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Bistable 10-nm-thick $YBa_2Cu_3O_{7-\delta}$ nanowires as new materials for single photon detectors

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Basic operation principles of SNSPDs

Appl. Phys. Lett. 79, 705 (2001)

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
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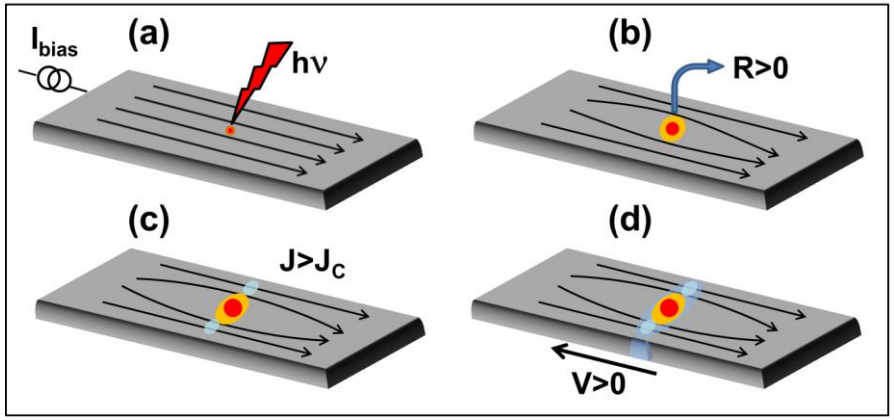
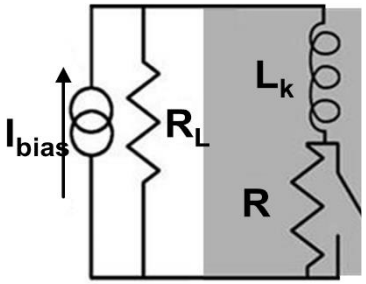
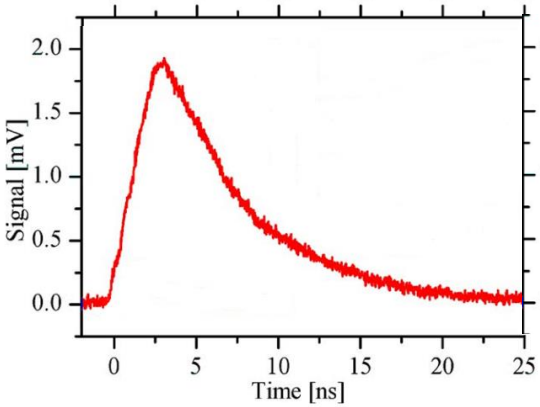
- quantum efficiency (≈93%)
- low dark counts (<1 s^{-1}),
- fast response time (few ps)
- broad spectral range







C.M.Natarajan et al., Supercond.Sci.Technol. 25, 063001 (2012)
A.Engel et al., Supercond.Sci.Technol. 28, 114003 (2015)
H.Bartolf, Fluctuation Mechanisms in Superconductors (2016)

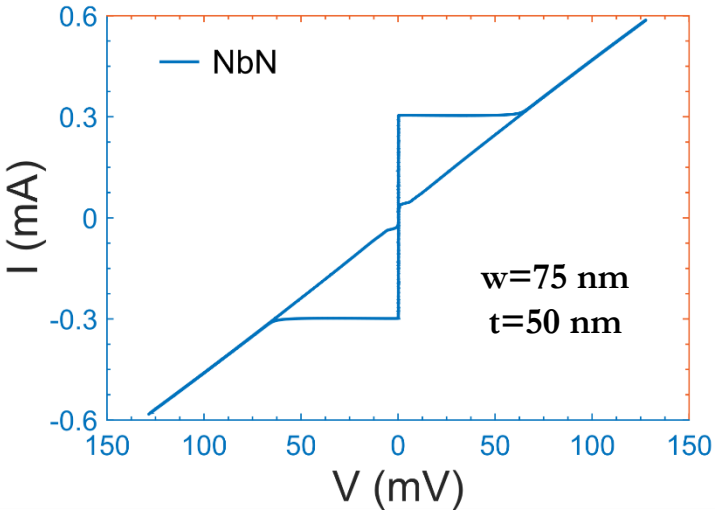
LTS materials for SNSPDs

The focus is only on Low-T_C Superconductors (NbN, TaN, Nb, WSi, etc…)

- **high critical current densities** (J_C up to $0.6 \cdot J_{dep}$)
  [*Henrich, Phys.Rev.B 86, 144504 (2012)*]
- **high sheet resistances** (≈ several kΩ)
  [*Ejrnaes, Appl.Phys.Lett. 91, 262509 (2007)*]
- **low thermal conductivities** ($\varkappa_{NbN} \approx 10^{-2}$-$10^{-1}$ $Wm^{-1}K^{-1}$)
  [*Stockhausen, Supercond.Sci.Technol. 25, 035012 (2012)*]

hysteretic IVCs

(self stabilizing hot spot [*Skocpol, J.Appl.Phys. 45, 4054 (1974)*])



When using ultrathin (≤10 nm) films:

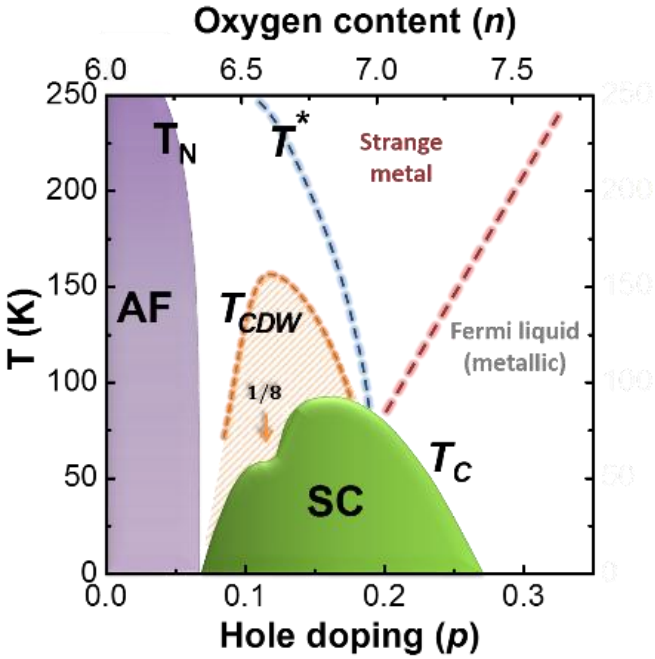
enhancement of:
- sheet resistance
- **critical current density**

[*Yurchenko, Appl.Phys.Lett 102, 252601 (2013)*]
[*Lin, Phys.Rev.B 87, 184507 (2013)*]

YBCO nanowires for SNSPDs

HTSs, and YBCO in particular, can be good candidates:

- high critical temperatures (>77 K)
- short coherence lengths (≈2 nm)
- fast quasiparticle recombination time (≈ps)

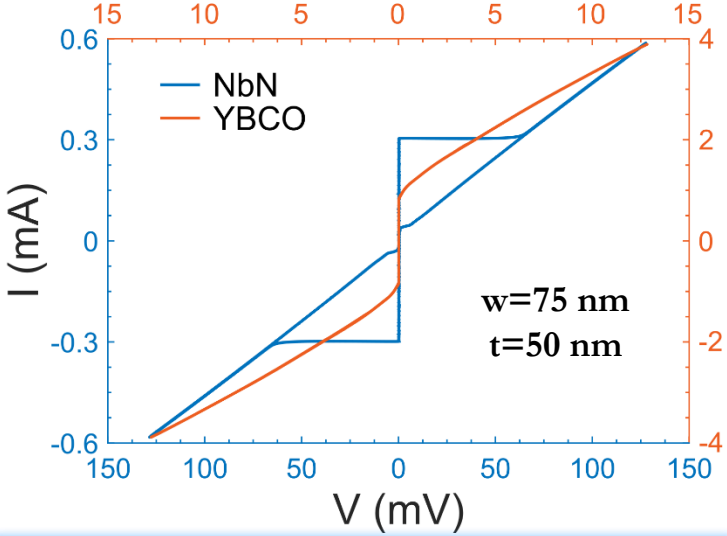


YBCO nanowires for SNSPDs

Materials with $C_e/C_{ph}|_{T=Tc} \ll 1$ are bad candidates for SNSPDs, unless their $J_C \rightarrow J_{dep}$
[*Vodolazov, Phys.Rev.Applied 7, 034014 (2017)*]

In YBCO, $C_e/C_{ph}|_{T=Tc} = 0.03$ [*Lindgren, Appl.Phys.Lett. 74, 853 (1999)*]

J_{dep} ($\approx 8 \cdot 10^7$ A/cm^2) has been achieved only in 50 nm thick nanowires [*Nawaz, Phys.Rev.Lett. 110, 167004 (2013)*]



IVCs are flux-flow-like ($\varkappa_{YBCO} \approx 15$ Wm^{-1}K^{-1})

N.Curtz et al., Supercond.Sci.Technol. 23, 045015 (2010)
R.Arpaia et al., Supercond.Sci.Technol. 27, 044027 (2014)
R.Arpaia et al., Physica C 509, 16 (2015)
M.Lyatti et al., arXiv:1603.03459 (2016)
P.Amari et al., arXiv:1612.07730 (2016)
H.Shibata et al., Supercond.Sci.Technol. 30, 074001 (2017)

The lack of bistability in the IVCs is a severe limitation for the employment of YBCO nanowires in SNSPDs

A HTS SNSPD has still not been realized!

YBCO nanowires for SNSPDs

Ultrathin (≤10 nm) films have to be used!

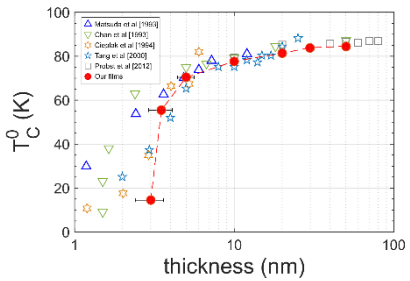
$\varkappa$ decreases, consequently to the increase of resistivity ϱ, via the Wiedemann-Franz law: $\varkappa(t) = L \cdot T/\varrho$ …

…but:
- in granular films, grain boundaries are present [*Levi, Europhys.Lett. 101, 67005 (2013)*]
- in ultrathin nanowires, the superconducting properties are degraded [*Curtz, Supercond.Sci.Technol. 23, 045015 (2010)*]

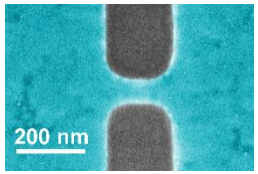
The J_C reduction brings to non-hysteretic IVCs even in ultrathin nanowires

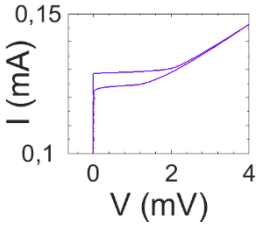
The goal is to get YBCO nanowires with bistable IVCs, keeping $J_C \approx J_{dep}$ even at thickness of few-unit-cells.

YBCO nanowires for SNSPDs

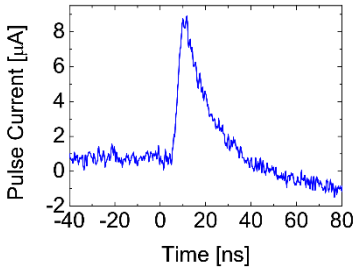


Grow ultrathin YBCO films, with properties intrinsic of the material





Pattern YBCO nanowires, preserving the superconducting properties

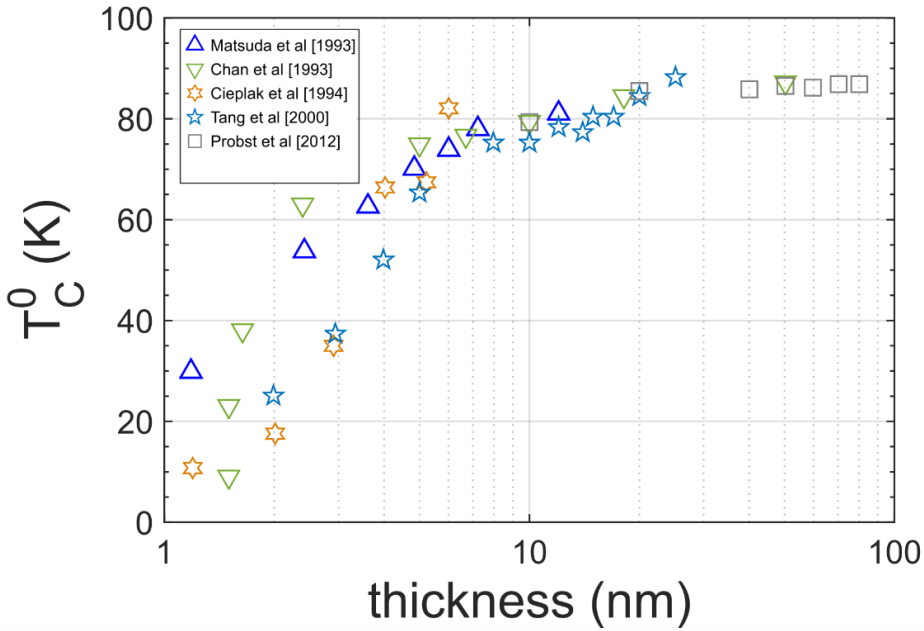


Test the nanowires in a dark count detection experiment to show the potentialities of these devices as SNSPDs

Ultrathin YBCO films

YBCO films, with thicknesses down to 3 nm, have been deposited on MgO (110) substrates.

[*R.Arpaia et al., Phys.Rev.B 96, 064525 (2017)*]



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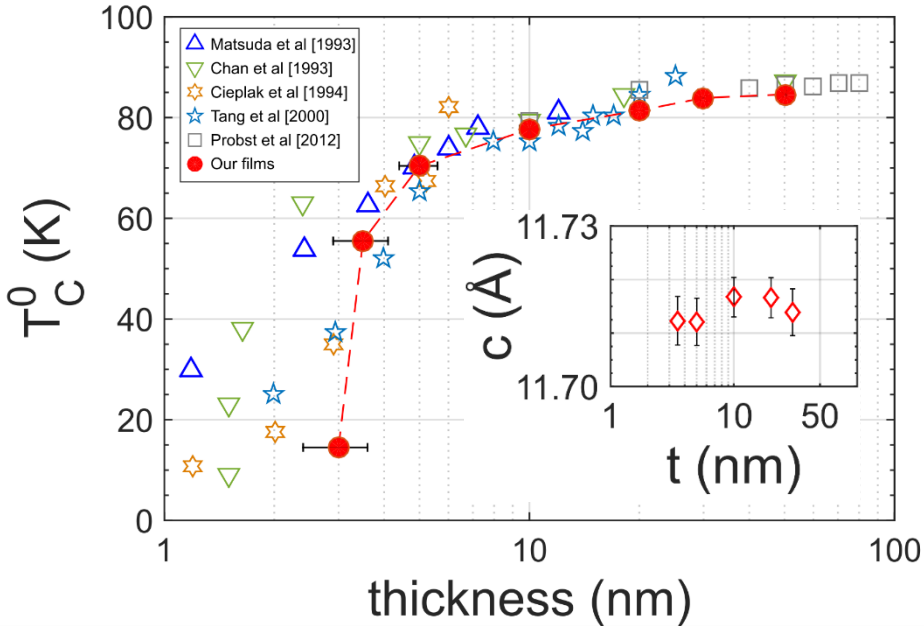
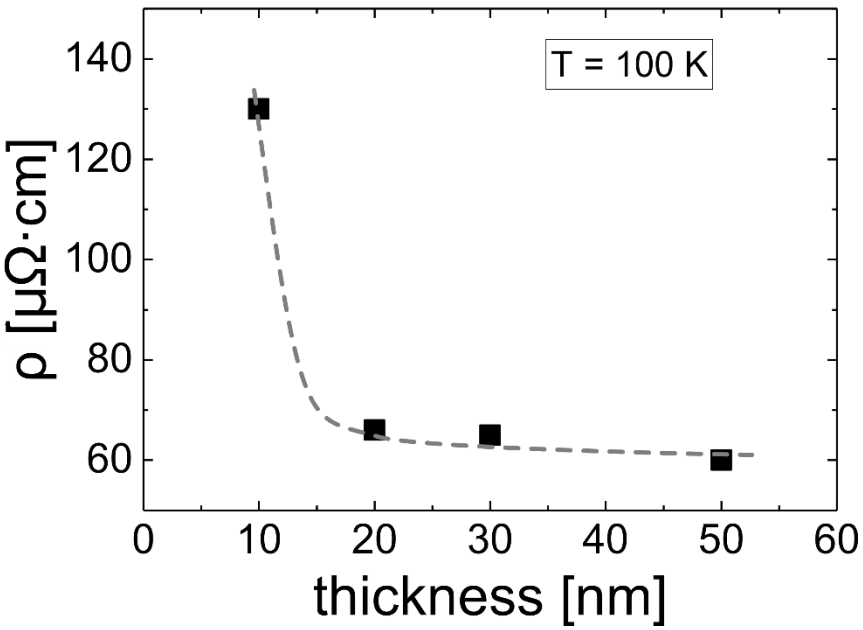


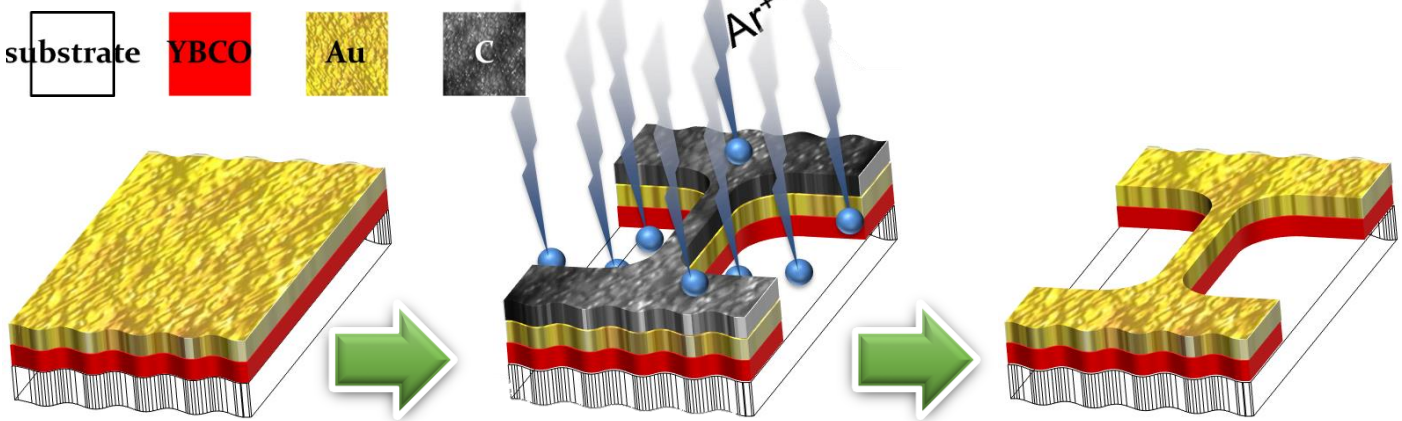


- The T_C^0 values are comparable, down to 5 nm, with the best results of PBCO/YBCO/PBCO multi-layers.
- The films preserve the oxygen doping level, being slightly overdoped at any thickness.
- The resistivity ϱ is thickness dependent below 15 nm. In particular, $\varrho_{10nm} > 2\varrho_{50nm}$.

First step toward the realization of few-unit-cell structures with properties representative of YBCO.

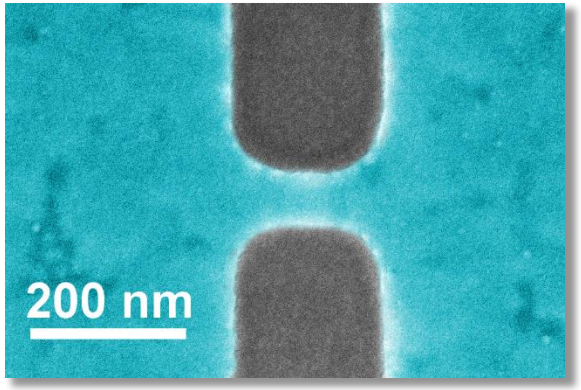
Ultrathin YBCO nanowires

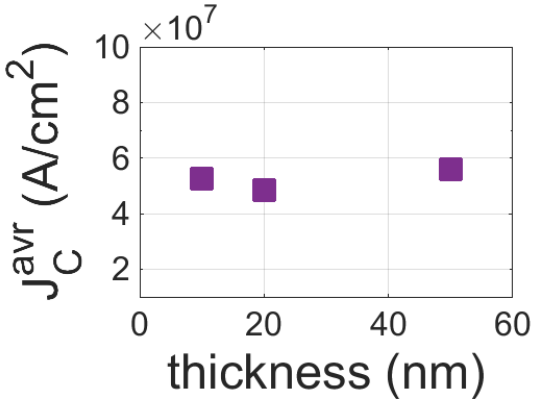
65 nm wide nanowires have been realized on 10 nm thick films, both with and without a protective Au capping layer, using an amorphous carbon mask in combination with e-beam lithography and Ar^+ ion etching. [*R.Arpaia et al., Phys.Rev.B 96, 064525 (2017)*]



[*Nawaz, Arpaia, Lombardi, Bauch, Phys.Rev.Lett 110, 167004 (2013)*]

[*Arpaia, Nawaz, Bauch, Lombardi, IEEE TAS 23, 1101505 (2013)*]



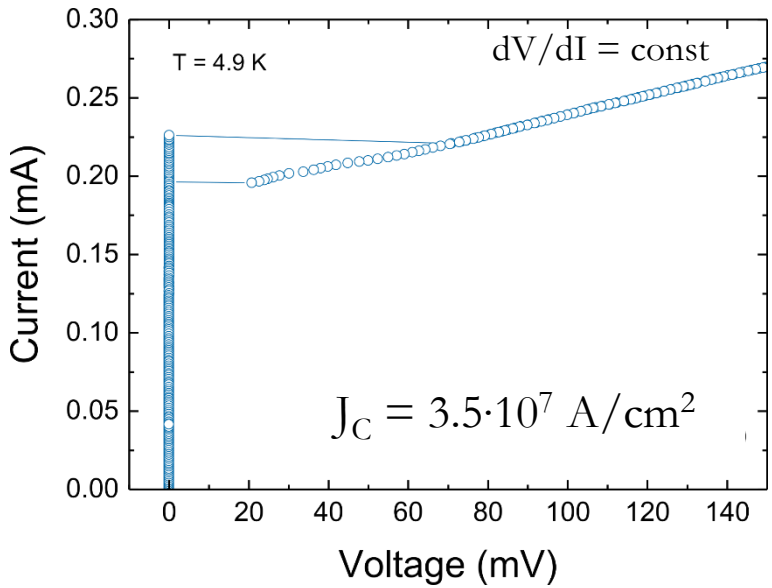


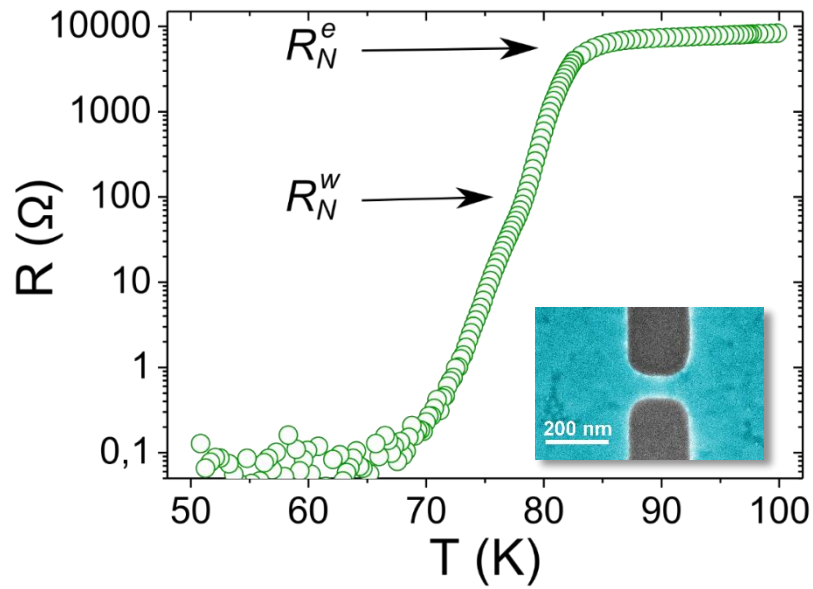
$J_C \rightarrow J_{dep}$ at any thickness

Superconducting properties not affected by the nanopatterning procedure

Ultrathin YBCO nanowires

- Bare nanowires, having $J_C \rightarrow J_{dep}$, are characterized by **hysteretic IVCs**, with a voltage switch, up to tens of millivolts, as soon as the critical current I_C is exceeded.





- Nanowires with $J_C \ll J_{dep}$ have flux-flow like IVCs.

- dV/dI is $\approx R_N^w$

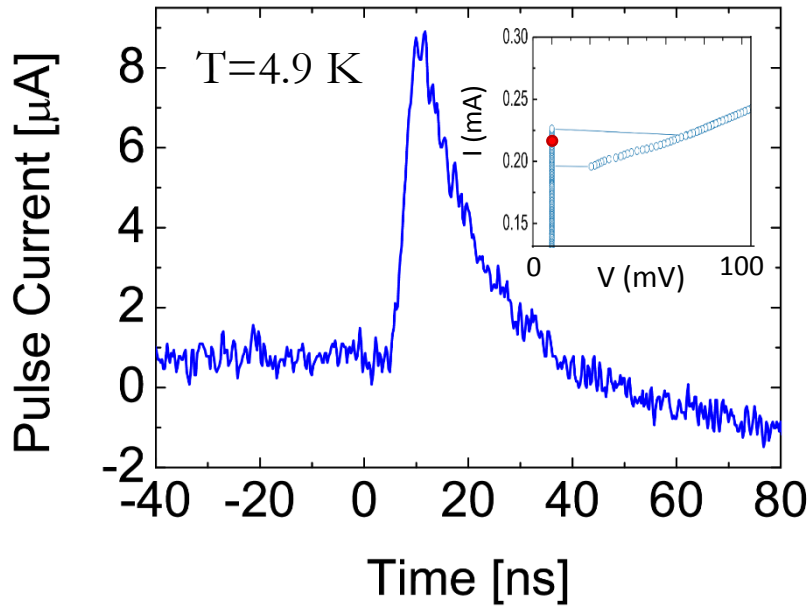
The bistability is favored by the lower value of thermal conductivity in ultrathin nanowires, characterized by critical current densities of the same order as the depairing value.

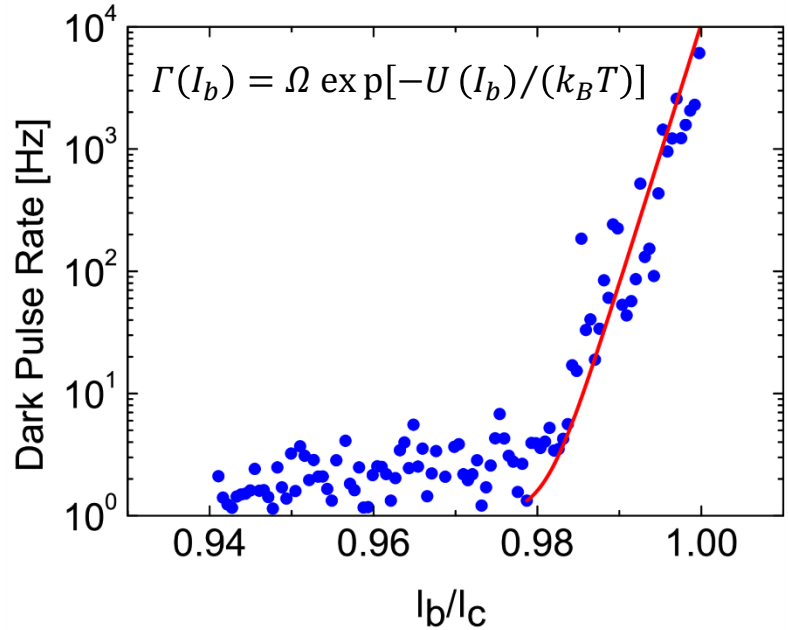
[*R.Arpaia et al., Phys.Rev.B 96, 064525 (2017)*]

Dark counts in ultrathin YBCO nanowires

Time-resolved dark-count events can been measured at T=4.9 K ***only*** on the 10 nm thick nanowires presenting a bistable IVC.

[*M.Ejrnaes, L.Parlato, R.Arpaia et al., submitted (2017)*]





$$U(I_b) = \frac{A(T)}{\varepsilon}\left[\ln\left(\frac{2.6\, I_C}{I_b}\right) - 1 + \frac{I_b}{2.6\, I_C}\right]$$

[*Bartolf, Phys.Rev.B 81, 024502 (2010)*]

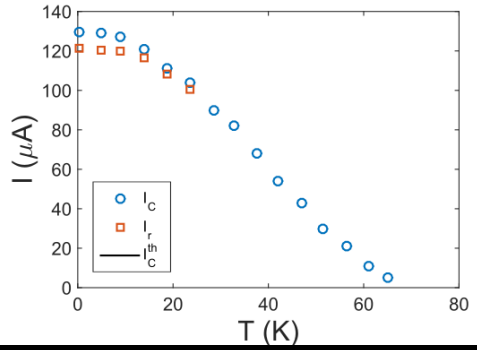
The exponential behavior of the dark count rate vs bias current can be explained considering a model based on VAP unbinding, **similarly to what observed in LTS SNSPDs.**

Conclusions and outlook

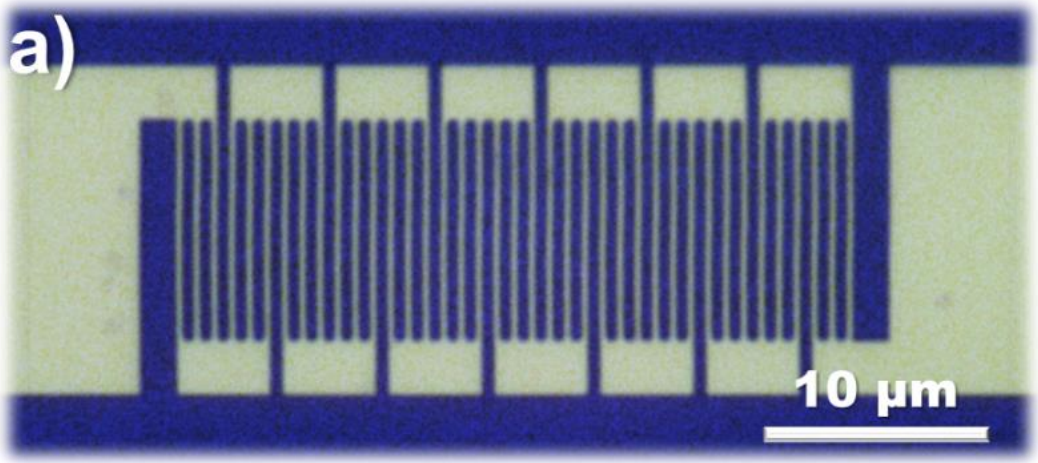
- By using ultrathin films presenting superconducting properties representative of YBCO, **we have realized 10 nm thick nanowires presenting hysteretic IVCs**, in which coexist:
  - ❑ Very small cross sections (down to 65x10 nm^2)
  - ❑ High critical current densities (of the same order as J_{dep})
  - ❑ Enhanced sheet resistances (kΩ, >> 50 Ω) [*R.Arpaia et al., Phys.Rev.B 96, 064525 (2017)*]

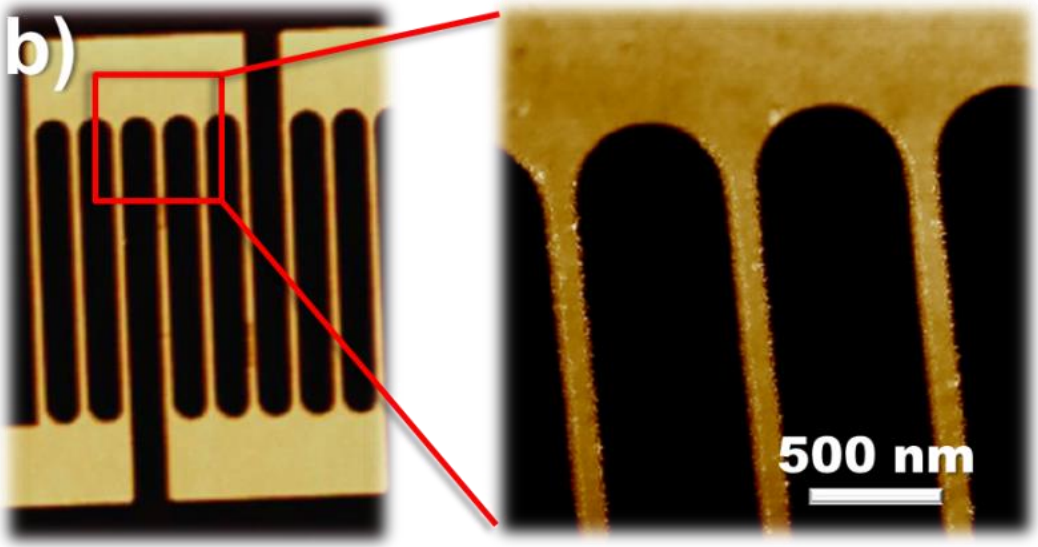
- **We have observed dark counts** in the hysteretic nanowires, which are compatible with a mechanism based on thermal unbinding of VAPs, similarly to LTS nanowires used for SNSPDs. [*M.Ejrnaes, L.Parlato, R.Arpaia et al., submitted (2017)*]

- We believe that the amplification of a small fluctuation into a measurable signal will motivate further investigation of our ultrathin YBCO nanowires in SNSPDs for operation at higher temperatures.



50 nm thick YBCO nanowires for photodetection: fabrication

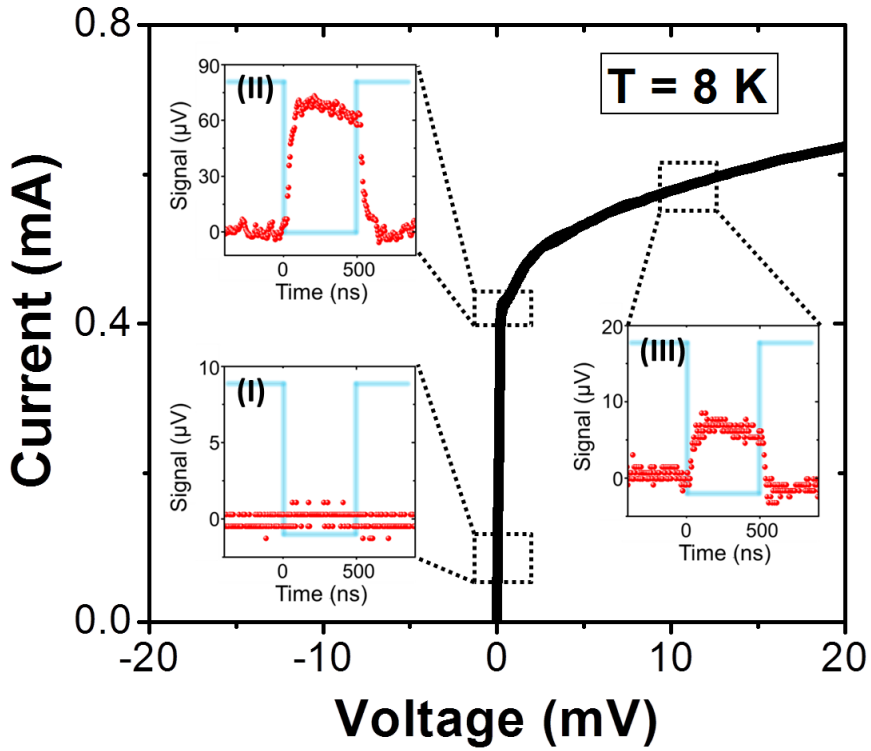


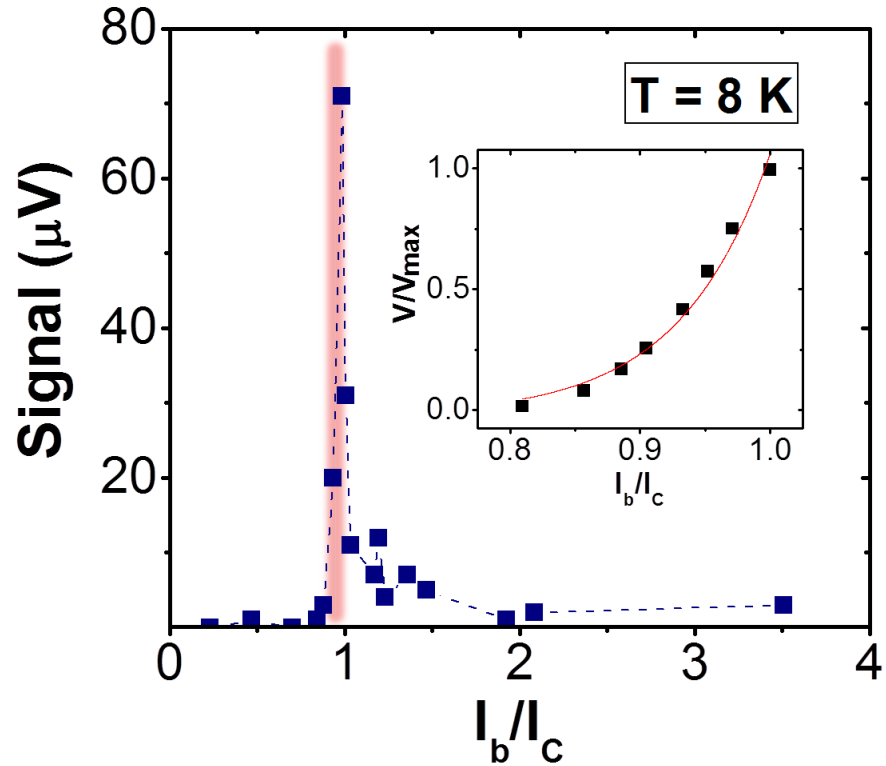


- Large areas have to be covered

parallel configuration (M. Ejrnaes et

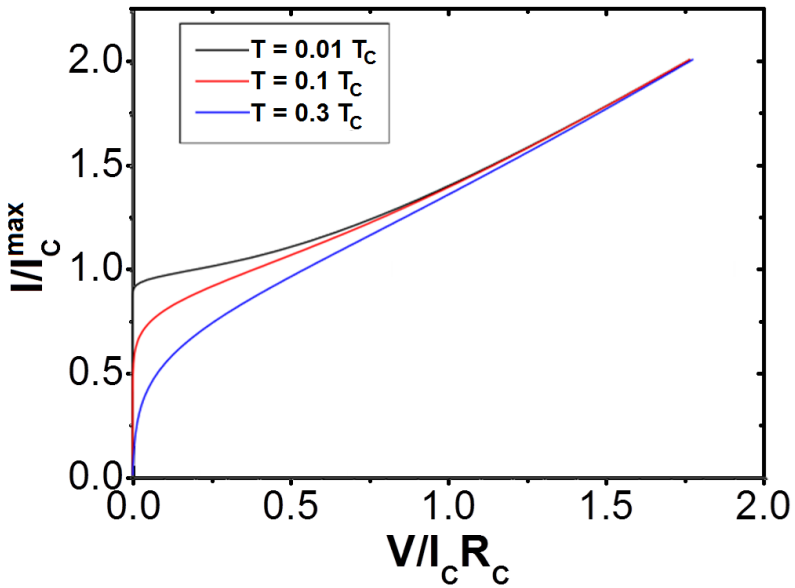
Photoresponse measurements on 50 nm thick YBCO nanowires

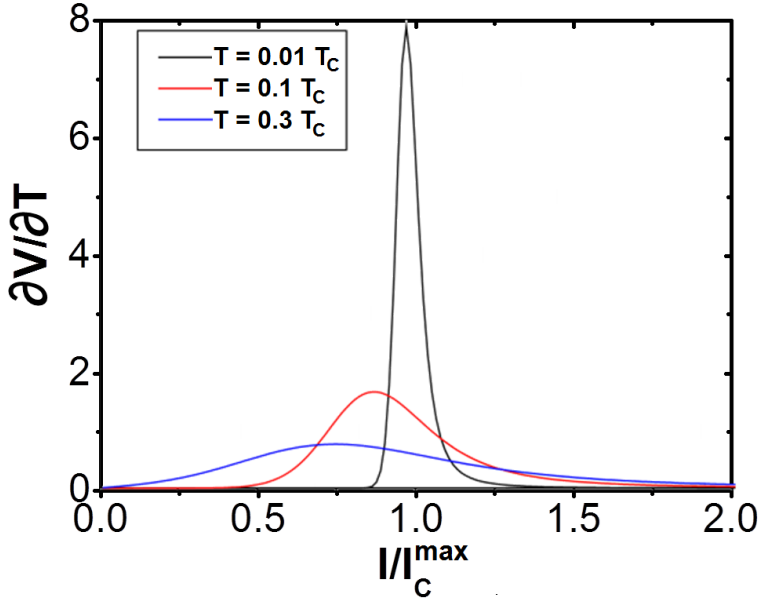


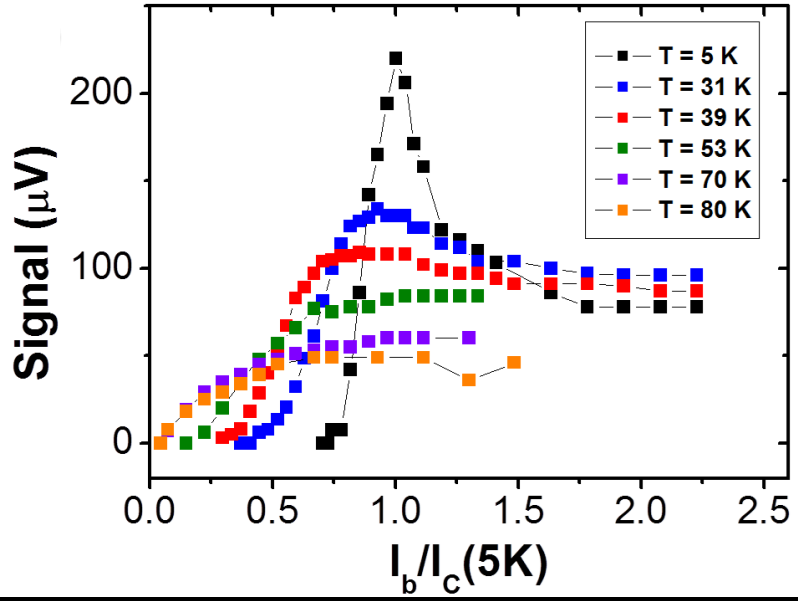


$$\lambda = 1550\ nm$$
$$F = 50\ nW/\mu m^2$$
$$t = 10 - 500\ ns$$
$$\tau_{rise} = \tau_{fall} = 3\ ns$$

Photoresponse measurements on 50 nm thick YBCO nanowires







The main contribution to the photoresponse signals has a bolometric nature