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Comparison of patterning silicon and silicon carbide using focused ion beam

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Introduction and motivation

Focused ion beam (FIB) milling of micro- and nano- structures has been widely used in various field of application. However, it is difficult to achieve complex 2D and 3D structures as many effects such as angle dependent sputter yield, redeposition and secondary sputtering have to be considered. FIB milling of different structures (simple and complex) is studied and compared for two different electronic materials, i.e., silicon and silicon carbide (SiC).

Apart from physical sputtering and redeposition, swelling produced during FIB processing by the tail of non-ideal ion beam shape should be considered when nanoscale precision is required. This effect is studied by scanning probe microscopy technique, e.g., topography of irradiated region is measured by atomic force microscopy (AFM) immediately after irradiation by an in-built AFM in silicon and SiC and compared with ex-situ measurements. The tail of the beam can also cause damage outside the processed region which will strongly influence the electrical properties of the material and this is measured using scanning spreading resistance microscopy (SSRM) for SiC.

Experimental

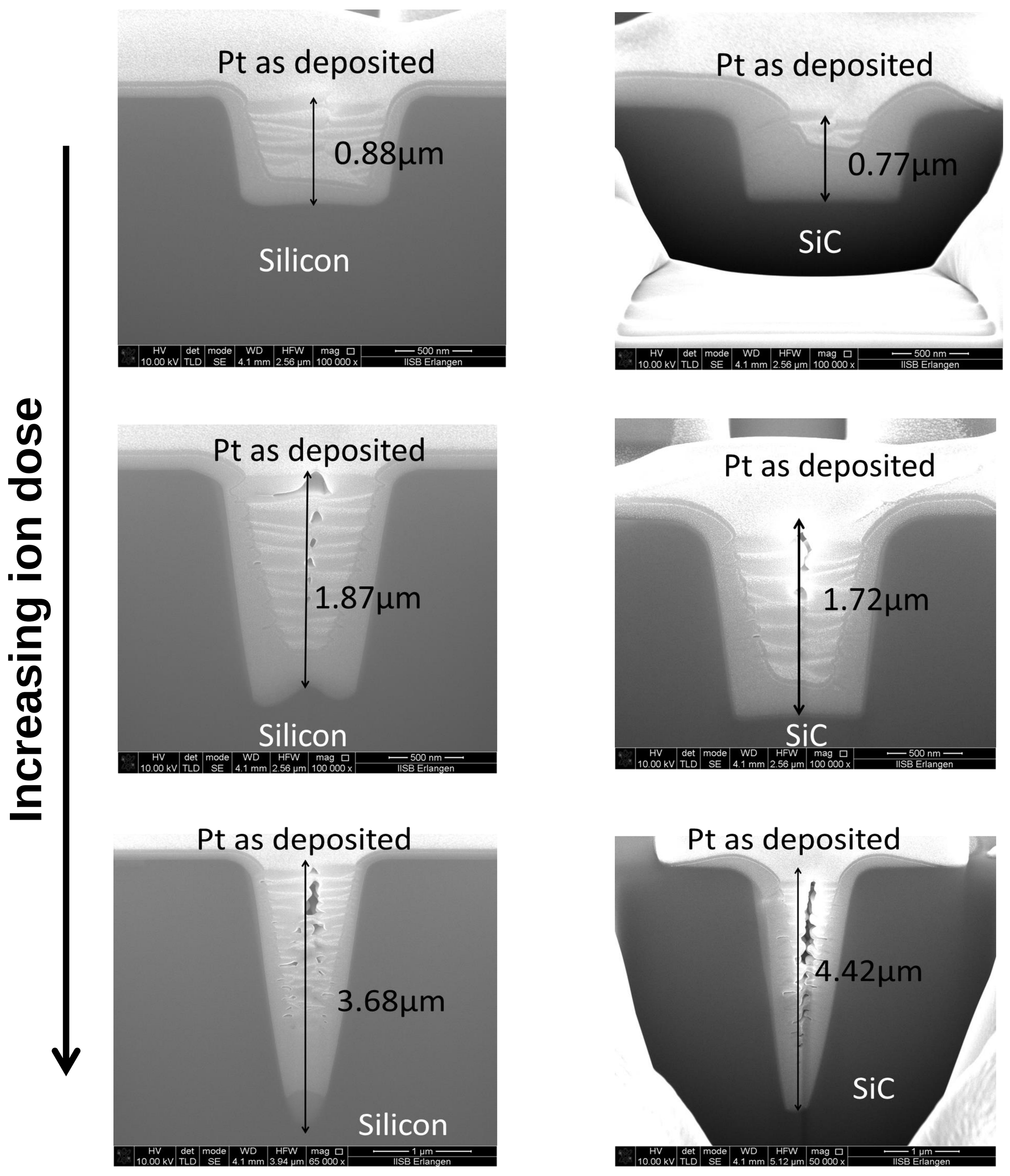
Focused Ion Beam (FIB)
- FEI Helios Nanolab 600
- Ion beam: 30 keV Ga ion
- Beam currents: 1.5 pA, 28 pA, 280 pA, 2800 pA
- Dose range: $4 \cdot 10^{13}$ cm^{-2} to $2 \cdot 10^{19}$ cm^{-2}
- Dwell time: 1 µs

In-situ topography measurement
- Ion irradiation: 30 keV Ga in Tescan Lyra FIB
- Topography: Tapping mode (Akiyama probes-Quartz tuning fork with micromachined silicon cantilever) Force constant = 5N/m

Ex-situ SPM measurements
- Bruker ICON
- Topography: Tapping mode AFM (silicon tips)
- Spreading resistance: Contact mode electrical measurement (diamond coated Si tip)

Results and discussion

Trenches and complex structures

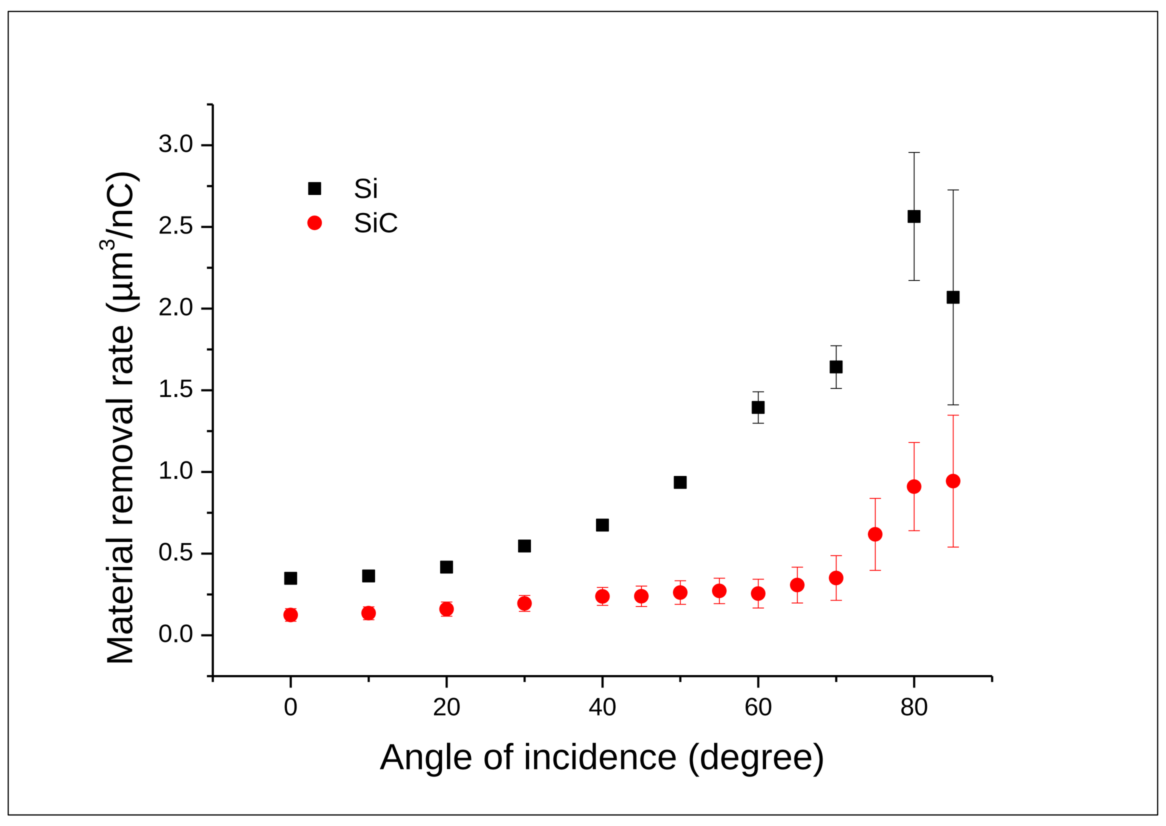


Aspect ratio ~1
Flat bottom in Si and SiC

Aspect ratio ~2
'W' shaped bottom in Si (2˚ sputtering by reflected ions); No 'W' shaped bottom in SiC

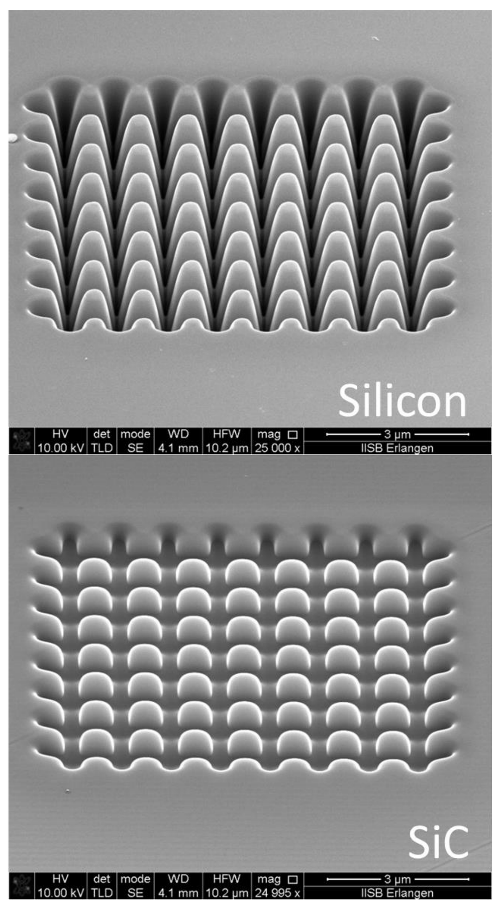
Side wall angle
- Si : 81˚± 1˚
- SiC : 84˚± 1˚

Aspect ratio ~4
'V' shaped trench in Si and SiC (due to redeposition)



Experimental angle dependent material removal rate for silicon* and SiC for 30 keV Ga ion.

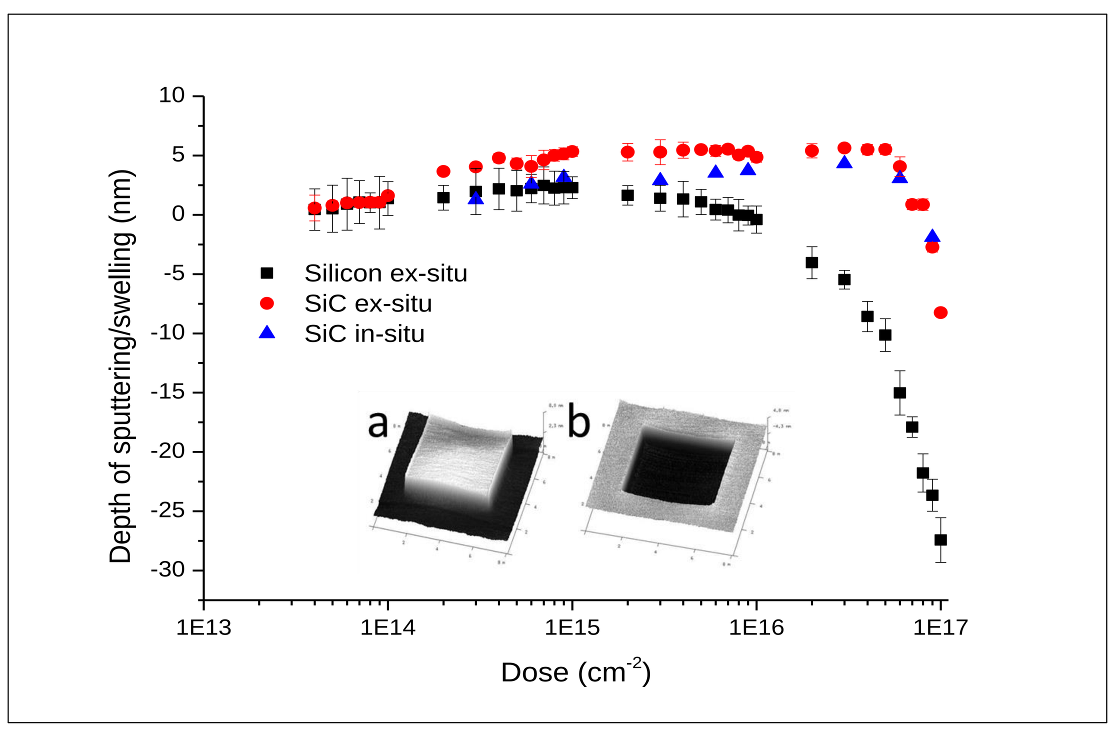
High aspect ratio structures by FIB milling → Angle dependent sputter yield with respect to the normal incidence is important



Structures fabricated by milling horizontal & vertical lines**

Process parameter
- ion beam current 2.8 nA
- periodicity 1000 nm
- patterning time 49 s (Si) and 99 s (SiC)

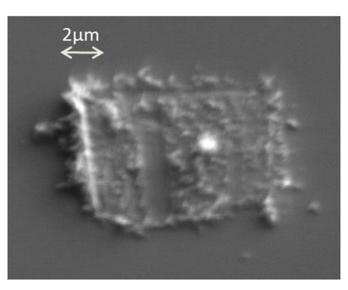
Swelling



Depth (or height) of irradiated structure (relative to non-irradiated surrounding) as a function of ion dose measured in Si (ex-situ) and SiC (ex-situ and in-situ)**. Inset:** (a)Swelling and (b)sputtering in SiC

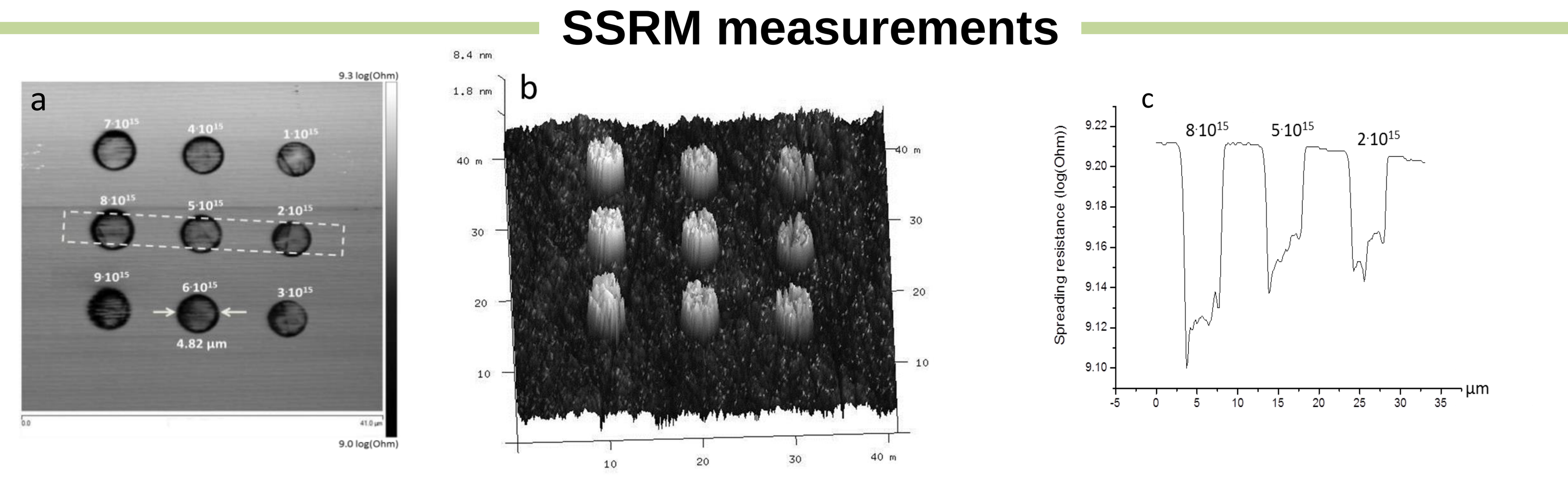
Swelling in SiC
- Maximum swelling measured (dose $3 \cdot 10^{16}$ cm^{-2})
  - ex-situ = 5.63 nm
  - in-situ = 4.32 nm
- Difference → no oxidation of irradiated surface for in-situ measurements

Swelling in silicon
- Measured only by ex-situ AFM
- In-situ measurement failed



Scratched bump (swollen region by Ga irradiation) in Si due to mechanical damage by AFM tip

SSRM measurements



(a) SSRM map of circles (diameter 4µm) **irradiated with Ga ion** dose ranging from $1 \cdot 10^{15}$ to $9 \cdot 10^{15}$ cm^{-2}**, (b) corresponding topography measurement in SiC and (c) sectional view of resistance** in log(ohm).

Summary

- Less difference in the angle dependent material removal rate for higher angle and normal incidence for SiC when compared to silicon→ No 'W' shaped bottom in the trench, aspect ratio of the complex structures produced in SiC is less than in silicon
- As oxidation was prevented for in-situ AFM measurement, swelling measured by in-situ AFM measurement is lesser than ex-situ measurement for SiC.
- SSRM measurement shows that the Ga irradiated region of SiC has lower resistance when compared to the non-irradiated surrounding. Whereas in Si, Ga irradiated region has higher resistance***

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