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

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 (2 μm x 25 μm)
The **SPELEEM** instrument

Spectroscopic **Photo-Emission** and **Low Energy Electron Microscope**

Diagram showing the components of the SPELEEM instrument:
- Sample
- X-ray beam
- Objective
- Illumination aperture
- Electron gun
- Condenser lenses
- Sector field
- Transfer field
- Intermed. lenses
- Contrast aperture
- Selected area aperture
- Slit
- Analyzer
- Screen
- Projector

Monochromatic images
The SPELEEM at ELETTRA
The Energy Filter

R = 100 mm
Pass Energy = 900 V
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

![Graph showing intensity (arb. units) vs. pixels with 300nm scale bar and 1 pixel = 2.9nm text.](image)
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

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 (As₄ 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
- $E_{\text{kin}} = 7.6 \text{ eV}$

TEM investigation

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

“Integral” Core Level Spectra

Spectra taken from a 1 µm x 1 µm sample area.

III-V stoichiometry after decapping confirmed.

XPEEM Core Level Imaging

**In 4d XPEEM image**

$hv = 99.0 \text{ eV, } E_{\text{kin}} = 76.25 \text{ eV}$

**Ga 3d XPEEM image**

$hv = 99.0 \text{ eV, } E_{\text{kin}} = 74.75 \text{ eV}$

Island Size in XPEEM

Island Size $\approx 60$ nm, consistent with LEEM and TEM

XPEEM Local Spectra

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

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

hv = 99.0 eV

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:

\[
\frac{n_{In}}{n_{Ga}} = \frac{I_{In}}{I_{Ga}} \cdot \frac{\sigma_{Ga}}{\sigma_{In}}
\]

Indium Surface Concentration Map

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

Wetting Layer Composition

- Segregation models predict the following In concentration profile:

- Measured composition is average across topmost layers:
  \[
  <x> = \sum x_i e^{-\frac{d_i}{\lambda}} / \sum e^{-\frac{d_i}{\lambda}}
  \]

- Shown profile would be measured as \(x \sim 0.75\), in agreement with our data.

Dot Composition from TEM

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

Indium depth concentration profiles

- Strong In segregation also on surface of dots.

- Add double layer with $x \sim 0.85 - 0.97$ (like WL) to surface.

- We would measure this profile as $x \sim 0.85$, in good agreement with our data.

Conclusions

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