Semiconductor Nanowires: current X-ray characterization and forthcoming challenges

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Overview

- Nanowires: new materials for photonics, photovoltaics & electronics
  - New heterostructures
  - Integration in devices

- Materials Challenge illustrated by:
  - InAs/InP & InP/InAs/InSb NWs
  - Strained-Si stripes, GaN

X-ray Techniques Challenge:
- Grazing Incidence, anomalous scattering,
- μ-Laue, coherent diffraction
For assemblies and single objects

Future studies
Further information needed: about strain, doping control, surface passivation…
Why to study nanowires?

Applications

Light emitters

Light Conversion

Heterostructures & dopings

Growth studies

Photonics, photovoltaics

& electronics

Band-gap engineering

Strain Relaxation

Composition Control

Homogeneity

Sensors

Micro-electronics

Batteries

Reliability

• Assembly: GlXRD

InAs/InP nanowires (Lund U.)

- Superlattice: 10 nm InP / 20 nm InAs

• Several contributions analyzed by changing the incidence
• Defect-free stacking and faults can be measured

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E-MRS, Nice
May 9th, 2011
J. Eymery

Strain and Shape of Epitaxial InAs/InP Nanowire Superlattice Measured by Grazing Incidence X-ray Techniques

Joff Eymery,* François Riedert, Vincent Favre-Nicolin, Odile Robach, Yann-Michel Niquet, Linus Fritberg, Thomas Mattisson, and Lars Samuelson
• Strain: in-plane reflections

(200) and (300) reflections correspond to planes $\perp$ to the surface

\[ \varepsilon_{yy} \]

\[ \text{Lattice parameter} \]

\[ \text{Intrinsic broadening due to the heterostructure} \]

• Quantification of the \textbf{epitaxial growth} (mosaictiy, bending…)

• Strain & relaxations in the NWs

In agreement with atomistic calculations

Mosaictiy:

NW: 0.5°
TW: 0.02°
S: 0.001°
• **Core-shell system:** InAs NW integration

![Diagram of core-shell system and transistors](image)

- Transistors
- Capacitors
- RF devices

**Bibliography**

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\[ \varepsilon_{\perp} \]

- **In-plane diffraction**
  - (-2 0 0) reflection

- **Out-of-plane diffraction** (Crystal Truncation Rods)

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**Small in-plane dilatation:**
- **Strain gradient (broadening)**
- **In agreement** with semi-empirical potential and continuum elasticity calculations

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**Quite large out-of-plane contraction:**
- **Internal reference**
- **Significant strain after Cr-deposition**

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**Strain tensor:** InAs in core/shell NW devices

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J. Eymery, V. Favre-Nicolin, L. Fröberg, and L. Samuelson

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• **Shape & size distribution:** Grazing Incidence Small Angle Scattering (GISAXS)

- Detector

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- **Hexagonal symmetry**

- **Size fluctuation** ($\Delta R/R < 8\%$)

Strain and Shape of Epitaxial InAs/InP Nanowire Superlattice Measured by Grazing Incidence X-ray Techniques

Joel Eymery, François Rieutord, Vincent Favre-Nicolin, Odder Robach, Yann-Michel Niguet, Linus Friberg, Thomas Mårtensson, and Lars Samuelson
• **Shape & core/shell thickness**: in NW devices

(Lund U. growth)

- Evolution of the Hexagonal shape
- Smoothening with HfO$_2$ and Cr deposition.
- Core/shell thicknesses

J. Eymery,$^1$,$^a$ V. Favre-Nicolin,$^1$ L. Fröberg,$^2$ and L. Samuelson$^2$

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• Assembly Study: Anomalous measurements

InSb/InP interface

Microscopy measurements

\[ I \propto \sum_j f(\vec{Q}, E_j) e^{i\vec{Q} \cdot \vec{r}_j} \]

\[ f(\vec{Q}, E) \approx f_0(\vec{Q}) + \{f_1(E) + if_2(E)\} \]

• Anomalous measurement: Sb absorption edge (around 30.5 keV)

Almost pure InSb

Energy (eV)

(201)_{\text{InSb}} : weak peak
Very sensitive to composition

(101)_{\text{InSb}} : strong peak
Not very sensitive to composition
• Study of QDs inserted in NWs

InP reciprocal lattice units (rlu)

InP Wurtzite (NW)

InP Substrate Zinc-Blende (S)

InP Zinc-Blende Twinned (TW)

InSb Zinc-Blende (NW)

InSb Wurtzite Twinned (TW)

InAs Wurtzite (NW)

Anomalous measurements on InAs peaks

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Single Object Studies: Coherent Diffraction Imaging (CDI)

Monochromatic wavelength

Beam size: 200x500 nm², $10^9 - 10^{11}$ ph/s, Trans. coh. length: ~20 µm

Phase retrieval methods

Advantages
- Spatial resolution
- Increase of diffraction pattern contrast
- Direct recovery of shape and strain

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Coherent x-ray wavefront reconstruction of a partially illuminated Fresnel Zone Plate.
• Insight of the information gained from CDI

- **Size and shape**: equiv. to TEM, SEM informations, but useful for buried structures

- **Analysis of stacking faults**
  - nature (from Bragg peak selection)
  - statistical distribution

Coherent diffraction imaging of single 95 nm nanowires.
Analysis of strain and stacking faults in single nanowires using Bragg coherent diffraction imaging
• Single Object Study: strain mapping
Active materials in transistors (PDSOI)

Single sSi etched wire (W=200 nm)

Perfect sSi structure + small bending (∼1 %)

Experiment

Calculation

Displacement field

• Very sensitive technique

ID01 @ ESRF

Elastic relaxation in patterned and implanted strained Silicon On insulator.

BM02 & BM32 @ ESRF

PhD F. Mastropietro +
• Single Object Study: Local strain mapping

InSb/InP interface

Analysis of strain and stacking faults in single nanowires using Bragg coherent diffraction imaging
• Single Object Study: Local strain mapping

Very sensitive method: 1 ML InAs in GaAs (MBE sample)

Analysis of strain and stacking faults in single nanowires using Bragg coherent diffraction imaging
**Single Object Studies: Micro-Laue Diffraction (µ-L)**

Polychromatic wavelength  
Beam size: 0.5x0.5 µm²  
1 s measurement !!

Top-view

GaN wires

Analysis of single Wires + mapping

Epitaxial relationships...
• Single Object Studies: Micro-Laue Diffraction (μ-L)
Polychromatic wavelength  Beam size: 0.5x0.5 μm²  1 s measurement !!

Strange structures…

• Micro-Laue on the branches of tripods.
• Orientation matrix and structure by Laue indexing

Fluo mapping
• Single Object Studies: Micro-Laue Diffraction (µ-L)

Polychromatic wavelength  Beam size: 0.5x0.5 µm²  1 s measurement !!

High resolution…

Zoom: Screw dislocation
Inside one GaN wire

High resolution measurement of a peak

Simulation
Conclusions

- Complementary techniques
  - Grazing Incidence
  - Coherent diffraction
  - Polychromatic μ-beam

- New fields
  - Position of a quantum dot in a wire by coh. ciff.
  - Devices in complex buried environment
  - In-situ experiments (growth, working devices…)
  - Use (non coherent) nanobeams (ERSF upgrade)

- Many systems to study
  - Photonics, photovoltaics & electronics
  - + spintonics, metals…

Two examples…

**CL emission spectra of a single GaN wire with Si:n-doped and un-intentionally doped segments.**

Fluorescence, peak broadening…

**Core-shell InGaN/GaN quantum wells. Light emission devices (LEDs)**

Fluorescence: In- composition fluctuation μ-diffraction: defects, local strain…
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Have fun with X-rays
(NB/ to get this picture use E~70 keV and MOVPE GaN wires)

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