IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2014 (Preview 1).
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CHALMERS

$YBa_2Cu_3O_{7-\delta}$ NANOWIRES FOR ULTRASENSITIVE MAGNETIC FLUX AND OPTICAL DETECTORS

Riccardo Arpaia

MC2-Quantum Device Physics Laboratory
Chalmers University of Technology
Göteborg - Sweden

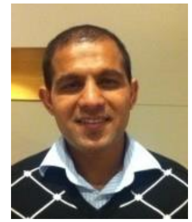
ASC Charlotte August 11, 2014

$YBa_2Cu_3O_{7-\delta}$ NANOWIRES
FOR ULTRASENSITIVE MAGNETIC FLUX AND OPTICAL DETECTORS


Marco Arzeo
Phd student


Reza Baghdadi
Phd student


Sophie Charpentier
Post doc


Shahid Nawaz
Phd


Thilo Bauch
Professor

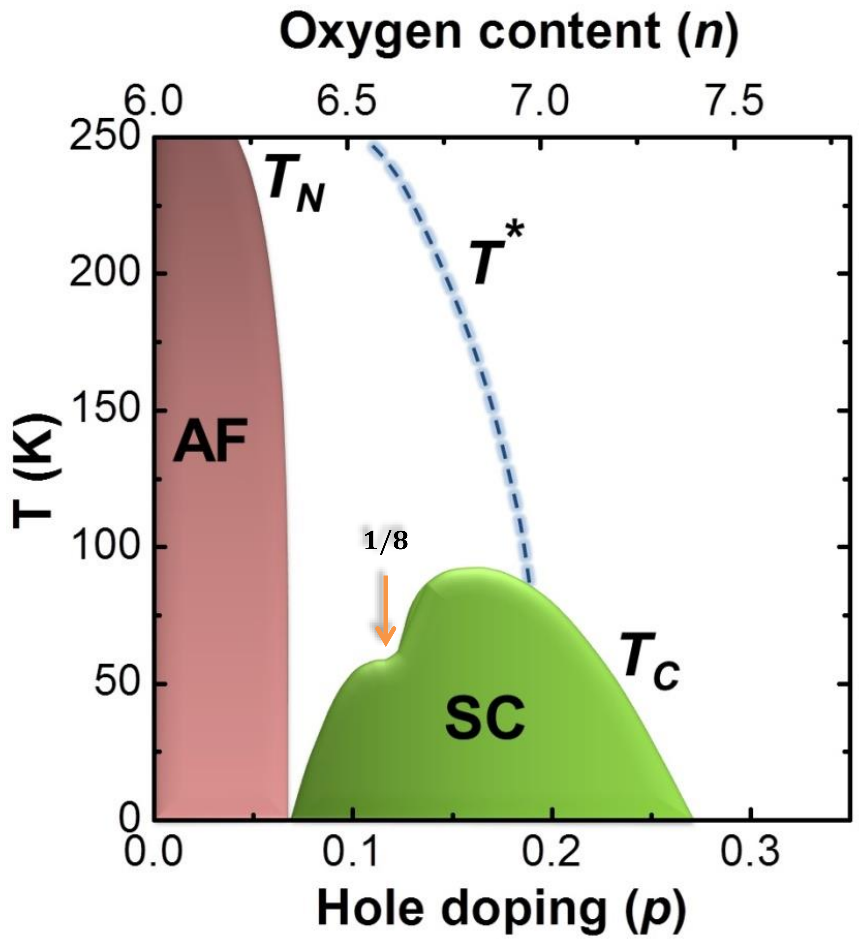

Floriana Lombardi
Professor

In collaboration with:

- **CNR-SPIN Institute UOS-Napoli, Italy**
- **Dipartimento di Fisica, Università Federico II, Napoli, Italy**

(L. Parlato, M. Ejrnaes, R. Cristiano, F. Tafuri, G. P. Pepe)

$YBa_2Cu_3O_{7-\delta}$



Nanoscale order

NATURE · VOL 375 · 15 JUNE 1995

LETTERS TO NATURE

Evidence for stripe correlations of spins and holes in copper oxide superconductors

J. M. Tranquada*, B. J. Sternlieb†, J. D. Axe*, Y. Nakamura† & S. Uchida†

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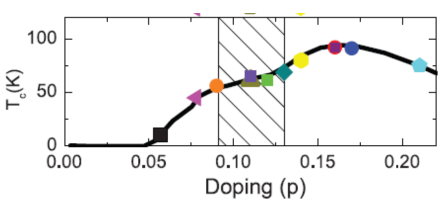
SCIENCE VOL 337 17 AUGUST 2012

REPORTS

Long-Range Incommensurate Charge Fluctuations in $(Y,Nd)Ba_2Cu_3O_{6+x}$

G. Ghiringhelli,[1*] M. Le Tacon,[2] M. Minola,[1] S. Blanco-Canosa,[2] C. Mazzoli,[1] N. B. Brookes,[3] G. M. De Luca,[4] A. Frano,[2,5] D. G. Hawthorn,[6] F. He,[7] T. Loew,[2] M. Moretti Sala,[3] D. C. Peets,[2] M. Salluzzo,[4] E. Schierle,[5] R. Sutarto,[7,8] G. A. Sawatzky,[8] E. Weschke,[5] B. Keimer,[2*] L. Braicovich[1]



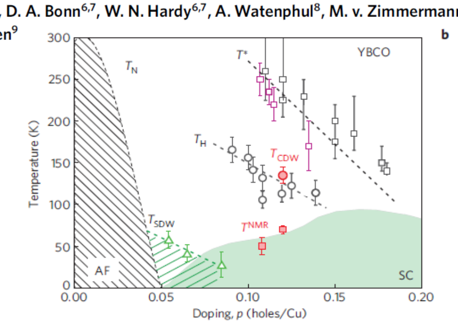
nature physics

LETTERS

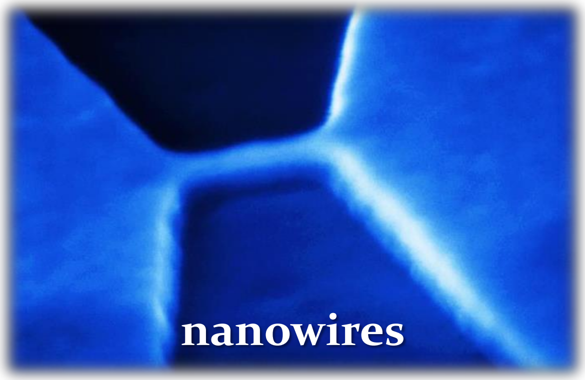
PUBLISHED ONLINE: 14 OCTOBER 2012 | DOI: 10.1038/NPHYS2456

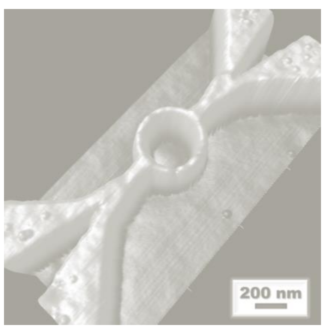
Direct observation of competition between superconductivity and charge density wave order in $YBa_2Cu_3O_{6.67}$

J. Chang[1,2*], E. Blackburn[3], A. T. Holmes[3], N. B. Christensen[4], J. Larsen[4,5], J. Mesot[1,2], Ruixing Liang[6,7], D. A. Bonn[6,7], W. N. Hardy[6,7], A. Watenphul[8], M. v. Zimmermann[8], E. M. Forgan[3] and S. M. Hayden[9]



Outline/YBCO nanostructures



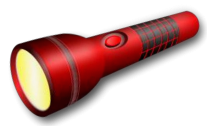


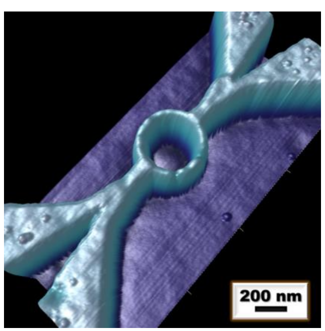
nanorings

nanoSQUIDs

nanowires for photodetection

Outline/YBCO nanostructures





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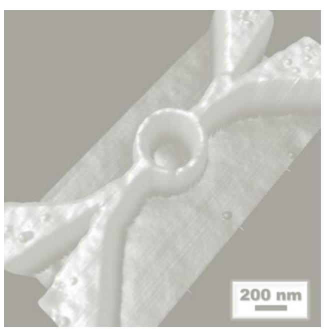
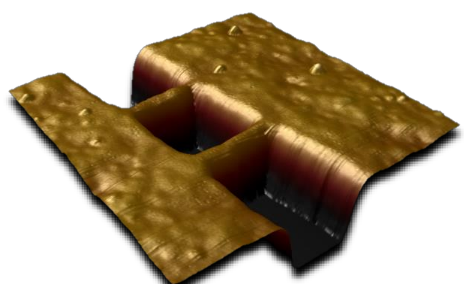


nanorings



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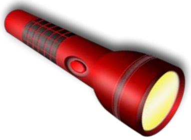

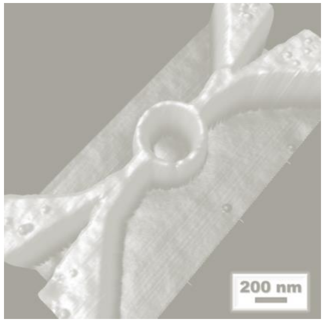

nanorings

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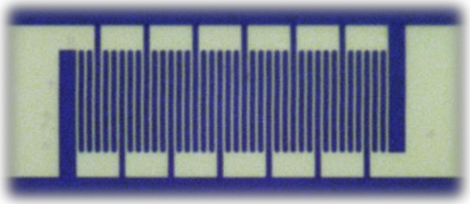
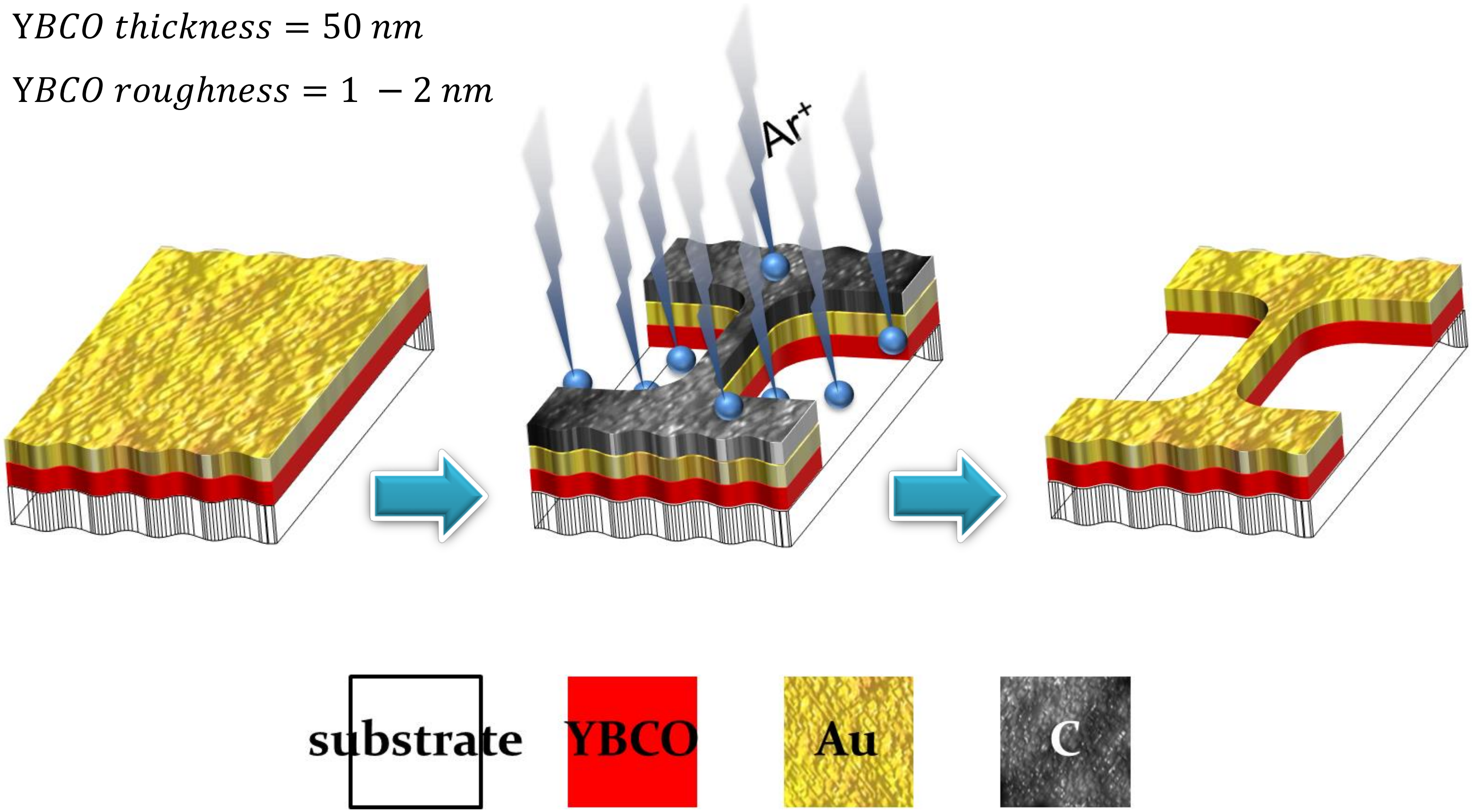


nanowires for photodetection

Improved nanopatterning for YBCO nanowires

$YBCO\ thickness = 50\ nm$

$YBCO\ roughness = 1\ - 2\ nm$



R. Arpaia, S. Nawaz, F. Lombardi, T. Bauch, ***IEEE Trans. App. Sup.*** **23, 1101505 (2013)**

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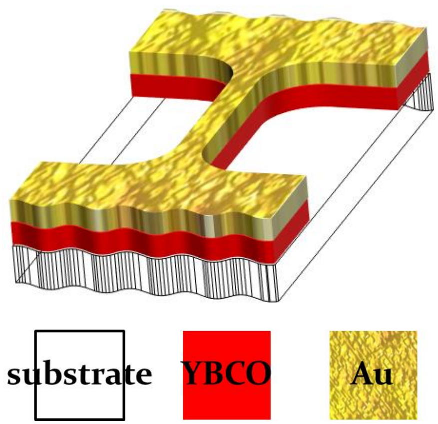
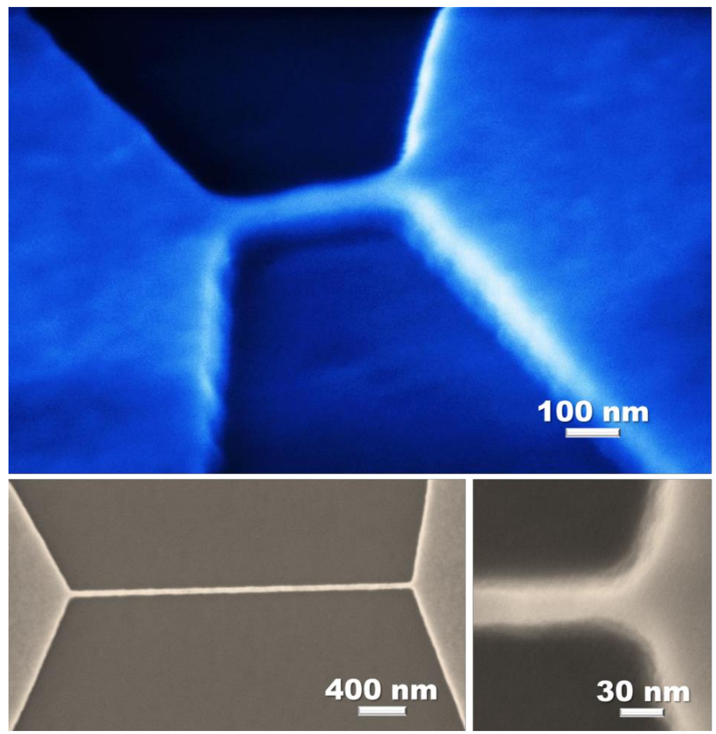
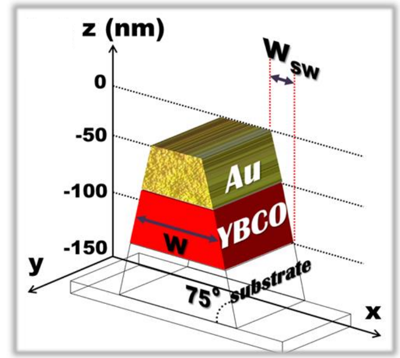




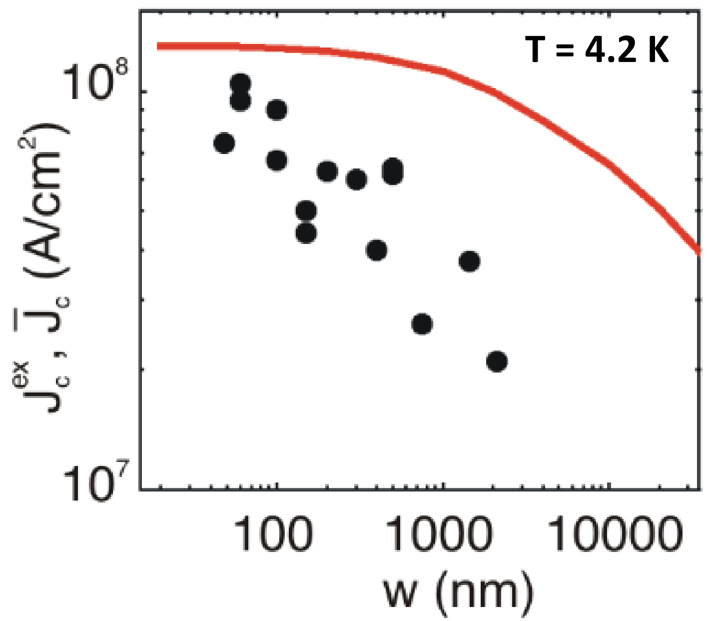


w *down to* $50\ nm$

R. Arpaia, S. Nawaz, F. Lombardi, T. Bauch, ***IEEE Trans. App. Sup.*** **23, 1101505 (2013)**

Benchmarking the quality of YBCO nanowires

Critical current densities close to the depairing limit



$$J_{GL}^{d} = \Phi_0/(3\sqrt{3}\pi\mu_0\lambda_L^2\xi) \ = 1-3 \cdot 10^8 \ \text{A/cm}^2$$

S. Nawaz, R. Arpaia, F. Lombardi and T. Bauch, ***Phys.Rev.Lett.*** **110, 167004 (2013)**

S. Nawaz, R. Arpaia, T. Bauch, F. Lombardi, ***Physica C*** **495, 33 (2013)**

Why nanoSQUIDs?

To develop quantum limited magnetic flux sensors

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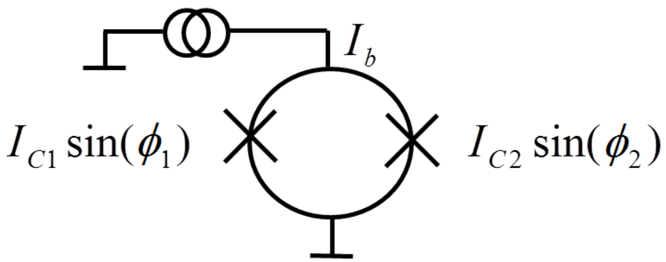
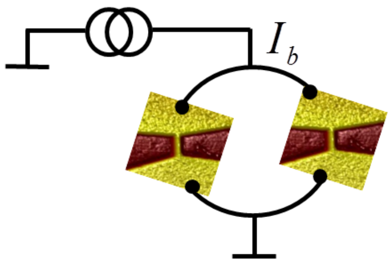
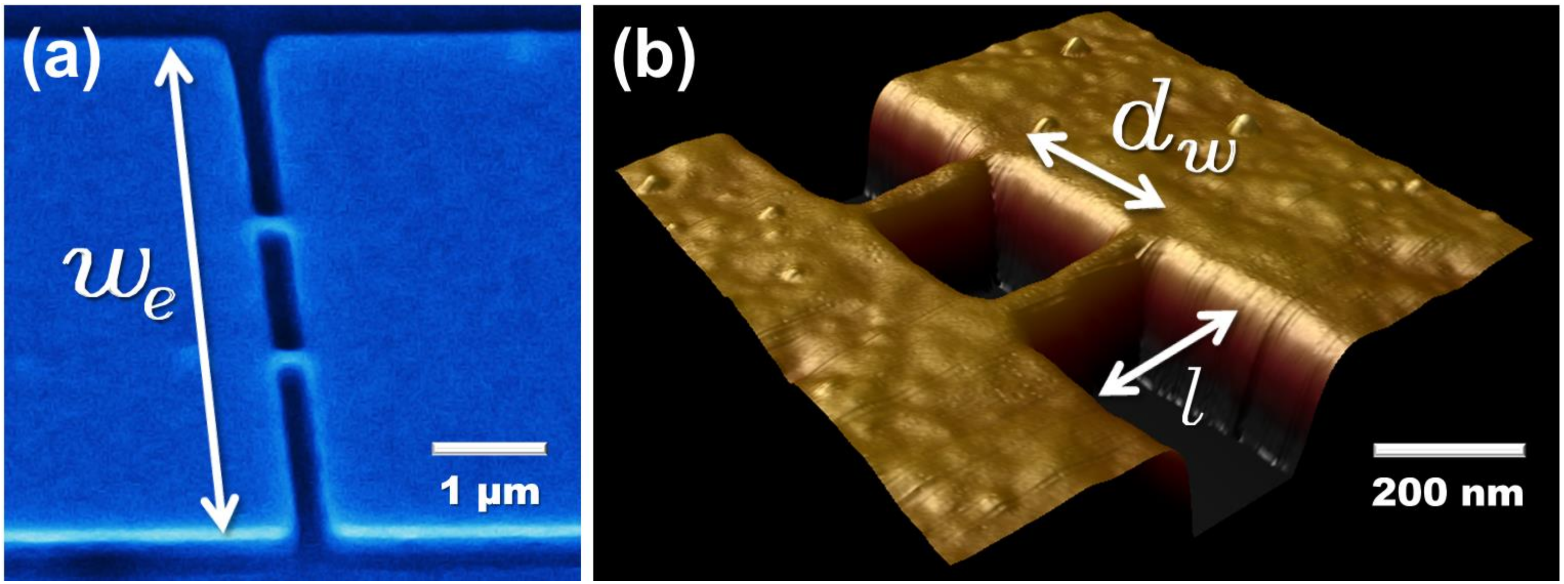
Why Dayem bridge configuration?





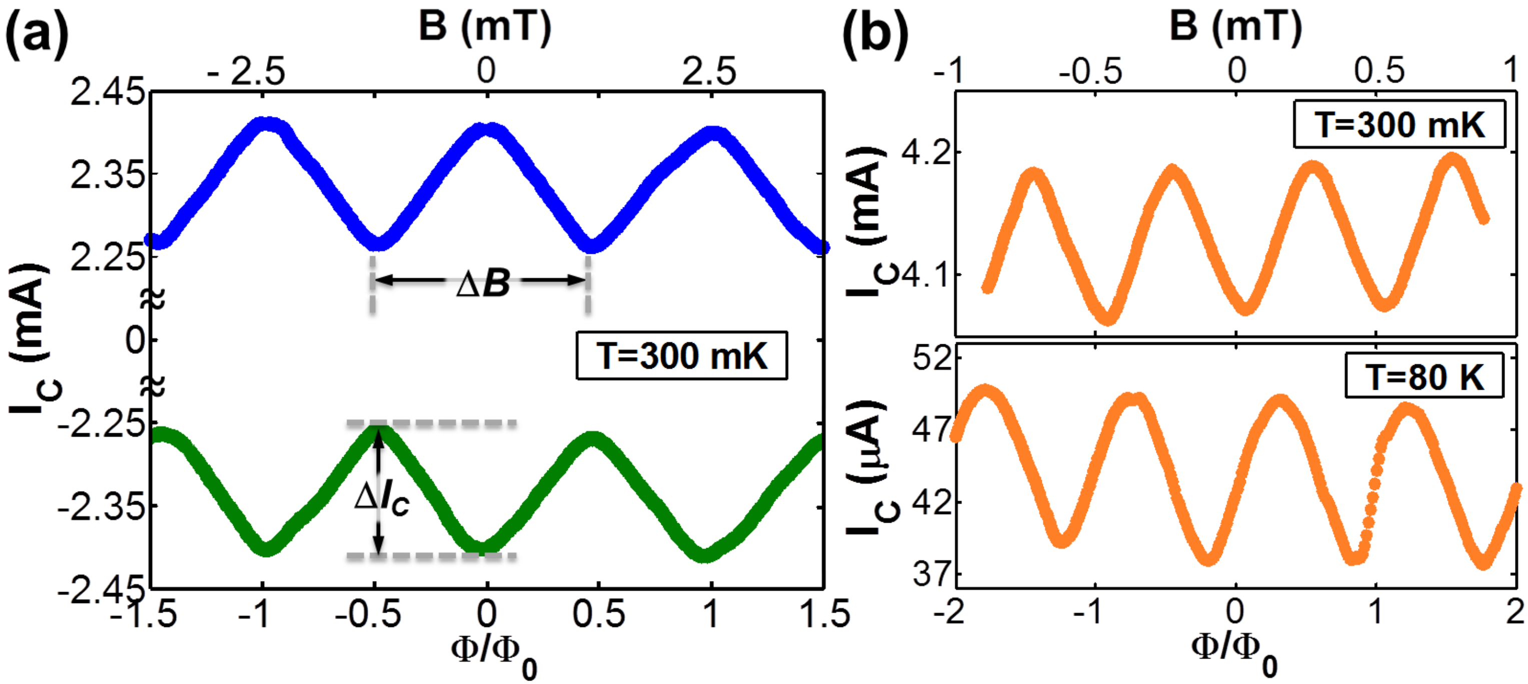
The use of conventional barriers implies several drawbacks

YBCO nanoSQUID implementing nanowires



R. Arpaia, M. Arzeo, S.Nawaz, S.Charpentier, F.Lombardi, T.Bauch, ***Appl.Phys.Lett. 104, 072603*** **(2014)**

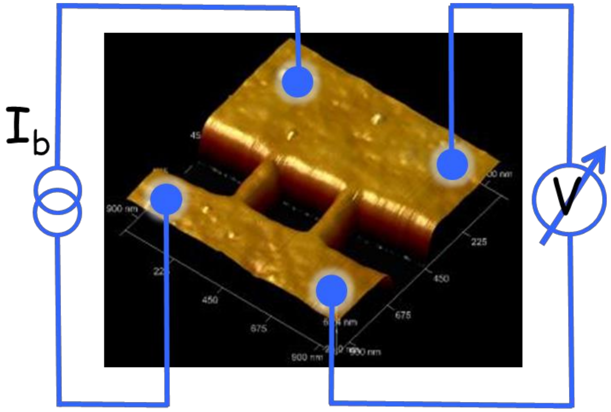
YBCO nanoSQUID implementing nanowires

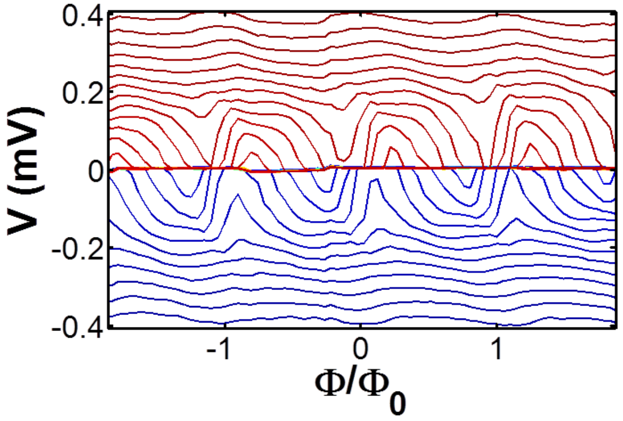


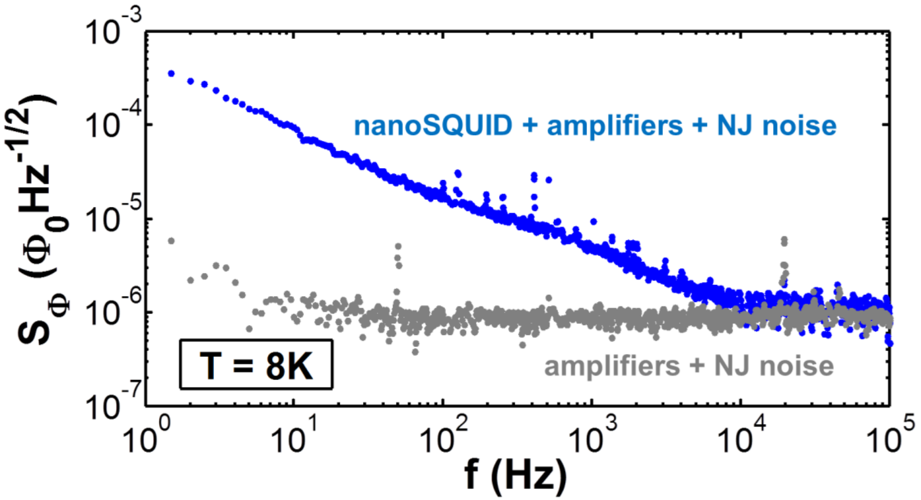
First experimental demonstration of ***critical current modulation in the full temperature range*** *below the transition temperature T_C*

R. Arpaia, M. Arzeo, S.Nawaz, S.Charpentier, F.Lombardi, T.Bauch, ***Appl.Phys.Lett. 104, 072603*** **(2014)**

YBCO nanoSQUIDs: sub-$\mu\Phi_0/Hz^{1/2}$ flux sensitivity







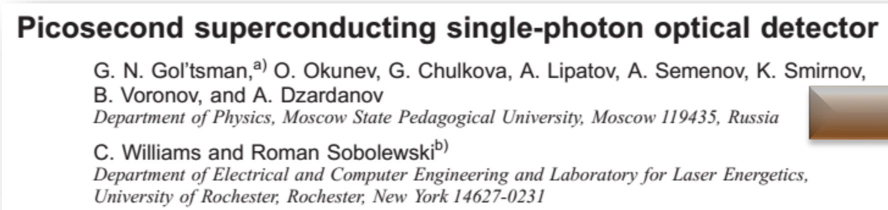
White noise level **better than 1 $\mu\Phi_0/Hz^{1/2}$** at 8 K
Best sensitivity ever measured in HTS SQUIDs

- Detection of magnetic nanoparticles in high magnetic fields
- Single spin detection?

R. Arpaia, M. Arzeo, S.Nawaz, S.Charpentier, F.Lombardi, T.Bauch, ***Appl.Phys.Lett. 104, 072603*** **(2014)**

YBCO nanowires for photodetection: aim

Realization of Single Photon Detectors, generally based on the **hot spot** mechanism.



Picosecond superconducting single-photon optical detector

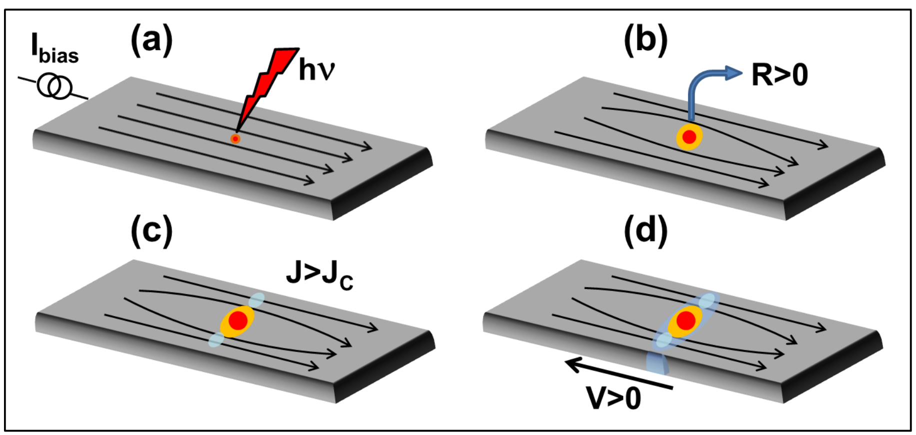
G. N. Gol'tsman,[a] O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, and A. Dzardanov
Department of Physics, Moscow State Pedagogical University, Moscow 119435, Russia

C. Williams and Roman Sobolewski[b]
Department of Electrical and Computer Engineering and Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14627-0231

G. N. Gol'tsman et al., ***APL* 79, 705 (2001)**

- detection efficiencies
- low dark counts (<1 s^{-1}),
- fast time response (few ps)

The focus at the moment is only on LTSs (NbN, MgB_2, etc…)



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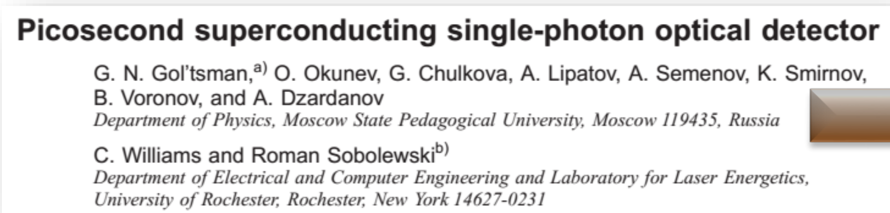

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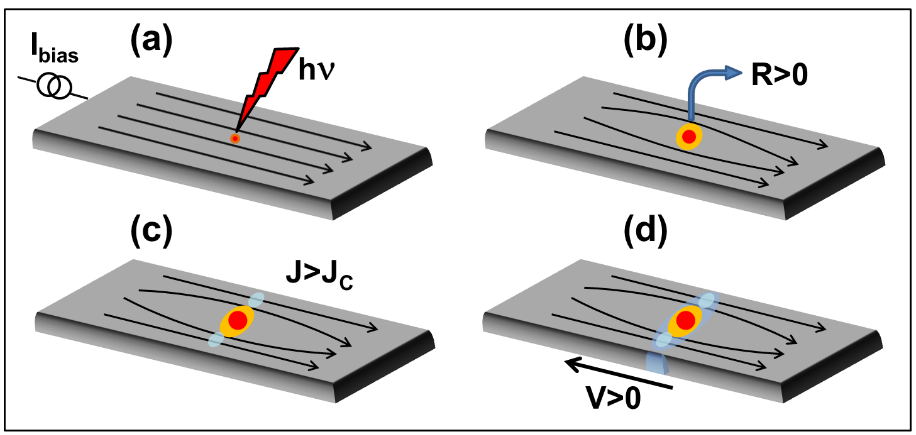
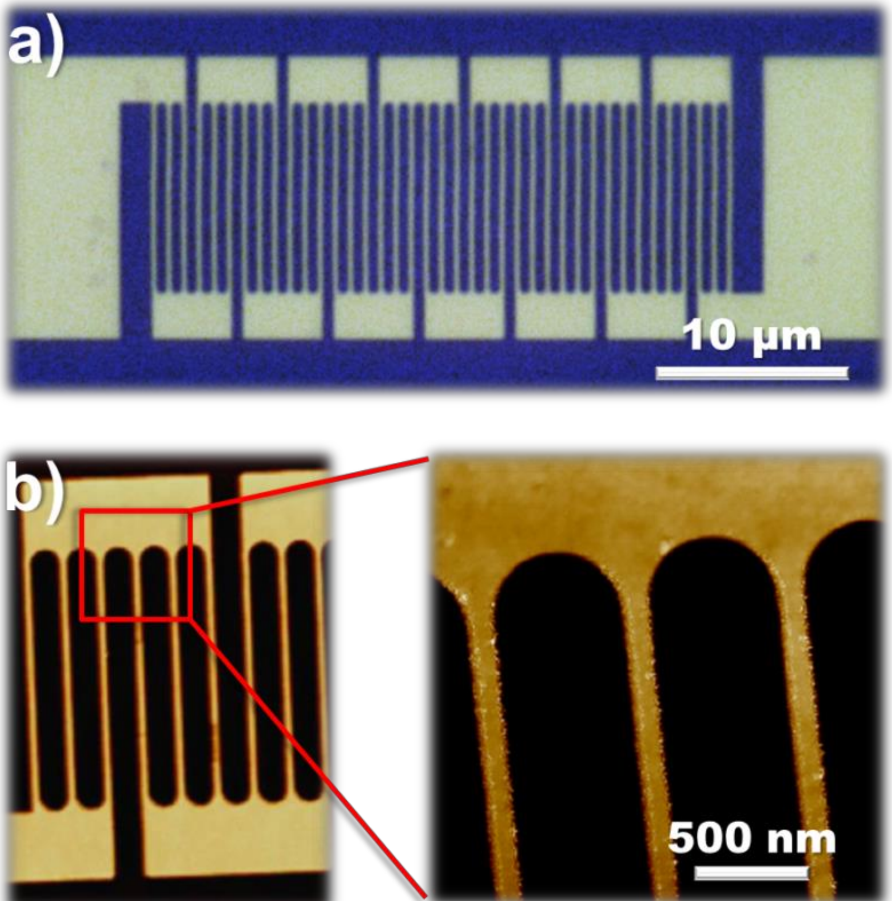


YBCO can be a good candidate:
- wider T working range
- fast thermalization dynamics

But:
- Limitation in the nanopatterning

YBCO nanowires for photodetection: fabrication

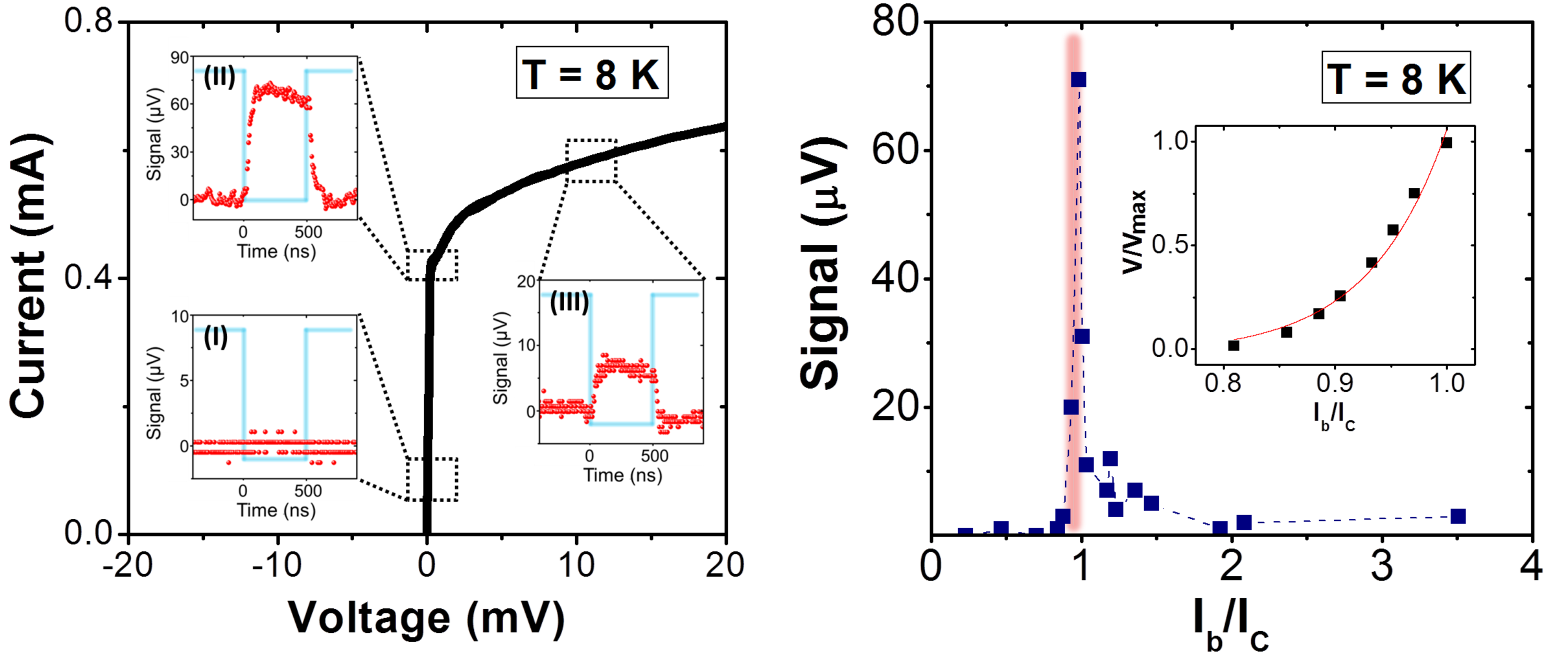


- Large areas have to be covered

parallel configuration (M. Ejrnaes et al., ***SuST* 22, 055006 (2009)**), with wire lenghts up to **10 µm (A=30 x 10 µm^2)**

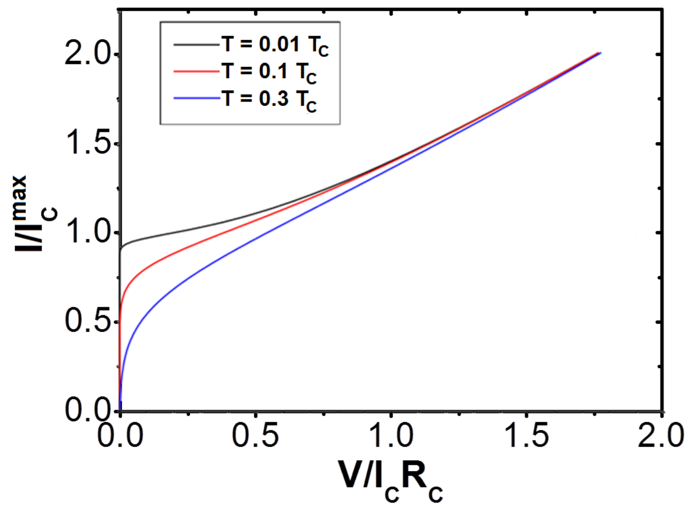
- Au capping has to be etched

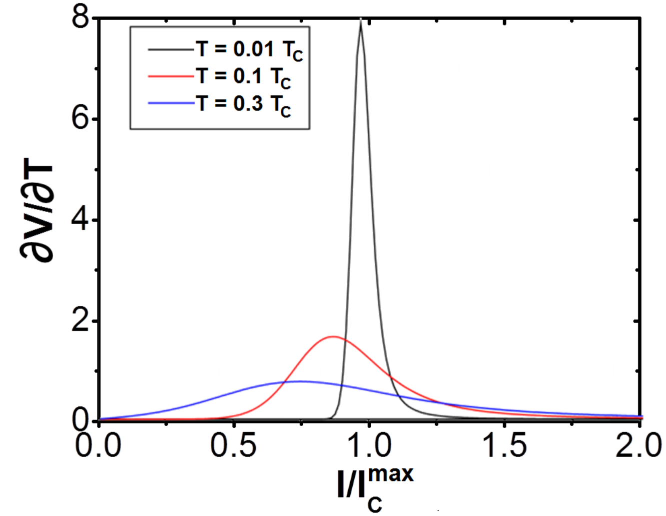
Photoresponse measurements on YBCO nanowires



$$\lambda = 1550\ nm$$
$$F = 50\ nW/\mu m^2$$
$$t = 10 - 500\ ns$$
$$\tau_{rise} = \tau_{fall} = 3\ ns$$

Photoresponse measurements on YBCO nanowires





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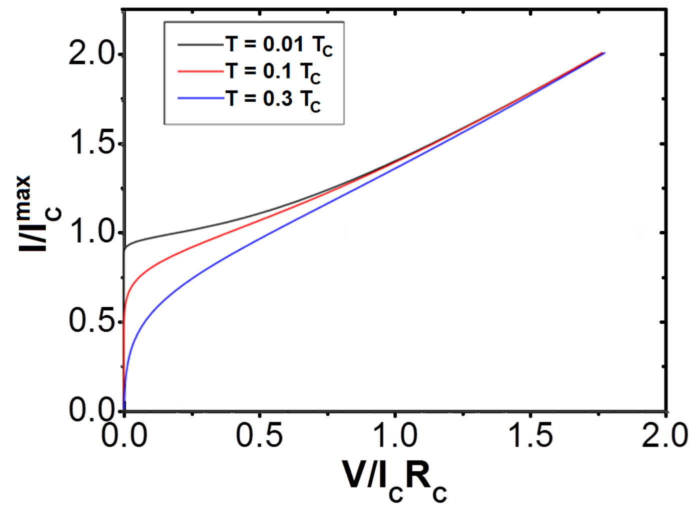

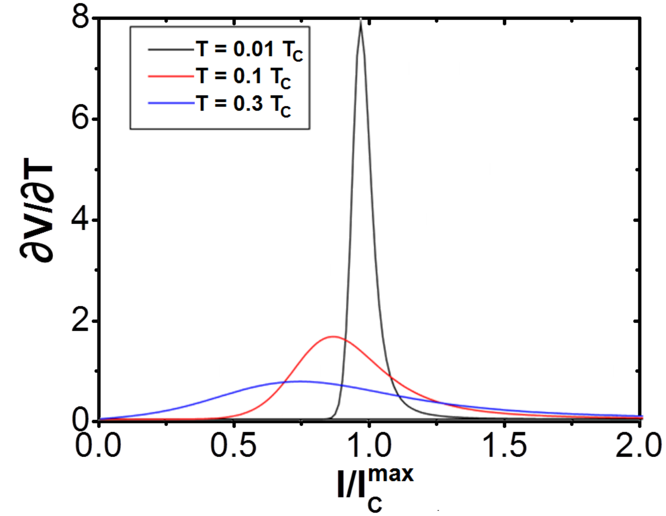

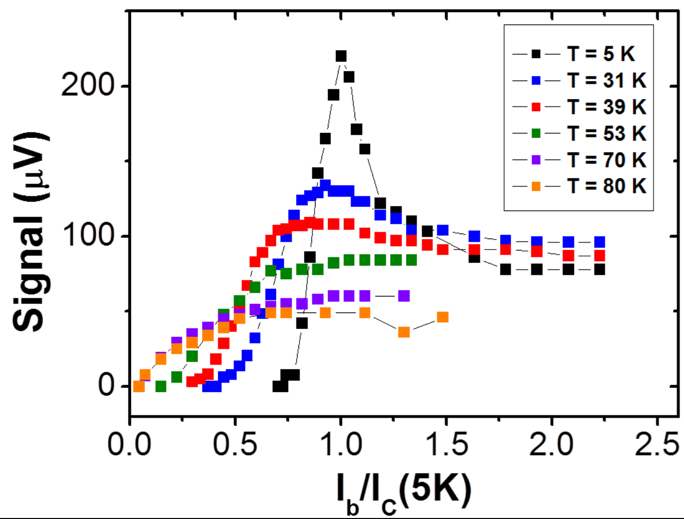

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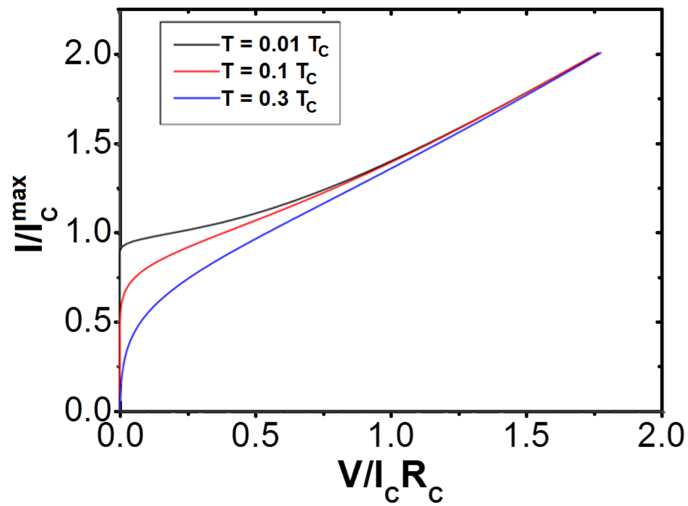
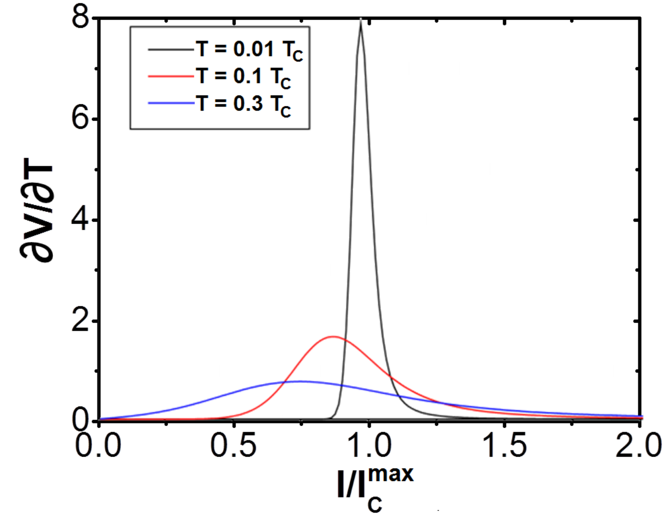
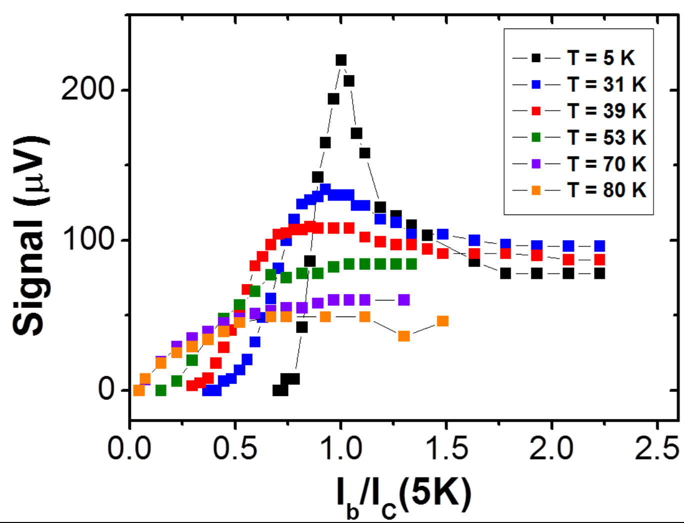
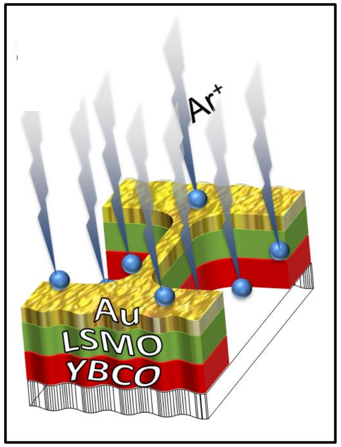


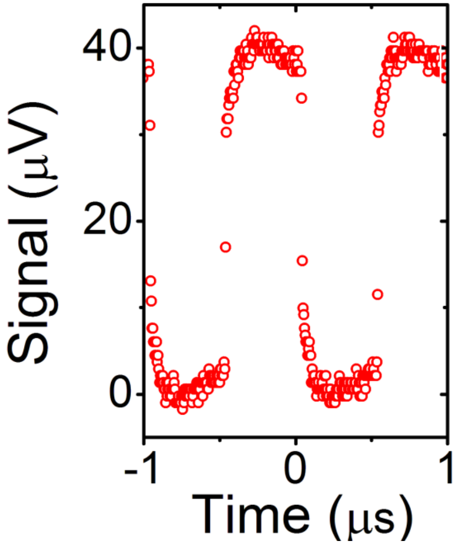




The main contribution to the photoresponse signals has a bolometric nature

Outlook: YBCO/LSMO nanowires





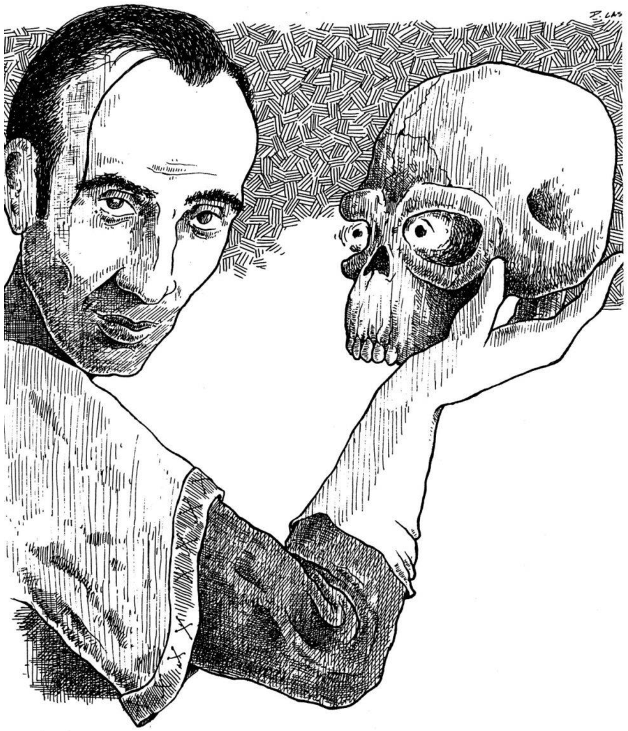
$La_{0.7}Sr_{0.3}MnO_3$ could play an effective role:

- as a capping.
- as a manganite.

R. Arpaia, M. Ejrnaes, L. Parlato, R. Cristiano, M. Arzeo, T. Bauch, S. Nawaz, F. Tafuri, G. P. Pepe, F. Lombardi, ***Supercond. Sci. Technol.*** **27, 044027 (2014).**

Outlook: YBCO nanorings

2e or not 2e?



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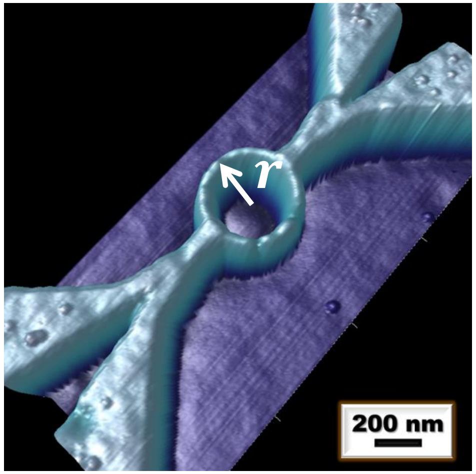

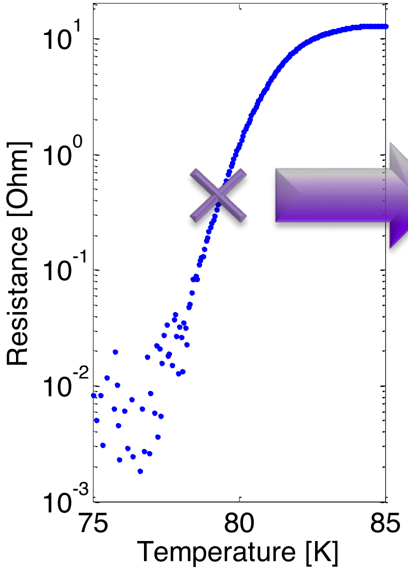

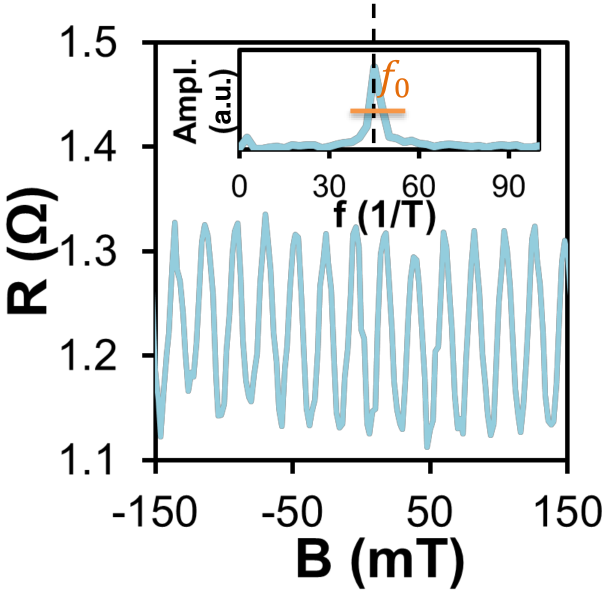

$$\Phi_0 = \pi r^2 / f_0 \qquad \Phi_0 = \quad h/2e$$

R. Arpaia, S. Charpentier, R. Toskovic, T. Bauch, F. Lombardi, ***Physica C* (2014)**, DOI: 10.1016/j.physc.2014.06.015

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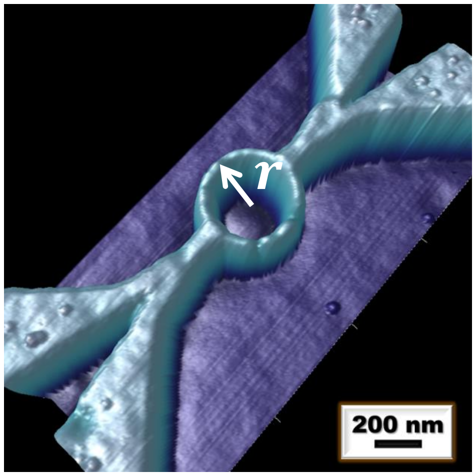
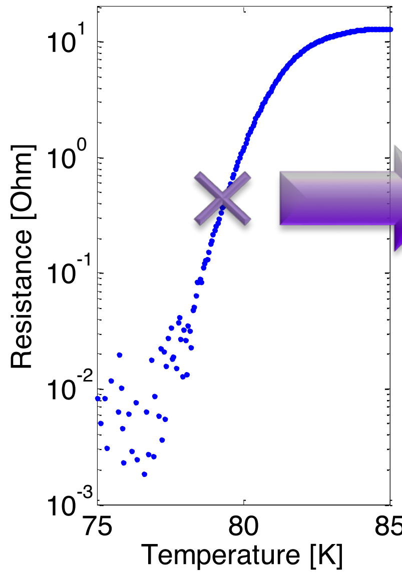
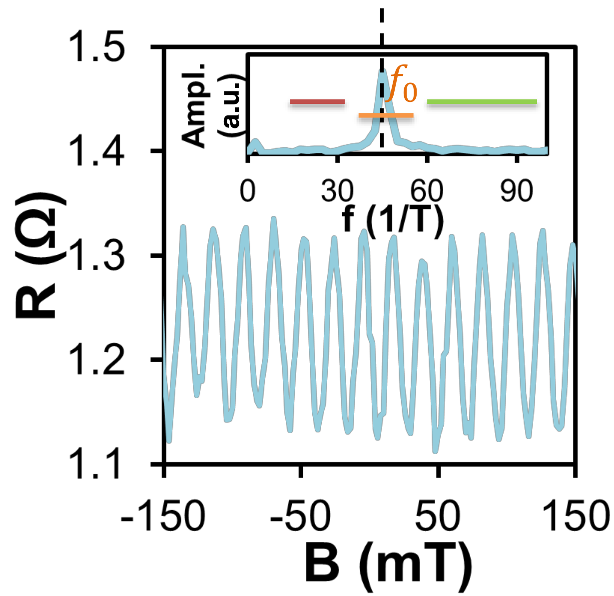






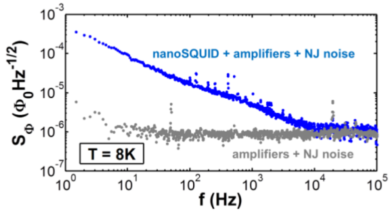
$$\Phi_0 = \pi r^2 / f_0 \qquad \Phi_0 = \begin{cases} h/e \\ h/2e \\ h/4e \end{cases}$$

R. Arpaia, S. Charpentier, R. Toskovic, T. Bauch, F. Lombardi, ***Physica C* (2014)**, DOI: 10.1016/j.physc.2014.06.015

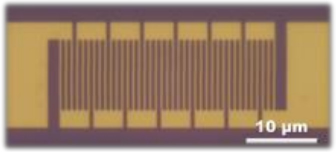
Summary

- We fabricated YBCO nanowires with properties close to the as grown film, that are model systems to study the intrinsic properties of the HTS

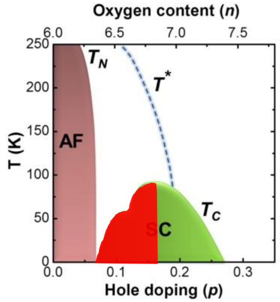
- We can employ these nanowires in devices with outstanding sensitivity to magnetic flux (record white flux noise in nanoSQUIDs)



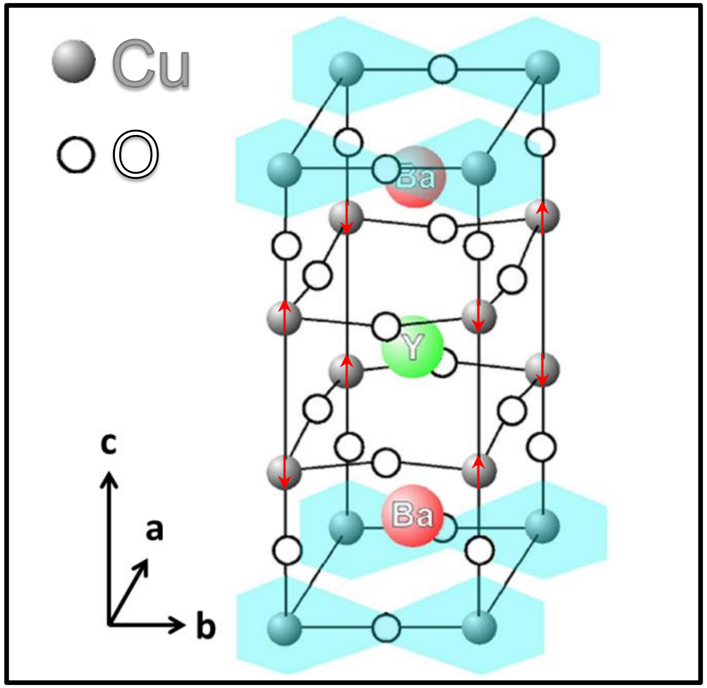
- We observed photoresponse from parallel nanowires, covering very large areas, although the single photon limit is still not reached.



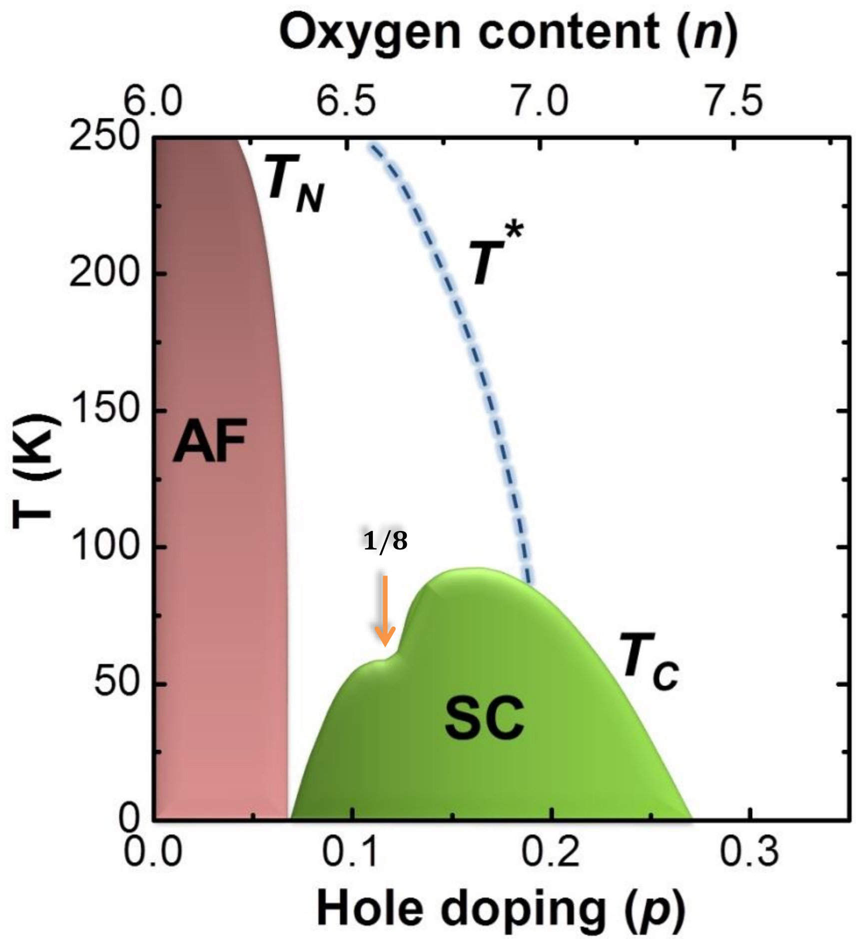
- A sharp peak in the FFT spectrum of the $R(B)$ oscillations of the nanorings represents solid ground for future experiments on underdoped YBCO nanorings, where different values of the flux quantum (h/e, $h/2e$, $h/4e$) might be detected.



$YBa_2Cu_3O_{7-\delta}$ cell

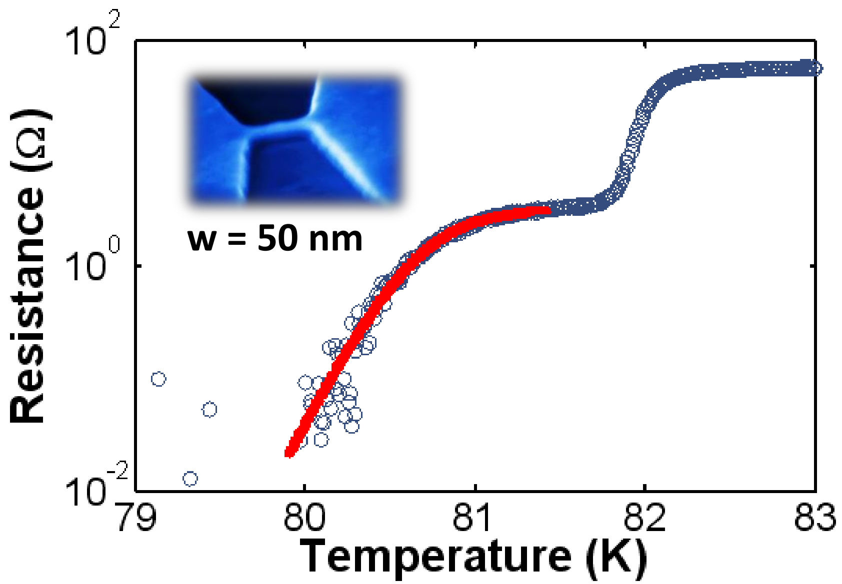


$a = 3.82$ Å
$b = 3.89$ Å
$c = 11.69$ Å



Benchmarking the quality of YBCO nanowires

II. Same critical temperature of the unpatterned films



S. Nawaz, R. Arpaia, F. Lombardi and T. Bauch, ***Phys.Rev.Lett.* 110, 167004 (2013)**

S. Nawaz, R. Arpaia, T. Bauch, F. Lombardi, ***Physica C* 495, 33 (2013)**

R. Arpaia, D. Golubev, R. Baghdadi, M. Arzeo, G. Kunakova, S. Charpentier, S. Nawaz, F. Lombardi, T. Bauch, ***Physica C* (2014)** DOI: 10.1016/j.physc.2014.06.002

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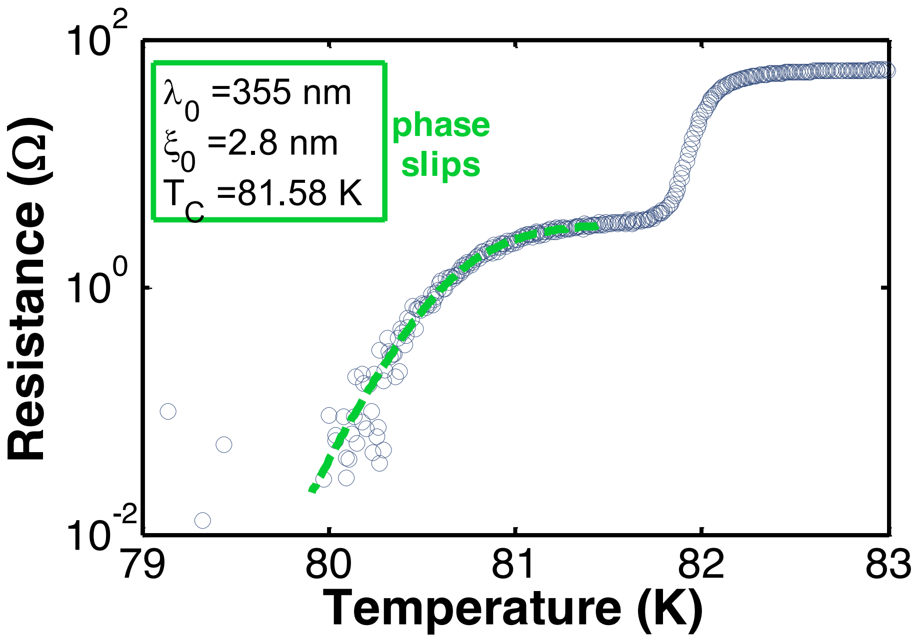

$$R_{Little}(T) = R_N \exp\left(-\frac{\Delta F(T)}{k_B T}\right)$$

$$R(T) = \left[R_{Little}^{-1}(T) + R_{sh}^{-1}\right]^{-1}$$

S. Nawaz, R. Arpaia, T. Bauch, F. Lombardi, ***Physica C* 495, 33 (2013)**

R. Arpaia, S. Nawaz, F. Lombardi, T. Bauch, ***IEEE Trans. App. Sup.* 23, 1101505 (2013)**

Benchmarking the quality of YBCO nanowires

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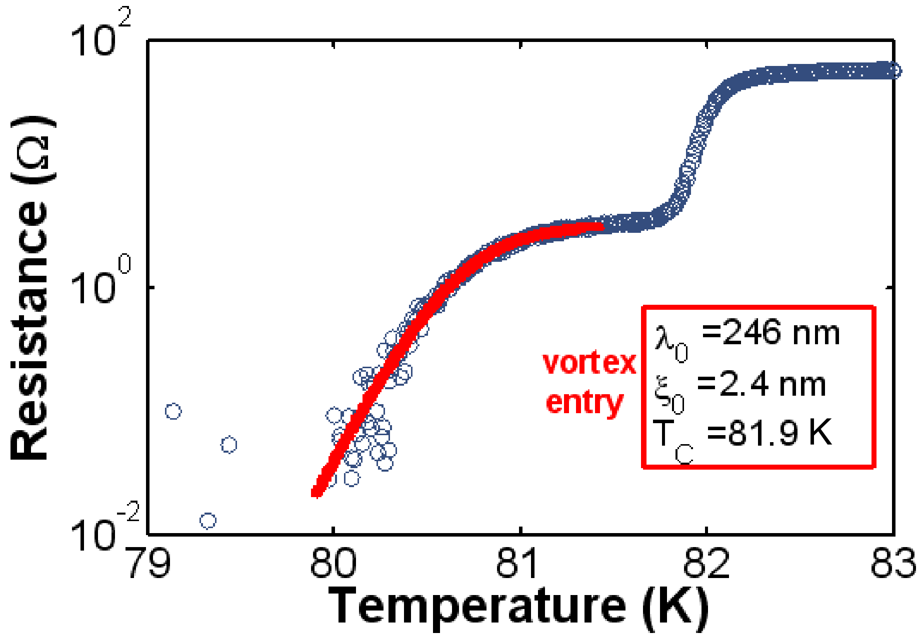

$$R_v(T) = R_\square \sqrt{2\pi}(1+\pi)\frac{l\xi}{w^2}\left(\frac{\mu^2}{k_B T}\frac{\Phi_0^2 t}{4\pi\mu_0\lambda_L^2}\right)^{3/2}\exp\left(-\frac{\mu^2}{k_B T}\frac{\Phi_0^2 t}{4\pi\mu_0\lambda_L^2}\ln\frac{w}{\pi\xi}\right) \qquad R(T) = \left[R_v^{-1}(T) + R_{sh}^{-1}\right]^{-1}$$

R. Arpaia, D. Golubev, R. Baghdadi, M. Arzeo, G. Kunakova, S. Charpentier, S. Nawaz, F. Lombardi, T. Bauch, ***Physica C* (2014),** DOI: 10.1016/j.physc.2014.06.002

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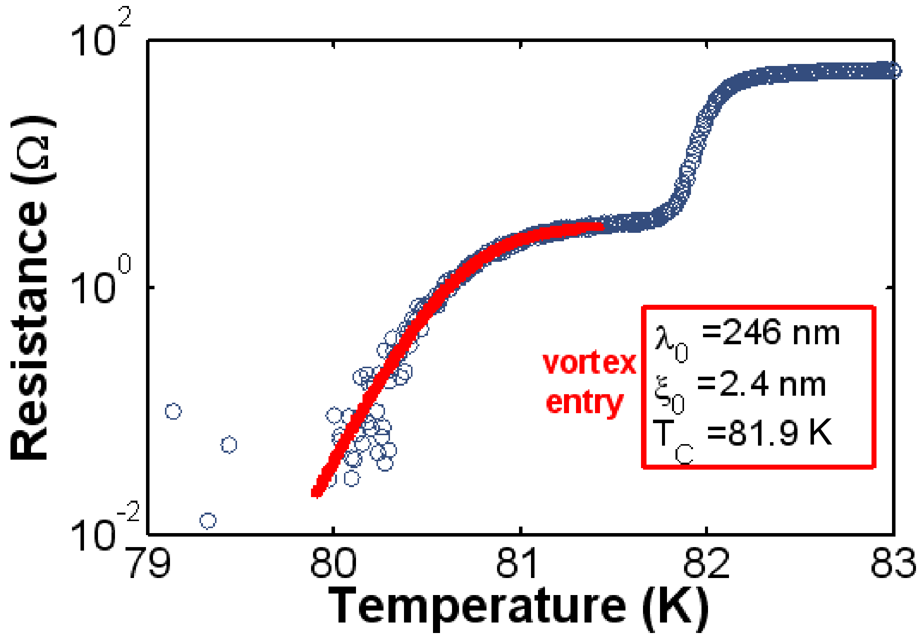

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R. Arpaia, D. Golubev, R. Baghdadi, M. Arzeo, G. Kunakova, S. Charpentier, S. Nawaz, F. Lombardi, T. Bauch, ***Physica C*** **(2014),** DOI: 10.1016/j.physc.2014.06.002

IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2014 (Preview 1).
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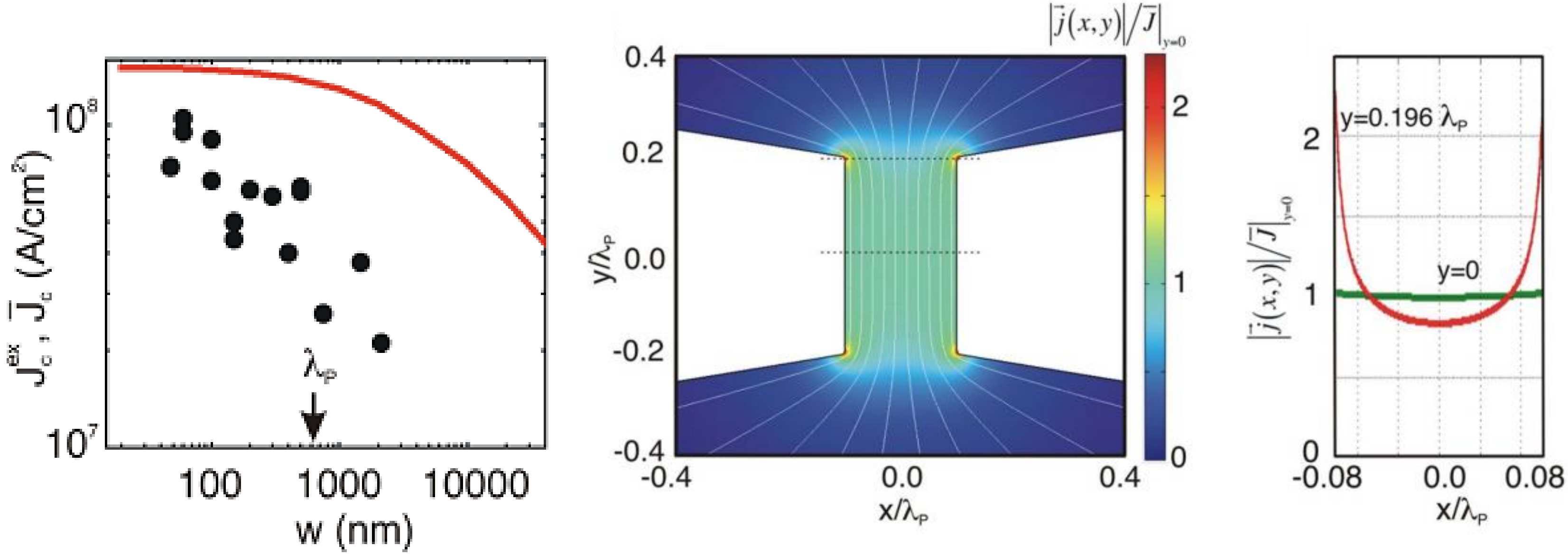
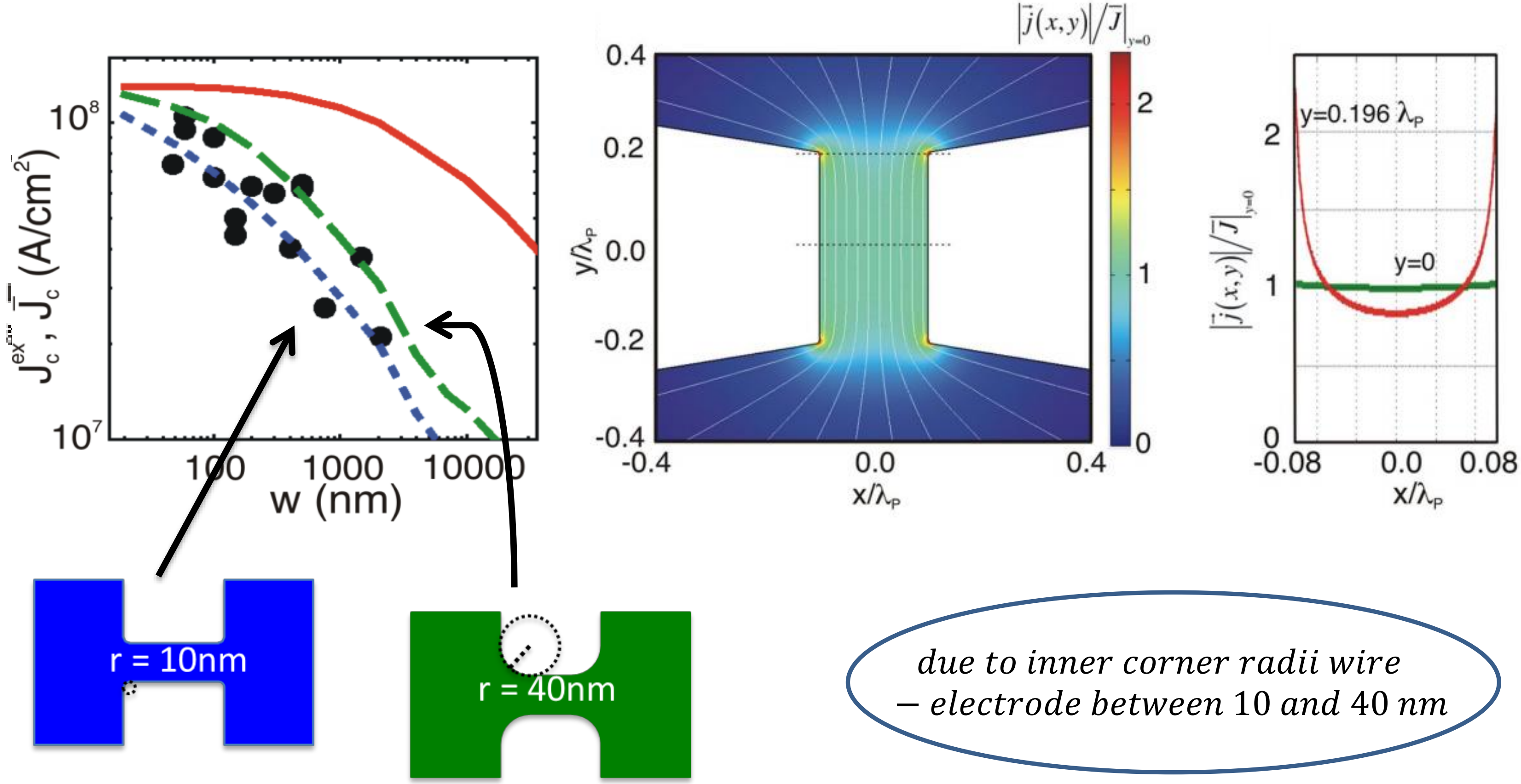
Current crowding



S. Nawaz, R. Arpaia, F. Lombardi and T. Bauch, ***Phys.Rev.Lett.*** **110, 167004 (2013)**

Current crowding

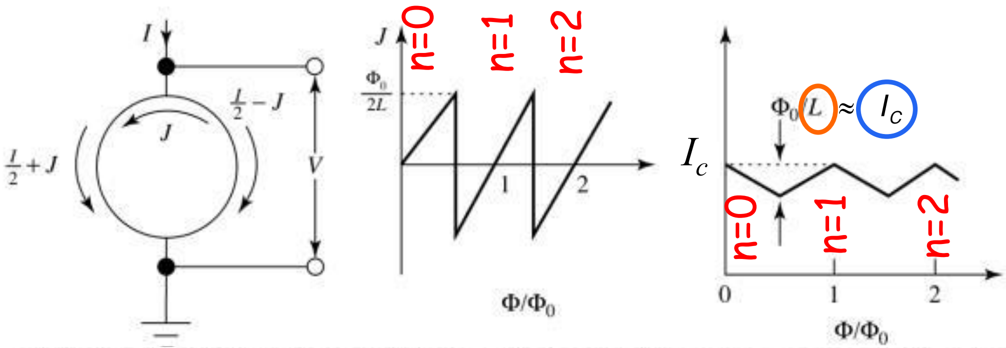


due to inner corner radii wire – electrode between 10 *and* 40 *nm*

S. Nawaz, R. Arpaia, F. Lombardi and T. Bauch, ***Phys.Rev.Lett.*** **110, 167004 (2013)**

NanoSQUID implementing nanowires: model

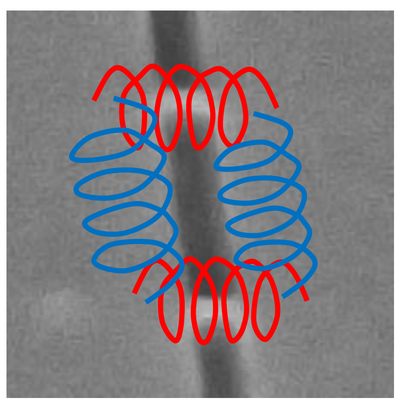
$$\Phi + \mu_0 \oint \lambda_L^2 \overrightarrow{j_S} \cdot d\vec{r} = n \cdot \frac{h}{2e}$$



J. Clarke. in H. Weinstock and R. W. Ralston eds. *The new superconducting electronics*, pages 123–180. Kluwer publishers, The Netherlands, 1993.

$$L^{exp} \approx \frac{I_C}{I_C}$$

$$L^{num} = \frac{I_C L_{loop}}{0}$$



L_{loop}=L_{wire}+$L_{electrode}$

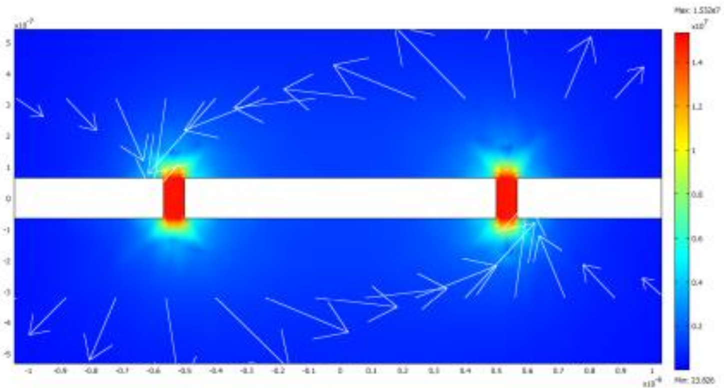
YBCO nanoSQUIDs:
comparison with numerical simulations

from measurement

$$^{\exp}_{L} \approx \frac{I_C}{I_C}$$

$$\beta_L^{sim} = \frac{I_C L_{loop}}{\Phi_0}$$

calculate numerically

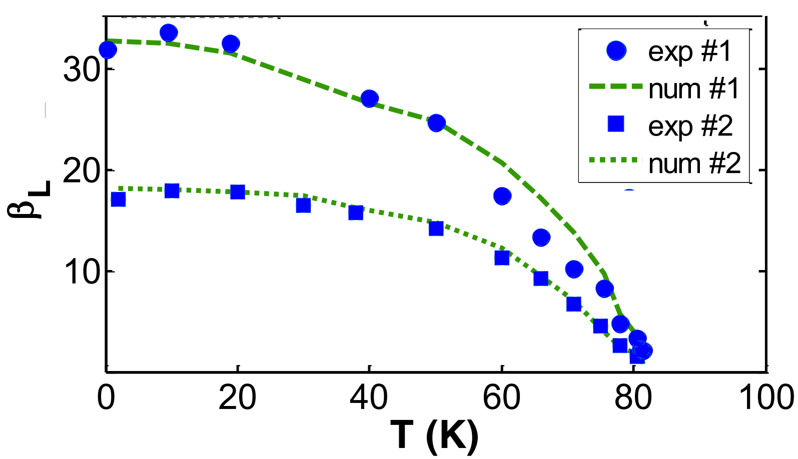


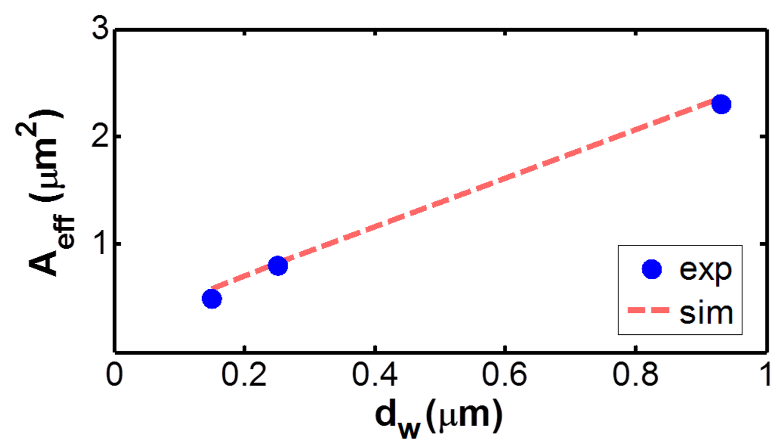
from measurement

$$A_{eff}^{\exp} = \frac{\Phi_0}{\Delta B}$$

$$A_{eff}^{sim} = \frac{m}{I_{cir}}$$

calculate numerically





R. Arpaia, M. Arzeo, S.Nawaz, S.Charpentier, F.Lombardi, T.Bauch, ***Appl.Phys.Lett. 104, 072603*** **(2014)**

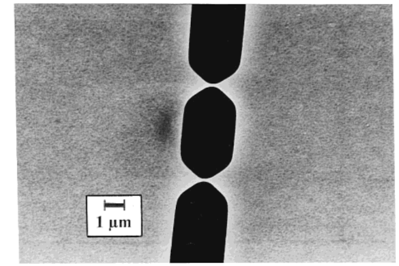
YBCO nanoSQUIDs in literature

Appl. Phys. Lett. **65** (19), 7 November 1994

dc SQUIDs based upon $YBa_2Cu_3O_7$ nanobridges

J. Schneider, M. Mück, and R. Wördenweber
Institute of Thin Film and Ion Technology (ISI), Research Centre Jülich (KFA), :

$\times 100\ \mathrm{nm}^3$ (l,w,d).[11] Even for a calculated $\beta_L \approx 1$, no significant modulation of the critical current was observed for our HTS SQUIDS, i.e., $\Delta I_c/I_c \ll 1$. The relatively high volt-

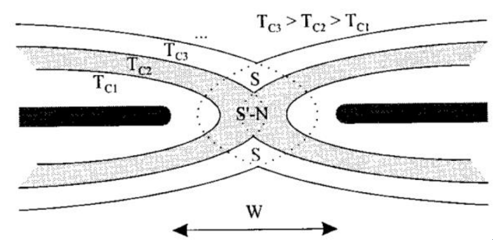


Appl. Phys. Lett., Vol. 68, No. 8, 19 February 1996

Superconducting quantum interference devices based on YBaCuO nanobridges

M. V. Pedyash,[a)] D. H. A. Blank, and H. Rogalla
Low Temperature Division, Department of Applied Physics, University of Twente, P.O. Box 217, 7500 AE Enschede, the Netherlands

for weak link SQUIDs. To explain this phenomenon, we considered degradation of superconductor in the nanobridge area, which leads to a local suppression of T_c and to a transition from SNS to SS′S-type junctions with decreasing temperature. This approach allows us to explain the experimen-

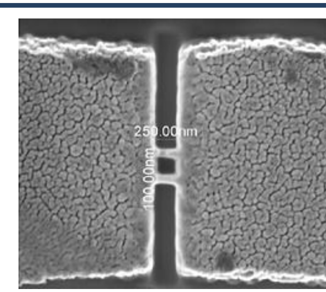


Nanotechnology **19** (2008) 315304 (5pp)

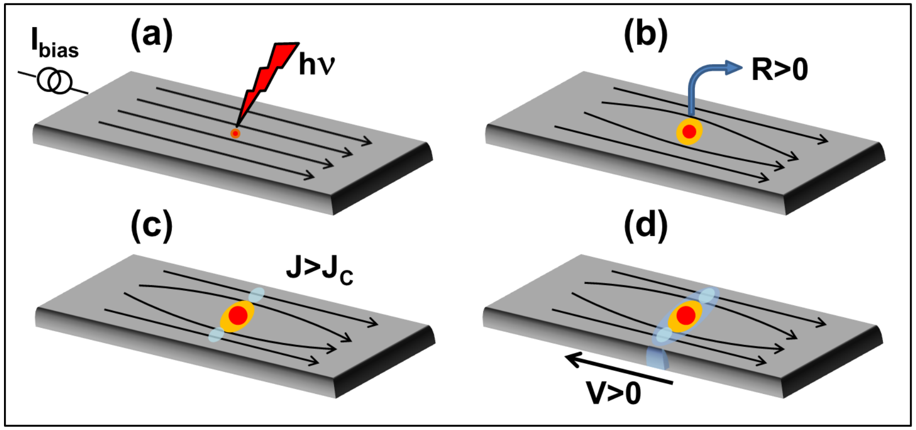
Fabrication and characterization of high-T_c $YBa_2Cu_3O_{7-x}$ nanoSQUIDs made by focused ion beam milling

C H Wu[1,6], Y T Chou[2], W C Kuo[2], J H Chen[3], L M Wang[3], J C Chen[4], K L Chen[4], U C Sou[4], H C Yang[4] and J T Jeng[5]

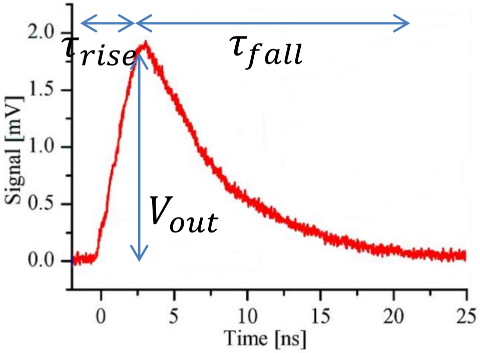
damaged by FIB milling. The characteristics of a SQUID were not observed. The reason is that no weak links were formed in the device's nanobridges.



SNSPDs: working principles



Characteristic parameters:



$$\tau_{rise} = \frac{L}{Z + R_N}$$

$$\tau_{fall} = \frac{L}{Z}, \qquad \text{where} \quad L = \frac{\mu_0 \lambda^2 l}{wd}$$

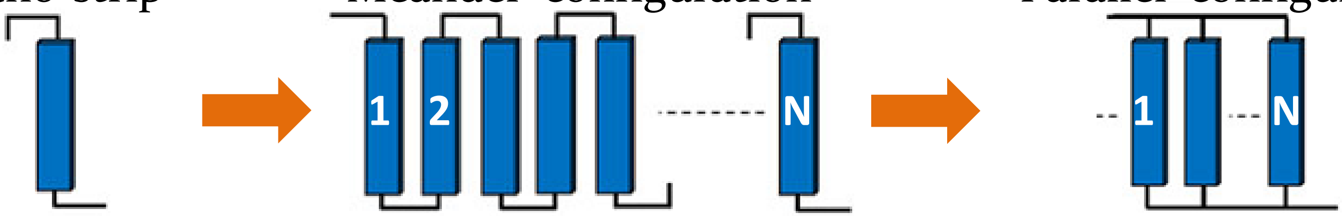
$$V_{out} = \mathrm{k} \cdot I_b \propto J_c$$

SNSPDs: the parallel configuration (I)

Very small volumes have to coexist with **large areas**

How to reach these conditions simultaneously?

Nano-strip | Meander configuration | Parallel configuration



L^s, I_c^s | $L^m = N \cdot L^s, \quad I_c^m = I_c^s$ | $L^p = L^s/N, \quad I_c^p = N \cdot I_c^s$

The SNSPDs with parallels are based on the ***cascade switching regime*** mechanism: the output signal is generated when the switch to the normal state occurs in cascade in all the nanowires forming the device.

A cascade switching superconducting single photon detector

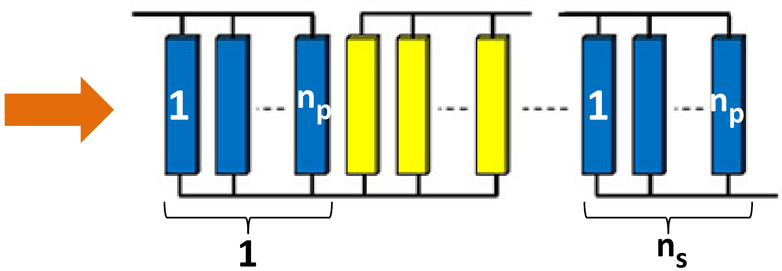
M. Ejrnaes and R. Cristiano
Istituto di Cibernetica "E. Caianiello" del C.N.R., 80078 Pozzuoli, Italy
O. Quaranta and S. Pagano[a)]
Dipartimento di Fisica "E. R. Caianiello," Università di Salerno, 84081 Baronissi, Italy
A. Gaggero
Istituto di Fotonica e Nanotechnologie del C.N.R., 00156 Roma, Italy and University of Roma TRE, Via Vasca Navale 84, 01146 Roma, Italy
F. Mattioli and R. Leoni
Istituto di Fotonica e Nanotechnologie del C.N.R., 00156 Roma, Italy
B. Voronov and G. Gol'tsman
Moscow State Pedagogical University, Moscow 119345, Russia

M Ejrnaes et al., ***APL*** **91, 262509 (2007)**

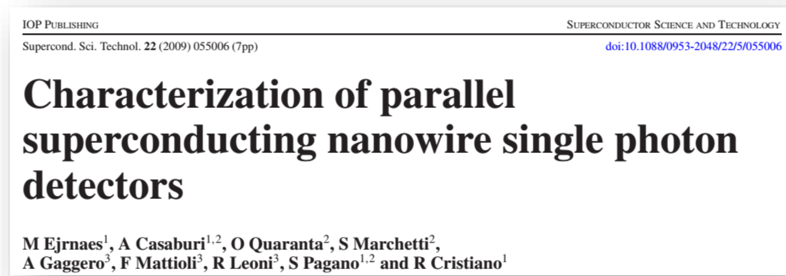
SNSPDs: the parallel configuration (II)

To properly trigger the cascade switch of all the parallel nanowires, it is necessary to confine the currents in the parallel nanowires

Series-parallel configuration



$$L = (n_s/n_p) \cdot L_s, \qquad I_c = n_p \cdot I_c^S$$


IOP PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY
Supercond. Sci. Technol. **22** (2009) 055006 (7pp) doi:10.1088/0953-2048/22/5/055006

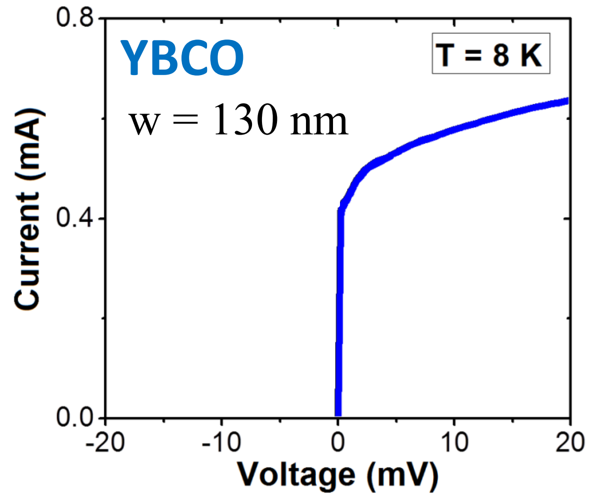
Characterization of parallel superconducting nanowire single photon detectors

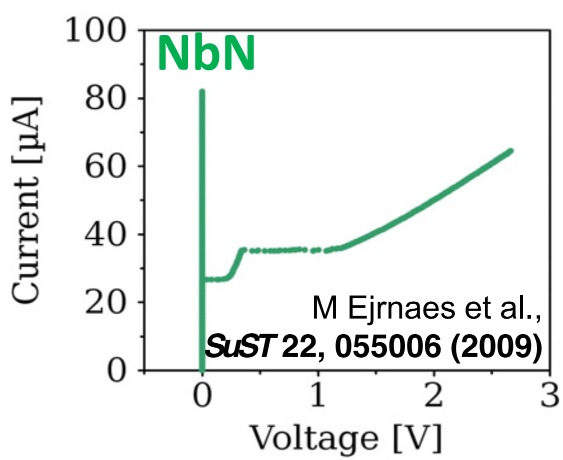
M Ejrnaes[1], A Casaburi[1,2], O Quaranta[2], S Marchetti[2], A Gaggero[3], F Mattioli[3], R Leoni[3], S Pagano[1,2] and R Cristiano[1]

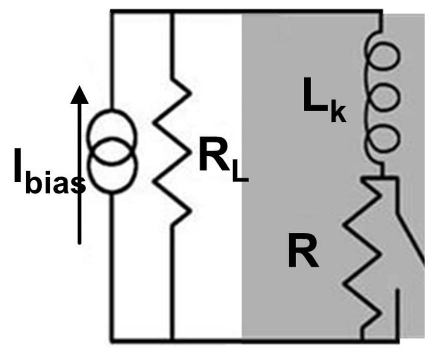
M Ejrnaes et al., ***SuST*** **22, 055006 (2009)**

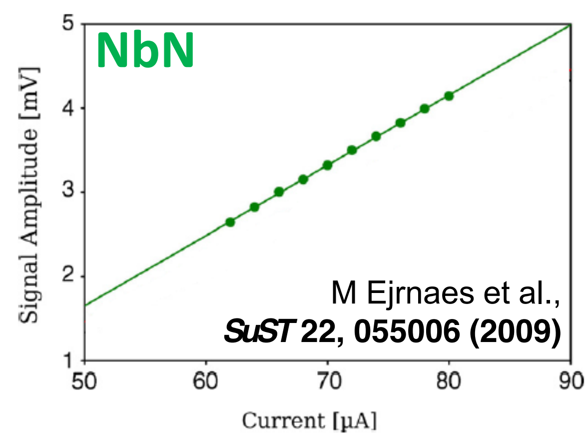
IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), October 2014 (Preview 1).
ASC 2014 presentation and paper 2EPo1D-08; 1st Prize in Best Student Paper Contest, Electronics.

YBCO nanowires for photodetection:
IV characterization – comparison with NbN SNSPDs

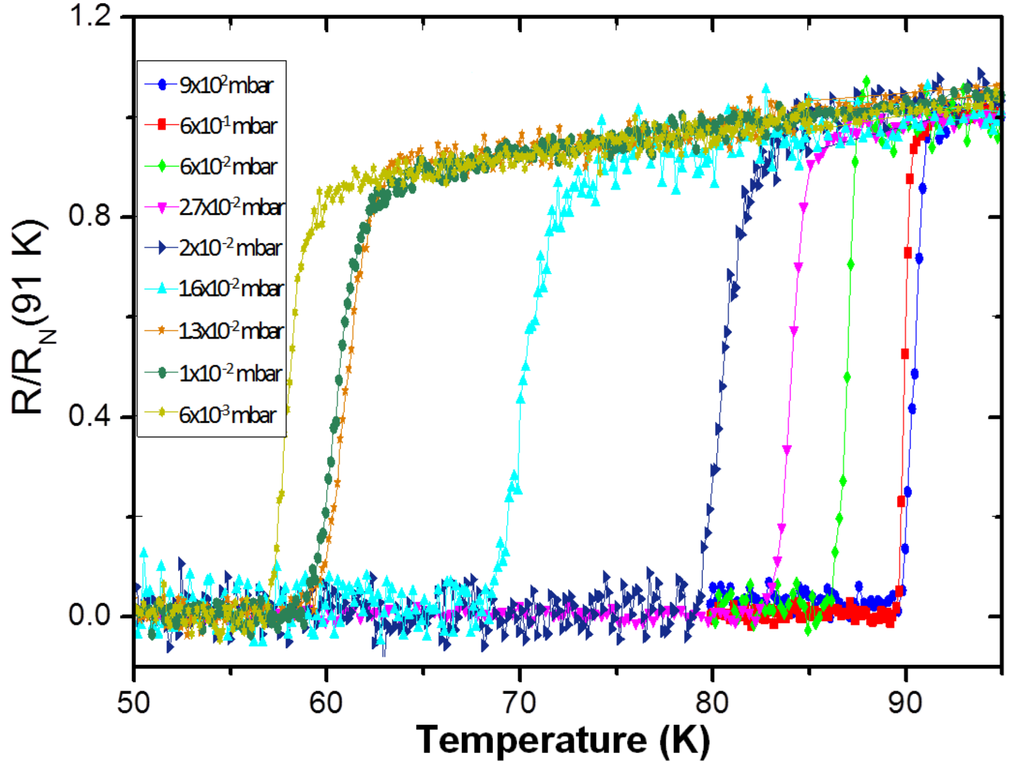


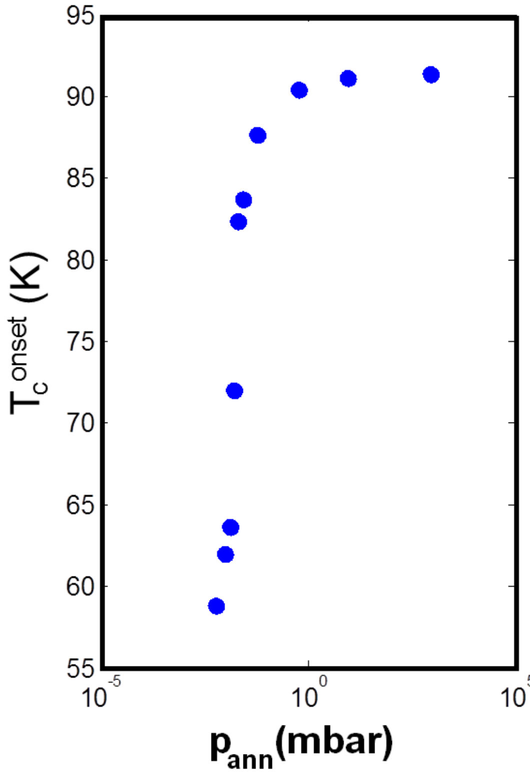






Underdoped YBCO films

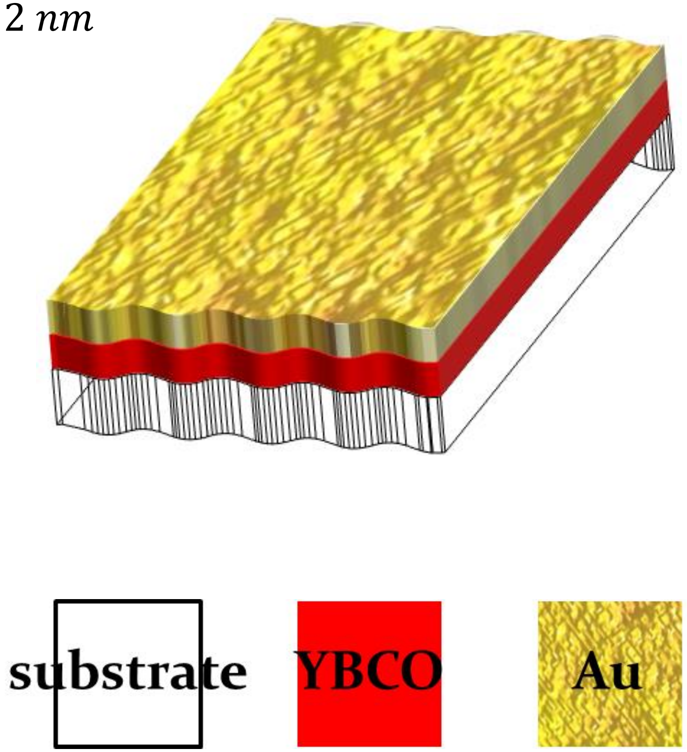




Improved nanopatterning for YBCO nanowires

$YBCO\ thickness = 50\ nm$

$YBCO\ roughness = 1\ - 2\ nm$



R. Arpaia, S. Nawaz, F. Lombardi, T. Bauch, ***IEEE Trans. App. Sup.*** **23, 1101505 (2013)**

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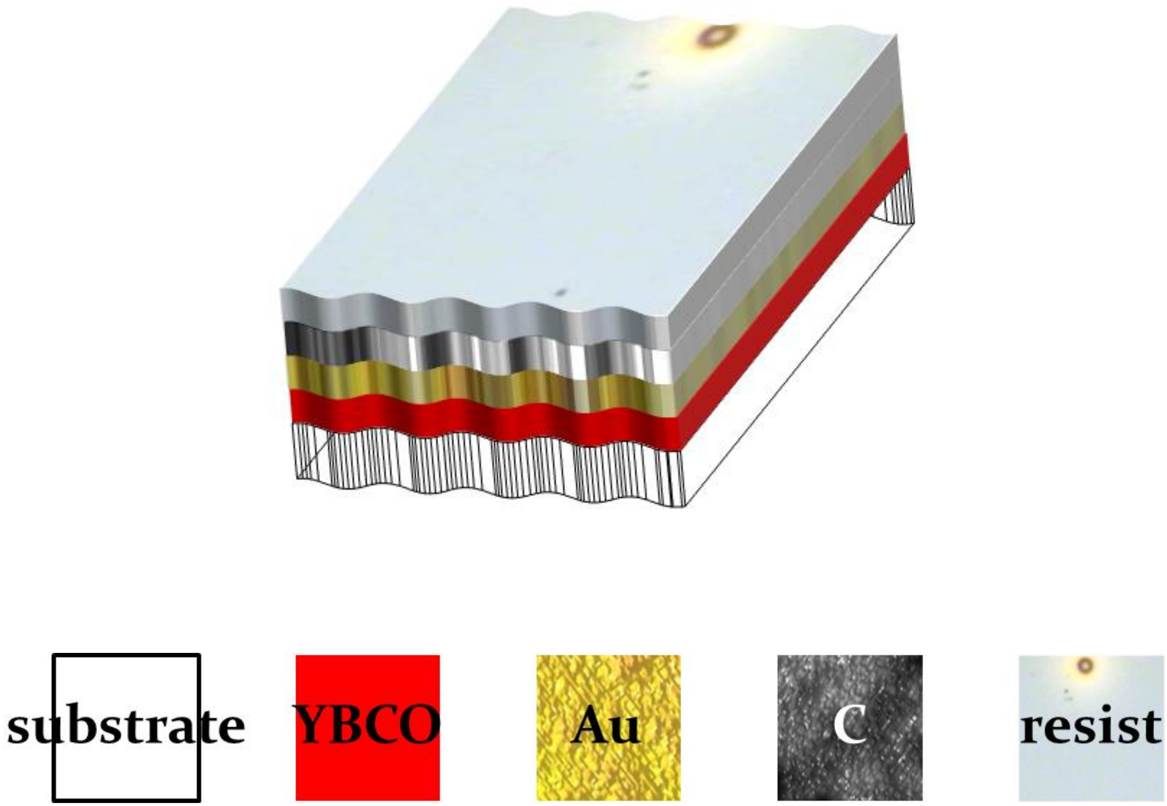

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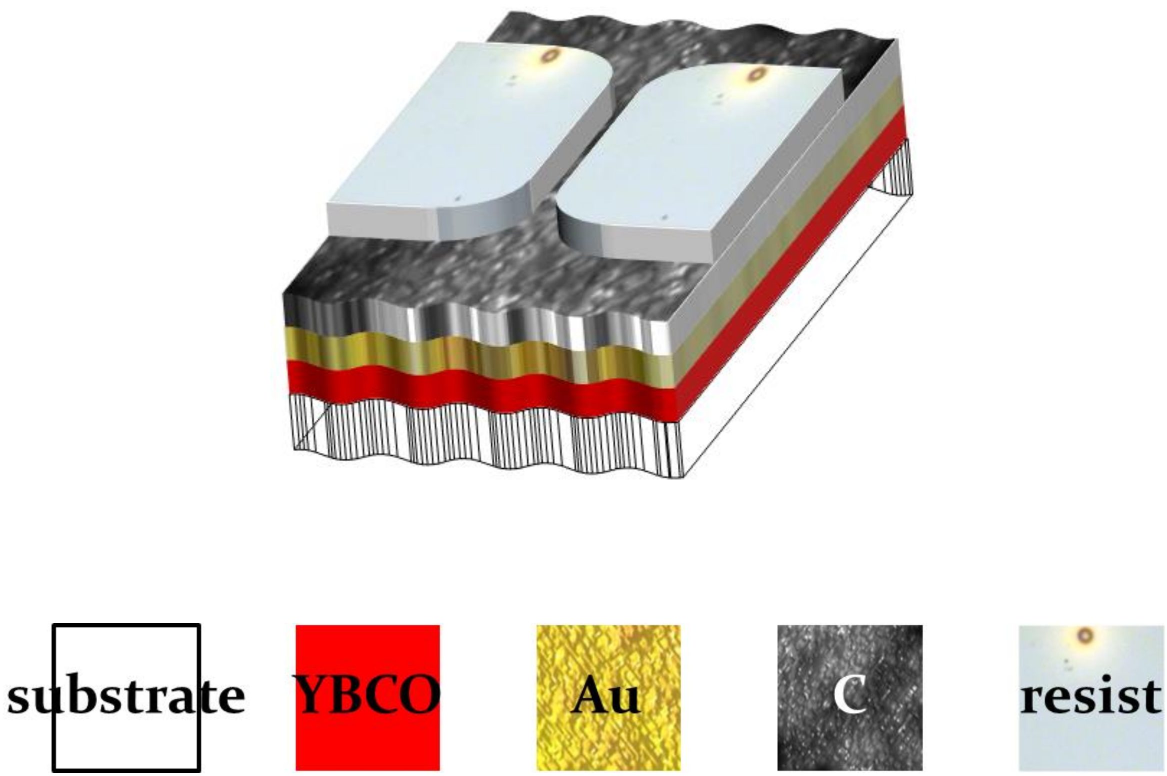

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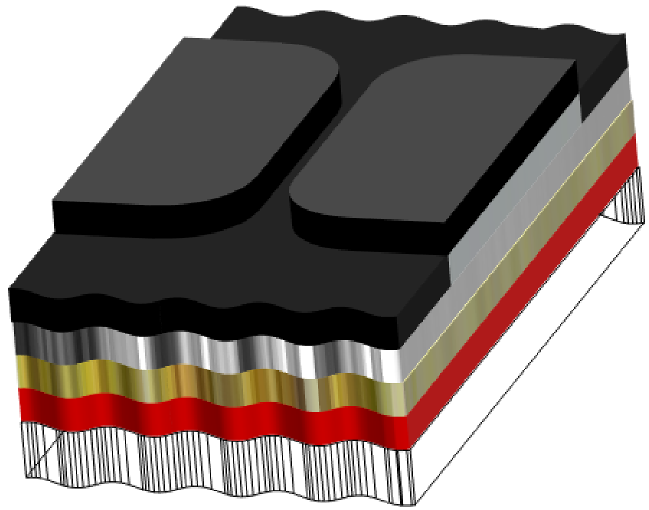

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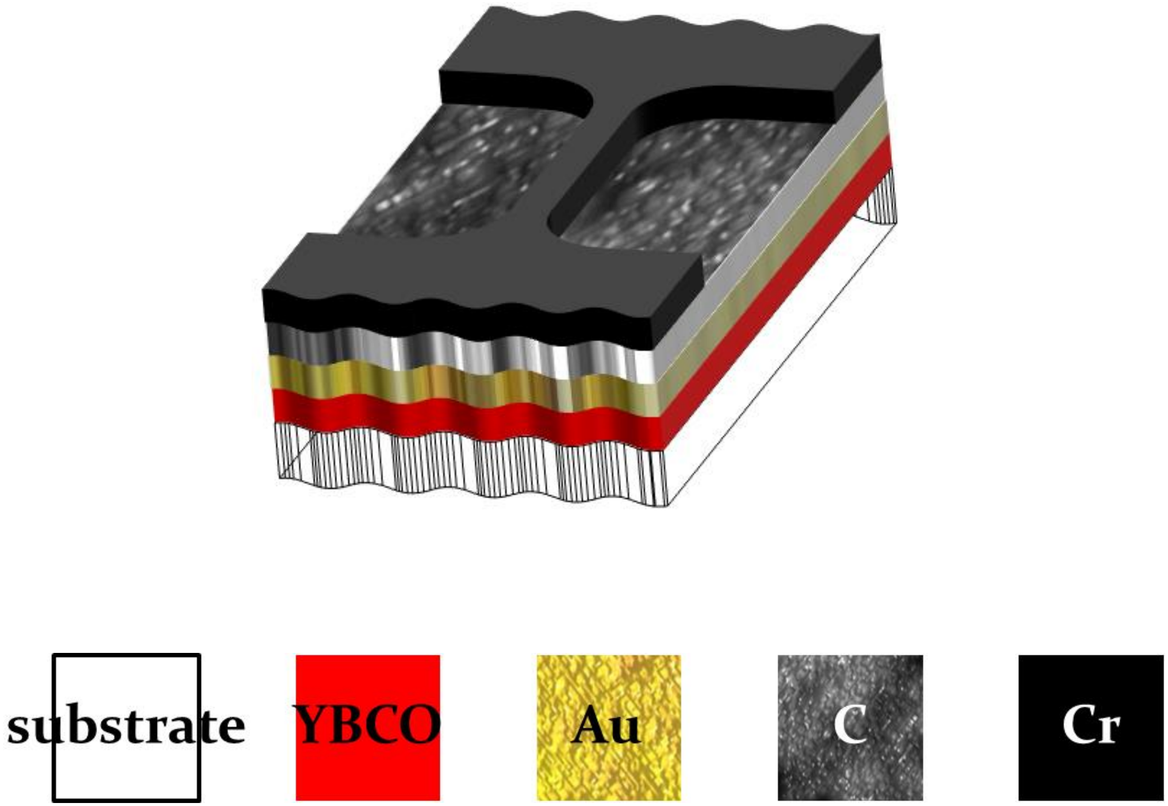

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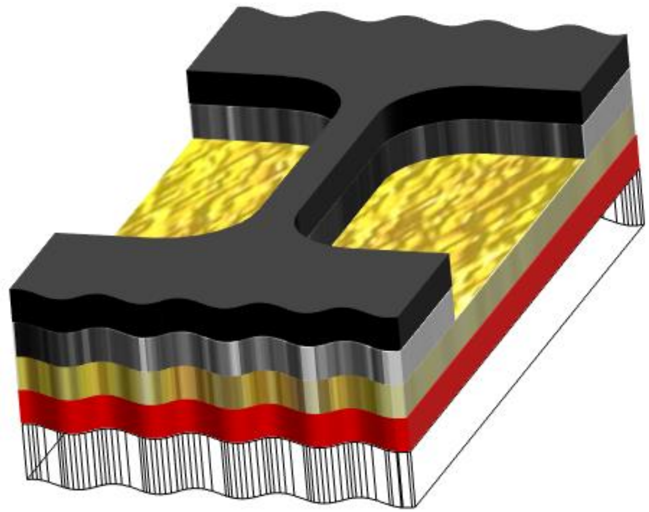

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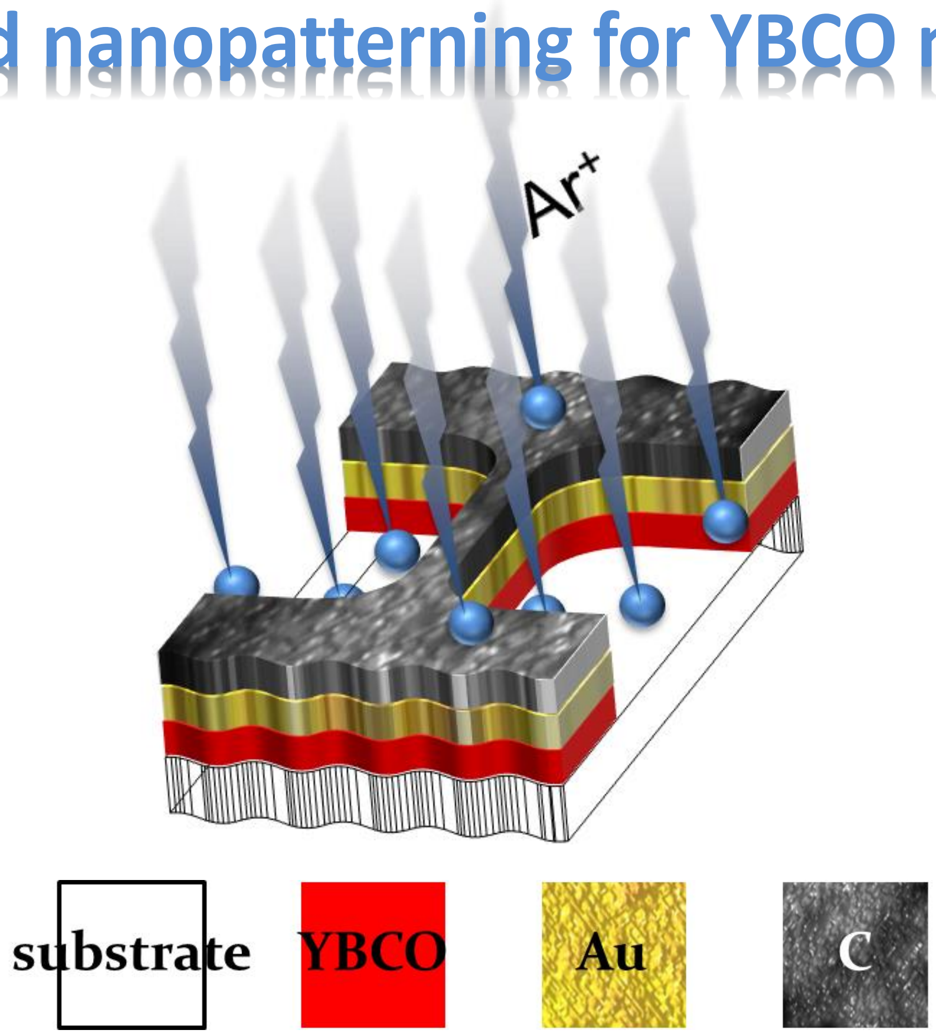

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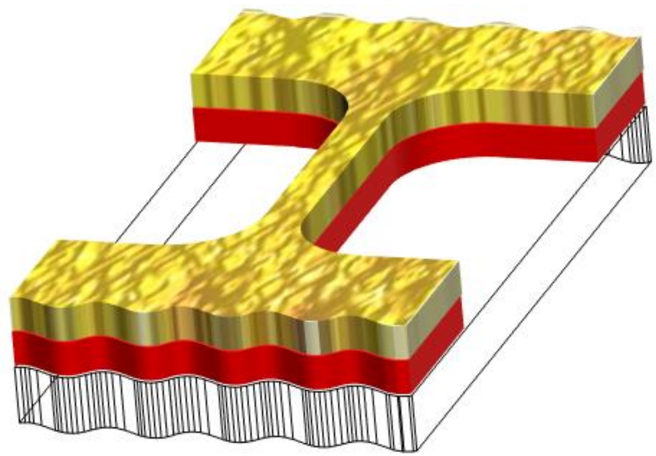

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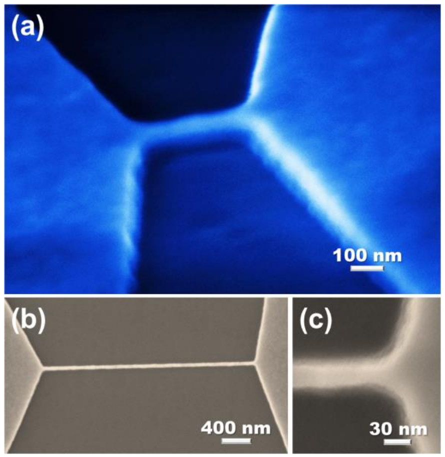

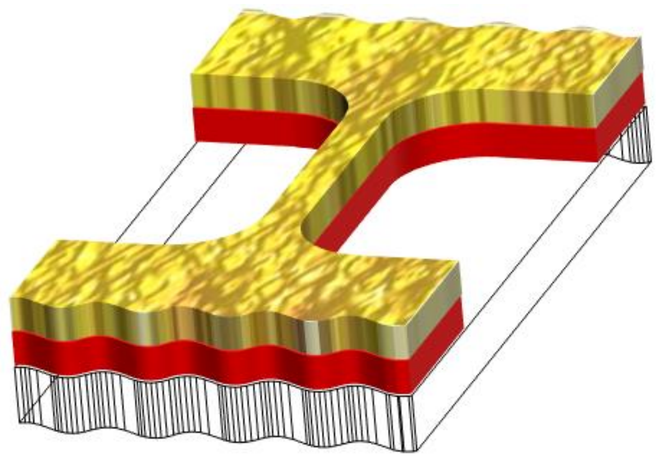

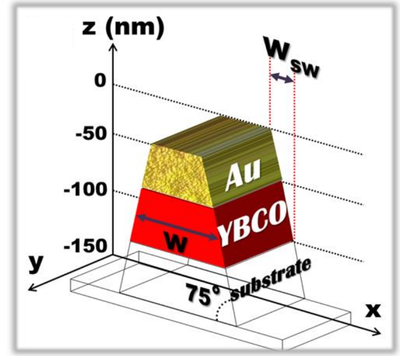

w *down to* $\mathbf{50}\ nm$

R. Arpaia, S. Nawaz, F. Lombardi, T. Bauch, ***IEEE Trans. App. Sup.*** **23, 1101505 (2013)**