ELSEVIER

Thin Solid Films 420–421 (2002) 579–583

thin solid films

www.elsevier.com/locate/tsf

Study on the low-angle forward-reflected neutral beam etching system for SiO_2 etching

M.J. Chung, D.H. Lee, G.Y. Yeom*

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

Abstract

In this study, the effect of various reactive gases, such as SF_6, NF_3, CF_4 and Ar, on the SiO_2 etch rate was investigated using a low-angle forward-reflected neutral beam technique, where the neutral beam is formed at the reflector by low-angle reflection of ions extracted from the ion gun. The results showed that most of the ions extracted from the ion gun were neutralized and formed a neutral beam by the low-angle reflection technique, regardless of gas species. When SiO_2 was etched using energetic reactive radical beams of SF_6, NF_3, CF_4 and Ar formed by the reflection technique, SF_6 showed the highest SiO_2 etch rate, while Ar showed the lowest. The highest etch rate by SF_6 was related to the high flux of energetic radicals formed by the reflection and chemical reactivity of these radicals, while the lowest etch rate by Ar was due to the lack of chemical reactivity, even though the flux of the energetic neutral is similar to that of SF_6. The SiO_2 etch rate was affected by the random low-energy reactive radicals emitted from the ion source, in addition to the energetic radicals formed by the reflection of the energetic ions. Vertical SiO_2 etch profiles could be obtained with the low-angle forward-reflection technique, suggesting the formation of a near-parallel energetic radical beam.

Keywords: Neutral beam; SiO_2 etching; Fluorine-based gas

1. Introduction

Charge-induced damage during plasma etching is one of the biggest problems that has 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 [1–6], and one of the techniques to avoid this problem is to use neutral beam etching.

In previous studies, a prototype etcher of low-angle forward-reflected neutral beam was developed, in which all reactive ions extracted from an ion gun impact on a flat surface at 5–15° to produce a near-parallel radical beam flux [7–9]. Using this prototype neutral beam system, the characteristics of the neutral beam and photoresist etch rate were investigated using oxygen as a reactive gas [10]. However, this prototype showed some problems, such as low neutral flux, non-uniformity within the wafer and a bulky reflector.

In this study, a new low-angle forward-reflected neutral beam system having a compact reflector has been proposed to obtain higher neutral flux and better uniformity within the wafer, and the characteristics of this system, such as the degree of neutralization and scattering of the beam, and the characteristics of SiO_2 etching were investigated. To etch SiO_2, the effect of various fluorine-based gases, such as SF_6, NF_3 and CF_4, in addition to Ar were investigated and the SiO_2 etch profiles were 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 RF ion gun and a reflector, was used to form a neutral beam. A schematic diagram of the source used in this experiment is shown in Fig. 1. A homemade 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

---

*Corresponding author. Tel.: +82-31-270-7395; fax: +82-31-277-6565.

E-mail address: minjae@mail.skku.ac.kr (G.Y. Yeom).

0040-6090/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0040-6090(02)00845-3

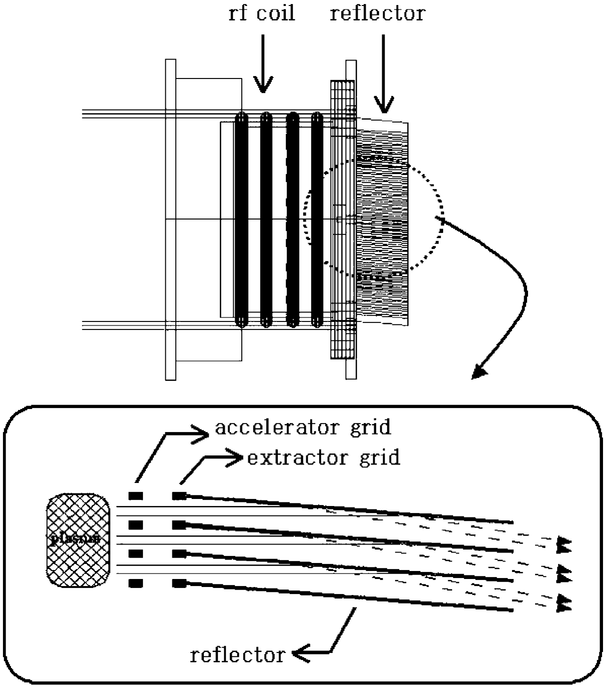

Fig. 1. Schematic representation of a low-angle forward-reflected neutral source.

assembly and 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 the source (extractor grid) was grounded. The reflector was made of a perforated aluminum block, with the axes of the holes in the reflector fabricated to have 5° angle with the ion beam 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, and therefore to neutralize the extracted ions.

The ions emerging without neutralization at the reflector were measured using a Faraday cup as a function of the acceleration voltage of the accelerating grid. The Faraday cup and 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 and to examine the etch anisotropy of the SiO_2, and thus the directionality of the reflected neutral beam. As the etch gases, SF_6, NF_3, CF_4 and Ar were used and fed to the ion gun with a flow rate from 3 to 15 sccm. The chamber pressure was maintained between 0.093 and 0.13 Pa. The SiO_2 etch rate was measured as a function of the acceleration voltage of the accelerator, the flow rate and the distance between the reflector and sample (5–14 cm) for various etch gases. Among these, the measurement of SiO_2 etch rate as a function of the distance between the reflector and sample was carried out to determine the effect of collisional loss of the energetic neutral, because significant collisional loss could be expected when the distance between the reflector and sample is long at the pressure range used in the experiment. 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 reflector (with and without reflector in front of the ion source) and acceleration voltage on the ion current density measured with a Faraday cup for the gases SF_6, NF_3, CF_4 and Ar. The flow rate of these gases was maintained at 7 sccm. The distance between the Faraday cup and the reflector was 5 cm and the Faraday cup was located normal to the incident ion beam. As shown in the figure, the increase in voltage to the acceleration grid increased the ion current density measured, possibly due to the increased extraction of ions at the higher voltage, without scattering at the grids. Significant differences in the ion current density values measured were not observed among the different gases, even though Ar and SF_6 showed slightly higher ion current density compared to CF_4 and NF_3. However, when measurements were carried out in the presence of the reflector, the ion current density values were significantly lower compared to those measured without the reflector for all the gases investigated. The significant decrease in ion current density detected with the reflector for all gases appears to be related to neutralization of the ions during reflection at the reflector, and therefore most of the ions appear to be neutralized.

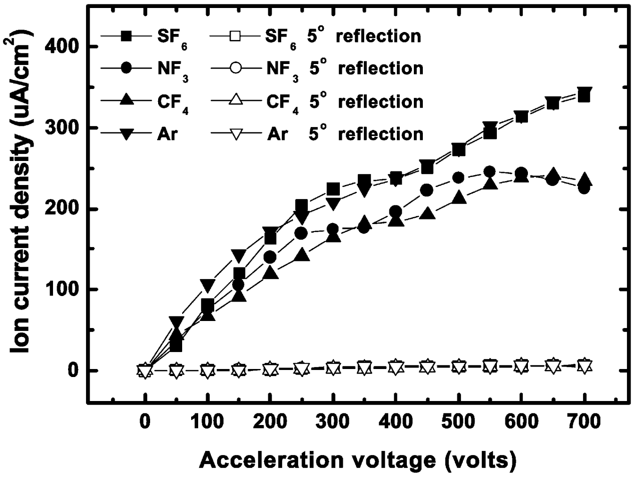

Fig. 2. Ion-beam current density as a function of ion source acceleration voltage with/without reflector for various gases such as SF_6, NF_3, CF_4 and Ar. Distance between the reflector and Faraday cup, 5 cm; gas flow rate, 7 sccm.

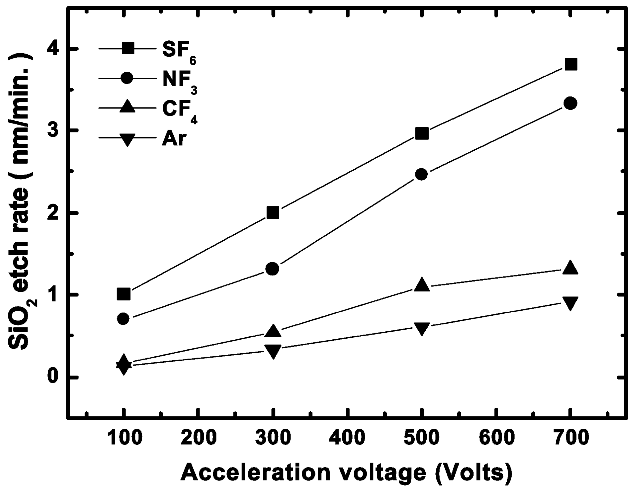

Fig. 3. SiO_2 etch rate with the reflector as a function of acceleration voltage of the ion source for SF_6, NF_3, CF_4 and Ar. Distance between the reflector and sample, 5 cm; gas flow rate, 7 sccm.

Fig. 3 shows the effect of acceleration voltage of the ion source on the SiO_2 etch rate for SF_6, NF_3, CF_4 and Ar with the reflector. The distance between the sample and the reflector was 5 cm and the gas flow rate was 7 sccm for all of the gases. Even though almost no ions were detected with the reflector, if the ions were neutralized, SiO_2 should be etched by the energetic radicals formed after reflection of the energetic reactive ions at the reflector. As shown in the figure, the SiO_2 etch rate increased with increasing acceleration voltage of the ion source for all gases. In addition, SF_6 showed the highest SiO_2 etch rate, while Ar showed the lowest. The increase in SiO_2 etch rate with increasing acceleration for all the gases appears to be due to the increased energy of the reflected neutrals formed by the neutralized reactive ions. As shown in Fig. 2, SF_6 and Ar showed the higher ion current density compared to CF_4 and NF_3 without the reflector. The highest SiO_2 etch rate for SF_6 with the reflector appears to be due to the high radical flux to the sample originating from the high reactive ion flux to be neutralized at the reflector. Even though the neutralized ion flux of Ar appears to be similar to that of SF_6 from the results of the ion current density shown in Fig. 2, Ar showed the lowest etch SiO_2 rate due to the lack of chemical reaction with SiO_2. The other gases, CF_4 and NF_3, showed SiO_2 etch rates higher than Ar due to chemical reaction of the neutralized ion fluxes with SiO_2, even though these fluxes were lower. The difference in SiO_2 etch rate between NF_3 and CF_4 might reflect the influence on etching of random neutral flux emitted from the ion source by the gas flow, because the dissociation rate of NF_3 is known to be higher than that of CF_4 [11], in addition to the influence of energetic reactive ions neutralized at the reflector. Also, the NF_3 etch rate is higher than that of CF_4 because C–F polymers formed on the SiO_2 surface by CF_x radicals emitted from ion source using CF_4 gas can impede SiO_2 etching.

Fig. 4 shows the effect of gas flow rates of SF_6, NF_3, CF_4 and Ar on the SiO_2 etch rate with the reflector. The distance between the reflector and the sample was also maintained at 5 cm and the acceleration voltage was 700 V. As shown in the figure, the increase in Ar flow rate did not change the SiO_2 etch rate; however, the increase in reactive gas flow rates for SF_6, NF_3 and CF_4 increased the SiO_2 etch rate. The negligible effect of Ar flow rate on the etch rate possibly indicates a negligible change in ion current density from the ion gun with the flow rate. The increase in SiO_2 etch rate with increasing reactive gas flow appears to be due to increased random reactive radicals, rather than ions emitted from the ion source. Therefore, the SiO_2 etch rate appears to be further increased due to the increased low-energy random radical flux assisting the physicochemical reaction of energetic radicals.

Fig. 5 shows the effect of the distance between the reflector and sample on SiO_2 etch rate for SF_6 and Ar. As shown in the figure, the etch rate for SF_6 decreased with increasing distance, while that for Ar remained similar. The insignificant effect of the distance between the reflector and sample for Ar appears to indicate insignificant scattering of Ar neutrals formed after reflection of the ions extracted from the ion gun. The decrease in SiO_2 etch rate with increasing distance, however, is possibly related to a decrease in random reactive radicals emitted from the ion gun by the gas flow or to the scattering of energetic reactive radicals formed after reflection of the reactive ions. That is, the degree of scattering during reflection might be different for Ar and SF_6. The difference in the degree of scattering for different gas species after reflection is currently under investigation.

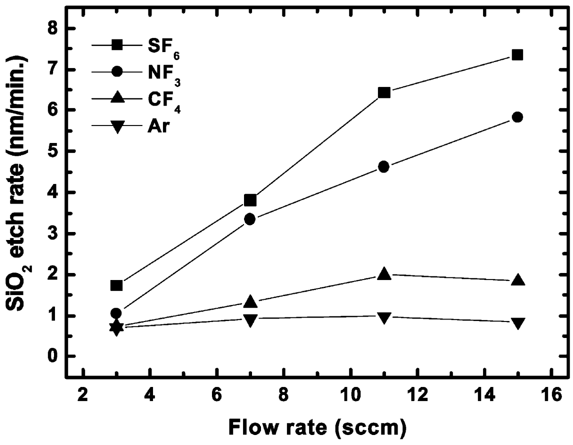

Fig. 4. SiO_2 etch rate with the reflector as a function of gas flow rates of SF_6, NF_3, CF_4 and Ar. Distance between the reflector and sample, 5 cm; acceleration voltage, 700 V.

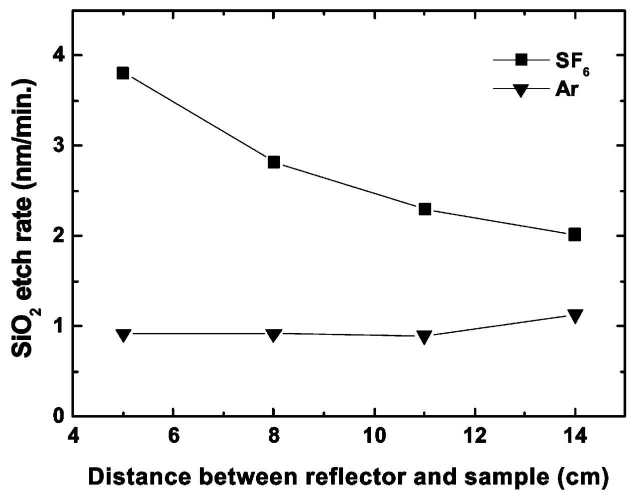

Fig. 5. SiO_2 etch rate with reflector as a function of the distance between the reflector and sample for SF_6 and Ar. Acceleration voltage, 700 V; gas flow rate, 7 sccm.

Fig. 6 shows scanning electron micrographs of SiO_2 profiles etched using a SF_6 neutral beam formed by the low-angle forward reflection method. SiO_2 was masked with a photoresist. SiO_2 etch profiles were vertical, regardless of the acceleration voltage, flow rate and distance between the reflector and the sample. Vertical etch profiles shown in the figure indicate that near-parallel reactive radical beams are obtained in our experiment by the low-angle forward reflection technique, even though a random radical flux emitted by the ion gun is also present. Obtaining this near-vertical SiO_2 etch profile in our experiment is also related to the characteristics of SiO_2 etching, which requires not only reactive species that can form volatile products, but also the bombardment of energetic particles that can break the Si–O bonding. Therefore, random reactive radicals existing in the environment with negligible energy did not contribute to sidewall etching, where bombardment by energetic neutrals is not available.

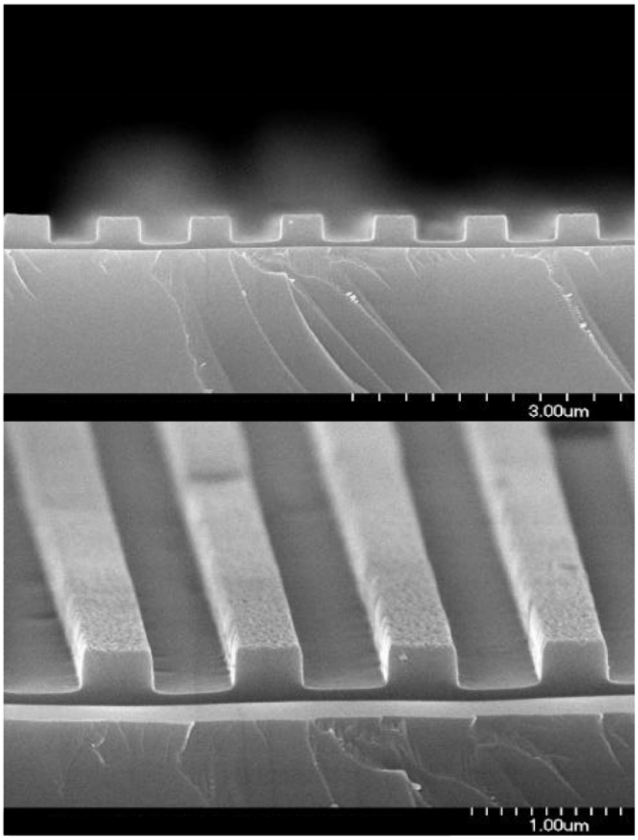

Fig. 6. Two SEM micrographs of SiO_2 etch profile with SF_6 by the low-angle reflected neutral beam source. Etch mask, photoresist; acceleration voltage, 700 V; extraction voltage, grounded; gas flow rate, 7 sccm; Distance between reflector and sample, 5 cm.

4. Conclusions

In this study, the effect of various reactive gases, such as SF_6, NF_3 and CF_4, and Ar on the SiO_2 etch rate was investigated using a low-angle forward-reflected neutral beam technique for various acceleration voltages of the ion gun, flow rates and distances between the reflector and sample.

This study showed that most of the ions extracted from the ion gun were neutralized by the low-angle reflection. When SiO_2 was etched using energetic reactive radical beams of SF_6, NF_3, CF_4 and Ar formed by the reflection of reactive ions, SF_6 showed the highest SiO_2 etch rate, possibly due to the high energetic radical flux formed by the reflection of the ions. Energetic Ar neutral flux formed by the reflection of the Ar ions was similar to that of SF_6. However, due to the lack of reactivity with SiO_2, the SiO_2 etch rate was the lowest. The SiO_2 etch rate was partially affected by the random reactive radical flux emitted from the ion source, and therefore the increase in SF_6, CF_4 and NF_3 flow rates increased the SiO_2 etch rate due to the increase in chemical reaction by the random reactive radicals. Even though random reactive radicals were present, SiO_2 etch profiles were vertical, regardless of the acceleration voltage of the ion gun, the flow rate and the distance between the reflector and sample, which indicates the formation of near-parallel energetic radical beams by the low-angle reflection of ions extracted at the ion gun.

Acknowledgments

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.

References

[1] T. Yunogami, K. Yokogawa, T. Mizutani, J. Vac. Sci. Technol. A 13 (3) (1995) 952.

[2] M.J. Goeckner, T.K. Bennett, J.Y. Park, Z. Wang, S.A. Cohen, International Symposium on Plasma Process-Induced Damage, 1997, p. 175.
[3] J. Yamamoto, T. Kawasaki, H. Sakaue, S. Shingubara, Y. Horiike, Thin Solid Films 225 (1993) 124.
[4] K. Yokogawa, T. Yunogami, T. Mizutani, Jpn. J. Appl. Phys. 35 (1996) 1902.
[5] S.R. Leone, J. Appl. Phys. 34 (1995) 2073.
[6] A. Szabo, T. Engel, J. Vac. Sci. Technol. A 12 (1994) 648.
[7] C.F. Abrams, D.B. Graves, J. Vac. Sci. Technol. A 16 (5) (1998) 3006.
[8] B.A. Helmer, D.B. Graves, J. Vac. Sci. Technol. A 16 (6) (1998) 3502.
[9] U. Thumm, J. Ducree, P. Kurpick, U. Wille, Nucl. Instrum. Methods B 157 (1999) 11.
[10] D.H. Lee, J.W. Bae, S.D. Park, G.Y. Yeom, Thin Solid Films 398 (2001) 647.
[11] K. Koike, T. Fukuda, S. Fujikwa, M. Saeda, Jpn. J. Appl. Phys. 36 (1997) 5724.