A Multi-Scale Study on Silicon-Oxide Etching Processes in C$_4$F$_8$/Ar Plasmas

SUI Jiaxing (眭佳星)$^1$, ZHANG Saiqian (张赛谦)$^1$, LIU Zeng (刘增)$^1$, YAN Jun (阎军)$^2$, DAI Zhongling (戴志玲)$^1$

$^1$School of Physics and Optoelectronic Technology, Dalian University of Technology, Dalian 116024, China
$^2$Department of Engineering Mechanics, Dalian University of Technology, Dalian 116024, China

Abstract A multi-scale numerical method coupled with the reactor, sheath and trench model is constructed to simulate dry etching of SiO$_2$ in inductively coupled C$_4$F$_8$ plasmas. Firstly, ion and neutral particle densities in the reactor are decided using the CFD-ACE+ commercial software. Then, the ion energy and angular distributions (IEDs and IADs) are obtained in the sheath model with the sheath boundary conditions provided with CFD-ACE+. Finally, the trench profile evolution is simulated in the trench model. What we principally focus on is the effects of the discharge parameters on the etching results. It is found that the discharge parameters, including discharge pressure, radio-frequency (rf) power, gas mixture ratios, bias voltage and frequency, have synergistic effects on IEDs and IADs on the etched material surface, thus further affecting the trench profiles evolution.

Keywords: plasma etching, multi-scale model, trench profile, surface process

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(Some figures may appear in colour only in the online journal)

1 Introduction

Plasma etching as an irreplaceable process in integrated circuit (IC) manufacturing craft provides us with many unique advantages [3]. This technical breakthrough realizes anisotropic etching and contributes to the shrinking of the IC feature scales during the past decades [2]. In fluorocarbon plasmas, which are usually used to etch SiO$_2$, ionization, decomposition and adsorption etc. will generate different particles and polymers. These particles are leading actors in the etching process. The CF$_2$ is the main species to impact both ion enhanced chemical etching and ion sputtering, and contributes to the surface deposition during etching [3]. A great deal of attention has been paid to the effects of ions and neutrals on etching SiO$_2$ [3–6]. Barela [6] revealed that C$_2$F$_4$ and CF$_2$ are the main dissociation products in C$_4$F$_8$/Ar plasma discharges. Besides, many works have been done to study other factors that affect the etching rates and morphology [7–10]. It was found that the IEDs, IADs at the substrate affect not only the etching rates but also the trench profile morphology. Researchers found that different IADs are partly attributed to the fluorocarbon polymer film and led to different etching rates. Additionally, in allusion to the effects of IEDs and IADs, the impact of fluorocarbon polymer films on etching needs to be reckon with. Rueger [9] found that a thin steady fluorocarbon film played an important role in determining etching rates, and slight variations of the film thickness contributed greatly to the variations of the SiO$_2$ etching rates.

In the multi-scale model we employed, the reactor model built by CFD-ACE+ can self-consistently calculate ions density used at the sheath boundary, and then the sheath model will give out IEDs and IADs accurately. Similarly, the IEADs can be used in the trench model, thus the multi-scale model can be self-consistently formed with the three models stated above. However, few studies combined three such models to research the etching processes [11–14]. Hokestra [11,12] studied etching profiles with the hybrid plasma equipment model (HPEM) coupled with a Monte-Carlo simulation. However, the influencing factors like charging, and the local surface coverage have not been included. Vyvoda put the emphasis on poly-silicon feature profile evolution in a combined model [13]. Zhang [14] coupled the global, sheath and trench model to simulate dry etching processes in recent works. However, both the densities and fluxes of ion and neutral given by the global model are still not accurate enough.

In this paper, the plasma density and potential distributions in the reactor are first given with CFD-
ACE+, which is more accurate than Ref. [14]. Then, the parameters are used as the sheath boundary condition in the next calculations. The reactor model and sheath model are coupled applied to obtain ion densities and IEADs impinging on the substrate. The transport characteristics of ions and neutrals in both sheath and trench are considered when simulating the trench profile evolution. Thus, the distributions of reactant particles at the featured surface are obtained by means of the trench model. Finally, we simulated the profile evolution under the condition of different discharge parameters by combining a surface reaction model [15] with a cell removal method [16]. A brief model description is given in section 2. Results are discussed in section 3 and ultimately the concluding remarks are shown in section 4.

2 Model descriptions

2.1 ICP module with CFD-ACE+

In this article, we study the etching of SiO2 masked by the insulating photoresist in C$_4$F$_8$/Ar plasmas. The reactor model, the 1D sheath model and 2D trench model are coupled to study the groove profile evolution. A multi-turn spiral coil is around the dielectric plasma chamber, and the frequency is 13.56 MHz. Otherwise, a separate 13.56 MHz rf source is connected to the substrate to independently control the incident ions [17].

![ICP reactor model](image)

**Fig.1** Schematic diagram of the ICP reactor model

The ICP model built with CFD-ACE+ is shown in Fig. 1. This model consists of mass, momentum, and enthalpy balance equations with appropriate boundary conditions set for ions, neutrals and electrons. Due to their different characteristics, ion, neutral species and electrons are treated in different ways. The heavy particles (ions and neutrals) fluxes densities are solved from the transport equations. Precisely, the mobility of ions accords with the Langevin formula:

$$
\mu_{ij} = \frac{13.853 \times 10^{-4}}{v_{ij}/m_i}, \quad (1)
$$

where $\alpha_{ij}$ is the polarizability in Å$^3$ and $m_i$ is the reduced mass of the ions and neutrals. Rather than solving the mass balance equation, electron number density is obtained from the quasi-neutrality criterion and ambipolar electric field. In addition, the flux densities, including ions, neutrals and electrons, are calculated via the drift diffusion approximation. The temperature of neutrals and ions is assumed to be the same and described by the enthalpy balance equation. The electron temperature is gained from the electron energy balance. Thus, the densities of neutral, charged species and electrons can be given in this model.

One set of the gas phase reactions coefficients for C$_4$F$_8$ plasma is provided in Table 1. Ionizations, dissociations, attachments as well as recombinations of charged and neutral species are inclusive in this data sheet. The general formula of a coefficient is $k_v = AT_e^B \exp(-\frac{C}{T_e})$. (2)

Neglecting the etching reactions of the substrate surface due to its futilities on the chamber gas, and we only consider ions recombination on chamber sidewalls, i.e. Ar$^+$, C$^+$, F$^+$, C$_2$F$_{y}^+$ that absorb electrons and become neutral particles.

2.2 Sheath model

With CFD-ACE+, the authors can self-consistently calculate ions density, potential distribution, which are used as the sheath boundary conditions. To independently get command of plasma generation and ion bombardment in low pressure, high density plasmas, a separate rf-bias is usually applied to the electrode. A sheath will form at the adjacent area to the substrate placed on the bias electrode. Ions transport characteristics in the sheath are important for the ion fluxes and velocities arriving at the substrate surface, and eventually affect the etching and deposition processes.

In this part, a hybrid sheath model (fluid and MC) [14,29] is presented. The spatial and temporal profiles for variables like electric potential, sheath thickness etc. in the sheath are firstly calculated by the fluid model. Considering the ion-neutral collisional effects, Monte-Carlo will work out the IEDs and IADs with the results computed in a fluid model.

For either positive or negative ions, we have every reason to neglect the ions thermal motion effects in that the ion temperature is much smaller than the directional velocity in the sheath district. Thus, ion velocity $u_i(x,t)$, ion density $n_i(x,t)$ and the electric potential $V_i(x,t)$ can be described by the cold fluid equations,

$$
\frac{\partial u_i}{\partial t} + u_i \frac{\partial n_i}{\partial x} = -\frac{q}{m_i} \frac{\partial V}{\partial x} - vn_i, \quad (3)
$$

$$
\frac{\partial n_i}{\partial t} + \frac{\partial (n_i u_i)}{\partial x} = 0, \quad (4)
$$

and the Poisson equation that governs the electric potential,

$$
\frac{\partial^2 V_i}{\partial x^2} = -\frac{e}{\varepsilon_0} (n_+ - n_- - n_e), \quad (5)
$$

where $m_i$ is the ion mass, $q$ is the ion charges, $v$ is the collision frequency between ion and neutrals, $\varepsilon_0$ is the permittivity of free space, and $n_e(x,t)$ is the electron density.
Table 1. The set of gas phase reaction coefficients for C₄F₈/Ar plasma

<table>
<thead>
<tr>
<th>Reaction</th>
<th>E_{th} (eV)</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Reference or comment</th>
</tr>
</thead>
</table>

Electron impact reactions

1. Ar+e→Ar⁺+2e
2. Ar+e→Ar⁺+e
3. C₄F₈⁺→C₄F₇⁺+CF₂+2e
4. C₄F₈⁺→C₄F₇⁺+C₂F₄⁺+2e
5. C₄F₈⁺→2C₂F₄⁺+e
6. C₂F₄⁺→C₂F₃⁺+2e
7. C₂F₂⁺→2CF⁺
8. C₂F₂⁺→CF₂⁺+CF⁺
9. CF₄⁺→CF⁺+F+2e
10. CF₄⁺→CF⁺+2e
11. CF₄⁺→CF⁺+F⁻
12. CF₃⁺→CF²⁺+2e
13. CF₃⁺→CF⁺+2e
14. CF₂⁺→CF⁺+F⁻
15. CF₂⁺→CF⁺+F⁻
16. CF₂⁺→CF⁺+F⁻
17. CF₂⁺→CF⁺+F⁻
18. CF⁺+e→CF⁻+F+e
19. CF⁺+e→CF⁻+F+e
20. CF⁺+e→CF⁻+F+e
21. F₂⁺+e→2F⁺
22. F⁺+e→F+e⁻+F⁻
23. F⁺+e→F+2e
24. C⁺+e→C⁺+2e
25. F⁺+e→F⁺+2e

Ion recombination reactions

26. C⁺+F⁻→C⁺+F
27. CF⁺⁺→CF⁺⁺+CF
28. C₃F⁺⁺→C₂F₄⁺+CF₂
29. C₂F⁺⁺→CF⁺⁺+CF₂+2F₂
30. CF⁺⁺→CF⁺⁺+CF⁻+F⁻
31. CF⁺⁺→CF⁺⁺+CF⁻+F⁻
32. CF⁺⁺→CF⁺⁺+CF⁻+F⁻

Neutral recombination reactions

33. C₂F⁺⁺→C₂F₁⁺⁺
34. CF⁺⁺→CF₂⁺⁺
35. CF⁺⁺→CF⁺⁺+F⁻
36. CF⁺⁺→CF⁺⁺+F⁻

Associative collisional detachment

37. CF⁺⁺→CF⁺⁺+e

aThe cross sections from the pertinent reference are integrated over Maxwellian electron energy distribution.
bLower than the corresponding ionization threshold.
cThe coefficient is calculated by the formula of Plumb and Rayan. [27]

For electrons, we assume that they have suffered sufficient collisions, the velocity satisfies the Maxwellian velocity distributions and the electron density conforms to the Boltzmann relation:

\[ n_e(x, t) = n_0 \exp\left(\frac{eV(x, t)}{k_B T_e}\right), \]  

where \( n_0 \) is the density of bulk plasma, \( k_B \) is the Boltzmann constant and \( T_e \) is the electron temperature.

In addition, the appropriate boundary conditions are needed to solve the aforementioned equations. Ions get their kinetic energy while going through a pre-sheath, and enter the sheath with Bohm velocity. The modified Bohm critical \(^1\) is

\[ u_i(d_s, t) \geq \left[ \frac{eT_e(1 + \alpha_e)}{M(1 + \alpha_i)} \right]^{1/2}, \]  

where \( d_s \) is the position of the plasma sheath boundary, \( \alpha_e \equiv n_+ / n_e \) is the ratio of negative ions to electrons, \( \gamma = T_e / T_i \) is the temperature ratio of electrons to ions, and the boundary position \( d_s \) is decided by the density of ions, electron and negative particles at the sheath.
edge where the quasi-neutral state will serve the purpose
\[
n_{+}(d_{x}, t) = n_{e}(d_{x}, t) + n_{-}(d_{x}, t). \tag{8}
\]
Then, we assume that the potential at the sheath edge
\[
V(d_{x}, t) = 0,
\]
\[
V(0, t) = V_{e}(t), \tag{9}
\]
where \(V(d_{x}, t)\) is the electric potential at the sheath edge and \(V_{e}(t)\) is the bias voltage applied on the electrode.

In \(C_{2}F_{5}/Ar\) plasma, many particles are needed to be taken into consideration, such as \(F^{+}, F, C^{+}, C, CF_{2},\) \(CF, CF_{2}^{+}, CF_{2}, Ar^{+},\) \(Ar\) etc. Because the density of neutrals is much larger than that of ions, we only consider collisions between ions and neutrals, and the ion-impact collision can be ignored. Charge exchange (cx) and elastic (el) collisions will be in view. For \(Ar^{+}\)-\(Ar\) collisions, the cx and el collisional cross sections are respectively
\[
\sigma_{cx} = 47.0505 \times (1.0 - 0.0577 \ln \varepsilon)^{2}, \tag{11}
\]
\[
\sigma_{el} = 40.04 \times (1.0 - 0.0563 \ln \varepsilon)^{2}, \tag{12}
\]
and Langevin collision cross section \([20]\) is
\[
\sigma_{L} = \left( \frac{\pi \alpha_{p} \varepsilon_{L}^{2}}{\varepsilon_{0} m} \right)^{1/2} \frac{1}{v_{0}}, \tag{13}
\]
where the cross section is in \(10^{-20} \text{ m}^{2}\) and ion impact energy \(\varepsilon\) is in eV. \(\alpha_{p}\) is the polarizability value of species \([30-33]\). The collision cross sections between all these ions and neutrals are based on Eqs. (11)-(13). When molecular ions or neutrals are involved in the two body collisions, the cross section is proportional to the total atom number involved in a collision process.

Different cross sections can help us to determine the type of collision on the basis of the mean free path and tell which kind of collision process will occur. The ion scattering angle and the velocity after the collisions will be recorded until ions arrive at the substrate surface. Finally, by fulfilling the statistical analysis of all ion’s incident energies and angles, we can get the IEDs and IADs on the substrate.

### 2.3 Trench model

Besides of intrinsic physicochemical properties of etchant and etched materials, the re-deposition of the byproduct can also affect the profile to a certain degree. In order to use a cellular removal method and surface coverage method to simulate the trench evolution progress, the trench domain is meshed into grid cells. Here, we neglect the local electric field in the trench because of its small scale and low charge density. The trench model employed the fluxes of ions and radicals as well as the energy and incident angle of ions to give out the etching and deposition yield expressions. The surface model includes \(F, C_{2}F_{5}\) or general fluorocarbon species and polymer site balances. The adsorption of fluorocarbon radicals on the surface, carbon sputtering, recombination of adsorbed fluorocarbon radicals as well as ion deposition, and ion-enhanced deposition have also been considered.

The \(F, C_{2}F_{5}\) and polymer site balances can be written as follows,
\[
\frac{d(SiO_{2})}{dt} = s_{F}(1 - \theta_{TOT})/j_{F} - 2 \beta_{F} \theta_{FION} = 0, \tag{14}
\]
\[
\frac{d(C_{2}F_{y})}{dt} = \sum_{y} \delta_{yCF,CF}(1 - \theta_{TOT}) - y_{C} \theta_{C,F,ION} - k_{REC} \theta_{C,F,F} = 0, \tag{15}
\]
\[
\frac{d(P)}{dt} = \sum_{i} x_{i} y_{i} \theta_{FION} + \beta_{C,F,ION} + \beta_{C,F,F} \theta_{F/F} + \theta_{F/F} = 0. \tag{16}
\]

The \(SiO_{2}\) etching yield expression \([11]\) is:
\[
y_{SiO_{2}} = \sum_{i} x_{i} y_{SP,i} (1 - \theta_{TOT}) + \beta_{SP} \theta_{SP} + \beta_{CF,CF}, \tag{17}
\]
\[
+ K(T) R_{F} (1 - \theta_{CF,F} - \theta_{FP}), \text{ if } \theta_{F} < 1, y_{SP,i} > 0; \tag{18}
\]
with \(x_{i}\) the fraction of the total current carried by ion, \(y_{SP,i}\) the rate coefficient of physical sputtering caused by ion, \(\beta\) the ion-enhanced etching coefficient, \(K(T)\) the dimensionless coefficient and \(\theta\) the surface coverage, where \(\theta_{TOT} = \theta_{F} + \theta_{CF} + \theta_{FP}\).

If \(\theta_{F} > 1\), the surface is covered totally by polymer. The \(SiO_{2}\) deposition yield expression is \([11]\):
\[
y_{SiO_{2,dep}} = \sum_{i} x_{i} y_{A,i} + \beta_{CF,CF} + \beta_{CF,CF} - \beta_{F/P} \theta_{F/F} = \theta_{P} > 1. \tag{19}
\]

In the cellular removal method, the grid cells are set according to the materials. In this study, the cell size is \(1 \text{ nm}\), it also means that when one ion arrives at some cell, the oxide silicon atom number is subtracted correspondingly. In accordance with this law, the etch yield is calculated in the surface reaction model, and until that all the atoms in one cell are removed, the oxide silicon cell would convert to an empty cell. After the etch step, the boundary of space and material will be updated, and the surface advancement with the passage of time would be achieved as the etching process.

It is worth noting that, ion reflection has significant impressions on the trench profile. The reflected ion fluxes can be concentrated on the two edges of the trench bottom, which will result in the micro-trenching. Although Molecular Dynamics can be used to precisely predict the ion behavior when and after its injection on the wall, it may expend huge computational expense. At the same time, the time scale is too small to achieve the whole process of etching simulation. In this paper, we just consider a simplified situation, where the ions reflect specularly when they incident onto the surface at grazing angles, the collision is elastic and no energy loss happens in the progress. Simultaneously, low energetic ions can be reflected randomly at the surface \([34]\) or attached there.
Here, the ion reflection will not happen in the case that the off-normal incident angle is less than 60° \(^{[14]}\), however, it will make such a phenomenon possible when their kinetic energy is over 30 eV.

3 Results and discussions

Fig. 2 shows the one-dimensional spatial distribution of ion density corresponding to different discharge conditions. Clearly and intuitively, we just display the main ions’ spatial distribution along the X-slice. All these ions in the center of the chamber are much more than that at the edges. From Fig. 2(a) and (b), we learn that as the discharge pressure increases, all of the ion fluxes become larger, especially for etching ions (\(\text{CF}_2^+, \text{F}^+\) etc.). Therefore, the increasing discharge pressure results in a higher ionization rate. Moreover, the ion fluxes will increase with the source power increased, which is revealed by Fig. 2(b) and (c).

Fig. 3 shows the IADs impinging on the substrate under different discharge parameters. From Fig. 3(a) and (b), analysis shows that more ions would incident with more off-normal dispersive angles when the pressure increases, which is on account of more frequent collision progresses under larger pressure. Comparing Fig. 3(b) with (c), it reveals that source power has important affections on the IADs. With the increasing of source power, the IADs become more concentrated, especially for etching ions (\(\text{CF}_2^+, \text{etc.}\)). Fig. 3(b), (d) and (e) show that the influence of rf-bias frequency on IADs is not very apparent. Fig. 3(b) and (f) show the ion angular dispersive characters under the action of different bias voltages. The bigger the bias voltage, the better the ions’ directionality. This is because the potential drop only has an impact on the vertical acceleration to substrate irrespective of collisions among ions.

![Fig. 2 The one-dimensional spatial distribution of ions.](image-url)  
(a) Power=900 W, Pressure=5 mTorr, (b) Power=900 W, Pressure=10 mTorr, and (c) Power=600 W, Pressure=10 mTorr

![Fig. 3 Ion angular distributions at the bias electrode under different discharge parameters.](image-url)  
(a) Power = 900 W, Pressure=5 mTorr, \(V_{\text{bias}}=100 \text{ V}, f_{\text{bias}}=13.56 \text{ MHz}\), (b) Power=900 W, Pressure=10 mTorr, \(V_{\text{bias}}=100 \text{ V}, f_{\text{bias}}=13.56 \text{ MHz}\), (c) Power=600 W, Pressure=10 mTorr, \(V_{\text{bias}}=100 \text{ V}, f_{\text{bias}}=13.56 \text{ MHz}\), (d) Power = 900 W, Pressure=10 mTorr, \(V_{\text{bias}}=100 \text{ V}, f_{\text{bias}}=27 \text{ MHz}\), (e) Power = 900 W, Pressure=10 mTorr, \(V_{\text{bias}}=50 \text{ V}, f_{\text{bias}}=13.56 \text{ MHz}\)
Fig. 4 shows the IEDs corresponding to different exoteric parameters. It reveals that every energetic particle follows the bimodal distribution. Fig. 4(a) and (b) indicate that when the pressure increases, the height of the high energy peak decreases more rapidly, and there are more ions tending to have low energy. This is because when the pressure increases, the energetic ions will transmit their energies to neutral particles after collision. The IEDs sketched in (b), (c) show that the increasing source power will lead to higher energy peaks of etching ions, and inversely high-energy peaks of depositional ions tend to be lower. From Fig. 4(b), (d) and (e), we can see that as the rf-bias frequency increases, we get more concentrated IEDs, and the width between two peaks decreases. Ions’ large inertia hinders them from responding to the high-speed electric shocks to get enough energy from the electric field when they pass through the sheath. Comparing Fig. 4(b) and (f), it is not too hard to see that ions tend to have larger kinetic energies, and the distribution extends to the high energy region as the bias voltage increases. These results illustrate that a larger bias voltage makes the potential drop across the sheath larger, so ions can get more energy while transporting across the sheath.

Fig. 5 displays the trench profile evolution under different discharge pressures. The lines in the trench represent the outline of trench profile at a certain time. We can see that each rate differs from one another corresponding to varied discharge pressures due to the different IEADs. As the pressure increases, IADs become more dispersive, as shown in Fig. 3, which will lead to sidewall etching. With the pressure increases, more low energy ions would be generated in the more frequent collisions between ions and neutrals, which is shown in Fig. 4, and then their different reflection behavior from that of high energy ions will influence the etched profile. Besides, the micro-trenching is generated at the corners of the trench bottom, which is caused by the ion reflection taking place at the trench sidewall. As the steps proceed, the trench becomes sharper or tapered.

Fig. 6 shows the trench profile evolution driven by different source powers. We can see when the rf power increases, the etching depth and etch rate rises. This phenomenon results from larger ion fluxes and higher ion energies, which has been shown in Fig. 2 and Fig. 3. Energetic ions can result in the larger etch yield, and thus the etch rate will be higher. Besides, the fluxes will increase, which relate to the trench profile evolution. Because of the aspect ratio dependent etching, the etch rate will gradually decrease with increasing etching depth, and the trench bottom will become sharper.
The trench profile evolutions under different gas mixture ratios are shown in Fig. 7. This figure shows that the etch rate is quite different in the case of different gas mixture ratio. With the decrease of CF$_2^+$, C$_2$F$_3^+$, F$^+$, ion sputtering and ion enhanced etching reactions occur slowly, while the polymer deposition dominates.

Fig. 8 unfolds the effect of rf bias frequency on the trench profile evolution. We can see that the etch rate does not change monotonously with the increasing frequency. To some extent, increasing the rf frequency will increase the etch rate, as shown in Fig. 8(a) and (b) respectively. However, further increasing the frequency to 27 MHz, the etch rate decreases as shown in Fig. 8(c). The corresponding IEDs are shown in Fig. 3(d) and (b) and (e), respectively. With the increase of the bias frequency, the width between the two energy peaks decreases, this is because less ions can respond to the rapid oscillating electric field. The high energy peak moves towards the smaller energy region, which can results in a smaller etch rate, while the low energy peak moves to a higher energy region, which can make the etch rate go up. The final etch rate should be reflected by the compromise of the two competing effects. When the frequency increases from 5 MHz to 13.56 MHz, more ions have energies larger than the threshold energy for sputtering or ion enhanced etching, and the smaller energy ions tend to have large energies as the low energy peak moves to a higher energy region, the etch rate increases although the high energy peak moves to a smaller energy region. When the frequency further increases to 27 MHz, the decrease of ion energies near the high energy peak dominates, this is what results in a smaller etch rate.

Fig. 9 displays the trench profile evolution under different bias voltages. When the bias voltage source increases, the depth and etch rate increases, and the fluxes remain unchanged neglecting the influence of bias source on the plasma generation. With the larger bias voltage, the ions get more kinetic energy across the larger potential drop through the sheath, which is shown in Fig. 4. Ions with averaged higher impact energies can give rise to the larger etch yield, so the trench will be etched more quickly. We can see that as the hours pass by, the aspect ratio increases with the increase of the trench depth, and the trench becomes sharper.
than two degrees, which is shown in Fig. 3. As well, the shield effect of the photoresist makes the lateral etch not very obvious (Figs. 5-9).

As the etch is processed, the increasing etching depth makes more ions reflect to the center of the etching trench, this is why the etching groove scale becomes smaller and smaller. On the other hand, the etching process is actually the compromise of etch and deposition. With the etching depth increased, the number of ions that can arrive at the bottom of the etching trench are on the decrease, which will slow down the etching rates. While deposition is mainly connected to the neutrals, the deposition rates are less affected than etching rates, so the deposition dominates before the etch is ended.

4 Conclusions

A multi-scale model coupling the reactor, sheath and trench model has been given to study the trench profile evolution under the condition of different discharge parameters. Results show that these parameters have synergistic influences upon the trench topography. Higher pressure can lead to a more dispersive IAD, and result in more serious lateral etching. Besides, the ion reflection behavior at the sidewalls and the ratio of neutral to ion flux will be changed under different pressures; these effects can influence the trench profile evolution. Higher rf source power can increase fluxes, and thus reduce the higher etch rate. For different gas mixture ratios, ions and neutrals like CF$_x^+$, C$_2$F$_x^+$ are changed significantly, which have a distinct impact on etching and deposition. When the rf frequency increases too much, many ions cannot respond to the high-speed electric shocks, so the energy distribution becomes concentrated and the energetic ions decrease. Therefore, a suitable rf bias frequency is important to improve the etch rate. With the bias voltage increases, ions can get more kinetic energy through the sheath where there is a larger potential drop. Based on the time-varying aspect ratio, the width has a crucial impact on the etch rate and trench profile evolution. Moreover, the photoresist profile slope cannot be ignored for trench topography.

Due to the fact that the pulsed-frequency source can reduce the charging effects on dielectric substrates surface and improve the etching quality, the influence of pulse-bias on etching will be studied in future work.

References