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THICKNESS DISTRIBUTION MEASUREMENT OF THIN FILMS

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THICKNESS DISTRIBUTION MEASUREMENT OF THIN FILMS

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Gu Peifu[1]

Abstract

Two calculated methods of film thickness of non cosine distribution and two measuring methods based on Fabry-Perot metal dielectric filters were presented. Some calculations and measurements were shown.

Key Words: Thickness distribution, thin films

O. INTRODUCTION

The even distribution of film thickness is very critical for obtaining thin films in many applications. For example, the interference filter used in astronomical observations, to a large extent, depends on the even distribution of film thickness for proper function. In other cases, the unevenness of films is desirable in order to obtain an appropriate thickness range. Therefore, calculating and measuring film thickness distribution is an essential part of thin film technology.

Here, two film thickness calculation methods will be given. In addition, two measuring methods based on Fabry-Perot metal dielectric filters were used to measure samples that have higher thickness evenness and to measure samples that have great fluctuation in their film thickness. In the end, significant measurements will be given.

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* Numbers in margins indicate foreign pagination. Commas in numbers indicate decimals.

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I. CALCULATION OF FILM THICKNESS DISTRIBUTION

Thickness of material which evaporates from evaporating source E and deposits on a spinning substrate S can be calculated as(fig. 1):

$$t = k\int_0^{2\pi} \frac{\cos^P\varphi\cos\theta}{r^2}\,d\phi \qquad (1)$$

In which, k=cm/$2\pi\sigma$, σ and m are the density and mass of the evaporating material respectively, c is a constant, φ, θ , r and ϕ are depicted in fig.1.

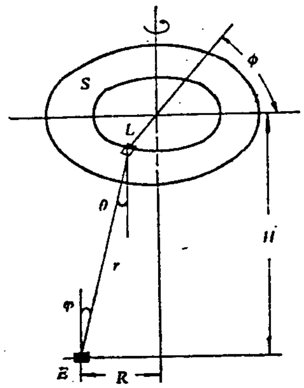

Fig. 1 The geometric position of evaporating source and substrate

Since cos φ =cosθ = H/r,

$$\gamma^2 = H^2 + R^2 + L^2 + 2RL\cos\phi$$

therefore equation(1) becomes

$$t = k\int_0^{2} \frac{H^{P+1}}{[H^2 + R^2 + L^2 + 2RL\cos\phi]^{\frac{p+3}{2}}}\,d\phi$$

Assuming ρ =h/R and a=L/R

$$t = \frac{k}{H^2}\int_0^{\pi} \frac{\rho^{P+3}}{[1 + \rho^2 + a^2 + 2a\cos\phi]^{\frac{p+3}{2}}}\,d\phi$$

The thickness of substrate center (L=0) is

$$t_0 = \frac{k\pi}{H^2}\frac{\rho^{P+3}}{[1+\rho^2]^{\frac{P+3}{2}}}$$

$$T = \frac{t}{t_0} = \frac{(1+\rho^2)^{\frac{p+3}{2}}}{\pi}\int_0^{\pi} \frac{d\phi}{[1+\rho^2+a^2+2a\cos\phi]^{\frac{p+3}{2}}}$$

Here T is film thickness distribution.

If assuming $S = 1 + \frac{a^2}{1+\rho^2}$ and $Q = \frac{2a}{1+\rho^2}$

$$T = \frac{1}{\pi}\int_0^{\pi}\frac{d\phi}{[S+Q\cos\phi]^{\frac{p+3}{2}}} \qquad (2)$$

By substituting different values for P, the film thickness distribution of different evaporation sources can be calculated. P=0 corresponds to a point evaporation source. P=1 corresponds to Knudsen's small surface source which is a cosine distribution. At the location where electron beams evaporate, P is often around 2-4.

Two simple methods are used to calculate thickness distribution T. The first is series expansion, (2) can be expanded as

$$T = \frac{1}{S^{\frac{p+3}{2}}}\left[1 + \frac{(p+3)(p+5)}{2!2^2}\frac{1}{2}\left(\frac{Q}{S}\right)^2 + \frac{(p+3)(p+5)(p+7)(p+9)}{4!2^4}\frac{3}{8}\left(\frac{Q}{S}\right)^4 + \cdots\right]$$

The calculation of the sum of the first 8 items is given in Table 1. It can also be solved as the following. Because when p=1, (2) can be simplified as

$$T = \frac{(H^2+L^2)^2(H^2+L^2+R^2)}{[(H^2+L^2+R^2)^2-4L^2R^2]^{3/2}}$$

As a = L/R increases, the discrepancy of film thickness calculation gets bigger when choosing the series expansion method. Therefore, the second calculation method -- Gauss integration is used instead. It can be simply described as /401

if $$\phi = \frac{(b-a)}{2}t + \frac{(b+a)}{2}$$

then $$\int_b^b f(\phi)d\phi = \left(\frac{b-a}{2}\right)\int_{-1}^{1} f(\phi(t))dt = \left(\frac{b-a}{2}\right)\sum_{i=1}^{n} H_i f(\phi(t_i))$$

Here ϕ (t_i) and corresponding values of H_i can be found in relevant mathematical manuals.

Suppose $\phi(t) = \frac{\pi}{2}(1+t)$ i.e. a=0, b= π

Then

$$\int_a^b f(\phi)d\phi = \frac{\pi}{2}\int_0^{\pi} f(\phi(t))dt = \frac{\pi}{2}\sum_{i=1}^{n} H_i f(\phi(t_i))$$

Therefore equation(2) can be written as

$$T = \frac{1}{2}\int_0^{\pi} \frac{dt}{[S+Q\cos(\phi(t))]^{\frac{p+3}{2}}} = \sum_{i=1}^{n} H_i \frac{1}{2[S+Q\cos(\frac{\pi}{2}(1+t_i))]^{\frac{p+3}{2}}}$$

When n=6, the calculated results are listed in Table 1. Apparently it agrees well with the results obtained when applying Gauss Integration.

TABLE 1. THICKNESS DISTRIBUTION T CALCULATED WHEN
ρ =1 AND P=1.

a	T		
	解 析 法 —1	级数展开法 —2	高斯积分法 —3
0.0	1.0000	1.0000	1.0000
0.1	1.0050	1.0050	1.0050
0.2	1.0194	1.0194	1.0194
0.3	1.0418	1.0418	1.0418
0.4	1.0697	1.0697	1.0697
0.5	1.0991	1.0991	1.0992
0.6	1.1249	1.1248	1.1250
0.7	1.1408	1.1405	1.1409
0.8	1.1404	1.1394	1.1405
0.9	1.1187	1.1164	1.1187
1.0	1.0733	1.0691	1.0731

Key: 1- Analysis 2- Series expansion 3- Gauss Integration

Fig.2 depicts the change of film thickness with the change in ρ when p=1. Interestingly enough, the film thickness distribution hardly changes when ρ is between 1.5 and 2.5, therefore it could be constant in this interval. Fig.3 shows the change of film thickness with the change in p when ρ =1 and 3.5. /402

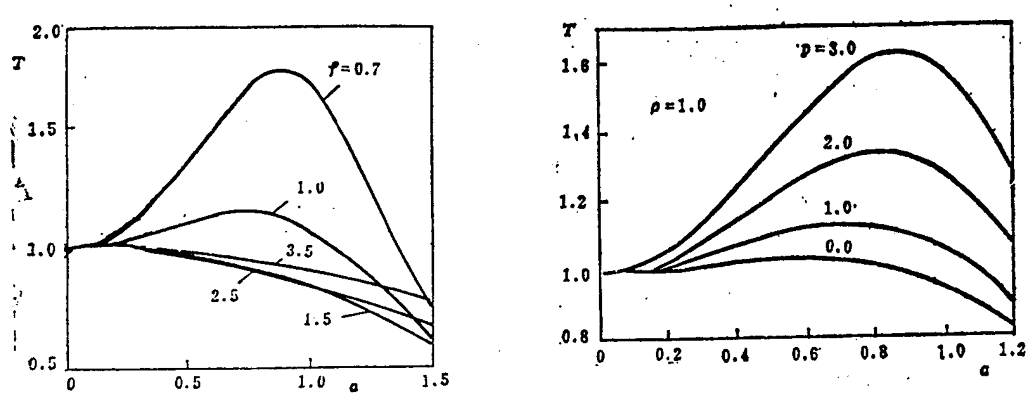

Fig.2 Film thickness distribution at various ρ when p=1.0.

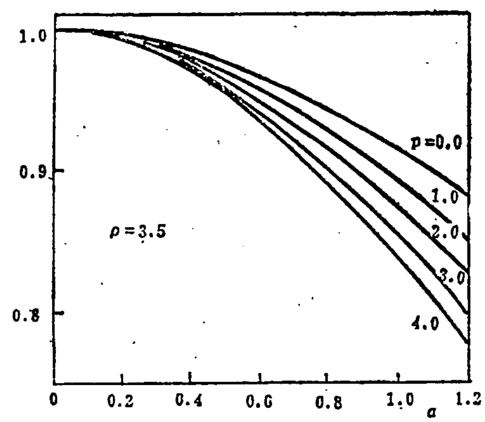

Fig. 3 Film thickness distribution at various ρ when ρ=1.0 and 3.5

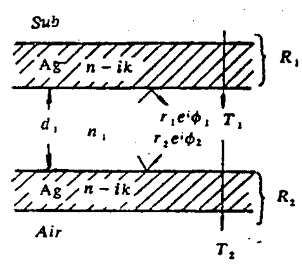

Fig. 4 Metal filters and their symbols

2. THE MEASUREMENT OF FILM THICKNESS DISTRIBUTION

The film thickness distribution measurement can be achieved by indirectly measuring peak value wavelength with a Fabry-Perot metal dielectric at various points.

As we know, when $(\delta+\phi_1+\phi_2)/2 = m\pi$

$$\frac{4\pi}{\lambda} n_1 d_1 \cos\theta + \phi_1 + \phi_2 = 2m\pi \qquad (3)$$

The filter has maximum transmittance

$$T_M = T_0/[1 + F \cdot \sin^2 (\frac{\delta + \phi_1 + \phi_2}{2})]$$

$$T_0 = T_1 \; T_2 / (1 - \sqrt{R_1 R_2})^2,$$

$$F = 4\sqrt{R_1 R_2} / (1 - \sqrt{R_1 R_2}),$$

From (3) we can obtain

$$2n_1 d_1 \cos\theta = (m - \psi) \lambda \qquad (4)$$

In which, $\psi = \frac{\phi_1 + \phi_2}{2\pi}$. If Ag layer is symmetric, then $\phi = \phi_1 = \phi_2 = \mathrm{tg}^{-1} \frac{2kn_1}{n^2 + k^2 - n_1^2}$ and when it is vertically projected, then (4) can be simplified as

$$2n_1 d_1 = (m - \psi)\lambda_0 \qquad (5)$$

If thickness d_1 is changed to $d_1 + \delta d_1$ with respect to the different positions of filters, and the refractive index between the layers n_1 is changed to $n_1 + \delta n_1$ with respect to different wavelength, and phase color scattering is changed to $\psi + \delta\psi$, consequently the peak value is changed to $\lambda_0 + \delta\lambda$ and then (5) can be written as

$$2 (n_1 + \delta n_1) (d_1 + \delta d_1) = (m - \psi - \delta\psi) (\lambda_0 + \delta\lambda) \qquad (6)$$ /403

If it is divided by (5), then

$$(1 + \frac{\delta n_1}{n_1})(1 + \frac{\delta d_1}{d_1}) = (1 - \frac{\delta\psi}{m - \psi}) (1 + \frac{\delta\lambda}{\lambda_0}) \qquad (7)$$

Let $T = 1 + \frac{\delta d_1}{d_1}$ be actual film thickness distribution from (7),

$$T = \frac{(1 - \frac{\delta\psi}{m - \psi})(1 + \frac{\delta\lambda}{\lambda_0})}{(1 + \frac{\delta n_1}{n_1})}$$

$$T = \left(1 + \frac{\delta\lambda}{\lambda_0}\right)\left[1 - \frac{\lambda_0}{m-\psi} \cdot \frac{\partial\psi}{\partial\lambda}\frac{\delta\lambda}{\lambda_0}\right]\left[1 + \frac{\lambda_0}{n_1}\frac{\partial n_1}{\partial\lambda}\frac{\delta\lambda}{\lambda_0}\right]^{-1}$$

$$T = \left(1 + \frac{\delta\lambda}{\lambda_0}\right)\left(1 - B\frac{\delta\lambda}{\lambda_0}\right)\left(1 + A\frac{\delta\lambda}{\lambda_0}\right)^{-1} \qquad (8)$$

in which $A = \frac{\lambda_0}{n_1}\frac{\partial n_1}{\partial\lambda}$ and $B = \frac{\lambda_0}{m-\psi}\frac{\partial\psi}{\partial\lambda}$ correspond to the phase change color scattering and inter-layer refractive index color scattering.

If inter-layer n_1 corresponds to ZnS, A can be solved from

$$n_1 = 2.239 + \frac{45200}{\lambda^2}$$

For MgF_2 underlayers, n_1=1.38, i.e. A=0. B can be solved from the relation between ϕ and ψ

$$\frac{\partial\psi}{\partial\lambda} = \frac{1}{\pi}\frac{\partial\phi}{\partial\lambda}$$

$$\frac{\partial\phi}{\partial\lambda} = \frac{\partial\phi}{\partial n}\frac{\partial n}{\partial\lambda} + \frac{\partial\phi}{\partial k}\frac{\partial k}{\partial\lambda} + \frac{\partial\phi}{\partial n_1}\frac{\partial n_1}{\partial\lambda}$$

$$= \frac{2}{(n^2+k^2-n_1^2)^2 + 4K^2 n_1^2}\left[K(n^2+K^2 n_1^2)\frac{\partial n_1}{\partial\lambda} + n_1(n^2-K^2-n_1^2)\right.$$

$$\left.\frac{\partial K}{\partial\lambda} - 2nKn_i\frac{\partial n}{\partial\lambda}\right]$$

in which the optical constancy of Ag can be expressed as

$$n = 0.525 - 1.825\times10^{-3}\lambda + 1.75\times10^{-6}\lambda^2$$

$$k = 3.41 + 8.7\times10^{-3}(\lambda - 546) \qquad \text{(wavelength 500-700nm)}$$

Hence, using (8), the film thickness distribution T can be easily calculated based on the change of peak value wavelength with respect to the different positions of filters.

The method described above can also be used to deal with filters with wide range of thickness, by changing the wavelength of incoming light while maintaining the vertical emittance measurement. If the evenness of filters does not fluctuate a bit, a more accurate method is to use single wavelength lightening(i.e. He-Ne laser) peak value wavelength which can be located by adjusting the incoming angle.

For a known scale m, $\cos\theta = \lambda/\lambda_0$, which is inferred from /404 (4) and (5). For a smaller incoming angle,

$$\cos\theta = 1 - \frac{\theta_0^2}{2n_1^2}$$

therefore

$$\frac{\delta\lambda}{\lambda_0} = -\frac{\theta_0^2}{2n_1^2} \tag{9}$$

In which both the color scattering of n_1 and ψ with respect to wavelength, and the change of Ag layer phase with respect to the change of incoming angle were omitted. When taking these into consideration, equation (4) becomes

$$2d_1(n_1+\delta n_1)\left(1-\frac{\theta_0^2}{2n_1^2}\right) = (m-\psi-\delta\psi)(\lambda_0+\delta\lambda) \tag{10}$$

By substituting δn_1 with $\frac{\partial n_1}{\partial\lambda}\delta\lambda$, $\delta\psi$ and $\frac{\partial\psi}{\partial\lambda}$ and $\frac{\partial\psi}{\partial\theta}\delta\theta$ dividing by (4), we find:

$$\frac{\delta\lambda}{\lambda_0} = \frac{-\frac{\theta_0}{2n_1^2} + \frac{1}{m-\psi}\frac{\partial\psi}{\partial\theta}\delta\theta}{1-A-B} \tag{11}$$

Since $\delta\lambda$ and θ^2_0 have a linear relationship, therefore $\frac{1}{m-\psi}\frac{\partial\psi}{\partial\theta}\delta\theta$ is a function of θ^2_0 , i.e. $C\theta^2_0$, hence (11) can be written as

$$\frac{\delta\lambda}{\lambda_0} = -\frac{\theta_0^2(1-2n_1^2C)}{2n_1^2(1-A-B)} \tag{12}$$

the fraction of C with respect to p and s is

$$C_p = -C_s = \frac{K(n^2+K^2+n_1^2)}{n_1\pi(m-\psi)[4k^2n_1^2+(n^2+K^2-n^2{}_1)^2]}$$

When C=A=B=0 (12) becomes (9). If (12) is written as

$$\frac{\delta\lambda}{\lambda_0} = -\frac{\theta_0{}^2}{2n_1^2} \qquad (13)$$

then $n_1' = n_1[1-A-B)(/1-2n_1{}^2C)]^{\frac{1}{2}}$ is the effective refractive index.

Therefore, based on (13), wavelength change can be calculated according to the corresponding inclination angle of the measured filter maxima. Consequently, the film thickness distribution can be calculated from (8).

In order to assess the effect of color scattering on the measuring error, (8) can be expanded as

$$T-1 = \frac{\delta\lambda}{\lambda_0}(1-A-B)$$

Let f=(1-A-B). T_M is the calculated film thickness that corresponds to the measured peak value drift, i.e.
$T_M - 1 = \delta\lambda/\lambda_0$
then $T-1 = (T_M-1)f$

Therefore $\delta T^2 = (\frac{\partial T}{\partial T_M})^2 \delta T_M + (\frac{\partial T}{\partial f})^2 \delta f^2$

$\frac{\partial T}{\partial T_M} = f, \quad \frac{\partial T}{\partial f} = T_M - 1$ /405

$\delta T^2 = f^2 \delta T_M{}^2 + (T_M - 1)^2 \delta f^2$

Assume $T_M-1 = 0.1$, we calculate $\delta f^2 = 0.014$, $f^2 \delta T_M{}^2 = 7.8 \times 10^{-6}$
$(T_M - 1)^2 \delta f^2 = 1.4 \times 10^{-4}$

Then we find $\delta T = 1.2 \times 10^{-2}$

Therefore, the thickness distribution measurement error arises from the second item, especially the error in f. This shows that the Fabry-Perot metal dielectric filter based measurement of film thickness distribution should take into account the refractive color scattering among the separating layers and metal layers.

Fig.5 are the set-ups used in the above measuring methods.

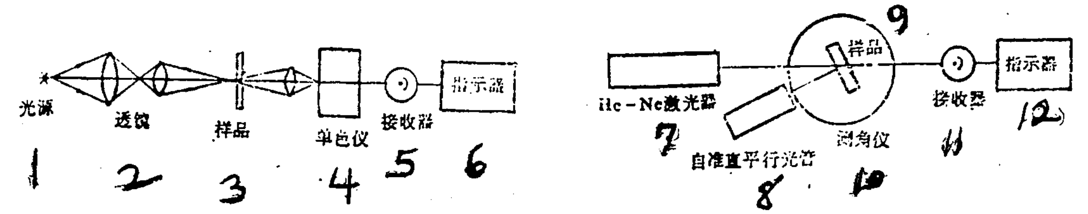

Fig.5 Measuring set-up diagram

Key: 1- light source 2- lens 3- sample 4- light filter 5- receptor 6- monitor 7- He-Ne laser 8 self-adjustable parallel light tube 9- sample 10- angle meter 11- receptor 12- monitor

3. MEASUREMENT RESULTS

Using above methods we measured 3 commonly used film (ZnS, Na_3AlF_6, MgF_2) thickness distributions. The following filters were used:

A1Ag8ZAg1G

A1Ag8CAg1G

and A1Ag4MAg1G

In which Z, C and M designate $\lambda_0/4$ film of ZnS, Na_3AlF_6 and MgF_2.

The sample is spun at 8 cycle/sec, the substrate temperature is room temperature, vacuum degree is $1\text{-}2\times10^{-5}$ Torr.

Fig. 6 and 7 shows the measurement at H/R=0.9 and 1.7. As we see from the figures, the actual curve diverges from the theoretical value to various extent(p=1). At H/R=1.7, the sequence is $Na_3AlF_6<ZnS<MgF_2$, in which MgF_2 shows the greatest diversion. At H/R=0.9, the sequence becomes $MgF_2< Na_3AlF_6<ZnS$. Different evaporation rate also affects film thickness distribution. At 1.7, the sequence is

$ZnS<Na_3AlF_6<MgF_2$, in which MgF_2 is affected greatly. At 0.9, the sequence changes to $ZnS<MgF_2<Na_3AlF_6$. At high evaporation rate, the distribution under these two given conditions tends to approach straight line T=1, in other words, thickness evenness has been improved. Comparing H/R=1.7 and 0.9, the constant value at H/R=1.7 is more striking than at 0.9. Even comparing the first time use and 3 time use evaporation source, the distribution at 1.7 is more stable, the sequence is $ZnS<Na_3AlF_6<MgF_2$, MgF_2 is the most unstable one, this is confirmed by fig. 2.

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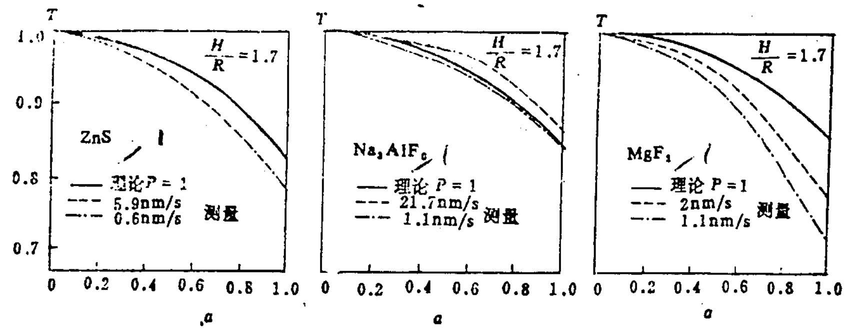
Therefore, in order to make an adjustable filter, H/R should be close to 1.7. In addition, $ZnS-Na_3AlF_6$ or $ZnS-MgF_2$ film thickness should be close . Furthermore, due to the great difference in vapor evaporation between new and old evaporation source, the evaporation source for low refractive index material should be replaced promptly, otherwise, the adjustable filter would not work.



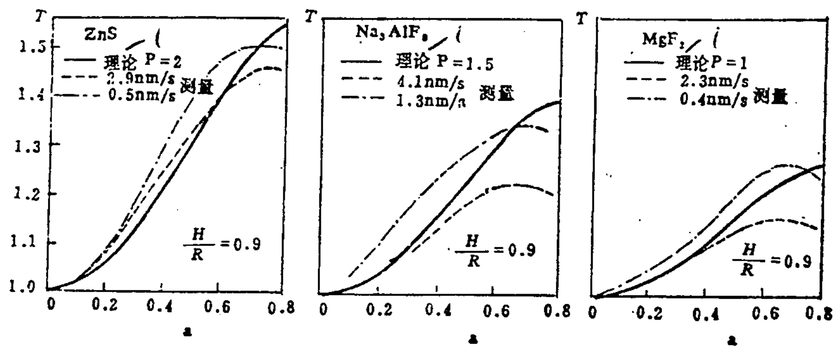


Fig.6 The comparison of three film layer thickness distribution with theory when H/R=1.7.

Fig.7 The comparison of three film layer thickness distribution with theory when H/R=0.9.

Key: 1- divergence.

We also measured film thickness distribution of ion assisted thin film. We found that the evenest film thickness distribution could be achieved by adjusting the distance and angle of ion gun from the target.

We would like to thank Prof. Lissberger at British Royal University for his help in our study.

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