Hard Mask Process Using Chemically Amplified 157-nm Resists

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We describe and evaluate a pattern transfer process suitable for 157-nm lithography. It consists of a hard mask (HM) process using an organic bottom anti-reflective coating (BARC) / SiN structure. The underlayer of the resist works well as an anti-reflection layer. We obtained a rectangular resist profile using three fluorine-containing resists and a 157-nm microstepper. One of the resists was a side-chain fluorinated resist and the others were main-chain fluorinated resists. The reactive ion etching (RIE) conditions were optimized to obtain a vertical HM profile and minimum critical dimension (CD) shift. Although the resist patterns could be transferred to SiN(70 nm) HM using any of the resists, the remaining resist thickness was insufficient for mass-production of semiconductor devices. Further improvement of the resist material and optimization of the resist process and etching conditions are necessary. However, using the HM pattern, we were able to fabricate a WSi / poly-Si 65-nm gate pattern using a high-NA microstepper (NA=0.85), and a tetra-ethyl-orso-silicate (TEOS)-SiO₂ 150-nm contact hole (C/H) pattern using a 0.60-NA microstepper. This clearly demonstrates that our HM process is the best candidate for sub-70nm-node semiconductor devices.

Keywords: 157-nm lithography, fluoropolymer, hard mask, gate and contact hole fabrication

1. Introduction

Optical lithography using an F₂ Laser (wavelength = 157 nm) is one of the most promising candidates for the mass-production of sub-70nm-node semiconductor devices. The polymers in the conventional resists used for 248-nm or 193-nm lithography readily absorb 157-nm wavelength light [1], so these resists are not applicable to 157-nm lithography. To reduce absorption at the 157-nm wavelength, various fluoropolymers for 157-nm lithography have been developed [2-10], and several resists with small absorption coefficients have shown fairly high resolution [9]. A thin resist is considered necessary for sub-70nm node lithography because the aspect ratio of the resist pattern must be smaller than 3 to prevent the collapse of the pattern [11]. Therefore, the thickness of a 157-nm resist should be less than 200nm. Although some fluoropolymers showed high reactive ion etching (RIE) durability comparable to that of an ArF resist [10], transferring the pattern to the underlayer is considered much more difficult for 157-nm lithography than for conventional 248-nm or

193-nm lithography. However, there are only a few reports on pattern transfer for 157-nm lithography [12-13].

In this paper, we describe a hard mask (HM) process that is suitable for 157-nm lithography. We have used the process for both gate and contact hole (C/H) fabrication. We also describe the pattern transfer capabilities of several newly developed fluorine-containing resists.

2. Experimental

2.1. Materials

Figure 1 shows HM structures for (a) gate and (b) C/H fabrication. We used SiN as the HM material. The film was deposited on the substrates using chemical vapor deposition (CVD). We used a WSi (50 nm) / poly-Si (50 nm) / SiO₂ (100 nm) / Si substrate as the gate structure, and a tetra-ethyl-orso-silicate (TEOS)-SiO₂ (500 nm) / Si substrate as the C/H structure. The thickness of the HM was adjusted to 70 nm for gate fabrication and 100 nm for C/H fabrication. We used DUV42 (Brewer Science) as a bottom anti-reflective coating (BARC). Three fluorine-containing resists

Fig. 1. Structures for BARC / SiN hard mask process.

Table 1. Resist properties.

Sample	Type	Base resin	Absorption ($/\mu\text{m}$)	Thickness (nm)	Transparency (%)
F-resist A	F in side-chain	Silsesquioxane	3.5	120	37.7
F-resist B	F in main-chain	TFE / norbornene	2.1	150	48.6
F-resist C	F in main-chain	Monocyclic fluorocarbon	0.8	250	64.2
KrF-resist	KrF modified	PHS	6.6	80	29.8

and a KrF-modified resist were evaluated, as summarized in Table 1. F-resist A is composed of silsesquioxane copolymers with a fluorine element in the side chain. F-resist B is composed of tetrafluoroethylene (TFE) copolymers with a fluorine in the main chain. F-resist C is composed of monocyclic fluorocarbon copolymers with a fluorine in the main chain. KrF-resist is composed of poly(hydroxystyrene). Although a thicker resist is desirable for the pattern transfer process, increasing the absorbance of the film is undesirable for resist patterning. The resist thickness of F-resist A, F-resist B, and KrF-resist was adjusted to 120, 150, and 80 nm, respectively, because of their relatively large absorption. The thickness of F-resist C was adjusted to 250 nm to prevent pattern collapse.

2.2. Resist processing

We used an Ultratech 157-nm microstepper (NA=0.60, illumination sigma (σ)=0.30) and an Exitech 157-nm microstepper (NA=0.85, σ =0.30) [14]. An alternating phase-shifting mask (alt-PSM) was used for gate fabrication and an attenuated phase-shifting mask (att-PSM, transparency=5%) was used for C/H fabrication. The resist films were obtained by spin-casting on anti-reflective substrates and pre-baking at 110-140°C for 60-90 sec in an ACT8 coater / developer (TEL). The exposed resists were developed in a TMAH solution using a 20-60 sec puddle process after post-exposure baking at

110-130°C for 60-90 sec in a TEL ACT8. The reactive ion etching (RIE) of the BARC / HM, WSi / poly-Si and TEOS-SiO₂ was done using a Unity II etcher (TEL). Top-down and cross-sectional images were obtained using Hitachi S-9300 and S-5000 scanning electron microscopes (SEM), respectively. The optical constants (refractive index n and extinction coefficient k) at the 157-nm wavelength were obtained using a variable-angle spectroscopic micrometer VUV-VASE302 (J. A. Woollam). Lithographic simulations were done using Prolith/3D (KLA Tencor).

3. Results and Discussion

3.1. Lithographic and etching evaluation

Table 2 summarizes the optical constants of the F-resist A, and HM materials at the 157-nm wavelength. Figure 2(a) shows the calculated reflectivity at the resist / SiN interface. The high reflectivity was due to the large extinction coefficient of SiN. It was therefore inefficient to attempt to prevent the standing-wave effect when the SiN was 70-nm or 100-nm thick. However,

Table 2. Optical constants (refractive index n , extinction coefficient k) at 157-nm wavelength.

Material	n	k
F-resist A	1.747	0.102
DUV42	1.674	0.227
SiN	2.079	1.085
Si	0.662	2.031

inserting a thin BARC between the resist and SiN (70 nm) significantly reduced reflectivity (Fig. 2(b)). The reflectivity was reduced to our target value (less than 2%) when the BARC was 30-nm thick. There was no significant difference in reflectivity between an SiN thickness of 70 nm and 100 nm. BARC also worked to prevent the expected tapered profile often observed at the bottom of a resist fabricated on some inorganic films [15-16]. Therefore, we applied DUV42 (at a thickness of 30 nm), which showed good compatibility with F-resist A-C and a relatively high etching rate, as an organic BARC on SiN. For the DUV42 / SiN HM RIE, we applied two sets of RIE conditions: the typical SiN etching condition (using $\text{CF}_4 / \text{O}_2 / \text{CH}_2\text{F}_2$ gases), and an optimized condition.

Figure 3(a) shows the 130-85-nm 1:1 line and space (L/S) pattern of F-resist A delineated using a 0.60-NA microstepper and an alt-PSM in an F-resist A (120 nm) / DUV42 (30 nm) / SiN (70 nm) / Si structure. F-resist A showed a good imaging performance and a rectangular profile. No

standing wave at the resist sidewall was observed for any of the patterns, demonstrating that the underlayer of the resist sufficiently decreased reflectivity at the resist / BARC interface. Figure 3(b) shows the results of $\text{CF}_4 / \text{O}_2 / \text{CH}_2\text{F}_2$ RIE. The remaining resist thickness was sufficient after BARC / SiN RIE. However, the SiN patterns showed an obviously tapered profile and there was a large critical dimension (CD) shift during RIE. A vertical profile and a minimum CD shift are needed, especially in gate fabrication. We then optimized the RIE conditions (source gases, power, pressure, etc.). Figure 3(c) shows the results of the optimized RIE, and Figure 4 shows the relative RIE rate of F-resist A, DUV42 and SiN under the both RIE conditions. Compared to the results obtained under the $\text{CF}_4 / \text{O}_2 / \text{CH}_2\text{F}_2$ gas condition, the RIE selectivity between the resist and SiN was low under the optimized condition because of the small amount of CF_x deposited on the resist during RIE. However, we obtained a good vertical pattern profile and a smaller CD shift.

Fig. 2. Calculated reflectivity of 157-nm light at resist/underlayer interface.

Fig. 3. Pattern profile of 130 / 100 / 85 nm 1:1 L/S (a) after development; (b) after DUV42 / SiN RIE for the $\text{CF}_4 / \text{O}_2 / \text{CH}_2\text{F}_2$ gas condition; and (c) after DUV42 / SiN RIE for the optimized condition. The structure of the film is F-resist A (120 nm) / DUV42 (30 nm) / SiN (70 nm) / Si. The exposure tool was a 0.60-NA microstepper using an alt-PSM.

Fig. 4. Relative RIE rate (vs. SiN) under the CF₄ / O₂ / CH₂F₂ gas condition or optimized RIE condition.

Fig. 5. Relative RIE rate (vs. KrF-resist) of the materials under the optimized RIE condition.

3.2. Evaluation of fluorine-containing resists

3.2.1. RIE durability

The four resists summarized in Table 1 were applied to the optimized HM RIE conditions. Figure 5 shows the relative RIE rate (versus KrF-resist) of the materials. The relative RIE rate of F-resist A was about 1.3, that of F-resist B was about 1.5, that of F-resist C was about 1.9, and those of both SiN and BARC were about 1.2.

Figure 6 shows the dependence of the relative RIE rate on the absorption coefficient. The relative RIE rate tended to increase with a decreasing absorption coefficient. The dependence of the relative RIE rate on the fluorine content is shown in Fig. 7. The relative RIE tended to increase with an increase in fluorine content under the optimized RIE condition. These results suggest that RIE durability and the transparency are in conflict with one another.

3.2.2. Surface roughness

Figure 8 shows the surface roughness of each resist after the optimized RIE. An ArF-resist (acrylic type) was also observed for reference (shown in Fig. 8(e)). The RIE time was fixed at 10 sec for all the resists. Slight roughness was observed even on the surface of the KrF-resist. The surface roughness of F-resist A and F-resist B was greater than that of the KrF-resist but less than that of the ArF-resist. Remarkably, the surface roughness of F-resist C was fairly low.

3.3.3. Pattern profile

Figure 9(a) shows 130-nm 1:1 L/S resist patterns delineated using a 0.60-NA microstepper and an

Fig. 6. The dependence of relative RIE rate (vs. KrF-resist) on the absorption constant under the optimized RIE condition.

Fig. 7. Dependence of relative RIE rate (vs. KrF-resist) on fluorine content under the optimized RIE condition.

Fig. 8. Cross-sectional SEM images of resist surface roughness after the optimized RIE.

Fig. 9. Pattern profile of 130-nm 1:1 L/S for DUV42 (30 nm) / SiN (70 nm) / Si substrate (0.60-NA microstepper using an alt-PSM, and $\text{CF}_4 / \text{O}_2 / \text{Ar}$ gas).

Fig. 10. Top-down SEM images of 130-nm 1:1 L/S for DUV42 (30 nm) / SiN (70 nm) / Si substrate (0.60-NA microstepper using an alt-PSM, $\text{CF}_4 / \text{O}_2 / \text{Ar}$ gas).

Table 3. Summary of etching evaluation for each resist.

Sample	Initial thickness (nm)	Remaining thickness (BARC loss) (nm)	RIE rate (vs KrF-resist) (nm/min)	Blanket RIE rate (vs KrF-resist) (nm/min)	LER (3 σ) (nm)
F-resist A	109.3	6.8	361.8 (1.37)	381.3 (1.31)	5.3
F-resist B	137.8	10.2	450.4 (1.70)	451.9 (1.55)	4.5
F-resist C	242.0	99.8	501.9 (1.90)	549.0 (1.88)	3.1
KrF-resist	71.7	0 (-4.2)	264.7 (1.00)	292.1 (1.00)	5.1

alt-PSM, (b) shows the results of BARC / HM RIE under the optimized condition, and (c) shows the results obtained after resist ashing. The KrF-resist showed a tapered profile because of its low transmittance (~30%), while the others showed a good rectangular profile. The RIE time was fixed at 17 sec for all the resists. This was just enough time to complete BARC / HM RIE. The remaining thickness after RIE was 6.8 nm for F-resist A, 10.2 nm for F-resist B, 99.8 nm for F-resist C, and 0 nm for KrF-resist. Slimming of the resist pattern after RIE was observed only in F-resist C. It may have been due to the low RIE durability of F-resist C. However, the pattern profiles of the SiN HM after RIE were fairly good using any of the resists. In addition, there was no residue after BARC / resist ashing.

3.3.4. Line edge roughness

Top-down images of the resists are shown in Fig. 10. We measured the line edge roughness (LER, 3 σ) after ashing. The LER of F-resist A and KrF-resist was relatively large at 5.3 nm and 5.1 nm, respectively, compared to that of F-resist B (4.5 nm). The LER of F-resist C was the best (3.1 nm) of the four resists. There are two possible reasons for this: (1) it is due to the tapered profile and the footing at the bottom of the resist, and (2), the inhomogeneous etching durability (shown in Fig. 8) may also have an effect on LER.

3.3.5. RIE selectivity

Table 3 summarizes the RIE evaluation results for each resist. The initial and remaining thicknesses were measured using cross-sectional SEM images. The RIE rate obtained for the patterning results and the blanket RIE rate are also summarized in Table 3. Note that the RIE rate calculated from the patterning results for the KrF-resist was corrected by using the blanket RIE rate of BARC. The patterning results agreed well with the blanket RIE rate.

3.3.6. Target property

All of the fluorine-containing resists were applicable to the optimized SiN (70-nm thick) HM process. However, the remaining thickness after RIE was insufficient for mass-production of semiconductor devices. We assume that more than 50% of the initial thickness should remain immediately after completion of the BARC / SiN RIE. Supposing that the initial resist thickness is 200 nm to prevent a pattern collapse, and more than 60% transmittance is required to obtain a high resolution (equivalent to F-resist C), the relative RIE rate (vs. KrF resist) should be less than 1.2 and the absorption coefficient should be less than 1.1 ($/\mu\text{m}$). To achieve this, we have to overcome the trade-off between RIE durability and transparency. This will require further improvements in resist materials, and optimization of the resist process and etching conditions. The target properties for a 157-nm resist at various thicknesses and transmittance levels (T) are summarized in Table 4.

Table 4. Target properties for 157-nm resists for the optimized RIE condition in a BARC (30 nm) / SiN (70 nm) structure.

Thickness (nm)	Relative RIE rate (vs KrF)	Absorption ($/\mu\text{m}$)		
		T=50%	T=60%	T=70%
150	<0.9	2.0	1.5	1.0
200	<1.2	1.5	1.1	0.8
250	<1.5	1.2	0.9	0.6

3.4. Gate and C/H fabrication

We fabricated the gate pattern using the optimized HM RIE conditions. The structure was F-resist A (120 nm) / DUV42 (30 nm) / SiN (70 nm) / WSi (50 nm) / poly-Si (50 nm) / SiO₂ (100 nm) / Si substrate. Figure 11 (a) shows 100-80 nm resist patterns delineated using a 0.60-NA microstepper and an alt-PSM, (b) shows the results

Fig. 11. Pattern profile of F-resist A (120 nm) / DUV42 (30 nm) / SiN (70 nm) / WSi (50 nm) / poly-Si (50 nm) / SiO₂ (100 nm) / Si structure (exposure tool was a 0.60-NA microstepper using an alt-PSM. Feature size was 100, 85, or 80-nm 1:1 L/S).

Fig. 12. Pattern profile of F-resist A (120 nm) / DUV42 (30 nm) / SiN (70 nm) / WSi (50 nm) / poly-Si (50 nm) / SiO₂ (100 nm) / Si structure (exposure tool was a 0.85-NA microstepper using an alt-PSM. Feature size was 75, 70, or 65-nm 1:1 L/S).

Fig. 13. Pattern profile of F-resist C (250 nm) / DUV42 (30 nm) / SiN (100 nm) / TEOS-SiO₂ (500 nm) / Si substrate (exposure tool was a 0.60-NA microstepper using a 5% att-PSM. Feature size was 150-nm C/H).

of BARC / SiN RIE, (c) shows the results after resist ashing, and (d) shows the results of WSi / poly-Si RIE (Cl_2 / HBr gas). We succeeded in fabricating an 80-nm gate pattern (the k_1 factor of the Rayleigh equation is equal to 0.31). Figure 12 shows the results of gate fabrication using a 0.85-NA microstepper and an alt-PSM. The 65-nm gate patterns were successfully fabricated ($k_1=0.35$). The pattern pitch was only 130 nm.

Next, we applied the optimized HM process to C/H fabrication. The structure was F-resist C (250 nm) / DUV42 (30 nm) / SiN (100 nm) / TEOS- SiO_2 (500 nm) / Si substrate. Figure 13 (a) shows the resist pattern after development exposed with a 0.60-NA microstepper using a 5% att-PSM, (b) shows the result of BARC / SiN RIE (under the optimized conditions), (c) shows the results after BARC / resist ashing, and (d) shows the results of TEOS- SiO_2 RIE (C_4F_6 / Ar / O_2 gas). The remaining resist thickness after BARC / SiN RIE was about 120 nm. F-resist C and DUV42 were clearly removed by ashing. We then obtained a 150-nm C/H pattern with a good profile.

4. Conclusions

We have described a hard mask process suitable for 157-nm lithography. Using a BARC (30 nm) / SiN (70 nm) structure, we fabricated a WSi / poly-Si 65-nm gate pattern with a 0.85-NA microstepper and a TEOS- SiO_2 150-nm C/H pattern with a 0.60-NA microstepper. This clearly demonstrates that our HM process is the leading candidate for sub-70nm-node semiconductor devices.

Acknowledgements

We would like to thank Dr. L. H. Chen and K. Inazawa (Tokyo Electron AT Ltd.) for the RIE evaluation, and O. Yamabe, N. Kanda, J. H. Kim, and T. Suganaga (Selete) for their help with the 157-nm patterning. We also thank Dr. N. Endo and W. Wakamiya (Selete) for their guidance and encouragement.

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