Jpn. J. Appl. Phys. Vol. 41 (2002) pp. 4074–4081
Part 1, No. 6B, June 2002

Mo/Si Multilayers with Different Barrier Layers for Applications as Extreme Ultraviolet Mirrors

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(Received October 30, 2001; accepted for publication January 23, 2002)

Pulsed laser deposition (PLD) and magnetron sputter deposition (MSD) have been used to prepare different types of Mo/Si multilayers for the extreme ultraviolet (EUV) spectral range. In the case of PLD prepared Mo/Si multilayers the deposition of 0.3–0.5 nm thick carbon barrier layers at the interfaces leads to a substantial improvement of the interface quality. This can be deduced from Cu-Kα reflectivity measurements and HRTEM observations. Consequently the EUV reflectivity has been substantially increased. For pure Mo/Si-multilayers prepared by MSD the deposition parameters have been optimized so that a normal incidence reflectivity of $R_{\rm EUV} = 68.7\%$ could be realized. Although this is one of the best experimental results achieved so far, there is still a gap between this experimental value and the theoretical limit ($R_{\rm EUV} = 75.5\%$). One of the main reasons for this discrepancy is the formation of intermixing zones at the interfaces. With B_4C and C barrier layers at the interfaces interdiffusion can be reduced. The resulting EUV reflectivity of this new type of EUV multilayers is 69.8% ($\lambda = 13.42$ nm, $\alpha = 1.5°$) and 71.4% ($\lambda = 12.52$ nm, $\alpha = 22.5°$). [DOI: 10.1143/JJAP.41.4074]

KEYWORDS: Mo/Si, C, B_4C, barrier layers, EUV, multilayer, mirror, optics, magnetron sputter deposition, PLD

1. Introduction

For a long time Mo/Si multilayers as near normal incidence mirrors for the extreme ultraviolet (EUV) radiation have been of great interest and were first reported by Barbee.[1)] During the last couple of years the investigations on these multilayers have been strongly increased due to their use in a potential next generation lithography process for the semiconductor industry, namely EUV lithography. Besides this main driving force for the Mo/Si multilayer research various other applications for EUV mirrors exist: EUV photoemission microscopy, EUV spectroscopy and EUV bandpass filters for synchrotron radiation.[2)]

For all applications high reflectivity of the mirrors is one of the most important prerequisites for the optical systems. Provided that atomically flat substrates are available (surface roughnesses with $\sigma_{\rm rms} \approx 0.1$ nm), which is especially difficult for curved substrates, the performances of the optical systems depend only on the quality of the Mo/Si multilayer stacks. With different deposition methods near normal incidence reflectivities of typically 69% can be obtained with a pure Mo/Si multilayer stack. The highest values reported so far are 69.5% (at photon wavelength $\lambda = 13.0$ nm and angle of incidence $\alpha = 1.5°$) with Mo/Si multilayers deposited by electron beam evaporation in combination with ion beam smoothing[3)] and 68.7% ($\lambda = 13.4$ nm, $\alpha = 5°$) at multilayers prepared by magnetron sputter deposition (MSD).[4)] Using our coating device we have confirmed the best results so far obtained by MSD (Fig. 1).

While the number of publications relating to the basic Mo/Si multilayer configuration is rather high, only a few groups dealt with diffusion and reaction barriers within Mo/Si multilayers. The principal aim of these investigations was the improvement of the thermal stability of the layer stacks. Feigl[5,6)] have used Mo_2C barrier layers of a thickness of 0.6 nm. They succeeded to improve the thermal stability but for the multilayers with Mo_2C barrier layers they observed a considerable loss of reflectivity compared to their pure Mo/Si system ($Mo/Mo_2C/Si/Mo_2C$: $R_{\rm EUV} = 59.9\%$ at $\lambda = 13.3$ nm, $\alpha = 1.5°$, Mo/Si: $R_{\rm EUV} = 67.5\%$ at $\lambda = 13.0$ nm, $\alpha = 1.5°$). Takenaka[7,8)] have shown that even with carbon barrier layers, with a thickness of 0.3 nm, the heat resistance can be drastically improved. The EUV reflectivity measurements have resulted in values of 54.0% ($\lambda = 14.2$ nm, $\alpha = 5°$) for as deposited Mo/C/Si/C multilayers with $d_{\rm C} = 0.3$ nm and 52.8% ($\lambda = 14.4$ nm, $\alpha = 5°$) for as deposited Mo/Si multilayers.

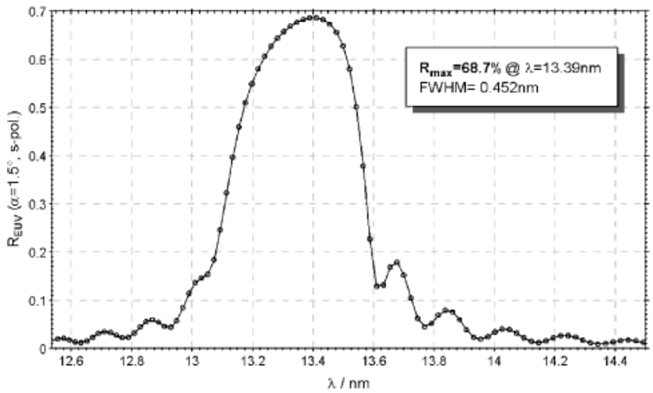

Fig. 1. EUV reflectivity of pure Mo/Si-multilayers ($d_{\rm period} = 6.82$ nm, $\Gamma = d_{\rm Mo}/d_{\rm period} = 0.39$, number of periods $N = 65$) prepared by MSD. The measurements were carried out by the PTB at the synchrotron storage ring BESSY2 in Berlin.

Very recently S. Bajt[9)] has reported reflectivities of 70.0% ($\lambda = 13.5$ nm, $\alpha = 5°$) for Mo/Si multilayers with tiny barrier layers at both interfaces. This supports the idea that a further increase of the EUV reflectivity is only possible if one is able to minimize or even avoid the formation of the typical intermixing zones at the Mo/Si interfaces consisting of amorphous $MoSi_2$.

2. Model Considerations

Concerning the highest possible EUV reflectivity in the spectral range $\lambda = 12.5$–16 nm the optimum multilayer stack,

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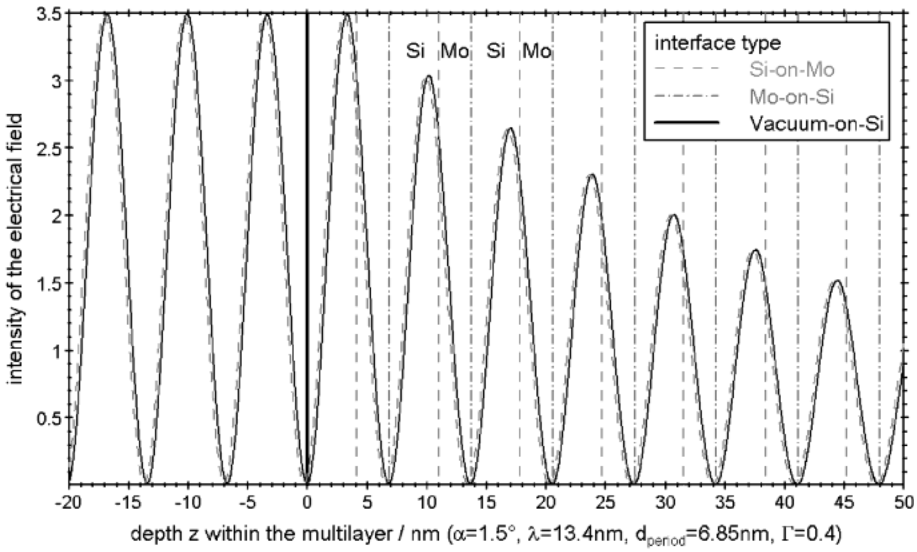

Fig. 2. Distribution of the electrical field intensity within a Mo/Si multilayer in the case of maximum reflectivity (Bragg condition fulfilled). The field strength is high at the interfaces Si-on-Mo and low at the Mo-on-Si interfaces. Therefore a thin barrier layer even of absorbing material at this interface will not affect the field distribution and the EUV reflectivity. The dotted line shows the electrical field intensity in the case of a 0.5 nm thick W barrier layer at the Mo-on-Si interface.

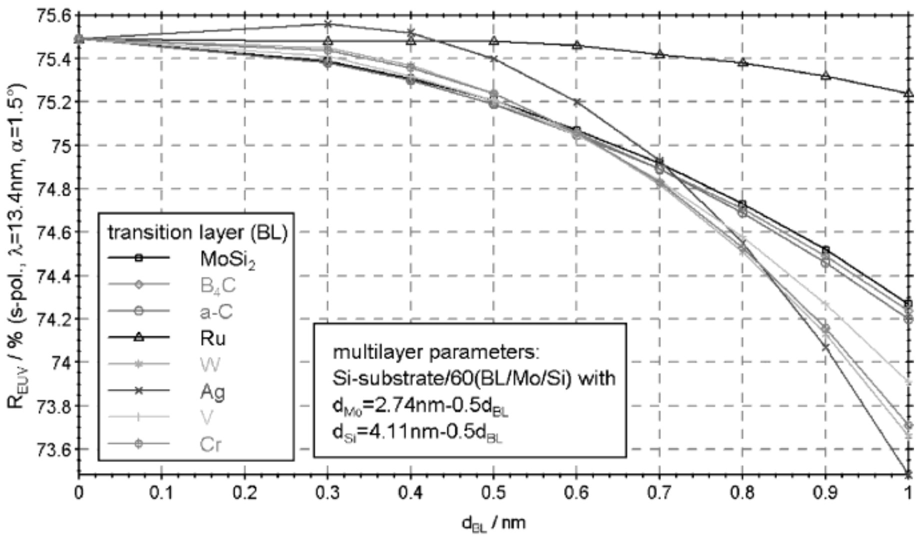

Fig. 3. Calculations of EUV reflectivity depending on the thickness of barrier layers of different materials at the Mo-on-Si interface.

consisting of two layers per period, is the Mo/Si structure. Calculations using the IMD software package written by Windt[10] show that, assuming ideally flat and abrupt interfaces as well as individual layers having bulk densities of the elements mentioned, the maximum reflectivity is 75.5% at a photon wavelength $\lambda = 13.4$ nm and an angle of incidence $\alpha = 1.5°$. Due to imperfections of real Mo/Si multilayers the experimentally obtained reflectivity is a few percent lower: $R_{\mathrm{EUV}} = 68.7\%$ at $\lambda = 13.4$ nm and $\alpha = 1.5°$. One of the main reasons for this discrepancy is the formation of intermixing zones at the interfaces. From HRTEM micrographs it can be concluded that for multilayers prepared by MSD the thicknesses of the intermixing zones are 1.2 nm for Mo-on-Si and 0.7 nm for Si-on-Mo. Therefore a further improvement of the EUV reflectivity requires the complete suppression or at least reduction of these intermixing zones. This could be achieved by the introduction of tiny interdiffusion barrier layers. The aim of this section is to select from an idealized point of view promising materials and thicknesses of different barrier layers with respect to highest possible EUV reflectivities of the appropriate period configurations.

When the Bragg condition is fullfilled a standing electrical wave field with the wavelength equal to the period thickness is formed within the multilayer (Fig. 2). Considering the amplitude of this standing wave we can see that the nodes and antinodes are at fixed positions of the multilayer stack. This results in the fact that at the locations of the nodes of the electrical field—i.e. at the interface Mo-on-Si—the addition of EUV-absorbing barrier layers will only weakly affect the electrical field and the EUV reflectivity. Hence any material that is suitable as diffusion and reaction barrier can be used at the Mo-on-Si interface provided that the barrier layer prepared is thin enough. Calculations show that, regardless of the material that is used as barrier, the EUV reflectivity is $> 75\%$ for barrier layers with thicknesses $d \leq 0.6$ nm (Fig. 3). For silver barrier layers even a higher reflectivity compared to that of the ideal Mo/Si-system is possible. Other promising candidates are ruthenium-even a barrier layer of $d = 1.0$ nm

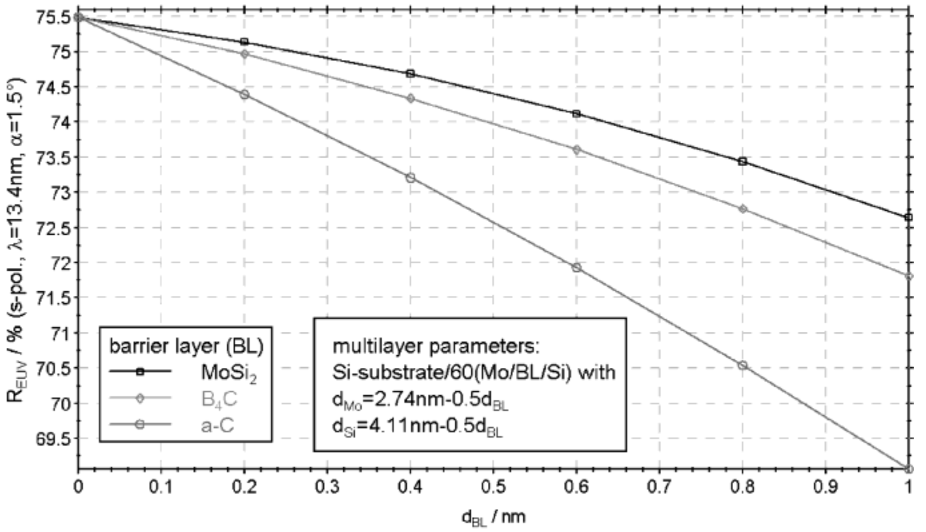

Fig. 4. Calculations of EUV reflectivity depending on the thicknesses of B_4C and C barrier layers in comparison to $MoSi_2$ transition layers at the Si-on-Mo interface.

results in a calculated EUV reflectivity of 75.2%- and carbon or boroncarbide. Nevertheless, a final decision has to consider the suitability of the particular material as an inhibitor of diffusion and reaction between the individual layers of Mo and Si.

Looking at the Si-on-Mo interface the situation is completely different: the standing wave field has an antinode at this interface and therefore absorption of barrier layers at this stack position will strongly affect the EUV reflectivity. From calculations we can conclude that even materials with a lower EUV absorption like boroncarbide or carbon cause a stronger loss of reflectivity than $MoSi_2$ does if the thickness of these barrier layers approaches the size of the $MoSi_2$ intermixing zones (Fig. 4). Knowing that the thickness of the $MoSi_2$ transition layer is about 0.7 nm at the Si-on-Mo interface, an increase of the EUV reflectivity can only be realized if barrier layers thinner than 0.5 nm for B_4C or 0.3 nm for C prevent the interdiffusion.

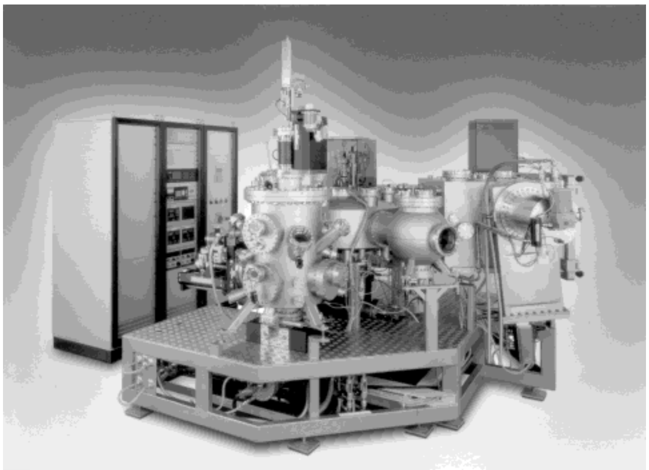

Fig. 5. Photograph of the hybrid system consisting of a central handling system (in the middle), the PLD chamber (in front), the MSD chamber (right), the sample magazine (right in front) and the sample load lock (not visible).

3. Experimental Setup

Recently a new hybrid coating plant has been realized in our laboratory that allows the alternating application of the two thin film preparation techniques pulsed laser deposition (PLD) and MSD without interupting vacuum conditions. The system (Pink company, Wertheim, Germany) consists of a central handling chamber, two deposition chambers (PLD and MSD), one sample magazine and the load lock (Fig. 5). The maximum substrate size is 150 mm in diameter.

The concept of the large area PLD system has been adopted from existing systems and was described elsewhere.[11–13] For the deposition of Mo/Si multilayers we have used the parameters mentioned in.[11]

The set-up of the MSD system is very similar to that used by Windt.[14] Inside the sputter chamber with a square footprint four magnetrons (Ångstrøm Sciences, Duquesne, PA, USA) are mounted (face up) along the diagonals (Fig. 6). The targets with a size of $304.8 \times 88.9 \times 6.35\,mm^3$ are arranged in such a way that Mo is positioned opposite to Si. The two remaining magnetrons are equiped with materials of barrier, buffer or capping layers (*e.g.* B_4C, C, W, Ru, Ag). The target-substrate distance can be chosen between 50 and 100 mm. The thicknesses of the individual layers are controlled by altering the angular frequencies ω_R depending on the angle ϕ relative to the starting position. For the deposition of the multilayers described in this work we have used the typical parameters in the following ranges:

- $\omega_R(Mo) = 1.4$–1.8 rpm, $\omega_R(Si) = 0.3$–0.5 rpm, $\omega_R(C) = 0.5$–5 rpm, $\omega_R(B_4C) = 0.5$–5 rpm, $\omega_R(W) = 1$–3 rpm, $\omega_R(Ag) = 3$–5 rpm
- Magnetron source power: P(Mo) = 250–300 W, P(Si) = 200–250 W, P(C) = P(B_4C) = P(W) = 150 W, P(Ag) = 50 W
- Base pressure: $p < 2.0\cdot10^{-8}$ mbar
- Sputter gas: argon with a working pressure of 1–$1.5\cdot10^{-3}$ mbar.

4. Experimental Results

In this section we describe the results obtained with Mo/Si multilayers having diffusion and reaction barrier layers at the interfaces. The first part deals with PLD prepared Mo/Si mul-

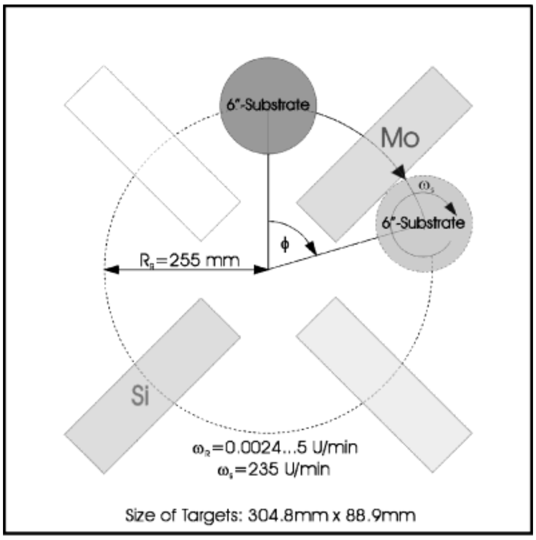

Fig. 6. Scheme of the target-substrat arrangement inside the sputtering chamber. The two positions between Mo and Si are occupied by barrier, buffer or capping layer materials.

tilayers with C barrier layers, in the second part MSD prepared Mo/Si multilayers with B_4C and C barrier layers are considered.

HRTEM micrographs, Cu-Kα reflectographs and diffractographs are analyzed to investigate stack parameters and microstructure of the multilayers.

4.1 *Carbon barrier layers in Mo/Si multilayers prepared by PLD*

Due to the quasi-ion beam assisted coating process of PLD (for parameters of particle flux from laser induced plasmas see *e.g.*[15]) the interfaces between the individual layers of the stack are extremely smooth. But not only the interface roughness is important to obtain multilayers of high reflectivity, also the interface diffuseness must be low to ensure a steep gradient of electron density contrast between absorber and spacer layers, i.e. Mo and Si. It turned out that this is a critical point in PLD prepared multilayers. The higher kinetic energy of the condensing particles leads to the activation of diffusion and reaction processes which result in an absorber composition that is closer to amorphous $MoSi_2$ than to pure Mo. It is difficult to determine precisely the composition of the absorber layer but we found that by reducing laser power density at the target surface the average kinetic energy of the plasma-emitted particle flux is lowered and as a consequence the amount of silicon penetrating the absorber also decreases. But even for the lowest possible laser power density the amount of silicon is so high that the reduction of the optical contrast between absorber and spacer decreases the reflectivity of the Mo/Si multilayers by more than 20%.

To investigate the influence of carbon barrier layers at the particular interfaces we prepared three sets of test samples with the following stack configurations:

- P1: Si-substrate/C/5(Mo/C/Si)
- P2: Si-substrate/C/5(Mo/Si/C)
- P3: Si-substrate/C/5(Mo/C/Si/C)

with $d_C = 0.7$ nm for all specimens. From Cu-Kα reflectivity measurements and TEM investigations it could be concluded that interdiffusion mainly occurs at the Si-on-Mo interface. Comparing the samples of P1 and P2 sets we see that for the same deposition parameters in all layer stacks the period thickness of P2 specimens is ≈ 0.75 nm lower than that of P1. This indicates interdiffusion at the interface Si-on-Mo, which was also confirmed by TEM investigations, where we observe an interdiffusion zone with a thickness of ≈ 2.4 nm (Fig. 7(b)).

Considering samples of P1, where the C barrier layer is at the Si-on-Mo interface, we do not observe such a strong interdiffusion (Fig. 7(a)). Nevertheless the period thickness of P1 compared to P3 is ≈ 0.25 nm lower than expected when the additional C layer thickness in P3 is taken into account. This leads to the assumption, that interdiffusion also occurs at the Mo-on-Si interfaces. For a final decision whether it is necessary also to integrate carbon barrier layers at the Mo-on-Si interfaces we prepared 40-period multilayers with (a) barrier layers at both interfaces and (b) only at the Si-on-Mo interfaces ($d_C = 0.3 \ldots 0.5$ nm). Subsequently the specimens were characterized by EUV reflectivity measurements. From the difference in reflectivity of typically 10% between the two systems we can conclude, that for PLD prepared multilayers the use of barrier layers is mandatory at both interfaces. By optimizing the deposition parameters (laser pulse power density, laser pulse frequency, target movement, target-substrate distance) we are able to prepare multilayers by PLD having an EUV reflectivity of typically 60%.[11]

4.2 *Barrier layers in Mo/Si multilayers prepared by MSD*

The comparison of PLD and MSD shows that the mean energy of the particles arriving at the substrate is substantially higher in case of PLD. Therefore in MSD to a lower extent the activation of diffusion and reaction processes and ballistic intermixing effects should happen in the individual layers due to reduced interaction between the different atoms and ions of the particle flux and atoms of the transient layer surface. Hence EUV coatings of a high reflectivity can also be prepared using pure Mo/Si multilayers (Fig. 1). But, as already mentioned in §3, intermixing zones of amorphous $MoSi_2$ are formed, which restrict the EUV reflectivity of the pure Mo/Si system to typically 69%. To improve this reflectivity level for high quality optics an investigation about an advantageous effect of the application of diffusion inhibitors has been initiated.

4.2.1 *B_4C barrier layers*

Due to the encouraging results of the model calculations (Fig. 4) at first we tested the B_4C compound as a material for diffusion barriers. Three sets M1-M3 of 40-period multilayers having different period stack configurations all involving B_4C layers of $d_{B_4C} = 0.3$–0.5 nm were prepared:

- M1: Si- or ULE-Substrate/60(Mo/B_4C/Si)
- M2: Si- or ULE-Substrate/60(Mo/Si/B_4C)
- M3: Si- or ULE-Substrate/60(Mo/B_4C/Si/B_4C).

The period thicknesses of the samples were kept constant within an intervall of 6.8–6.9 nm, the ratio of the Mo and Si layer thicknesses is $d_{Mo}/d_{Si} \approx 2/3$ (i.e. $d_{Mo} = 2.3$–2.7 nm, $d_{Si} = 3.5$–4.1 nm).

Results obained by HRTEM, X-ray reflectometry and diffractometry are shown in Figs. 8–10. The HRTEM micrographs in Fig. 8 show cross sections of each stack configuration mentioned above. In comparison to the basic Mo/Si stack Fig. 8(a) shows that the period of M1 samples consists

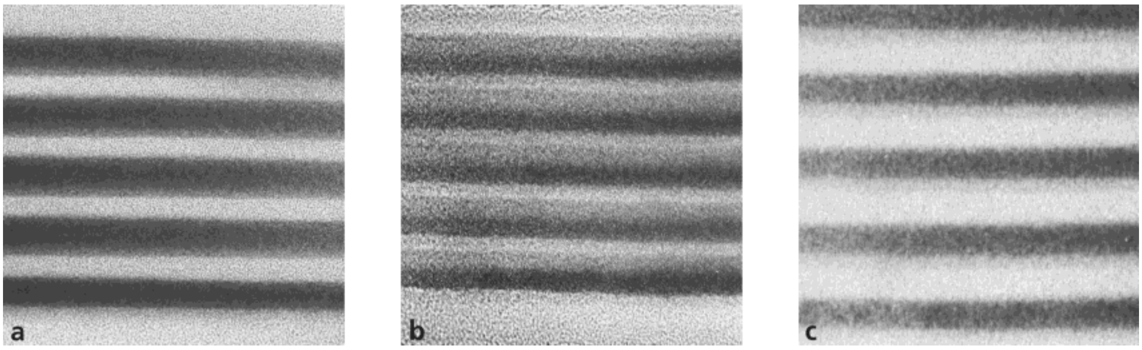

Fig. 7. Cross-sectional HRTEM images of Mo/Si multilayers prepared by PLD with C barrier layers at different interfaces: a: C at the Si-on-Mo interface, b: C at the Mo-on-Si interface, c: C at both interfaces ($d_C = 0.7$ nm in all cases).

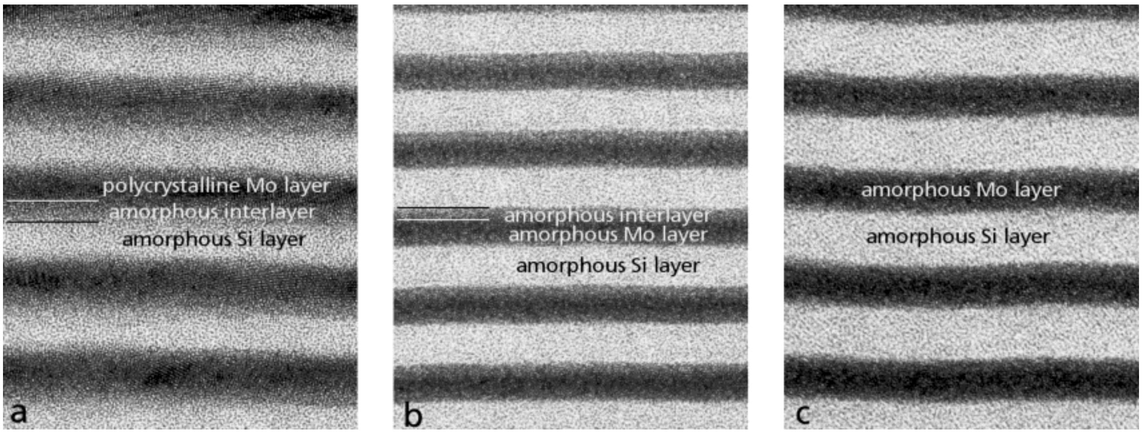

Fig. 8. Cross-sectional HRTEM images of Mo/Si multilayers prepared by MSD with B_4C barrier layers at different interfaces: a: B_4C at the at the Si-on-Mo interface, b: B_4C at the Mo-on-Si interface, c: B_4C at both interfaces ($d_{B_4C} = 0.5$ nm in all cases).

of a polycrystalline Mo layer with only one amorphous intermixing zone at the Mo-on-Si interface and an amorphous Si spacer. Within the error level the thickness of the intermixing zone is equal to the thickness of the amorphous interlayer in pure Mo/Si at the Mo-on-Si interface ($d \approx 1.2$ nm). In contrast to pure Mo/Si multilayers M1 samples do not exhibit amorphous interlayers at the Si-on-Mo interfaces. There is a sharp transition from the polycrystalline Mo layer to the amorphous Si layer at this interface.

In Fig. 8(b) a much steeper gradient of the electron density was found at the Mo-on-Si interface. No interlayer was observed at this interface. Considering the microstructure of the Mo layer a significant difference between the pure Mo/Si multilayer and M2 samples is found: in difference to the pure Mo/Si stack no lattice fringes of the Mo layers can be found in M2 samples. We verified this for different samples and we believe that this is no artifact of the specimen preparation. At the Si-on-Mo interface similar to the pure Mo/Si stack an amorphous $MoSi_x$ interlayer was found. The comparison of the thicknesses of these interlayers results in a slighly higher value: $d = 0.9$–1.0 nm for M2 samples, $d \approx 0.7$ nm for pure Mo/Si samples.

In Fig. 8(c) sharp interfaces at either of the absorber sides are shown. In contrast to pure Mo/Si multilayers we observed in M3 samples only two separated layers per period without any interdiffusion layer. The morphology of the Mo layer also differs from that in the pure Mo/Si stack: as in M2 samples no lattice fringes are found.

Cu-Kα reflectometry results in similar reflectographs for pure Mo/Si multilayers and M1-M3 samples (Fig. 9). Due to the changed ratio $\Gamma = d_{Mo}/d_{period}$ the individual Bragg reflection peak intensities are changed relative to each other. Nevertheless the number of detectable Bragg reflection peak orders is 12 in all cases. The analysis of the shape of the Bragg peaks shows no systematical difference in the half widths (FWHM) of the Bragg peaks.

Cu-Kα diffractometry carried out in the Θ–2Θ step scan mode shows significant differences of the diffraction patterns of Mo/Si multilayers with and without B_4C barrier layers at the Mo-on-Si interface (Fig. 10).

Measurements of pure Mo/Si multilayer specimens show a diffraction peak at 40.6° (FWHM = 4.1°) corresponding to the (110) lattice plane of bcc Mo. The (110) diffraction peak of M1 samples resembles that of pure Mo/Si, but the peak position is shiftet to smaller angles (39.7°) and the FWHM is slightly reduced (3.9°). Diffractographs of M2 and M3 samples show a pattern with (110) diffraction peaks of strongly decreased intensities and increased FWHM. Furthermore the center of gravity of the peaks is shifted towards smaller angles, which indicates an increase of the Mo lattice parameters by $\approx 2\%$.

First EUV reflectivity measurements of M1 and M2 samples resulted in the following values:

- M1: $R_{EUV} = 67.9\%$ ($\lambda = 13.51$ nm, $\alpha = 1.5°$)
- M2: $R_{EUV} = 67.3\%$ ($\lambda = 13.43$ nm, $\alpha = 1.5°$).

Both reflectivities are lower than those of pure Mo/Si multilayers.

For M1 multilayers the EUV reflectivity is typically 0.5% lower than that of pure Mo/Si multilayers. This decrease could be caused by a barrier layer composition not equal to

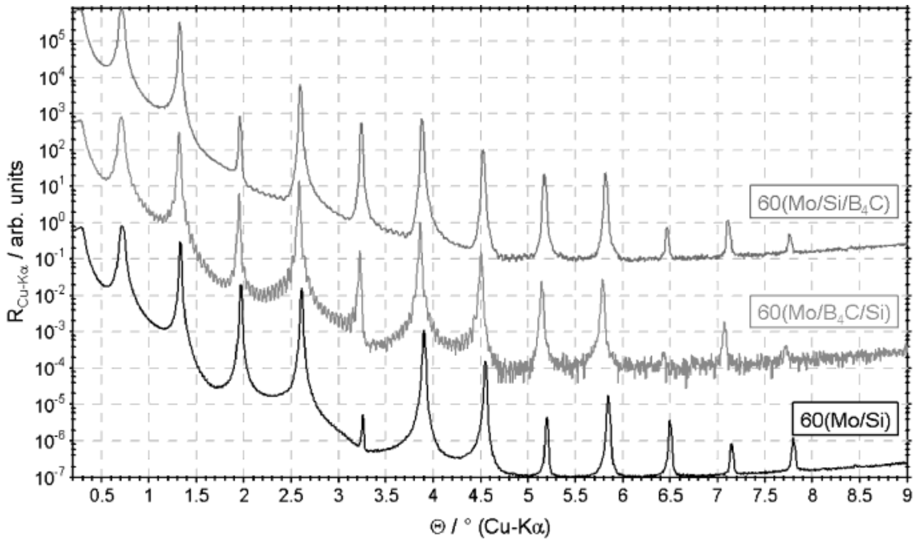

Fig. 9. Cu-Kα reflectographs of Mo/Si multilayers with B_4C barrier layers at different interfaces. For Cu-Kα radiation B_4C acts as spacer material, therefore the ratio $\Gamma = d_{\rm Mo}/d_{\rm period}$ is changed. The number of observable Bragg reflection peaks (12) indicates that no difference of the interface roughness of the three multilayer configurations exists.

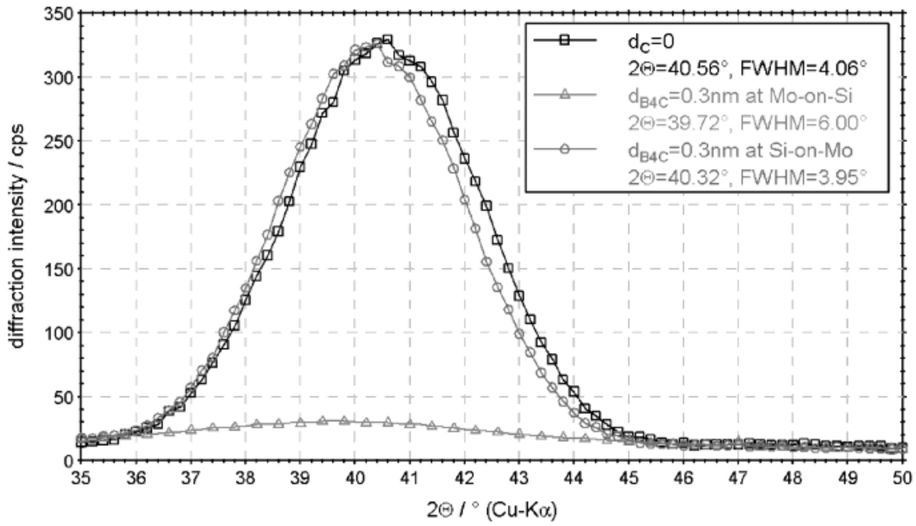

Fig. 10. Mo (110) diffraction peaks of Mo/Si multilayers prepared by MSD with B_4C barrier layers with a thickness of 0.3 nm at different interfaces.

B_4C. A higher amount of C within the nominal B_4C compound will strongly affect the EUV reflectivity (Fig. 4). A barrier layer with a thickness of 0.5 nm consisting of pure C instead of B_4C would lead to an EUV reflectivity decrease of 1.5%. One solution could be the reduction of the thickness of the B_4C barrier layer at the Si-on-Mo interface.

The EUV reflectivity of M2 samples is more than 1% lower than that of pure Mo/Si multilayers. This difference can easily be understood when looking at the HRTEM pictures of these samples. The increased thickness of the interdiffusion zone at the Si-on-Mo interface compared to pure Mo/Si multilayers causes stronger absorption of the electrical field. Even small thickness changes of the interdiffusion layers at this interface have a strong impact on the EUV reflectivity. In pure Mo/Si multilayers the Mo layers grow on amorphous Si layers and crystallize abrupt at a thickness of ≈ 2 nm.[16] Despite a thickness > 2 nm of the Mo layers with B_4C barrier layers at the Mo-on-Si interfaces no crystallization of the Mo layers happens. It is not completely understood what the reasons for this changed behavior are. Possibly interdiffusion of the barrier layer elements B and/or C into the growing Mo layers occurs and the B and/or C atoms in solution in the Mo layers inhibit the formation of Mo crystallites. As already mentioned[16] crystallization of Mo does not happen in pure Mo/Si multilayers until a critical thickness is reached. This can be stated for sputter coated systems where in general the Si concentration in the Mo layers is low enough. The observations in PLD prepared Mo/Si multilayers support this interpretation: the high concentration of Si in the Mo layers stabilizes the amorphous state of the Mo layers even for thicknesses > 2 nm. Following this interpretation we can suppose that the critical concentration of C and/or B in the Mo layers below that the transition between amorphous and crystalline growth happens is always exceeded in our M2 and M3 samples. An amorphous character of the Mo layers can be an advantage if we take into account that amorphous films normally grow smoother than polycrystalline films of the same thickness. But, there can also be a disadvantage: polycrystalline films have a density which is almost identical with the bulk density of the material, whereas the density of amorphous layers is in

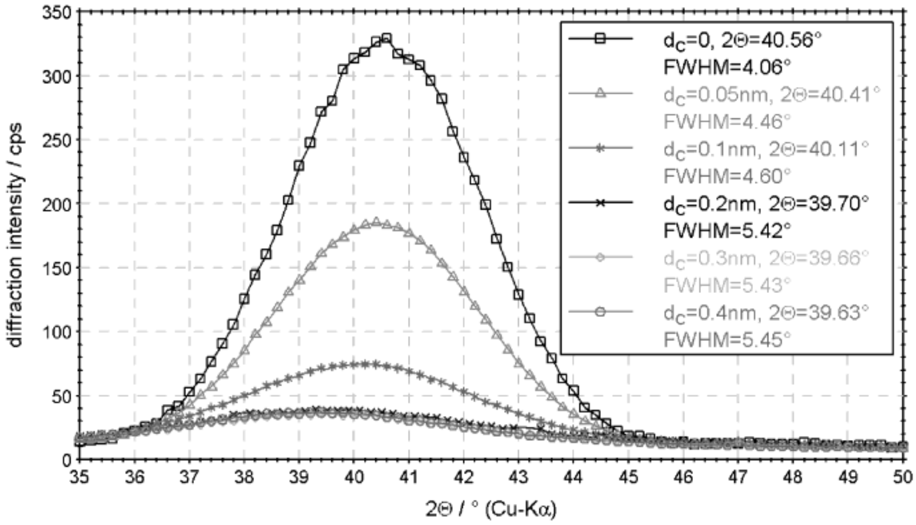

Fig. 11. Mo (110) diffraction peaks of Mo/Si multilayers prepared by MSD with C barrier layers of different thicknesses at the Mo-on-Si interface showing a continous transition from crystalline to amorphous state of the Mo layer.

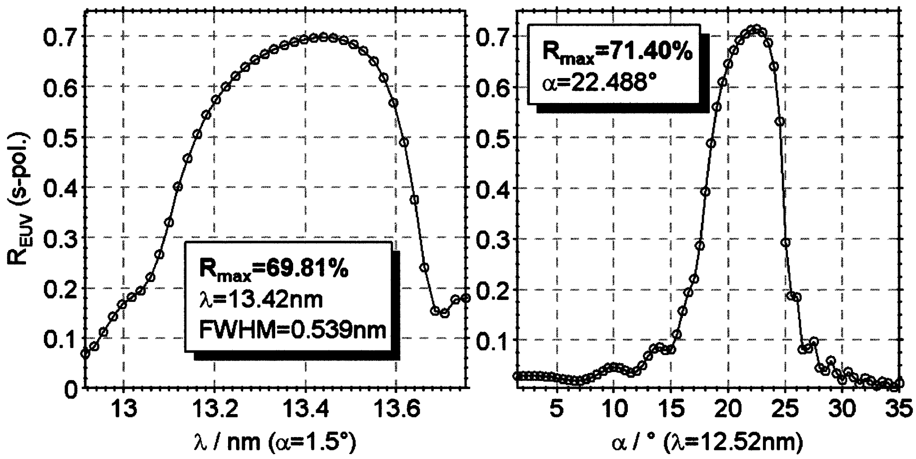

Fig. 12. EUV reflectivity (measured at PTB/BESSY2) of Mo/Si multilayers with B_4C and C barrier layers ($d_{period} = 6.86$ nm, $d_{B_4C} \approx d_C \approx 0.2$ nm, $d_{Mo} \approx 2.6$ nm, $d_{Si} \approx 3.9$ nm, $N = 60$) at fixed $\alpha = 1.5°$ (left hand side) and fixed $\lambda = 12.52$ nm (right hand side).

most cases lower. Therefore amorphous Mo layers could lead to a decrease of the optical contrast between spacer and absorber. Furthermore the increased Si-on-Mo interlayer thickness with amorphous Mo layers decreases the maximum EUV reflectivity. For an advancement of the reflectivity the application of barrier layers at either of the absorber interfaces is mandatory. In this case intermixing zones could not be observed in the stacks (Fig. 8). Future investigations will be carried out on multilayers with barrier layers at both interfaces of various thicknesses.

4.2.2 C barrier layers

Similar experiments for preparation and characterization as described for the B_4C-type have been caried out for the C-type barrier containing multilayers. Due to the model calculations (Figs. 3 and 4) C barrier layers are more suitable for the Mo-on-Si interface. Therefore multilayers with the following stack configuration were prepared:

- M4: Si-Substrate/60(Mo/Si/C) with $d_C = 0.05$–0.4 nm

For these samples the Mo and Si layer thicknesses are constant ($d_{Mo} \approx 2.7$ nm, $d_{Si} \approx 4.1$ nm).

Our investigations were mainly focused on the Cu-Kα diffractometry to get information about the microstructure of the Mo layers depending on the thickness of the barrier layers. The Mo(110) diffraction peaks of various stack configurations are shown in Fig. 11. We found that with increasing barrier layer thickness from $d_C = 0$ to $d_C = 0.4$ nm the diffraction intensity decreases down to $\approx 10\%$, the peak position shifts to smaller angles from 40.6° to 39.6° and the FWHM increases from 4.1° to 5.5°. Up to a thickness of $d_C = 0.2$ nm a continuous transition was observed. A further increase of the C barrier layer thickness results in rather small changes of the diffraction peaks (Fig. 11). Possibly at the thickness of 0.2 nm the C layer forms a continuous film and the growth of the Mo layer is no longer influenced by the Si layer underneath. This gives a measure how thick the barrier layers at least must be to achieve a substantial influence on the chemical driving forces gained by the Si layer.

With these results described so far the following multilayer type was prepared:

- M5: ULE/59(Mo/B_4C/Si/C)/Mo/B_4C/Si with $d_{B_4C} \approx d_C \approx 0.2$ nm, $d_{Mo} \approx 2.6$ nm, $d_{Si} \approx 3.9$ nm.

The EUV reflectivity measurements shown in Fig. 12 exhibit maximum reflectivities of 69.8% at a photon wavelength $\lambda = 13.42$ nm and an angle of incidence $\alpha = 1.5°$ and 71.4% at

$\lambda = 12.52$ nm and $\alpha = 22.5°$ (Fig. 12). In comparison to pure Mo/Si multilayers an advancement of the EUV reflectivity of $> 1\%$ was proven. Since this has been one of the first attempts to prepare specimens with effective barrier layers we believe that from a continued optimization of this new type of Mo/Si based EUV mirrors a further increase of the EUV reflectivity is possible.

Acknowledgments

This work has been partially supported by the Bundesministerium für Bildung und Forschung (BMBF) (FKZ-number 13N7886) as well as by the companies Carl Zeiss Oberkochen and Jenoptik Jena. We would like to thank F. Scholze, J. Tümmler, B. Meyer, K. Vogel from PTB/BESSY2 Berlin for numerous EUV reflectivity and uniformity measurements. For fruitful discussions and contributions to the temperature behavior of Mo/Si multilayers having B_4C barrier layers (publication in preparation) we would like to thank Th. Böttger, D.C. Meyer and P. Paufler from IKFP, TU Dresden.

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