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CF_4-Based Neutral-Beam Etch Characteristics of Si and SiO_2 Using a Low-Angle Forward-Reflected Neutral-Beam Etching System

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In this study, energetic reactive neutral beams were formed with H_2/CF_4 by using a low-angle forward-reflected neutral-beam technique, and the etch properties of Si, SiO_2, and the photoresist (PR) were investigated. The results showed that, when Si and SiO_2 were etched with an energetic reactive radical beam generated with CF_4, etch rates of Si and SiO_2 higher than 210 Å/min and 230 Å/min, respectively, could be obtained. However, the etch selectivities of Si and SiO_2 to the PR were lower than 0.7. Increasing the H_2 gas ratio in H_2/CF_4 increased the etch selectivity of Si and SiO_2 to the PR, similar to reactive ion etching by H_2/CF_4, and by using 50 %H_2/50 %CF_4, etch selectivities of Si and SiO_2 higher than 1.5 and 2.5, respectively, could be obtained.

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I. INTRODUCTION

Charge-induced damage during plasma etching is one of the biggest issues to be solved for the realization of deep submicron semiconductor devices and future nanoscale devices. Several low-damage processes have been proposed to avoid this charge-related damage, and one of the techniques is to use neutral beam etching [1–9].

A neutral beam is generally formed by using a plasma source to produce reactive ions and then neutralize the ions during their extraction from the plasma source [3, 5, 6]. In our experiment, a neutral beam was formed by reflecting all the reactive ions extracted from an inductively coupled plasma (ICP) ion gun off a flat surface tilted at a small angle of 5° relative to the ion-beam's direction to produce a nearly parallel neutral beam flux [10–14]. In this study, the Si, SiO_2, and photoresist (PR) etch rates, and the etch selectivities of Si and SiO_2 to the PR were investigated using the low-angle forward-reflected neutral-beam system (LAFRN) for various grid voltages, CF_4 gas flow rates, and H_2 percentages in CF_4/H_2 [15].

II. EXPERIMENTS

In this experiment, a low-angle forward-reflected neutral-beam source, which is composed of an rf ion source and a planar-reflector, was used to form a neutral beam. Fig. 1 shows a schematic diagram of the LAFRN beam system used in this study. A 150-mm diameter three-grid ICP ion source was used as the ion gun. The rf power applied to the ICP source was varied from 100 to 1000 W at a frequency of 13.56 MHz. The ions from the ICP source were extracted using a three-grid assembly. The first grid (acceleration grid) located close to the plasma was used to accelerate the ions ; a potential of +100 ∼ +400 V (V_a; acceleration voltage) was applied to the grid, and one of –20 V (V_e) was applied to the middle grid (extraction grid). The third grid (ground grid), which was located outside the source and was in contact with the reflector, was grounded.

A low-angle neutralizing reflector composed of a parallel stack of polished conductors and having a 5° angle relative to the ion-beam's direction was located outside the ICP ion source. To measure the neutralization efficiency, we measured the ion flux (J_a) from the source before the reflection at the reflector and the ion flux (J_b) from the source after the reflection at the reflector (therefore, the remaining ion flux after the reflection at the reflector) at the same process conditions by using a Faraday cup; the ratio of $(J_a - J_b) \times 100/J_a$ was taken as the neutralization efficiency. The measured neutralization efficiency of the reflector was approximately 99.7 % for the experimental conditions. More details of the neutral-beam etching apparatus can be found elsewhere [10–14].

As samples, thermally grown SiO_2 and Si wafers patterned with photoresist were used to investigate the etch rates of the CF_4-based neutral beam formed after the reflection of the reactive ions off the reflector. As the

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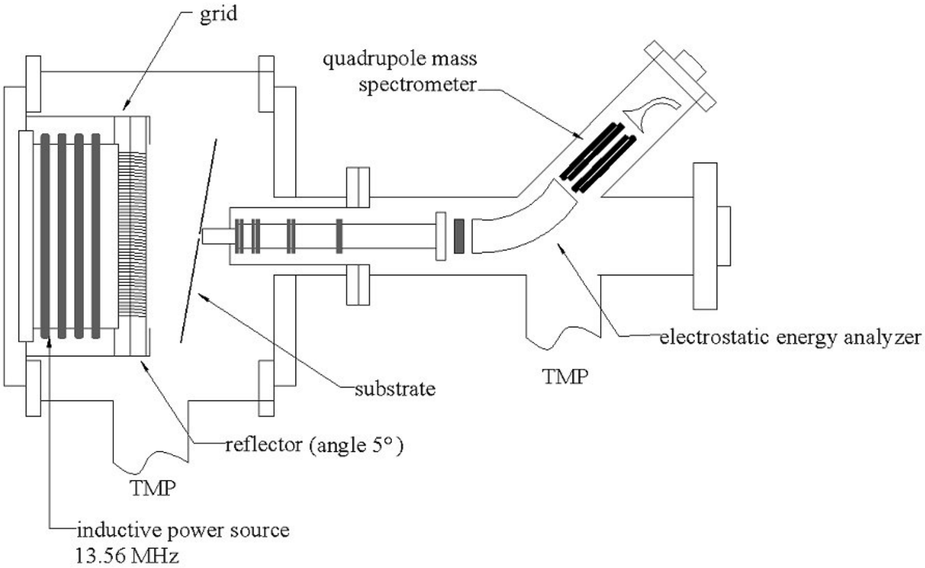

Fig. 1. Schematic diagram of the low-angle forward-reflected neutral-beam system used in the experiment.

etch gas, CF_4 was used and was supplied to the ion gun at gas flow rates of 5 ∼ 20 sccm; H_2 was used as an additive gas at gas flow rates of 2.5 ∼ 10 sccm. The Si, SiO_2, and PR etch rates were measured using a step profilemeter (Tencor Inc., Alpha-Step 500) as functions of the acceleration voltage, the CF_4 flow rate, and the H_2 percentage in the CF_4/H_2 mixture at a total flow rate of 15 sccm. The substrate plate was positioned perpendicular to the reflected neutral beam and was maintained at room temperature. To find the directionality of the CF_4-based neutral beam generated by the LAFRN system, we etched silicon patterned with a 50-nm wide hardmask and observed its etch profile by using scanning electron microscopy (SEM; Hitachi SE-4700).

III. RESULTS AND DISCUSSION

Fig. 2 shows the etch rates of Si and SiO_2 and their etch selectivities to PR as functions of the acceleration voltage (V_a). The rf power to the gun was 300 W, and 15-sccm CF_4 was used. The chamber pressure was 0.9 mTorr. As Fig. 2 shows, with increasing acceleration voltage, the etch rates of Si, SiO_2, and PR increased almost linearly. The SiO_2 etch rate was a little higher than the Si etch rate; however, the PR etch rates were much higher than the etch rates of Si and SiO_2. Therefore, the etch selectivities of Si and SiO_2 to the PR were lower than 0.5 and remained similar. Increasing the acceleration voltage to the gun not only increases the energy of the neutral beam incident on the substrate but also increases the flux of the extracted energetic neutrals. Therefore, the increase in the etch rates in the Si, SiO_2, and PR is related to the increase in the flux and the energy of the energetic reactive neutrals.

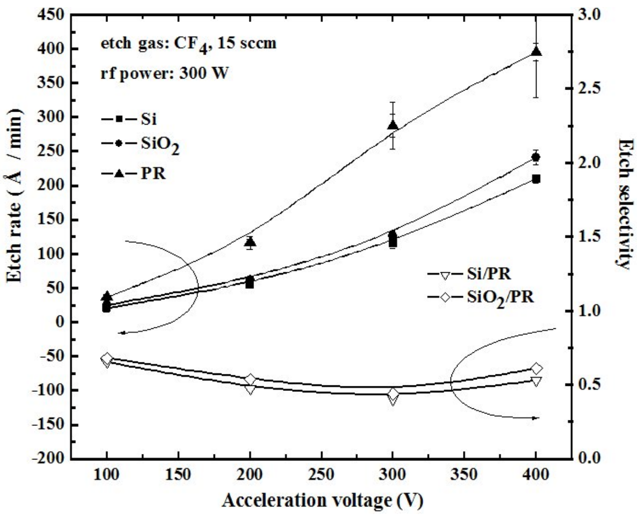

Fig. 2. Si, SiO_2, and PR etch rates and etch selectivities of Si and SiO_2 to the PR as functions of the acceleration voltage of the source (rf power: 300 W; CF_4 flow rate: 15 sccm).

Fig. 3 shows the effect of the gas flow rate on the etch rates of Si, SiO_2, and PR and on the etch selectivities of Si and SiO_2 to the PR. The rf power was maintained at 300 W, and the acceleration voltage (V_a) was maintained at 400 V. Varying the CF_4 gas flow rate from 5 sccm to 20 sccm caused the chamber pressure to change from 0.3 mTorr to 1.2 mTorr. As Fig. 3 shows, with increasing CF_4 gas flow rate, the etch rates of Si, SiO_2, and PR increased slowly, and, similar to Fig. 2, the SiO_2 etch rate was a little higher than the Si etch rate, and the PR etch rate was the highest; therefore, the etch selectivities of Si and SiO_2 to the PR were lower than 0.7 even though the etch selectivities to the PR increased slightly with increasing CF_4 gas flow rate. Increasing the CF_4

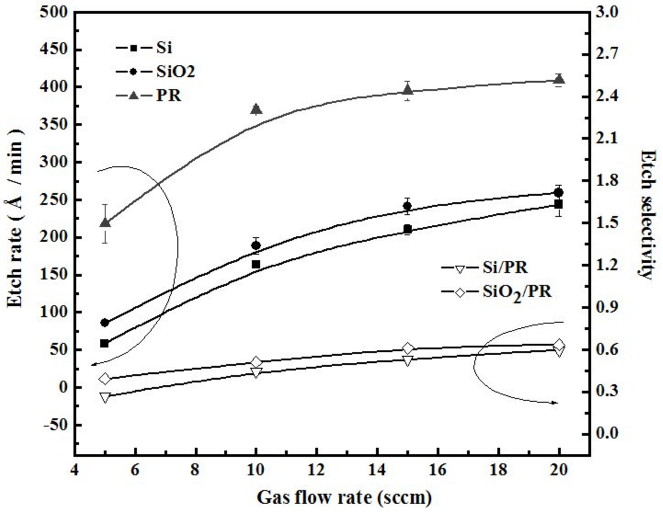

Fig. 3. Si, SiO_2, and PR etch rates and etch selectivities of Si and SiO_2 to the PR as functions of the CF_4 flow rates to the source (rf power: 300 W; acceleration voltage: 400 V).

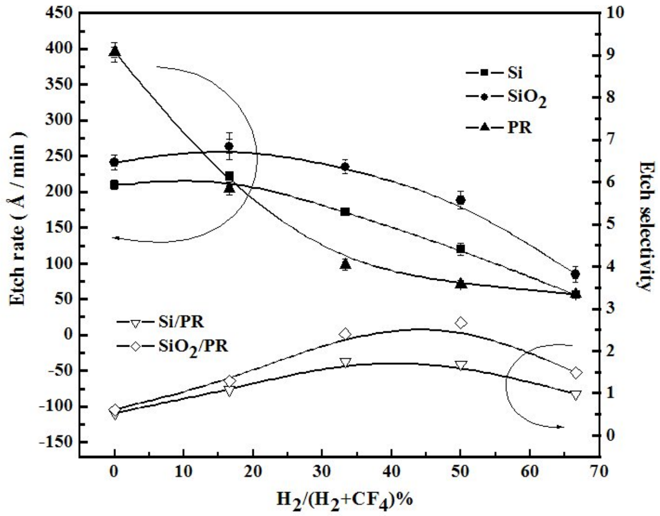

Fig. 4. Si, SiO_2, and PR etch rates and etch selectivities of Si and SiO_2 to the PR as functions of the H_2 percentage in the CF_4/H_2 mixture (rf power: 300 W; acceleration voltage: 400 V; total gas flow rate of the CF_4/H_2 mixture: 15 sccm).

gas flow rate increases the energetic neutral beam flux and the background low-energy radicals, not the energy of neutral beam. Therefore, the increasing etch rates of Si, SiO_2, and PR with increasing CF_4 gas flow rate are related increases in both the energetic neutral-beam flux and the background radical flux. The increase in the Si etch rate with increasing acceleration voltage and CF_4 gas flow rate, similar to that of the SiO_2 etch rate shown in Figs. 2 and 3, appears to indicate the importance of chemical etching, in addition to the physical etching, in the etching by a CF_4 neutral beam used in this experiment. A previous study showed that, when SF_6 was used to etch Si and SiO_2, the Si etch rate was about 10 times faster than the SiO_2 etch rate and the PR etch rate was very high [12]. In etching by SF_6, due to the high flux of background F radicals, the etchings of Si and the PR, which are spontaneously etched by F radicals, are much higher than that of SiO_2, which requires physical bombardment in the etching. Therefore, we believe that, by using various gas mixtures, acceleration voltages, *etc.* to control physical etching and chemical etching, the etch rates and the etch selectivities can be controlled for neutral-beam etching as for reactive-ion etching.

To improve the etch selectivities of Si and SiO_2 to the PR, we added H_2 to CF_4 and investigated the effect of H_2 percentage in CF_4/H_2 on the etch rates and the etch selectivities. Fig. 4 shows the effect of the H_2 percentage in the CF_4 /H_2 gas mixture with a total gas flow rate of 15 sccm on the etch rates of Si, SiO_2, and the PR and on the etch selectivities of Si and SiO_2 to the PR. The rf power to the source was maintained at 300 W, and the acceleration voltage was kept at 400 V. As Fig. 4 shows, when the H_2 percentage was increased from 0 to about 50 %, the PR etch rate was decreased significantly while the etch rates of Si and SiO_2 were decreased less significantly; therefore, the etch selectivities of Si and SiO_2 to the PR increased with increasing H_2 percentage up to 50 %. The significant decrease in the PR etch rate with H_2 percentage appears to be related to the formation of CH_x polymers on the PR surface. With 50 %H_2/50 %CF_4, the etch selectivities of Si and SiO_2 to the PR could be increased to above 1.5 and 2.5, respectively, even though the etch rates of Si and SiO_2 decreased slightly. We believe that higher etch selectivities to PR can be obtained for the neutral-beam etching system, similar to a conventional reactive-ion etching system, by using fluorocarbon gas mixtures having high C/F ratios.

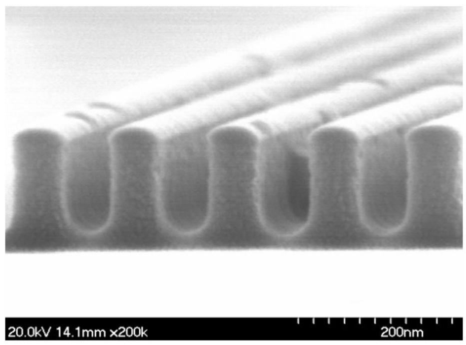

Fig. 5. SEM micrograph of the Si etch profile obtained by using a CF_4 neutral beam generated by the low-angle reflected neutral-beam source (rf power: 300 W; acceleration voltage: 400 V; CF_4 gas flow rate: 15 sccm).

To find the directionality of the CF_4-based neutral beam generated in our experiment, we etched Si with a 50-nm wide pattern and observed its etch profile by using SEM. An rf power of 300 W, an acceleration voltage of 400 V, and a CF_4 flow rate of 15 sccm were used to etch Si, and the result is shown in Fig. 5. As the figure shows, a vertical Si etch profile was observed, indicating the formation of a highly parallel CF_4-based neutral beam by the LAFRN system.

IV. CONCLUSION

In this study, as one of the low-damage etching techniques, a CF_4-based neutral beam was formed using a LAFRN system, and the effects of the H_2/CF_4 gas mixture, the acceleration voltage, and the gas flow rate on the etching characteristics of Si, SiO_2, and PR were investigated. Increasing the acceleration voltage and the CF_4 gas flow rate to the neutral-beam source increased the etch rates of Si and SiO_2; however, the etch selectivities of Si and SiO_2 to the PR were lower than 0.7. With 50 $\%H_2$/50 $\%CF_4$, the etch selectivities of Si and SiO_2 to the PR could be increased to 1.5 and 2.5, respectively, without significantly decreasing the etch rates of Si and SiO_2. The 50-nm-wide Si etch profile obtained by using the CF_4-based neutral beam was vertical; therefore, we believe that a neutral beam can be applied to nanoscale etching requiring low electrical damage.

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