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Modified thickness distribution model for large-diameter optical coatings

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A B S T R A C T

Based on the analysis on molecules collisions model and film packing density, a modified thickness distribution model for large-diameter optical coatings has been proposed from consideration of optical thickness. The experimental result is given to support a good agreement with theoretical model.

Optical coating process, as one of the most critical modern optical technologies, is widely used in various fields, such as imaging industry, astrophysics research, optical communications, laser technology. Many factors affect the coating's performance as well as its optical constants, and the film thickness plays a key role among them [1].

The conventional thickness distribution model is established by the following assumptions [2]:

1. No collisions occur between the vapor and residual gas molecules during the deposition process.
2. All molecules arrived at the surface of substrate and deposited as the same density as bulk materials.
3. The arrival mass at the substrate follows Knudsen's theory, and does not change with time.

In this traditional model, the collisions are always ignored. However, considering the geometry size and collocations in large caliber coating machine, the long transmission distance of vapor molecules leads to the increased contribution of the collisions. Additionally, the vapor flux arriving at the substrate with a greater angle can induce the lower packing density [3–6]. Taking into account these factors above, a proper modification of the conventional model is proposed to analyze the thickness uniformity for large-diameter optical coatings in this paper.

According to the conventional model, the relationship between evaporation source and deposition area is demonstrated as Fig. 1.

The thickness of a growing film at certain position on a substrate surface can be determined by the following equation [7]:

$$t = C \times \frac{\cos^n \phi \, \cos \theta}{r^2} \tag{1}$$

Considering the variation of film packing density $p_f(\theta)$ at oblique incidence $(\theta \neq 0)$, the thickness of a specified location can be expressed as follows:

$$t = C \times \frac{\cos^n \phi \, \cos \theta}{r^2} \times \frac{1}{p_f(\theta)} \tag{2}$$

In the case of oblique incidence, it follows from the geometry considerations that the packing density of location with θ incident angle comparing with 0 point [8], then we obtain:

$$\frac{p_f(\theta)}{p_f(0)} = \frac{2 \cos \theta}{\cos \phi [1 + \cos(\theta - \phi)]} \tag{3}$$

For large caliber coating machine, the collisions can be calculated from the perspective of mean free path. K. S. Fancy have deduced a model for physical vapor deposition process considering the collisions between evaporating particles in the vacuum condition [9,10]. We refer the idea and propose the modified thickness distribution model, thus taking into account the collisions, the calculated equation of thickness can be modified to be:

$$t = C \times \frac{\cos^n \phi \, \cos \theta}{r^2} \times \frac{1}{p_f(\theta)} e^{-r/\overline{\lambda}} + \sum_i C \times \frac{\cos^n \phi_i \, \cos \theta_i}{{r_i}^2} \left(1 - e^{-r_i/\overline{\lambda_i}}\right) \frac{f(\phi_i', \theta_i')}{p_f(\theta_i')} \tag{4}$$

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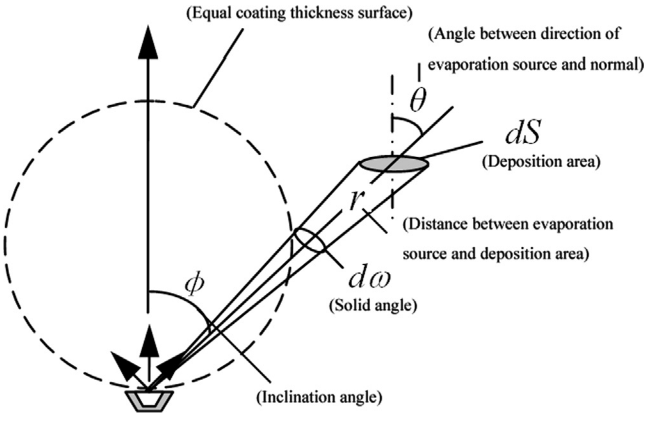

Fig. 1. Small plane evaporation source.

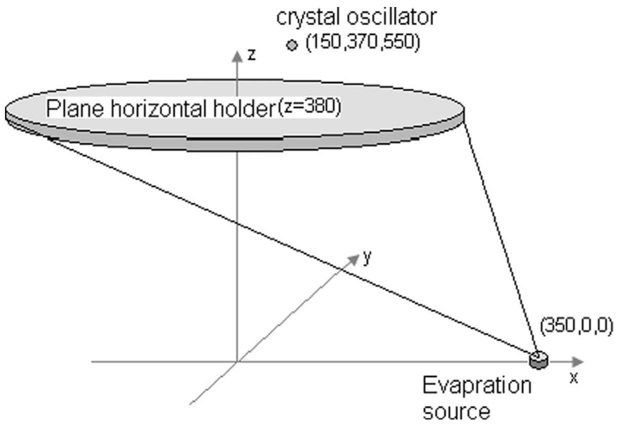

Fig. 2. Structure of vacuum chamber.

here the first part of Eq. (4) represents the molecules arrived at the substrate without collisions. The sum is to consider the contribution of all collisions over the vacuum space. Here function $f(\phi',\theta')$ describes the distribution of reflected molecules in the collision.

So far, all the calculated thickness was physical thickness. In this study film uniformity is defined as the ratio of optical thickness with respect to the diameter and at the center of desired area. In Eq. (5), ot defines as the optical thickness, n_s and n_v are the refractive index of the deposited coating without and with voids, respectively.

$$\frac{ot}{ot_0}=\frac{n\times t}{n_0\times t_0}=\frac{p_f\times n_s+(1-p_f)\times n_v}{p_{f0}\times n_s+(1-p_{f0})\times n_v}\times\frac{t}{t_0} \tag{5}$$

Experiments were carried out using SiO_2 as the deposition material. The coating system is equipped with an e-gun evaporation source, and IC-5 crystal oscillator, shown in Fig. 2. The thickness and refractive index values were obtained by using the extreme point of transmittance spectrum measured by Lambda 900 UV/VIS/NIR spectrophotometer.

According to the early experimental results, the SiO_2 emission pattern of evaporation source is $\cos^{1.5}$.

Keeping the holder stationary, the packing density and optical thickness distribution along x-axis was obtained at a low pressure of 1.8×10^{-3} Pa in Fig. 3.

`The inclination angle Φ of needle-like structure is given by tangent relationship: $\Phi=\arctan(0.5\cdot\tan\theta)$. We assume that the collision molecules have the same probabilities reflected to all directions.

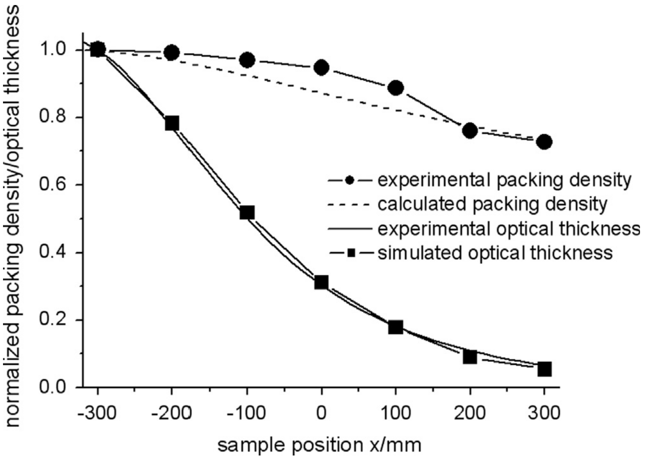

Fig. 3. Packing density and optical thickness distribution at 1.8×10^{-3} Pa.

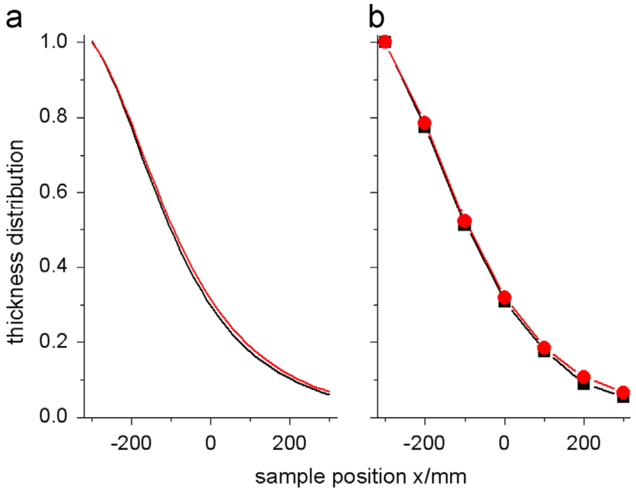

Fig. 4. Comparison of optical thickness distribution curves with physical thickness distribution, black line for optical thickness distribution curves and red for ones of physical thickness. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The comparison with physical thickness distribution is illustrated in Fig. 4, black line for optical thickness distribution curves and red for ones of physical thickness. It has good agreement with experimental data, which indicated the modification effective.

The theoretical thickness distribution of SiO_2 single layer can be determined in a more reasonable way by the modified thickness distribution model.

As we are interested mainly in the uniformity of deposited optical coating, we have proposed that their properties should be characterized by the optical thickness distribution.

In future research we will consider other material and the uniformity of multi-layers optical films over large areas independent of the shape of vacuum chambers or fixtures.

Acknowledgements

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