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Novel absorber stack for minimizing shadow effect in extreme ultraviolet mask

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Finding an optimized absorber stack is becoming a more critical issue in the fabrication of extreme ultraviolet (EUV) mask since it is directly related to the performance of lithography such as pattern fidelity and productivity. Optical simulation, deposition, and measurement have been conducted to establish an optimized absorber stack including antireflection coating (ARC), absorber layer, and capping (or buffer) layer, which satisfies major requirements for EUV mask applications. TaN and the other absorber candidates do not show acceptable reflectivity value (lower than 5%) in deep ultraviolet (DUV) wavelength region (199 or 257 nm) for pattern inspection. DUV reflectivity can be lowered by applying C and Al_2O_3 layers as top ARCs for 199 and 257 nm wavelengths, respectively, while keeping the EUV reflectivity at 13.5 nm less than 1%. ARC-covered TaN absorber stacks result in a reduction of printed CD variation owing to the mitigation of the shadow effect. However, long-term stability and fabricability of these stacks should be examined further. © *2006 American Vacuum Society.* [DOI: 10.1116/1.2393295]

I. INTRODUCTION

As the development of the extreme ultraviolet lithography (EUVL) progresses, EUV mask has received increased attention because it is directly related to the performance of the EUV lithography process. Typical EUV mask consists of several layers; absorber for EUV absorption, buffer for protection from absorber etch damage, capping for oxidation resistance of multilayer, and multilayer for EUV reflectance.[1–3] The off-axis incident angle of EUV light into the patterned mask imposes a new issue, which is called a shadow effect,[4–6] and this is influenced by the thickness and the material combination of the absorber stack. The absorber stack without the buffer layer is beneficial to reduce the shadow effect, but the capping layer should provide an effective etch stop property instead of buffer layer in this case.[7] TaN is a strong candidate for absorber material due to high absorption at EUV wavelength and lower etch bias,[1,8] and ruthenium (Ru) has been proposed as a capping material due to oxidation resistance as well as high EUV reflectivity.[9,10] Elimination of buffer layer is possible with this material combination due to high etch selectivity of TaN to Ru, which can simplify the mask fabrication process and reduce the shadow effect.[7,10] Deep ultraviolet (DUV) reflectivity of the stack is another important issue to insure the DUV contrast for pattern inspection.[11] In this article, a new absorber stack which satisfies EUV and DUV reflectivity requirements is proposed with reduced shadow effect.

II. EXPERIMENT

The deposition of the Mo/Si multilayers and TaN-based absorber stacks was conducted by using magnetron sputtering system specially designed to fabricate the EUV mask, which can hold five different targets with three dc and two rf power sources. The simulation for optical properties was conducted by using the reflectivity calculation program, TFCALC 3.5.6.[12] The material parameters used for the simulation were obtained from the CXRO database[13] and optical constant handbook.[14] For successful optimization of an absorber stack, several candidate materials were chosen for capping layer, buffer layer, absorber layer, and antireflection coating (ARC) if necessary. After the optimization through simulation, the stacks were deposited to confirm the properties predicted in the simulation such as reflectivities at 13.5, 199, and 257 nm. Etch selectivity was also investigated between buffer and absorber materials. Aerial image simulation was performed by SOLID-EUV of Sigma-C.[15] In the simulation, the optical parameters were EUV wavelength of 13.5 nm, off-axis illumination angle of 6°, a numerical aperture of 0.15, a partial coherence of 0.6, and the demagnification factor of 4. The aberration effect was not considered in this calculation. EUV reflectivity was measured in the photoemission spectroscopy beamline at Pohang accelerator

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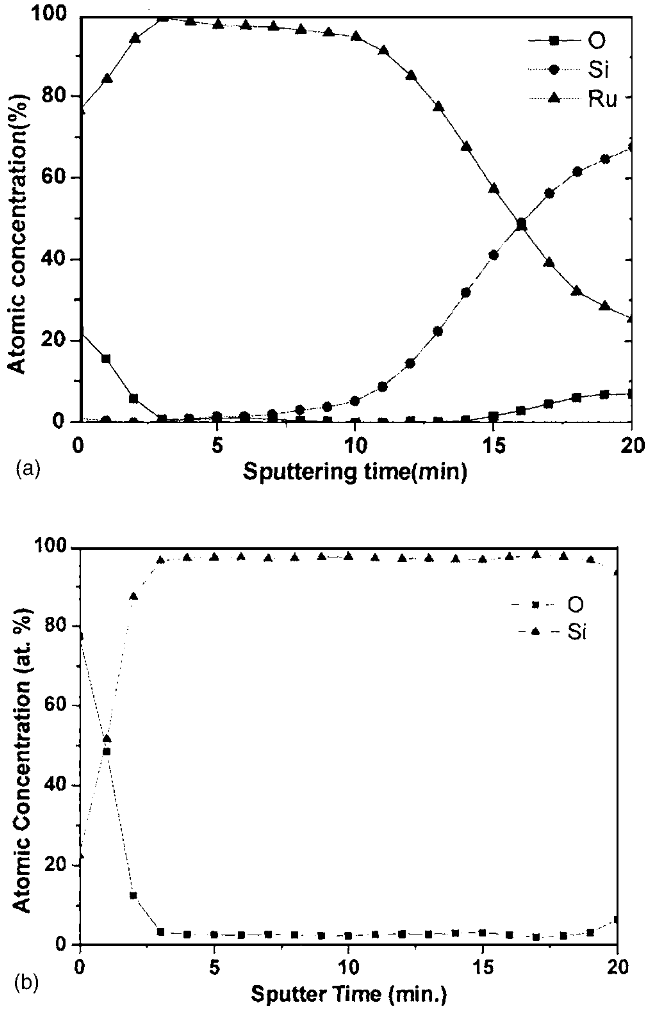

FIG. 1. AES depth profile showing oxygen concentration on (a) Ru-capped and (b) Si-terminated samples.

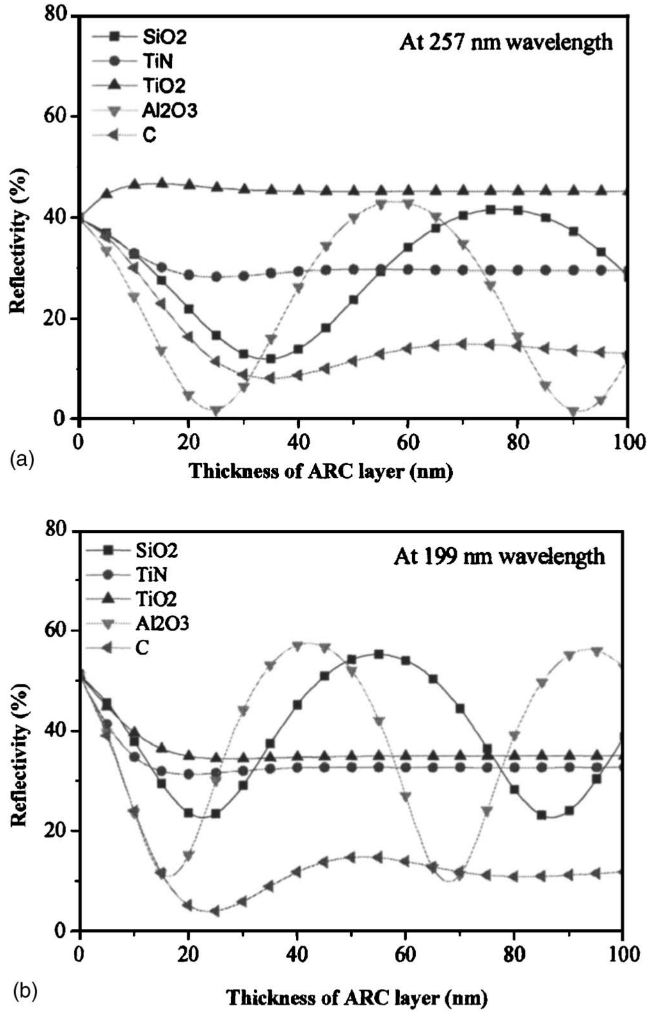

FIG. 2. DUV reflectivity simulations at (a) 257 nm and (b) 199 nm with thickness variations of SiO_2, TiN, TiO_2, Al_2O_3, and C ARCs in ARC/49 nm TaN/2 nm Ru/monolayer structure.

laboratory which is a bending magnet beamline with a monochromator resolution of 1800 at 13.5 nm wavelength. DUV reflectivity was measured by DUV reflectometer, which can provide values of n and k from measurements of transmittance and reflectance over a broad spectrum of wavelengths (190–1000 nm).

III. RESULTS AND DISCUSSION

Ru capping has been proposed for mask as well as optics applications.[7,16] To confirm the oxidation resistance, two samples of 30 nm Si and 10 nm Ru/30 nm Si coated on Si substrate were analyzed by Auger electron spectroscopy with Ar sputtering rate of ~1 nm/min. Ru capped sample shows lower oxygen peak concentration of ~20%, while Si-terminated sample shows ~80% oxygen peak concentration at the surface, as can be seen in Fig. 1. The 40 period Mo/Si multilayer terminated with Si was prepared, and the rms surface roughness was measured to be 0.113 nm. Slight improvements in roughness ($\Delta \approx -0.025$ nm) and peak EUV reflectivity ($\Delta R \approx 1\%$) were obtained with Ru capping compared to the Si-terminated multilayer. Since the etch selectivity of TaN absorber to Ru layer is quite high (~20),[10] Ru has a high potential to be used as a combined buffer/capping layer. Although TaN layer exhibits a high absorption of EUV light, the reflectivity of TaN at DUV wavelength is high like the other metals. For the pattern inspection, high DUV contrast between Ru capped multilayer and absorber pattern is required. DUV reflectivity (at 257 or 199 nm) of Ru capped multilayer is about 50% and that of TaN absorber on Ru capped multilayer is about 30%, which shows the need for ARC. For the selection of an ARC material, reflectivity simulation was performed at 257 and 199 nm with thickness variations of SiO_2, TiN, TiO_2, Al_2O_3, and C with ARC/49 nm TaN/2 nm Ru/monolayer structure (Fig. 2). Al_2O_3 at 257 nm and C at 199 nm exhibit reflectivity below 5%, which satisfies the class-A requirement.[5] Since the EUV and DUV reflectivities are dependent on the thickness of the absorber layer as well as that of the ARC, optimized thickness of Al_2O_3/TaN/2 nm Ru/ML was obtained from reflectivity simulation, as shown in Figs. 3(a) and 3(b). As can be seen, DUV reflectivity is less sensitive to the TaN absorber thickness due to the small penetration depth. The thickness

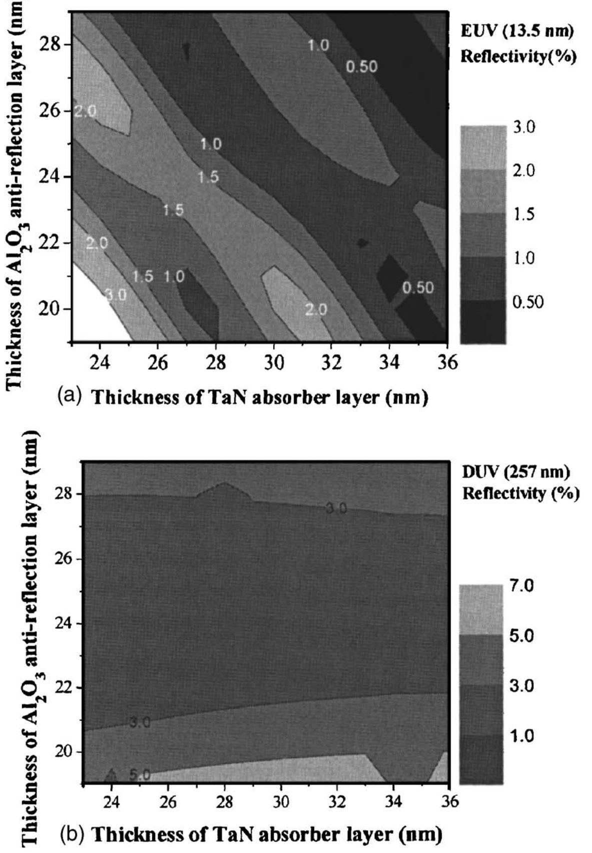

FIG. 3. (a) EUV (13.5 nm) and (b) DUV (257 nm) reflectivity simulation contour with the thickness variations of Al_2O_3 and TaN in Al_2O_3/TaN/2 nm Ru/monolayer.

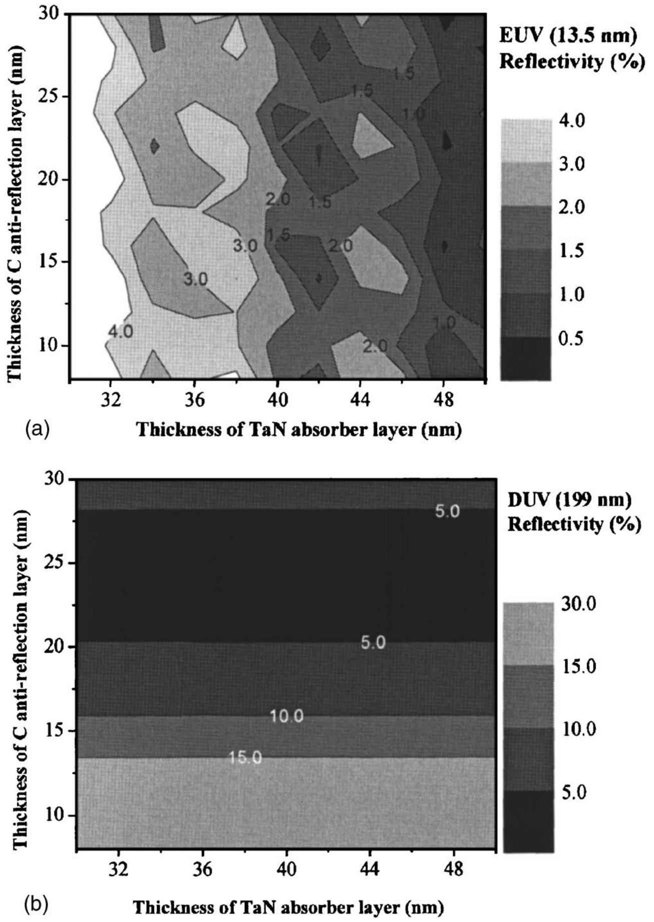

FIG. 4. (a) EUV (13.5 nm) and (b) DUV (199 nm) reflectivity simulation contour with the thickness variations of C and TaN in C/TaN/2 nm Ru/monolayer.

window which satisfies both EUV and DUV reflectivity requirements can be acquired by overlapping these two graphs. Very low EUV reflectivity values are obtained with 20 nm Al_2O_3/27 nm TaN (0.97%) and 21 nm Al_2O_3/34 nm TaN (0.38%). DUV reflectivity at 257 nm in both cases is below 5%. The total thicknesses of the absorber stacks are 47 and 55 nm in these cases. For 199 nm DUV inspection wavelength, same simulation process was performed with C/TaN/2 nm Ru/monolayer structure (Fig. 4). DUV reflectivity is almost independent of TaN absorber thickness at 199 nm even though it shows thickness dependency at larger wavelength (>500 nm). The thickness conditions which satisfy the DUV reflectivity requirement (<5%) are 22 nm C ARC/42 nm TaN (~1% EUV reflectivity) and 22 nm C ARC/48 nm TaN (~0.5% EUV reflectivity).

To investigate the shadow effect in ARC-covered and TaN terminated stacks, aerial image intensity was calculated. Mask pattern in the simulation was designed with 200 nm line and space (1:1), which is equivalent to the 50 nm line and space pattern at the wafer plane with 4× demagnification. Through our calculation of aerial image width for various threshold lines (0.1–0.5), we found out that the threshold line of 0.15 is the best choice by comparing the resist image for identical condition. The printed CD was shown as a function of the absorber stack height for Al_2O_3-ARC, C-ARC, and TaN terminated stacks in Fig. 5. It should be noted that TaN terminated stack does not meet the DUV reflectivity requirement. Reduction of printed CD variation owing to the mitigation of shadow effect is obtained by applying ARC, while satisfying EUV and DUV

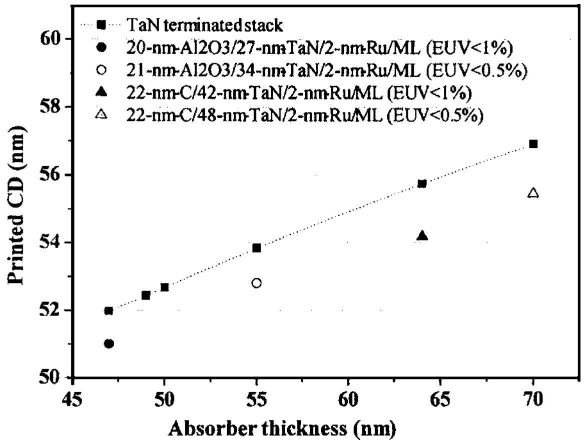

FIG. 5. Printed CD as a function of absorber pattern height based on the two-dimensional mask EM model simulation for Al_2O_3-ARC, C-ARC, and TaN terminated stacks.

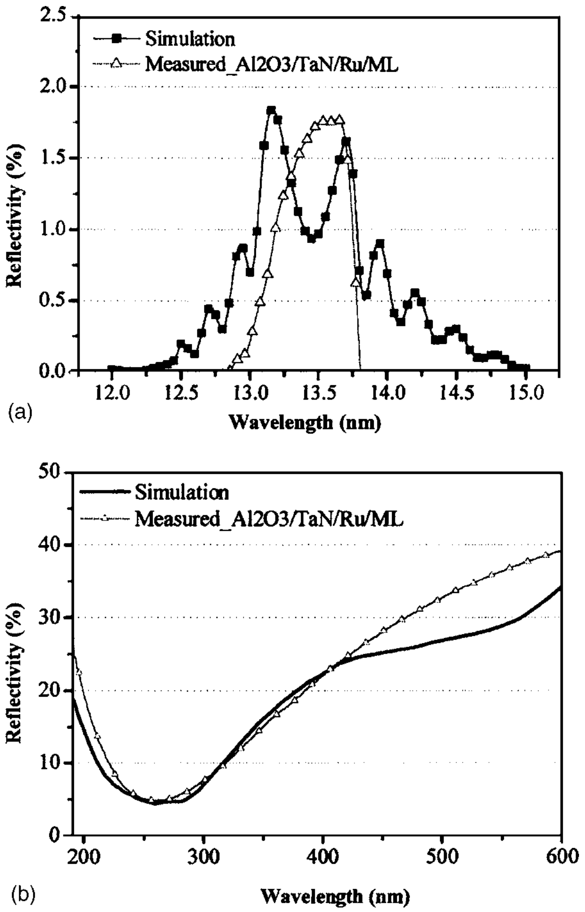

FIG. 6. (a) EUV and (b) DUV reflectivities measured and simulated on Al_2O_3/TaN/Ru/ML structure. All ARC-applied stacks satisfy DUV reflectivity requirement ($<5\%$).

reflectivities as well. It can be clearly shown that the printed CD depends on the absorber stack materials as well as the geometrical stack height.

Figure 6 shows empirical EUV and DUV reflectivities, and is compared with the simulated results. Measured EUV reflectivity shows a little difference from the simulated value ($\sim 1\%$ at 13.5 nm), and this can be caused by the deviation in thickness and film density. It is expected to be able to reduce the gap through more precise control of the process. The DUV reflectivity at 257 nm satisfies the $<5\%$ requirement and matches closely with the simulation result.

IV. CONCLUSION

An optimization study for absorber stack of EUVL mask was conducted, and a novel structure which meets the requirements was proposed. As a capping layer, Ru can improve EUV reflectivity, surface roughness, and oxidation resistance compared to the Si-terminated multilayer. Also Ru layer shows good etch selectivity to TaN absorber layer, which supports the applicability of Ru for a combined buffer/capping function. Improved DUV inspectability at 257 and 199 nm can be obtained using Al_2O_3 and C as an ARC on the TaN absorber, and the optimized absorber stacks with these ARCs can alleviate the shadow effect. However, long-term stability issue of the stack still remains for further study.

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