History of DIP Progress

Scheer Lab

Progress report
DIP
Scheer group

May 2010

- Local probe of the proximity effect in mesoscopic structures
- STS at Co dots on superconducting Al
- Magnetoresistance of Pt nanocontacts
- Magnetoresistive effects in Co/Pd multilayers on self-assembled nanoparticles
- Influence of local defects on UCF

Attractive Pair Interaction in Gold probed by Proximity Effect with Aluminum
and
Possible Magnetic Ordering in Atomic Chains of Pt and Pd

S. Egle, C. Espy, H.-F. Pernau, F. Strigl, R. Waitz,
M. Wolz, C. Debuschewitz, W. Belzig, E. Scheer

November 2010

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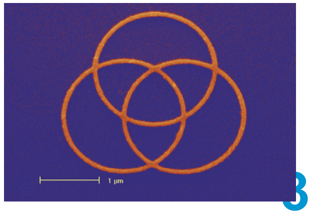

Outline

November 2010

- **Attractive pair interaction in noble metals probed by the proximity effect with Al**
- **Magnetoresistance of Pt nanocontacts**
- Outlook: Competition between superconductivity and magnetism in Co dots covered by superconducting Al
- Outlook: Induction of spin-triplet superconductivity in S-FM(I)-N systems

Enhanced Proximity Effect in Al/Au bilayers

First Results:
Long-Ranged Proximity Effect in S/FI/N Systems
and
Magnetoresistance of Al Networks

C. Espy, M. Wolz, M. Wolf, C. Sürgers, O. Sharon, W. Belzig, F. Strigl, E. Scheer

December 2011

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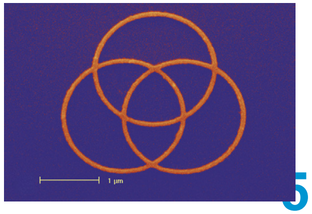


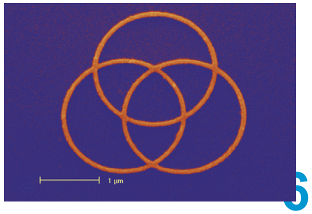
Long-Ranged Proximity Effect in Al/EuS/Ag probed by Scanning Tunneling Spectroscopy

with M. Wolz, M. Wolf, C. Sürgers, W. Belzig

Theory:
F. S. Bergeret, A. F. Volkov, K. B. Efetov, Phys. Rev. Lett. **86,** 4096 (2001); *Rev. Mod. Phys.* **77,** 1321 (2005);

M. Eschrig, Phys. Today 64, 43 (2011);

December 2011



Outline

March 2013

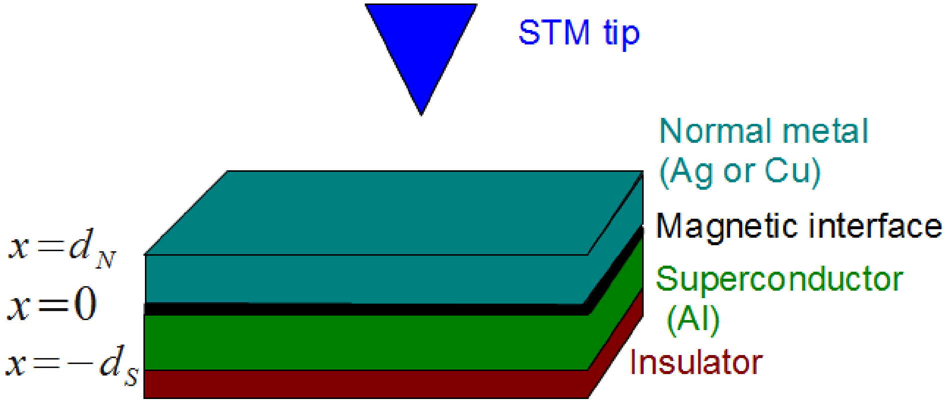
- **Induction of spin-triplet superconductivity in S-FI-N systems**
- **Magnetoresistance oscillations in superconducting loops and networks**

Spn Triplet: Introduction

- Conventional superconductors: even frequency pairing
- Odd frequency pairing (OFP) in F/S can be induced by symmetry breaking
- OFP: Gap is odd function of frequency or time: S=0, l=1 or S=1, l=0
- Problem: short penetration depth in F(~ξ_F, few nanometers)
- Odd-frequency pairing created by spin-active interface?
- Possibility to detect odd-frequency, spin triplet pairing?
- Interface plays an important role: DOS calculated using Usadel equation, measured using STS

Spin active interface

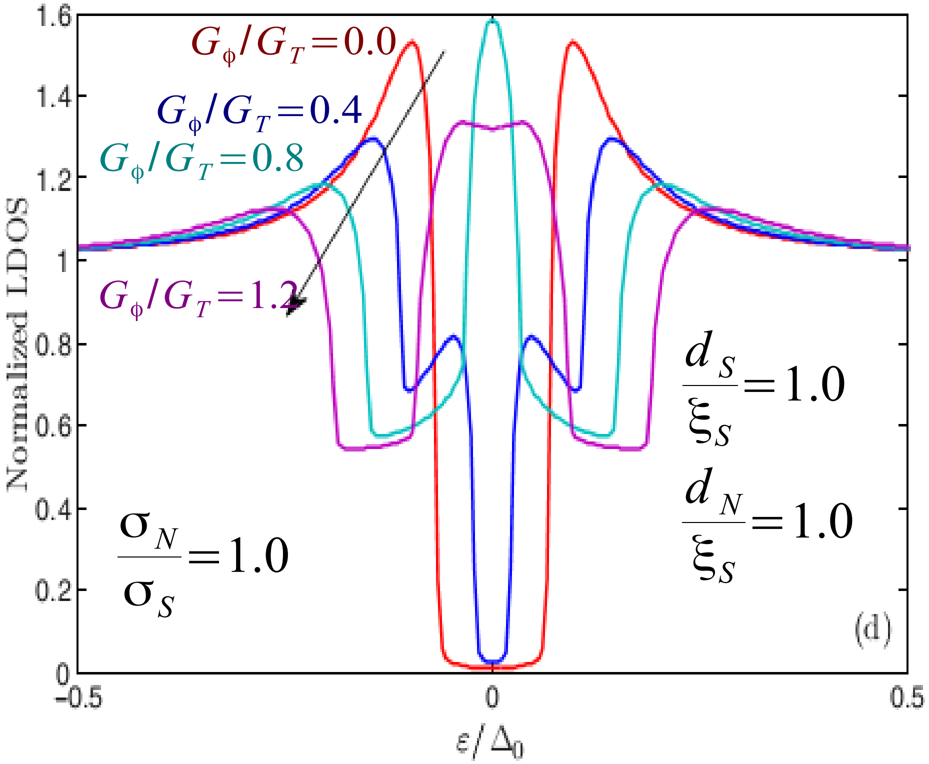
- Boundary conditions depend on barrier conductance G_T
- Additional parameter G_Φ, describing the spin “activity” of the interface
- Describes particles being reflected at the interface
- G_Φ can be ≠ 0 for $G_T \to 0$ (ferromagnetic insulator)
- Different transmission probabilities for spin up and down
- Spin dependent conductivities and phase shifts
- G_Φ / G_T is crucial for the shape of the density of states



Density of states

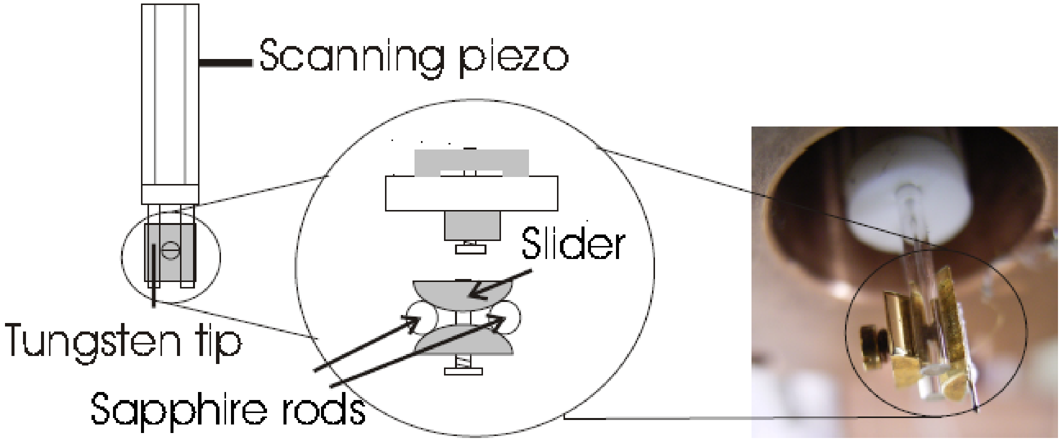
- DOS at zero energy vanishes if $G_\Phi < G_T$ (minigap)
- $G_\Phi > G_T$: enhanced N(0)
(spin triplet superconductivity)

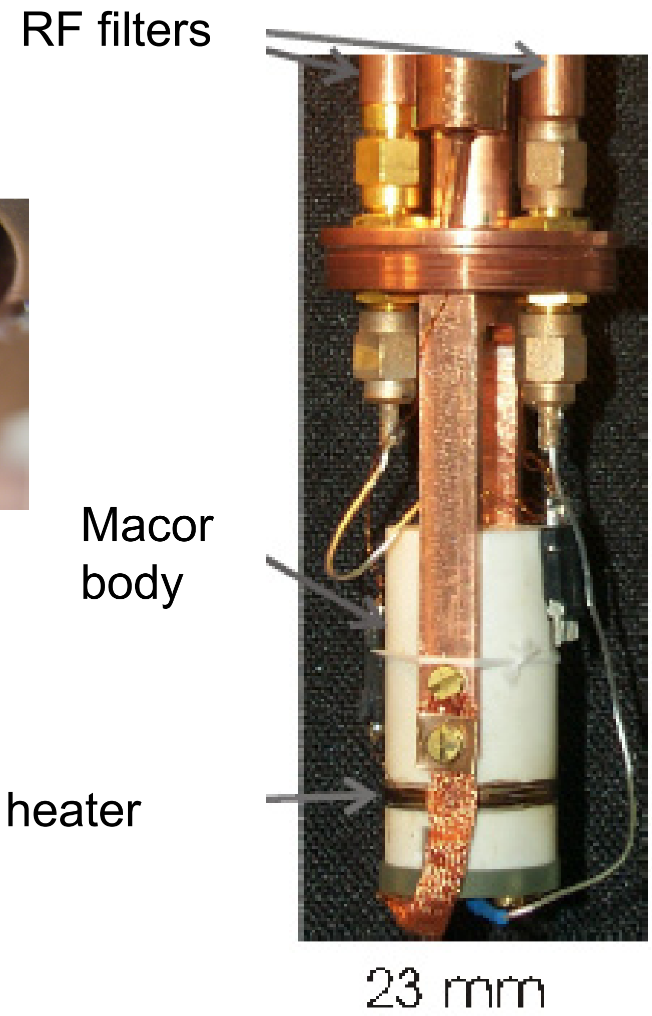
$$N\frac{(\epsilon=0)}{N_0}=\Re\frac{G_\phi}{\sqrt{G_\phi^2-G_T^2}}$$



J. Linder et al. PRB **81**, 213404 (2010)

Experimental setup

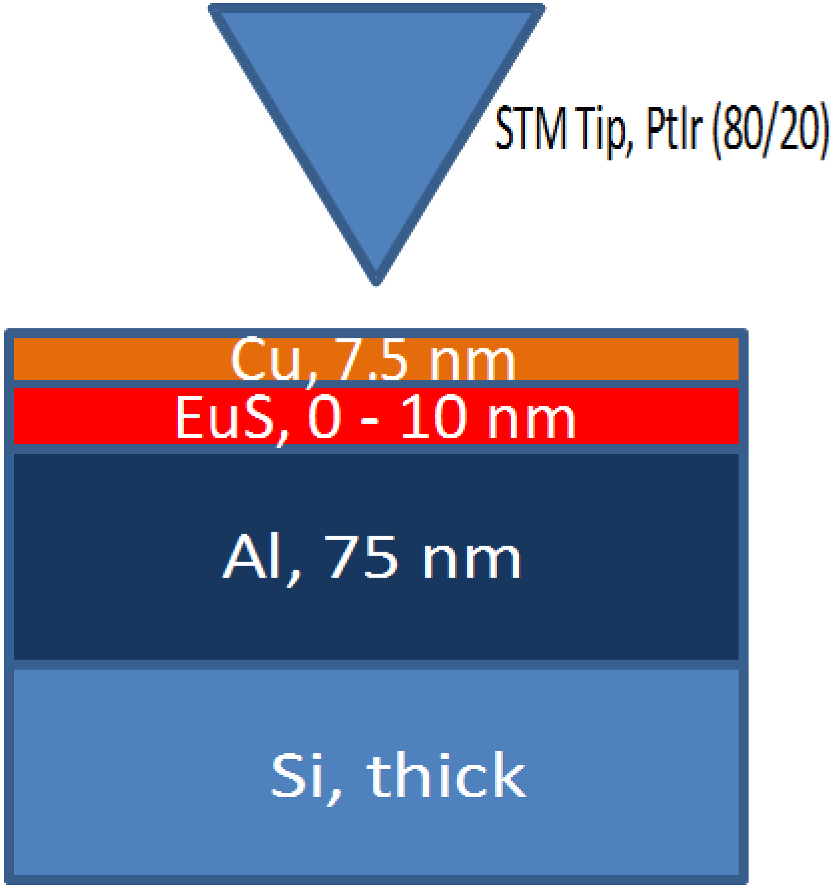




Requirements to STM:
- High energy resolution
- Non-magnetic

F. Mugele et al. Rev. Sci. Instrum. **67,** 2557 (1996)
N. Moussy et al. Rev. Sci. Instrum. **72,** 128 (2001)
C. Debuschewitz et al, J. Low Temp. Phys. **147**, 525 (2007)

Sample (prepared in Karlsruhe)



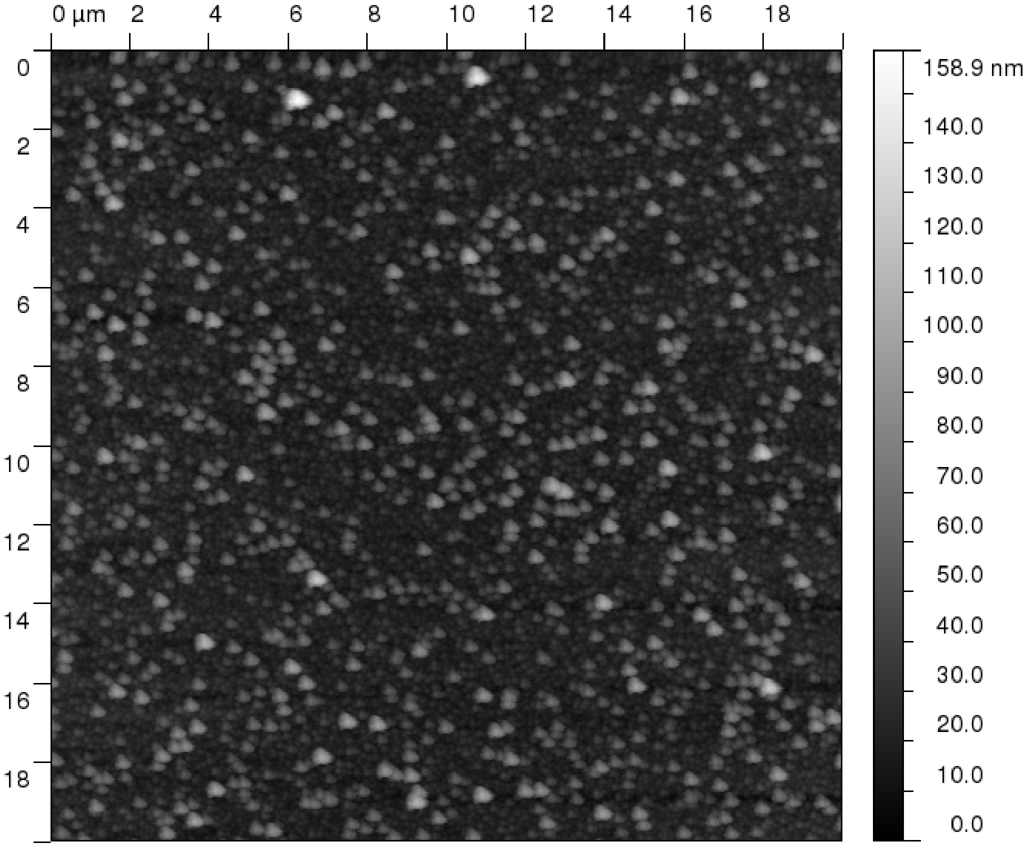
STM Tip, PtIr (80/20)

Cu, 7.5 nm

EuS, 0 - 10 nm

Al, 75 nm

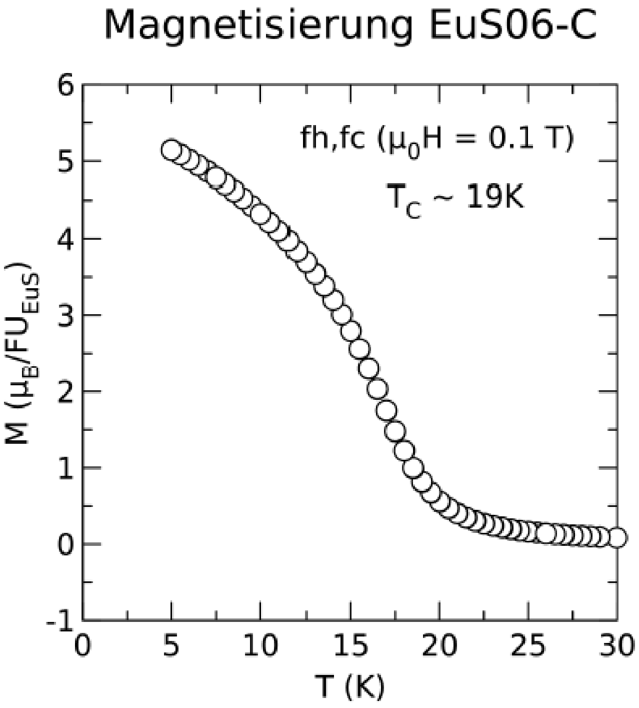
Si, thick



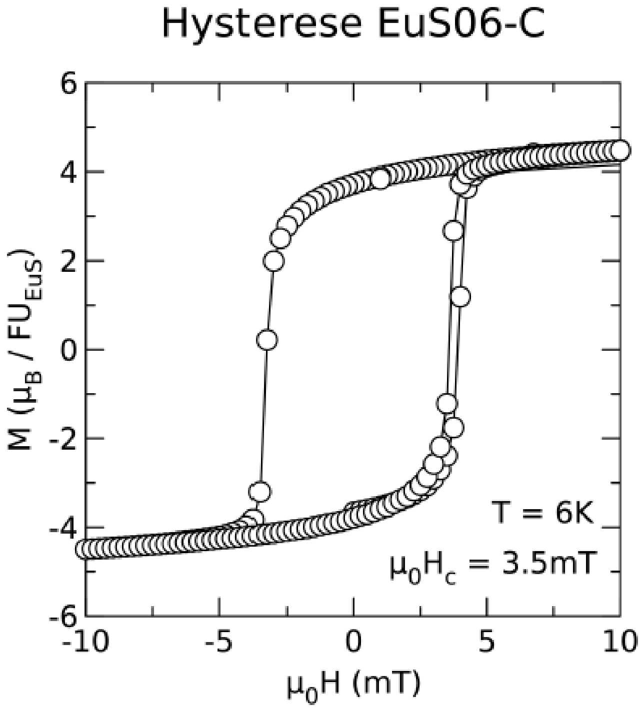
Film characterization

- Thick EuS film (d = 25 nm)
- SQUID magnetometry by G. Fischer, PI

T_C ~ 19K (bulk: 16.6 K)

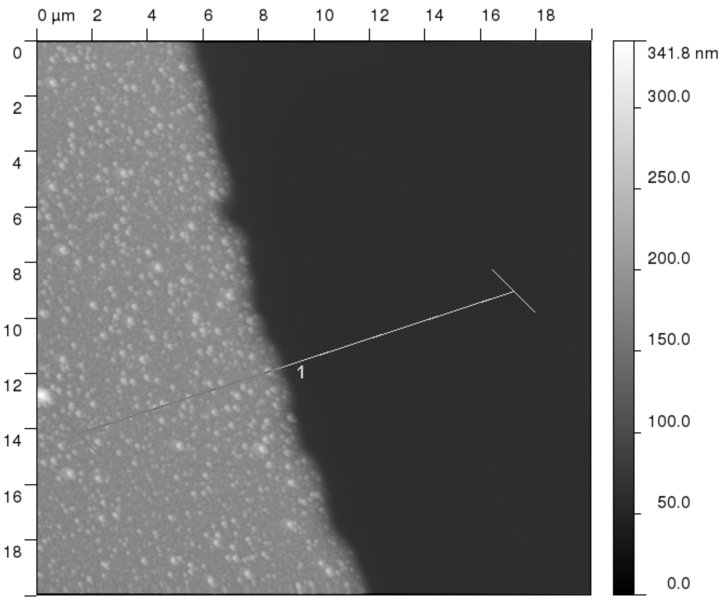

Magnetisierung EuS06-C

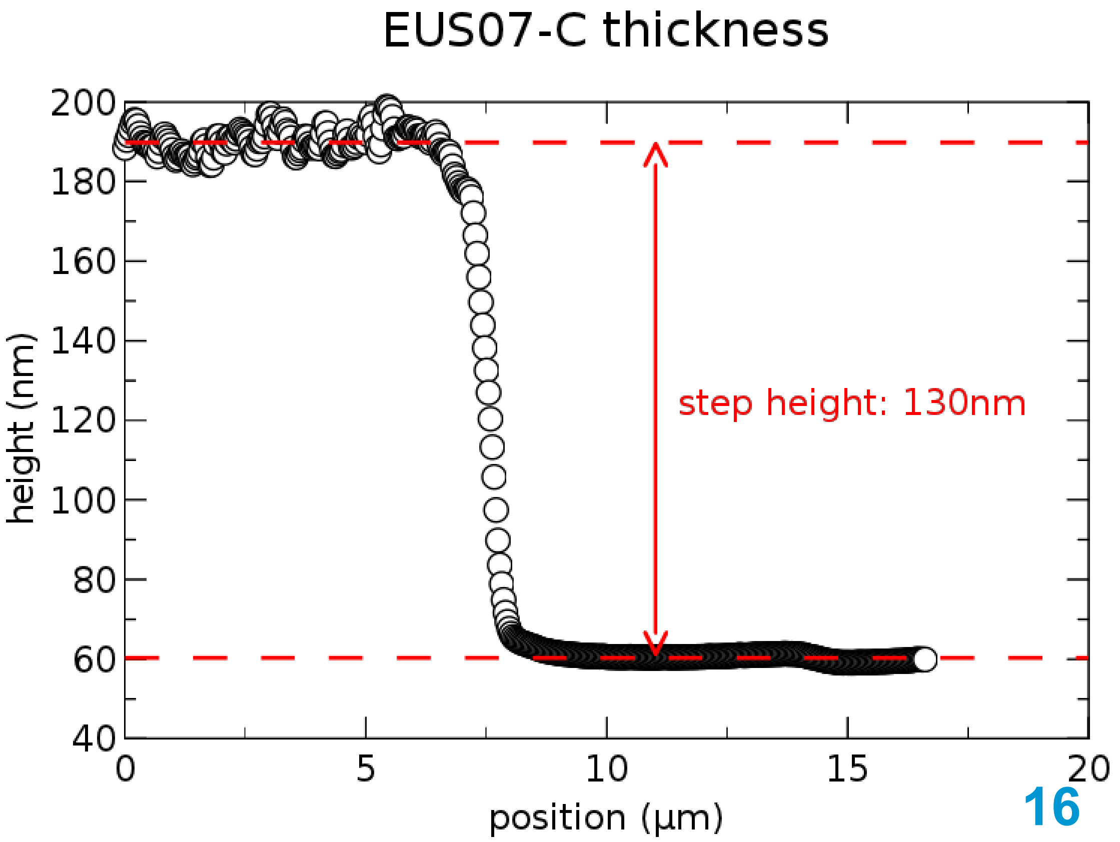
Coercive field: μ_0H_c ~ 3.5mT


Hysterese EuS06-C

Thickness of sample

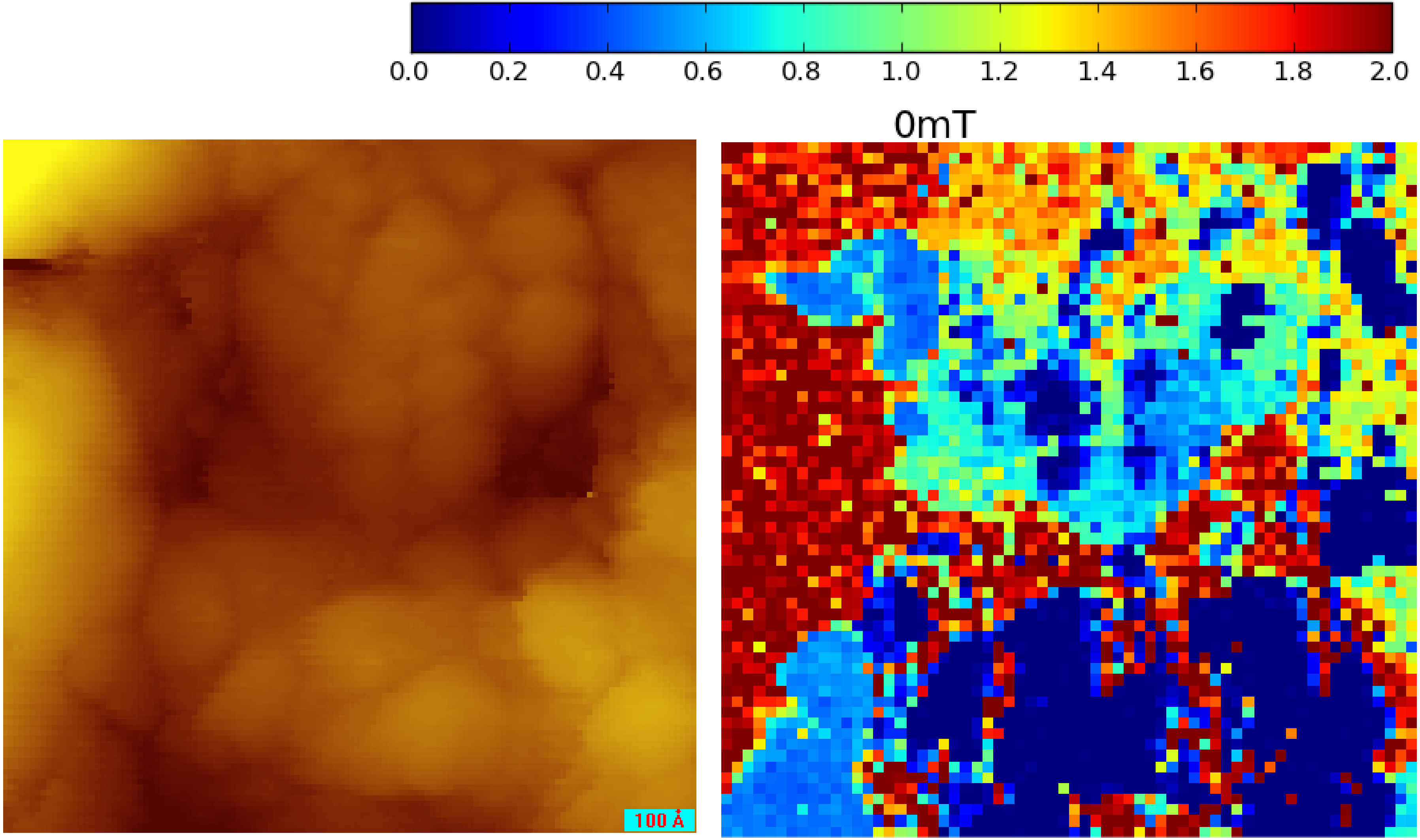
AFM measurement by Michael Wolf, Karlsruhe



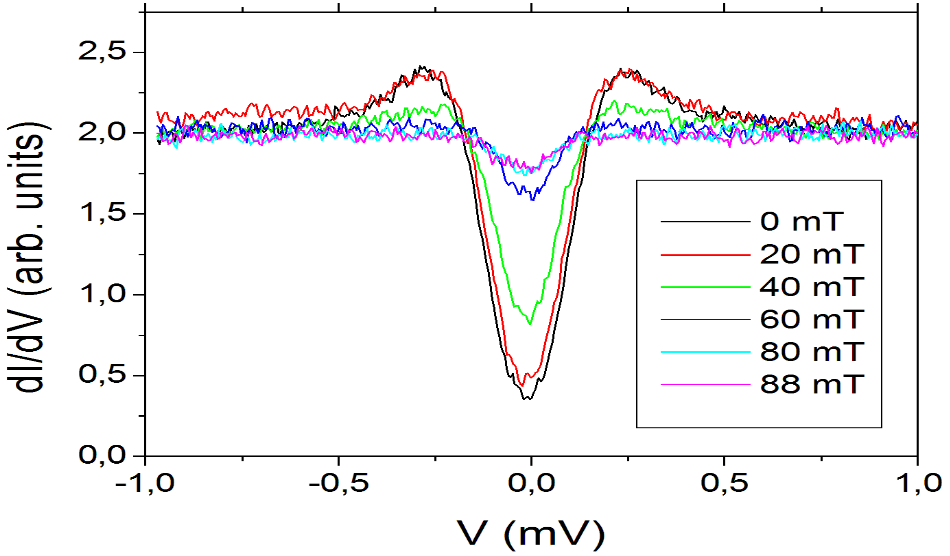


Topography – dI/dV(x,y,V=0)

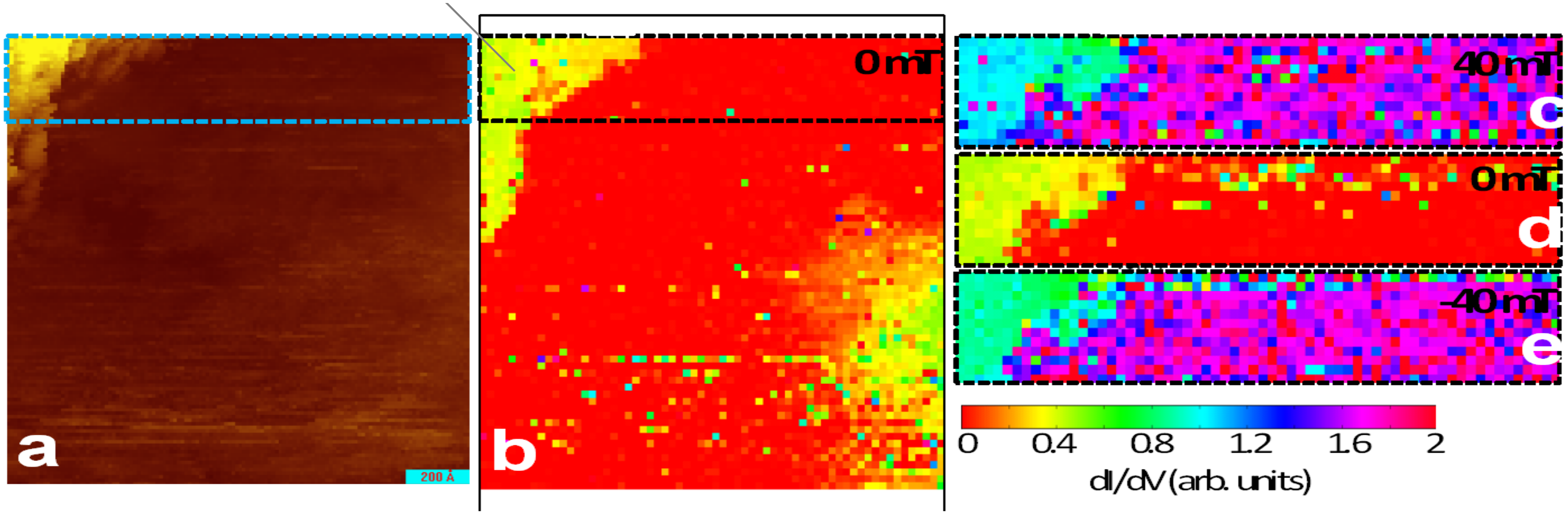
- Simultaneous Measurement: 100 x 100 nm², 196 mK, 10 MOhm



Magnetic field dependence

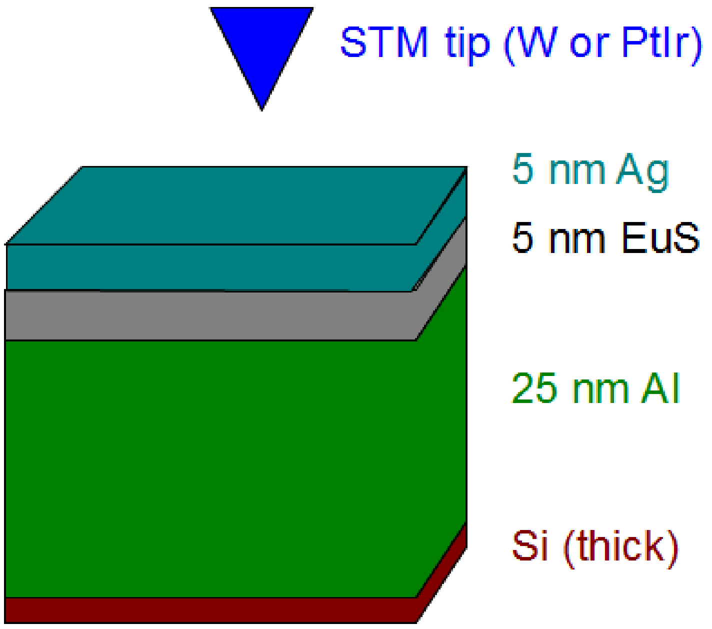


- Area with suppressed SC
- Superconductivity survives up to higher fields
- Signature of spin triplet superconductivity?

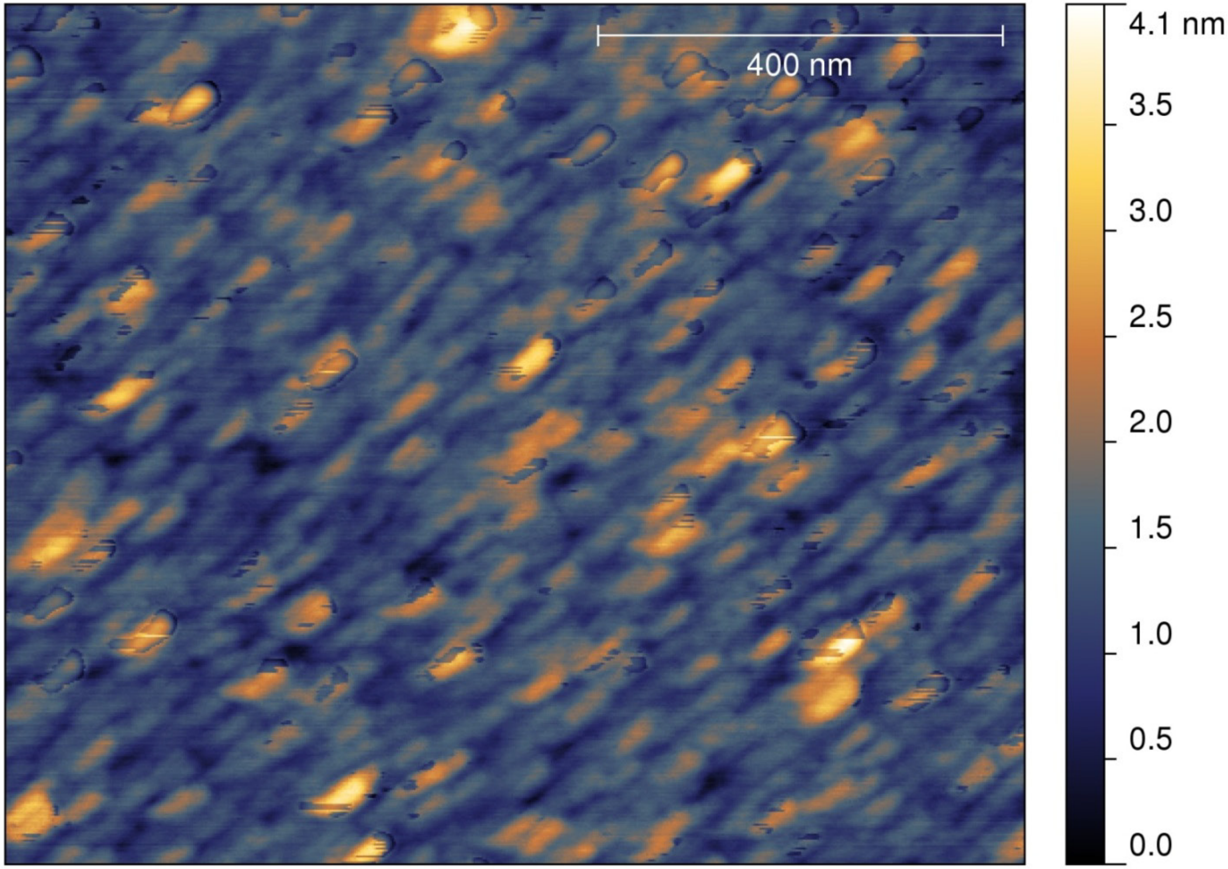


Experimental setup for Al/EuS/Ag

- \+ Sample fabrication at KIT (Wolf & Sürgers)
- \+ Tunneling resistance 10 MΩ
- \+ Lockin measurement of dI/dV
- \+ High energy resolution
- \+ Base temperature ~250 mK
- \+ Magnetic field in plane 0.5 T
- \+ Magnetic field out of plane 1 T

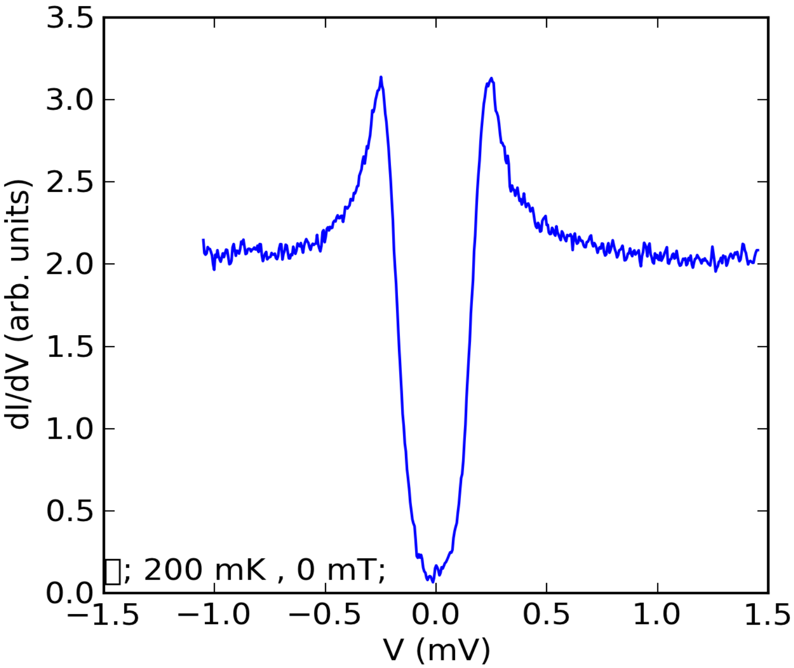


AFM micrograph



Thin aluminum film
rms roughness ~ 0.6nm

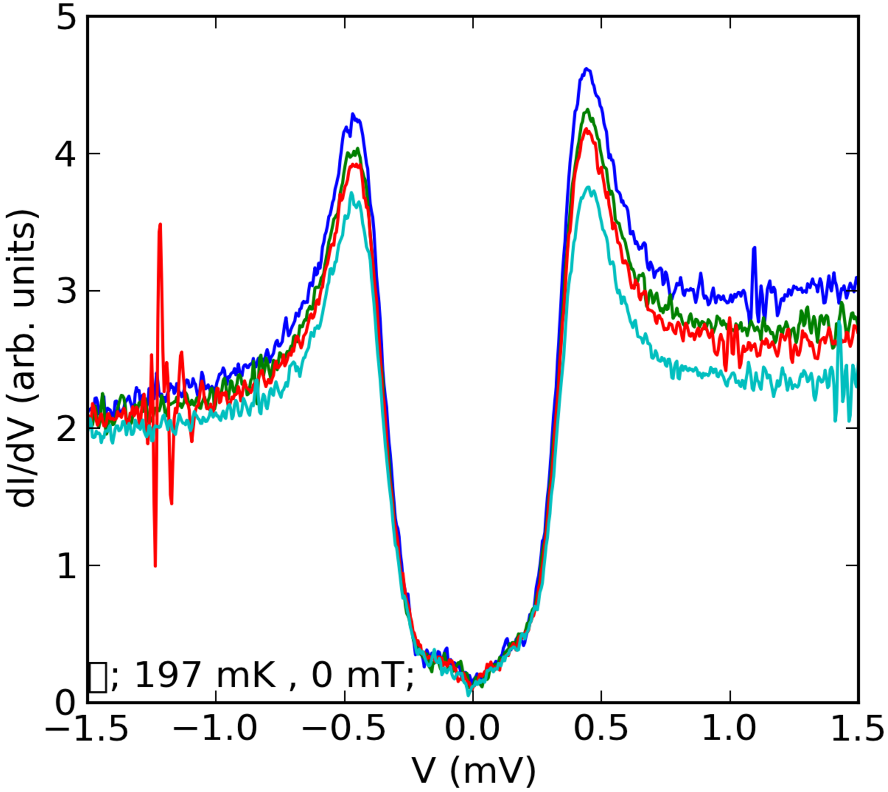
dI/dV spectra



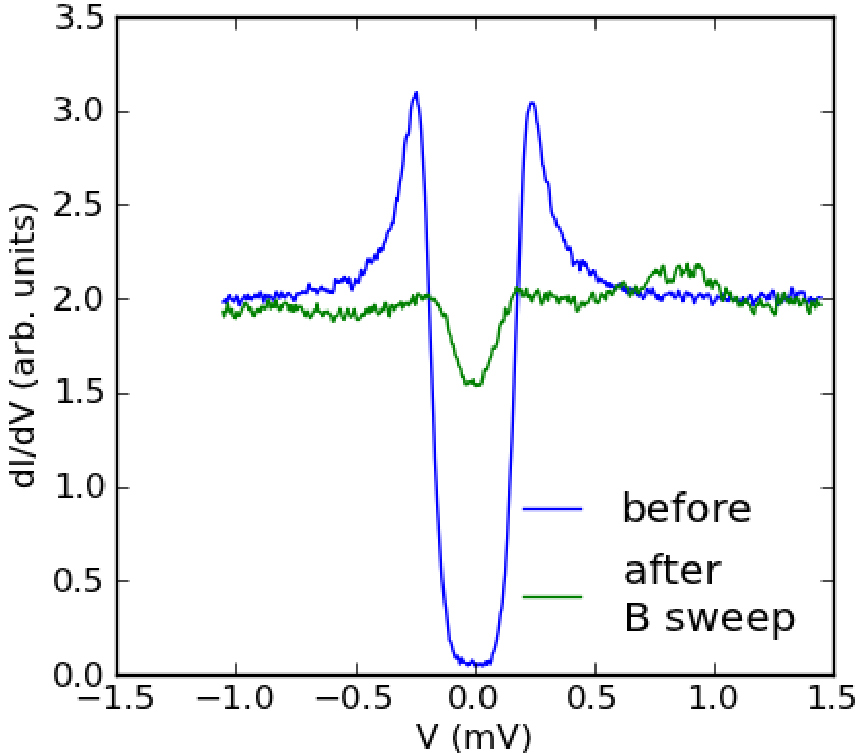
- Pronounced spatial dependence of spectra despite smooth topography
- First spectrum after 2nd cool down (new tip)
- Typical spectrum observed at many positions

Spectra at different positions

- + Anomaly at V=0?
- + noisy measurement



After magnetic field sweep

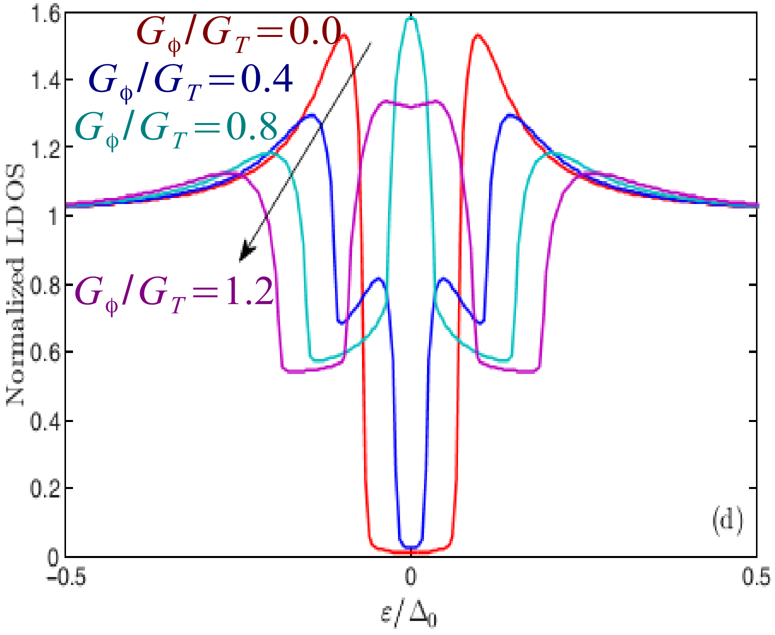


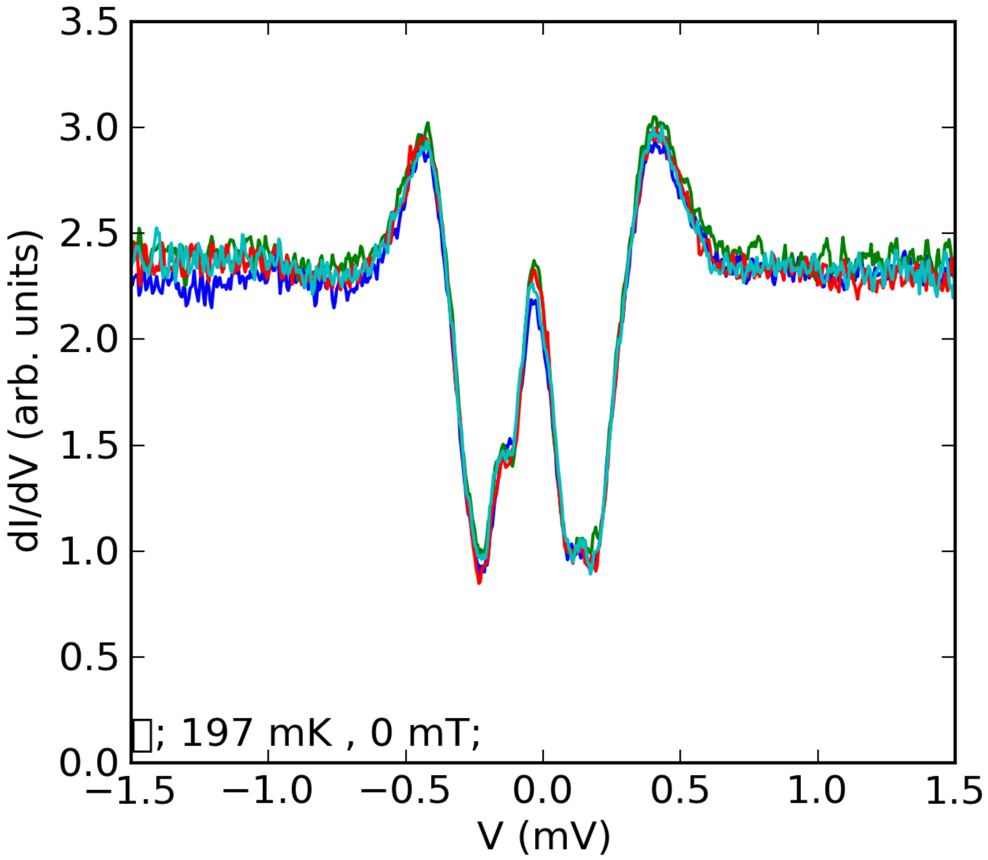
Spectra before and after magnetic field sweep

Trapping of flux?

Spectra at different positions

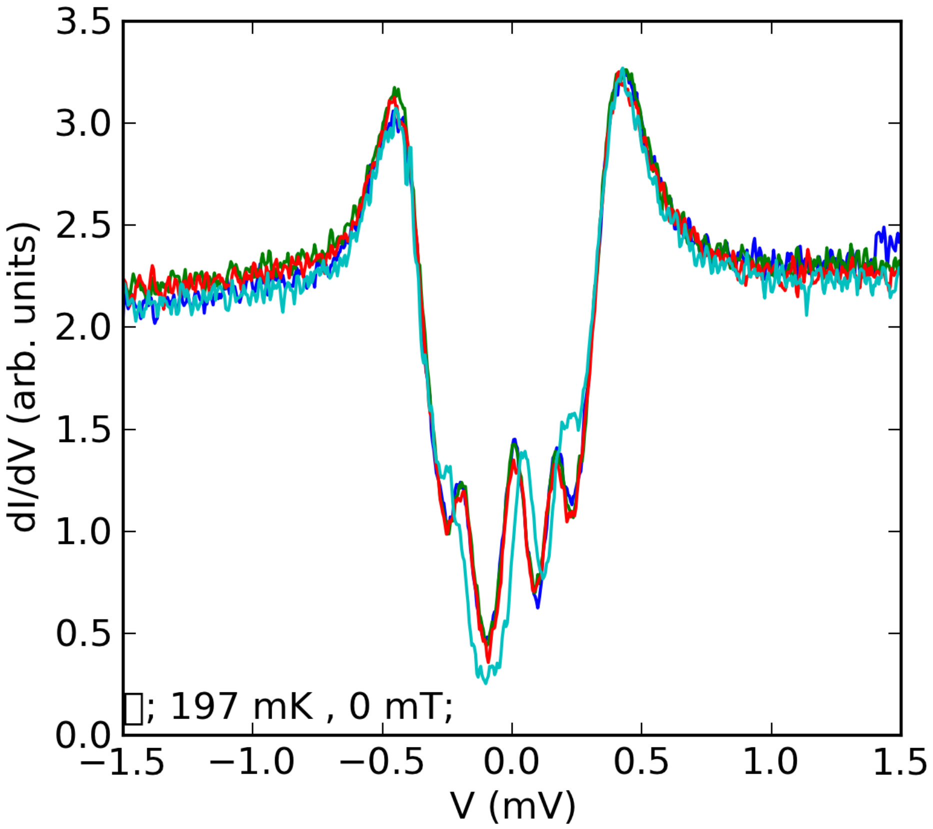
- Spectrum shows zero energy peak
- Asymmetric





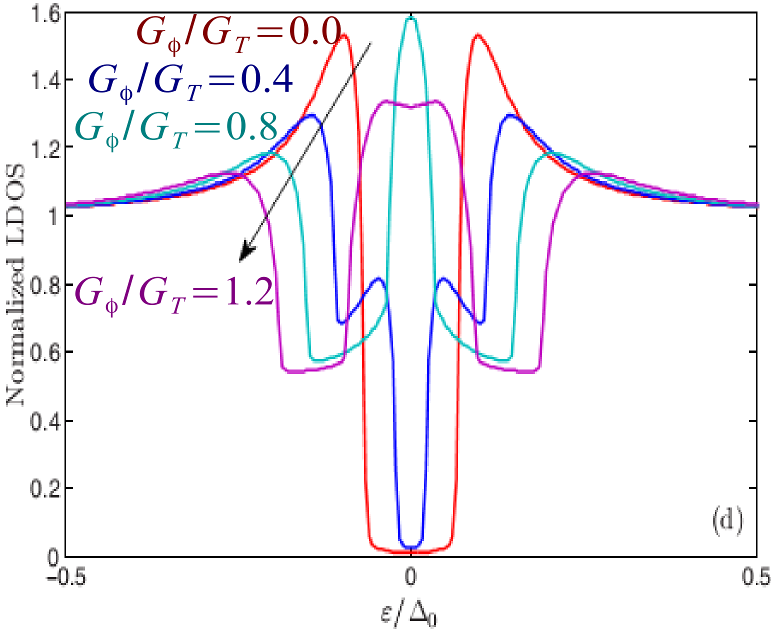
Spectra at different positions

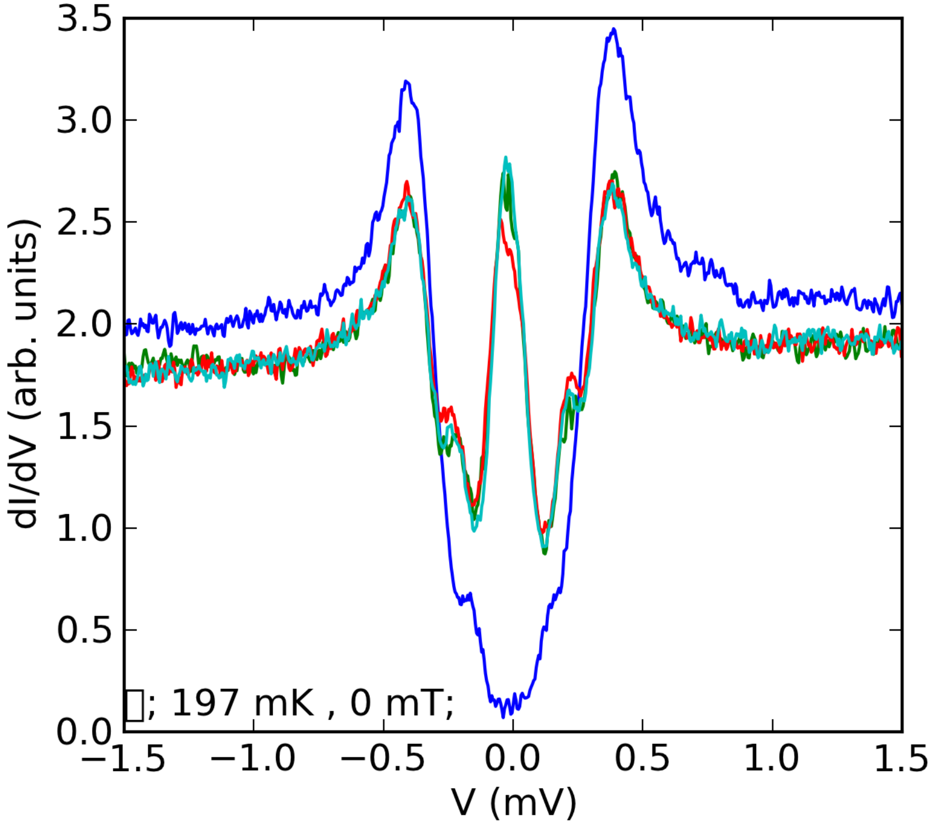
Five peaks: not predicted by theory



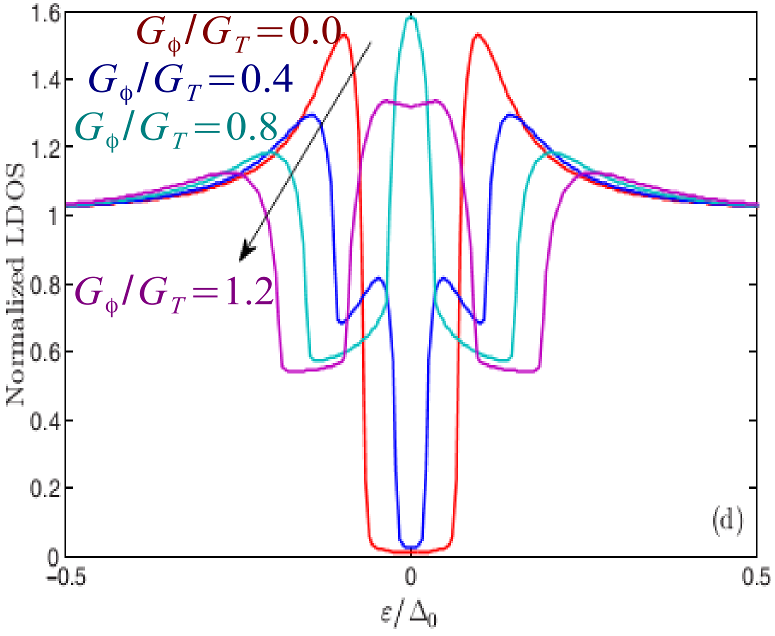
Spectra at different positions

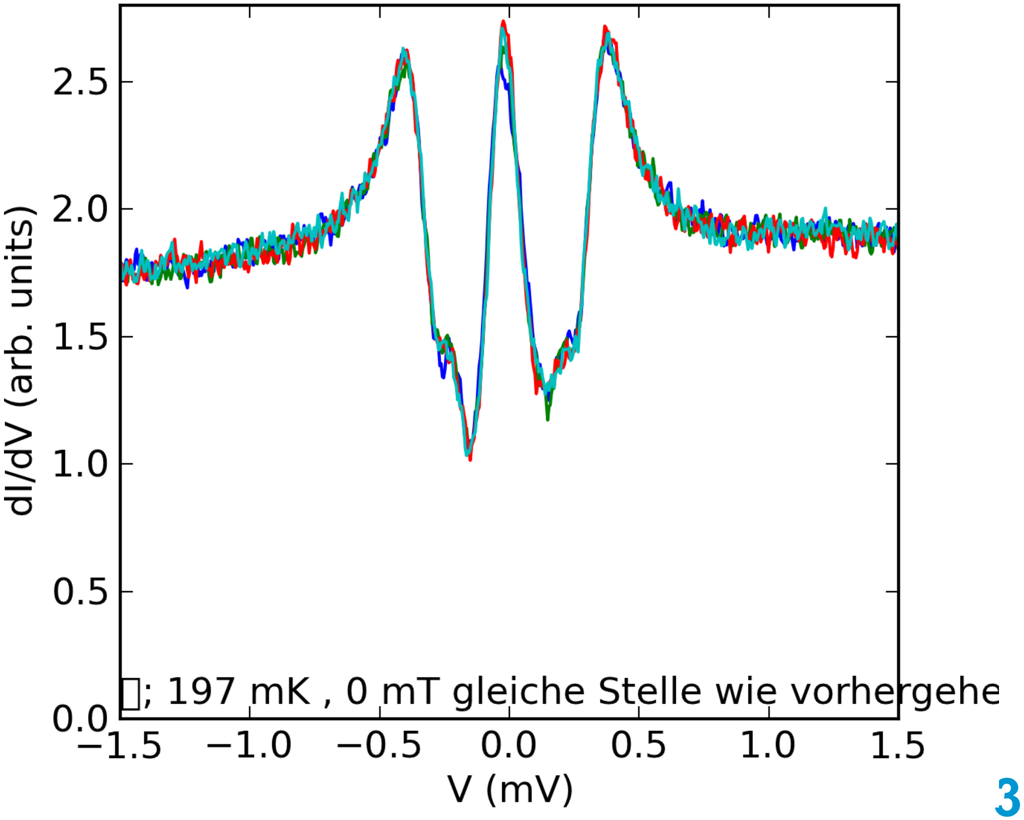
No intentional change of Experimental conditions





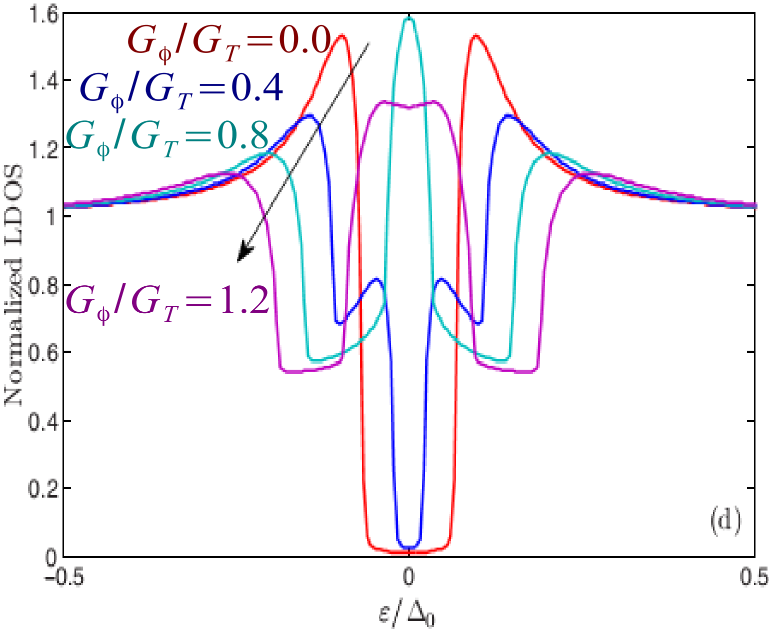
Spectra at different positions

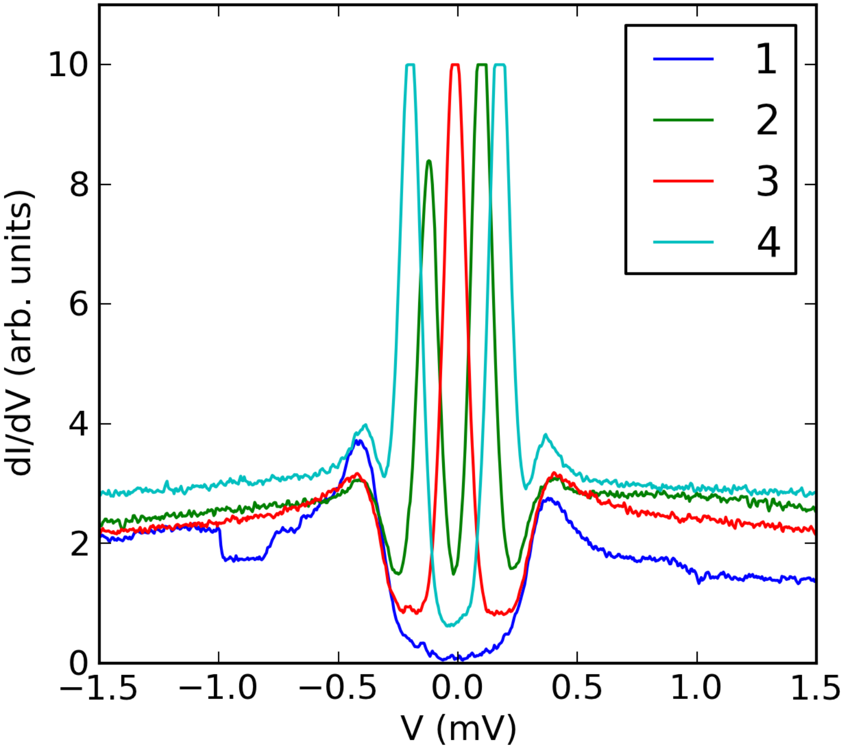




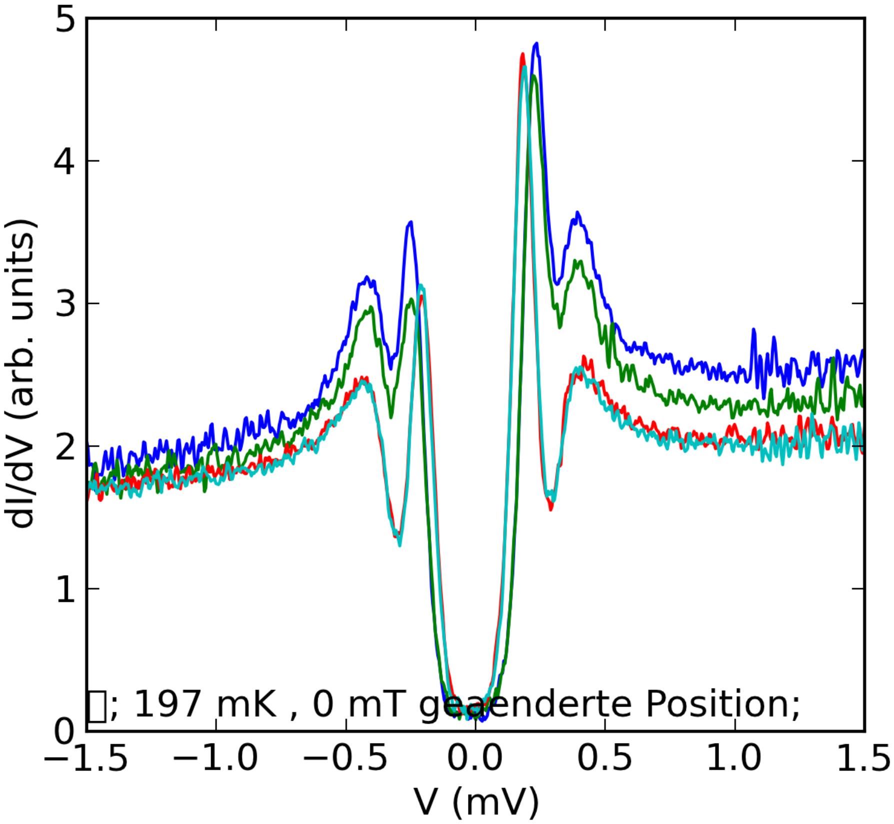
Spectra at different positions

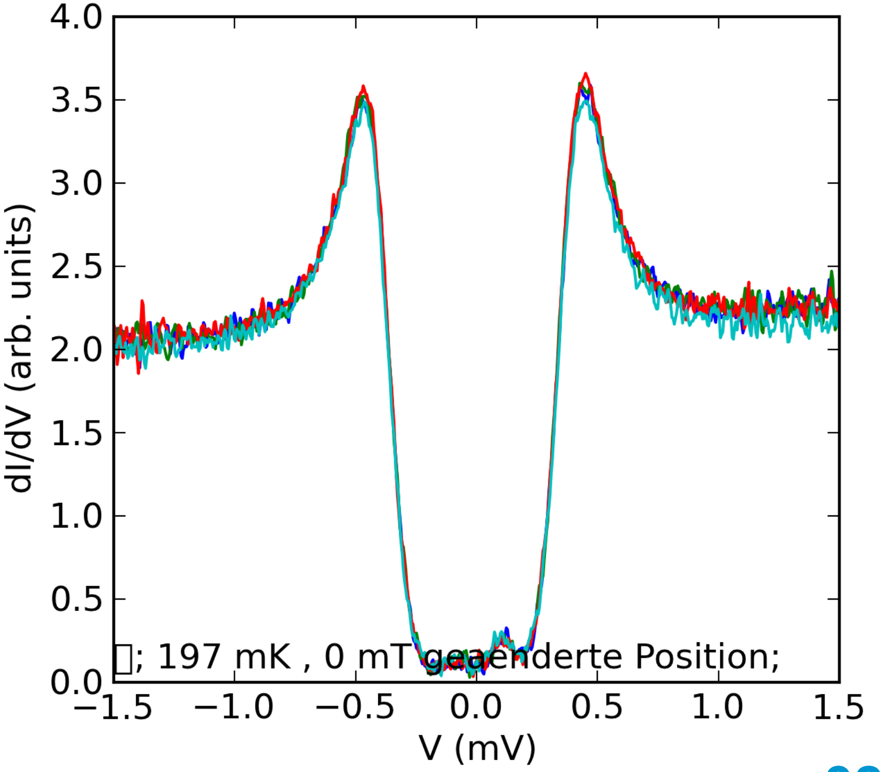
- 4 consecutive measurements
- Very high peaks cut off by lockin



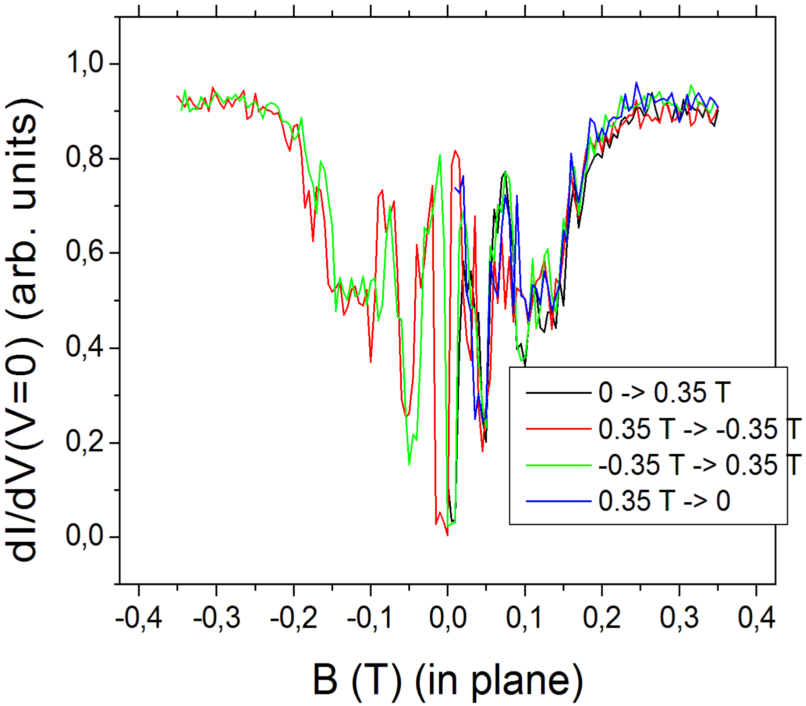


Spectra at different positions





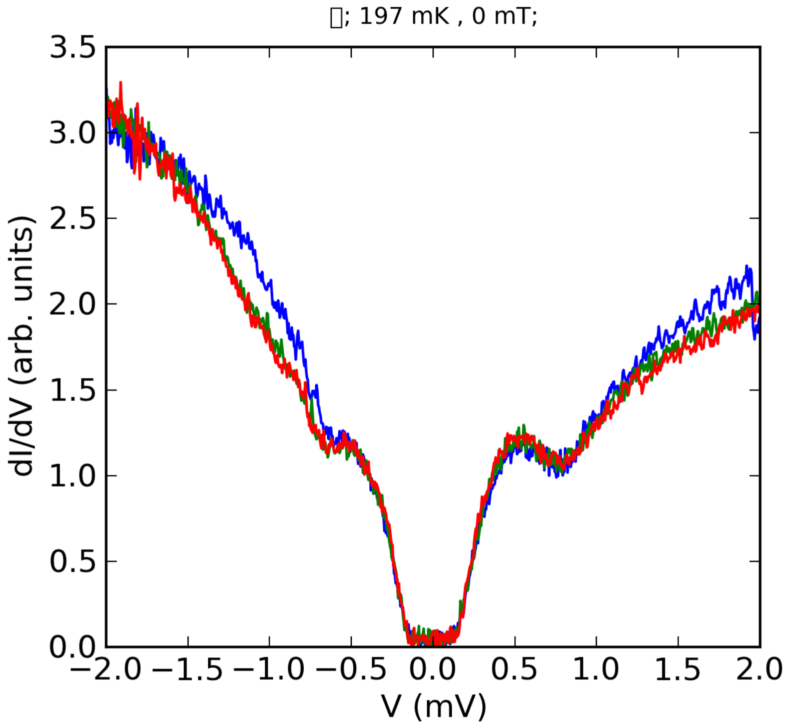
dI/dV(B, V=0)

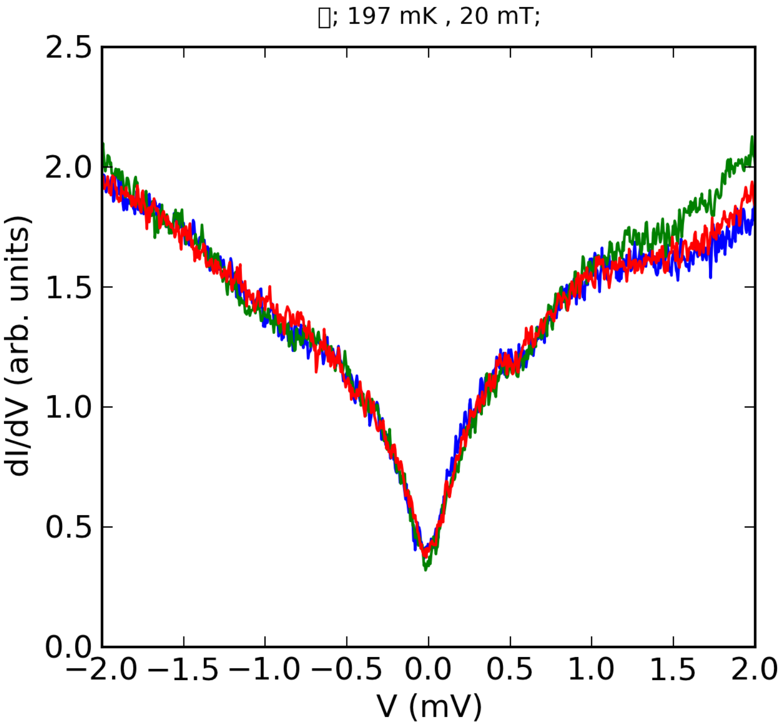


- Oscillation of differential conductance in magnetic field
- Trapped magnetic flux?
- Influence of proximity effect?

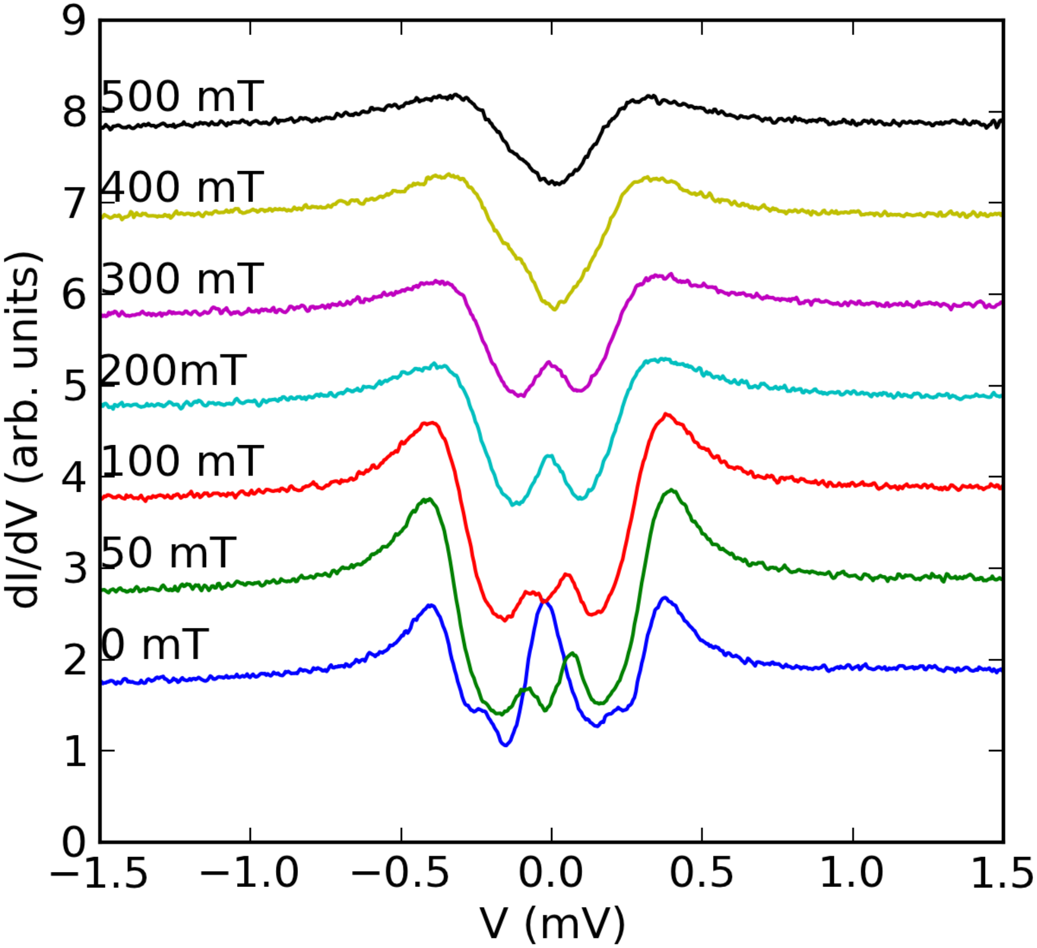
dI/dV-spectra in parallel magnetic field

\+ Different shapes of observed spectra

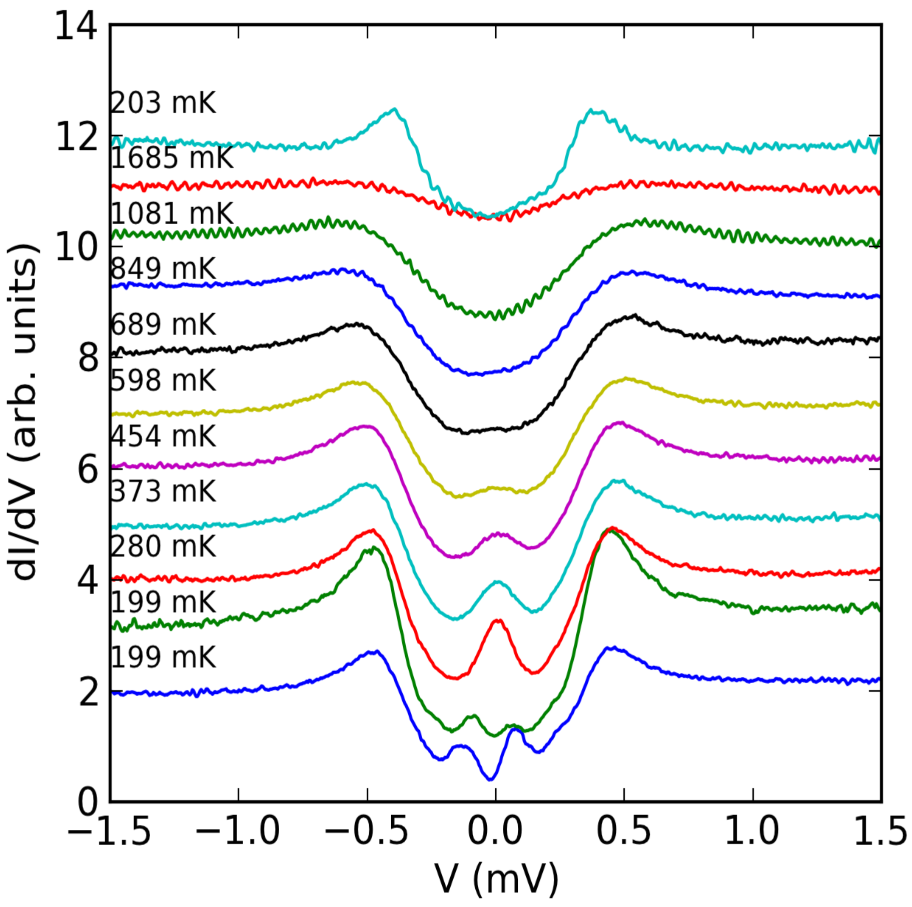




In plane magnetic field



Temperature dependence



- Sometimes instable
- High noise level at higher temperatures
- Does not return to original shape
- Mechanical change of contact?

Outlook

Systematic continuation of measurements :

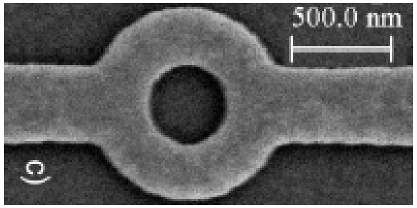
- samples with varying nominal parameters
- improvement of interface

Magnetoresistance oscillations in SC loops

Single loop

e.g. 200 nm YBCO ring: Carillo et al., PRB 81 (2010)

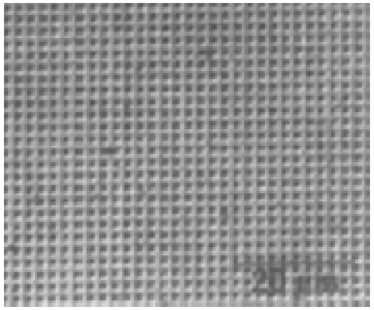
Problem with inhomogeneities



Simple network

e.g. 2x2µm^2 YBCO network: Gammel et al., PRB 41 (1990)

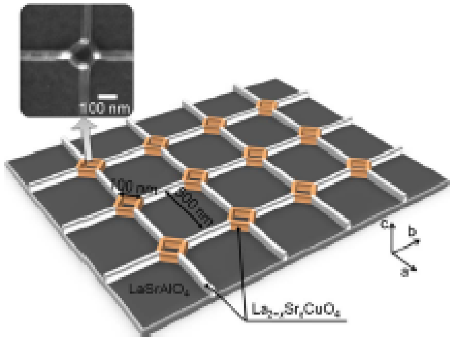
Statistical averaging over inhomogeneities, but interdependent loops



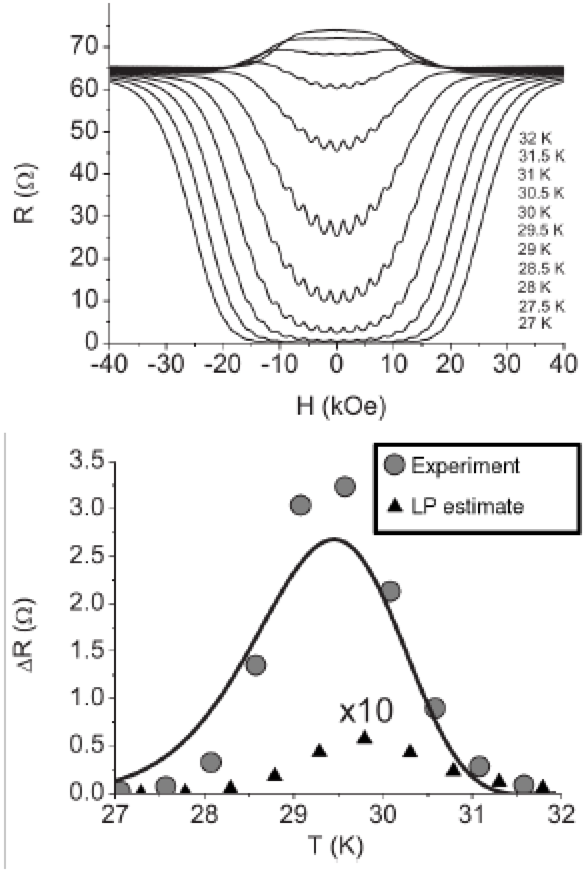
Double network

e.g 100-500 nm LSCO network: Sochnikov et al., PRB 82 (2010)

Statistical averaging over inhomogeneities and independent small loops



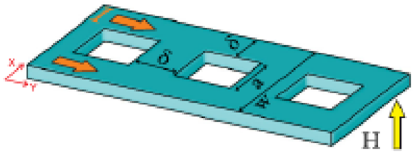
Enhanced amplitude w.r.t. Little Parks



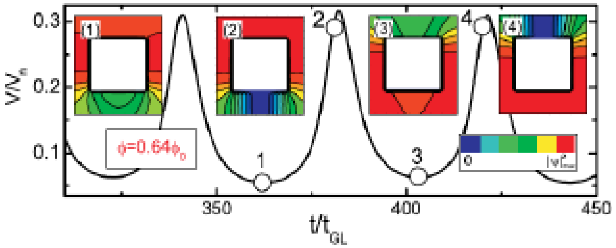
Sochnikov et al., PRB 82 (2010)

- Resistance oscillation with magnetic field (here: $H_0 = \frac{\Phi_0}{A_{smallloop}} \approx 2300\,\mathrm{Oe}$ $\hat{=}230\,\mathrm{mT}$)
- Amplitude way too high to be explained by LP-effect

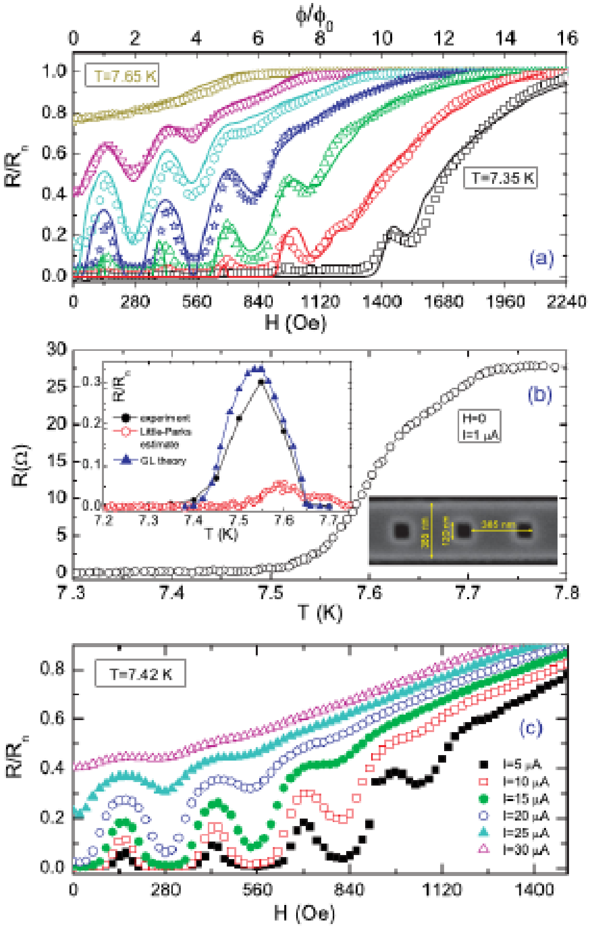
Niobium loops



- Current tunes barrier for vortex entry and exit and drives vortices.
- Thermally excited vortices not needed
- Numerical solution of the generalized time-dependent GL-equations

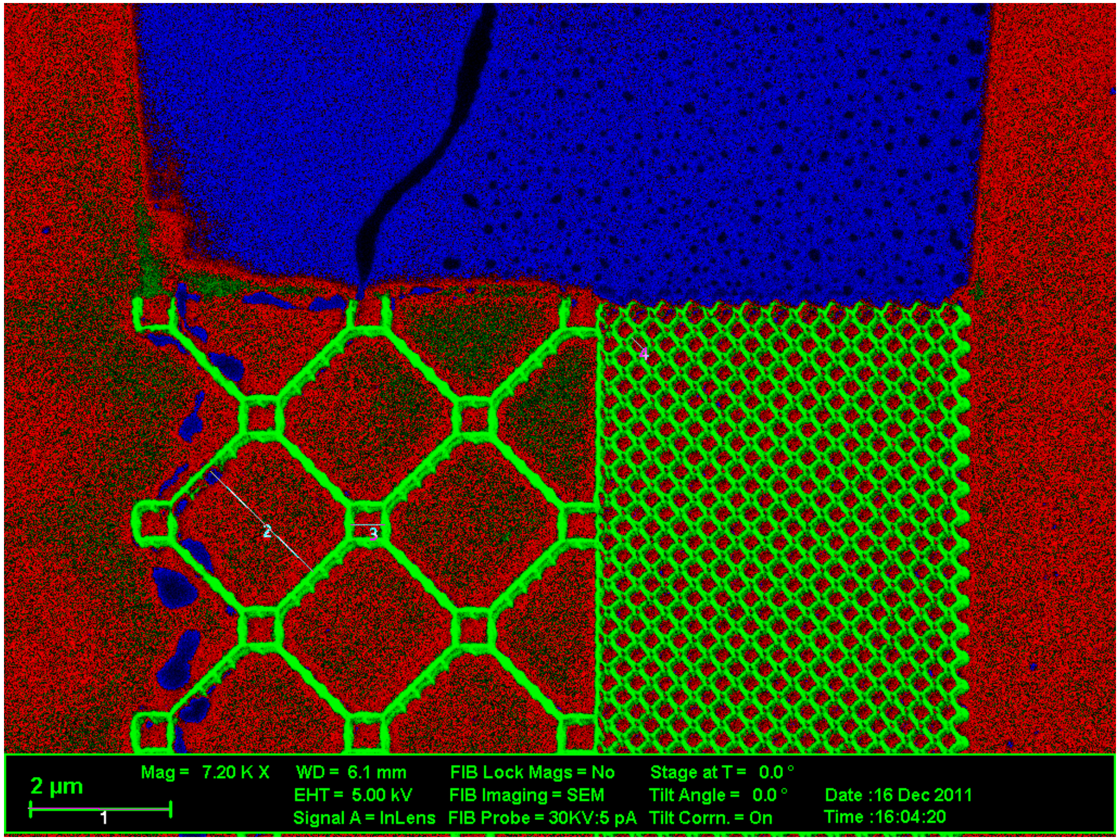


Berdiyorov et al., PRL 109 (2012)



First steps to measure Al loop arrays

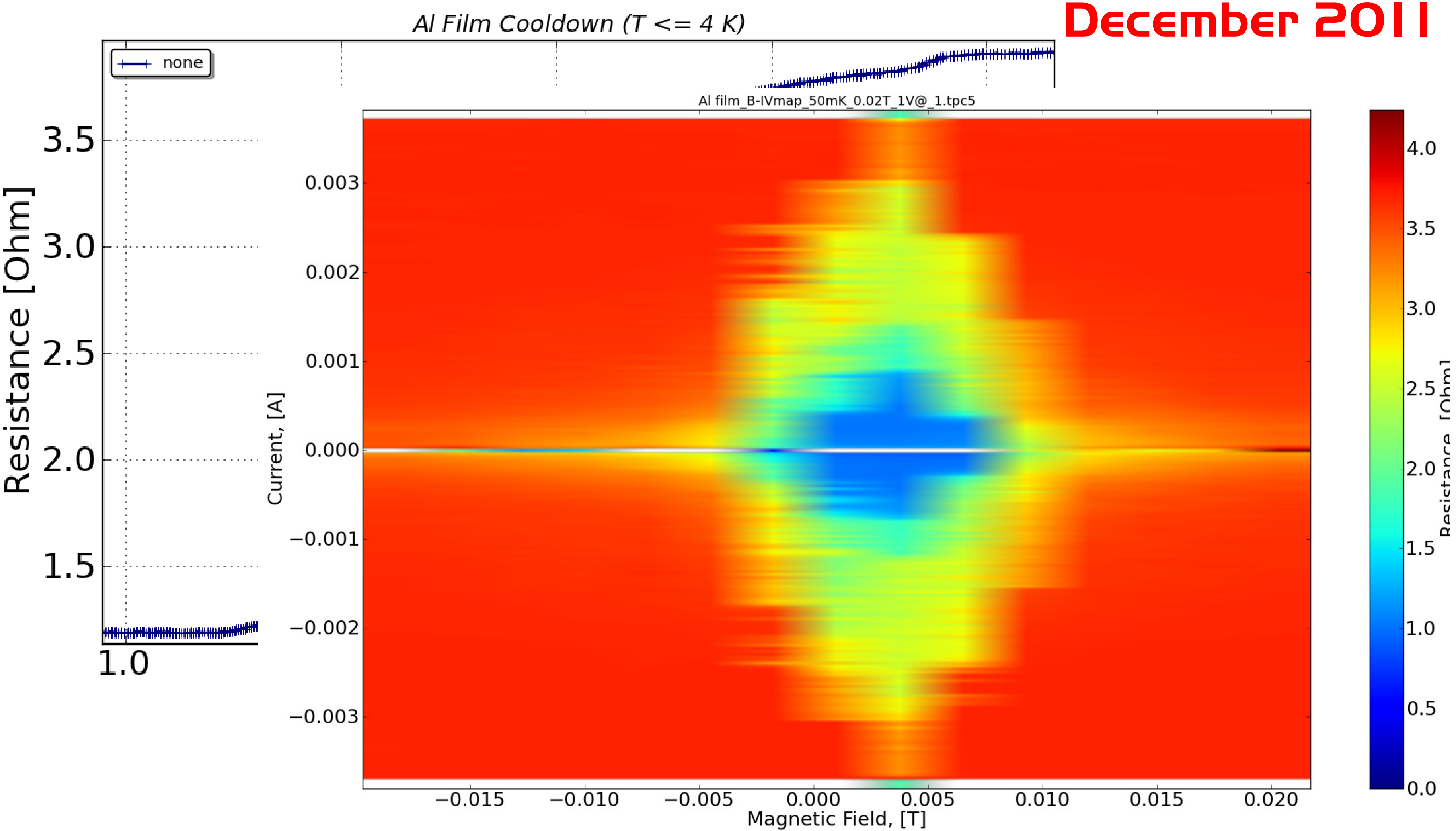
Chris Espy & Omri Sharon



December 2011

Al thin film, unpatterned, d = 30 nm

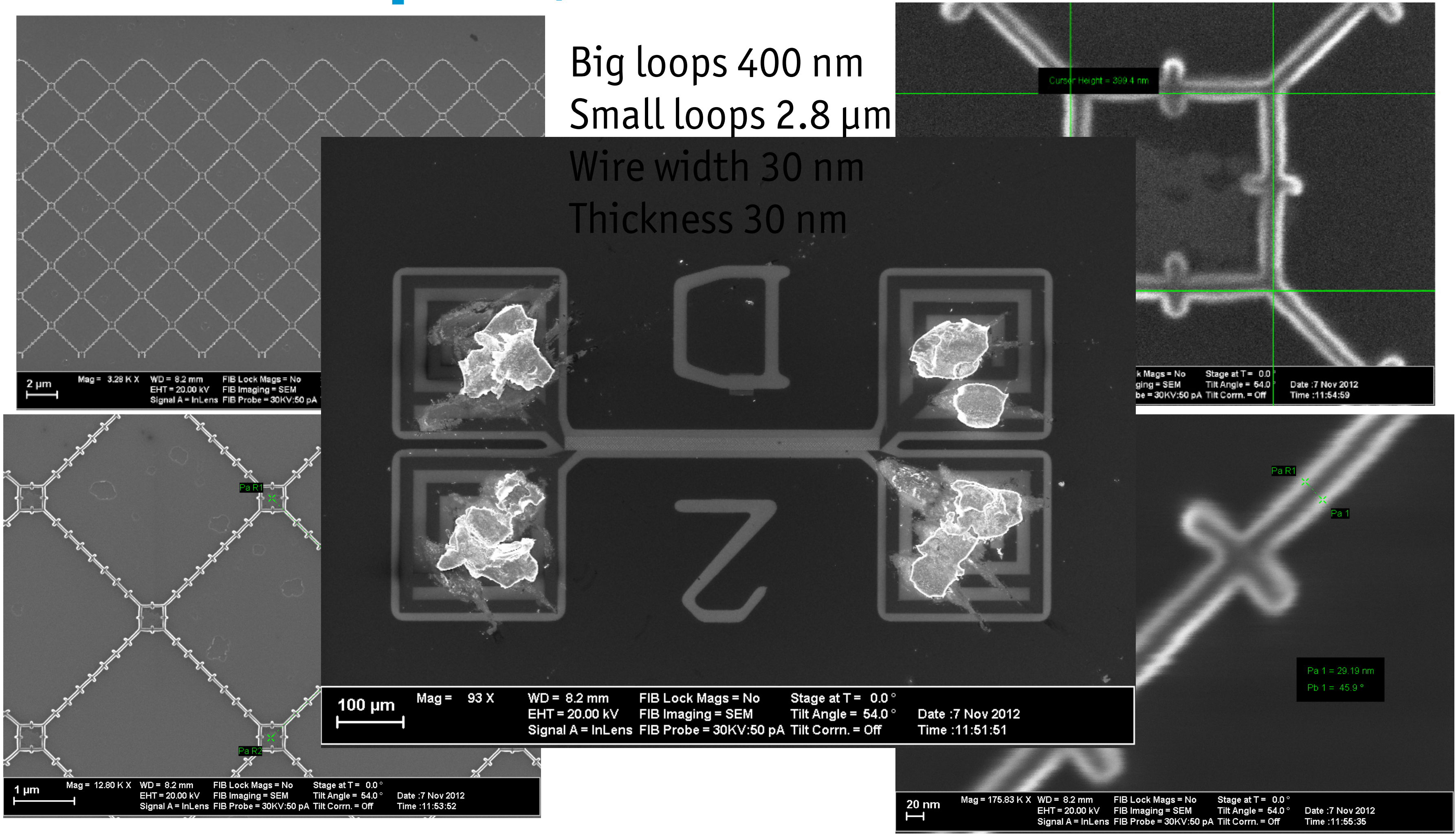
December 2011



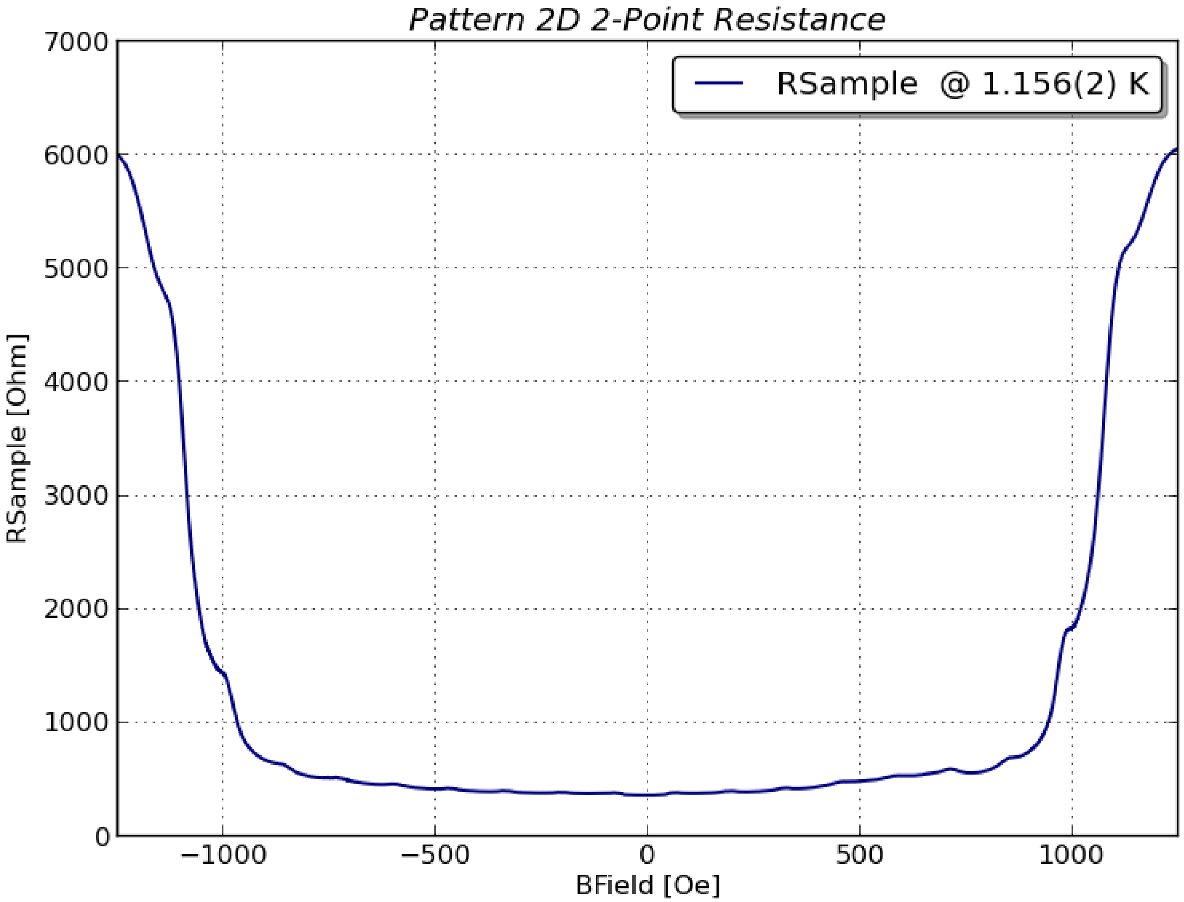
New samples, 11/2012

Al, Pattern 2D

Big loops 400 nm
Small loops 2.8 µm
Wire width 30 nm
Thickness 30 nm



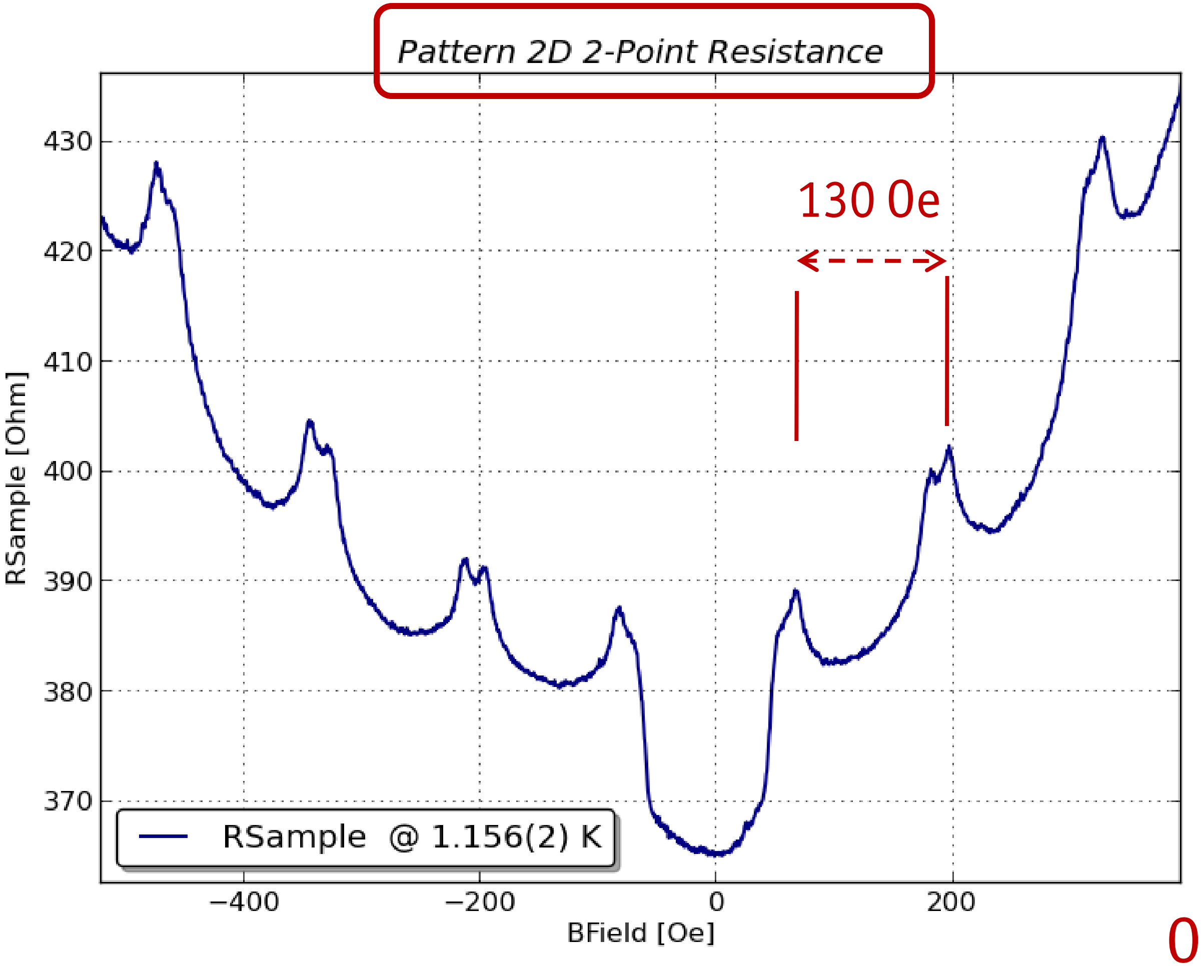
First measurements @ pattern 2D



Bulk values of Al
B_c : 100 Oe
λ: 5 nm
ξ: 1-2 µm

Thin diffusive films:
ξ: 100-300 nm

First measurements @ pattern 2D



Expected periodicity
for h/2e oscillations

Small loops 130 Oe
Big loops 2.6 Oe

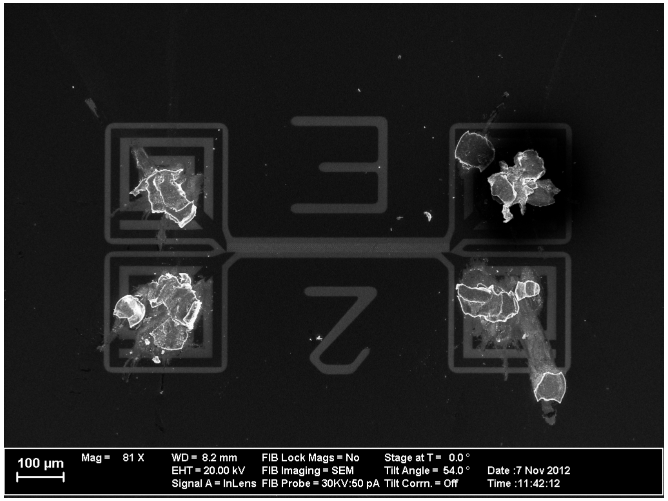
Expected periodicity
for h/e oscillations

Small loops 260 Oe
Big loops 1.3 Oe

Origin of double peaks?

New samples, 11/2012

Al, Pattern 2E



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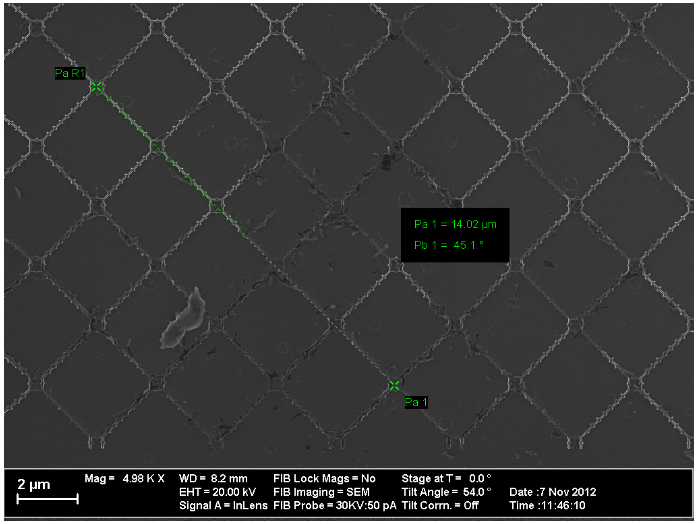
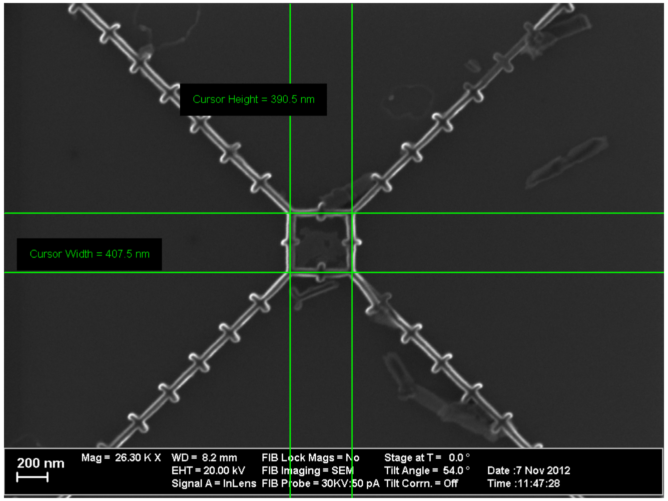
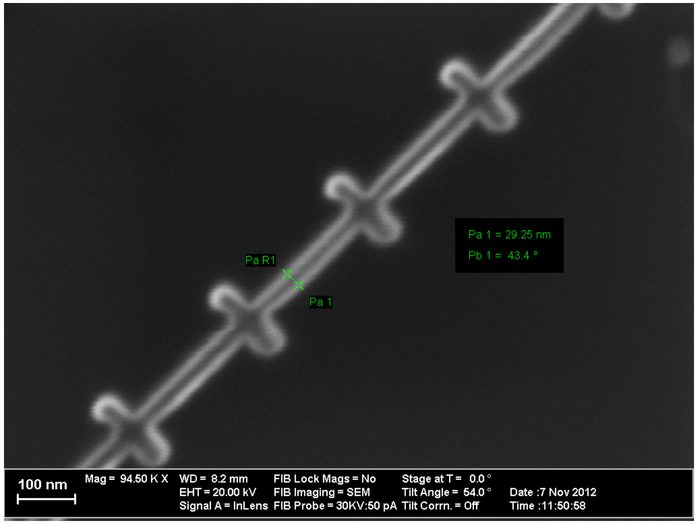
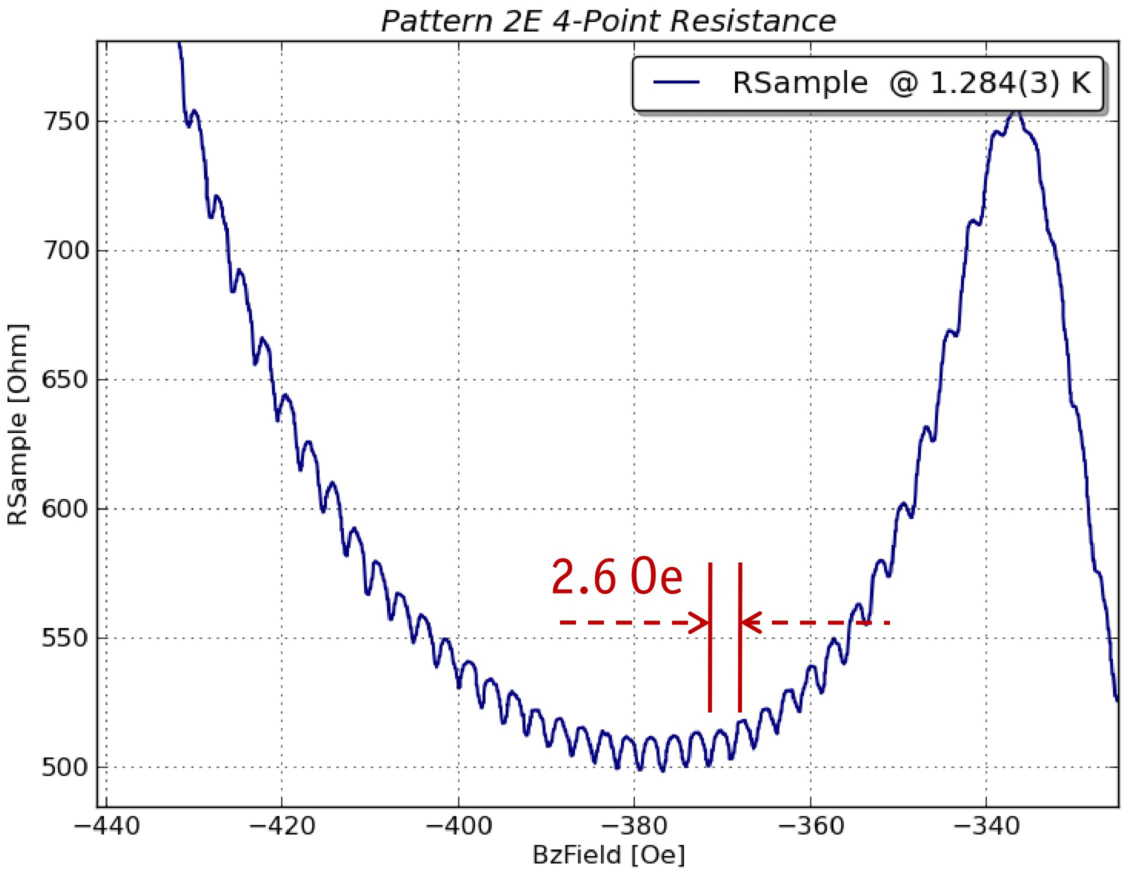






First measurements @ pattern 2E



Expected periodicity
for h/2e oscillations

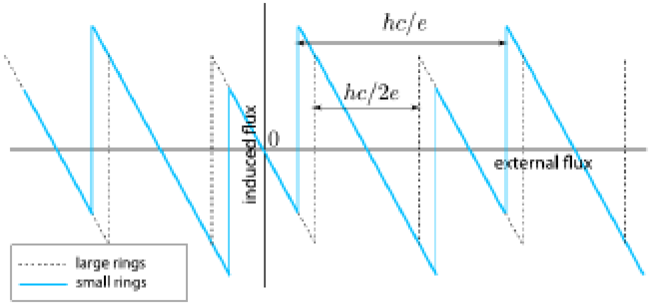
Small loops 130 Oe
Big loops 2.6 Oe

Expected periodicity
for h/e oscillations

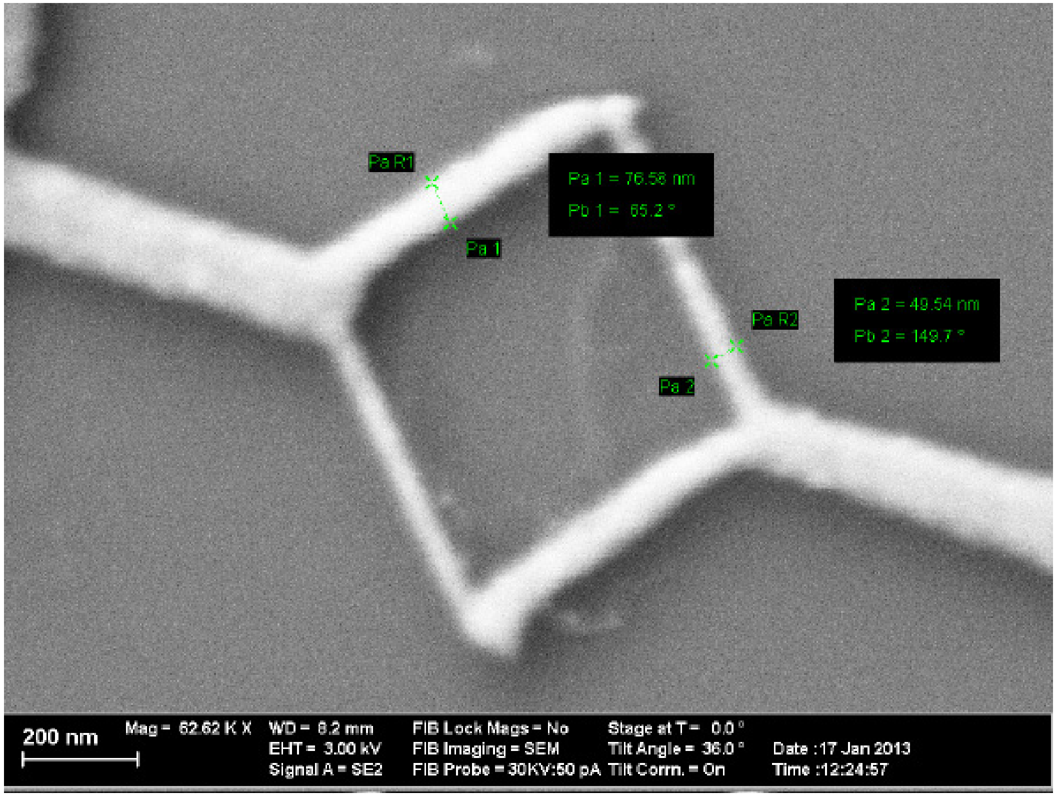
Small loops 260 Oe
Big loops 1.3 Oe

Single loop

h/e oscillations predicted for d < ξ



V. Vakaryuk, PRL 101 (2008)



Outlook

Systematic continuation of measurements:

- Search for h/e oscillations
- Variaton of loop geometry
- Study samples with varying granularity -> varying ξ/λ (Type I vs. Type II)
- Pb samples?