Study of Resist Pattern Roughness on 0.15 μ m KrF Lithography

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Resist pattern edge roughness of a chemically amplified resist for 0.15 μ m KrF excimer laser lithography has been studied. The linewidth 3σ critical dimension (CD) dispersion of the chemically amplified positive working resist increases significantly from 3.0 nm to 18.5 nm upon reduction of the film thickness for the 0.15 μ m isolated line pattern, and shows pattern size dependence. After the gate etching process, the pattern edge roughness was almost the same as the linewidth 3σ CD dispersion on the resist film before the etching. From gas chromatography-mass spectrometry (GC-MS) analysis of the residual solvent in the resist film, the solvent density was found to decrease as the film thickness decreased. The relationship between residual solvent density and linewidth 3σ CD dispersion for the 0.15 μ m pattern before and after the etching process was observed. From the process condition dependence investigation, it was determined that the resist pattern edge roughness could be reduced by optimizing the baking conditions mainly determined by the prebake temperature.

Key Words: Resist Pattern Edge Roughness, Chemically Amplified Resist, Residual Solvent, 0.15 μ m KrF Lithography

1. Introduction

The degree of integration in semiconductor integrated circuits has been increased, and recently the device manufacturing process according to the 0.15 μ m design rule has been developed using KrF excimer laser lithography. When the resolution of resist pattern size is below the exposure wavelength (248 nm), several problems of pattern quality occur in the case of the chemically amplified resist process [1].

In the past, to accomplish pattern fabrication of less than 0.15 μ m feature size using KrF lithography exposure tools, resist

materials of higher resolution with a rectangular resist profile were required. Accordingly, with the need to reduce the minimum feature size, the lithographic technology has been improved to obtain high resolution and CD accuracy.

In mass production using KrF lithography, an organic antireflective coating (ARC) or inorganic ARC process and a thin film fabrication process that improve the lithography process margin are popular; however, actual devices have a step height, and there exist some factors leading to resist profile degradation.

The taper, undercut, tailing and fringe profiles are indication of deterioration caused

mainly by the influence of optical and chemical interactions between the resist and substrate, variation of reflectivity and mismatch of acid diffusion length [2-3].

The resist and ARC process have been optimized to obtain rectangular resist profiles on topographical substrates; however, another CD variation still remains on the resist pattern.

Resist pattern edge roughness [4-9] is one of the most serious problems leading to CD variation in $0.15\ \mu\text{m}$ level devices. In particular, in the logic gate layer, gate linewidth control accuracy is the most important parameter governing device performance, and therefore, must be realized for CD controllability.

In this study, the influence of resist pattern edge roughness factors and of the process conditions on the KrF lithography process has been investigated.

2. Experimental

2.1. Process Conditions

Two types of chemically amplified positive working resists consisting of propylene glycol monomethyl ether acetate (PGMEA) and ethyl lactate (EL) as solvents, were used. Resist films of thickness ranging from 0.3 to $1.0\ \mu\text{m}$, were spin-coated onto BARC applied WSi gate substrates and subjected to pre-exposure hot plate baking (PB) at 80 - 120°C for 90 seconds. They were then subjected to post-exposure hot plate baking (PEB) at 110°C for 90 seconds, developed in 2.38% aqueous tetramethyl ammonium hydroxide (TMAH) solution for 60 seconds and finally rinsed in deionized water.

Exposures were performed using a KrF excimer laser stepper with N.A. of 0.60 and $\sigma = 0.75$. A conventional binary mask and conventional illumination conditions were used. The environment was free of basic contaminants ($\text{NH}_3 < 1\text{ppb}$). The reactive ion etching (RIE) conditions included Cl_2 gas chemistry.

Pattern wafer metrology and evaluation of resist resolution were performed using an S8840 (Hitachi) scanning electron microscope (SEM) and an S5000 (Hitachi) cross-sectional

SEM. The remaining solvent in the resist films was quantitatively analyzed by GC-MS using a HP-5890A/5970MSD spectrometer (Hewlett-Packard). The resist morphology was measured using an atomic force microscope (AFM) nanoscope III (Digital Instruments).

3. Results and Discussion

3.1. Pattern Edge Roughness on Gate Layer

Figure 1 shows the top-view SEM image of $0.15\ \mu\text{m}$ and $0.20\ \mu\text{m}$ isolated line resist patterns of $0.3\ \mu\text{m}$ film thickness before etching. The $0.20\ \mu\text{m}$ resist pattern edge has a smooth sidewall. On the other hand, the $0.15\ \mu\text{m}$ pattern edge exhibits roughness. The pattern edge roughness causes the reduction in CD accuracy. The size of the $0.15\ \mu\text{m}$ linewidth 3σ CD dispersion measured using SEM in 32 points was $18.5\ \text{nm}$ and that of the $0.20\ \mu\text{m}$ line was $3.0\ \text{nm}$.

Fig. 1. Resist pattern of (a) $0.15\ \mu\text{m}$ and (b) $0.20\ \mu\text{m}$ isolated lines for $0.3\ \mu\text{m}$ thick film.

The pattern edge roughness of the chemically amplified positive working resist significantly increases on reducing the thickness of the film on the $0.15\ \mu\text{m}$ logic gate pattern. It has become a significant problem as the design rule has approached $0.15\ \mu\text{m}$ in the case of the conventional KrF lithography process, resulting in a deterioration in CD controllability.

Figure 2 is a plot of the linewidth 3σ CD dispersion as measured using SEM with respect to film thickness for $0.15\ \mu\text{m}$, $0.18\ \mu\text{m}$

Fig. 2. Resist pattern edge roughness of 0.15 μm , 0.18 μm and 0.20 μm isolated lines.

and 0.20 μm isolated line patterns. In the case of the 0.15 μm pattern, resist roughness increased with decreasing film thickness, but in the case of 0.18 μm and larger patterns, resist roughness was not observed. It shows that the pattern edge roughness dependence on film thickness is governed by pattern size. It is noted that even an extremely low roughness of the devices near 0.15 μm , cannot be ignored since its influence on linewidth control accuracy becomes more significant in the lithography and etching processes.

Figure 3 shows the 0.15 μm and 0.20 μm isolated line patterns after gate etching under the same process conditions as those in

Fig. 3. After etching pattern of (a) 0.15 μm and (b) 0.20 μm isolated lines for 0.3 μm thick resist film.

figure 1. The pattern edge roughness of the resist film was clearly transferred by etching. Roughness, after BARC etching and substrate etching, was still present when edge roughness was present before etching.

Figure 4 shows plots of linewidth 3 σ CD dispersion for a 0.15 μm isolated line pattern with film thickness before and after etching. It indicates that pattern edge roughness before and after etching is almost unchanged. In the 0.18 μm and 0.20 μm patterns, edge roughness was absent after the etching process.

Fig. 4. Pattern edge roughness before and after etching of 0.15 μm isolated line.

3.2. Quantitative Analysis of Residual Solvent

To study the pattern edge roughness, we analyzed the residual solvent by GC-MS of a resist film subjected to PB, exposure and PEB.

As the first step, we analyzed the PGMEA content in the resist material as the main solvent component. Figure 5 shows the PGMEA solvent content per 1 μm cube in films with respect to resist film thickness. The PGMEA density decreased from 1.4×10^{-5} ng/ μm^3 to 3.7×10^{-6} ng/ μm^3 as the film thickness decreased from 1.0 μm to 0.3 μm . The PGMEA density was found to depend on resist film thickness.

Fig. 5. Concentration of residual PGMEA density as a function of resists thickness.

Fig. 6. Concentration of residual EL density as a function of resists thickness.

As the second step, we investigated the EL solvent in resist materials. Figure 6 shows that the amount of EL solvent in films depends on resist film thickness. The plot also indicates the relationship between the density of the residual solvent and film thickness.

From GC-MS analysis, the residual solvent density was determined by resist film thickness under the same process condition. These results indicate that the pattern edge roughness is determined by the solvent density in the resist film after processing, rather than by the nature of the solvent. The baking temperatures were the same for all the samples on the hot bake plate so that the thin film sample was higher in

calories than the thick film sample. The difference in calorie efficiency was found to influence the residual solvent concentration for several resist film thicknesses. The residual solvent density was reported to be related to the acid diffusion length. This may be one of the reasons why the resist roughness depends on film thickness.

The relationship between PGMEA content in different film thickness and linewidth 3σ CD dispersion for $0.15\mu\text{m}$ before and after etching is shown in figure 7. This result indicates that the residual solvent density was related to the resist pattern edge roughness.

Fig. 7. Residual solvent density dependence of resist pattern edge roughness on $0.15\mu\text{m}$ isolated line.

3.3. Effect of Process Conditions

We have evaluated the effect of process conditions, such as baking temperature and exposure dose, on pattern edge roughness.

Figure 8 shows isolated line patterns in the case of PB temperatures of 80°C and 100°C . The linewidth 3σ CD dispersions are 5.0nm and 18.5nm , and residual PGMEA contents are $2.3 \times 10^{-5}\text{ng}/\mu\text{m}^3$ and $1.3 \times 10^{-5}\text{ng}/\mu\text{m}^3$, respectively, as shown in figure 9. The residual solvent density was proportional to the PB temperature. With decreasing PB temperature, the linewidth 3σ CD dispersion decreased and smooth pattern edges were obtained. The PB temperature has a large influence on the resist pattern edge

(a)

(b)

Fig. 8. Comparison of pattern edge roughness at different PB temperatures ; (a) 100°C (b)80°C.

Fig. 9. PB temperature dependence of residual solvent density of 0.6 μ m resist thickness.

roughness which caused by residual solvent density.

The effect of the PEB temperature on the remaining PGMEA content was also investigated. The residual solvents also depended on the PEB temperature, but to a smaller extent as compared to the PB temperature dependence. From these results, it was observed that the resist pattern edge roughness could be reduced by optimizing the baking conditions, mainly the PB temperature, which provided one way of reducing the pattern edge roughness during the processing step.

Finally, we investigated the influence of

(a) Ra : 1.4nm, Rmax : 13.9nm

(b) Ra : 1.7nm, Rmax : 18.8nm

Fig. 10. AFM images of (a) unexposed and (b) 5.5mJ/cm² : 1/2Eth dosage exposed resist.

exposure dose. Figure 10 shows the AFM resist top-surface topography of 0 mJ/cm² and 5.5 mJ/cm² (1/2Eth dosage) exposed areas after development on a 0.3 μ m thick film. The average roughness Ra values were 1.4nm and 1.7nm, and roughness max-min Rmax values were 13.9 nm and 18.8 nm, respectively. Resist surface roughness depended on the exposure dose, and the roughness of an unexposed area was less than that of an exposed area. This suggests the linewidth dependence of resist pattern edge roughness which relate to the degradation of aerial images of pattern edges. The aerial image contrast of the 0.15 μ m isolated line at the pattern edge was lower than that of the 0.20 μ m

pattern. Therefore the influence of pattern edge roughness on device characteristics increases with low contrast lithography, such as in the case of a below $0.15\ \mu\text{m}$ design rule.

4. Conclusions

We evaluated the pattern edge roughness in the case of the $0.15\ \mu\text{m}$ KrF lithography. The linewidth 3σ CD dispersion of a chemically amplified positive working resist significantly increases from 3.0 nm to 18.5 nm upon reducing the film thickness on the $0.15\ \mu\text{m}$ isolated line pattern, and it shows a pattern size dependence. After the gate etching process, the pattern edge roughness is almost the same as the linewidth 3σ CD dispersion on the resist film before the etching.

From the analysis of the residual solvent in the resist film by GC-MS, the PGMEA content per unit volume was found to decrease as the film thickness decreased. In the case of using EL as a solvent, a relationship between the density of the residual solvent and film thickness was observed. These results indicate that the residual solvent is one of the reasons behind the resist roughness dependence on film thickness. The relationship between residual solvent content and linewidth 3σ CD dispersion for $0.15\ \mu\text{m}$ patterns before and after etching was observed.

We confirmed the dependence on process conditions such as PB temperature, PEB temperature and exposure dose of resist pattern

roughness. The resist pattern roughness could be reduced by optimizing the baking conditions, mainly determined by the PB temperature. The influence of exposure dose on resist top-surface topography suggested the resist pattern edge roughness dependence of linewidth.

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