Atomic-scale investigations formation and aging processes of EUV optics

Joost Frenken, *ARCNL, Amsterdam, The Netherlands*

- Brief introduction of ARCNL
- Special Scanning Tunneling Microscopy
- Movies: *live* formation of Si-Mo interfaces
  live kinetic roughening of Mo film
  live ion erosion

ARCNL

ARCNL

Advanced Research Center for Nanolithography

MISSION

The research of ARCNL focuses on fundamental physics in the context of technologies for (nano)-lithography, primarily for the semiconductor industry.

PARTNERS

Foundation for Fundamental Research on Matter (FOM/NWO), University of Amsterdam, VU University Amsterdam, ASML

LOCATION

Amsterdam Science Park, The Netherlands

FOM NWO FOM Institute AMOLF Universiteit van Amsterdam VU Vrije Universiteit Amsterdam Gemeente Amsterdam Provincie Noord-Holland ASML

Scientific program

ARCNL

UNDER CONSTRUCTION

EUV Generation and Imaging
Stefan Witte & Kjeld Eikema

EUV Targets
Paul Planken

EUV Plasma Dynamics
Ronnie Hoekstra, Wim Ubachs & Oscar Versolato

Atomic Plasma Processes
Oscar Versolato

EUV Plasma theory
Collaborative structure (Jan van Dijk, TU/e)

Nanolayers
Joost Frenken

Nanophotochemistry
Fred Brouwer

EUV Photoresists
Sonia Castellanos Ortega

AMOLF-ARCNL group
Niklas Ottosson & Huib Bakker

HHG of EUV
Stefan Witte & Kjeld Eikema

Accelerator-based EUV
Coordinator: Ronnie Hoekstra

Integration
Joost Frenken (ARCNL) & Wim van der Zande (ASML)

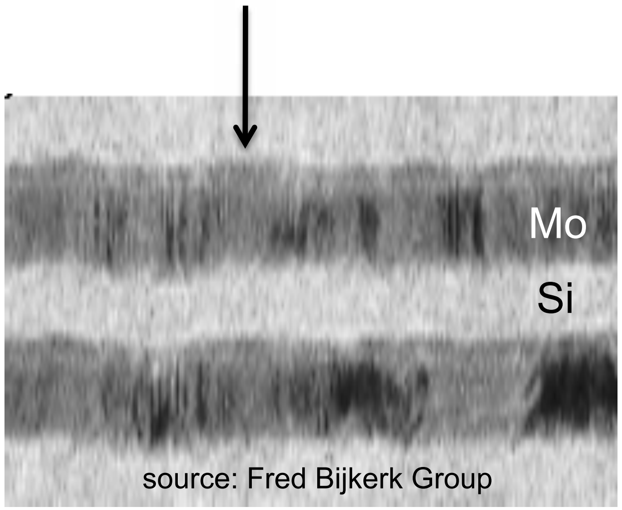
Temporary labs and offices

- Temporary laboratory
  600 m^2 lab space
  In use since mid October 2014

- Temporary offices
  (capacity 96 people)
  In use since end of December 2014
- Long-term housing (Matrix-VII) in preparation (complete in 2018)

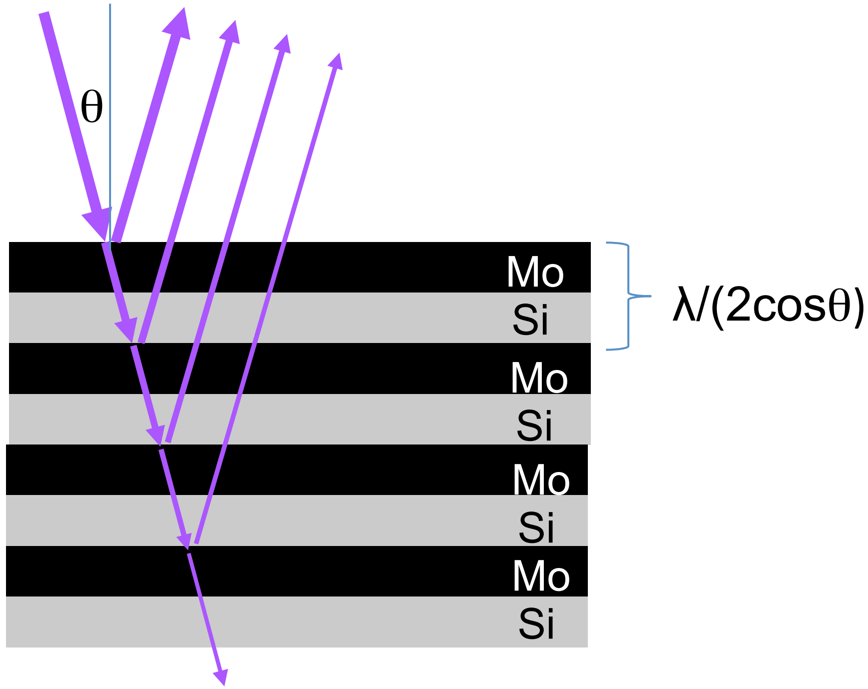
Interface formation in EUV-optics

Roughness + interface film



Mo_xSi_y

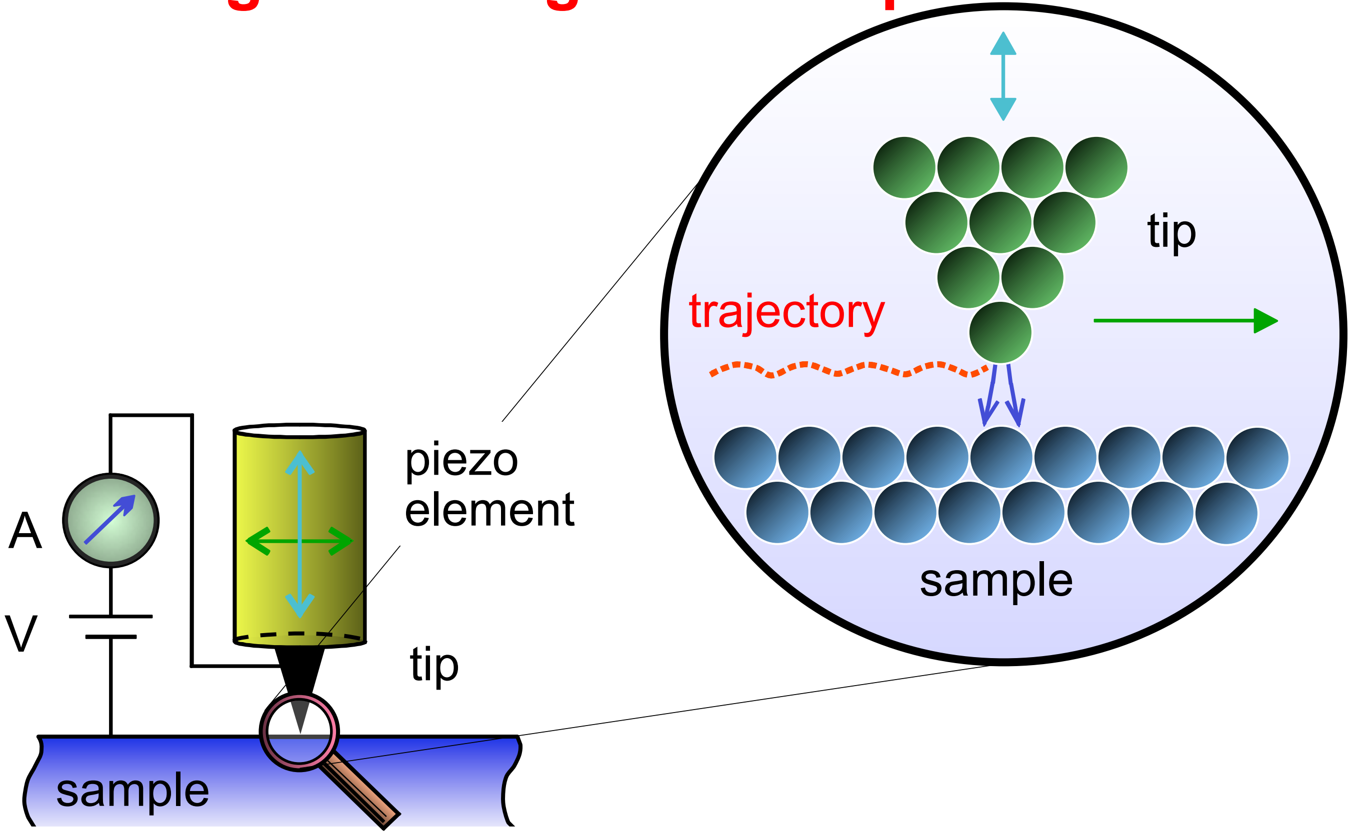
Mo_aSi_b



Why rough and graded!? Reduces reflectivity

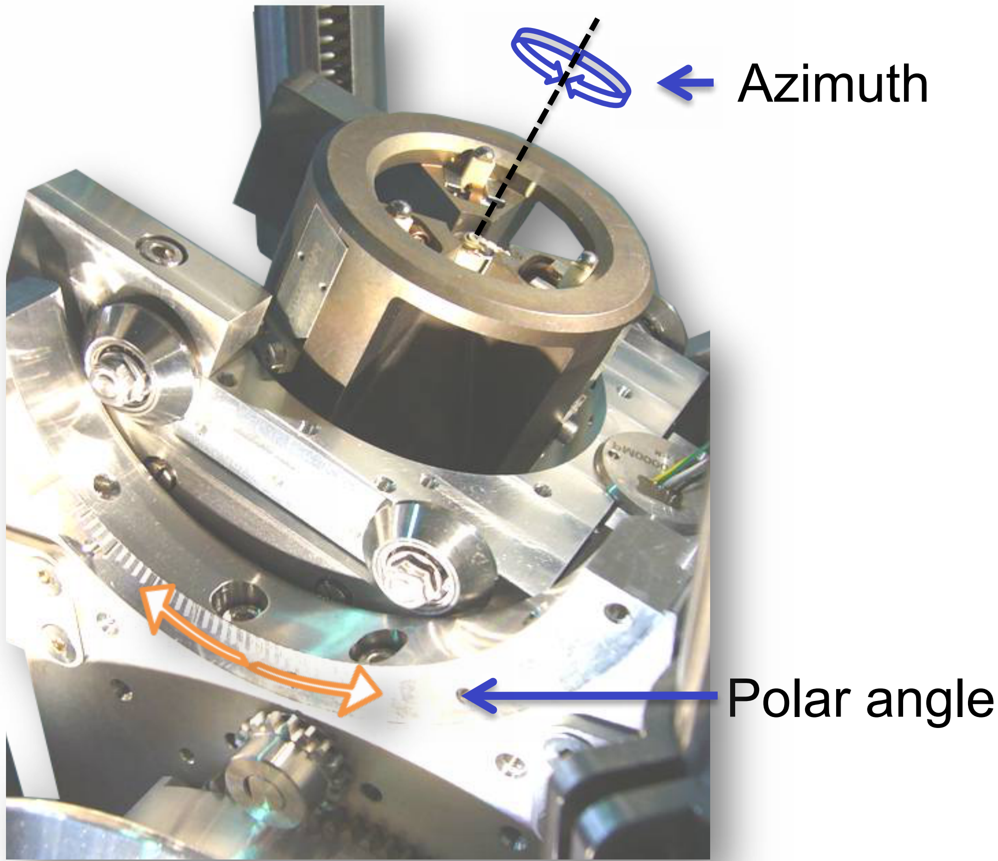
Principle of the STM

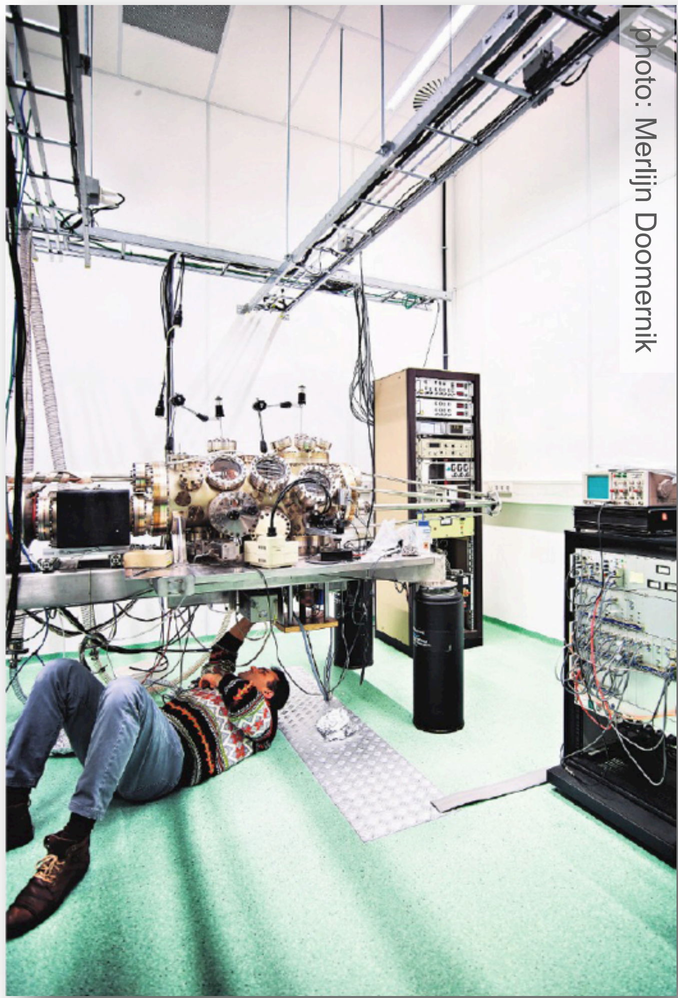
STM = 'Scanning Tunneling Microscope'



Depo-STM: in-situ growth / ion erosion

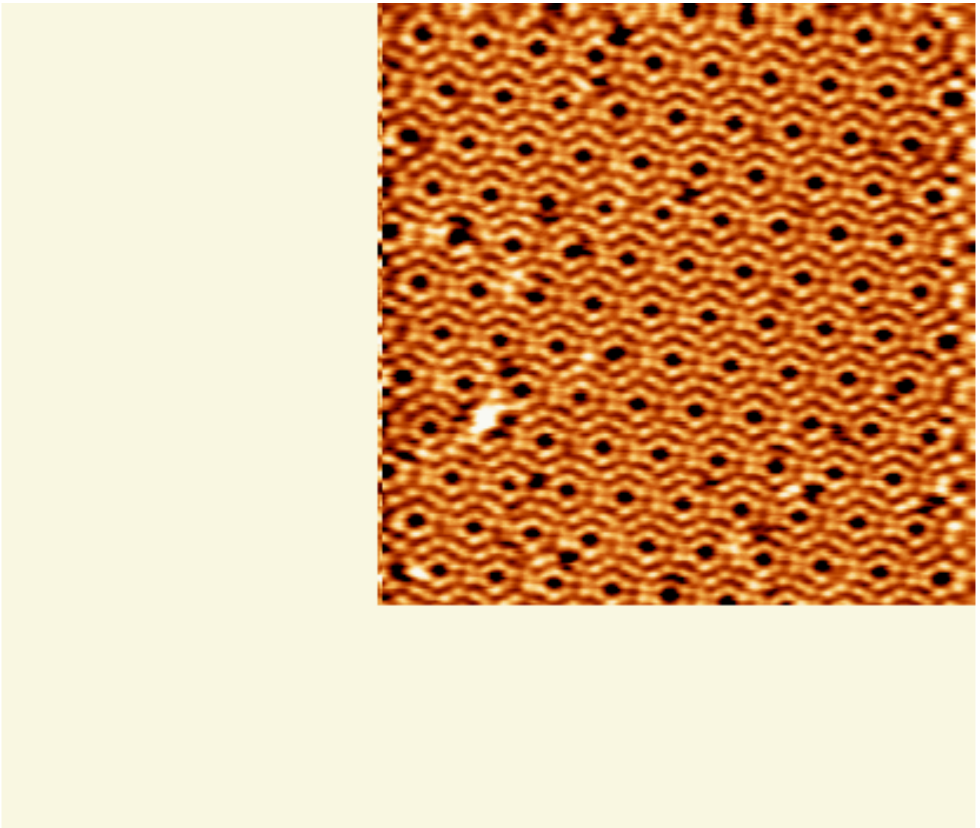
Marcel Rost and
Vincent Fokkema





Live growth: Mo deposition on Si(111)

initial stages: *silicide formation:* $MoSi_2$

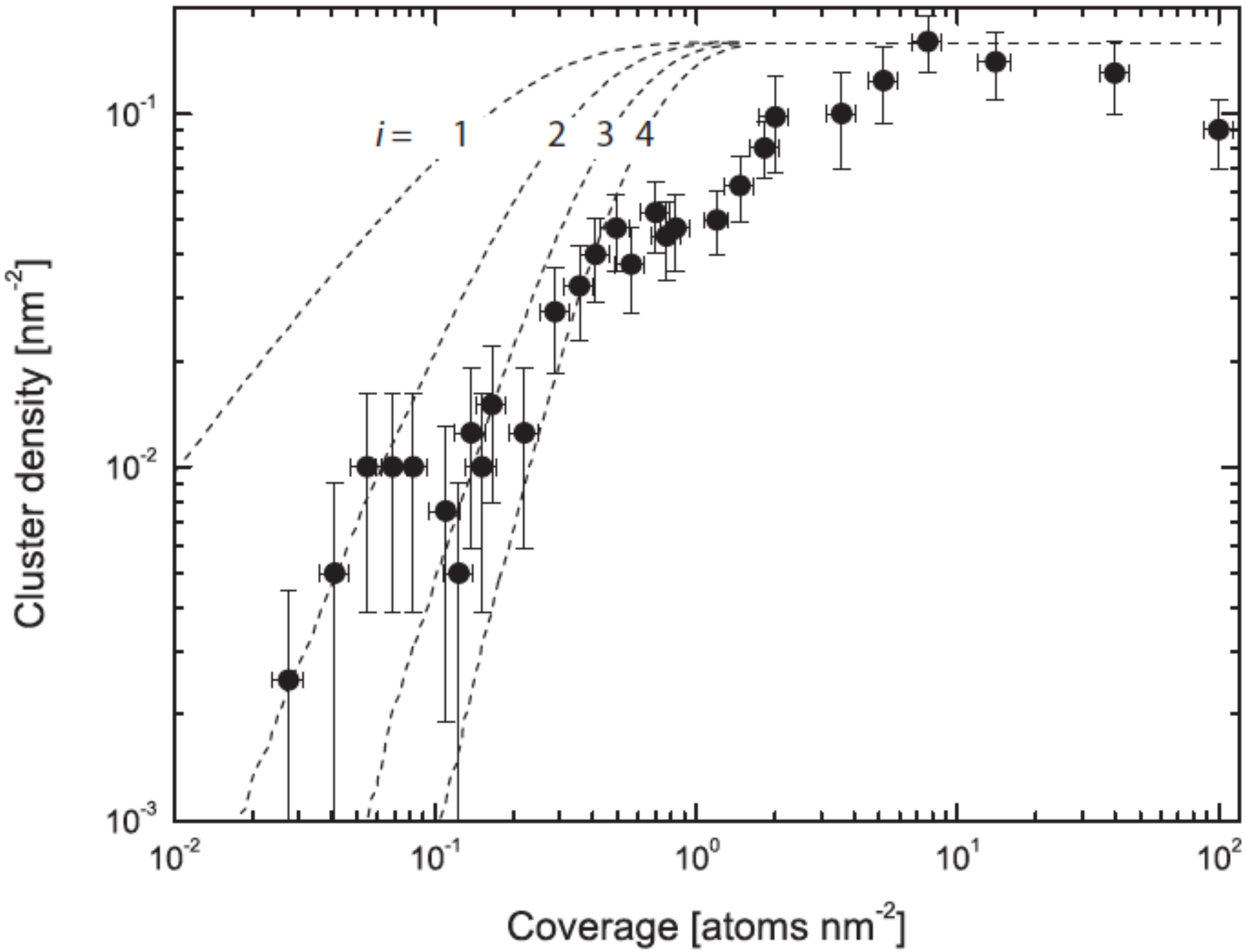


30 nm x 30 nm   1.7 s/frame
0-0.1 nm Mo

Marcel Rost
Vincent Fokkema

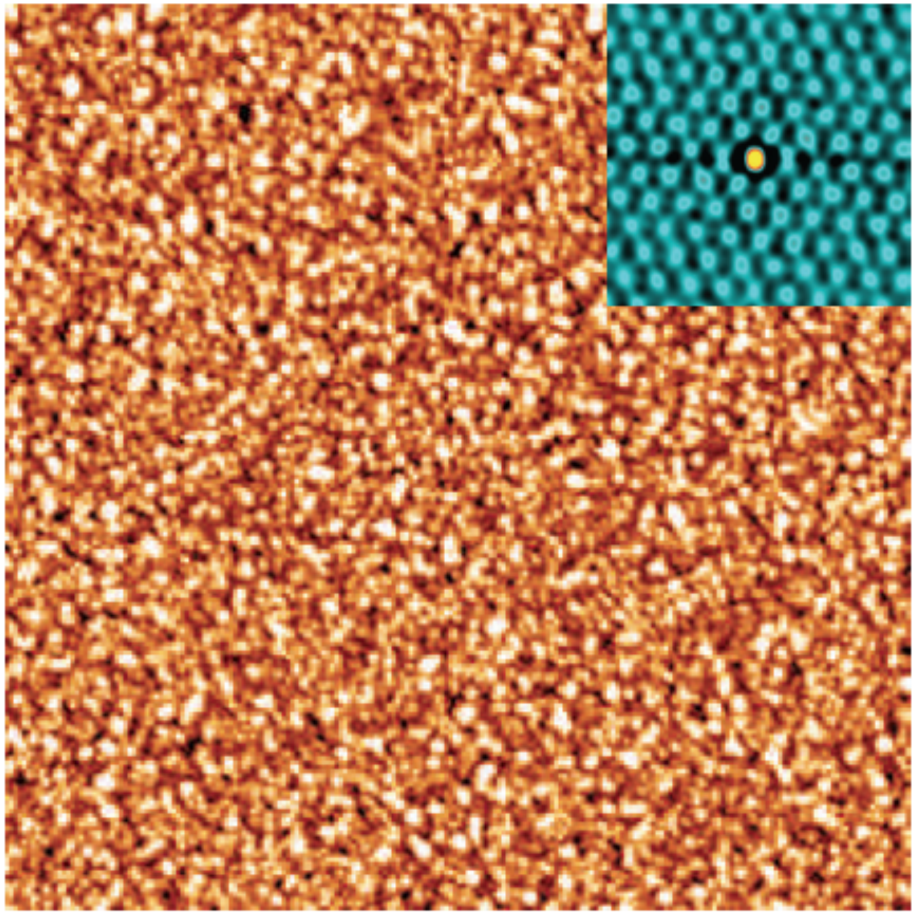
Clusters: number statistics

2 or 3 Mo atoms required to form stable $MoSi_2$ cluster; single Mo atoms remain ‘invisible’, diffusing rapidly within single 7x7 unit cell



Clusters: spatial statistics

Original image



75 nm x 75 nm

7.7 Mo atoms/nm^2

Autocorrelation function:

$$C_A(\vec{r},t) = \left\langle h(\vec{x},t)\, h(\vec{x}+\vec{r},t) \right\rangle$$

Conclusion:

1 cluster per 7x7 unit cell

=> diffusion barrier for Mo

Mo and MoSi$_2$ don't wet Si(111)

Surface free energies:

$$\gamma_{Si} < \gamma_{MoSi_2} < \gamma_{Mo}$$

Similar to scenario for Ni:

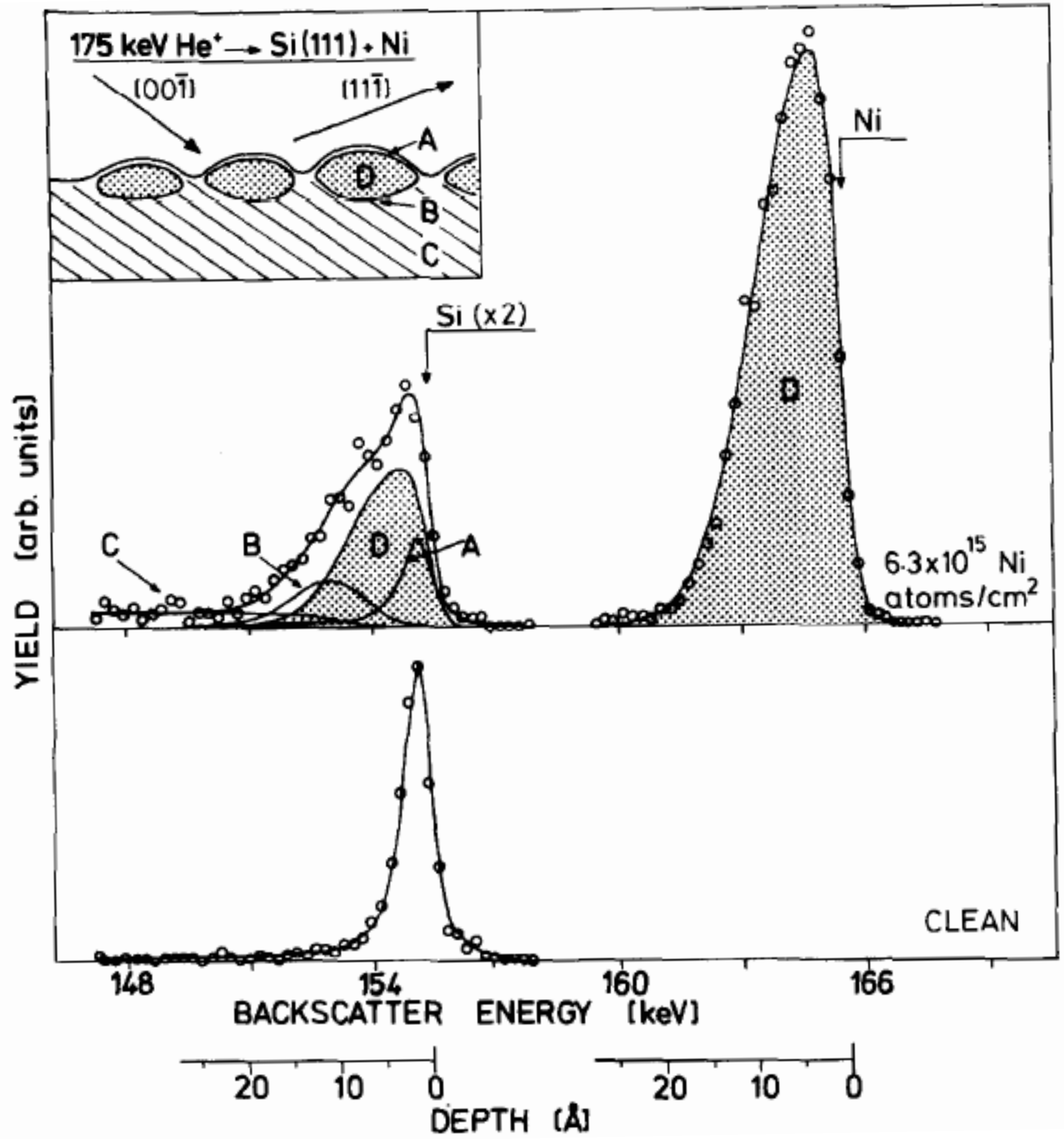
=> silicide islands

with Si skin

(diffusion of Si)

Van Loenen *et al.*

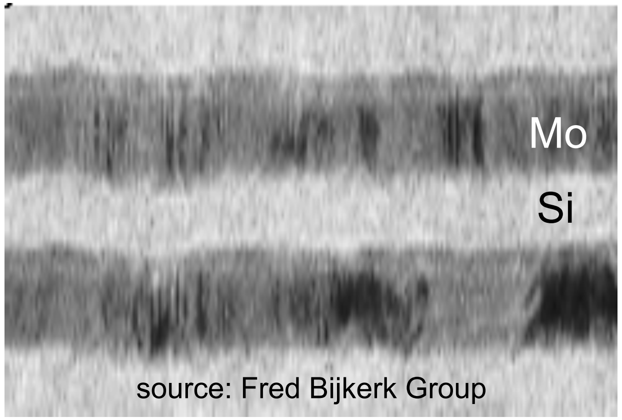
Surf.Sci. **157**, 1 (1985)



Mo and $MoSi_2$ don't wet Si, but Si wets *them*

Surface free energies:

$$\gamma_{Si} < \gamma_{MoSi_2} < \gamma_{Mo}$$

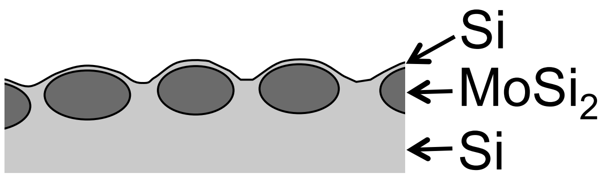


<u>Mo on Si:</u>

=> silicide islands

with Si skin

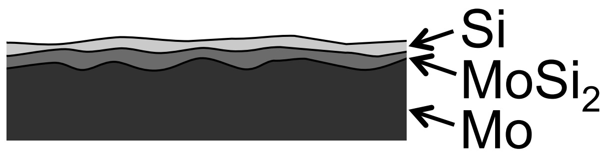
Mo film only after closure of silicide



<u>Si on Mo:</u>

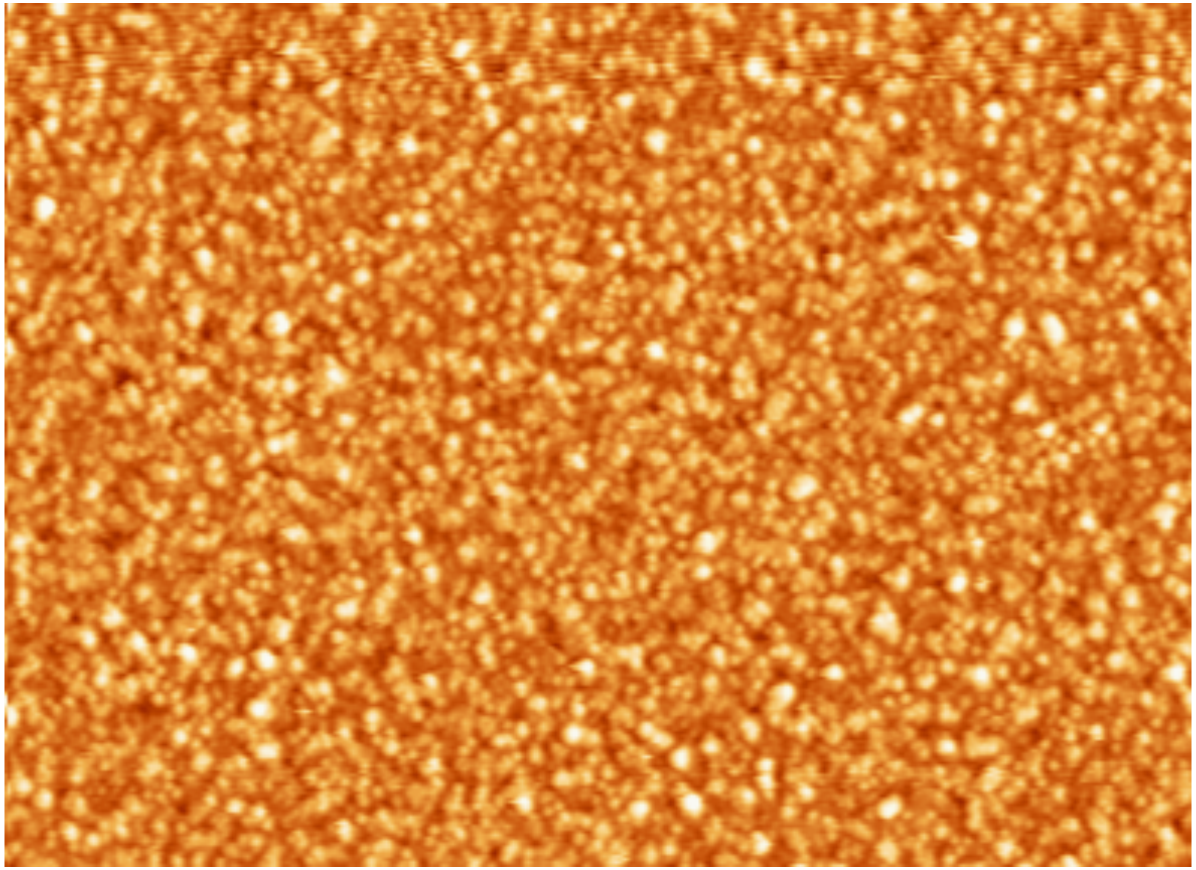
=> thin silicide film

Si overgrows it quickly



Kinetic roughening of Mo on Si

Later stages: polycrystalline Mo growth



75 nm x 55 nm
0.2-5 nm Mo

Mo on Si: roughening statistics

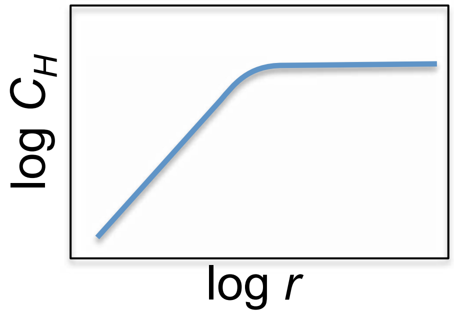
$$w(t)=\left\langle\left[h(\vec{x},t)\right]^2\right\rangle$$ rms height variation

$$C_A(\vec{r},t)=\left\langle h(\vec{x},t)h(\vec{x}+\vec{r},t)\right\rangle$$ autocorrelation function

$$C_H(\vec{r},t)=\left\langle\left[h(\vec{x},t)-h(\vec{x}+\vec{r},t)\right]^2\right\rangle$$ height correlation function

$$C_H(\vec{r},t)\propto r^{2H} \qquad r\ll\xi$$

$$C_H(\vec{r},t)=2w^2 \qquad r\gg\xi$$

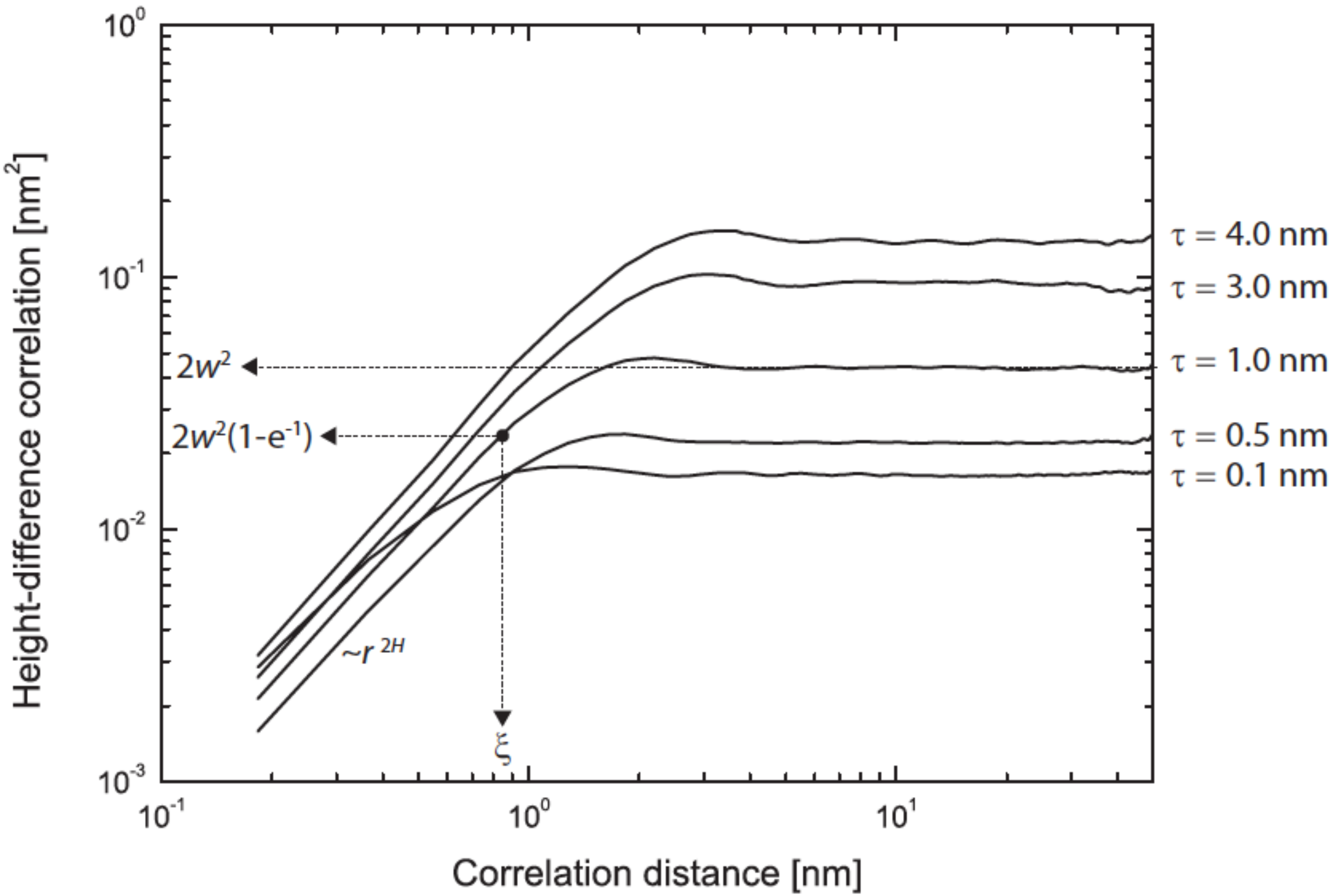


Scaling for kinetic roughening:

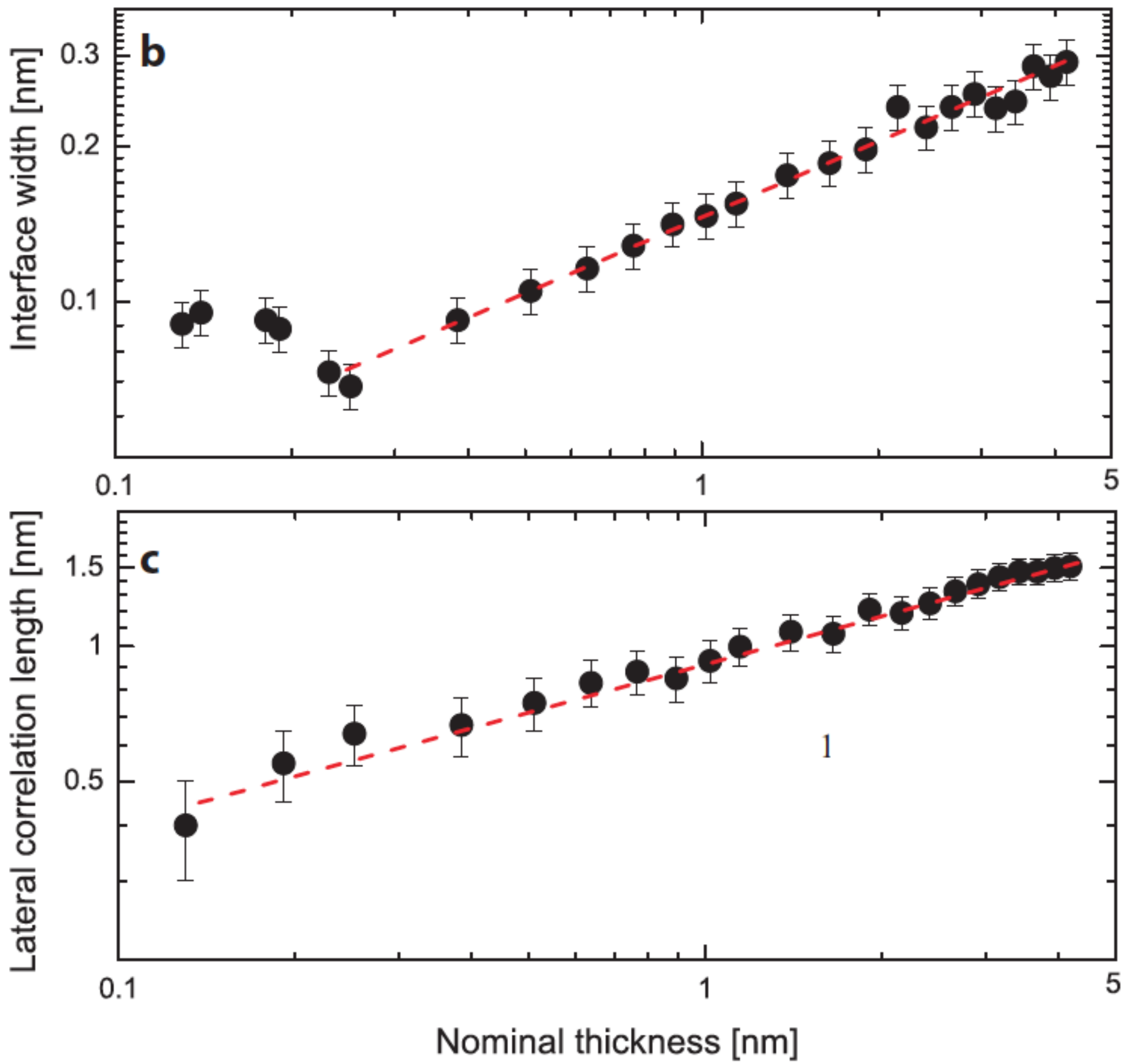
correlation length $\xi(t)\propto t^{1/z}$

roughness $w(t)\propto t^{\beta}$

Mo on Si: roughening statistics



Mo on Si: roughening statistics



$$\beta = 0.49 \pm 0.02$$

$$1/z = 0.34 \pm 0.02$$

Exponents β and 1/z match *Grain-Boundary Crossing model*

Live erosion: 800 eV Ar^+ => Si(111) 7x7

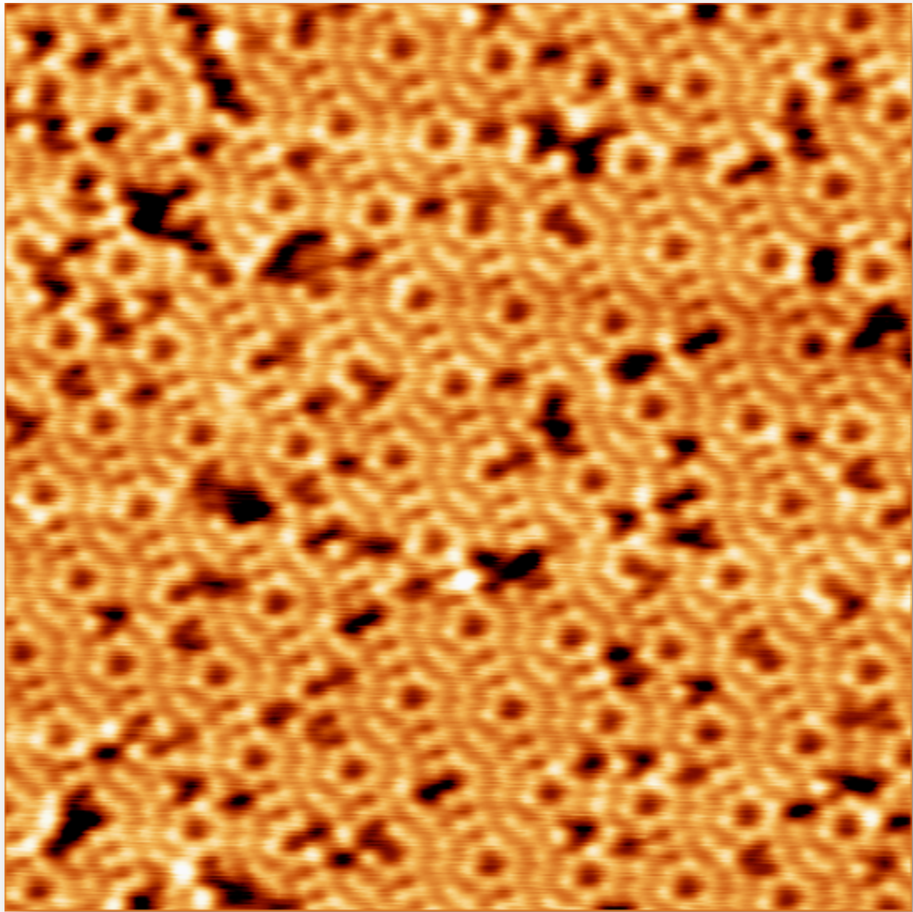
Conditions:

•T = 293 K

•25 x 25 x 0.2 nm^3
•2 V x 200 pA

•10 s / frame
•416 frames

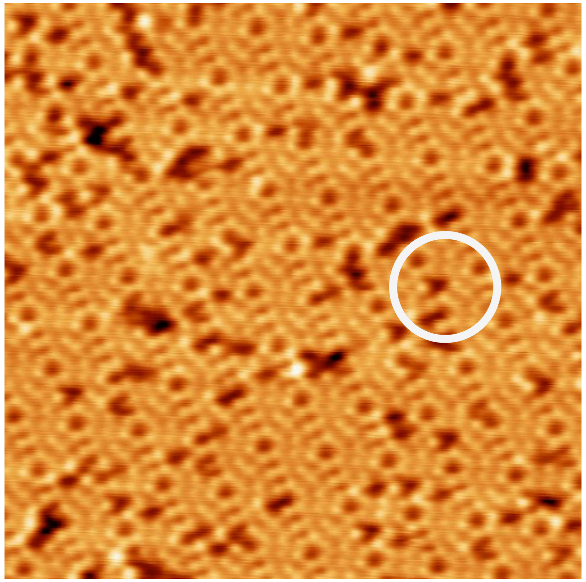
•Polar angle: 75°
•1-3 ions per frame



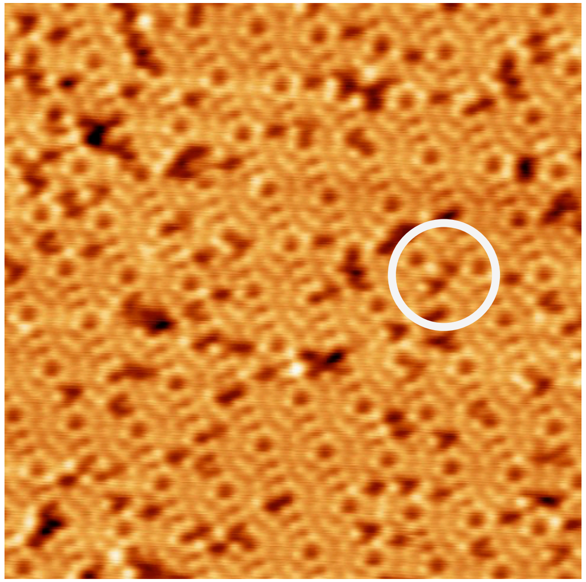
Marcel Rost
Vincent Fokkema

Individual impact events

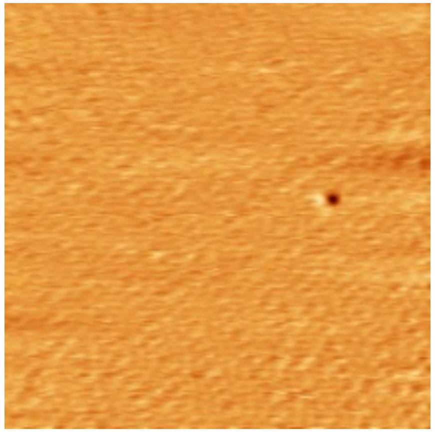
Frame *i*



Frame *i* +1



F(*i* +1) - F(*i*)



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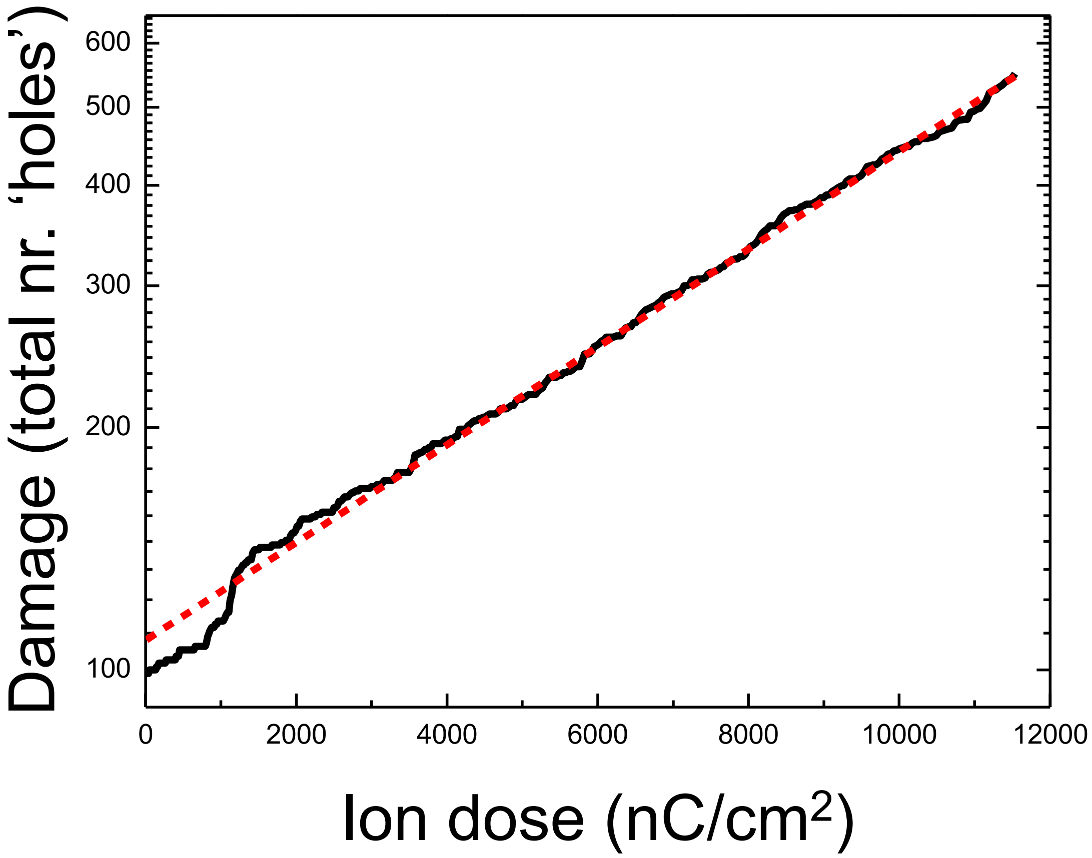
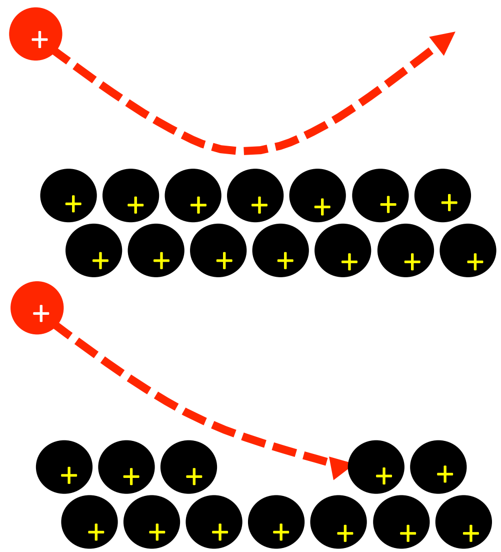
Erosion rate proportional to damage



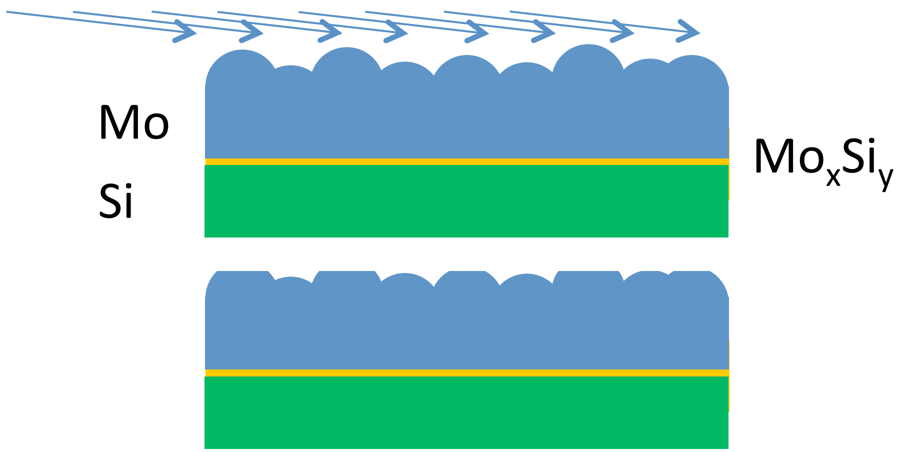


- Removal rate is proportional to the damage already done
- Perfect Si(111)-7×7 is almost perfectly reflective for 800 eV Ar^+ at 75°

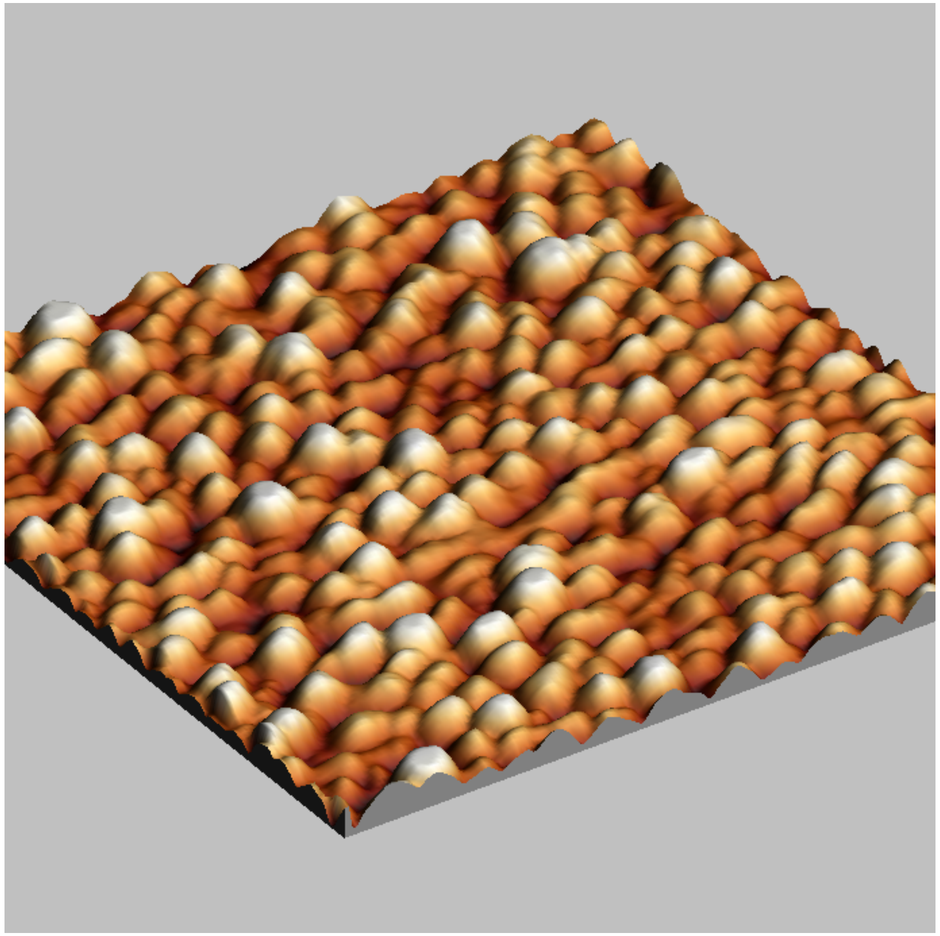
Ion smoothening of deposited Mo

grazing incidence: *ion 'shaving'*

Grazing incidence Ar^+



Shaving:
Scattering, Sputtering & Shadowing
→ **Smoothening**



95 nm x 95 nm x 2.5 nm

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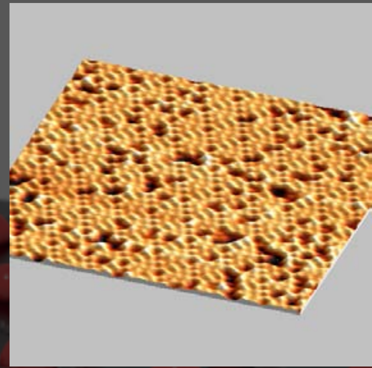
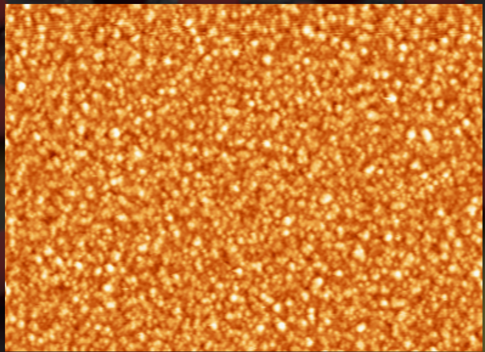
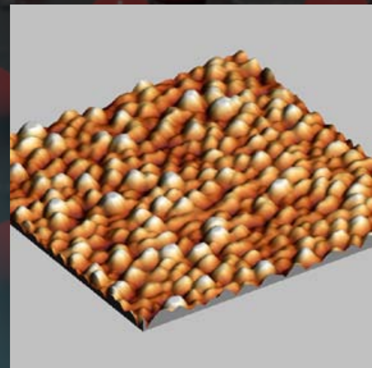
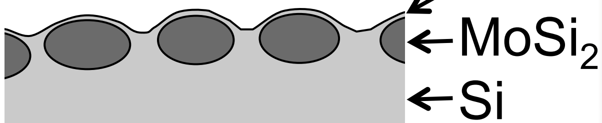
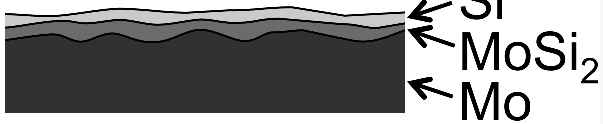


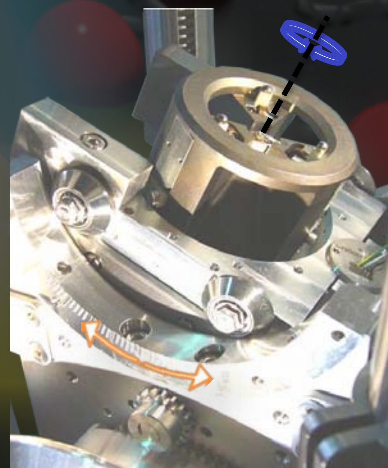


www.ARCNL.nl









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