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# Damage during $SiO_2$ Etching by Low-Angle Forward Reflected Neutral Beam

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In this study, energetic reactive radical beams were formed with $SF_6$ using a low-angle forward reflected neutral beam technique and the etch properties of $SiO_2$ and possible damage induced by the radical beam were investigated. The results showed that when $SiO_2$ was etched with the energetic reactive radical beams generated with $SF_6$, $SiO_2$ etch rates higher than 22 nm/min could be obtained. Also, when the etch damage was studied in terms of the capacitance–voltage ($C$–$V$) and current–voltage ($I$–$V$) characteristics of metal-nitride-oxide-silicon (MNOS) and metal-oxide-silicon (MOS) devices exposed to the radical beams, nearly no etch damage could be found. [DOI: 10.1143/JJAP.41.L1412]

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

Plasma etching is one of the key technologies in the fabrication of deep submicron silicon based integrated circuits. However, plasma etching has a serious disadvantage in that the energetic charged particles such as positive ions and photons generated in the plasma cause radiation damage, which cause physical defects, 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 in order to avoid these problems is the use of low-energy neutral beam etching.

In the previous study, a low-angle forward reflected neutral beam etching apparatus was developed.[7] In this etcher, all of the reactive ions extracted from an ion gun are reflected on the flat wafer surfaces or on the hole surfaces of the perforated 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 dioxide ($SiO_2$) anisotropically. In this study, the etch properties of $SiO_2$ were investigated with $SF_6$ gas using the low-angle forward reflected neutral beam etching system and possible neutral-beam-induced damage was examined through the electrical characteristics such as capacitance–voltage ($C$–$V$) and current–voltage ($I$–$V$) measurements.

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 laboratory-built 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 (Va) were applied to the grid located close to the source (accelerator grid) and the grid located outside of the source (extractor grid) was grounded. Figure 1 shows the schematic diagram of the low-angle forward reflected neutral beam source (ion source and reflector). The reflector was made of a perforated aluminum block where the axes of the holes in the reflector were fabricated to be tilted at 5° from the ion beam direction. The holes in the reflector were matched 1:1 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, and thus, to neutralize the extracted ions.

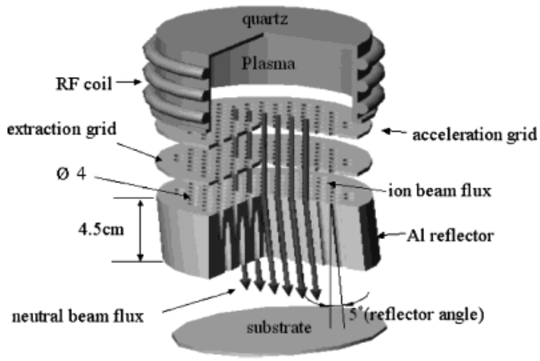


Fig. 1. Schematic diagram of the low-angle forward reflected neutral beam system used in the experiment.

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 gas, $SF_6$ was used and fed to the ion gun with the flow rate ranging from 4 to 13 sccm. The chamber pressure with the gas flow was maintained from 0.7 to 1 mTorr. The $SiO_2$ etch rate was measured as a function of acceleration voltage of the accelerator and flow rate.

In order to investigate the charging damage by the low angle forward reflected neutral beam, $C$–$V$ measurements were carried out using metal-nitride-oxide-silicon (MNOS) devices formed with 50-nm-thick low-pressure chemical vapor deposition (LPCVD) nitride and 3-nm-thick thermally grown $SiO_2$ on p-type Si. Before the $C$–$V$ measurement, a MNOS device was exposed to an oxygen neutral beam for the time to etch a 1.2-$\mu$m-thick photoresist.[10] Also, a separate MNOS device was exposed to an oxygen inductively coupled plasma (ICP) for the time to etch the same photoresist thickness and its $C$–$V$ characteristics were measured for comparison. As a reference, $C$–$V$ characteristics of another MNOS device formed without exposure to the ICP plasma or the neutral beam were also measured. Breakdown voltages of current–voltage ($I$–$V$) characteristics were measured by forming metal-oxide-silicon (MOS) devices on 15-nm-thick thermally grown $SiO_2$ on p-type silicon and exposing them to the above oxygen inductively coupled plasma from 1 to 2 min and to the above oxygen neutral beam from 15 to 60 min for the estimation of plasma charging damage. For the MNOS and MOS devices, 300 nm thick aluminum electrodes with the areas of 0.04

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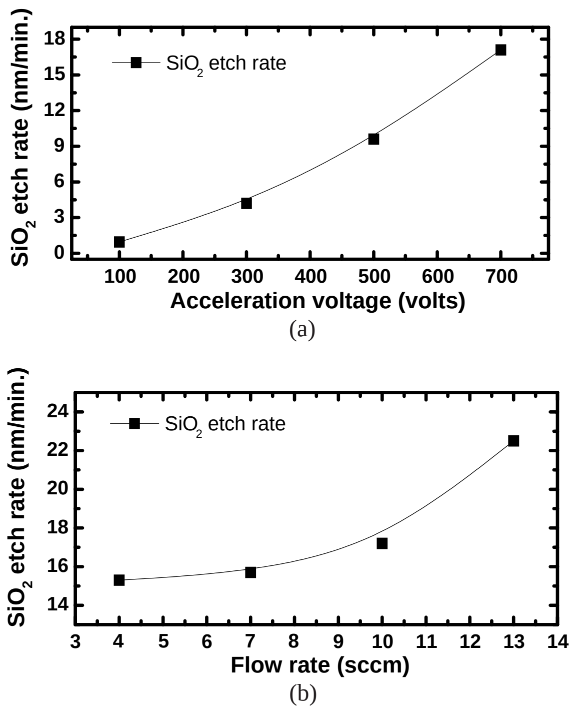


Fig. 2. $SiO_2$ etch rate with the reflector as a function of acceleration voltage of the ion source for 7 sccm of $SF_6$ gas flow rate (a) and as a function of gas flow rates of $SF_6$ for 700 V of acceleration voltage (b). (rf power to ion gun: 500 W, the distance between reflector and substrate: 5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

(200 $\mu$m × 200 $\mu$m in size) and 0.09 mm$^2$ (300 $\mu$m × 300 $\mu$m in size) were formed by a lift-off technique.

In the previous study, when the incident ions were reflected at a low angle, most of the incident ions were neutralized and, as the incident ions were reflected at lower angles, more ions were neutralized with a higher neutralization efficiency.[7] Previous results showed that more than 99.2% of incident ions were neutralized at the reflection angle of 5°. With the radical beam generated by the reflection at 5° with $SF_6$, $SiO_2$ was etched and the etch results are shown in Fig. 2. Figure 2(a) shows the effect of acceleration voltage of the ion source on the $SiO_2$ etch rates. The rf power supplied 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. As shown in the figure, the $SiO_2$ etch rate increased from about 2 to 18 nm/min with the increase of acceleration voltage of the ion source from 100 to 700 V. 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 observed in a previous study,[7] and therefore, is also related to 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.

Figure 2(b) shows the effect of $SF_6$ gas flow rate on $SiO_2$ etch rate. The rf power and the distance between the reflector and sample were also maintained at 500 W and 5 cm, respectively. The acceleration voltage supplied to the ion gun was 700 V. As shown in the figure, the increase of $SF_6$ gas flow rate from 4 to 13 sccm increased the $SiO_2$ etch rate from 15 to 22.5 nm/min. The increase of $SiO_2$ etch rate with the increase of $SF_2$ gas flow rate appears to be due to the increased ion beam flux from the ion source as also observed in the previous study,[7] 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, the $SiO_2$ etch rate observed in Fig. 2(b) is partially related to the increase of the low-energy radical flux emitted from the ion gun to the substrate which results in the increased physio-chemical reaction with $SiO_2$. As shown in the figure, by increasing the $SF_6$ flow rate to 13 sccm, a $SiO_2$ etch rate higher than 22 nm/min could be obtained.

Even though $SiO_2$ could be etched successfully with the low-angle forward reflected neutral beam technique, the major advantage in using the neutral beam is expected to be the reduction of the charging damage to the substrate, and, for the gate $SiO_2$ etching, the charging damage is recognized as one of the major problems to be solved. The degree of charging damage by the low-angle forward reflected neutral beam technique was estimated from the *C–V* characteristics of MNOS devices[11,12] exposed to the neutral beam. To measure the degree of charging damage, the MNOS devices were exposed to an oxygen neutral beam generated by 500 W of rf power, 0.7 mTorr (7 sccm) of oxygen, and 400 V of acceleration voltage. For comparison, the *C–V* characteristics of MNOS devices fabricated without exposure to the neutral beam and those of device exposed to an oxygen inductively coupled plasma were also measured. The conditions for the inductively coupled plasma were rf 500 W, −100 V of bias voltage, and 5 mTorr of oxygen. For the etching of 1.2-$\mu$m-thick photoresist, the oxygen inductively coupled plasma took 2 min while the oxygen neutral beam took 30 min. *C–V* characteristics of MNOS devices exposed to the above conditions were measured and the results are shown in Fig. 3. Figures 3(a) and 3(b) are the *C–V* characteristics of MNOS devices having aluminum electrodes of the size of (a) 200 $\mu$m × 200 $\mu$m and (b) 300 $\mu$m × 300 $\mu$m exposed to the oxygen inductively coupled plasma and the oxygen neutral beam for the time to etch 1.2 $\mu$m of photoresist, to measure the degree of charging damage. As a reference, the *C–V* characteristics of the NMOS devices that were not exposed to the inductively coupled plasma or to the neutral beam are shown in the figures. As shown, in the case of MNOS devices exposed to inductively coupled plasma, the flat band voltage was shifted, while no noticeable shift in flat band voltage was observed in the MNOS devices exposed to the oxygen neutral beam. The shift in flat band voltage means the creation of the positive charge at the $SiO_2$/Si interface.[10] Therefore, the charging damage by the plasma appears to occur if the conventional inductively coupled plasma is used, however, the charging damage appears to be minimized with the use of the neutral beam.

Breakdown voltages were measured from the *I–V* characteristics of the MOS devices exposed to the oxygen neutral beam from 0 (reference) to 60 min and the oxygen inductively coupled plasmas from 0 (reference) to 2 min to estimate the degree of radiation damage, and the results are shown in Fig. 4. Figures 4(a) and 4(b) show the effect of exposure time to the oxygen neutral beam (a) and to the oxygen inductively coupled plasma (b) on the *I–V* characteristics of MOS devices. As shown in the figure, in the case of MOS devices exposed to the inductively coupled plasma, the increase of exposure time from 0 to 2 min decreased the breakdown voltage of the MOS device while the MOS devices exposed to the

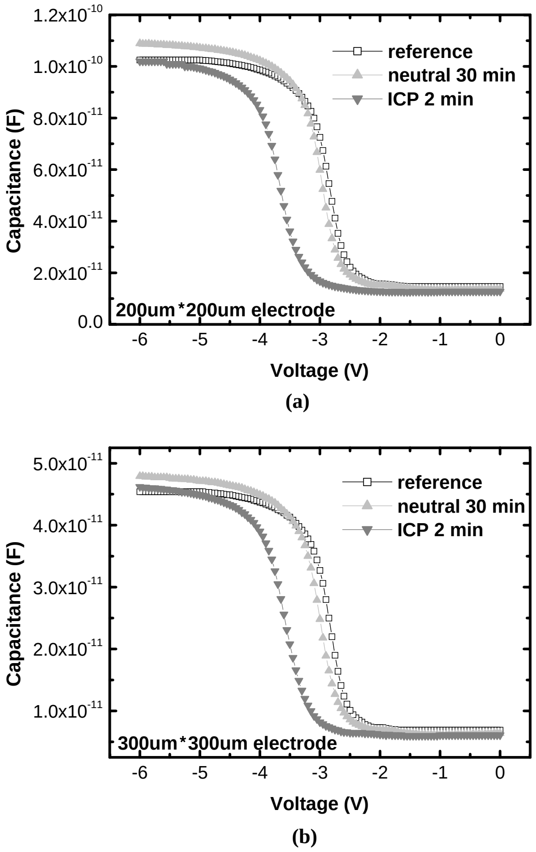


Fig. 3. $C$–$V$ characteristics of MNOS devices having aluminum electrodes of the size of (a) 200 $\mu$m × 200 $\mu$m and (b) 300 $\mu$m × 300 $\mu$m exposed to the oxygen inductively coupled plasma and the oxygen neutral beam for the time to etch 1.2 $\mu$m of photoresist, in order to measure the degree of charging damage. As a reference, the $C$–$V$ characteristics of the NMOS devices not exposed to the inductively coupled plasma or to the neutral beam are shown in the figures. (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 power of 500 W, −100 V of bias voltage, and 5 mTorr of oxygen.)

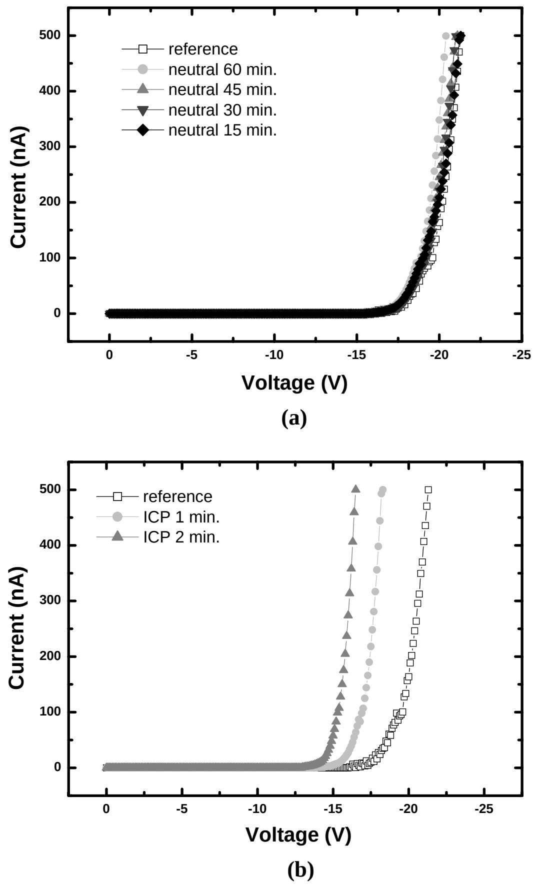


Fig. 4. $I$–$V$ characteristics of MOS devices exposed to oxygen neutral beam (a) or inductively coupled plasma (b) as a function of exposure time. (oxygen neutral beam: 500 W of rf power, 0.7 mTorr (7 sccm) of oxygen, and 400 V of acceleration voltage. Oxygen inductively coupled plasma: rf power of 500 W, −100 V of bias voltage, and 5 mTorr of oxygen.)

oxygen neutral beam up to 60 min did not show a 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 due to the increase of Si/$SiO_2$ interface trapped charge at the MOS device by the positive ion flux. Therefore, for the same thickness of photoresist etching, the etching by inductively coupled plasma caused the decrease of the breakdown voltage caused by the charging damage, and the charging damage could be removed by using a neutral beam instead of conventional inductively coupled plasma. Although $SF_6$ gas was not used in the estimation of charging damage, it is believed that similar results are expected when $SiO_2$ is etched with a $SF_6$ neutral beam.

In this study, the characteristics of a 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 using the $C$–$V$ characteristics of MNOS devices and the $I$–$V$ characteristics of MOS devices and compared with those of devices exposed to an oxygen inductively coupled plasma. 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 thus the $SiO_2$ etch rate higher than 22 nm/min could be obtained under our experimental conditions. When the charging damage was measured by forming MNOS and MOS devices and by exposing them to an oxygen neutral beam, no noticeable charging damage could be observed, while the devices exposed to oxygen inductively coupled plasma showed a significant change in the flat band voltage shift and breakdown voltage of the device.

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