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
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
Scientific program

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-ARCNLI group
Niklas Ottosson & Huib Bakker

HHG of EUV
Stefan Witte & Kjeld Eikema

Accelerator-based EUV
Coordinator: Ronnie Hoekstra
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

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

Azimuth

Polar angle
*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
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

Autocorrelation function:

\[ C_A(\bar{r}, t) = \langle h(\bar{x}, t) h(\bar{x} + \bar{r}, t) \rangle \]

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.
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
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

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

\[ C_A(\bar{r},t) = \left\langle h(\bar{x},t)h(\bar{x} + \bar{r},t) \right\rangle \]  \\
autocorrelation function

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

\[
C_H(\bar{r},t) \propto r^{2H} \quad r \ll \xi
\]

\[
C_H(\bar{r},t) = 2w^2 \quad r \gg \xi
\]

Scaling for kinetic roughening:

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

\[ w(t) \propto t^\beta \]  \\
roughness
Mo on Si: roughening statistics

![Graph showing height-difference correlation vs. correlation distance](image)

- Height-difference correlation [nm$^2$]
- Correlation distance [nm]
- Curves for different $	au$ values:
  - $	au = 4.0$ nm
  - $	au = 3.0$ nm
  - $	au = 1.0$ nm
  - $	au = 0.5$ nm
  - $	au = 0.1$ nm

- Theoretical expressions:
  - $2w^2$
  - $2w^2(1-e^{-1})$
  - $\sim r^{2H}$

- Length scale $\xi$
Mo on Si: roughening statistics

Exponents $\beta$ and $1/z$ match Grain-Boundary Crossing model

$\beta = 0.49 \pm 0.02$

$1/z = 0.34 \pm 0.02$
**Live erosion:** 800 eV Ar⁺ => Si(111) 7x7

**Conditions:**

- T = 293 K
- 25 x 25 x 0.2 nm³
- 2 V x 200 pA
- 10 s / frame
- 416 frames
- Polar angle: 75°
- 1-3 ions per frame
Individual impact events

Frame $i$

\[ F(i + 1) - F(i) \]

Frame $i + 1$
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⁺

Mo
Si
MoₓSiᵧ

Shaving:
Scattering, Sputtering & Shadowing → Smoothening

Marcel Rost
Vincent Fokkema

95 nm x 95 nm x 2.5 nm
Advanced Research Center for Nanolithography (ARCNL)

www.ARCNL.nl

MoSi2
Si
MoSi2
Si
Mo

ARCNL