PROCEEDINGS OF THE INTERNATIONAL CONFERENCE
NANOMATERIALS: APPLICATIONS AND PROPERTIES
Vol. 2 No 2, 02FNC23(4pp) (2013)

Specificity of Antireflective Coatings at Oblique Incidence of Light

A.P. Ovcharenko[1*], V.I. Bilozertseva[2], D.A. Gaman[2]

[1] V.N. Karazin Kharkov National University, Svobody Sq. 4, 61022, Kharkiv. Ukraine
[2] National Technical University "KPI", 21 Frunze str., 61002 Kharkov, Ukraine

(Received 15 June 2013; published online 03 September 2013)

The optical characteristics of a single-layer and double-layer antireflection coating for different substrates are considered. Methods of simultaneous blooming of *s* - and *p* - polarization component of light are shown. The refractive index and thickness of the layers necessary for blooming the substrates with a given refractive index at an arbitrary angle of light incidence are determined. The urgency of the task of creating new optical materials with low refractive index is shown.

Keywords: Antireflection Coatings, Nanorod Layer, Refractive Index, Polarization Component

PACS numbers: 42.25.Hz, 42.79.Ci, 42.79.Wc

1. INTRODUCTION

Reducing optical reflection from surfaces is important to many applications in optics. Numerous applications involving dielectric or semiconducting materials use the light that is transmitted through the material's surface. Examples of such application are optical lenses, windows, photovoltaic devices, and photodetectors.

This stimulates the emergence of a large number of theoretical and experimental works in this area. Research on the anti-reflective coatings is extensive, but little attention is paid to coatings for an arbitrary angle of incidence of light on the system. A very important issue is the possibility of simultaneous blooming of *s* - and *p* - polarized light components.

2. ACTUALITY OF OPTICAL COATINGS

Majority of optical systems contains more than one light transmitting element. Let us consider the dependence of the optical transmission on the number of interfaces in the system (Fig. 1)

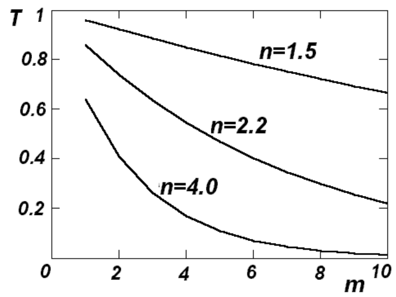


Fig. 1 – The dependence of the optical transmission T on the number of surfaces for plane-parallel plates with refractive indices equal 1.5, 2.2, 4.0

For example, the system of 5 glass plates with $n = 1.5$ transmits a little over 60% of the incident light. The situation is much worse for the material like germanium with $n = 4$. In this case the system with two elements transmits less than 17%, and for a four element system the transmission is less than 3%.

Figure 2 shows the transmittance of the plane-parallel plate versus light incidence angle.

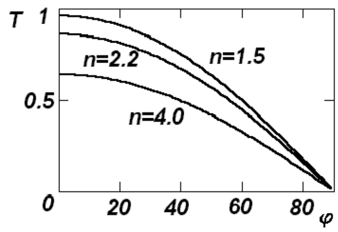


Fig. 2 – The dependence of optical transmission on the angle of incidence of light on the plate with different refractive indices.

It can be seen that with increasing light incidence angle transmittance decreases. The situation is getting worse by increasing the refractive index of the plate.

3. SINGLE-LAYER ANTIREFLECTION COATING

The simplest antireflection solution is a one-layer coating (Fig. 3).

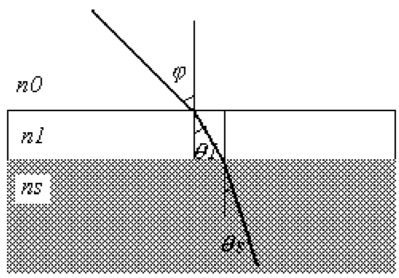


Fig. 3 – The scheme of a single-layer antireflection coating.

If the optical thickness of the film is $\lambda/4$, the expression for the reflection coefficient takes form

* apovcharenko@karazin.ua

$$R_{\lambda/4} = \left(\frac{n_1^2 - n_0 n_s}{n_1^2 + n_0 n_s} \right)^2 \qquad (1)$$

$R_{\lambda/4} = 0$ if the condition

$$n_1^2 = n_0 n_s \qquad (2)$$

If (2) is not satisfied, then (1) gives the value at the extremum. This extremum is a minimum or maximum, depending on whether more or less n_1 than n_s.

If $n_1^2 \neq n_0 n_2$, i.e. if $R \neq 0$, for all values of n_0 and n_1, there are two values of the refractive index of layer n_1'and n_1'', giving the same coefficients of reflection in an extreme point, see fig. 4.

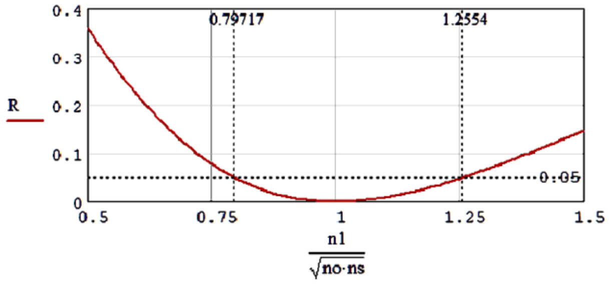


Fig. 4 – The values of reflection in extreme for $n_1^2 \neq n_0 n_2$.

These values are linked by condition $n_1' n_1'' = n_0 n_2$, so that $n_1' \leq \sqrt{n_0 n_2}$ and $n_1'' \geq \sqrt{n_0 n_2}$.

Coatings with such refractive indices give identical spectra of the reflection and transmission coefficients, as well as a phase shift occurring in the transmitted wave. The layers with refractive indices n_1'and n_1'' differ only in the phase shift arising in the wave reflection from the coating.

To obtain zero reflection in a quarter-wave film at given wavelength and angle of incidence θ_0 it is necessary to satisfy the condition (2) but if $\theta_0 \neq 0$ these formulas must be expressed in terms of the effective refractive indices u_j separately for s - and p-polarization components of the incident light.

Refraction angles θ_j in all mediums are linked among themselves and with angle of incidence by the Snell's law: $n_j \cdot \sin(\theta_j) = \text{const}$

$$u_j = \begin{cases} n_j c_j, & s - \text{component} \\ n_j / c_j, & p - \text{component} \end{cases} \qquad (3)$$

$$c_j = \cos(\theta_j).$$

Then we obtain:

$$u_1 = \sqrt{u_0 \cdot u_s} = \sqrt{n_0 \cdot \cos\theta_0 \cdot n_s \cdot \cos\theta_s} = n_1 \cdot \cos\theta_1 \qquad (4)$$

for s – component, and

$$u_1 = \sqrt{u_0 \cdot u_s} = \sqrt{\frac{n_0}{\cos\theta_0} \cdot \frac{n_s}{\cos\theta_s}} = \frac{n_1}{\cos\theta_1} \qquad (5)$$

for p – component.

As it is seen from (3) and (4) there are the mutually exclusive requirements for determining the refractive index for different polarization components

4. TWO-LAYER ANTIREFLECTION COATING

Much better results can be achieved using two-layer antireflection coating (fig. 5).

There are two types of two-layer antireflection coatings with equal optical thicknesses. For one of them

$$n_1^2 n_s = n_2^2 n_0 , \qquad (6)$$

This solution describes an important type of two-layer zero reflection coating, with the optical thickness of each layer equal to odd number of $\lambda_0/4$. For ease of calculation of spectral curves the relative unit ν is used; $\nu = \lambda_0/\lambda$, λ - the current wavelength. Fig.6 shows calculated optical reflection for different angles of light incidence.

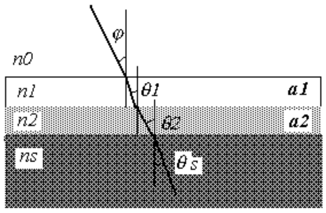
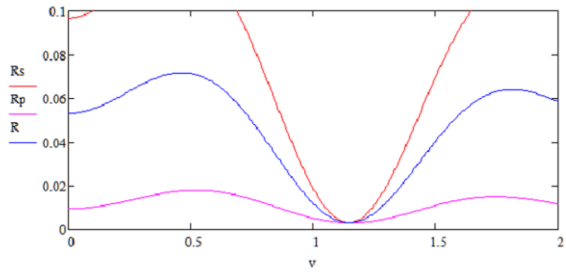
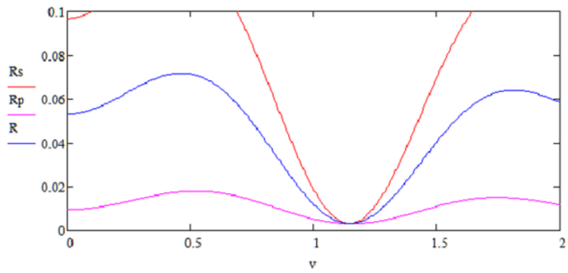


Fig. 5 – Scheme of a two-layer antireflection system



a



b

Fig. 6 – Calculated optical reflection for two-layer antireflection coating. Angles of light incidence equals 0° (a) and 45° (b). n_1=1.38, n_2=1.701, n_s=1.52

For another of them for

$$n_1 n_2 = n_0 n_s , \qquad (7)$$

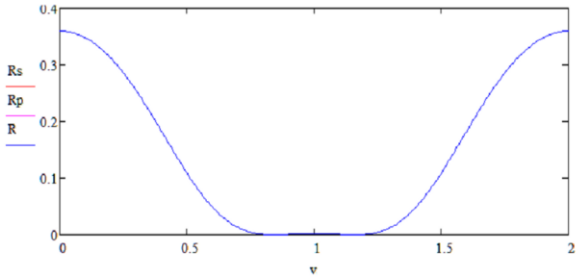
there are two zero minimum of reflection, the position of which is defined by condition

$$\text{tg}^2\,\beta = \frac{n_1^2 n_2 - n_0^2 n_1}{n_1^3 - n_0^2 n_2} , \qquad (8)$$

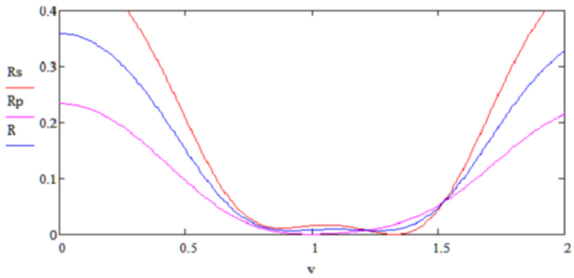
where $\beta_j = 0{,}5\pi\nu a_j c_j$ – phase thickness of the layer,

$a_j = 4n_jt_j\lambda_0^{-1}$ - optical layer thickness n_jt_j, expressed in terms of quarter of wavelength λ_0. Value a_j=1 corresponds to the quarter-wave layer.

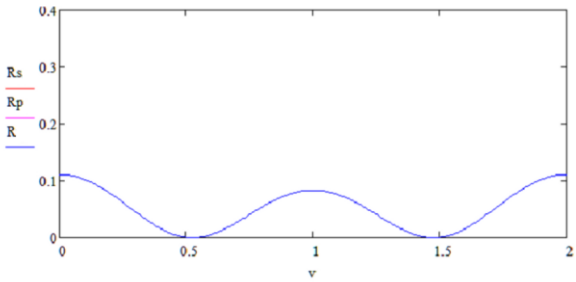
This coating design is applicable only for high refractive index substrates and is not suitable for glasses. On fig. 7 one can see solutions for two substrates: with n_s=4 and n_s=2. Low refractive index of substrate reduces to increasing of reflection between minimums. To solve this problem some refractive indexes of antireflective coating are to be less that any solid have. Such values can be achieved by using nanoporous structures [1,2,3].



a



b



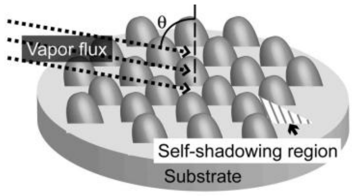
c

Fig. 7 – Calculated two-layer coating reflection for two substrates: with n_s=4 (angles of light incidence equals 0° (a) and 45° (b)) and n_s=2 at normal incidence of light (c)

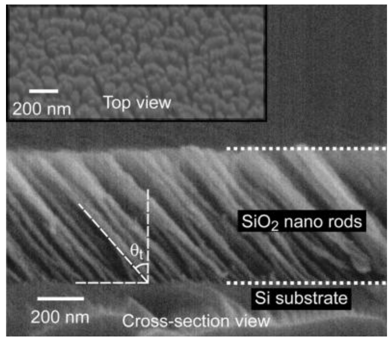
5. LOW REFRACTIVE INDEX LAYERS

Oblique-angle deposition is a technology by which to grow porous, sculptured thin films as a result of the self-shadowing effect during the deposition process. Fig. 8a shows the deposition principle of oblique-angle deposition. A random growth fluctuation in the substrate produces a shadow region that the subsequent incident vapor flux cannot reach. Also produced is a high edge where the incident flux is deposited preferentially, thereby creating an array of oriented rods [3].

Fig. 8b shows a scanning electron micrograph (SEM) of the SiO_2 nanorod layer grown by oblique angle e-beam deposition on a Si substrate [3]. The SiO_2 nanorods are uniformly distributed with a tilt angle of θ_t=45°. The gap between SiO_2 nanorods is less than 30 nm, much smaller than the wavelength of visible light and hence sufficiently small to minimize optical scattering. The refractive index of this nanorod layer within visible spectrum is about 1,087.



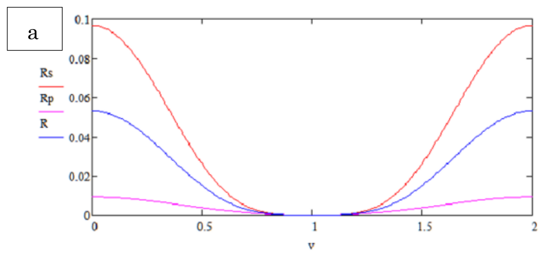
a



b

Fig. 8 – Schematic of oblique-angle deposition (a). Top and cross-sectional views of a SEM for a SiO_2 nanorod layer (b) [3]

So we have calculated two-layer antireflection coating based on porous layers for oblique light incidence for usual glass (n_s=1.52), see fig. 9. By technique of least squares that parameters were matched: the optical thicknesses a_1, a_2, and necessary refractive indexes of corresponding layers n_1 and n_2.



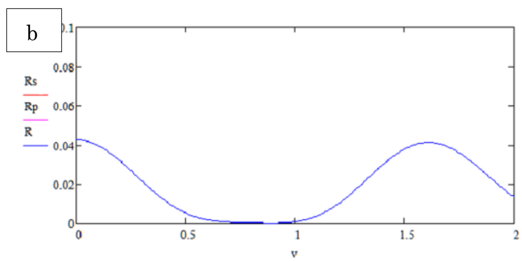


Fig. 9 – Reflection of calculated two-layer nanoporous coating on glass (n_s = 1.52) on different angles of light incidence: 45° (a) and 0° (b). Matched parameters: a_1 = 1.318, a_2 = 1.178, n_1 = 1.086, n_2 = 1.339

For this matched parameters, if optical thicknesses are set equal to 1, plots will look like on fig. 7, but with low reflection.

To illustrate the advantages of nanostructured layers, the Fig. 10 shows the calculated transmission curves of double-layer nanostructured coatings in comparison with the usual four-layer solid one on the wavelength scale. As it is seen, the first one allows get even better results by half number of layers.

6. CONCLUSION

Fabrication of omnidirectional antireflective coatings promotes a development of new nanoporous materials with low refractive index.

The low refractive index thin films are expected to have a wide range of applications and to be well suited for improved multilayer reflectors, optical resonators, and photonic crystals.

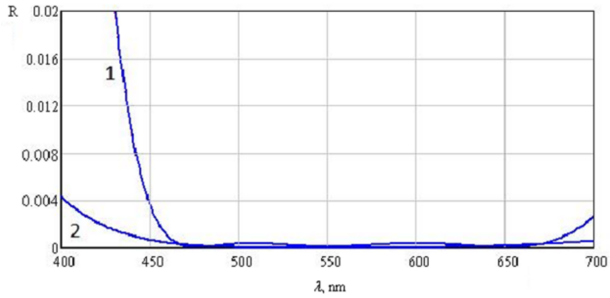


Fig. 10 – The spectral dependencies of the reflectance R for coated glass substrate ($n_s = 1.52$) at normal light incidence. Curve 1 – four-solid-layer antireflective coating with optical thicknesses $\lambda/4 - \lambda/2 - \lambda/4 - \lambda/4$ with corresponding refractive indexes $n_1 = 1.38$, $n_2 = 2.35$, $n_3 = 1.548$, $n_4 = 1.38$. Curve 2 – two layer coating, $n_1 = 1.1$, $n_2 = 1.356$.

REFERENCES

1. Ashok K. Sood, Adam W. Sood, Roger E. Welser, Gopal G. Pethuraja, Yash R. Puri, Xing Yan, David J. Poxson, Jaehee Cho, E. Fred Schubert, Nibir K. Dhar, Dennis L. Polla, Pradeep Haldar, Jennifer L. Harvey, *Materials Sciences and Applications* No3, 633 (2012).
2. E. F. Schubert, J. K. Kim, J.-Q. Xi, *phys. stat. sol. (b)* **244** No8, 3002 (2007).
3. J.-Q. Xi, Jong Kyu Kim, E. F. Schubert, Dexian Ye, T.-M. Lu, and Shawn-Yu Lin, *Opt. Lett.* **31**, No5, 601 (2006).