Thin film silica nanocomposites for anti-reflection coatings

Nanostructured Metal Oxide Thin Films
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ANTI REFLECTIVE COATINGS
Anti-reflective Coatings – Applications
Specular reflection of light from an surface

Incident beam
Air
Refractive index $n_0$
$n_0 = 1$

Reflected beam

Substrate
Refractive index $n_m$
Glass $n_m = 1.52$

Transmitted beam

Still water is an example of specular reflection

$$R = \left( \frac{n_0 - n_m}{n_0 + n_m} \right)^2$$

$R$ = reflection
$n_0$ = refractive index air
$n_m$ = refractive index of material

For a typical glass or polymer window 4.5-5% of incident light is lost at normal incidence.
Specular reflection – effect of incident angle

Fresnel Equations - Describes the behaviour of light when moving between media of different refractive indices

\[ R_p = \frac{\tan^2(\theta - \varphi)}{\tan^2(\theta + \varphi)} \]
\[ R_s = \frac{\sin^2(\theta - \varphi)}{\sin^2(\theta + \varphi)} \]

Snell’s Law – Law of refraction

\[ n_0 \sin \theta = n_m \sin \varphi \]
Reflection of light from a thin film coated surface

When $p_a$ and $p_b$ are $\pi$ out of phase and have equal amplitude, the magnitude of the reflected wave is zero.

For zero reflectance, constructive interference amplify wave and destructive interference wave cancelled.

For zero reflectance

$\text{Incident beam}$

$\theta$

$\text{Reflected beam}$

$n_0$

$n_1$

$h$

$n_m$

$\text{Transmitted beam}$

$\text{Out of phase}$

$\text{Destructive interference}$

$\text{In Phase}$

$\text{Amplify wave}$

$\text{Wave cancelled}$
Reflection of light from a thin film coated surface

At normal incidence

\[ R = \frac{n_1^2 \left( \frac{h_0 - n_m}{n_0 + n_m} \right)^2 \cos^2 k_0 h + (n_0 n_m - n_1^2)^2 \sin^2 k_0 h}{n_1^2 \left( n_0 + n_m \right)^2 \cos^2 k_0 h + (n_0 n_m + n_1^2)^2 \sin^2 k_0 h} \]

Reflection of substrate determined by the RI of the substrate and air

Both equations are trying to achieve 0% reflection

when \( k_0 h = \frac{\pi}{2} \) or \( d = \frac{\lambda_f}{4} = \frac{\lambda_0}{4n_1} \)

Then

\[ R = \left( \frac{n_0 n_m - n_1^2}{n_0 n_m + n_1^2} \right)^2 \]

Therefore, if \( n_1 = \sqrt{n_0 n_m} \) \( R = 0\% \)
Reflection of light from a thin film coated surface

To satisfy the conditions required for a coating that provides a reflection of 0% an example:

Refractive index Air \( n_0 = 1 \)

Refractive index Material \( n_m = 1.52 \) for glass

Refractive Index of coating \( n_1 = 1.23 \)

Thickness of coating \( d_1 = 112\text{nm} \)

Wavelength \( \lambda = 550\text{nm} \)

\[
\begin{align*}
n_1 &= \sqrt{n_0 n_m} \\
\therefore n_1 &= \sqrt{1 \times 1.52} \quad = 1.23
\end{align*}
\]

\[
\begin{align*}
d &= \frac{\lambda_0}{4n_1} \\
\therefore d &= \frac{550\text{nm}}{4(1.23)} \quad = 112\text{nm}
\end{align*}
\]

RefRACTive index of coating \( (n_1) \) is equal to the square root of refractive index of the substrate \( (n_m) \)

\[
R = 0\%
\]
Single layer anti-reflection coatings – continuous layer coatings

Substrate:
- Glass \( n_m = 1.52 \)
- Quartz \( n_m = 1.55 \)
- Polycarbonate \( n_m = 1.58 \)
- CR39 \( n_m = 1.48 \)

Coating: Fluorides lowest naturally occurring RI
- \( \text{CaF}_2 \) \( n_m = 1.43 \)
- \( \text{MgF}_2 \) \( n_m = 1.38 \)

Not low enough RI to satisfy equations and achieve 0% reflection in a single coat
Also water soluble

Ophthalmic substrates are already low refractive index.
Limited number of potential coatings available.
Could go multi layer?

5 layer zirconium fluoride based system.

Deposited by PVD.

Optics good.

Expensive.
**VISARC™ Technology – Single layer nanoparticle coatings**

Particles dispersed in binder

From equations know an RI of 1.23 is needed for R=0%

1.16 is too low \( \therefore \) more binder can be added to bring RI up and increase mechanical strength

**Silicate binder with varying particle loadings**

ARC’s Coating Structure

There is also a binder compound between the particles which is tailored to match the coating and substrate.

The binder and particle combination matches the refractive indices.

The formulation controls the thickness.

Spin or dip coating – one pass.

Single layer nanoparticles anti-reflection coatings

Blank Glass slide

Divergence between experiment and theory – broad band coating

Experimental data

Very low reflection!

Single layer coating on glass

Thickness=112nm
Refractive index (film) = 1.27
Refractive index (glass) = 1.52
Formed with 20-25nm porous particles

Divergence we think is due to particles scattering effects lowering reflection in the blue-green

\[ R = \frac{n_i^2 (n_0 - n_m)^2 \cos^2 k_0 h + (n_0 n_m - n_i^2)^2 \sin^2 k_0 h}{n_i^2 (n_0 + n_m)^2 \cos^2 k_0 h + (n_0 n_m + n_i^2)^2 \sin^2 k_0 h} \]
MECHANICS
Mechanical strength

• Coating industry has optimum conditions for a coating to be mechanically strong

• ASTM methods for testing

  - Steel wool - Type 0000 Steel Wool 1kg loading, 10 passes
  - Pencil hardness- Pencil lead of different hardness passed over the coating until it fails. Then assign the lead hardness ie. 4H
  - Sand abrasion – Falling sand at a predetermined height onto the coated substrate
  - Bayer – Oscillating sand over the sample
**ASTM and nanoscratch testing**

- ASTM standard tests –
  - Do not give much information on underlying structure
  - Not all quantitative
- OAS are working on correlating ASTM tests with nanoindentation

![Steel wool scratches on coated polycarbonate](image1.png)

![Nanoscratch test on PVD coated lens](image2.png)
**Nanoindentation – Scratch testing**

**Nanoindentation** – A finely controlled increasing load is applied to a given substrate and the response is measured.
Nanoscratch – Film flexing effect on polymer window

Film Failure at scratch distance of 176μm and depth of 4-5.5μm

Failure depth over 20X film thickness

2nd Topography (after scratch test)

1st Topography (before Scratch)
Brittle failure at low loads

Compression but no failure
Mechanical properties of thin films – Nanoparticle thin films

Some compression of nanoparticle film – but no brittle failure

Nanoparticle film will flex with the substrate until the underlying substrate fails.

A 120nm thick film can be flexed to >4 microns with slight plastic deformation
Nanoparticle film flexibility allows the coating to withstand steel wool abrasion testing to ASTM standards.

Diamond tip impact crater – coating on polycarbonate lens.

Coating after steel wool abrasion

No film cracking observed with diamond tip impact crater.
Film will withstand sand drop impact testing.
Conclusions

• Nanoparticle based coatings allow wet chemical single layers to be deposited as replacements for multilayer PVD anti-reflection coatings for ophthalmic applications.

• The optical transmission is improved by the use of nanoparticles due to scattering effects – the transmission in the blue-green is significantly improved.

• The structure allows a fairly close match to the mechanical properties of the substrate and a much thinner layer. The layer will flex with the substrate and not undergo brittle failure.
Thanks for listening!

Any questions?

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