Analysis of the magnitude and distribution of low loss thin film

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Total loss test of the high-reflective (HR) film coated on super-smooth silica substrate by dual ion beam sputtering (DIBS) is based on the well-established cavity ring-down technique. Scattering and transmittance are tested by integral scattering and transmittance measuring apparatus, after which absorption is calculated. At 632.8 nm wavelength, the magnitude and distribution of thin film loss are researched for both s- and p-polarization, and the reflectivities are 0.99986, 0.99997, and 0.99962, respectively. Based on the analysis, the tested scattering is less than its real value.

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With the advent of the laser standard system and high precision laser measurement system, user can now expect decrease in thin film loss. Requirements for high quality optical film thus accelerate with the emergence of new developments in film production. With advancements in substrate polishing and film production, laser films with pure loss (i.e., absorption and scattering) less than 100 ppm can be regularly applied. This can also impede high-reflective (HR) films with whole loss (i.e., transmittance, absorption, and scattering) less than 10 ppm[1,2].

In this letter, HR film coated on super-smooth silica substrate by dual ion beam sputtering (DIBS) is studied. Whole loss of the thin film is tested by optical cavity decay time method, and scattering and transmittance losses are measured by integrated scattering and transmittance measuring apparatus. Absorption loss can then be determined.

Loss in HR film is composed of scattering loss (S), transmittance loss (T), and absorption loss (A), which is shown as

$$\delta = S + T + A. \tag{1}$$

Two groups of HR film samples at wavelength of 632.8 nm were tested and analyzed: The first group of HR film had Sub//H(LH)^{11}//Air with angle of incidence θ at 45°. The second group has Sub//H(LH)^{18}//Air with angle of incidence θ at 22.5°. Sub was fused silica, and the center wavelength λ is 632.8 nm. H and L represented the high and low refractive index materials with optical thickness of $\lambda/4$. Here, H and L were Ta_2O_5 and SiO_2, respectively, and their optical constants were calculated by a single layer[3]. Table 1 depicts the calculated data.

Scattering and transmittance losses were tested by integrated scattering and transmittance measuring apparatus (Russia). Repeatability was better than 2 ppm for 50-ppm scattering and transmittance. Figure 1 shows the principle of the scattering measurement. Polarization of the measured beam of light is optional.

In 1961, Bennett *et al.* defined total integrated scattering (TIS)[4]. The relation between TIS and root mean square (RMS) roughness σ is identified, on the condition that $\sigma/\lambda \ll 1$, which is expressed as

$$\begin{aligned}\mathrm{TIS} &= 1 - \frac{R}{R_0} = 1 - \exp[-(4\pi\sigma\cos\theta_i/\lambda)^2] \\ &= (4\pi\sigma\cos\theta_i/\lambda)^2,\end{aligned} \tag{2}$$

where R_0 and R represent whole reflectance in all directions and direct reflection, respectively; θ_i and λ are angle of incidence and wavelength of incident ray respectively.

The RMS of the surface was tested by a ZYGO surface profile measurement apparatus. However, the surface could also be characterized by quasi-Brewster angle technique[5], which suggests that the slope angle is

Table 1. Calculated Data of the Two Groups of HR Film

Group No.	A (ppm)		T (ppm)	
	s-Polarization	p-Polarization	s-Polarization	p-Polarization
1	9	23	101	4579
2	12	15	3	14

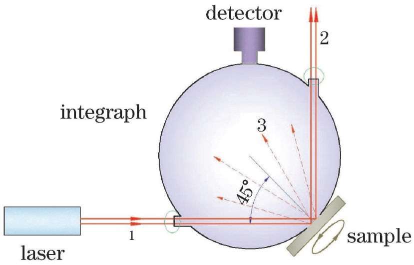

Fig. 1. Scheme of integrated scattering and transmittance measuring apparatus.

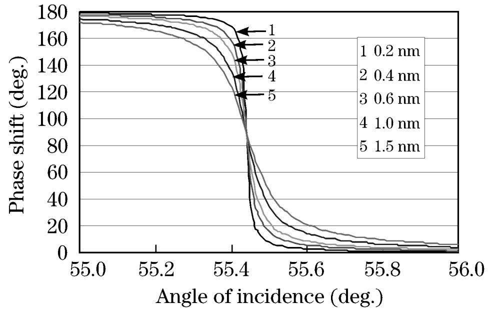

Fig. 2. Phase shift as a function of angle of incidence near Brewster angle at wavelength of 900 nm for silica substrate with different TSR.

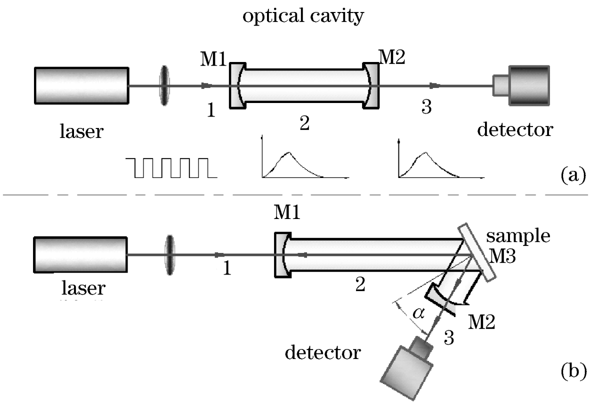

Fig. 3. Scheme of optical cavity loss measuring apparatus. (a) Linear cavity used in calibration and (b) V cavity for measuring sample.

dominated by top surface roughness (TSR) similar to the commonly used RMS roughness. Figure 2 depicts the relation between phase shift and surface roughness.

Test of total loss was based on the well-established cavity ring-down technique. Instrument precision was typically less than 1% of the total measured loss, resulting in a precision better than 1 ppm for 100-ppm losses. Hence, both s- and p-polarization can be performed.

Figure 3 is the scheme of the total loss test where a is linear cavity used in calibration and b is V cavity, which could measure the loss of HR film at both 22.5° and 45°. Laser wavelength was 635 nm. Measurement error was less than 1 ppm for wavelength 632.8 nm, and the stability of the optical cavity loss measuring apparatus was ±1.5 ppm[3].

Table 2 gives the scattering data of the first group of samples, where $\lambda = 632.8$ nm and $\theta_i = 45°$. Obviously, scattering, which is tested by the integrated scattering and transmittance measuring apparatus, is lower than the calculated value in relation to RMS roughness. This phenomenon is determined by the structure of the integrated scattering and transmittance measuring apparatus. As shown in Fig. 1, scattering around the incident aperture and transmitting aperture are not included in the test data. From Table 2, TIS and TSR of the surface are almost consistent.

Tables 3 and 4 provide the results of the first and second group samples, respectively. In the first group, only s-polarization is analyzed; in the second group, both s- and p-polarization are analyzed. Based from the

Table 2. Scattering Data of First Group of Preview

Serial No.	Sample No.	Test Data				Calculated Data
		TIS_{test}-P (ppm)	TIS_{test}-S (ppm)	RMS (nm)	TSR (nm)	TIS_{RMS} (ppm)
1	S1	10	13	0.372	0.308	27
2	S2	11	10	0.368	0.293	27
3	S3	9	11	0.379	0.328	28
4	S4	9	14	0.384	0.332	29
Average Data		10	12	0.376	0.315	28

Table 3. First Group of Preview Test Data

Serial No.	Sample No.	Test Data			Calculation Data	
		δ (ppm)	S (ppm)	T (ppm)	A (ppm)	R
1	S1	137	13	104	20	0.999863
2	S2	141	10	106	25	0.999859
3	S3	137	11	103	22	0.999863
4	S4	144	14	102	28	0.999856
Average Data		140	12	104	24	0.999860

Table 4. Second Group of Preview Test Data

Serial No.	Sample No.	Test Data						Calculation Data			
		δ (ppm)		S (ppm)		T (ppm)		A (ppm)		R	
		p-	s-	p-	s-	p-	s-	p-	s-	p-	s-
1	S5	39	31	5	9	13	4	21	18	0.999961	0.999969
2	S6	36	30	6	9	14	3	16	18	0.999963	0.99997
3	S7	40	29	6	9	12	4	22	16	0.99996	0.999971
4	S8	37	31	6	10	14	4	17	17	0.999963	0.999969
Average Data		38	30	6	9	13	4	19	17	0.999962	0.99997

analysis before, the test value of scattering is less than the real value, and thus, the calculated value of A should be higher than its real value. Moreover, the test value of transmittance is almost consistent with theoretical value. However, scattering and absorption loss should be reduced to achieve lower optical film loss. This indicates that substrate polishing and film deposition techniques should be researched unceasingly in the future.

In conclusion, HR film coated on super-smooth silica substrate by DIBS is utilized. Magnitude and distribution of the thin film loss are studied for both s- and p-polarization. Through the tests and analyses, the value obtained from the scattering test is less than its real value, and thus, the calculated absorption is likewise less than its real value.

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