Materials Science and Engineering C 23 (2003) 221–224

MATERIALS SCIENCE & ENGINEERING C

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Etch damage evaluation of low-angle, forward-reflected neutral beam etching

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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, an energetic reactive neutral beam of SF_6 was formed using a low-angle, forward-reflected neutral beam technique and the etch properties of SiO_2 and possible neutral beam-induced damage were investigated. The result showed that, when the neutral beam was formed by the low-angle reflection of the reactive ions generated by the ion gun, most of the reactive ions were neutralized after the reflection at the reflector. When SiO_2 was etched with the energetic reactive neutral beams of SF_6, the increase of acceleration voltage and SF_6 gas flow rates applied to the ion gun increased the SiO_2 etch rate possibly due to the increase of energy and flux of the neutrals at the reflector, respectively. Using the neutral beam, a SiO_2 etch rate higher than 22 nm/min could be obtained. Also, when etch damage was estimated by measuring the breakdown voltage of SiO_2 after the exposure to the oxygen neutral beam, no noticeable damage of SiO_2 could be observed.
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Keywords: Neutral; Etching; Low damage

1. Introduction

Plasma etching is one of the key technologies in the fabrication of deep submicron silicon-based integrated circuit. However, plasma etching has a serious disadvantage due to the energetic charged particles such as positive ions and photons generated in the plasma which causes radiation damage causing physical defect, increased gate oxide breakdown, charging, etc. To avoid these charge-related and physical impact-related damages, several low-damage processes have been proposed [1–6]. One possible alternative to avoid these problems is a low-energy neutral beam etching.

In the previous study, a neutral beam etcher called "low-angle, forward-reflected neutral beam etching apparatus" has been developed [7]. In this etcher, all of the reactive ions extracted from an ion gun are reflected on a flat surface or on a perforated hole block tilted by a low angle (from 5° to 15°) from the ion beam direction to produce a near-parallel neutral beam flux [8,9]. This neutral beam source has been devised to be scaleable and also to etch polymer and silicon anisotropically.

In this study, the etch rates and the etch properties of SiO_2 have been investigated with SF_6 gas using the low-angle, forward-reflected neutral beam etching system and possible neutral beam-induced damage was examined through electrical characteristics such as I–V measurements.

2. Experimental

In this experiment, a low-angle, forward-reflected neutral beam source, which is composed of an rf ion gun and a reflector, has been used to form a neutral beam. A home-made two-gridded inductively coupled plasma source was used as the ion gun. The rf power applied to the plasma source was 500 W with a frequency of 13.56 MHz. The ions from the plasma source were extracted using the two-grid assembly. Potentials ranging from +100 to +700 V (V_a) were applied to the grid located close to the source (accelerator grid) and the grid located outside of source (extractor grid) was grounded. The reflector was made of a perforated aluminum block where the axes of the holes in the reflector were fabricated to have 5° tilted from the ion beam

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PII: S0928-4931(02)00271-0

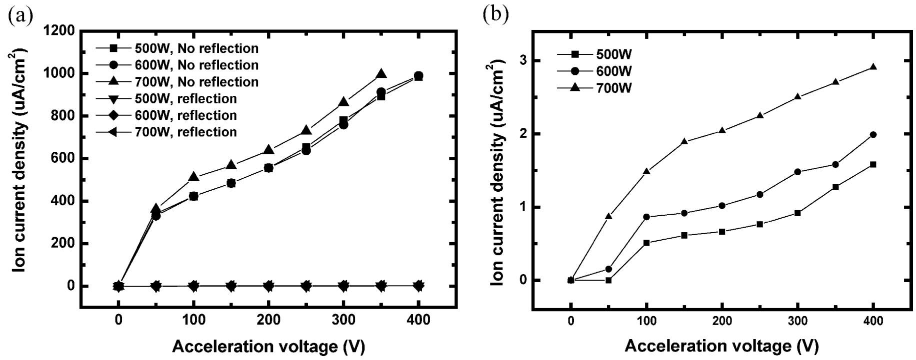

Fig. 1. Ion beam current density measured with a Faraday cup as a function of ion source acceleration voltage (V_a) without reflector (a) and with reflector (b) for SF_6 (rf power to ion gun: from 500 to 700 W; distance between the reflector and Faraday cup: 5 cm; SF_6 flow rate: 7 sccm).

direction. The holes in the reflector were 1:1 matched to the holes of the grids of the ion gun. The depth and diameter of the holes in the reflector were optimized to reflect all of the parallel ions extracted from the ion gun once, therefore, to neutralize the extracted ions.

The ions emerging without neutralization at the reflector were measured using a Faraday cup as a function of acceleration voltage of the accelerating grid. Faraday cup and the samples were located to have normal incident angle with the reflected beam. As the sample, SiO_2 thermally grown on silicon and patterned by photoresist was used to investigate the SiO_2 etch rate. As the etch gases, SF_6 was used and fed to the ion gun with the flow rate from 3 to 15 sccm. The chamber pressure with the gas flow was maintained from 0.093 to 0.13 Pa. The SiO_2 etch rate was measured as a function of acceleration voltage of the accelerator and flow rate.

In order to investigate the damage by the low-angle, forward-reflected neutral beam, $I-V$ measurement of metal-oxide-silicon (MOS) devices formed with 15-nm-thick thermally grown SiO_2 on p-Si was used. Before the $I-V$ measurement, the MOS device was exposed to an oxygen neutral beam for the time to etch 1.2-μm-thick photoresist. Also, a MOS device exposed to an oxygen inductively coupled plasma for the time to etch the same photoresist thickness and a MOS device formed without exposing to plasma or neutral beam were also fabricated for comparison. For the MOS devices, 300-nm-thick aluminum with the area of 0.01 mm^2 was formed by a lift-off technique.

3. Results and discussion

Fig. 1 shows the effect of reflector (with and without reflector in front of the ion source) and acceleration voltage of the ion gun on the ion current density measured by a Faraday cup for SF_6 gas. SF_6 flow rate was maintained at 7 sccm. The distance between the Faraday cup and the reflector was 5 cm and the Faraday cup was located to normal to the incident ion beam. As shown in the figure, when ion current density was measured without the reflector, the increase of voltage to the acceleration grid increased the measured ion current density, possibly due to the increased extraction of ions at the higher acceleration grid voltage without scattering at the grids. The ion current density measured after the reflection also increased with the increase of acceleration voltage; however, it was significantly lower compared to that measured without the reflector. The significant decrease of the detected ion current density with the reflector for all of the gases appears to be related to the neutralization of the ions during the reflection at the reflector, therefore, most of the ions appear to be neutralized.

Fig. 2(a) shows the effect of acceleration voltage of the ion source on SiO_2 etch rate measured with the reflector. The rf power to the ion gun was 500 W, the distance between the sample and the reflector was 5 cm, and the gas flow rate was 7 sccm. Even though almost no ions were

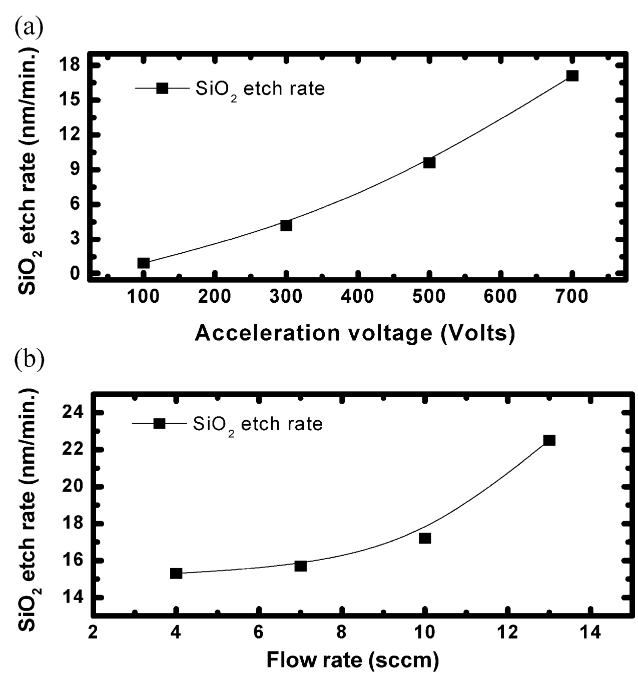

Fig. 2. SiO_2 etch rate with the reflector as a function of acceleration voltage of the ion source for 7 sccm of SF_6 gas flow rate (a) and as a function of gas flow rates of SF_6 for 700 V of acceleration voltage (b) (rf power to ion gun: 500 W; distance between reflector and Faraday cup: 5 cm).

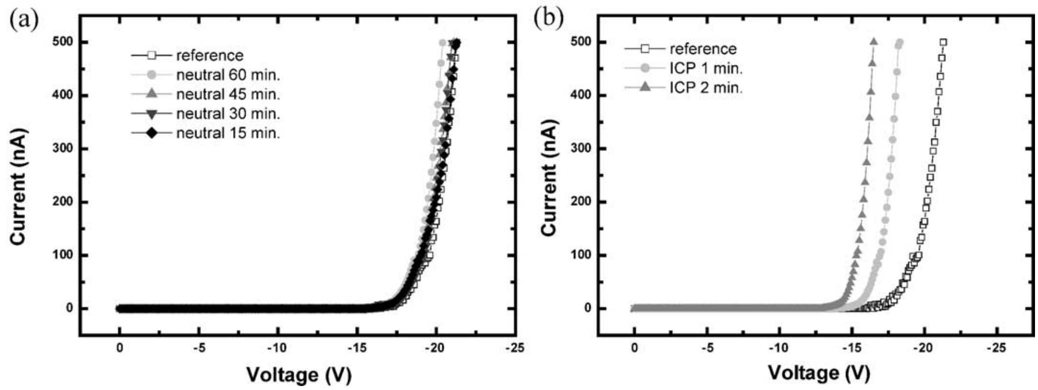

Fig. 3. $I-V$ characteristics of MOS devices exposed to oxygen neutral beam (a) or inductively coupled plasma (b) as a function of exposure time (oxygen neutral beam: 500 W of rf power, 0.7 mTorr (7 sccm) of oxygen, and 400 V of acceleration voltage; oxygen inductively coupled plasma: rf 500 W, -100 V of bias voltage, and 5 mTorr of oxygen). To etch 1.2 μm of photoresist, the oxygen inductively coupled plasma took 2 min while the oxygen neutral beam took 30 min.

detected with the reflector as shown in Fig. 1(b), if the ions were neutralized, SiO_2 should be etched by the energetic neutrals formed after the reflection of the reactive ions at the reflector. As shown in the figure, SiO_2 etch rate increased with the increase of acceleration voltage of the ion source. The increase of SiO_2 etch rate with the increase of acceleration voltage is related to the increase of ion flux extracted from the ion source as shown in Fig. 1(a), therefore, the increase of neutral flux after the reflection. The increase of SiO_2 etch rate with the increase of acceleration voltage is also related to the increased energy of the reflected neutrals formed by the neutralized reactive ions.

Fig. 2(b) shows the effect of SF_6 gas flow rate on SiO_2 etch rate with the reflector. The rf power and the distance between the reflector and sample were also maintained at 500 W and 5 cm, respectively. The acceleration voltage to ion gun was 700 V. As shown in the figure, the increase of SF_6 gas flow rate increased the SiO_2 etch rate. The increase of SiO_2 etch rate with the increase of SF_6 gas flow rate appears to be from the increased ion beam flux from the ion source observed (not shown), and which resulted in the increase of energetic neutral flux at the substrate. The increase of SF_6 gas flow rate to the ion gun increases not only the ion flux but also the low energy reactive radical flux emitted from the ion gun; therefore, SiO_2 etch rate observed in Fig. 2(b) is also related to the increase of low energy radical flux emitted from the ion gun by the physiochemical reaction with SiO_2. As shown in the figure, by increasing the SF_6 flow rate to 14 sccm, SiO_2 etch rate higher than 22 nm/min could be obtained.

The degree of charging damage by the low-angle, forward-reflected neutral beam technique was estimated by $I-V$ characteristic of MOS devices exposed to the neutral beam. To measure the degree of charging damage, the MOS devices were exposed to oxygen neutral beam generated by 500 W of rf power, 0.7 mTorr (7 sccm) of oxygen, and 400 V of acceleration voltage. To compare the damage, $I-V$ characteristics of MOS devices fabricated without exposing to the neutral beam (reference) and those exposed to an oxygen inductively coupled plasma were also measured. The condition for the inductively coupled plasma was rf 500 W, -100 V of bias voltage, and 5 mTorr of oxygen. For the etching of 1.2-μm-thick photoresist, the oxygen inductively coupled plasma took 2 min while the oxygen neutral beam took 30 min. $I-V$ characteristics of MOS devices exposed to the above conditions were measured as a function of exposure time and the results are shown in Fig. 3. Fig. 3(a) and (b) shows the effect of exposure time to the oxygen neutral beam and to the oxygen inductively coupled plasma, respectively, on the $I-V$ characteristics of MOS device. As shown in the figure, in the case of MOS devices exposed to inductively coupled plasma, the increase of exposure time increased the breakdown voltage of MOS device while the MOS devices exposed to the oxygen neutral beam did not show noticeable change in the breakdown voltage. The decrease of breakdown voltage with the increase of exposure time to oxygen inductively coupled plasma appears to be from the increase of Si/SiO_2 interface trapped charge at the MOS device by the positive ion flux. Therefore, for the same amount of photoresist etching, the charging damage could be removed by using neutral beam instead of conventional inductively coupled plasma. Even though we did not use SF_6 gas in the estimation of charging damage, we believe that similar results are expected when SiO_2 is etched with SF_6 neutral beam.

4. Conclusions

In this study, the characteristics of neutral beam and its SiO_2 etch characteristics with SF_6 gas have been studied using a neutral beam formed by low-angle, forward reflection of the ions extracted by an ion gun. Also, the degree of charging damage of SiO_2 exposed to an oxygen neutral beam was measured and compared with that exposed to an oxygen inductively coupled plasma. The result showed that most of the ions extracted from the ion gun were neutralized and formed a neutral beam by the low-angle reflection technique. When SiO_2 was etched with energetic reactive neutral beams of SF_6, the increase of acceleration voltage and SF_6 gas flow rates to the ion gun increased the SiO_2 etch rate, and the SiO_2 etch rate higher than 22 nm/min could be obtained in our experimental condition. When the charging damage was measured by forming MOS devices and by exposing to an oxygen neutral beam, no noticeable charging damage in the MOS devices could be observed, while the MOS devices exposed to oxygen inductively coupled plasma showed a significant change in the breakdown voltage of the device.

Acknowledgements

This work was supported by National Program for Tera-level Nanodevices of the Korea Ministry of Science and Technology as one of the 21st Century Frontier Programs.

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