Optimized bilayer hexamethyldisiloxane film as bottom antireflective coating for both KrF and ArF lithographies

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A new bilayer bottom antireflective coating (BARC) layer composed of hexamethyldisiloxane film stack is demonstrated for both KrF and ArF lithographies. By simply adjusting the gas flow rate ratio, the materials of the bilayer can be varied to have suitable optical constants as BARC materials working at both 248 and 193 nm wavelengths. The swing effect is experimentally shown to be reduced significantly on both silicon and Al-Si substrates. The bilayer scheme is also demonstrated to be capable of providing large thickness-controlled tolerance. © 2000 American Vacuum Society. [S0734-211X(00)11306-X]

I. INTRODUCTION

According to the *SIA Roadmap* in 1999,¹ the KrF and ArF excimer laser based lithographies with resolution enhanced techniques are regarded as the main technology that would lead to the generation below 130 nm. The problems of critical dimension control caused by highly reflective substrates are very serious in deep ultraviolet (DUV) wavelength regimes.^{2,3} A bottom antireflective coating (BARC) layer that can serve the purpose for both 248 and 193 nm is therefore desirable since, apart from the convenience of use, the process and learning curve will be simplified significantly.

Conventional spin-coated organic BARC⁴ relies on the absorption of reflected light through a relatively thick film. It tends to planarize the topography on a substrate, resulting in varying BARC thickness and then different reflections from the substrate. As feature size continues to shrink into the subquarter-micron regime and the stepper projection system shifts to shorter wavelengths, organic BARC cannot easily meet the more stringent substrate and resist requirements. As a result, the use of chemical vapor deposition (CVD)-deposited films has been proposed as BARCs for DUV lithographies.^{3,5} CVD-deposited films can provide the possibility of completely eliminating the reflectance for various highly reflective substrates due to the tunability of both composition and thickness. Furthermore, CVD-deposited BARC has been found to be conformal to topographic substrates, so that critical dimension (CD) control is easily maintained during pattern transfer.⁶

The hexamethyldisiloxane (HMDSO) film has been demonstrated as a BARC in the form of either a single layer or a multilayer in the 193 nm wavelength regime.^{7,8} The vaporized liquid HMDSO is used as coating material in a conventional electron cyclotron resonance-plasma enhanced CVD (ECR-PECVD) process. The optical constants of suitable HMDSO films for BARC layers can be easily tuned by adjusting the gas flow rate ratio of oxygen to HMDSO during

deposition. The composition of the HMDSO films has been analyzed and the etching property of the HMDSO films for subsequent pattern-transfer processes has been studied.⁷ The deposition is conducted at room temperature, and issues caused by the thermal effect inherent to other deposition methods can be avoided. In summary, the HMDSO-based PECVD process has the following advantages: high deposition rate, low process temperature, easy film removal, potential cost reduction, and not hazardous (as compared with the SiH₄-based PECVD process). In this article, we demonstrate that an HMDSO bilayer BARC structure can work in both 248 and 193 nm wavelengths and can be done in one process step without changing to other materials.⁸

II. SIMULATION

Figure 1 shows the schematic diagram of our bilayer BARC structure. Layers 1 and 2 are deposited with different gas flow rate ratio of oxygen to HMDSO, and therefore result in different HMDSO film compositions. To find the optimum structures of the bilayer BARC, it is desirable to simulate first for time saving. The reflectance of the film stacks can be calculated by using the characteristic matrix method.⁹ Assume a beam is normally incident on a uniform and isotropic thin film, the reflectance R can be expressed as

$$R = \left(\frac{N_0 B - C}{N_0 B + C} \right) \left(\frac{N_0 B - C}{N_0 B + C} \right)^*, \quad (1)$$

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left(\prod_{r=1}^2 \begin{bmatrix} \cos \delta_r & (i \sin \delta_r)/N_r \\ i N_r \sin \delta_r & \cos \delta_r \end{bmatrix} \right) \begin{bmatrix} 1 \\ N_{\text{sub}} \end{bmatrix}, \quad (2)$$

where $N_r = n_r - ik_r$, and n_r, k_r are optical constants of each film stack; δ_r is the optical phase thickness equal to $2\pi N_r d_r / \lambda$ with d_r as physical film thickness and λ (248 or 193 nm) as exposure wavelength.

III. EXPERIMENT SETUP

The HMDSO films were deposited by employing an ECR-PECVD facility. The feed gases were HMDSO, O₂, and Ar. The ECR microwave power was set to 720 W and

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FIG. 1. Schematic diagram of a bilayer BARC structure.

the dc bias of the rf power supply was fixed at 800 V. The chamber pressure during deposition was 2.0×10^{-4} Torr and the substrate was not heated during the whole process.

To characterize the deposited HMDSO films, the reflectance and the transmittance spectra of HMDSO films were measured by using an optical spectrometer (Hitachi, U3501). The film thickness was obtained separately by using an ellipsometer at 632.8 nm, and the optical constants of HMDSO films were then calculated by employing the $R-T$ method.¹⁰

IV. RESULTS AND DISCUSSION

A. Reflectance swing curve

The swing effect caused by optical interference between the fields reflected from both air/resist and resist/substrate interfaces will lead to the variation of exposure dosage, and thus induce the issue of CD control in an optical lithography process. A CVD-deposited BARC can have constant thickness over the topography of a substrate, but the resist film may have various thicknesses, leading to a familiar swing curve effect.

A simple model of resist reflectance swing ratio can be expressed as follows:⁴

$$S \cong 4\sqrt{R_1 R_2} e^{-\alpha D}, \quad (3)$$

where R_1 is the reflectance at the resist/air interface; R_2 is the reflectance at the resist/substrate or resist/BARC interface depending on the existence of the BARC; α is the resist absorption coefficient; and D is the resist thickness. Therefore, it is important to reduce R_2 when a BARC structure is used. Here, the reflectance contours at the interface between the resist and BARC have been calculated for different substrates and the reflectance swing curves were simulated and measured.

The HMDSO films with optical constants (1.77, 0.10), (1.90, 0.287) at 248 nm and (1.85, 0.19), (2.10, 0.550) at 193 nm were chosen as constituents of a bilayer structure. The resists used here are TER-1 (Microlithography Chemical Corp.) for 193 nm and K30G (JSR) for 248 nm. Simulated reflectance contours at the interface between the resist and BARC are shown in Fig. 2 for various thicknesses of layers 1 and 2 on different substrates, such as Si, Al-Si, and W-Si.

(a)

(b)

(c)

FIG. 2. Simulated reflectance contours at the interface between the resist and BARC for various thickness of layers 1 and 2 on substrate: (a) Si, (b) Al-Si, (c) W-Si. Solid lines are for 248 nm and dashed lines are for 193 nm. The shadow regions show where the reflectance is less than 1% for both 193 and 248 nm.

(a)

(b)

FIG. 3. Simulated and measured reflectance swing curves of resists: (a) TER-1 for 193 nm and (b) K30G for 248 nm coated on a silicon substrate before and after the deposition of the bilayer BARC.

The shadow region is where the reflectance is less than 1% for both 248 and 193 nm, and the optimum thickness of each layer should be around 75 and 95 nm.

1. Bilayer BARC structure for a silicon crystal substrate

The reflectance swing curves of the resist coated on silicon substrates with (solid line) and without (dashed line) BARC were simulated, and the results are shown in Figs. 3(a) and 3(b) for 193 and 248 nm, respectively. For 193 nm, the reflectance exhibits a sinusoidal variation from about 5% to 45% for the resist thickness ranging from 300 to 600 nm before adding the BARC layer. The variation is reduced to about 5%–7% with the bilayer BARC in place. For 248 nm, the reflectance varies from about 5% to 50% for the resist thickness ranging from 550 to 850 nm before adding the BARC layer; then the variation is reduced to about 5.5%–

(a)

(b)

FIG. 4. Simulated and measured reflectance swing curves of resists: (a) TER-1 for 193 nm and (b) K30G for 248 nm coated on an aluminum film before and after the deposition of the bilayer BARC.

9.5% with the bilayer BARC in place. The results indicate that the use of such an HMDSO based bilayer BARC can significantly reduce the swing effect that is incurred in the resist, and CD control is expected to be improved.

2. Bilayer BARC structure for an aluminum film

Similarly, for an aluminum film deposited on a silicon substrate, the same HMDSO bilayer structure described above can also be used to reduce the reflectance between the resist and aluminum interface. The reflectance swing curves of resists were simulated; and the results are shown in Figs. 4(a) and 4(b) for 193 and 248 nm, respectively. For 193 nm, the reflectance exhibits a sinusoidal variation from about 5%

(a)

(b)

(c)

FIG. 5. Simulated reflectance contours for various thickness of layers 1 and 2 on the substrates of: (a) Si, (b) Al-Si, and (c) W-Si. Solid lines are for 248 nm and dashed lines are for 193 nm. The shadow regions show where the reflectance is less than 3% for both 193 and 248 nm.

(a)

(b)

FIG. 6. Measured reflectance spectra of single and bilayer BARC structures coated between a resist layer and (a) a silicon substrate; (b) an Al-Si substrate.

to 55% for the resist thickness ranging from 300 to 600 nm before adding the BARC layer, however, the variation is reduced to about 5%–7% with the bilayer BARC in place. For 248 nm, the reflectance varies from about 20% to 70% for the resist thickness ranging from 550 to 850 nm before adding the BARC layer, but becomes about 5%–10.5% with the bilayer BARC in place. Therefore, the same bilayer BARC is shown to significantly reduce the swing effects that occur in the resists coated on both Al-Si and Si substrates.

B. Tolerance test

Because it is impossible to measure the spectrum of the reflectance between the resist/BARC interface directly, a bi-layer antireflective (AR) coating on different substrates was investigated for tolerance testing. The HMDSO films with optical constants (1.68, 0.053), (1.90, 0.287) at 248 nm and (1.65, 0.045), (2.10, 0.550) at 193 nm were chosen as con-

(a)

(b)

FIG. 7. Measured reflectance spectra of a bilayer BARC structure on a Si substrate for a tolerance test when (a) layer 1 thickness varies with layer 2 thickness fixed at 75.5 nm; (b) layer 2 thickness varies with layer 1 thickness fixed at 26.8 nm.

stituents of a bilayer structure. The result of the simulated reflectance contour for the Si substrate is shown in Fig. 5(a). The shadow region is where the reflectance is less than 3% for both 248 and 193 nm. The reflectance goes to nearly zero for both 248 and 193 nm when the thickness of layer 1 is around 25 nm and the thickness of layer 2 is around 75 nm. Also, the results of the simulated reflectance contours for the Al-Si and W-Si substrates are depicted in Figs. 5(b) and

5(c), respectively. The optimum conditions of our bilayer AR coating for both Al-Si and W-Si are almost the same as the condition for the Si substrate. It demonstrates that we can use the same bilayer AR coating structure for Si, Al-Si, and W-Si substrates simultaneously in this case.

To confirm the simulated results, the bilayer films described above were fabricated and measured. As shown in Fig. 6(a), less than 1.5% reflectance is obtained in both 248 and 193 nm regions by using the bilayer HMDSO films on a silicon substrate. Also shown are single layer structures at 248 and 193 nm for comparison. With the same bilayer HMDSO films on Al-Si substrate, less than 2.5% measured reflectance was obtained in both 248 and 193 nm as shown in Fig. 6(b). These experimental results are all consistent with our simulation results.

The tolerance in HMDSO film thickness control was also measured. Shown in Figs. 7(a) and 7(b), respectively, are two cases in which the reflectance remains within 3%: first, when the thickness of layer 1 is about 75.5 ± 5 nm with the layer 2's thickness fixed; second, when the layer 1's thickness is fixed and the thickness of layer 2 is about 26.8 ± 5 nm. The measured results are consistent with the simulated ones. Since the deposition rate for each layer is approximately 1 nm/s, irrespective of the gas flow rate ratio of oxygen to HMDSO, we can have ± 5 s tolerance in thickness control. The uniformity of the HMDSO film across the whole 4 in. wafer is about $\pm 1.25\%$. It was shown that not only can the AR coating be successfully fabricated for both 248 and 193 nm wavelengths simultaneously, but also the thickness control tolerance is greater in the bilayer scheme.

V. CONCLUSIONS

The bilayer HMDSO film deposited by the conventional ECR-PECVD process is found to be an effective BARC structure for both KrF and ArF lithographies. The same BARC structure is suitable for use on Si and Al-Si substrates. The thickness tolerance is also demonstrated on a silicon substrate, which may be helpful in increasing the process window.

¹http://public.itrs.net/1999_SIA_Roadmap/Home.htm.

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