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Thin Solid Films 398–399 (2001) 647–651

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Development of a low angle forward reflected neutral oxygen beam for materials processing

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Abstract

In the fabrication of new silicon-based devices any process-related damage such as electrical charging and surface modification, remaining during the processing, may cause problems due to the size limitation of the devices. Therefore, less damaging etching processes are required. In this study, a neutral oxygen beam was formed using a low angle forward reflected neutral beam technique and studied to determine the possibility of it being used as an anisotropic etching technique without charging. The degree of neutralization and etch characteristics were also investigated. When an ion beam was reflected at a reflection angle $< 15^\circ$ (the angle between ion beam direction and the reflector surface), most of the ions reflected were neutralized and lower reflection angles gave higher degrees of neutralization. Complete neutralization of the ions in the reflected beam could be made by installing a retarding grid system between the sample and the reflector and by applying a potential higher than the maximum ion energy of the beam. Photoresist (PR) etching was carried out with the neutralized oxygen radical flux and anisotropic etch profiles could be obtained suggesting a directional neutral beam. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Plasma etching; Silicon devices; Neutral oxygen beam

1. Introduction

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 due to the energetic charged particles such as positive ions and photons generated in the plasma, which cause radiation damage, notching, charging, etc. To avoid these charge-related damages, several low-damage processes have been proposed such as hyperthermal atomic beam, ion-neutral scattering, layer-by-layer etching, etc [1–6].

In this study, a novel technique, a low angle forward reflected neutral beam etching technique, has been developed and 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. In this exper-

iment, effects of ion source conditions, the reflection angle and the distance between the ion beam source and the substrate with the degree of the neutralization of the ion beam, after the reflection on the reflector, were investigated. Also a method to remove the remaining ions emitted after the reflection was attempted. To verify the direction of the reflected neutral beam, photoresist etching was carried out and its etch profile was examined.

2. Experimental

In this experiment, an ion source and a reflector were used to form a neutral beam. The schematic of the experimental apparatus is shown in Fig. 1. A homemade two-gridded inductively coupled plasma source was used as the ion source. The source chamber was made out of a quartz cup and a four-turn Cu coil was wound around the cup to generate the plasma. The rf power applied in the coil was in the ranged from 250 to 350 W with a frequency of 13.56 MHz. Oxygen, at a flow rate of 4–12 sccm, was fed through the bottom of the cup. The

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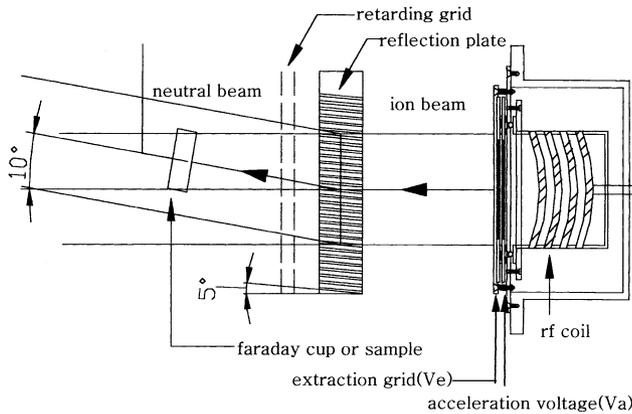


Fig. 1. Schematic representation of the low angle forward reflected neutral beam system.

ions were extracted using a specially designed two grid assembly located in front of the quartz cup and a potential ranging from 0 to +800 V (V_a) was applied to the grid located close to the source (accelerator grid) and a potential of -100 V (V_e) was applied to the grid located outside of the source (extraction grid).

The reflector was made from a parallel stack of polished silicon wafers supported by an Al block and was grounded to the chamber. The reflector angle could be changed by rotating the Al block. However, to prevent the ion beam from passing through the reflector without hitting the reflector and also to ensure the reflection occurs only once, different gap widths between silicon wafers were used for different reflection angles. The reflection angles used in the experiment were 5° and 15° (the gaps between the silicon wafer was 3 mm for 5° and 6 mm for 15°).

Some of the ions were not neutralized after the reflection, therefore, a retarding grid system made from two mesh screens (the one close to sample was grounded and the other close to the reflector was varied from 450 to 800 V) were installed between the sample and the reflector [4]. The ion flux emerging without neutralization was measured using a Faraday cup as a function of rf power of the ion source, acceleration voltage of the accelerator, oxygen flow rate, reflection angle and the distance between the ion source and the Faraday cup (14–28 cm). The photoresist etch rate was also measured by replacing the Faraday cup with photoresist-covered silicon wafers. The Faraday cup and the photoresist-covered wafers were located to obtain normal incident angle of the reflected beam. Blank photoresist layers on silicon masked by patterned SiO_2 was also used to examine the etch anisotropy of the photoresist, therefore, to examine the directionality of the reflected neutral beam. Etch depth was measured by a step profilometer and the etch anisotropy was observed using a field emission scanning electron microscope (SEM).

3. Results and discussion

To study effect of the reflection plate on the neutralization of the ions from the ion source, the ion currents extracted from the source before and after the reflection were measured using a Faraday cup. Fig. 2 shows the effects of reflection plate and acceleration voltage of the ion source on the ion current density measured by a Faraday cup. The rf power to the ion source was also varied from 250 to 350 W. Pure oxygen with the flow rate of 4 sccm was used to generate plasmas in the source. The reflection angle was 5° . The distance between the Faraday cup and the ion source was 21 cm. As shown in Fig. 2, when the ion currents were measured after the reflection plate, the currents were decreased drastically for all of rf power and acceleration voltage conditions. When the ion currents were measured without the reflector, increasing acceleration voltage and increasing rf power increased the ion current. However, when the ion currents were measured after the reflection, the ion currents did not change with the rf power even though they increased with the acceleration voltage slightly. Without the reflector, the increase of ion current with rf power is believed to be from the increase of oxygen ion density in the source and therefore, the increase of ion flux extracting from the source.

To understand the behavior of ion flux detected with the reflector as a function of acceleration voltage and rf power, ion currents were measured at different reflection angles and the results are shown in Fig. 3 for 5° and 15° of the reflection angle. Other conditions were the same as those in Fig. 2. As shown in Fig. 3, ion currents measured with 5° of the reflection angle showed slightly lower ion currents than those measured with 15° . However, the ion currents measured for both angles did not show a noticeable change of ion current with rf power.

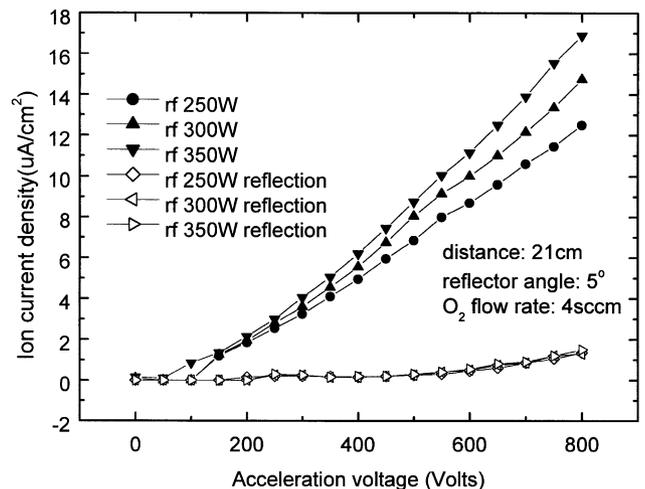


Fig. 2. The ion beam current density as a function of ion source acceleration voltage (V_a) with/without the reflector.

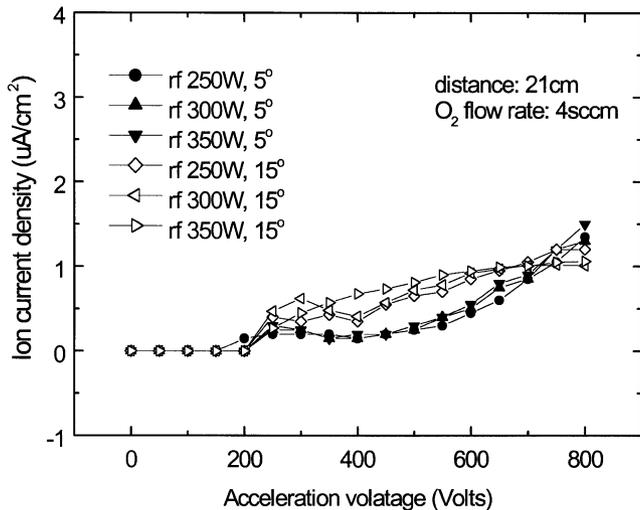


Fig. 3. Ion beam current density as a function of ion source acceleration voltage for 5 and 15° of reflection angle.

Also there is no significant increase of ion current with the increase of acceleration voltage. The negligible sensitivity of ion current to rf power and acceleration voltage compared to that without the reflector is probably originated from the significant neutralization of the ions extracted from the ion source after the reflection. The higher ion current measured for 15° suggests less neutralization at the higher reflection angle.

In the etching of nanometer scale devices, a small amount of charged particles remaining after the reflection may cause serious electrical damage to the device. Therefore, a retarding grid system was installed between the Faraday cup and the reflector and positive potentials were applied to remove the ions remaining after the reflection. Fig. 4 shows the effect of retarding grid potential on the ion current collected at the Faraday cup. The oxygen flow rate was 4 sccm and rf power was 350 W. In Fig. 4a, the reflection angle was 5° and the distance between the ion source and the cup was 21 cm. The acceleration voltage to the grid was varied from 300 to 700 V. As shown in Fig. 4 the increase of retarding grid potential decreased the ion current collected at the Faraday cup and nearly zero current was detected above a potential close to the acceleration voltage. In the case of Fig. 4b, ion current was measured as a function of retarding grid potential with the reflection angle of 15° and the acceleration voltage of 300 V. As shown in the figure, the ion currents were dropped to zero for all of the conditions when the retarding grid potential was higher than the acceleration voltage even though there is increase of ion current with the increase of retarding potential below the acceleration voltage for the distance of 14 and 21 cm. Similar results were obtained when 450 V of acceleration voltage was applied instead of 300 V (not shown). The variations

of ion currents shown in Fig. 4a,b below the acceleration voltage are not well understood. However, it is seen that, by applying a retarding grid potential higher than the acceleration voltage, nearly all of the ions remaining after the reflection are removed by the grid.

Using the neutralized oxygen radicals obtained after the reflection at the reflector, photoresist was etched and the etch rate was measured as a function of the reflection angle, acceleration voltage, the distance between sample and ion source and oxygen flow rate. The results are shown in Fig. 5a,b,c. The rf power to the ion source was 350 W.

To remove ions arriving at the sample, the retarding grid described in Fig. 4 was located between the sample and the reflector and a retarding potential higher than the acceleration voltage was applied. In Fig. 5a, the effect of acceleration voltage on the photoresist etch

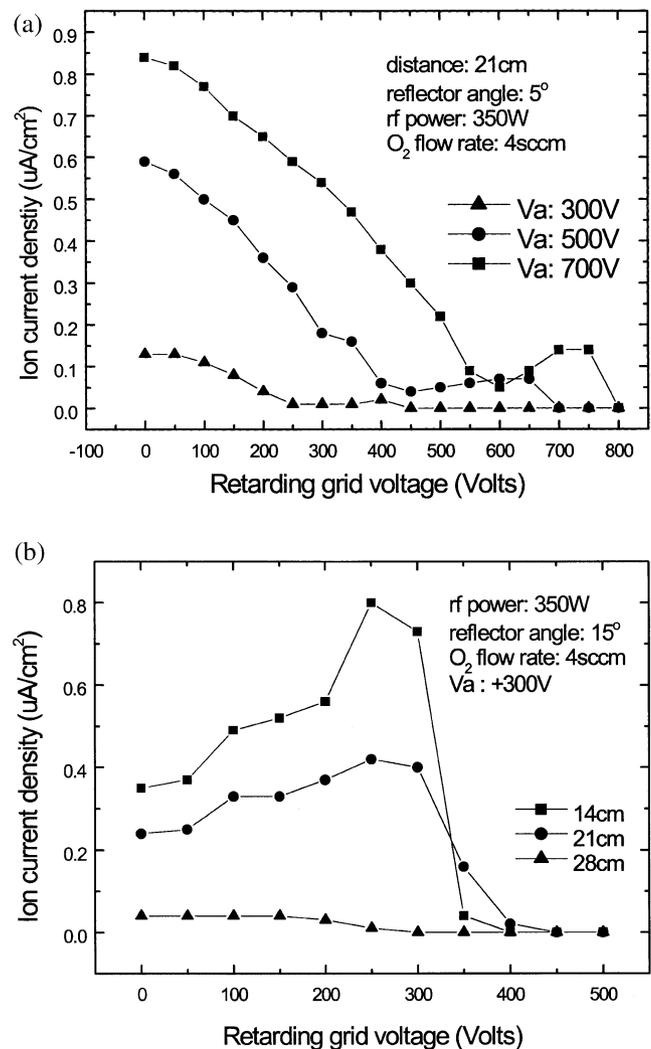


Fig. 4. The ion beam current density as a function of retarding grid voltage at ion source acceleration voltage of 300, 500 and 700 V (a). Ion beam current density as a function of retarding grid voltage at reflector to the ion source grid distances of 14, 21 and 28 cm (b).

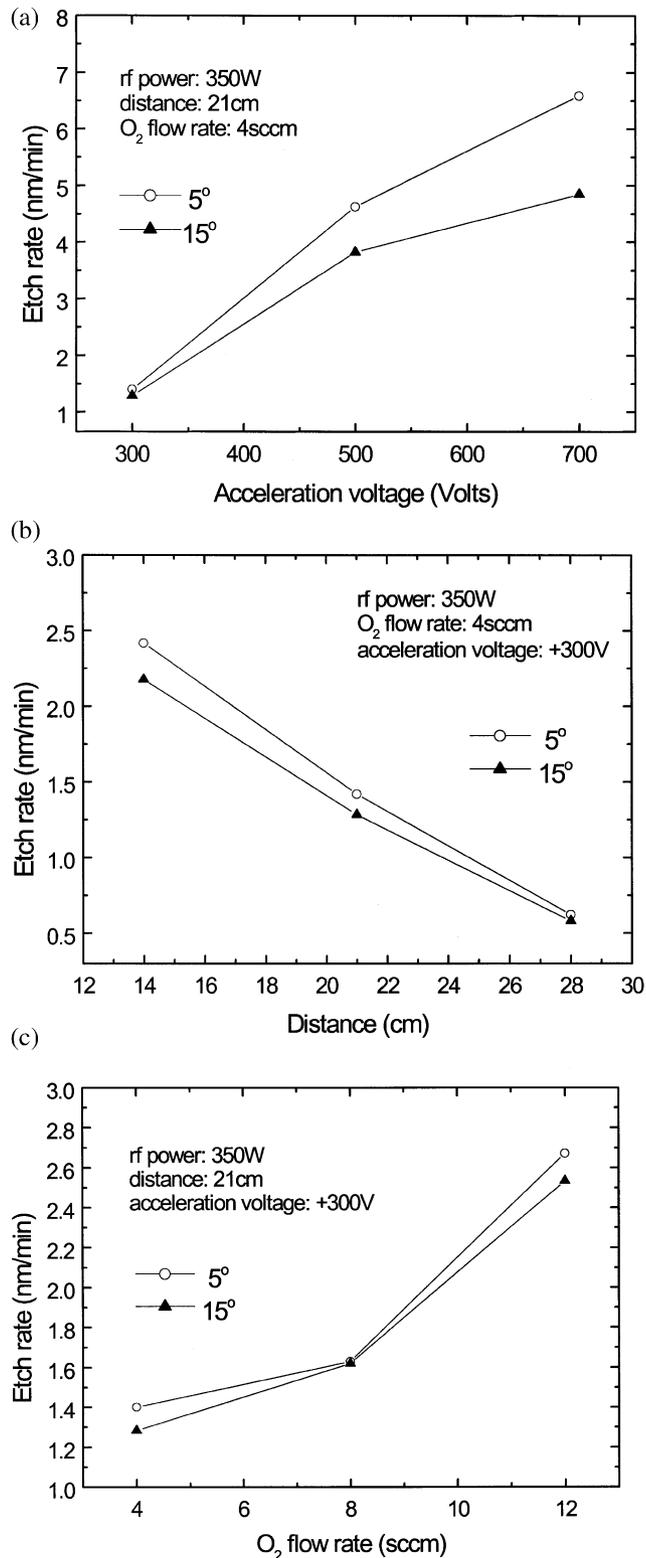


Fig. 5. The etch rate as a function of ion source acceleration voltage (a). The PR etch rate as a function of distance between the reflector and ion source grid (b). The PR etch rate as a function of O₂ flow rates (c).

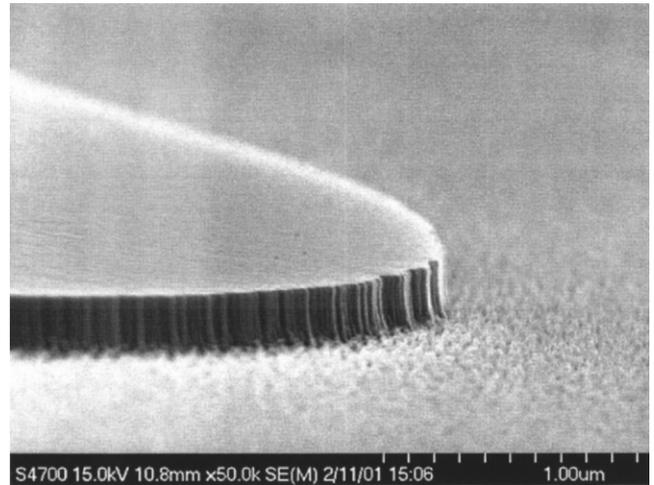


Fig. 6. The SEM micrographs of the PR etch profile by low angle reflected neutral beam.

rate is shown for 5 and 15° of reflection angle. The distance between the sample and the ion source was maintained at 21 cm and oxygen flow rate was 4 sccm. As shown in the Fig. 4 the increase of acceleration voltage increased the photoresist etch rate and the etch rate for 5° of reflection was higher. The increased etch rate with acceleration voltage is related to the increase of ion flux extracted from the ion source, therefore, the increase of neutral flux was after the reflection. The lower etch rate with 15° of reflection angle is due to the lower neutralization as suggested in Fig. 3. The lower degree of neutralization with the higher reflection angle is similar to the results obtained by Helmer et al. [7,8]. Fig. 5b shows the effect of distance between the sample and the ion source on the photoresist etch rate for a 5 and 15° reflection angle. The acceleration voltage was 300 V and the oxygen flow rate was 4 sccm. As shown in the figure, the increase of the distance decreased the photoresist etch rate for both reflection angles possibly due to the scattering of neutral flux. The lower reflection angle showed a higher etch rate similar to that in Fig. 5a, suggesting higher neutral flux to the substrate. In Fig. 5c, the effect of oxygen flow rate on the photoresist etch rate is shown for both reflection angles. The distance between the sample and the ion source was 21 cm and the acceleration voltage was 300 V. The increase of oxygen flow rate increased the photoresist etch rate because the increase of the oxygen flow rate to the ion gun increased the ion beam flux from the ion gun, which resulted in the increase of neutral flux at the substrate (not shown).

Even though the photoresist could be etched without ion flux, it does not guarantee whether the etch was carried out by random oxygen radicals, emitted from the ion source, or directional neutral beam, neutralized at the reflector. Therefore, blank photoresist masked

with patterned SiO₂ was etched and the etch anisotropy was observed using a SEM, the result is shown in Fig. 6. As shown in the figure, an anisotropic etch profile could be obtained. The anisotropy of the etch profile was consistent for all of the oxygen flow rates, the rf power, the reflector angle and the acceleration voltage studied in our experimental conditions (not shown). Therefore, it is believed that the etching shown in Fig. 5 is from the directional neutral flux formed by the reflection at the reflector.

4. Conclusions

In this study, a directional oxygen neutral beam was formed using a low angle forward reflected neutral beam technique. When the ion beam was reflected at a reflector at a reflection angle from 5 to 15°, most of the ions appear to be neutralized and a lower reflection angle gave a higher neutral flux.

The remaining ions emerging after the reflection could be removed by installing a retarding grid system between the sample and the reflector and by applying a potential higher than the acceleration voltage. Photoresist etching was carried out with the completely neutralized oxygen flux and anisotropic etch profiles could be obtained,

confirming the formation of the directional neutral beam flux by the low angle forward reflection technique.

Acknowledgements

This work was supported by the 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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