Surface compositional profiles of InAs/GaAs quantum rings

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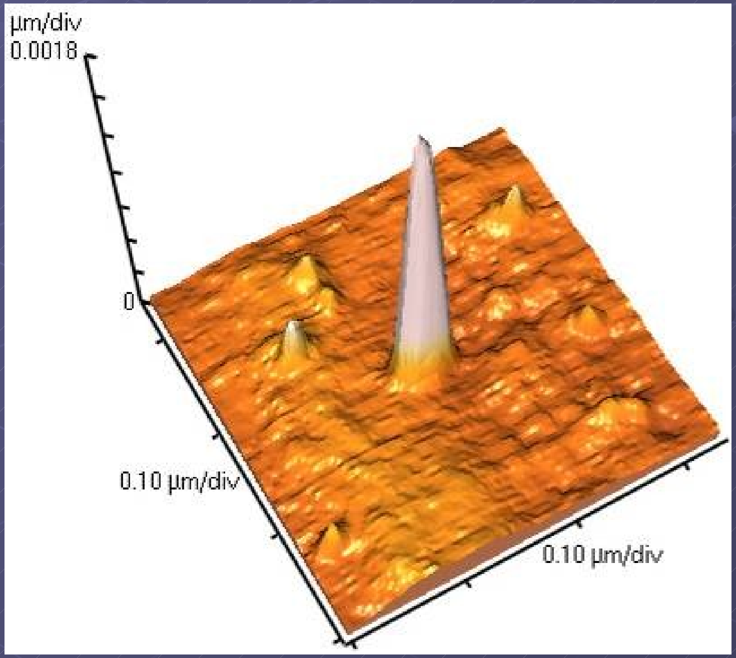
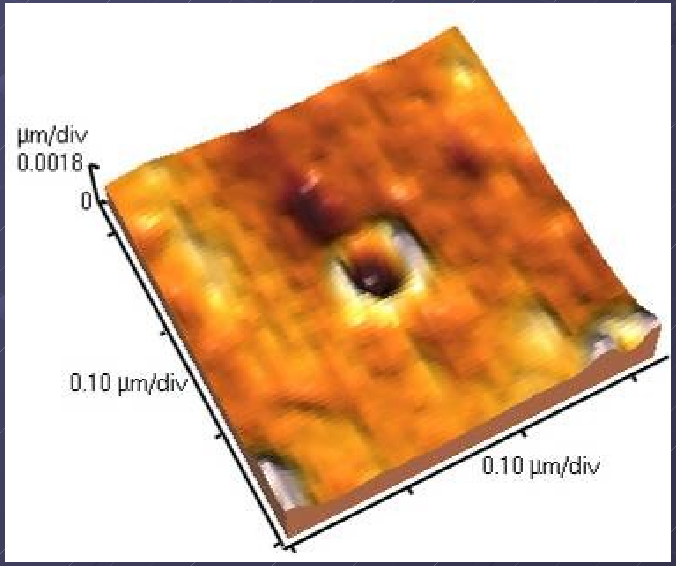
What are SA QRs ?

- Thin (a few nm) GaAs cap on a SK QD in appropriate conditions ⇒ drastic shape transformation



InAs/GaAs QD



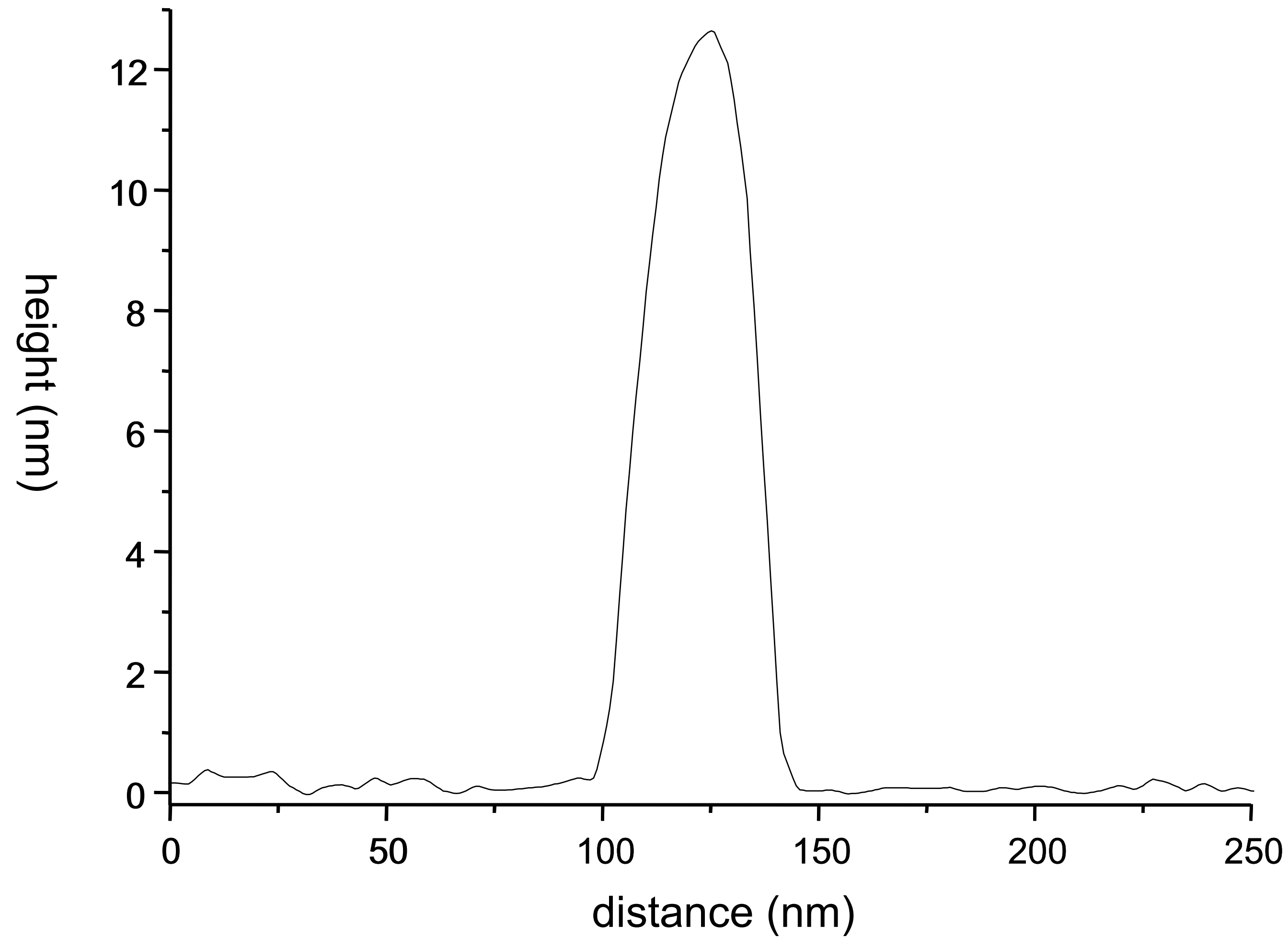
+ 2nm GaAs + 30” annealing

Physical properties of QRs

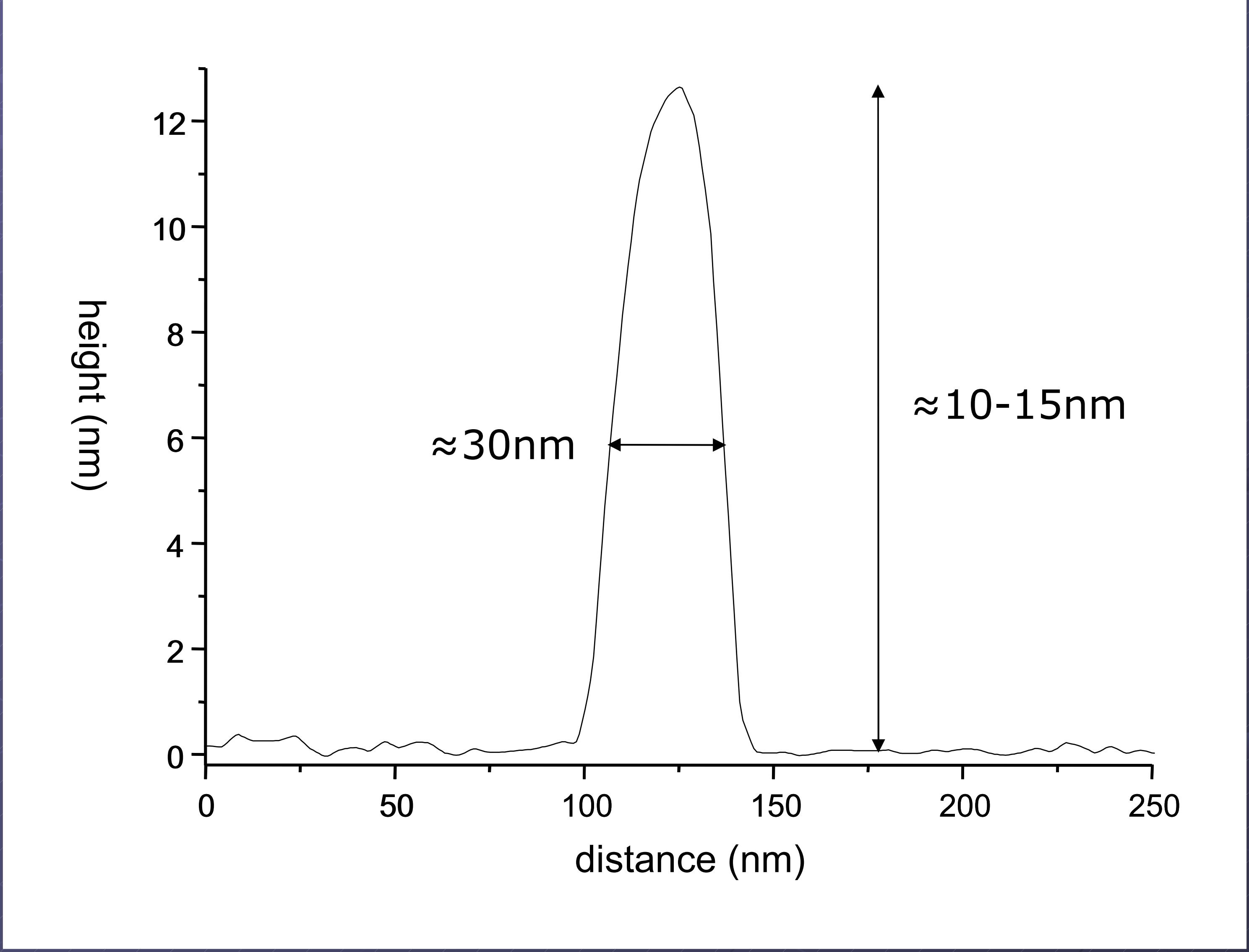
- Non-simply connected geometry ⇒ symmetry change in electron wavefunction; electrical and optical properties different from QDs.
- Magnetic properties:
  - Mesoscopic rings (top-down): influence of scattering, large number of filled quantum states
  - SA QRs: scatter-free, few-electron quantum limit
- Size bridge between mesoscopic and molecular ring structures: unique property of trapping magnetic flux and persistent current, not affected by random scatterers and not requiring very large magnetic fields.

A. Lorke et al., Phys. Rev. Lett. 84, 2223 (2000)
N. A. J. M. Kleemans et al., Phys. Rev. Lett. 99, 146808 (2007)

Typical sizes of InAs/GaAs QRs



Typical sizes of InAs/GaAs QRs



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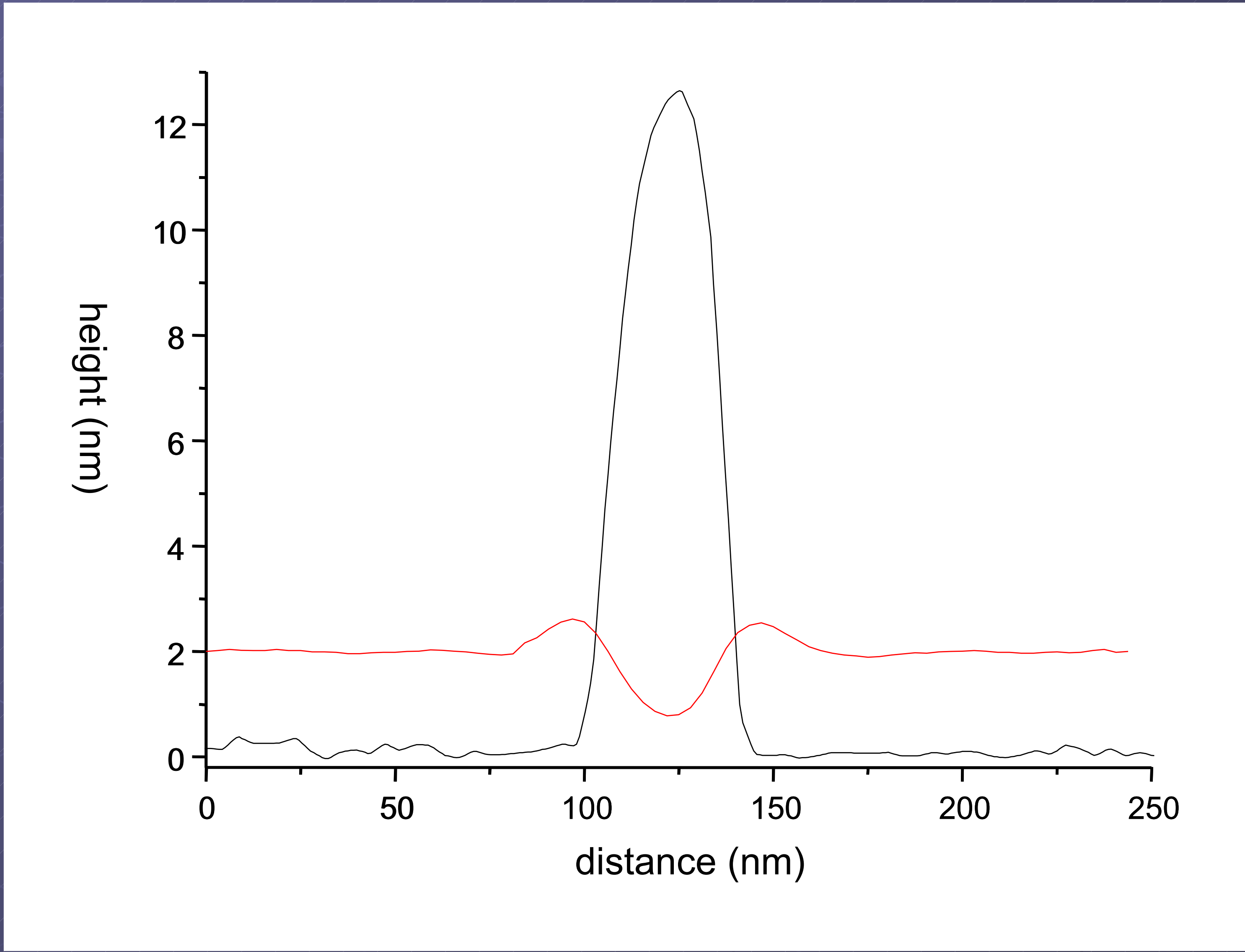

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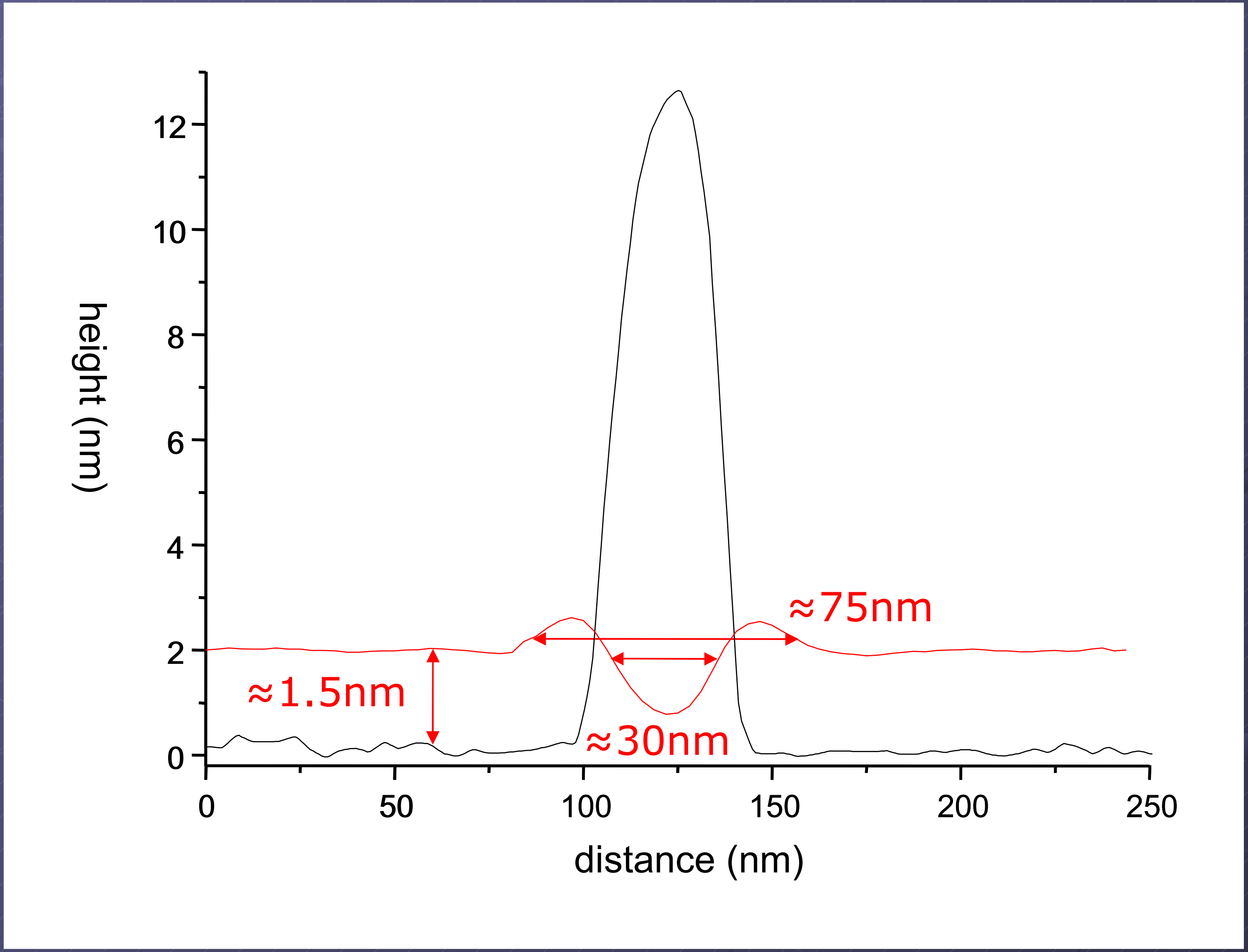
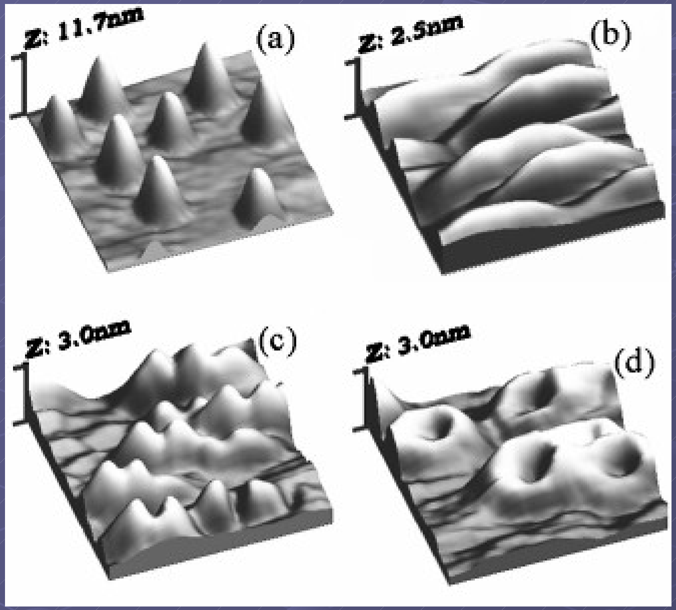


Influence of growth conditions



250 nm X 250 nm AFM images of

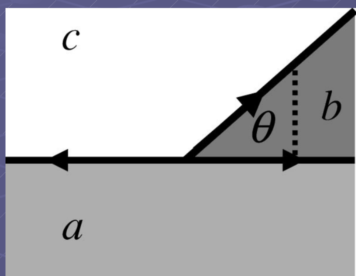
- a QD grown at 540 °C,
- a QD after 2 nm capping at 540 °C with As_4,
- a QD after 2 nm capping at 500 °C with As_4, and
- a QD after 2 nm capping at 500 °C with As_2.

- High T, As_4: high Ga diffusion anisotropy ⇒ elongated mounds along [1-10]
- Low T, As_4: In-Ga alloying: low surface mobility, no rings
- Low T, As_2: Reduced alloying; Ga: low, isotropic mobility; In: high mobility ⇒ In material redistribution (outward diffusion) ⇒ ≈ round structures with center hole

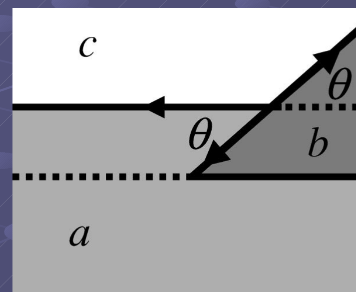
Granados and Garcia, APL 82 (2003) 2401

Formation mechanisms: Wetting droplet instability

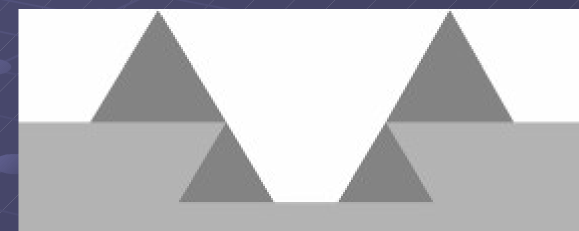
SK island



partially capped island



ring (dewetting)



$$\gamma_{ac} = \gamma_{ab} + \gamma_{bc}\cos\theta$$

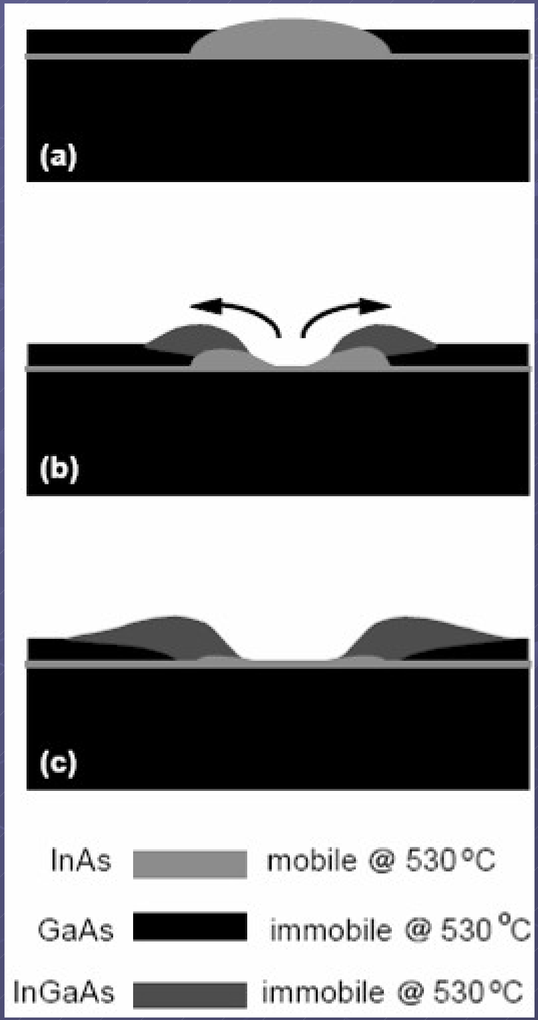
$$\gamma_{ac} + \gamma_{ab}\cos\theta = \gamma_{bc}\cos\theta$$

$$\Rightarrow \Delta F = \gamma_{ab}(1 + \cos\theta)$$

- Unbalanced surface force in partially capped islands
- New equilibrium shape by dewetting
- Purely qualitative equilibrium model
- No In-Ga intermixing
- In depleted core

Blossey and Lorke, Phys. Rev. E 65, 021603 (2002).

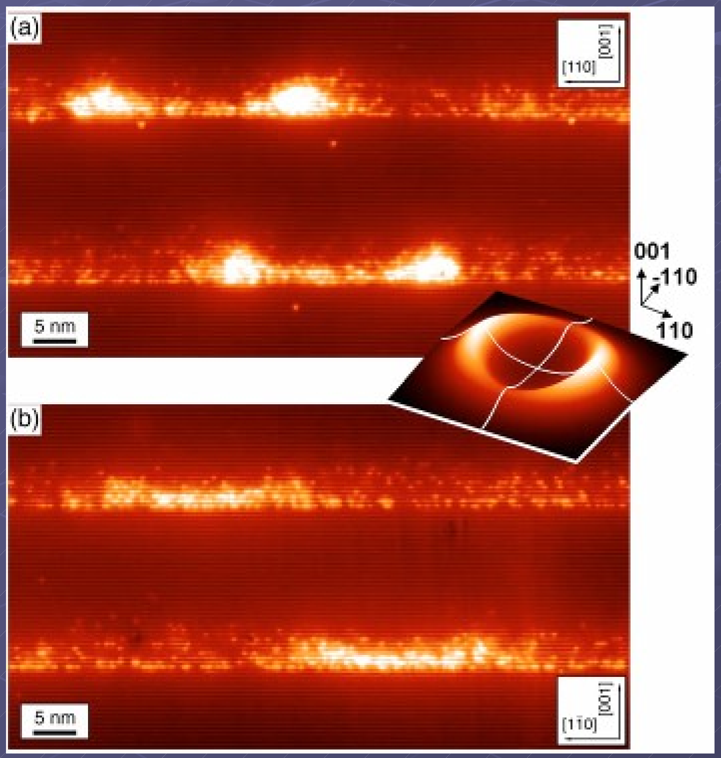
Formation mechanisms: In diffusion



- GaAs deposition: strain relaxation in InAs ⇒ no GaAs on top of dots
- Annealing: outward diffusion of mobile In (Ga immobile @ 530°C) ⇒ void at the center.
- Possible alloying ⇒ immobile InGaAs, stop diffusion
- Qualitative kinetic model
- Origin of diffusion?

Lorke et al., Jpn. J. Appl. Phys. 40, 1857 (2001).

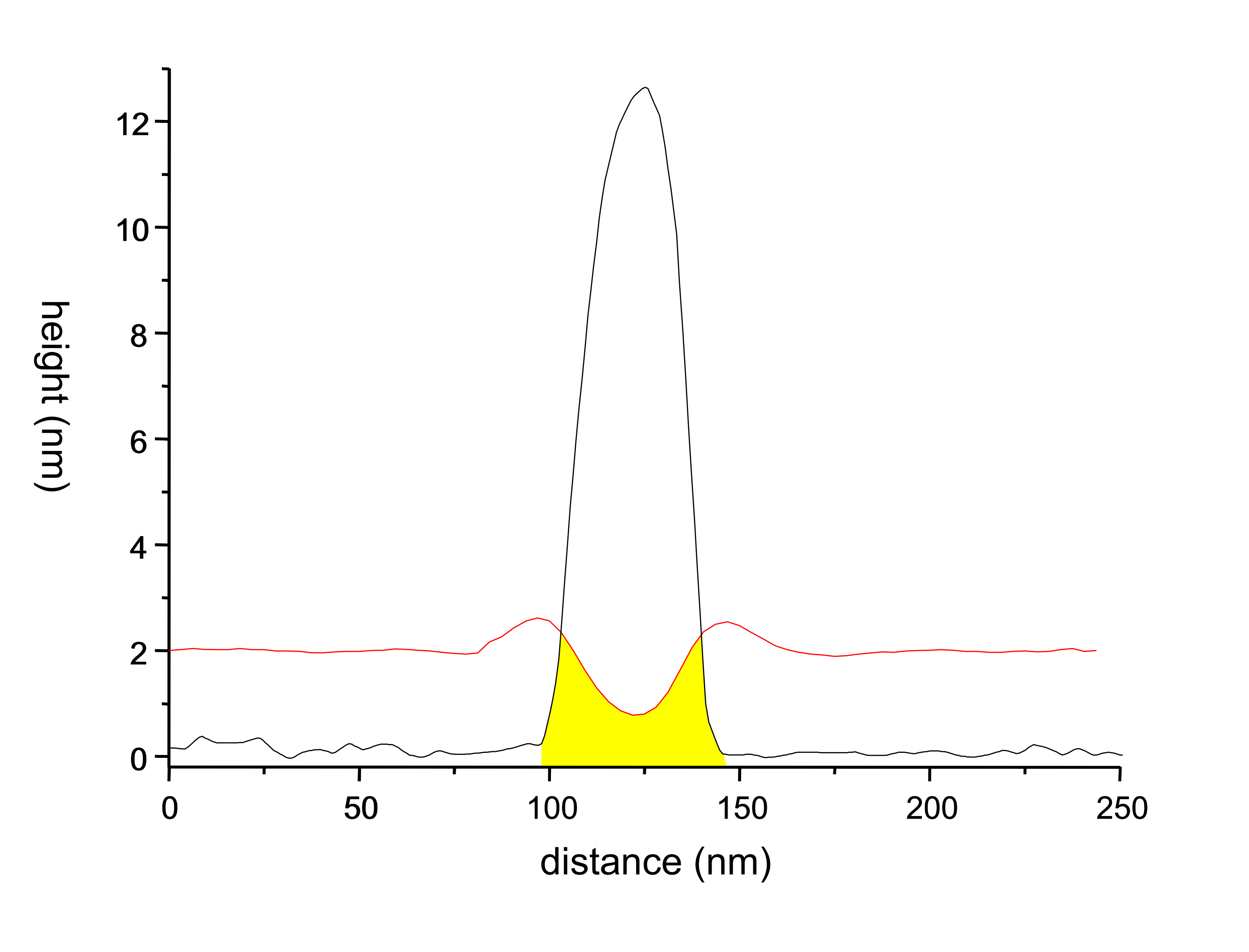
Composition studies: XSTM



P. Offermans, et al. APL 87, 131902 (2005)

- GaAs-overgrown rings
- In-rich crater (x ≈ 0.55)
- Size ≈ 20nm vs. AFM size ≈ 100nm
- Top view-AFM images erupted material, X-sec images residual QD material
- QR alteration by GaAs deposition (strain-driven interdiffusion, segregation)?

Typical sizes of InAs/GaAs QRs



Outline

- Introduction
- Composition mapping of self-assembled QRs by XPEEM
- Modeling of QR composition
- Conductivity mapping of QRs by c-AFM

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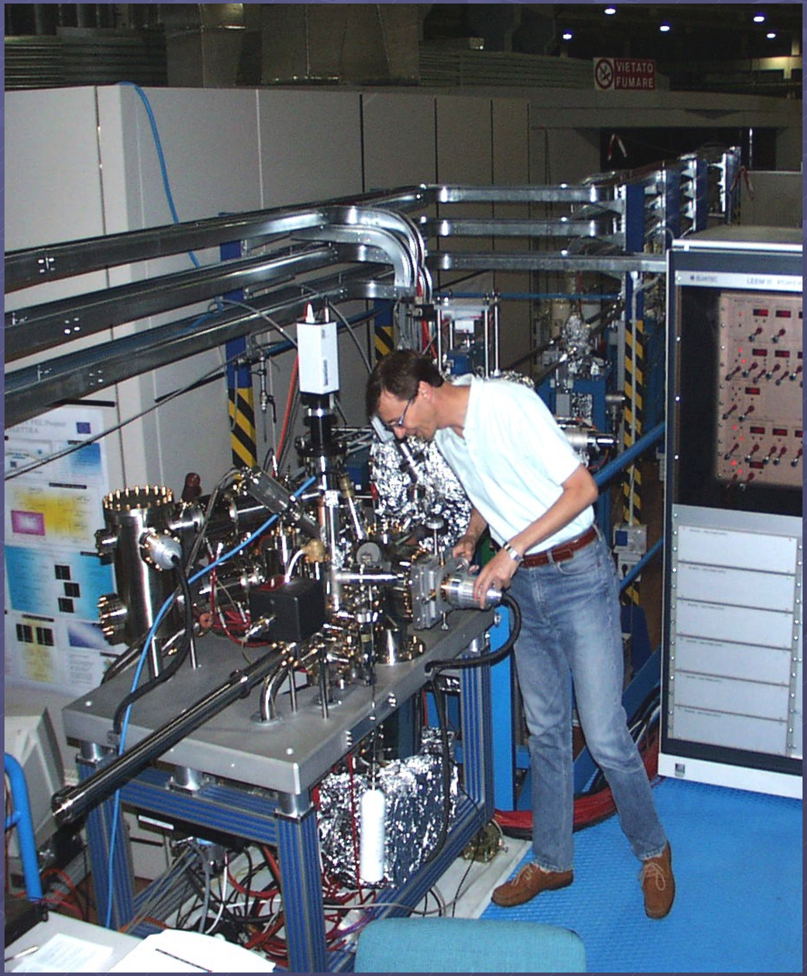
The Nanospectroscopy Beamline at ELETTRA

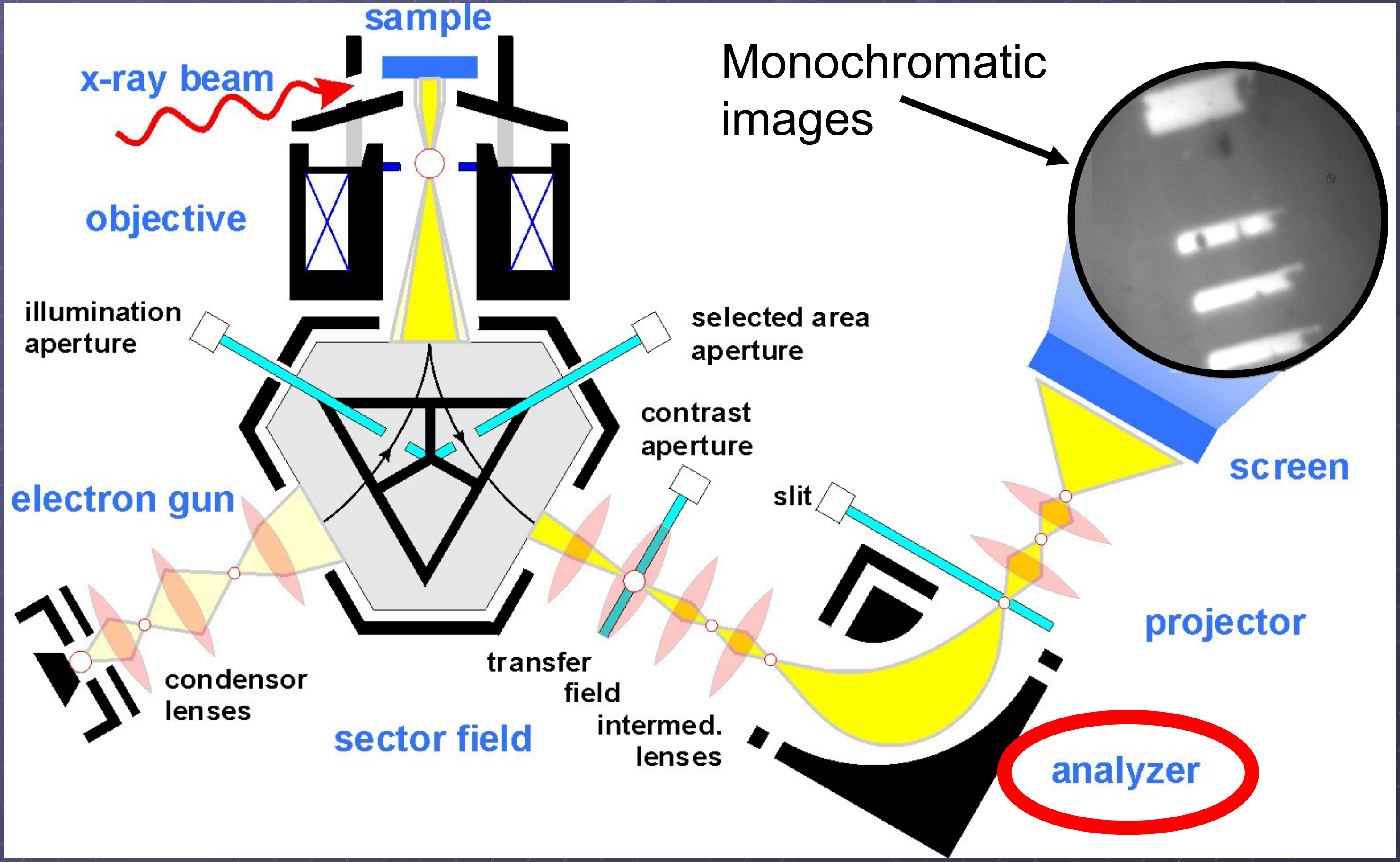


- Best energy resolution: 250 meV
- Best lateral resolution: 25 nm

- Variable polarization
- 20 - 1000 eV
- Photon flux 10^{13} ph/s
- Small spot (2 μm x 25 μm)

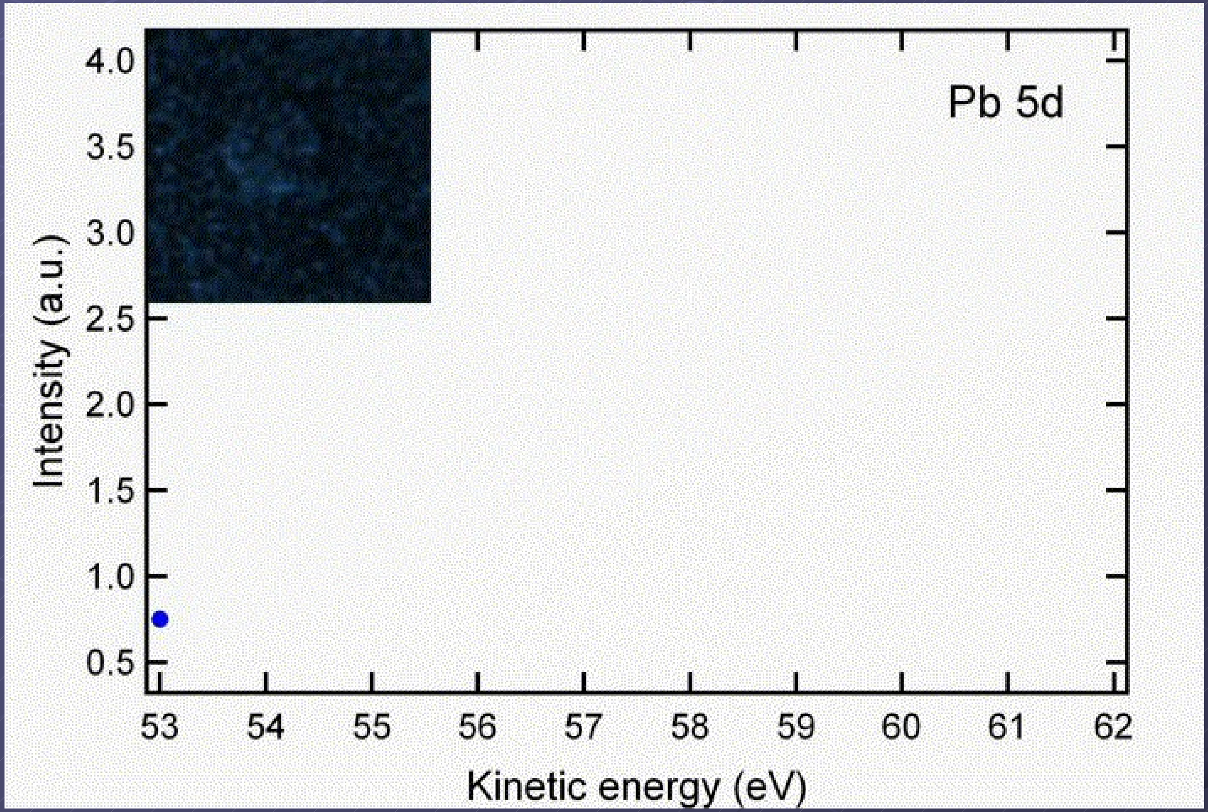
The SPELEEM instrument

Spectroscopic Photo-Emission and Low Energy Electron Microscope



XPEEM: Core Level Spectroscopy

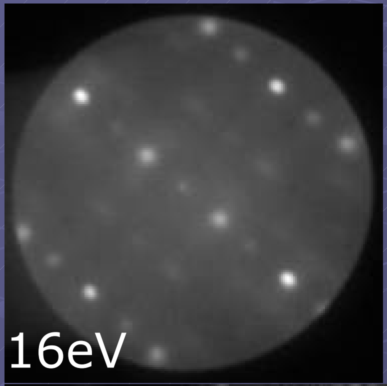
- Pb/W(110), Pb 5d core level, hν = 80 eV
- Best energy resolution: 250 meV



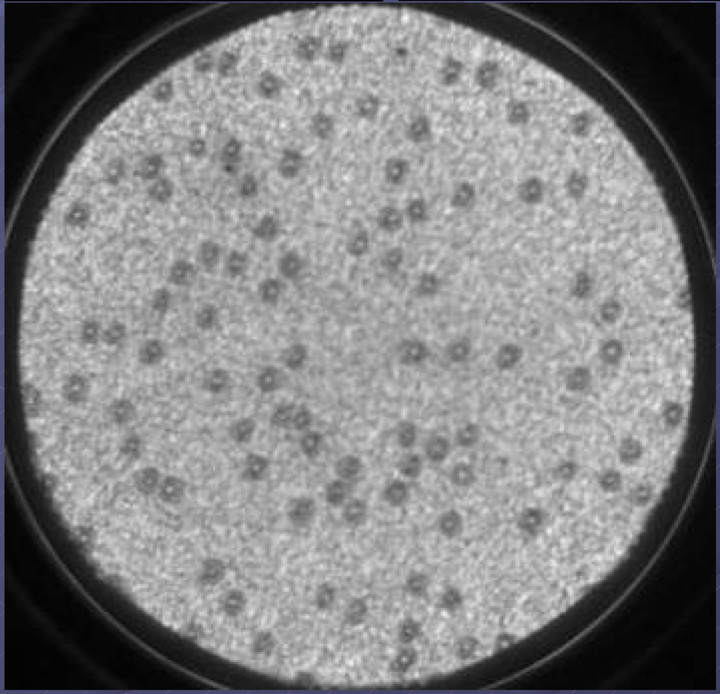
Our experiment

- InAs/GaAs QRs by MBE:
  - 2ML InAs @ 540°C + 2nm GaAs @ 490°C + 30” annealing @ 490°C + As capping protection @ RT
- Thermal decapping @ Nanospectroscopy beamline (≈450°C)
- LEED, LEEM, XPEEM
- $\Delta x \approx 25$nm, $h\nu = 80$ eV
- Core levels: Ga 3d, In 4d, BE ≈ 20 eV
- KE ≈ 60 eV $\Rightarrow \lambda \approx 0.5$nm

Morphology after decapping

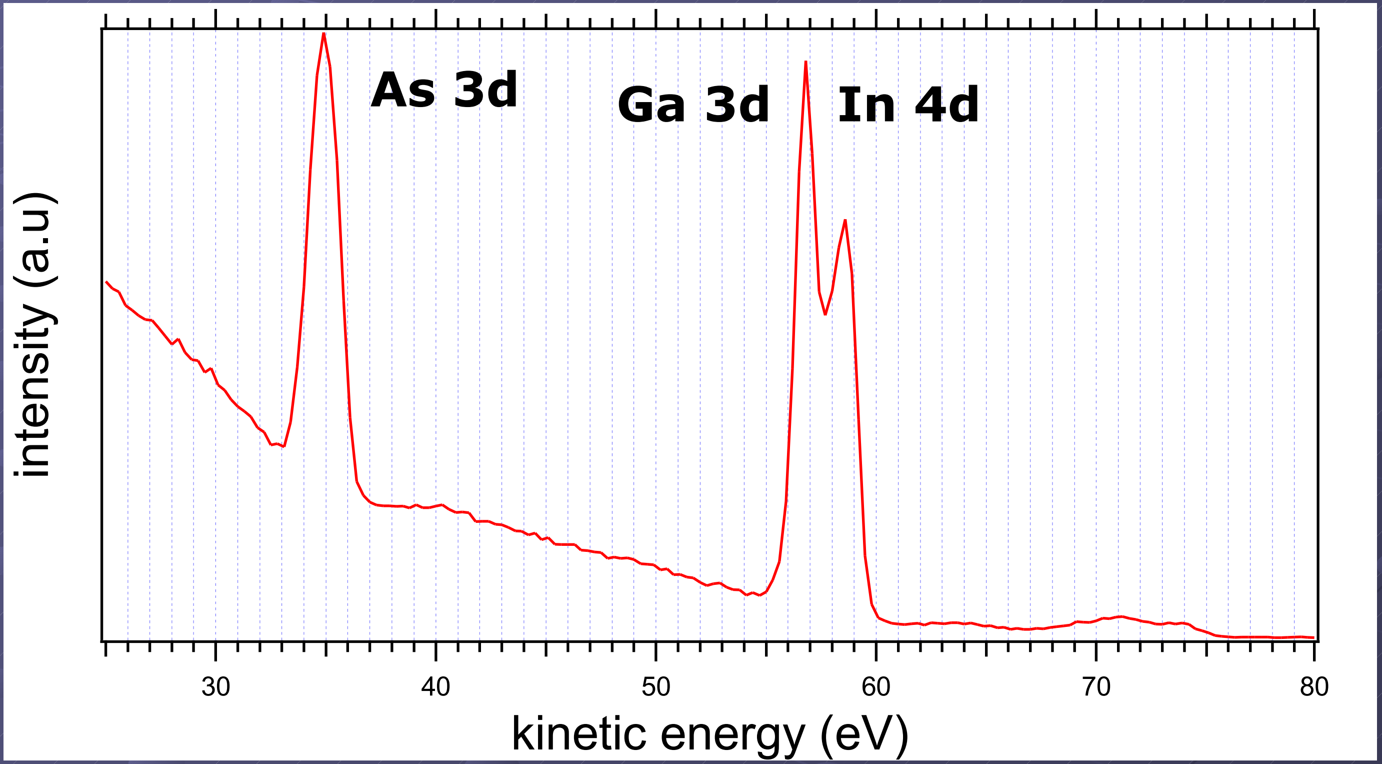


LEED (3X1) or (3x2) (As-rich)



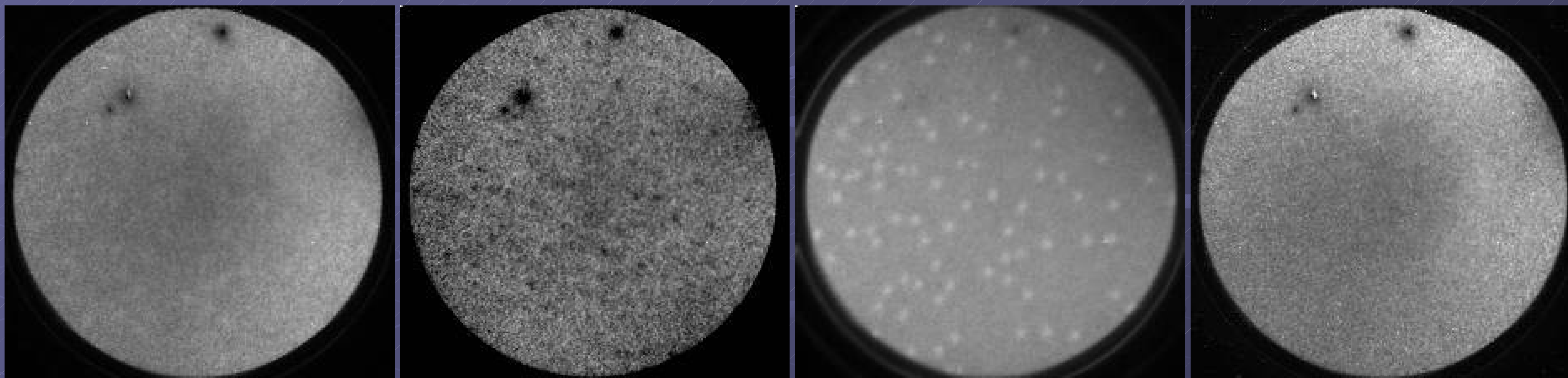
LEEM: 2.7eV, FOV 2μm
QRs: dark, almost symmetric, doughnut-shaped,
OD ≈ 70nm, ID ≈ 17nm

Integral XPS spectrum

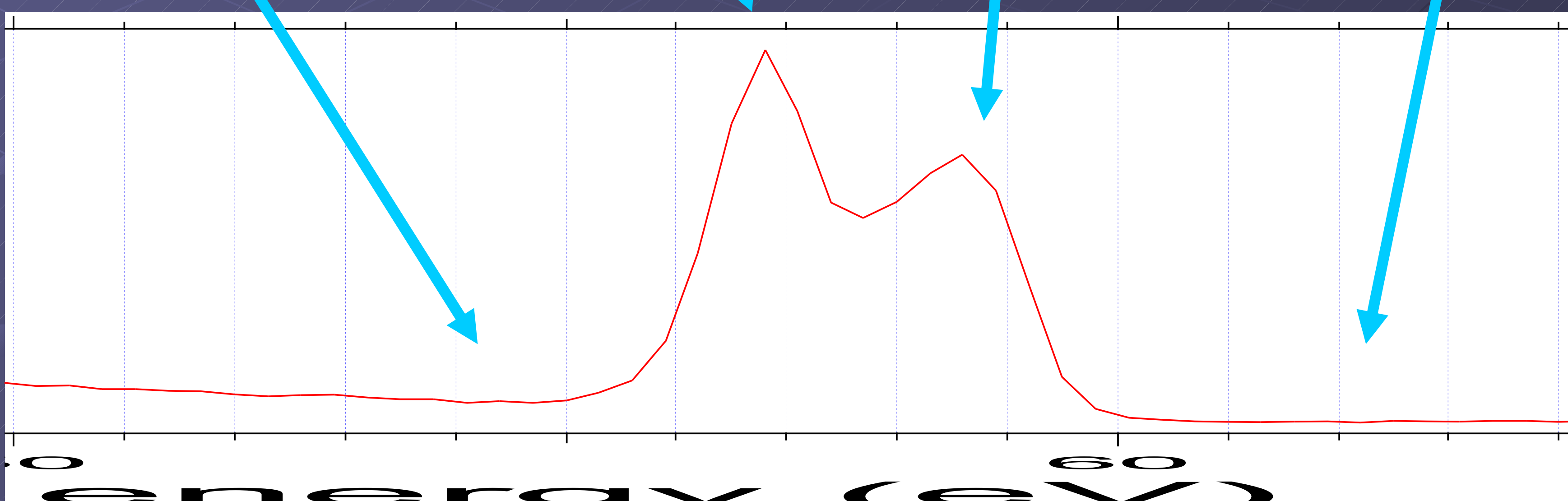


- Correct As/(Ga, In) ratio
- No detection of oxides
- Ga 3d, In 4d resolved but need deconvolution

Core level XPEEM images

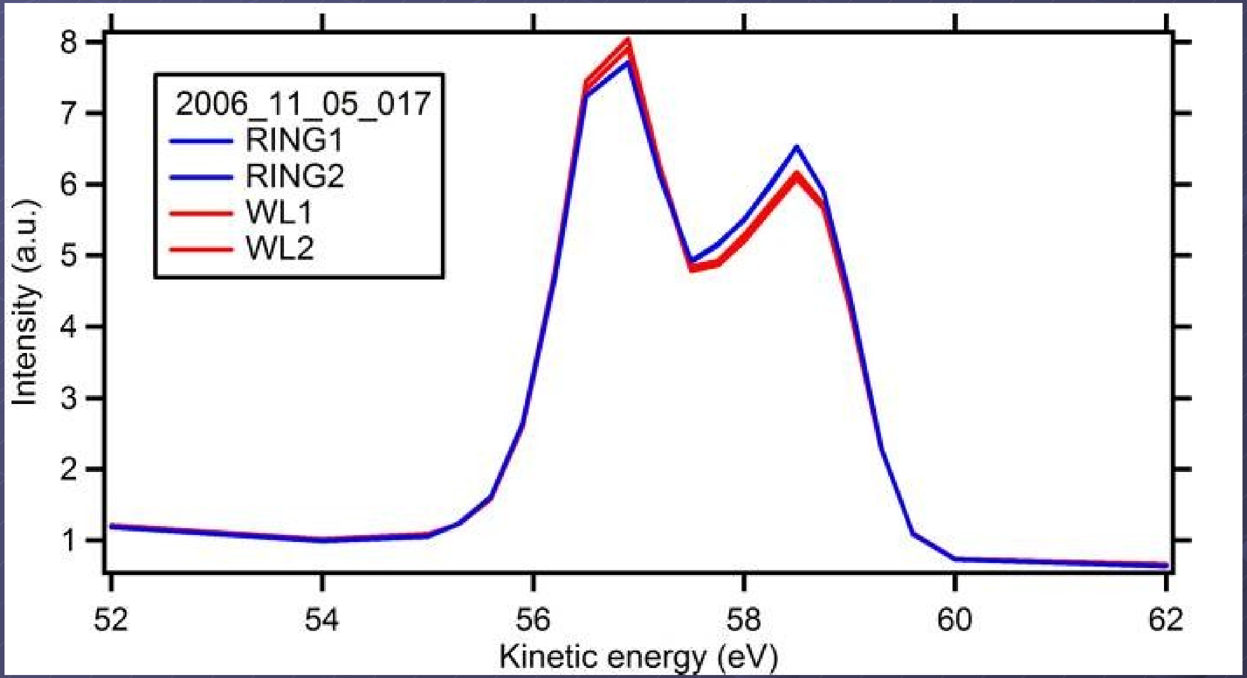


54 eV   Ga 3d 56.7 eV   In 4d   58.6 eV   62 eV



Determination of composition

- Spatially-resolved PE spectrum in the 50-63eV range
- Step = 0.3eV, 2x2 Lee filter



Determination of composition

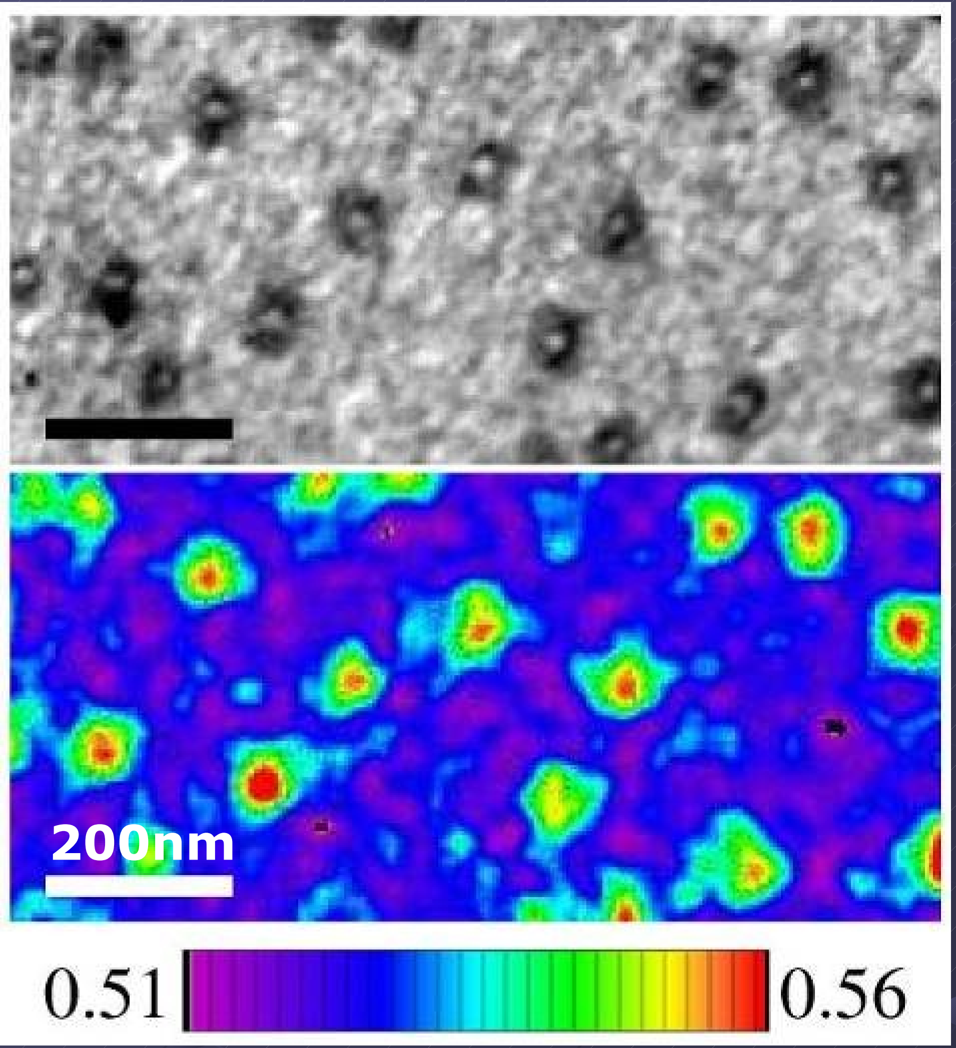
- Point-by-point PE intensity *I* of Ga 3d & In 4d CLs (fit)
- Similar KE ⇒ same λ ≈ 0.5nm

$$x = \frac{\sigma_{Ga3d} I_{In4d}}{\sigma_{Ga3d} I_{In4d} + \sigma_{In4d} I_{Ga3d}}$$

σ = photoioniz. XS

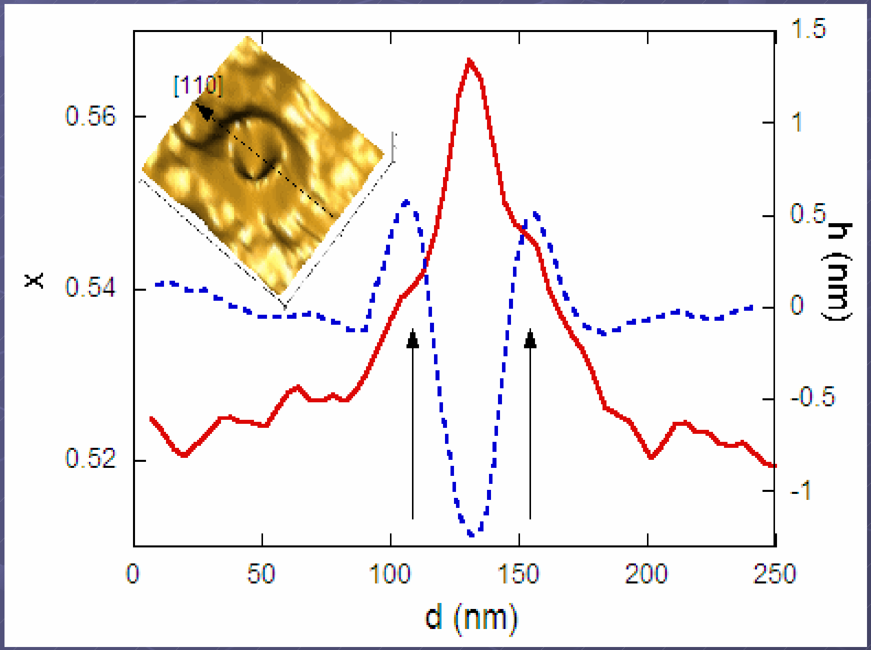
$$x = \sum_{i=1}^{\infty} x_i e^{-d_i/\lambda} \Big/ \sum_{i=1}^{\infty} e^{-d_i/\lambda}$$

d_i = depth of monolayer i



x_WL ≅ 0.52 <
x_rim ≅ 0.55 <
x_core ≅ 0.57

Composition profiles



- 10x average **AFM** and **x**, [110] profiles
- Similar along [-110]
- Double structure: slope change on rims
- Central peak: residual dot (same as X-sections)
- Rim: ejected material (more alloyed with GaAs)
- Planar region: too high x for segregation alone ⇒ ejected material everywhere between dots

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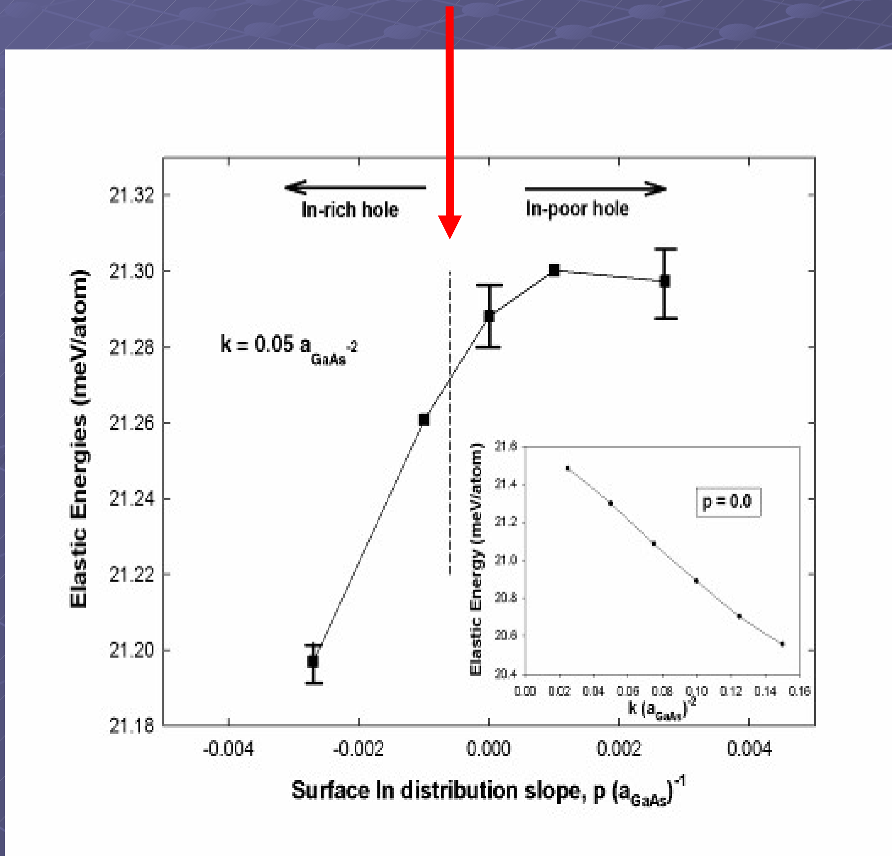
- Modeling of QR composition (R. Magri, U Modena)
- Conductivity mapping of QRs by c-AFM

Modeling of QR composition

- Atomistic model of ring of up to 2.5 millions of atoms
- Shape fixed (given by AFM profile)
- Identifies In atom distribution that minimizes total (~ elastic) energy of the system
- Strain energy is lower
  - when In segregates to the surface
  - when In partially remains in the hole

Modeling of QR composition

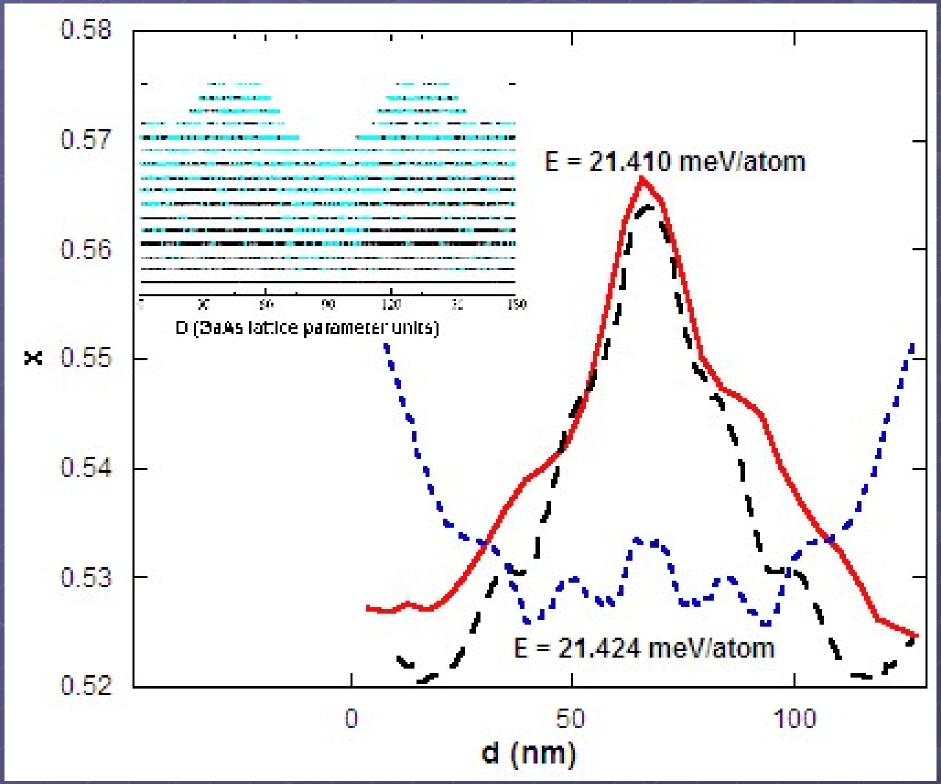
Experimental profile



- Dependence of elastic energy on *k* (inset) and *p.*
- *k*: tendency to surface hole segregation.
- *p*: tendency to keep an In-rich core.

$$x(r,\delta) = (x_0 \pm p \cdot r) \cdot \exp\left(-k(\delta - d_0(r))^2\right)$$

Modeling of QR composition



- Apparent concentration profiles obtained through

$$x = \sum_{i=1}^{\infty} x_i e^{-d_i/\lambda} \Big/ \sum_{i=1}^{\infty} e^{-d_i/\lambda}$$

- Red: XPEEM profile
- Black: p = -6 x 10^{-4} a_{GaAs}^{-1} (In-rich core)
- Blue: p = +6 x 10^{-4} a_{GaAs}^{-1} (In-poor core)
- Inset: section of a ring model with In-rich core

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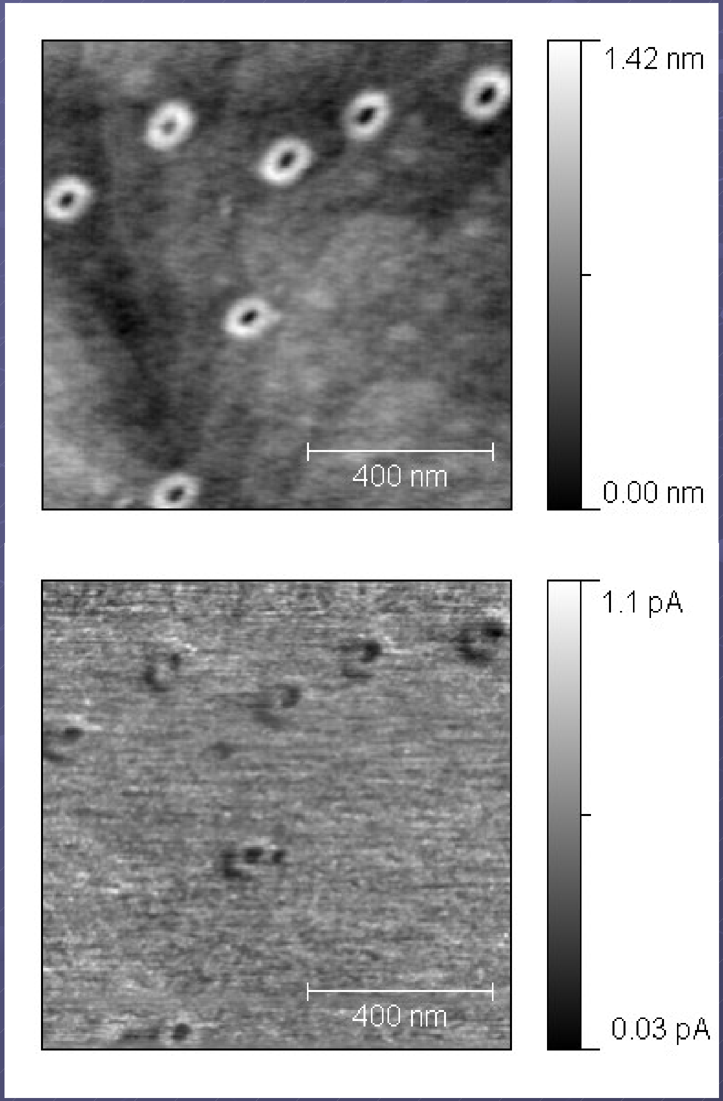
  - Surface conductivity ⇔ surface composition

C-AFM Experiment

- QRs on n^+ GaAs (to achieve low resistance)
- Measurements in N_2 atmosphere (no local anodic oxidation)
- Simultaneous topography and current mapping in contact mode
- Local I-V measurements

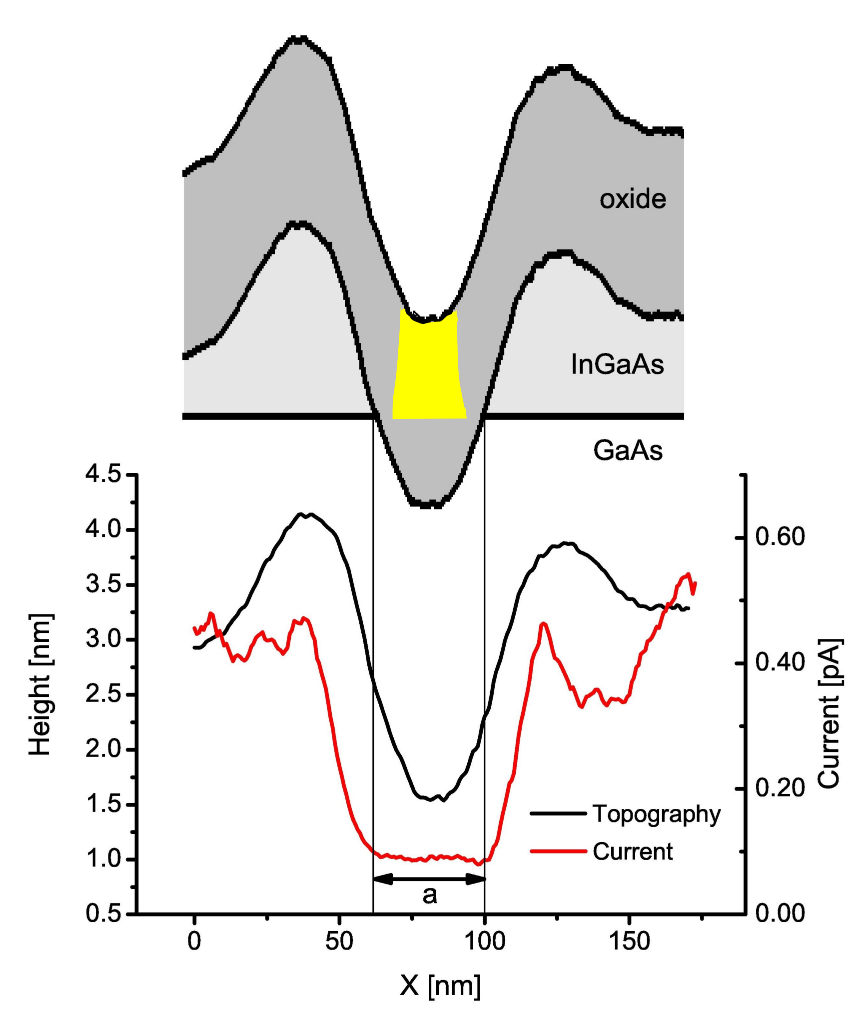
Current maps on QRs



- Topography (top) and current maps (bottom) of QRs at -2.5V tip bias.
- $I_{rim} > I_{WL} > I_{center}$
- BUT I should increase with x (InAs has smaller band gap and Schottky barrier than GaAs) such as QD
- $\Rightarrow$ effect of surface oxidation?

T. Mlakar, S. Heun et al.: APL 92 (2008) 192105

Effect of surface oxidation



- Larger hole in current than topography: oxide thicker than InGaAs layer
- Low *I* in the center ⇔ complete InGaAs oxidation down to the substrate (~1nm)
- Higher *I* on rims and WL: unoxidized InGaAs below the oxide

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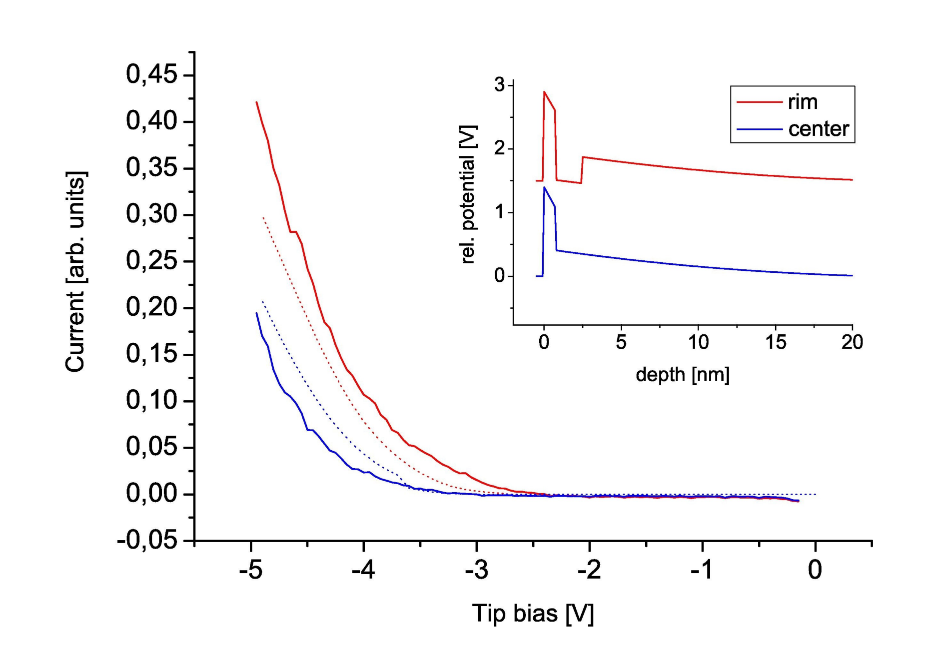
I-V characteristics



- 1D CB profiles with composition profile from experiment and top 1nm oxidized
- Model of I-V from metal to semiconductor through a potential barrier, with simulated band profiles including oxide (dashed lines)
- Measured I-V curves on QR rim and centers (continuous lines)
- Good qualitative agreement

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Summary

- Experimentally observed In profile
  - More indium in the center of the ring
- Ring structure with higher In content in the center is energetically favored.
- Future directions: kinetics of QR formation (time evolution, temperature dependence)
- UHV C-AFM on clean samples (no effect of oxide)

Coworkers

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