Mo-based multilayer for beyond EUV lithography

Naoki Hayase[a], Masashi Yoshimura[b], Satoru Suzuki[a], Shinji Yamakawa[a], Tetsuo Harada[a]

[a] Center for EUV lithography, LASTI, University of Hyogo, 1-1-2 NewSUBARU synchrotron radiation facility, Ako-gun Kamigori Kouto, Hyogo 678-1205, Japan

[b] SPring-8 Service Co., Ltd., Ako-gun Tatsuno Kouto 1-20-5, Hyogo 679-5165, Japan

Abstract: Beyond EUV (BEUV) lithography has been developing for further downscaling of semiconductor devices. We propose Mo_2N/B multilayer (ML) for designing high-reflectance, high-durability BEUV mirrors. **Background:** High-reflectance MLs are key components for photomasks and BEUV optic, and their performance depends on optical constants and interfacial stability. La-based ML has reported a reflectivity of over 60%, but it concerns chemical stability to water vapor in air and BEUV-induced hydrogen plasma in lithography. Therefore, alternative materials are required to improve the durability. **Aim:** We investigate the reflectivity and the durability of Mo_2N/B ML as an alternative of La-based ML. **Approach:** We fabricated Mo_2N/B ML by unbalanced magnetron sputtering, and evaluated the BEUV reflectivity and EUV-induced hydrogen plasma durability at NewSUBARU synchrotron radiation facility. The profile of Mo_2N/B MLs was assessed by using XRR, and STEM-EDX. **Results:** BEUV reflectivity obtained 8.5% by ML of 80 pairs and the XRR remained unchanged after storage in air over 1 month, which confirmed its chemical stability. EUV accelerated lifetime tests observed no blister formation during 8 hours of irradiation. **Conclusion:** This work demonstrated the potential of durability in Mo_2N/B ML, offering a viable Mo-based design. We observed the interfacial state of the ML considering diffusion, roughness, and crystallinity, suggesting the pathway to improve BEUV reflectivity.

Keywords: beyond EUV; multilayer; reflectivity; durability; XRR; STEM-EDX; EUV-induced plasma.

E-mail: hayase@lasti.u-hyogo.ac.jp

1 Introduction

Beyond extreme ultraviolet (BEUV) lithography at 6.x nm has been developing for high-volume manufacturing beyond 6 nm half pitch [1]. The BEUV exposure system is based on the Bragg reflection as well as EUV, and requires a precisely engineered multilayer (ML) for mirrors and photomasks. High-reflectance, high-durability MLs are essential for improving mask lifetime and energy efficiency in BEUV lithography.

La-based MLs have been studied as promising candidates, and reported 64.1% of BEUV reflectivity in La/LaN/B ML [2-4]. However, La-based materials are concerned about their chemical stability with moisture in air and BEUV-induced hydrogen plasma in lithography [5]. B as high-refractive index material is also required to be protected from oxidation such as a capping layer [6]. Mo-based MLs have been reported to have a reflectivity around 9.4% in Mo/B of 100 pairs, but previous works have not discussed their durability and chemical state [7,8].

In this study, we propose Mo_2N/B ML with the potential for high-reflectance and high-durability. We fabricated Mo_2N/B MLs by unbalanced magnetron sputtering and assessed these performances by reflectometry and EUV accelerated lifetime tests at the NewSUBARU synchrotron radiation facility. We analyzed the chemical states and the interfaces in Mo_2N/B by using X-ray reflectivity (XRR) and energy dispersive X-ray spectroscopy in STEM (STEM-EDX).

2 Experiments and Results

We use unbalanced magnetron sputtering (UBMS) for Mo_2N/B ML deposition. This UBMS can provide argon (Ar) and nitrogen (N_2), and we setup to N_2 within 20% in total as following Ref [9,10]. The base pressure before deposition is on the order of 10^{-5} Pa, and the working pressure during sputtering is 0.7 Pa. The purity of Mo and B sputtering targets are both 99.9%.

Fig. 1-(a) shows the XRR measurements at 0.135 nm wavelength both on 1 day and 39 days after deposition in Mo_2N/B ML of 80 pairs as sample #1. These peak intensities were constant and the estimated thickness and roughness of Mo_2N/B were 1.37 nm/2.11 nm and 0.5 nm, respectively.

Fig. 1-(b) shows that the reflectivity at 6.60 nm wavelength measured after 30 and 39 days after deposition at NewSUBARU synchrotron radiation facility. The reflectivity was 8.5% both at 73° of grazing angle, indicating that the roughness and film density change is negligible.

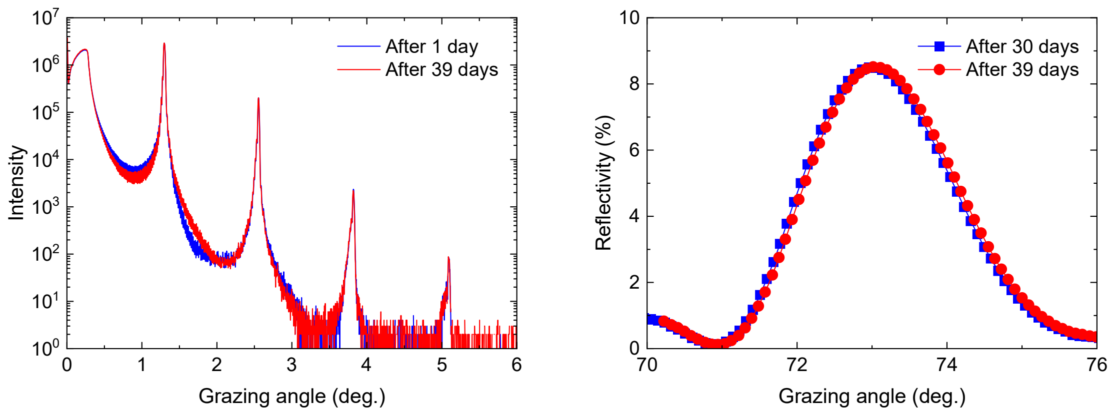

Fig. 1 (a) XRR measurements after 1 day and 39 days in sample #1, (b) Reflectivity at 6.60 nm in sample #1.

Fig. 2 shows the STEM-EDX result of sample #1. C-based capping layer was deposited on the sample #1 for cutting process, and kept vacuum state from the cutting process to STEM-EDX observation. The estimated thickness of Mo_2N/B was 1.42 nm/2.42 nm, including the interfacial diffusion layer of around 0.4 nm.

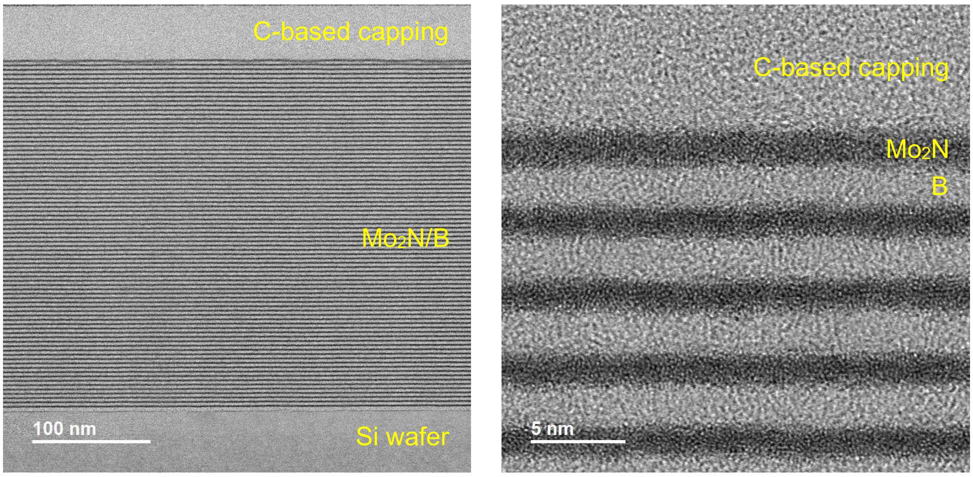

Fig. 2 Cross-sectional STEM image of Mo_2N/B ML in sample #1.

Fig. 3 shows the high-angle annular dark-field (HAADF) and the EDX images of B, C, N, O, Si, Mo, and Ar in sample #1. Since the B-K and Mo-L emission lines overlap, the B distribution within the Mo_2N layers cannot be distinguished. The N-K signal is distributed throughout the ML, whereas a higher O-K and Ar-K lines are observed in each B layer. These results indicate that oxygen is incorporated into the B layers, while nitrogen is distributed in the ML.

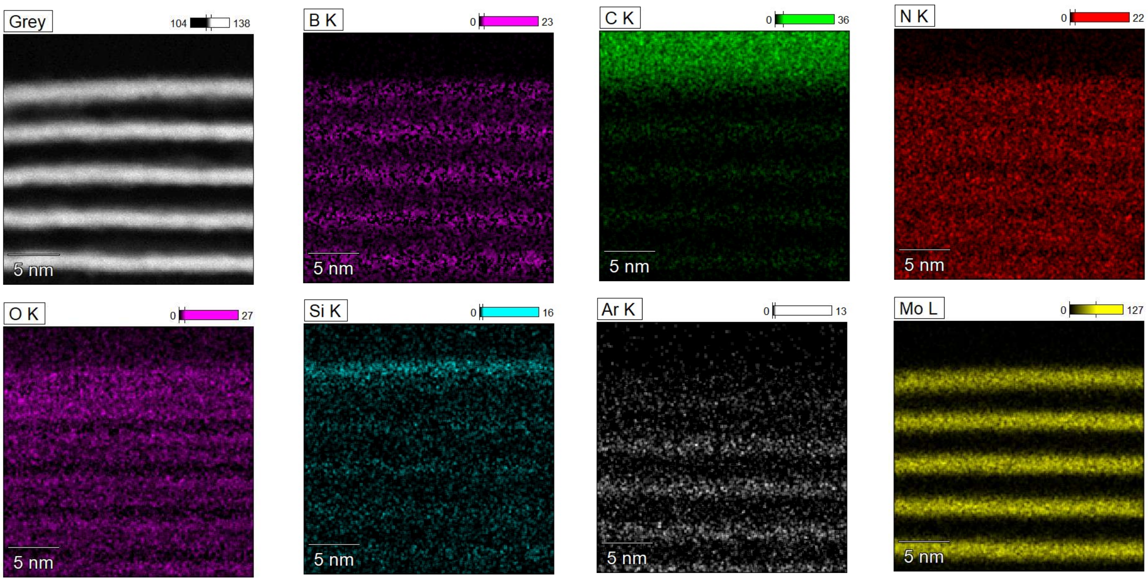

Fig. 3 EDX images of B, C, N, Mo, O, Si, and Ar in sample #1.

Fig. 4 shows the fast Fourier transform (FFT) of high-resolution TEM images obtained from the Mo_2N and B layers in sample #1. The Mo_2N layer exhibited crystalline diffraction rings (No. 1- to 4) with a weak diffuse scattering as the coexistence of crystalline and amorphous. In contrast, the B layer showed a diffuse halo pattern (B-1 and B-2), indicating an amorphous. Similar diffraction characteristics were observed both near the surface and at the center of the ML, indicating that these structural features are maintained throughout the ML, consistent with the unchanged XRR profile after one month in air.

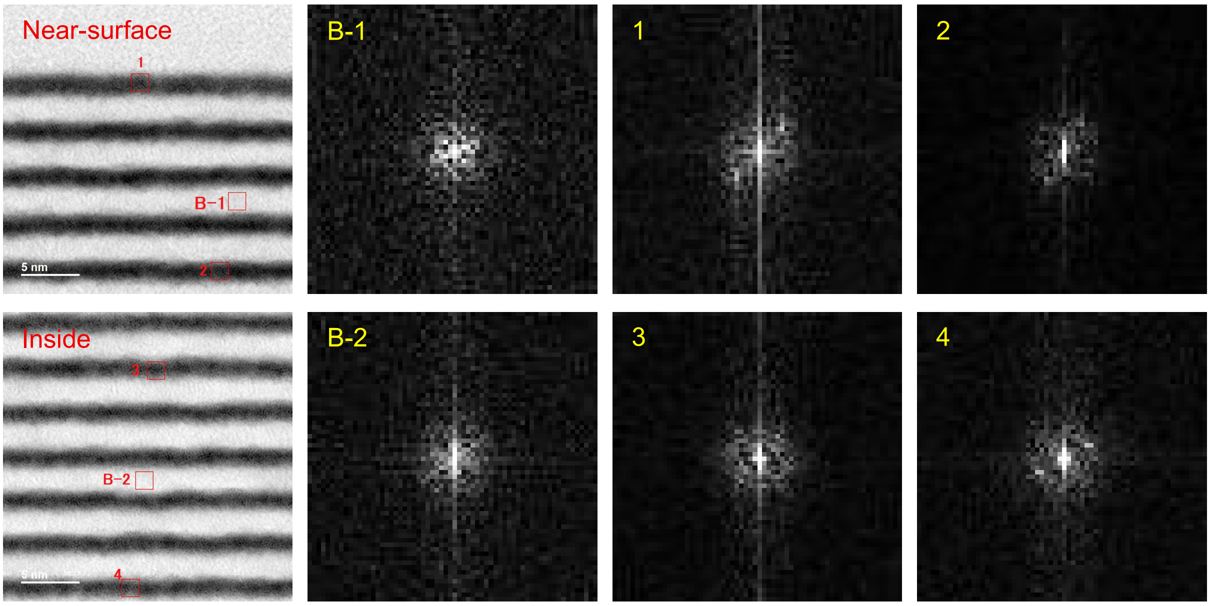

Fig. 4 FFT of HRTEM images in Mo_2N and B layers of sample #1.

Fig. 5-(a) shows the results of the EUV accelerated lifetime tests conducted on samples #2 and #3. Each sample was irradiated with EUV light under a hydrogen pressure of 70 Pa and a water-vapor pressure of 3×10^{-3} Pa, respectively. The microscope images in Figs 5-(b) and (c) show the surfaces of #2 and #3 after EUV irradiation, and the significant color changes were observed in irradiated regions, whereas no blister formation (film delamination) was detected.

Figs. 5-(d) and (e) show the XAS spectra of samples #3 aim to evaluate the oxidation by water vapor. The result denotes a decrease in the N K-edge absorption intensity and an increase in the O K-edge absorption intensity in irradiated- and unirradiated regions, indicating nitrogen loss and oxidation after irradiation under the water-vapor atmosphere. The chemical state after irradiation under hydrogen, and the origin of the color change in #2 remains to be determined.

(a)	#2	#3
ML	Mo_2N/B	
Number of pairs	80	130
Background gas	H_2	H_2O
Intensity (W/ cm^2)	34.57	33.30
Time (hour)	8	4
Pressure (Pa)	70	3×10^{-3}
Dose (kJ/cm^2)	995.62	479.52
Result	No blister	No blister

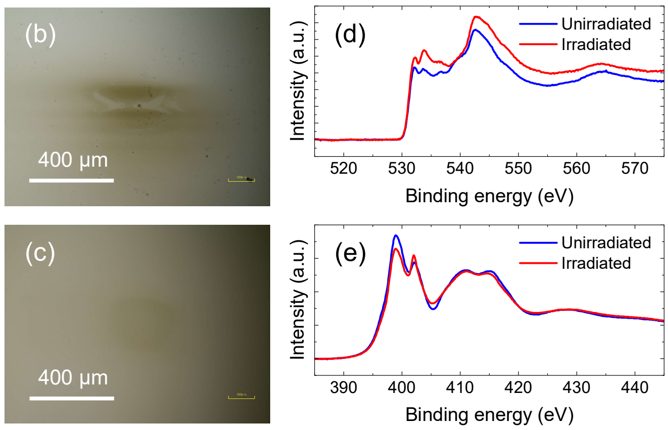

Fig. 5 (a) Test conditions, (b) and (c) Microscope images in #2 and #3 after the irradiation, (d) O K-edge by XAS results in sample #3, (e) N K-edge by XAS in sample #3.

3 Conclusion

We proposed and fabricated Mo_2N/B ML as new candidate mirror for BEUV lithography. The BEUV reflectivity obtained 8.5% and the XRR remained unchanged after deposition and over a month later in air. The EUV accelerated lifetime test observed no blister formation in the ML during 8 hours of irradiation under hydrogen. The STEM-EDX results indicate the interfacial diffusion layers as around 0.4 nm and oxidation of B through the Mo_2N/B ML. Our results confirmed the chemical stability of Mo_2N/B interface, and the characterization of interfacial diffusion originating from deposition, indicating the clue to improve its reflectivity.

Disclosures

The authors declare that there are no financial interests, commercial affiliations, or other potential conflicts of interest that could have influenced the objectivity of this research or the writing of this paper.

Code, Data, and Materials Availability

The data that supports the findings of this study are available from the corresponding authors on request and https://github.com/nhayase/JM3-260092L-1.

Acknowledgments

This work was partially supported by Hyogo Earthquake Memorial 21st Century Research Institute, Hyogo Foundation for Science and Technology, Tanaka Kikinzoku Memorial Foundation, and Takahashi Industrial and Economic Research Foundation.

References

1. H. J. Levinson, “Lithography at the end of scaling,” *Jpn. J. Appl. Phys.* **65** 020802 (2026).
2. T. Tsarfati, R.W.E. van de Kruijs, E. Zoethout, E. Louis, F. Bijkerk, “Reflective multilayer optics for 6.7 nm wavelength radiation sources and next generation lithography,” *Thin Solid Films* **518**, 1365–1368 (2009).
3. I. A. Makhotkin, E. Zoethout, R. van de Kruijs, S. N. Yakunin, E. Louis, A. M. Yakunin, V. Banine, S. Müllender, F. Bijkerk, “Short period La/B and LaN/B multilayer mirrors for~ 6.8 nm wavelength,” *Opt. Express* **21**(24), 29894-29904 (2013).
4. D. S. Kuznetsov, A. E. Yakshin, J. M. Sturm, R. van de Kruijs, E. Louis, F. Bijkerk, “High-reflectance La/B-based multilayer mirror for 6. x nm wavelength,” *Opt. Lett.* **40**(16), 3778-3781 (2015).
5. D. J. Morgan, “Core-level spectra of metallic lanthanides: Lanthanum (La),” *Surf. Sci. Spectra* **31**(1), 014010 (2024).
6. L. B. Bayu Aji, A. A. Baker, J. H. Bae, A. M. Hiszpanski, E. Stavrou, S. K. McCall, S. O. Kucheyev, “Degradation of ultra-thin boron films in air,” *Appl. Surf. Sci.* **448**, 498-501 (2018).
7. A. F. Jankowski, P. L. Perry, “Characterization of Mo/B4C multilayers,” *Thin Solid Films* **206**(1-2), 365-368 (1991).
8. C. Montcalm, P. A. Kearney, J. M. Slaughter, B. T. Sullivan, M. Chaker, H. Pépin, C. M. Falco, “Survey of Ti-, B-, and Y-based soft x-ray–extreme ultraviolet multilayer mirrors for the 2-to 12-nm wavelength region,” *Appl. Opt.* **35**(25), 5134-5147 (1996).
9. N. Haberkorn, S. Bengio, S. Suárez, P.D. Pérez, M. Sirena, J. Guimpel, “Effect of the nitrogen-argon gas mixtures on the superconductivity properties of reactively sputtered molybdenum nitride thin films,” *Mater. Lett.* **215**, 15-18 (2018).
10. N. Haberkorn, S. Bengio, H. Troiani, S. Suárez, P.D. Pérez, P. Granell, F. Golmar, M. Sirena, J. Guimpel, “Thickness dependence of the superconducting properties of γ- Mo2N thin films on Si (001) grown by DC sputtering at room temperature,” *Mater. Chem. Phys.* **204** 48-57 (2018).

Biographies and photographs for the other authors are not available.