Silicon growth and etching by oxygen and selenium: evolution of Si(111)-7×7 surface structure and morphology

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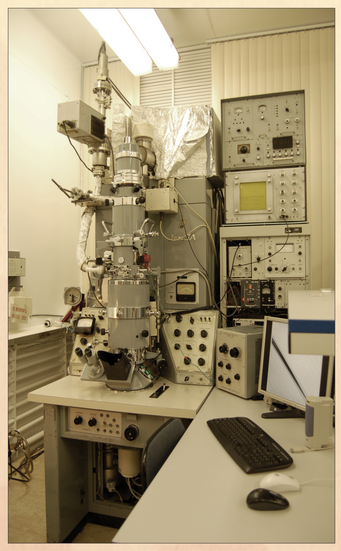
Si-based electronics downscales gradually to 1 nm where next-generation devices will require the production of ultrathin films and superlattices with atomically sharp interfaces and, potentially, self-ordered 3D nanostructures promising for a range of applications [1–3]. Therefore, single monatomic steps always existing on crystalline substrates become a significant object of surface engineering [4], and the investigation of wafer-scale surface treatments (e.g. growth, etching, metal adsorption) fosters the control over substrate surface morphology at the monatomic step level to improve the properties of overlying films.

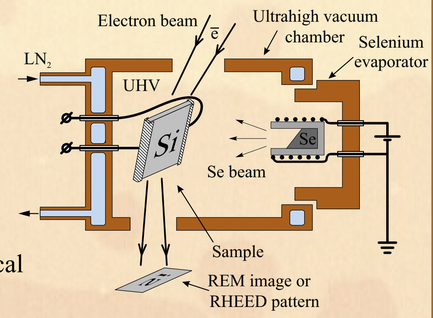
[1] F. Grillot *et al.* Nanophotonics (2020) 20190570.
[2] S. Pandya *et al.* Sci. Rep. 6 (2016) 26075.
[3] D. Diaz-Fernandez *et al.* Appl. Surf. Sci. 455 (2018) 227.
[4] Henryk Turski *et al.* Appl. Surf. Sci. 484 (2019) 771.

In situ ultrahigh vacuum (UHV) reflection electron microscopy (REM)



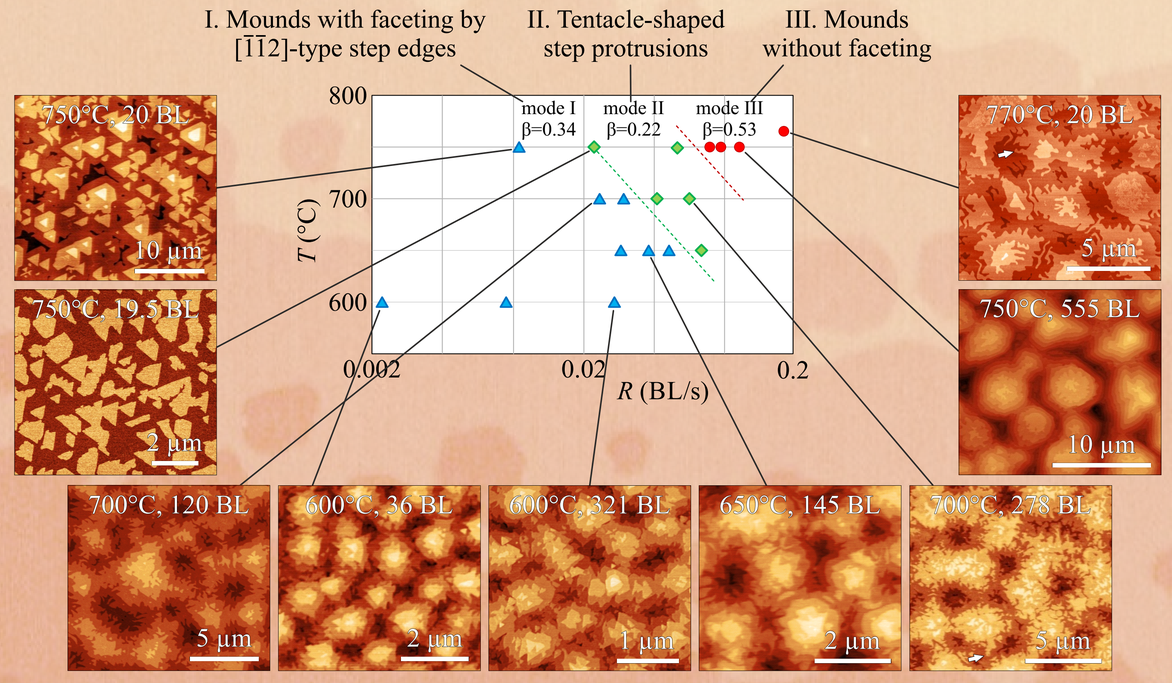
Ultrahigh vacuum reflection electron microscope based on JEM-7A

- Accelerating voltage – 100 kV;
- High spatial resolution;
- Visualization of single monatomic steps;
- Ultrahigh vacuum (P<10^{-8} torr);
- Resistive heating of a sample;
- Wide range of temperatures: from room temperature up to the melting point;
- *In situ* observation of morphological and structural transformations of sample surface;
- Sublimation and deposition of various substances (Si, Ge, O_2, Se, Cu, Bi, etc.);
- REM image foreshortening by a factor of ~50–80.

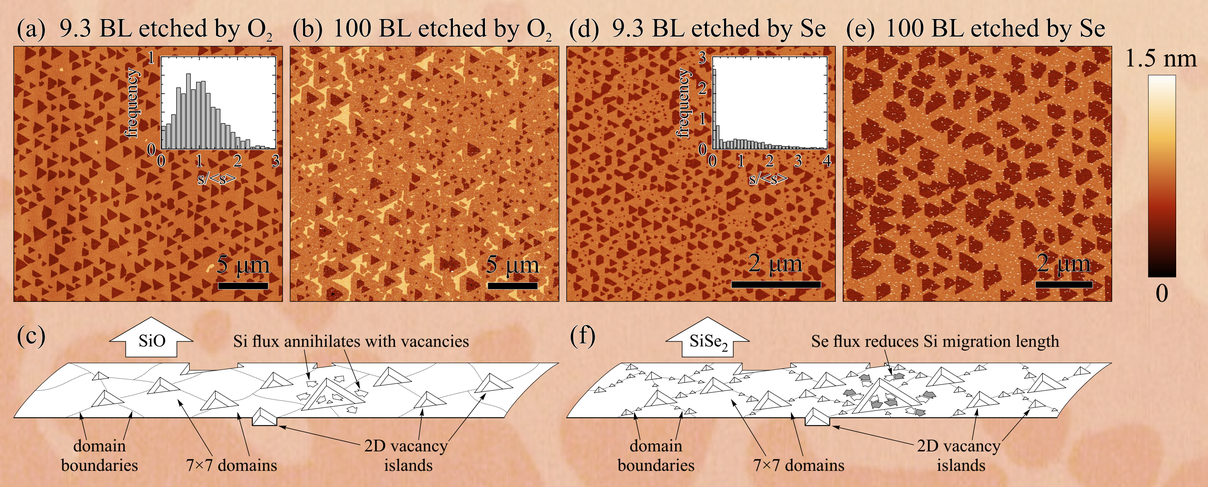


Schematic representation of UHV REM sample chamber equipped with silicon, selenium, or oxygen evaporator

R–T map of morphological instability modes during Si growth

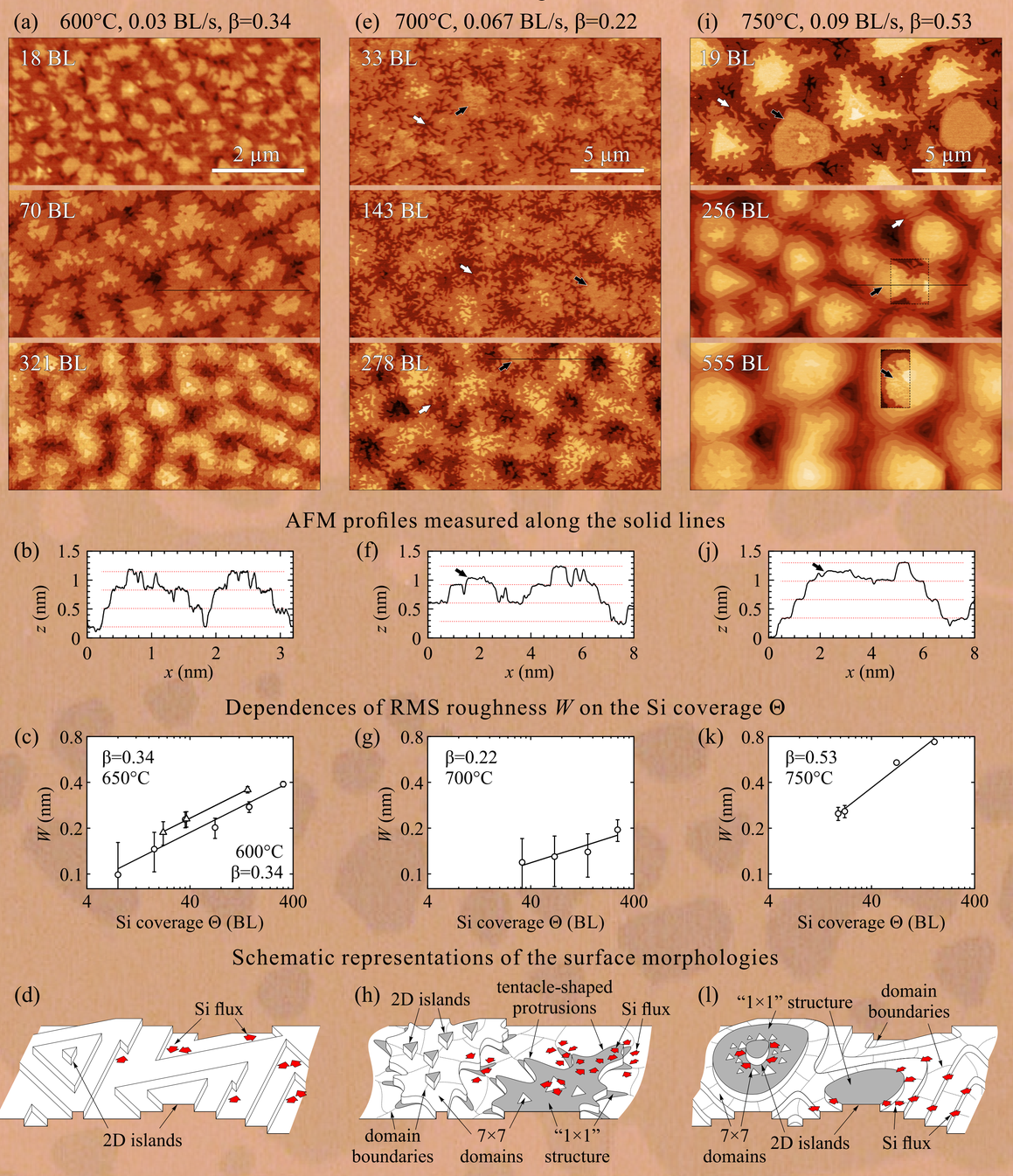


Singular Si(111) surface etched at 750°C by oxygen and by selenium



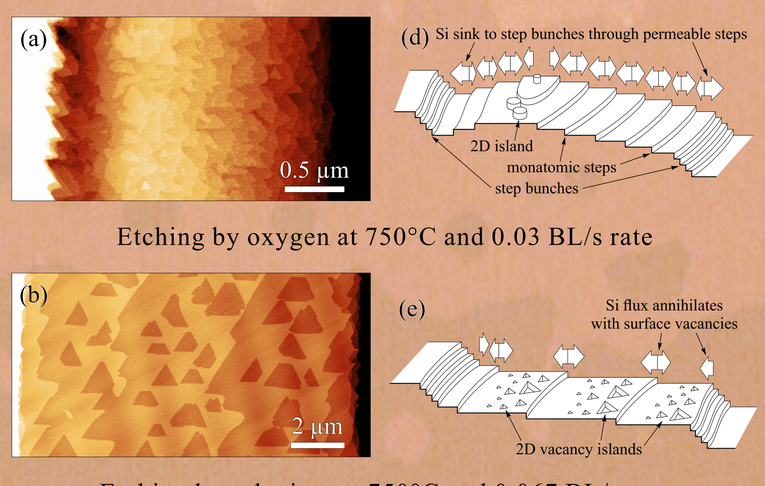
Insets in (a) and (d) show normalized island size distributions. (c) and (f) are schematic representations of (a) and (d) surface morphologies, respectively. White and grey arrows denote Si and Se fluxes, respectively.

Evolution of the singular Si(111) surface morphology under the conditions of different instability modes



Si(111) surface between step bunches after prolonged surface treatments

Si growth at 600°C and 0.03 BL/s rate



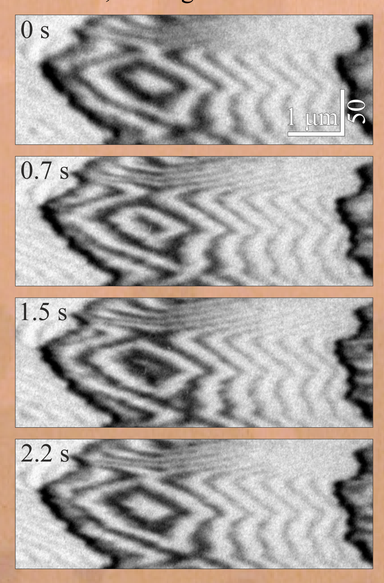
Etching by oxygen at 750°C and 0.03 BL/s rate

Etching by selenium at 750°C and 0.067 BL/s rate

Si and Se fluxes are denoted by white and grey arrows, respectively.
1 BL = 1.56×10^{15} cm^{-2}

Valley-like morphology during etching by Se

In situ REM images
730°C, etching rate 0.46 BL/s



Stepped valley-like surface morphology is formed between step bunches during prolonged Si(111) surface etching by Se. Evolution of such self-organized patterns is periodic [5].
[5] D.I. Rogilo *et al.* J. Cryst. Growth. 529 (2020) 125273.

Summary

We have shown that the interplay of local structural transitions and complex surface mass transfer governs the non-trivial morphological evolution of the Si(111)-7×7 surface exposed to a Si molecular beam, an oxygen atmosphere, or a Se molecular beam. During Si growth, the appearance of disordered high-atom-density "1×1" phase changes Si mass transport routes and causes transitions between different mounding modes. When Si(111) surface is etched in a vacuum, diffusion of Se adatoms stabilizes the singular Si(111) surface but excavates the step-bunched surface by creating stepped multilevel valley-like morphology analogously to the formation of the pyramidlike waves triggered by Si adatom diffusion during Si growth.

Acknowledgments

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