Graphoepitaxial Josephson junctions for quantum interferometers

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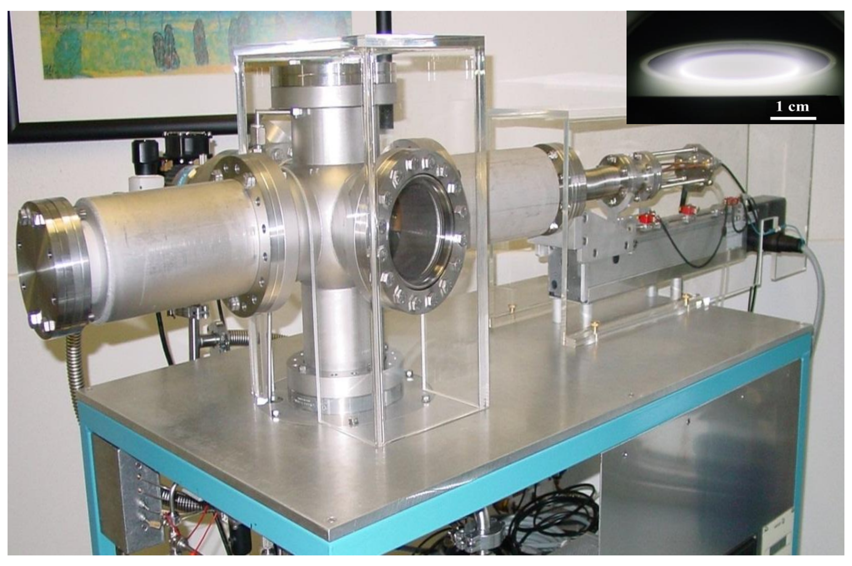
Abstract

We investigate the microstructures of graphoepitaxially-grown high-T_c films and their influence on the transport properties of step edge Josephson junctions and superconducting quantum interferometers (SQUIDs), which are intended for magnetoencephalography. The importance and relevance of brain studies is reflected, for example, in the "Human Brain Project" (EU) and the "BRAIN Initiative" (USA). Low noise SQUIDs based on epitaxial thin film heterostructures containing the high temperature (high-T_c) superconductor $YBa_2Cu_3O_{7-x}$ (YBCO) are used, for example, as ultrasensitive magnetometers and gradiometers for magnetoencephalography with a magnetic field resolution of ~ 3 fT/√Hz at 77 K.

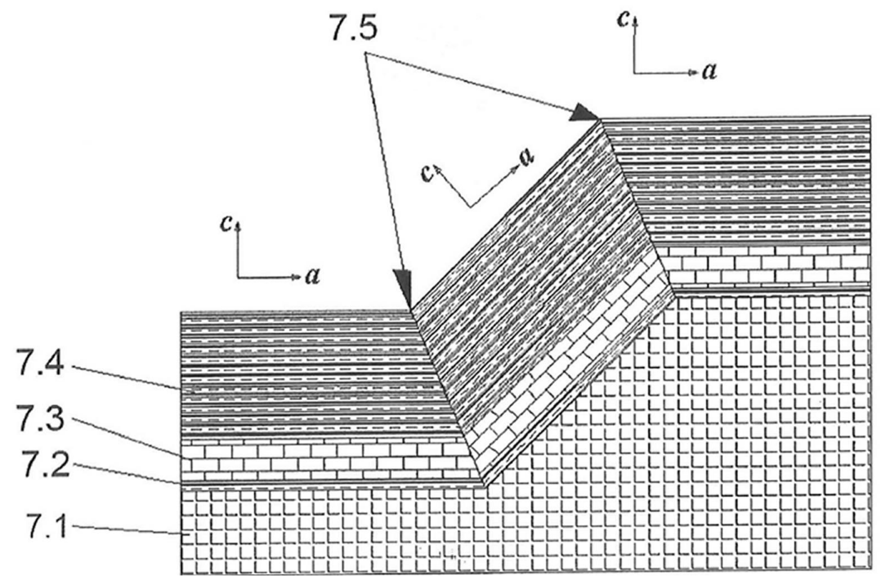
The noise properties and other electron transport properties of SQUIDs and related superconducting circuits are determined by their microstructure on the scale of the coherence length, which is ~ 1 nm in YBCO. This is why there is a need for optimization and careful monitoring of microstructure in high-T_c films, Josephson junctions and SQUIDs on the atomic scale using atomic force microscopy and high-resolution scanning and transmission electron microscopy (HRSEM and HRTEM).

We have prepared high-T_c superconducting heterostructures for SQUIDs with graphoepitaxial step edge Josephson junctions on single crystal MgO substrates and investigated them using complementary characterization techniques, including atomic force microscopy (AFM), scanning electron microscopy (SEM) and HRTEM. High-T_c films, Josephson junctions and SQUID magnetometers were fabricated by high-oxygen-pressure magnetron sputtering from stoichiometric polycrystalline targets. An in-plane orientation of the grains in the YBCO films and heterostructures was realized by using textured substrate surfaces to achieve graphoepitaxial growth of the YBCO films over the substrate step edges.

Fabrication of films and Josephson junctions

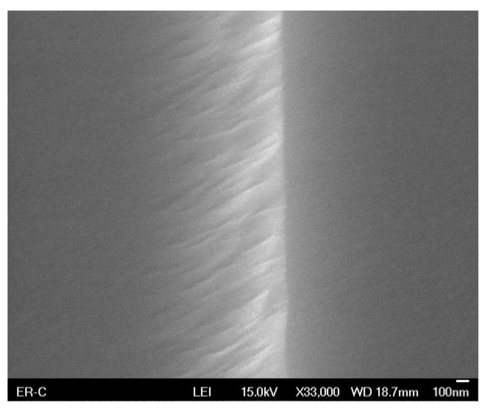


High oxygen pressure sputtering system (see [1], [2], and [3]).

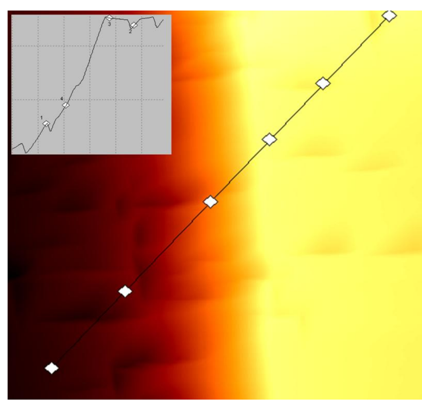


Step-edge junction with buffer layers: (7.1) textured MgO substrate with a step edge, (7.2) seed layer of YBCO (7.3) $SrTiO_3$ blocking buffer layer, (7.4) high-T_c film, (7.5) two 45° [100] grain boundaries [4].

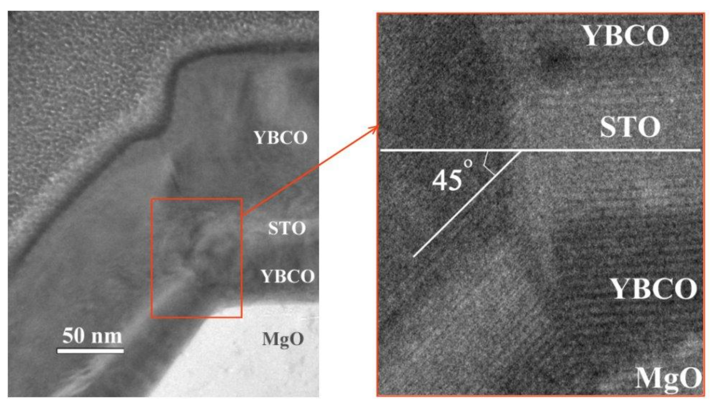
Microstructural properties of a new type of high-T_c Josephson junction



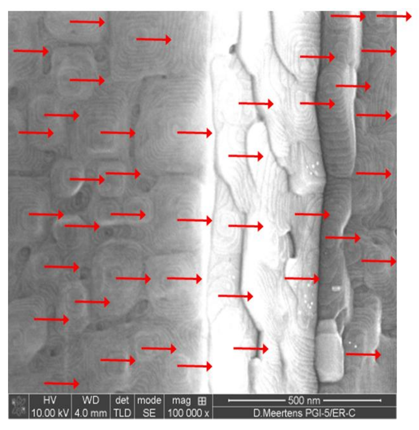
HRSEM image of a substrate step edge. Height of the step is about 300 nm. The scan area is 3 µm x 4 µm.



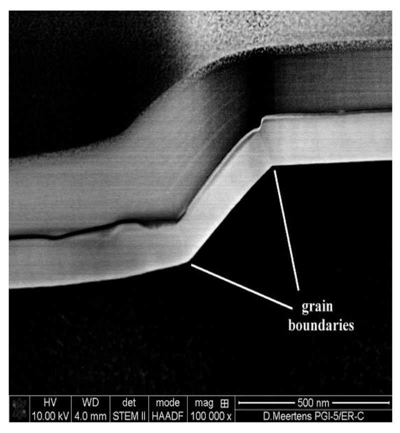
AFM image of a textured substrate step edge. Height of the step is about 300 nm. The scan area is 5 µm x 5 µm.



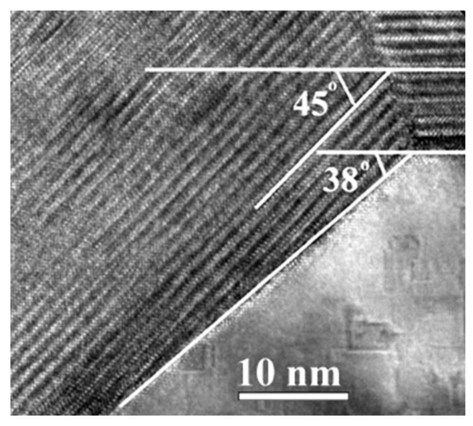
TEM image of an YBCO-$SrTiO_3$-YBCO heterostructure deposited on the upper corner of a substrate step [6].



HRSEM image showing the aligned orientation of grains in the YBCO film deposited on the step-edge with surface texturing [5].



Cross-section of an edge structure in a FIB-prepared specimen [6].

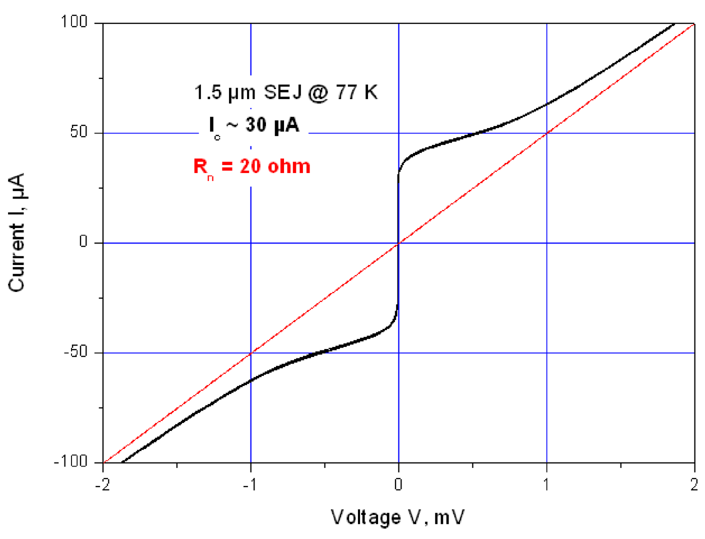


HRTEM image of the YBCO film deposited on the upper corner of the substrate step [6].

Electron transport properties

We have used oxide heterostructures prepared by high oxygen pressure deposition and different patterning methods for the production of high-T_c superconducting devices including SQUIDs, which are integrated in magnetic field measurement systems for magnetic microscopy of microstructures and electrical circuits, for geomagnetic surveys, for and biomagnetic measurements, for the non-destructive evaluation of materials and for many other applications.

Josephson junctions



I-V curve of Josephson junction on a textured step-edge: $I_c \approx 30$ µA, $R_n \approx 20$ ohm, $I_cR_n \approx 600$ µV at 77 K. I_cR_n was increased up to about 6 mV at 4.2 K.

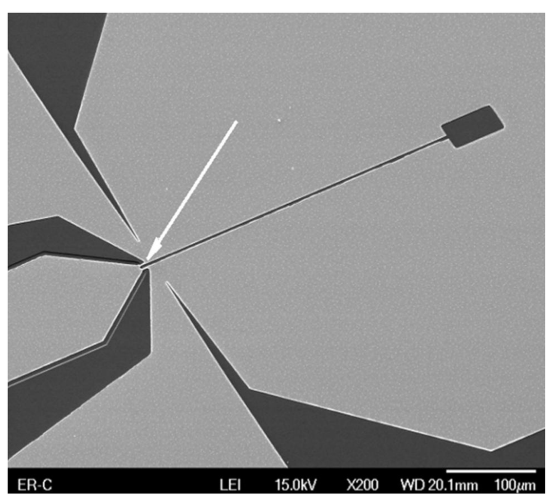
The graphoepitaxial high-T_c Josephson junctions (JJs) demonstrated much smaller capacitance compared to typical capacitance of low-T_c Josephson junctions:

Low-T_c JJs: $C \approx 1$ pF
High-T_c JJs: $C \approx 10$ fF

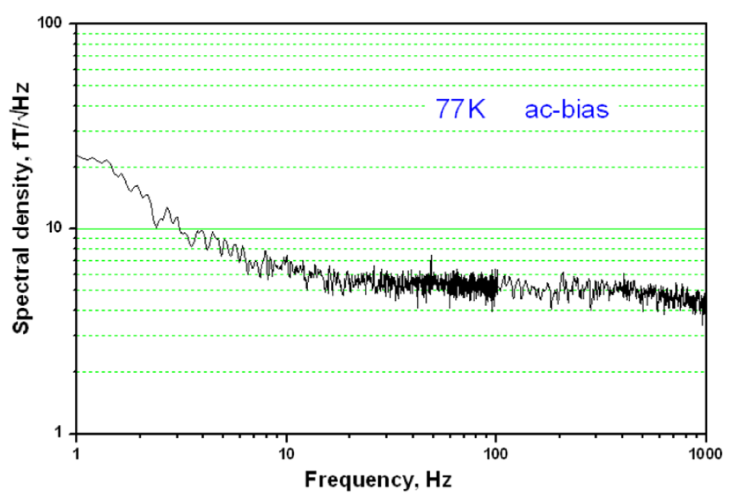
Such small capacitance of the graphoepitaxial high-T_c Josephson junctions is advantageous for magnetic flux resolution of high-T_c DC SQUIDs:

$$S_\Phi \approx 32 k_B T L (LC/\beta_C)^{1/2}$$

Quantum interferometers (SQUIDs)



SEM image of a DC SQUID with two step-edge Josephson junctions, a 1 mm washer and a 3 mm direct-coupled pickup loop. The position of the step-edge junctions is marked by an arrow.



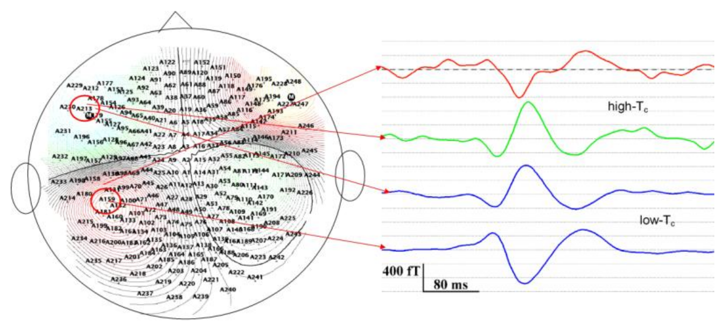
Noise spectrum of high-T_c DC SQUID magnetometer.

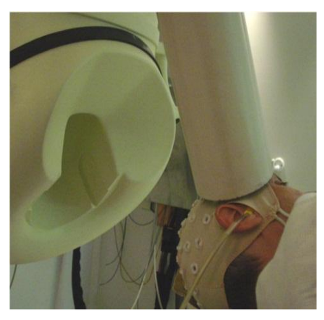
Sensitivity ~ 0.4 nT/Φ_0

Magnetic field resolution ~ 5 fT/√Hz at 77 K

Prospective applications for quantum interferometers

- **SQUIDs for biomagnetic measurements**: non-invasive investigation of multiple time-dependent sources of weak magnetic field generated by the human brain by magnetoencephalography. The importance and relevance of brain studies is reflected, for example, in the "Human Brain Project" (EU) and the "BRAIN Initiative" (USA).





Results of measurements of an auditory evoked field obtained using a high-T_c SQUID sensor (red and green curves) and low-T_c SQUID sensors (blue curves). Right – a photograph of MEG measurement with a high-T_c SQUID [7,8].

- **SQUID systems for geomagnetic surveys**: to find oil in very deep layers underground: see http://www.tristantech.com/prod_geomagnetic.html and http://www.supracon.com, as well as http://www.csiro.au/Organisation-Structure/Divisions/Earth-Science--Resource-Engineering/geophysics/Superconducting-quantum-interference-devices.aspx. This is an **energy-related application**.

Photograph of geomagnetic airborne measurement with an 8-channel high-T_c SQUID tensor magnetometer system.

References

1) U. Poppe, J. Schubert and W. Evers "Method of fabricating thin layers from high-temperature oxide superconductors", *Patent US4965248* (1990)
2) U. Poppe, N. Klein, U. Dähne, H. Soltner, C. L. Jia, B. Kabius, K. Urban, A. Lubig, K. Schmidt, S. Hensen, S. Orbach, G. Müller, and H. Piel, "Low-resistivity epitaxial $YBa_2Cu_3O_{7-x}$ thin films with improved microstructure and reduced microwave losses," *J. Appl. Phys.*, **71** 5572 (1992)
3) M. I. Faley and U. Poppe, "Sputtering sources for high-pressure sputtering with large targets and sputtering method", *Patent DE201010049329* (2012)
4) M. I. Faley, "Reproduzierbarer Stufen-Josephson-Kontakt" *Patent DE102012006825* (2013).
5) M. I. Faley, D. Meertens, U. Poppe and R. E. Dunin-Borkowski, "Graphoepitaxial high-T_c SQUIDs", *Journal of Physics* (2014).
6) M. I. Faley, D. Meertens, U. Poppe and R. E. Dunin-Borkowski, "Graphoepitaxial Josephson junctions and DC SQUIDs", *IEEE Xplore* (2013) DOI: 10.1109/ISEC.2013.6604264
7) M. I. Faley, U. Poppe, R. E. Dunin-Borkowski , M. Schiek, F. Boers, H. Chocholacs, J. Dammers, E. Eich, N. J. Shah, A. Ermakov, V. Yu. Slobodchikov, Yu. V. Maslennikov, and V. P. Koshelets, "High-T_c DC SQUIDs for magnetoencephalography", *IEEE Trans. Appl. Supercond.* **23** 1600705 (2013)
8) J. Dammers, H. Chocholacs, E. Eich, F. Boers, M. I. Faley, R. E. Dunin-Borkowski and N. Jon Shah, "Source localization of brain activity using helium-free interferometer", *Appl. Phys. Lett.* **104**, 213705 (2014); http://dx.doi.org/10.1063/1.4880097.