IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January 2016.
KRYO 2015 oral presentation. Not submitted for publication.

Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

HfTi-nanoSQUIDs for nanoscale magnetic detection

PTB Berlin
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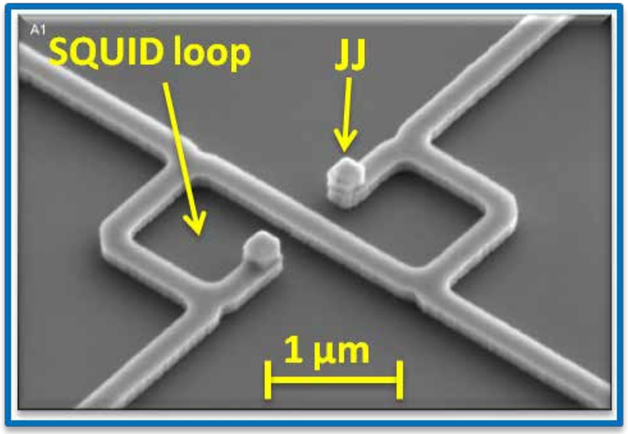
PTB Braunschweig
Oliver Kieler, Johannes Kohlmann, and Thomas Weimann



SQUID – Applications at PTB

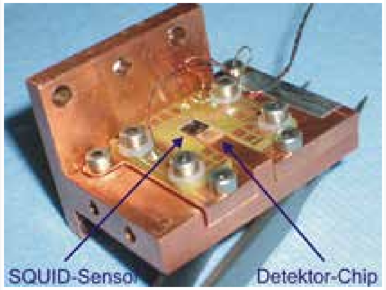
Biomedical Analytical Methods

- MCG
- MEG,
- LF-MRI
- Nano particles

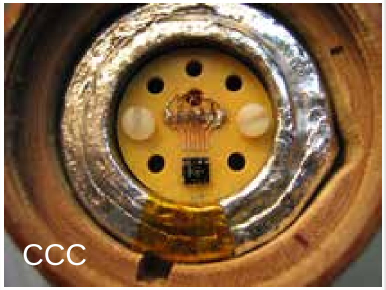
Metrology

TT-Thermometry

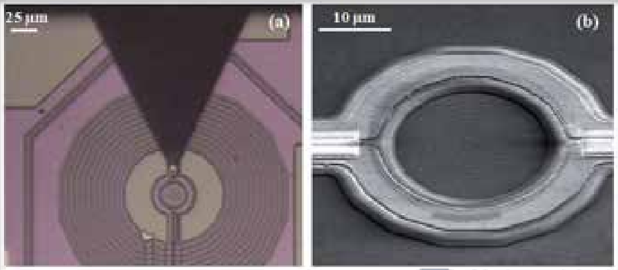
Single Photon Detector



Resistance Metrology



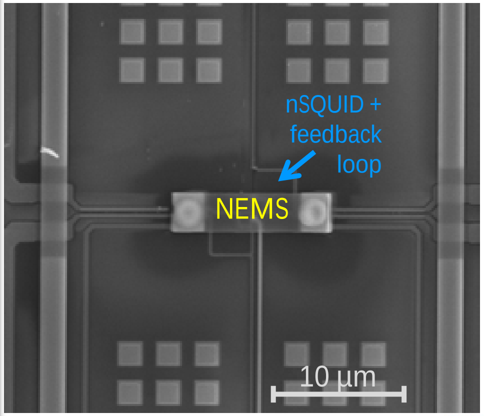
Material Characterization



Integrated SQUID susceptometer (PTB) Universidad Zaragoza

Susceptometry

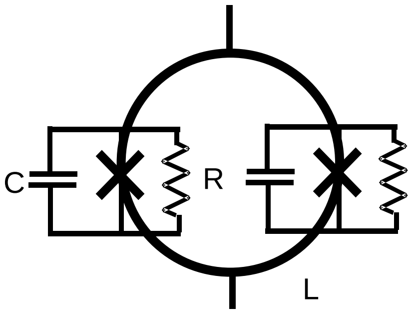
Readout of NEMS

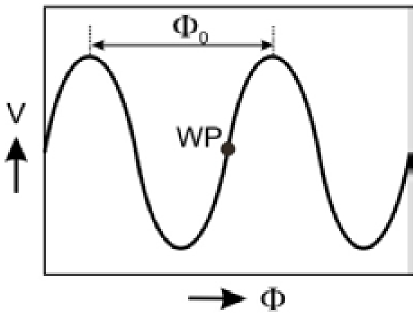


NanoSQUID (PTB) - NEMS (NPL) combination NPL National Physical Laboratory

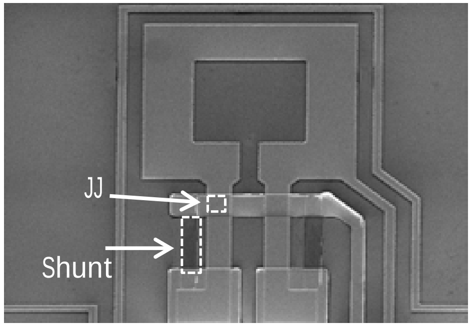
Dc SQUIDs

dc SQUID





C junction capacitance
L SQUID loop inductance
R resistance
F magnetic flux
F_0 flux quantum
V voltage
WP working point

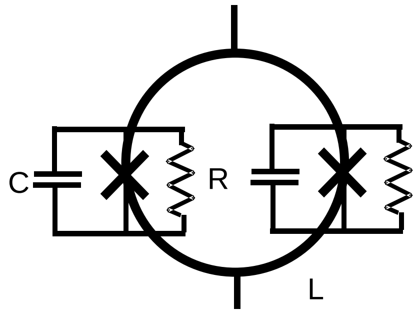


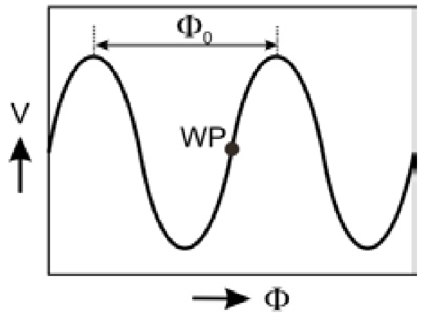
Washer SQUID with SIS junctions ($Nb/AlO_x/Nb$)

Periodic flux-to-voltage characteristic.

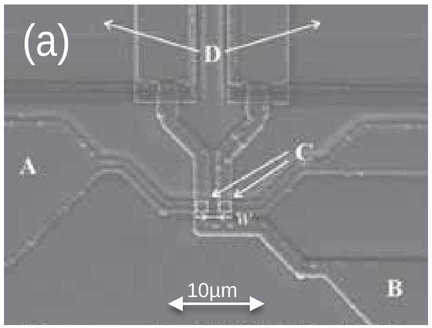
Dc SQUIDs

dc SQUID

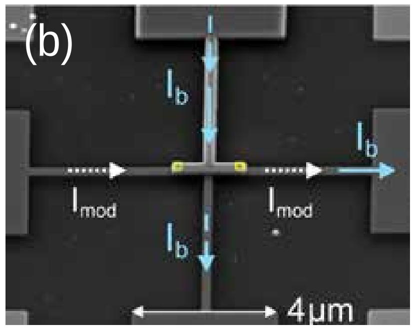




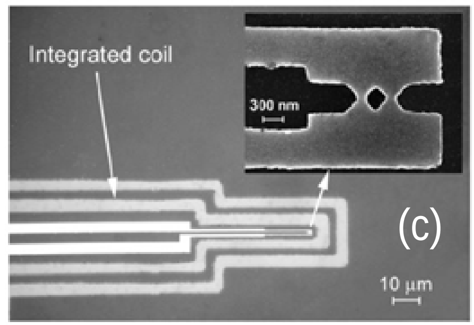
- C junction capacitance
- L SQUID loop inductance
- R resistance
- F magnetic flux
- F_0 flux quantum
- V voltage
- WP working point



Washer SQUID with cross-type SIS junctions (Nb/AlOx/Nb),
M. Schmelz et al., Appl. Phys. Lett. 102, 192601 (2015)



SQUID with SNS junctions (Nb/HfTi/Nb), microstrip geometry,
R. Wölbing et al., Appl. Phys. Lett. 102, 192601 (2013)

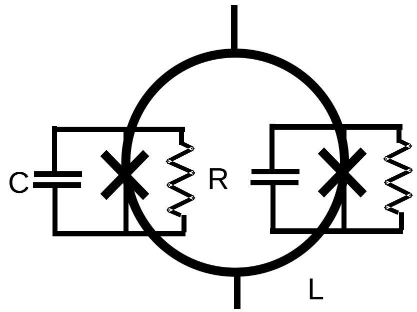


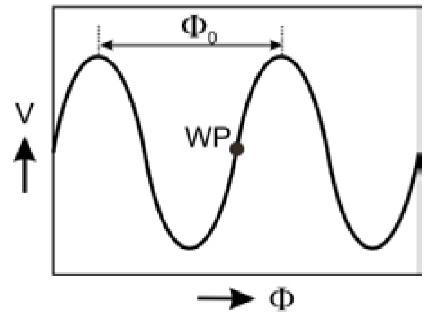
SQUID with constriction junctions, Nb/Al bilayer
C. Granata et al, Nature Nanotechnol. 19, 275501 (2006)

Periodic flux-to-voltage characteristic.

Dc SQUID Readout

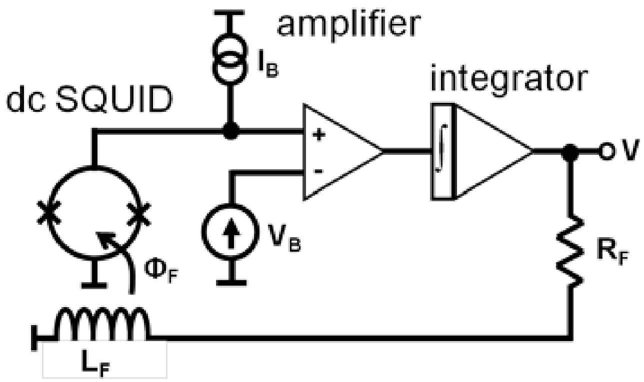
dc SQUID

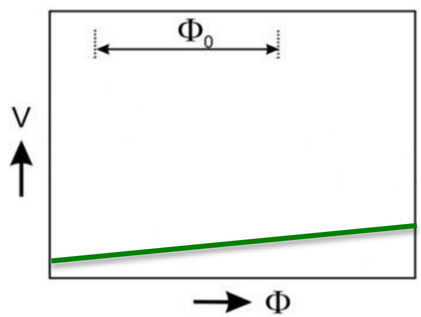




C	junction capacitance
L	SQUID loop inductance
F	magnetic flux
F_0	flux quantum
V	voltage
V_B	bias voltage
I_B	bias current
R_F	feedback resistor
F_F	feedback flux
WP	working point

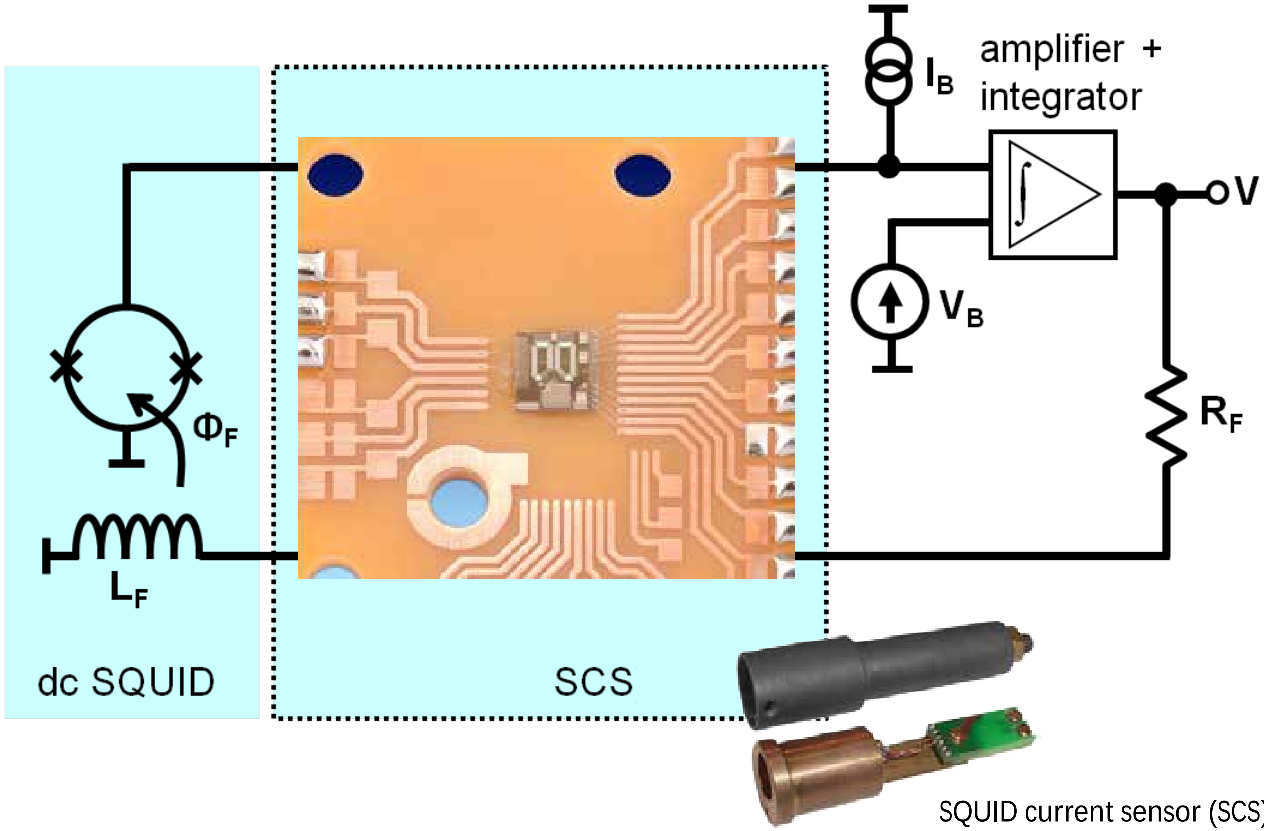
Flux-locked loop (FLL) operation





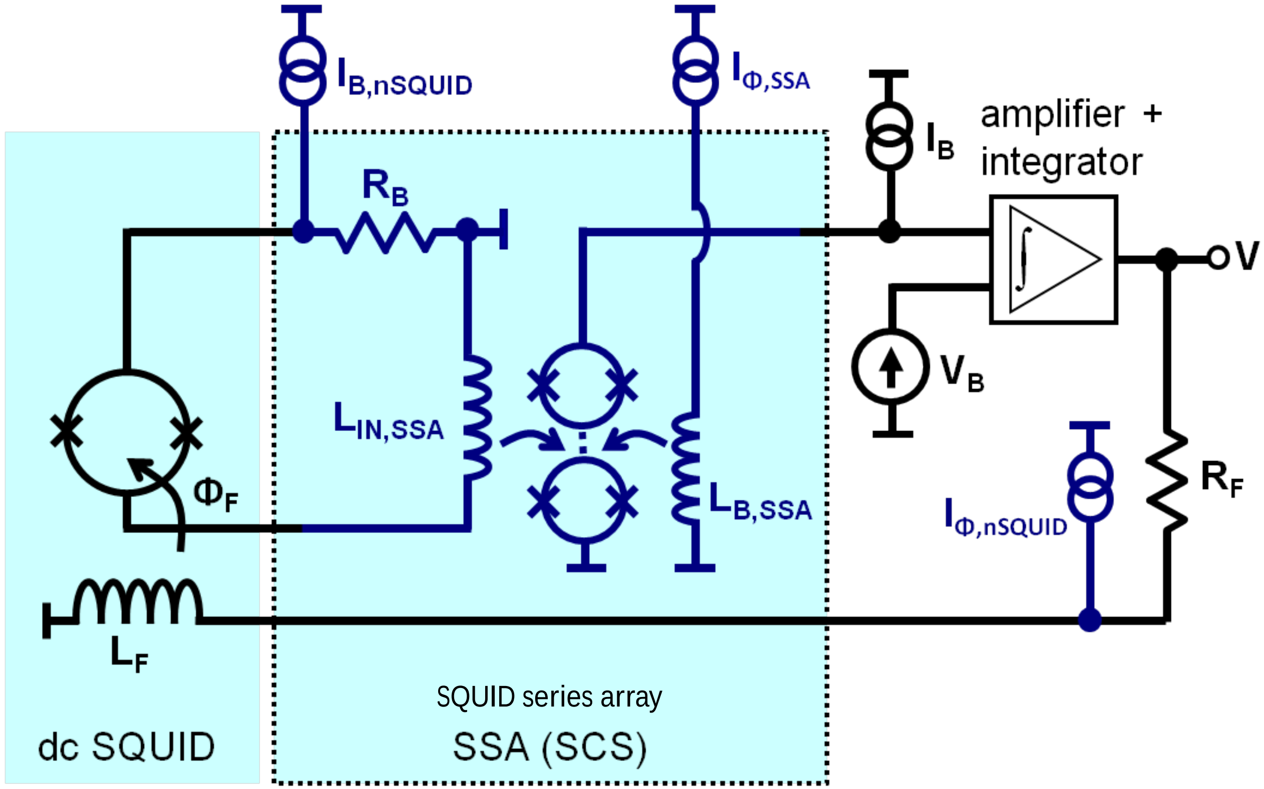
WP is kept stable on the periodic flux-to-voltage characteristic.

Dc SQUID Readout



SQUID current sensor (SCS)
in a Nb shielding (Magnicon GmbH)

2-stage Readout



Demands for High Energy Resolution

$$\varepsilon = S_{\Phi}/(2L)$$

$$S_{\Phi} \approx 2L * 16k_B T * (LC)^{1/2}$$

- efficiency ~ coupling or filling factor

  → small dimensions → lower **SQUID inductance** + **junction capacitance**
- high energy resolution → low and ultra-low **temperatures**
- high dynamic range
- high tolerance against applied magnetic field

Nb/HfTi/Nb-NanoSQUIDs

Josephson junctions:

Intrinsically shunted SNS Junctions with HfTi

Nominal lateral size: **ca. 200nm x 200nm** (180nm/220nm/240nm/260nm)

Nominal barrier thickness: **30nm**

Distance between JJs: ≤ 1µm

Design: PTB Berlin

Fabrication: PTB Braunschweig

SQUID Sensors:

§ SQUID gradiometers

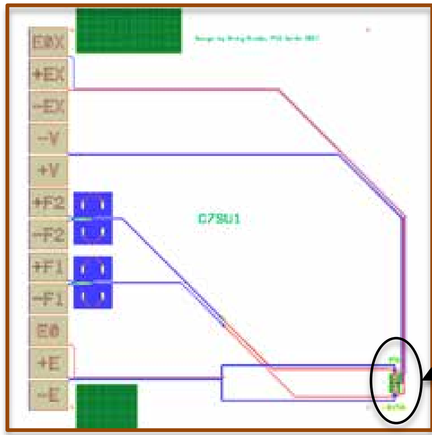
§ SQUID current sensors

Complements:

§ feedback

§ rf filter

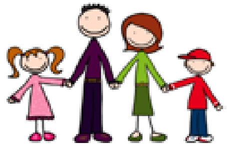
§ 3 (4) different transformers

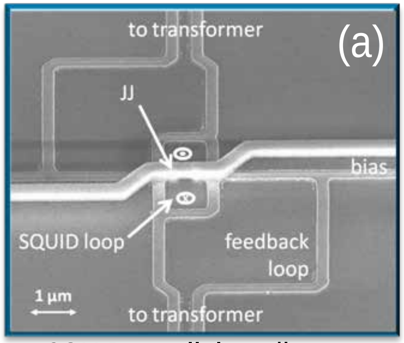


nSQUID with transformers

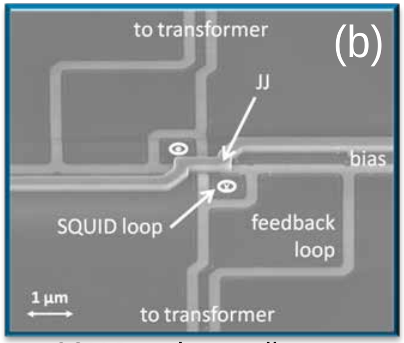
Chip
3mm x 3mm

Device Family

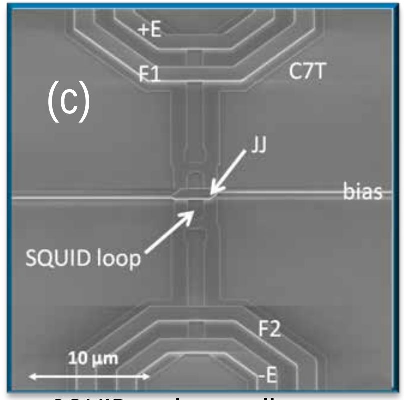




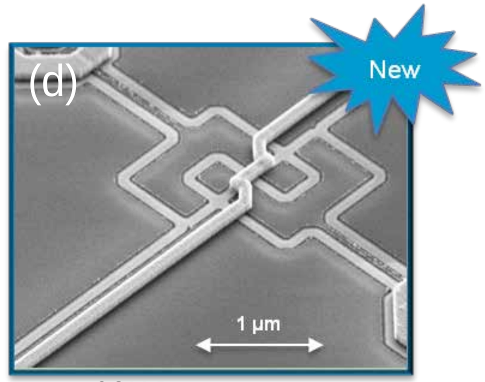
nSQUID parallel gradiometer



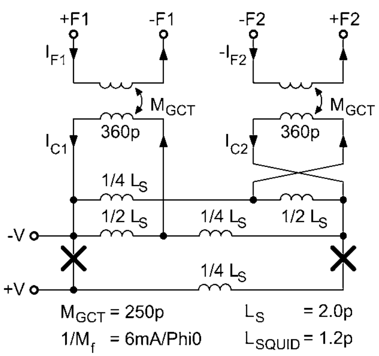
nSQUID series gradiometer

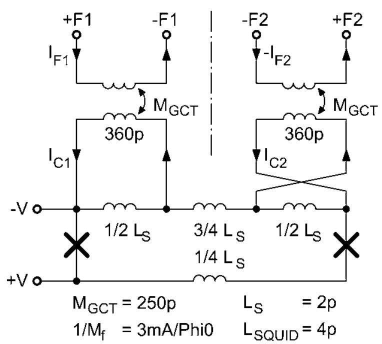


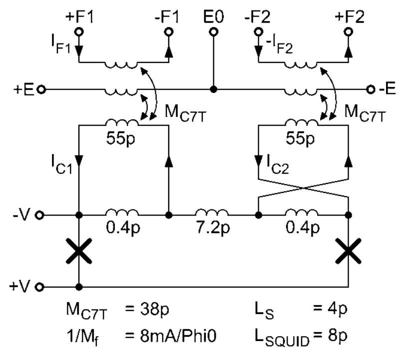
µSQUID series gradiometer



nSQUID current sensor



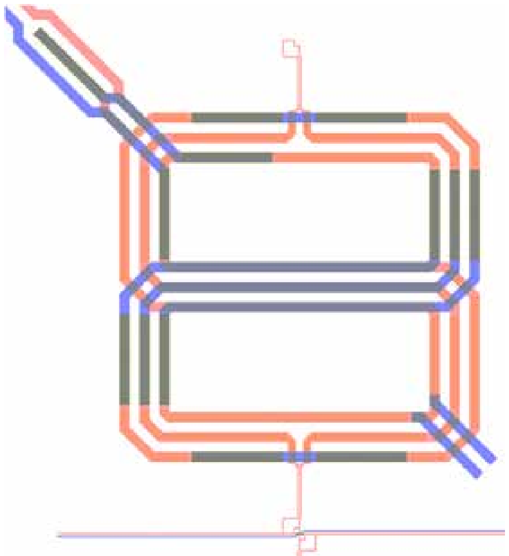




S. Bechstein et al., „HfTi-nanoSQUID gradiometers with high linearity,"
Applied Physics Letters 106, 072601 (2015); doi: 10.1063/1.4909523

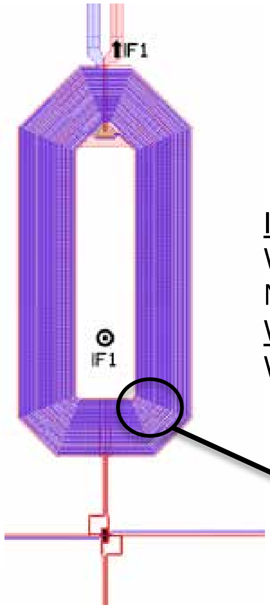
Transformers of Gradiometers

Gradiometric Coupling Transformer (GCT)

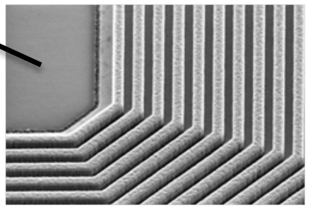


Width of lines 2µm
Thickness of Nb layer 200nm

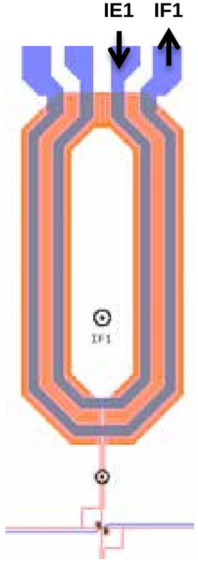
Bias Reversal Transformer (BRT)



Input coil:
Width of lines 200nm
Number of turns 24
Washer:
Width of washer 10µm



C7 Transformer (C7T)



Width of lines 1.5µm
Width of washer 8µm

Fabrication

PTB

- Clean room center Braunschweig
- Electron beam lithography
- Chemical mechanical polishing process (CMP)
- Supporting structures consisting of Nb1 and HfTi integrated in design
    - homogeneous polished junctions
    - negligible small changes of I_c across the wafer area
    - protecting isolation @ bridges (e.g. filters)

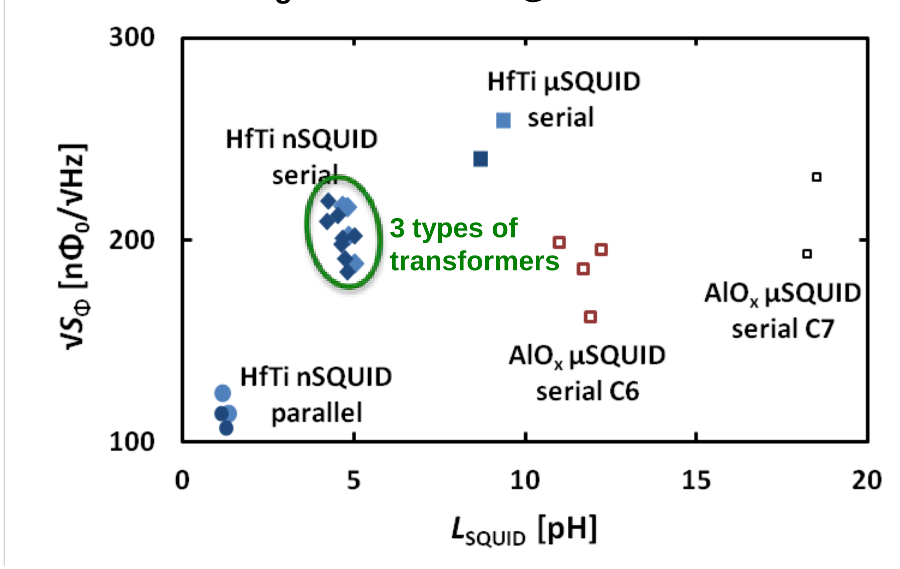
Clean room center (PTB Braunschweig).

high rate of yield

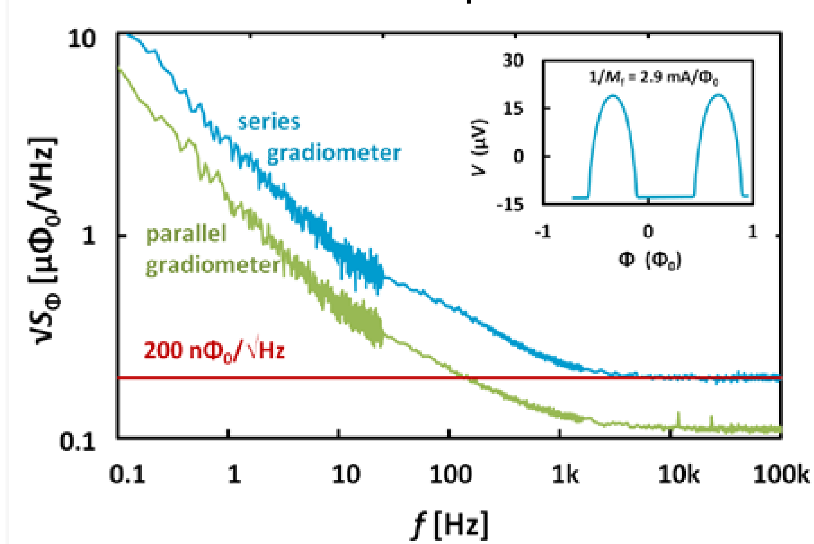
Inductance and Flux Noise

Setup: 2-stage configuration with SSA, FLL mode

Magnetic flux noise @ 20kHz … 50kHz



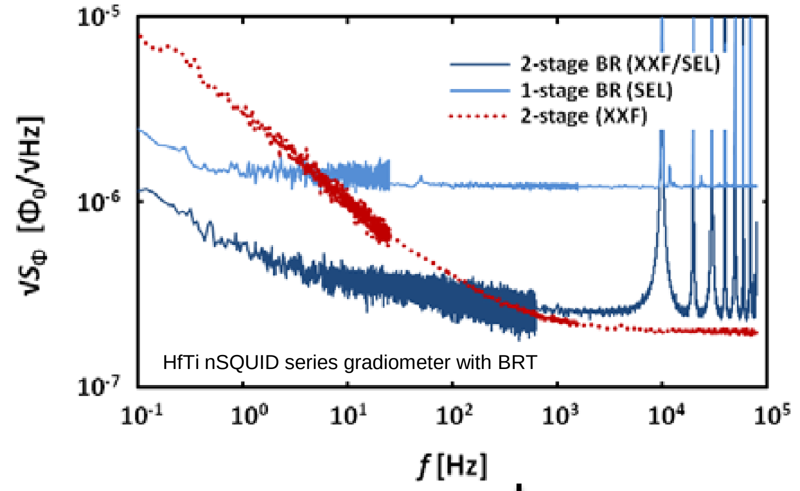
Noise spectra

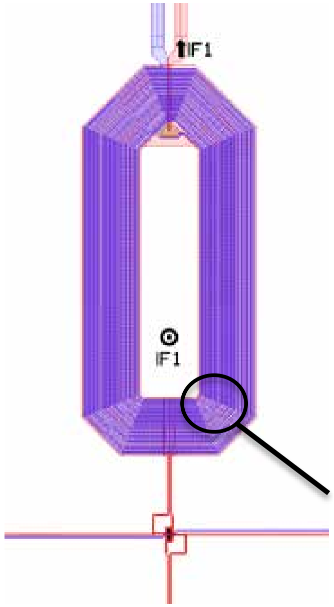


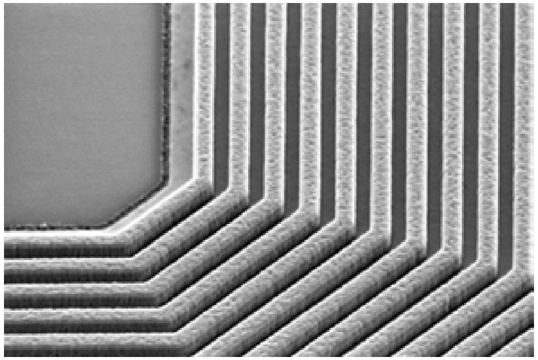
magnetic flux noise independent on type of transformer
110 $n\Phi_0/\sqrt{Hz}$ achievable

Low-Frequency Flux Noise

Typical noise spectrum







Section of Bias Reversal Transformer (BRT).
Width of lines: 200nm, number of turns: 24.

2-stage readout with modified XXF/SEL FLL electronics

low-frequency noise reduced with bias reversal in 2-stage configuration
à source: fluctuations (I_c, R)

S. Bechstein et al., „HfTi-nanoSQUID gradiometers with high linearity,“ *Applied Physics Letters* 106, 072601 (2015); doi: 10.1063/1.4909523

Susceptometer Application

Setup: 2-stage configuration with SSA, FLL mode

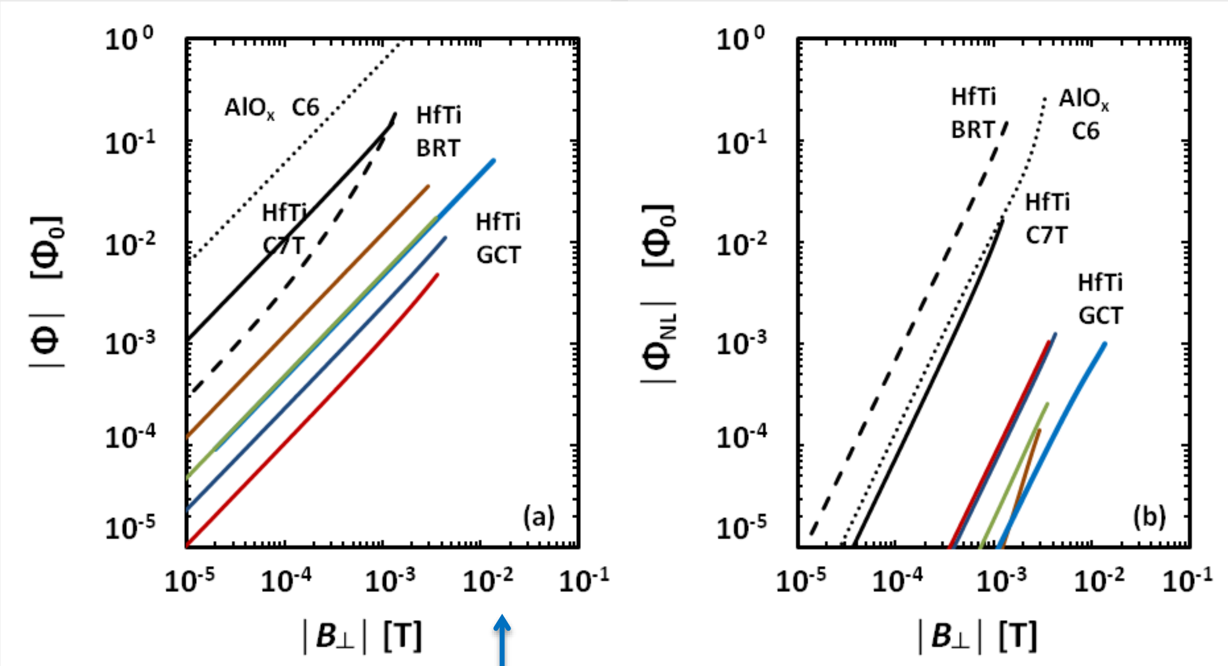
Measurement setup:

nSQUID locked in FLL mode
(2-stage configuration)

linear increased/decreased excitation field
$0 < |B_p| \leq |B_{max}|$

output signal
fit: polynomial of 6th degree

Φ_{LIN} Φ_{NL}



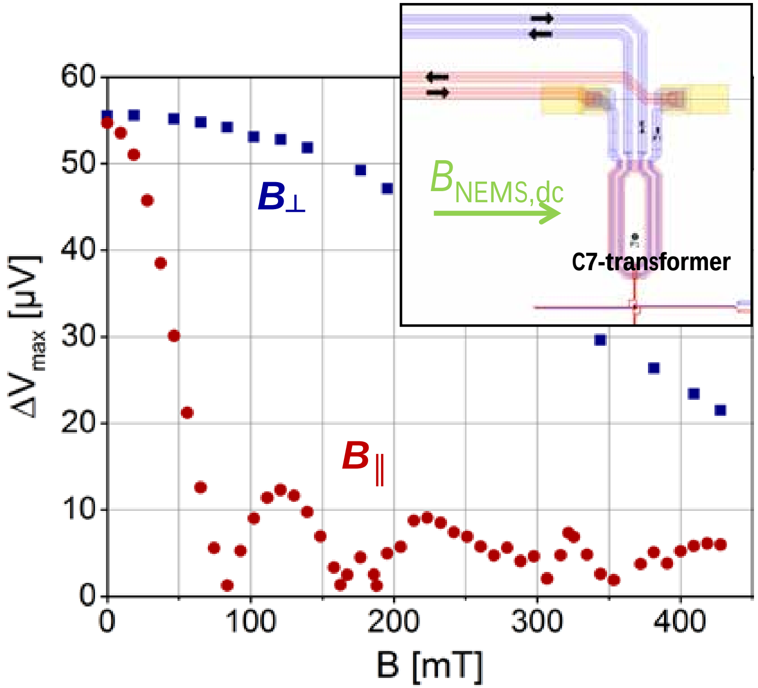
Improved design: $B_{max, GCT}$ ≈ 15mT

HfTi-nanoSQUID gradiometers with GCT: linear (a) and nonlinear (b) part very low

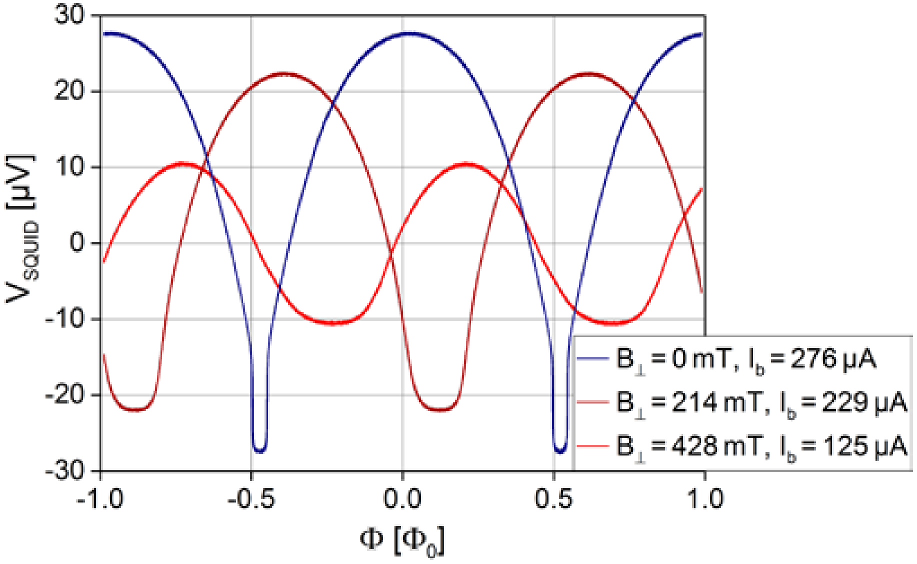
suitable for susceptometer applications J

NEMS Application

Setup: 1-stage configuration, AMP mode



Maximum voltage swing of a nanoSQUID series gradiometer with C7-transformer versus dc magnetic field.

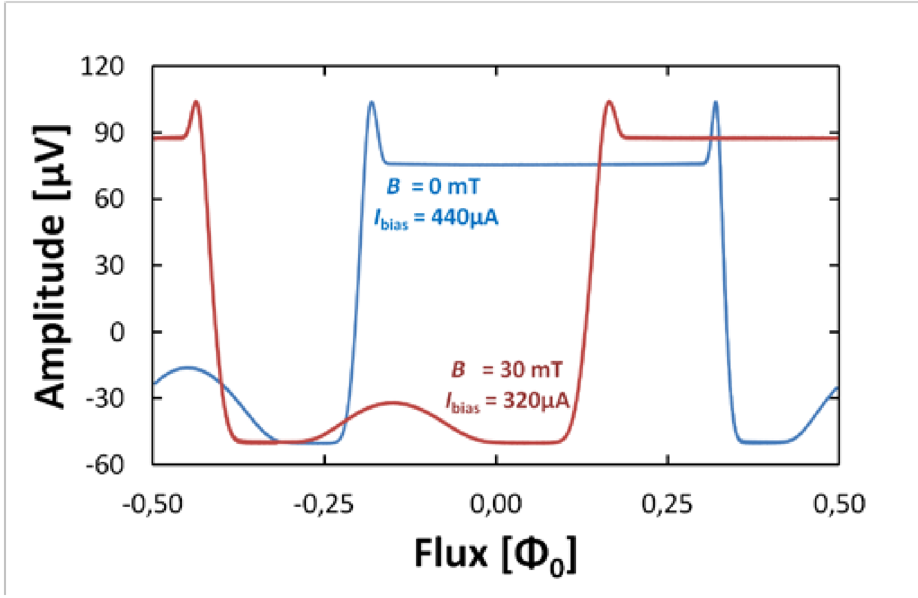


Voltage across the nanoSQUID series gradiometer versus magnetic flux (perpendicular to the SQUID loop).

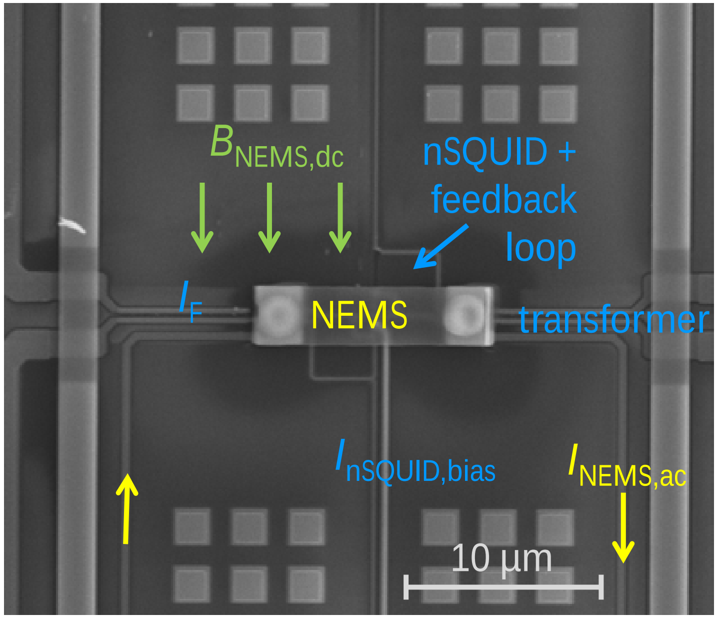
suitable for NEMS readout J

NEMS Application

Setup: 2-stage configuration with SSA, AMP mode



Voltage of a
nanoSQUID series gradiometer with GCT/SSA combination
versus magnetic flux.



Section of a combination of
a nanoSQUID series gradiometer with GCT and NEMS
(cooperation with NPL).

suitable for NEMS readout J

Summary / Outlook

Milestone: new family of HfTi-nanoSQUID sensors

- technology well established
- complex sensors
  gradiometers and current sensors with transformers, feedback circuitry, rf filters
- low level of nonlinearity → susceptometer application
- field tolerance of at least a few mT up to a few 100mT → NEMS readout
  depending on operation and type of transformer

Outlook:

- design
  - further improvement of field tolerance, smaller structures (transformers)
  - further adaption to each application (further specialization)
- measurements
  - susceptometer measurements together with partners
    (nano particles, molecules, single spin detection)
  - NEMS readout

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KRYO 2015 oral presentation. Not submitted for publication.

Thank you:

Corinna Neubauer
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