Superconducting Quantum Interference Devices
-useful tools for
quantum metrology and material characterization

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Content

• SQUID basics
• SQUID current sensors
• micro and nanoSQUIDs
• SQUID applications
What is a SQUID?

It’s a very sensitive detector of magnetic flux changes.

**DC-SQUID**

Superconducting ring

Bias current $I_b$

Voltage $V(\Phi)$

Magnetic flux $\Phi$

Josephson junction
How does the SQUID work?

**Main problems:**

- Very small voltage across the SQUID: $V_{pp} \approx 10...50 \ \mu V$
- Transfer coefficient $V_\Phi = \delta V / \delta \Phi$ depends on SQUID working point
- Very small linear flux range: $\Phi_{lin} \ll \Phi_0$

**Main tasks of a SQUID electronics:**

- Amplifies the weak SQUID voltage without adding noise
- Linearizes transfer function to provide sufficient dynamic range
How does a SQUID work?

Flux Locked Loop (FLL) with direct SQUID read-out

FLL linearizes the V-Φ characteristics and enables high dynamic range (100 Φ₀)

V ∝ Φ

T ≤ 5K
How does a SQUID work?

Commercial SQUID electronics

Joint development of PTB and

Other suppliers e.g. Supracon/Germany, Starcryo/US
Example of a LTS SQUID magnetometer

To measure $B$, a fairly large sensing area is needed, because $\Phi = \int B dA$

**Multiloop SQUID magnetometer**

\[
L = 400 \text{ pH}
\]

**Noise @ $T = 4.2$ K**

\[
\sqrt{S_\Phi} = 2.6 \mu \Phi_0/\sqrt{\text{Hz}} @ 1\text{kHz}
\]

\[
\sqrt{S_B} = 1.2 \text{ fT}/\sqrt{\text{Hz}} @ 1 \text{ kHz}
\]

Chip-size: 7.2 mm x 7.2 mm

Nb/AlOx/Nb thin-film technology
SQUID development and application at PTB

SQUID technology
- Thin-film technology
- Read-out electronics
- Cryogenic parts

Metrology
- LT thermometry
- Cryogenic Current Comparators for resistance metrology

Biomedical diagnostics
- Magnetocardiography
- Magnetoencephalography
- Low-field NMR/MRI
- Drug design
- Susceptometry
- MRX with magnetic nanoparticles

Radiation detection
- Astrophysics (ground and satellites)
- X-Ray spectrometers
- Single photon detection

Material characterization
- Susceptometry
- Defect detection
- NMR

Read-out of NEMS resonators
- NanoSQUID with NEMS resonator (NPL)

Micro- and nanoSQUIDs for magnetic detection in the nanoscale

Technology transfer
- Making sensors and electronics commercially available
- License agreements
Biomedical diagnostics

Shielded 304-channel systems with conventional SQUID magnetometers

Fetal MCG

Berlin Magnetically Shielded Room II
Berlin Magnetically Shielded Room II

Features of BMSSR:

- Shielding factor: $> 8 \times 10^6$ for $f > 0.01$ Hz, $1 \times 10^8$ for $f > 6$ Hz
- Wall noise: $< 1.5 \text{ fT} / \sqrt{\text{Hz}}$
- Mechanical vibrations: $< 2.5 \mu\text{m}$ (Gantry $< 5 \mu\text{m}$)
- Residual static field: $< 2$ nT
- Residual gradient: $< 6$ pT/cm

- Inner room size: $2.9 \times 2.9 \times 2.8$ m$^3$
- Illumination through glass fibres
- Air-conditioned
- 4 sliding doors driven by pneumatic air
- Doors are blown up to reduce gap

Passive magnetic shielding:
- 7 layers of MU-Metall
- 1 eddy current shield

Double coil system
- For active shielding
- For earth field compensation

Wooden gallery

Rf shield: $12 \times 12 \times 12$ m$^3$
2 mm galvanized steel sheet

Massive concrete foundation

Test coil system
Construction site of Berlin Magnetically Shielded Room

Conventional SQUID multi-channel system – low-field NMR

304 SQUID-Sensor

2 samples of distilled water

\[ B_{Detection} = 1.5 \, \mu T \]

\[ f_{Resonance} = 64 \, \text{Hz} \]

\[ B_{Polarization} = 250 \, \mu T \]

3 seconds

Low-noise cryostats with warm bore and shielding

SQUID system with integrated superconducting magnetic shield

for
• animal MCG
• magnetorelaxometry of magnetic nanoparticles

Small animal magnetocardiography

Measurement in low-noise cryostats with warm bore and shielding

MCG of wild-type anesthetized mice

\[ \Delta B_{pp} = 5.3 \text{ pT} \]

Right: 5 s averaged (37 beats)

Wild-type mouse model

Measurements performed according to the German Animal Welfare Law
Requirements for novel bio-diagnostic methods

Novel bio-diagnostic techniques

Low-field NMR and MRI
Magnetic nanoparticle analysis for
  magnetic particle imaging
  magnetic drug targeting
  immuno-assays
  hyperthermia cancer treatment

Measurements have to be performed in
  applied magnetic field (μT)
  and/or after pre-polarization of the sample (mT)

Integrated magnetometers are not suited for these techniques

-
How to make a SQUID current sensors?

I – current to be measured
Example: magnetometer with superconducting pickup coil

\[
\begin{align*}
T & \leq 5 \text{ K} \\
M_f & \text{ (SQUID current sensor)}
\end{align*}
\]
Example: magnetometer with superconducting pickup coil

Pickup coil can be wire-wound or thin-film
Size of pickup coil can be easily adopted to the experimental needs
large coils
micro coils
gradiometers etc.

A variety of SQUID current sensors is required!
SQUID current sensors

Current sensor with SQUID array

- low input inductance, 3 nH to 6 nH *)
- high dynamic range
- high sensitivity
  \[ \sqrt{S_1} < 5 \text{ pA}/\sqrt{\text{Hz}} @ 0.1\text{K} *) \]
- power dissipation \( \sim 1 \text{ nW} *)

Current sensor with single SQUID

- high input inductance, 24 nH to 1.8 \( \mu \text{H} *)
- high sensitivity

Current sensor with single frontend SQUID and 2\textsuperscript{nd} stage SQUID array

- high input inductance, 24 nH to 1.8 \( \mu \text{H} *)
- high sensitivity
  \[ \sqrt{S_1} < 0.05 \text{ pA}/\sqrt{\text{Hz}} @ 0.1\text{K} *) \]
- power dissipation \( \sim 2 \text{ nW} *)

*) values for PTB devices
SQUID current sensors

2-stage SQUID current sensor

- front-end: single-SQUID, read out with 16-SQUID array
- different sizes
- adjustable input current limiter
- can be operated with conventional FLL electronics

Robust SQUID multi-channel system

18 SQUID module

Nb capsule

Pickup coil

SQUID current sensor

To readout electronics

To pickup coil

79.2 mm
Somatosensory evoked brain activity:

- electric stimulation at median nerve at 0 sec
- N20 measured ~20 msec after stimulation contra-laterally

Unpublished measurements by R. Körber, J. Storm
Robust SQUID multi-channel system – low-field NMR test

Sample: distilled water
Detection field 2.56 µT
Resonance frequency: 109 Hz
Polarisation field 35 mT (centre sample)

Sample inside polarising coil
Detection field coil

Unpublished measurements by R. Körber, J. Storm

Shown are the amplitude spectra with the respective fits

R. Körber, J. Storm, PTB
Application example: NMR

**Wire-wound pickup coil:**
SQUID NMR of $^3$He within a nanofluidic cavity

- **NMR Receiver Coil**
- **Glass**
- **Fill Line**
- **Cavity**
- **Silicon**

$h = 635 \text{ nm}$

$B_0 = 32 \text{ mT}$

$T = 0.9...10 \text{ mK}$

$p = 0....5.5 \text{ bar}$


**Thin-film pickup coil:**
SQUID NMR of $^3$He gas

- **Nb**
- 18 turns
- $400 \mu\text{m} \times 400 \mu\text{m}$
- $400 \text{nH}$

Bonding pads

A. Shibahara et al. *AIP Advances* 4, 027107 (2014)
SQUID current sensor read-out of TES IR photon counter

TES from NIST

2 channel module

Optical fiber

Fiber coupled detector module at 10 mK platform

Operation in cryogen free 3He/4He system

- TES X-ray microcalorimeters at NASA/GSFC
- SSA chip directly mounted on Cu block close to TESs
- 6keV pulse $\rightarrow \Delta \Phi_{SQ} = 1.3 \Phi_0$
SQUID noise thermometers

Nyquist Formel \( \langle U^2 \rangle = 4k_B TR \Delta f \)

Integrated current sensing noise thermometer

Magnetic field fluctuation thermometer

Chip with SQUID current sensor and noise resistor

3x3 mm\(^2\) SQUID gradiometer chip

Cu, 5N8
These SQUID noise thermometers have to be calibrated at one reference temperature only.

\[ T = T_{\text{Ref.}} \frac{S_{\Phi}(f_p, T_{\text{Ref}})}{S_{\Phi}(f_p, T_{\text{Meas}})} \quad \text{with } f_p \text{ plateau frequency} \]
MFFT mounted in cryogen-free $^3$He/$^4$He- dilution refrigerator
The resistive SQUID noise thermometer

Measurements used for establishing PLTS-2000!

15 hours measuring time!

NanoSQUID read-out with SQUID array current sensor
- Working point adjustment with auxiliary coil
- Additional coil for excitation of nanoparticle
nanoSQUIDs with SQUID current sensor readout

He dip stick for nanoSQUID measurement

- Superconducting coil for working point adjustment: 18 mT
- Superconducting magnetization coil for sample excitation: 60 mT

nanoSQUIDs with SQUID current sensor readout

nanoSQUID with magnetic nanoparticle


Modified V-Φ characteristics

Bare SQUID

With particle
MicroSQUID susceptometers

**Layout**

fully integrated SQUID susceptometer with SQUID a amplifier

**Parameters**

maximum sample field: 1.8 $\mu \Phi_0/\sqrt{Hz}$

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MicroSQUID susceptometers

SQUID susceptometers application

Characterization of molecular magnets

(a) Dip pen nanolithography of CoO@Apoferritin dots
(b) SEM image of pickup loop with dots
(c) and (d) AFM images and profiles of CoO@Apoferritin dots deposited onto SiO$_2$ and Nb substrates, respectively.

Top: in-phase ac magnetic susceptibility of $10^7$ CoO@Apoferritin molecules
Bottom: in-phase susceptibility of $10^{-9}$ Kg of CoO@Apoferritin

microSQUIDs with integrated nano-loops

Susceptometer with nanoloop

Nanoloop size:
Inner diameter: 450 nm
Linewidth: 250 nm
Nb thickness: 250 nm

Nanoloop fabricated with FIB (Focused Ion Beam) etching

Permalloy sample, excitation with 250 µT rms

nanoSQUIDs with SNS junctions

SQUIDs for operation in magnetic fields

NanoSQUIDs with overamped Nb/HfTi/Nb junctions perform very good.

Manufactured using e-beam lithography and chemical mechanical polishing

R. Wölbing et al., Appl. Phys. Lett. 102, 192601 (2013)

\[ \sqrt{S_\Phi} = 250 \text{ } n\Phi_0/\sqrt{\text{Hz}} \]
\[ \sqrt{S_n} = 29 \mu_B/\sqrt{\text{Hz}} \]  \text{ @ B < 50 mT}

\[ \sqrt{S_\Phi} = 680 \text{ } n\Phi_0/\sqrt{\text{Hz}} \]
\[ \sqrt{S_n} = 79 \mu_B/\sqrt{\text{Hz}} \]  \text{ @ B < 0.5 T}

Use this technology for waferscale SQUID fabrication of microSQUIDs.
Summary and outlook

- Conventional SQUID technology (Nb/AlO$_x$/Nb) meets requirements of a wide range of applications: biomagnetic research, metrology, nanoscale magnetic detection.

- SQUID current sensors for various applications are already available on a commercial basis.

- MicroSQUIDs fabricated using common technology are an attractive alternative to real nanoSQUIDs. They can be fabricated on a waferscale.

- Novel nanoSQUID designs with Nb/HfTi/Nb junctions are promising candidates for nanomagnetic detection in magnetic fields.