Effect of light irradiation from inductively coupled Ar plasma on etching yields of SiO$_2$ film by CF$_3$ ion beam injections

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Abstract. Effects of light irradiation on etching yields of SiO$_2$ films by CF$_3$ ion beams have been investigated with a low-energy mass selected ion beam system. An inductively coupled plasma (ICP) from Ar gas was used as the light source. The spectrum of light emitted from the Ar ICP was measured by vacuum ultraviolet and visible monochromators. Etching yields of SiO$_2$ films by 470 eV CF$_3$ ion beam injections were obtained from the ratio of the number of incident CF$_3$ ions to that of removed SiO$_2$ atoms during the ion beam injection process with or without simultaneous light irradiation from the Ar ICP. The incident ion number was evaluated from the integration of temporal evolution of ion beam current. The number of removed atoms can be obtained from the etched depth of SiO$_2$ films measured by a laser interferometer. It is found that the obtained SiO$_2$ etching yield by simultaneous irradiation of CF$_3$ ions and photons from the light source was smaller than that by ion beam irradiation only.

1. Introduction
Carbon tetrafluoride (CF$_4$) gases are widely used in semiconductor etching processes. Etching yields of various materials due to fragment ions produced in CF$_4$ gas-based plasmas provide useful information on the control of manufacturing processes. The fragment elements produced from CF$_4$ gas and their kinetic energies play an important role in the etching processes. The etching yields of silicon dioxide (SiO$_2$) films by fragment ions (F$^+$, CF$^+$, CF$_2^+$, and CF$_3^+$) from CF$_4$ gas in the energy range of 250-2000 eV have been measured with ion beam devices [1-3].

In addition to the ion energy, ultraviolet (UV) light, which can cause excitation of substrate atoms and therefore change their average bond energies, may play an important role in CF$_4$ gas-based plasma processes [4, 5]. Although it is important to evaluate effects of UV light on etching processes, the influence of Ar inductively coupled plasma (ICP) light has not been extensively investigated yet so far. In this experiment, SiO$_2$ films were irradiated by light from an Ar ICP in addition to a CF$_3$ ion beam for the investigation of the influence of UV light on the etching yields.

2. Experimental apparatus
This experiment was carried out in a low-energy mass selected ion beam system [6]. This system consists of a Freeman-type ion source, an extractor electrode, a magnetic-field-based mass selector, a
deflector, a decelerator, a process chamber, and a mass-energy analyzer, as shown in figure 1. From the source gas (Ar-diluted CF₄ gas), F, CF, CF₂, CF₃ ions were produced in addition to Ar ions in the ion source chamber. These ions were extracted by a high voltage of -25 kV applied to the extractor electrode. The ions were separated by the mass selector, so that only desired ion species (CF₃ ions in the present experiment) remained in the beam line without impurity ions. The mass-selected ion beam was then deflected by a small angle, the process of which removed high energy neutral species generated by charge exchange reactions with residual gases in the beam line. Finally, the ion beam was decelerated to the desired kinetic energy and injected to the SiO₂ thin film formed thermally on a Si substrate. The ion injection angle was normal to the substrate. The quality of the ion beam (i.e., energy and mass distribution of incident ions) was examined by the mass-energy analyzer (balzers, PPM-421).

The substrate was set at the sample holder on the manipulator. The sample holder was connected with an ammeter (KEITHLEY, 6485). A Mo orifice plate which was connected with the ground was set at 4 mm in front of the substrate surface. The diameter of the orifice was 7.5 mm. The ion beam irradiated the substrate surface through the orifice, the current of which was measured by the ammeter. The substrate was set at room temperature.

Etching yields of the SiO₂ film were determined from the ratio of the number of incident CF₃ ions to that of removed SiO₂ atoms during the ion beam injection process. The incident ion number was evaluated from temporal evolution of the ion beam current. The number of removed atoms can be obtained from the etched depth of SiO₂ film measured by a laser interferometer.

In the present experiment, the etching yield due to ion injections only was compared with that due to simultaneous ion and light irradiation. The substrate surface was irradiated with a light source at an oblique angle (50 degree), as shown in figure 2. In the present experiment, the light source was an Ar ICP. The base pressure in the Pyrex chamber (50 mm in diameter, 350 mm in length) of ICP device was about 0.4 Pa and the pressure of Ar gas was 4-5 Pa. The Ar plasma was produced by a 13.56 MHz power source (NIHON KOSHUHA, HFS-005) at 16-30 W. The distance between the ICP device and the substrate was about 40 cm. The Ar ICP light was set to pass through an MgF₂ window, which allows light with the wavelength of 110 nm or longer to pass through.

3. Experimental results
Firstly, the spectrum of light emitted from the Ar ICP was measured. The Ar ICP light had a wide spectrum including UV and visible light. Figure 3 shows a vacuum ultraviolet emission spectrum (110-290 nm) of the Ar ICP measured by a Seya-Namioka monochromator which was connected with the ICP device through the MgF₂ window. Line spectra of impurities (hydrogen H, carbon C, nitrogen N, and oxygen O) are seen in the 110-200 nm region while the emission is dominated by NO(γ) bands in the 200-290 nm region [7]. It is seen that there are no dominant line spectra of Ar in this region. The UV light intensity measured by a UV power meter (HAMAMATSU, H8025-146, sensitive range = 120-200 nm) were found to be 8 μW/cm². Figure 4 shows an emission spectrum of the Ar ICP.
measured through the Pyrex chamber by a monochromator (Ocean Optics, HR4000) in the visible region (350-800 nm). Line spectra of Ar and H are seen in figure 4.

A mass spectrum in the ion source was measured by scanning the mass selector current. It was found that the intensity of CF$_3$ ions was the largest among all fragment ions produced from CF$_4$ gas. Therefore, we select CF$_3$ as the injection ions.

The energy distribution of CF$_3$ ions was measured by PPM-421. In this case the peak energy of the CF$_3$ ion was found to be 470 eV. The full width at the half maximum (FWHM) of the distribution was about 5 eV.

Figure 5 shows the temporal evolution of the ion beam current during the etching process of a SiO$_2$ film by CF$_3$ ions with Ar ICP light. The beam current of CF$_3$ ions was 0.18 $\mu$A and almost constant during the process. The power of ion beam was 190 $\mu$W/cm$^2$, which was larger than the power of UV light (8 $\mu$W/cm$^2$). The injecting particle number of CF$_3$ ions was evaluated by integrating temporal evolution of the beam current.

After the ion beam injection experiment, the etched depth of each SiO$_2$ film was measured by a laser interferometer. The thickness of SiO$_2$ film before the ion beam injection was 103 nm. Figure 6 shows the profile of a SiO$_2$ film thickness after ion beam injections. A hollow region due to the etching of SiO$_2$ film can be seen near the center in figure 6. The diameter of etched region is about 8 mm, corresponding to the size of Mo orifice. The number of etched atoms can be calculated from the volume integration of etched depth and the density of SiO$_2$ film.

Etching yields of the SiO$_2$ film were calculated from the ratio of the number of injected CF$_3$ ions to that of etched SiO$_2$ atoms. The etching yield of SiO$_2$ by the CF$_3$ ion beam without Ar ICP light was evaluated to be 1.1. On The other hand, the etching yield of SiO$_2$ by the CF$_3$ ion beam with Ar ICP light was 0.85. Therefore, the etching yield of the SiO$_2$ film by CF$_3$ ions with Ar ICP light was slightly smaller than that without Ar ICP light. The reduction of etching yield by the light irradiation suggests the interaction of ion beam and Ar ICP light. When the substrate was irradiated by Ar ICP light only, etching of the film was not observed.

4. Summary

Effects of Ar ICP light on etching yields of SiO$_2$ films by CF$_3$ ions were investigated with a low-energy mass selected ion beam system. Prior to the ion beam injection experiment, the spectrum of light emitted from the Ar ICP was measured. Line spectra of impurities (H, C, N, and O) were seen in the 110-200 nm region while the emission was dominated by NO($\gamma$) bands in the 200-290 nm region. On the other hand, line spectra of Ar and H were seen in the visible region (400-800 nm). The ion beam quality was investigated by PPM-421. It was found that the peak ion energy was 470 eV and FWHM of the energy distribution was about 5 eV. We have evaluated the etching yields of SiO$_2$ films by CF$_3$ ion beams with or without light irradiation. The etching yields were compared among the three
cases: (1) ion beam injections only, (2) simultaneous irradiations with the ion beam and the light from the Ar ICP, and (3) irradiations with the light from the Ar ICP only. Prior to the experiment, we expected that the excitation of substrate materials by UV lights may result in weakening of atomic bonds temporarily and ion injections into the materials under such conditions may increase the etching yield. However, the experiment showed that the obtained SiO\(_2\) etching yields by simultaneous irradiation of CF\(_3\) ions and photons from the light source were smaller than those by ion beam irradiations only. This difference in etching yields may be caused by the modification of CF\(_x\) polymer formation on the substrate surface during the ion beam etching process.

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References
[1] Ishikawa K, Karahashi K, Tsuboi H, Yanai K and Nakamura M 2003 *J. Vac. Sci. Technol. A* **21** L1
[2] Karahashi K, Yanai K, Ishikawa K, Tsuboi H, Kurihara K and Nakamura M 2004 *J. Vac. Sci. Technol. A* **22** 1166
[3] Yanai K, Karahashi K, Ishikawa K and Nakamura M 2005 *J. Appl. Phys.* **97** 053302
[4] Ishikawa K, Okigawa M, Ishikawa Y, Samukawa S and Yamasaki S 2005 *Appl. Phys. Lett.* **86** 264104
[5] Samukawa S, Jinnai B, Oda F and Morimoto Y 2007 *Jpn. J. Appl. Phys.* **46** L64
[6] Yoshimura S, Toh A, Sugimoto S, Kiuchi M and Hamaguchi S 2006 *Jpn. J. Appl. Phys.* **45** 8204
[7] Rahman A, Yalin A P, Surla V, Stan O, Hoshimiya K, Yu Z, Littlefield E and Collins G J 2004 *Plasma Sources Sci. Technol.* **13** 537