Method to accurate calibrate deposition rates of EUV multilayer coatings

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Random thickness error is an important factor which effects the calibration accuracies of deposition rates for extreme ultraviolet (EUV) multilayer coatings fabricated by sputter deposition techniques. A least square fitting method is proposed to determine deposition rates and extract random thickness errors accurately. The validity of this method is shown by evaluating two deposition systems with control abilities of ~0.1 nm and better than 0.01 nm respectively.

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Multilayer reflective optics are basic elements for extreme ultraviolet (EUV) and X-ray applications[1]. In such applications, multilayer interference coatings composed of alternate layers of scattering material (absorber) and transmissive material (spacer) are deposited to meet spectral response requirements[2]. Due to the confinement of rather short application wavelength, typical multilayer optics have stringent specifications. For example, run to run specifications for period thicknesses of Mo/Si multilayer coatings is 0.025 nm for EUV lithography systems[3]. It is obvious that high thickness control accuracy is needed to meet such specifications.

Typically, magnetron sputter or ion beam sputter technique is used to deposit multilayer coatings. The advantage of these sputter techniques is the stability of deposition rates during deposition processes. By virtue of this advantage, layer thicknesses of coatings could be controlled precisely by simply setting appropriate deposition times. However, thickness errors caused by random factors usually occur during deposition processes and induce deviations of optical characters of multilayer coatings. Therefore, method to accurate determine deposition rates and extract random thickness errors should be developed to avoid this phenomena. In this letter, a least square fitting method is proposed solve this problem. The validity of this method is shown by evaluating two deposition systems with control abilities of ~0.1 nm and better than 0.01 nm respectively.

Period thicknesses of multilayer coating composed by two materials could be represented as

$$t^{\mathrm{A}} \times V^{\mathrm{A}} + t^{\mathrm{B}} \times V^{\mathrm{B}} + \Lambda = d, \tag{1}$$

where t^{A} and t^{B} are deposition times, V^{A} and V^{B} are deposition rates of two materials, and Λ is a constant value, which means an overall effect aroused from some factors, such as the expansion or contraction of period thicknesses caused by interdiffusion of materials[4], or extra deposited thickness when samples moving in and out deposition areas[5]. When we consider a series coating experiments at a fixed technique settings (fixed nominal current, voltage, etc.) and take random errors into account, Eq. (1) could be rewritten as

$$\begin{pmatrix} t_1^{\mathrm{A}} & t_1^{\mathrm{B}} & 1 \\ t_2^{\mathrm{A}} & t_2^{\mathrm{B}} & 1 \\ \cdots & \cdots & \cdots \\ t_n^{\mathrm{A}} & t_n^{\mathrm{B}} & 1 \end{pmatrix} \cdot \begin{pmatrix} \left(V^{\mathrm{A}}+\delta V_1^{\mathrm{A}}\right) & \left(V^{\mathrm{A}}+\delta V_2^{\mathrm{A}}\right) & \cdots & \left(V^{\mathrm{A}}+\delta V_n^{\mathrm{A}}\right) \\ \left(V^{\mathrm{B}}+\delta V_1^{\mathrm{B}}\right) & \left(V^{\mathrm{B}}+\delta V_2^{\mathrm{B}}\right) & \cdots & \left(V^{\mathrm{B}}+\delta V_n^{\mathrm{B}}\right) \\ (\Lambda+\delta\Lambda_1) & (\Lambda+\delta\Lambda_2) & \cdots & (\Lambda+\delta\Lambda_n) \end{pmatrix} = \begin{pmatrix} \left(d_1^{\mathrm{A}}+\delta d_1^{\mathrm{A}}\right)+\left(d_1^{\mathrm{B}}+\delta d_1^{\mathrm{B}}\right)+(\Lambda+\delta\Lambda_1) \\ \left(d_2^{\mathrm{A}}+\delta d_2^{\mathrm{A}}\right)+\left(d_2^{\mathrm{B}}+\delta d_2^{\mathrm{B}}\right)+(\Lambda+\delta\Lambda_2) \\ \cdots \\ \left(d_n^{\mathrm{A}}+\delta d_n^{\mathrm{A}}\right)+\left(d_n^{\mathrm{B}}+\delta d_n^{\mathrm{B}}\right)+(\Lambda+\delta\Lambda_n) \end{pmatrix}, \tag{2}$$

where V^{A}, V^{B}, and Λ are expected values of all experiments, which means

$$V^{\mathrm{A}} = \frac{1}{i}\sum_{i=1}^{\infty} V_i^{\mathrm{A}}, V^{\mathrm{B}} = \frac{1}{i}\sum_{i=1}^{\infty} V_i^{\mathrm{B}}, \Lambda = \frac{1}{i}\sum_{i=1}^{\infty} \Lambda_i. \tag{3}$$

To solve deposition rates, least square fitting process could be applied to Eq. (2). Let us define results of deposition rates in the least square fitting process to Eq. (2) as $(V^{\mathrm{A}})' = V^{\mathrm{A}} + \Delta V^{\mathrm{A}}$, $(V^{\mathrm{B}})' = V^{\mathrm{B}} + \Delta V^{\mathrm{B}}$, $(\Lambda)' = \Lambda + \Delta\Lambda$ respectively. The residual error $[\nu^2]/n$ of the least square process can be divided to three parts:

$$[\nu^2]/n = \{[\nu^2]/n\}_1 + \{[\nu^2]/n\}_2 + \{[\nu^2]/n\}_3, \tag{4}$$

$$\{[\nu^2]/n\}_1 = \left[\sum_{i=1}^{\infty} \left(\Delta V^{A} \times t_i^{A} + \Delta V^{B} \times t_i^{B} + \Delta\Lambda\right)^2\right] / n, \tag{5}$$

$$\begin{aligned}&\left\{\left[\nu^2\right]/n\right\}_2\\&=\left\{\sum_{i=1}^{\infty}\left[2\times\left(\Delta V^A\times t_i^A+\Delta V^B\times t_i^B+\Delta\Lambda\right)\times\delta d_i\right]^2\right\}/n\\&=2\times E[(\Delta V^A\times t_i^A+\Delta V^B\times t_i^B+\Delta\Lambda)\times\delta d_i]=0,\end{aligned}\tag{6}$$

$$\left\{\left[\nu^2\right]/n\right\}_3=\sum_{i=1}^{n}[(\delta d_i)^2]/n=D\left(d_i\right).\tag{7}$$

Therefore, the value of $[\nu^2]/n$ represented by Eq. (4) is the sum of two parts, which are Eqs. (5) and (7) respectively. In fact, $[\nu^2]/n$ is only effected by Eq. (5), because Eq. (7) has a constant value. It is obvious that $[\nu^2]/n$ could get the minimum value, which is zero, in case that $\Delta V^{\mathrm{A}}=\Delta V^{\mathrm{B}}=\Delta\Lambda$=0.

From above analysis, we can draw the conclusion that when the number of experiment in a deposition series is accumulated large enough, the value of the residual error will approach to the variance of random period thickness errors. At the same time, deposition rates will convergent to their true values. In this case, expected values of deposition rates could be determined, random period thickness errors could also be extracted.

Mo/Si multilayer coating samples were deposited to verify this method. Two coating systems were used to fabricate these samples. One is a low cost home made magnetron sputter deposition system, which is estimated to has a lower thickness control accuracy relatively. Another one is a high end ion beam sputter coating system (Oxford Ionfab600), which is estimated to has a higher thickness control accuracy. Period thicknesses of coating samples were measured by X-ray diffraction method[2].

Deposition times and measured period thicknesses of all coating samples are listed in Tables 1 and 2. Deposition rates of these series coating processes derived by using least square method are shown in Tables 3 and 4.

The convergence of deposition rates to their true values can be seen from Tables 3 and 4. This is accompanied with the approaching process for the standard deviation of period thickness errors to the variance, which is also shown in Tables 3 and 4. The convergence of deposition rates help us to find random thickness errors, as shown in Fig. 1.

Table 1. Deposition Times and Period Thickness Test Results in Series Tests Performed by Magnetron Sputter Deposition

Test Lable	t_{Mo} (s)	t_{Si} (s)	$d_{\mathrm{Mo/Si}}$ (nm)
1	30	30	6.80
2	40	30	8.48
3	30	40	7.39
4	30	50	7.84
5	30	60	8.25
6	40	60	9.95
7	17	110	8.56
8	19	90	7.88
9	40	40	8.98

Table 2. Deposition Times and Period Thickness Test Results in Series Test Performed by Ion Beam Sputter Deposition

Test Lable	t_{Mo} (s)	t_{Si}(s)	d (nm)
1	120	120	12.78
2	180	180	19.61
3	210	150	18.41
4	126	87	10.46
5	150	200	20.04

Table 3. Calculated Deposition Rates and Standard Deviations of Random Period Thickness Errors in the Series Test Performed by Magnetron Sputter Deposition

Data Used	V_{Mo} (nm/s)	V_{Si} (nm/s)	Λ (nm)	Standard Deviation
1–3 Run	0.168	0.059	-0.01	
1–4 Run	0.1657	0.052	0.2933	0.0286
1–5 Run	0.163	0.048	0.52	0.0415
1–6 Run	0.1645	0.0485	0.4537	0.0384
1–7 Run	0.1649	0.0483	0.4503	0.0357
1–8 Run	0.1657	0.0482	0.4245	0.0359
1–9 Run	0.1657	0.0482	0.4242	0.0339

Table 4. Calculated Deposition Rates and Standard Deviations of Random Period Thickness Errors in the Series Test Performed by Ion Beam Sputter Deposition

Data Used	V_{Mo} (nm/s)	V_{Si} (nm/s)	Λ (nm)	Standard Deviation
1–3 Run	0.03692	0.07692	–0.88	
1–4 Run	0.03691	0.07695	–0.8848	0.0008
1–5 Run	0.03693	0.07693	–0.8845	0.001

Furthermore, control accuracies of coating systems, which is a key parameter for multilayer coating depositions, can be estimated from values of random period

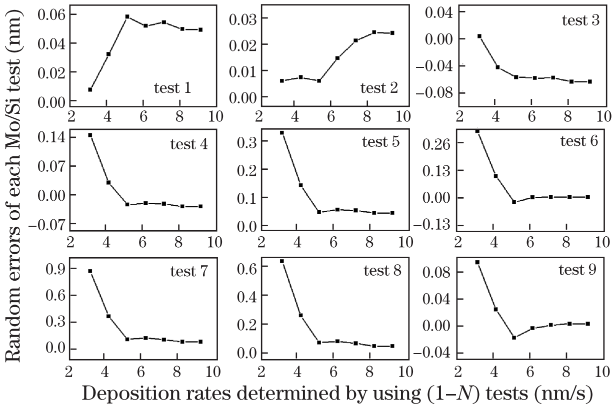

Fig. 1. Approaching process of random errors to their true values in series tests by magnetron sputter deposition.

thickness errors. For the magnetron sputter coating system, stand deviations $\sigma(\delta)$ of Mo/Si coating samples is about 0.03 nm. If we take 3σ criterion into account, the period thickness control accuracy is about 0.1nm. For the ion beam sputter system, the stand deviation $\sigma(\delta)$ is lower than 0.001 nm, which means it has a much higher control accuracy than the magnetron sputter system. It is obvious that the ion beam coating system can meet higher control requirements, such as 0.01 nm.

In conclusion, we develope a new method based on the least square process to calibrate deposition rates accurately. By using this method, deposition rates and random period thickness errors can be derived accurately. Furthermore, control accuracies of coating systems can be estimated. All of these data are key parameters to fabricate high performance EUV multilayer optics.

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