Track formation in $SrTiO_3$

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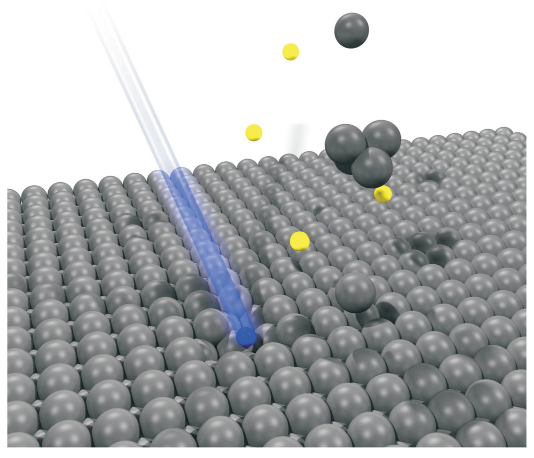
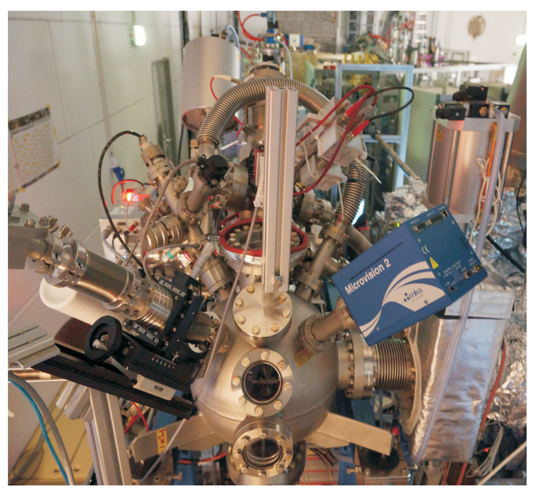
Goals

- Investigation of energy dissipation processes during and after swift heavy ion (SHI) irradiation
- Analysis of ion induced structural modifications on the surface down to atomic level
- Determination of ionization probabilities under SHI irradiation
- Analysis of ionization processes to understand nano-structure formation in insulators



Experiment

- Irradiation experiments at the M1 UNILAC beamline of GSI (Darmstadt, Germany)
- In-situ scanning probe microscopy set-up (Omicron) for characterization of the surface in ultra high vacuum
- multi-axial sample stage for irradiations with different angles of incidence and varying SHI energies
- Time-of-Flight-mass-spectrometer (TOF-MS) combined with VUV-laser for analysis of secondary ions and neutrals emitted during sputtering process

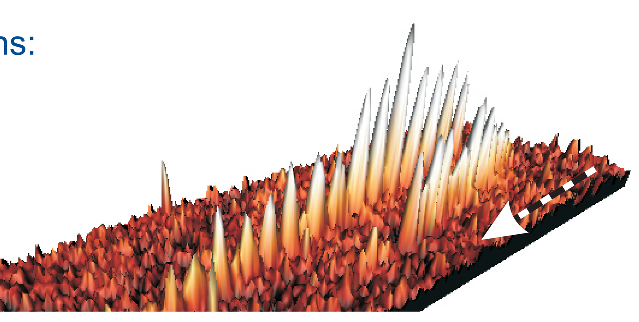


Analysis of surface tracks via atomic force microscopy

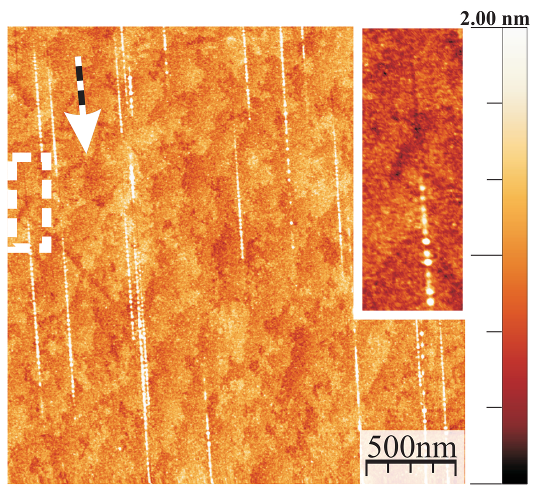
Irraditation of insulators

Irradiaton of $SrTiO_3$ with SHI leads to permanent modifications:

- 90° irradiation → hillocks (height ≈ 5 nm, diameter ≈ 10 nm)
- small angle (< 6°) → chains of hillocks [1]
  → novel feature - a rift - at the beginning of the chain of hillocks



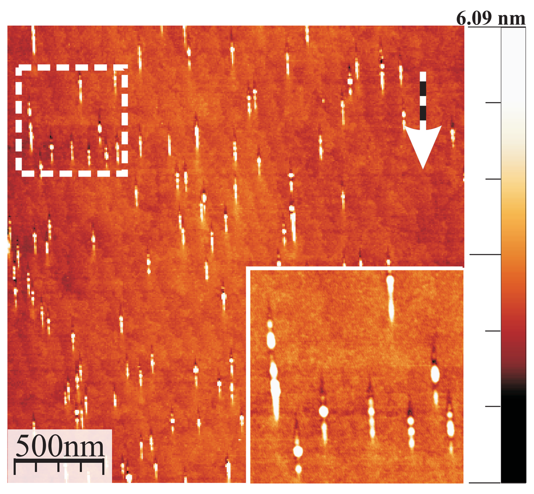
$SrTiO_3$



NC-AFM image of $SrTiO_3$
Δf = -22 Hz, f_{center} = 181 kHz
$^{136}Xe^{21+}$; 4.8 MeV/u; 1.5°
Stopping power ≈ 29 keV/nm

Chain of hillocks:
length 690 nm ± 187 nm

Rift:
length 186 nm ± 50 nm
width 9 nm ± 2 nm
depth 0.3 nm ± 0.1 nm

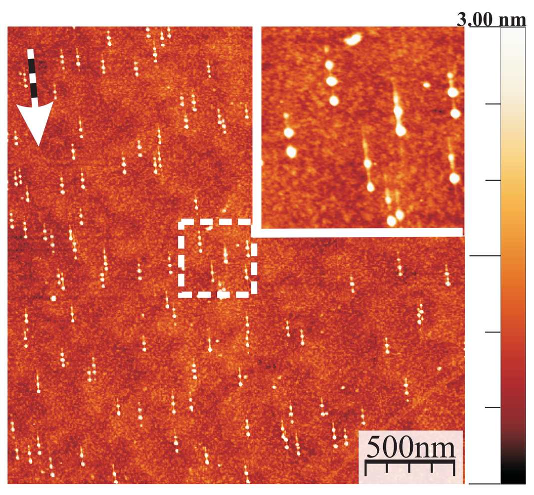


NC-AFM image of $SrTiO_3$
Δf = -22 Hz, f_{center} = 181 kHz
$^{238}U^{28+}$; 3.6 MeV/u; 5.8°
Stopping power ≈ 48 keV/nm

Chain of hillocks:
length 109 nm ± 20 nm

Rift:
length 66 nm ± 13 nm
width 12 nm ± 4 nm
depth 0.7 nm ± 0.3 nm

TiO_2



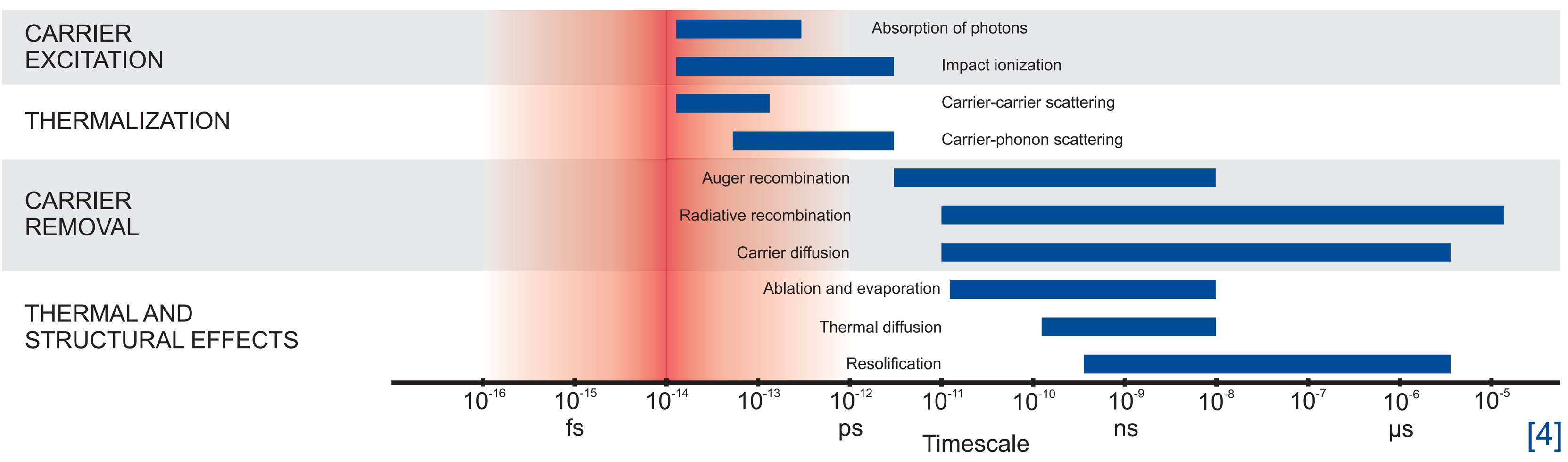
NC-AFM image of TiO_2
Δf = -23 Hz, f_{center} = 181 kHz
$^{136}Xe^{21+}$; 4.8 MeV/u; ≈ 2°
Stopping power ≈ 28 keV/nm

No rifts observed

Discussion

There are different approaches to explain SHI induced material modifications:

- Thermal-Spike-Model [2]
  - Deposition of MeV/u ion energy in electronic sub-system of the target (~10^{-16} - 10^{-14} s)
  - Electron-phonon-coupling transfers energy to lattice subsystem (~10^{-14} - 10^{-11} s); leads e.g. to phase transitions (melting, sublimation, ...)
    → quantitative reproduction of energy threshold for track formation and radii [3]
    → model for explanation of chains of hillocks in combination with inhomogeneous electron density [5]
    → ↯ TiO_2 and $SrTiO_3$ have nearly same melting and boiling temperatures ($T_{m/b,TiO2}$ = 1855°C/2972°C, $T_{m,SrTiO3}$ = 2040°C/>3000°C, $T_{m/b,SrO}$ = 2460°C/3200°C)
    → no sign for a thermal decomposition process as in the case of SiC [6] because one found neutral particles of all species in SNMS-spectra
- Coulomb-Explosion-Model [7]
  - Ionization of atoms along the trajectory of MeV/u ion
  - Repulsion of charged target ions by Coulomb force
  - Possible particle emission of ionized particle [8]
    → Ionization probability of Sr in $SrTiO_3$ should be higher and lead to higher sputter yield of $SrTiO_3$ in comparison to TiO_2, which would explain the distinct rift formation (→ use a TOF-MS)
    → ↯ $SrTiO_3$ particles eject only as neutral clusters

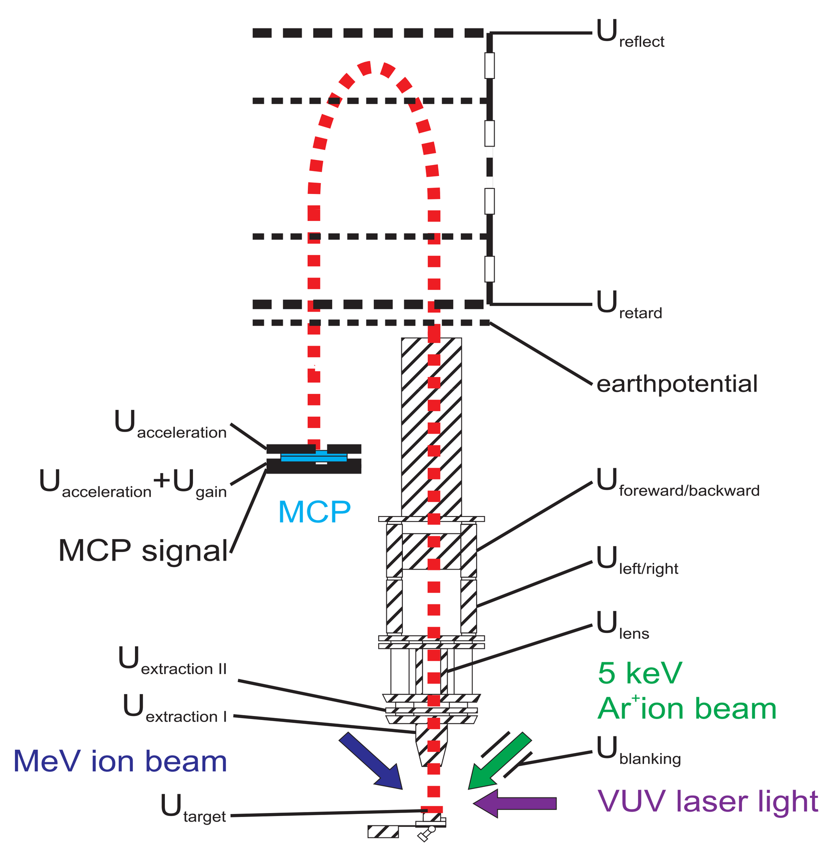


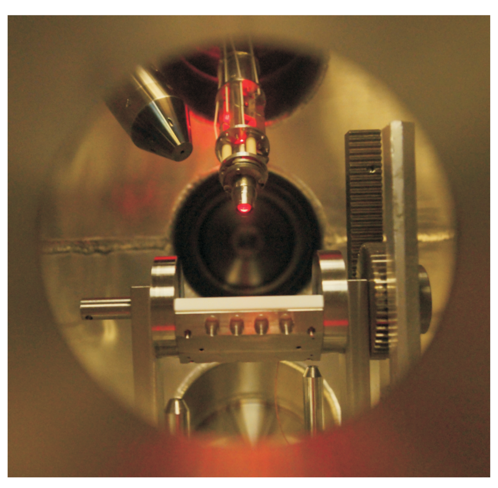
[4]

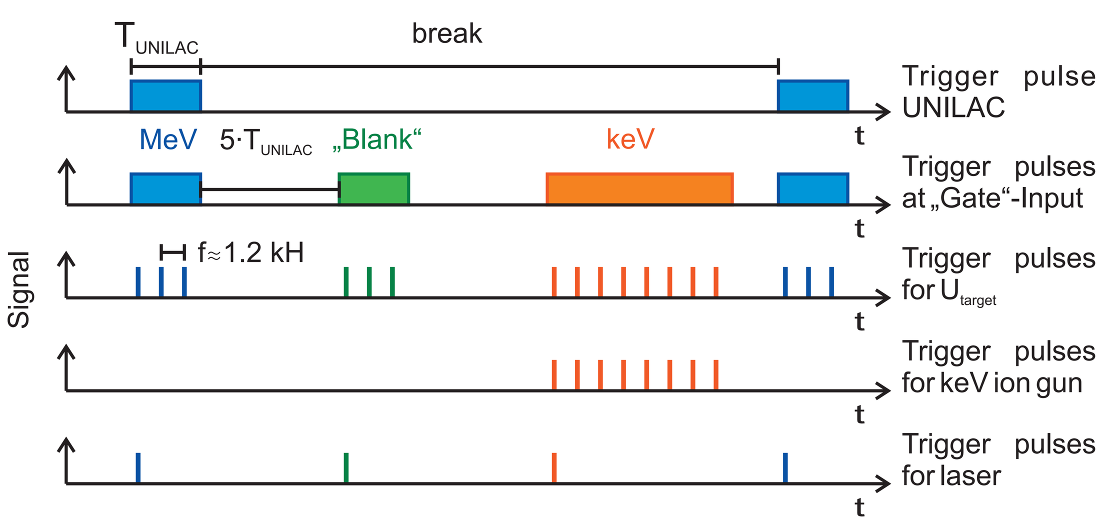
Analysis of sputtered secondary particles

New TOF-MS set-up

- New reflectron-based TOF-MS at M1 branch of UNILAC beamline in 2014
- MeV/u or keV ions are used to sputter target materials
- Secondary ions are accelerated by U_{Target} into the spectrometer, are separated by their mass-to-charge ratio during their time of flight, and are detected at a MCP → SIMS
- Laser post-ionization (λ = 157 nm, 7.9 eV) makes secondary neutrals accessible → SNMS
- Quasi-simultaneous acquisition of six different spectra during one UNILAC MeV ion pulse by newly designed measuring protocol
- Interleaved keV sputter cleaning protocol for measurements of pure metal surfaces
- Pulse mapping protocol for determination of MeV/u ion pulse form



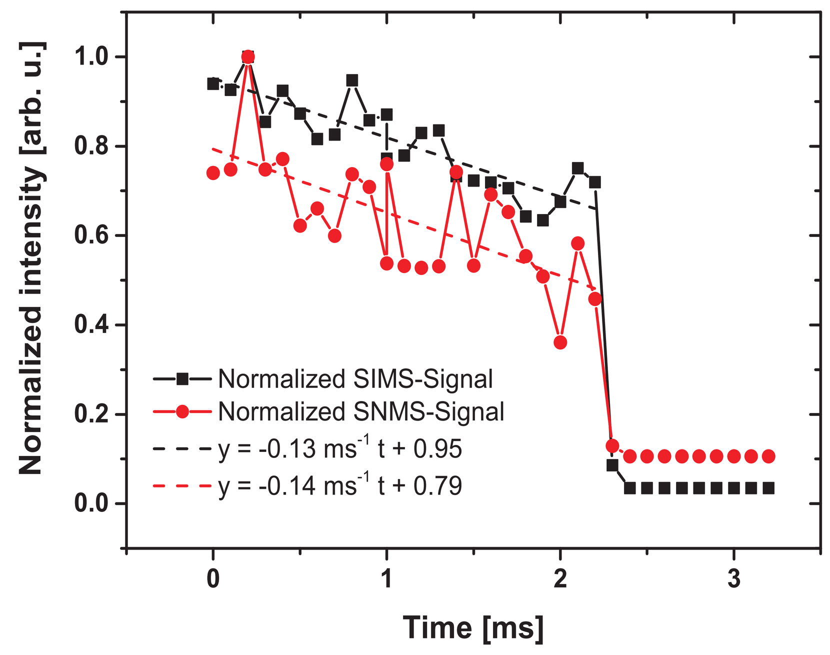


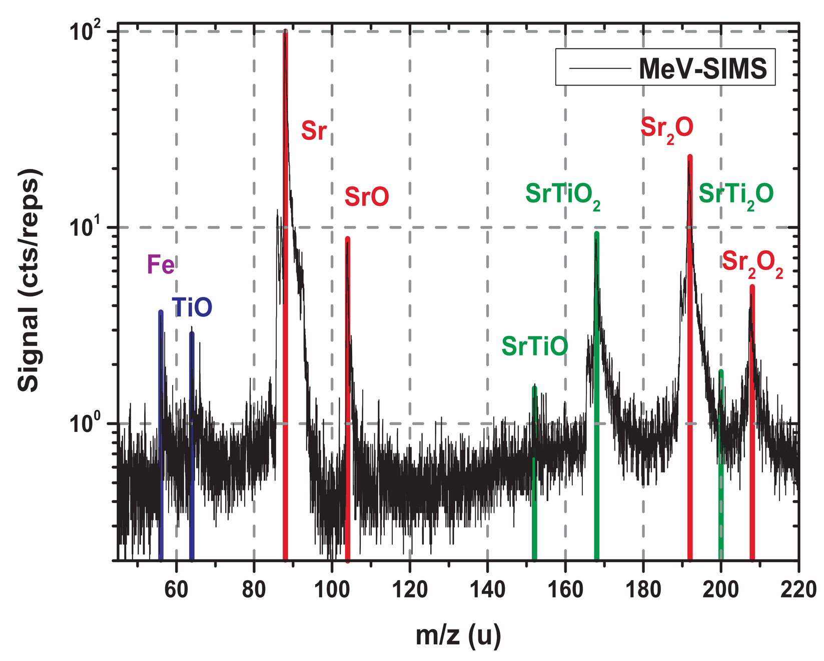


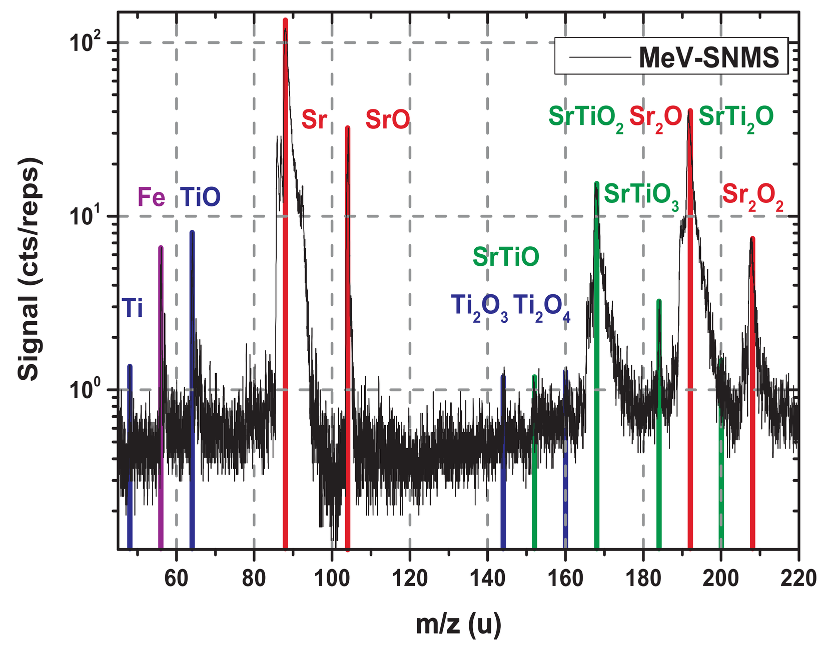
Mass spectra of $SrTiO_3$

SIMS- (upper panel on the right hand side) and SNMS-signal (lower panel on the right hand side) of $SrTiO_3$ irradiated with $^{197}Au^{26+}$ 4,8 MeV/u (stopping power ≈ 28 keV/nm)

- Sr and its oxides dominate both spectra
- No $SrTiO_3$-peak visible in SIMS
- Ti and its oxides better detectable in SNMS
- Possible mechanisms for ionisation by Sr^+ cationization
- No influence of heating caused by MeV/u ion irradiation is observed for the signal (here Sr^+) during irradiation (see normalized intensities of Sr^+-Peak during pulse mapping)







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