Pattern Transfer Process Using Spun-on Carbon Film for KrF and ArF Lithography

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Dry etch resistance and antireflective performance were studied for a spun-on carbon film containing 90.4wt% of carbon. The refractive index of the spun-on carbon film at KrF wavelength (248 nm) is \( n=2.17 \), \( k=0.37 \) and that at ArF wavelength (193 nm) is \( n=1.44 \), \( k=0.39 \). The bilayer BARC system composed of upper spun-on glass (SOG) and lower spun-on carbon was evaluated. It reduces the reflectivity to 1% for KrF wavelength and 0.5% for ArF wavelength and the variation of the substrate thickness can be ignored. Resist profiles are obtained without any footing, residue, or standing-wave. The etch resistance of the spun-on carbon film is 1.3 times greater than that of the thermally oxidized novolak film (i.e., conventional under-layer for trilayer resist process).

Keywords: KrF lithography, ArF lithography, thinner resist, bottom antireflective coating (BARC), pattern transfer, spun-on carbon film

1. Introduction

The thin resist process has been examined with a view to enlarging the lithographic process window for DUV lithography.[1] The process is subject to serious problems: strong thin film interference in resists and inadequate performances as an reactive ion etching (RIE) mask in the substrate fabrication. To solve those problems, a bilayer bottom antireflective coating (BARC) system, composed of an upper silicon oxide deposited by a low pressure chemical vapor deposition (LPCVD) and a lower sputtered carbon, has been reported.[2] The advantage of this process is that substrates can be etched with a small etch bias due to the higher RIE resistance of carbons. However, the processes of LPCVD and sputtering deposition increase the cost of ownership (COO). In order to meet the requirement of antireflection, etch properties, and COO, we have developed a bilayer BARC system composed of upper spun-on glass (SOG) and lower spun-on carbon. These films can be easily spin-coated with the same coater track as for the resist coater.

2. Experiment

2.1. Material

The spun-on carbon film was prepared by spin-coating a cyclohexanone solution of the spun-on carbon polymer and being baked at 180 °C for 60 seconds and 300 °C for 120 seconds, successively. The ratios of carbon, oxygen, and hydrogen in the spun-on carbon film were 90.4wt%, 4.6wt%, and 4.6wt%, respectively. The SOG film was prepared by spin-coating a propylene glycolic monopropyl ether solution of the poly(methylsiloxane) and being baked at 200 °C for 60 seconds and 300 °C for 60 seconds, successively. The bilayer BARC was formed by coating the SOG film on the spun-on carbon film.

2.2. Lithography

The refractive indices of each film were measured with a spectroscopic Sorpra ellipsometer. The resist is coated on bilayer BARC on the SiO2/Si substrate. The reflectivity to resist and absorbance of exposure light in the resist were calculated by in-house software, taking into consideration of multi-reflection in each film. Table I shows the refractive indices used in the calculation.

For the KrF lithography, the resist pattern is fabricated as follows. The environmentally stable
A chemically amplified positive (ESCAP) type resist (300 nm) was coated on bilayer BARC composed of upper SOG (80 nm) and lower spun-on carbon (300 nm), and baked at 130 °C for 60 seconds after coating, and then baked again at 130 °C for 90 seconds after exposure. The resist pattern was formed by being exposed by a KrF scanning stepper (NA=0.68, σ=0.75) with a 2/3 annular aperture, and then being developed with a 2.38% tetramethylammonium hydroxide (TMAH) aqueous solution.

For the ArF lithography, the resist pattern is fabricated as follows. The cyclic olefin-maleic anhydride (COMA) type resist (200 nm) was coated on bilayer BARC composed of upper SOG (110 nm) and lower spun-on carbon (300 nm), and baked at 110 °C for 60 seconds after coating, and then baked again at 130 °C for 90 seconds after exposure. The resist pattern was formed by being exposed by an ArF scanning stepper (NA=0.6, σ=0.75) with a 2/3 annular aperture, and then being developed with a 2.38% TMAH aqueous solution.

The process window was calculated using exposure-defocus plots (an ED-tree program) for critical dimension (CD) tolerance of ±10% of the CD target.

2.3. Etching
Blanket etch rate of the spun-on carbon film was measured with CF₄/O₂/Ar RIE, which is typical etch condition for etching dielectrics substrate, in order to evaluate the RIE resistance during substrate RIE. It was compared with 15 kinds of organic films including thermally oxidized novolak (i.e., conventional under-layer for trilayer resist process) and sputtered carbon. The pattern transfer demonstration was performed at the gate level of 1G bit dynamic random access memory (DRAM). The resist pattern was transferred to SOG using a fluorine based RIE. The SOG pattern is transferred to the spun-on carbon film using an oxygen based RIE. The spun-on carbon pattern was transferred to 200-nm-thick SiN using CF₄/O₂/Ar RIE.

3. Results and discussions
3.1. Optical properties
Figure 1 shows the spectra of refractive index of the spun-on carbon film. The sputtered carbon film has absorption in the wavelength of alignment light (550 - 700 nm) due to π bond in the graphite structure and alignment failure sometimes occurs. On the other hand, the spun-on carbon film is transparent to that wavelength and alignment mark can be clearly detected.

The refractive index of the spun-on carbon film at the KrF wavelength (248 nm) is n=2.17, k=0.37, and that at ArF wavelength (193 nm) is n=1.44, k=0.39. Antireflective performance of bilayer BARC system was evaluated using SiO₂/Si for the
substrate. In the case that the substrate is transparent to the exposure wavelength like SiO2, the variation of the substrate thickness induces the variation of absorbance in the resist because multi-reflection occurs in substrate.\[3\] In order to estimate the variation of absorbance in the resist with varying SiO2 thickness, the swing ratio was calculated by varying the thickness of the spun-on carbon film. The swing ratio was determined by the variation in amplitude of the absorbance in the resist on the occasion of varying SiO2 thickness from 450 nm to 550 nm normalized by the absorbance in the resist at the 500-nm-thick SiO2. In this calculation, the SOG thickness was set at 80 nm and 110 nm for KrF lithography and ArF lithography, respectively. Figure 2 shows the swing ratio plotted against the thickness of the spun-on carbon film. For a thinner thickness of the spun-on carbon film, absorbance is sensitive to substrate thickness. As the thickness of the spun-on carbon film is increased, absorbance variation is reduced because the spun-on carbon film becomes opaque. When the thickness of the spun-on carbon film is increased to more than 250 nm for KrF lithography and 160 nm for ArF lithography, swing ratio can be reduced less than 0.5%. In the case of the conventional organic BARC, opaque thickness is difficult to use because the thick organic BARC cannot be etched using thinner resists due to poor selectivity of BARC/resist. On the other hand, in the case of bilayer BARC system, these films can be etched as discussed later and the variation of the substrate thickness can be completely ignored. Figure 3 shows the reflectivity at resist/SOG interface on the occasion of varying SOG thickness with the thickness of SiO2 and the spun-on carbon film set at 500 nm and 300 nm (i.e., opaque thickness), respectively. Reflectivity is reduced to 1% for the KrF wavelength and 0.5% for the ArF wavelength due to multi-reflection in the SOG film. Smaller reflectivity for ArF wavelength is due to the smaller difference of the refractive index between the resist and the spun-on carbon film. To summarize, the bilayer BARC system results in good antireflective performance for lithography on transparent substrate.

3.2. Lithography performance

Figure 4(a) and 5(a) shows the resist patterns and the process margin of 130 nm equal line and space using KrF lithography, respectively. Figure 4(b) and 5(b) shows the resist patterns and the process margin of 110 nm equal line and space using ArF lithography, respectively. For both types of lithography, resist profiles are obtained without any footing or residue on SOG. Standing-wave effects in the resist are not observed. The lithographic window sufficient for the early stage of manufacturing level of 1G bit DRAM is obtained for 130 nm equal line and space pattern by using KrF lithography (i.e., dose margin of 10% at 0.3 depth of focus) and 110 nm equal line and
3.3. Etch performance

Figures 6(a)-6(c) show the blanket etch rates of the spun-on carbon film under CF$_4$/O$_2$/Ar RIE (SiN RIE condition) versus carbon, oxygen, and ohnishi parameter [4], respectively, in comparison with 15 kinds of organic films. The etch rate of SiN under this etch condition is 300 nm/min. The organic film containing higher carbon content and smaller oxygen content is considered to have lower etch rate because carbon has the lowest sputtering yield among elements of organic material and oxygen increases ashing of the polymer.[4] As was expected, the etch rates are decreased with the increase of carbon and the decrease of oxygen. Increasing the carbon content and decreasing the oxygen content of the polymer to the ultimate value (Carbon:90.4wt%, Oxygen:4.6wt%) at which it can be spin-coated, the RIE resistance of the spun-on carbon film is increased to 1.3 times higher than that of thermally oxidized novolak (i.e., conventional under-layer for trilayer resist process). Concerning ohnishi parameter, the etch rates tend to decrease with the decrease of the ohnishi parameter. However, detailed behavior of etch rates can not be explained only by it.

The spun-on carbon film was applied to the gate fabrication of 1G bit DRAM. The film structure was resist/SOG/spun-on carbon/SiN=300/80/300/200 nm. If SiN is etched only by the resist pattern, the resist thickness is required to be more than 400 nm due to the low etch selectivity of SiN/resist(=~0.85). By using the bilayer BARC process, slightly more than 200 nm of resist thickness is required toetchSiN because of the adequate etch selectivity for each etching step; the etch selectivities of SOG/resist (SOG RIE), spun-on carbon/SOG (spun-on carbon RIE), and SiN/spun-on carbon (SiN RIE) are 2, 30, and 1, respectively. For the comparison, the thermally oxidized novolak film (500 nm) was also applied to the fabrication of the gate structure in place of the spun-on carbon film. The exposure was performed with KrF scanner. Figure 7 shows the cross-sectional profiles of 130 nm equal line and space pattern of the thermally oxidized novolak film.

Fig. 7. (a) Cross-sectional profiles of the etched 130 nm equal line and space pattern of the thermally oxidized novolak film. (b) Same as (a) but for using the spun-on carbon film.

Fig. 8. (a) Cross-sectional profiles of 130 nm equal line and space pattern of SiN fabricated by using the spun-on carbon film. (b) Same as (a) but for 160 nm isolate pattern

Table II. Etch bias between resist pattern and etched SiN at the gate level

<table>
<thead>
<tr>
<th>RIE mask</th>
<th>Dense</th>
<th>Isolate</th>
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<tbody>
<tr>
<td>Thermally oxidized novolak</td>
<td>5 nm</td>
<td>67 nm</td>
</tr>
<tr>
<td>Spun-on carbon</td>
<td>3 nm</td>
<td>34 nm</td>
</tr>
</tbody>
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nm equal line and space patterns after spun-on carbon RIE in comparison with those after novolak RIE. While the thermally oxidized novolak pattern has bowing, the spun-on carbon film is vertically etched. The bowing is considered to originate from the weaker resistance to the oxygen etchant. Figure 8 shows the cross-sectional profiles of 130 nm equal line and space pattern and 160 nm isolate pattern of the etched SiN pattern in the case of using the spun-on carbon film. Table II shows the etch bias defined by the width of the etched SiN pattern minus the width of the resist pattern. The etch bias between dense and isolate pattern in the case of using spin-on carbon is 31 nm, which is half of that using thermally oxidized novolak (i.e., 62 nm). The difference is considered to arise as follows. In order to reduce the bowing of novolak, deposition gas chemistries are used for the oxygen based RIE because deposition protects the sidewall of the novolak pattern. Deposition for the isolate pattern occurs more easily than for the dense pattern. Therefore, isolate pattern fabricated by using the novolak film has larger positive bias than that fabricated using the spun-on carbon film.

4. Conclusions
RIE resistance and antireflective performance were studied for a spun-on carbon film containing 90.4 wt% of carbon. The refractive index of the spun-on carbon film at KrF wavelength is \(n=2.17\), \(k=0.37\) and that at ArF wavelength is \(n=1.44\), \(k=0.39\). The bilayer BARC system composed of upper SOG and lower spun-on carbon was evaluated. It reduces the reflectivity to 1% for KrF wavelength and 0.5% for ArF wavelength and the variation of substrate thickness can be ignored. Resist profiles are obtained without any footing, residue, or standing-wave. The RIE resistance of the spun-on carbon film is 1.3 times greater than that of the thermally oxidized novolak film (i.e., conventional under-layer for trilayer resist process). It was demonstrated that the gate structure of 1 G bit DRAM was fabricated with the reduced etch bias using bilayer BARC system. It lessens the resist thickness required for fabricating the substrate and has the potential to enlarge the process margin.

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References