Profile simulation of gas chopping based etching processes

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Abstract
A simulation program based on a phenomenological surface etching reaction model and on a reactant transport model including shadowing and diffuse particle reflection at the sidewalls was developed to investigate the dependence of the etching rate and profile quality of Gas Chopping Deep Reactive Ion Etching Processes (GChDRIE) on process parameters and sample temperature. The simulations are in good agreement with the experimental results. The dependence of the heating characteristics on the geometry (area, thickness) of teeny MEMS devices or membrane-like silicon samples during microstructuring by means of plasma etching was investigated using FE simulations. It was found that membrane-like samples are considerably heated unless the membrane area is sufficiently small (< ≈ 5 mm²) and/or is sufficiently thick (≈ 500 µm).

1. Introduction
Several theoretical models exist for the etching reaction between fluorine and silicon. [1-3] The results of these models are local instantaneous etching rates or etching yields, whereas the prediction of the etching profile is beyond the scope of these models. The comparison of these models with experiments and their application to profile prediction requires a detailed knowledge of plasma species concentrations and velocity and energy distributions, which are often not or not exactly known to the process designer, or even to the researcher. [3] Models which predict the profile for gas chopping deep RIE (GChDRIE) are few, and, because of the intended application of the authors, the sidewall quality (roughness) was not modeled. [4-6] In this work a simulation model is presented to predict the etching profile for (GChDRIE) [7-10] processes, including the modeling of the sidewall roughness, and the sample temperature dependence. The program includes a surface reaction model based on phenomenological etching rate model, and a reactant transport model, which includes shadowing of particles and diffuse reflection of particles at the sidewall. The model is intentionally simplified in order to, first, reduce the number of free parameters, and second, to allow the determination of these required parameters from etching rate and profile shape data.

The microstructuring of silicon membranes or membrane-like samples becomes increasingly important for the fabrication of micro electromechanical systems (MEMS) and sensors, transducers, cantilevers [11] or next generation lithography masks. [12] Since the use of modern plasma etching techniques incorporates the use of high density plasma sources (inductively coupled plasma, ICP), a considerable amount of power is deposited in the sample, which causes the sample temperature to rise. The temperature distribution in the sample depends on the input power, the exothermic etching reaction, the thermal contact to the cooled cathode, and on the sample geometry. Since there is a relatively large gap between the backside of face-up placed membranes and the cathode, because of the wafer ring surrounding the membrane, the thermal contact between membrane-like samples and the cathode is less efficient than that of wafer samples. Therefore, the heating problem is a more critical issue especially for membrane-like samples. In order to get an estimate of the membrane temperature during etching, the temperature distribution on membrane-like samples was calculated using FE simulations.

2. Experimental
The etching and deposition experiments have been carried out in a commercially available plasma etcher (System 100 from Oxford Plasma Technology) equipped with an inductively coupled plasma source (ICP). The samples are placed on a cryogenic table specially designed for the handling of MEMS. [13] Optical lithography with photoresist mask was used to structure the wafers.

Etching and deposition rate data has been collected for process parameters listed in table 1.

<table>
<thead>
<tr>
<th>SF₆ [sccm]</th>
<th>chemical etching</th>
<th>chemical + ion-enhanced etching</th>
<th>deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar [sccm]</td>
<td>20 .. 150</td>
<td>20 .. 150</td>
<td>-</td>
</tr>
<tr>
<td>CHF₃ [sccm]</td>
<td>-</td>
<td>-</td>
<td>40</td>
</tr>
<tr>
<td>CH₄ [sccm]</td>
<td>-</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>p [mTorr]</td>
<td>20</td>
<td>5 .. 50</td>
<td>55</td>
</tr>
<tr>
<td>ICP [W]</td>
<td>600</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>DC [V]</td>
<td>0 (rf off)</td>
<td>50 .. 170</td>
<td>0 .. 70</td>
</tr>
<tr>
<td>T [°C]</td>
<td>-100 .. +100</td>
<td>-100 .. +100</td>
<td>-50 .. +100</td>
</tr>
</tbody>
</table>
3. Modelling
A complete simulation for plasma etching processes consists of 3 individual model descriptions for the 3 major effects:

a) Plasma reactor model: This model should, based on the input parameters like etch chamber geometry, applied power, gas flows and gas mixtures, and operating pressure, predict the output parameters like concentrations of reactive species (radicals, ions), and their angular and energy distribution functions. These output parameters are the input parameters for the

b) Transport model, which describes the transport of the "plasma" species from the sheath to the surface of the processed sample. The output parameters of the transport model are local flow rates and local angular distributions of individual plasma species. The flow rates and distributions may be different for each individual point of the surface. The model should consider the influence of the geometry of the sample on the transport properties, e.g. it should consider the shadowing of plasma species at the mask, and calculate the resulting reduction of the flow rates. The local flow rates and distributions are the input parameters for the

c) Surface reaction model. The surface model calculates, based on individual local flow rates of plasma species such as ion or reactive radicals, the local etching (or deposition) rates, for each point of the surface. The geometry of the surface is locally modified according to the local etching or deposition rates. The final geometry of the surface at the end of the simulated process time represents the obtained etching profile.

According to this outline, it seems that the individual models are all decoupled from each other, that is, the foregoing model simply supplies the input parameters of the following model, without feedback from the following models. However, in reality this assumption is not true. For instance, the concentration of plasma species may be diminished by a high open area density of the sample (micro loading). Here, the surface model feeds back to the plasma reactor model. Also, the sample geometry and surface modifications (such like passivation or fluorination), as calculated by the surface model, influence the local sticking probabilities, which in turn affects the transport model. For simplicity and faster program execution, the models have been partially decoupled. The development of a plasma reactor model is beyond the scope of this work. Rather than calculating the concentration of plasma species from process parameters like gas flows or excitation powers, they are obtained by comparing the model calculations with the experimental results, and calibrate the concentrations and distributions accordingly.

3.1 Surface Model
The gas chopping etching process consists of 3 cycles [9, 10]:
1.) Deposition of a polymer film, which serves as a passivation layer. All area covered by the polymer is not etched.
2.) Removal of the polymer film, preferably at the bottom of the trench, mainly due to ion bombardment.
3.) Etching of the clean silicon surface, due to pure chemical etching and ion-enhanced etching.

Therefore, the model must describe 3 major effects: polymer deposition, polymer removal (due to sputtering), and reactive ion etching of silicon.

a) Polymer deposition
The assumption was made that the polymer deposition rate \( DR \) is equal to the local monomer flow \( \Phi_{mono} \) times the temperature dependent deposition yield factor \( \eta_{dep} \):

\[
DR = \eta_{dep} \Phi_{mono} \quad (1)
\]

Due to lack of more detailed experimental data, no distinction was made between different monomer species, such like CF\(_1\), CF\(_2\), etc. Instead, all the flows of different monomer species are lumped together into one integral monomer flow, which represents the mean effective monomer flow. Likewise, the deposition yield also is an integral effective deposition yield.

b) Polymer removal.
The assumption is made that the polymer is removed mainly due to ion bombardment. This assumption is supported by the experimental finding that the polymer is removed preferably at the bottom of the trench (which is subject to ion bombardment), while the sidewalls (which receive a much lower ion flow, but also a high flow of neutrals) remain passivated by the polymer film. Therefore, the removal or the etching rate of the polymer film \( ER_{poly} \) is equal to the local ion flow times the polymer sputter yield factor \( \eta_{sp} \):

\[
ER_{poly} = \eta_{sp} \Phi_{ion} \quad (2)
\]

c) Etching of blank silicon
Silicon is etched due to thermal (or spontaneous) etching by radicals, i.e. atomic fluorine, and due to ion-enhanced etching, where ion bombardment of the surface aids in the removal of silicon. It is understood that energetic ion bombardment of a fluorinated silicon surface provides the required activation energy to form volatile products (SiF\(_2\), SiF\(_3\)). Physical sputtering of the silicon surface is neglected here, because for the usual process conditions the effect of physical sputtering can be neglected. There are different models describing this effect, reported in the literature. The simplest model is to equal the total silicon etching rate \( ER_{tot} \) with the sum of the local fluorine flow \( \Phi_{f} \),
times the temperature dependent thermal etching yield factor \( \eta_{\text{chem}} \), and the local ion energy flow \( \Phi_{\text{ion}} \) times the temperature dependent ion-enhancement factor \( \eta_{\text{ion}} \). The local ion energy flow \( \Phi_{\text{ion}} \) is given by

\[
\Phi_{\text{ion}} = \frac{ER_{\text{ion}} \cdot \Phi_{\text{ion}}}{\eta_{\text{ion}}} \quad (4)
\]

This model is formally identical to a simultaneously etching due to thermal etching and physical sputtering. In this simplified model, it is implicitly assumed that a given ion-enhancement yield factor is only valid for a certain fluorine surface coverage, and that the fluorine surface coverage nearly does not vary. In this case, the ion-enhancement yield factor can be considered a constant.

The thermal etching yield factor \( \eta_{\text{chem}} \) is often being of Arrhenius form. [14] This temperature dependence was found from data of atomic fluorine beam experiments. In the case of plasma etching, however, not only fluorine atoms impinge on the surface, but also contaminations from the masking material (photoresist), the chamber walls (oxygen from the quartz cylinder), and from the process gases themselves (sulfur or carbon compounds, from the SF\(_6\) or CHF\(_3\) gas feeds, respectively), which adsorb and interact on the surface. We believe, that it's due to these interactions, that we do not observe an Arrhenius-like temperature dependence of the thermal etching yield. Instead of making further assumptions or investigations on the nature of such contaminates and their interactions, we simply extract the thermal etching yield factor from chemical etching rate data. A more detailed etching rate model explicitly considers the dependence of the ion-enhanced etching yield on the fluorine surface coverage \( \Theta \). This is in accordance with the "reactive spot model". [15] Gray et al. have published a phenomenological model of fluorine-based plasma etching based on this approach. [1] The model presented in this work is similar. The ion-enhanced etching rate \( ER_{\text{ion}} \) is the product of the temperature dependent ion-enhancement reaction probability \( \eta_{\text{ion}} \), the fluorine surface coverage \( \Theta \), and the ion energy flow \( \Phi_{\text{ion}} \).

\[
ER_{\text{ion}} = \eta_{\text{ion}} \cdot \Theta \cdot \Phi_{\text{ion}} \quad (3)
\]

\[
ER_{\text{ion}} = ER_{\text{chem}} + ER_{\text{ion-end}} = \eta_{\text{chem}} \Phi_{\text{F}} + \eta_{\text{ion-end}} \Phi_{\text{ion}} \quad (3)
\]

The degree of the fluorine surface coverage is defined as the ratio of adsorbed fluorine atoms per unit area, to the maximum possible surface coverage \( \Theta_{\text{max}} \).

\[
\Theta_{\text{max}} = \frac{n m_{\text{Si}}}{m_{\text{F}}} \quad (5)
\]

By balancing the fluorine flow to the surface and the consumation of fluorine by the etching of silicon, one can write the effective adsorption flow \( J_{\text{adv}} \) as

\[
J_{\text{adv}} = s_0 (1 - \Theta) \Phi_{\text{F}} - B \cdot ER_{\text{ion}} \quad (6)
\]

The first term is the fluorine flow adsorbed at the surface. The effective sticking probability is the sticking probability of a clean surface, \( s_0 \), times the number of clean silicon surface sites, \( \Theta - \Theta_{\text{max}} \) (Langmuir adsorption). The last term denotes the loss in adsorbed fluorine due to ion-enhanced etching of silicon. Thermal desorption of fluorine is neglected in this model.

In order to calculate the loss term in the site balance, it is assumed that \( b \) surface fluorine atoms are consumed by etching one silicon atom by ion-enhanced etching. If the reaction product for ion-enhanced etching is SiF\(_2\), then \( b=2 \), whereas \( b=4 \) for SiF\(_4\). As a the etching products are a mixture of SF\(_2\) and SF\(_4\) [1], it was assumed \( b=2.5 \). The flow rates (atoms per area and time) can also be expressed in units of the surface coverage per time, by dividing equation (6) by the maximum possible surface coverage. In this way, the site balance writes more conveniently.

\[
J_{\text{adv}} = s_0 (1 - \Theta) \Phi_{\text{F}} - \frac{b}{n \kappa} \cdot ER_{\text{ion}} \quad (7)
\]

where \( J_{\text{adv}} = J_{\text{adv}} / \Theta_{\text{max}} \) and \( \Phi_{\text{F}} = \Phi_{\text{F}} / \Theta_{\text{max}} \). In steady state, the net surface adsorption flow is zero, hence the surface coverage becomes:

\[
\Theta = \frac{s_0 \delta \Phi_{\text{F}}}{s_0 \Phi_{\text{F}} + \frac{a}{n \kappa} \eta_{\text{ion-end}} \Phi_{\text{ion}} / \Phi_{\text{ion}}} \quad (8)
\]

Here, \( \Phi_{\text{ion}} \) is the ion energy flow in units of surface coverage per time.
The profile calculations are done by a self developed profile simulation program based on a string algorithm. The profile simulation is 2 dimensional, therefore, the simulated profiles represent long trenches rather than circular holes. (More details will be published in the author's Ph. D. thesis.[17])

3.2 Transport Model
The required input parameters of the surface model are the local flow rates, which are delivered by the transport model. Since the operating pressure is below 50 mTorr, and the width of the features typically is in the range of less than 10 µm, molecular flow can be assumed. For further simplifications, reflections of ions at the sidewalls or any distortions of ion trajectories due to charging are neglected. In the simplest case, only direct line-of-sight shadowing is considered. That is, only particles with a direct line-of-sight to a certain point at the surface can reach that point. By comparing the simulation calculations with the experimental results, it was found that the direct line-of-sight shadowing underestimates the flow of neutrals to the surface. It was assumed, that the diffuse reflection of particles from the surface play an important role in the transport of the neutrals. The indirect flow onto each point of the surface, originating from the diffuse reflection of particles from all other points of the surface is calculated by Monte Carlo simulations separately from the profile simulation with a self-developed two dimensional Monte Carlo flow simulation program. [17] An analytical function \( \Phi = f(sw, bt, AR) \) was fitted to the simulation results, where \( \Phi \) is the integral flow rate at the bottom, divided by the bottom area (bottom mean flow rate). This formula was used to calculate the flow of diffusely reflected neutrals. The profile of the trench was approximated by a perfectly vertical sidewall. (This assumption is not a strong constraint, since in reality; usually perfectly vertical sidewalls are achieved. However, simulation results must be carefully checked if profiles much different from vertical profiles are obtained.) Furthermore, it was assumed that all sidewall area is covered by polymer, and all bottom area is free of polymer (clean silicon). Sticking probabilities for the particles to a polymer surface and to a silicon surface were varied in 4x4 steps from zero to 1. In this aspect, the presented model extends previously published work, [18] where sidewall reactions have been neglected. The aspect ratio of the trenches was varied from 1 to 25.

The assumption that all area of the sidewall is covered by polymer, and all bottom area is free from polymer is a good approximation for most cases. However, it is not always met. If the sidewall polymer is partially removed (sidewall erosion), or, if the polymer gradually "pulls back" from the bottom and the sidewall area close to the bottom of the trench, this assumption is violated. Moreover, since the surface fluorine coverage affects the effective roughnes of the sample backside ant the table is approximated by a homogenous gap of 5 µm. The sample is heated by a constant homogenous heat flow (10 kW/m²) through the sample's top surface (Neuman boundary condition). Helium backing at 5 Torr provides thermal contact between sample and table. The surface, originating from the diffuse reflection of particles from all other points of the surface is calculated by Monte Carlo simulations separately from the profile simulation with a self-developed two dimensional Monte Carlo flow simulation program. [17] An analytical function \( \Phi = f(sw, bt, AR) \) was fitted to the simulation results, where \( \Phi \) is the integral flow rate at the bottom, divided by the bottom area (bottom mean flow rate). This formula was used to calculate the flow of diffusely reflected neutrals. The profile of the trench was approximated by a perfectly vertical sidewall. (This assumption is not a strong constraint, since in reality; usually perfectly vertical sidewalls are achieved. However, simulation results must be carefully checked if profiles much different from vertical profiles are obtained.) Furthermore, it was assumed that all sidewall area is covered by polymer, and all bottom area is free of polymer (clean silicon). Sticking probabilities for the particles to a polymer surface and to a silicon surface were varied in 4x4 steps from zero to 1. In this aspect, the presented model extends previously published work, [18] where sidewall reactions have been neglected. The aspect ratio of the trenches was varied from 1 to 25.

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3.3. Temperature Simulations
During the optimization of the etching process for the membrane trenches, it was observed that processes which worked well for wafers, did fail on membranes. It was suspected that this was due to the heating of membrane-like samples during the etching process. In order to investigate this problem, thermal simulations, using the FE program "TOCHNOG" [19] were carried out.

For simplicity, the circular shaped samples (with 10 cm diameter, wafer thickness 600 µm) were aproximated by a quadratical shape (with 10 cm edge length). Only heat conduction was considered as a heat transport mechanism. The sample is placed on a cooled sample holder ("table") which is kept at constant temperature of 12°C (Dirichlet boundary condition). Helium backing at 5 Torr provides thermal contact between sample and table. The surface roughness of the sample backside ant the table is approximated by a homogenous gap of 5 µm. The sample is heated by a constant homogenous heat flow (10 kW/m²) through the sample's top surface (Neuman boundary condition). No heat is transferred through the sample's edge surface (adiabatic boundary condition). The membrane diameter is varied from 1 to 60 mm, and the membrane thickness is varied from 5 to 590 µm.

4. Simulation results

4.1 Transport Simulations
Simulations for diffuse reflection transport of neutral particles, entering the top of the trench with isotropic velocity distribution, have been calculated for values of the sidewall sticking probability \( P_{sw} = 0.01; 0.1; 0.5; \) and 1, the bottom sticking probability \( P_{bt} = 0; 0.1; 0.5; \) and 1, and aspect ratios \( AR \) from 1 to 25. 100,000 particles were used to calculate the particle flow for one parameter point \( P_{sw}, P_{bt}, AR \), except for the low sidewall and bottom sticking probabilities, where a higher number of particles (200,000 or 350,000) have been used. The simulation results for the normalized mean flow density at the bottom \( P \) were approximated by an analytical function

\[
\Phi = P_{bt} \left( u \cdot P_{sw}^2 + \alpha + \beta \cdot P_{sw} \right) \arctan \left( \frac{\gamma}{d + 2 \cdot AR \sqrt{P_{sw} P_{bt} + c}} \right),
\]

(9)

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with $\alpha$, $\beta$, $\gamma$, $u$, $c$, and $d$ being constants, which are listed in Table 2. This analytical approximation can quite well reproduce the simulation results, with the exception of zero sidewall sticking probability, where the agreement between simulations and fit is not very good, although the trends are still in good agreement. However, this is only the theoretical limit case of a full reflective sidewall, which in reality is hardly achieved. For higher sidewall sticking probabilities, the agreement between the simulation results and the fit is good.

Table 2: Parameters of the analytical fit for the diffuse reflection transport model.

<table>
<thead>
<tr>
<th>Parameter symbol</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
<th>$u$</th>
<th>$c$</th>
<th>$d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>value</td>
<td>0.40</td>
<td>0.20</td>
<td>1.4</td>
<td>-0.25</td>
<td>0.022</td>
<td>-0.17</td>
</tr>
<tr>
<td>error</td>
<td>0.05</td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.005</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Note: Since $d$ is negative, for certain combinations of (low) sticking probabilities and low aspect ratio, the denominator can become zero or even negative, which is an indicator for the fact that this approximation formula is not suited for low (< 1) aspect ratios.

For high aspect ratio etching, the decrease in particle flow to the bottom with increasing aspect ratio is most important, since the etching rates (according to the models presented in paragraph 3) depend linearly on the neutral flow. For sticking probabilities close to unit, the decrease of the bottom flow with increasing aspect ratio (or trench depth) is more pronounced than for low sticking probabilities. (Fig. 1)

![Fig. 1: Normalised mean neutral flow to the bottom of the trench vs. aspect ratio for sidewall sticking probabilities (sw) of 0.1 (a) and 0.5 (b) and various bottom (bt) sticking probabilities. Simulation results (dotted lines) and the analytical fit (broken line) are in good agreement.](image)

4.2. Profile Simulations

For the diffuse reflection transport model, the fit equation (9) was used to calculate the flow. In addition to the explanations in paragraph 3.2, equation (9) was normalized to the flow for aspect ratio $AR=1$, because the neutral flow to the surface and the yield factor were determined from low aspect ratio etching rates, in order to get the "open field" properties. Yield factors obtained from open field data (low aspect ratio) are independent from transport properties and it can be assumed that in this case the particle flow to the surface originates from the full solid angle. Normalizing the particle flow rates to those of arbitrarily chosen standard process conditions allows for a consistent determination of the yield factors. The transport properties can be extracted from high aspect ratio etching rates and profile shapes for purely chemical etching, i.e. $rf=0$ watts. Likewise, the ion angular dispersion is obtained from high aspect ratio ion-enhanced etching profiles.

Etched and simulated profiles for GChDRIE process and simulation parameters listed in Table 3 are shown in Fig. 2. Simulated and experimental profiles are in good agreement. The simulation reproduces the depth of the trench, the profile slope and the sidewall roughness (size of the "ripples"). As the sample temperature and the operating pressure during the etching cycle are increased, the etching rate and the size of the sidewall ripples are increased. Also, the profile slope becomes slightly negative. These effects are also reproduced by the simulation (Fig. 2b).
4.3. Temperature simulations
For a standard membrane of 10 cm wafer size (4” wafer), 5 µm thickness and 60 mm membrane diameter, an increase in temperature of about 30 degrees was found for a input power density of $10^4$ W/m². This result is consistent with the results of Muller et al., who investigated similar samples. [20] However, due to technical constraints, it was not possible to actually measure the temperature of the membrane. By comparing the etching rates and surface qualities of etching processes on membranes (cathode temperature set to 12°C) and wafers (cathode temperatures varied from 10°C to 100°C), it can be concluded that the simulated temperature rise of about 30°C is consistent with the experiment.

Table 3: Process and simulation parameters.

<table>
<thead>
<tr>
<th></th>
<th>Fig 2a) etching</th>
<th>deposition</th>
<th>Fig 2b) etching</th>
<th>deposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>time [sec]</td>
<td>17</td>
<td>19</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>SF₆ [sccm]</td>
<td>10</td>
<td>-</td>
<td>10</td>
<td>-</td>
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<tr>
<td>Ar [sccm]</td>
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<tr>
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<td>CH₄ [sccm]</td>
<td>-</td>
<td>7</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>p [mTorr]</td>
<td>6</td>
<td>55</td>
<td>20</td>
<td>55</td>
</tr>
<tr>
<td>ICP [W]</td>
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<td>600</td>
<td>600</td>
</tr>
<tr>
<td>DC [V]</td>
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<td>50</td>
<td>110</td>
<td>50</td>
</tr>
<tr>
<td>T [°C]</td>
<td>30</td>
<td>30</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Ion angular spread [°]</td>
<td>0.5</td>
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<td>0.8</td>
<td>-</td>
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<td>Neutral sidewall sticking probability [1]</td>
<td>0.1</td>
<td>0.5</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Neutral bottom sticking probability [1]</td>
<td>0.1</td>
<td>0.5</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>number of cycles</td>
<td></td>
<td>24</td>
<td></td>
<td>24</td>
</tr>
</tbody>
</table>

Fig. 2: Simulated and experimental profiles. a) temperature=30°C, pressure=6 mTorr. b) Temperature=100°C, pressure=20 mTorr (refer to table 3). Depth, etching rate, profile slope and sidewall roughness of the simulated profiles are in good agreement with the experimental profile.
Since the temperature rise linearily depends on the input power, which is a parameter not exactly known and also subject to be changed due to process optimization, it was investigated whether the membrane heating could be reduced or eventually eliminated by changes in the membrane geometry. Therefore, the thickness and the membrane area was varied, and the maximum temperature at the top side of the membrane was simulated. It was found that geometry changes do not affect the maximum membrane temperature, unless the membrane area becomes very small (< 5 mm $^2$) (Fig. 3a) or the membrane becomes very thick (more than 400 µm). (Fig. 3b)

Fig. 3 Results of the temperature simulations. Maximum sample temperature as function of the membrane diameter (a) for membranes thicknesses of 5 and 100 µm thickness, and as function of the membrane thickness (b) for 60 mm membrane diameter.

From these results it was concluded that the membrane heating could not be reduced by modifications of the membrane geometry compatible to the device specifications. Therefore it is important to know the temperature dependence of the etching process, which was investigated by profile simulations and confirmed by the experiments.

5. Summary and Outlook
A 2D profile simulator for GChDRIE processes based on a phenomenological etching rate model considering the sample temperature was developed. Reactant transport is calculated by a direct shadowing (ions) or a diffuse reflection (neutrals) model. The temperature of membrane-like samples is estimated by FE simulations. It was found that the developed simulation model reproduces the experimental profiles within good agreement. Therefore it is concluded that the profile simulation is a promising approach. Further development would include the consideration of redeposition effects, a stronger coupling of the transport model with the surface model, the extension of the profile simulation to 3 dimensions, and the coupling with a plasma reactor simulation model.

References:
[19] URL: http://tochnog.sourceforge..net/