Effect Optimized Thickness on the Performance of Multilayer Antireflection Coatings for VIS and IR (3-5) µm Bands

Adnan H. Mohammed
Department of Physics, College of Education, Al-Mustansiryah University

Received : 07/04/2011 Accepted : 29/05/2011

ABSTRACT
The work devoted to the design multilayer antireflection coatings for normal incidence in VIS and IR (3-5) µm bands to reduce reflectance from glass, germanium(Ge), silicon(Si) and zinc selenide (ZnSe). The first task was development a software programme to design and simulate the performance of multilayer coatings and secondly, the programme verification to match published researches. After these tasks the designed layers are optimized for their performance by varying their thickness to get performance for three layers is very close to four layers. The analysis has shown that the proposed process was effective in some studied regions.

INTRODUCTION
The antireflection (AR) coating is the most used optical coating in all the optical systems, in order to reduce the losses. Thus, to achieve a high quality (AR) coating is a need in the optical systems in some applications.
antireflection coatings are required for the reduction of surface reflections. In
other not only reflection is reduced but also transmittance is increased
considerably (that means that absorption coefficient k ≈0) [1, 2].
The theory of antireflection coating is examined by many authors [3, 4] for
determining the optimum thickness and materials to be used as ARCs on
polished or textured silicon. The matrix formula [1, 5] is usually employed for
calculation of reflection coefficient. In this paper, we present the result of
calculations obtained by our computer programme of three and four-layers
ARCs on different substrate.

**THEORY**

These basic equations for designing and simulating the performance of
multilayer coatings
are based on boundary conditions for Maxwell’s equations at mth interface and
are given as these equations as .

\[
E_{m-1}^{t} = \frac{1}{2} \left( 1 + \frac{n_m}{n_{m-1}} \right) E_{m}^{t} e^{i\phi_m} + \frac{1}{2} \left( 1 - \frac{n_m}{n_{m-1}} \right) E_{m}^{r} e^{-i\phi_m}
\]  
(1)

\[
E_{m-1}^{r} = \frac{1}{2} \left( 1 + \frac{n_m}{n_{m-1}} \right) E_{m}^{t} e^{i\phi_m} + \frac{1}{2} \left( 1 - \frac{n_m}{n_{m-1}} \right) E_{m}^{r} e^{-i\phi_m}
\]  
(2)

Equations (1& 2) may be formed as Matrix formula, is used to evaluate the
reflectance a multilayer system on glass. Si, Ge and ZnSe substrates. Matrix
formula of N layers interlocked between two semi-infinite mediums is given in
Ref. [5]

\[
\begin{vmatrix}
E_{m-1}^{t} \\
E_{m-1}^{r}
\end{vmatrix} = \frac{1}{2} \begin{vmatrix}
1 + \frac{n_m}{n_{m-1}} & e^{i\phi_m} \\
1 - \frac{n_m}{n_{m-1}} & e^{i\phi_m}
\end{vmatrix} \begin{vmatrix}
1 - \frac{n_m}{n_{m-1}} & e^{-i\phi_m} \\
1 + \frac{n_m}{n_{m-1}} & e^{i\phi_m}
\end{vmatrix} \begin{vmatrix}
E_{m}^{t} \\
E_{m}^{r}
\end{vmatrix}
\]
Where $i^2 = -1$, $n_m$ is the real refractive index of $m^{th}$ layer, $\phi_m$ is the phase thickness of $m^{th}$ layer, $\varphi = 2\pi n_m d_m / \lambda$ with $d_m$ as physical film thickness and $\lambda$ (400-700nm, 3-5µm) in this work.

The system shown in Fig.1 is characterized by matrix formula which relates the amplitudes of electromagnetic field components at ($m$-1) interface with the incident electromagnetic field components at $m$ interface thus, the consideration requires that the last layer (substrate) completely defined, at the last layer then electromagnetic wave travels in infinite thickness medium (that is means $\varphi_m$ equal to zero and there is no reflected wave therefore ($E_{m}^{+r} = 0$, $E_{m}^{-r} = 1$).

$$\begin{vmatrix}
E_{m-1}^{-r} \\
E_{m-1}^{-r}
\end{vmatrix} = \frac{1}{2} \begin{vmatrix}
1 + \frac{n_m}{n_{m-1}} e^{i\varphi_m} & \left(1 - \frac{n_m}{n_{m-1}}\right) e^{-i\varphi_m} \\
1 - \frac{n_m}{n_{m-1}} e^{i\varphi_m} & \left(1 + \frac{n_m}{n_{m-1}}\right) e^{i\varphi_m}
\end{vmatrix} \begin{vmatrix}1 \\
0
\end{vmatrix}$$

the reflectance of each layer is gradually included to reach to the incidence medium (almost air), the reflectance and transmittance are given as

$$R = \left(\frac{E_{0}^{-r}}{E_{0}^{+r}}\right)^2 \quad (3)$$

$$T = \frac{n_{m-1}}{n_0} \left(\frac{E_{m}^{-r}}{E_{0}^{-r}}\right)^2 \quad (4)$$

The reflectance, transmittance and absorptance are then related by $R + T + A = 1$. The solution of this matrix formula is a laborious job for multilayer coatings. Based on the matrix formula, we have developed a software program to design and simulate the performance of multilayer coatings.
Effect Optimized Thickness on the Performance of Multilayer Antireflection Coatings for VIS and IR (3-5) µm Bands

Fig. 1: A multilayer stack scheme of 4-layers on a semi-infinite substrate $n_s$

The $+$, $-$ sign of $E_{m-1}^{-r}$, $E_{m-1}^{+r}$, $E_m^{-r}$ and $E_m^{+r}$ represent what take place upper and lower $m^{th}$ interface (up and down interface are denoted by symbol (-) and (+)) respectively.

**MODELING AND ANALYSIS**

Thin film materials are required to have certain characteristics to become a potential candidate for multilayer structures. This includes high transparency, homogeneity, high packing density, good adhesion, low stress, hardness and ability to survive in different environmental and deposition conditions [1]. These materials are then used to reduce reflection from the surfaces, which are basically caused by the sharp variation of the refractive index at the incident medium-substrate interface. Multilayer coating structures based on those materials have wide band of applications in electronics, optoelectronics, optics and optoelectronics equipments.

**(A) Visible Region:** The reflectance profile of three and four -layer coatings comprising of one layer and two layers are almost more effective [1, 8]. We have modeled such coatings on glass substrate at a design wavelength of 550 nm. The performance of the three layer Air/MgF2/CeO2/SiO/Glass coating is further improved by the addition of forth layer. The reflectance is further reduced by four-layer design comprising
Air/MgF2/ZnS/CeO2/SiO2/Glass), but the important feature of this design is the zero reflectance at two spectral points and the maximum and average reflectance has appreciably reduced to 0.039% and 0.4%, respectively. The combined reflectance plot of the four layers configurations is shown in Fig. 1. This application of multiple encourages the use of multi-layers to achieve wide transmission bands by increasing number of layers. The optimization of thickness of the three layers coatings shown in the figure reduces reflectance in some regions (525-625) nm to reach at 575 nm to 0.097% without optimization of thickness while the reflectance at the same spectral points remains lower.

Table-1: Design data and reflectance values for all configurations on glass

<table>
<thead>
<tr>
<th>No. of layers</th>
<th>Mat.</th>
<th>Refr. index(n)</th>
<th>Thickness (d nm)</th>
<th>Rp%</th>
<th>Rave</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>d1(nm)</td>
<td>d2</td>
<td>d3</td>
</tr>
<tr>
<td>Three layers</td>
<td>MgF2</td>
<td>1.38</td>
<td>99.6</td>
<td>97</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>CeO2</td>
<td>2.2</td>
<td>125</td>
<td>122.5</td>
<td>127.5</td>
</tr>
<tr>
<td></td>
<td>SiO</td>
<td>1.8</td>
<td>78.5</td>
<td>76.9</td>
<td>80</td>
</tr>
<tr>
<td>Four layers</td>
<td>MgF2</td>
<td>1.38</td>
<td>99.6</td>
<td>58.25</td>
<td>62.5</td>
</tr>
<tr>
<td></td>
<td>ZnS</td>
<td>2.36</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CeO2</td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>SiO2</td>
<td>1.8</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* calculated within the band (450-700) nm

Wavelength was 0.167% for four layers design, these results are very clear in the associated figure. However, the magnitude of reduction in reflectance with the optimizing thicknesses of three layers showed in the Figure 1 shift the reflectance curve for d2, d3, and d4 thicknesses towards the left and right respectively with respect (d1) where, d1 represents the thickness without use optimizing thicknesses. The Optimization of thickness of three layers is used for obtaining the performance is close to the four layers, but the effect of this process was very small comparison with four layer coating within the studied bands. This may suggest that the performance requirements are not very stringent. The reduction...
Effect Optimized Thickness on the Performance of Multilayer Antireflection Coatings for VIS and IR (3-5) μm Bands

Adnan

in reflectance with the addition fourth layer was pretty for obtaining ARC within VIS band

Fig. 2: Simulated reflectance for configuration on glass showed in table 1. The associated figure to show the indicated features of main figure.

(B) Infrared region: Ge, Si and ZnSe have been used as substrates material as they are commonly used in 3-5μm band for many optical and electro-optical applications [1]. All these substrates exhibit a very high reflectance value in the
said spectrum. In most of the applications, this high value of reflectance is not acceptable as it reduces the total energy reaching the detector surface with every increasing optical component in the system or device. Therefore, it is necessary to reduce their surface reflectance by applying ARC.s. The materials used as film layers are ZrO2, Si, CdTe, BaF2, Y2O3 and ZnS, MgF2. All these materials are suitable for antireflection films in the desired region of wavelength [1, 8]. The reflectance of bare germanium substrate in 3.5mm is 36%. Multilayer coatings can be used to reduce this value to an appreciably low level [12]. We have modeled such coatings on germanium substrate at a design wavelength of 4mm. The process starts from a three layers model, and a layer are increased to reduce the value of maximum and average reflectance over the desired band. The single and two layers are not effect for obtaining ARC.s. as in three and four layers [1]. Table 2 shows the model data and calculated values of maximum and average reflectance over the entire band for a three layers modal. The data shows that the maximum and average value of reflectance has decreased form 0.57% and 0.4% respectively while of the four layers the values were 2.9% and 0.7% respectively. The maximum and average value of reflectance for three layers were smaller than four layers but the performance for four layers within the range 3.4-4.6µm were 0.5% and 0.15% respectively for the said values. Optimization of thickness for three and four layers shows that the maximum and average value of reflectance were 1.16%, 0.42% and 2.02%, 0.68% respectively. The combined reflectance plot of the two designs is shown in Fig. 2. We note that three layers with optimization of thickness verify the goal of the work.

### Table-2: Design data and reflectance values for all configurations on germanium

<table>
<thead>
<tr>
<th>No. of layers</th>
<th>Material</th>
<th>Refractive index(n)</th>
<th>Thickness (d nm)</th>
<th>Maximum ref. (Rp %)</th>
<th>Ref. average Rave</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>d1 (µm)</td>
<td>d2 (µm)</td>
<td>Rp(d1)%</td>
</tr>
<tr>
<td>Three layers</td>
<td>Si</td>
<td>3.42</td>
<td>0.29</td>
<td>0.44</td>
<td>0.203</td>
</tr>
<tr>
<td></td>
<td>ZnS</td>
<td>2.24</td>
<td>0.72</td>
<td>0.72</td>
<td>0.532</td>
</tr>
<tr>
<td></td>
<td>MgF2</td>
<td>1.38</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Effect Optimized Thickness on the Performance of Multilayer Antireflection Coatings for VIS and IR (3-5) μm Bands

| Four layers | Si   | 3.42 | 0.29 | 2.9  |
|            | CdTe | 2.24 | 0.44 | 2.02 |
|            | ZrO2 | 2.05 | 0.48 | 0.7  |
|            | MgF2 | 1.38 | 0.72 | 0.68 |

Fig.-3: Simulated reflectance for configuration germanium showed in table 2. The associated figure show the indicated feature of main figure

The reflectance from bare silicon substrate surface is 30% [1]. This value is lower as compared to the germanium, as it has got a lower refractive index in
the given spectrum. Similar procedure of layer addition has been employed to model and analyze multilayer structures for reducing reflectance from the substrate. Table 3 shows the model data with maximum and average values of reflectance for two configurations. Fig. 3 shows the combined plots for three and four layer configurations. However, in this case the performance for three layers configurations is even better and the design curve with Optimization of thickness is more flatland comparatively closer to the horizontal axis. Only two materials are used in four layers configuration. This shows that proper optimization not only helps in getting good performances but also tend to reduce unnecessary variety of materials which is very critical in manufacturing process. In the figure 3, shifting to the right side (upper wavelength values) is obtained. The associated of the main figure shows the effect of optimization of thickness of four layers in it notes that the curve was more flat than the other designs, it is closer to the horizontal axis. The maximum and average reflectance do not show in this work, it is clearly the performance ARC.s. was good agreement with the work goal within (4-7.5) µm

**Table-3: Design data and reflectance values for all configurations on silicon**

<table>
<thead>
<tr>
<th>No. of layers</th>
<th>Material</th>
<th>Refractive index(n)</th>
<th>Thickness (d nm)</th>
<th>Maximum refractance (Rp %)</th>
<th>Reflectance average Rave %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>d1 (µm)</td>
<td>d2 (µm)</td>
<td>Rp(d1) %</td>
<td>Rp(d2) %</td>
<td>Rave (d1) %</td>
</tr>
<tr>
<td>Three layers</td>
<td>CdTe</td>
<td>2.64</td>
<td>0.38</td>
<td>0.39</td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td>ZrO2</td>
<td>2.05</td>
<td>0.48</td>
<td>0.49</td>
<td>2.46</td>
</tr>
<tr>
<td></td>
<td>MgF2</td>
<td>1.38</td>
<td>0.72</td>
<td>0.735</td>
<td>1.4</td>
</tr>
<tr>
<td>Four layers</td>
<td>ZnS</td>
<td>2.24</td>
<td>0.41</td>
<td>0.525</td>
<td>1.68</td>
</tr>
<tr>
<td></td>
<td>MgF2</td>
<td>1.38</td>
<td>1.44</td>
<td>1.84</td>
<td>-------</td>
</tr>
<tr>
<td></td>
<td>ZnS</td>
<td>2.24</td>
<td>0.88</td>
<td>1.12</td>
<td>-------</td>
</tr>
<tr>
<td></td>
<td>MgF2</td>
<td>1.38</td>
<td>0.72</td>
<td>0.92</td>
<td>-------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-----</td>
</tr>
</tbody>
</table>
Effect Optimized Thickness on the Performance of Multilayer Antireflection Coatings for VIS and IR (3-5) µm Bands

Adnan

Fig.-4: Simulated reflectance for configurations on silicon showed in table 1. The associated figure shows the indicated features of main figure

Table -4: Design data and reflectance values for all configurations on zinc selenide

<table>
<thead>
<tr>
<th>No. of layers</th>
<th>Material</th>
<th>Refractive index(n)</th>
<th>Thickness (d nm)</th>
<th>Maximum ref. (Rp %)</th>
<th>Ref. average Rave %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>d1 (µm)</td>
<td>d2 (µm)</td>
<td>Rp(d1) %</td>
<td>Rp(d2) %</td>
</tr>
<tr>
<td>Three layers</td>
<td>ZrO₂</td>
<td>2.05</td>
<td>0.48</td>
<td>0.49</td>
<td>1.13</td>
</tr>
<tr>
<td></td>
<td>Y₂O₃</td>
<td>1.73</td>
<td>0.58</td>
<td>0.59</td>
<td>1.29</td>
</tr>
<tr>
<td></td>
<td>BaF₂</td>
<td>1.3</td>
<td>0.77</td>
<td>0.785</td>
<td></td>
</tr>
<tr>
<td>Four layers</td>
<td>ZrO₂</td>
<td>0.48</td>
<td>0.39</td>
<td>0.39</td>
<td>1.73</td>
</tr>
<tr>
<td></td>
<td>Y₂O₃</td>
<td>0.58</td>
<td>0.475</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ZrO₂</td>
<td>0.48</td>
<td>0.59</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MgF₂</td>
<td>0.72</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* calculated within the band (3.4-5) µm
The reflectance of bare ZnSe substrate is 16.81% [1]. Multilayer antireflection coatings are employed on the substrate to drastically lower this value. Table 4 shows the model data and calculated values of maximum and average reflectance for three and four layer structures to reduce the reflectance from the substrate. Figure 4 shows the combined plots of the configurations. The sharp fall in the reflectance values at the lower side is observed. The showed values of maximum and average value of reflectance for three layers were smaller than four layers within the band (3.4-5) μm. thus, three layers ARC.s. with optimization of thickness may be verified the goal of this work and the performance may be developed by increasing run of design programme.

Multilayer antireflection coatings for normal incidence in VIS and IR (3.5mm) band have been modeled for three and four layers configuration. The performance of three layers configuration has been optimized for obtaining performance of three layers to be close from the performance for four layers. The analysis of these designs reveal that three layers ARC.s. with optimization
Effect Optimized Thickness on the Performance of Multilayer Antireflection Coatings for VIS and IR (3-5) µm Bands

Adnan

of thickness was effective in some studied bands and the performance may be developed by increasing run of design programme.

REFERENCES


320