Plasma sheath tailoring by a magnetic field for three-dimensional plasma etching

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Three-dimensional (3D) etching of materials by plasmas is an ultimate challenge in microstructuring applications. In the past, several attempts have been explored to reach 3D plasma processing capabilities including the charging of 3D structures in the plasma sheath to steer the ions [1], alternating chemistry during trench etching [2] and affecting trench charging by magnetic fields [3].

In our recent work [4] we proposed a method to reach controllable 3D structures by using masks in front of the surface in a plasma etch reactor in combination with local magnetic fields. This combination of electric and magnetic fields can modify the plasma sheath region and thereby modify the ion flux to reach 3D directionality during etching and deposition. This effect has the potential to be controlled by modifying the magnetic field and/or plasma properties to adjust the relationship between sheath thickness and mask feature size. However, because the guiding length scale is the plasma sheath thickness, which for typical plasma densities is at least tens of micrometers or larger, controlled directional etching and deposition target the field of microstructuring, e.g., of solids for sensors, optics, or microfluidics.

We investigated our approach both experimentally and by means of a 2d3v particle-in-cell/Monte Carlo collisions simulation (PIC/MCC). The etching experiments are performed in an inductively coupled plasma (ICP) at a pressure of 2 Pa with an additional RF-bias voltage applied to the substrate and metallic mask with a frequency of 13.56 MHz. The experiments as well as the simulation showed a modification of the etching profiles when using a magnetic field in combination with a metallic mask compared to the mask alone. Fig. 1 (a) and (b) show the etching profiles for both with and without a magnetic field for the etching of a-C:H layers and Silicon respectively. In both experiments the case with the magnetic field shows a modified etching trench with enhanced etching on the right-hand side of the trench (when the magnetic field is pointing out of the plane). The PIC/MCC simulation of a similar geometry showed an enhanced ion flux on the same side of the slit, which can be seen in Fig. 1 (c).

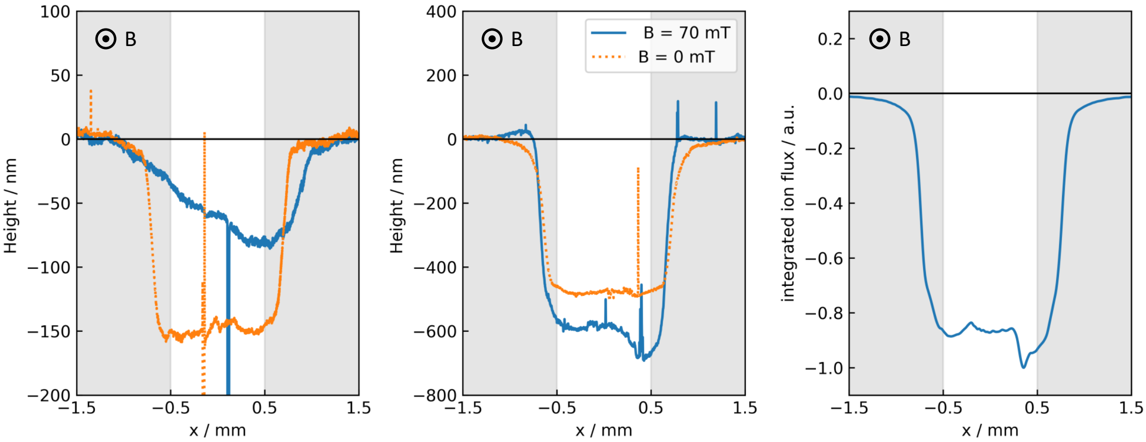

Fig. 1: 3D etching profiles of a-C:H in an argon-oxygen plasma with -100 V self-bias (a) and of silicon in a C:F plasma with -150 V self-bias (b) as well as the integrated ion flux from the simulation at 100 V applied voltage (c).

The simulation further revealed that the $\mathbf{E}\times\mathbf{B}$ drift of the electrons causes an asymmetric penetration of the plasma into the mask structure, as illustrated in Fig. 2 (a). This tailored local sheath expansion modifies the plasma density distribution and the transport when the plasma penetrates the mask during an RF cycle creating a 3D etch profile. Additionally, redeposition and ion scattering can further modify the etching profile, as illustrated in Fig. 2 (b).

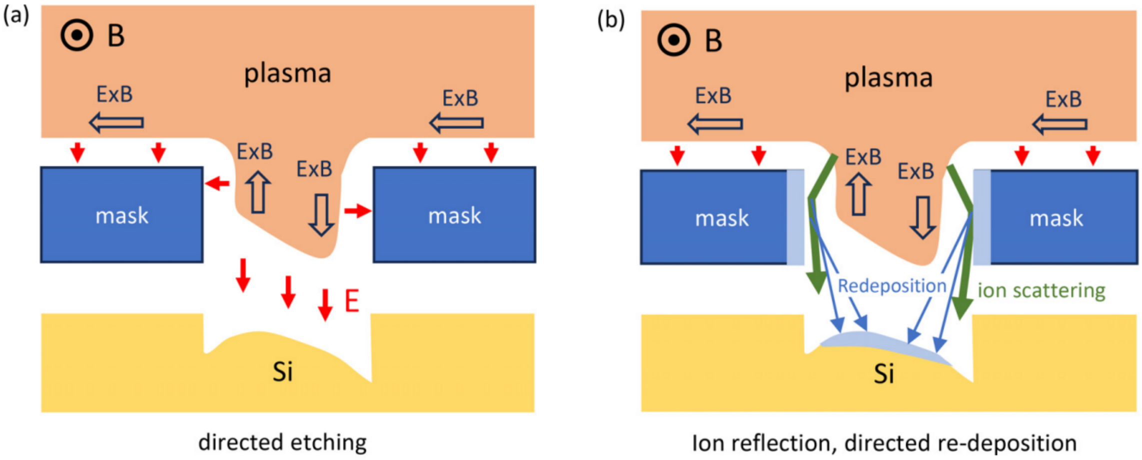

Fig. 2: Mechanisms to create a 3D deposition or etching profile: (a) varying penetration of the plasma into the mask structure depending on the $\mathbf{E}\times\mathbf{B}$ drifts, (b) ion focusing and re-deposition from the mask.

References

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