Extreme-ultraviolet multilayer mirrors deposited using radio-frequency-magnetron sputtering: the influence of self-bias voltage on reflectivity and roughness

2001 J. Phys.: Condens. Matter 13 3969

(http://iopscience.iop.org/0953-8984/13/18/307)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **13** (2001) 3969–3976 www.iop.org/Journals/cm PII: S0953-8984(01)19891-7

Extreme-ultraviolet multilayer mirrors deposited using radio-frequency-magnetron sputtering: the influence of self-bias voltage on reflectivity and roughness

M Putero-Vuaroqueaux and B Vidal

L2MP, Faculté des sciences de Saint Jérôme, Case 131, 13397 Marseille Cédex 20, France

E-mail: magali@l2mp.u-3mrs.fr (M Putero-Vuaroqueaux) and vidal@ms131u11.u-3mrs.fr (B Vidal)

Received 8 December 2000, in final form 15 March 2001

Abstract

Mirrors for the imaging optics of extreme-ultraviolet (EUV) lithography systems require optimal reflectivity. In this paper, results on Mo/Si multilayers for EUV radiation are reported. The multilayers were deposited using radio-frequency-magnetron sputtering; during deposition the self-bias voltages were measured, and the influence of their variation on the multilayer reflectivity and roughness was tested. The samples were characterized using small-grazing-angle x-ray reflectivity and their performance was evaluated by measuring the EUV reflectivity at near-normal incidence. The results show that high reflectivity (>67%) and low roughness values (<2.5 Å) can be obtained, depending on the stability of the self-bias voltage during deposition.

1. Introduction

Currently, optical projection lithography is used to print the complex patterns that define integrated circuits onto semiconductor wafers. Continued improvements in optical lithography have enabled the printing of ever finer features, the smallest feature size decreasing by about 30% every two years [1–3]. Using deep-ultraviolet radiation with a wavelength of 193 nm, the feature size can be reduced to 100 nm. However, to continue decreasing the integrated circuit size, to make them faster and more powerful, it is necessary to develop potential successors to optical projection lithography. These are known as 'next-generation lithographies' (NGL). Extreme-ultraviolet (EUV) lithography, with the wavelength used in the range of 11 to 14 nm, is one of the leading NGL technologies, being developed for features smaller than 100 nm [2, 4, 5].

The current designs for a EUV lithography tool entail the use of several optics designed to reflect the EUV light at near-normal angles of incidence in most cases. However, the normal-incidence reflectivity of all materials is very low at soft-x-ray wavelengths. The problem is overcome by coating the optical surface with multilayer films. Therefore, the optics for EUV lithography consist of crystalline silicon or glass–ceramic substrates, that can be flat or curved, and coated with reflective Mo/Si or Mo/Be multilayer films, depending on the wavelength used. The Mo/Si multilayer system represents a good material combination because of the high contrast between the optical constants of Si and Mo, and the low absorption of Si [6]. DC-magnetron sputtering is used by several groups (see for example [7–12]) to develop Mo/Si multilayer mirrors with reflectivity higher than 65%. As DC-magnetron sputtering does not allow one to sputter non-conducting targets (because of charge accumulation at the target surface), doped Si must be used in DC sputtering, instead of pure Si. This difficulty can be overcome by using RF-magnetron sputtering, a single RF-sputtering apparatus being used to deposit electrically conducting, semiconducting and insulating coating.

In general, two main specifications must be achieved by the EUV multilayer coating:

- First, the EUV reflectivity must be optimized (higher than 65%), because a generic imaging system for EUV lithography consists of several mirrors, and there must be minimal intensity loss between the EUV source and the substrate on which the integrated circuit is to be printed.
- Secondly, the multilayer roughness must be minimized because it produces non-specular scattering that has a drastic effect on the image formation and the resolution in the imaging system. In fact, non-specular scattering due to roughness decreases the useful throughput of the optical system and produces a background halo which reduces the contrast of the image [13]. Improvement of the image resolution, due to the reduction of the roughness value (less than about 2.5 Å), is the main goal.

In this paper, results obtained on RF-magnetron-sputtered Mo/Si multilayers are presented. A great number of parameters are involved and can influence the layer deposition during RF-magnetron sputtering (Ar pressure and stability, generator power, ...). For this study, we analysed the influence of one parameter, the self-bias voltage, on the multilayer quality. Both the small x-ray reflectivity and EUV reflectivity spectra are examined, and the influence of the self-bias-voltage stability (measured during deposition) on the multilayer quality (roughness and reflectivity) is discussed.

2. Experiment

Mo/Si multilayer films were deposited in a RF-magnetron-sputtering system [14]. The base pressure was 1×10^{-7} Torr, and during deposition argon gas was used and maintained at a constant pressure of 2 mTorr. In order to avoid change in the deposition conditions, the substrate temperature was maintained at 3 °C during deposition. The RF power of the generator was respectively 270 W and 160 W at Si and Mo targets, with the distance between sources and substrate less than 10 cm. The average self-bias voltages between the sample and the Si and Mo cathodes were 135 ± 5 V and 93 ± 3 V; their variations were measured during deposition: one measurement of the self-bias voltage was performed for each cathode at the beginning of each layer, allowing the self-bias-voltage evolution to be measured during deposition. This measurement was performed during deposition with a digital voltmeter that is coupled to the cathodes and to the PC that monitors the full process [15]. The regulation of the self-bias voltage can be achieved using generators which are able to adjust the RF power in order to keep the self-bias voltage at a constant value during the experiment. However, for the experiments presented in this paper, the self-bias voltage was not adjusted during the deposition (no regulation) but just measured, and the RF power was kept at a constant value. The theoretical bilayer period which must be realized was between 68.5 Å and 69.5 Å, with a Mo fraction around 0.4, depending on the angle of incidence and the wavelength at which each mirror was to be used. For all samples, 40 bilayer periods were used: in fact, it can easily be shown that, due to the material absorption, such a number of periods is sufficient to obtain the optimum reflectivity. The substrates used in this study were (100) silicon wafers one or two inches in diameter, and 3 mm to 5 mm thick. The cleaned wafers were briefly rinsed with methanol before the deposition.

For this general study we produced various multilayers in order to optimize the deposition parameters. In this paper, we present results obtained on three typical samples. These samples were produced for different working conditions:

- samples ma083 and ma085 should be used to reflect a 13 nm wavelength, with an incidence angle (grazing angle) of, respectively, 75° and 85°;
- sample ma075 should be used to reflect a 13.4 nm wavelength, with an incidence angle of 85°.

A specular x-ray reflectivity (XRR) investigation was performed at near-grazing incidence on a conventional two-circle x-ray diffractometer, using a standard fine-focus Cu x-ray tube, with a (111) Ge crystal primary-beam monochromator to select the Cu Kα_1 radiation. A divergence slit of 50 μm in front of the monochromator and a receiving slit of 200 μm were used. The angular beam divergence was 0.0055°. XRR allows one to determine the multilayer characteristics, such as the layer thicknesses and roughness: the bilayer period and the thickness of each material were determined by fitting small-angle XRR (SAXRR) peaks using the classical matrix thin-film method of analysis [16–19]. To evaluate the influence of the interfacial roughness, the ideal plane in the multilayer stack was changed into a rough surface by variation of each element in the matrix, i.e. by the introduction of a Debye–Waller-like attenuation factor which modified the reflectivity coefficients of all interfaces, as extensively described in reference [19]. The method used allows one to estimate the average height of the roughness of each layer (Mo and Si layers). The calculation program allows one to take into account any shift of the layer thickness and/or of the roughness through the stack; no correction was included to account for variation of the illuminated area at very-near-grazing angles (however, it is always lower than the sample length). By using this method for the calculations, we consider only the specular reflectivity and do not take into account the self-correlation function of the interface position. In practice, such a model is useful for estimating the average values of the layer roughness causing reflectivity losses. To obtain a complete description of the roughness profile from the substrate up to the surface, including the lateral and vertical correlation lengths, non-specular scans and the analysis of the diffuse scattering are unavoidable [21]; however, this is not the subject of this paper, and will be discussed in a forthcoming article [21].

Moreover, an 'at-wavelength' characterization (at the wavelength used for the mirrors) was also performed: reflectance measurements in the EUV range were performed using a synchrotron radiation source (LURE Laboratory, Orsay, France). These measurements were conducted either at 5° off-normal incidence over the wavelength ranges 11 nm to 15 nm, or at a fixed wavelength (13 nm) over the angle-of-incidence ranges 70° to 86°. The layer roughness was also estimated by fitting these spectra and compared to the roughness deduced from SAXRR analysis.

3. Results and discussion

The SAXRR of sample ma083 is shown in figure 1 where both simulated and experimental curves are plotted. First all, figure 1 shows that the first 12 Bragg peaks appear distinctly and

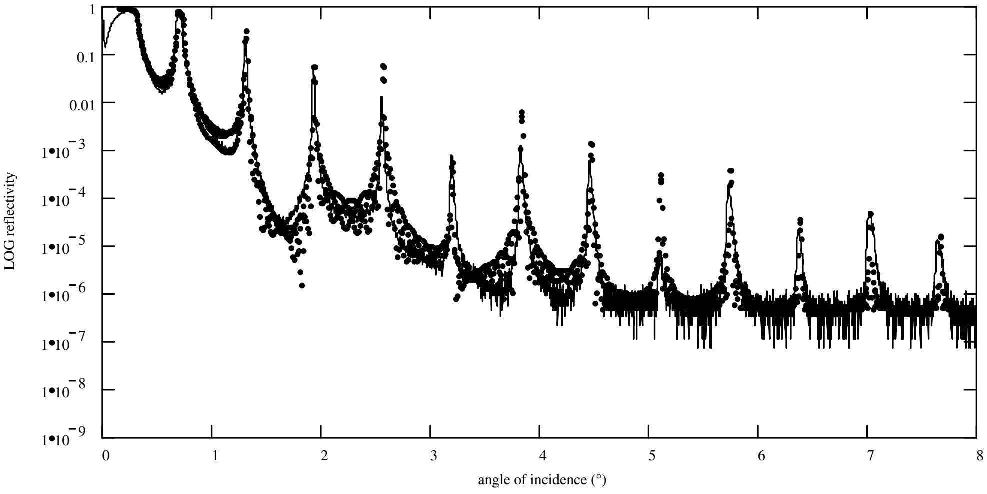

Figure 1. SAXRR measurements on sample ma083; the points correspond to the simulated data.

are not broadened. This clearly proves that there is no visible layer thickness evolution through the multilayer from the substrate up to the surface: in fact, a shift in the period value due to any modification in the deposition conditions should broaden the last Bragg peaks. Moreover, as high-order Bragg reflections are strongly suppressed by interface roughness, the sharpness and intensity of these 12 Bragg maxima indicate beyond doubt the existence of a smooth interface. SAXRR simulations provide an evaluation of the average roughness for the substrate and for Si and Mo layers: these results are reported in table 1; the uncertainties in the layer thickness and roughness were determined by changing each of these parameters until the simulation did not fit the experimental reflectivity. For sample ma083, table 1 shows that the Si roughness (1.7 Å) is lower than the Mo roughness (2.3 Å) (and not the reverse).

Table 1. Sample characteristics deduced from SAXRD measurements: σ is the average roughness height; the subscript 's' refers to the substrate; d, d_{Si} and d_{Mo} are respectively the bilayer, Si-layer and Mo-layer thicknesses; γ is the Mo fraction: $\gamma = d_{\mathrm{Mo}}/d$.

Sample	Substrate	σ_s (Å)	d (Å)	γ	d_{Si} (Å)	σ_{Si} (Å)	d_{Mo} (Å)	σ_{Mo} (Å)
ma083	Si 1″, 3 mm	2.8 ± 0.1	69.4	0.396	41.9 ± 0.1	1.7 ± 0.1	27.5 ± 0.1	2.3 ± 0.1
ma075	Si 2″, 5 mm	2.7 ± 0.1	68.6	0.437	38.6 ± 0.2	2.2 ± 0.1	30.0 ± 0.2	2.8 ± 0.1
ma085	Si 1″, 3 mm	3.0 ± 0.1	67.6	0.423	39.0 ± 0.2	2.4 ± 0.1	28.6 ± 0.2	4 ± 0.1

For samples ma075 and ma085, SAXRR simulation results (reported in table 1) show that the average roughness is increased compared with the results for ma083, with however the same relationship between Si and Mo roughness ($\sigma_{\mathrm{Si}} < \sigma_{\mathrm{Mo}}$) maintained. A high value of 4 Å is characteristic of the Mo layers of sample ma085.

For all samples, other simulations were performed including one with variable roughness for Mo and Si layers (linear from the substrate up to the surface), and one using a four-layer model to take into account any interlayer at the Mo-on-Si and/or Si-on-Mo interfaces. Other simulations were also performed with a Si layer roughness greater than that of the Mo layer. All of these simulations produced worse fits that those presented in table 1, i.e. showed that the differences in layer roughness of each type of interface from the substrate up to the surface as well as the interlayers at the interfaces are small enough to be neglected in specular XRR simulation [21].

Figure 2 shows the EUV reflectivity of sample ma083 according to angle of incidence for two different wavelengths: this sample exhibits a high value of the reflectivity ($R = 67.9\%$) at the specified wavelength and incidence angle (13 nm and 75.2°). For a different angle, a comparable response is obtained at a different wavelength (12.6 nm; see further).

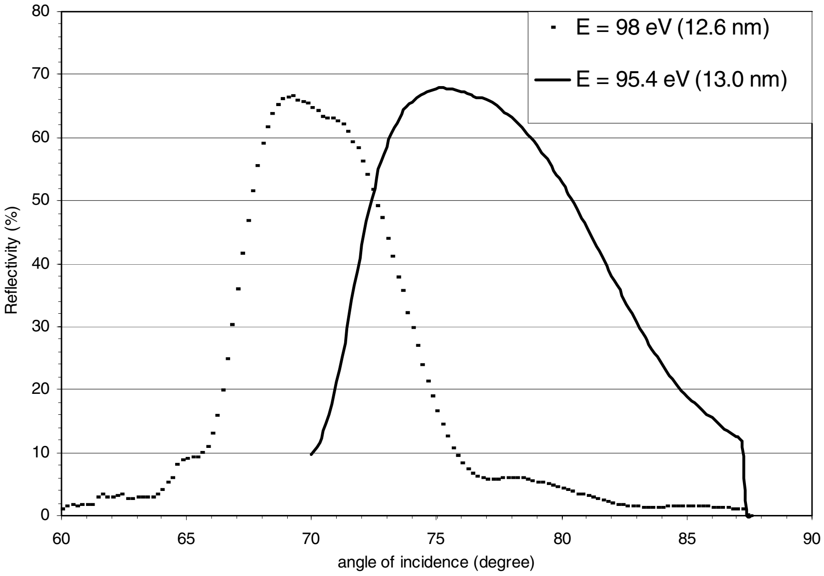

Figure 2. EUV reflectivity measurements on sample ma083 according to angle of incidence for two different wavelengths.

For samples ma075 and ma085, the EUV reflectivity measured at 85° is plotted in figure 3: both samples exhibit EUV spectra centred at wavelengths very close to their own specifications (respectively 13.37 nm and 13.05 nm for the desired specifications of 13.4 nm and 13.0 nm). However, the reflectivities of these samples are lower than that of ma083 (especially for sample ma085: $R < 50\%$).

Table 2 summarizes the EUV results (experimental data and roughness deduced from simulations) for the three samples, as well as the average self-bias voltages measured during the multilayer deposition; the error in the self-bias voltage indicates the maximal oscillations observed during deposition. Two main points can be analysed:

(1) the layer roughnesses deduced from EUV reflectivity simulations (see table 2) are in good agreement with the values calculated from the SAXRR simulations (see table 1): for all samples, the roughness values obtained through the two kinds of measurement (at 0.154 nm and 13 nm) differ by less than 0.6 Å. Moreover, SAXRR simulations, as well as EUV simulations, show that sample ma083 exhibits the smallest roughness, and sample ma085 the highest one. It is worthwhile to note that, using specular SAXRR measurement, accurate control of the average roughness is possible, even if non-specular measurements are necessary to obtain the complete set of roughness parameters.

(2) Optimal mirror performances very close to the desired values are obtained when the self-bias voltage is very stable (sample ma083 with oscillations less than 1% of the average value for both Si and Mo cathodes). Higher variations (10% in the case of the Mo cathode

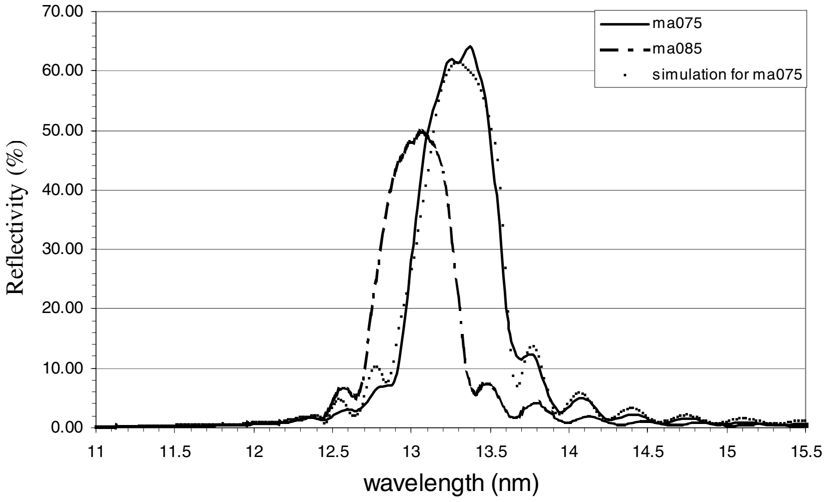

Figure 3. EUV reflectivity measurements on samples ma075 and ma085 according to wavelength; the angle of incidence is 85° in both cases; the simulated data are also plotted for sample ma075.

Table 2. EUV reflectivity and deposition characteristics of the sample: R is the reflectivity, λ the wavelength, E the energy, θ the angle of incidence; V_{Mo} and V_{Si} are the self-bias voltages measured during deposition.

	EUV reflectivity				Simulation		Self-bias voltages	
Sample	E (eV)	λ (nm)	θ (deg)	R (%)	σ_{Si} (Å)	σ_{Mo} (Å)	V_{Si} (V)	V_{Mo} (V)
ma083	98.0	12.6	69.2	66.6	1.8 ± 0.2	2.5 ± 0.2	141.0 ± 0.4	96.0 ± 0.45
	95.4	13.0	75.2	67.9				
ma075	92.7	13.37	85	64.2	2.1 ± 0.2	2.3 ± 0.2	130.0 ± 0.6	89.5 ± 0.5
ma085	95.0	13.05	85	49.6	2.8 ± 0.2	3.7 ± 0.2	140.5 ± 1	94 ± 5

for sample ma085) lead to higher roughnesses of Mo and Si layers and hence to a lower reflectivity of the samples. Such a correlation is so clear that to avoid a drastic decrease of the reflectivity, as in the case of ma085 (see figure 2), it is indisputable that oscillations of the bias voltage must be carefully *measured* and reduced. This phenomenon is very significant: whatever the samples, the self-bias voltage are more stable for Si than for Mo, and the Si layers always exhibit a lower roughness than the Mo ones (see tables 1 and 2); in contrast, when the fluctuations of the self-bias voltage are low and comparable for the two materials ($\Delta V/V \approx 5 \times 10^{-3}$), the reflectivity values of the mirrors are of the same order (samples ma083 and ma075). In the case of larger self-bias-voltage oscillations ($\Delta V/V \approx 5 \times 10^{-2}$ during Mo deposition of ma085), the roughness is increased and the reflectivity is drastically decreased ($R < 50\%$).

Therefore, the control of the self-bias-voltage oscillation during the deposition seems to be the pertinent parameter to minimize the roughness and hence to obtain a high EUV reflectivity.

Indeed, the self-bias voltage is developed on the cathode due to the capacitive coupling between the generator and the cathode. Thus, it cannot be adjusted but is just measured, and any change in the Ar plasma (caused by a change of pressure, dissipated power in discharges etc) is reflected in the target self-bias voltage. Moreover, the self-bias voltage is directly related to the ion energy distribution (and thus to the ejected sputtered atoms) [19], and it is known that the ion energy distribution is one of the primary factors governing the deposition characteristics in plasma-aided processes [20]. Consequently, any variations of the self-bias voltage in the magnetron process will induce changes in the sputtered atom energy, and have an influence on the layer roughness.

Then, the reduction of self-bias-voltage oscillations allows one to produce high-performance EUV mirrors. Moreover, an additional effect results from such an improvement: the possibility of extending the working range of the mirror, keeping the high reflectivity value. As seen in figure 2, the mirror ma083 presents a high reflectivity ($R = 66.6\%$) at 12.6 nm and 69.2°. This performance is very close to the specified one and represents an interesting exploitation of wider working conditions. Simulations for sample ma083 showed that this mirror should have this reflectivity level between 12.44 nm and 13.66 nm, and for an incidence angle between 65° and 90°.

Finally, another result of notable interest is considered: generally, the layer roughness is lower than that of the substrate (see table 1). This means that the average interfacial roughness measured by means of SAXRR (thus at high spatial frequencies) should result from the intrinsic roughness of the growth process and not from replication of the substrate roughness. This result is in good agreement with the results obtained by Stearns *et al* [13]: indeed, the authors have shown that at the lowest spatial frequencies ($<10^{-3}$ nm^{-1}) the multilayer film exactly replicates the substrate roughness, but at higher spatial frequencies ($>10^{-1}$ nm^{-1}) the film deposited using magnetron sputtering tends to reduce the substrate roughness.

4. Conclusions

In summary, this study shows that high-reflectivity ($R > 65\%$) EUV mirrors can be obtained using RF-magnetron sputtering. The performance of such mirrors is strongly related to low values of roughness which are dependent on the self-bias-voltage stability, which can be achieved using controlled Ar pressure and stable power generators. Our results indicate that, when the self-bias voltage is stable (oscillation lower than 1%), the layer roughness is lower than 2.5 Å in most cases, and there is no visible variation in layer thickness through the multilayer. Moreover, the multilayer does not seem to replicate the substrate roughness. Extension of the working conditions seems to be an additional effect of the small roughness value.

To complete the multilayer roughness study, further experiments are in progress: roughness correlation will be analysed by means of x-ray diffuse scattering in comparison with atomic force microscopy measurements; both techniques can be used to characterize the high-frequency roughness. Finally, transmission electron microscopy will be performed to analyse any atom diffusion through the interfaces [21].

Acknowledgments

The authors would thank Dr R Marmoret and Dr G Soullié for performing the EUV reflectivity measurements at the LURE Laboratory (Orsay, France; beamline SA23). This work was supported by the French programme PREUVE; funding was provided by the French government through the MEFI (French Ministry of Economy and Finance and Industry).

References

[1] Stulen R H and Sweeney D W 1999 *IEEE J. Quantum Electron.* **35** 694

[2] Derbyshire K 1998 *Solid State Technol.* **41** 78
[3] Bjorkholm J E 1998 *Intel Technol. J.* Q **3** 1
[4] Gwyn C W, Stulen R H, Sweeney D W and Attwood D 1998 *J. Vac. Sci. Technol.* B **16** 3142
[5] Taylor J S, Sommargren G E, Sweeney D W and Hudyma R M 1998 *Proc. SPIE* **3331** 580
[6] Stearns D G, Rosen R S and Vernon P 1991 *J. Vac. Sci. Technol.* A **9** 2662
[7] Jergel M, Holy V, Majkova E, Luby S, Senderak R, Stock H J, Menke D, Kleineberg U and Heinzmann U 1998 *Physica* B **253** 28
[8] Mirkarimi P B 1999 *Opt. Eng.* **38** 1246
[9] Mirkarimi P B, Bajt S and Wall M A 2000 *Appl. Opt.* **39** 1617
[10] Montcalm C, Spiller E, Wedowski M, Gullikson E M and Folta J A 1999 *Proc. SPIE* **3676** 710
[11] Slaughter J M *et al* 1994 *J. Appl. Phys.* **76** 2144
[12] Feigl T, Pommiès M and Kaiser N 1998 Investigation on multilayer coatings for EUV spectral region *Fraunhofer Institut fur Angewandte Optik und Feinmechanik (Jena) Annual Report 1998*
[13] Stearns D G, Gaines D P and Sweeney D W 1998 *J. Appl. Phys.* **84** 1003
[14] Vidal B and Marfaing J 1991 *Opt. Eng.* **30** 636
[15] Cilia M, Yakschin A, Trambly H, Vidal B and Bretagne J 1998 *Thin Solid Films* **312** 320
[16] Parrat L G 1954 *Phys. Rev.* **95** 359
[17] Névot L 1978 *PhD Thesis* Université de Paris-Sud, Orsay
[18] Lee P 1981 *Opt. Commun.* **37** 159
[19] Vidal B and Vincent P 1984 *Appl. Opt.* **23** 1794
[20] Shadid R 2000 *J. Appl. Phys.* **87** 7647
[21] Putero-Vuaroqueaux M and Vidal B 2001 Comparison of interfacial roughness propagation and correlation in Mo/Si multilayers deposited using ion beam sputtering and RF-magnetron sputtering, in preparation