IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), April 2017.
Oral presentation at KRYO 2016. No manuscript was submitted for hardcopy journal publication.

Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin
Nationales Metrologieinstitut

Development of Nb NanoSQUIDs Based on SNS Junctions for Operation in High Magnetic Fields

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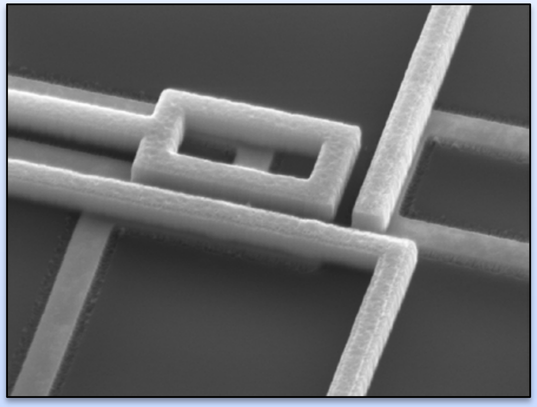
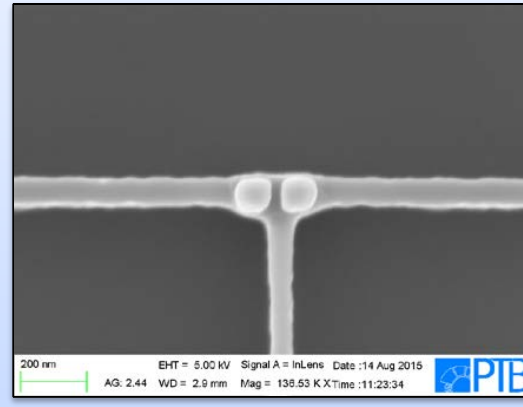
Outline



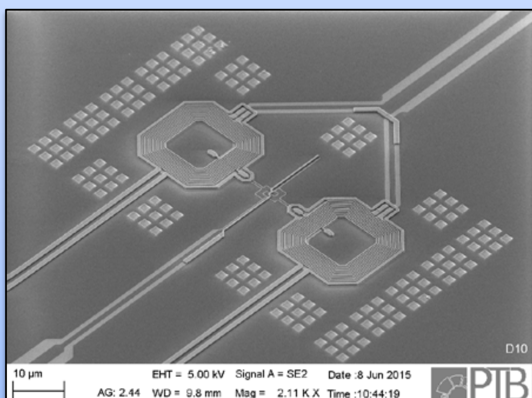


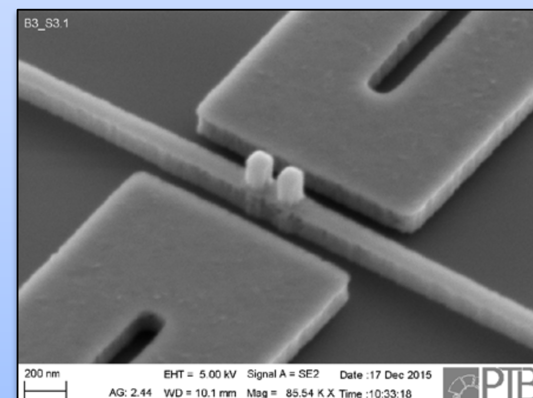
Motivation

Technology

Results

Outlook





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Motivation

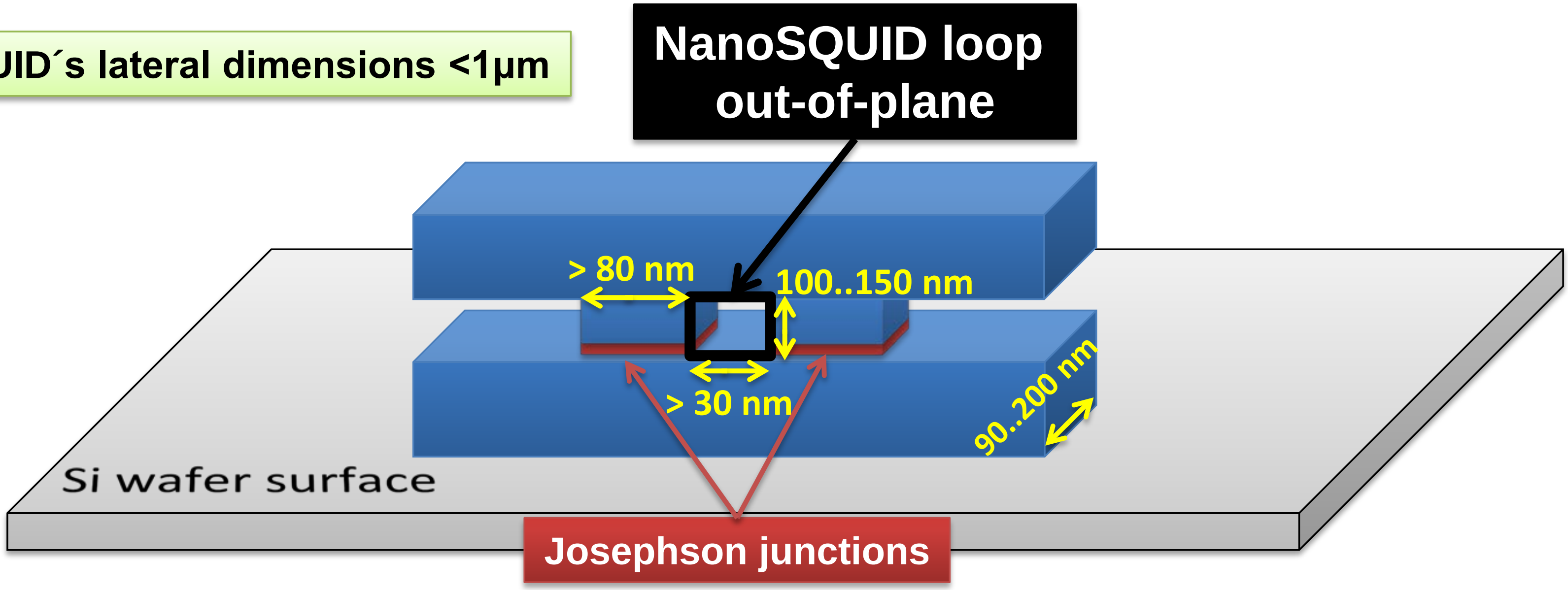
C. Granata and A. Vettoliere, "Nano Superconducting Quantum Interference device: A powerful tool for nanoscale investigations," *Phys. Rep.*, vol. 614, pp. 1–69, 2016.

Why we use SNS instead of SIS?

- critical current densities about 1000 times higher (up to about 1 MA/cm^2)
- no need for external shunt resistor enables downscaling of the SQUID sensor to sub-µm size
- very small junction capacitance keeps the $\beta_C < 1$ (non-hysteretic IV)

Motivation: Our NanoSQUID

SQUID´s lateral dimensions <1µm



- **High spatial resolution for localization of MNP**
- **High stability to external magnetic fields**
- **Better coupling to the field of the magnetic particle**

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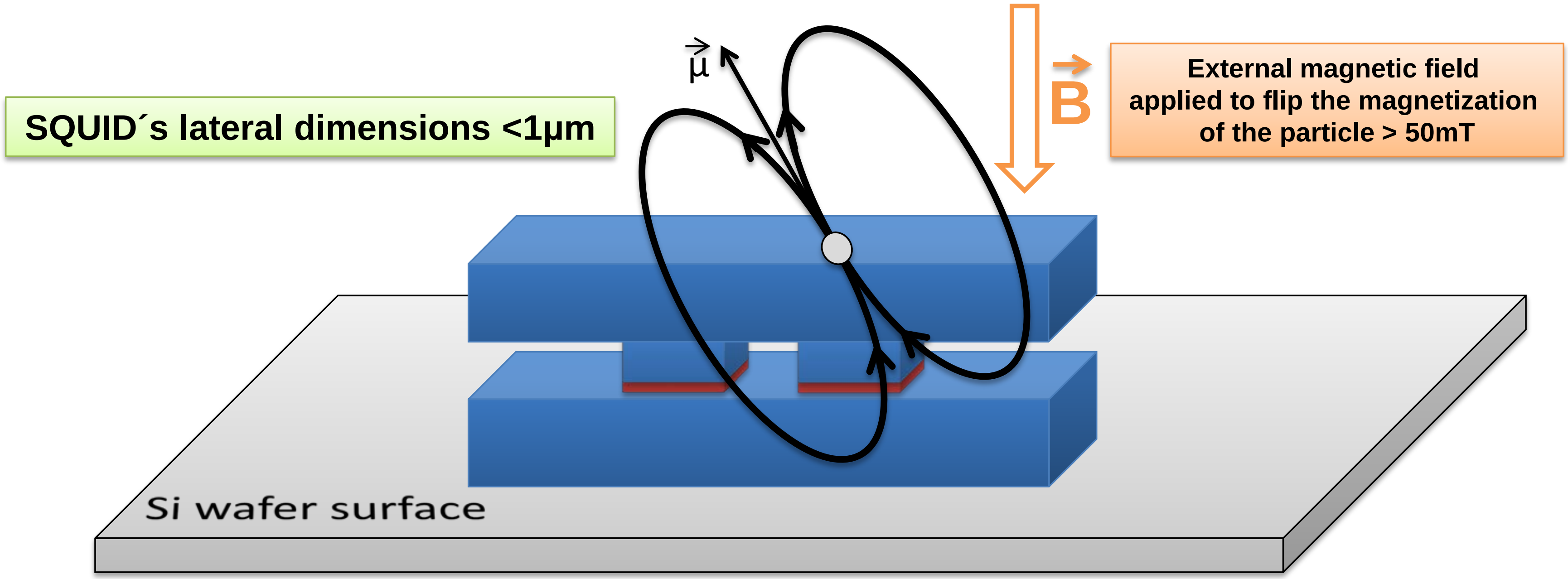
Motivation: Our NanoSQUID

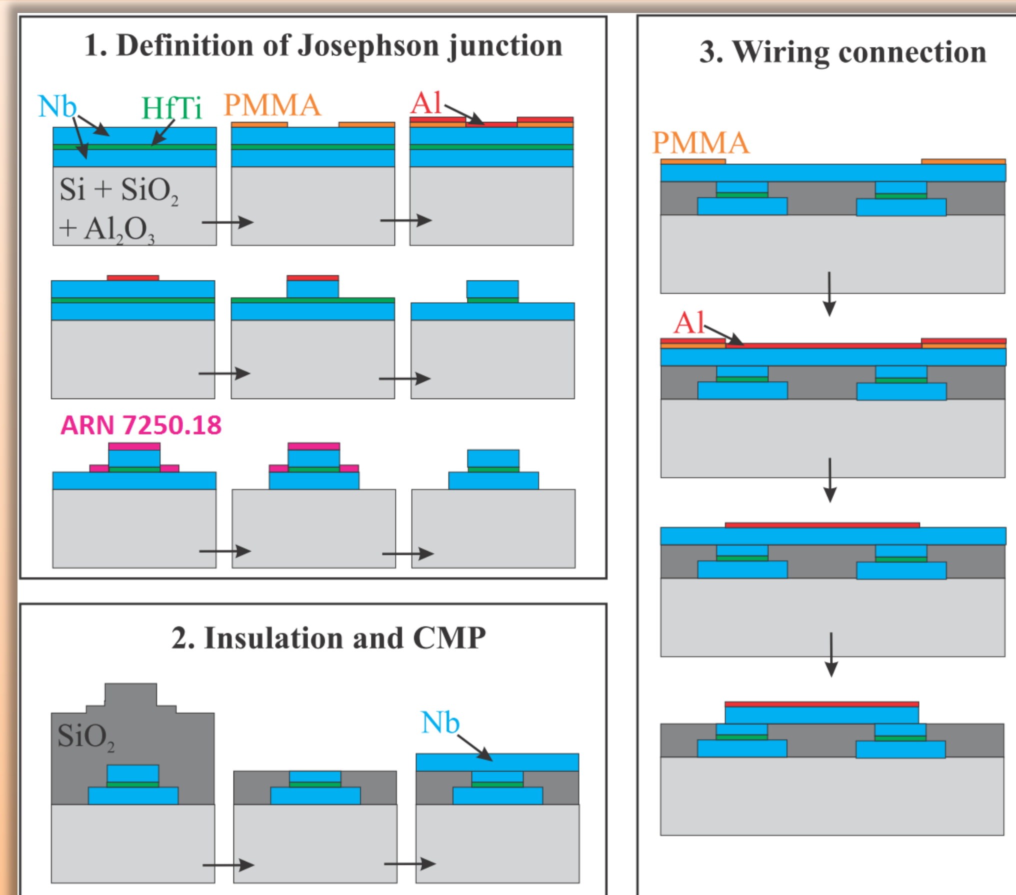


- **High spatial resolution for localization of MNP**
- **High stability to external magnetic fields**
- **Better coupling to the field of the magnetic particle**

Technology: SNS with HfTi Barrier

electron-beam-lithography
high alignment precision

chem.- mechan. Polishing (CMP)
planar layer interconnection



- designs with high complexity and high yield are feasible
- in-plane and out-of-plane loop orientations in one device

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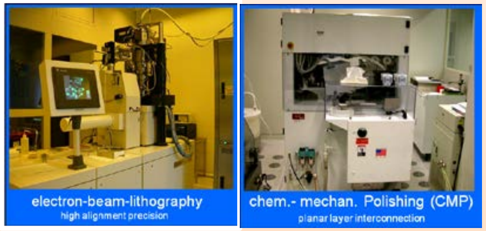
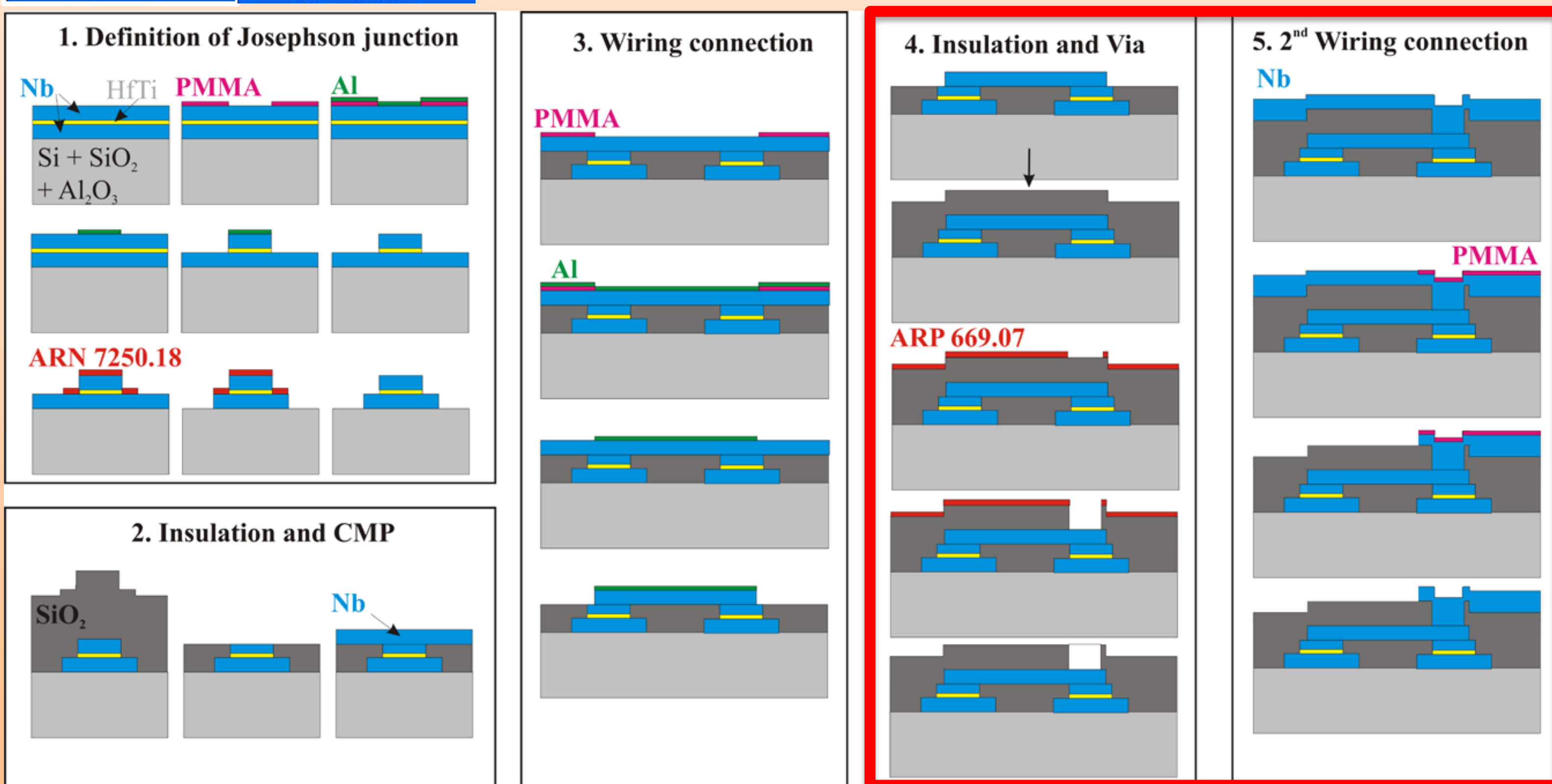
Advanced Technology



- Layer structure is extended by an additional Nb layer for auxiliary components (coils, transformers)
- It offers more free space and more freedom in designing of superconductive devices



Results Related to our Technology

- J. Nagel, O.F. Kieler, T. Weimann, R. Wölbing, J. Kohlmann, A.B. Zorin, R. Kleiner, D. Koelle, and M. Kemmler, "Superconducting quantum interference devices with submicron Nb/HfTi/Nb junctions for investigation of small magnetic particles", Appl. Phys. Lett. 99 (2011) 032506 (3 pp).
- R. Wölbing, J. Nagel, T. Schwarz, O. Kieler, T. Weimann, J. Kohlmann, A. B. Zorin, M. Kemmler, R. Kleiner, and D. Koelle, "Nb nano superconducting quantum interference devices with high spin sensitivity for operation in magnetic fields up to 0.5 T", Appl. Phys. Lett. 102 (2013) 192601 (4 pp).
- A. Buchter, J. Nagel, D. Rüffer, F. Xue, D.P. Weber, O.F. Kieler, T. Weimann, J. Kohlmann, A.B. Zorin, E. Russo-Averchi, R. Huber, P. Berberich, A. Fontcuberta i Morral, M. Kemmler, R. Kleiner, D. Koelle, D. Grundler, and M. Poggio, "Reversal mechanism of an individual Ni nanotube simultaneously studied by torque and SQUID magnetometry", Phys. Rev. Lett. 111 (2013) 067202 (5 pp).
- J. Nagel, A. Buchter, F. Xue, O. F. Kieler, T. Weimann, J. Kohlmann, A. B. Zorin, D. Rüffer, E. Russo-Averchi, R. Huber, P. Berberich, A. Fontcuberta i Morral, D. Grundler, R. Kleiner, D. Koelle, M. Poggio, and M. Kemmler, "Nanoscale multifunctional sensor formed by a Ni nano¬tube and a scanning Nb nanoSQUID", Phys. Rev. B 88 (2013) 064425 (7 pp).
- A. Buchter, R. Wölbing, M. Wyss, O. F. Kieler, T. Weimann, J. Kohlmann, A. B. Zorin, D. Rüffer, F. Matteini, G. Tütüncüoglu, F. Heimbach, A. Kleibert, A. Fontcuberta i Morral, D. Grundler, R. Kleiner, D. Koelle, and M. Poggio, „Magnetization reversal of an individual exchange-biased permalloy nanotube", Phys. Rev. B 92 (2015) 214432 (7 pp).
- S. Bechstein, F. Ruede, D. Drung, J.-H. Storm, O. F. Kieler, J. Kohlmann, T. Weimann, and T. Schurig, „HfTi-nanoSQUID gradiometers with high linearity", Appl. Phys. Lett. 106 (2015) 072601 (4 pp)
- J. Beyer, M. Klemm, J. H. Storm, O. Kieler, T. Weimann, V. Morosh, „Noise of dc-SQUIDs with planar sub-micrometer Nb/HfTi/Nb junctions", Superc. Sci. Technol. 28 (2015), 085011.

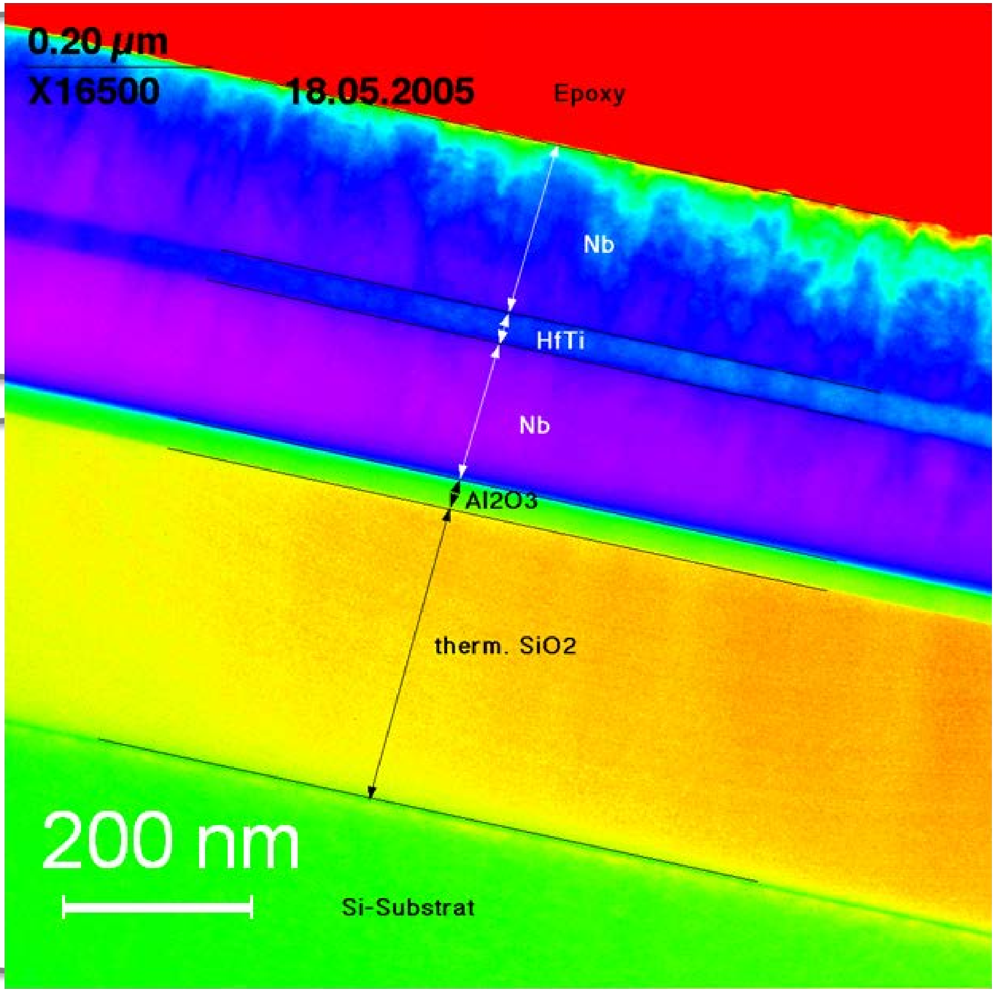
Layer Structure

The Trilayer:

Nb (Top): **200 nm** (superconductor)
HfTi: **20…30 nm** (normal metal)
Nb (Base): **160 nm** (superconductor)

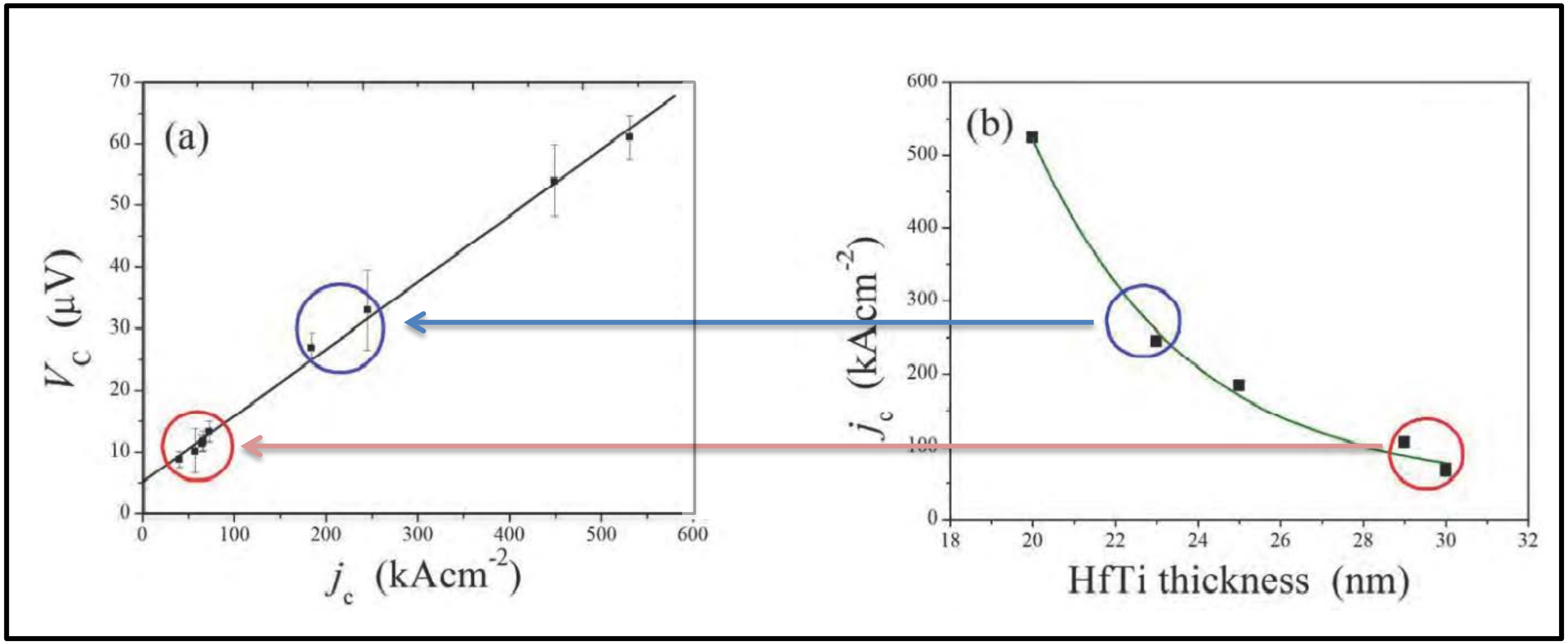
30 nm Al_2O_3 etching stop

Si substrate with 300 nm thermal oxidized SiO_2



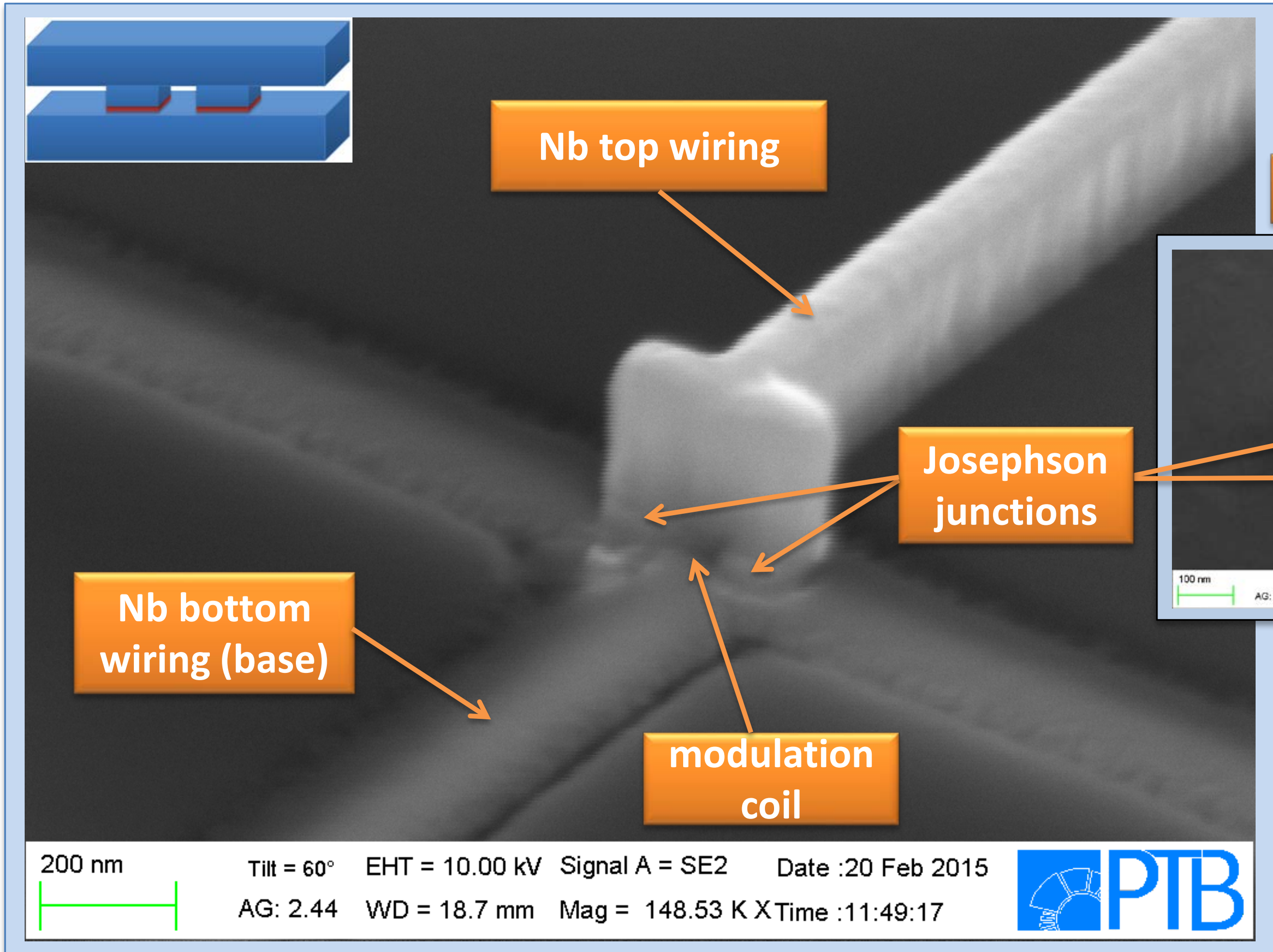
Kieler, O.F.; Iuzzolino, R. & Kohlmann, J. (2009). Sub-µm SNS Josephson junction arrays for the Josephson arbitrary waveform synthesizer, *IEEE Transactions on Applied Superconductivity,* Vol.19, No.3, (June 2009) pp. 230-233.

Critical Parameters on Demand

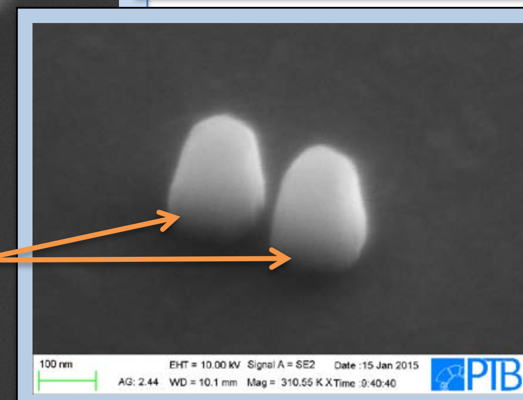


- Parameters of the Josephson junctions can be adjusted
- High reproducibility of the parameters

Results: NanoSQUID Type A



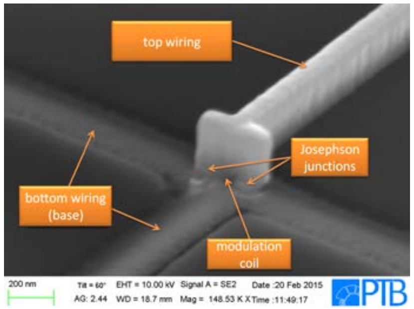
d(HfTi) = 20,5 nm



JJ area = 90 nm x 90 nm

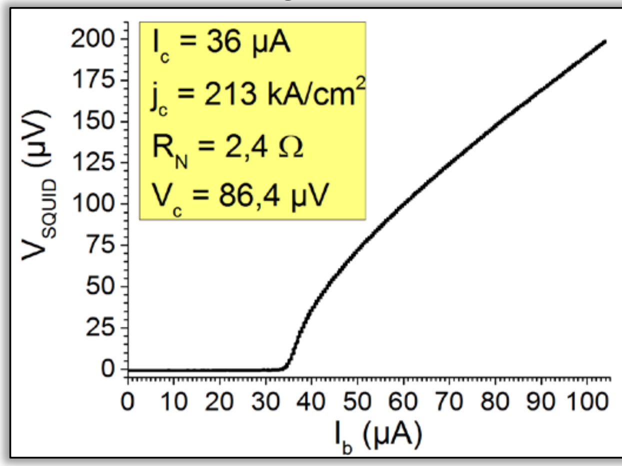
JJ spacing = 100 nm

Results: NanoSQUID Type A

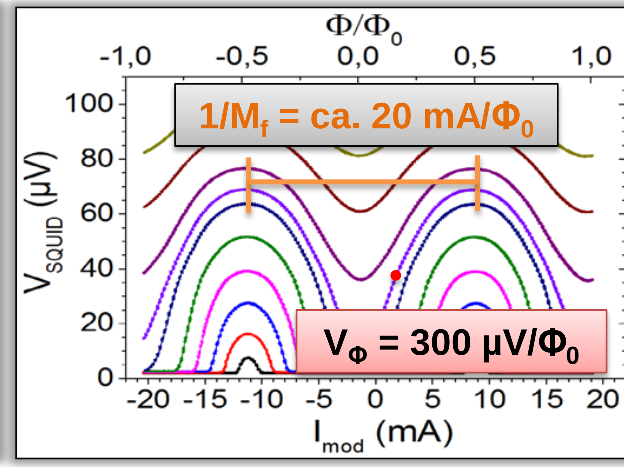


All measurements were made at 4.2 K

Current-Voltage Characteristics



V-Φ- Characteristics



$\beta_L = I_c L / \Phi_0 = 0.2$

L = 11 pH

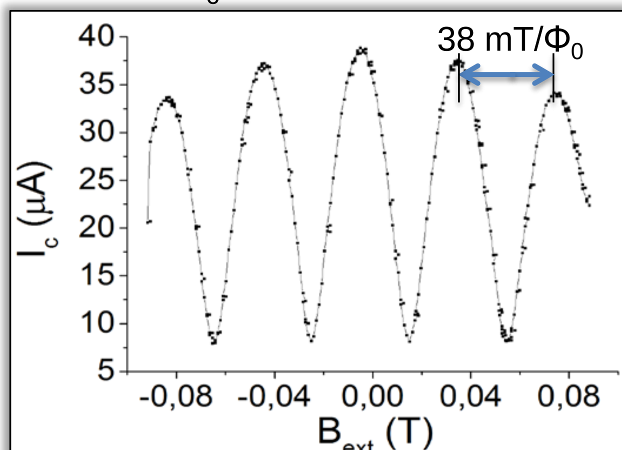
$\Gamma = 2\pi k_B T / I_0 \Phi_0 =$

10×10^{-3}

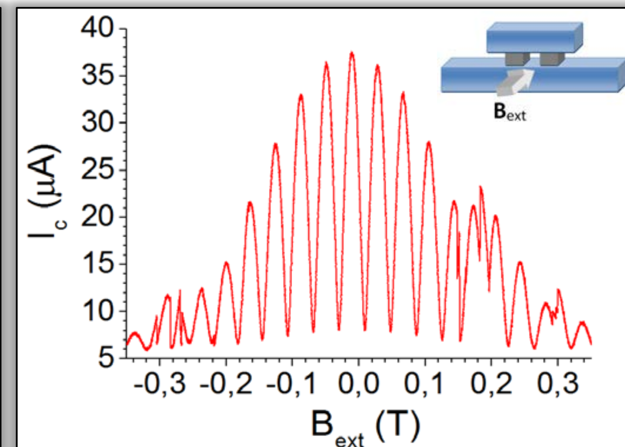
$A_{SQUID,eff}$ = 0.05 µm²

j_c homogeneous

I_c Modulations



Fraunhofer-Like Pattern



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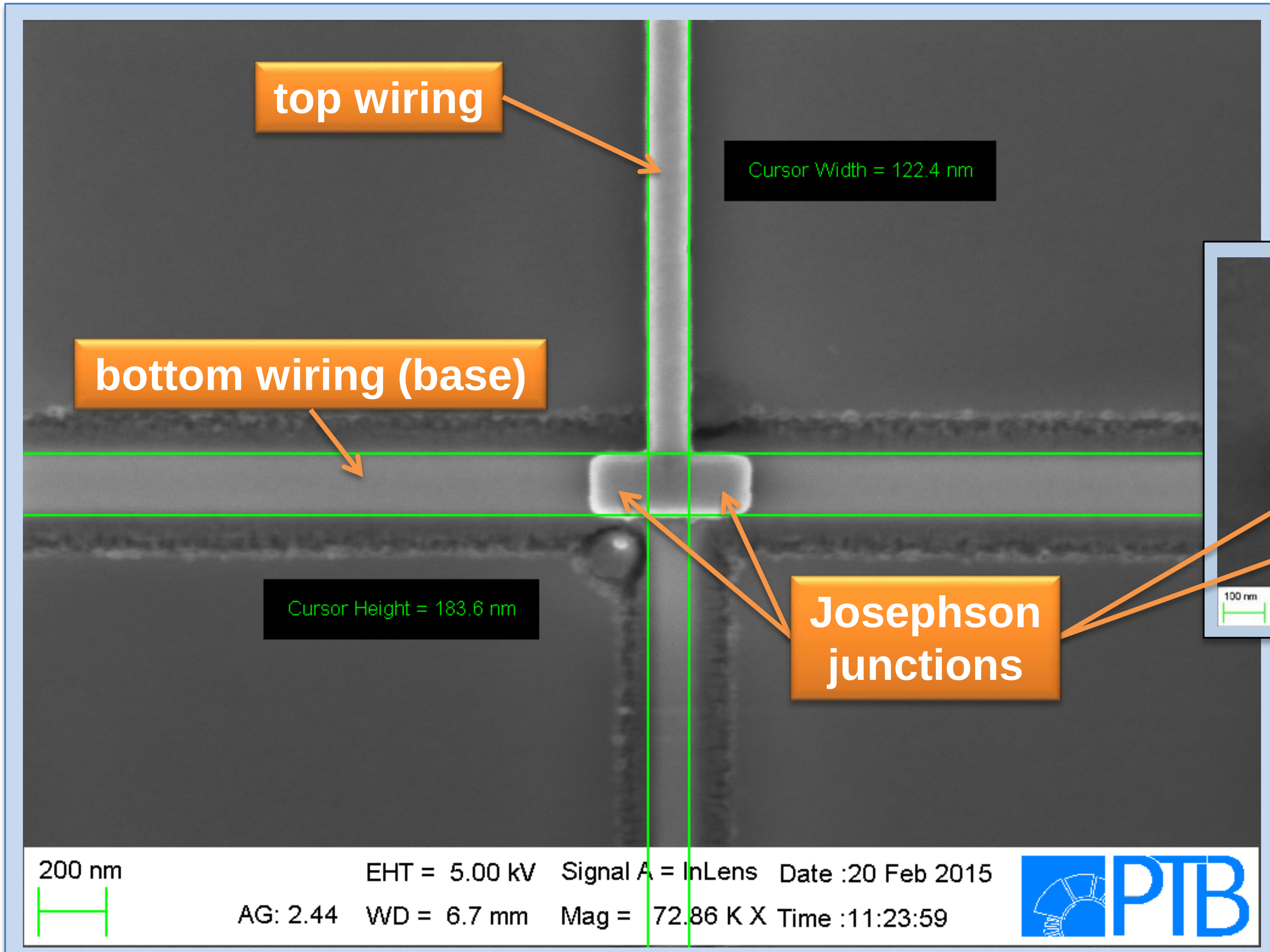
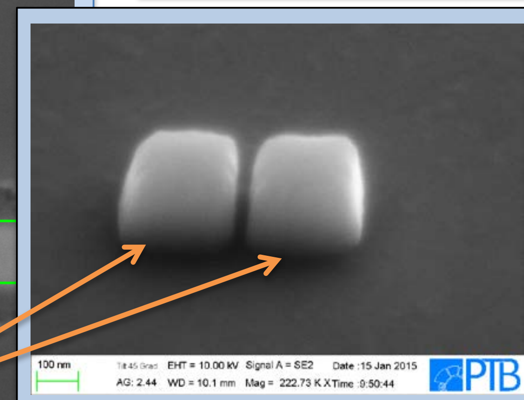
Results: NanoSQUID Type B



d(HfTi) = 20.5 nm



JJ area = 150 nm x 150 nm

JJ spacing = 60 nm

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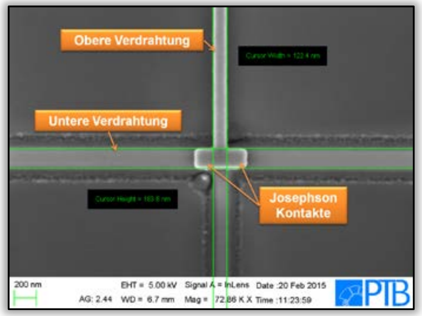
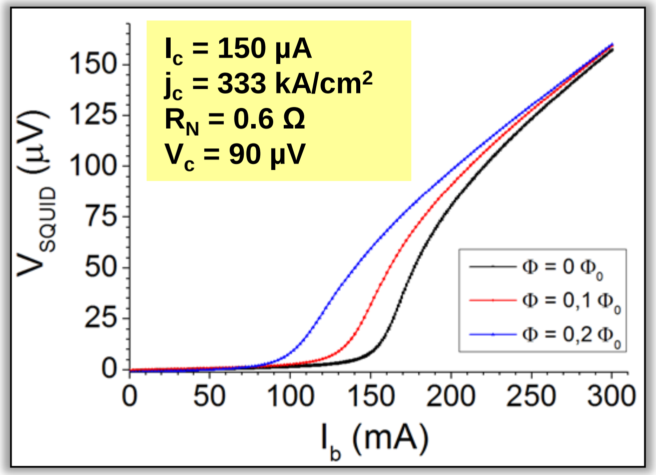
Results: NanoSQUID Type B

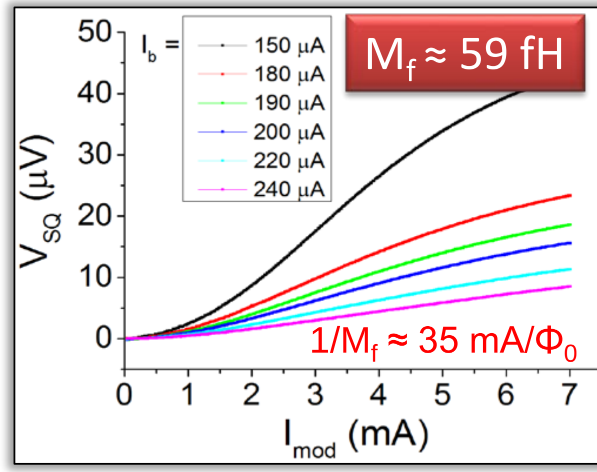


All measurements were made at 4.2 K

Current-Voltage Characteristics



V-I_{mod}- Curve



$\beta_L = I_c L / \Phi_0 = 0.25$

$L = 2.7$ pH

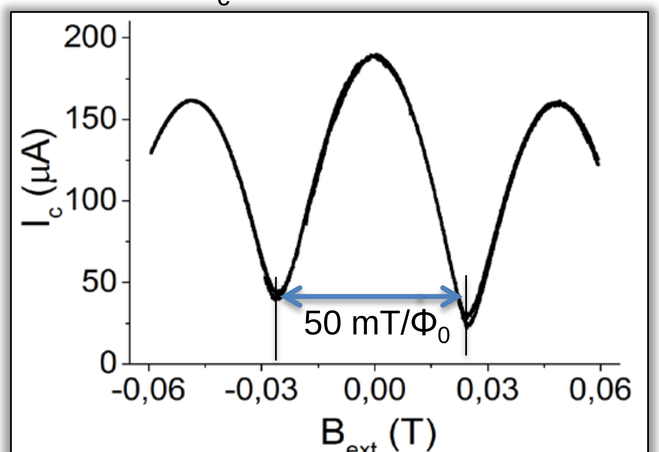
$\Gamma = 2\pi k_B T / I_0 \Phi_0 =$

2.3×10^{-3}

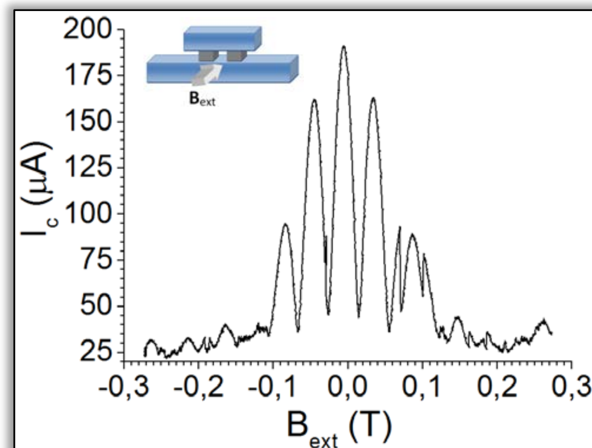
$A_{SQUID,eff} = 0.04\ \mu m^2$

j_c homogeneous

I_c Modulations

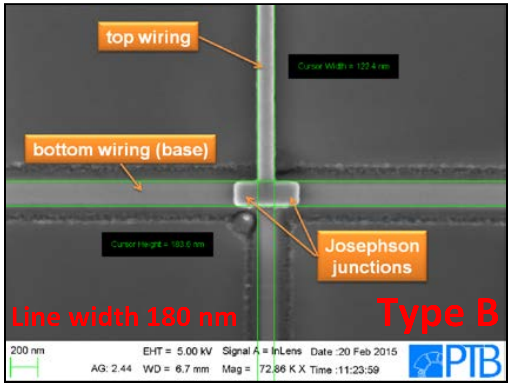


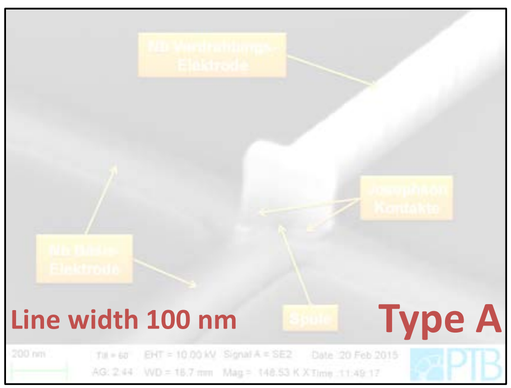
Fraunhofer-Like Pattern

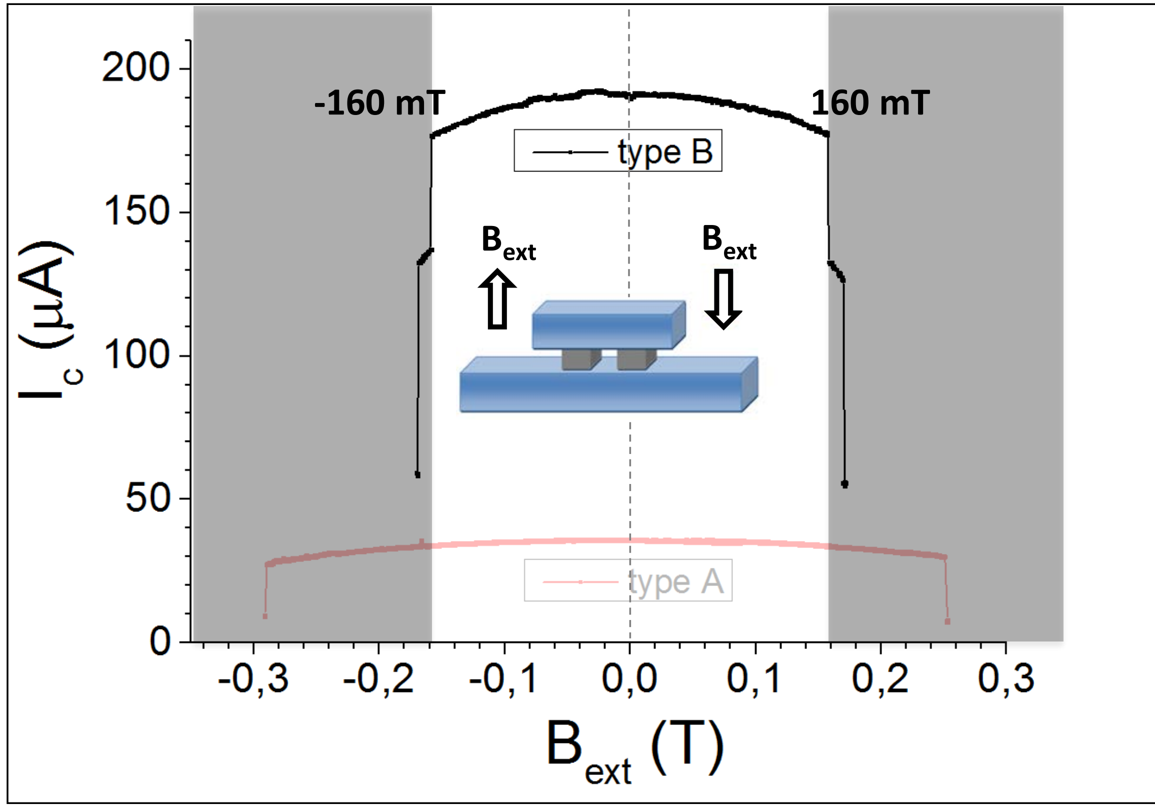


Results: NanoSQUID Type A, Type B

Stability in External Magnetic Field







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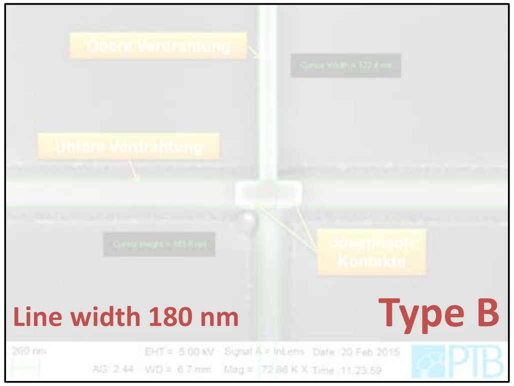
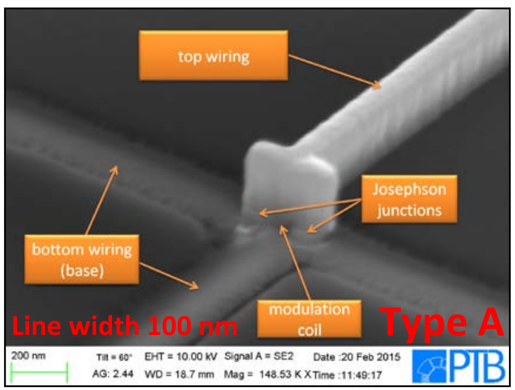
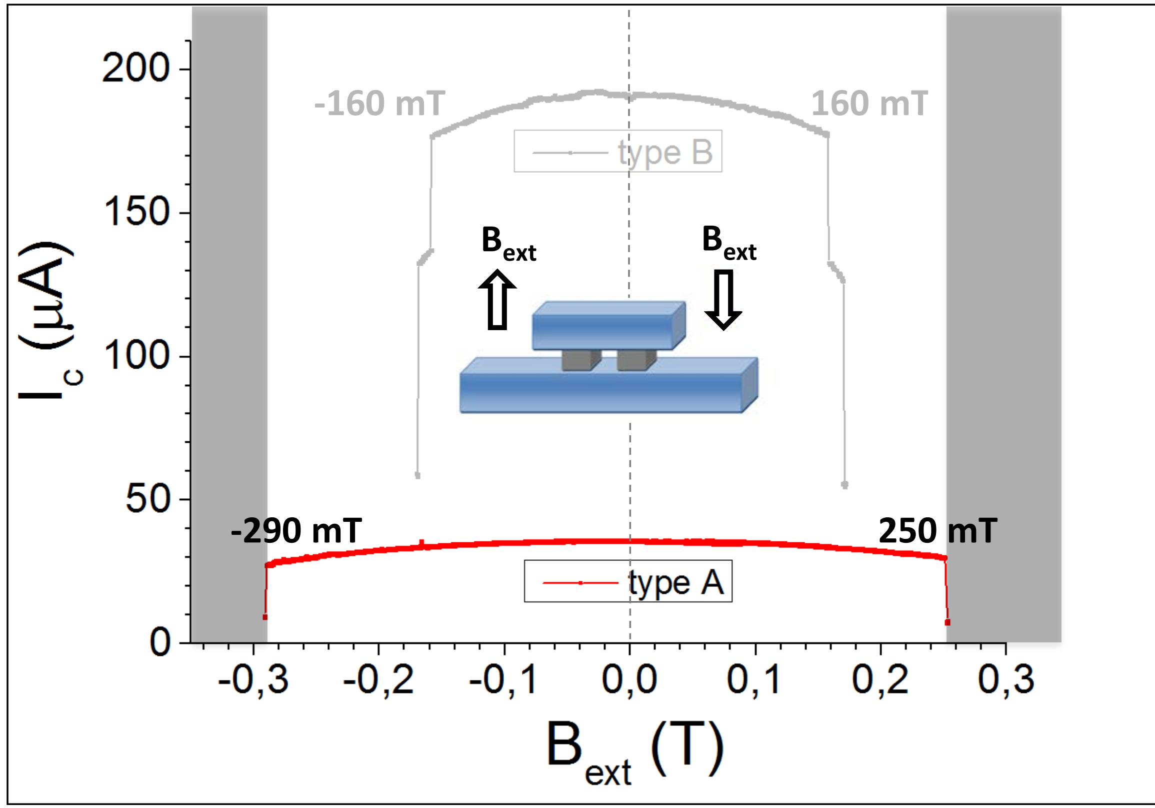
Results: NanoSQUID Type A, Type B

Stability in External Magnetic Field

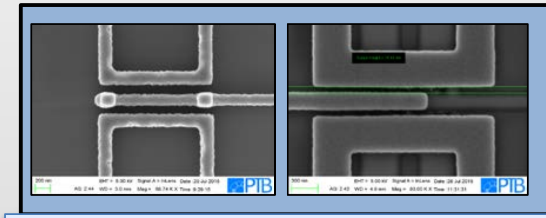






Results: Type C

NanoSQUID Sensor Data



JJ area: 150 nm x 150 nm

SQUID loop: 1µm x 100nm

Gap (input coil-SQUID): 100 nm

I_c = 200 µA

R_N = 0.5 Ω

V_c = 100 µV

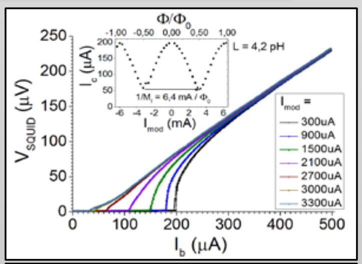
j_c = 444 kA/cm²

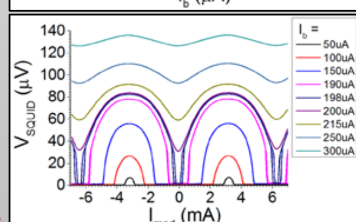
$1/M_f$ = 6.4 mA/Φ_0

$\beta_L = I_c L / \Phi_0$ = 0.4

L = 4.2 pH

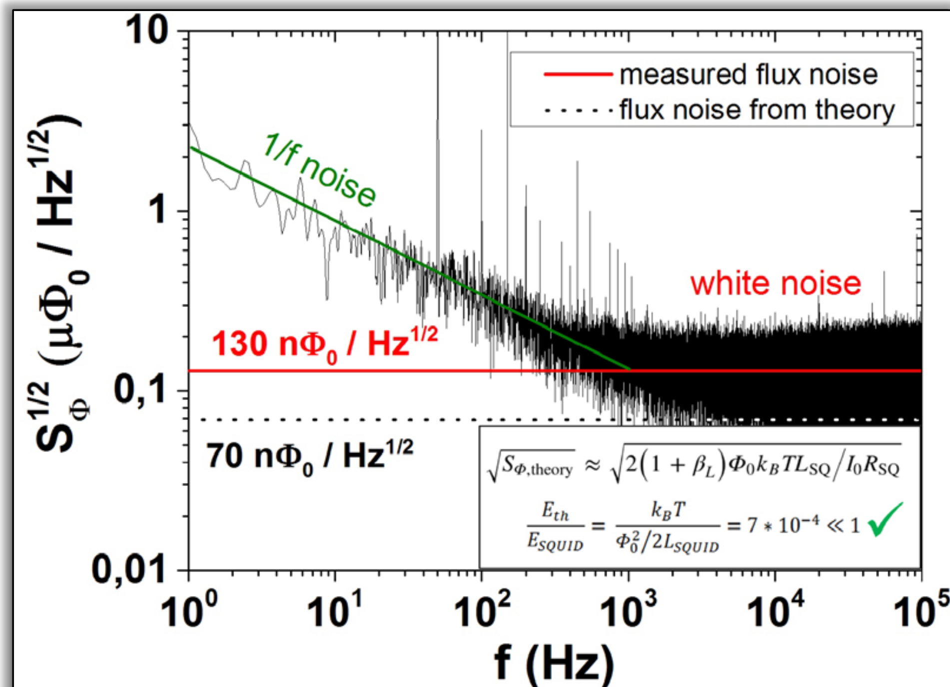
A_{SQUID} = 0.1 µm²





Very high critical current densities!

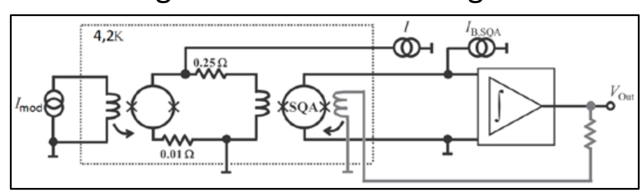
Flux Noise



$$\sqrt{S_{\Phi,\mathrm{theory}}} \approx \sqrt{2(1+\beta_L)\Phi_0 k_B T L_{SQ} / I_0 R_{SQ}}$$

$$\frac{E_{th}}{E_{SQUID}} = \frac{k_B T}{\Phi_0^2 / 2L_{SQUID}} = 7 * 10^{-4} \ll 1$$

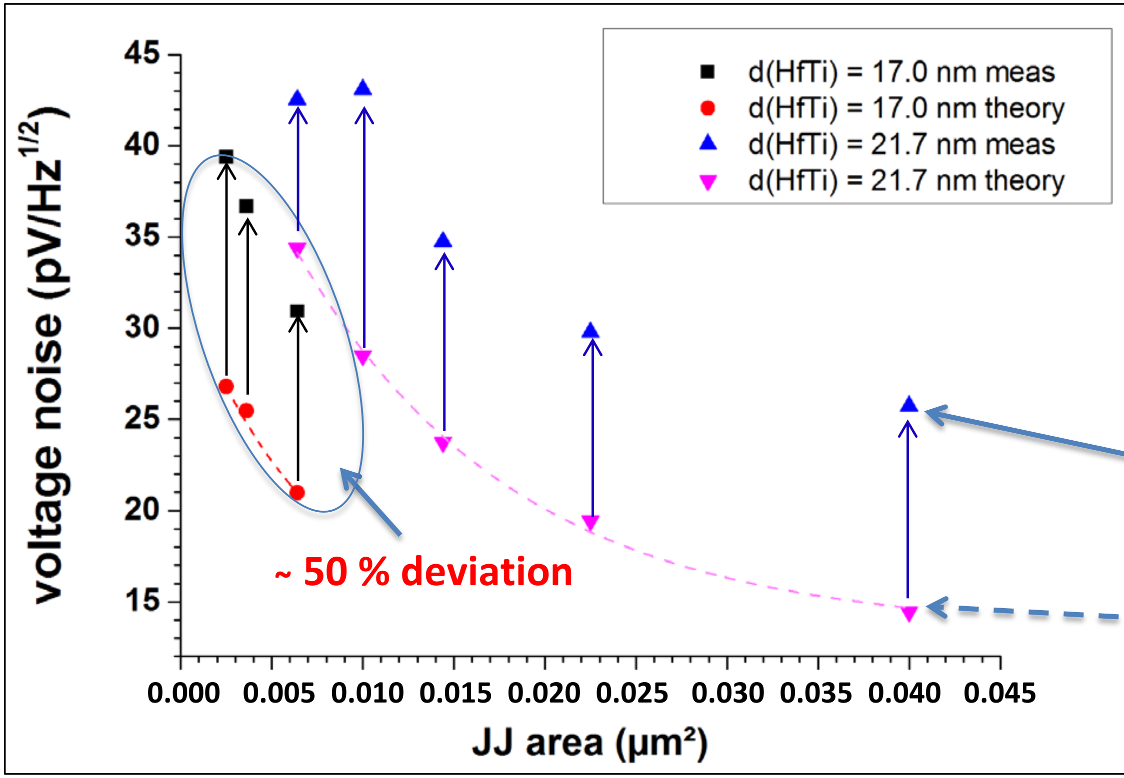
2-stage measurement configuration



$$S_\mu^{1/2} = S_\Phi^{1/2} / \phi_\mu$$

→ **10 μ_B /Hz$^{1/2}$**

Voltage Noise of Single JJs



Johnson-Nyquist Noise:

$S_V^{1/2} = (4k_B T R_N)^{1/2}$

Bath temperature:

T = 4.2 K

↓

Effective JJ Temperature:

$T_{JJ\ eff.} \approx 9$ K

measurement

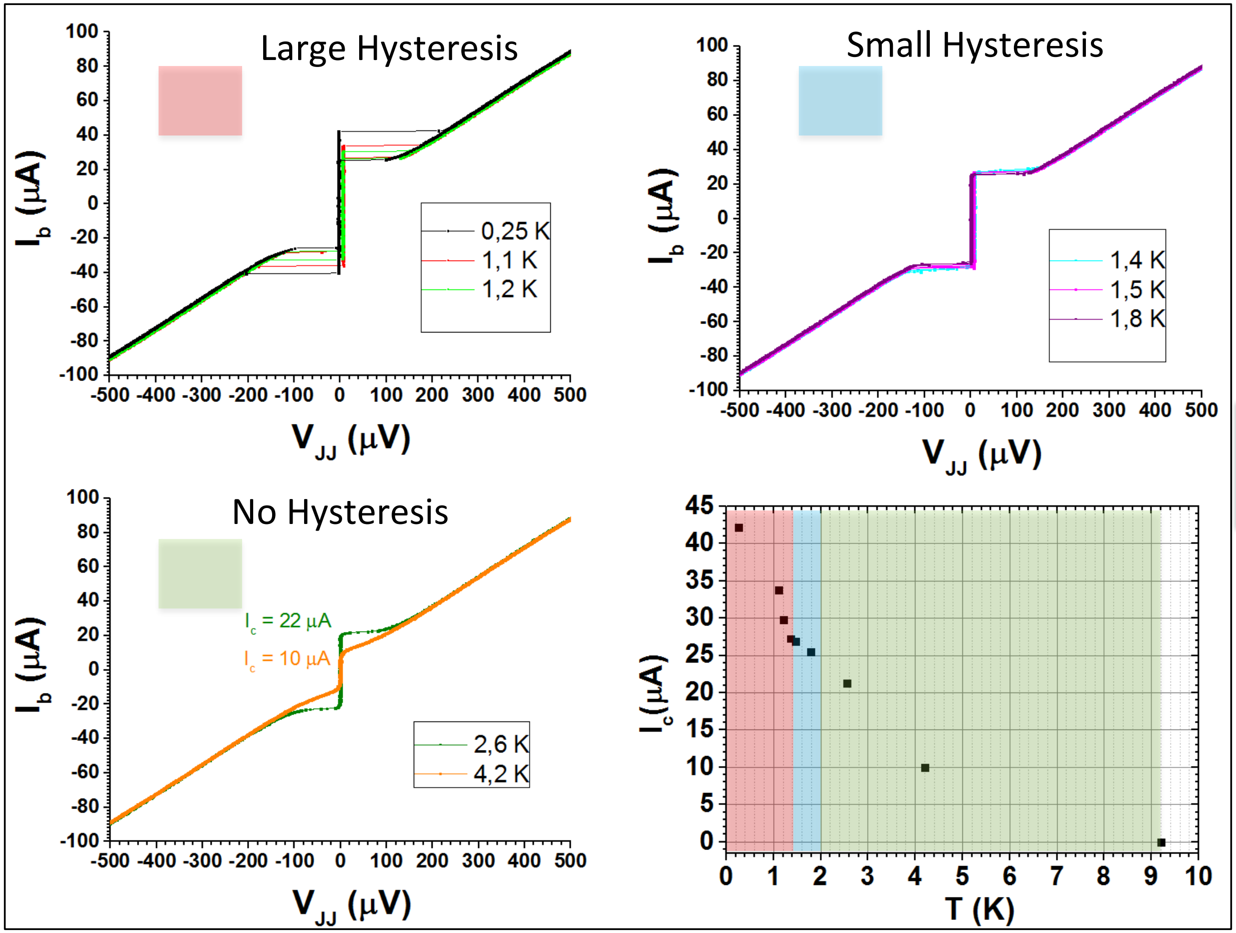
~ 60 % deviation

theory

Similar self-heating effect in Nb/HfTi/Nb SQUID devices was reported in:

❖ J. Beyer, M. Klemm, J. H. Storm, O. Kieler, T. Weimann, V. Morosh, „Noise of dc-SQUIDs with planar sub-micrometer Nb/HfTi/Nb junctions", Superc. Sci. Technol. 28 (2015), 085011.

Temperature Behavior of a Single JJ



JJ: 80 nm x 80 nm

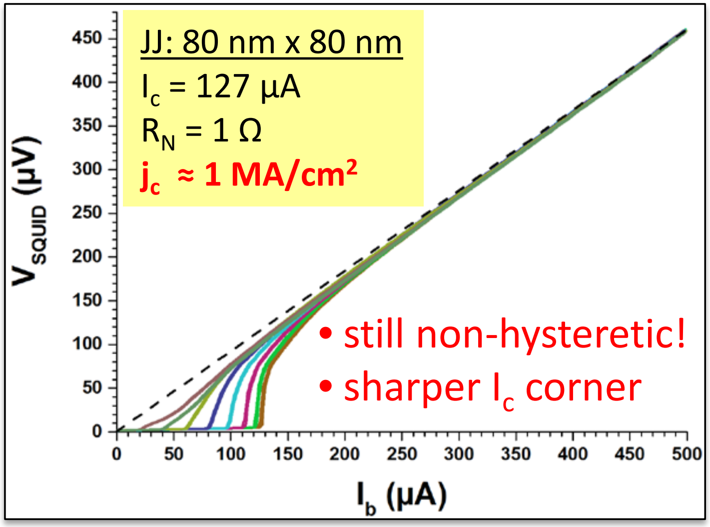
d(HfTi) = 20.5 nm

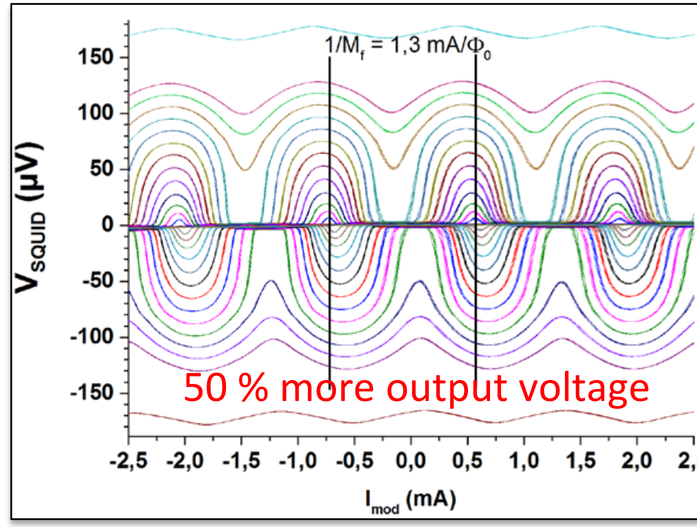
R_N = 6.2 Ω = const

SQUIDs nonhysteretic:
1.4 K....4.2 K !

High Critical Current Density j_c

All measurements are made at T = 4.2 K

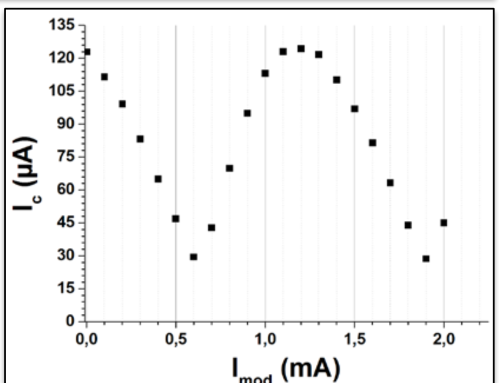




$\beta_L = I_c L / \Phi_0 \approx 0.3$

↓

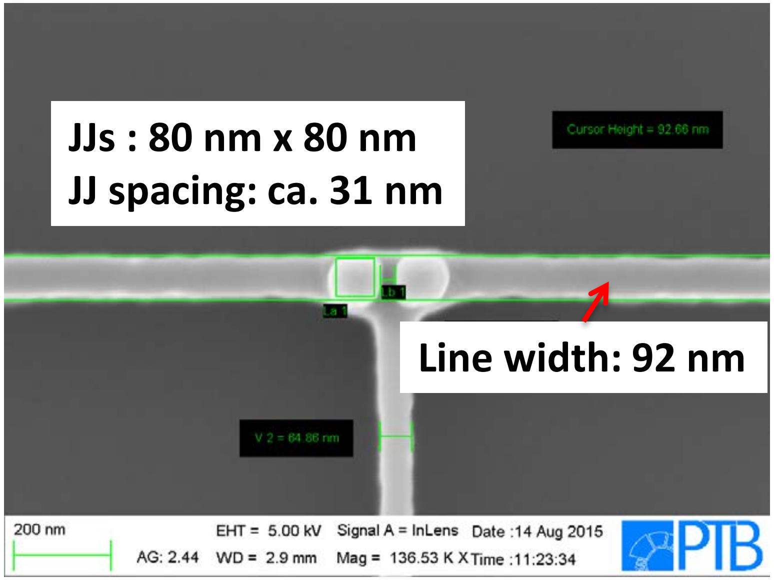
L ≈ 5 pH

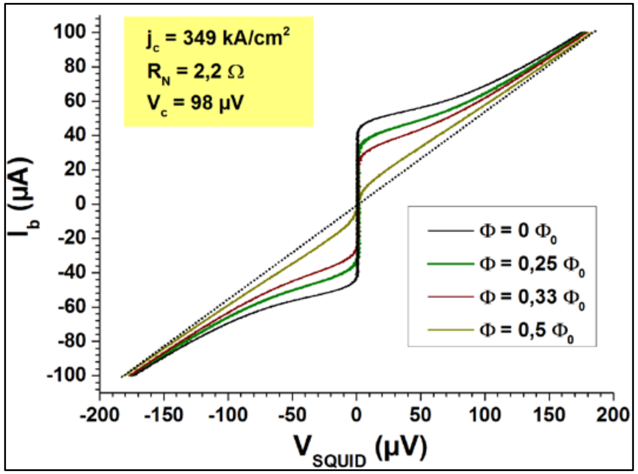


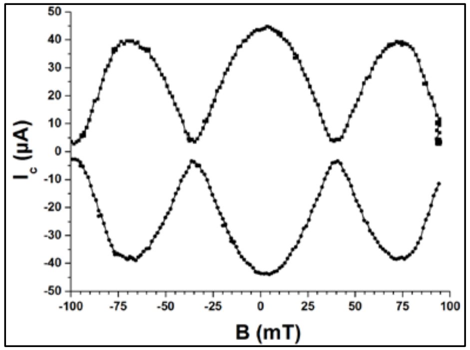
Comparison of the Gamma parameter
$\Gamma = 2\pi k_B T / I_0 \Phi_0$

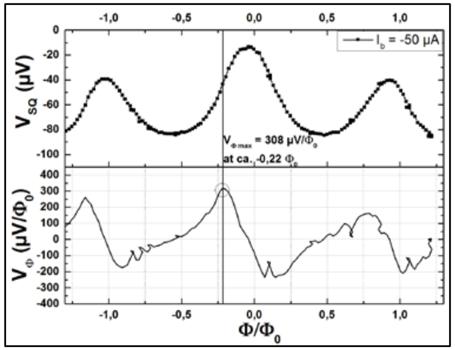
Type A (j_c = 213 kA/cm²)	This nanoSQUID (j_c = 1 MA/cm²)
10×10^{-3}	$2{,}7 \times 10^{-3}$

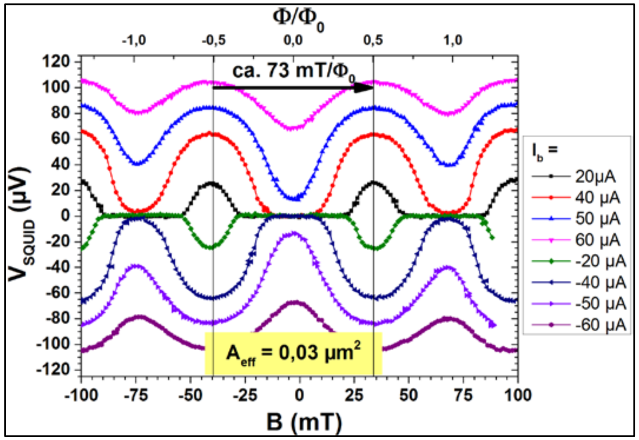
Our Smallest NanoSQUID





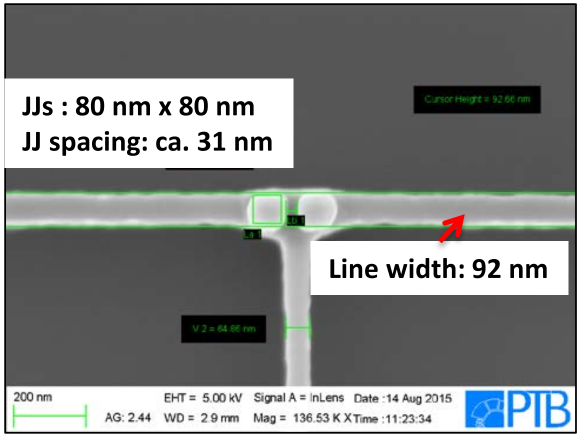


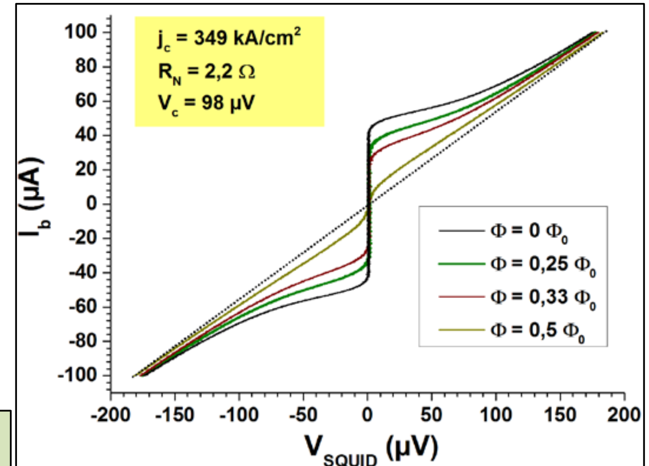




All measurements are made at T = 4.2 K

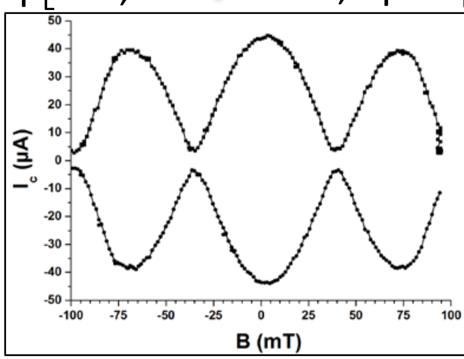
Our Smallest NanoSQUID

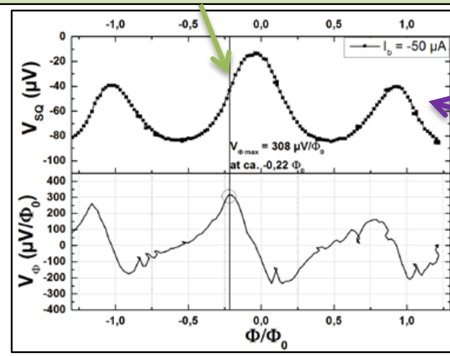


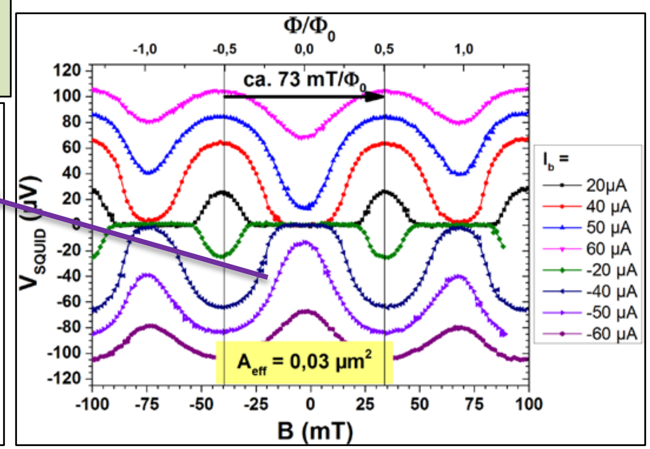


Optimal working point:
V_Φ = 308 µV/Φ_0 at
Φ = -0,22 Φ_0, I_b = -50 µA

$\beta_L \approx 0{,}1 \longrightarrow L \approx 5{,}1$ pH







All measurements are made at T = 4.2 K

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), April 2017.
Oral presentation at KRYO 2016. No manuscript was submitted for hardcopy journal publication.

Summary and Outlook

- effective area down to **0,03 µm²** , JJ spacing down to **31 nm**
- Josephson junctions down to **80 x 80 nm²**
- narrow line width **92 nm**
- stability in high magnetic fields up to **290 mT**
- low level of white noise **130 nΦ_0 /Hz$^{1/2}$**
- spin sensitivity: **10 μ_B /Hz$^{1/2}$** → towards single spin sensitivity
- noise properties in applied magnetic fields and at different temperatures
- simulation of the optimum parameters using experimental data

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Thank you

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