AFM Nanolithography Studied by Spectromicroscopy

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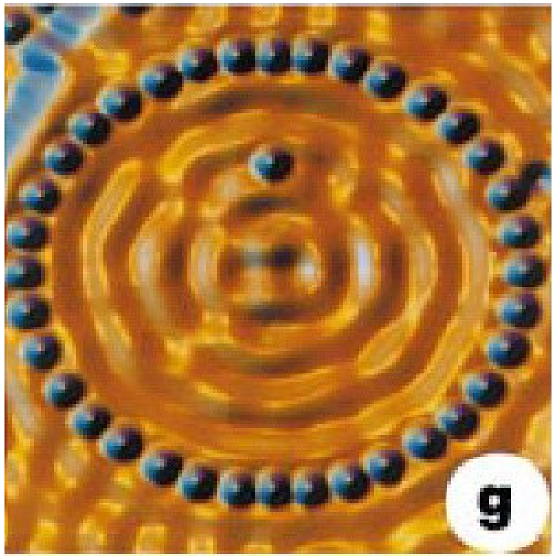
Outline

- AFM local anodic oxidation
  - How to fabricate nanodevices with AFM
- Spectromicroscopy
  - How to measure chemical properties with lateral resolution on a nanometer scale
- Si oxides
- GaAs oxides

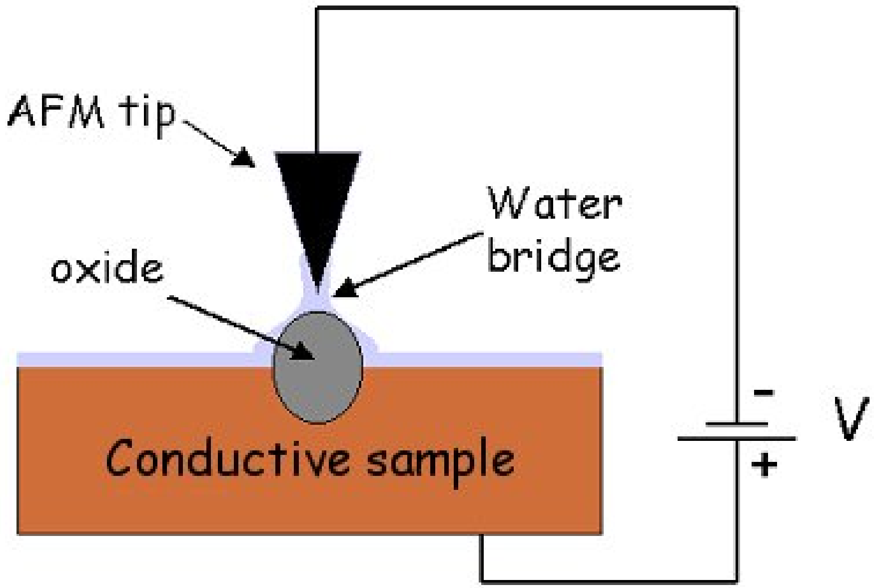
Motivation

- Nanolithography for fabrication of state-of-the-art semiconductor nanostructures
- Basic research and quantum device applications
- Approaches:
  - Traditional lithography
  - Proximal probes (STM or AFM)



H.C. Manoharan, C.P. Lutz,
D.M. Eigler: Nature **403** (2000) 512

Local Anodic Oxidation (LAO)



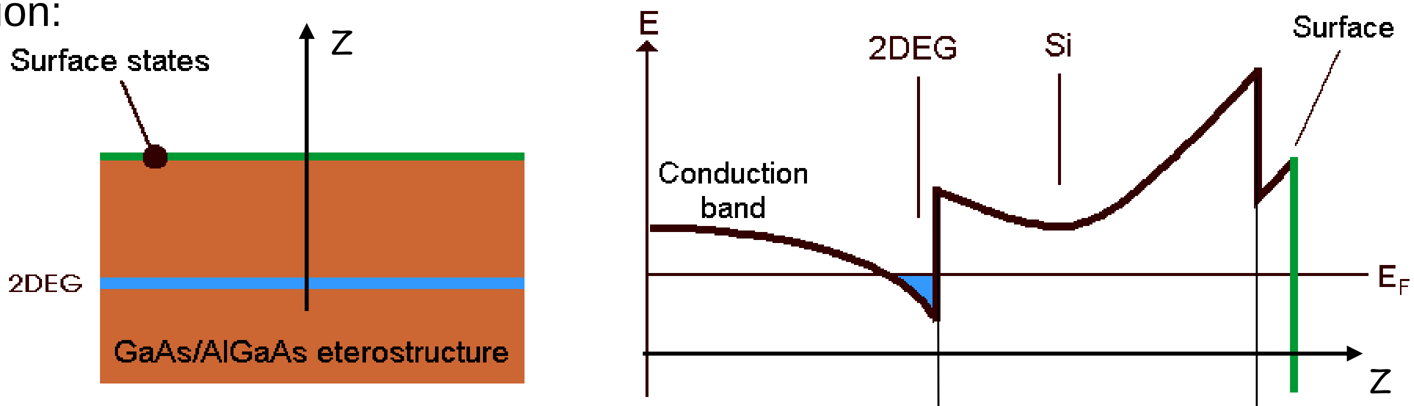
- Water electrolysis
  $H_2O \rightarrow H^+ + OH^-$.
- OH^- groups migrate towards the sample.
- Oxide penetration induced by the intense local electric field.

Versatile tool at relatively low cost

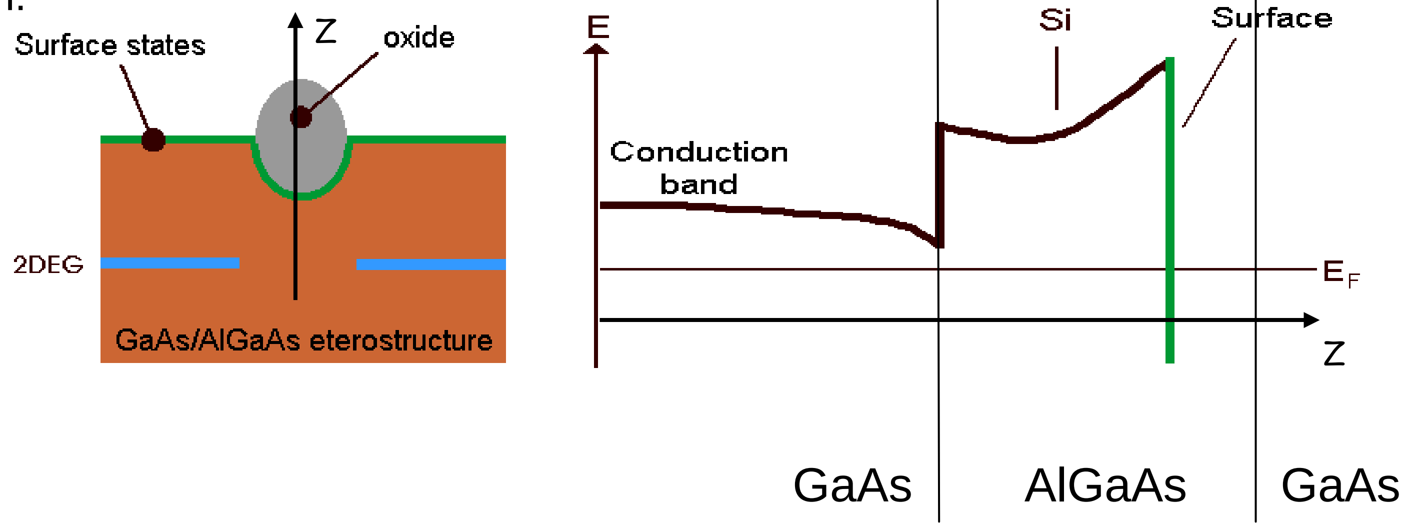
High lateral resolution but small area

LAO on GaAs/AlGaAs

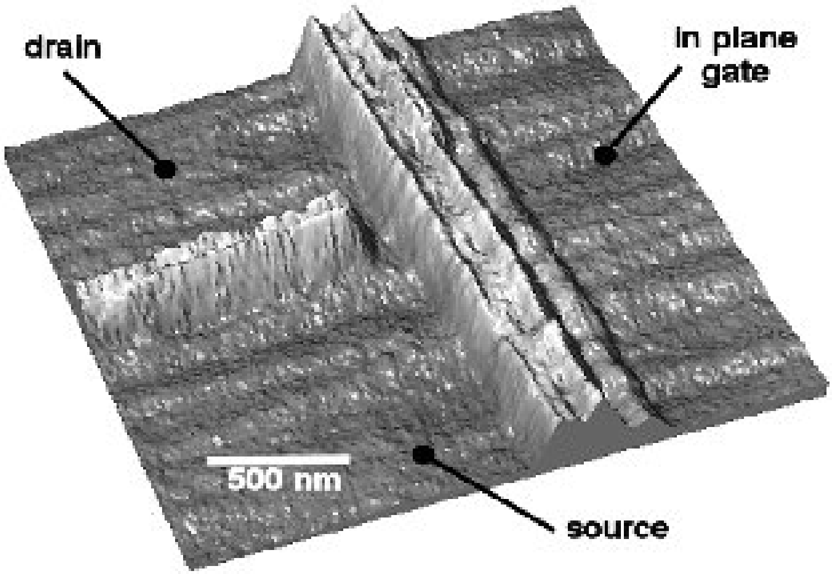
Before oxidation:

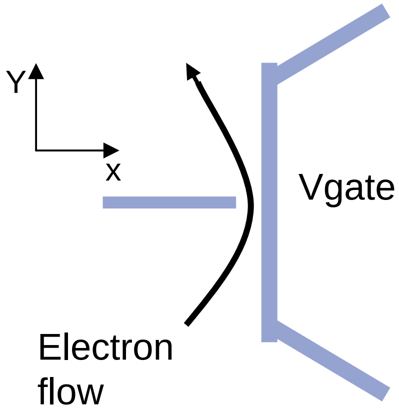


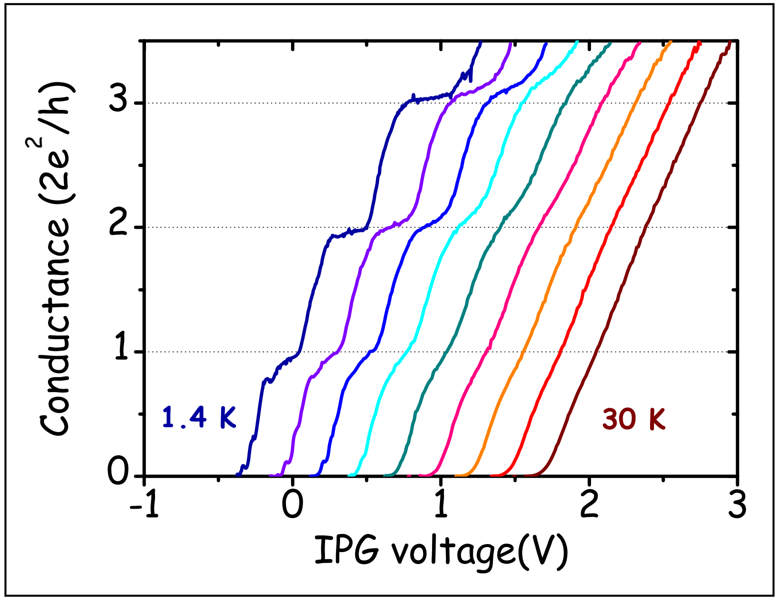
After oxidation:



Quantum Point Contact







G. Mori et al, JVST B, submitted.

Setup for Lithography on GaAs

Thermomicroscope Microcope CP-Resource

Sample Preparation Parameters

- Si samples:
  - Si(100) n-type,
    $\rho = 4\ \Omega$cm.
  - AFM in air.
  - Contact mode.
  - Si tip.
  - Humidity 65%.
  - Scan speed 0.5 μm/s.
  - Substrate grounded,
    tip voltage from -6 V to
    -14 V.
- GaAs samples:
  - GaAs(100) n-type,
    $\rho = 2 \times 10^{-3}\ \Omega$cm.
  - AFM in controlled atm.
  - Tapping mode.
  - Si tip (B doped).
  - Humidity controlled.
  - Scan speed 0.5 μm/s.
  - Tip grounded,
    substrate voltage from
    +12 V to +18 V.

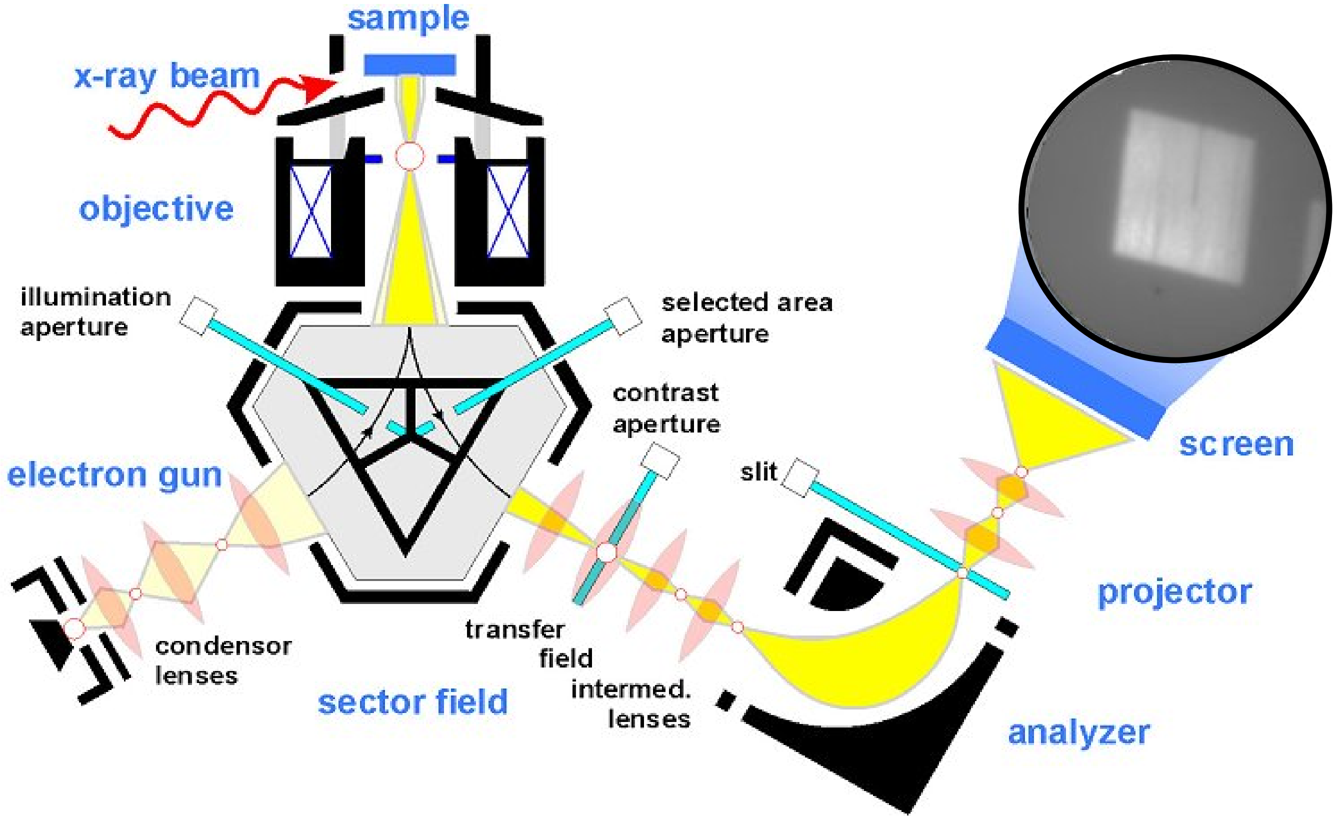
Why Spectroscopic Microscopy?

- Lack of information on the oxidation process and on the chemical nature of the grown oxides.
- Information on the uniformity of the grown oxides (electrical and chemical properties).
- Effect of oxidation parameters.

- Lack of reliable microscopic techniques able to perform chemical spectroscopy on such small structures.

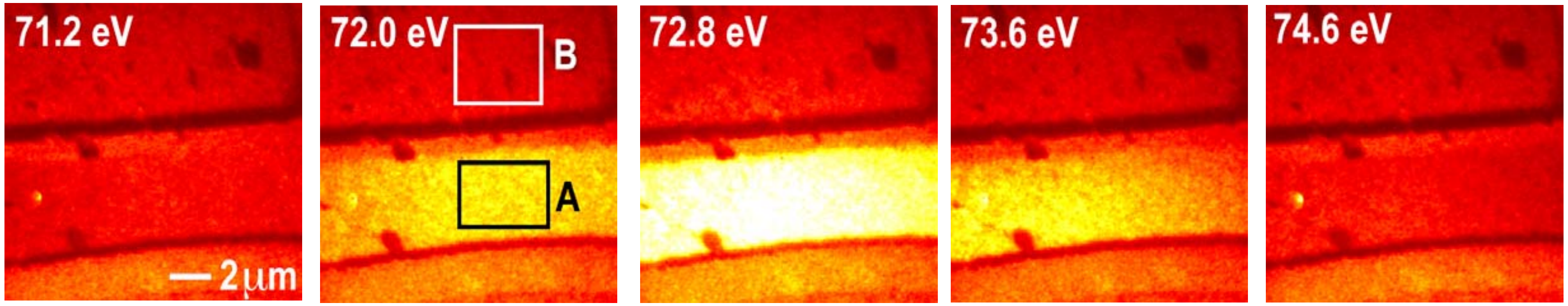
The SPELEEM at Elettra

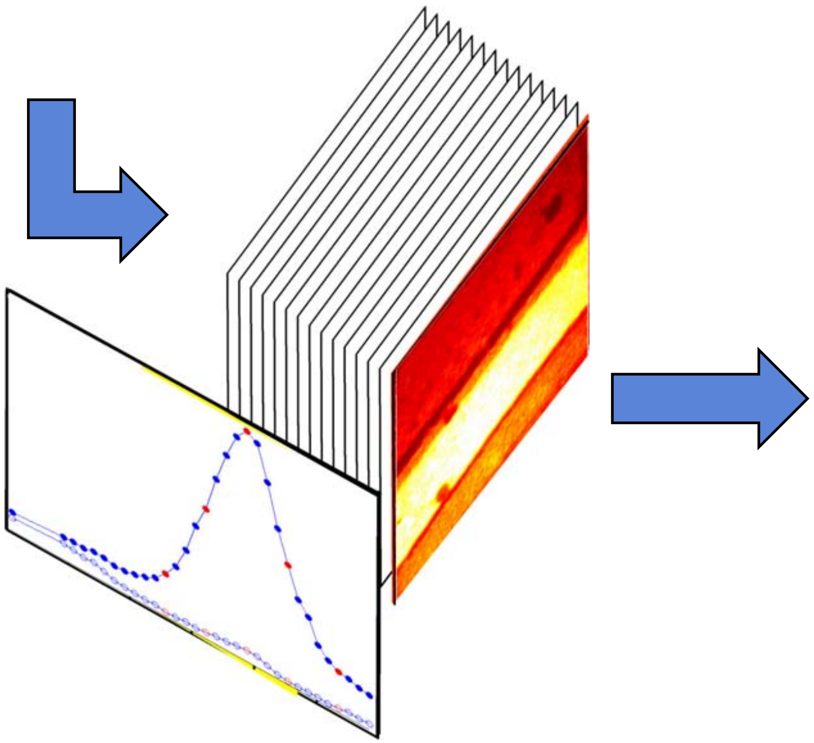
Spectroscopic photoemission and low energy electron microscope

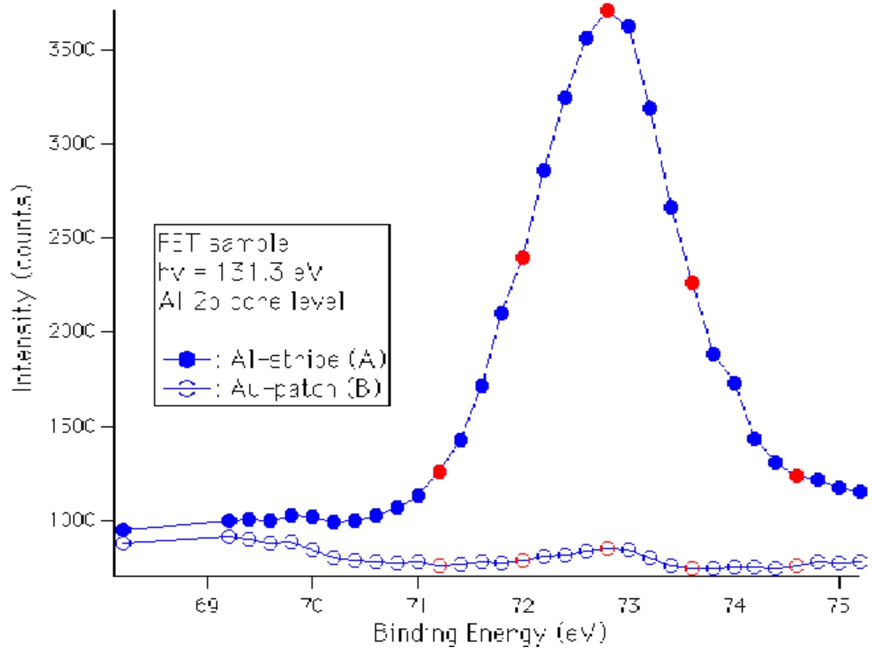


Photon energy range: 20 - 1000 eV (here: 130 eV)
Energy resolution 300 meV, lateral resolution in XPEEM 30 nm

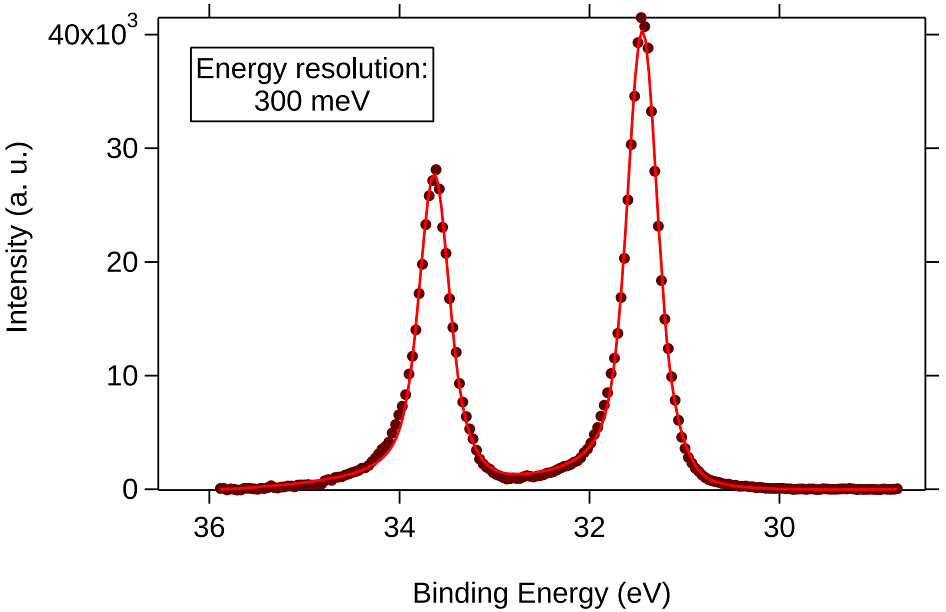
Spectroscopy With XPEEM



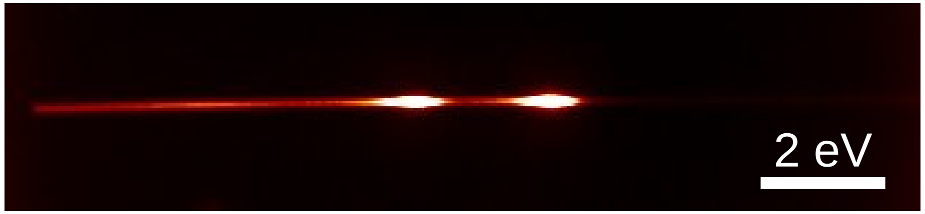


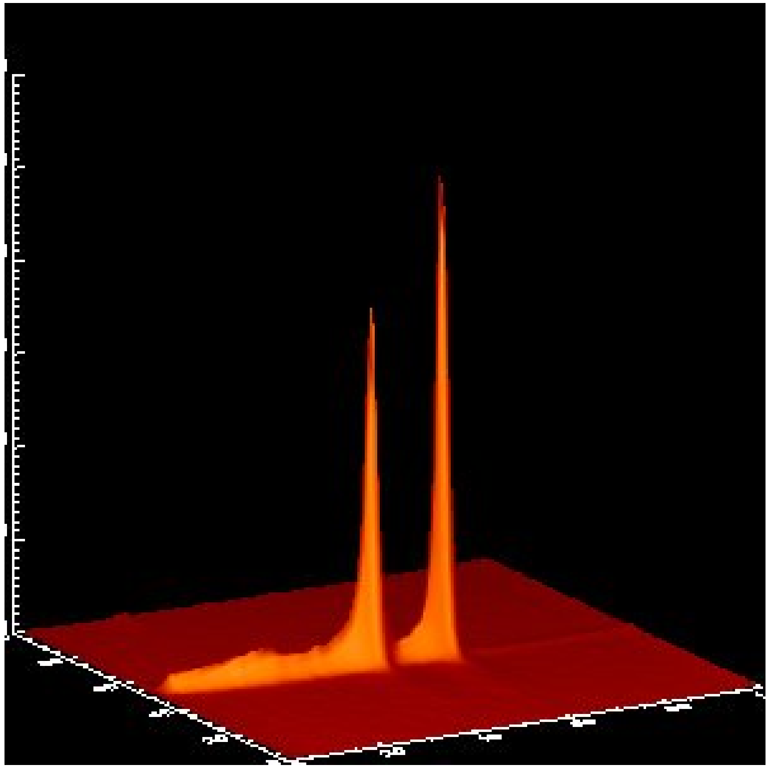


Dispersive Plane

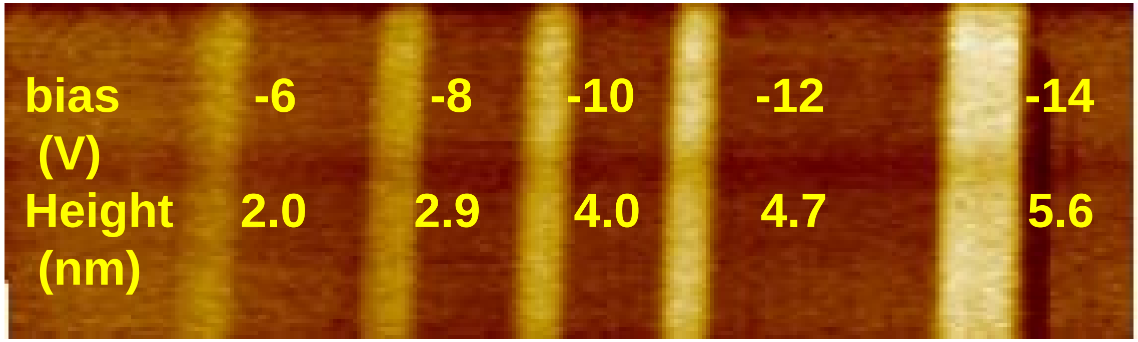


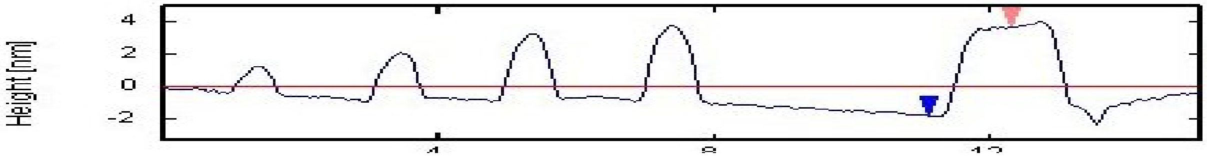
clean W(110),
W 4f core level

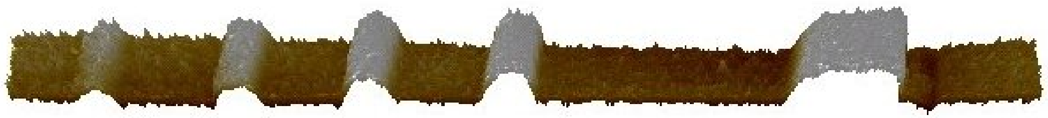




Si Oxide: Sample





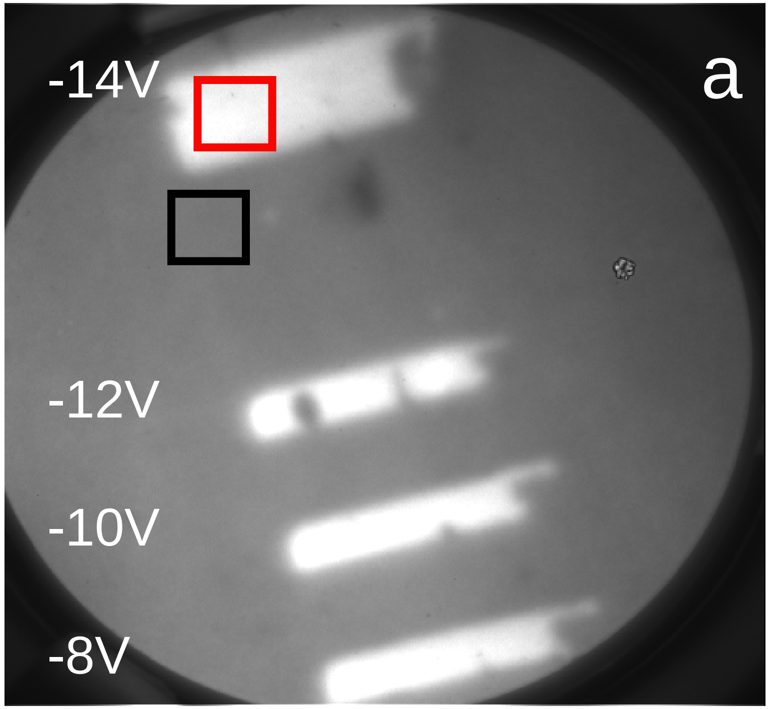


Morphology studied after oxidation by AFM.
Thickness increases with writing voltage!

M. Lazzarino, S. Heun, B. Ressel, K. C. Prince, P. Pingue, and C. Ascoli: Appl. Phys. Lett. **81** (2002) 2842.

Si Oxide: Image Contrast at Si 2p

Field of view 12 µm, hv = 132.5 eV, energy resolution: 1 eV

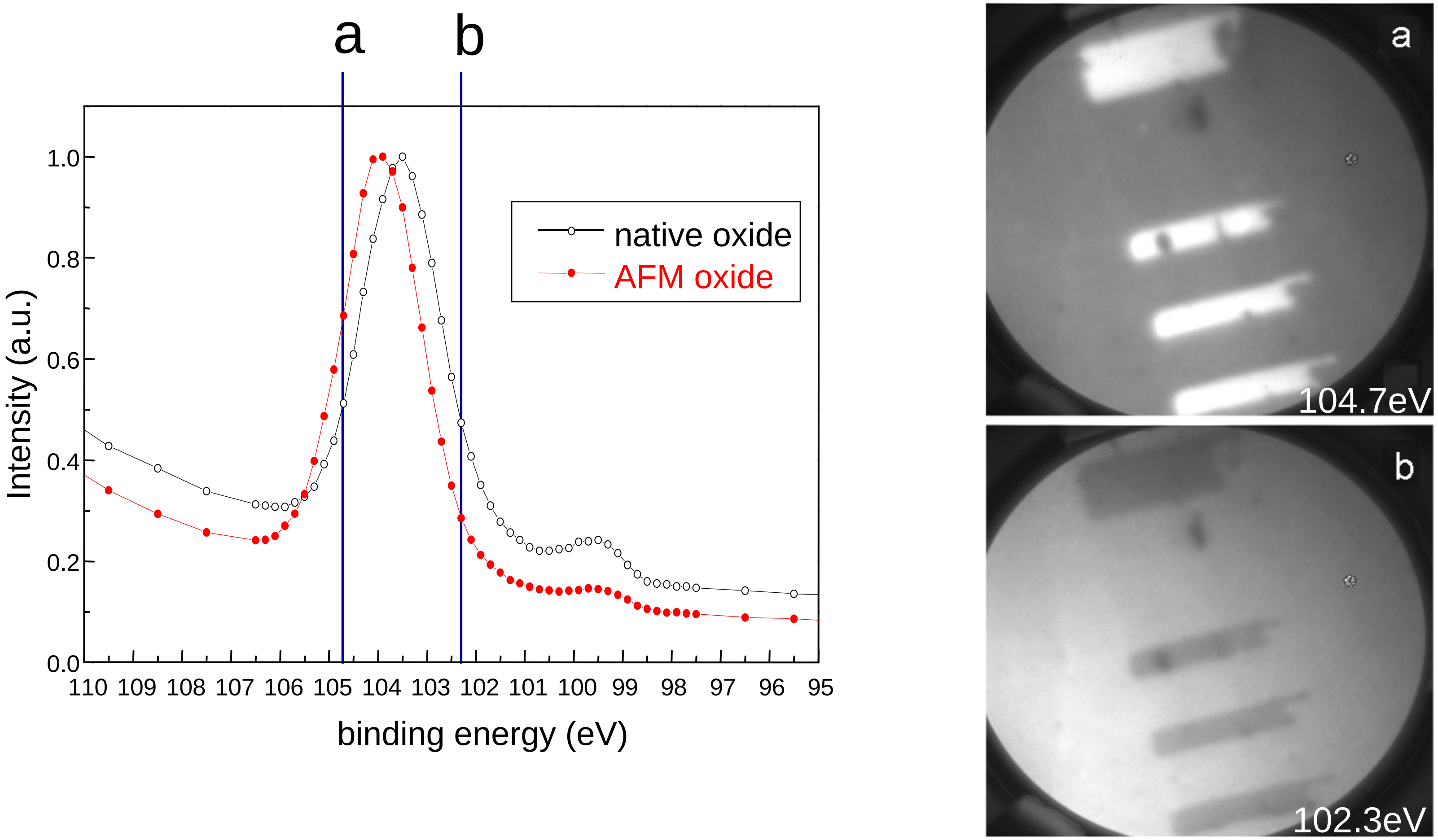


Binding energy 104.7 eV

- Contrast inversion
- Within each stripe: uniform intensity
- Unbiased tip does not induce oxidation

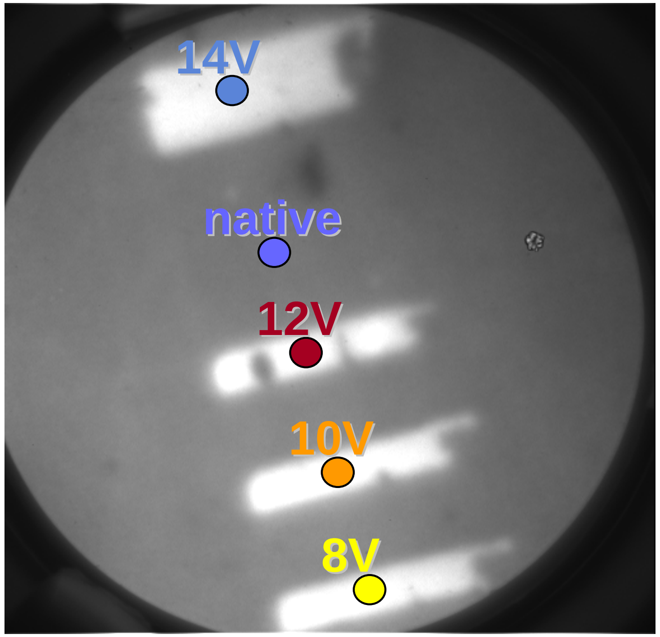
M. Lazzarino, S. Heun, B. Ressel, K. C. Prince, P. Pingue, and C. Ascoli: Appl. Phys. Lett. **81** (2002) 2842.

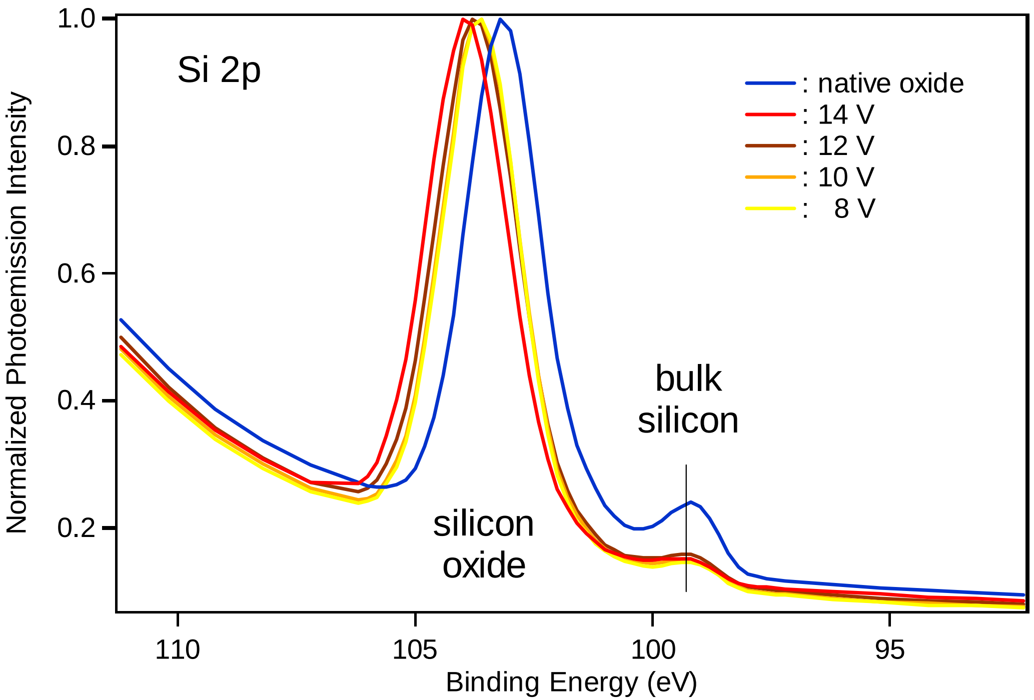
Si Oxide: Spectroscopy at Si 2p



M. Lazzarino, S. Heun, B. Ressel, K. C. Prince, P. Pingue, and C. Ascoli: Appl. Phys. Lett. **81** (2002) 2842.

Si Oxide: Writing Voltage Effect





ΔE = 3.97 eV (native)

ΔE = 4.62 eV (U = 14V)

ΔE = 4.46 eV (U = 12V)

ΔE = 4. 41 eV (U = 10V)

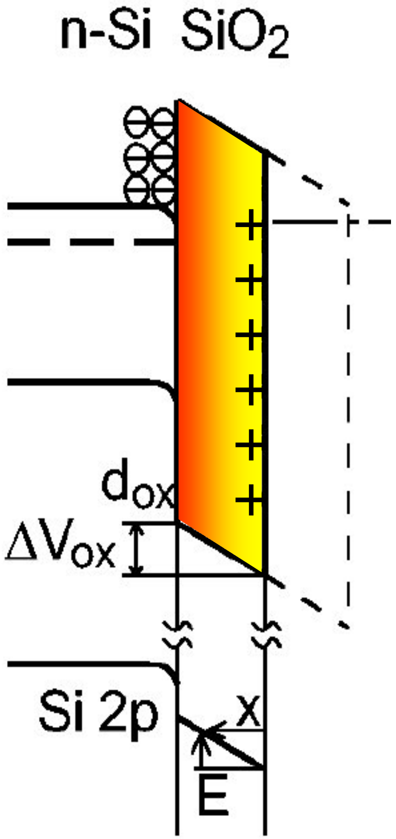
ΔE = 4.39 eV (U = 8V)

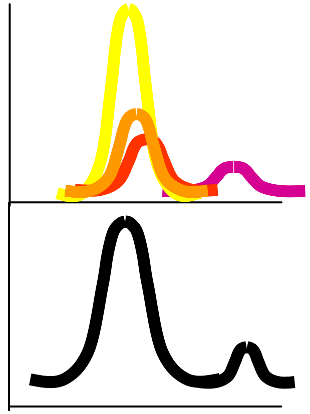
Shift (Si_{bulk} - SiO_x) increases with increasing writing voltage (oxide thickness).

M. Lazzarino, S. Heun, B. Ressel, K. C. Prince, P. Pingue, and C. Ascoli: Appl. Phys. Lett. **81** (2002) 2842.

Si Oxide: Charging Effects

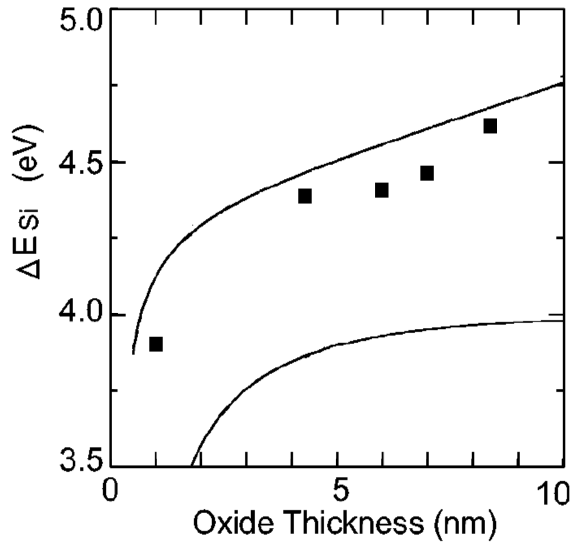
H. Kobayashi, T. Kubota, H. Kawa, Y. Nakato, and M. Nishiyama: Appl. Phys. Lett. **73** (1998) 933.



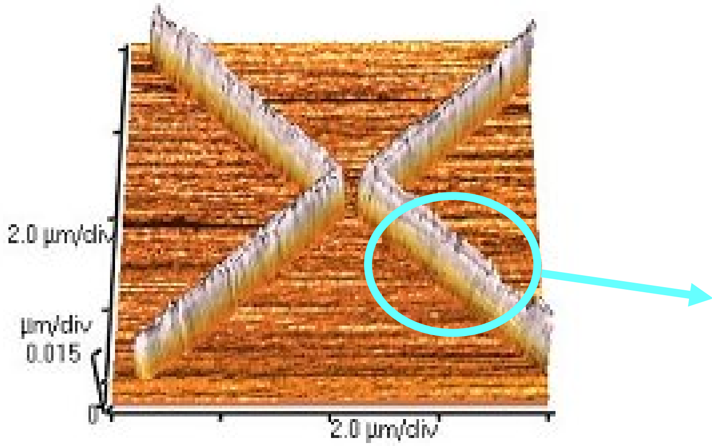


Intensity decreases due to escape depth effect
Charged (yellow) layer contribution is more important

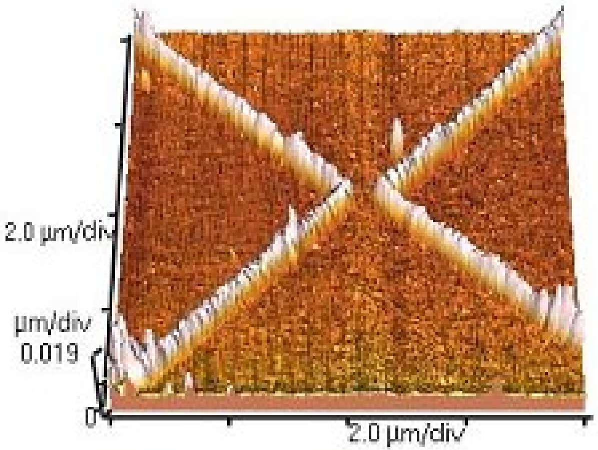
Squared points: our data
Line: Kobayashi model



GaAs Oxide: Photon Exposure



AFM before: height 18nm

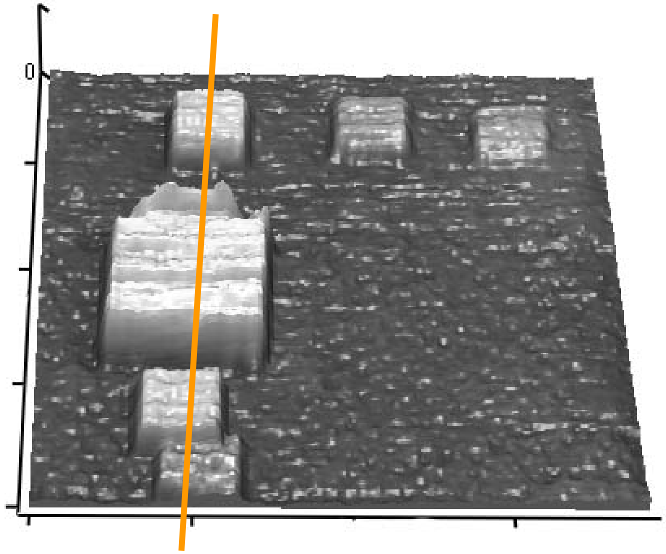


AFM after: height 13nm

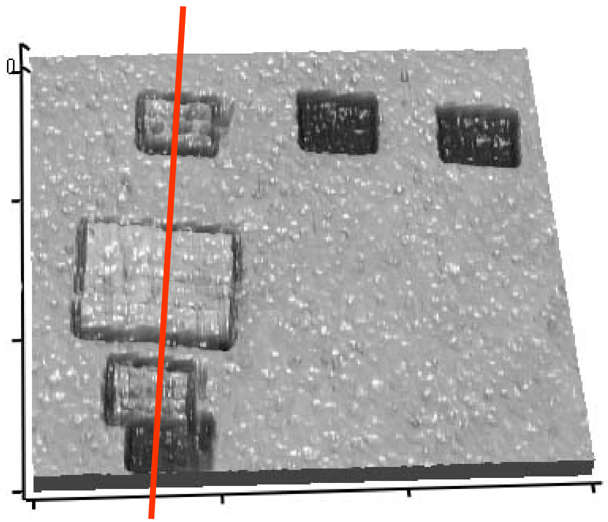
Images taken with secondary electrons

- Photon energy: 125 eV
- Kinetic energy: 4 eV
- Field of view: 10 µm
- One image every 2 sec

GaAs Oxide: Desorption

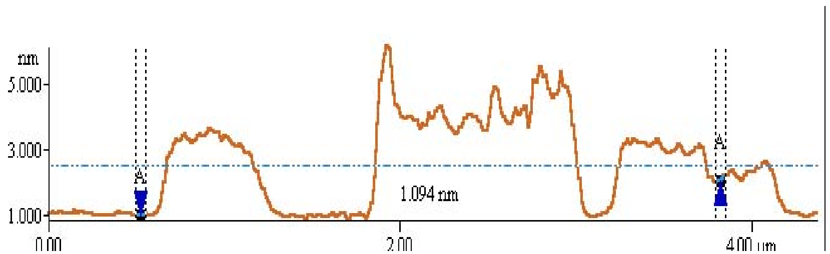


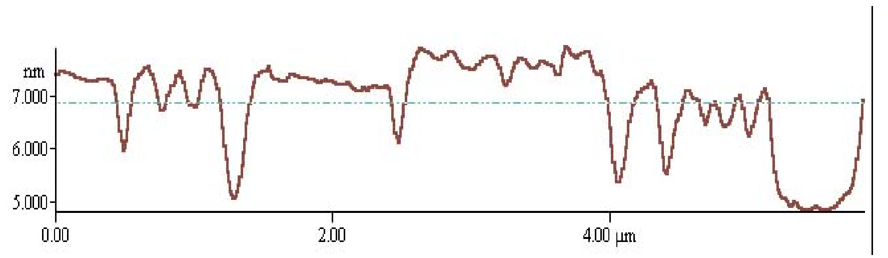
hv



AFM topography taken before photon exposure

AFM topography of the same region taken after exposure

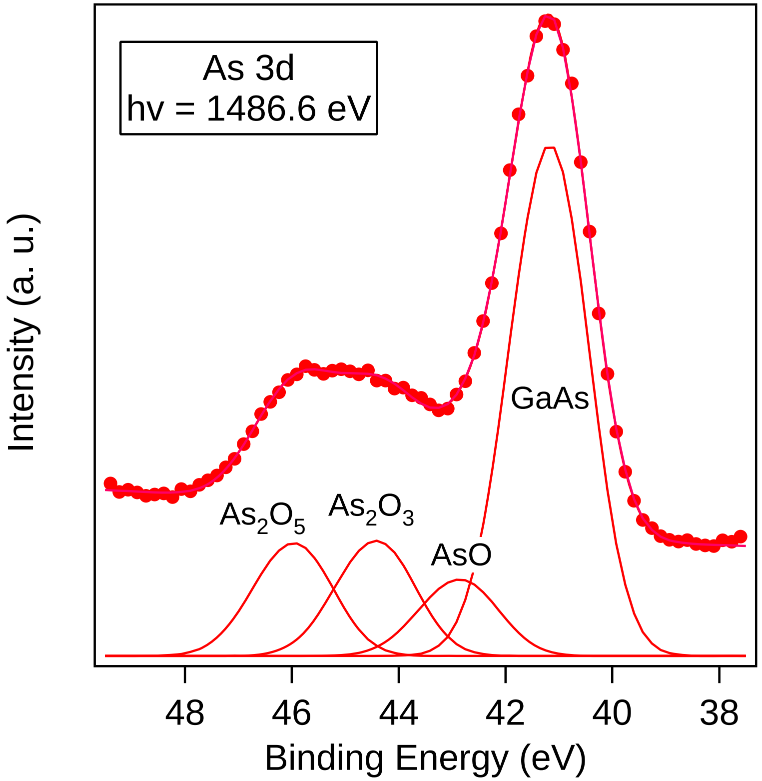




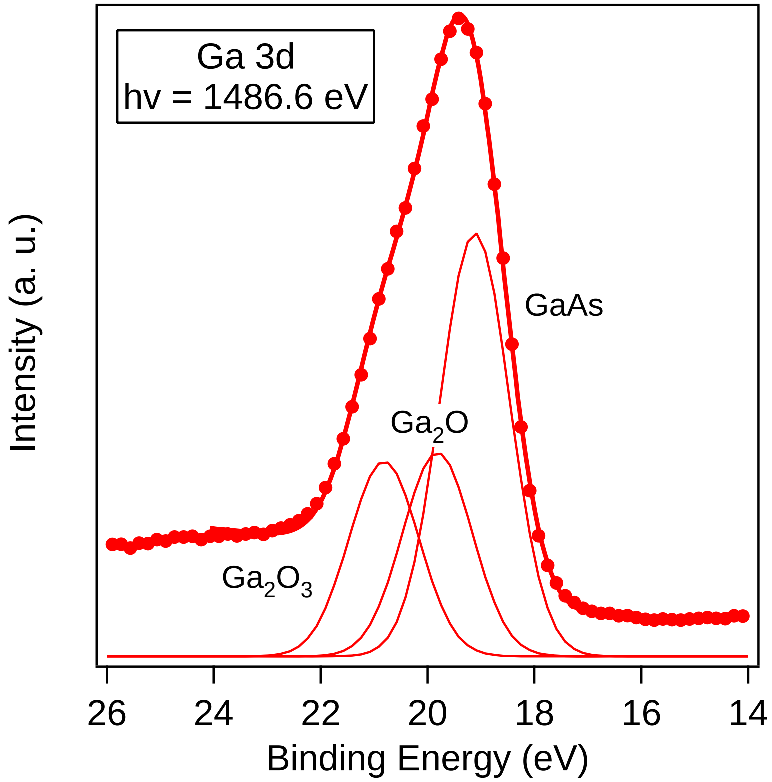
2 - 5 nm of GaAs oxide have been desorbed

Spectra From GaAs Wafer (XPS)

X-ray Photoelectron Spectroscopy (hv = 1486.6 eV) on native GaAs oxide



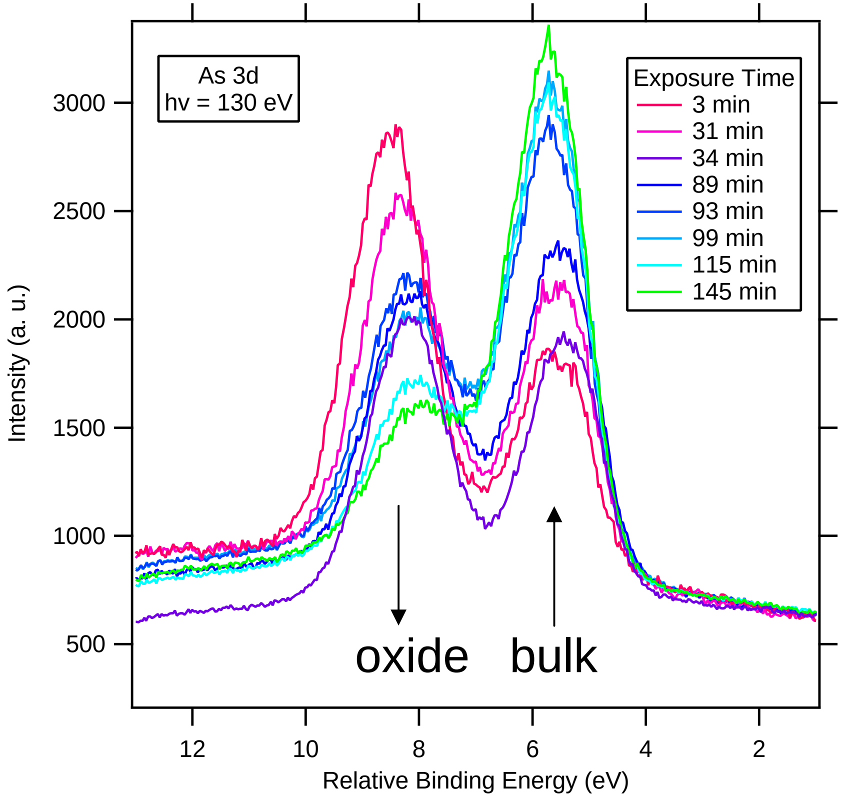
As 3d

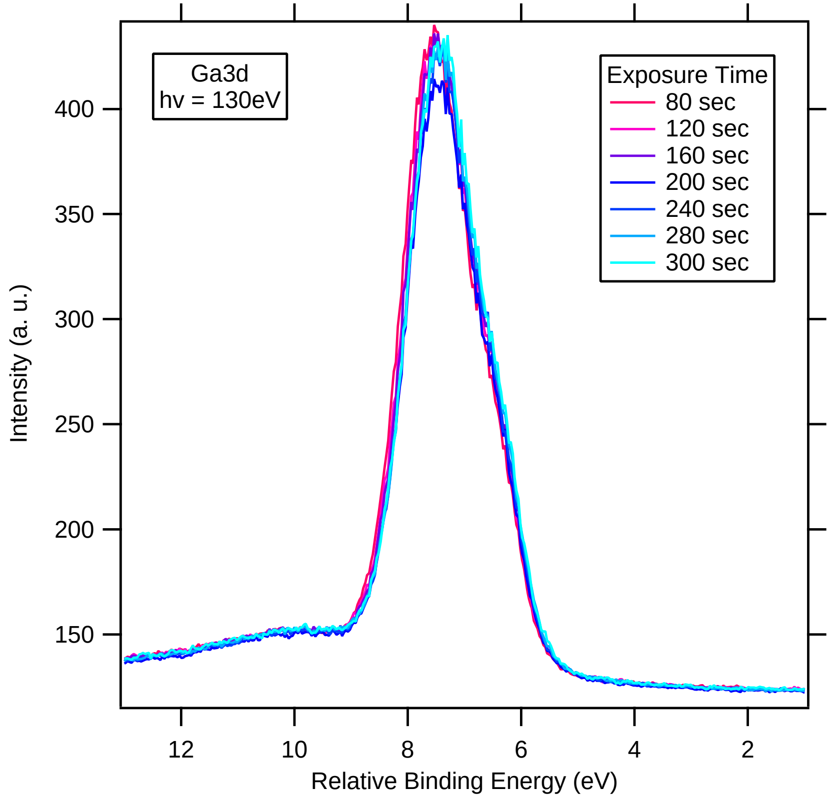


Ga 3d

Spectra From GaAs Wafer (DP)

Time resolved spectroscopy with SPELEEM using Dispersive Plane (hv = 130 eV)



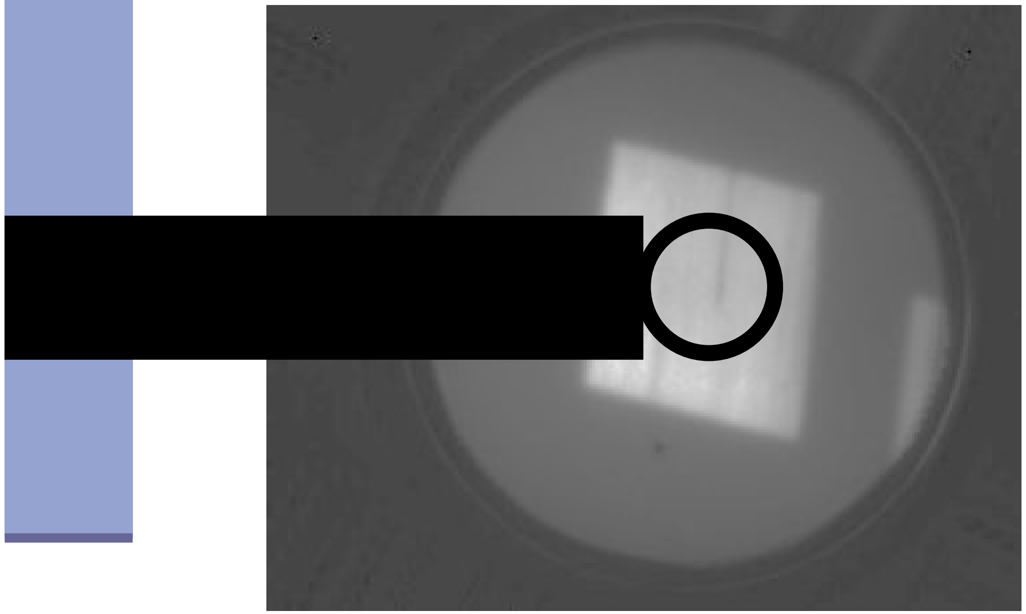


As 3d
total exposure time: 145 min = 8700 sec

Ga 3d
300 sec

Spectra From AFM GaAs Oxide

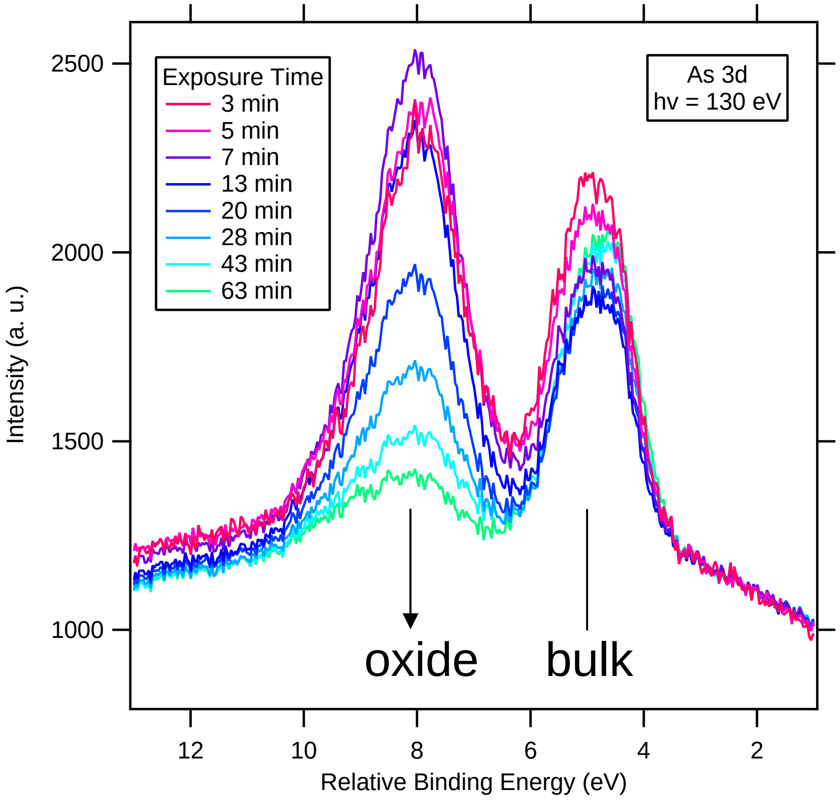
Time resolved spectroscopy with SPELEEM using Dispersive Plane (hv = 130 eV)



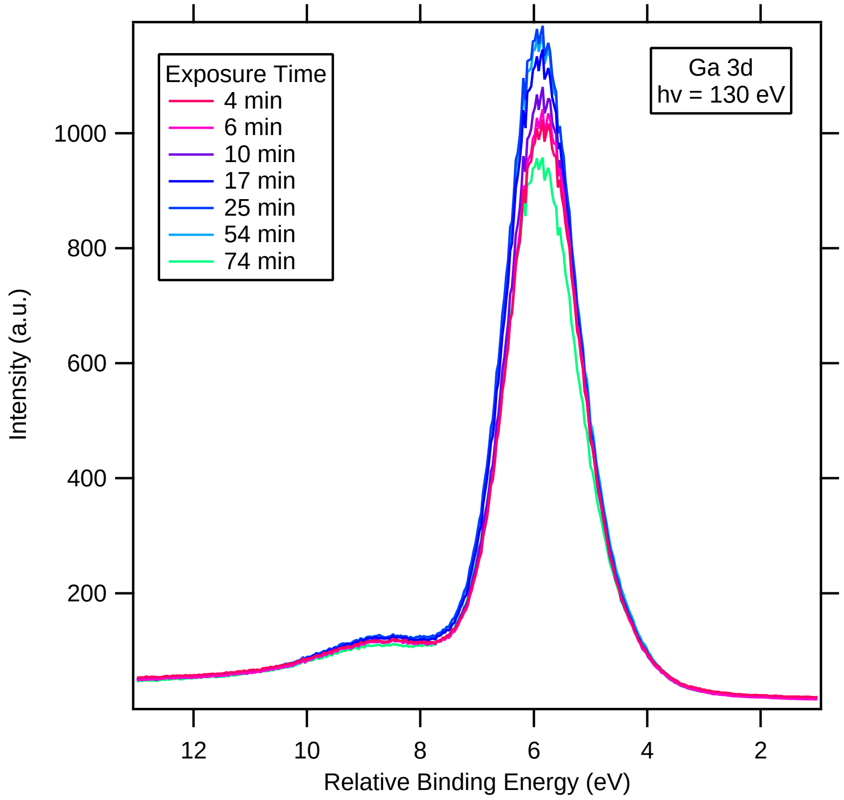
- Sample S03B
- Hole (3,2)
- Writing voltage 15 V
- Structure height 3 nm
- Image taken with secondary electrons:
  - Photon energy: 130 eV
  - Kinetic energy: 0.3 eV
  - Field of view: 10 µm

Spectra From AFM GaAs Oxide

Time resolved spectroscopy with SPELEEM using Dispersive Plane (hv = 130 eV)



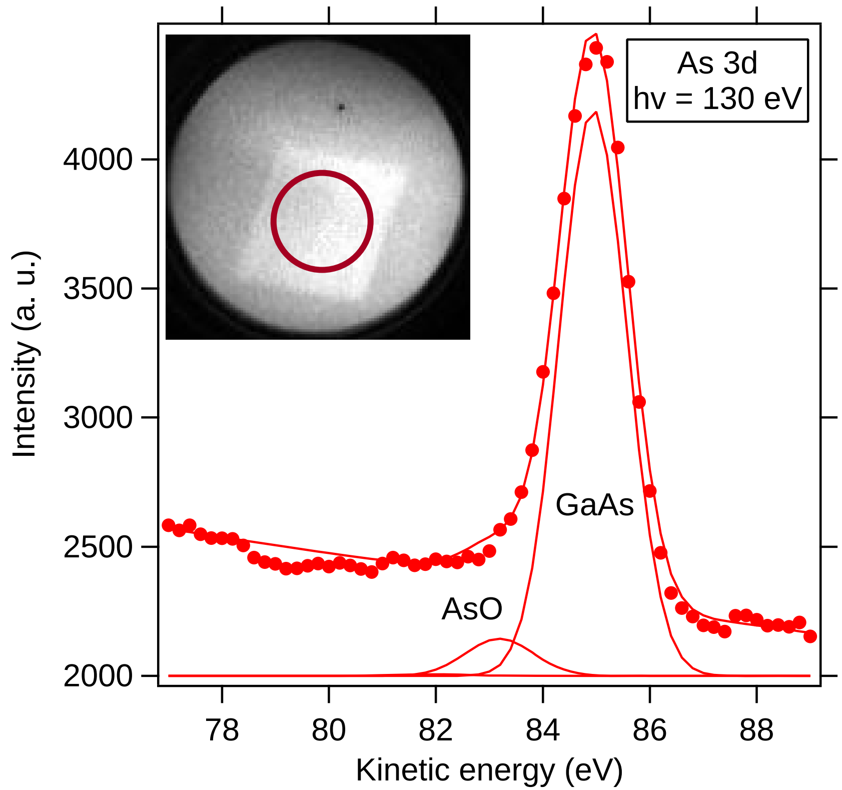
As 3d

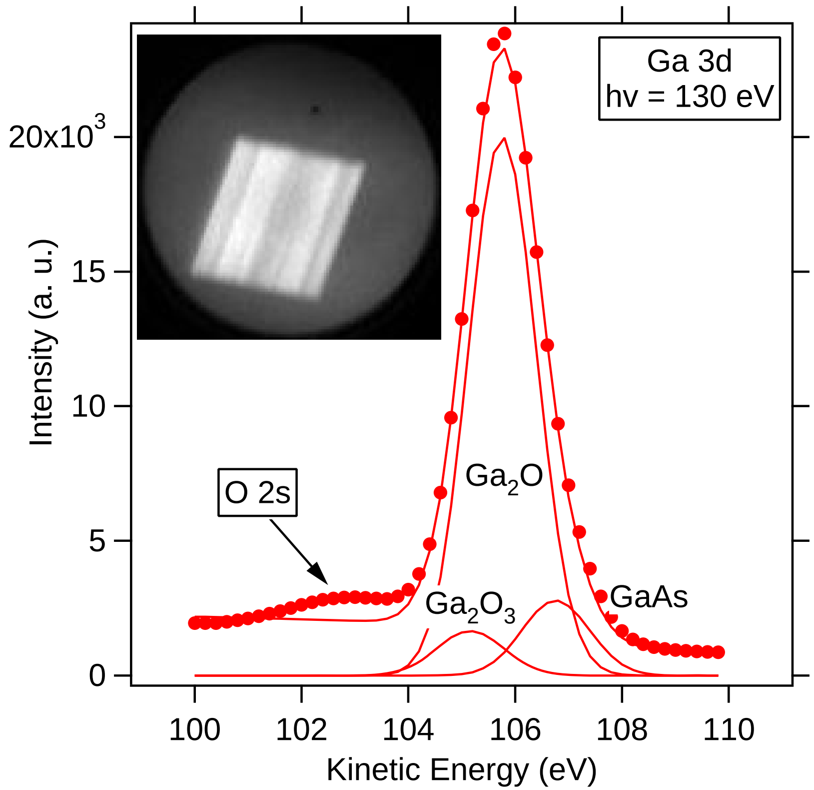


Ga 3d

total exposure time: 76 min

Spectra From AFM GaAs Oxide





As 3d

Ga 3d

photon energy: 130 eV

Summary

- Si oxide:
  - The AFM induced oxidation produces chemically uniform, stoichiometric SiO_2 with dielectric properties comparable to those of thermal SiO_2.
- GaAs oxide:
  - Photon assisted partial desorption of the AFM-grown oxide was observed.
  - All As oxides and the oxygen-rich Ga oxides are desorbed.
  - Photon flux and energy are comparable to those to be used in the next generation lithography at 13 nm.