



Приготовление, свойства и применения ВТСП пленок, переходов и ПТ СКВИДов.

М. И. Фалей

3. Dezember 2012

План доклада

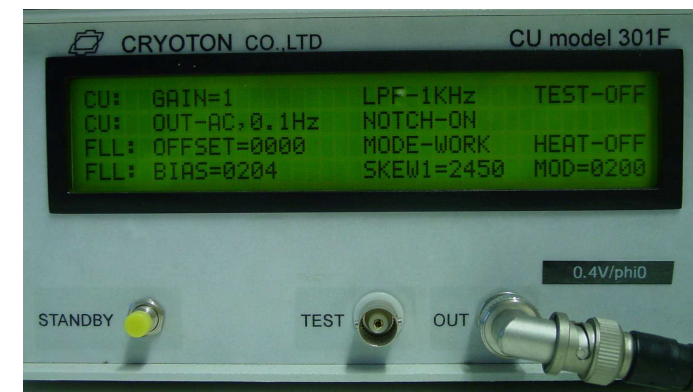
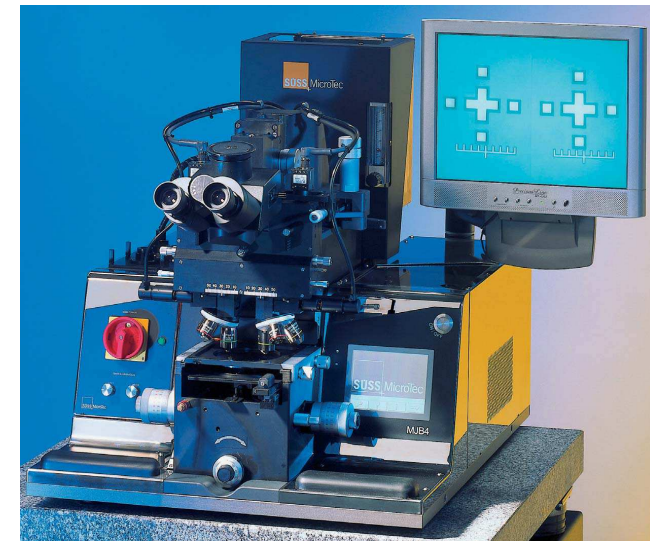
- Введение.
- Приготовление и свойства ВТСП пленок, джозефсоновских переходов и ПТ СКВИДов.
- ВТСП СКВИДы для биомагнитных систем.
- Магнитоэнцефалография с помощью ВТСП СКВИДов.
- Выводы.
- Перспективы.

Введение

- За последние годы произошел прогресс в изучении микроструктурных свойств и технологии ВТСП пленок, джозефсоновских переходов и СКВИДов, обзор которых будет приведен в докладе.
- ВТСП ПТ СКВИДы достигли чувствительности $\sim 4 \text{ фТ/Гц}^{1/2}$ при 77 К сравнимой с чувствительностью НТСП (4.2 К) МЭГ систем и могут послужить заменой низкотемпературным СКВИДам в системах МЭГ. Наблюдаемое в последнее время увеличение стоимости жидкого гелия стимулирует разработку ВТСП ПТ СКВИДов конкретно для МЭГ. В представляемой здесь работе были проделаны первые шаги в данном направлении.
- Сотрудничество между ИРЭ и Юлихом уже принесло множество положительных результатов для обеих сторон. Есть возможности его укрепить в бóльшем диапазоне исследований. Об этом также будет вкратце обсуждено в докладе.

HT_c DC SQUID technology at PGI-5 FZJ

- **High oxygen pressure (~3 mbar) dc- and rf-magnetron sputtering:
YBCO: T_c ≈ 93 K and J_c ≈ 6 MA/cm² at 77 K.**
- **DUV Mask Aligner MJB4 (SÜSS MicroTec).
Resolution < 0.5 μm.**
- **AC-bias DC SQUID electronics from
Cryoton Co Ltd.**

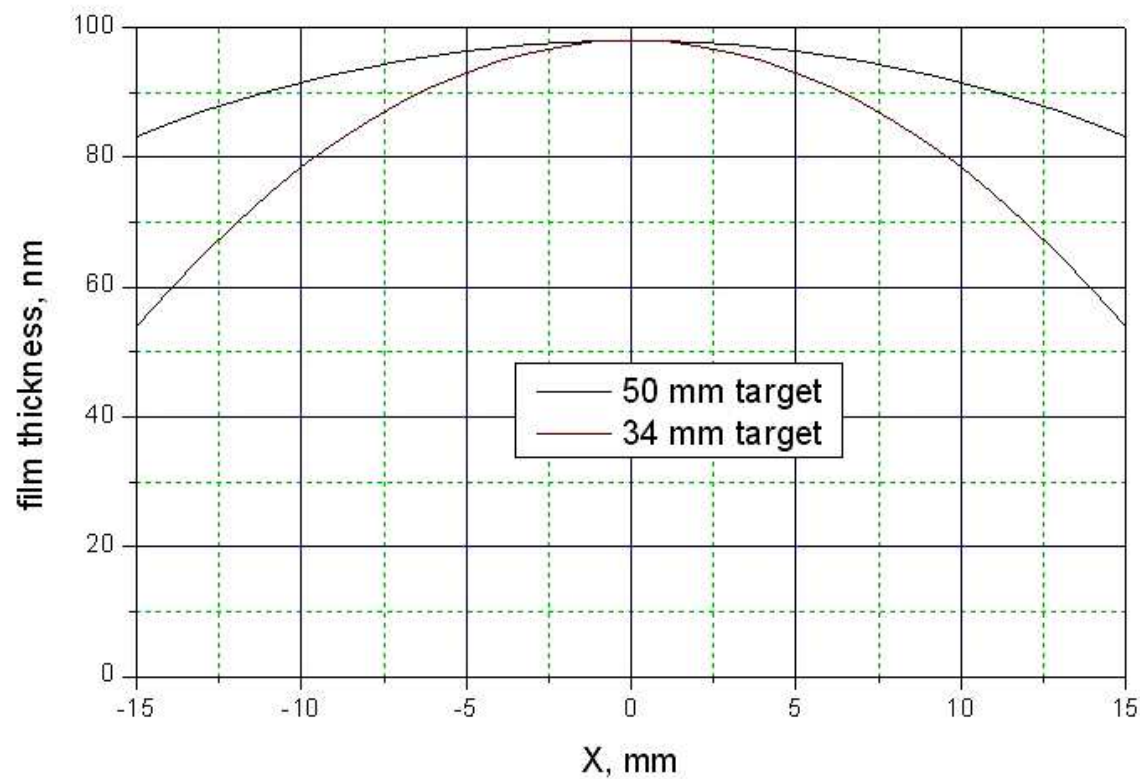
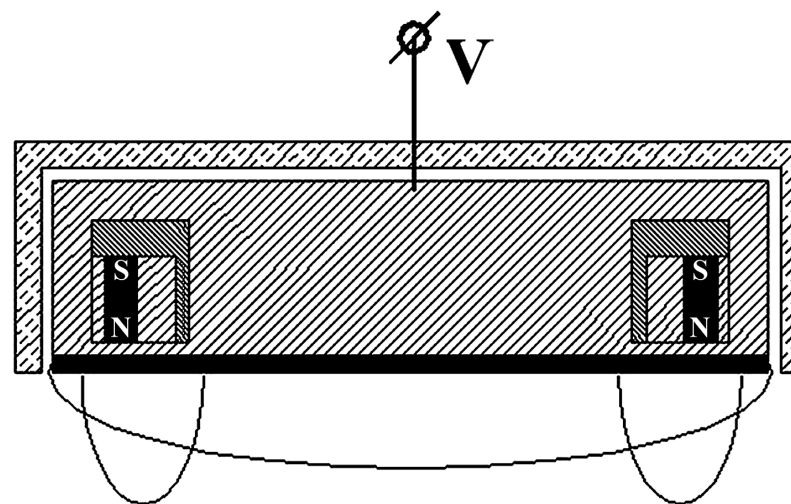


Microstructural analysis at PGI-5 in FZJ

- **Scanning electron microscope JEOL 7400F** for the analysis of the physical and chemical microstructure of solid state materials at nanometer resolution.
- **FEI Helios Nanolab 400s FIB system** for UHRTEM sample preparation equipped with SEM, EDAX microanalysis system and Pt deposition.
- **HRTEM FEI Titan 60-300 PICO** with resolution of about 50 pm at 300 kV is a unique fourth generation field emission gun transmission electron microscope equipped with a high-brightness electron gun, a monochromator unit, and a Cs probe corrector.
- **AFM, etc.**



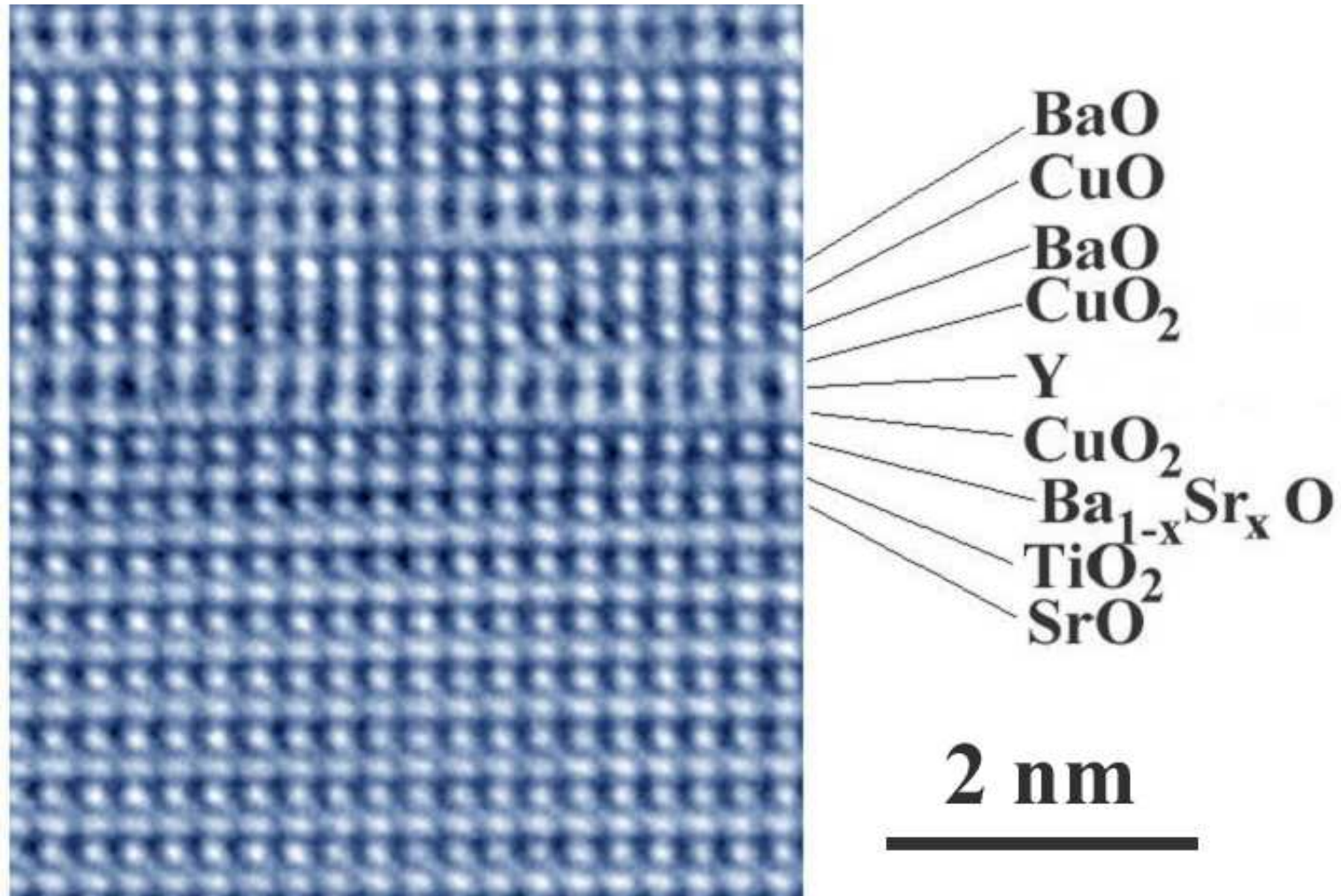
Магнетронное распыление оксидных пленок и гетероструктур



M. I. Faley and U. Poppe (2010)

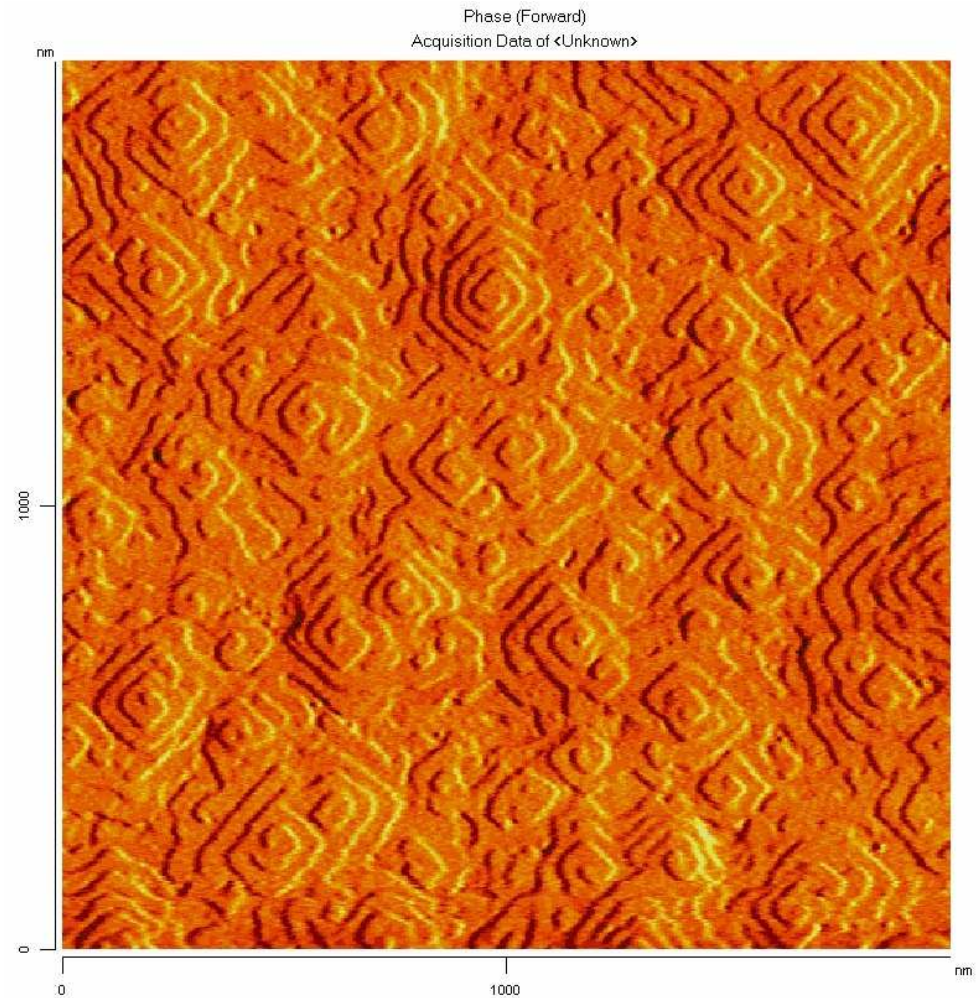
Patent WO2012051980.

HRTEM пленки YBCO на подложке SrTiO3



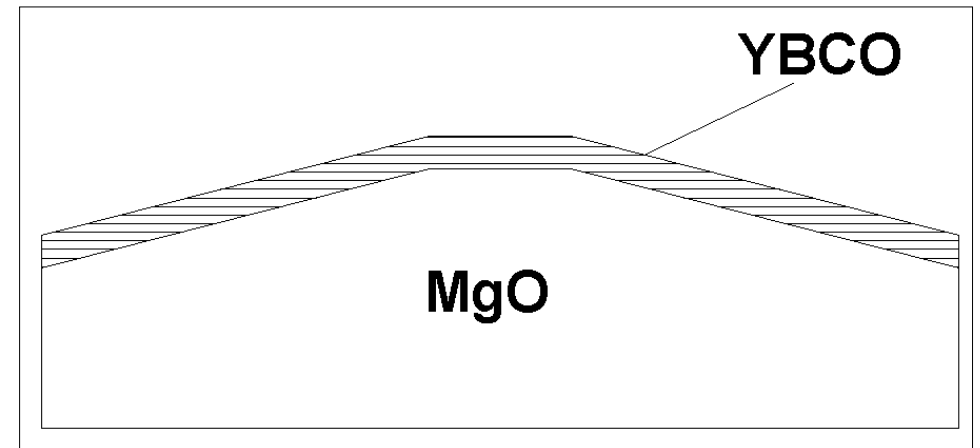
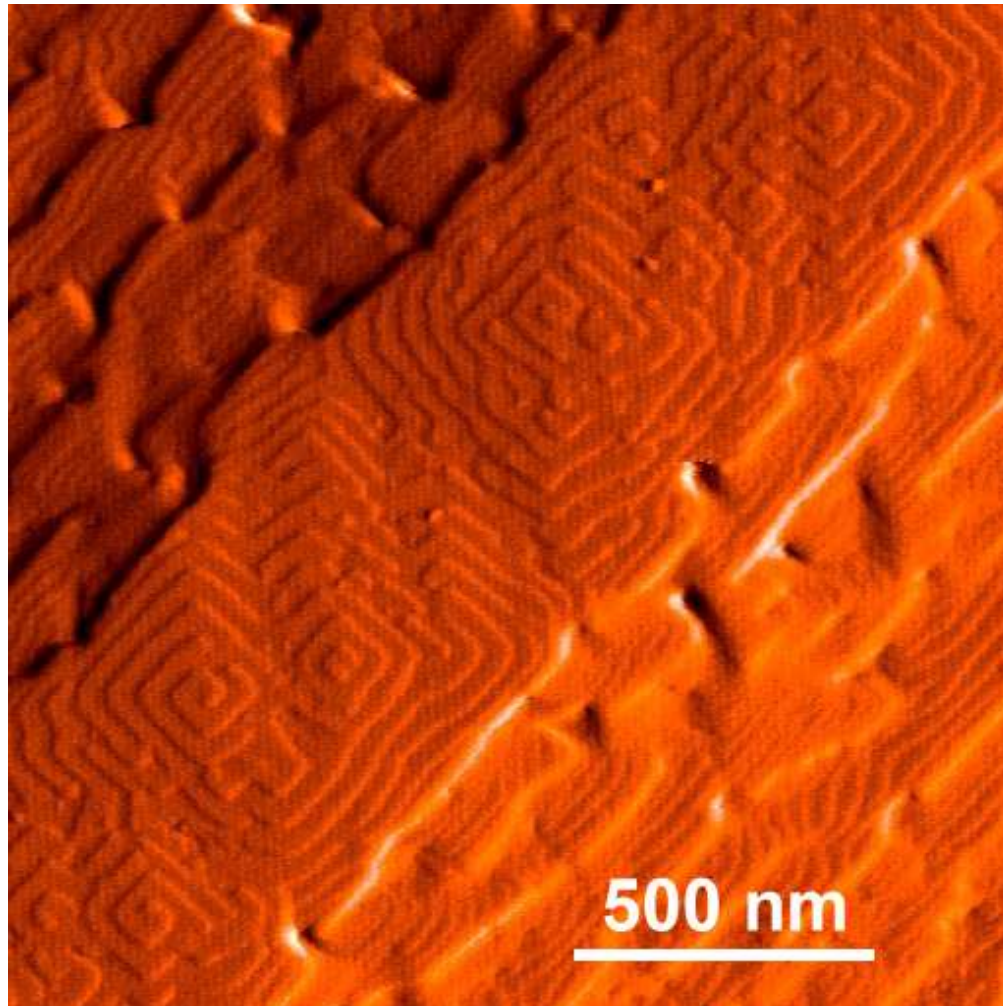
M. I. Faley, In "Applications of High- T_c Superconductivity", ISBN 978-953-307-308-8, 147 (2011).

YBCO пленки подложках MgO



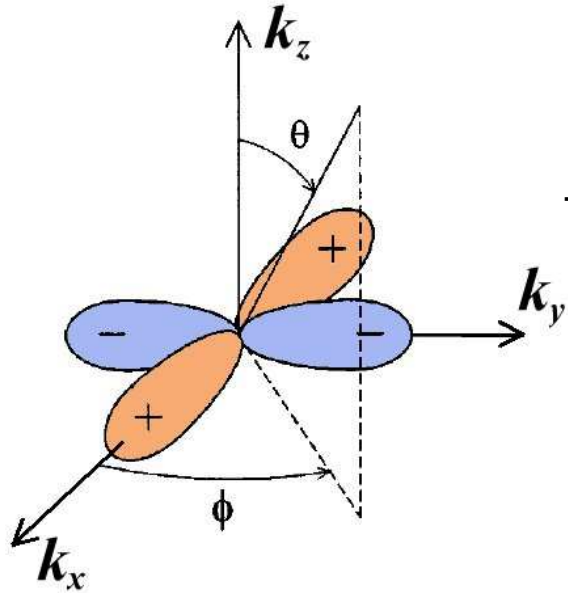
AFM images ($2\mu\text{m} \times 2\mu\text{m}$) of surfaces of 130 nm thick YBCO films deposited on as-received (left) MgO substrates and on IBE-cleaned (right) MgO substrates.

Пленка YBCO на структурированной IBE подложке MgO



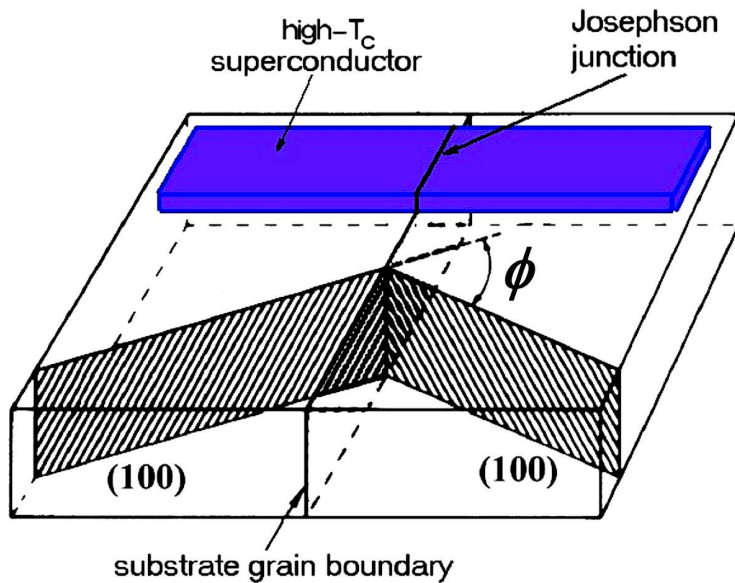
AFM image of a 140 nm thick YBCO film deposited on IBE-cleaned trapezoidal feature on a (100) MgO substrate with about 3 degree slopes (left picture). The sketch of the structure is shown in the right picture.

High- T_c Josephson junctions and d-wave symmetry

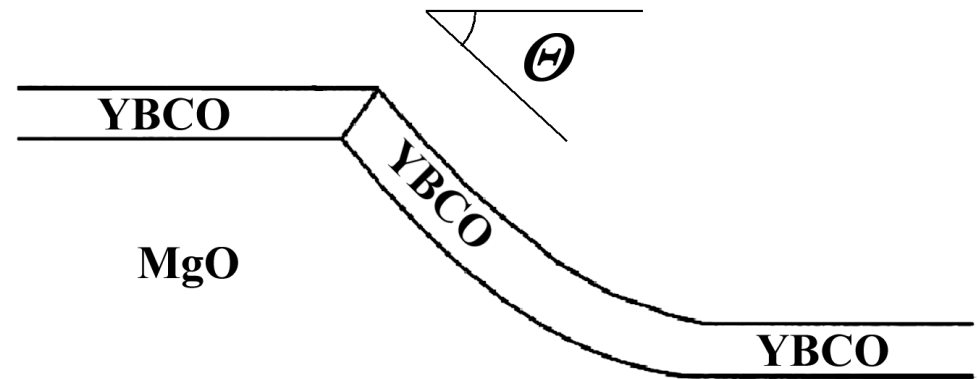


The SC gap function in $d_{x^2-y^2}$ symmetry in momentum space

$$\Delta(\hat{k}) \sim k_x^2 - k_y^2 = (\cos^2 \phi - \sin^2 \phi) \sin \theta = \cos(2\phi) \sin \theta$$



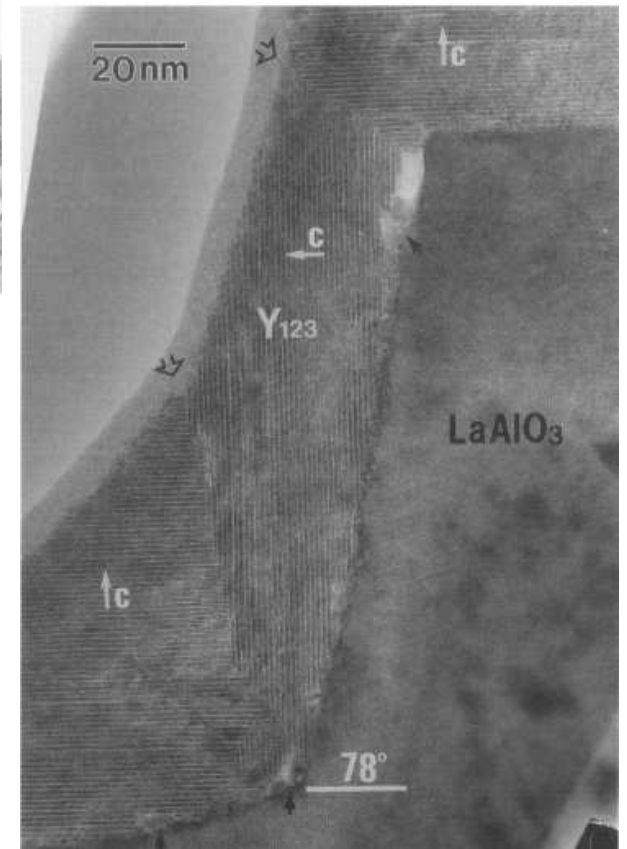
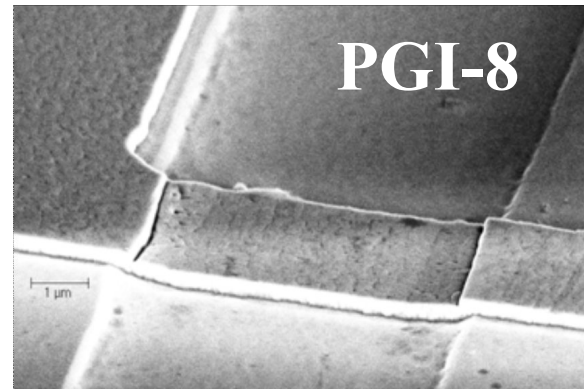
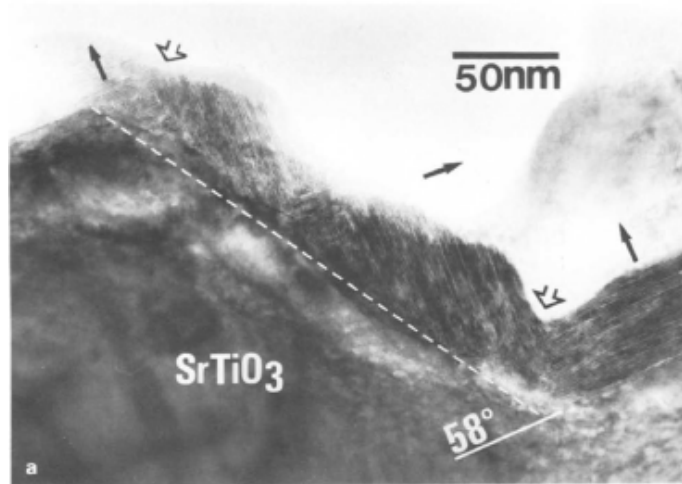
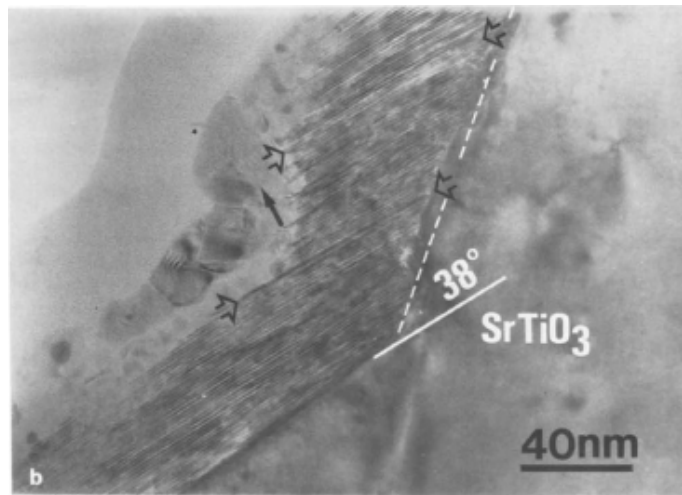
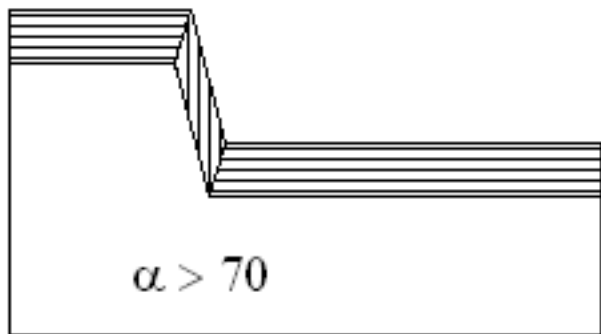
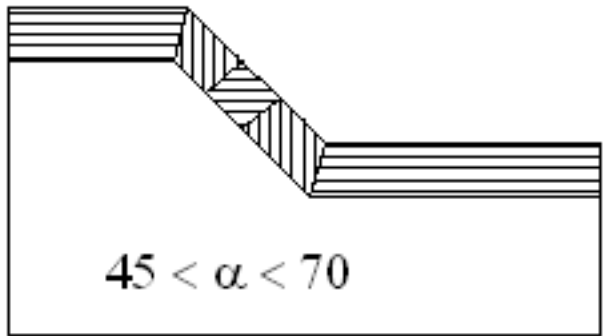
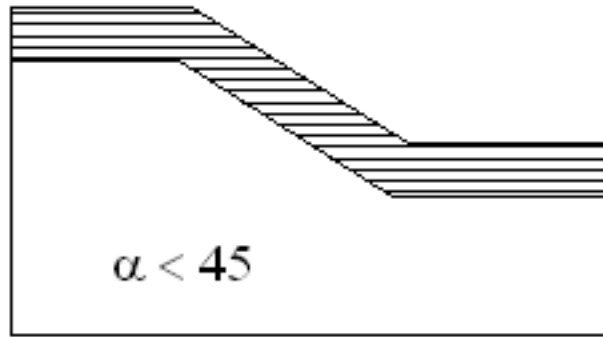
Bicrystal Josephson junction



Slide-type step-edge Josephson junction

C. Foley, patent US6514774 (2003)

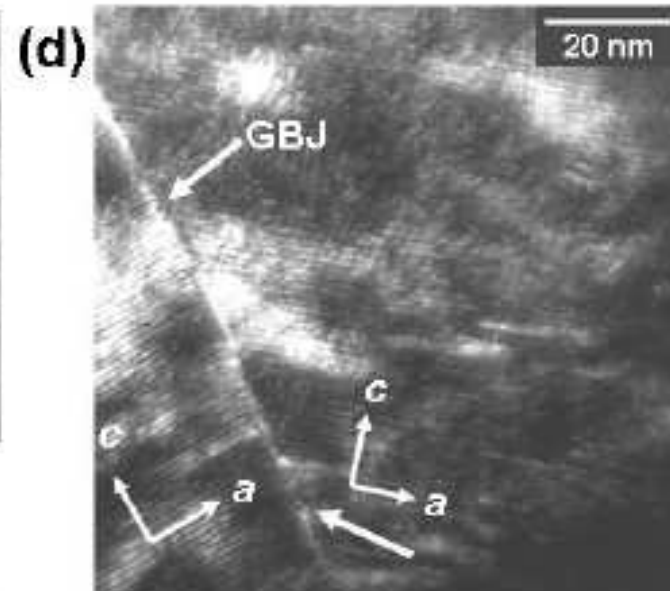
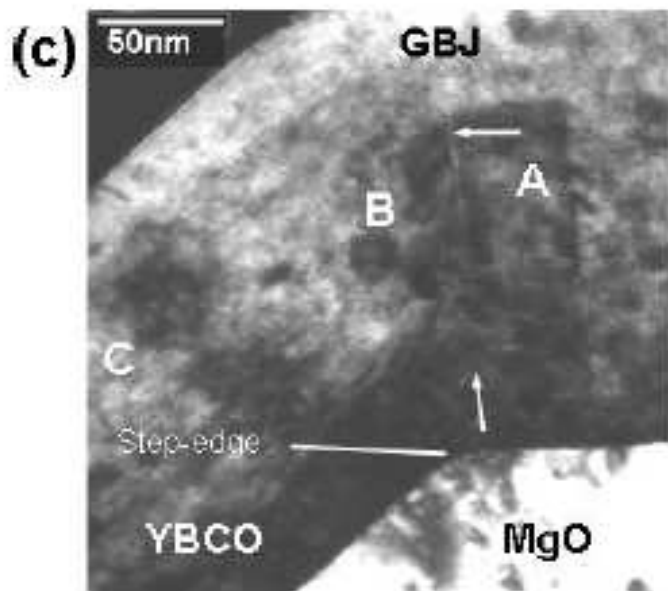
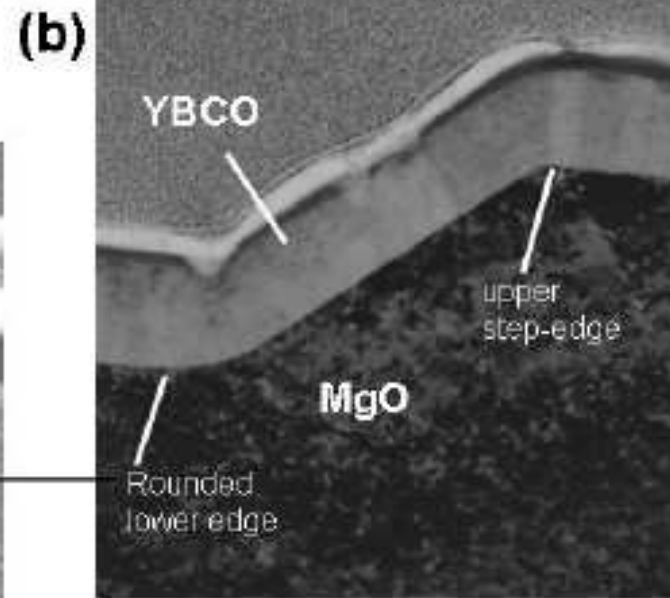
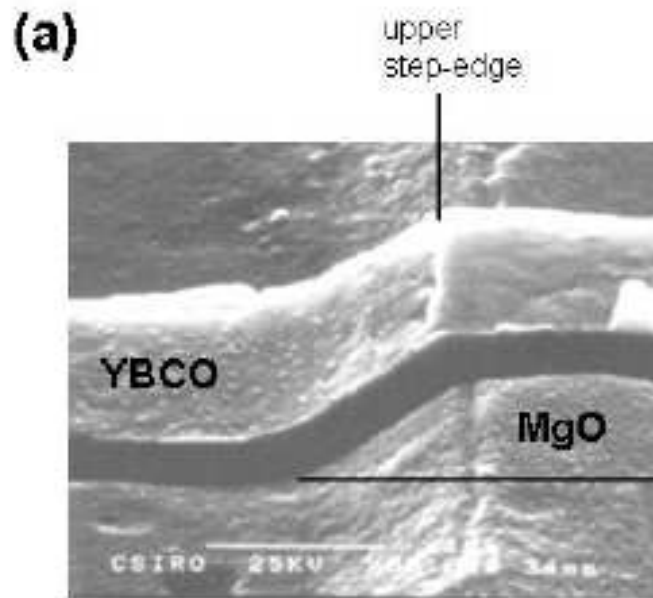
Old type step-edge junctions



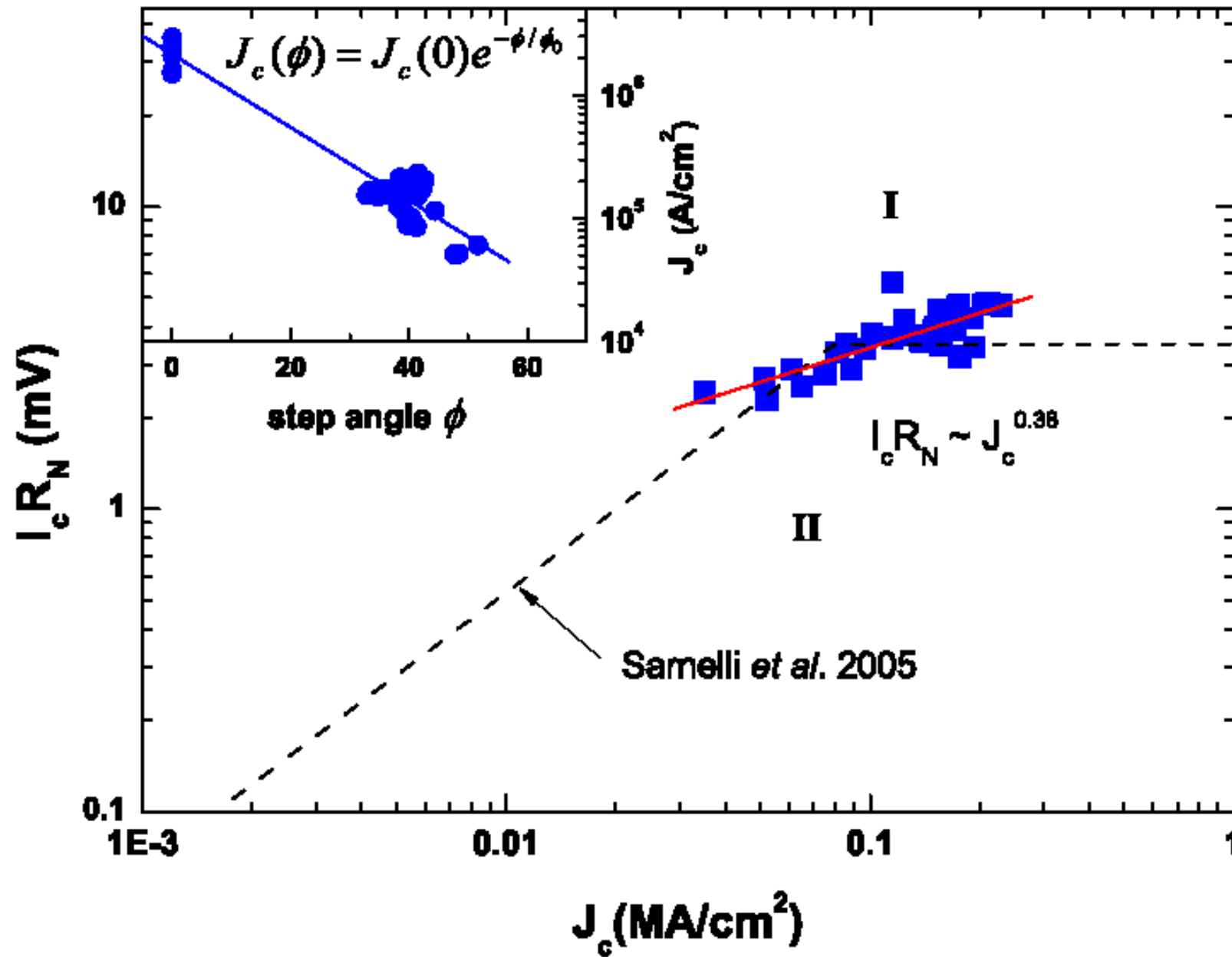
C L Jia et al., *Physica C*
175 545 (1991)

C L Jia et al., *Physica C* 196 211 (1992)

Step-edge junctions on MgO

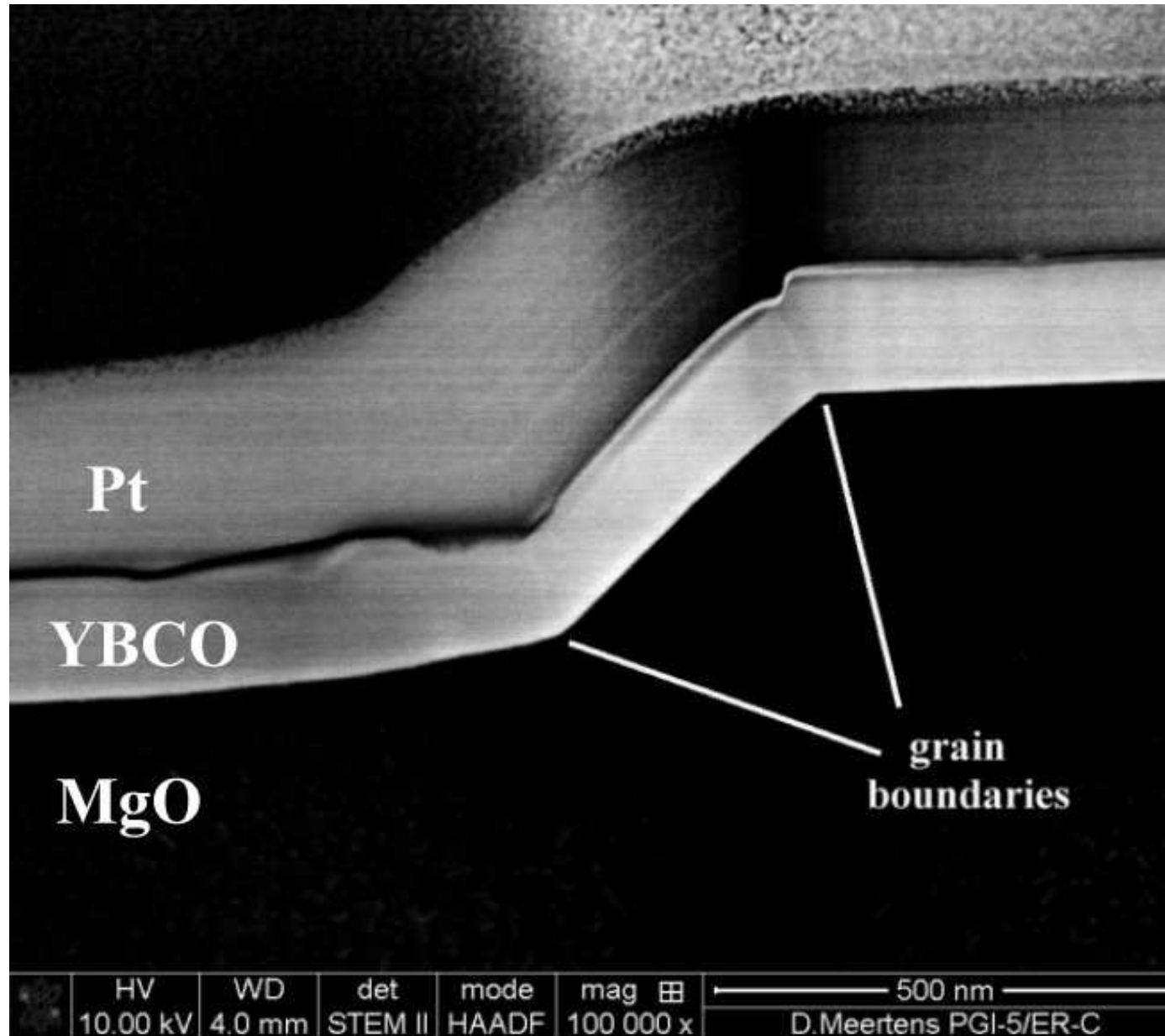


Slide-type step-edge junctions

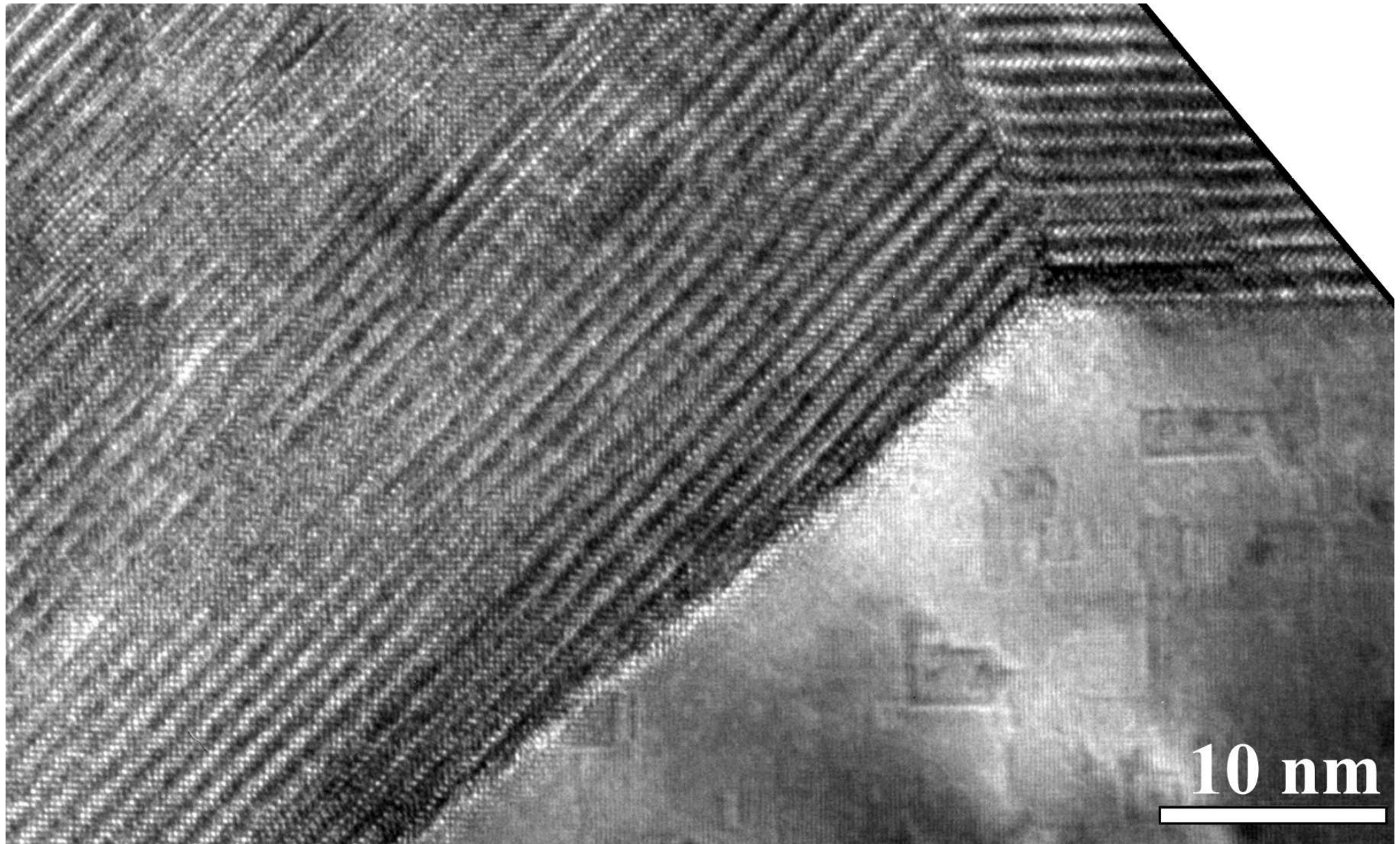


Mitchell and Foley, *SuST* 23 065007 (2010)

TEM image of a step-edge junction on MgO substrate



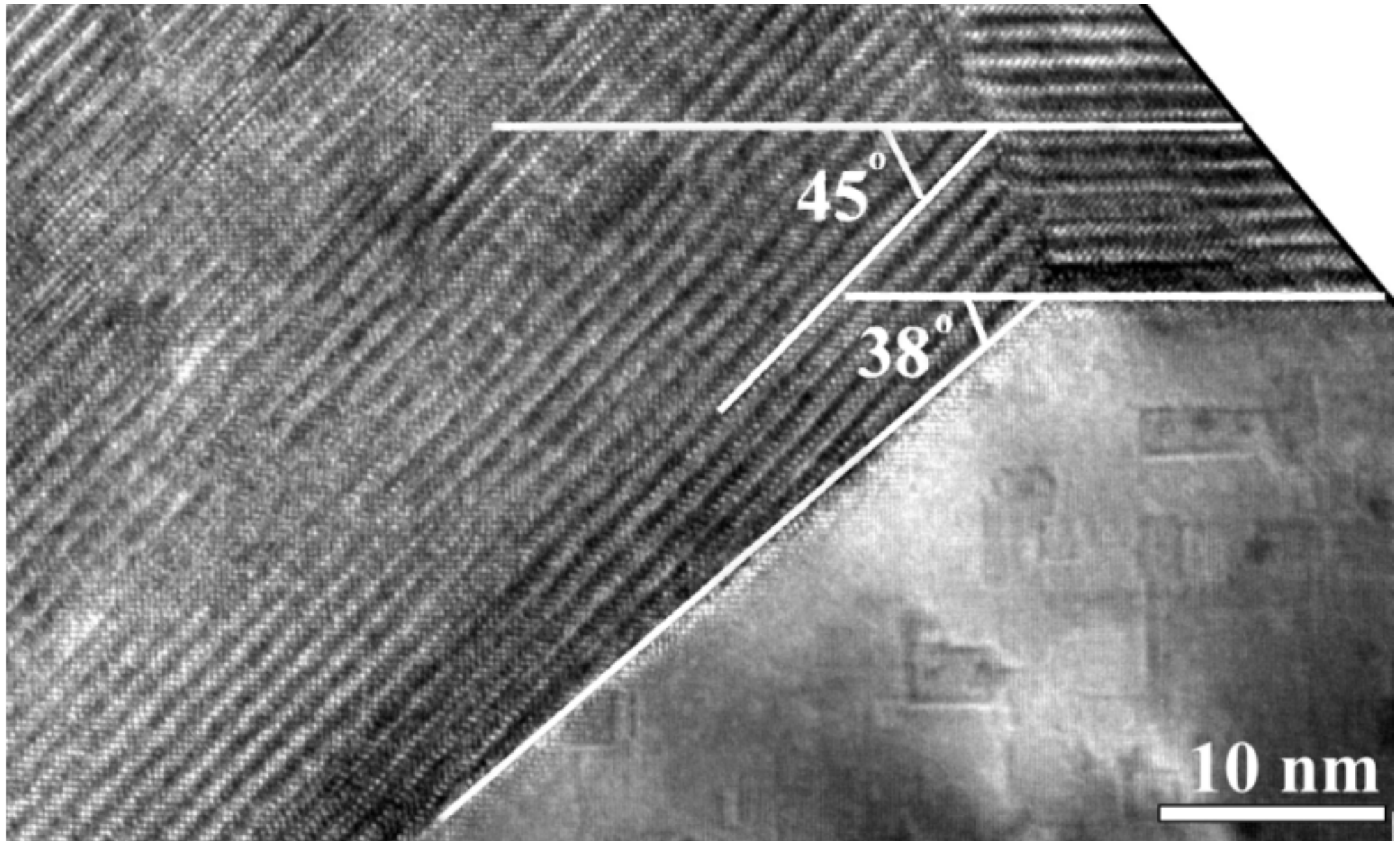
HRTEM of YBCO deposited on the textured step edge



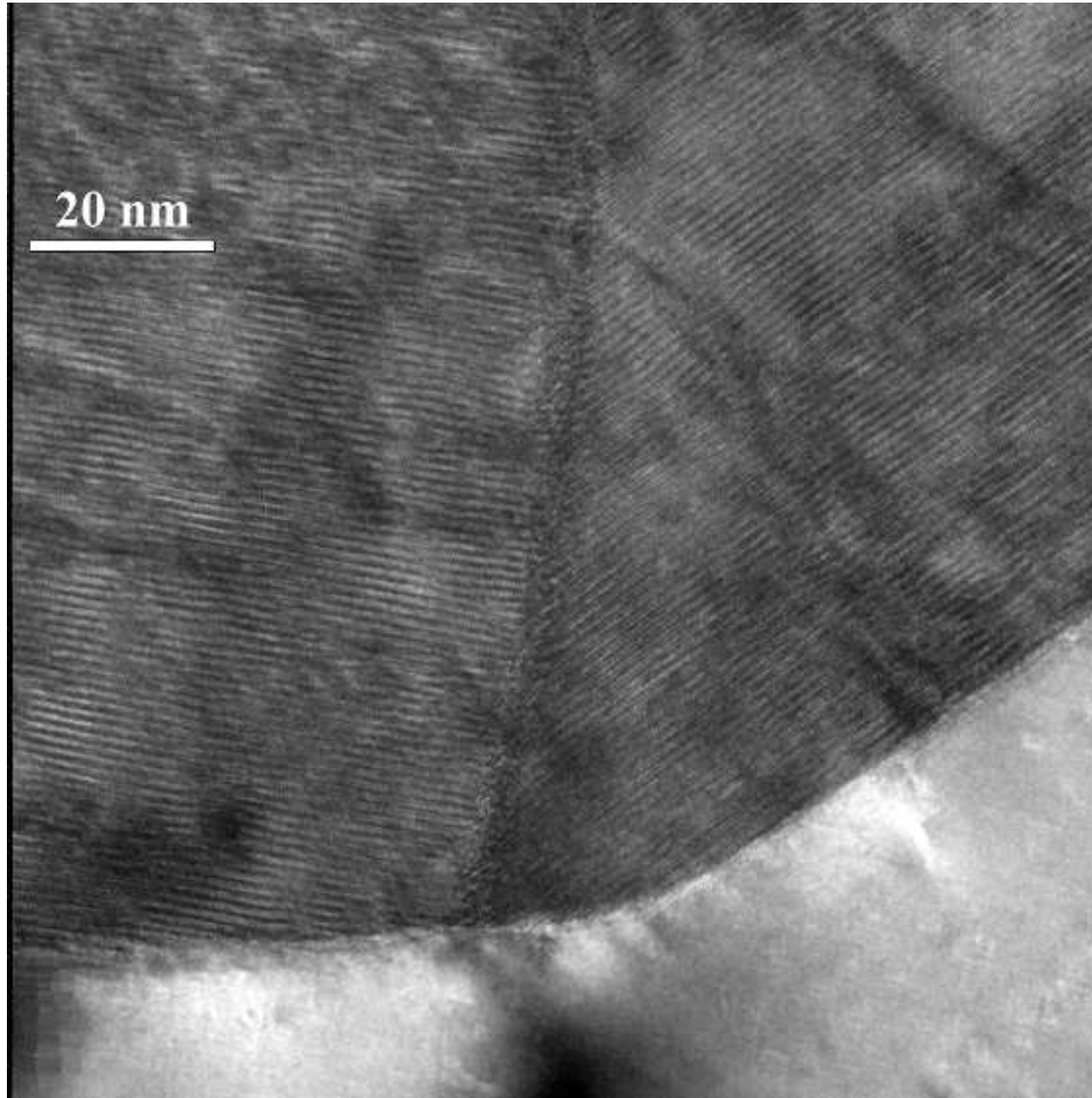
HRTEM image of the YBCO film deposited on the top of the step edge.

M. I. Faley et al., Accepted for IEEE Trans Appl.Supercond. (2013)

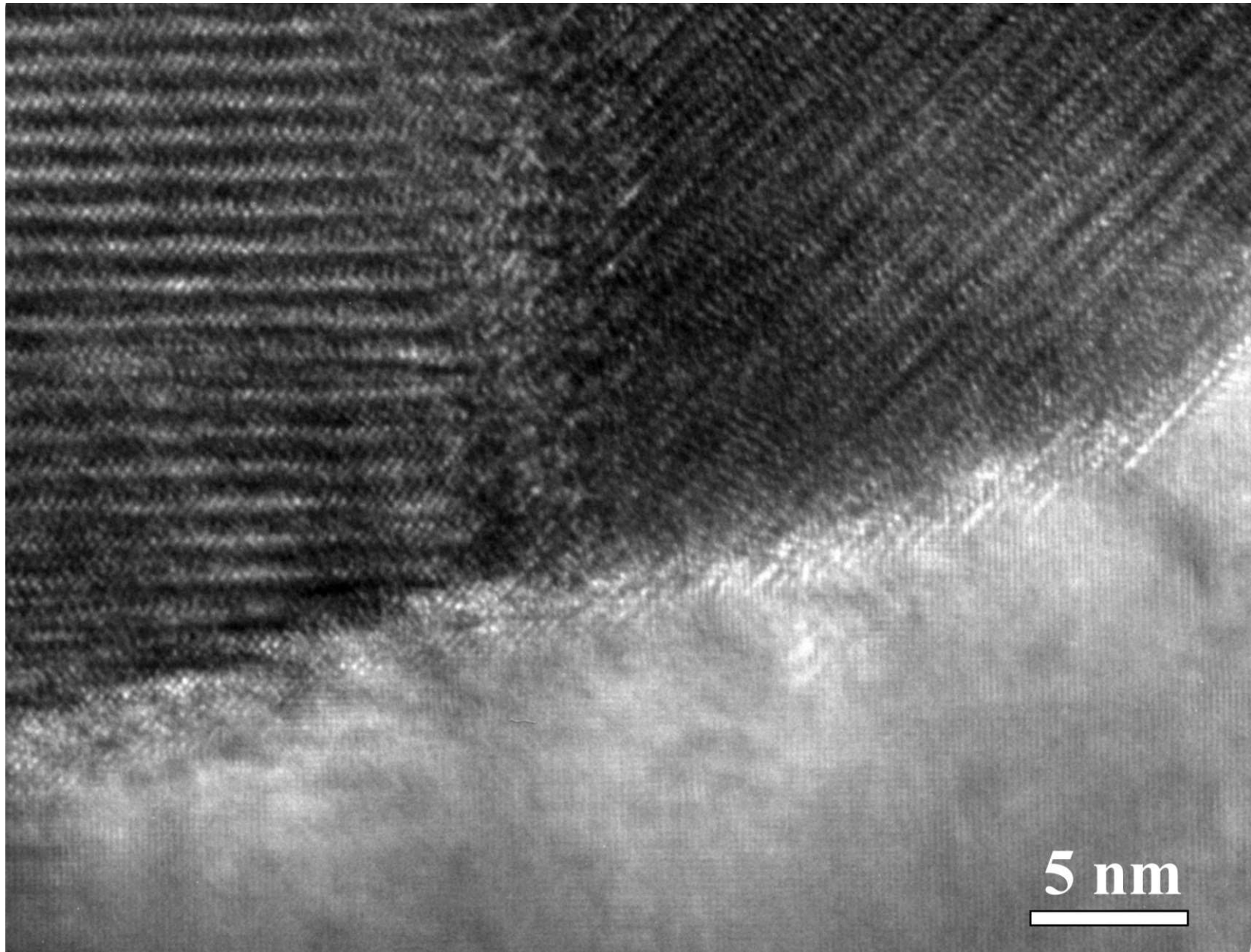
HRTEM image of the YBCO film deposited on the top of the step edge.



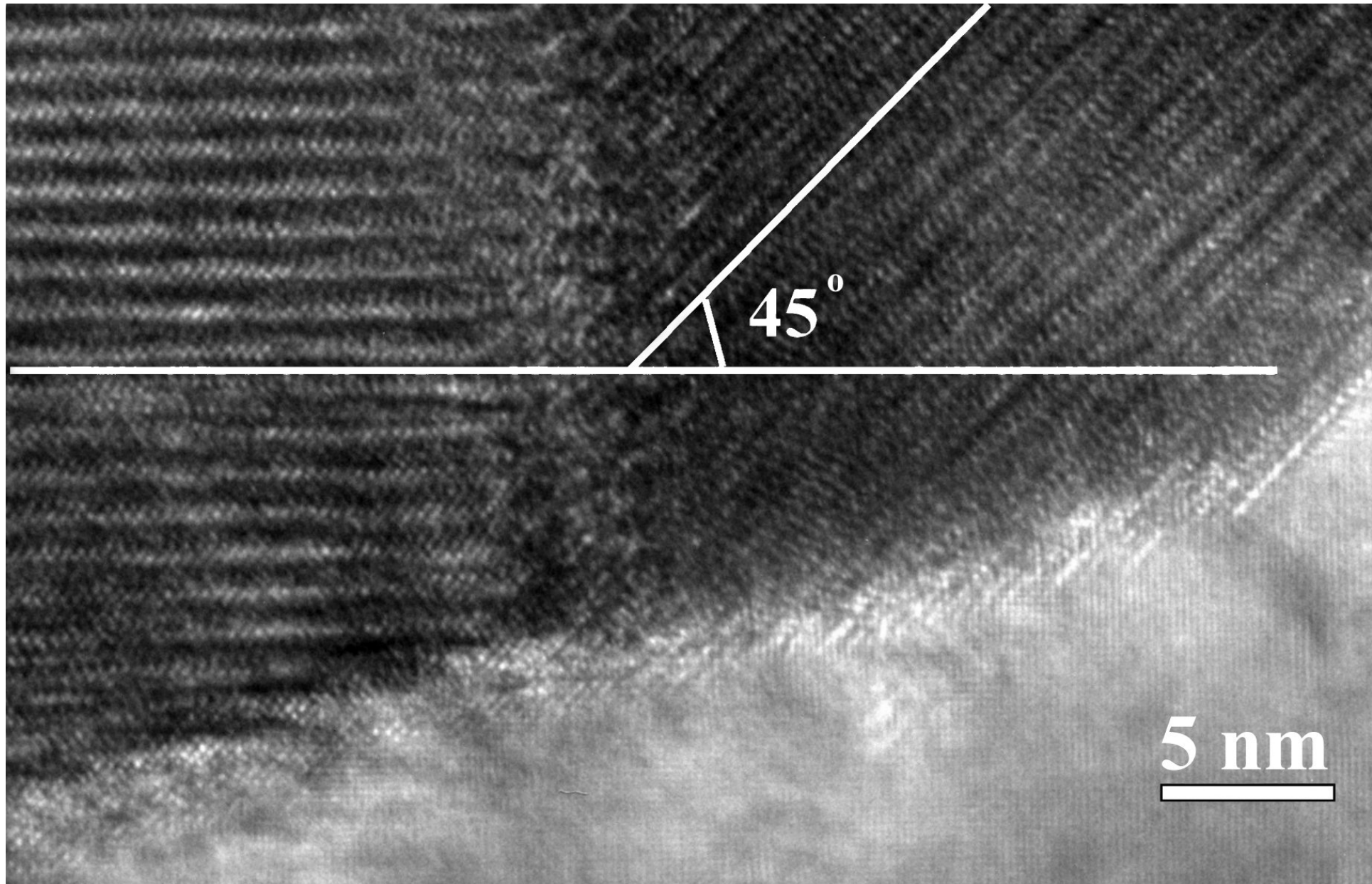
HRTEM image of the YBCO film deposited on the bottom of the MgO step edge.



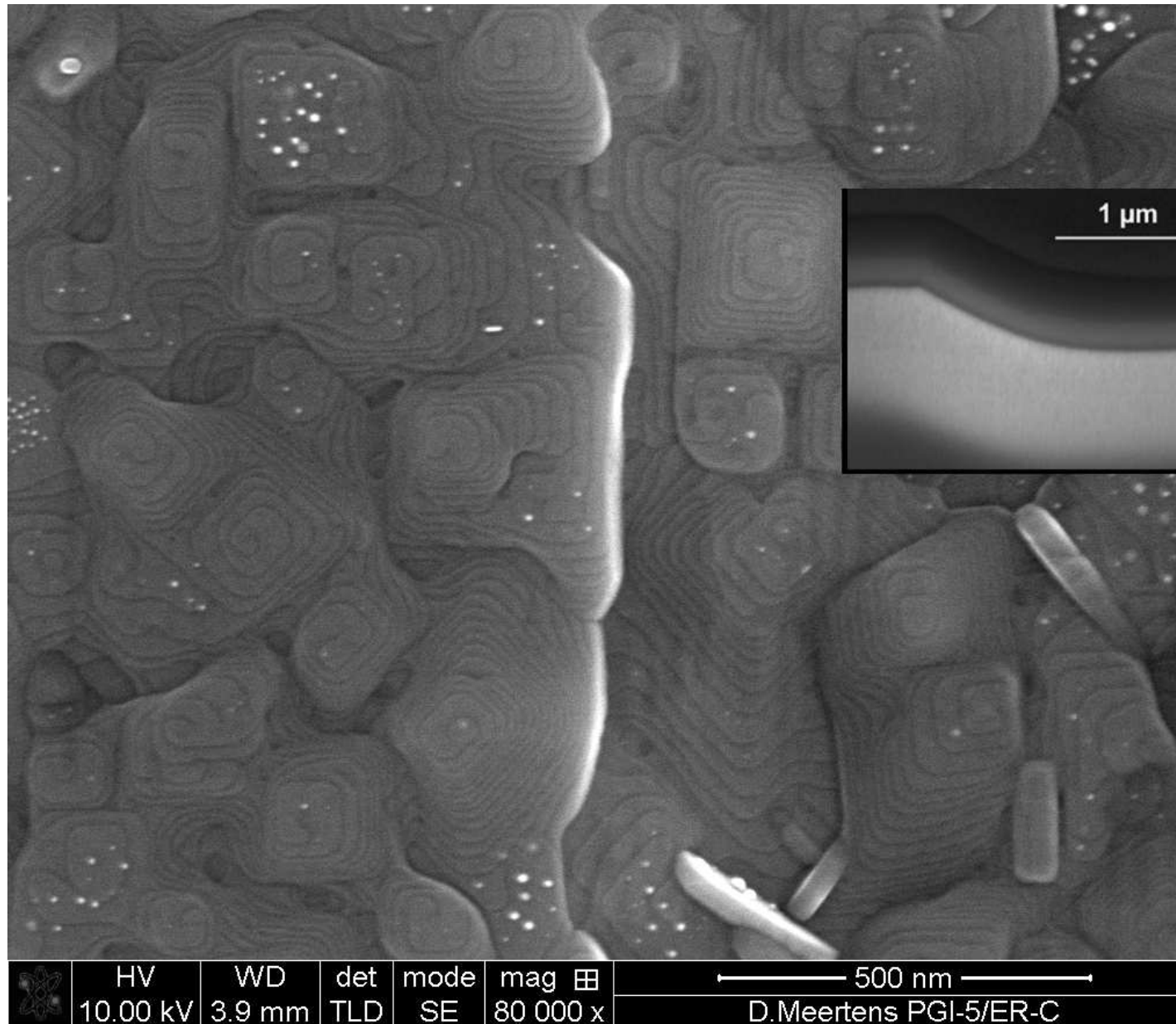
HRTEM of YBCO deposited on the textured step edge



HRTEM of YBCO deposited on the textured step edge

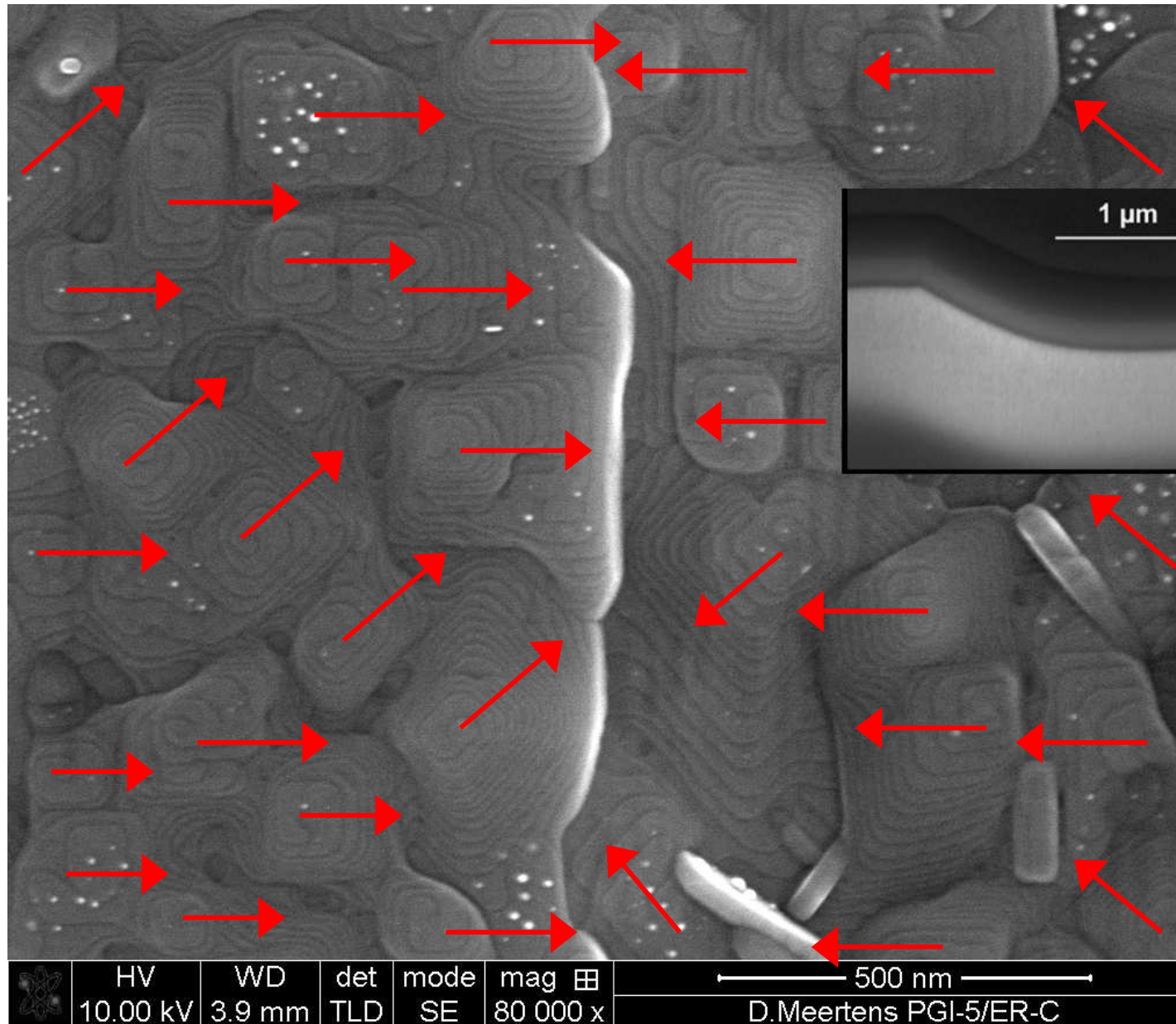


Step-edge junction without surface texturing



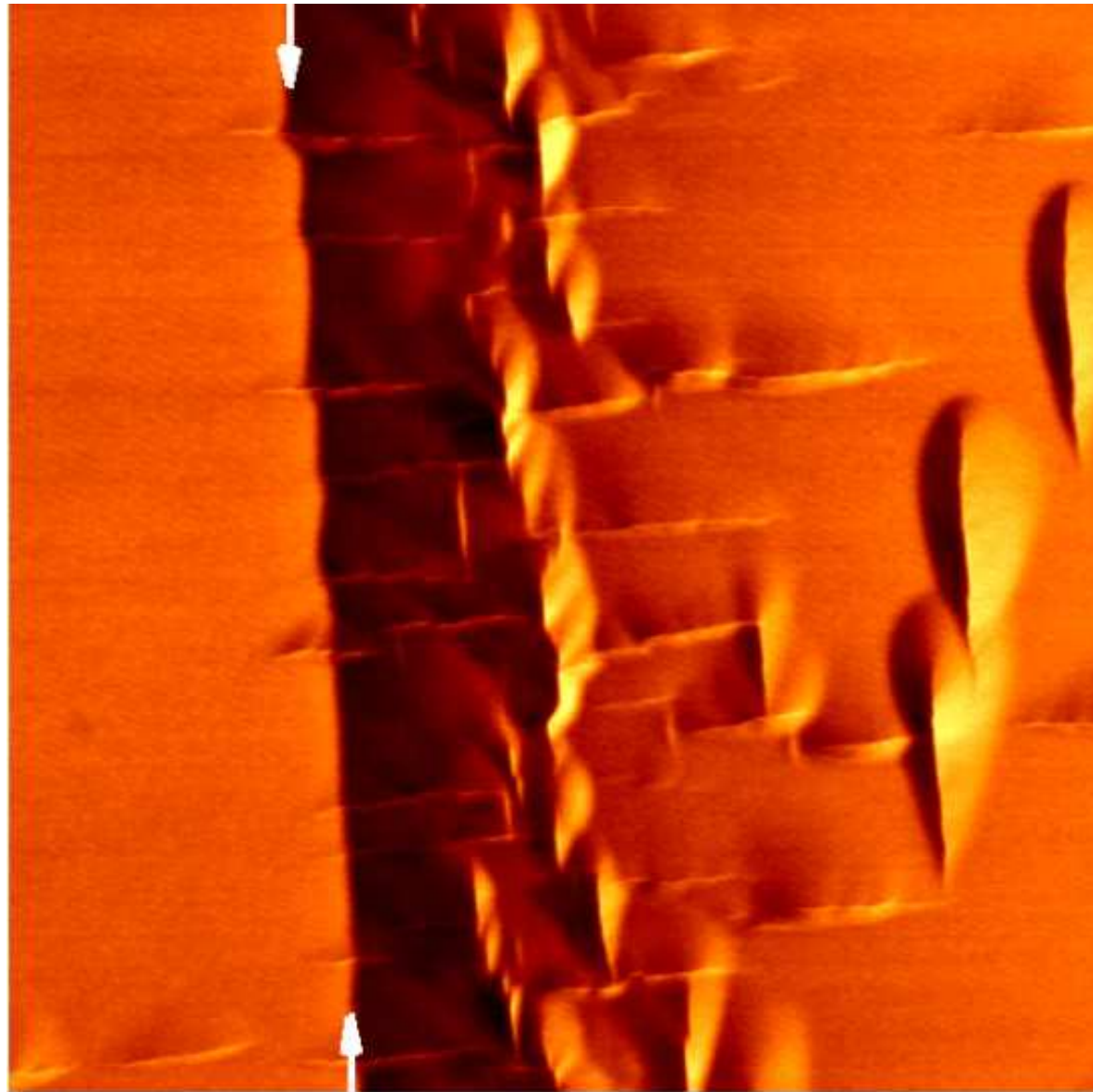
SEM image of the surface of an YBCO film deposited on an MgO substrate step edge without surface texturing. The inset shows a cross-section of a similar substrate edge structure made by FIB-milling.

Step-edge junction without surface texturing



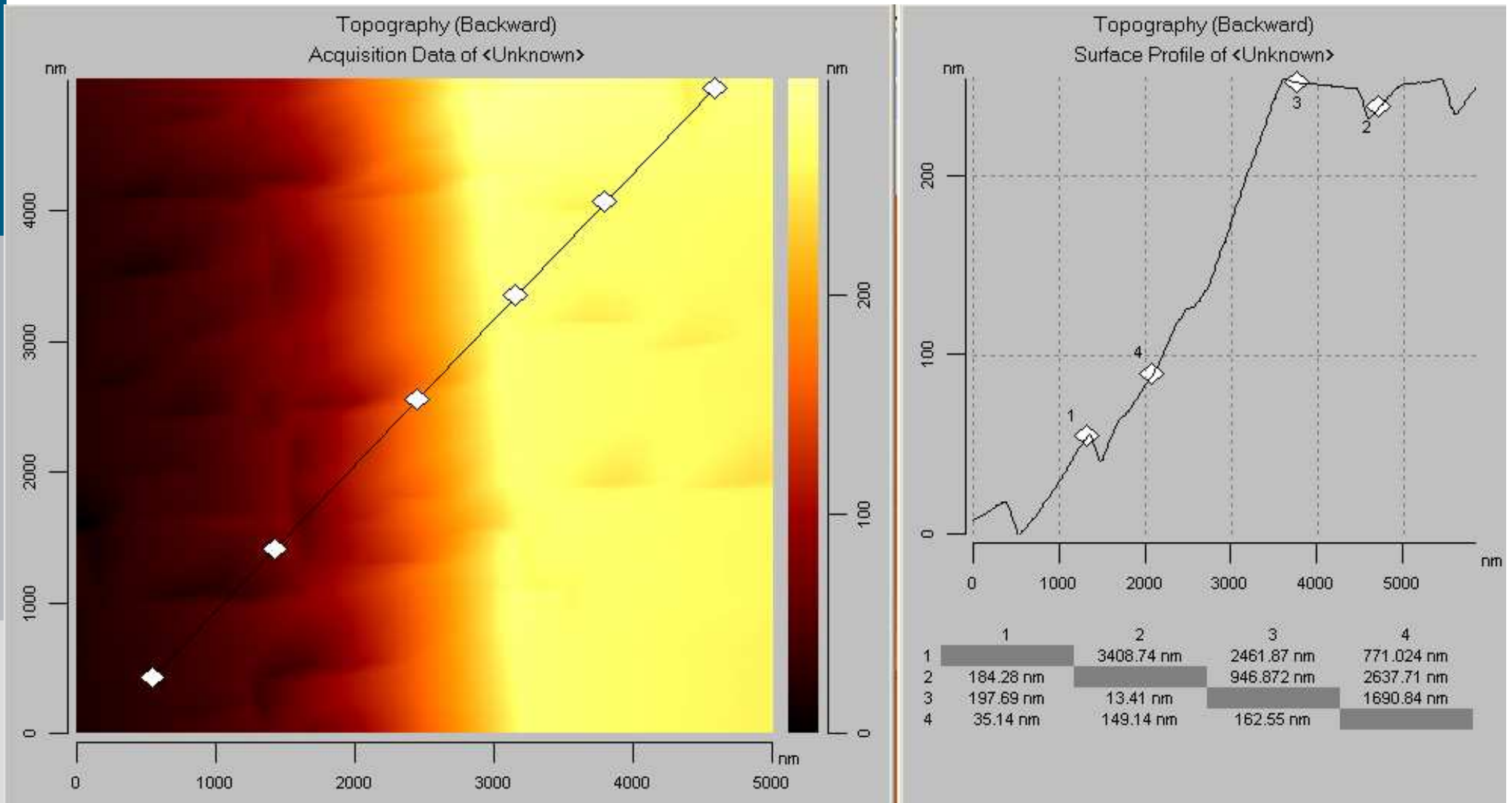
SEM image of the surface of an YBCO film deposited on an MgO substrate step edge without surface texturing. The inset shows a cross-section of a similar substrate edge structure made by FIB-milling.

Textured surface of step edge on MgO



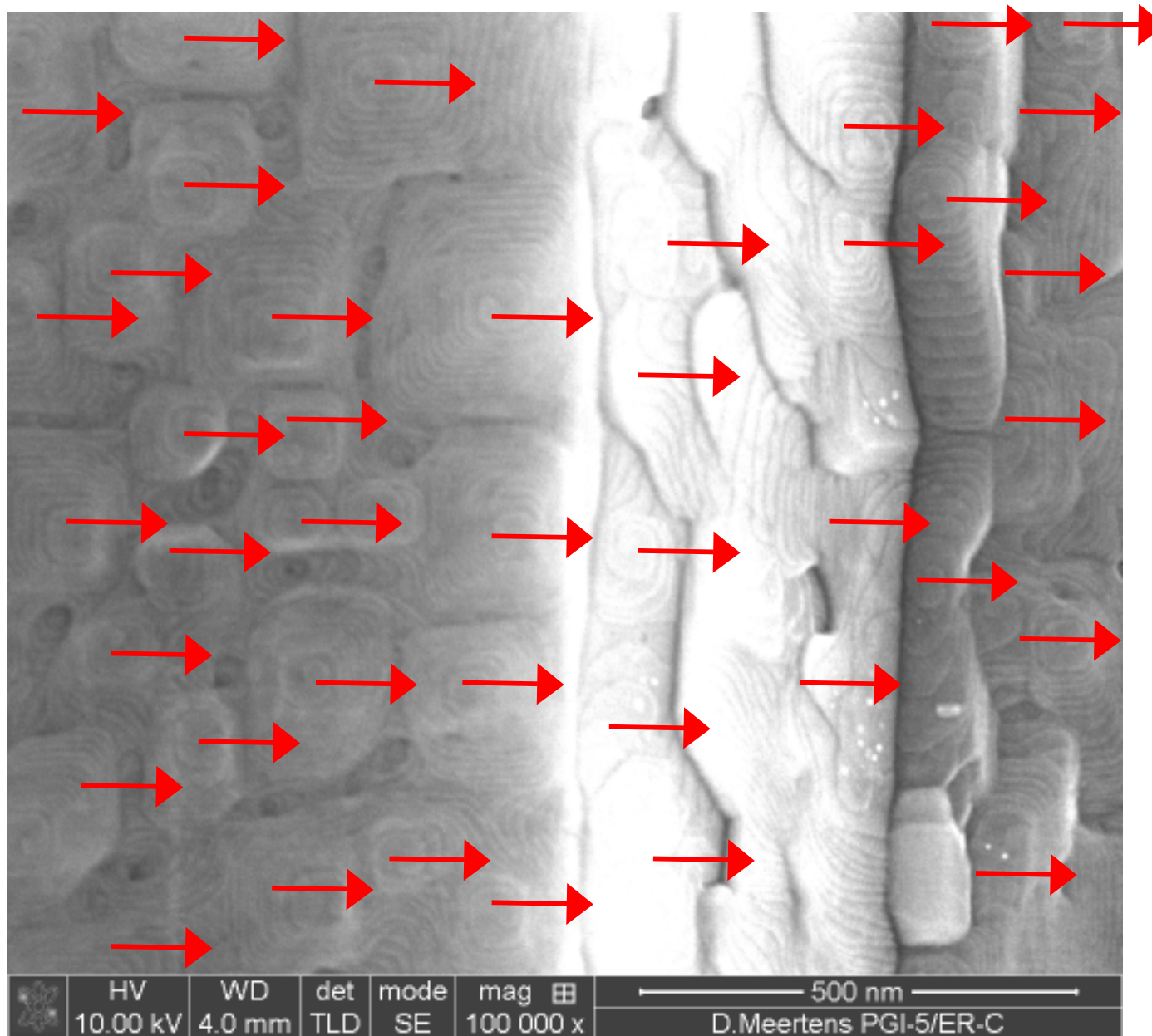
AFM-image of an IBE-textured surface of a step edge on MgO.

Textured surface of step edge on MgO



AFM-image of an IBE-textured surface of a step edge on MgO.

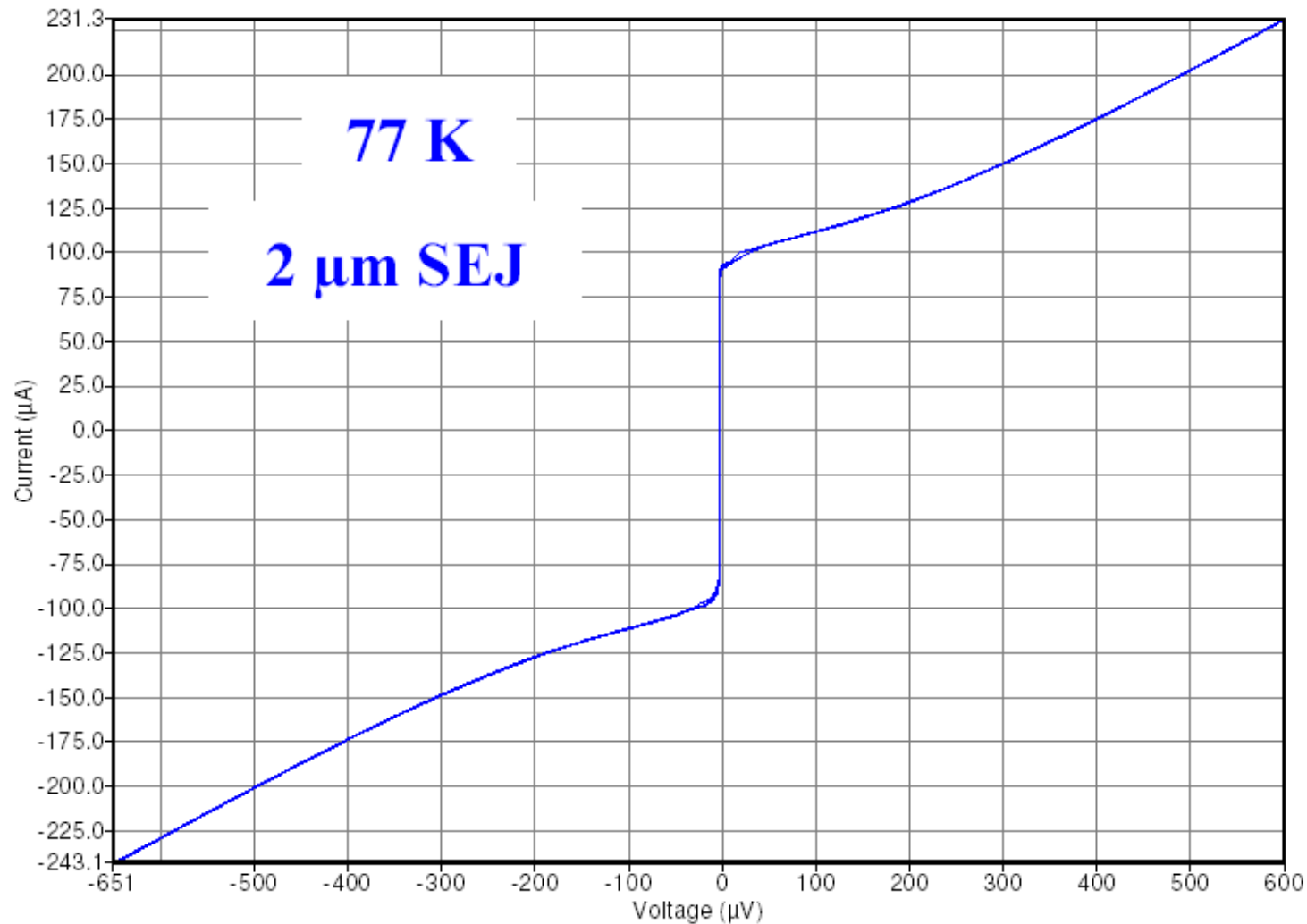
YBCO film deposited on the step-edge with surface texturing



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

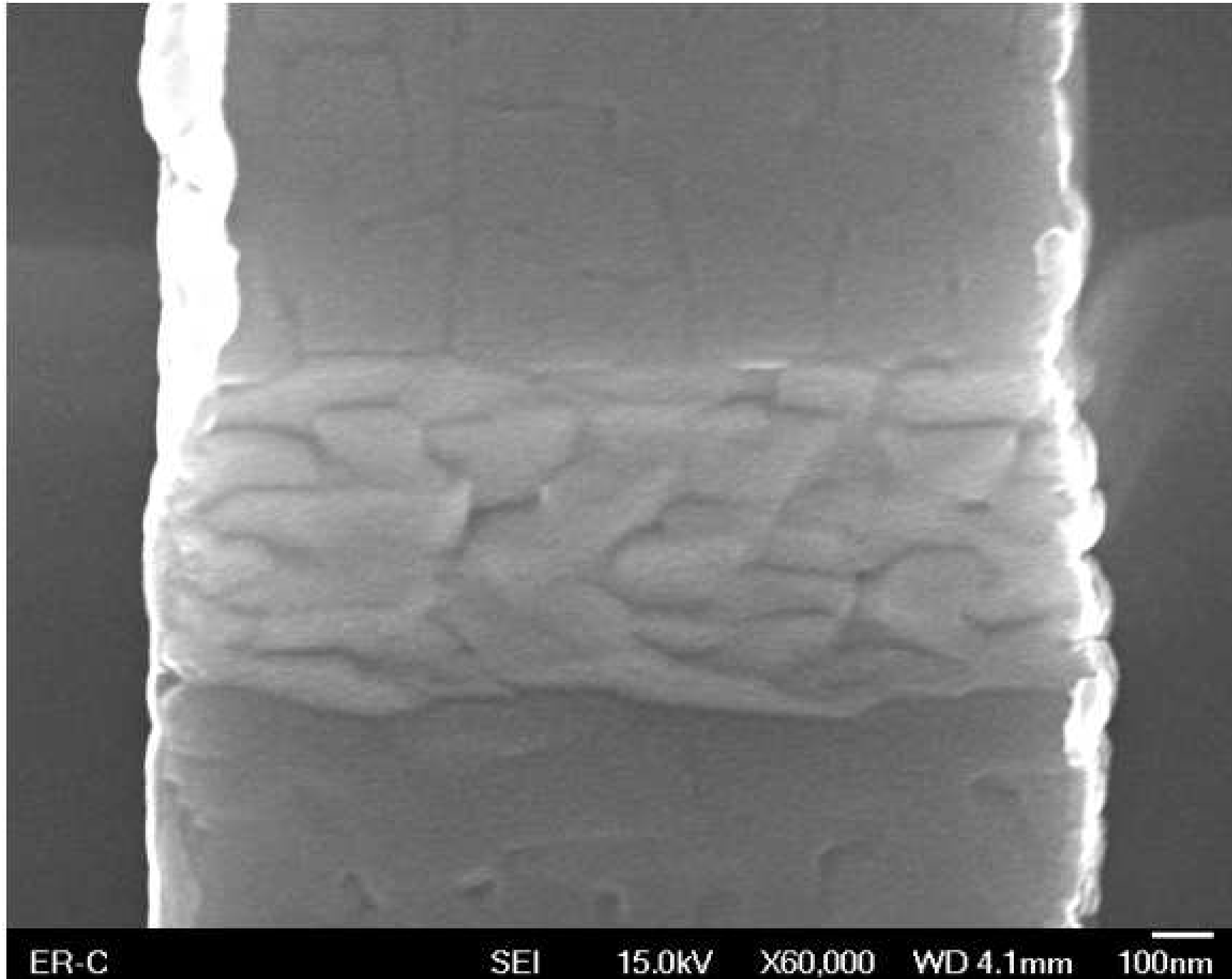
Slide-type step-edge junctions

(shunted SEJ, 4-May-2012)

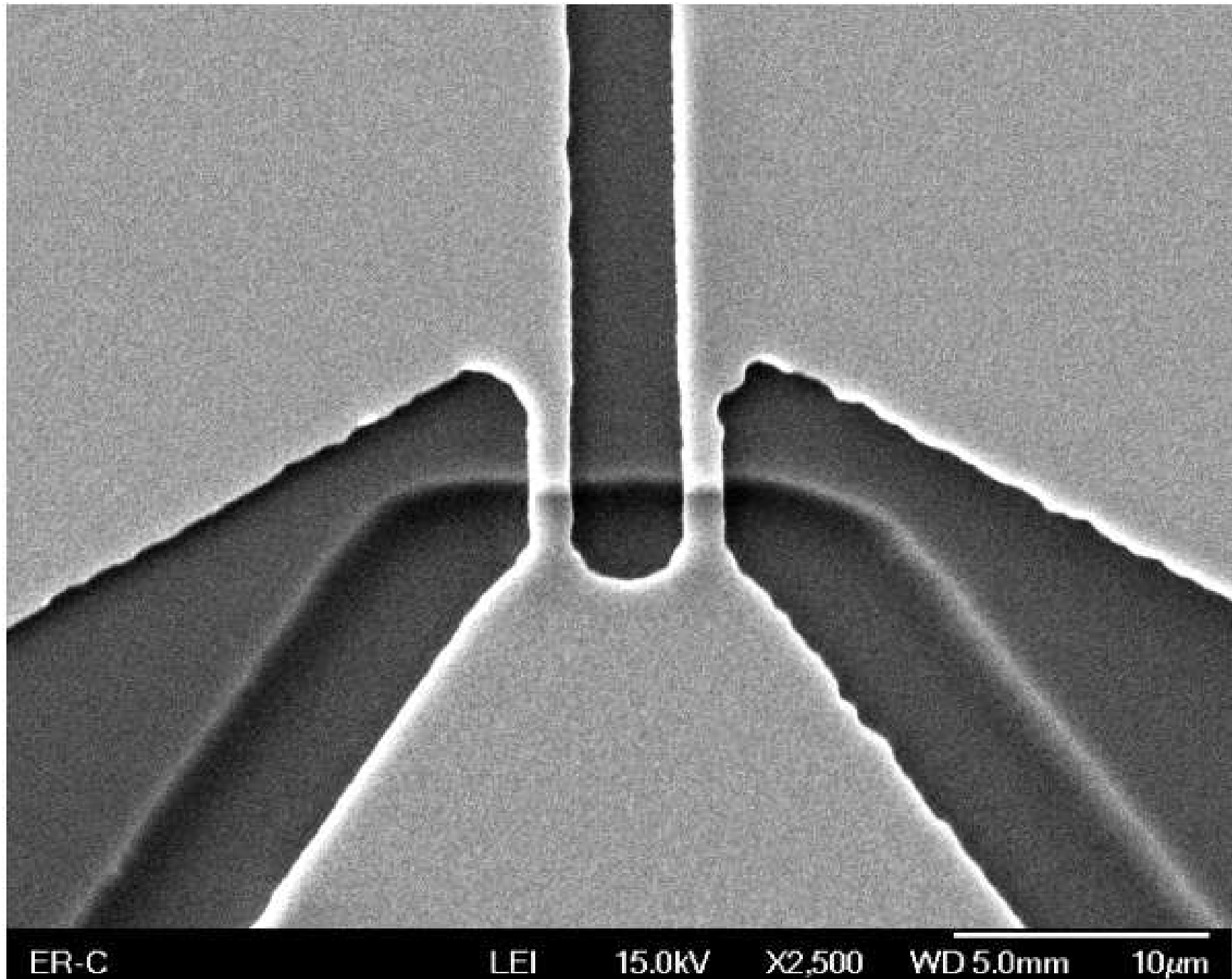


IVC of a Pt-shunted Josephson junction on a textured and AE-buffered MgO substrate slide-type step-edge: $I_c = 100 \mu\text{A}$, $R_n = 3 \text{ ohm}$, $I_c R_n = 300 \mu\text{V}$ at 77 K

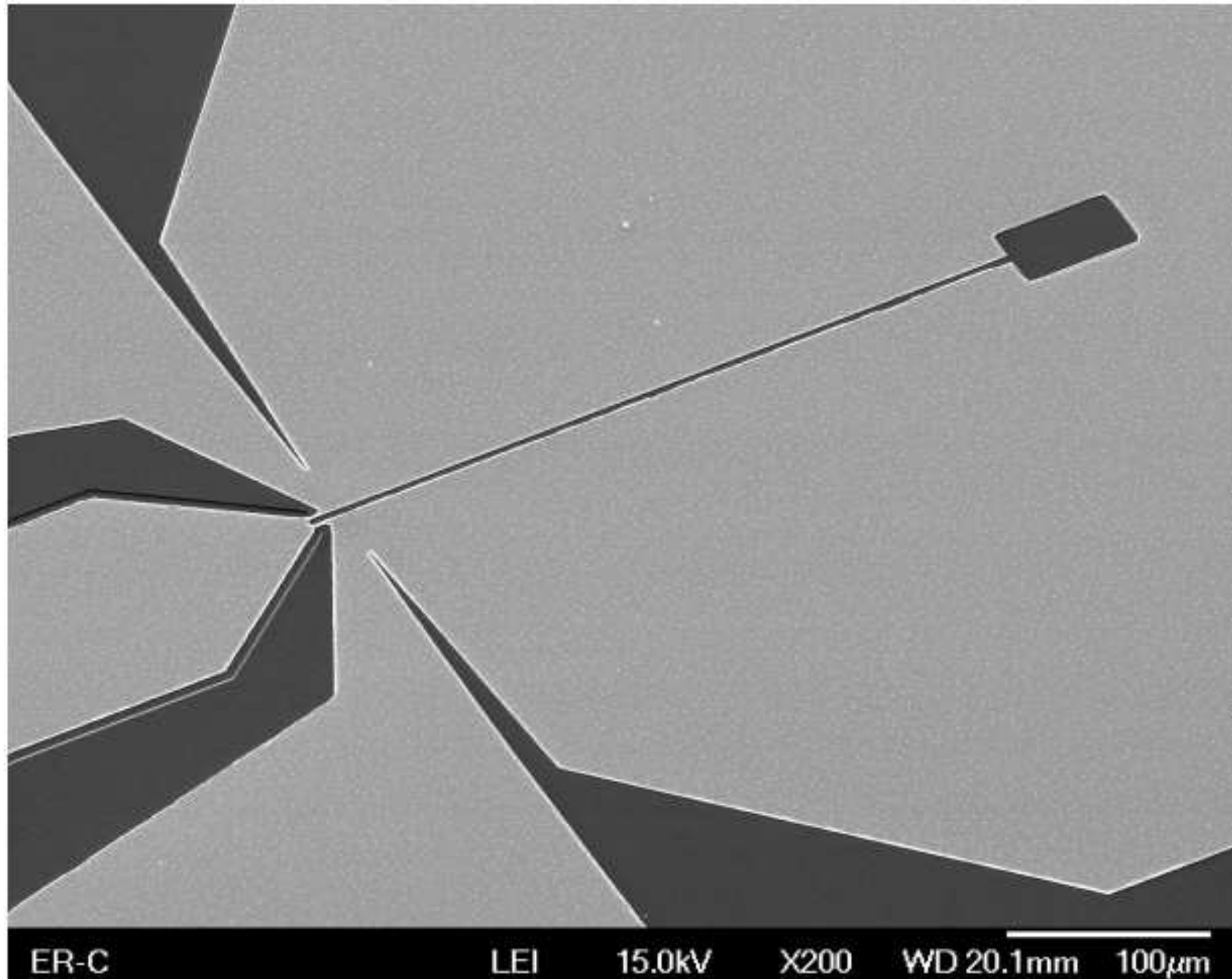
High- T_c DC SQUID with step-edge Josephson junctions



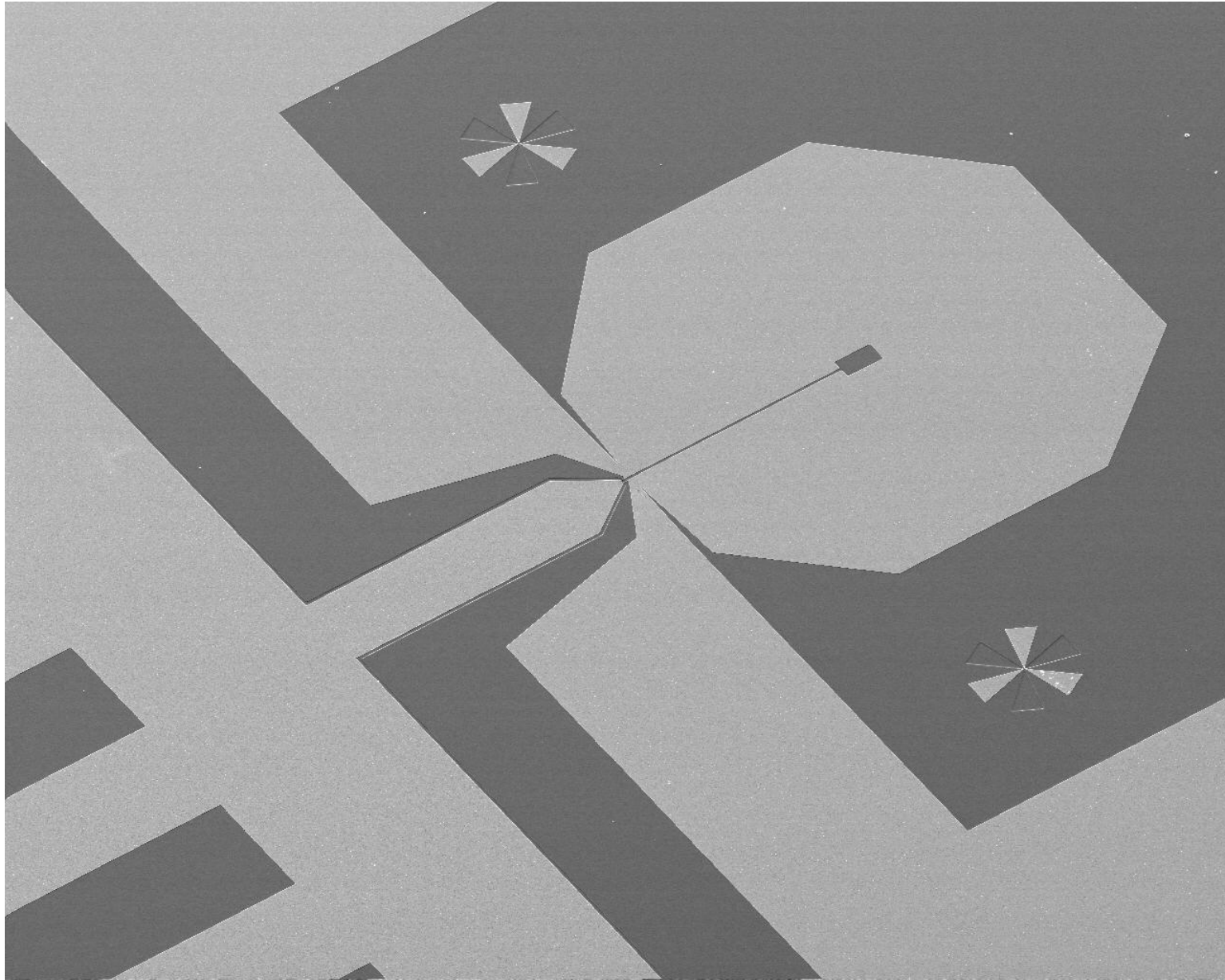
High- T_c DC SQUID with step-edge Josephson junctions



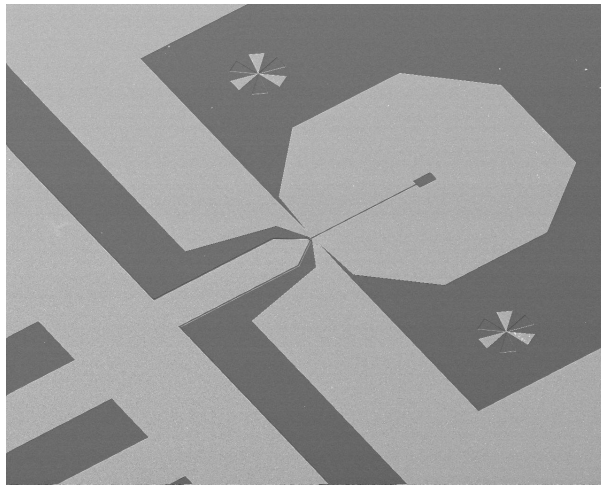
High- T_c DC SQUID with step-edge Josephson junctions



High- T_c DC SQUID with step-edge Josephson junctions



ВТСП ПТ СКВИДЫ для биоманитных исследований



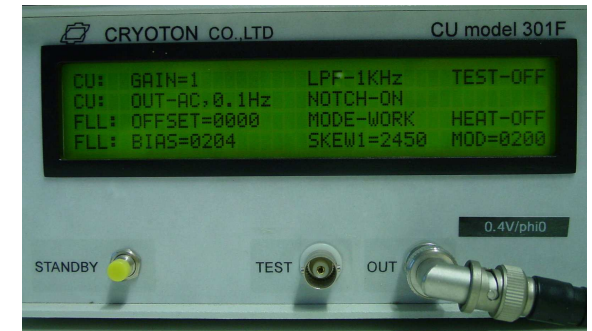
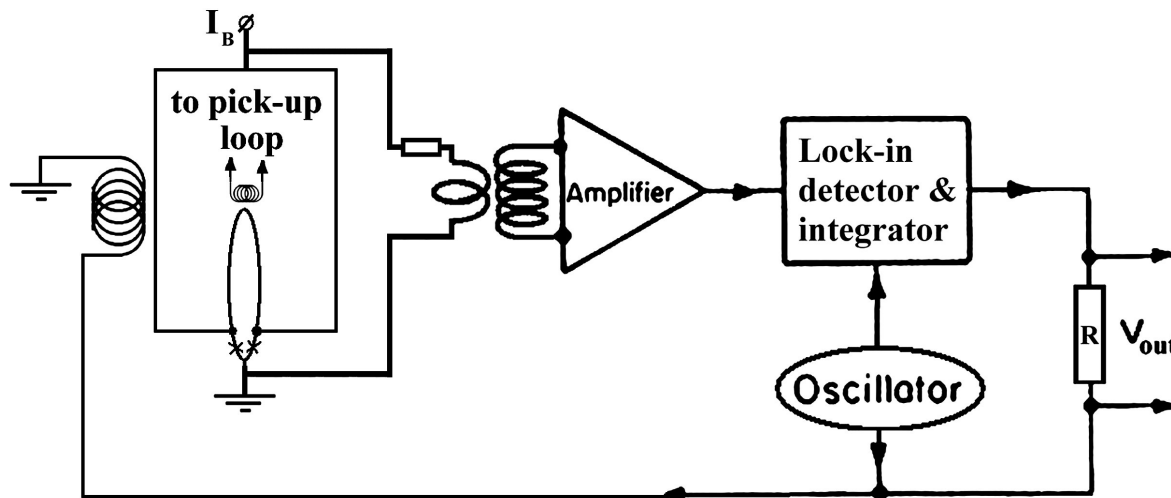
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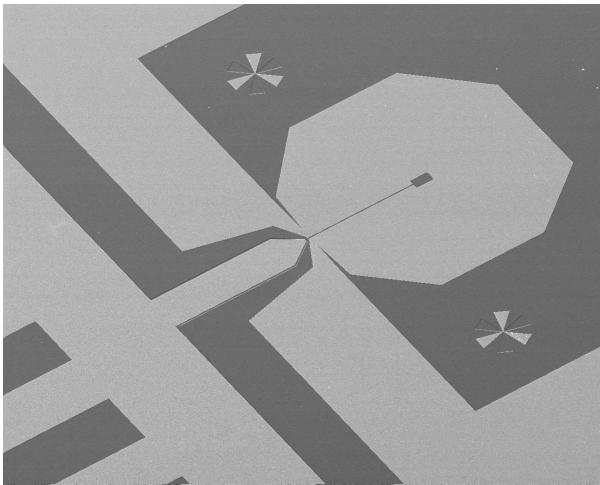


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(AC-bias DC SQUID electronics from Cryoton Co Ltd.)

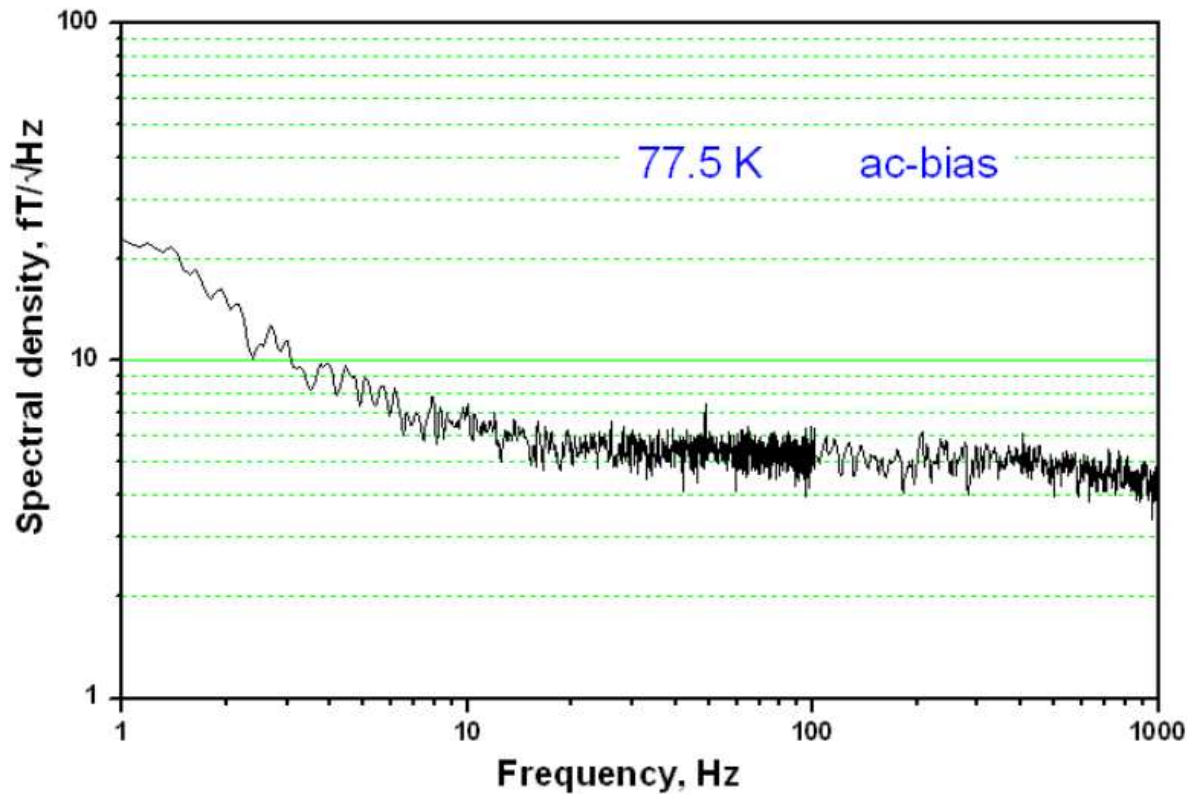
ВТСП ПТ СКВИДЫ для биоманитных исследований



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Field sensitivity: $0.4 \text{ nT}/\Phi_0$

← Noise spectral density

Field resolution $B_N(L_S)$ and voltage swings δV_{pp} for inductively coupled high- T_c DC SQUIDS

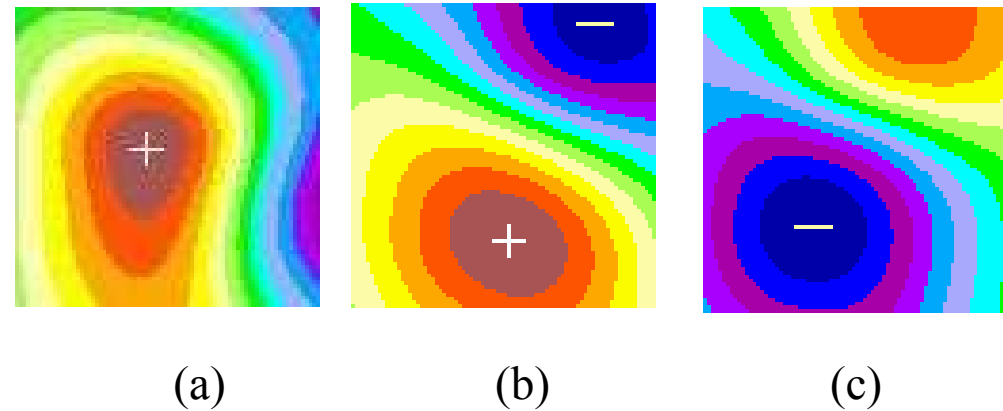
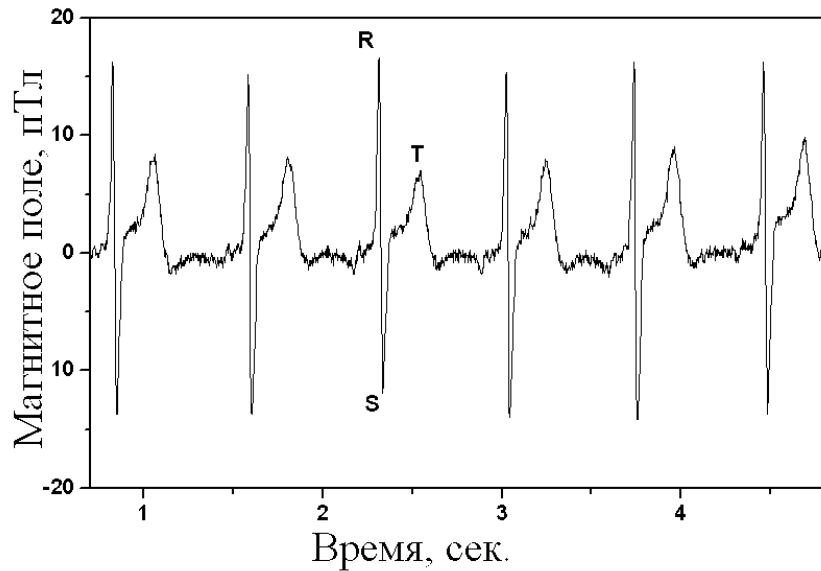
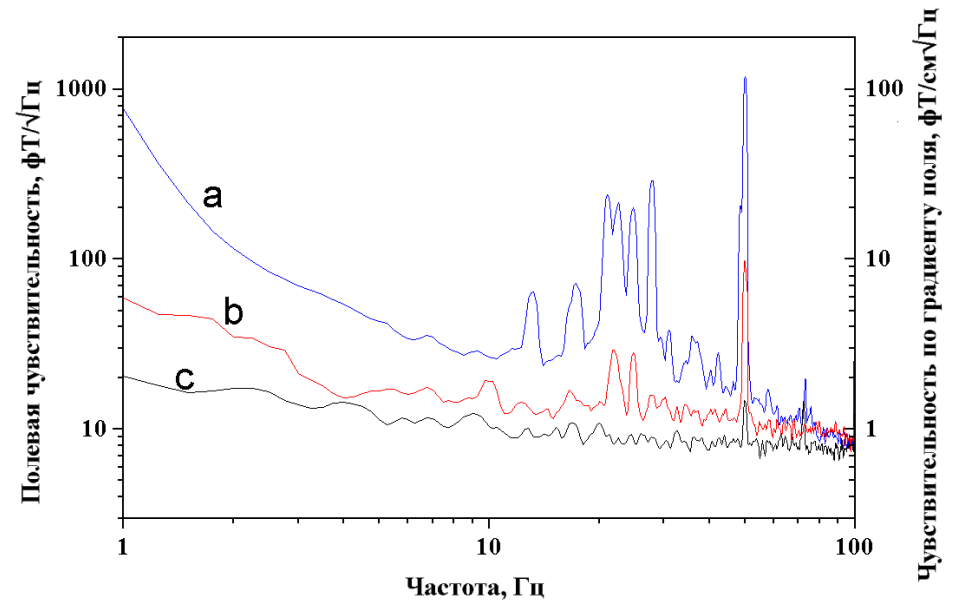
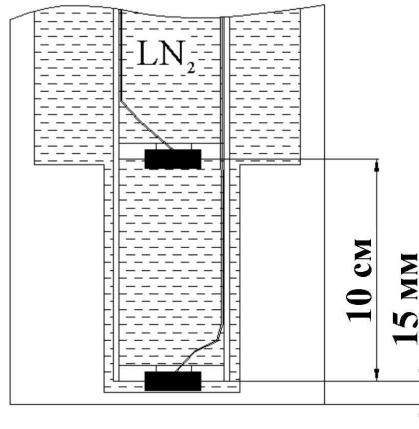
$$B_N = \frac{L_{pu} + L_i}{kA_{pu} \sqrt{L_i L_S}} S_{\Phi}^{1/2}$$

$$S_{\Phi} = \frac{S_V}{\left(\frac{\partial V}{\partial \Phi}\right)^2} \approx \frac{\frac{12k_B T}{R_N} \left[\frac{R_N^2}{2} + \frac{L_S^2}{4} \left(\frac{\partial V}{\partial \Phi}\right)^2 \right] + S_{Ve}}{\left(\frac{\partial V}{\partial \Phi}\right)^2}$$

$$\frac{\partial V}{\partial \Phi} \approx \frac{4}{\Phi_0} \cdot \frac{I_c R_n}{1 + \frac{2L_S I_c}{\Phi_0}} \cdot \exp\left(1 - 3.5\pi^2 \frac{k_B T L_S}{\Phi_0^2}\right)$$

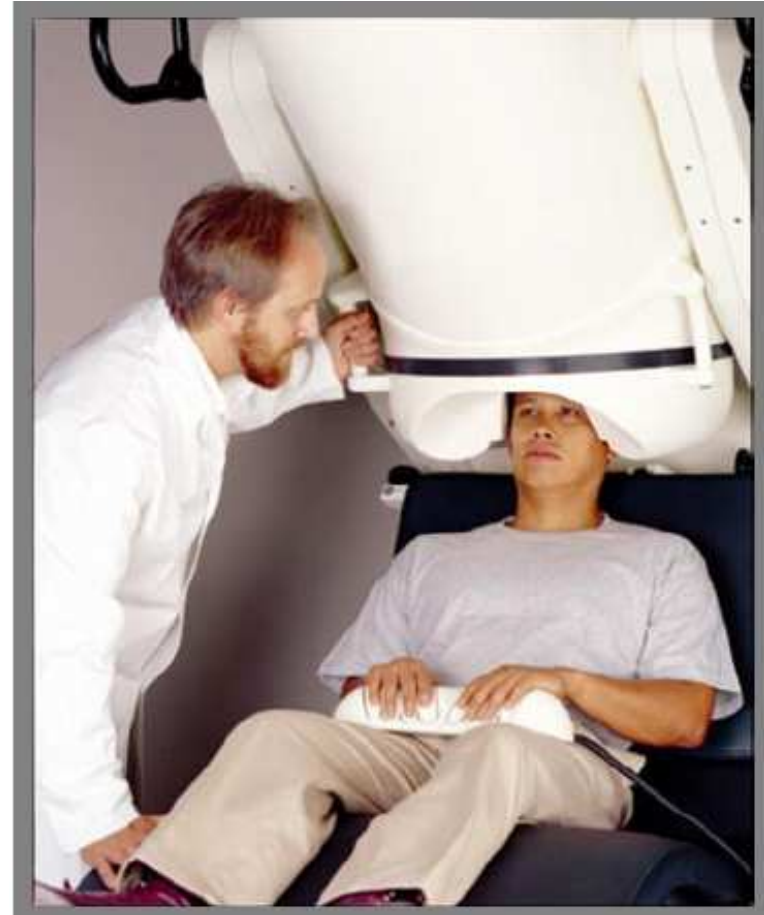
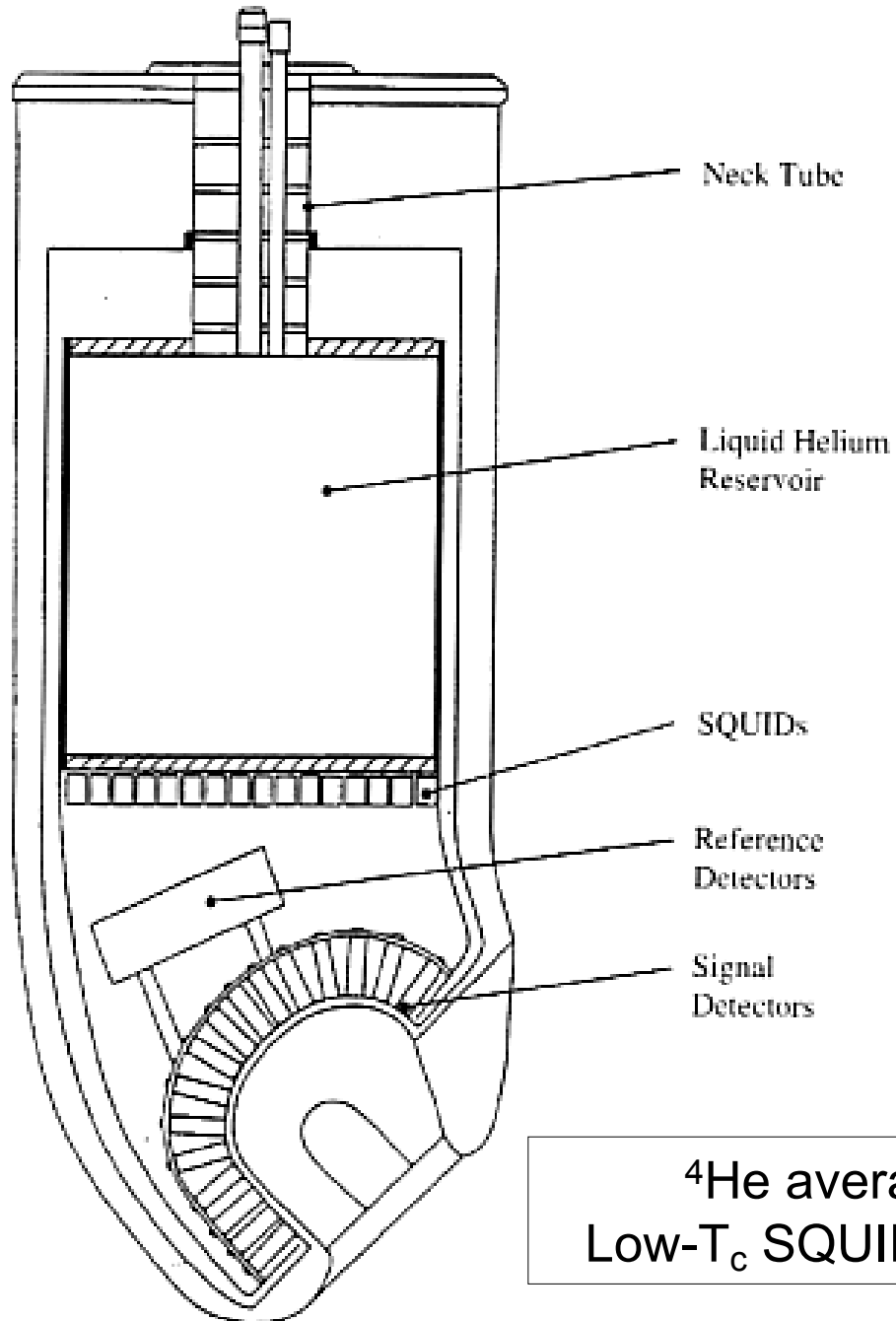
K. Enpuku et al., *J. Appl. Phys.* **78**, 3498 (1995)

Биомагнитная система для МКГ на основе двух ВТСП ПТ СКВИД магнитометров



Измеренный в реальном времени МКГ сигнал и распределение магнитного поля по области сканирования в моменты времени: (a) R-, (b) S-, and (c) T- пиков.

Low- T_c SQUID MEG system available at INM-4 in FZJ

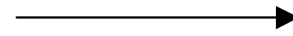


248-channel-MEG system
“Magnes© 3600 WH” 4D-Neuroimaging

^4He average refill interval is twice per week,
Low- T_c SQUIDs with white noise $\approx 5 \text{ fT}/\sqrt{\text{Hz}}$ at 4.2 K

Low- T_c DC SQUID sensors:
 ^4He refill interval: twice a week,
20-mm sensors $\sim 3 \text{ fT}/\sqrt{\text{Hz}}@4.2\text{K}$

To be replaced by

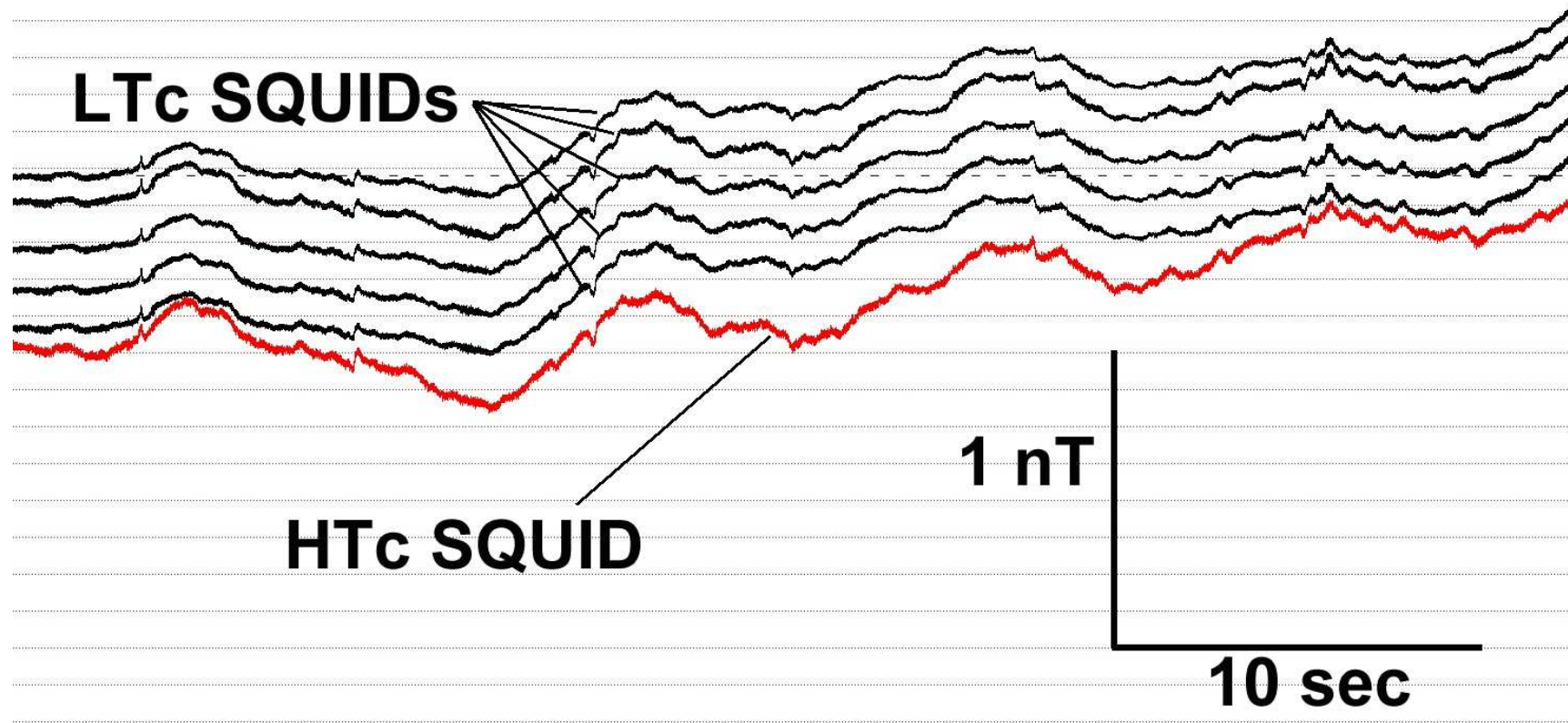


High- T_c DC SQUID sensors:
 N_2 refill interval: once a month,
20-mm sensors $\sim 3 \text{ fT}/\sqrt{\text{Hz}}@77\text{K}$

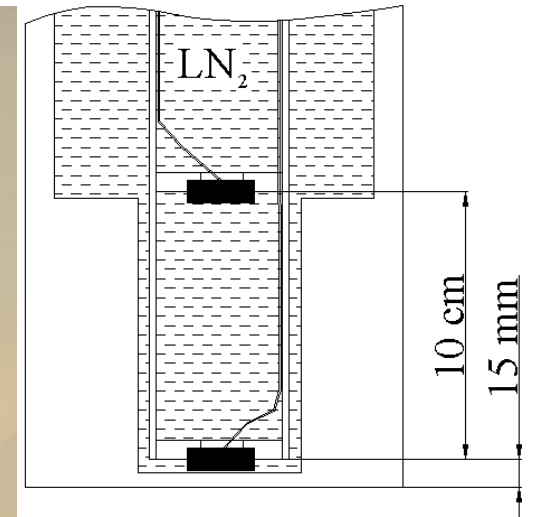
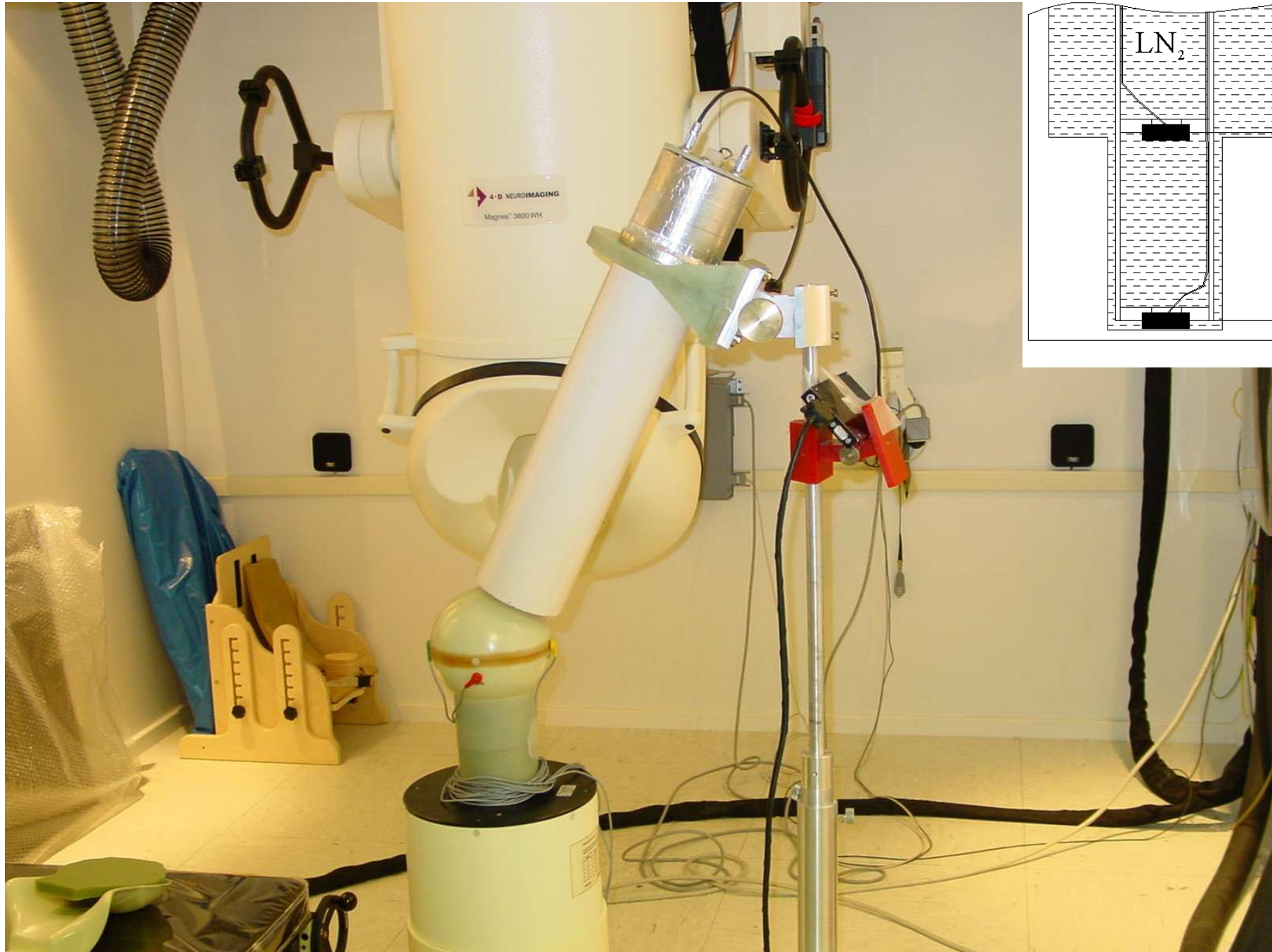
Advantage: liquid nitrogen is cheaper, it is more convenient in use, and liquid nitrogen cryostats require replenishing with the cryogen much less often than liquid helium cryostats.



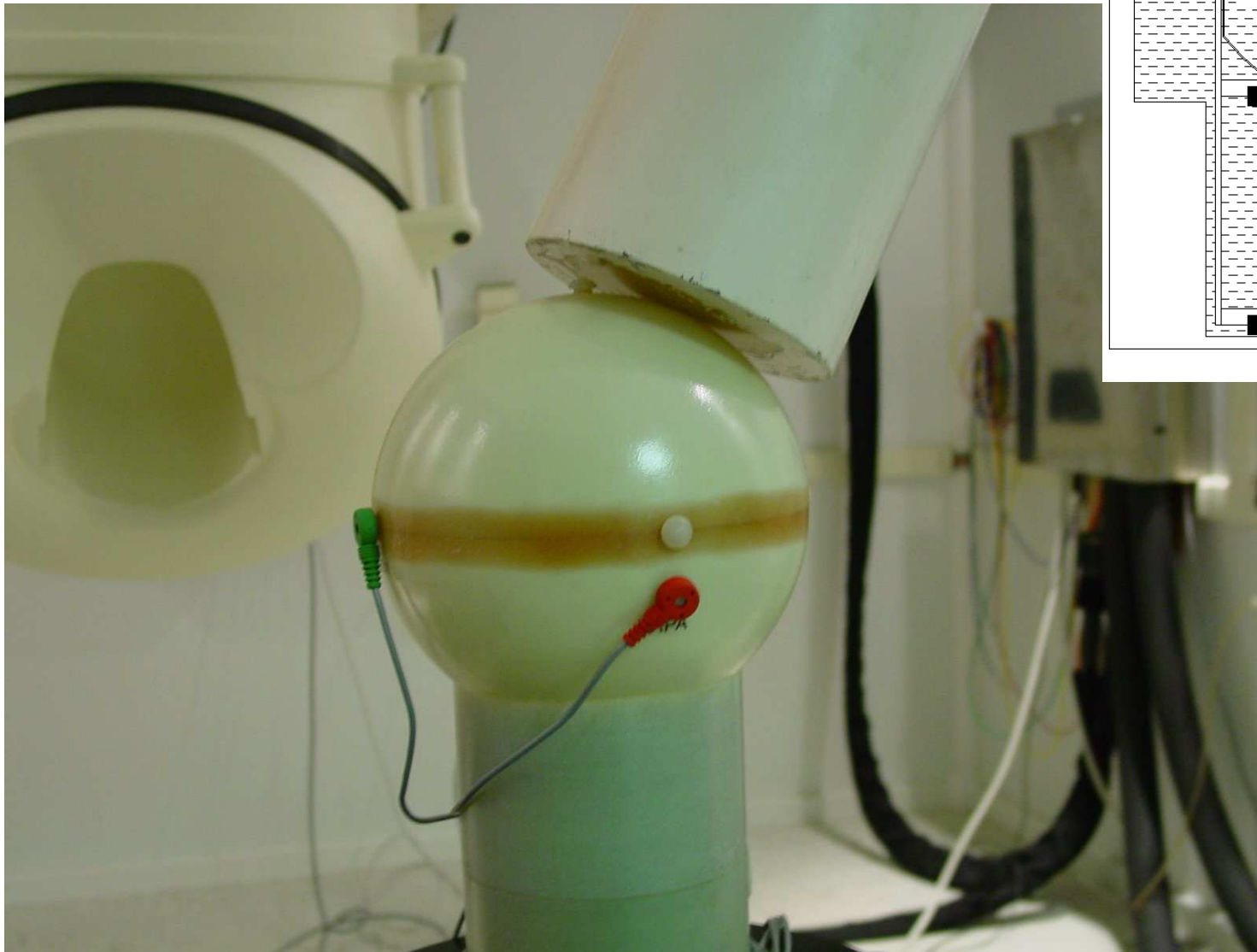
Real-time signals of low- T_c and high- T_c systems in the MSR of INM FZJ



MSR of INM-4 FZJ

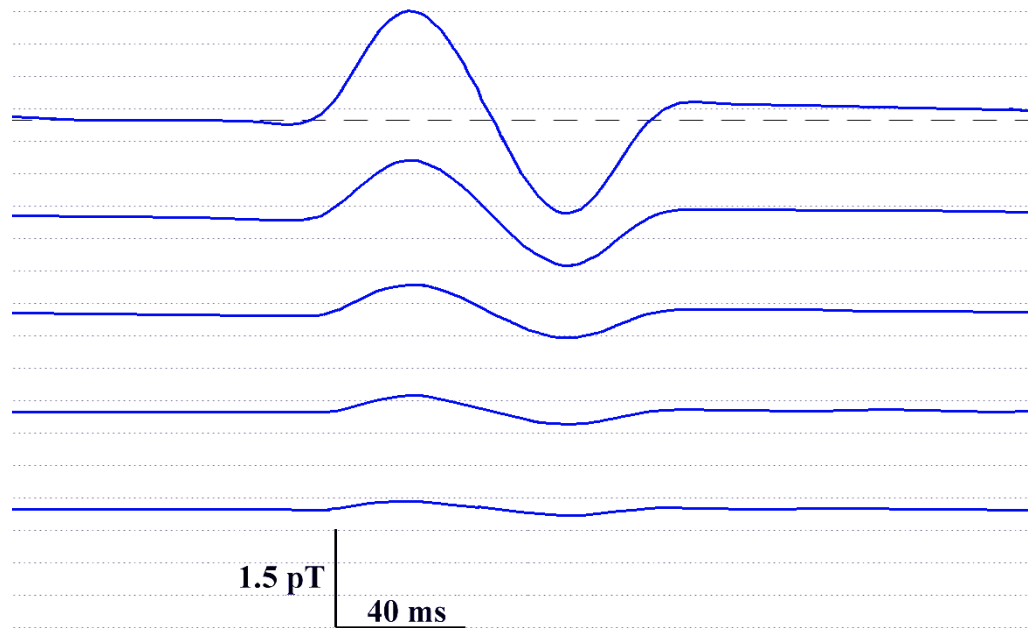


Measurements with current dipole in a head phantom



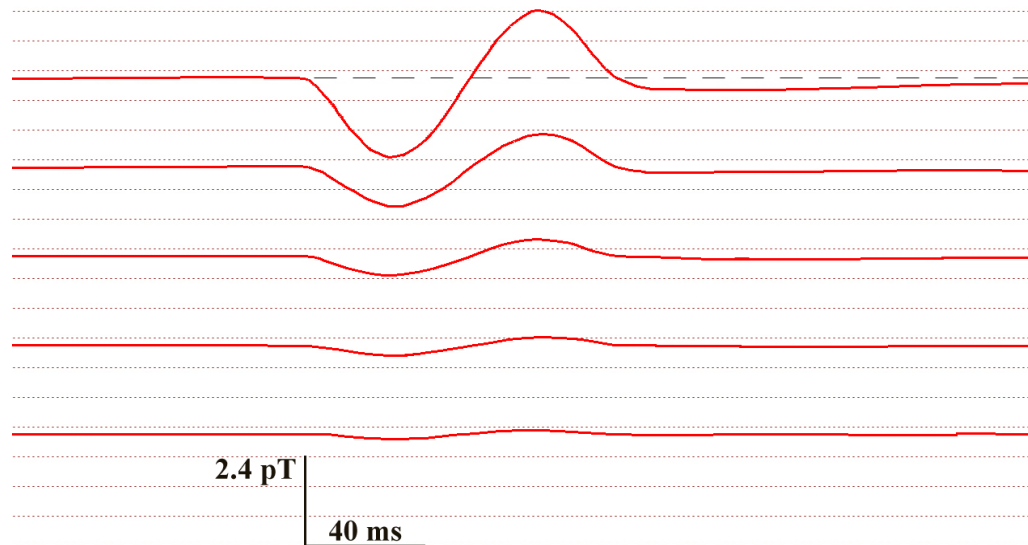
Measurement with high- T_c system and saline filled head phantom with 5 individually selectable current dipoles at calibrated positions, between 1.5 and 5.5 cm below the surface

Results of measurements with head phantom



The peak-to-peak magnetic fields measured by low- T_c system were 3.2 pT, 1.6 pT, 800 fT, 400 fT and 200 fT.

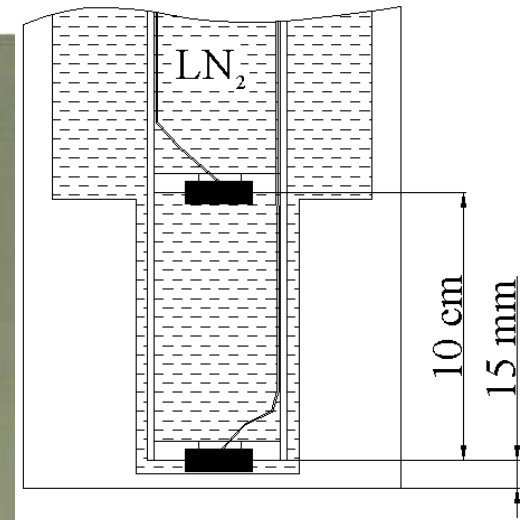
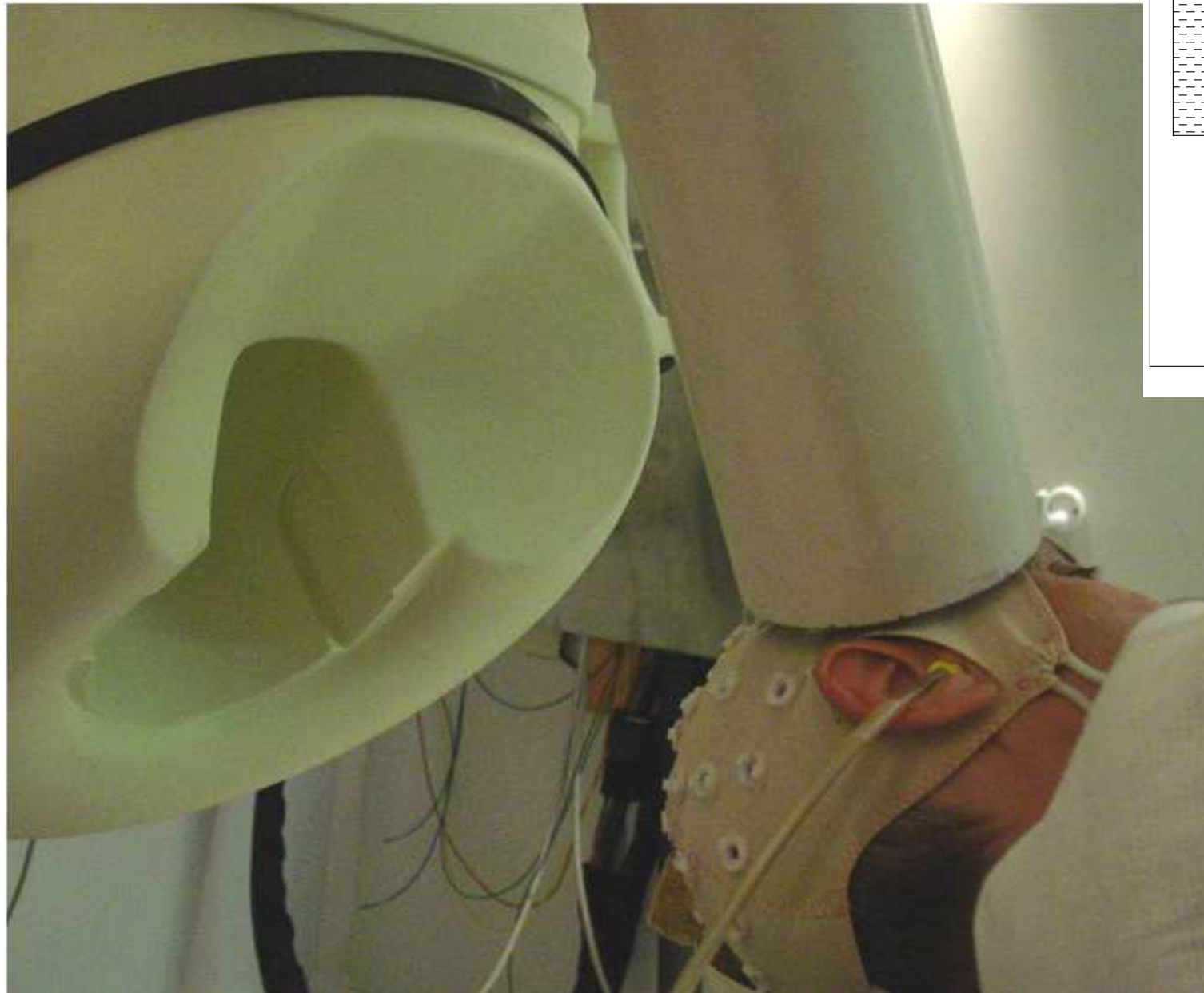
Measurements obtained using a low- T_c DC SQUID



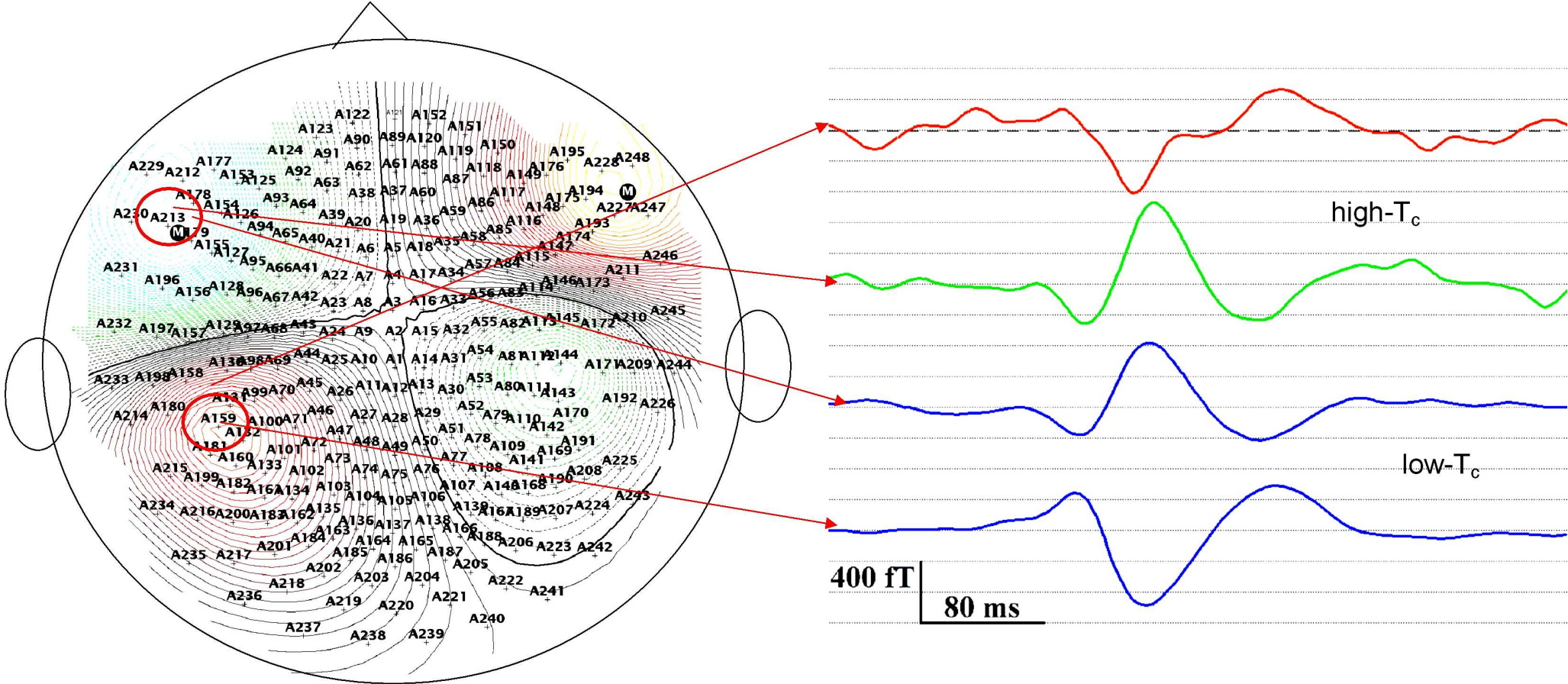
and the high- T_c DC SQUID.

Both data sets show averages over 100 epochs and were band-pass filtered from 3 to 30 Hz.

Photograph of MEG measurement with high- T_c SQUID



Contour plot of auditory evoked field and arrangement of low- T_c sensors



Epoch: 1 **Latency: 104.963 ms** **Date: Wed Jun 29 10:36:16 2011**
Contour Min: -420 ft **Contour Max: 360 ft** **Contour Step: 10 ft**
Smoothed: ON

Выводы

- Получены высококачественные ВТСП пленки, джозефсоновские переходы и ПТ СКВИДы на подложках MgO. Изучены их микроструктурные и электротранспортные свойства.
- Изучен графоэпитаксиальный рост пленок YBCO на ступеньках на подложках MgO. Обнаружена возможность управления направлением роста пленок в плоскости *ab* и две преимущественные ориентации вертикального роста: 0° и 45° , что позволило создать воспроизводимые 45-градусные переходы на ступеньке (подана заявка на патент).
- Чувствительность ВТСП СКВИДов достаточна для наблюдения магнитоэнцефалографии человека с отношением сигнал/шум приближающимся к отношению сигнал/шум коммерческой НТСП МЭГ системы.

Перспективы

- **Изготовление и исследование многоканальных систем для МЭГ.**
- **Апробирование новых переходов для приема и генерации терагерцового излучения.**
- **Другие применения ВТСП переходов и СКВИДов.**
- **Сотрудничество по биомагнитным и терагерцовым измерительным системам.**