Effect of substrate thickness on the etching rate of diffractive optical elements

Anton Savchenko*, Christof Pruß*, Alois Herkommer*, Stephan Reichelt*

** Institut für Technische Optik, Universität Stuttgart*

mailto:anton.savchenko@ito.uni-stuttgart.de

We present a study on how substrate thickness affects the etching rate. A simulation model was developed that allows to predict a change in the etching rate with the sample thickness.

1 Introduction

Reactive ion etching enables fabrication of nanometer-sized features [1]. In this process, chemically reactive radicals and ions, generated inside a plasma, interact with the material. This results in the removal of the material – etching [2].

Thickness of pulse compression gratings can reach several millimeters [3]. Yet little is reported on how thickness of a substrate affects the etching rate. Here we present results of our experiments and simulations on the effect of the substrate on the etching rate.

2 Experiment

We conducted a series of etching experiments on fused silica samples with thicknesses $h = 2$ mm, 5 mm, and 10 mm on the RIE system Sentech Si500XL. We patterned samples with diffraction gratings and etched them in a fluorocarbon inductive plasma discharge changing only the coil power (ICP power). Results of these experiments are presented in Fig. 1.

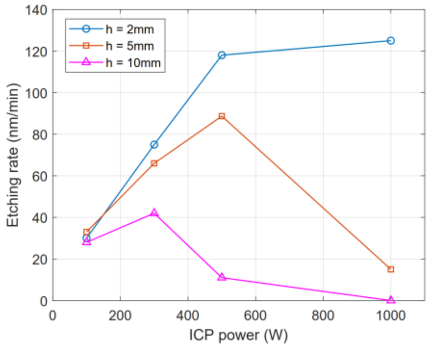

Fig. 1. Etching rate vs. ICP power for samples of different thickness.

For the 2 mm sample, ER rises monotonically with ICP power, while for 5 mm and 10 it peaks mid-range and then rapidly drops. Etching completely stopped at 1000 W ICP power on 10 mm thick sample.

3 Simulation

We use a fluid model combined with an Equivalent Electric Circuit (EEC) model to simulate the plasma sheath region. The fluid model approximates electron and ion behavior in the plasma sheath using macroscopic quantities such as density and velocity [4]. The EEC model represents the plasma sheath region as an electric circuit: ion motion is modeled as an ion source, motion of electrons – as a diode, and the sheath region together with the substrate – as capacitors in series. In a general case, the substrate is smaller than the electrode and therefore two electrical paths have to be included in EEC as shown in Fig. 2, one for the current through the substrate and another for the current through the electrode. Using Kirchhoff's law a differential algebraic equation (DAE) system is formed. Solving the fluid model together with DAE allows to obtain a spatio-temporal map of the sheath potential V_w, ion density n_i, and velocity u_i.

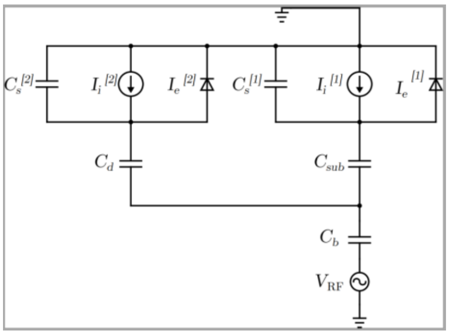

Fig. 2. Equivalent electric circuit for the two current paths through substrate and electrode.

As an example, Fig. 3 shows the sheath potential over the substrate and the electrode. In this case ICP power equals 500 W, thickness of fused silica substrates 2 mm, and sample diameter is half of electrode diameter. As can be seen, sheath potential is much smaller over the dielectric sample than over the open electrode.

The sheath potential and ion energy $E_i = \frac{m_i u_i^2}{2}$ for 500 W ICP power is plotted in Fig. 4 as function of

submitted: 31.07.2025 published: 30.09.2025

the sample capacitance $C_{sub} = \frac{A_{sub}\varepsilon_{FS}\varepsilon_0}{h_{sub}}$. Both ion energy and sheath potential follow the power law as a function of sample capacitance and plummet with an increased sample thickness.

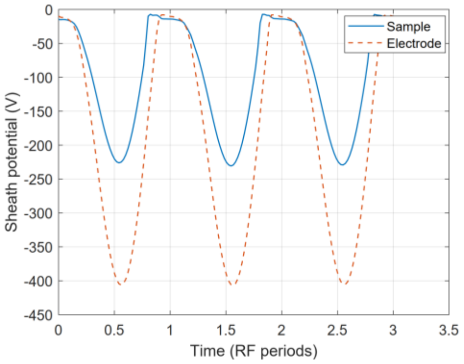

Fig. 3. Sheath potential over sample (solid blue) and open part of the electrode (dashed red). ICP power 500 W, fused silica sample with thickness 2 mm.

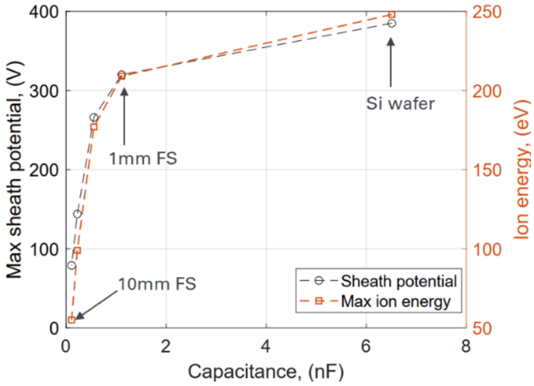

Fig. 4. Maximum sheath potential (left scale) and ion energy (right scale) as a function of sample capacitance. FS stands for fused silica.

4 Comparison with etching experiments

A balance between surface passivation and material removal governs the etching process [2]. Four main mechanisms contribute to the etching of fused silica:

1. Physical sputtering by high-energy ions;
2. Chemical etching by energetic ions;
3. Etching by radicals;
4. Polymer deposition by radicals and low-energy ions.

Based on these mechanisms we developed a model for the prediction of the etching rate. This model is based on the model initially proposed by Gottscho et al. [5]. We have added the effect of the physical sputtering and a time-dependence of the ion energy. The modified equation for the etching rate (ER) is shown below:

$$\mathrm{ER} = \left(\frac{1}{\alpha \mathrm{ED_N}} + \frac{1}{\beta\sqrt{\mathrm{ED}_i^{chem}}}\right)^{-1} + \gamma\sqrt{\mathrm{ED}_i^{sput}}, \qquad (1)$$

where $\mathrm{ED_N}$ stands for energy density of radicals and $\mathrm{ED}_i^{\square}$ - energy density of ions. Coefficients α, β, and γ are used to perform a linear regression. Results of the fit to the experimental etching rate values are shown in Fig. 5.

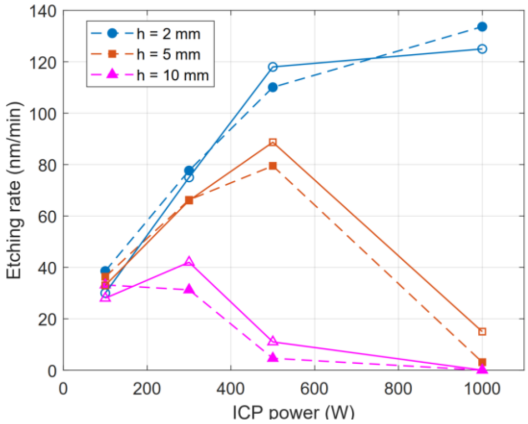

Fig. 5. Etching rate vs. ICP power. Simulations results (dashed lines) and experimental values (solid lines).

Goodness of fit R^2 equals to 0.97, 0.95, and 0.86 for samples with thickness h = 2 mm, 5 mm, and 10 mm respectively. R^2 close to 1 indicates a good fit between the simulation model and experimental data.

5 Conclusion

We have presented results on the dependence of the etching rate on the substrate thickness. Our fluid-EEC model predicts the dependence of etching rate on thickness of the substrate, matching with experiments with $R^2 \geq 0.86$.

6 Acknowledgements

Gefördert durch: BMWK aufgrund eines Beschlusses des Deutschen Bundestages und DFG - Projekt 54555282.

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submitted: 31.07.2025 published: 30.09.2025