Thin Solid Films 637 (2017) 43–48

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Angular dependences of SiO_2 etch rates at different bias voltages in CF_4, C_2F_6, and C_4F_8 plasmas

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ARTICLE INFO

Article history:
Received 26 October 2016
Received in revised form 23 March 2017
Accepted 24 March 2017
Available online 24 March 2017

Keywords:
Angular dependence
Etch rate
Faraday cage
Fluorocarbon plasma
Steady-state fluorocarbon film

ABSTRACT

The angular dependences of SiO_2 etch rates at different bias voltages for in CF_4, C_2F_6, and C_4F_8 plasmas were investigated using a Faraday cage system. When the bias voltage was −400 V, the normalized etch yields (NEYs) reached a maximum at 70° in CF_4 and C_2F_6 plasmas, while they decreased monotonically with ion-incident angle in a C_4F_8 plasma. This was because the thickness of the steady-state fluorocarbon film formed on the SiO_2 surface was minimized at an ion incident angle of 70° in CF_4 and C_2F_6 plasmas, while much thicker fluorocarbon films were deposited in a C_4F_8 plasma. When the bias voltage was as high as −1200 V, the thicknesses of the steady-state fluorocarbon films were very thin (less than 2 Å) and nearly unchanged at all ion-incident angles for CF_4 and C_2F_6 plasmas, resulting in nearly the same shape of the NEY curves. In a C_4F_8 plasma, the NEY showed a maximum at an ion-incident angle of 50° because the thickness of the steady-state fluorocarbon film was minimized at this angle.

1. Introduction

Plasma etching of SiO_2 contact holes is one of the key processes in the fabrication of ultra large scale integrated (ULSI) devices [1–4]. In that process, fluorocarbon gases such as CF_4, C_2F_6, and C_4F_8 are widely used as discharge gases [5–7]. As the minimum feature size keeps decreasing, precise control over etch profiles is strongly required during SiO_2 contact hole etching. During plasma etching, the direction of ions incident on the surface of a substrate is not always vertical due to their angular distributions. Therefore, an understanding of the change in etch rate with the angle between the incident ion and the substrate surface is essential to predict and control etch profiles.

The use of a Faraday cage is useful for investigating the angular dependence of etch rates because it allows accurate control over the directions of the ions bombarding the substrate surface [8]. Many studies on the angular dependence of SiO_2 etch rates using Faraday cages have been reported [7–9]. Fluorocarbon plasmas such as CF_4, CHF_3, and C_4F_6 plasmas were used under different process conditions in the cited studies. Discharge chemistry affects etch characteristics such as etch rate. This implies that the angular dependence of SiO_2 etch rates can be affected by discharge chemistry. Therefore, it is necessary to compare the angular dependence of SiO_2 etch rates in various fluorocarbon plasmas under the identical process environments. In addition to discharge chemistry, the bias voltage is also important as it directly determines the energy of ions bombarding the substrate. However, a comprehensive analysis of the effect of discharge chemistry on the angular dependence of SiO_2 etch rates at different bias voltages has not been performed.

In this study, the SiO_2 etch rates at various ion-incident angles in CF_4, C_2F_6, and C_4F_8 plasmas were presented in order to investigate the effect of discharge chemistry on the angular dependences of SiO_2 etch rates. A Faraday cage system was used to control the angle of ions incident on the substrate. The effect of the bias voltage was also investigated by measuring the SiO_2 etch rates at −400 and −1200 V in each fluorocarbon plasma.

2. Experiment

2.1. Inductively coupled plasma system

Etch experiments were performed in an inductively coupled plasma system, as described in a previous study [8]. The inner diameter of the reaction chamber was 200 mm. Separate 13.56 MHz radio-frequency (rf) power generators were used independently to ignite a plasma and bias a sample. The source power was applied to a three-turn coil through a matching box, while the bias power was applied via an electrode with a diameter of 110 mm. A dielectric window (quartz) was located below the induction coil, and the distance between the dielectric window and the electrode was 100 mm.

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http://dx.doi.org/10.1016/j.tsf.2017.03.047
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2.2. Faraday cage system

A Faraday cage was used to investigate the angular dependence of the etch rates. The Faraday cage was fixed to the electrode in the reaction chamber. The Faraday cage used is a closed box consisting of a cylindrical stainless-steel sidewall (20 mm in height) and a stainless-steel cover grid. The grid diameter and pitch were 0.025 mm and 0.229 mm, respectively. Because the top plane of the Faraday cage was made of a conductive grid, the ions entered the cage perpendicular to the sheath formed along the top plane. The electric potential in the cage was uniform and unaffected by external electric fields. Therefore, the ions travelling inside the cage maintained their initial direction. The utility of a Faraday cage in plasma processing has been reported previously [10–14].

Fig. 1 shows the Faraday cage and substrate arrangement [8]. The ion-incident angle (θ) is defined as the angle between the ion incident direction and the surface normal to the substrate. As the inside of the cage is free of electric fields, the angle of ions incident on a sample substrate could be accurately controlled by varying the angle of the sample holder, which was located inside the cage. In this study, the ion-incident angles were varied in the range 0–90°. The substrates were 500-nm-thick SiO_2 films thermally grown on a p-type Si wafer. Each substrate was cut into a $10 \times 5\ mm^2$ rectangle and placed on the sample holder. The sample holder was fixed on a 3-mm-thick quartz wafer, which was used as the bottom plate.

2.3. Etching of SiO_2

CF_4, C_2F_6, and C_4F_8 were separately used as discharge gases. The following process conditions were maintained for all discharge gases: pressure = 10 mTorr, flow rate = 30 sccm, source power = 250 W, bias voltage = −400 and −1200 V, and electrode temperature = 15 °C. The low (−400 V) and high (−1200 V) values of bias voltage were selected to effectively observe the effect of bias voltage on the angular dependence of the SiO_2 etch rate.

2.4. Measurements of the etch rate

The etch rates (or deposition rates) of the samples were obtained by measuring changes in the thickness of the substrate film with a thickness meter (model SecraThick 2000-Deluxe). In all cases, the thickness was measured at 9 mm from the bottom of the sample holder.

3. Results

Fig. 2 shows the etch rate (ER) and normalized etch rate (NER) of SiO_2 as a function of ion-incident angle at a bias voltage of −400 V in CF_4, C_2F_6, and C_4F_8 plasmas. As seen in Fig. 2(a), the etch rates monotonically decreased with increasing ion-incident angle in all plasmas. When the ion-incident angle was 90°, the etch rates became negative. This indicates that a net deposition occurred at this angle because deposition and etching take place simultaneously in fluorocarbon plasmas. In the C_4F_8 plasma, the etch rate of SiO_2 decreased more rapidly than those in the CF_4 and C_2F_6 plasmas, and the deposition of the fluorocarbon film was observed at a lower ion-incident angle (~60°).

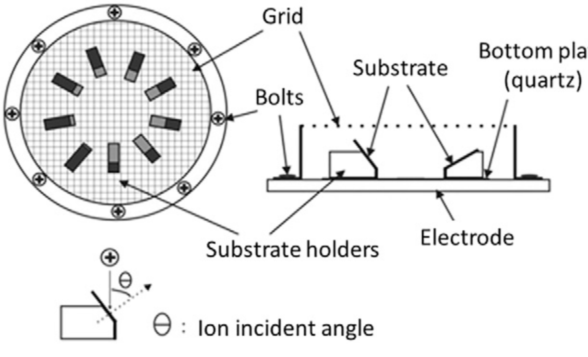

Fig. 1. Schematic diagrams of the Faraday cage and the substrate arrangement in the cage [8]. The ion-incident angle (θ) is defined as the angle between the ion-incident direction and the surface normal to the substrate.

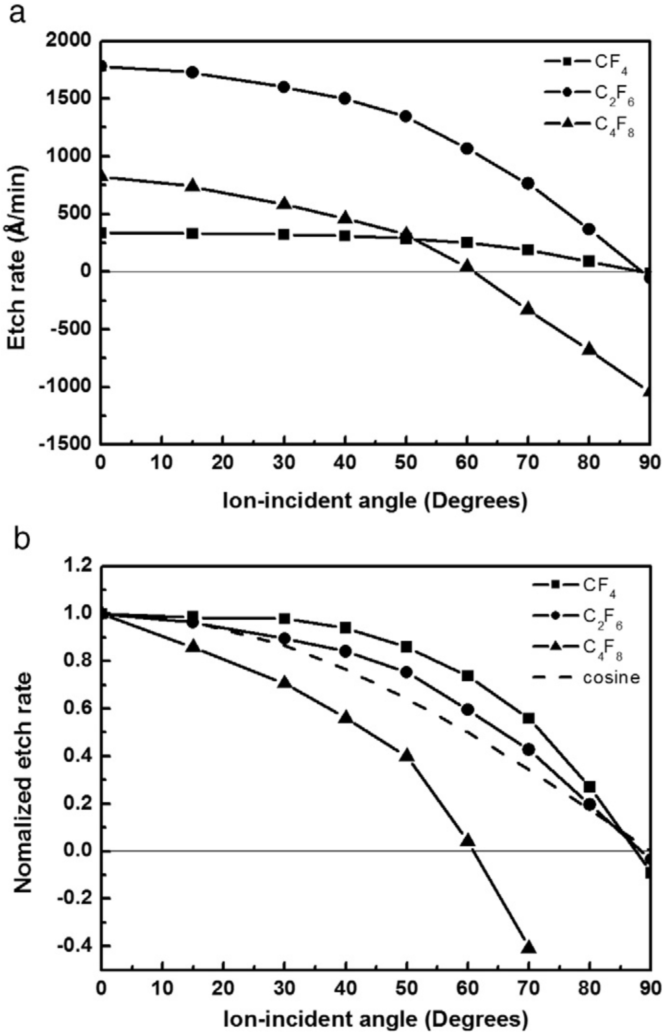

Fig. 2. Angular dependences of (a) etch rates and (b) normalized etch rates of SiO_2 at a bias voltage of −400 V in CF_4, C_2F_6, and C_4F_8 plasmas.

In order to clearly observe the extent to which the etch rate decreases with ion-incident angle, the NER as a function of ion-incident angle is shown in Fig. 2(b). The NER was obtained by normalizing the ER at a specific angle with respect to the ER on the horizontal surface. In the NER curve, the dotted line represents the cosine distribution, which is known to correspond to the changes in the flux of ions incident on the sample [6]. In the CF_4 and C_2F_6 plasmas, the NERs exceeded the cosine values except for 90°. On the other hand, the NERs in the C_4F_8 plasma were below the cosine values at all ion-incident angles. The behavior of the NERs in the various fluorocarbon plasmas implies that etching of SiO_2 is affected by factors additional to the flux of ions incident on the substrate surface.

Fig. 3 shows the ER and NER of SiO_2 as a function of ion-incident angle at a bias voltage of −1200 V in the CF_4, C_2F_6, and C_4F_8 plasmas. As in the case of a low bias voltage (−400 V), the etch rates at a high bias voltage (−1200 V) decreased with increasing ion-incident angle, shown in Fig. 3(a). As expected, the etch rates at −1200 V were higher than those at −400 V at all ion-incident angles in the corresponding plasmas. It is interesting to note that even the deposition rate of