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Effects of Axial Magnetic Field on Neutral Beam Etching by Low-Angle Forward-Reflected Neutral Beam Method

Dohaing LEE*, ByungJae PARK and Geunyoung YEOM†

Department of Materials Engineering, Sungkyunkwan University, Jangan-Gu Chunchun-Dong 300, Suwon 440-746, South Korea

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A low axial magnetic field was applied to an inductively coupled plasma (ICP) ion source used to generate a neutral beam for a low-angle forward-reflected neutral (LAFRN) beam system, and its effects on the ICP ion source and the features of Si and SiO_2 etching using the LAFRN beam system for SF_6 gas were investigated. As a result of applying a low axial magnetic field of approximately 20 G, a significant increase in $SF_3{}^+$ ion flux extracted from the source was observed among the various reactive ions generated using SF_6 gas, and the etch rates of Si and SiO_2 using a neutral beam formed by the magnetically enhanced SF_6 ICP source were also increased. The application of the low axial magnetic field also improved the etch uniformity of the neutral beam etching system. [DOI: 10.1143/JJAP.44.L63]

KEYWORDS: low-angle reflection, neutral beam, etching, low damage, SiO_2, magnetic field

Charge-induced damage during plasma etching is one of the biggest issues to be solved for the realization of 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 for avoiding this problem is to use neutral beam etching.[1–9]

A neutral beam is generally formed by producing reactive ions using a plasma source and, then neutralizing 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 on a flat surface, tilted at a small angle (from 5° to 15°) from the ion beam direction, to produce a near-parallel neutral beam flux.[10–12] One of the problems of these neutral beam sources is a low neutral beam flux due to the use of multiple grids used to extract nearly parallel ions from the ion gun.

In this study, as a method of increasing the flux of the neutral beam, a low axial magnetic field was applied to the ICP ion source and the characteristics of the extracted reactive ion beam and the etch characteristics of Si and SiO_2 using the neutral beam generated with SF_6 gas were studied by the low-angle forward-reflected neutral (LAFRN) beam method.

Figure 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 800 to 1000 W at a frequency of 13.56 MHz. At the ICP ion source, an axial electromagnet was installed, as shown in Fig. 1, and a low magnetic field from 0 to 60 G was applied to the ion source. The ions from the ICP source were extracted using the three-grid assembly. The first grid (acceleration grid) located close to the plasma was used to accelerate the ions and a potential of $+200 \sim +400$ V (V_a) was applied to the grid. The middle grid (extraction grid) was grounded and a potential ranging from 0 to +200 V (V_d) was applied to the third grid (deceleration grid), which was located outside the source, for the deceleration of the ions. Therefore, the total energy given by the grid assembly to the ions exiting the grid assembly is the difference between the acceleration potential and the deceleration potential.

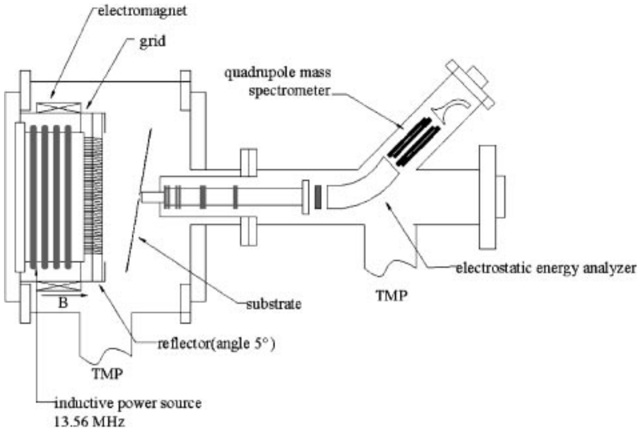

Fig. 1. Schematic diagram of low-angle forward-reflected neutral beam system used in experiment.

A low-angle neutralizing reflector composed of a parallel stack of polished conductors and having a 5° angle to the ion beam direction was located outside the ICP ion source. The potential of the reflector was maintained at the same potential as the deceleration grid. The 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.[10–12] As samples, thermally grown SiO_2 and Si wafers patterned with photoresist were used to investigate etch rates of the neutral beam formed after the reflection of the extracted reactive ions on the reflector. As the etch gas, SF_6 was used and supplied to the ion gun at a gas flow rate of 40–50 sccm. The Si and SiO_2 etch rates were measured using a step profilemeter (Tencor Inc., Alpha-Step 500) as functions of deceleration voltage with and without the magnetic field. The substrate plate was positioned perpendicular to the reflected neutral beam and was maintained at room temperature. At the substrate position, as shown in the figure, a quadrupole mass spectrometer (QMS) (Hiden Analytical Inc.; EQP1000) was located to measure the flux of extracted ion species and their energy distribution from the ICP ion gun when the reflector

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*E-mail address: glow@skku.edu
†E-mail address: gyyeom@skku.edu

was not installed.

When a small axial magnetic field of up to approximately 20 G was applied to the ICP ion source the ion flux of the ICP ion gun increased, however, an increase in axial magnetic field of up to 60 G decreased ion flux(not shown). An increase in the plasma density of ICP-type plasmas by the application of a small axial magnetic field was also observed in other experiments.[13,14] The application of an axial magnetic field of 10 G to the ICP-type plasma sources increased plasma density to approximately 100% and the further increase in axial magnetic field decreased plasma density. The exact axial magnetic field showing the highest plasma density appears to be dependent on the system size and configuration. The increased plasma density in the source is believed to result from a helicon-type resonance effect even though further investigation is required. Figure 2 shows the QMS data of the various ion fluxes extracted from the ICP ion source measured without the reflector with/without an axial magnetic field of 20 G. SF_6 was supplied to the source at a rate of 50 sccm and the acceleration grid voltage was maintained at +200 V while the extraction and the deceleration grid voltages were maintained at 0 V. The inductive power to the ICP source was 800 W. As shown in the figures, various SF_x^+ ion fluxes were extracted from the source and, among these ion fluxes, SF_3^+ ions showed the highest flux. Also, as a result of the application of an axial magnetic field of 20 G, these ion fluxes extracted from the ICP source were increased from 100% to more than 200%.

The energy distribution of the ion flux with/without the axial magnetic field was investigated for SF_3^+ ions and the results are shown in Fig. 3. The plasma condition and grid voltages were the same as those in Fig. 2. As shown in the figure, when there was no magnetic field, the SF_3^+ ion energy showed double peaks located near 160 eV and 200 eV. The formation of the double ion energy peaks for the ions extracted from the ICP ion source is known to result from the energy loss of a number of ions due to collisions between the extracted ions and background neutrals or from the fluctuation of the plasma potential (that is, time-varying plasma potential).[15–17] As a result of the application axial magnetic field of 20 G, as shown in the figure, the low-energy peak near 160 eV decreased and the high-energy peak near 200 eV increased, therefore, the SF_3^+ ion energy distribution changed to a monoenergetic peak corresponding to the total potential applied to the grid system. Therefore, the double ion energy peak shown for SF_3^+ ions formed without the magnetic field appears not to result from collisions with background neutrals but to result from the time-dependent plasma potential in the ICP ion source. The application of the magnetic field of 20 G not only increases the plasma density but also decreases the rf antenna voltage at a given power. A portion of the rf antenna voltage is capacitively coupled to the plasma through the quartz tubing between the plasma and the rf antenna. The double ion energy peaks shown for the SF_3^+ ions originate from the time dependence of the plasma potential in the source caused by the rf antenna voltage. As a result of the application of the magnetic field, rf antenna voltage decreases, therefore, the time dependent plasma potential also decreases, therefore, the ion energy distribution of the SF_3^+ ions extracted from the plasma also decreases resulting in more monoenergetic ions. The monoenergetic ion flux obtained by the application of a small axial magnetic field might be beneficial in the processing of future devices because the etch selectivity between different materials could be controlled by regulating the energy of the reactive ions extracted from the source using the differences in the binding energies of the materials.

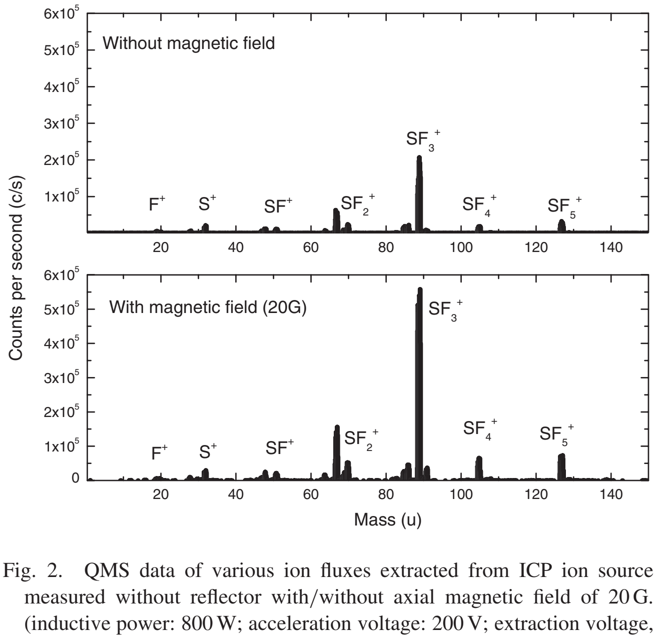

Fig. 2. QMS data of various ion fluxes extracted from ICP ion source measured without reflector with/without axial magnetic field of 20 G. (inductive power: 800 W; acceleration voltage: 200 V; extraction voltage, deceleration voltage: 0 V, SF_6 gas flow rate: 50 sccm)

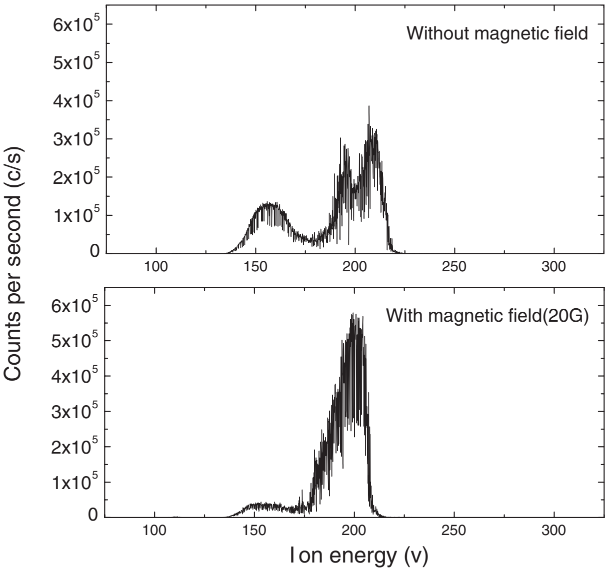

Fig. 3. Ion energy distribution of SF_3^+ with/without axial magnetic field of 20 G. (inductive power: 800 W; acceleration voltage: 200 V; extraction voltage, deceleration voltage: 0 V, SF_6 gas flow rate: 50 sccm)

Using the ICP source with/without the axial magnetic field of 20 G and with the 5 reflector for the formation of a neutral beam with the reactive ions extracted from the source, Si and SiO_2 etching was carried out with SF_6 at 50 sccm, an inductive power of 1000 W, and an acceleration voltage of 400 V and the results are shown in Fig. 4. To control the energy of the ions, and therefore to control the energy of the neutrals formed by the reflection of the extracted reactive ions, the voltage applied to the deceler-

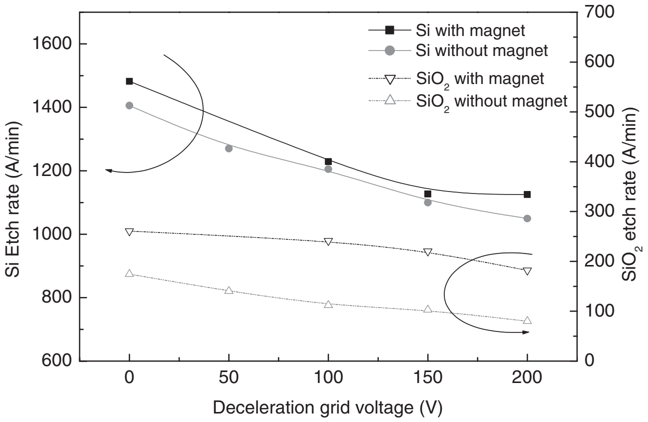

Fig. 4. Si and SiO$_2$ etch rates with/without axial magnetic field of 20 G as functions of deceleration voltage of ion source. (rf power: 1000 W; acceleration voltage: 400 V, extraction voltage: 0 V, SF$_6$ gas flow rate: 50 sccm)

ation grid was changed from 0 to 200 eV for the ions extracted and neutrals to have from 400 to 200 eV, respectively, as a result of the deceleration of the ions when passing through the deceleration grid. The change in the energy distribution of the extracted ions as a result of the use of the deceleration grid was negligible under our experimental condition. As shown in the figure, the etch rates of Si and SiO$_2$ using the reflected neutrals decreased with increasing deceleration grid voltage due to the decrease in ion energy extracted from the grid. Therefore, when the total energy of the neutrals bombarding the Si and SiO$_2$ surfaces is 200 eV, the Si and SiO$_2$ etch rates were approximately 1100 Å/min and 75 Å/min, respectively. However, as a result of the application of axial magnetic field of 20 G, the Si and SiO$_2$ etch rates increased to 1200 Å/min and 175 Å/min, respectively, at a neutral energy of 20 G. Therefore, an increase of approximately 10 to more than 100% in etch rates could be obtained by the application of a small axial magnetic field due to the increased energetic neutral beam flux and improved energy distribution, as suggested from Fig. 2 and 3. The small increase in the Si etch rate compared with the increase in the SiO$_2$ etch rate appears to result from the more chemically enhanced etch characteristics of Si etching while SiO$_2$ etching has more ion-enhanced etching characteristics.

The application of a small axial magnetic field not only improved the flux and energy distribution of the source but also improved the uniformity of the etching using the neutral beam. Figure 5 shows the Si etch depth distribution measured after etching using a SF$_6$ neutral beam with/without an axial magnetic field of 20 G for an inductive power of 1000 W, an acceleration voltage of 400 V, and with SF$_6$ at 40 sccm. The voltage to the extraction grid and the deceleration grid was maintained at 0 V. The measured etch uniformities in the effective area of 100 mm diameter for the cases with and without the magnetic field were 16% and 7%, respectively, therefore, a significant improvement in etch uniformity could be obtained by the application of the magnetic field. The improvement in etch uniformity appears to result from the increase in plasma density near the chamber wall side of the ICP ion source induced by the application of the axial magnetic field.

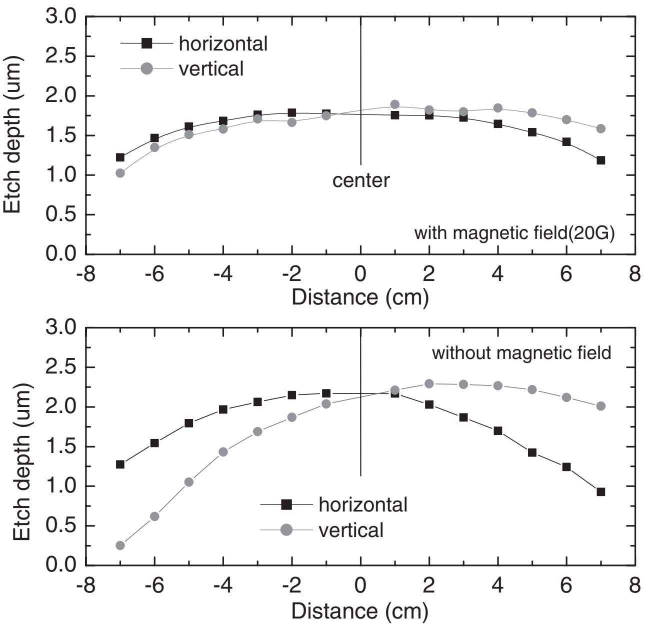

Fig. 5. Etch depth uniformity for a 150 mm source with/without axial magnetic field of 20 G. (rf power: 1000 W; acceleration voltage: 400 V: extraction voltage and deceleration voltage: 0 V; SF$_6$ gas flow rate: 40 sccm)

In this study, the effect of a small axial magnetic field on the ion flux and ion energy distribution of the ICP ion source used to generate a neutral beam flux and the etch characteristics of Si and SiO$_2$ using a SF$_6$ neutral beam formed by the reflection of the ions extracted from the ICP ion source were investigated. As a result of the application of a small axial magnetic field to the SF$_6$ ICP ion source, the various SF$_x{}^+$ ion fluxes were increased from approximately 100 to more than 200% and the energy distribution of the ions changed to a monoenergetic one. Due to the increase in ion flux of the ion source, the Si and SiO$_2$ etch rates using the neutral beam formed by the reflection of the extracted ions were also increased by 10% for Si etching and by more than 100% for SiO$_2$ etching. The application of the axial magnetic field also improved the etch uniformity of our neutral beam etching system.

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