C. If the classical single layer AR of one QWOT of MgF_2 is applied to polymer surfaces at these low temperatures, it will not be dense and will not be likely to have good adhesion to the polymer. Such coatings could possibly still be used on interior lens surfaces if they are not exposed or handled by the end-user. MgF_2 coatings have historically obtained higher density and good adhesion by being deposited at 250-300°C, where the depositing atoms do not quickly lose their energy before being able to move into more consolidated (low energy) positions among the already deposited atoms. Willey and Shakoury[4] overcame this temperature limitation by supplying the needed energy during deposition at room temperature by ion assisted deposition (IAD) with nitrogen atoms. These coatings were deposited without added process heat and had full density and hardness for potential use on exterior optical surfaces.

The micro-etching approach for plastic or polymer optics has been extensively investigated with success by Schulz, et al.[5,6] and others.

AR COATING OF FREEFORM SURFACES

The technical problem for a freeform optical surface can be simply viewed as the same problem as that of an AR coating for a hemisphere. The hemisphere has areas that are at every possible angle of incidence (AOI) from 0° to 90° and in all azimuths. The further question is then: “at what range of AOI for incoming rays is the AR needed to perform in that particular area of the freeform surface?” In the simple case of a collimated beam of light incident on the optical axis of the hemisphere, in any given segment, it will have a single unique AOI between 0° and 90°. If the hemisphere is illuminated at some arbitrary AOI with a beam of significant divergence, each area will have a variety of AOIs. This is the same situation as with some general freeform optical surface.

Any smooth surface will reflect increasingly more light with increasing AOI (as illustrated in Fig. 5) for a glass or plastic surface of index 1.52. The p-polarization of the incident light will reflect less light up to the Brewster Angle (57° in this case) where it reflects zero, and it then increases to 100% at 90°. The s-polarization increases continually with AOI until it is 100% at 90°. This illustrates the challenge of an AR for a hemisphere or general freeform surface at large angles. From a practical point of view, it might be wise to only consider attempting ARs for AOI of less than 60° or 70°.

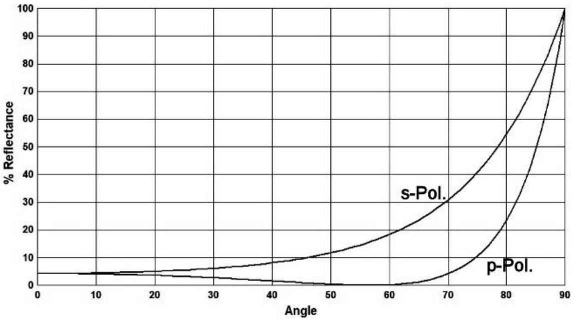

Figure 5. Reflectance versus AOI of a 1.52 index surface as a function of angle.

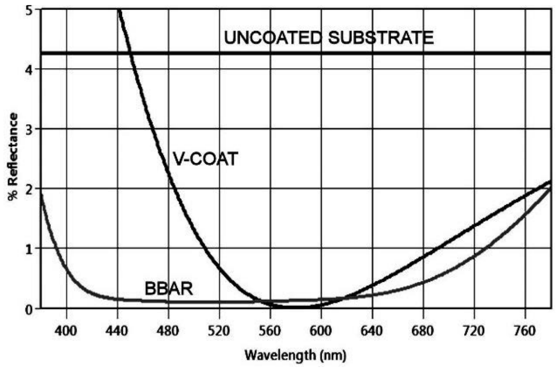

Figure 6. Reflectance of a broad band AR coating compared to an uncoated substrate and a V-Coat.

Another well-known factor is that the effects of an interference coating such as an AR will shift to shorter wavelengths with increasing AOI. Figure 7 shows the common 4-layer broad band AR (BBAR) coating at 0° and 60° of Fig. 6, which has been optimized for the visible spectrum (380-780 nm), at 0° AOI. A means to overcome these limitations due to AOI effects is to have a very BBAR coating so that the long wavelength increase in %R does not move so far to the left (shorter wavelengths) as to cause any problems.

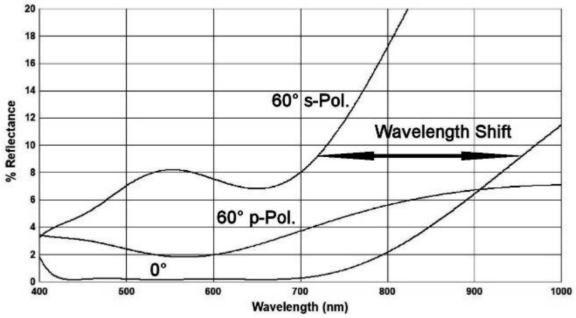

Figure 7. Common BBAR for visible spectrum from Fig. 6 at 0° and 60° AOI. This shows the angle effects on wavelength and reflectance.

OBTAINING VERY LOW INDEX LAYERS

Willey[1] showed that lowest limit for the average reflectance (%R_{ave}) over a very broadband AR coating was determined by the index of refraction of the last layer approximating the concept of Figure 1. The overall effect of such an AR coating is to reduce the residual reflection of the substrate to make it appear nearly as though the substrate were composed of the index of that last layer. Therefore, in the case of the lowest reported nano-porous (NP) SiO_2 (1.132), the %R_{ave} over a very broad bandwidth could be as low as 0.383%. The principal drawback of these NP SiO_2 layers is that they cannot be touched by anything, or they will be crushed into ineffectiveness. This, however, could be acceptable for lens and window surfaces internal to an optical system.

Figure 8 illustrates the performance which can be achieved with a coating having the ideal index profile of Fig. 1.

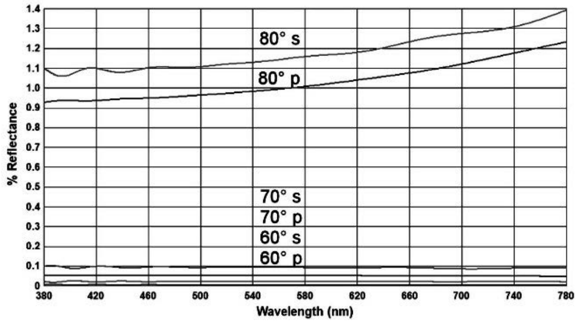

Figure 8. Ideal AR coating at 0°, 60°, 70°, and 80°. Note: %R scale of this figure is maximum at 1.4%R.

ALD processes have matured extensively since the turn of the century. Figure 9 represents a typical process for producing Al_2O_3 by ALD. A precursor gas is flowed over all the exposed surfaces of a substrate, but only a monolayer attaches confor-

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mally to that surface. The precursor which has not attached to the surface is purged away, and a second gas is flowed over the surface. This second gas reacts with the molecules of the first gas to produce one atomic layer of Al_2O_3. This process is repeated as many times as necessary to obtain the required thickness.

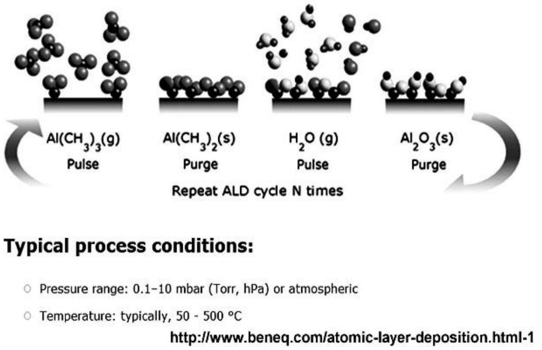

Figure 9. ALD process to produce a single conformal atomic layer of Al_2O_3.

The ideal/perfect AR concept discussed above, when combined with the recent achievements of ALD, will allow us to do what is needed for an AR coating on freeform surfaces. This is demonstrated in Figure 8. This shows a case of an AR coating with less than 0.1% reflectance over the whole visible spectrum for all AOI up to 60°. Note that the %R scale of Fig. 8 goes from 0 to only 1.4% reflectance. This is the ultimate coating concept for freeform optics. A helpful partial solution to the freeform surface AR need can be provided by ALD. As mentioned above, ALD provides a conformal coating which is the same thickness on all exposed surfaces independent of the surface orientation. In certain classes of freeform surface AR requirements, this may be all that is needed. If the ALD stack could further have the ideal index profile, then this would solve almost all AR problems. However, obtaining very low indices approaching that of the air medium has not been possible until recent years.

Ghazaryan, et al.[7] have reported the practical deposition of NP SiO_2 by ALD of alternating SiO_2 and Al_2O_3 and then chemical etching away the Al_2O_3 to leave the NP SiO_2 structure. The effective index was controlled between 1.132 and 1.400. Figure 10 is from their paper showing the effective refractive indices which they achieved. Figure 11 is the result of applying the Herpin principal as in Figs. 2 and 3 using this 1.132 for the low and 1.65 (like Al_2O_3) for the high index material. This can be seen as quite an improvement when compared on the same scale to Fig. 7.

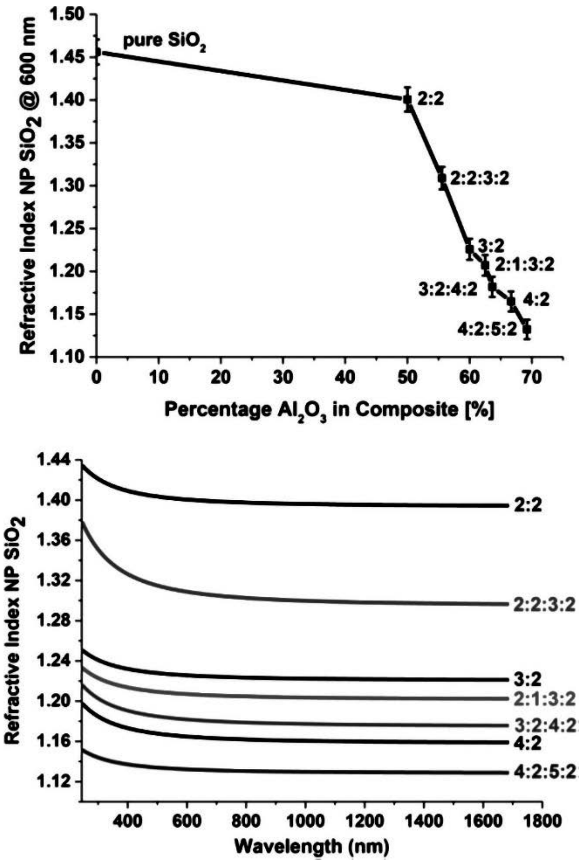

Figure 10. Refractive indices of NP SiO_2 obtained by Ghazaryan, et al.[7] down to ~1.132.

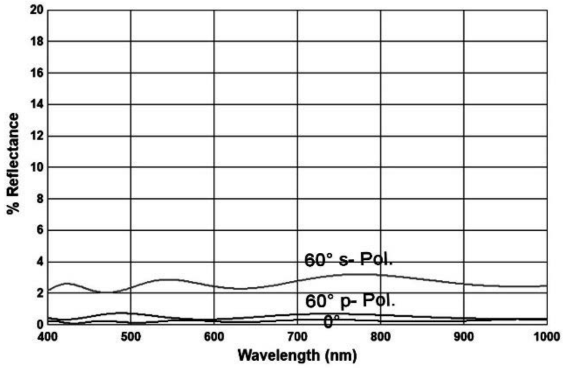

Figure 11. Results of applying the 1.132 for the low index to a Herpin approximation of the ideal index profile of Fig. 1.

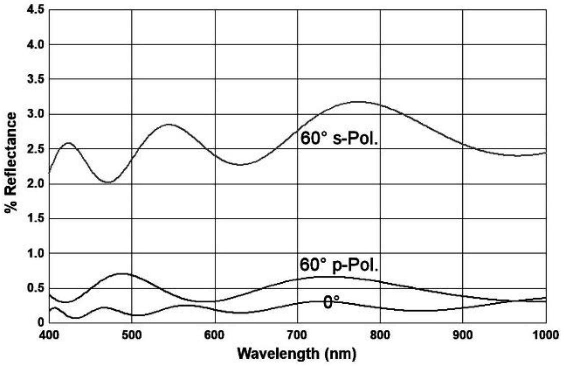

Figure 12. Results of applying the 1.132 for the low index to a Herpin approximation of the ideal index profile of Fig. 1 as seen in Fig. 11.

CONCLUSIONS

The technology now exists to closely approximate the ideal very broadband AR coating on any regular or freeform optical surface which is otherwise protected from abrading forces.

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