Materials challenges in EUV lithography

Joost Frenken

ARCNL

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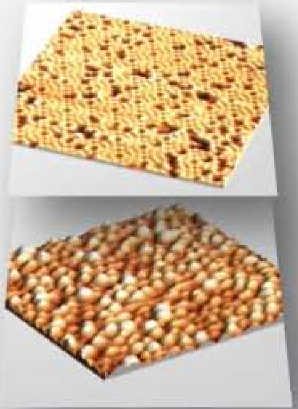

- Motivation: - about ARCNL (who, when, where, why)
- Technical: - special scanning tunneling microscopes
- Examples: - atom-by-atom deposition
  - ion erosion

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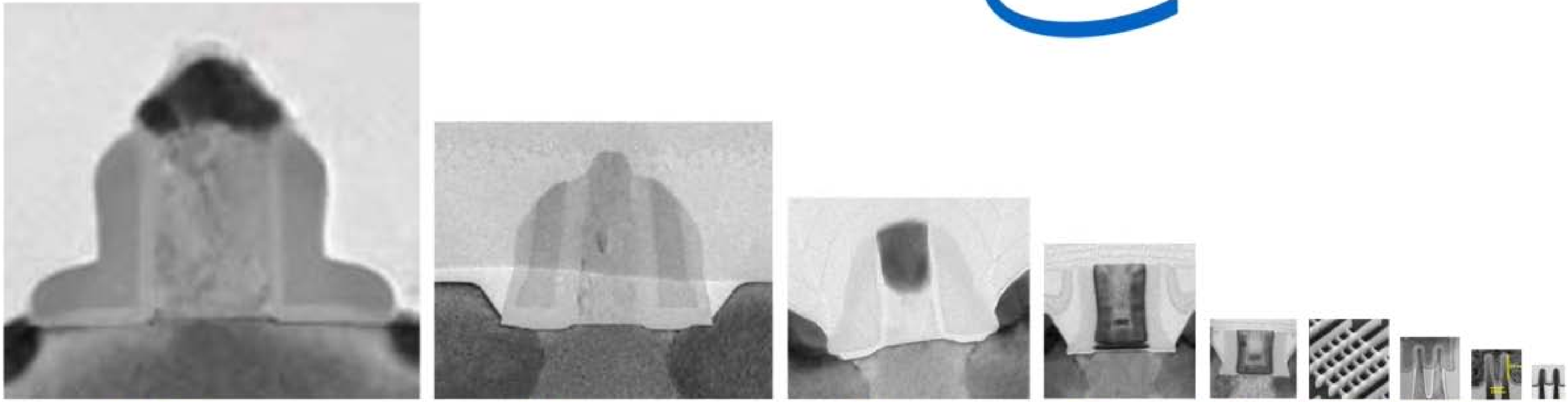
Moore's law: all about lithography

(nano)transistors by intel



130 nm	90 nm	65 nm	45 nm	32 nm	22 nm	14 nm	10 nm	7 nm
2001	2003	2005	2007	2009	2011	2014	2017	2019

Modern lithography tool

extreme ultraviolet light
λ = 13.5 nm

Source: ASML

ARCNL

Advanced Research Center for Nanolithography

Our partners

Universiteit van Amsterdam

VU Vrije Universiteit Amsterdam

ASML

NWO

- Research institute with ~100 researchers, technicians and support staff
- Connected with UvA en VU
- Strong link with ASML

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

ARCNL

www.arcnl.nl

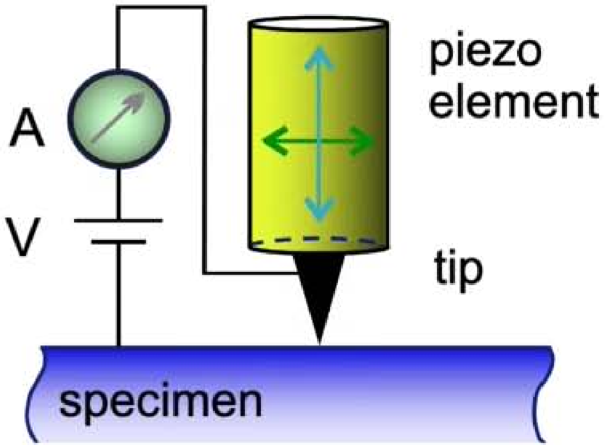
Scientific program

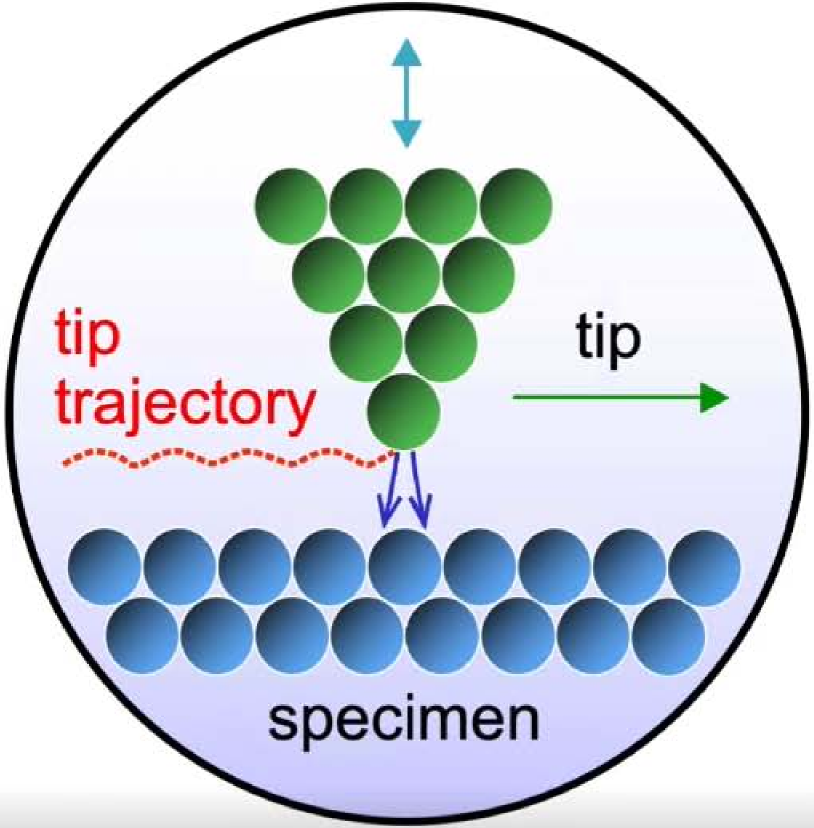
- Three departments
- Final growth stage
- ~ 100 people
- blue = tenure track

SOURCE *Oscar Versolato*	METROLOGY *Stefan Witte*	MATERIALS *a.i. Joost Frenken*
EUV Plasma Processes *Oscar Versolato, Ronnie Hoekstra & Wim Ubachs* tenure 2019	EUV Generation & Imaging *Stefan Witte & Kjeld Eikema*	Nanolayers *Joost Frenken*
Ion interactions *Ronnie Hoekstra* 2020..	Light-Matter Interaction *Paul Planken*	Contact Dynamics *Bart Weber* *Steve Franklin* 2019
	Computational Imaging *Arie den Boef*	Materials & Surface Science for EUVL *Roland Bliem* 2019
	HHG & EUV Science *Peter Kraus*	EUV Photoresists *Sonia Castellanos* left 2020
	Nanoscale Imaging & Metrology *Lyuba Amitonova* 2019	Nanophotochemistry *Fred Brouwer*

INTEGRATION
Joost Frenken (ARCNL), Marjan Fretz (ARCNL) & Wim Symens (ASML)

Scanning tunneling microscopy





Variable-temperature STM

High speed

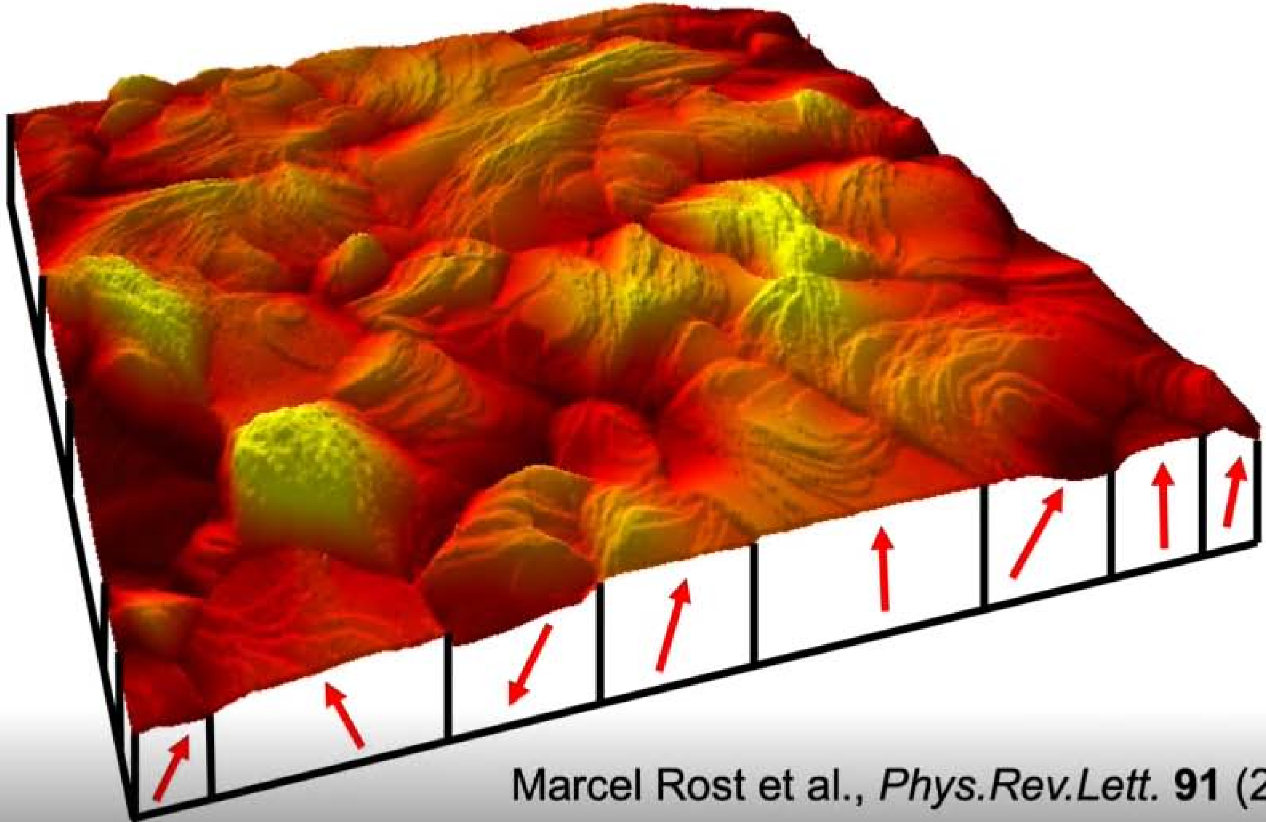
- Speed: ***video-STM***
  0.01 – 25 frames/s (256x256 pixels) x2

Variable temperature

- Range: - *50 K – 1300 K*
- Sweep: - *full T-range:*
  same area in sight' over 300 K
- 'Secret':- *finite-element analysis*

Hoogeman *et al.*, Rev.Sci.Instrum. **69** (1998) 2072
M.J. Rost *et al.*, Rev.Sci.Instrum. **76** (2005) 053710

Evolution of polycrystalline films



Marcel Rost

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Marcel Rost et al., *Phys.Rev.Lett.* **91** (2003) 026101

Gold film directly after deposition

height image

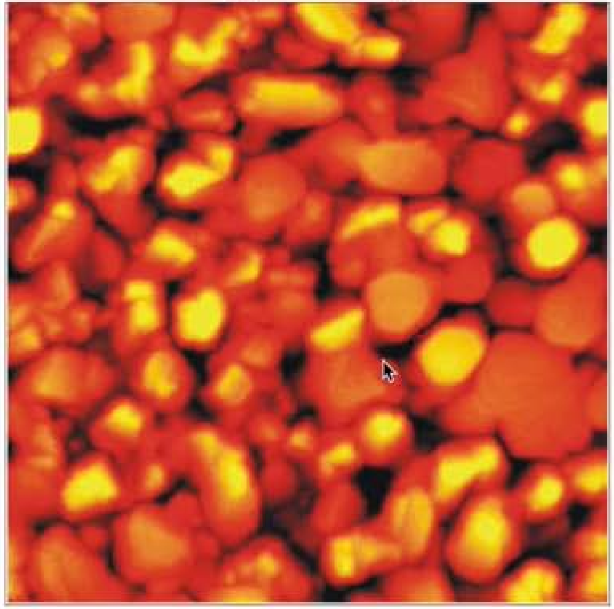
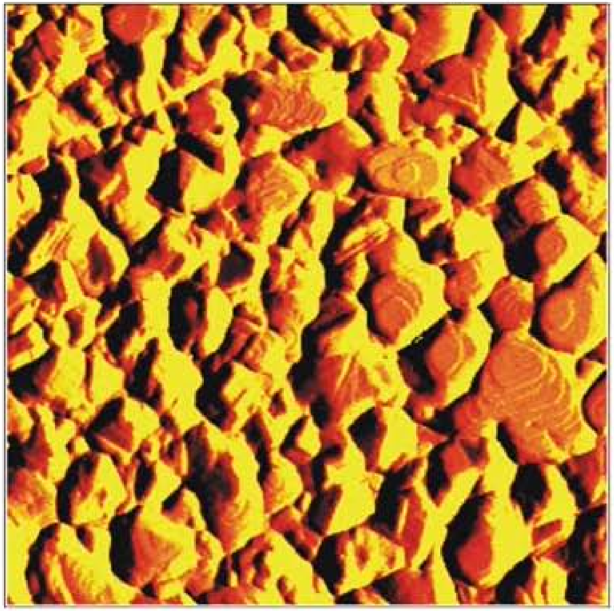


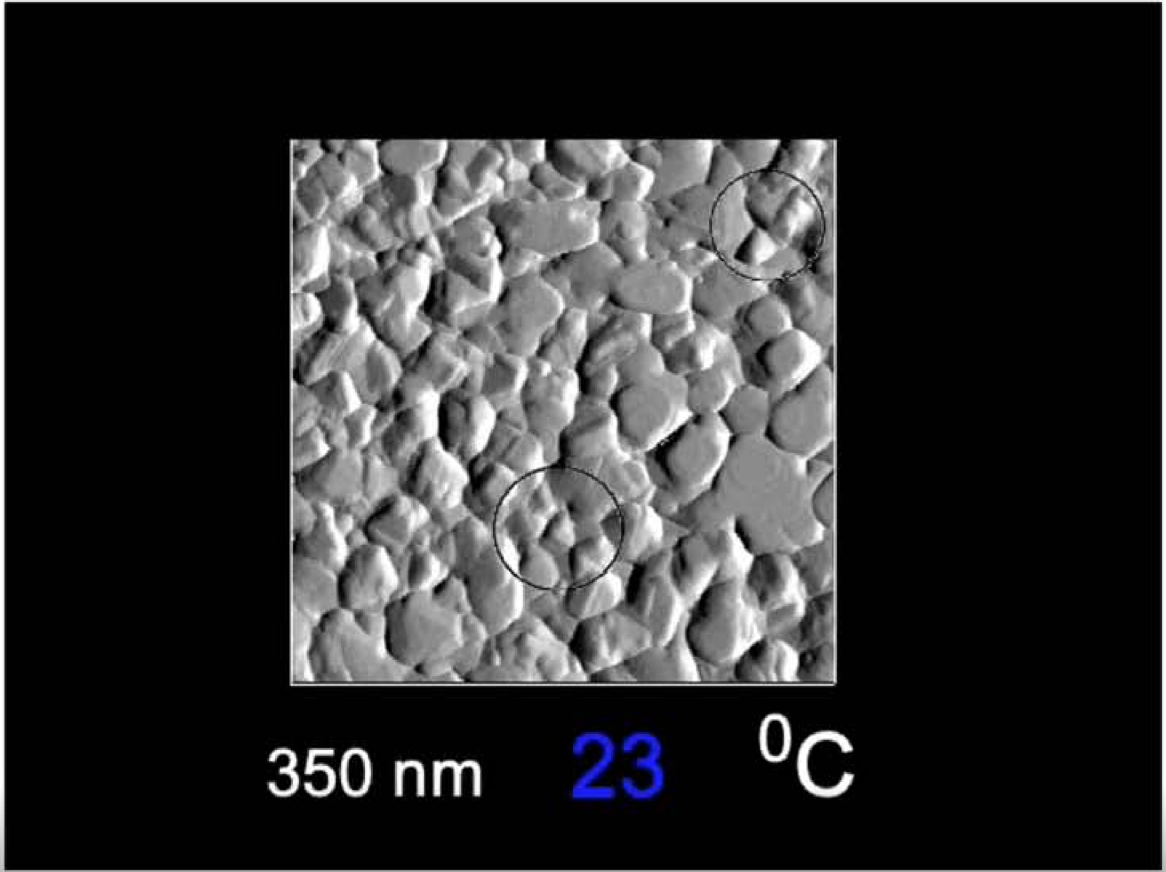
Image 350 nm × 350 nm
total height range 8.4 nm

differentiated (slope)

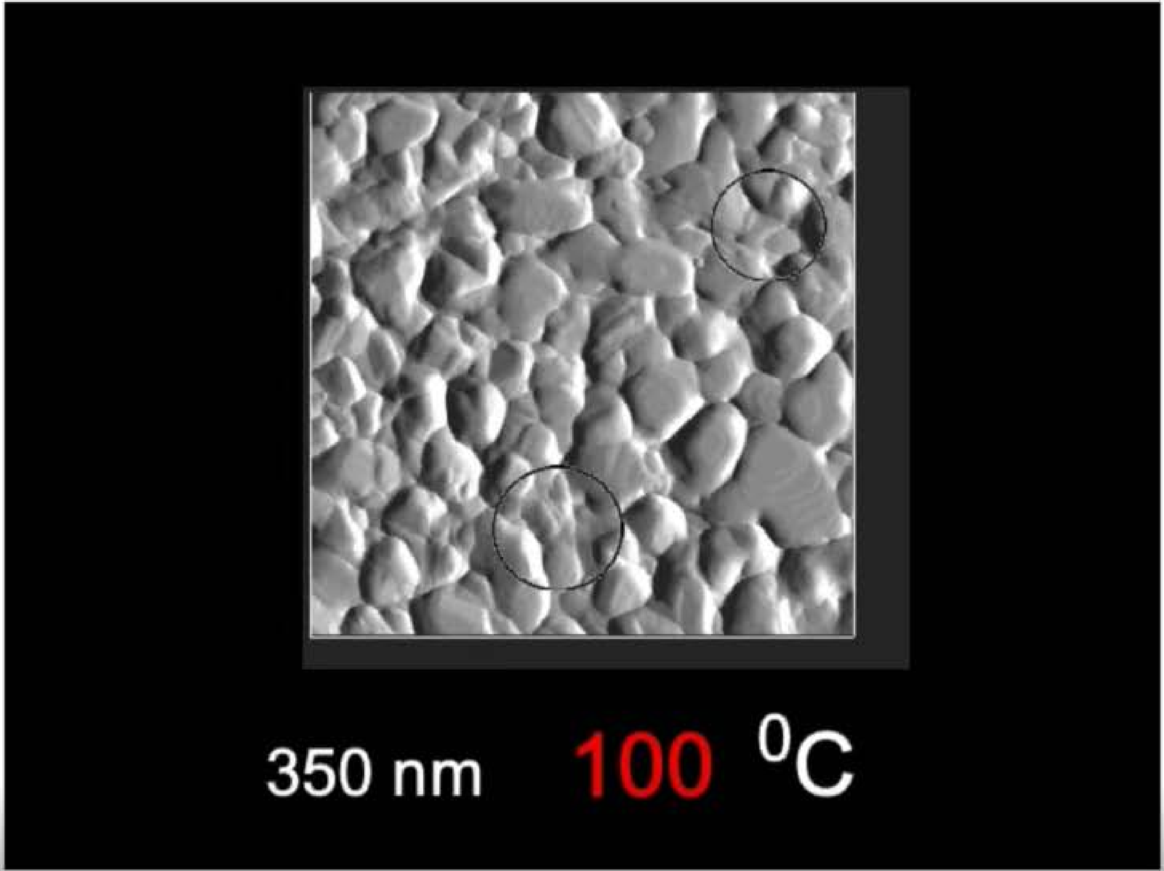


V_t = -0.7 V
$I_t \approx$ 0.05 nA

Initial stage: 23°C → 100°C (258 min)



Initial stage: 23°C → 100°C (258 min)



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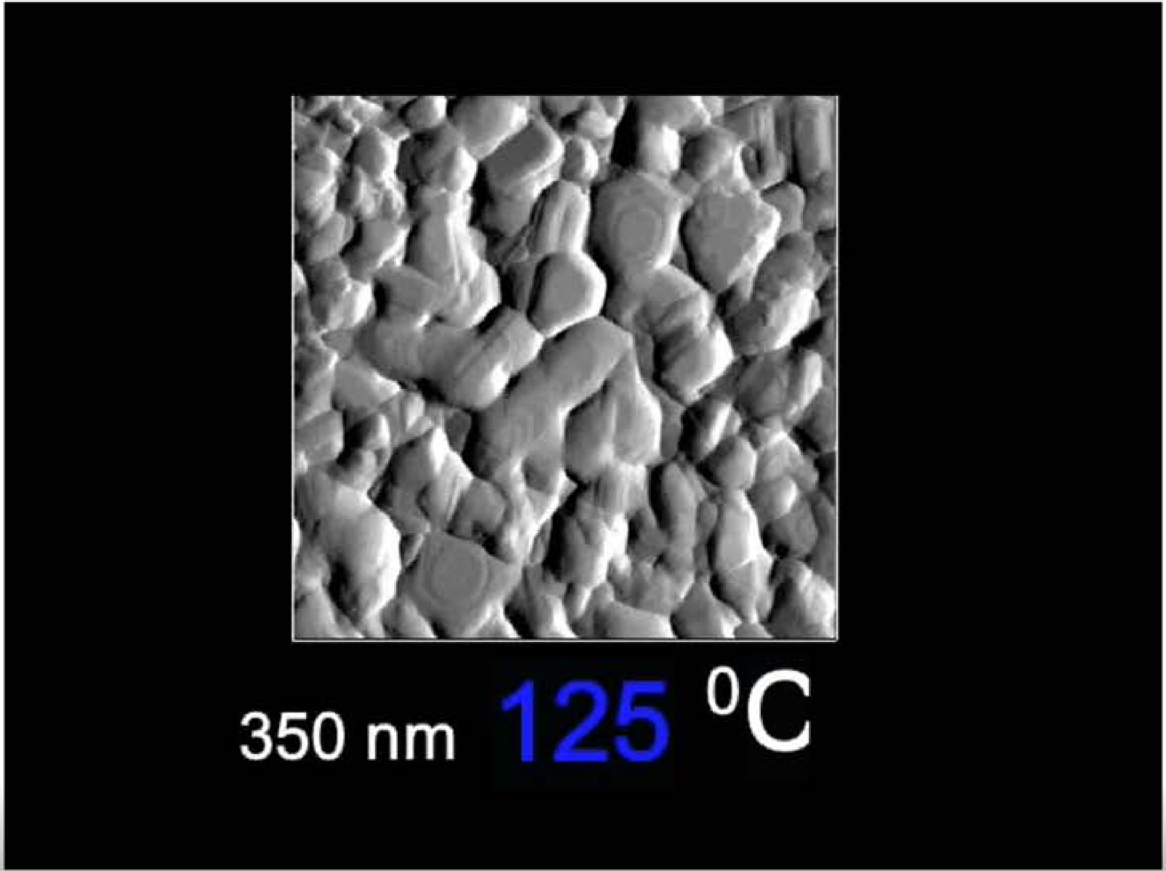
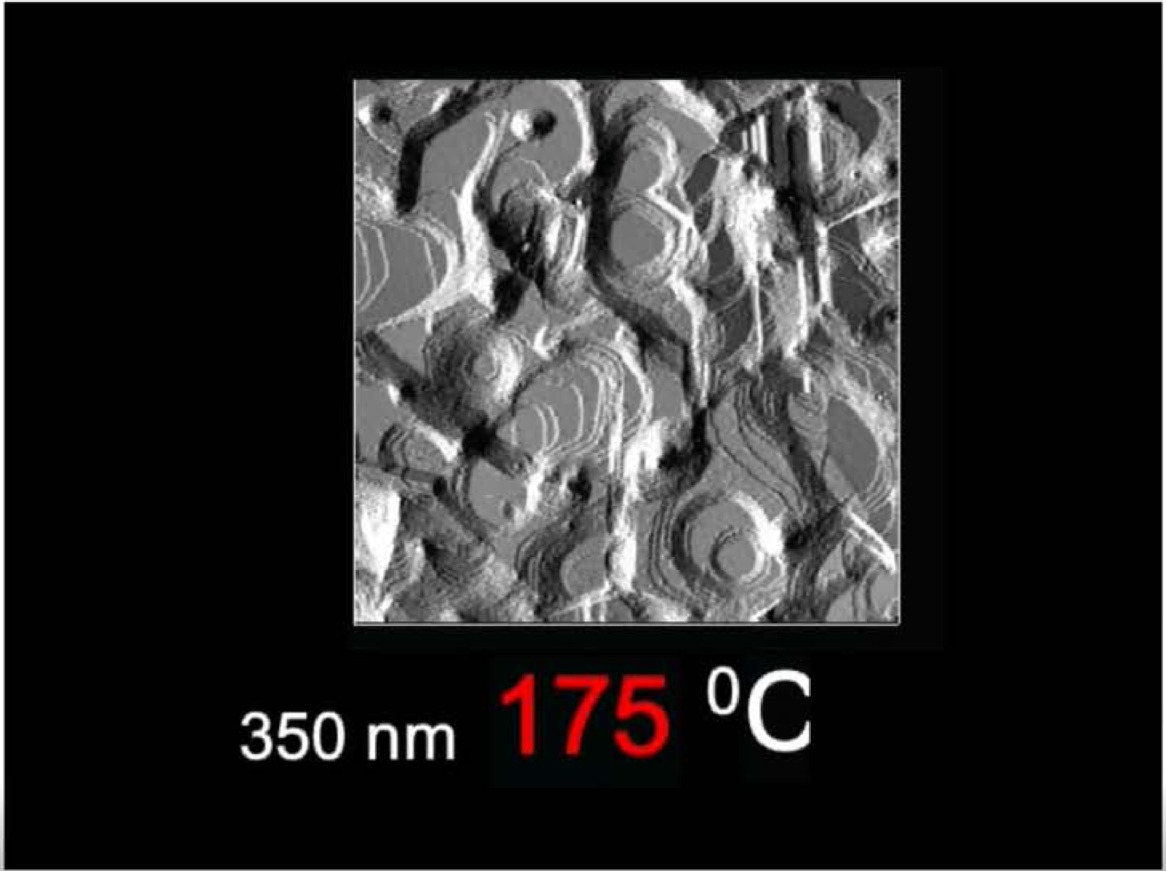
Intermediate: 125°C → 175°C (394 min)



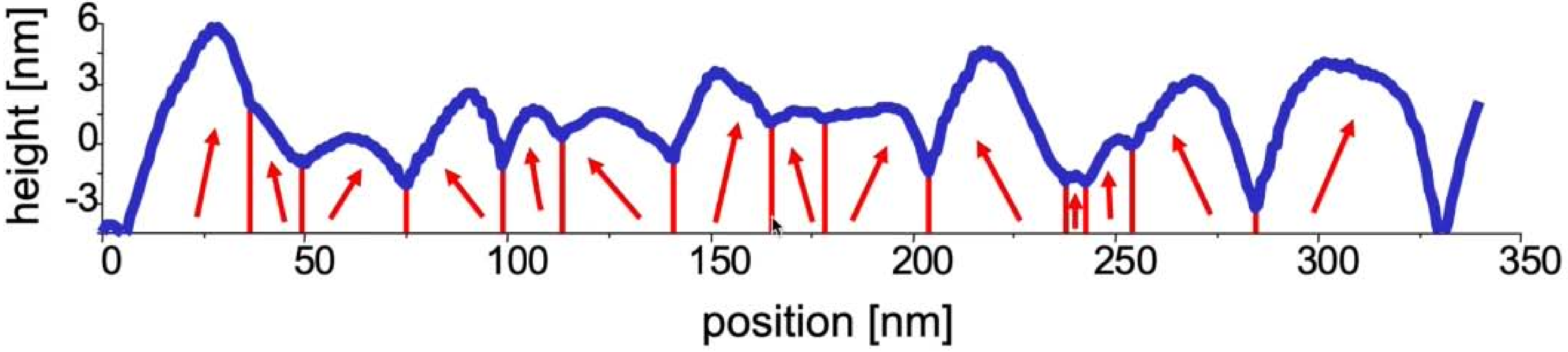
ARCNL

Intermediate: 125°C → 175°C (394 min)

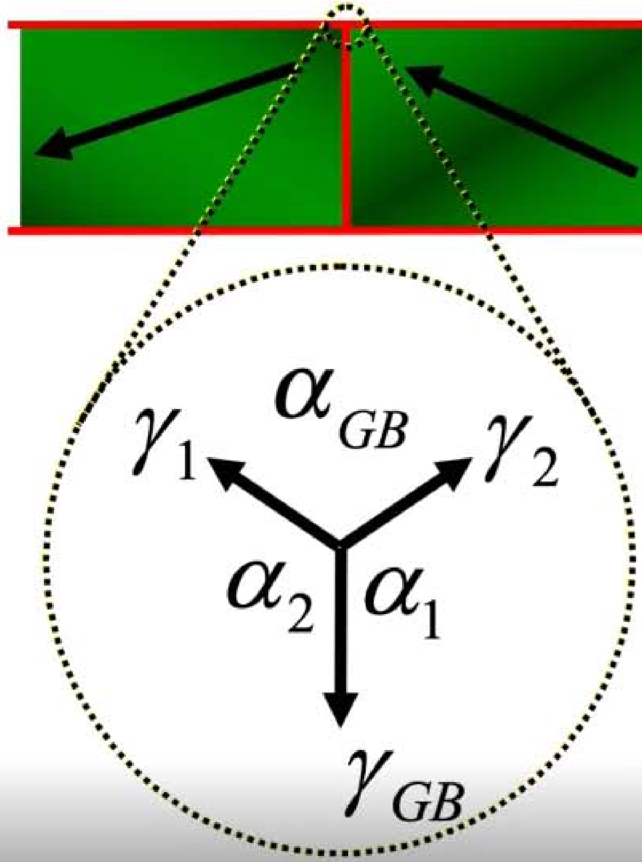


Typical height line: grooves at the GB's

(directly after deposition)



Equilibrium shape at the triple point (line)

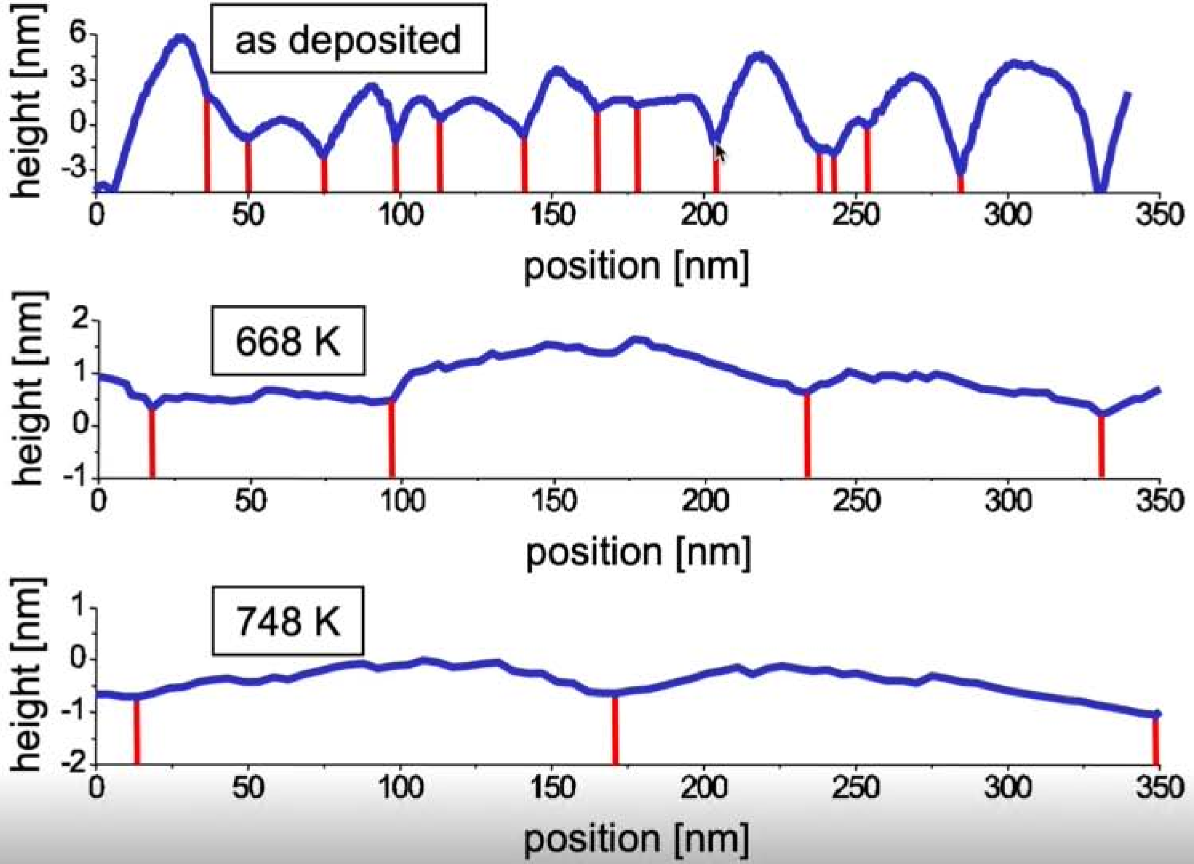


$$\gamma_1 \simeq \gamma_2 = \gamma_s$$

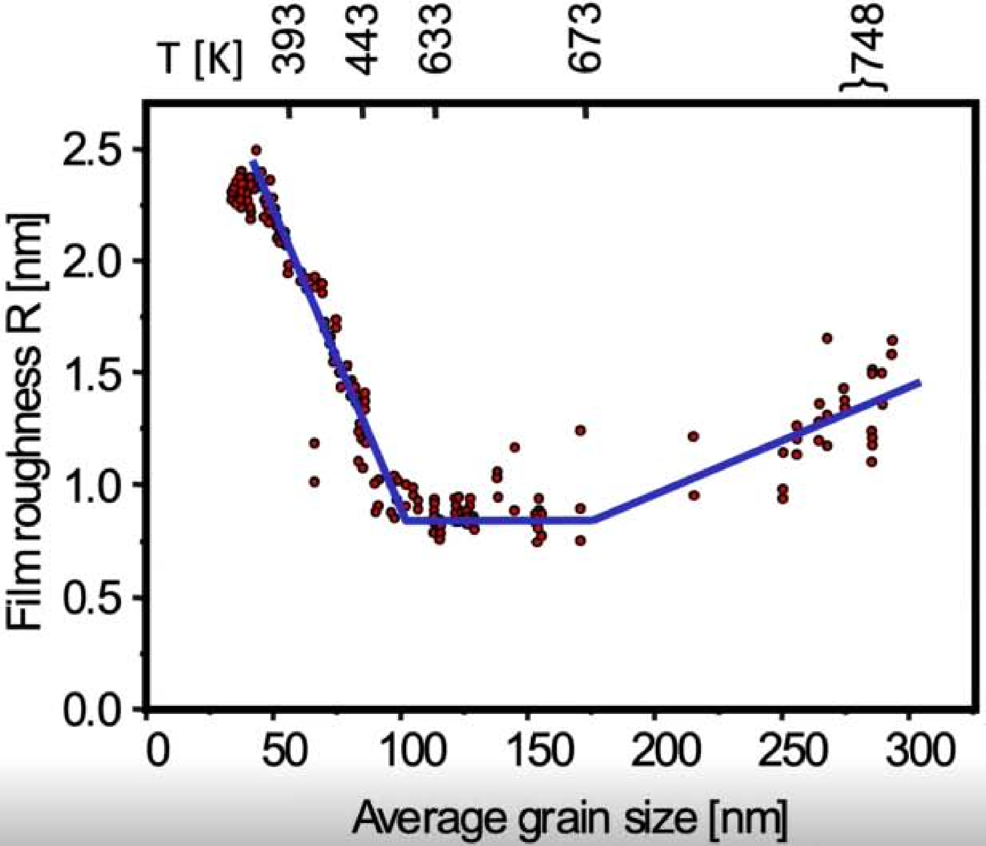
$$\Rightarrow$$

$$\alpha_{GB} \simeq 2\arccos\left(\frac{\gamma_{GB}}{2\gamma_s}\right)$$

Evolution of grains and roughness



Evolution of film roughness

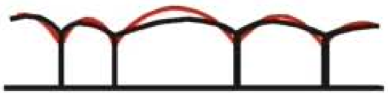


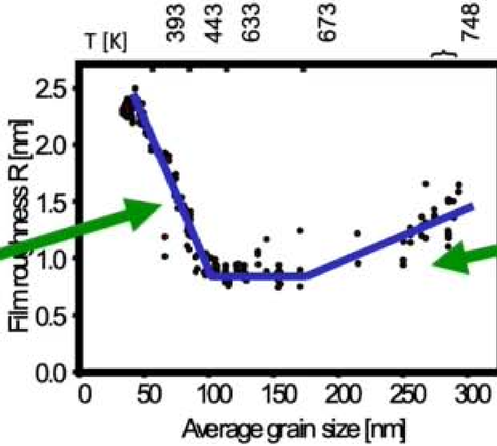
Initial *DE*CREASE followed by *IN*CREASE!!?

Explanation: roughness evolution

Surface at all times in equilibrium with grain boundary structure of film

Decreasing average grain boundary energy





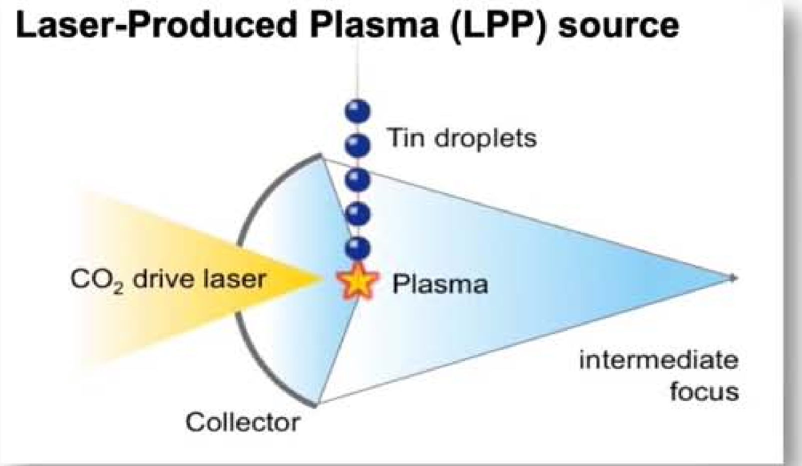
Grain growth: self-similar scaling

Thin films in EUV optics

EUV optics

Collector lens:
polished with precision of 50 pm !!!

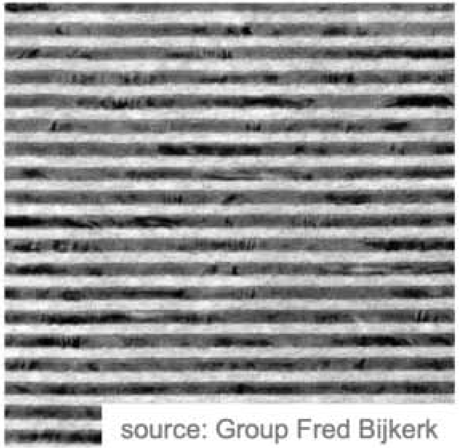
ZEISS CARL ZEISS SMT



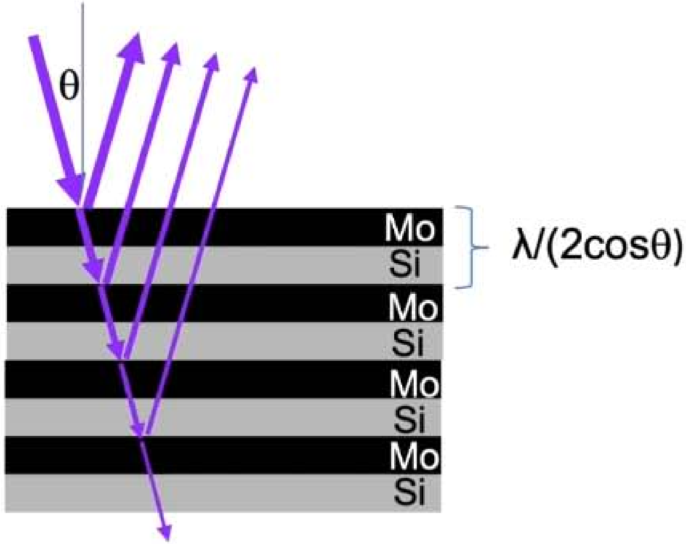
Thin films in EUV optics

EUV optics

Mirror for **13.5** nm light
thickness of 1 double-layer: **6.25 nm**



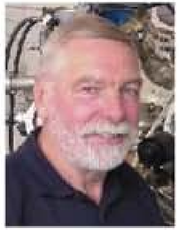
source: Group Fred Bijkerk



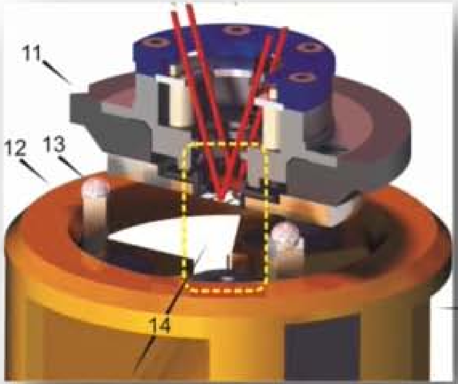
Depo-STM: in-situ growth and erosion

Cristina
Sfiligoj

Victor
Vollema



Jan
Verhoeven



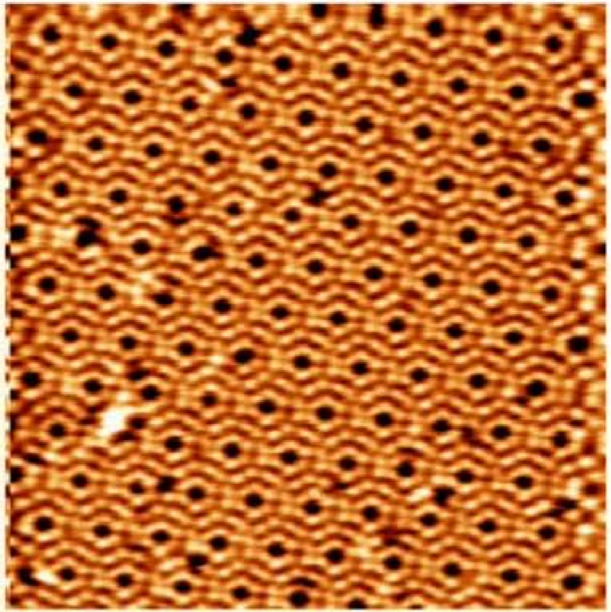
Atom-by-atom deposition: Mo on Si

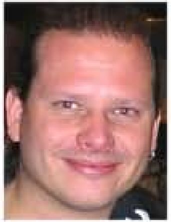
30 nm x 30 nm
1.7 s/frame

slow deposition
of 0.1 nm Mo
on clean Si(111)

Si-Mo interface becomes
rough and graded:

silicide formation



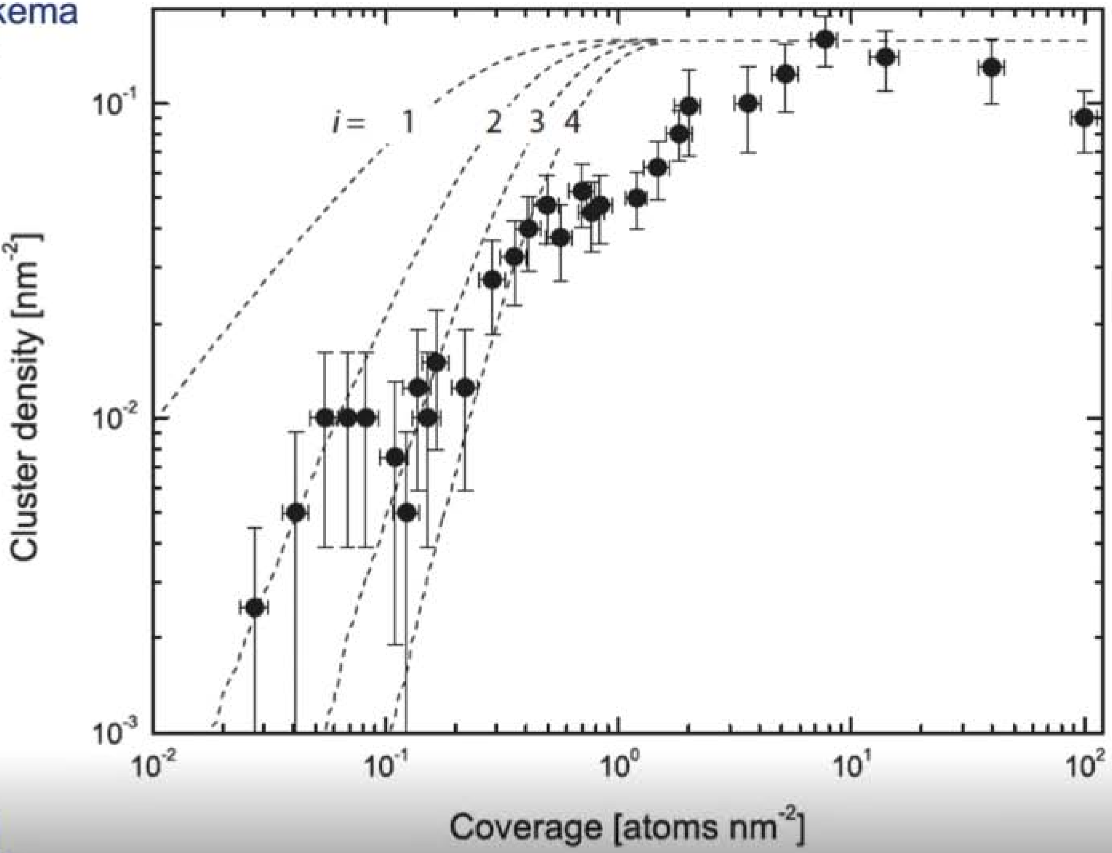


Marcel
Rost

Vincent
Fokkema

Clusters - number statistics

Vincent Fokkema
Marcel Rost

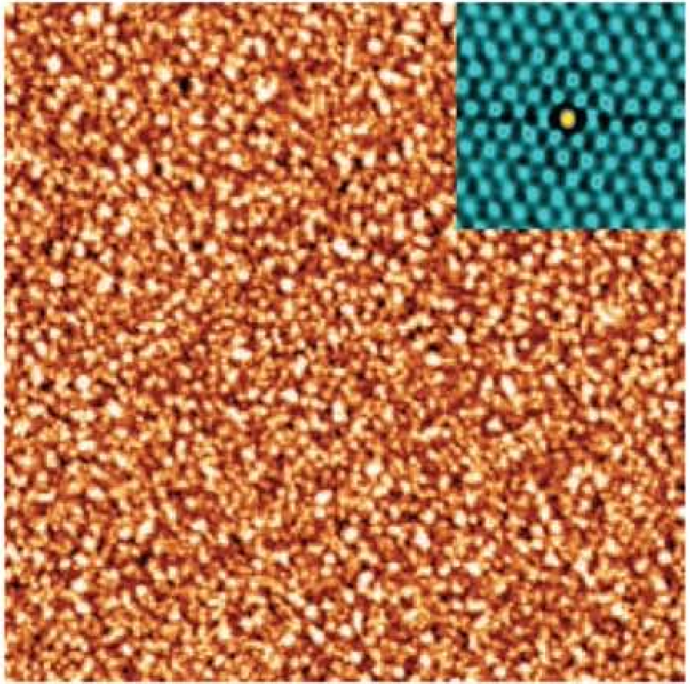


- 2 or 3 Mo atoms required to form stable $MoSi_2$ cluster;
- single Mo atoms remain 'invisible', diffusing rapidly within single 7x7 unit cell

Clusters – spatial statistics

Vincent Fokkema
Marcel Rost

Original image



75 nm x 75 nm
7.7 Mo atoms/nm^2

Autocorrelation function:

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

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:

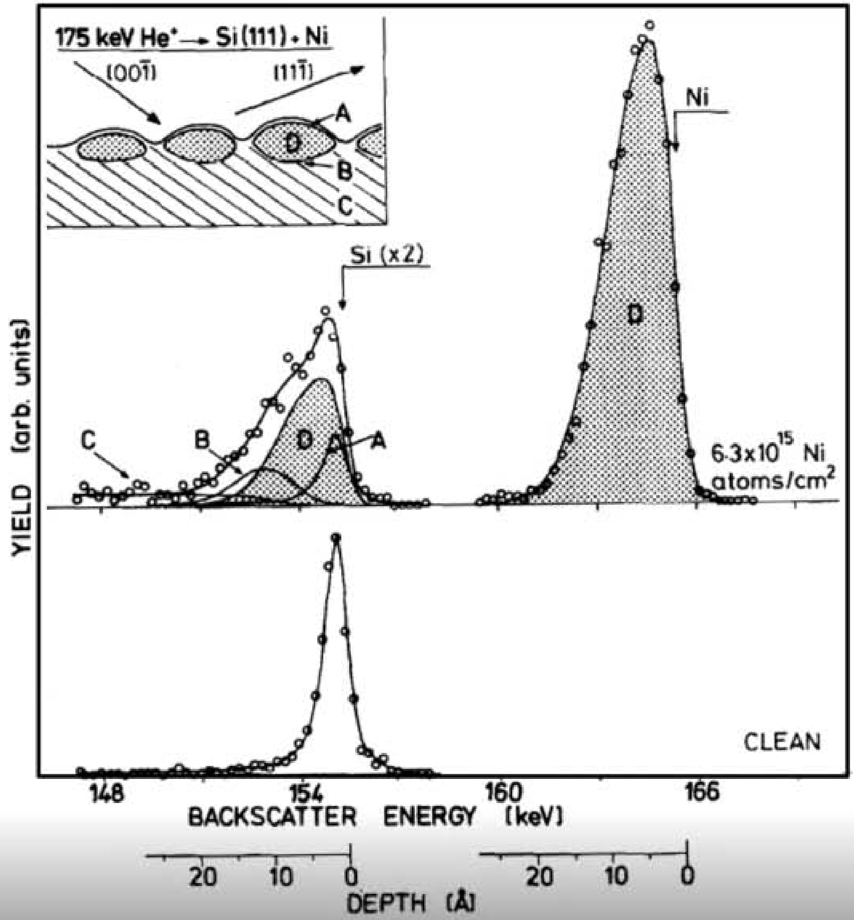
=> silicide islands

with Si skin

(diffusion of Si)

Van Loenen *et al.*

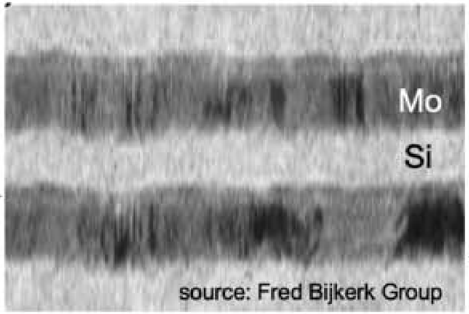
Surf.Sci. **157**, 1 (1985)



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

Surface free energies:

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



Mo on Si:

=> silicide islands

with Si skin

Mo film only after closure of silicide

Si on Mo:

=> thin silicide film

Si overgrows it quickly

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Later growth stage: Mo on Si(111)

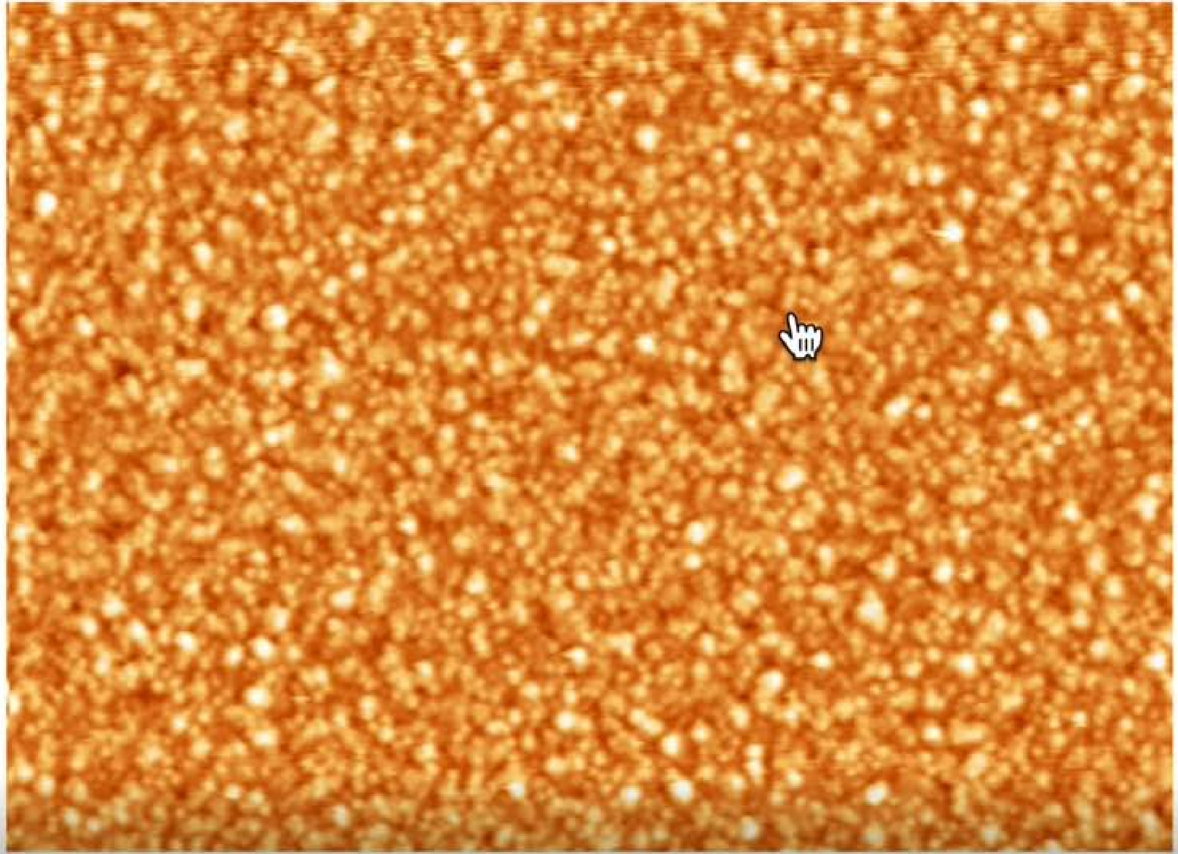
Vincent Fokkema
Marcel Rost

e-beam evaporator
0.2 – 5.0 nm Mo

75 nm x 55 nm

polycrystalline Mo growth

kinetic roughening



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

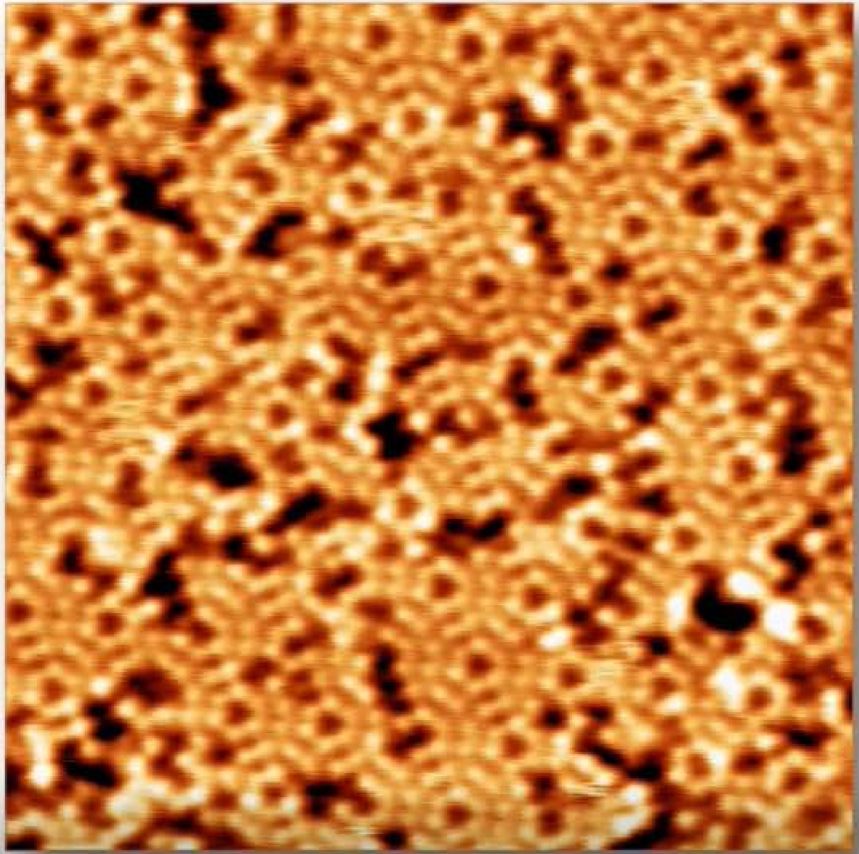
Conditions:

•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



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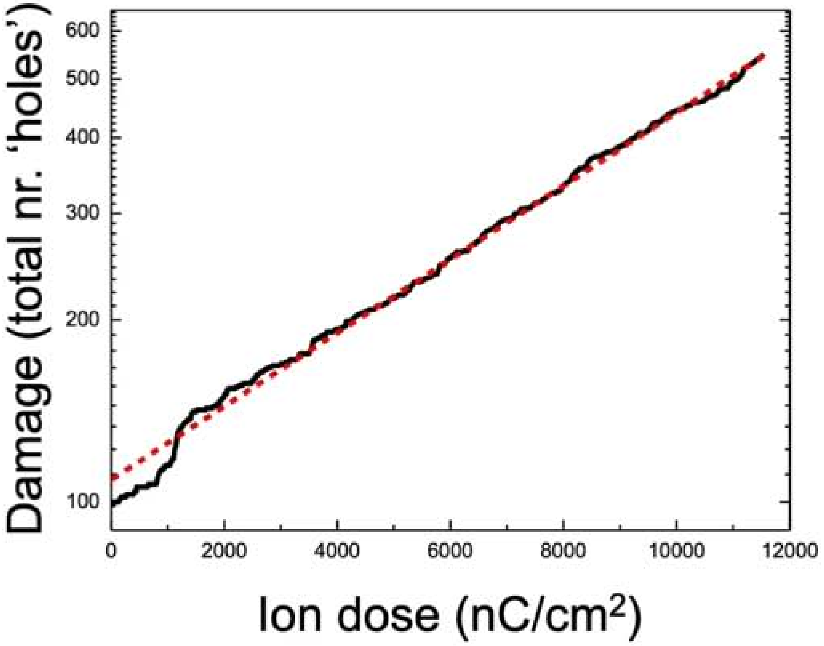
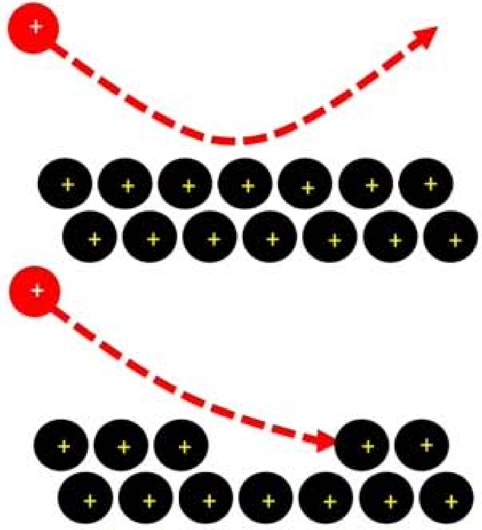
Erosion rate proportional to damage





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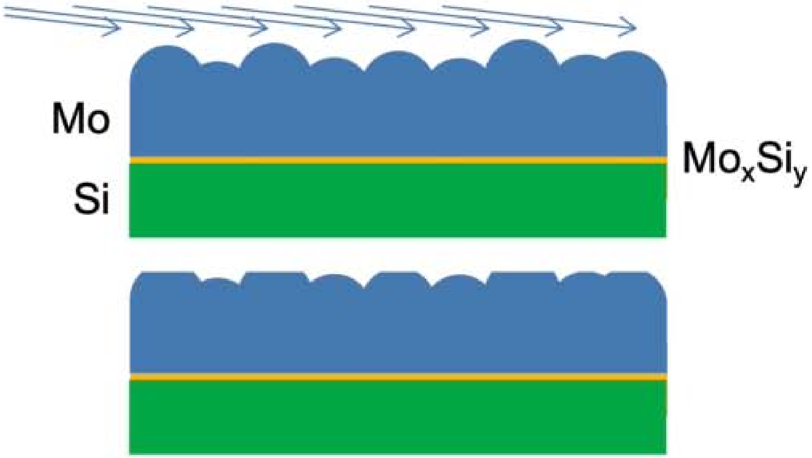
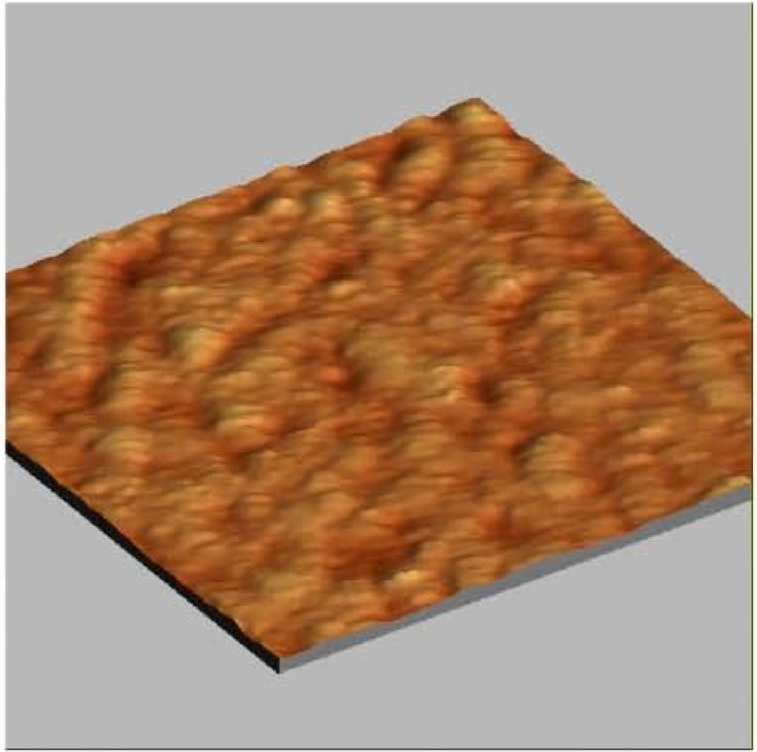
Ion smoothening of deposited Mo

grazing incidence Ar^+ ion 'shaving'



Scattering, Sputtering & Shadowing
→ Smoothening



95 nm x 95 nm x 2.5 nm

Marcel Rost
Vincent Fokkema

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Victor Vollema, Jan Verhoeven

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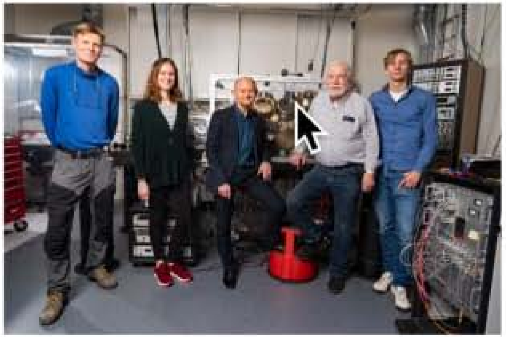
Vincent Fokkema, Marcel Rost,
and many others!

Kamerlingh Onnes Laboratory, Leiden University, Netherlands

Gertjan van Baarle, Alexei Ofitserov, *and others*

Leiden Probe Microscopy BV, Leiden, Netherlands



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