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Flip-Chip High-T_c DC SQUID Magnetometer with a Ferromagnetic Flux Antenna

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Outline

- Introduction
- Fabrication of Josephson junctions, SQUID and ferromagnetic antenna
- Assembling and properties of SQUID with ferromagnetic antenna
- Summary and outlook

Introduction

Available high-T_c flip-chip DC SQUID magnetometers:

1. Based on epitaxial $YBa_2Cu_3O_{7-x}$ (YBCO) films and operate at 77 K.

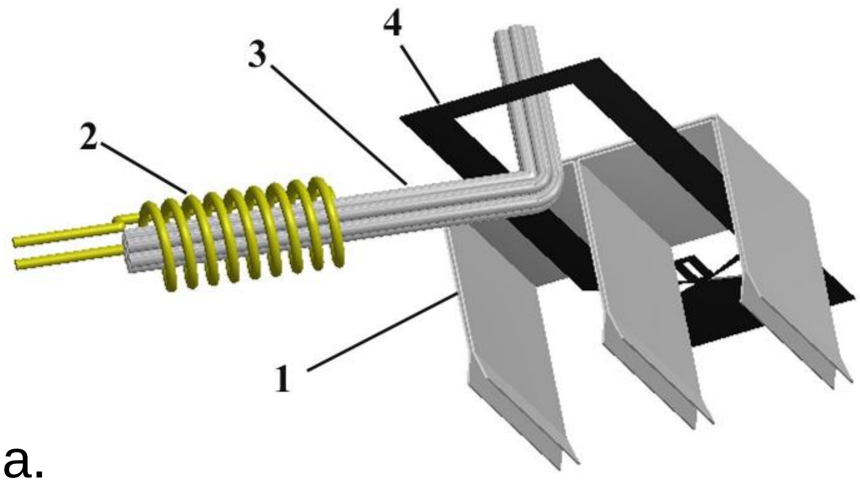
2. Contain DC SQUID and thin-film superconducting multilayer flux transformer with multiturn input coil that are made on different substrates and coupled inductively with each other.

3. Encapsulated in fiberglass capsules with integrated heater and modulation coil.

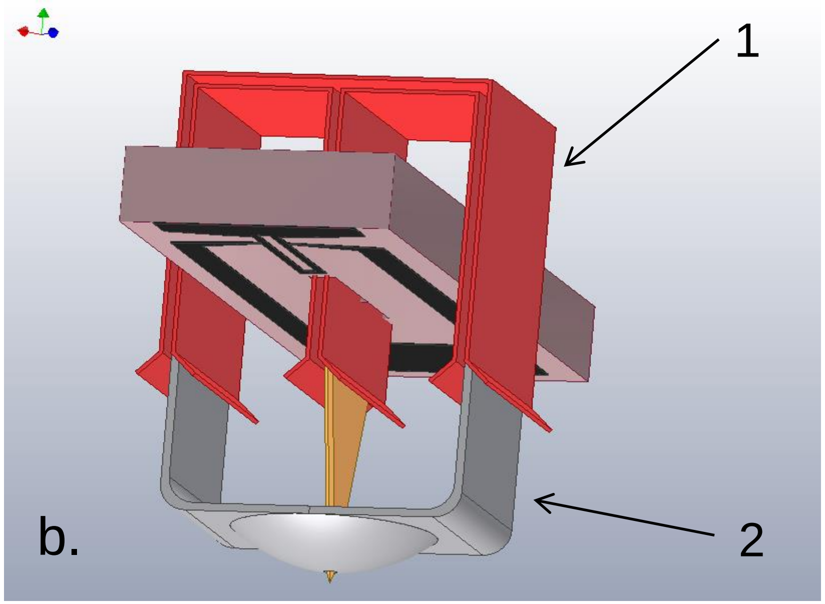
4. Magnetic field resolution is propotional to $D^{-3/2}$, where D is a diameter of pick-up loop (~4 fT/√Hz at 77 K for D = 20 mm).

5. There is a need to improve sensitivity further without increasing D. (for magnetoencephalography, etc.)

High-T_c DC SQUID microscope with FM flux antenna



a.

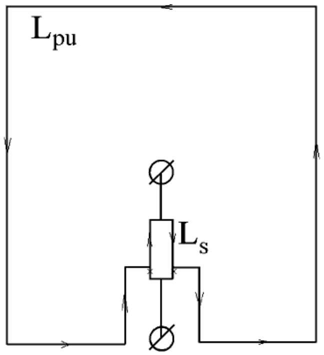


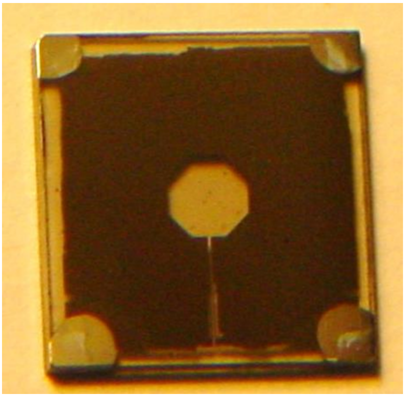
b.

(a) Sketch of a DC SQUID assembled with the low temperature part of magnetic flux antenna (1) and a coil (2) wounded around a bunch of ferromagnetic wires (3) leading flux modulation and feedback signals to pick up loop (4) of the SQUID, (b) sketch of SQUID with magnetic flux antenna (1) assembled with its room temperature counterpart (2). The permalloy tip and the permalloy foil for return of magnetic flux are placed in the cryostat window at room temperature while SQUID operates at 77 K.

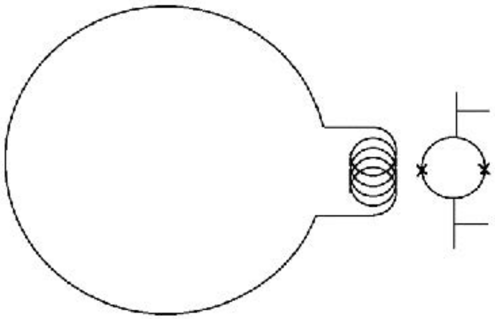
M. I. Faley et al., *IEEE Transactions on Appl. Supercond*. **27**, No.4, 1600905 (2017).

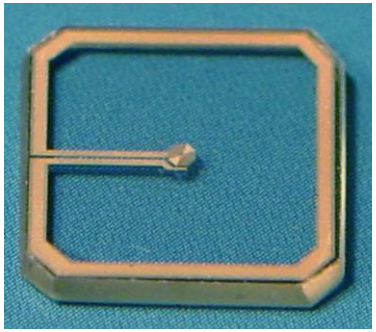
Introduction



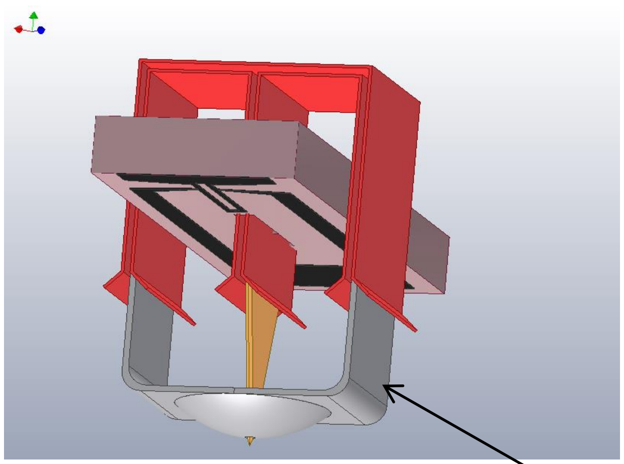


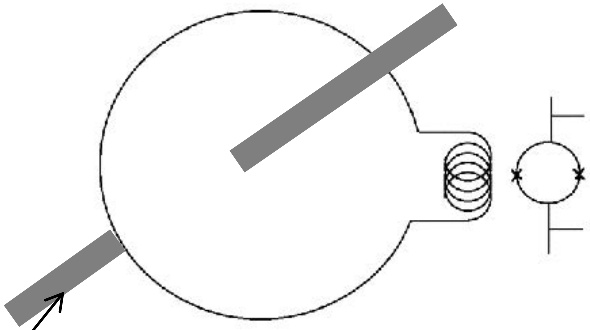
DC SQUIDs with directly coupled pickup loop





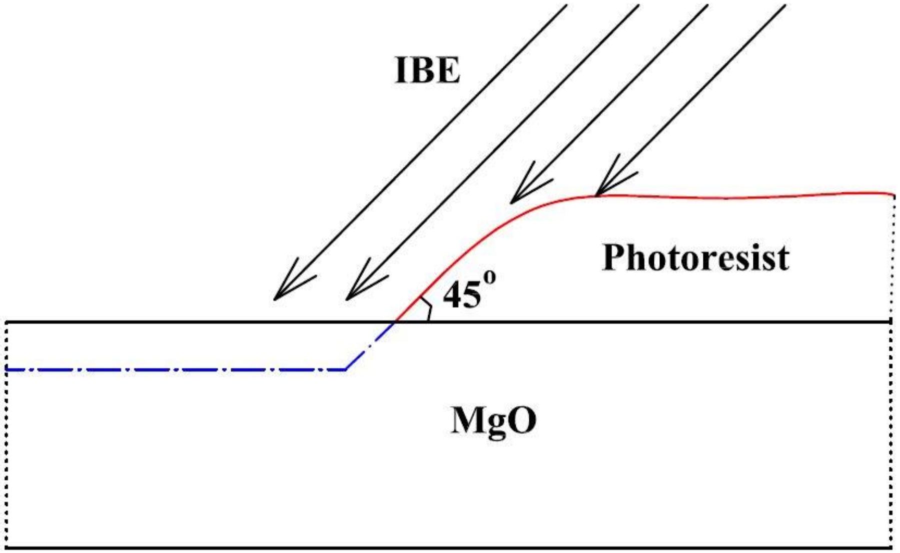
DC SQUIDs with inductively coupled flux transformer

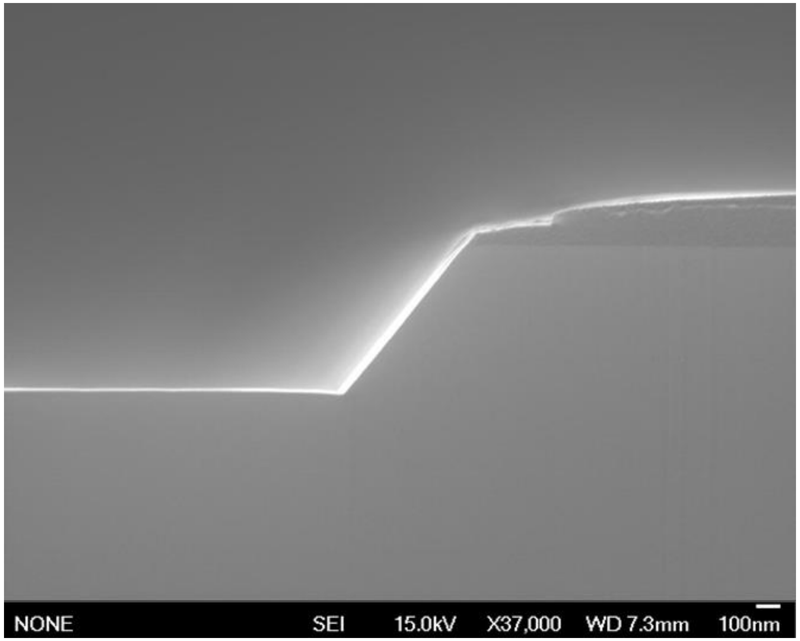




… with ferromagnetic flux antennas

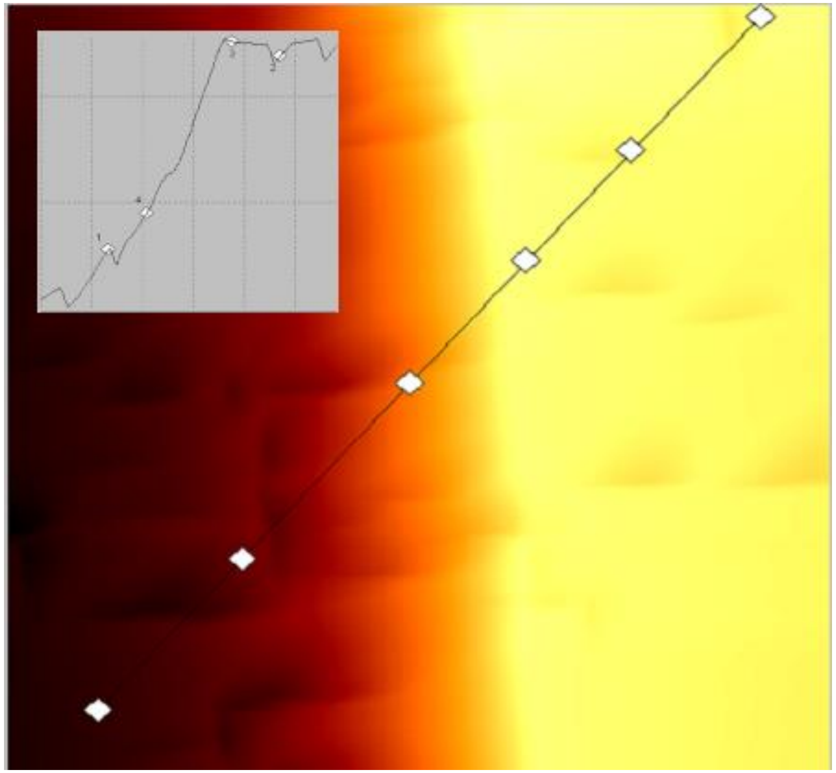
Preparation of step on surface of MgO substrate

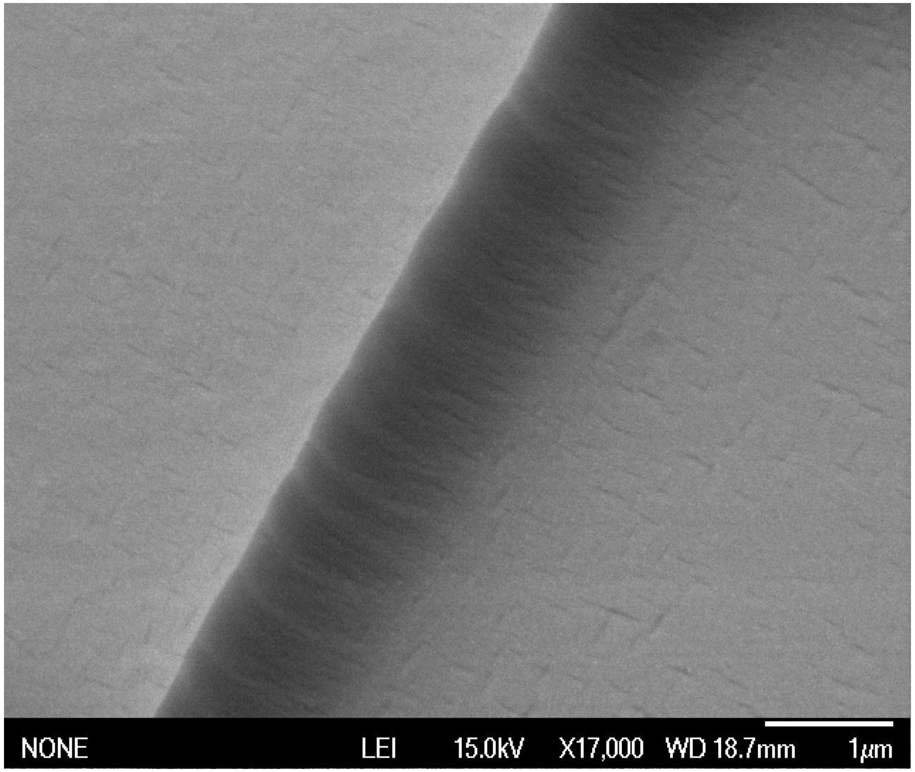




Formation of 45° step on surface of MgO substrate by ion beam milling over the edge of nLOF2010 photoresist.

Textured step edge on MgO substrate

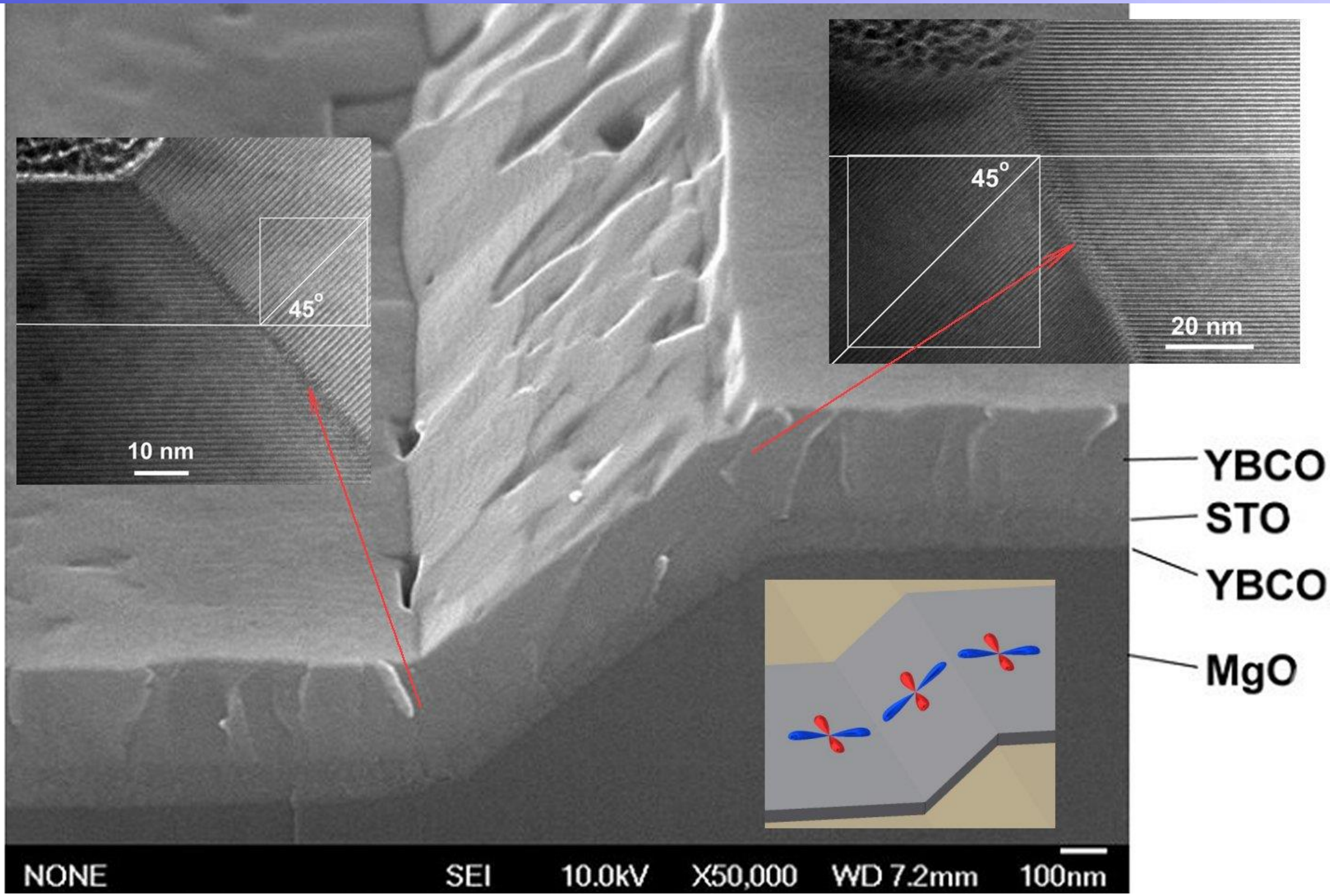




AFM and SEM images of a textured step edge on MgO substrate after second ion beam milling

M. I. Faley et al., *IEEE Trans Appl. Supercond.* , 2013, 2016

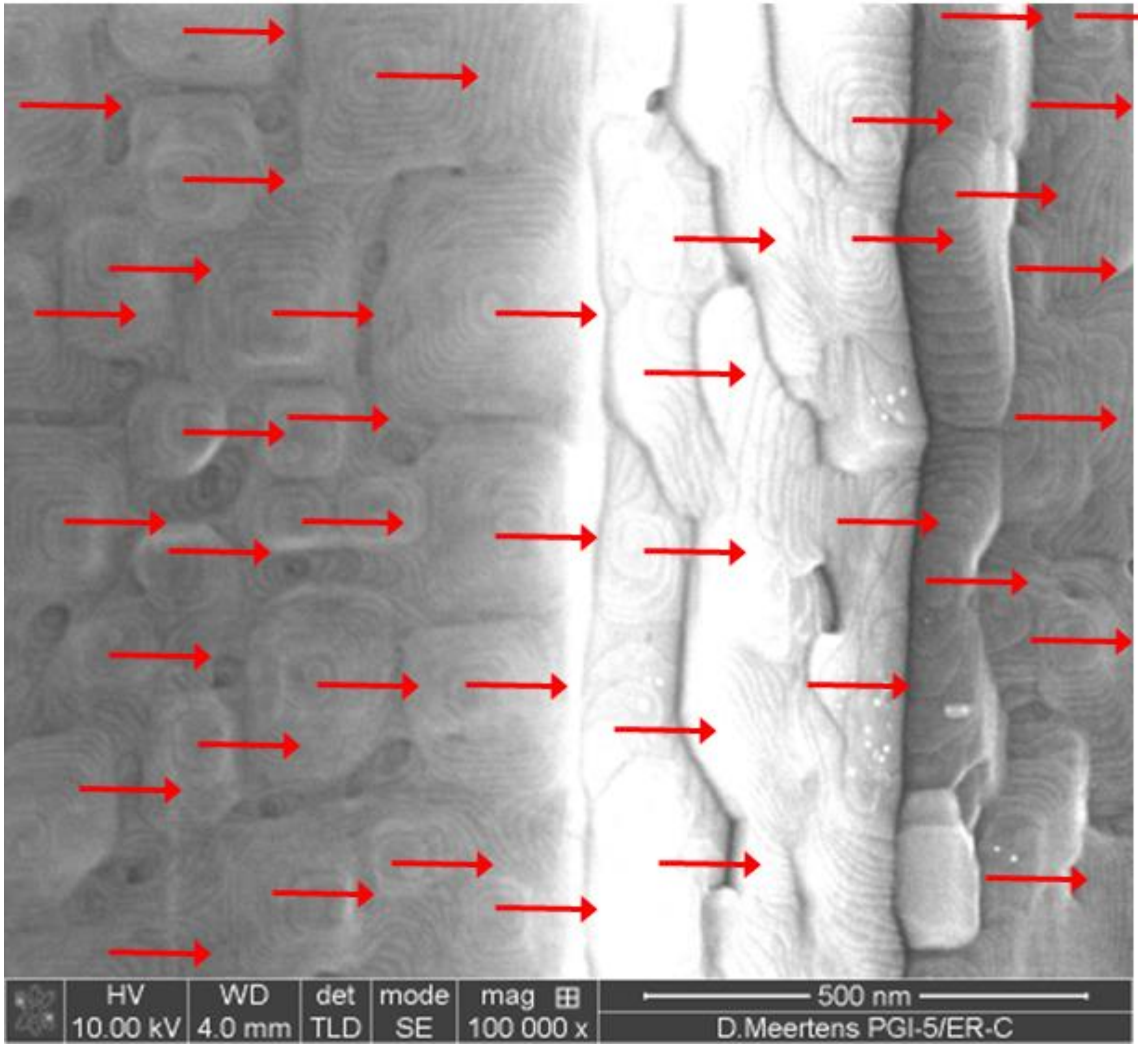
New type of high-T_c Josephson junction: graphoepitaxial step-edge junctions on MgO substrates



M. I. Faley, Patent US 9666783 B2 granted 30.05.2017.

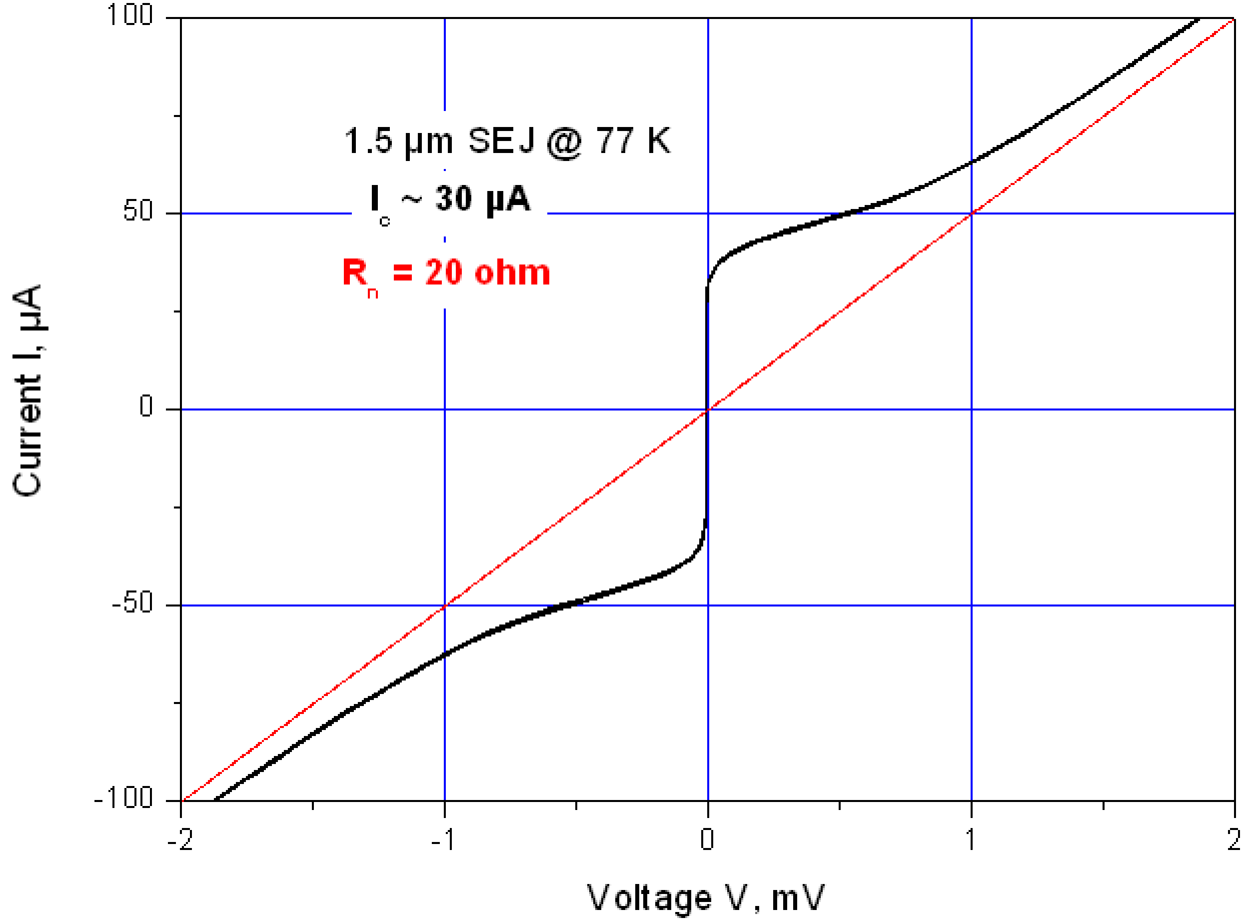
M. I. Faley et al., Superconductor Science and Technology 30, 083001 (2017).

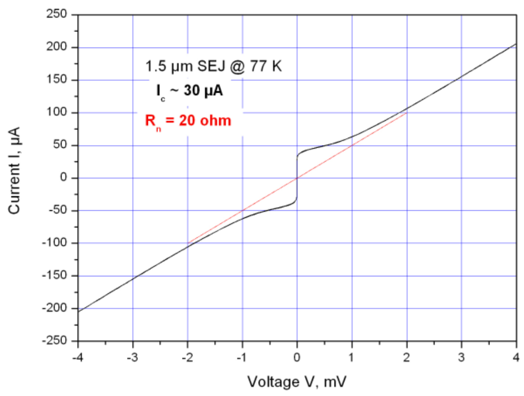
Surface microstructure of step-edge Josephson junction



SEM image showing the aligned orientation of grains in the YBCO film deposited on the step-edge with surface texturing.

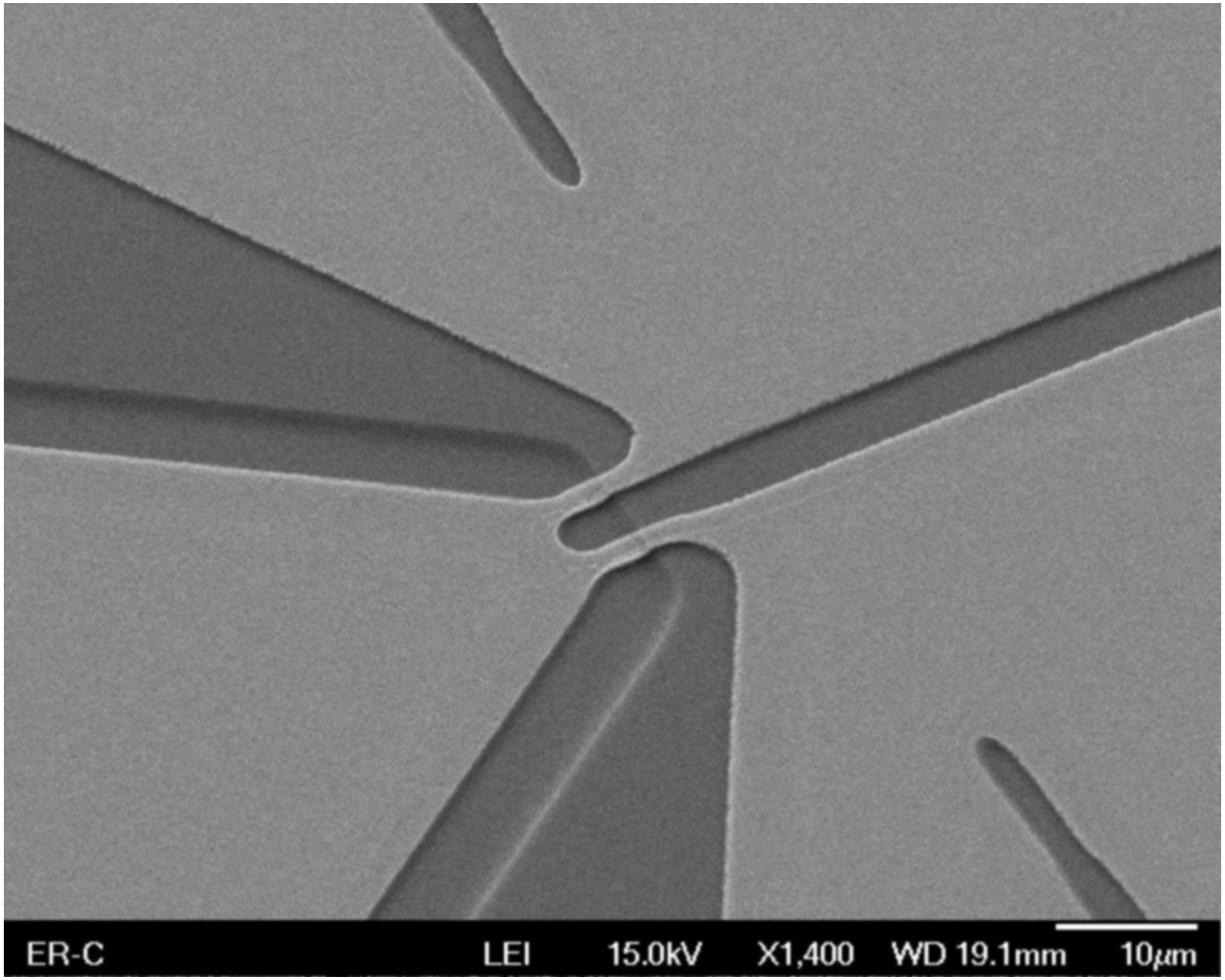
Graphoepitaxial Josephson junctions





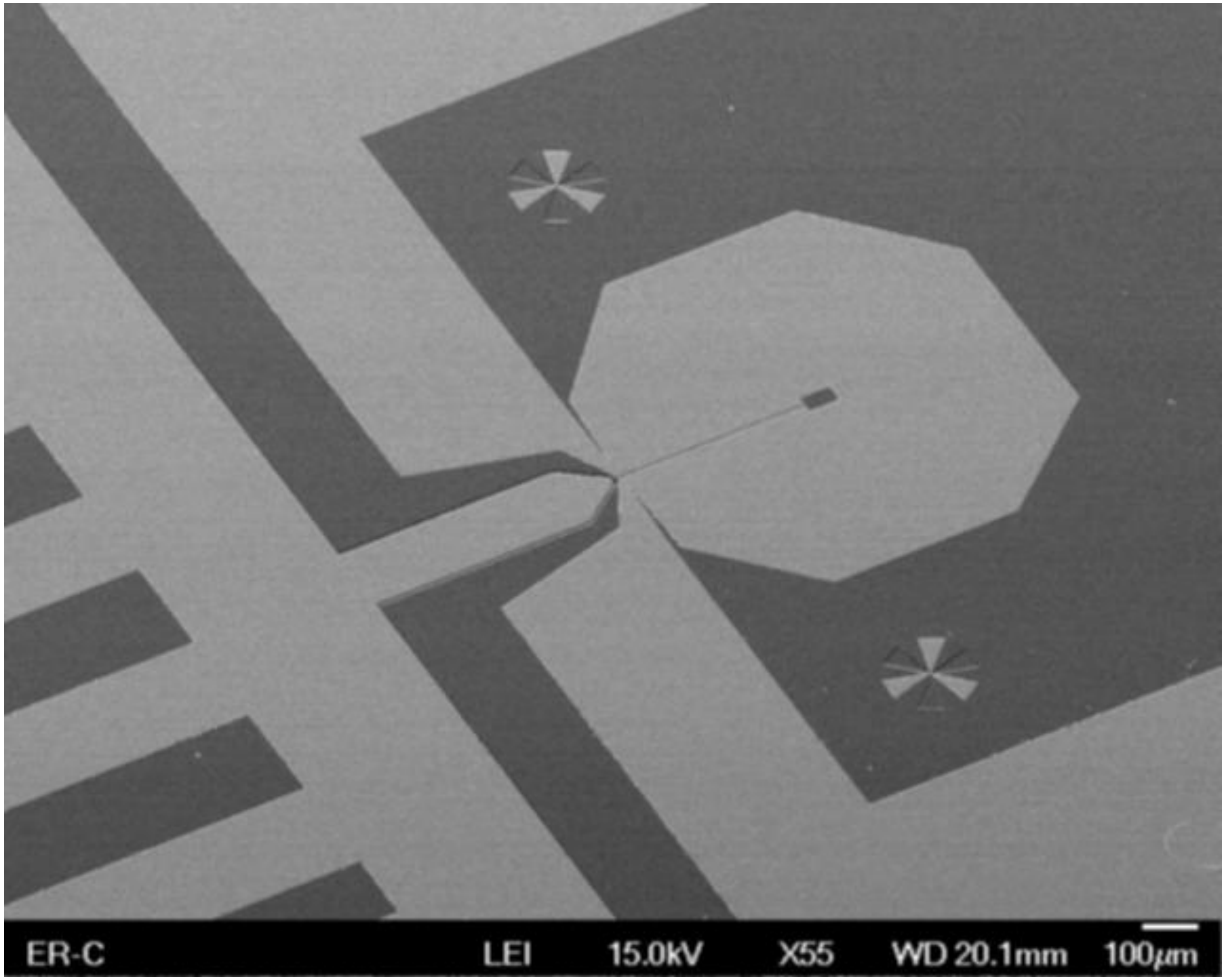
I-V characteristics of Josephson junction on a textured MgO substrate step-edge:
I_c= 30 µA, R_n = 20 ohm, I_cR_n = 600 µV at 77 K

Graphoepitaxial DC SQUIDs



SEM image of two Josephson junctions of a DC SQUID prepared on a textured MgO substrate step

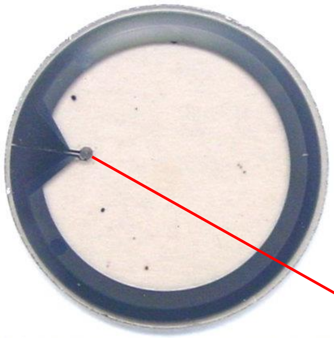
Graphoepitaxial DC SQUIDs



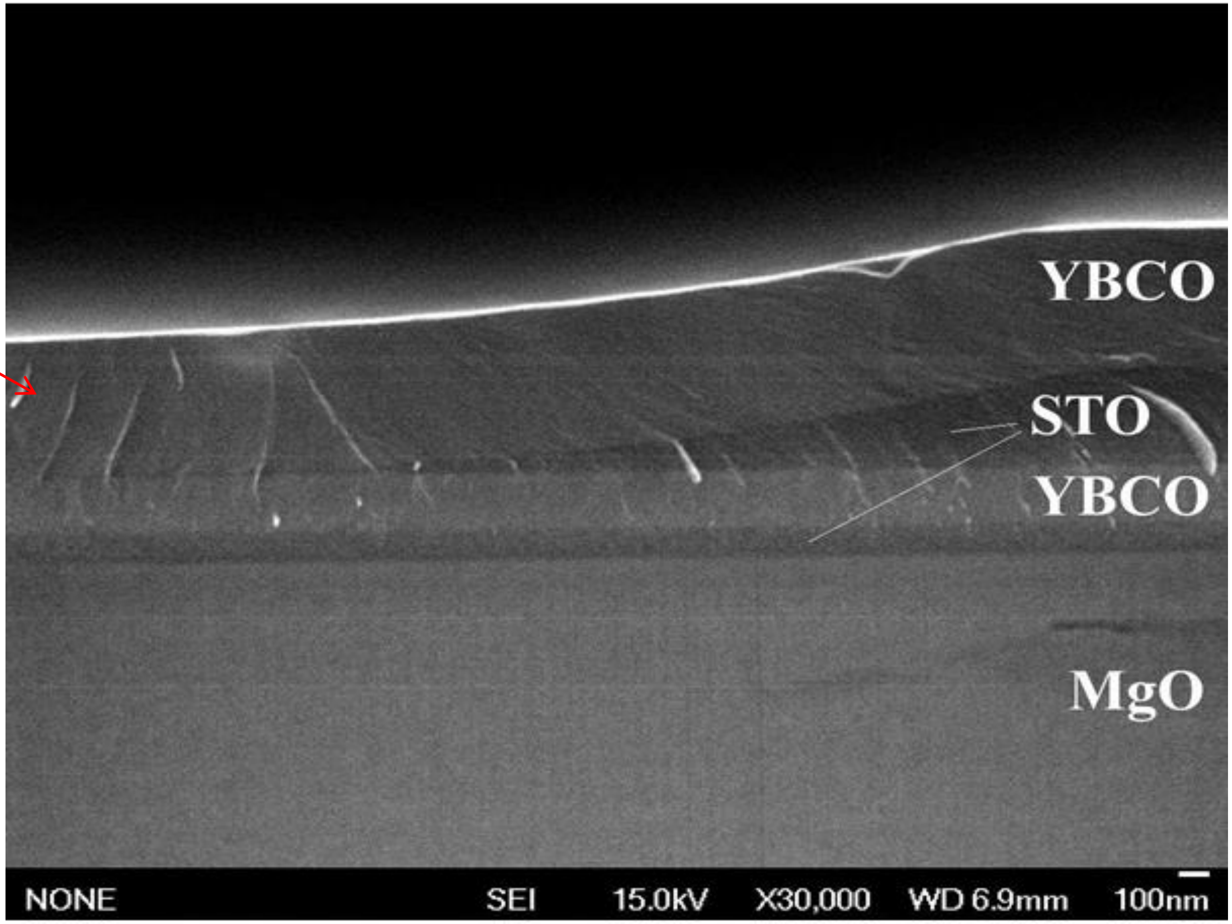
SEM image of a DC SQUID prepared on a textured step on MgO substrate

M. I. Faley et al., *IEEE Trans Appl.Supercond*. **23** 1600705 (2013)

High-T_c superconducting (SC) flux transformer

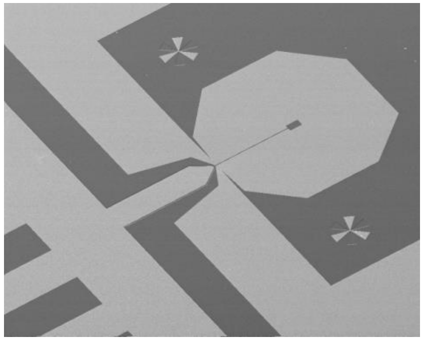


20-mm SC flux transformer



Cross-sectional SEM image showing edge area of interconnection in the input coil of the high-T_c SC flux transformer prepared on buffered MgO (100) wafer.

Flip-chip DC SQUIDs with 20-mm inductively coupled SC flux transformer



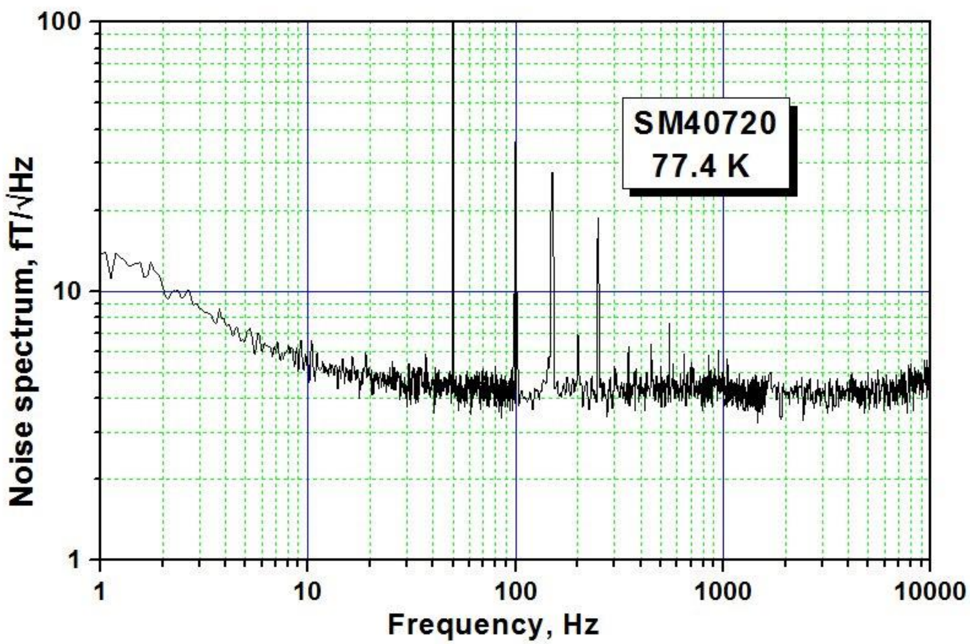
DC SQUID

+

20-mm SC flux transformer

=

DC SQUID magnetometer

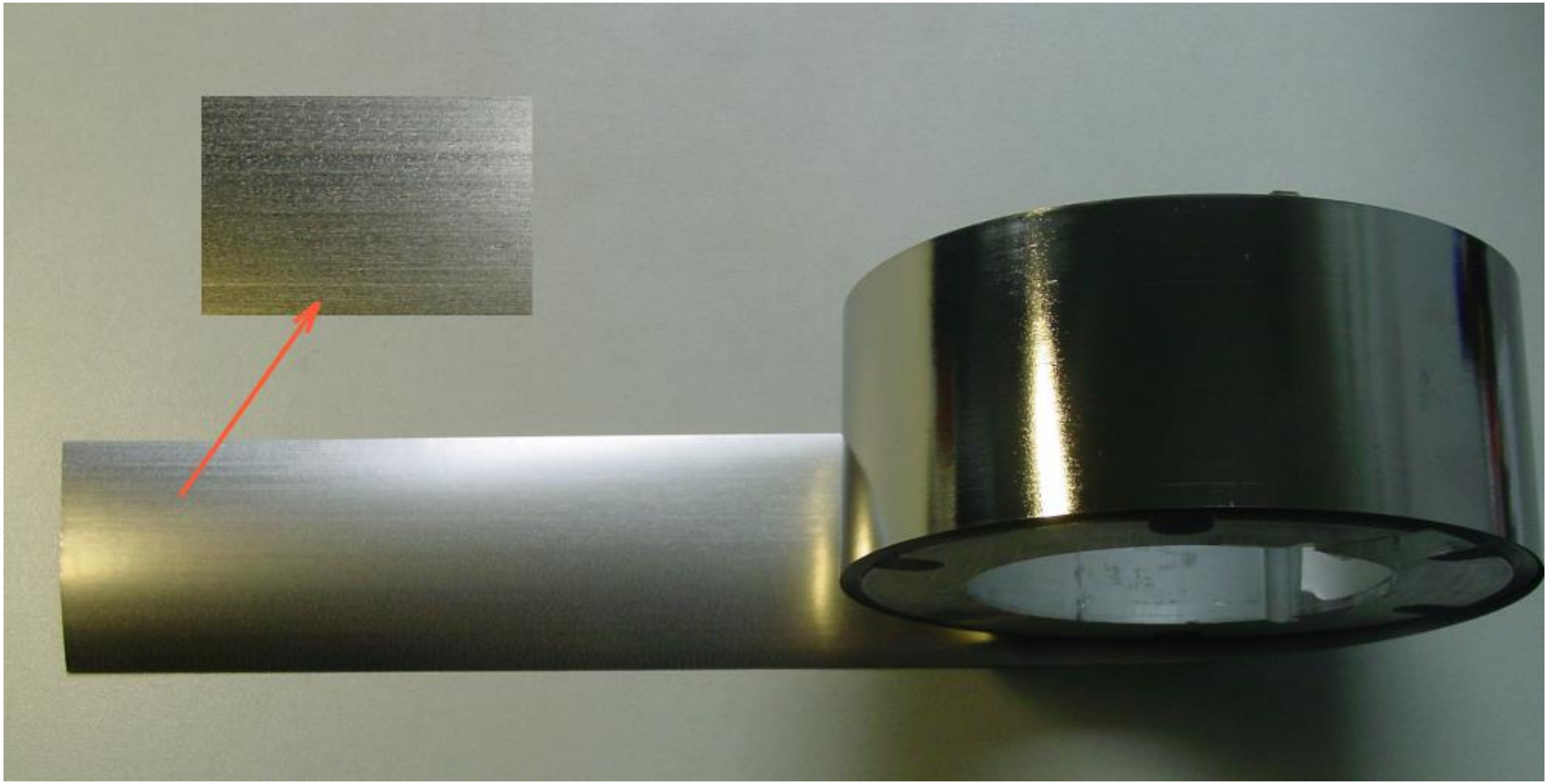


Sensitivity ~ 0.4 nT/Φ_o

Magnetic field resolution ~ 4 fT/√Hz

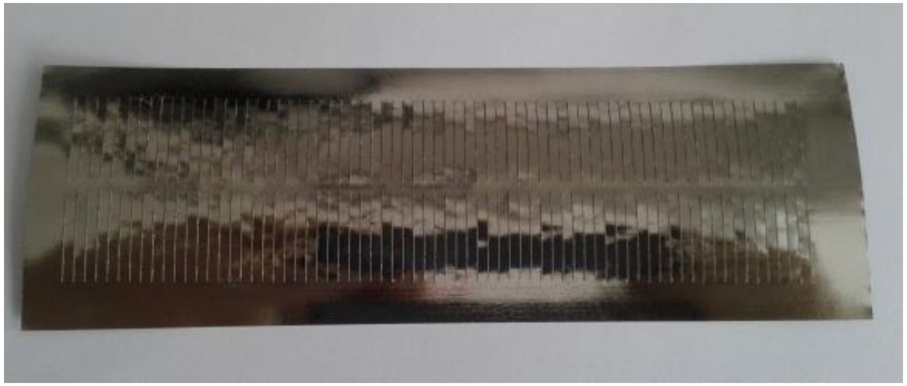
M. I. Faley et al., *IEEE Trans Appl.Supercond*. **25** 1601605 (2015)

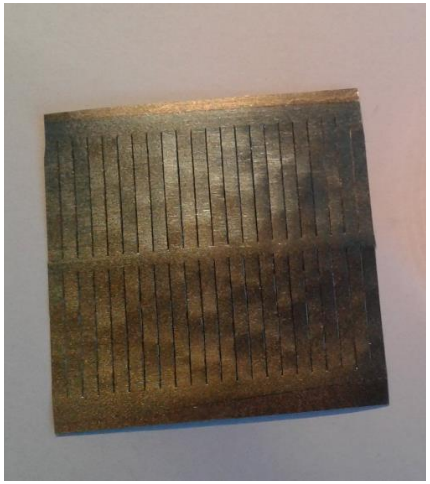
Ferromagnetic amorphous metal foil Vitrovac 6025

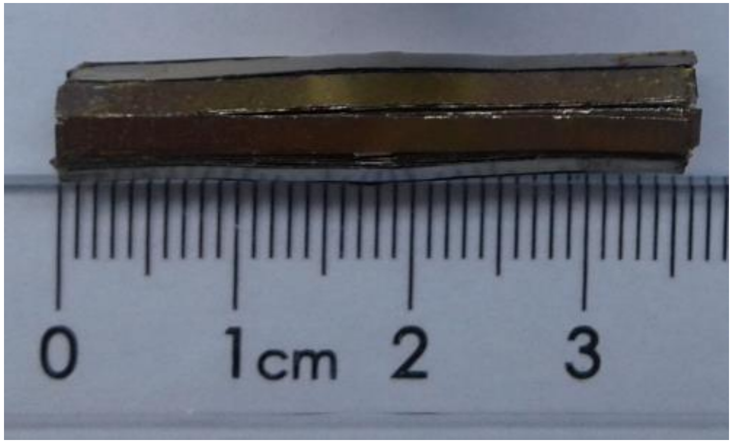


Photography of bobbin of Vitrovac 6025 foil. Linear pattern of grooves in the rolling direction indicates the direction of easy magnetization.

Ferromagnetic antenna (FMA) from amorphous metal foil Vitrovac 6025

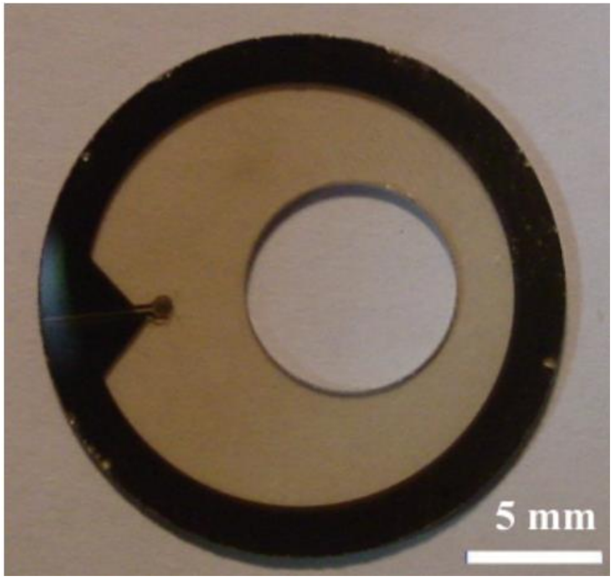






Preparation of insulated stripes and antenna from the Vitrovac 6025 foil.

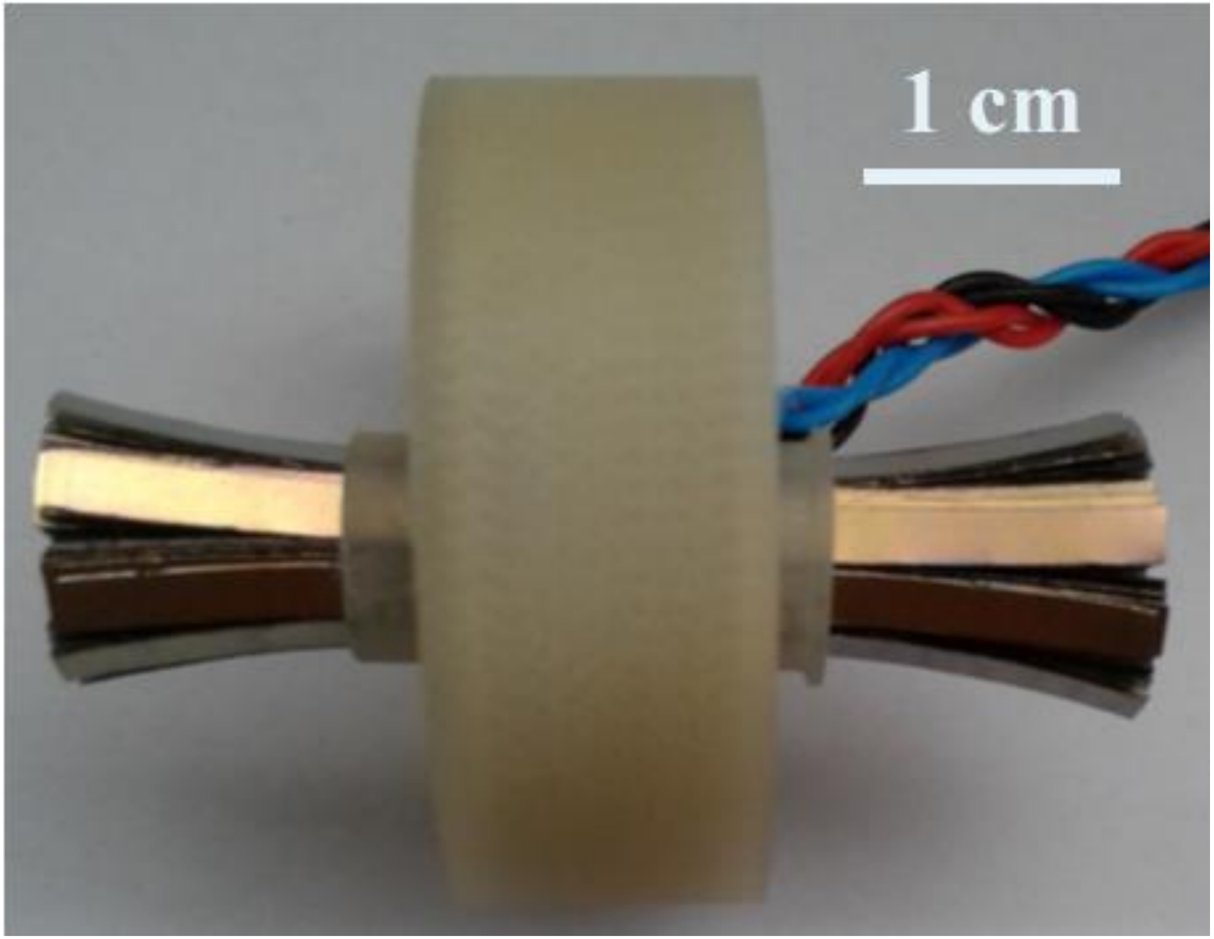
Superconducting (SC) flux transformer with a hole



Photography of 20-mm SC flux transformer with a 9-mm hole.

Photography of 20-mm SC flux transformer with a 9-mm hole inside fiberglass cap and a fiberglass tube in the holes.

SQUID magnetometer with FMA



Photography of encapsulated 20-mm high-T_c flip-chip DC SQUID magnetometer with ferromagnetic antenna (FMA)

Effective magnetic permeability of FMA

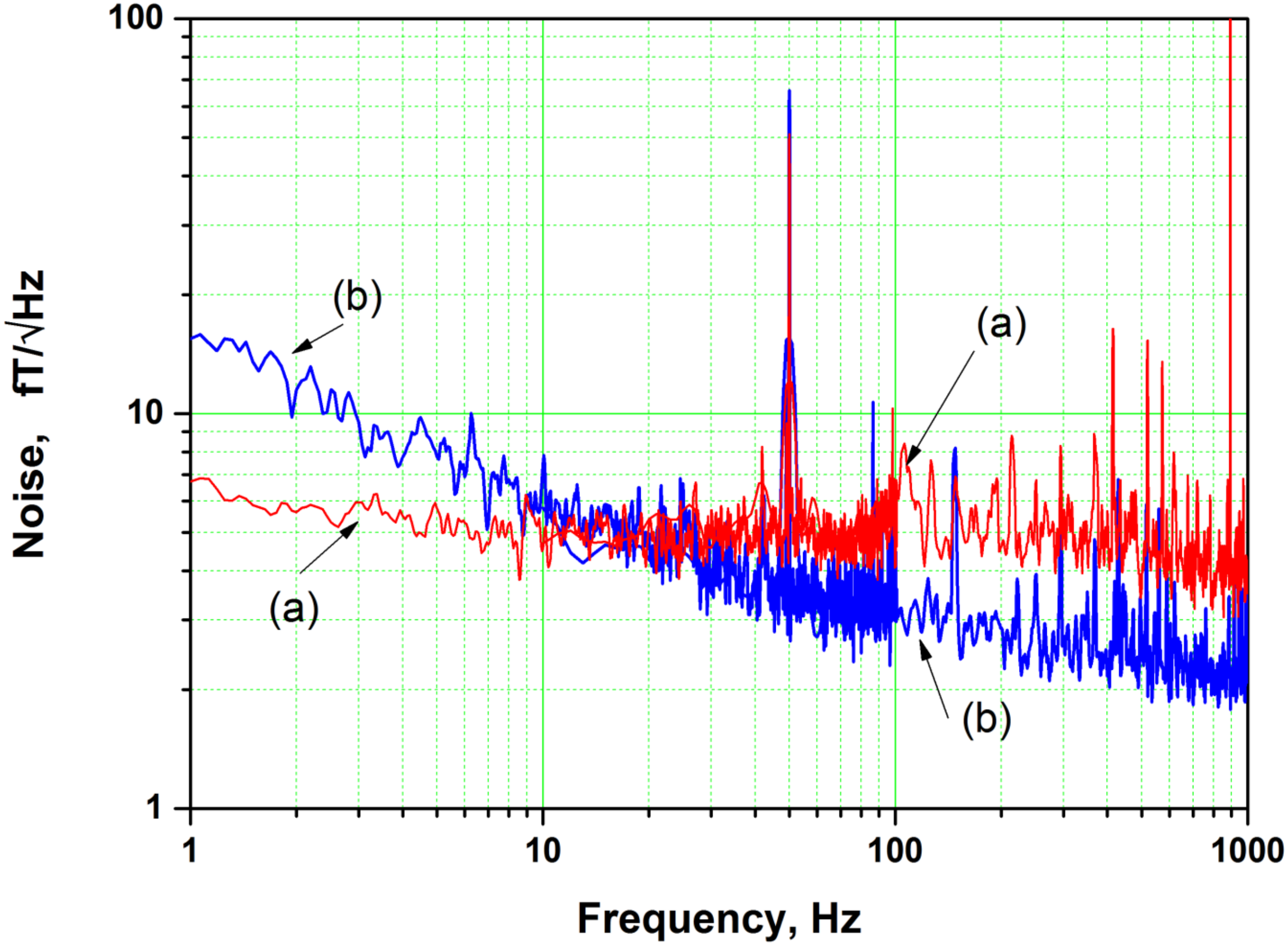
Demagnetization coefficient: $N_z(m) = \frac{\ln(2m) - 1}{m^2}$, where m = L/d

Effective magnetic permeability: $\mu_{eff} = \frac{\mu_r}{1 + N_z \frac{d_1^2}{d_2^2}(\mu_r - 1)}$

$\mu_r = 70000$

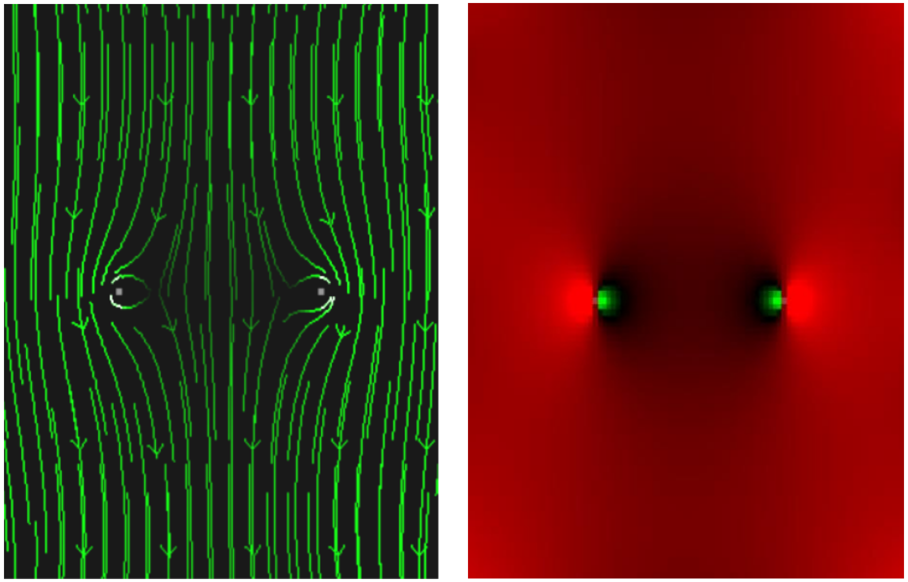
L = 15 mm, d_1 = 6 mm, d_2 = 6 mm	L = 35 mm, d_1 = 6 mm, d_2 = 10 mm
↓	↓
$N_z = 0.1$, $\mu_{eff} = 10.3$	$N_z = 0.043$, $\mu_{eff} = 64.8$
$\partial B/\partial \Phi \cong 0.27$ nT/Φ_0	$\partial B/\partial \Phi \cong 0.18$ nT/Φ_0

Ferromagnetic amorphous metal foil Vitrovac 6025

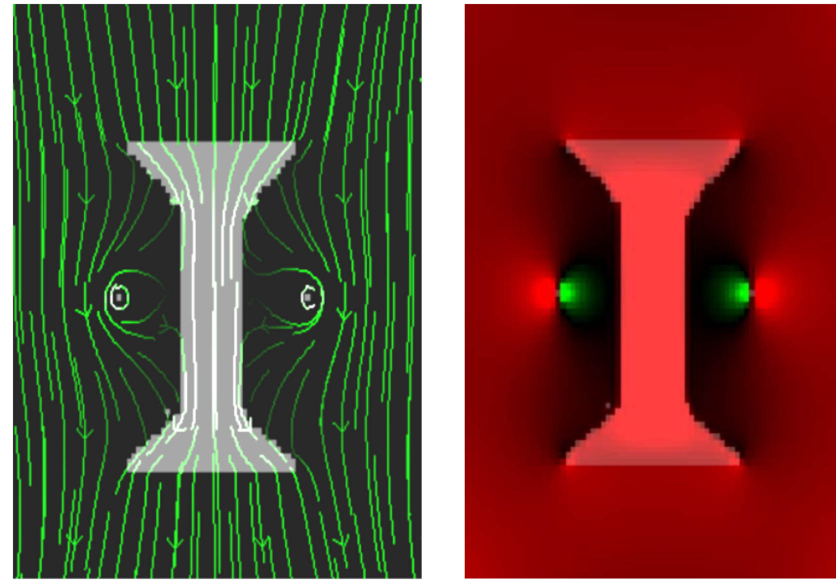


Noise spectra of high-T_c DC SQUID magnetometer obtained at 77 K: (a) without ferromagnetic antenna and (b) with ferromagnetic antenna measured inside shields consisting of 3 shields of µ-metal tubes and one double-wall SC shield.

Simulation of current loop with FMA



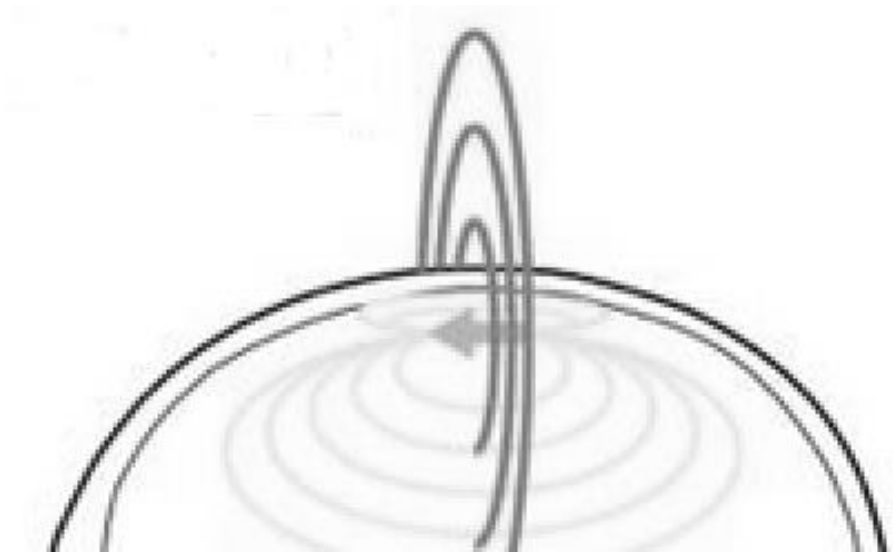
Computer simulations for a current loop: (a) magnetic field lines and (b) component of magnetic field parallel to axis of the current loop.



Computer simulations for a current loop with a ferromagnetic antenna: (a) magnetic field lines and (b) component of magnetic field parallel to axis of the current loop.

Prospective application for SQUIDs with FMA

- Biomagnetic measurements: MEG, magnetic nanoparticles, etc.
- Monitoring of ion beam current in accelerometers.
- Geomagnetic measurements.
- Non-destructive evaluation.



Conclusions

- The use of the novel ferromagnetic antenna has improved the flux-to-field transformation coefficient from ~0.4 nT/Φ_0 to ~0.18 nT/Φ_0 and the magnetic field resolution from ~4 fT/√Hz to ~2 fT/√Hz at 77 K and frequency ~1 kHz.

- At lower frequencies, a stronger increase of noise was detected for the magnetometer with ferromagnetic antenna and at frequencies below 10 Hz magnetometer without ferromagnetic antenna still demonstrated a better magnetic field resolution.

- Flip-chip high-T_c SQUIDs with FMA can be used for biomagnetic measurements, monitoring of ion beam current in accelerometers, geomagnetic measurements and for non-destructive evaluation.