Surface compositional gradients of InAs/GaAs quantum dots

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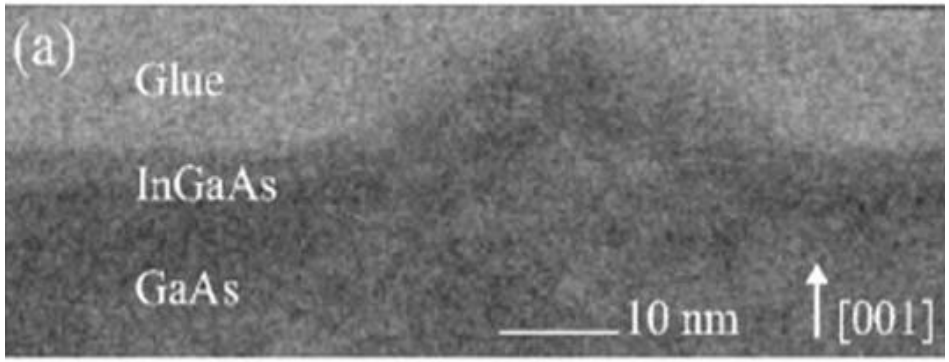
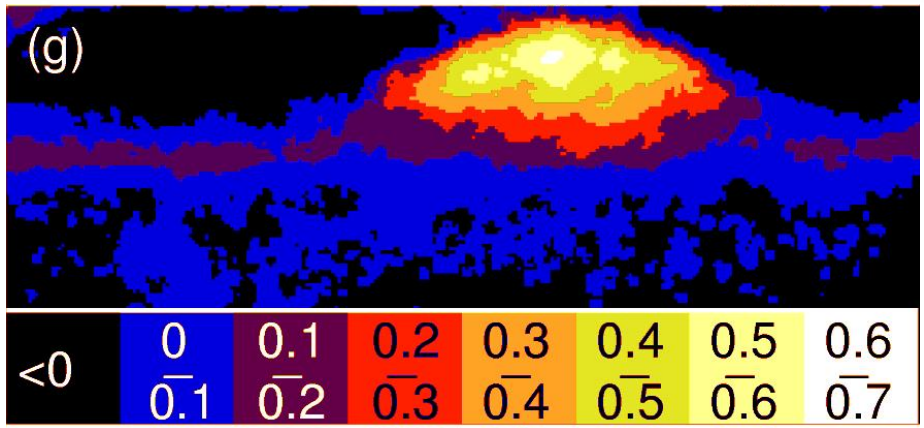
Motivation

- Quantum Dot Applications based on their particular electronic properties (confinement)
- Strain-driven self-assembly (SK-growth)
- Model systems: InAs/GaAs, Ge/Si
- Intermixing and alloying allow for partial strain relaxation
- Composition (gradients) within the dot influence energy levels and shift the emission wavelength

Concentration Profiles

- Concentration maps
  - in cross-section: TEM

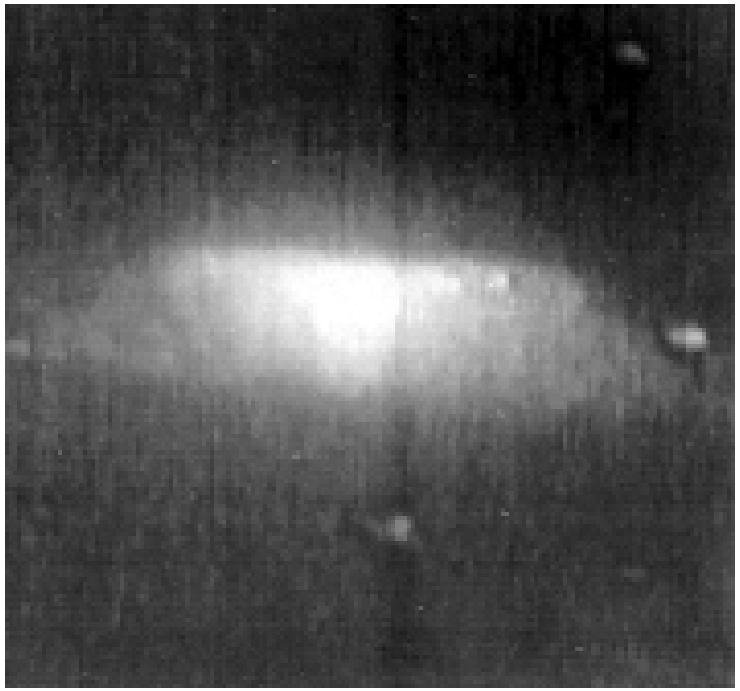




Walther et al.,
PRL **86** (2001) 2381

Concentration Profiles

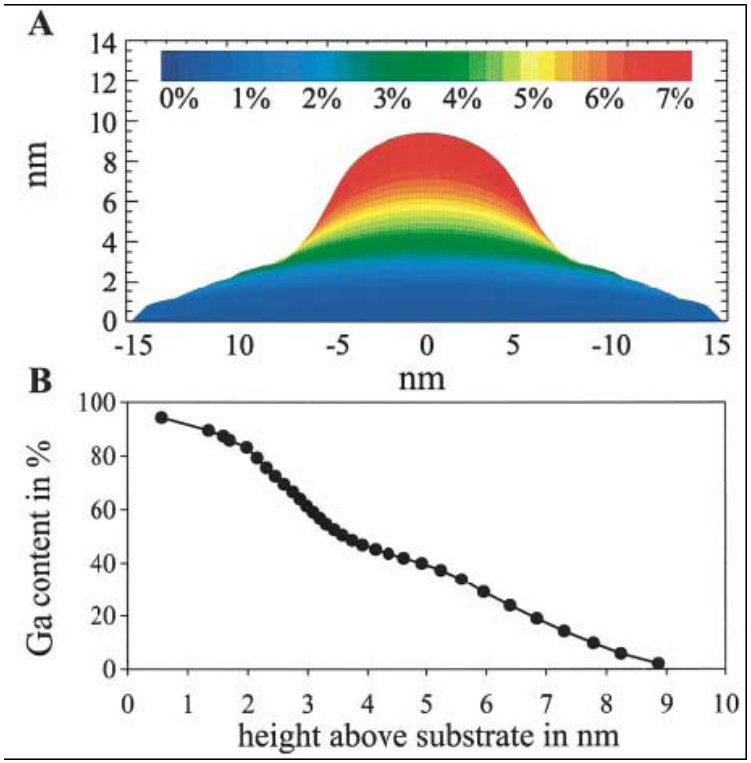
- Concentration maps
  - in cross-section: TEM, STM



Liu et al., PRL **84** (2000) 334

Concentration Profiles

- Concentration maps
  - in cross-section: TEM, STM, XRD

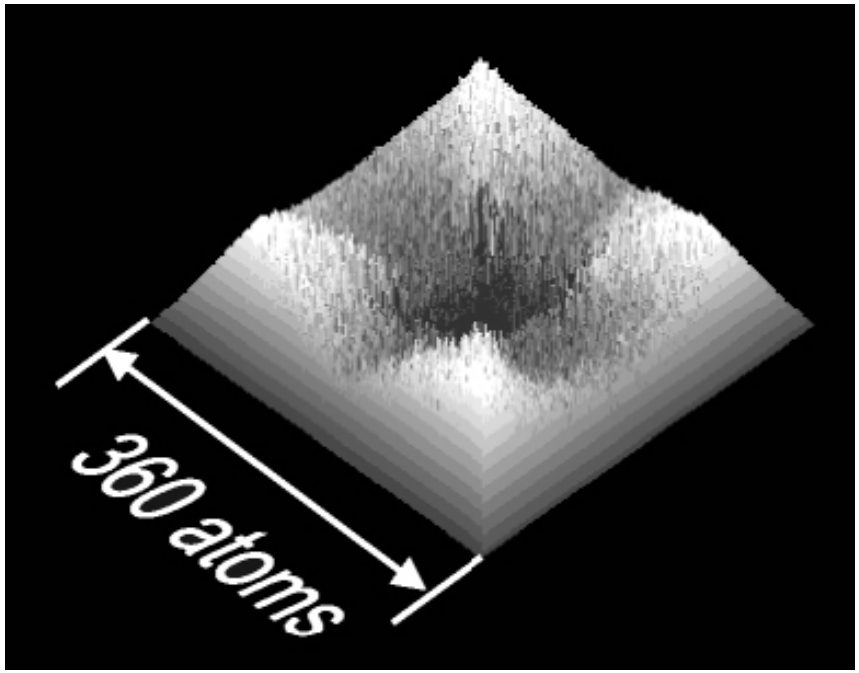


Kegel et al., PRL **85** (2000) 1694

Concentration Profiles

- Concentration maps
  - in cross-section: TEM, STM, XRD
  - in top-view: etching (Ge > 65%)

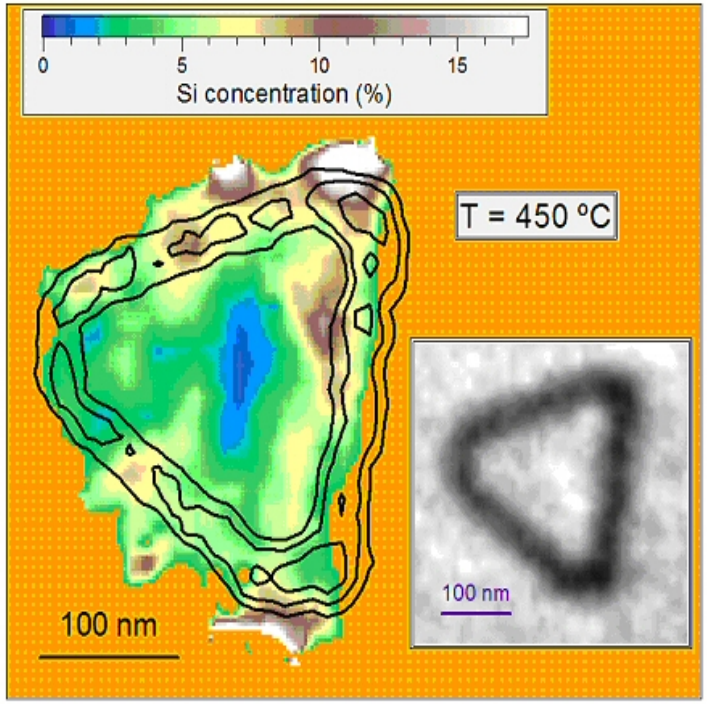
Complementary views
Full 3D mapping



Denker et al., PRL **90** (2003) 196102

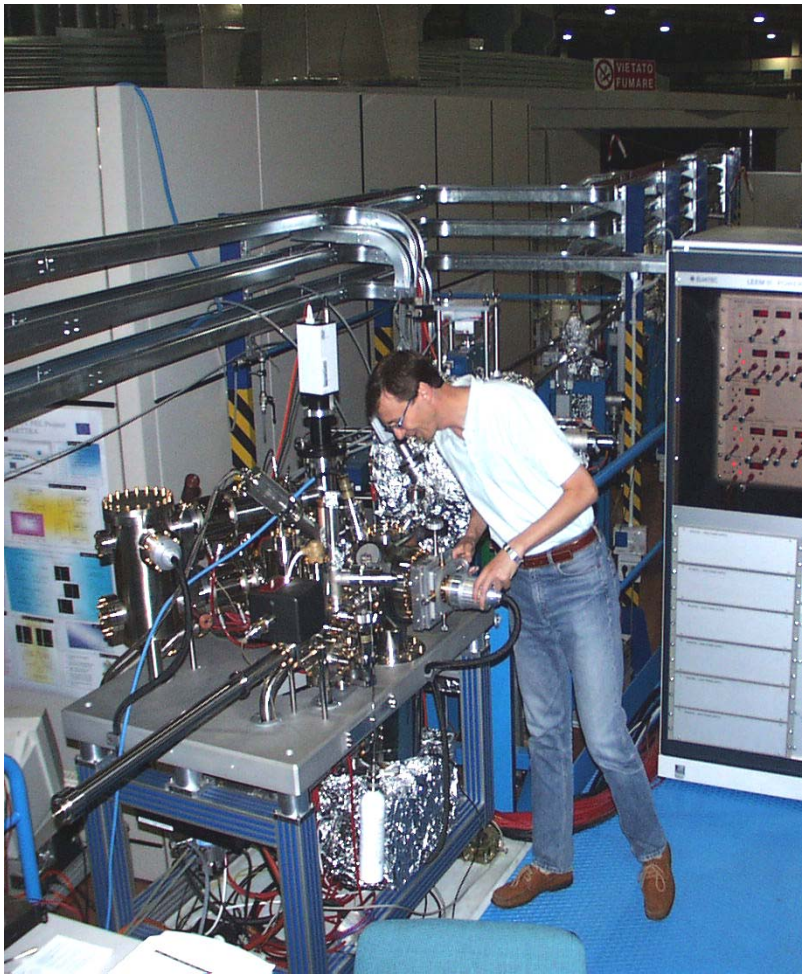
Concentration Profiles

- Concentration maps
  - in cross-section: TEM, STM, XRD
  - in top-view: etching, XRM



F. Ratto et al.: Small **2** (2006) 401.

The SPELEEM at ELETTRA

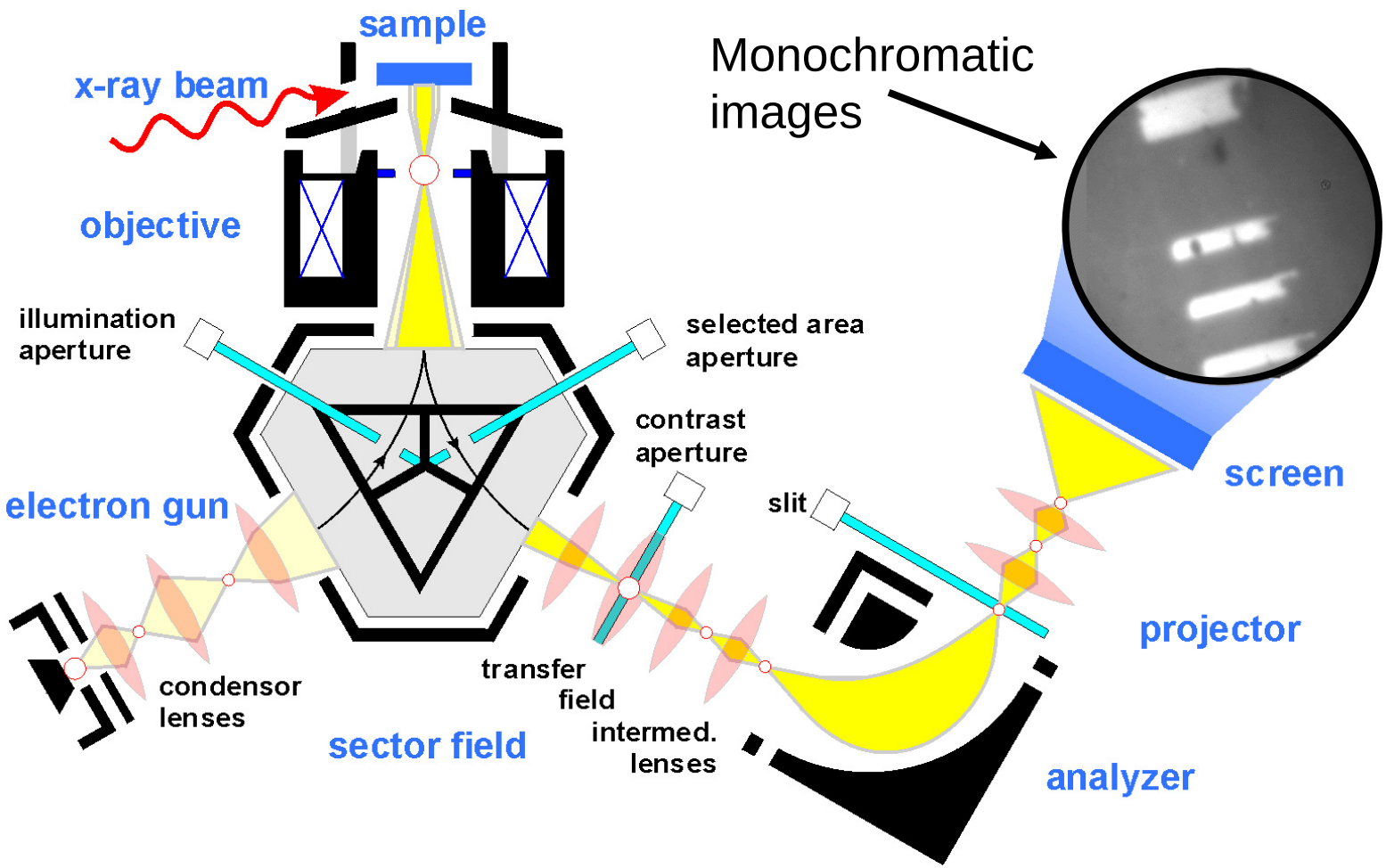


- Best energy resolution: 250 meV
- Best lateral resolution: 25 nm

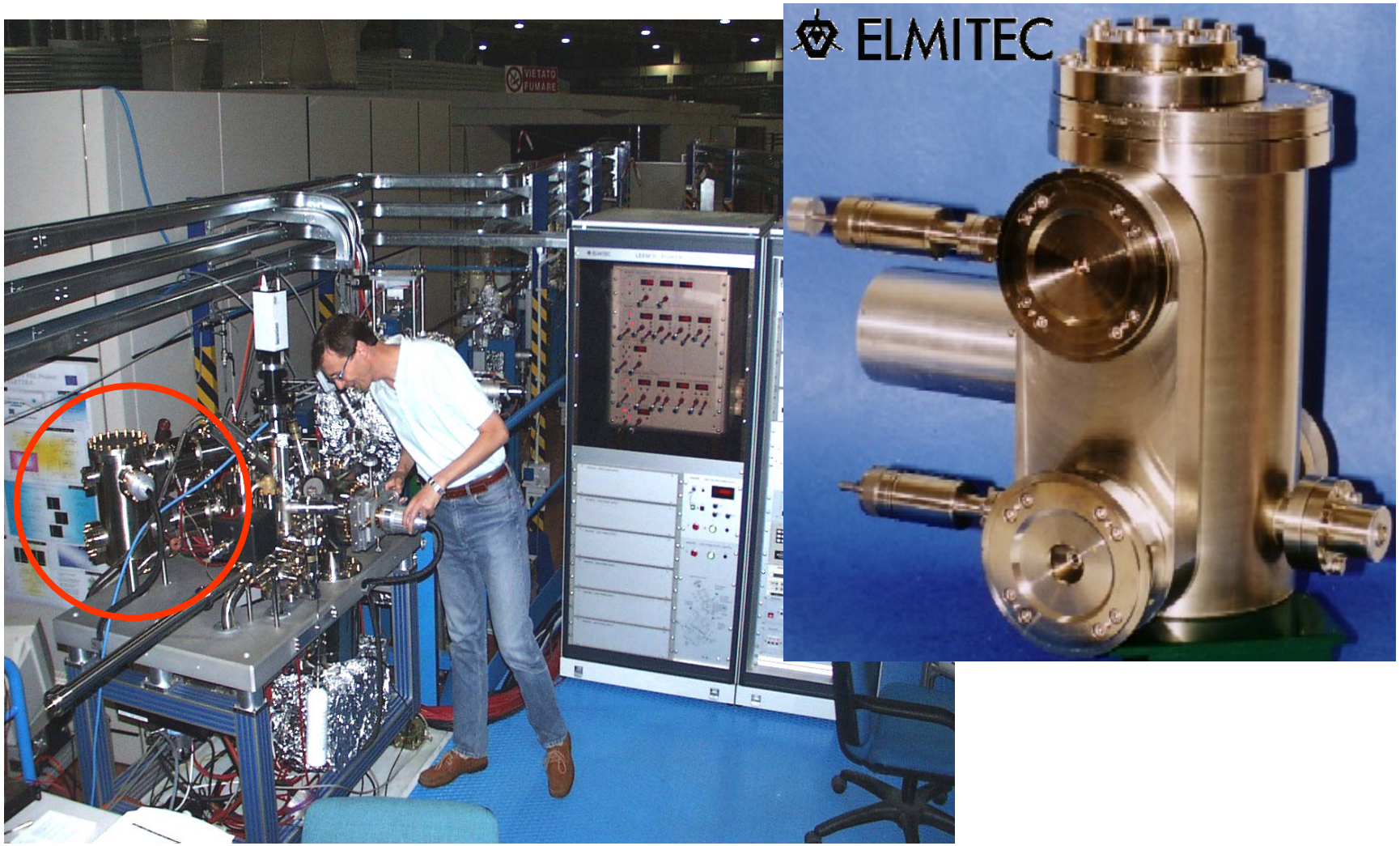
- Variable polarization
- 20 - 1000 eV
- Photon flux 10^{13} ph/s
- Small spot (2µm x 25 µm)

The SPELEEM instrument

Spectroscopic Photo-Emission and Low Energy Electron Microscope

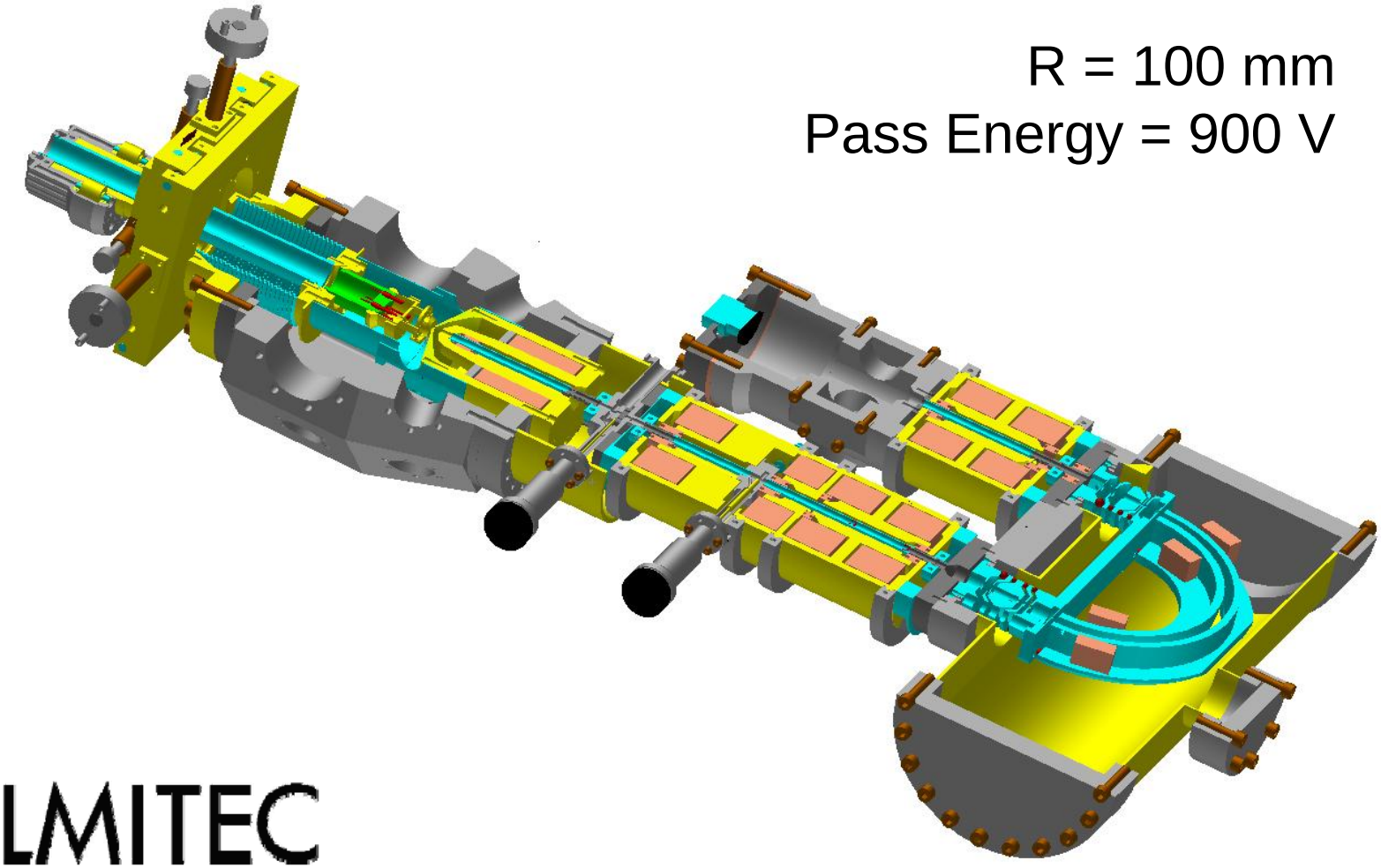


The SPELEEM at ELETTRA



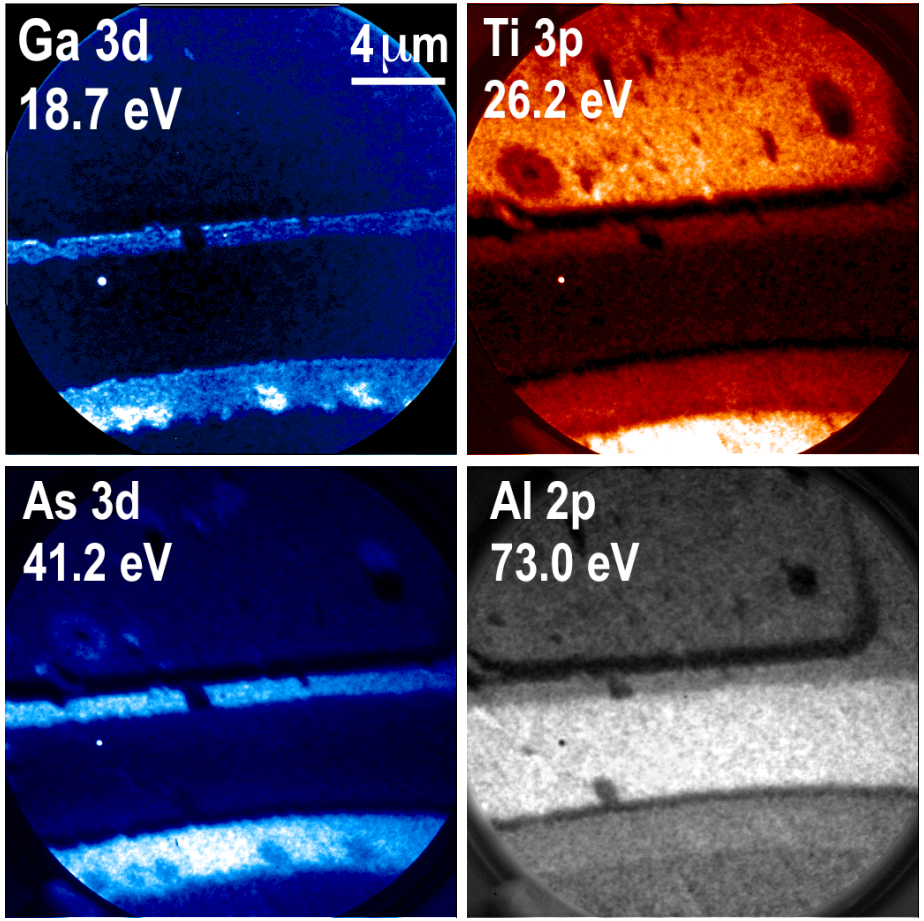
The Energy Filter

R = 100 mm
Pass Energy = 900 V

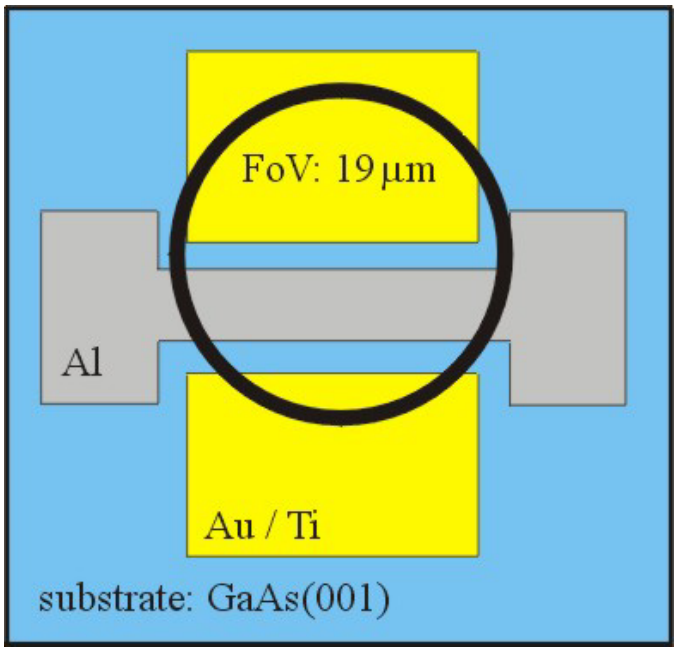


ELMITEC

XPEEM: Spectroscopic Microscopy

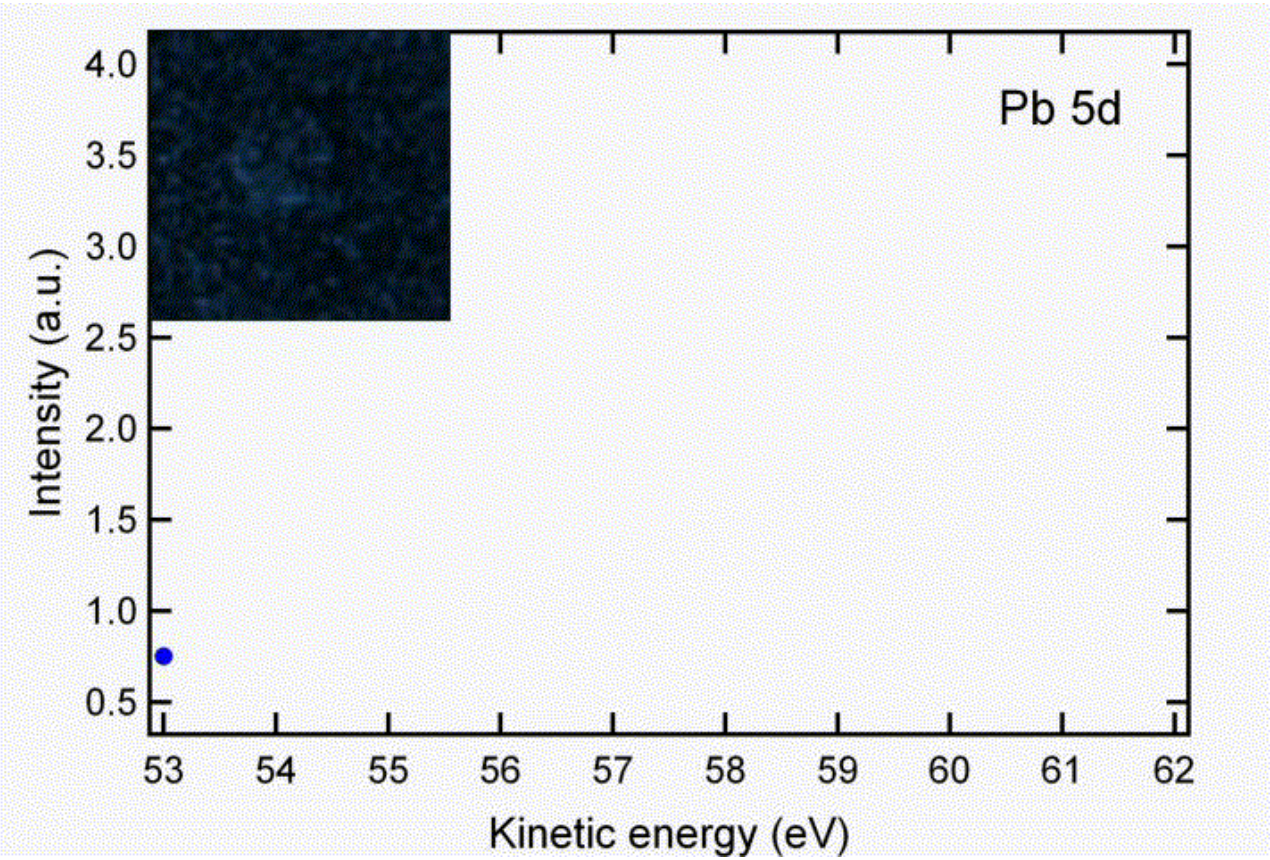


- Images from a Field Effect Transistor (FET) at different binding energies.
- Photon energy 131.3 eV.



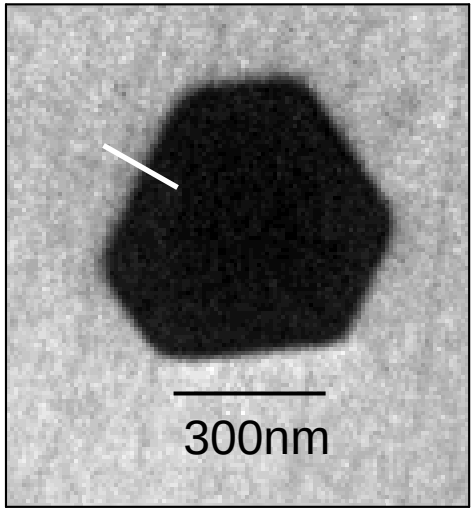
XPEEM: Core Level Spectroscopy

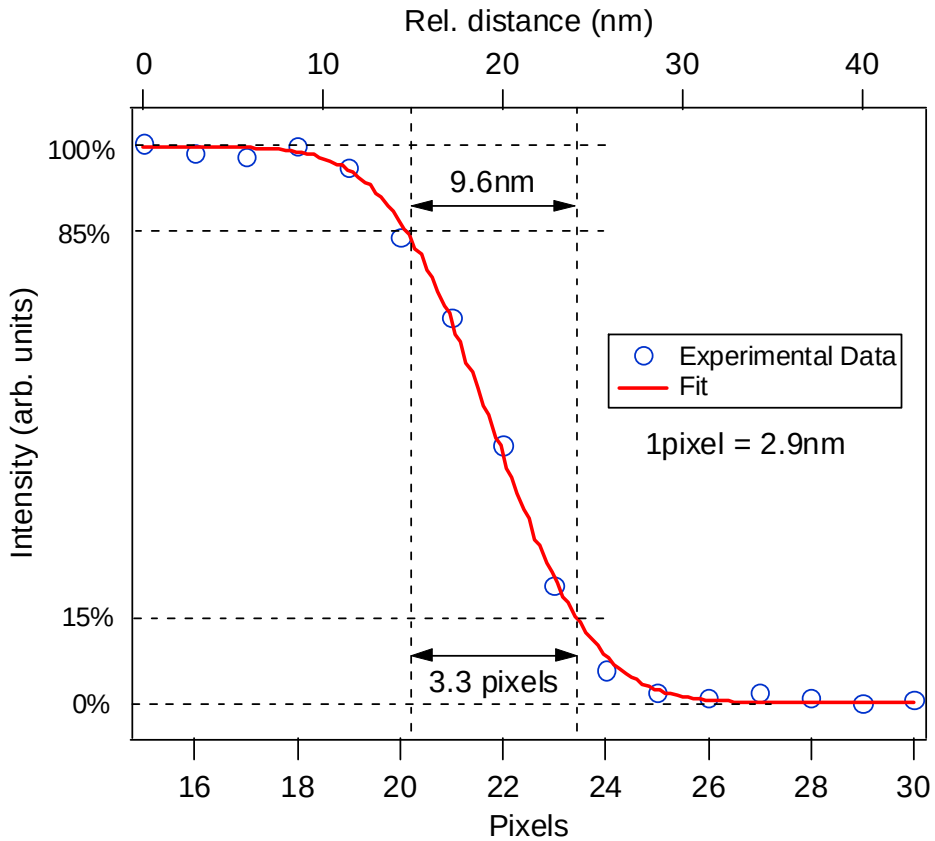
- Pb/W(110), Pb 5d core level, hv = 80 eV
- Best energy resolution: 250 meV



Lateral resolution in LEEM mode

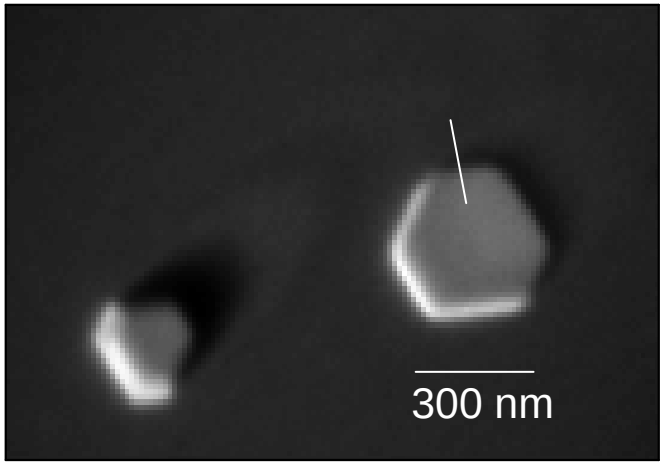
- Pb/W(110), E = 11 eV
- Lateral resolution: 10 nm

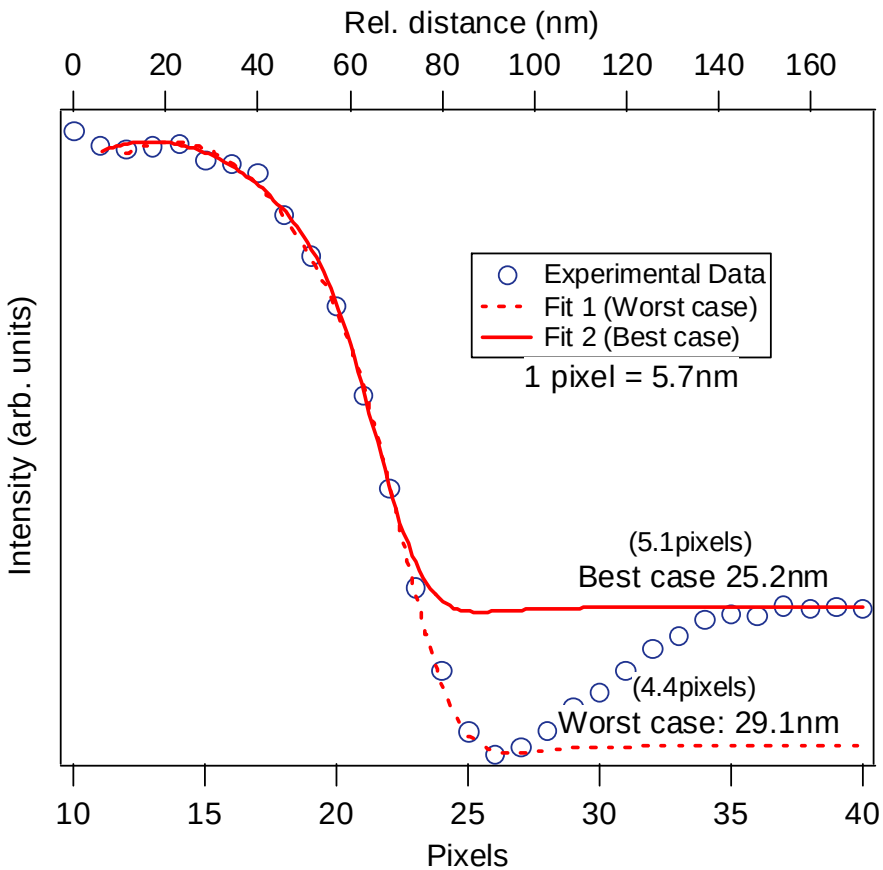




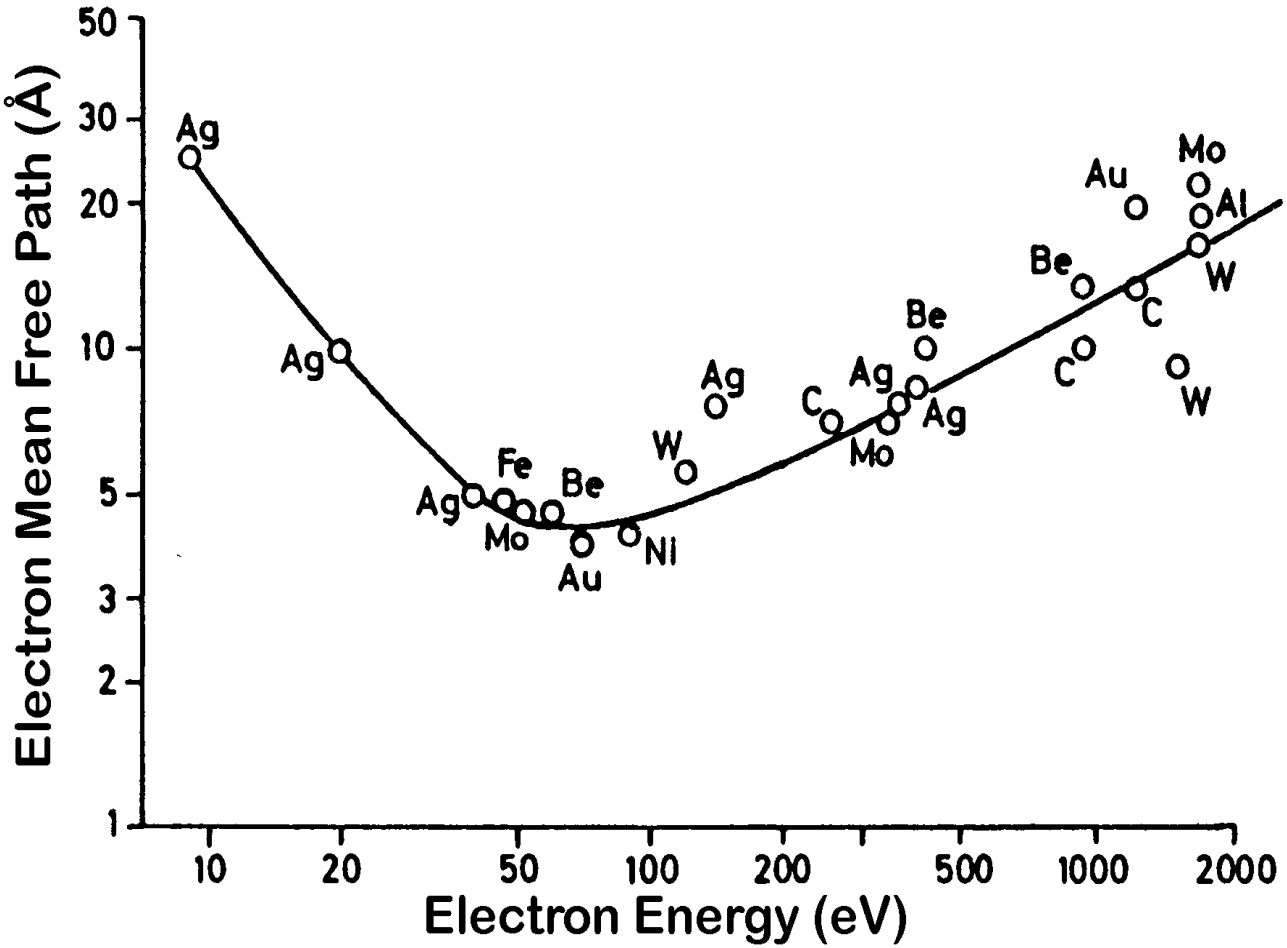
Lateral resolution in XPEEM mode

- Pb/W(110), Pb $5d_{5/2}$, hv = 80 eV, KE = 58.2 eV
- Lateral resolution: 25 nm





Photoelectron Mean Free Path

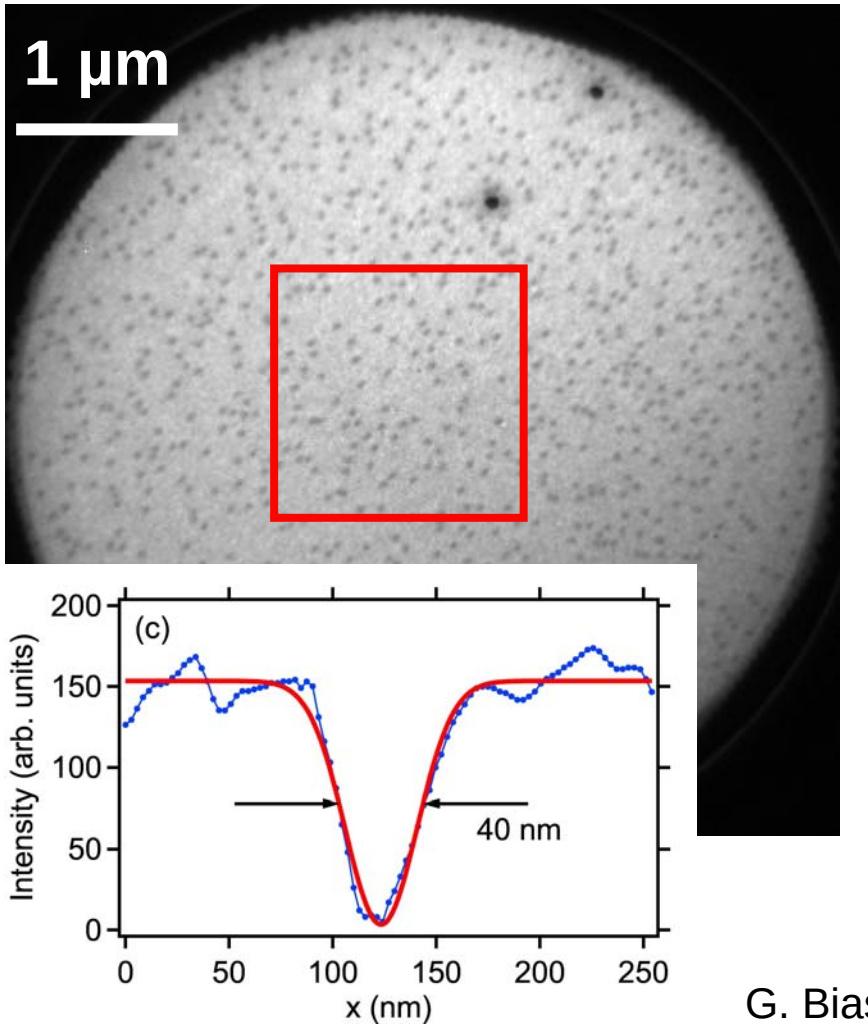


M. P. Seah and W. A. Dench: Surf. Interface Anal. **1** (1979) 2.

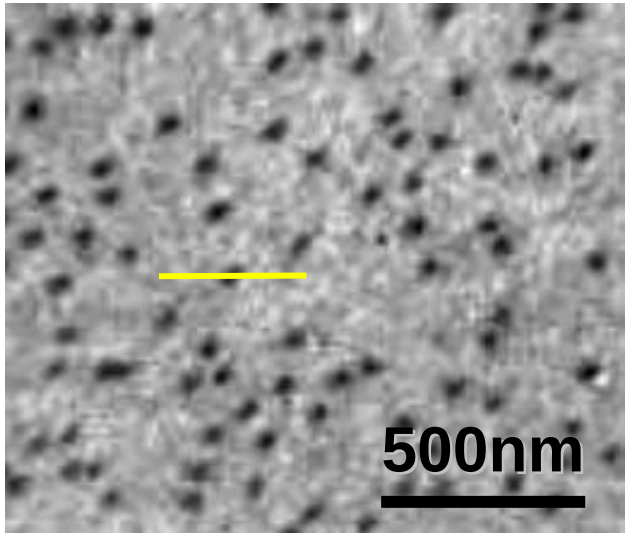
HM1416: Growth Parameters

- Substrate n^+-GaAs(100)
- Si-doped buffer grown @ 600°C : 200 nm GaAs, 200 nm GaAs/AlAs superlattice, 200 nm GaAs
- 2.3 ML InAs deposited @ 540°C in cycles of 0.2 ML InAs @ 0.03 ML/s, followed by 3 sec growth interruption (As_4 partial pressure p = 8.5 x 10^{-6} Torr)
- Rapid cooldown to 70°C, then As capping for 2 hours at p = 2.0 x 10^{-5} Torr
- Sample decapped in microscope chamber at 410°C, LEED: 2x4

InAs/GaAs Islands (LEEM)

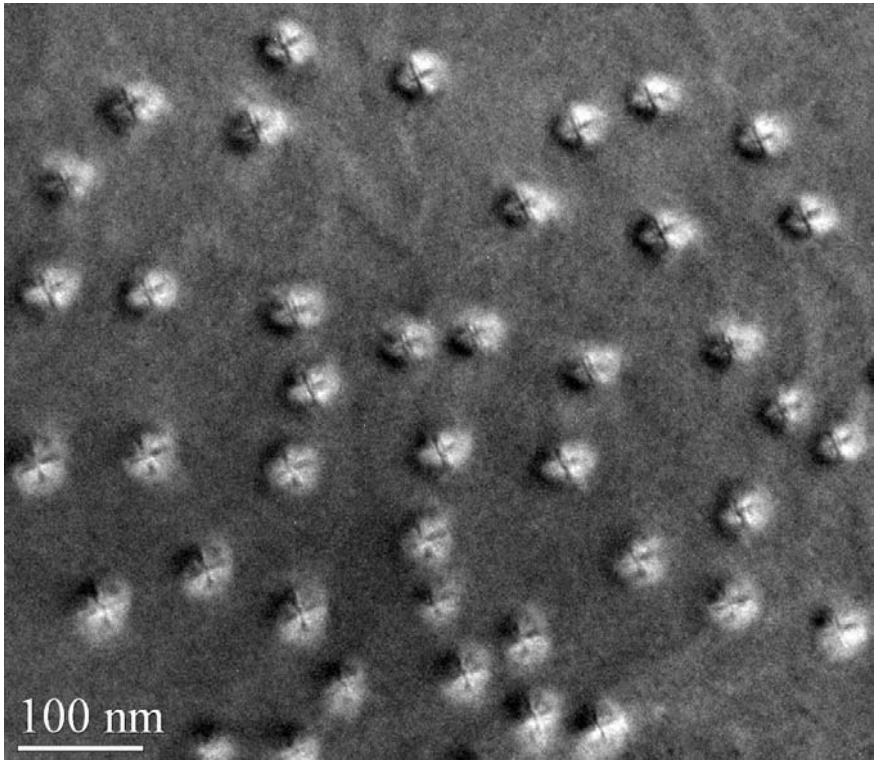


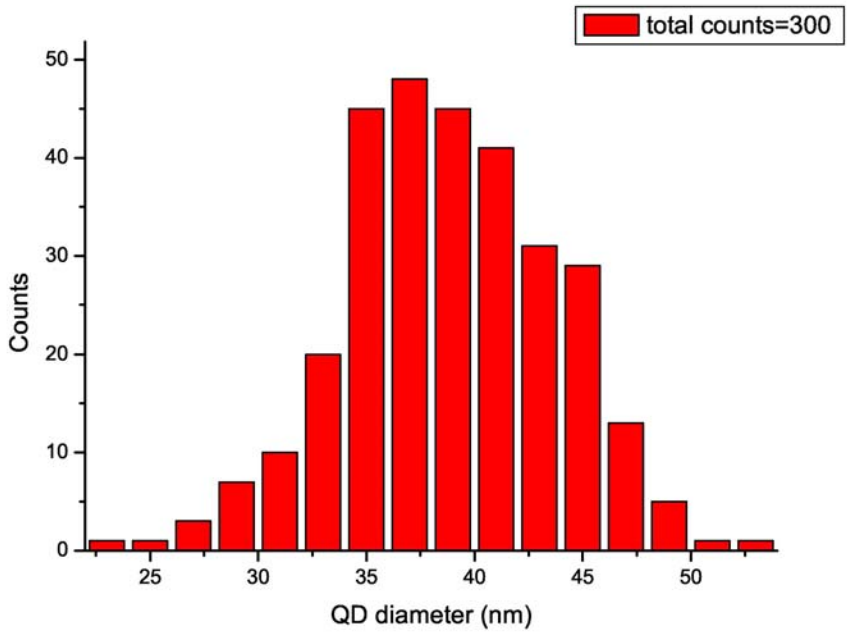
- Electron Microscopy
- LEEM
- 5 µm FOV
- E_{kin} = 7.6 eV



G. Biasiol et al.: Appl. Phys. Lett. **87** (2005) 223106.

TEM investigation

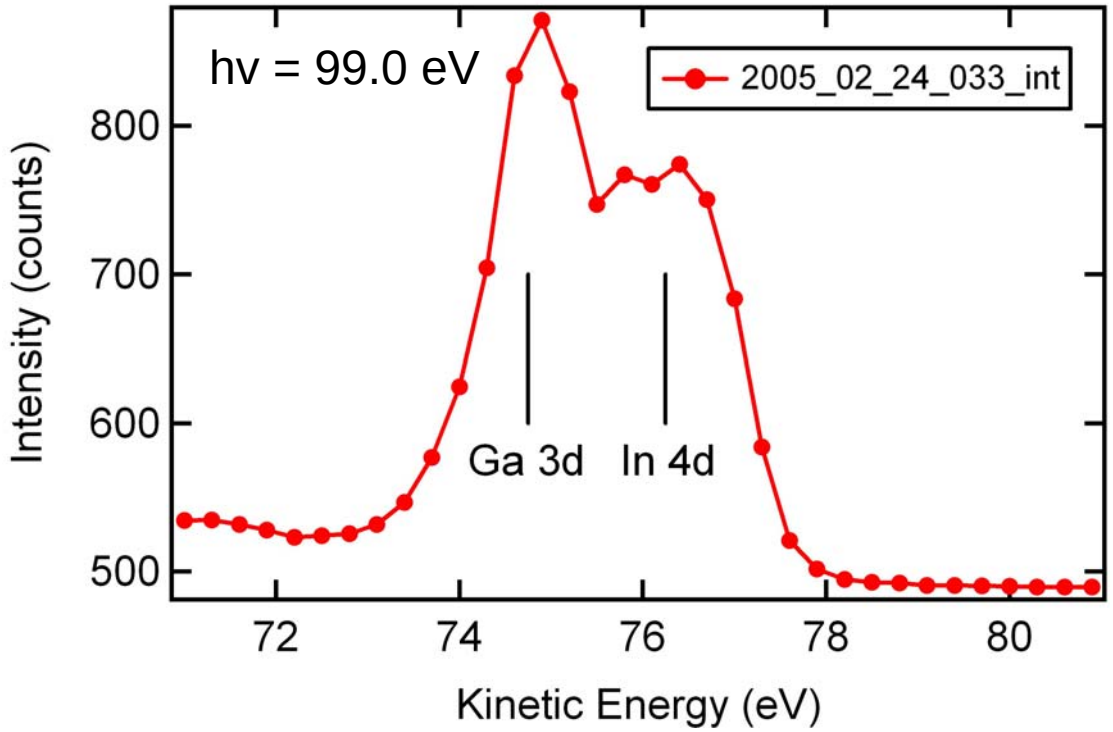




- Sample imaged in [100] plan view geometry
- Islands are coherent, i.e. no dislocations

S. Heun et al.: J. Nanosci. Nanotech., submitted.

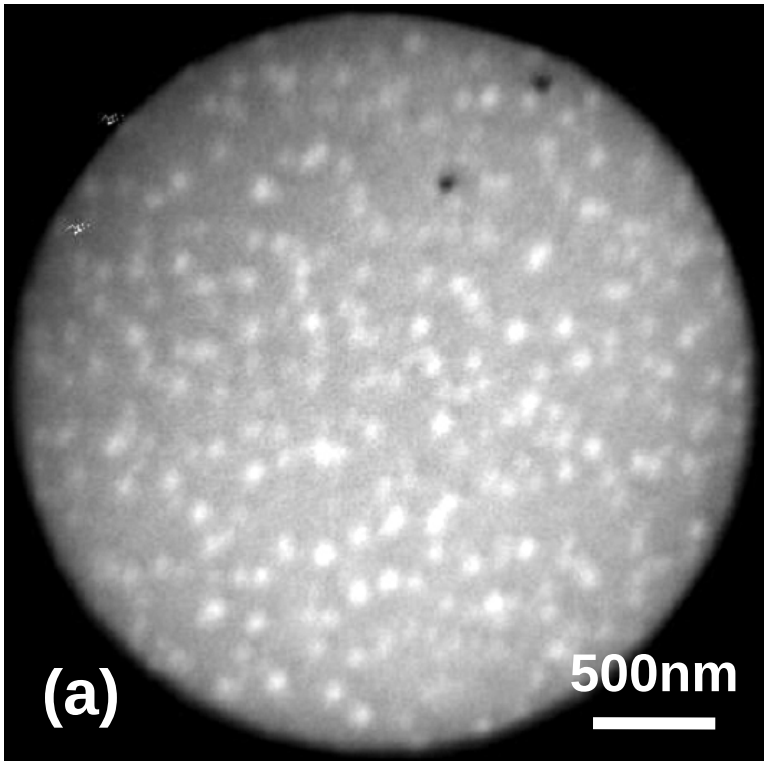
“Integral” Core Level Spectra

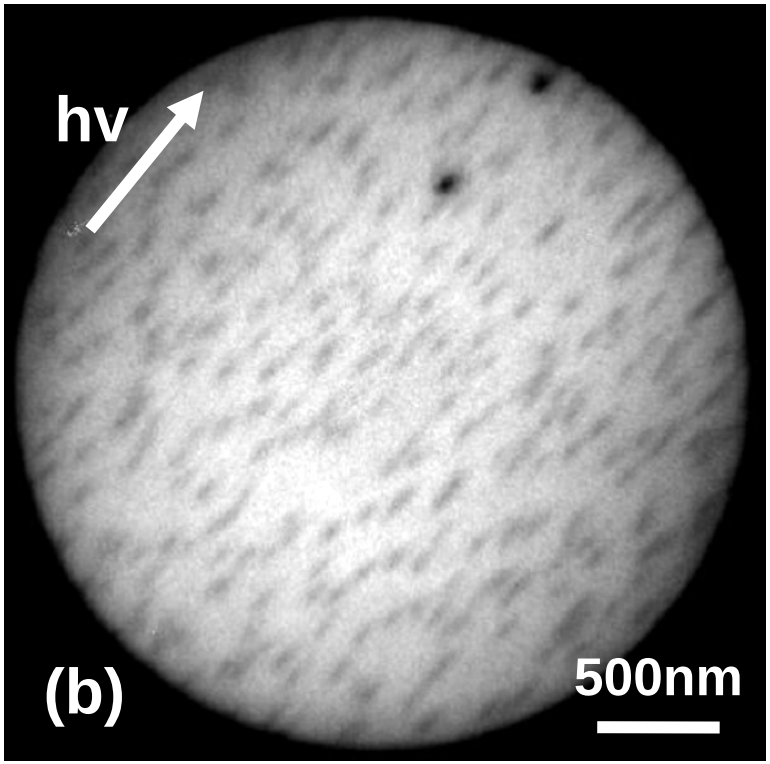


- Spectra taken from a 1 µm x 1 µm sample area.
- III-V stoichiometry after decapping confirmed.

G. Biasiol et al.: Appl. Phys. Lett. **87** (2005) 223106.

XPEEM Core Level Imaging





In 4d XPEEM image

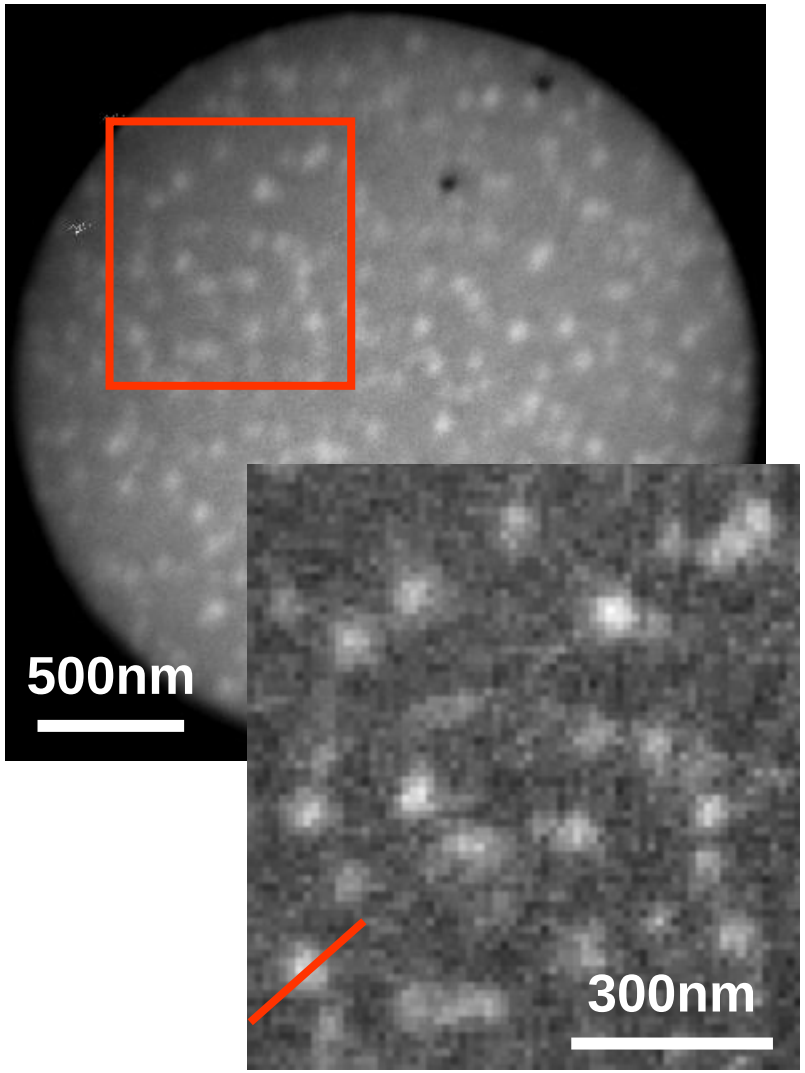
hv = 99.0 eV, E_{kin} = 76.25 eV

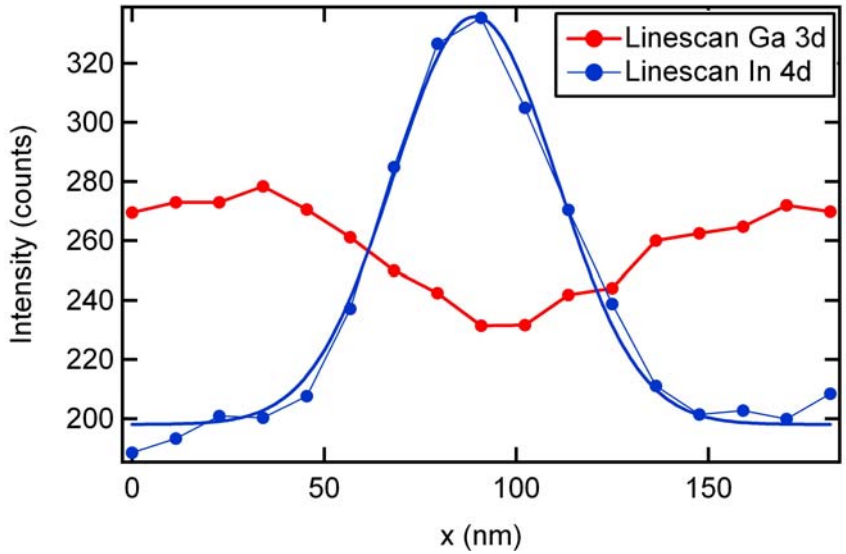
Ga 3d XPEEM image

hv = 99.0 eV, E_{kin} = 74.75 eV

G. Biasiol et al.: Appl. Phys. Lett. **87** (2005) 223106.

Island Size in XPEEM

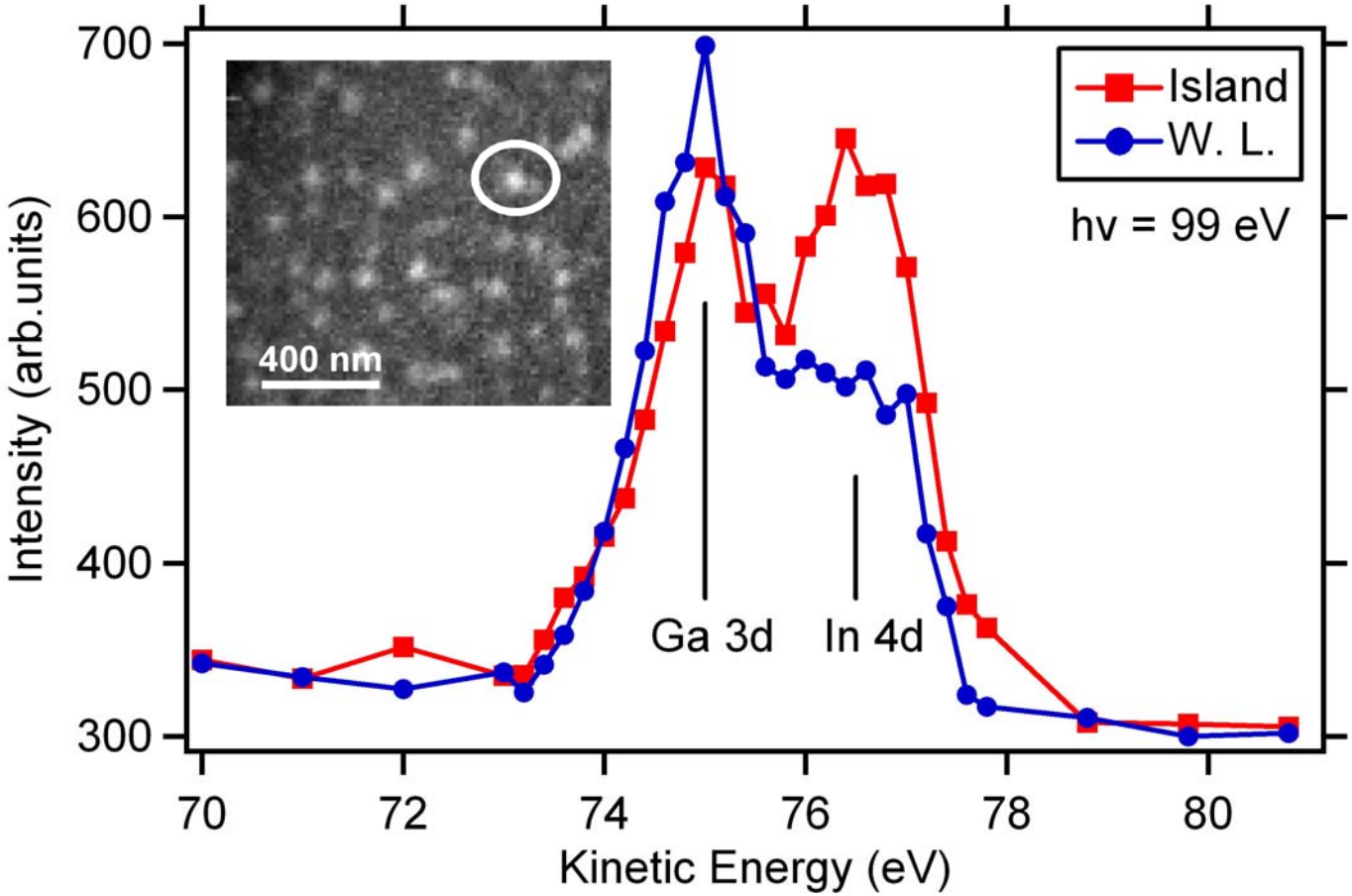




Island Size ≈ 60 nm, consistent with LEEM and TEM

G. Biasiol et al.:
Appl. Phys. Lett. **87** (2005) 223106.

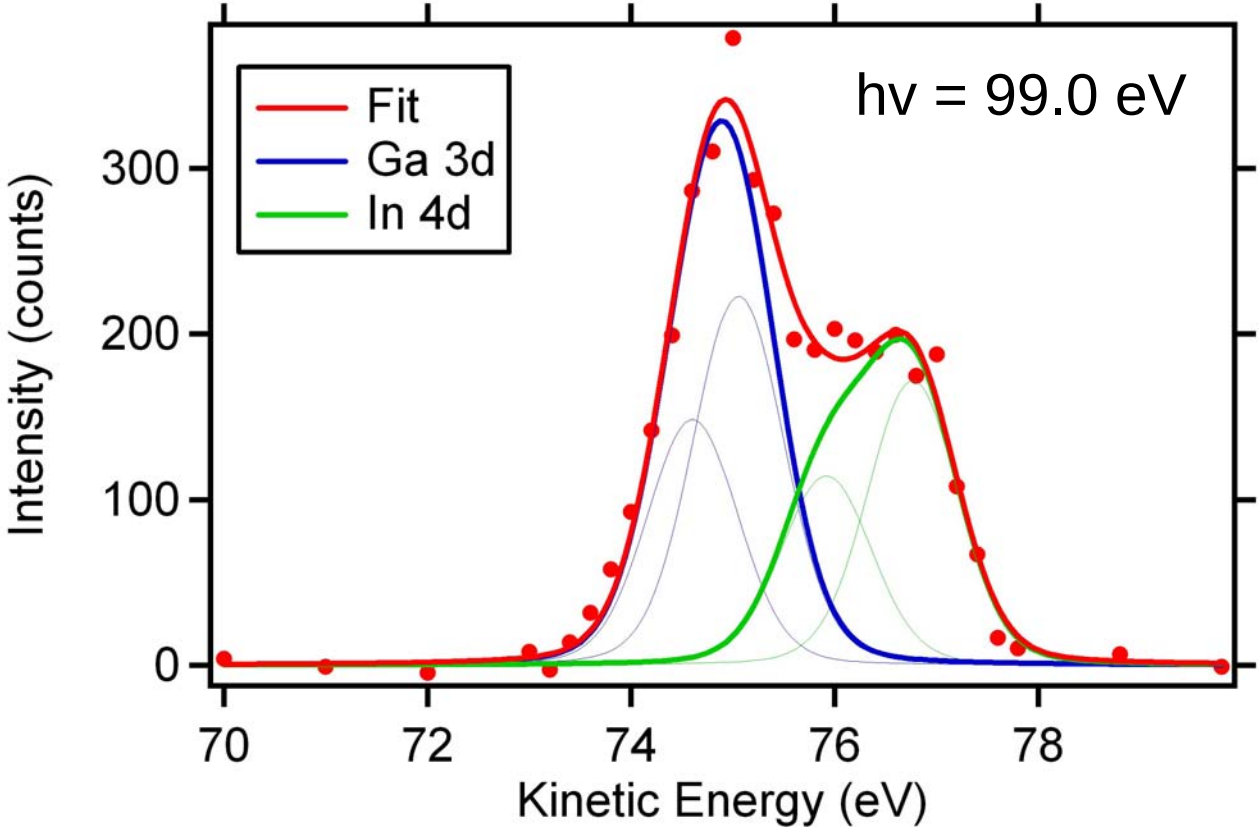
XPEEM Local Spectra



Integration area 25 nm x 25 nm, energy resolution ≈ 1 eV

G. Biasiol et al.: Appl. Phys. Lett. **87** (2005) 223106.

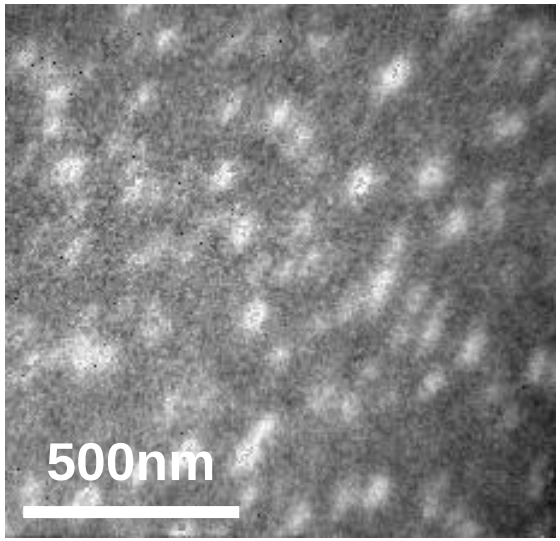
Core Level Line Profile Analysis



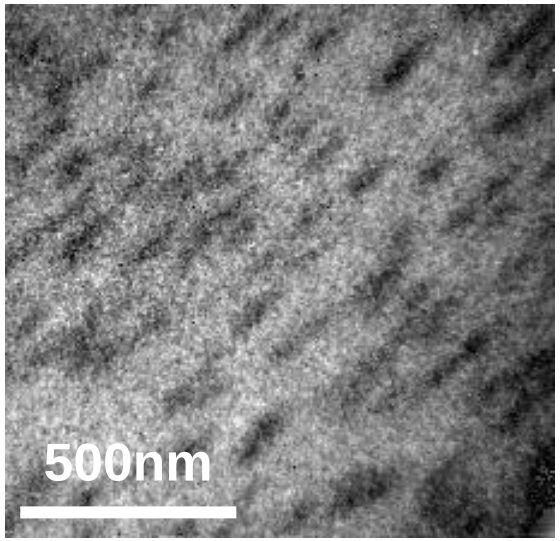
Spectrum from Wetting Layer, Shirley Background subtracted
Gauss 1 eV, Lor 0.16 eV, BR 1.5, SO: Ga 3d 0.45 eV, In 4d 0.85 eV

G. Biasiol et al.: Appl. Phys. Lett. **87** (2005) 223106.

2D Fit of XPEEM Data



In 4d peak area
Min: 220, Max: 520



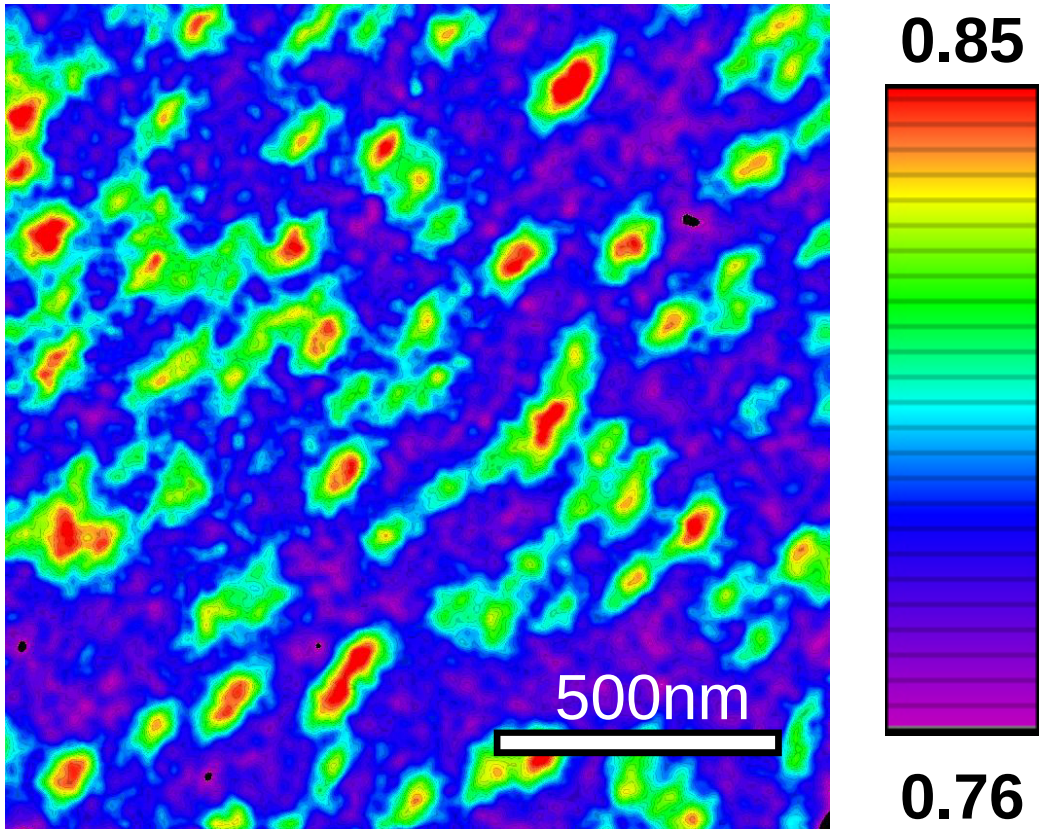
Ga 3d peak area
Min: 270, Max: 470

Ratio of Number of Atoms: $$\frac{n_{In}}{n_{Ga}} = \frac{I_{In}}{I_{Ga}} \cdot \frac{\sigma_{Ga}}{\sigma_{In}}$$

G. Biasiol et al.: Appl. Phys. Lett. **87** (2005) 223106.

Indium Surface Concentration Map

$$\frac{n_{In}}{n_{tot}} = \frac{I_{In}\sigma_{Ga}}{I_{In}\sigma_{Ga} + I_{Ga}\sigma_{In}}$$



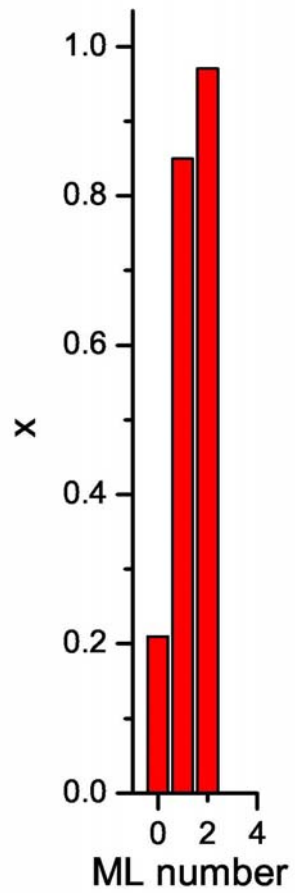
G. Biasiol et al.: Appl. Phys. Lett. **87** (2005) 223106.

Wetting Layer Composition

- Segregation models predict the following In concentration profile:
- Measured composition is average across topmost layers:

$$< x >= \sum x_i e^{-\frac{d_i}{\lambda}} \Big/ \sum e^{-\frac{d_i}{\lambda}}$$

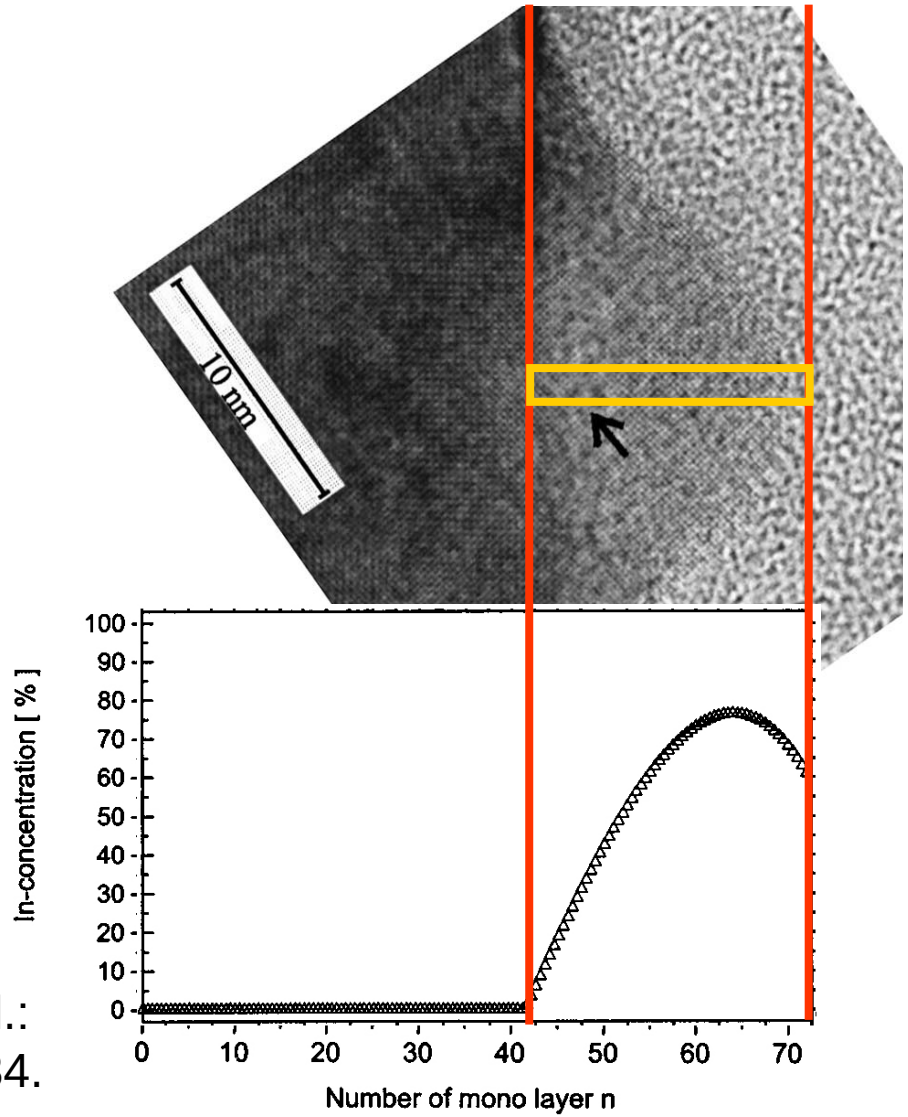
- Shown profile would be measured as x ~ 0.75, in agreement with our data.



O. Dehaese et al.:
Appl. Phys. Lett. **66** (1995) 52.

Dot Composition from TEM

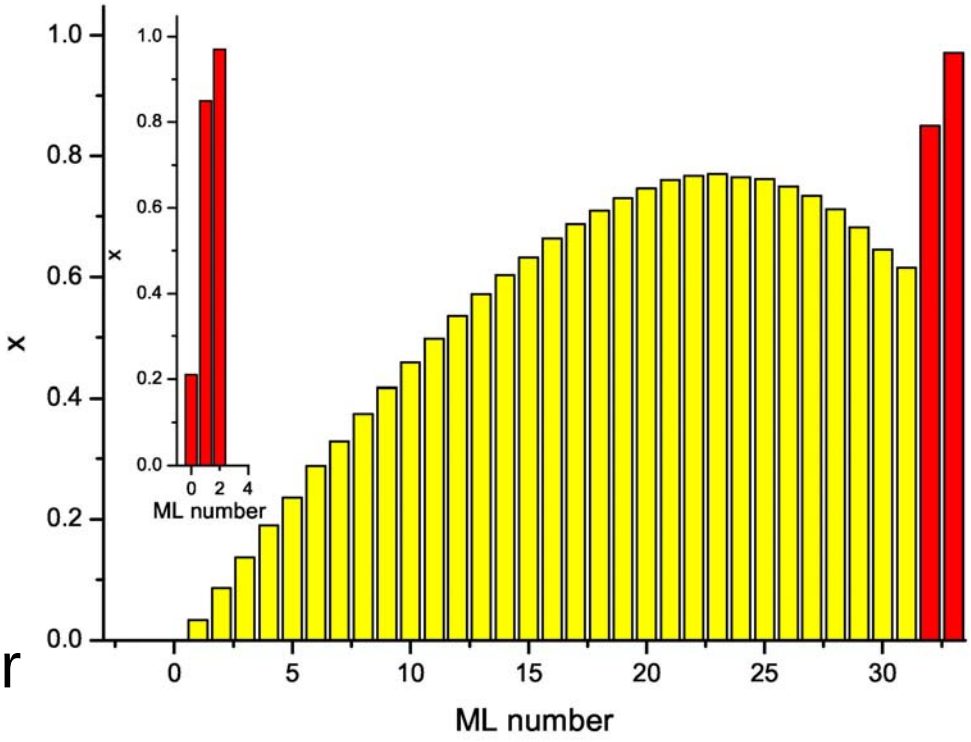
- At surface: x ~ 0.6
- Max of x ~ 0.8 at 10 ML below the surface
- We would measure this profile as x ~ 0.65
- Our data: x ~ 0.85



A. Rosenauer et al.:
Phys. Rev. B **64** (2001) 245334.

Indium depth concentration profiles

- Strong In segregation also on surface of dots.
- Add double layer with x ~ 0.85 - 0.97 (like WL) to surface.
- We would measure this profile as x ~ 0.85, in good agreement with our data.



G. Biasiol et al.: Appl. Phys. Lett. **87** (2005) 223106.

Conclusions

- Surface concentration maps of InAs/GaAs quantum dots by SPELEEM.
- Dot composition neither pure InAs nor homogeneous $In_xGa_{1-x}As$.
- In concentration decreases from center (high) to borders (low) of dots.
- In segregation (x ~ 0.9) on surface of dots and WL.
- Inportant piece of information for a better understanding of buried QDs.