High reflectance of reflective-type attenuated-phase-shifting masks for extreme ultraviolet lithography with high inspection contrast in deep ultraviolet regimes

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Phase-shifting masks are a vital resolution enhance technique that will be used in extreme ultraviolet (EUV) lithography beyond the 20 nm node. In this article, we demonstrate a structure for a reflective-type attenuated phase-shifting mask, which is based on a Fabry–Perot structure with common materials in EUV masks. The mask structure not only performs 180° phase shift with high reflectance at EUV wavelength, but also has high inspection contrast at deep ultraviolet (DUV) wavelength. The top layer of mask structures exhibits good conductivity, which can alleviate the charging effect during electron-beam patterning. The reflectance ratio of the absorber stack could be tuned from 32.6% ($\mathrm{TaN/SiO_2/Mo}$) to 4.4% ($\mathrm{TaN/SiO_2/TaN}$) by choosing different bottom layers and thickness. The inspection contrast could be raised to 99% with large thickness-control tolerance. © *2004 American Vacuum Society.* [DOI: 10.1116/1.1813450]

I. INTRODUCTION

Extreme ultraviolet (EUV) lithography is one of the leading candidates for patterning semiconductor devices for sub-50 nm generations. According to the recent International Technology Roadmap for Semiconductor (ITRS), the resolution enhance techniques (RET) such as phase-shifting-masks (PSM), are also essential in EUV lithography for sub-20 nm nodes.[1] In deep ultraviolet (DUV) lithography, a high transmittance attenuated phase-shifting mask (HT-APSM) can perform better than a conventional attenuated PSM to improve depth of focus and resolution by destructive optical interference at the edges of features.[2] Therefore, designing a high reflectance of reflective-type APSM for EUV lithography is imperative.

In recent years, various materials for absorbers and buffer layers have been evaluated for EUV mask applications.[3] TaN and Cr films are the leading choices for absorber materials, and $\mathrm{Si_3N_4}$ and $\mathrm{SiO_2}$ films are chosen as the buffer layers.[4] However, TaN and Cr films are high reflectance at the inspection wavelength (257 or 365 nm). The high reflectance decreases the inspection contrast between multilayer mirror and absorber stacks. Therefore, increasing the inspection contrast by decreasing the reflectance of the absorber stack at the inspection wavelength is important. Single-layer dielectric antireflective coatings (ARC), such as silicon nitride films, are used to increase the inspection contrast.[5]

Generally, mask layers are patterned by electron-beam lithography. There is an intrinsic electron accumulation problem that causes electron deflection. The problem will become more serious as the feature size of EUV mask decreases to less than 200 nm.[6] To avoid the pattern distortion, the mask layer should have good conductivity. The single-layer antireflective coatings, which are dielectric materials with poor conductivity, are not suitable as mask layers for electron-beam patterning.

In this article, we demonstrate a structure for reflective-type attenuated phase-shifting mask, which is based on a Fabry–Perot structure with common materials of EUV masks. The mask structure not only performs 180° phase shift with high reflectance at EUV wavelength, but also has high inspection contrast at deep ultraviolet wavelength. The top layer of mask structures exhibits good conductivity, which can alleviate the charging effect during electron-beam patterning. The reflectance ratio between the absorber stack and multilayer mirror could be tuned by choosing different bottom layers and thickness. The inspection contrast could be raised to 99% with large thickness-control tolerance. The total thickness of the absorber stacks is retained thin enough to meet the stack height requirement to prevent the geometric shadow effect.

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TABLE I. Optical constants of EUVL mask materials at 13.5 and 257 nm wavelengths.

	13.5 nm		257 nm	
	n	*k*	*n*	*k*
SiO_2	0.978 18	0.010 77	1.504 10	0.000 00
Si	0.999 32	0.001 83	1.640 26	3.918 24
Mo	0.921 25	0.006 42	1.715 73	3.745 31
Si_3N_4	0.973 43	0.009 32	2.247 52	0.002 34
TaN	0.926 00	0.043 63	2.496 74	1.525 68
Cr	0.932 46	0.038 88	0.860 40	2.116 20

II. SIMULATION

In this article, we simulate the optical behavior of a reflective APSM by utilizing the optical multilayer thin film theory.[7] The optical constants of molybdenum (Mo), silicon (Si), tantalum nitride (TaN), chromium (Cr), silicon dioxide (SiO_2), and silicon nitride (Si_3N_4) at EUV and DUV wavelengths are obtained from a database by using the method of linear interpolation.[8–10] Table I shows the optical constants of EUVL mask materials at 13.5 nm exposure and at 257 nm inspection wavelengths, respectively.

To characterize the reflectance behaviors, we assume the multilayer (ML) mirror consist of 40-layer pairs of Mo and Si with layer thickness of 2.8 and 4.1 nm, respectively. The Mo/Si ML mirror is deposited on low thermal expansion material substrate and then covered by buffer and absorber layers. We assume the thickness of the buffer to be about 60 nm to meet the requirement of focused ion beam (FIB) repair stage. The reflectance of ML areas at repair and final stages is controlled at 60%.

Figure 1 shows the phase of two portions of patterned structures, φ_1 and φ_2. The optical path difference (OPD) is defined as the phase shift between the void and the absorber stack. R_1 and R_2 are the reflectance of the ML mirror and the absorber stack, respectively. For analysis of the reflectance and phase shift, thin film interference theory was introduced. The exposure conditions used in simulation are 13.5 nm wavelength, *s*-polarized, and 5 deg incidence angle.

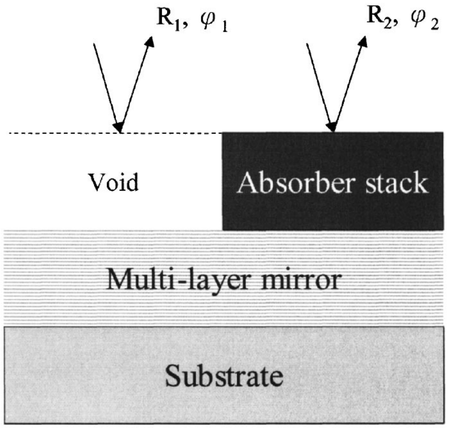

FIG. 1. Diagram of the concept of reflective-type attenuated phase shift mask.

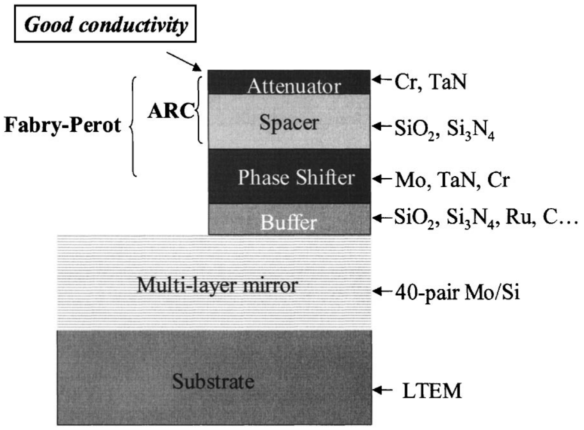

FIG. 2. Diagram of Fabry–Perot-type attenuated phase-shift mask.

III. RESULTS AND DISCUSSION

A. Absorber stack

Shown in Fig. 2, is the structure of the absorber stack arranged with buffer, phase shifter, spacer, and attenuator. The buffer can protect the under-ML mirror from damage during etch and repair processes. The phase shifter causes the optical path difference, which has a large refractive index difference to air at the EUV wavelength. The suitable materials for the phase shifter are Mo, TaN, and Cr. The spacer of the Fabry–Perot-type ARC must be a transparent material at the DUV inspection wavelength. The minimum reflectance wavelength can be tuned by tuning the thickness of the spacer. SiO_2 and Si_3N_4 are the common materials which meet the spacer requirement. The attenuator is a thin metallic film, such as TaN or Cr, with suitable optical constants to match the spacer to induce the destructive interference at the DUV inspection wavelength. Based on this concept, we demonstrate the high reflectance APSM composed by the TaN/SiO_2/Mo stack, and the normal reflectance APSM composed by the TaN/SiO_2/TaN stack.

B. Reflectance and phase shift of absorbers in EUV wavelength region

Figure 3 shows the reflectance and phase shift of the TaN/SiO_2/Mo stack at 13.5 nm. The thickness of the TaN layer and SiO_2 layer is fixed at 4.4 and 27.2 nm, respectively, to maintain the good DUV inspection contrast. As the Mo layer thickness increases, the reflectance of the absorber stack is varied sinusoidally with a small decrease, and the relative phase shift is increased linearly. As the 180° phase shift thickness of the Mo layer is 30.1 nm, and the reflectance ratio (R_1/R_1) is 32.6% at 13.5 nm, the structure can satisfy the requirements of high reflectance APSM. Figure 3 also shows that phase shift is $180° \pm 10°$ as the thickness of Mo layer ranges from 29 to 35 nm.[5]

Similarly, Fig. 4 illustrates the reflectance and phase shift of a low reflectance APSM structure composed with the

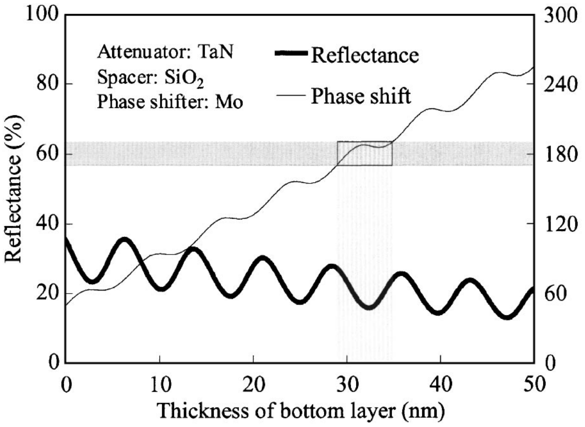

FIG. 3. Reflectance and phase shift of $TaN/SiO_2/Mo$ stack structure at 13.5 nm.

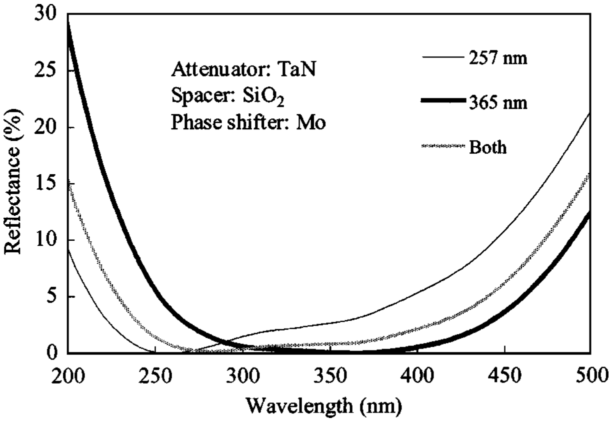

FIG. 5. Reflectance of $TaN/SiO_2/Mo$ absorber stack in the inspection wavelength regime.

$TaN/SiO_2/TaN$ absorber stack. The thickness of the top TaN layer and SiO_2 layer is fixed at 1.9 and 31.8 nm, respectively, to get good DUV inspection contrast. As the thickness of the bottom TaN film is increased, the reflectance of the absorber stack decreases rapidly with small ripples, and the phase shift is increased linearly. This is different from the previous high reflectance APSM structure because the extinction coefficient of a TaN film is one order larger than a Mo film in extreme ultraviolet regimes. At 180° phase shift, the thickness of the bottom TaN films is 30.4, 35.7, and 40.7 nm, and the corresponding reflectance ratio (R_2/R_1) is 4.4%, 4.3%, and 0.9% at 13.5 nm.

C. Reflectance of absorbers in DUV inspection wavelength region

The reflectance of ML mirror is about 60% in the DUV regime. The reflectance of EUV mask absorber stacks such as TaN or Cr is larger than 30%. Therefore, decreasing the reflectance of the absorber stack to increase the inspection contrast is essential. In this article, by controlling the thickness of the spacer and top attenuator layers, the reflectance of the absorber stack can be decreased to less than 1%. Figure 5 demonstrates the reflectance of $TaN/SiO_2/Mo$ absorber stack in the DUV inspection regime. Like the 4.4 nm of the top TaN layer and 27.2 nm of the SiO_2 layer, the reflectance can be reduced to less than 1% at 257 nm. We can also tune the thickness of SiO_2 and top TaN films to shift the minimal reflectance regime to 365 nm or another desired inspection wavelength.

Similarly, Fig. 6 shows the reflectance of $TaN/SiO_2/TaN$ absorber stack in the inspection wavelength regime. The reflectance is lower than 1% at 257 nm, like the thickness 1.9 nm of top TaN layer and 31.8 nm of SiO_2 layer. We can also tune the thickness of the absorber structure for another inspection wavelength.

D. Inspection contrast and thickness variation tolerance

The inspection contrast is less than 30% between the ML mirror and conventional TaN and Cr absorber stacks without adding antireflective coatings. The inspection contrast should be larger than 40% for defect identification.[11] Figure 7 shows the inspection contrast depending on the thickness variation of the $TaN/SiO_2/Mo$ absorber stack. With as the change of thickness, the inspection contrast decreases. The SiO_2 layer

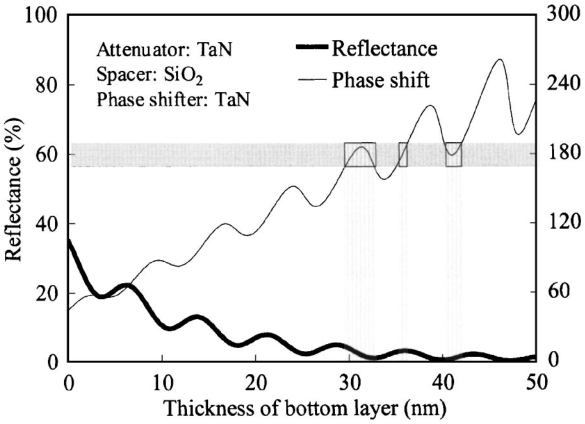

FIG. 4. Reflectance and phase shift of $TaN/SiO_2/TaN$ stack structure at 13.5 nm.

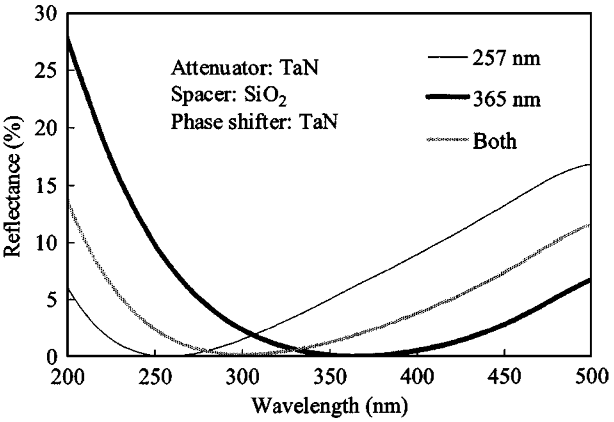

FIG. 6. Reflectance of $TaN/SiO_2/TaN$ absorber stack in the inspection wavelength regime.

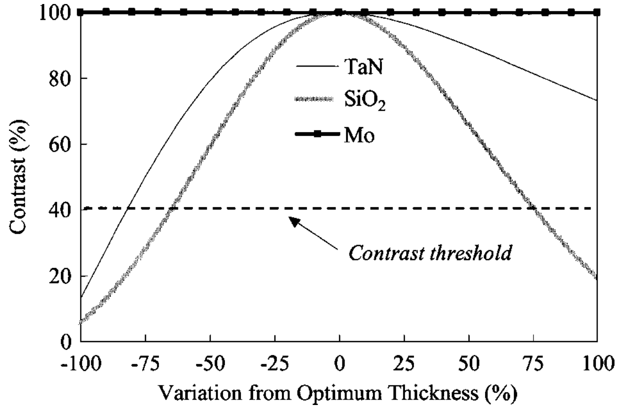

FIG. 7. Inspection contrast depending on the variation of film thickness in the TaN/SiO_2/Mo absorber stack.

is found to be the most sensitive layer in the absorber structure. The inspection contrast can remain larger than 40% as the thickness variation of the SiO_2 layer ranges from −63% to 75%.

Similarly, the inspection contrast depending on the variation of TaN/SiO_2/TaN thicknesses is shown in Fig. 8. The most sensitive SiO_2 layer is shown with −85%–88% thickness-variation-tolerance range. For the large thickness-tolerance range, we can tune the thickness of the absorber structure to meet the requirements of reflectance ratio and phase shift in the EUV regime for reflective-type APSM applications.

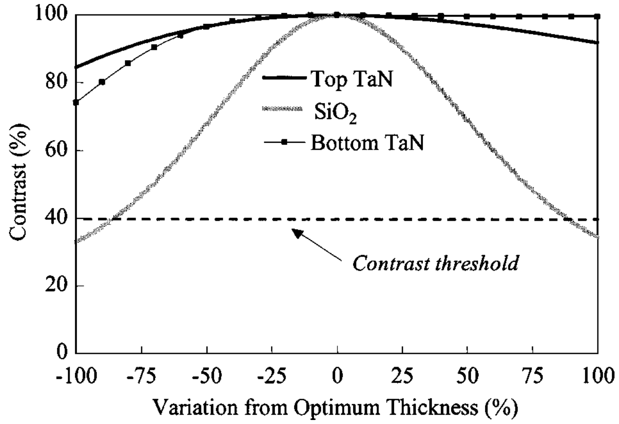

FIG. 8. Inspection contrast depending on the variation of film thickness in the TaN/SiO_2/TaN absorber stack.

IV. CONCLUSIONS

In this article, we demonstrated a structure for a reflective-type attenuated phase-shifting mask, which is based on a Fabry–Perot structure with common materials of EUV masks. The mask structure not only performs 180° phase shift with high reflectance at EUV wavelength, but also has high inspection contrast at deep ultraviolet wavelength. The top layer of mask structures exhibits good conductivity, which can alleviate the charging effect during electron-beam patterning. The reflectance ratio of the absorber stack could be tuned from 32.6% (TaN/SiO_2/Mo) to 4.4% (TaN/SiO_2/TaN) by choosing different bottom layers and thickness. The inspection contrast could be raised to 99% with large thickness-control tolerance. For the large thickness-tolerance range, we can tune the thickness of the absorber structure to meet the requirements of reflectance ratio and phase shift in the EUV regime for various reflective-type APSM applications. The total thickness of the absorber stacks is less than 80 nm to meet the stack height requirement to prevent the geometric shadow effect.

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