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


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Motivation


Why we use SNS instead of SIS?

• critical current densities about 1000 times higher (up to about 1 MA/cm²)

• 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**
- **NanoSQUID loop out-of-plane**
  - > 80 nm
  - 100..150 nm
  - > 30 nm
  - 90..200 nm

- **Si wafer surface**
- **Josephson junctions**

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

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

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External magnetic field applied to flip the magnetization of the particle > 50mT
**Technology: SNS with HfTi Barrier**

- **1. Definition of Josephson junction**
  - Nb
  - HfTi
  - PMMA
  - Al
  - Si + SiO₂ + Al₂O₃
  - ARN 7250.18

- **2. Insulation and CMP**
  - SiO₂
  - Nb

- **3. Wiring connection**
  - PMMA
  - Al

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

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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

The Trilayer:

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

30 nm Al$_2$O$_3$ etching stop

Si substrate with 300 nm thermal oxidized SiO$_2$

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Critical Parameters on Demand

- Parameters of the Josephson junctions can be adjusted
- High reproducibility of the parameters
Results: NanoSQUID Type A

JJ area = 90 nm x 90 nm

JJ spacing = 100 nm

d(HfTi) = 20.5 nm

Nb top wiring

Nb bottom wiring (base)

modulation coil

Josephson junctions

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Results: NanoSQUID Type A

Current-Voltage Characteristics

- $I_c = 36 \, \mu A$
- $j_c = 213 \, kA/cm^2$
- $R_N = 2.4 \, \Omega$
- $V_c = 86.4 \, \mu V$

V-Φ Characteristics

- $1/M_f = \text{ca. } 20 \, mA/\Phi_0$
- $V_\Phi = 300 \, \mu V/\Phi_0$

Fraunhofer-Like Pattern

$I_c$ Modulations

- $\beta_L = I_cL / \Phi_0 = 0.2$
- $L = 11 \, pH$
- $\Gamma = 2\pi k_B T/I_0 \Phi_0 = 10 \times 10^{-3}$
- $A_{\text{SQUID,eff}} = 0.05 \, \mu m^2$
- $j_c$ homogeneous

All measurements were made at 4.2 K.

Oral presentation at KRYO 2016. No manuscript was submitted for hardcopy journal publication.
Results: NanoSQUID Type B

- **JJ area**: 150 nm x 150 nm
- **JJ spacing**: 60 nm
- **d(HfTi)**: 20.5 nm
- **Cursor Width**: 122.4 nm
- **Cursor Height**: 183.6 nm

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

Current-Voltage Characteristics

\[ I_c = 150 \mu A \]
\[ j_c = 333 \text{ kA/cm}^2 \]
\[ R_N = 0.6 \Omega \]
\[ V_c = 90 \mu V \]

\[ \beta_L = \frac{I_c L}{\Phi_0} = 0.25 \]
\[ L = 2.7 \text{ pH} \]
\[ \Gamma = 2\pi k_B T / I_0 \Phi_0 = 2.3 \times 10^{-3} \]
\[ A_{\text{SQUID,eff}} = 0.04 \mu m^2 \]
\[ j_c \text{ homogeneous} \]

V-I\text{mod-} Curve

\[ 1/M_f \approx 35 \text{ mA}/\Phi_0 \]

I\text{c} Modulations

Fraunhofer-Like Pattern

All measurements were made at 4.2 K
Results: NanoSQUID Type A, Type B

Stability in External Magnetic Field

Oral presentation at KRYO 2016. No manuscript was submitted for hardcopy journal publication.
Results: NanoSQUID Type A, Type B

Stability in External Magnetic Field

Line width 180 nm

Line width 100 nm

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Results: Type C

NanoSQUID Sensor Data

- JJ area: 150 nm x 150 nm
- SQUID loop: 1µm x 100nm
- Gap (input coil-SQUID): 100 nm

- \( I_c = 200 \, \mu A \)
- \( R_N = 0.5 \, \Omega \)
- \( V_c = 100 \, \mu V \)
- \( j_c = 444 \, \text{kA/cm}^2 \)
- \( 1/M_f = 6.4 \, \text{mA}/\Phi_0 \)
- \( \beta_L = I_c L / \Phi_0 = 0.4 \)
- \( L = 4.2 \, \text{pH} \)
- \( A_{\text{SQUID}} = 0.1 \, \mu m^2 \)

Very high critical current densities!

Flux Noise

- \( S^{1/2} = 130 \, n\Phi_0 / \text{Hz}^{1/2} \)
- \( 70 \, n\Phi_0 / \text{Hz}^{1/2} \)
- \( 10 \, \mu_B / \text{Hz}^{1/2} \)

2-stage measurement configuration

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AG 2.43, Viacheslav Morosh

nanoSQUIDs

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Voltage Noise of Single JJs

Johnson-Nyquist Noise:
\[ S_V^{1/2} = (4k_B T R_N)^{1/2} \]

Bath temperature:
\[ T = 4.2 \text{ K} \]

Effective JJ Temperature:
\[ T_{JJ \text{ eff.}} \approx 9 \text{ K} \]

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

Temperature Behavior of a Single JJ

JJ: 80 nm x 80 nm

d(HfTi) = 20.5 nm

\( R_N = 6.2 \ \Omega = \text{const} \)

SQUIDs nonhysteretic: 1.4 K...4.2 K !
High Critical Current Density $j_c$

All measurements are made at $T = 4.2$ K

- $J_J: 80 \text{ nm} \times 80 \text{ nm}$
- $I_c = 127 \mu\text{A}$
- $R_N = 1 \Omega$
- $j_c \approx 1 \text{ MA/cm}^2$

- still non-hysteretic!
- sharper $I_c$ corner

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

$L \approx 5 \text{ pH}$

50 % more output voltage

Comparison of the Gamma parameter

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

<table>
<thead>
<tr>
<th>Type A</th>
<th>This nanoSQUID</th>
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<tbody>
<tr>
<td>$(j_c = 213 \text{ kA/cm}^2)$</td>
<td>$(j_c = 1 \text{ MA/cm}^2)$</td>
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<td>$10 \times 10^{-3}$</td>
<td>$2,7 \times 10^{-3}$</td>
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Our Smallest NanoSQUID

JJs: 80 nm x 80 nm
JJ spacing: ca. 31 nm

Line width: 92 nm

$I_c$ = 349 kA/cm²
$R_n$ = 2.2 Ω
$V_c$ = 98 μV

All measurements are made at $T = 4.2$ K
Our Smallest NanoSQUID

**Optimal working point:**

\[ V_\Phi = 308 \, \mu V/\Phi_0 \text{ at } \Phi = -0.22 \, \Phi_0, \quad I_b = -50 \, \mu A \]

- \( \beta_L \approx 0.1 \quad L \approx 5.1 \, \mu m \)
- \( J_{Js} : 80 \, nm \times 80 \, nm \)
- \( JJ \text{ spacing: } ca. 31 \, nm \)
- \( Line \text{ width: } 92 \, nm \)
- \( A_{eff} = 0.03 \, \mu m^2 \)
- \( J_c = 349 \, kA/cm^2 \)
- \( R_n = 2.2 \, \Omega \)
- \( V_e = 98 \, \mu V \)
- \( \Phi_0 = \frac{hc}{2e} \)
- \( \phi = \phi_0 \cdot \frac{n}{N} \)
- \( \phi_0 = \frac{hc}{2e} \)
- \( \frac{\phi}{\phi_0} = \frac{1}{N} \)
- \( \frac{\phi}{\phi_0} = \frac{1}{N} \)

All measurements are made at \( T = 4.2 \, K \).
Summary and Outlook

- Effective area down to $0.03 \, \mu m^2$, JJ spacing down to $31 \, nm$
- Josephson junctions down to $80 \times 80 \, nm^2$
- Narrow line width $92 \, nm$
- Stability in high magnetic fields up to $290 \, mT$
- Low level of white noise $130 \, n\Phi_0 / Hz^{1/2}$
- Spin sensitivity: $10 \, \mu B / Hz^{1/2}$ → 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