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Characteristics of neutral beam generated by reflection on a planar-type reflector and its etching properties

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Abstract

In the fabrication of nano-scale silicon-based devices, any process-related damage such as electrical charging and surface modification remaining during the processing may cause serious problems due to the size limitation of the devices. Therefore, etching processes with no or negligible damage are required. In this study, a low-angle forward reflected neutral beam apparatus with a planar-type reflector attached to the ion source has been used and its effect on the formation of neutral beam and the characteristics of the neutral beam flux have been investigated. The results showed that most of the ions extracted from the ion source were neutralized and formed a neutral beam by the low-angle reflection from the planar-type reflector, and when Si and SiO_2 were etched with the reactive radical beams generated with SF_6, high etch rates and vertical etch profiles could be obtained with the low-angle forward-reflection technique.

Keywords: Neutral beam; Planar-type reflector; Low-angle forward-reflection technique

1. Introduction

Charge-induced damage during the plasma etching is one of the biggest problems that have to be solved for deep submicron semiconductor devices, as well as future nanoscale devices. To avoid this charge-related damage, several low-damage processes have been proposed, and one of the techniques to avoid this problem is to use neutral beam etching [1–6].

In previous studies, a prototype etcher using a low-angle forward-reflected neutral beam was developed where all the energetic reactive ions extracted from an ion source are reflected from a flat surface, at an incident angle between 5° and 15°, to produce a near-parallel neutral beam flux [7–9,12]. Also, a hole-type compact reflector was proposed in order to improve the neutral beam flux and beam uniformity within the wafer, and the etch properties of SiO_2 were investigated with various fluorine-based gases such as etch rate, etch profile and charging damage [10,11].

In this study, a new low-angle forward-reflected neutral beam system having a compact planar reflector has been proposed to obtain higher neutral flux and lower beam energy loss, and its characteristics were investigated for various grid voltages and gas flow rates. Also, the neutral beam energy was investigated using a quadrupole mass spectrometer and the SiO_2 etch profile for 50-nm scale was investigated as a measure of directionality of the neutral beam.

2. Experimental

In this experiment, a low-angle forward reflected neutral beam source, which is composed of an r.f. ion source and a planar-reflector, has been used to form a neutral beam. Fig. 1 shows the schematic diagram of the low-angle forward reflected neutral beam source (ion source and reflector). A laboratory-built two-gridded inductively coupled plasma source was used as the ion source. The r.f. power applied to the plasma source was 400 W with a frequency of 13.56 MHz. The ions from the plasma source were extracted using the two-grid assembly. A potential ranging from +100 to +400 V (Va) was applied to the grid located close to the source (accelerator grid) and a potential from 0 to −400 V (Ve) was applied to the grid located outside of the source (extractor grid). The reflector was made from a parallel stack of polished stainless steels supported by an aluminum block, with the axes of the

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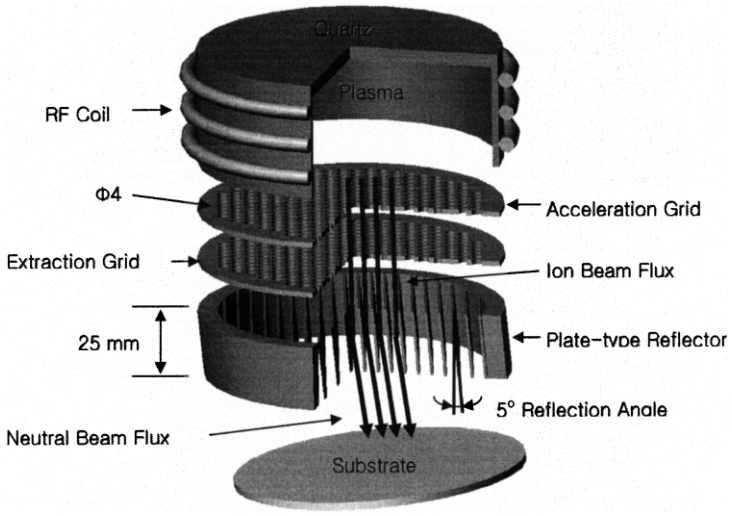

Fig. 1. Schematic diagram of the low-angle forward reflected neutral beam system used in the experiment.

reflector fabricated to have 5° angle to the ion beam direction. The plates of the reflector were matched to each hole of the grid of the ion source. The depth of the plate of the reflector was optimized with 25 mm to reflect all of the parallel ions extracted from the ion source and, therefore, to neutralize the extracted ions. The details of the ion source dimensions, reflector dimensions, and the ion source operations conditions can be found elsewhere [9–11]. The ion energy distributions of the ions extracted from the ion source and the neutral energy distribution of the neutralized ions after the reflection on the reflector were measured using a quadrupole mass spectromter (QMS) (Hiden Analytical Inc.; EQP 1000 series).

As the samples, p-type (100) Si wafers and SiO_2 wafers thermally grown on Si were used, and those wafers were patterned by photoresist to investigate the etch rate, etch selectivity, and to examine the etch anisotropy. SF_6 was used as the etch gas and was fed to the ion source with the flow rate ranging from 5 to 25 sccm. The chamber pressure with the gas flow was maintained from 0.04 to 0.12 Pa. Si and SiO_2 etch rates were measured as a function of acceleration voltage of the accelerator, extraction voltage of the extractor, and SF_6 gas flow rate. Etch depth was measured with a step profilometer and the etch anisotropy was observed using a field-emission scanning electron microscope (FE-SEM).

3. Results and discussion

Fig. 2 shows the effect of SF_6 gas flow rate on Si and SiO_2 etch rates. The r.f. power supplied to the ion source was 400 W and the distance between the sample and the reflector was 4 cm. The acceleration voltage and extraction voltage supplied to the ion source were 400 V and −100 V, respectively. As shown in the figure, the increase of SF_6 gas flow rate from 10 to 25 sccm increased the Si etch rate from 60 to 123 nm/min and also increased the SiO_2 etch rate from 15 to 16.6 nm/min. The increase of Si and SiO_2 etch rates with the increase of SF_6 gas flow rate appears to be due to the increased ion beam flux from the ion source as observed in the previous study [9], and which resulted in the increase of neutralized ion flux to the substrate. The increase of Si etch rates was faster than that of SiO_2 as shown in the figure and it appears to be due to the higher sensitivity of Si etching to the neutral flux compared to that of SiO_2 etching.

Fig. 3 shows the effect of acceleration voltage of the

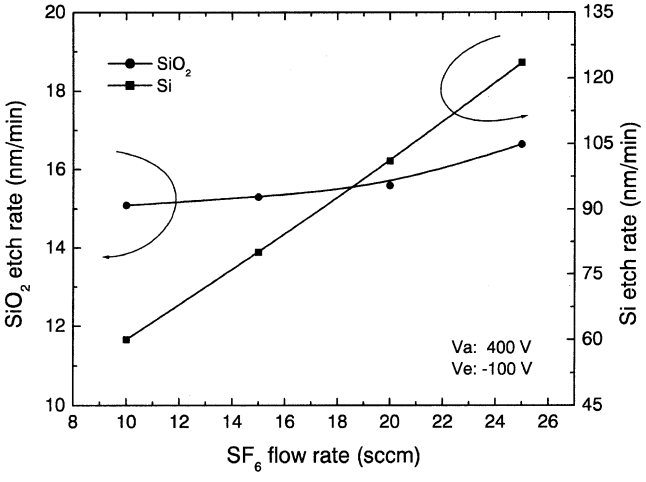

Fig. 2. SiO_2 and Si etch rates with the reflector as a function of SF_6 gas flow rates. (r.f. power to ion source; 400 W; acceleration voltage; 400 V; extraction voltage: −100 V; distance between reflector and substrate: 4 cm).

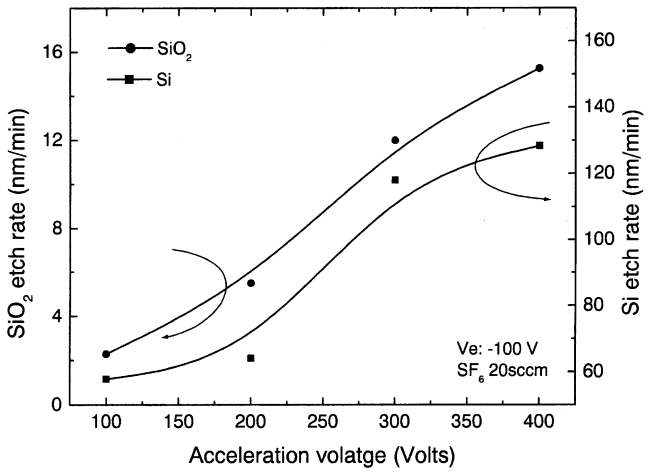

Fig. 3. SiO_2 and Si etch rates with the reflector as a function of acceleration voltage of the ion source. (r.f. power to ion source: 400 W; acceleration voltage: 400 V; extraction voltage; −100 V; distance between reflector and substrate: 4 cm).

ion source on the Si and SiO_2 etch rates. The r.f. power supplied to the ion source was 400 W, the distance between the sample and the reflector was 4 cm, the extraction voltage of the ion source was −100 V, and the SF_6 gas flow rate was 20 sccm. As shown in the figure, the Si etch rate increased from approximately 57 to 128 nm/min with the increase of acceleration voltage of the ion source from 100 to 400 V, and the SiO_2 etch rate also increased from approximately 2.3 to 15.2 nm/min. The increase of Si and SiO_2 etch rates with the increase of acceleration voltage appears related to the increase of energy of ions extracted from the ion source. The increased ion energy will increase the neutral beam energy after the reflection of the ions at the reflector, therefore, the increased neutral energy appears to increase the etch rates of Si by factor of 2, and SiO_2 by factor of 8. However, the increase of SiO_2 etch rate with acceleration voltage was faster than that of Si etch rate. Also, when the accelerate voltage was increased, the extracted ion flux was also increased as observed in a previous study [9]. Therefore, when the results in Figs. 2 and 3 are compared, it can be concluded that the Si etch rate is more sensitive to the flux of the neutrals while the SiO_2 etch rate is more sensitive to the energy of the neutrals.

Fig. 4 shows the effect of extraction voltage of the ion source on the Si and SiO_2 etch rates. The r.f. power and the distance between the reflector and sample were also maintained at 400 W and 4 cm, respectively. The acceleration voltage of the ion source was 400 V, and the gas flow rate was 20 sccm. As shown in the figure, when the extraction voltage was changed from 0 to −100 V, the etch rates of Si and SiO_2 decreased slightly and when the voltage was further changed from −100 to −200 V, the Si and SiO_2 etch rates increased slightly even though the change of the etch rates was not significant. The change of extraction voltage does not change the energy of the extracted ions; instead, it can change the flux of the ions by changing the degree of convergence of the ions during the extraction through the grid system. Therefore, the flux of the neutral beam to the substrate can be changed. In fact, when the change of the neutral flux was measured with extraction voltage using a quadrupole mass spectrometer (QMS), the change of the neutral flux was similar to the results of the etch rates shown in Fig. 4(not shown). The change of Si etch rates with the extraction voltage from 0 to −200 V was approximately 15% while that of SiO_2 etch rate was approximately 11% and the more significant change of Si etch rate with the extraction voltage appears to be from the higher sensitivity of Si etching to magnitude of neutral flux as mentioned above.

Fig. 5 shows (a) the ion energy distribution of the ions extracted from the ion source and (b–e) the neutral energy distribution of the neutralized ions at the substrate after the reflection on the reflector as a function of acceleration voltage (Va) using a QMS. The r.f. power and gas flow rate to the ion source were 400 W and 10 sccm, respectively. To better understand the neutralization of the ions at the reflector and the change of energy during the reflection more easily, Ar was used instead of SF_6. The acceleration voltage to the ion source was in the range from 0 to 80 V while extraction voltage was kept at 0 V. The energy scan range investigated by QMS was −100 to 100 V, therefore, the process parameters including the process gas were not the same as the conditions used in the etching of Si and SiO_2 shown in Figs. 2–4. However, it is believed that the basic characteristics of neutralization of ions at the

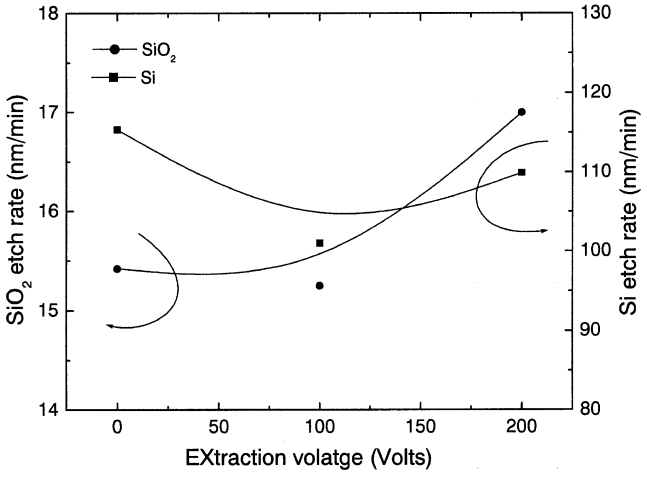

Fig. 4. SiO_2 and Si etch rates with the reflector as a function of extraction voltage of the ion source. (r.f. power to ion source: 400 W; acceleration voltage: 400 V; extraction voltage: −100 V; distance between reflector and sample: 4 cm).

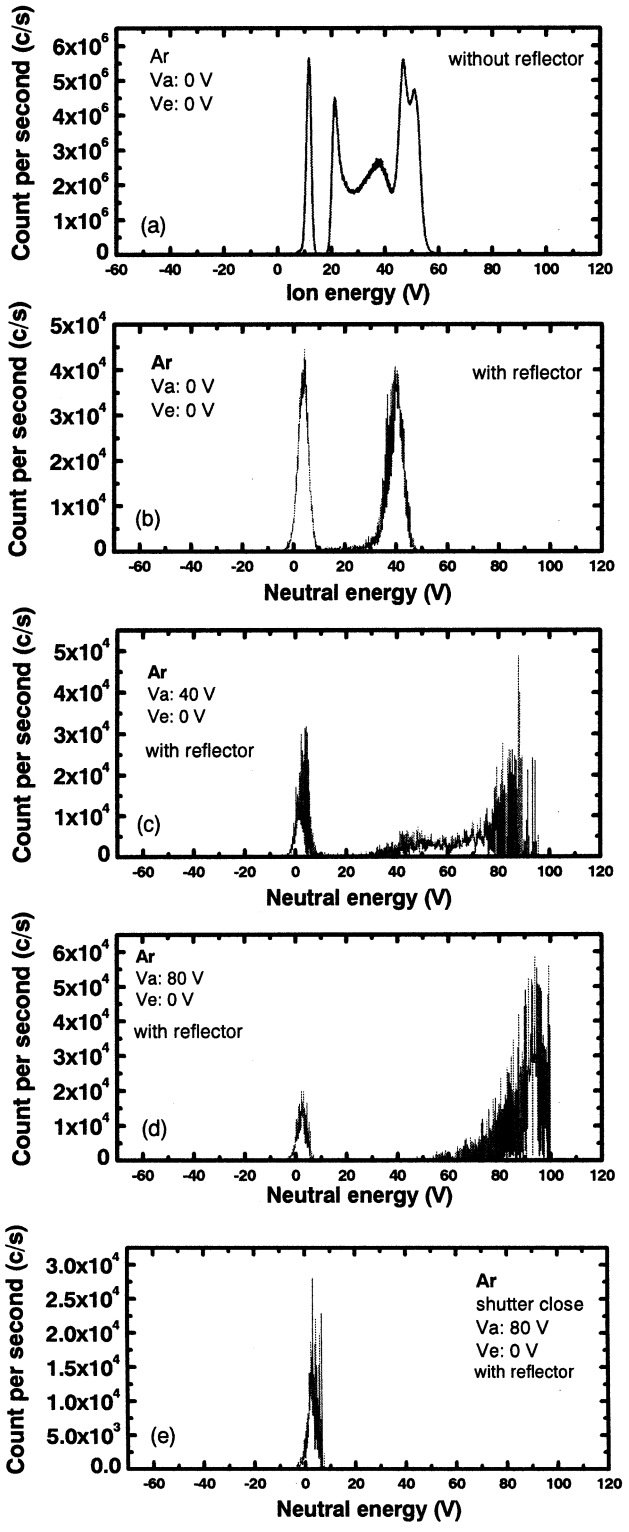

Fig. 5. Ion energy distribution of Ar^+ without reflector (a) and neutral energy distribution of Ar with reflector for 0 V (b), 40 V (c), and 80 V (d) of acceleration voltage. Neutral energy distribution measured for the condition in (d) with a shutter installed in front of the reflector (e) (r.f. power: 400 W; extraction voltage: 0 V, SF_6 gas flow rate: 20 sccm, and distance between reflector and QMS: 15 cm).

reflector and the energy of the neutrals after the reflection can be qualitatively understood.

Fig. 5a shows the ion energy distribution of the extracted ions from the ion source measured without the reflector. No voltages were applied to the grid system. As shown in the figure, even without the application of voltage to the grids, the extracted ions showed a distribution of energy. There was a low-energy range with a peak at approximately 12 eV and a high-energy range from 20 to 60 eV showing peaks at 20 eV and near 50 eV. The high-energy range appears to be from the ions accelerated to the grid by the plasma sheath voltage in the ion source while the low-energy range appears to be from the ions' lost energy by the scattering with the neutrals, grids, etc. in the chamber before they are collected by the QMS. Fig. 5b shows the energy distribution of neutralized ions after the reflection at the reflector for the condition shown in Fig. 5a. The energy of the neutrals was measured by ionizing the neutrals using the ionizer at the QMS. More than 99% of the ions reflected at the reflector were neutralized as investigated by previous researches [9,10]. As shown in Fig. 5b, the energy of the neutrals after the reflection was also distributed into two ranges with peals at 0 eV and 40 eV, respectively. When the data of Fig. 5b were compared with that of Fig. 5a, it is believed that the range of the ions with the peak at 12 eV decreased to the neutrals with near 0 eV during the neutralization at the reflector, and the range of the ions from 20 to 60 eV decreased to the neutrals with a range from 10 to 50 eV having a peak at 40 eV. Due to the low detection efficiency of the energetic neutrals with QMS compared to ions, the detection count per second for the neutrals is much lower than that for ions and only the neutrals with high intensity might be detected on the QMS such as the one with 40 eV peak. Therefore, during the neutralization by the reflection at the 5° angle reflector, the ions appear to loose approximately 10–15 eV, however, the neutrals formed after the reflection appear to keep the rest of the energy.

Fig. 5b, c and d show the effect of acceleration voltage from 0 to 80 V on the change of neutral energy measured by QMS. As shown in the figures, the increase of acceleration grid voltage increased the energy of the neutrals having high-energy range. In the case of neutrals having the low-energy range with a peak near 0 eV, the peak intensity decreased with the acceleration voltage. The low-energy neutrals with the peak at 0 eV include not only the neutralized energetic ions reflected at the reflector but also the randomly oriented neutrals extracted from the ion source without ionization at the ion source, and the latter forms the background pressure of the chamber. The decrease of the low-energy neutral intensity with the increase of acceleration voltage appears related to the decrease of energy losses of neutralized ions due to random collision with grids and

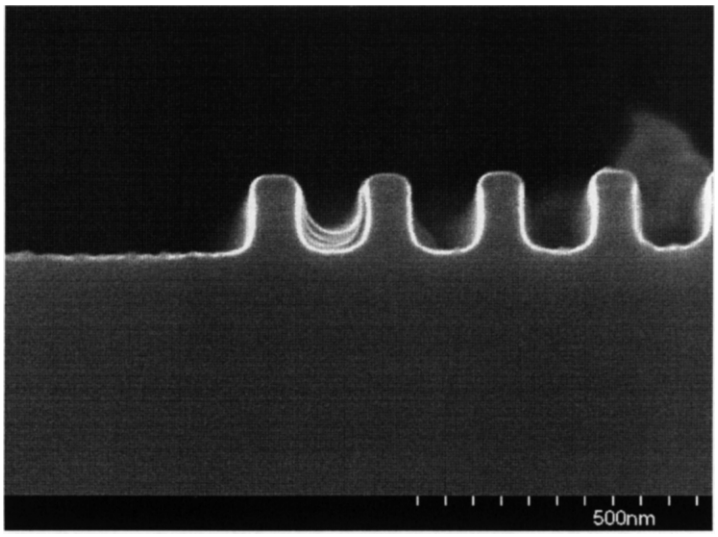

Fig. 6. SEM micrograph of SiO_2 etch profile with SF_6 by the low-angle forward reflected neutral beam. (r.f. power: 400 W; extraction voltage: −100 V, distance between reflector and substrate: 4 cm, SF_6 gas flow rate: 20 sccm).

other surfaces, not with the reflector, by the increased directionality of the extracted ions by the voltage gradient formed between the grids. Fig. 5e shows the neutral energy distribution measured for the condition in Fig. 5d with a shutter installed in front of the reflector, therefore, only randomly oriented neutrals can enter the QMS. The peak intensity at near 0 eV was similar to that in Fig. 5d and the high-energy neutral peak was vanished. Therefore, the low-energy peak shown in Fig. 5d is originated from the background pressure formed by the random neutrals extracted at the ion source and not from the energetic neutrals reflected at the reflector.

The energy of the neutrals with the high-energy range formed by the low-angle reflection of the accelerated ions can be changed as shown in Fig. 5b, c and d, and these neutrals could form a parallel neutral beam. To see the directionality of the neutral beam formed by the reflection of the energetic ions, SiO_2 patterned with 50-nm Cr lines was etched and the etch profile was observed using a SEM. Fig. 6 shows a SEM profile of SiO_2 etched using SF_6 by the low-angle forward reflection technique. R.f. power to the ion source was 400 W and the acceleration voltage and the extraction voltage were 400 V and −100 V, respectively. The distance between the reflector and the substrate was 4 cm and SF_6 flow rate was 20 sccm. As shown in the figure, a vertical SiO_2 etch profile was obtained indicating the formation of a parallel neutral beam by the low-angle forward reflection technique used in this experiment.

4. Conclusions

In this study, the characteristics of a neutral beam and its Si and SiO_2 etch characteristics with SF_6 gas have been studied using a new low-angle forward-reflected neutral beam system having a compact planar reflector.

When Si and SiO_2 were etched with the energetic reactive neutral beams of SF_6, formed by the neutralized ions reflected on the low-angle reflector as functions of acceleration voltage and flow rate to the ion source, the increase of acceleration voltage increased the SiO_2 etch rate more significantly and Si etch rate increased with the increase of SF_6 gas flow rate more effectively. The energy distribution of the ions extracted from the ion source and that of neutrals formed after the reflection of the ions at the reflector were measured using quadrupole mass spectroscopy, and the results showed that the energy of the ions extracted by the ion source is lost approximately 10–15 eV after the reflection and neutralization, however, the energetic neutrals were keeping the remaining energy and the energy of neutrals could be changed by changing the acceleration voltage to the ion source. The energetic neutrals were forming a parallel neutral beam, therefore, when SiO_2 patterned with 50-nm lines was etched using a SF_6 neutral beam, a vertical etch profile could be observed.

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