Evaluation of SF₆ Reactive Ion Etching Performance with a Permanent Magnet Located behind the Substrate based on a Simple Design Concept

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Reactive ion etching performance with a permanent magnet located behind the substrate was evaluated in a compact vacuum chamber configuration with 38 mm inner diameter. This study presents a simple design concept for a compact SF₆ plasma reactor that has high-density plasmas radially compressed by a magnetic field. The magnetic field lines, which are created by a solenoid coil and permanent magnet, effectively transport ions to the substrate located downstream from the plasma source, and thereby reduce losses of plasma to the radial boundaries of the compact chamber. An etching rate of ~6.0 µm/min was obtained with input RF power of 500 W, a pulsed plasma discharge with duty ratio of 10%, and chamber pressure of 0.2 Pa. The etching rate achieved in the present study was increased more than tenfold, in comparison with our previous study, performed under similar conditions but without a permanent magnet located behind the substrate.

1. Introduction

Over the past few decades, miniaturizing the design rule and developing large-area wafers have advanced, reducing the cost of semiconductor manufacturing processes, and increasing the scale of processing reactors. Meanwhile, small-scale processing reactors are especially in demand for research and development (R & D) in fields such as material and microelectromechanical system (MEMS) research. However, it is well known that plasma loss to the wall boundaries increases in the case of the small vacuum chambers typically used in such reactors. Especially in plasma etching equipment, maintaining sufficient plasma density is crucial, in order to obtain a satisfactory etching rate, because a decrease in plasma density results in a decreased number of reactive particles (i.e., radicals). To produce a large number of radicals, high gas pressure conditions are typically required; however, anisotropic reactive ion etching (RIE) should be performed under low gas pressure conditions, providing a collisionless sheath at the substrate surface. Such conditions, however, typically involve serious problems, such as ion-bombardment damage to the substrate surface and increased surface roughness.

In general, etching characteristics depend on the relation between etching rate and quality, as evaluated by substrate damage and anisotropy.

In the present study, we developed a compact RIE system for low gas pressure conditions by using high-density plasma source. Helicon wave plasma (HWP) discharge and electron cyclotron resonance heating (ECR) discharge methods have been widely used to produce high-density plasma under low gas pressure conditions. The HWP discharge method is operational for wide ranges of magnetic field and driving RF frequency, while the ECR discharge method requires frequency matching of \( \omega = \omega_{ce} \) (typically 87.5 mT for 2.45 GHz microwave), where \( \omega \) and \( \omega_{ce} \) are the microwave frequency and electron cyclotron frequency, respectively. The ECR discharge method typically employs a divergent magnetic field to achieve efficient plasma production and a large processing area. Therefore, the HWP discharge method is more flexible for the design of compact reactors than the ECR discharge method. Furthermore, in order to reduce plasma loss to the wall boundaries by separating the plasma core from the wall, some previous studies have introduced permanent magnets into the diffusion chamber or near the substrate.

In our research, we have effectively employed ion transport effect to the substrate along magnetic field lines, to obtain a desirable etching rate even in the case of a compact plasma reactor. In our previous study involving an SF₆ etching reactor, in which the magnetic field was produced solely by means of a solenoid coil, the potential use of permanent magnets was a key issue for further development of such a reactor.

The present study demonstrates a RIE system using an additional permanent magnet, located behind the substrate, which can reduce plasma loss to the chamber sidewall and increase the etching rate. This permanent magnet is especially used for controlling the divergent magnetic field downstream of the solenoid coil. In developing a compact etching reactor, the Si etching rate is one of the key parameters indicating reactor performance. Therefore the Si etching rate was here estimated on the basis of gas pressure and chamber volume, and actually evaluated through experimentation. An etching rate of ~6.0 µm/min was achieved based on a simple reactor design concept.

2. Design concept for the proposed SF₆ etching reactor

(i) Let us assume the high-density plasma discharge
under steady low gas pressure conditions (the HWP discharge method is typically operational at low gas pressure conditions of ~0.1 Pa), with a plasma density of ~10^18 m^-3, and with plasma loss reduced by a magnetic field, which effectively provides high-density plasma and resultant high-density radical production.

(II) The effective pumping speed $S^*$ is calculated by using chamber volume $V$. The chamber volume $V$ using a glass tube of 40 mm diameter and 166 mm length, as shown in Fig. 2(a) is calculated as ~0.2 l. The vacuum conductance in molecular flow $C_m$, in m^3/s, can be simply given by Knudsen’s equation

$$C_m = \frac{1}{6} \sqrt{\frac{2\pi RT D^3}{M L}},$$

where $R$ is the gas constant in J/(K・mol), $M$ is the molecular mass of SF₆ in kg/mol, $D$ is the chamber diameter in m, and $L$ is the chamber length in m. $C_m$ is calculated, at room temperature, as ~1260 l/min in this setup. The 5-mm gap between the inner chamber wall and the wafer stage at $z = 166$ mm [Fig. 2(a)] is considered an orifice with calculated vacuum conductance of ~390 l/min. Thus, the effective pumping speed $S^*$ is calculated as ~300 l/min.

(III) The average residual time $\tau$ is obtained by

$$\tau = \frac{V}{S^*}.$$

The residual time and the refresh rate are estimated as $\tau \sim 0.7 \times 10^{-3}$ min and $\sim 1500$ min^-1, respectively.

(IV) The neutral atom density, at room temperature and 1 Pa pressure, is $\sim 2.4 \times 10^{20}$ m^-3; the total neutral gas density after 1 minute ($n_{G1\text{min}}$), in m^-3, can be written as

$$n_{G1\text{min}} = 2.4 \times 10^{20} \rho \tau^{-1};$$

and $n_{G1\text{min}}$ is estimated as $\sim 7.2 \times 10^{22}$ m^-3, with a pressure $p$ of 0.2 Pa and refresh rate $\tau^{-1}$ in the present experiment.

(V) The total F-atom density after 1 minute ($n_{F1\text{min}}$), in m^-3, can be written as

$$n_{F1\text{min}} = f n_{G1\text{min}},$$

where the F-atom radical production efficiency $f$ is assumed to be 0.058 (as in Ref. 16); and $n_{F1\text{min}}$ is estimated as $\sim 4.2 \times 10^{21}$ m^-3 in the present setup.

(VI) If the ion assist effect in RIE system is assumed to be 10^17, Si etching rate by F-atom ERSi, in Å/min, can be estimated by

$$ERSi = 2.86 \times 10^{-12} n_{F1\text{min}} \sqrt{T_s} e^{-1248/T_s},$$

where $T_s$ is the surface temperature of the substrate in K; and the Si etching rate by F-atom ERSi can be estimated as $\sim 3.2 \mu$m/min at $T_s = 300$ K.

Based on above, we have designed and demonstrated a SF₆ etching reactor with a simple design concept, using the HWP discharge method, as summarized in the design flow chart in Fig. 1.

3. Experimental methods

Figure 2(a) shows the proposed compact plasma etching reactor. The inner and outer diameters of the insulating tube (Pyrex glass tube) were 36 mm and 40 mm, respectively. The glass tube was evacuated, using a turbo-molecular and rotary pump system connected to a grounded stainless steel (SUS) chamber (not shown), to a base pressure of $\sim 5 \times 10^{-4}$ Pa. The external DC magnetic field was produced by a water-cooled solenoid coil, whose top edge was at the axial position of $z = 60$ mm, and by a permanent magnet located behind the substrate.
With a solenoid coil current of 25 A, the plasma is transported and compressed by the magnetic field as shown in Fig. 2(b). The contour map at an r–z plane is inserted into Fig. 1(a) to show magnetic field strengths in Tesla and white lines show magnetic flux distributions in the contour map. Since the magnetic field produced by the solenoid diverges downstream, a cylindrical neodymium permanent magnet (8 mm length, 25 mm outer diameter, and 16 mm inner diameter) was embedded in the wafer stage, to maintain a strong magnetic field even near the substrate. The magnetic field strength on the substrate was approximately 27 mT, and was solely produced by the permanent magnet. A single-turn loop antenna for HWP discharge was wound around the glass tube at z = 0 mm, and connected to an RF power supply (maximum output power of 1 kW, with 13.56 MHz excitation frequency) through a matching box consisting of two variable capacitors. The input RF power for plasma production was pulsed with a duration time of 100 ms and repetition rate of 1 Hz, and with a duty ratio of 10%.

In this experiment, we used pulsed RF power because of the low thermal resistance of the Pyrex glass tube. The SF₆ gas was introduced from the top of the glass tube. The mass flow rate of SF₆ was controlled within a 5.0–sccm range, to maintain a chamber pressure of 0.2 Pa, which was measured with an ionization gauge connected to a side port of the grounded SUS chamber. The grounded SUS punching plate, located at z = −35 mm, provided an effective axial length in this experimental configuration. The water-cooled wafer stage had a mechanical chucking system to hold 12.5 mm substrates, and was connected to a DC power supply applying negative bias voltage of −450 V to prevent RF plasma production by the application of an RF power supply. The top edge of the wafer stage was at z = 166 mm, 10 mm from the bottom edge of the solenoid coil. For RF power monitoring at the plasma source, a directional coupler, inserted between the RF power supply and the matching box, was used to measure the forward and reflected RF powers, $P_f$ and $P_r$. The ratio of reflected RF power to forward RF power, $P_r/P_f$, was typically much less than 0.1. The self-bias voltage was directly measured by a voltage divider (100:1) located between the matching box and the wafer stage. A bare Si substrate was used for test etching in this experiment. To simply measure the etching depth, a micro-head spectral-interference laser displacement meter (SI-F01, Keyence) was used. The measurement range of the x–y plane and the depth resolution of the SI–F01 are 0.05–1.1 mm and 1 nm, respectively. For scanning the x–y plane, a mechanical driving stage was operated at 0.5 mm intervals.

### 4. Results and discussion

Figure 3 shows the surface morphology of the bare Si substrate, after being etched for 5 minutes by plasma irradiation (effective time), with RF power of 500 W (duty ratio of 10%; i.e., operating time = 50 minutes), DC bias...
of \(-450\,\text{V}\), and the SF\(_6\) gas pressure of 0.2 Pa. The irradiation area not covered by the wafer covering plate is 10 mm in diameter. The Si etching rate was estimated at \(\sim 6.0\,\mu\text{m/min}\), as shown in Fig. 3. This result is in good agreement with the SF\(_6\) etching rate estimated by Eq. (5). Hence, an etching rate of \(\sim 6.0\,\mu\text{m/min}\) was successfully achieved in a small-diameter vacuum chamber of 40 mm, and with a low SF\(_6\) gas pressure of 0.2 Pa. This high etching rate could have been obtained as a result of HWP production; however, the identification of the plasma discharge mode is our future work because there is no clear presence of the helicon wave in the present experiment. Typically, a B–dot probe is used to simply measure an excited RF magnetic field along the \(z\)-axis (i.e., an axial profile of the helicon wave), to approve propagation of the helicon wave\(^{21,22}\). In present experiment, however, there was no axial access port for installing a B–dot probe, and thus this issue must remain for future study. This high etching rate was the result of combining the high-density plasma discharge for effective plasma production, and magnetic profile control for effective plasma transport. From our previous results, the radial electron density profile was peaked and the radial center electron density near the substrate was increased 2–3 times in Ar plasmas, where the plasma production was considered to be unchanged by using the permanent magnet\(^{14}\). The permanent magnet installed behind the substrate was crucial to achieving the high etching rate of \(\sim 6.0\,\mu\text{m/min}\) compared with our previous result, because the plasma was compressed and intensified near the substrate. In dramatic contrast, an etching rate of only \(\sim 0.3\,\mu\text{m/min}\) was achieved without such a magnet\(^{20}\); meaning that a roughly twentyfold improvement in etching rate was achieved simply by the addition of the permanent magnet. The effect of the permanent magnet has also been observed in an increased physical ion etching rate for Si, of up to \(\sim 6.5\,\mu\text{m/min}\), at an input RF power of 1 kW, using a similar experimental setup\(^{14}\). Based on these results, we infer that the permanent magnet located behind the substrate results in dramatically increased ion induction into the substrate sheath. The roughness at the bottom of the etching surface of the plasma irradiation area increased in the range of \(P_{\text{RF}}> 150\,\text{W}\), possibly due to the low vacuum conductance around the wafer stage, because of the \(\sim 5\)-mm gap between the glass tube and the wafer stage. The present experimental setup is not sufficient to evacuate a large number of radicals and/or neutral particles, and the low vacuum conductance of the 5-mm-orifice-like gap causes a slowdown in the refresh rate of reactive products, which not only impedes the progress of the etching reaction but also produces a micro-masking effect. A relatively smooth Si surface was obtained at the edge of the irradiation area, because there the ion density and bombardment were lower than in the radial center region. This result suggests the ion energy control by electrostatic shielding located between the plasma source and the wafer stage. Finally, the SF\(_6\) dissociation rate might be increased due to the high plasma density near the substrate and the low-pumping speed around the 5-mm gap orifice, as in Ref. 23; these phenomena will be studied in detail in the near future. In the same timeframe, an experimental setup with high vacuum conductance and an additive gas (e.g., O\(_2\)) control system will be carried.

5. Conclusion

A compact SF\(_6\) plasma etching reactor incorporating a permanent magnet behind the substrate was developed, based on a simple design concept. The proposed reactor has a vacuum chamber diameter of 40 mm, and operates with a gas pressure of 0.2 Pa. We have successfully demonstrated the primary performance of the compact plasma etching reactor using high-density plasma production method, and have achieved an etching rate of \(\sim 6.0\,\mu\text{m/min}\) simply through the installation of a permanent magnet behind the substrate compared with our previous result of \(\sim 0.3\,\mu\text{m/min}\) and on the basis of a simple chamber design concept.

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Fig. 3 Surface morphology of the bare Si substrate etched for 5 minutes (effective time) with RF power of 500 W and DC bias of \(-450\,\text{V}\), and SF\(_6\) gas pressure of 0.2 Pa.
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