2D and 3D Nanoscale Measurements of Electric and Magnetic Fields in Functional Materials with Electron Holography

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DRESDEN concept

Off-axis electron holography (EH) is a transmission electron microscopy (TEM) technique that enables the reconstruction of the object exit wave function up to atomic resolution [1]. At medium (nanometer) resolution, EH is a powerful tool to map electric potentials and magnetic fields of nanoscaled materials in two dimensions (2D) [1]. Combined with tomographic methods, i.e. by performing electron holographic tomography (EHT), the electromagnetic field mapping is extended into 3D [2].

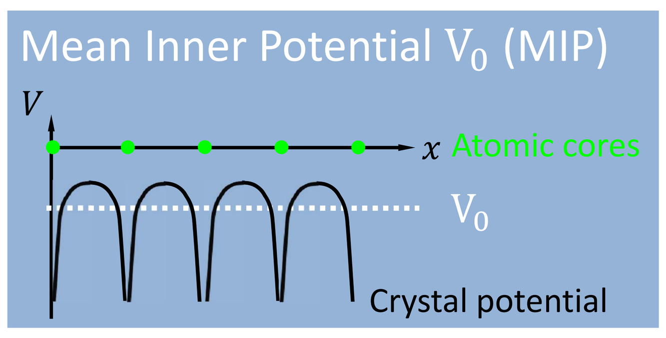
Motivation

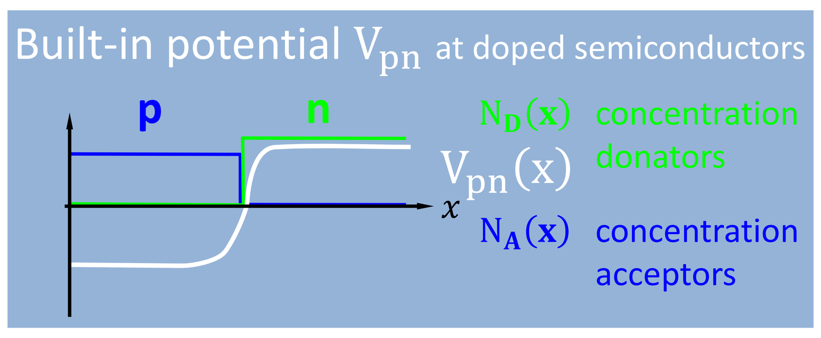
Phase shift φ of object exit wave proportional to **projected electro-magnetic potential**

$$\varphi(x,y) = \int_{-\infty}^{+\infty} \left(C_E\, V(x,y,z) - 2\pi \frac{e}{h} A_z(x,y,z) \right) \mathrm{d}z$$

with interaction constant $C_E = 0.0073\ ^{rad}/_{V\,nm}$ at 200 kV electron acceleration voltage

Object potential



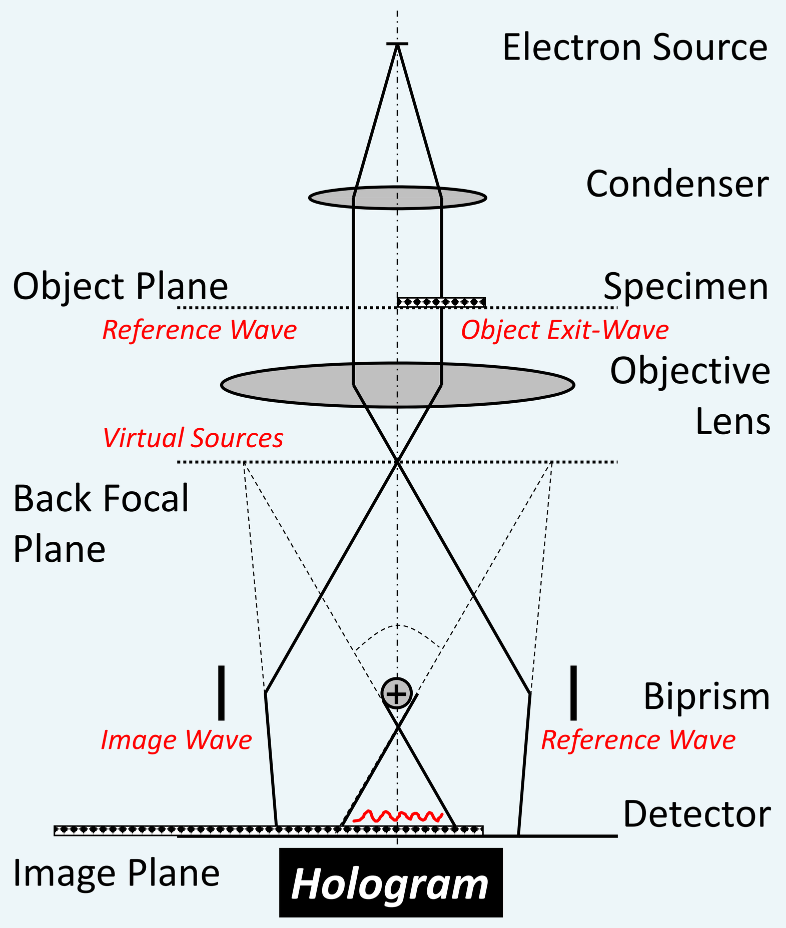


Holographic Techniques

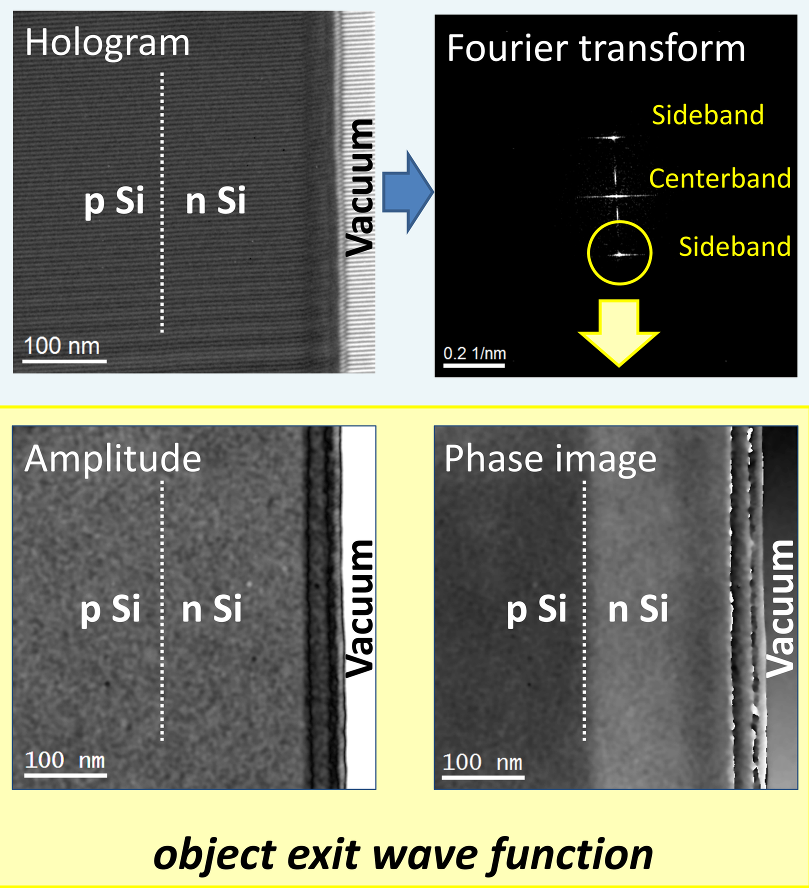
- **Medium resolution off-axis electron holography**
  ➔ Nanoscaled electric potentials and magnetic fields
  e.g. electric potentials at p-n junctions, surfaces, interfaces, defects
  magnetic B-fields in- and outside nanoparticles, nanostructured materials
- **Dark field electron holography**
  ➔ Nanoscaled real space strain mapping
  e.g. in transistors, buried oxide apertures, quantum dots
- **Atomic resolution off-axis electron holography**
  ➔ Atomic phase shifts (Which atom is where?)
- **Inelastic electron holography**
  ➔ Density matrix reconstruction
  e.g. coherence properties of plasmons
- **Electron holographic tomography**
  ➔ 3D reconstruction of nanoscaled electric potentials and magnetic fields

2D Holography

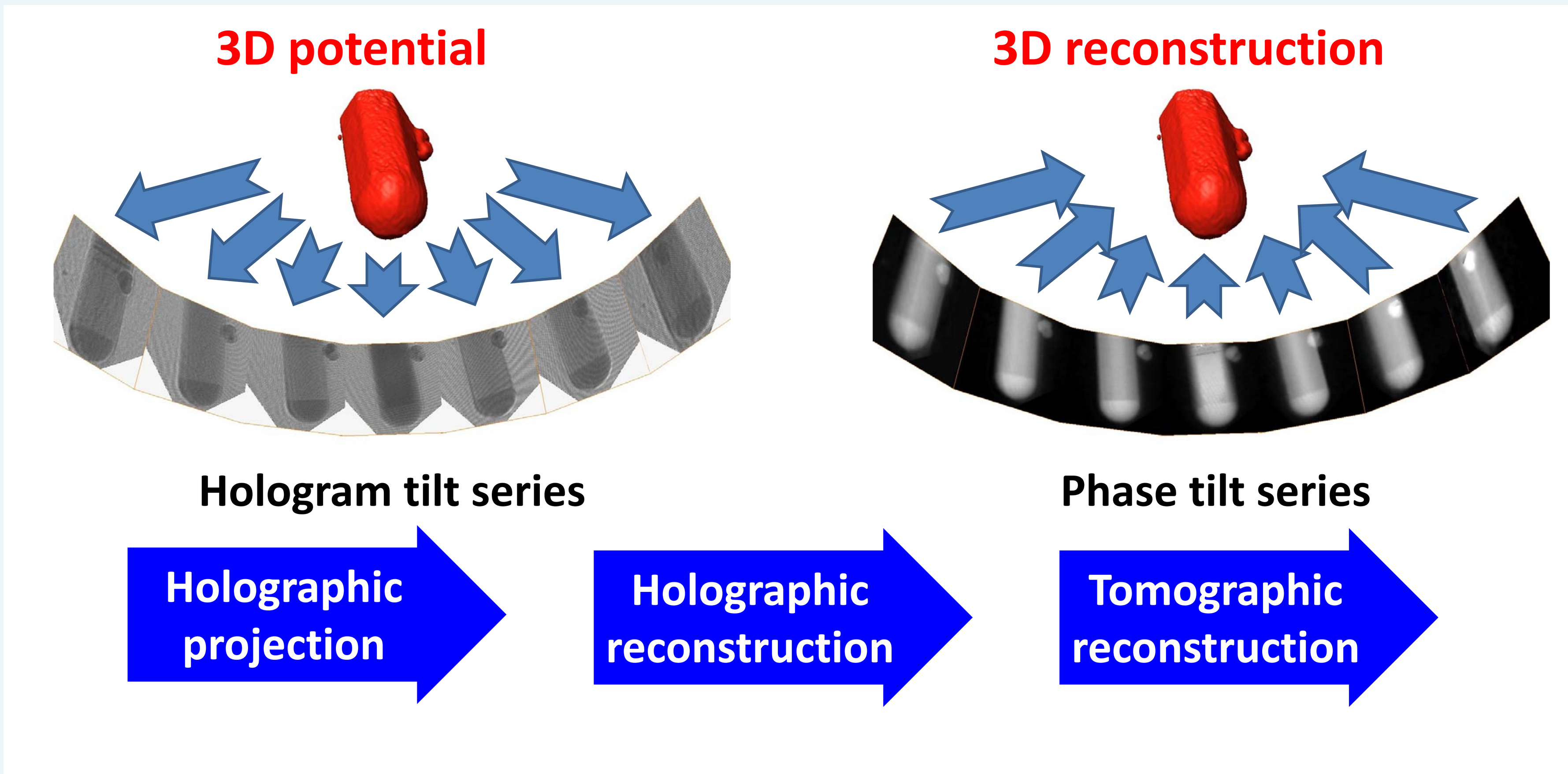
1. Acquisition in the TEM



2. Reconstruction in the computer



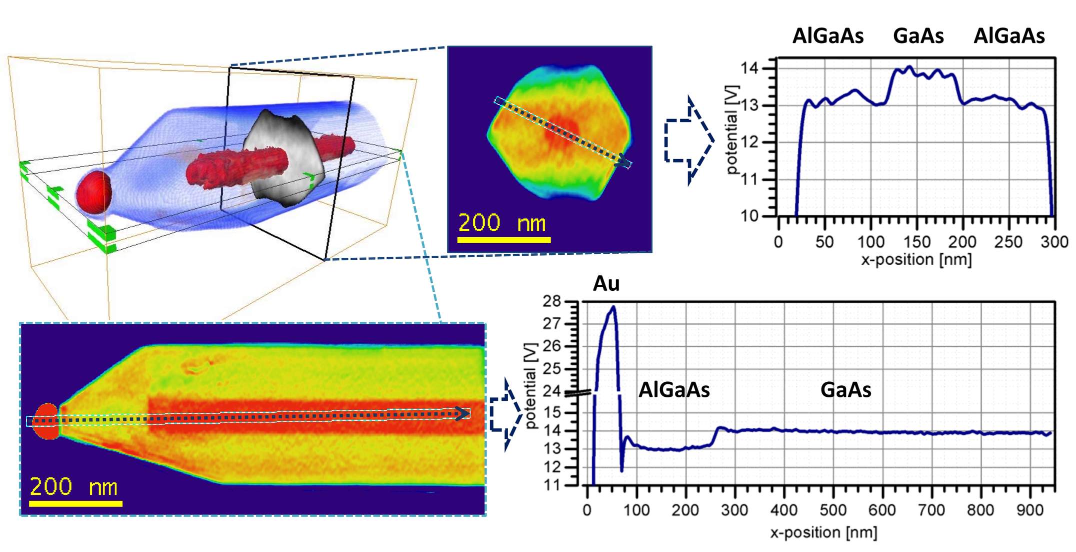
3D Holography



3D Electric potentials

3D morphology and chemical composition

- **EHT on GaAs/AlGaAs core-shell nanowire (NW) [3]**
- Grown by MOVPE along 111 direction using Au catalyst
- Diameter: 280 nm (70 nm GaAs core, 105 nm AlGaAs shell)
- V:III ratio while growing: 20
- Hologram tilt series from -69° to +72° in 3° steps at TEM Titan 80-300 "Berlin Holography Special" of Lehmann group, TU Berlin
- 3D reconstruction with W-SIRT



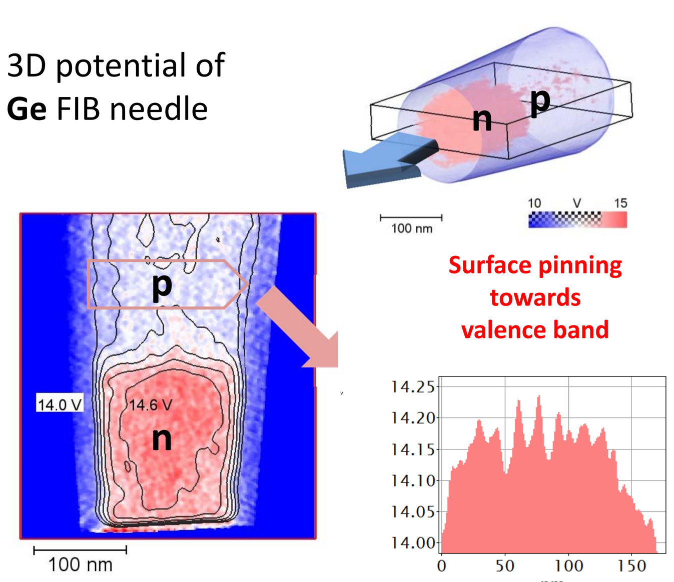
	MIP V_0 (Literature)	MIP V_0 (EHT)
GaAs	14.19 V [*]	13.9 V
$Al_{0.33}Ga_{0.67}As$	13.58 V [*]	13.2 V
Au	30.26 V [**]	28.0 V

[*] P Kruse et al., Ultramicroscopy **106**, (2006), p. 105.
[**] M Schowalter et al., Appl. Phys. Lett. **88**, (2006), p-232108

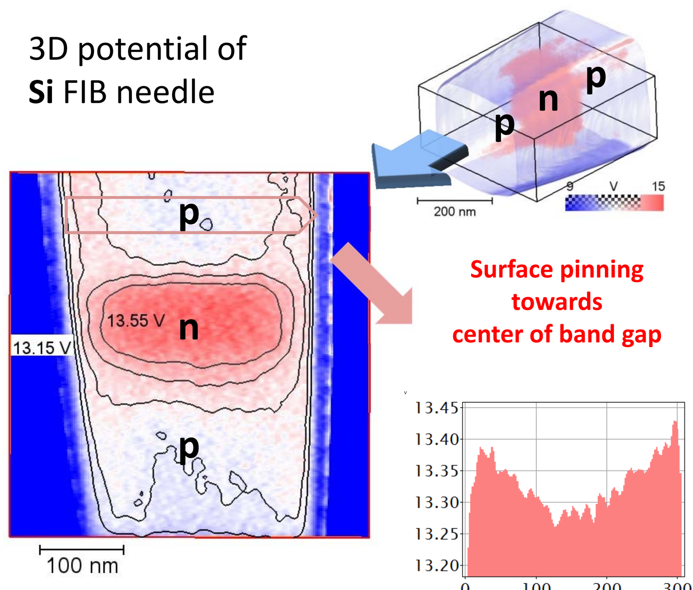
3D built-in potential V_{pn}

- **EHT on doped Si and Ge wafers [4]**
- FIB-preparation of rod-shaped samples
- Tilt range for EHT: -79° to +75° (±72°) for the Si (Ge) both in 2° steps
- 3D reconstruction with W-SIRT

3D potential of Ge FIB needle



3D potential of Si FIB needle

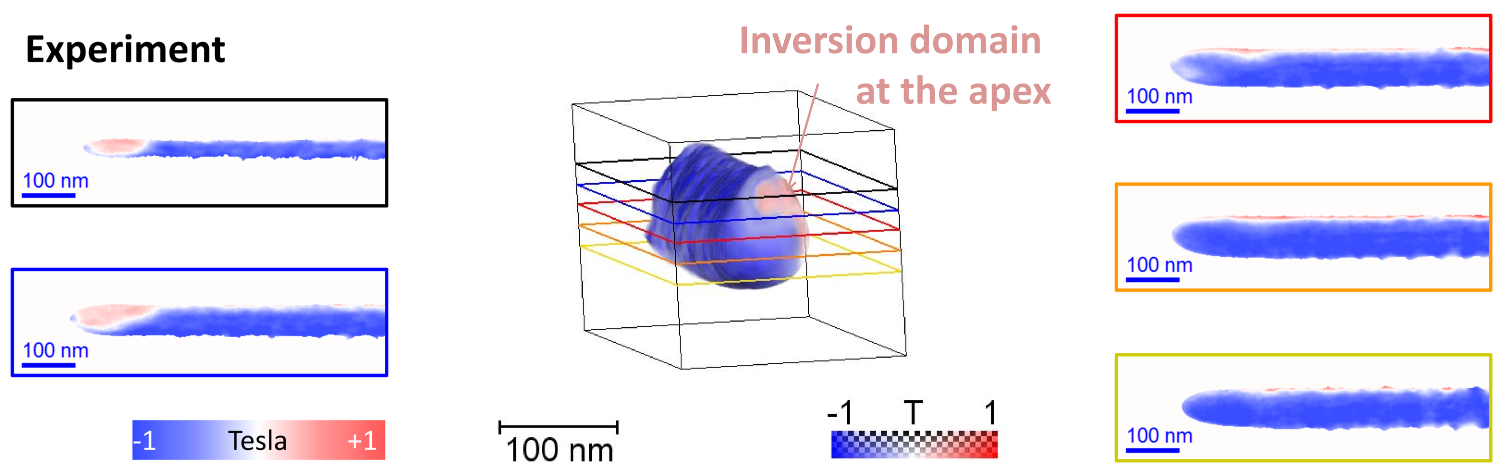


3D Magnetic fields

3D magnetic induction maps (B-field)

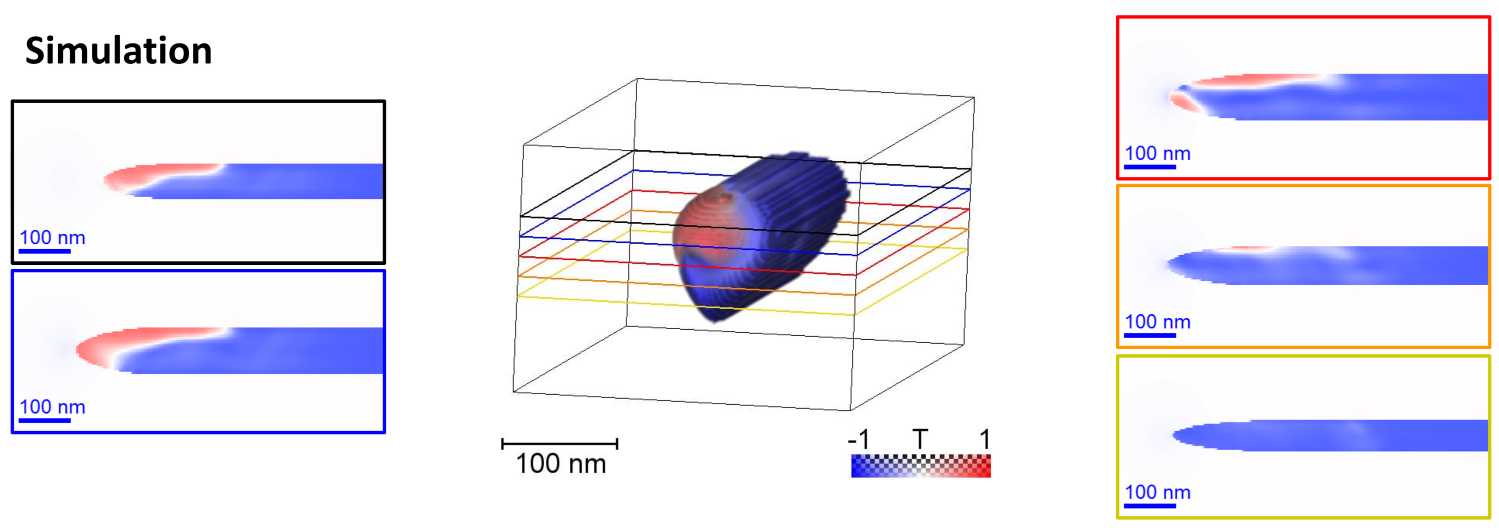
- **EHT on Co nanowire [5]**
- Grown by Focused Electron Beam Induced Deposition (FEBID)
- Tilt range for EHT: 360° in 3° steps
- Removal of MIP contribution by pairwise subtraction of phase images 180° tilted to each other
  ➔ Magnetic phase shift
- Calculation of derivative of magnetic phase shift ➔ Projected axial B-field component
- 3D reconstruction of axial B-field with W-SIRT

Experiment



- Static micromagnetic simulation of the remanent state of the Co FEBID NW, which solves the Landau-Lifschitz-Gilbert equation

Simulation



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[1] Lichte, H. and Lehmann, M., *Rep. Prog. Phys.* 71 (2008) p. 016102.
[2] Wolf, D., Lubk, A., Röder, F., and Lichte, H., *Curr. Op. in Solid State and Mat. Science* **17** (2013) p. 126
[3] Lubk, A., Wolf, D., Prete, P., Lovergine, N., Niermann, T., Sturm, S., and Lichte, H., *Phys. Rev. B* **90** (2014) p. 125404
[4] Wolf, D., Lubk, A., Lenk, A., Sturm, S., and Lichte, H., *Applied Physics Letters* **103** (2013) p. 264104
[5] Wolf, D., Rodriguez, L. A., Béché, A., Javon, E., Serrano, L., Magen, C., Gatel, C., Lubk, A., Lichte, H., Bals, S., Van Tendeloo, G., Fernández-Pacheco, A., De Teresa, J. M., Snoeck E., submitted (2015)