Emergence of nanostructures and nanopatterns under ion induced non-equilibrium conditions

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A plethora of nanoscale features and self-organized patterns emerge on surfaces which are irradiated by ion beams [1]. Depending on the irradiation conditions, i.e., ion mass, ion energy, charge state, incidence angle, sample temperature, very different kinds of surface morphologies are observed, like hexagonally ordered dots or pits, pyramids and inverted pyramids, or periodic asymmetric ripple patterns.

On amorphous or amorphized surfaces, the formation of periodic patterns under continuous ion irradiation results from the interplay of different roughening mechanisms, e.g., curvature dependent sputtering, ballistic mass redistribution, or altered surface stoichiometry on binary materials, and smoothing mechanisms, e.g., surface diffusion or viscous flow. The symmetry of these patters is determined by the ion beam direction, i.e., hexagonal near order at close to normal incidence and two-fold symmetry at off-normal incidence above ~45°. However, more intriguing patterns can also appear. Above the recrystallization temperature diffusion is affected by the Ehrlich-Schwoebel barrier on the crystalline surface: vacancies and ad-atoms are then trapped on terraces and can nucleate to form pits or mounds, respectively. Patterns formed in this “reverse epitaxy” regime exhibit crystalline facets and the symmetry of the patterns is determined by the crystal structure of the surface [2]. However, ballistic effects can also play a role and shape the resulting morphology [3].

The fundamental understanding of the pattern formation is already quite advanced. Simulations based on atomistic methods, such as molecular dynamics (MD) and kinetic Monte-Carlo (kMC), or by continuum equations can describe in most cases the experimental observations. The status of our current understanding and the predictive power of continuum theories to achieve full control of the ion-induced patterning process will be presented and discussed.

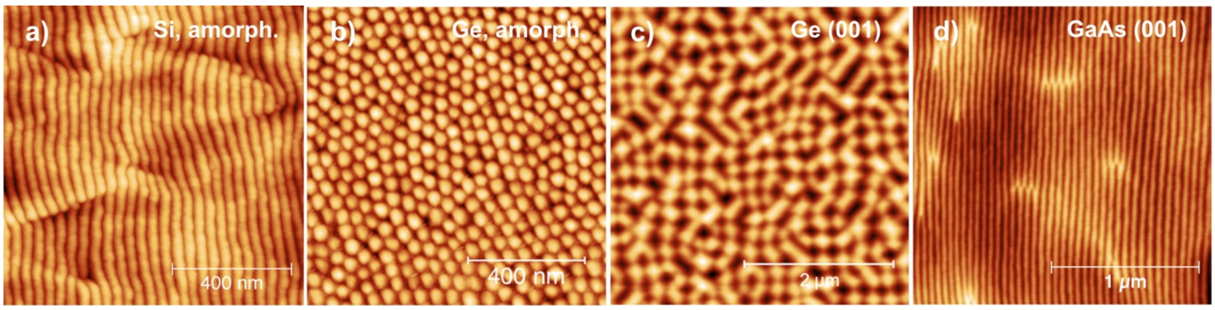

Fig. 1. Different types of ion-induced patterns observed after high-fluence irradiations: a) “classical” ripple pattern on amorphized Si by 500 eV Ar^+ at 67° incidence, b) hexagonal dot pattern on amorphized Ge by 20 keV Bi^+ at 0° incidence, c) pyramids and inverse pyramids on Ge(001) by 1 keV Ar^+, and d) periodic “saw tooth” patterns on GaAs (001) by 1 keV Ar^+ at normal incidence.

[1] Cuerno, Rodolfo *et al.*, J. Appl. Phys., **128**, 180902 (2020).
[2] Ou, Xin *et al.*, Nanoscale, **7**, 18928 (2015).
[3] Erb, Denise J. **et al.**, Phys Rev B, **104**, 235434 (2021).