Lithography applied to high-temperature superconductors

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Outline

- Outstanding Properties of Superconductors
- High Temperature Superconductors – Nano-Fabrication Challenges
- HTS for Next Generation Advanced Electronic Devices
  - Confined Geometries: Mesoscopic Effects / 3D vortex Dynamics
  - Engineered Pinning Landscapes: Fluxonic devices
  - Carrier Density Modulation: Mottronic Devices
  - Hybrid SC / FM Systems: Spintronic Devices

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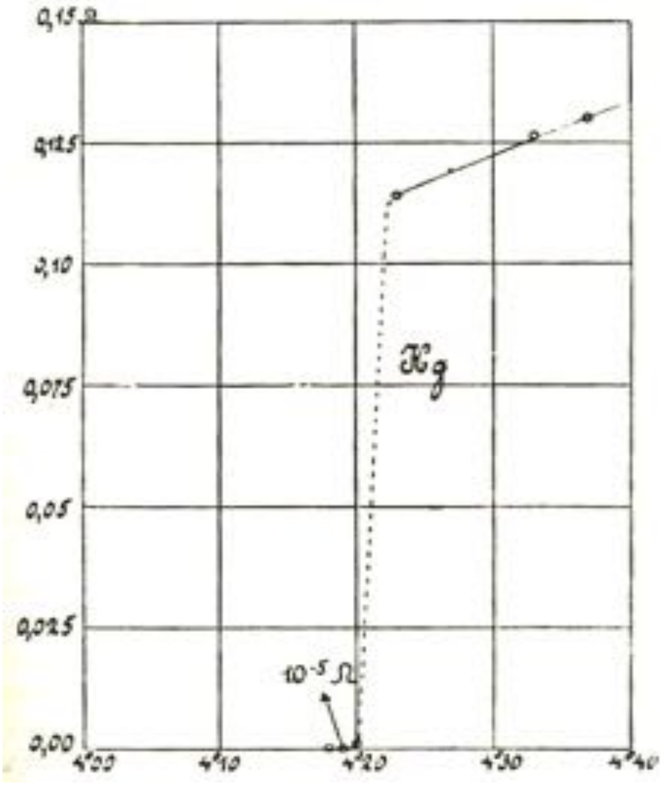
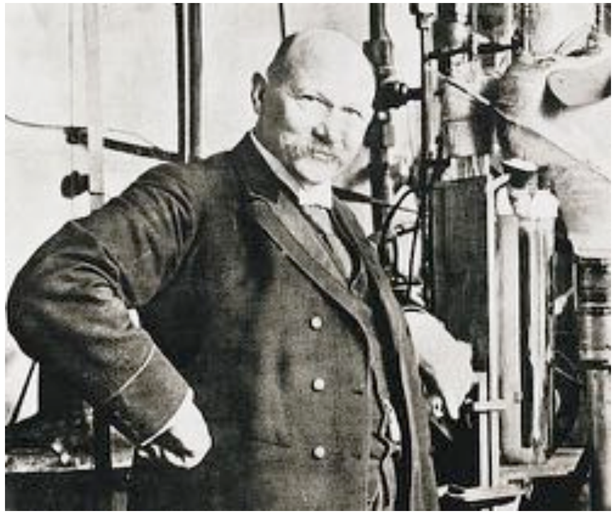
Superconductivity

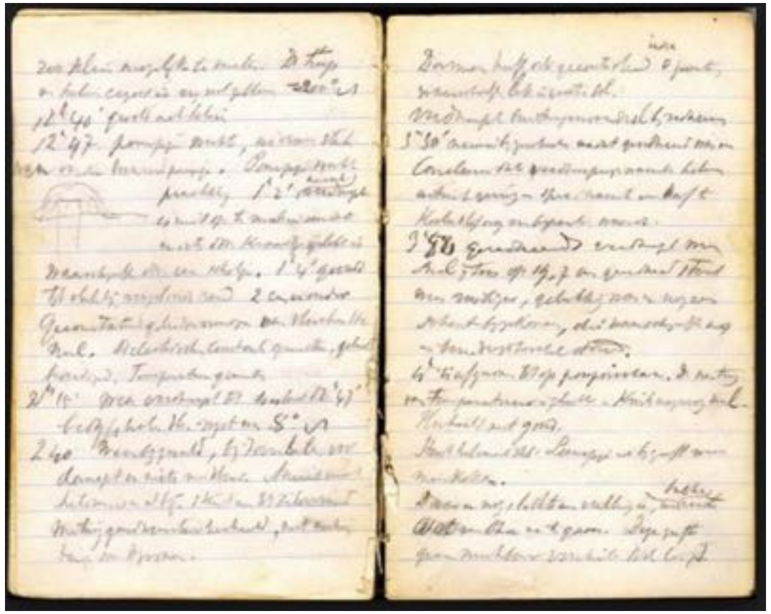
On 8 April 1911, Leiden Cryogenic Laboratory in the Netherlands

Heike Kamerlingh Onnes discovered the extraordinary phenomenon of superconductivity in mercury by **coincidence** when working on techniques to liquefy gases with the goal of reaching absolute zero.





As soon as liquid-helium temperature was reached the resistance became **"practically zero"**



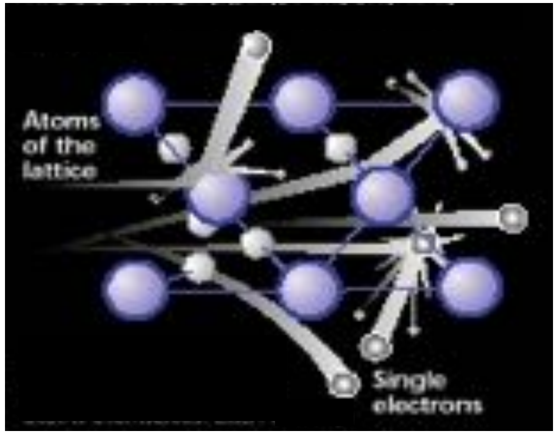
Nobel Prize (1913)
For his investigations on the properties of matter at low temperatures,[…]

Outstanding Properties of Superconductors

Unique Electrical Properties: PERFECT CONDUCTOR

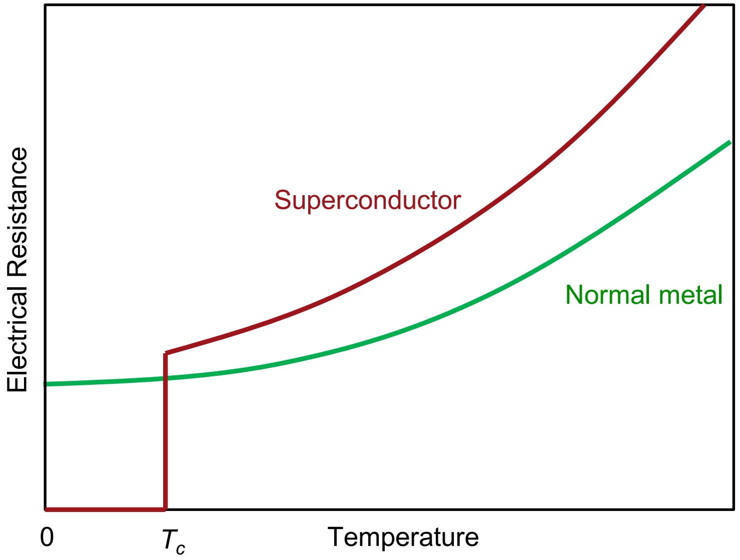
Normal State

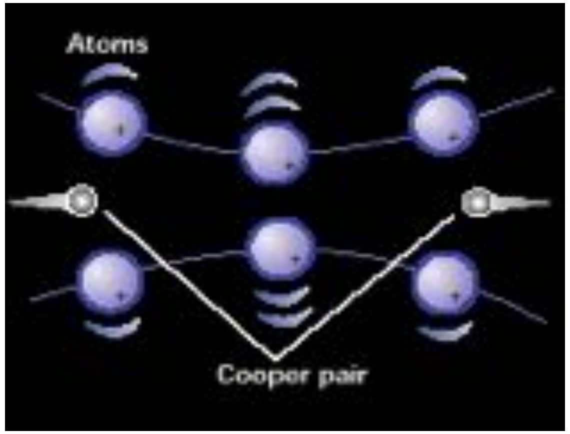
Electrical resistance due to collisions of incoherent electrons → energy losses



Superconducting State

Electrons are bounded in pairs → their movement is coherent and cannot be scattered at impurities → **NO** energy losses





Electrical conduction via Cooper pairs

Superior performance needed for new energy-saving technologies.

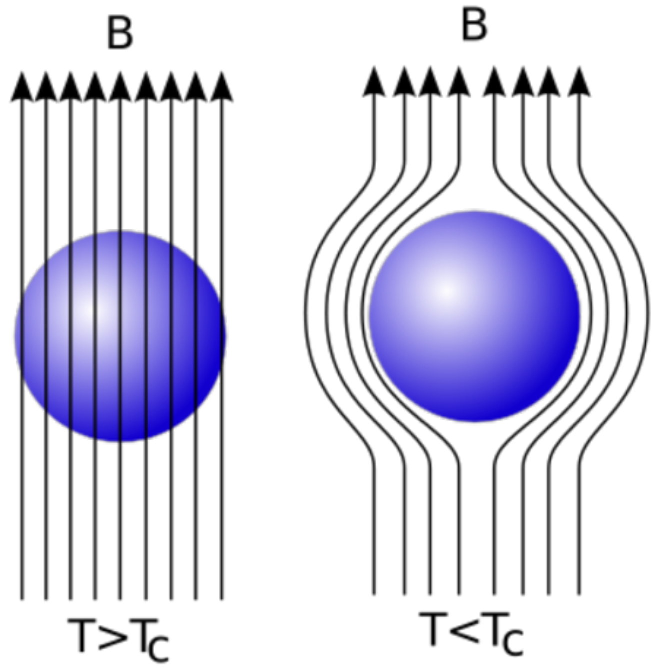
Outstanding Properties of Superconductors

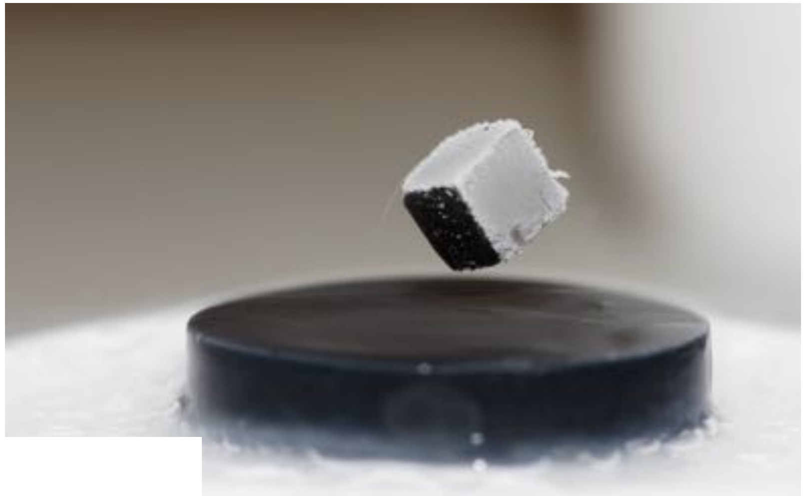
Unique Magnetic Properties: Perfect Diamagnet

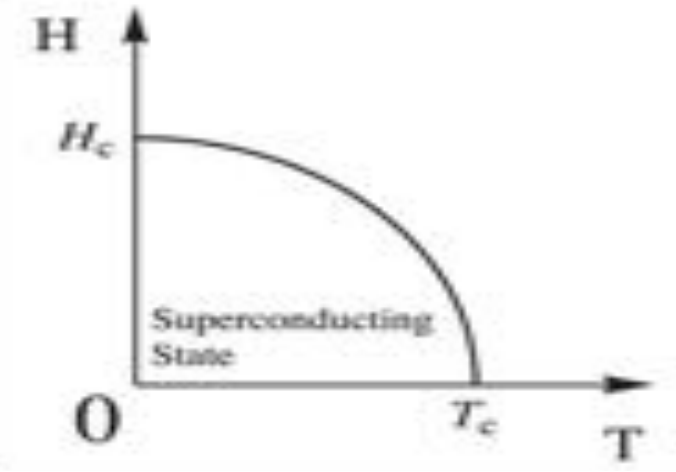
Meissner Effect

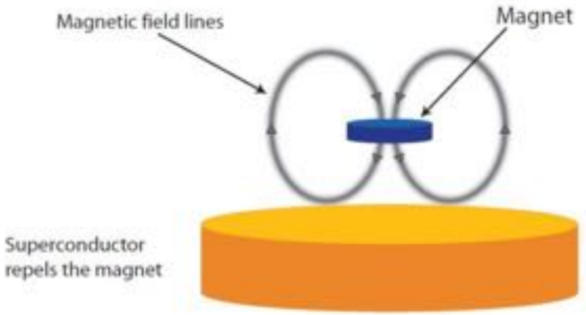
Materials in the superconducting phase expel magnetic fields

superconductors were more than just perfect conductors !
Superconductor Levitation

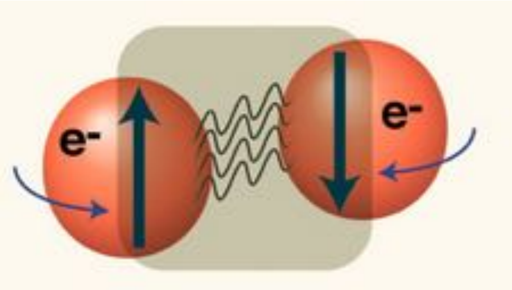




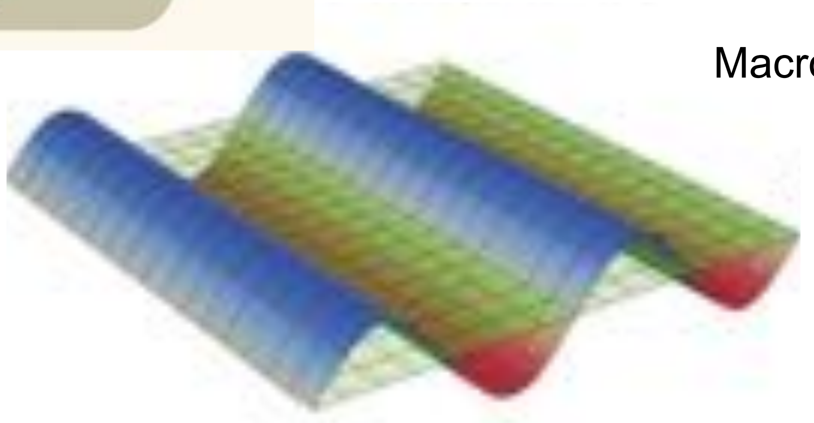




Quantum Coherence – Macroscopic Quantum Effects



Cooper pairs condensate in a single quantum coherent wave



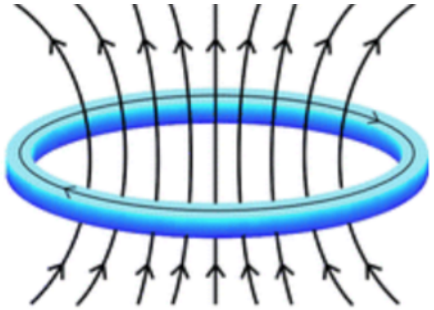
Macroscopic wave function that describes the system as a whole

$$|\psi_L|e^{i\phi}$$

Consequences:

Magnetic Field Quantization in units of a flux quantum $\Phi_0 = h/2e = 2.07 \cdot 10^{-15}$ Tm

$n\Phi_0$

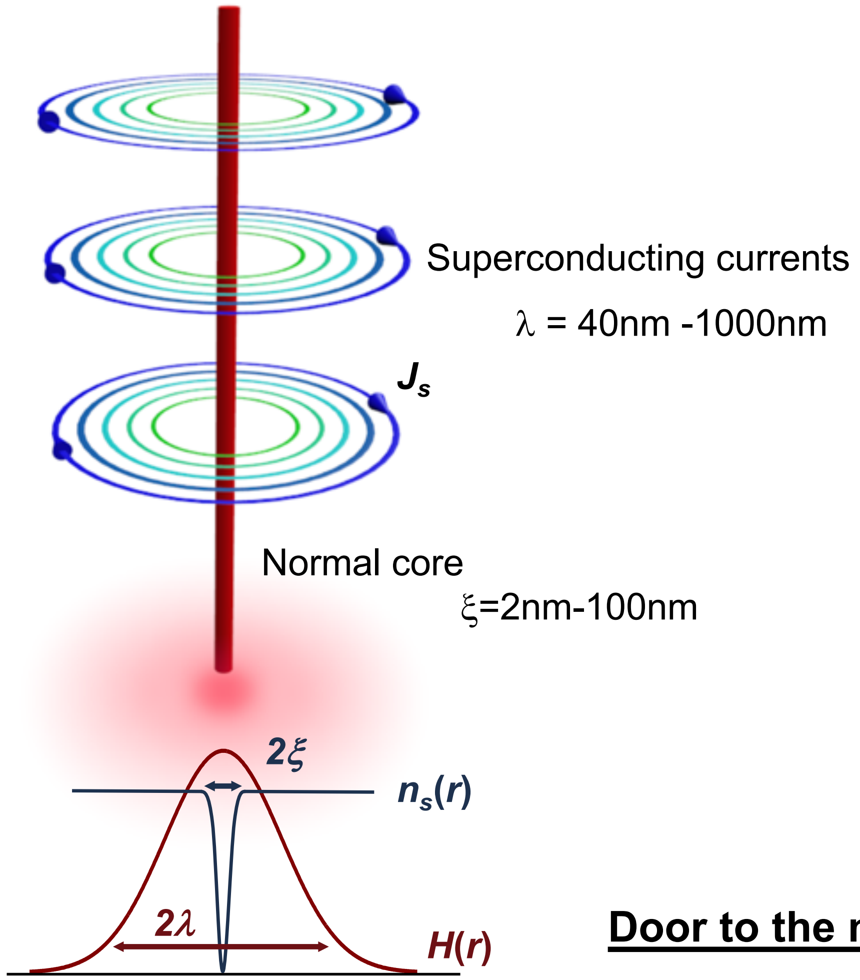


- The magnetic flux through a superconducting ring carrying persistent supercurrents is an integer multiple of a flux quantum

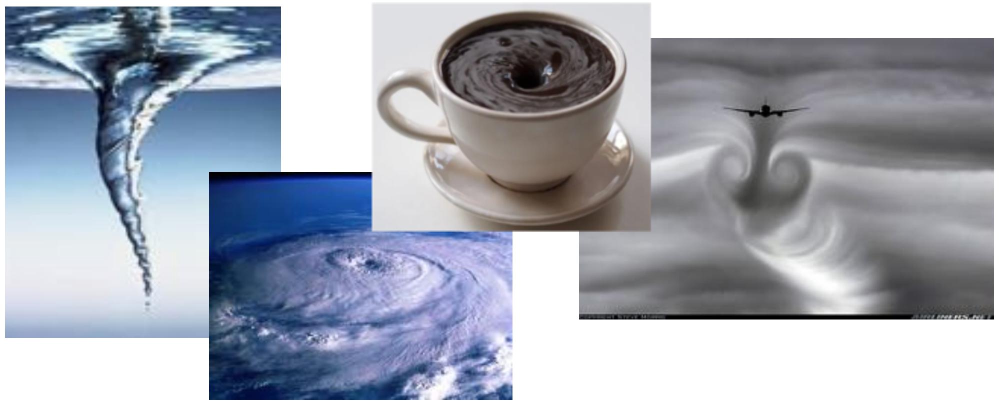
Vortex – Quantum Flux Lines

Quantum magnetic flux lines surrounded by supercurrents

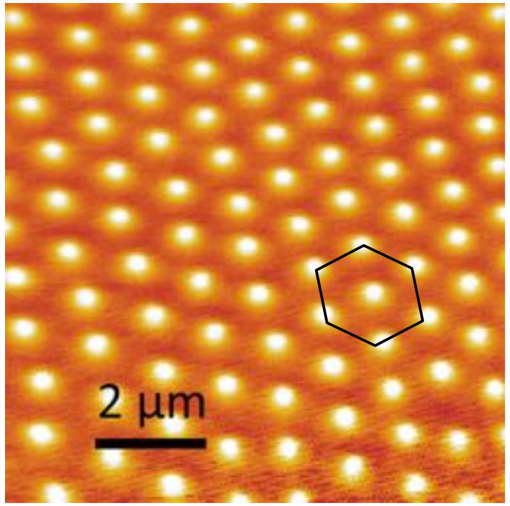
$\Phi_0 = h/2e = 2.07 \cdot 10^{-15}$ Tm^2



Vortex: mass of fluid that spins around an axis line



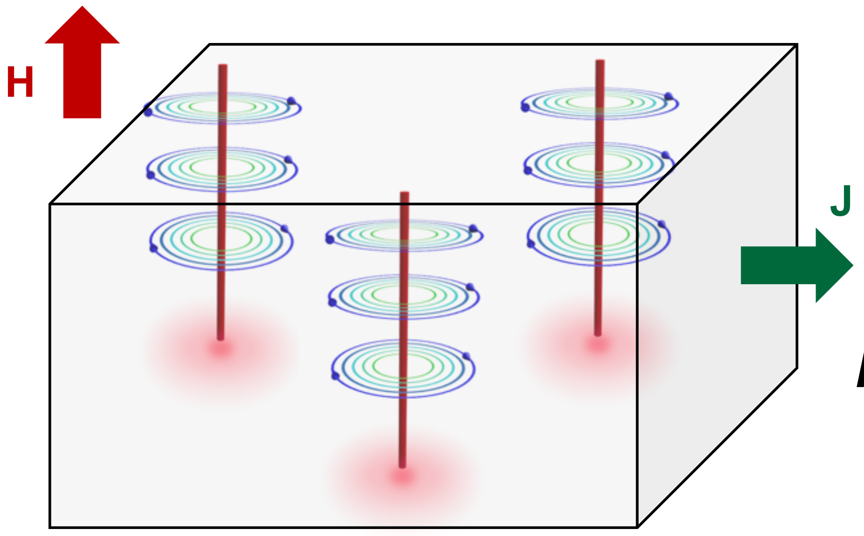
Abrikosov Lattice



MFM BSCCO, 40Oe

<u>Door to the nano-scale world !!</u>

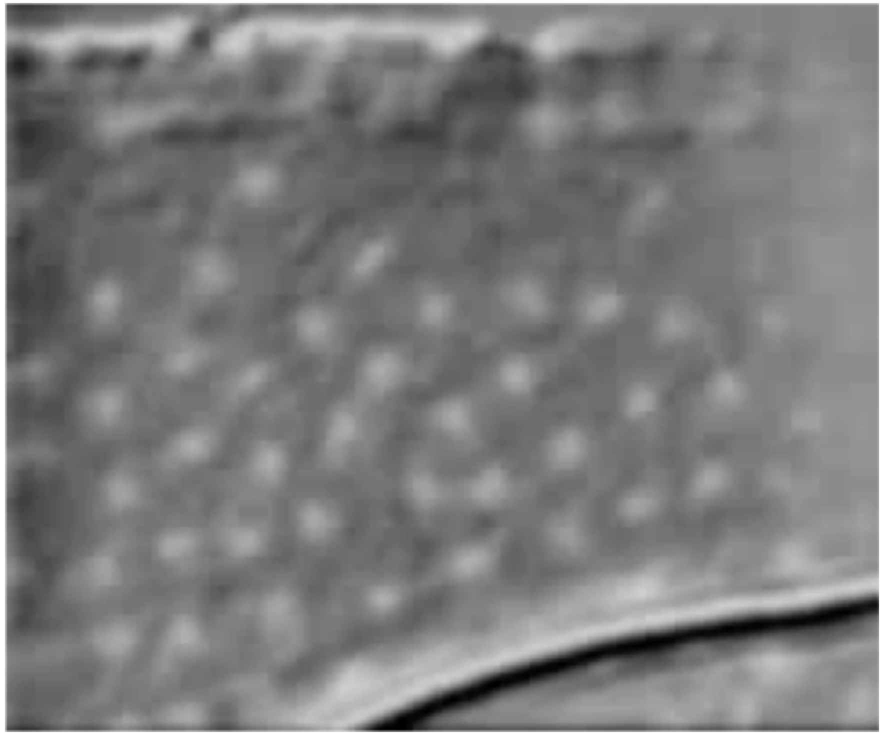
Vortex Motion: Dissipation



$F_L = J_c \times B$

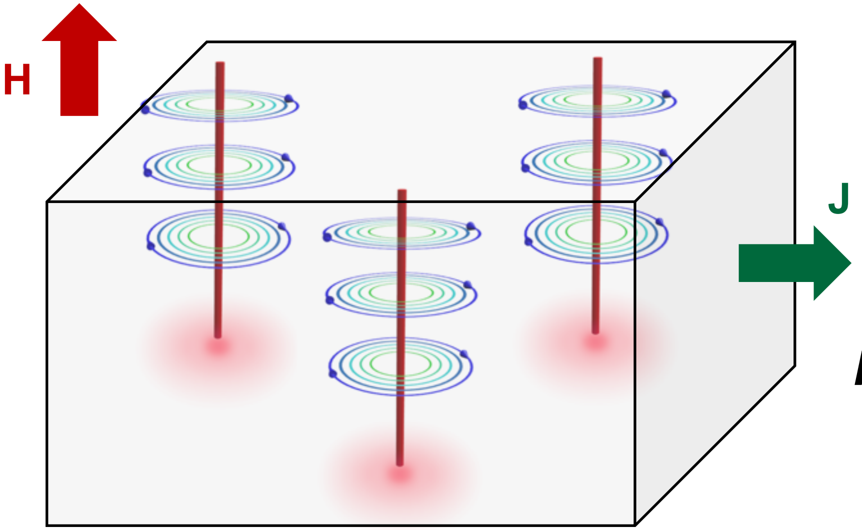
J_c, Critical current density << Depairing current (cooper pair breaking)

As soon as vortex (normal core) start to move across the superconductor, energy dissipation appears and it shows a resistance different from zero.



Movie window: 25x35 microns, NbSe2 crystal

Vortex Motion: Dissipation



J_c, Critical current density << Depairing current (cooper pair breaking)

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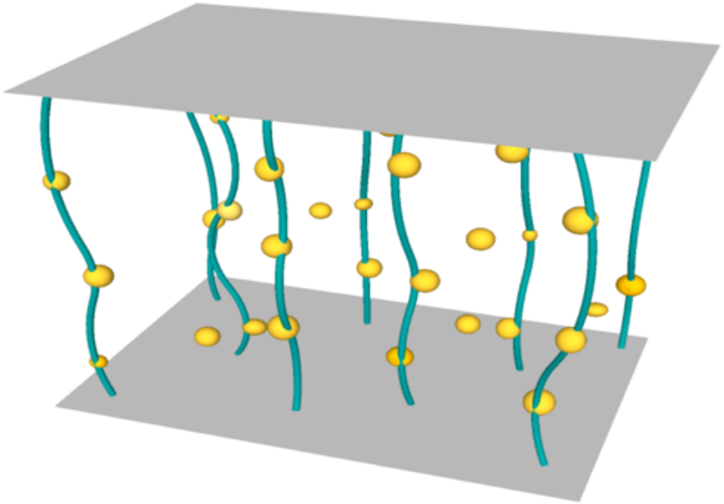
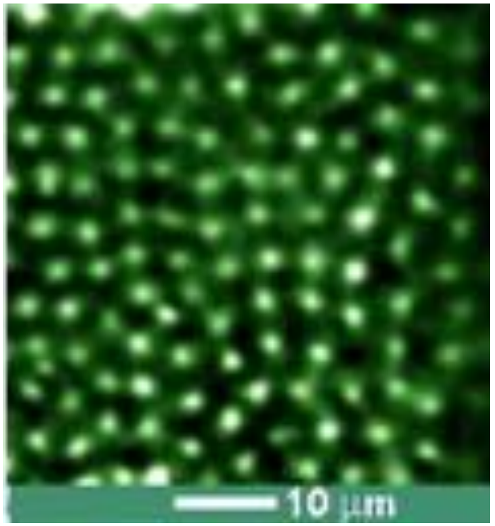
$$\boldsymbol{F_L = J_c \times B}$$

Vortex Pinning: Non superconducting regions with the size the core (ξ)

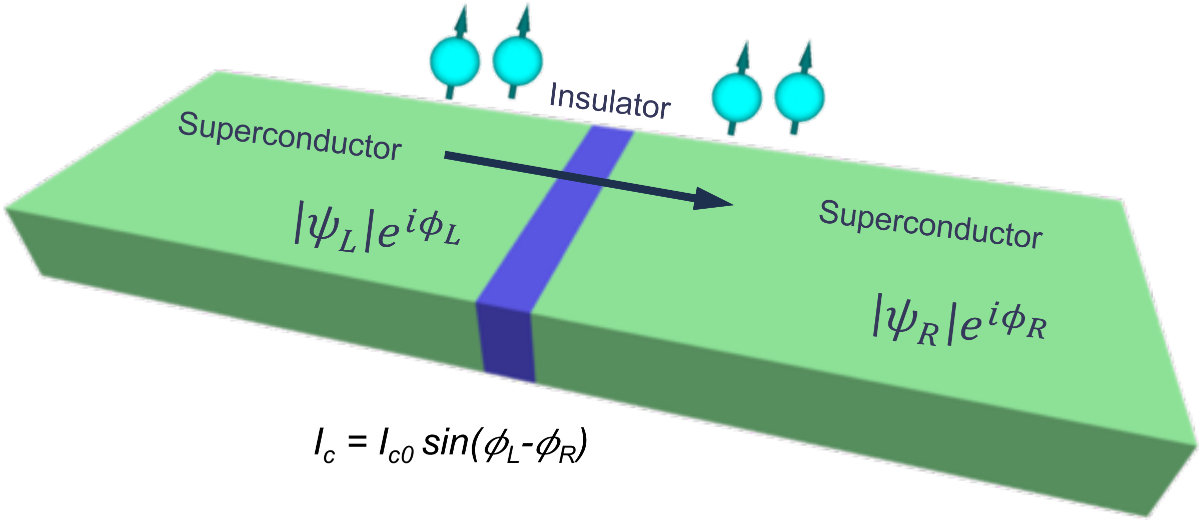
→ Avoid / control vortex motion

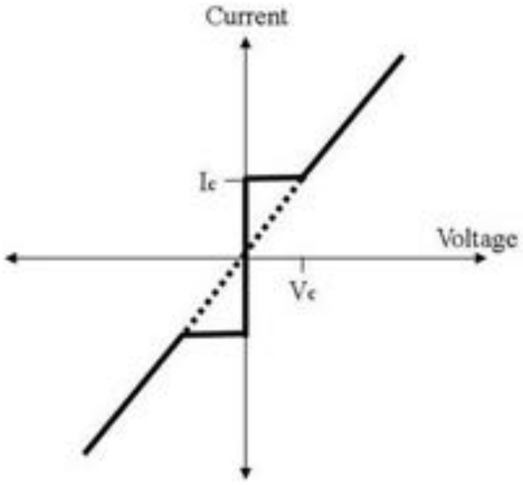




Josephson Effect

The Josephson effect results from the coupling of two superconductors across and insulator junction (tunnel S-I-S)



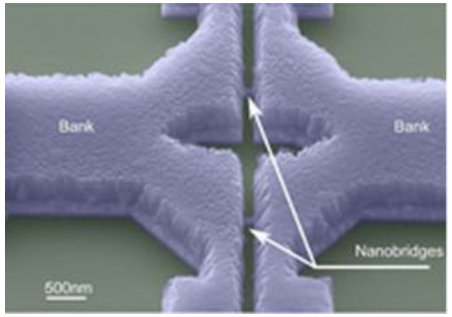


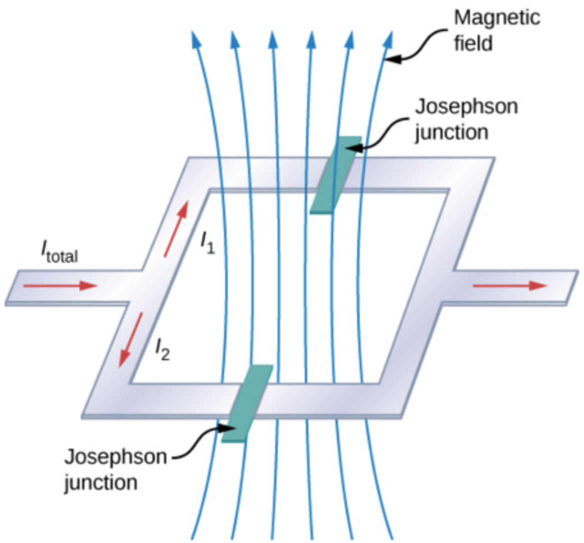
<u>Cooper pairs can electrically tunnel across two superconductors</u> separated by a thin insulating or normal metal barrier

Constitutes the basis of a number of superconductor applications such as quantum-interference devices (SQUIDs) for magnetometry, digital electronics, signal processing, or medical imaging

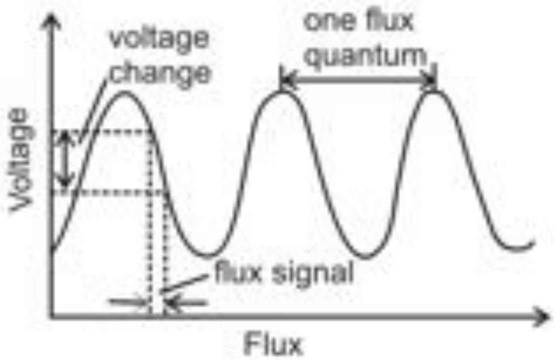
SQUID: Superconducting Quantum Interference Device

superconducting ring with two Josephson junctions junctions.





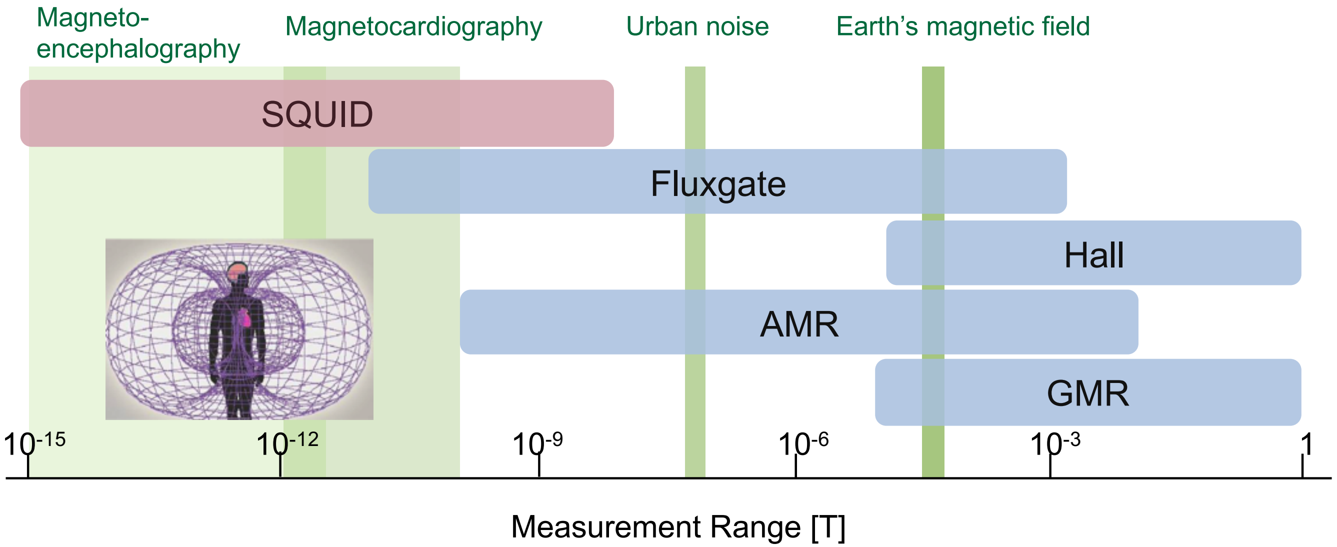
SQUIDs combine the Josephson effect with the quantization of magnetic flux in superconductors



Magnetic sensors with ultra-high sensitivity

$\Phi_0 = h/2e = 2.07 \cdot 10^{-15}$ Tm^2

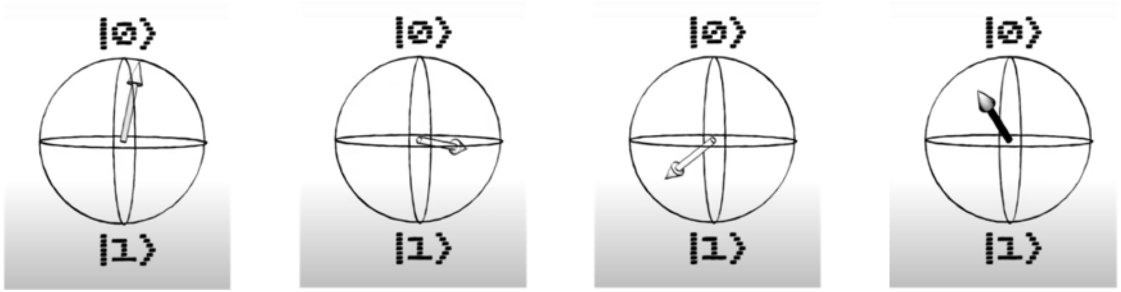
Large voltage changes associated with one flux quantum



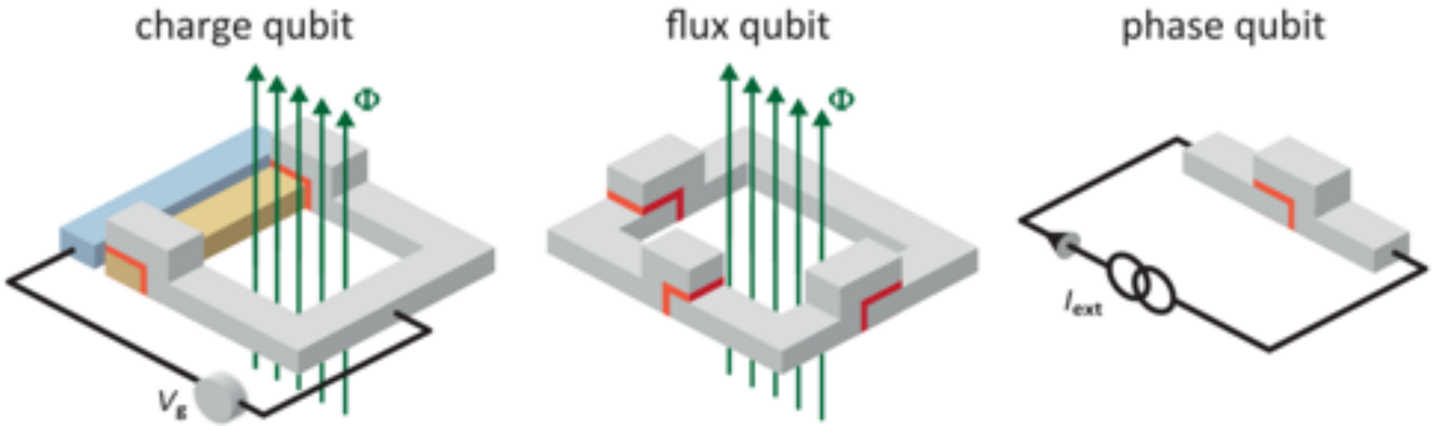
Josephson Junctions: Quantum Computers

Today’s computers are “classical” computers, they use binary logic based on bits equal to 0 or 1.

Quantum computers are be based on quantum bits called “qubits”, the <u>quantum state of which can be any linear superposition of 0 and 1 states</u>. This would enable to make the same calculation on a great number of values



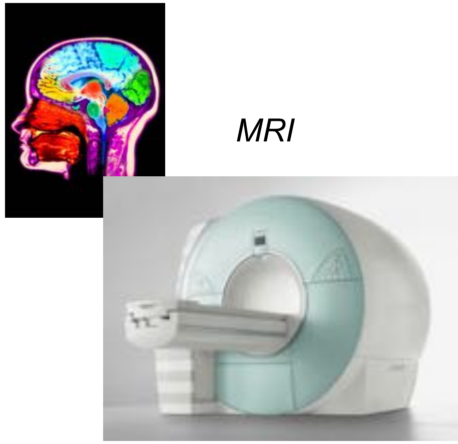
<u>Supercoducting qubits</u>
Each includes one or more Josephson junctions (shown in red).



Power Applications with Superconductors

Unique Properties

- Zero resistance to direct current
- Extremely high current carrying density
- Expulsion of externally applied magnetic field (Meissner Effect)



MRI

Fusion reactor

Synchrotron radiation guiding

Loss-less power cables

Levitating trains

Rotating Machinery

Medical Imaging *High Energy Physics* *Environment & Energy*

→ major impact on electric power transmission and also enable much smaller or more powerful magnets for motors, generators, energy storage, medical equipment and industrial separations

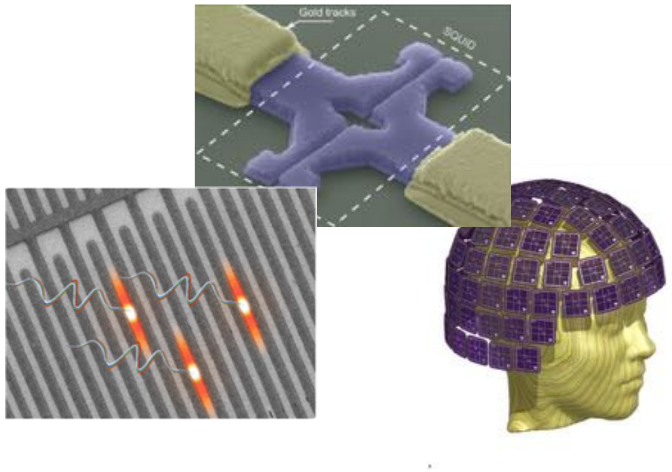
→ provides a mechanism for magnetic levitation

Energy-Efficient Electronic Applications with Superconductors

- Ultra-High sensitivity to magnetic field
- Zero dc resistance and extremely low resistance at high frequencies
- Low signal dispersion and quantum effects

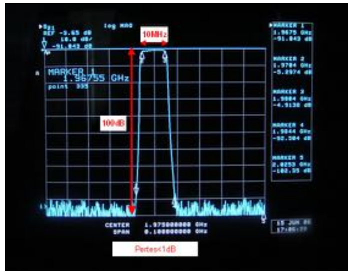
Ultra-sensitive and ultra-low power superconducting electronics

Sensors



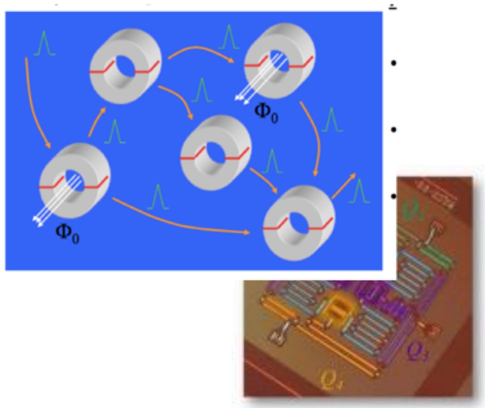
Ultra-high sensible sensors SQUID detectors, Transistor Edge Sensors (TES), Nanowire Single-Photon Detectors (SNSPD)

Communications technology



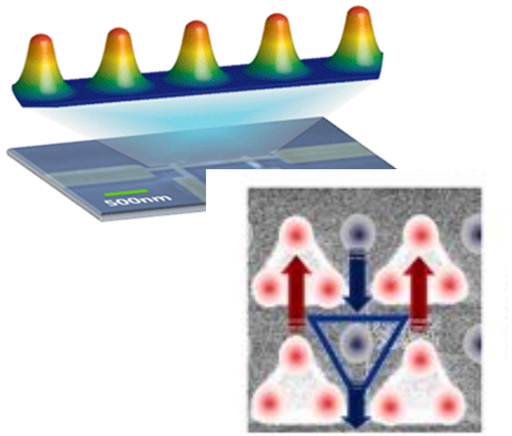
Microwave components, Filters, Passive devices for wireless communications

Digital information



High performance, high speed computation RSFQ & Qubits

Novel Functionalities



Fluxtronic concepts Rectifiers, Ratchets, Vortex guiding

Electronic devices mainly based on conventional low temperature metallic superconductors (Al, Pb, Nb,..)

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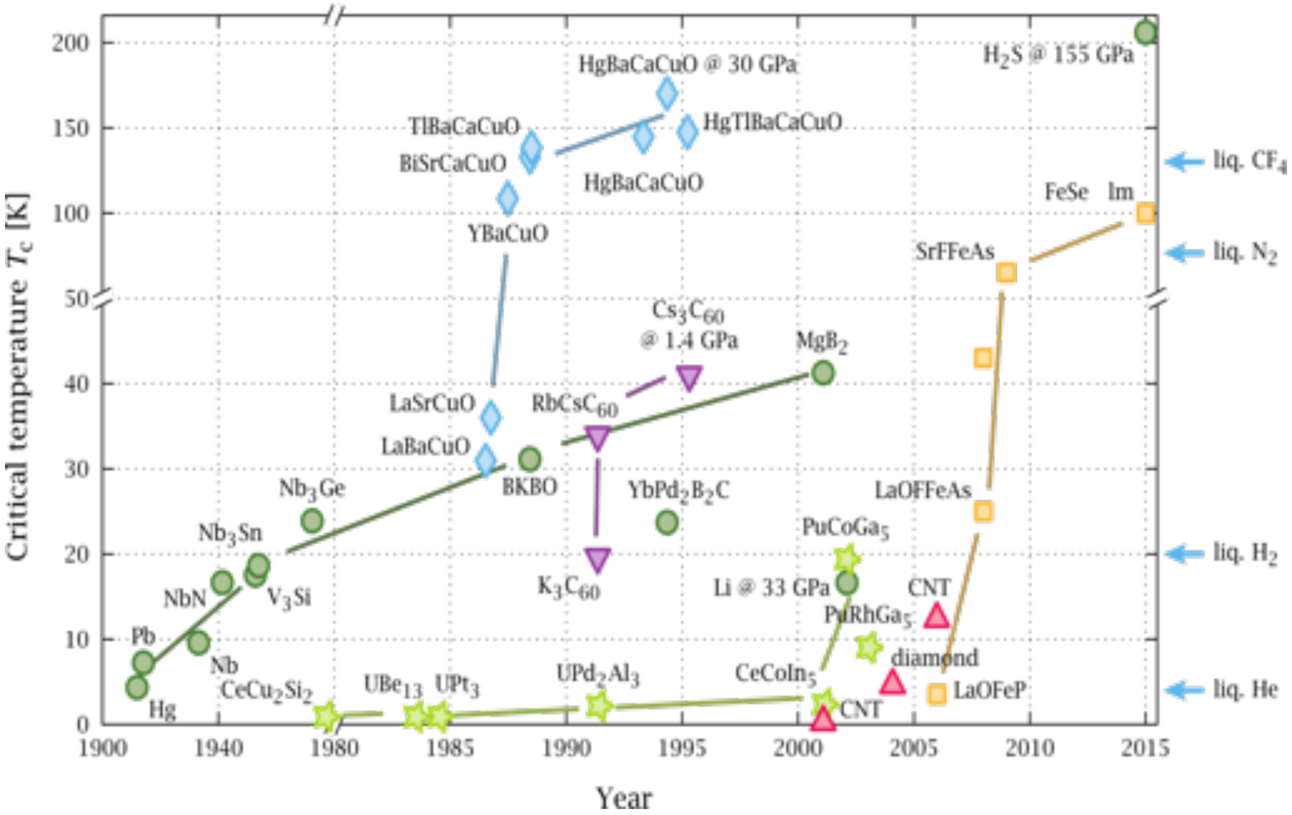
High Temperature Superconductors

1986: J.G. Bednoz and K.A. Müller

The discovery of HTS triggered a boom in research into the field.

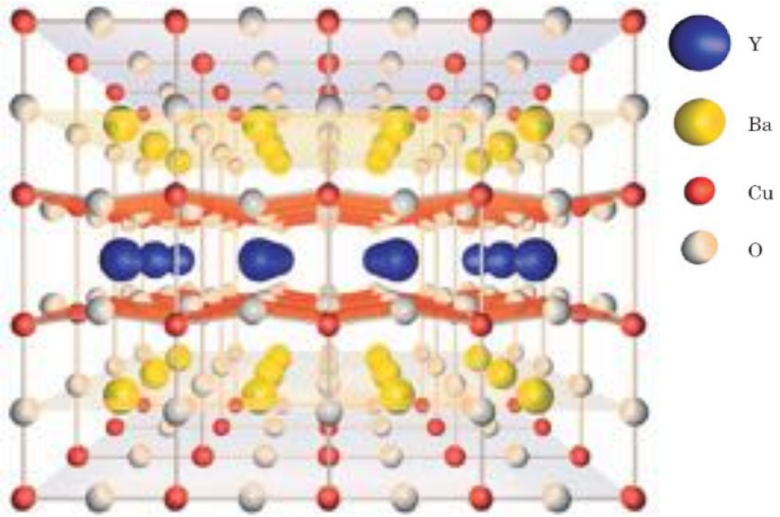
A revolution for material science !!



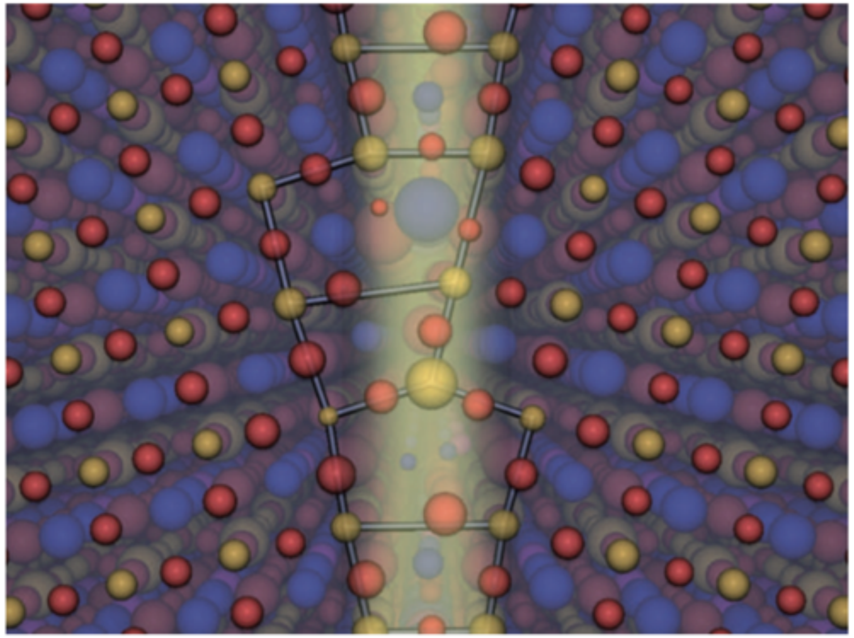
Operation up to much higher temperature and magnetic field → Promise of emergent SC technologies

HTS : Complex Materials with huge technological potential

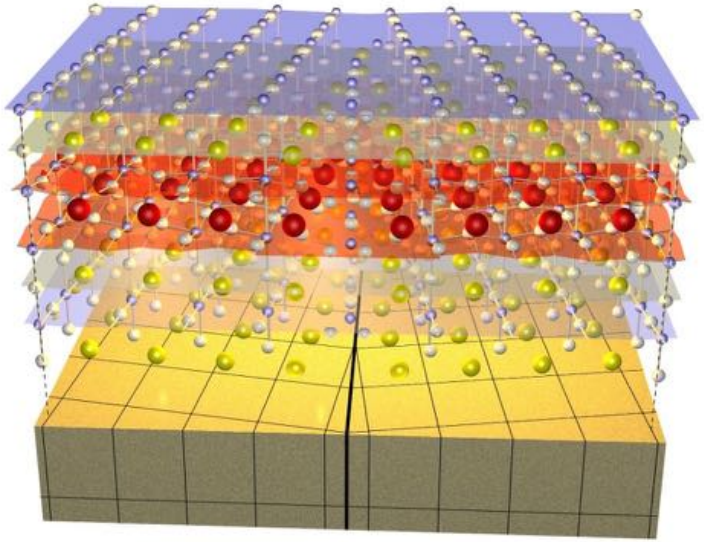
Highly anisotropic materials



SC properties very sensitive to the presence of grain-boundaries



2D-layered structure

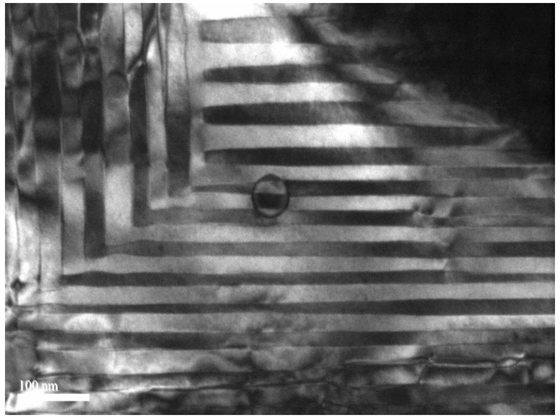


Films may be grown epitaxially on single crystalline substrates with good lattice mismatch

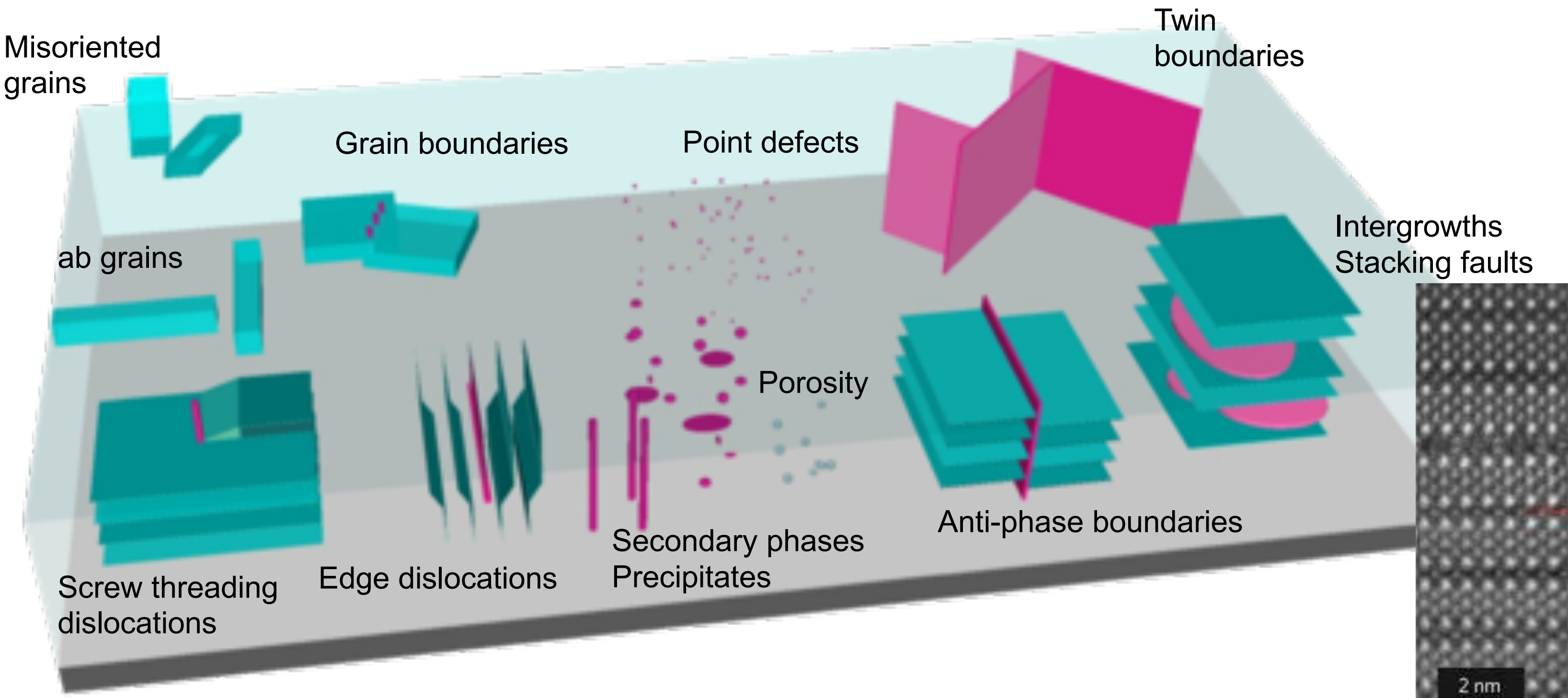
HTS : Complex Materials with huge technological potential

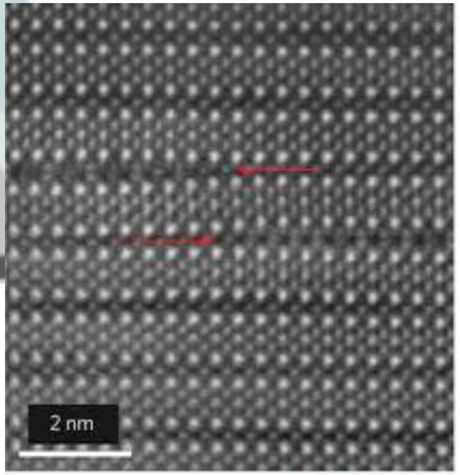
Intrinsic Pinning

Extremely small coherence lengths (ξ ~ 0.1 – 5 nm)



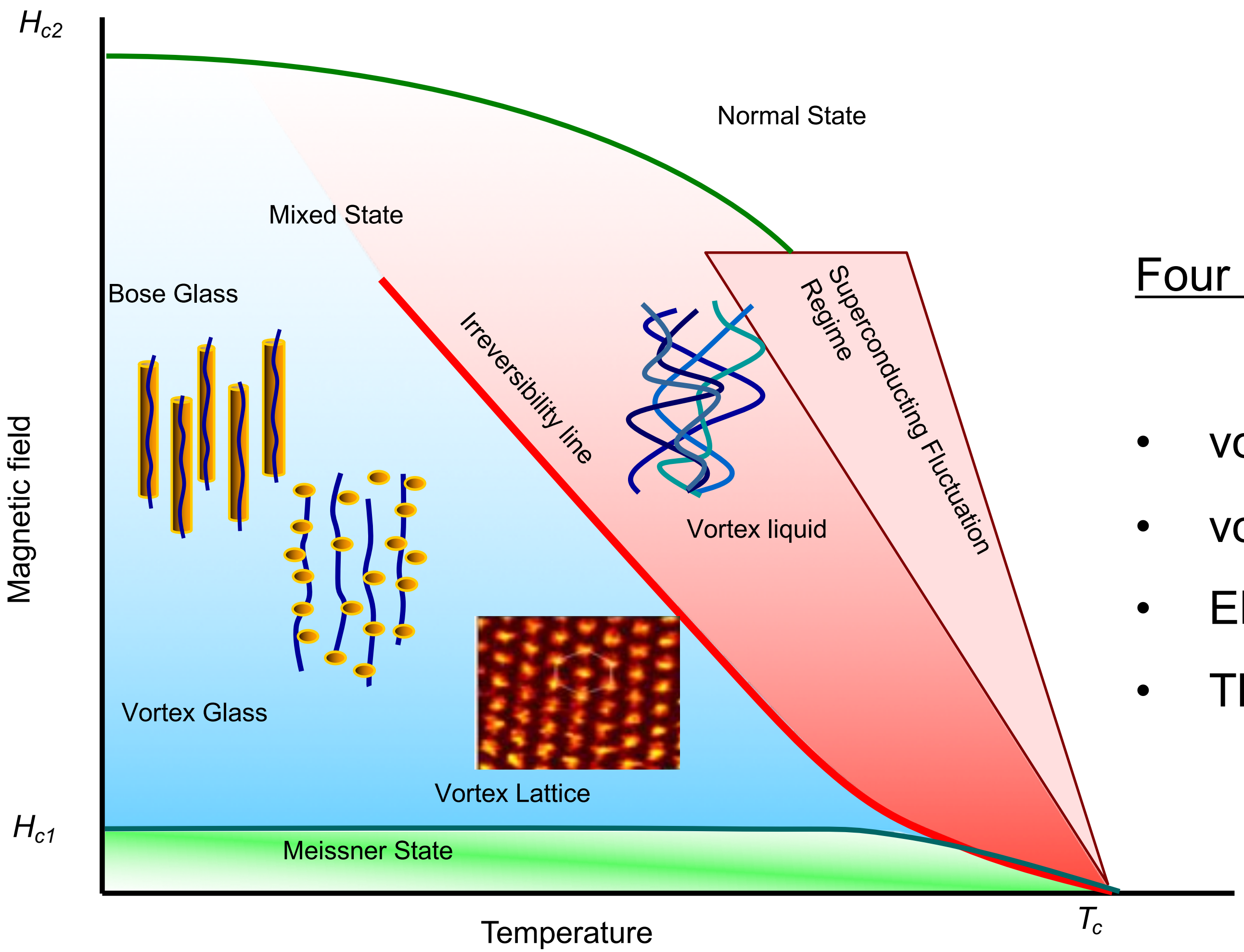
Intrinsic nanometric defects appearing during sample growth → Pinning centres





Magnetic phase diagram in a HTS

The interaction of the vortex lattice with system of pinning centres forms a complex vortex matter



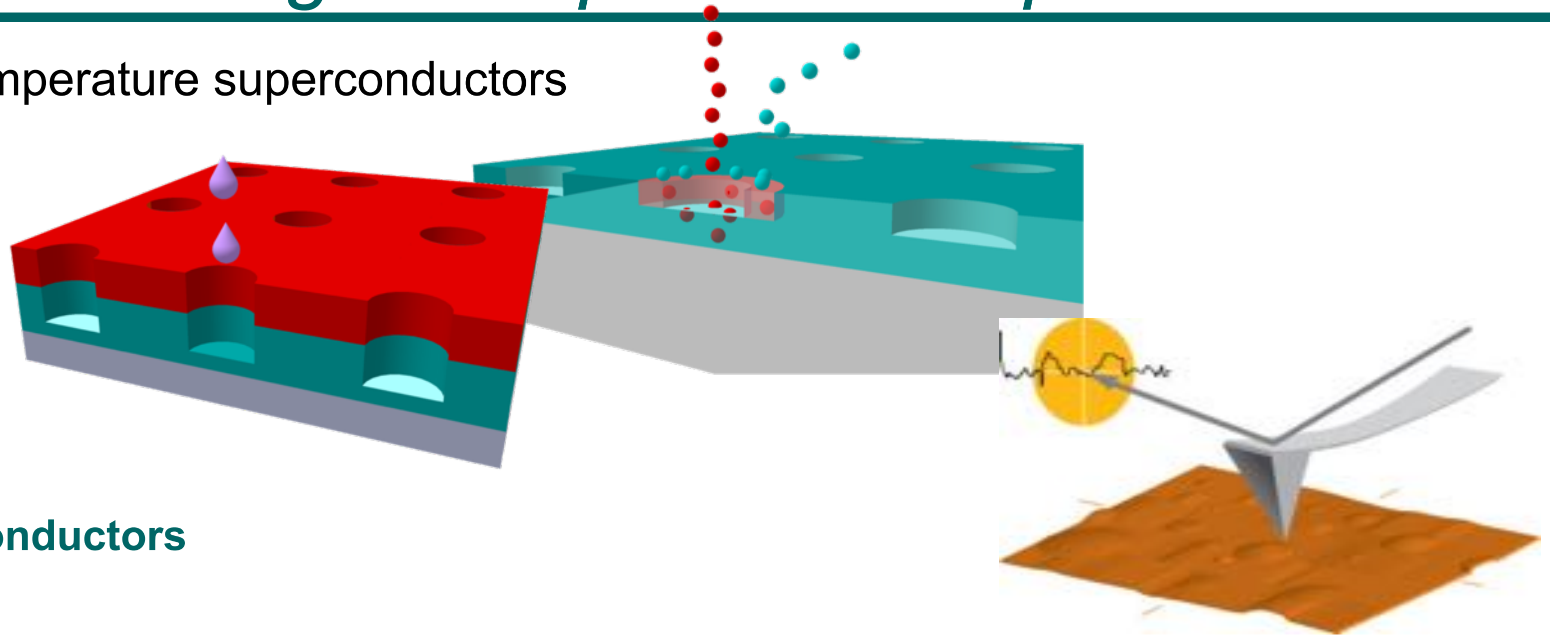
Four competing energies

- vortex-vortex Interaction → Ordered lattice
- vortex-defect interaction (pinning) → glass
- Elastic energy → 3D vortex
- Thermal energy → liquid

Nanofabrication of Cuprate High-Temperature Superconductors

Nanofabrication techniques for High temperature superconductors

- FIB
- EBL + Ion Milling
- EBL + Wet Etching
- c-AFM



Peculiar properties of the cuprate superconductors

- The 2D-layered structure
- Extremely small coherence length
- High sensitivity to nano-defects
- Requirement of epitaxial growth on lattice matched substrates
- Ceramic materials: Fragile, difficult to manipulate

→ Imposes extreme demands on the nano-fabrication

Nanofabrication of Cuprate High-Temperature Superconductors

Nanofabrication techniques for High temperature superconductors

- FIB
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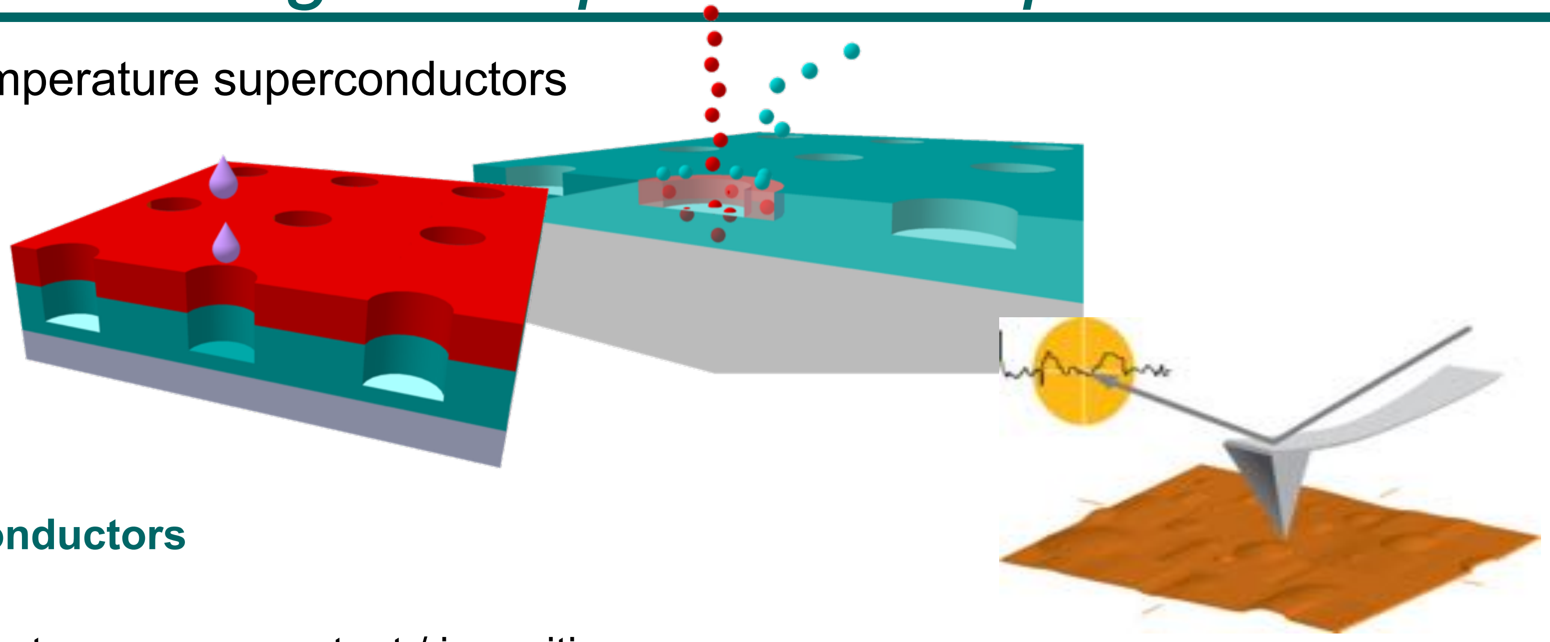


Peculiar properties of the cuprate superconductors

SC properties highly dependent on oxygen content / impurities

- Ion implantation can damage the material
- Local heating may easily deoxygenate the material

Epitaxial growth on lattice matched substrates

- Lift-off processes difficult to be implemented
- Integration on targeted substrates is a challenging task

Strong intrinsic pinning defects

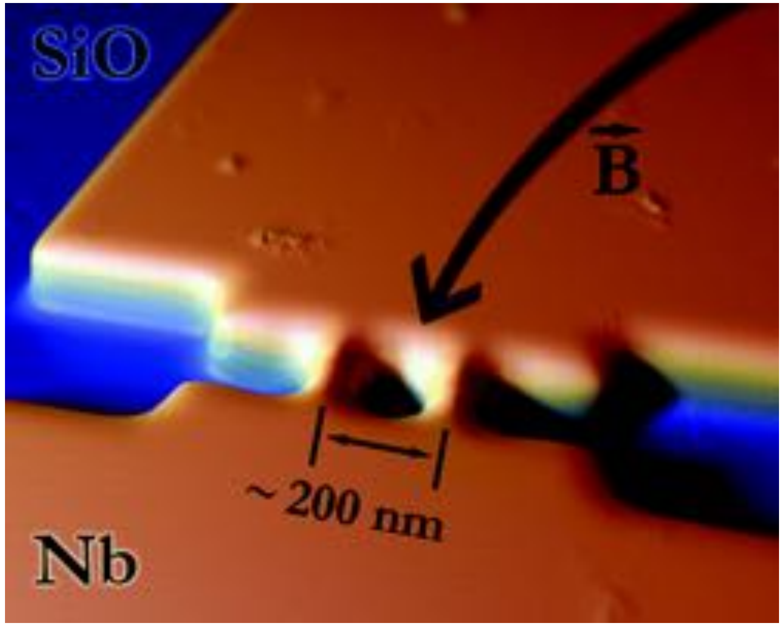
- Weaker impact of artificial defects to modify / control vortex dynamics

NanoSQUID Devices Based on Metallic Superconductors

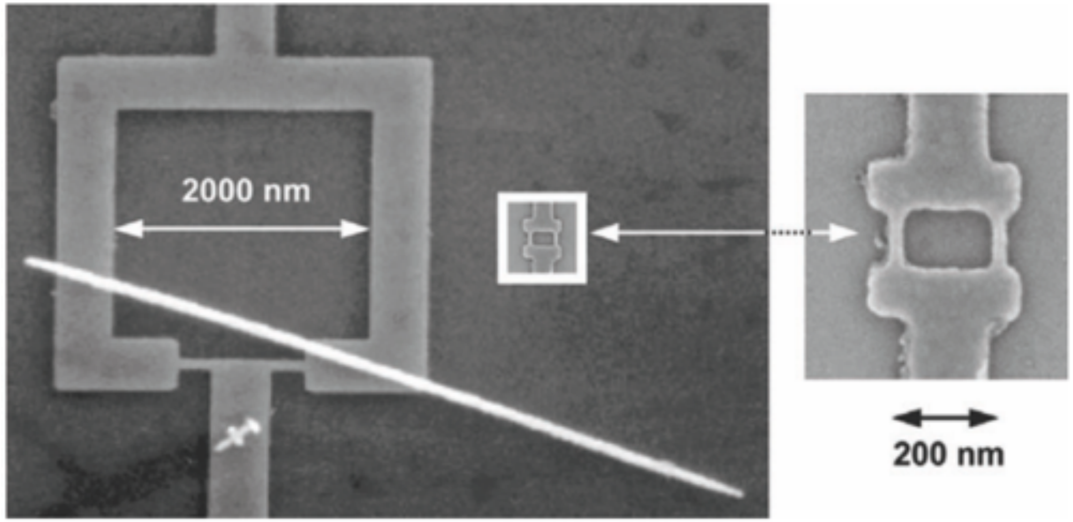
Constriction junctions

Josephson coupling can occur in superconducting constrictions with size similar or smaller than the coherence length

Narrow constrictions can be patterned either by EBL and subsequent ion milling or directly by FIB milling



Nb nanobridges (80nm) fabricated by FIB



Nb microSQUID & nanoSQUID fabricated by EBL

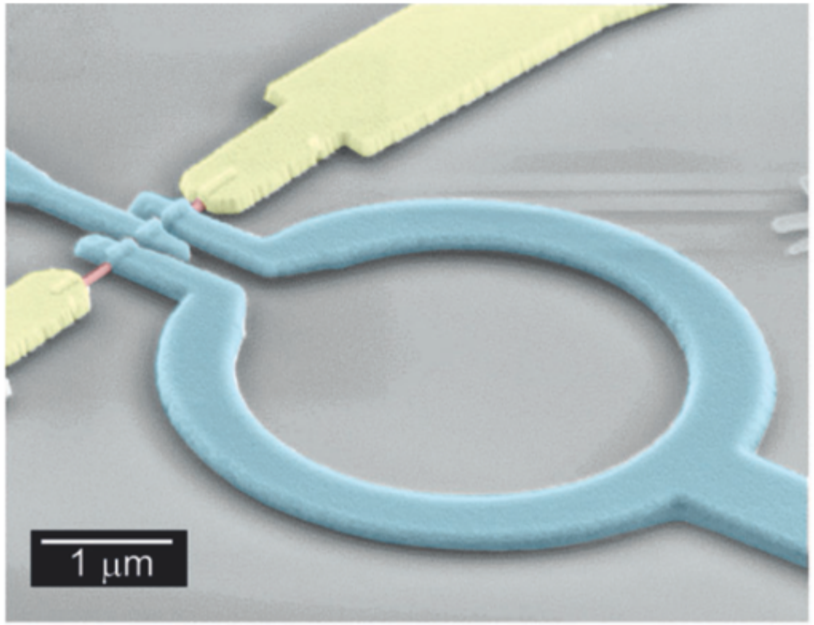
J.M. Martínez-Pérez & D. Koelle, NanSQUIDS, De Gruyter (2017), Troeman et al. Nano. Lett. 7, 2162 (2007)

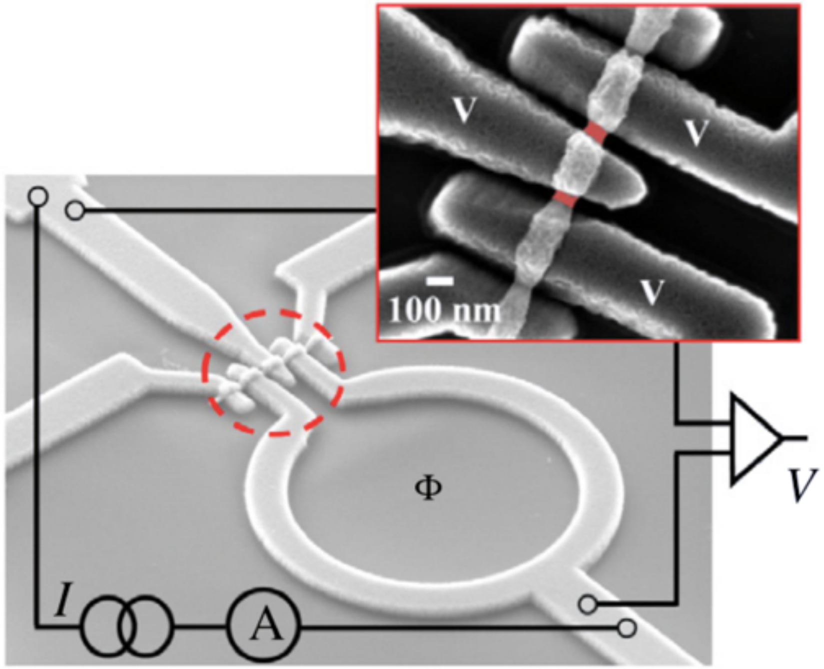
NanoSQUID Devices Based on Metallic Superconductors

Proximized structures

A normal metal in good contact between superconducting electrodes experiences superconducting correlations due to the proximity effect

SNS weak links: The N-region length governs the properties of the junctions





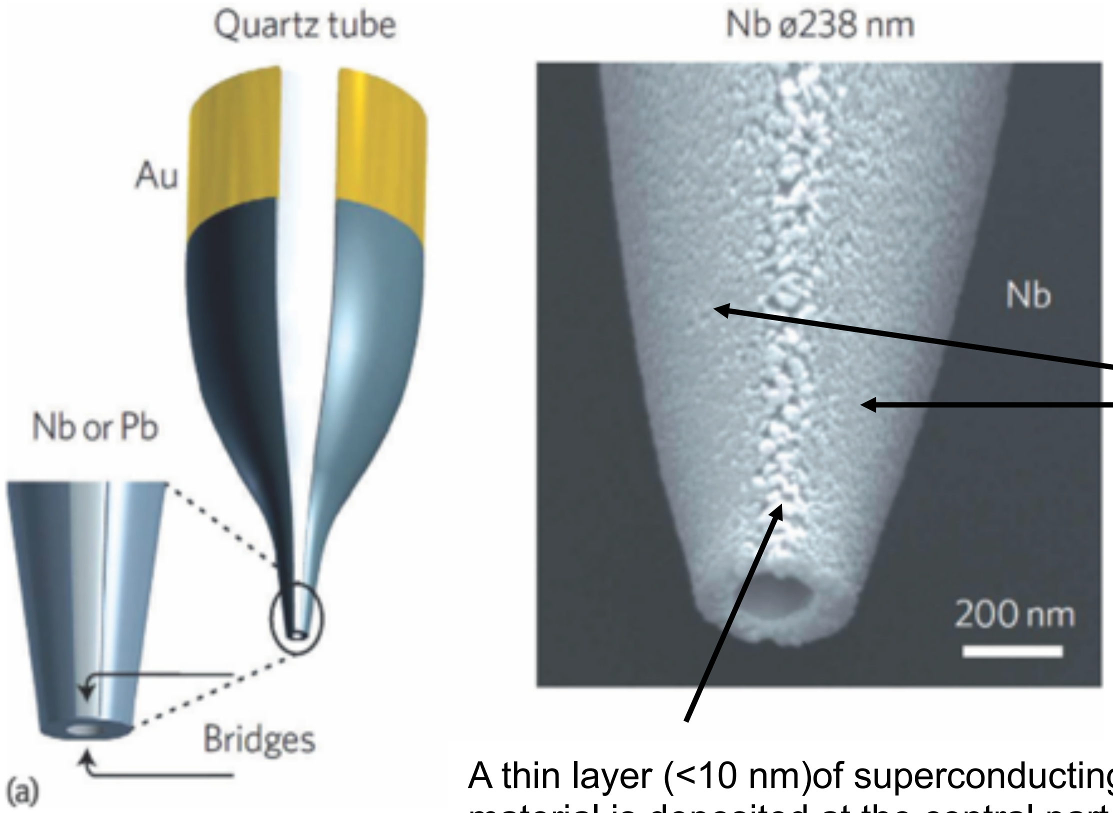
weak link between vanadium (V) superconducting electrodes and an indium arsenide (InAs) nanowire

J.M. Martínez-Pérez & D. Koelle, NanSQUIDS, De Gruyter (2017), Spathis et al. Nanotechnology 22, 105201 (2011)

NanoSQUID Devices Based on Metallic Superconductors

SQUID-on-tip (SOT) microscope

Deposition of a nanoSQUID directly on the apex of a sharp quartz pipette



Two thicker layers (>25nm) are deposited on the sides

A thin layer (<10 nm)of superconducting material is deposited at the central part

This procedure lead to the <u>smallest nanoSQUIDs fabricated so far</u>, with effective nano-loop diameters down to 50 nm

Vasyukov et al. Nat Nanotech. 8, 639 (2013)

NanoSQUID Devices Based on Cuprate Superconductors

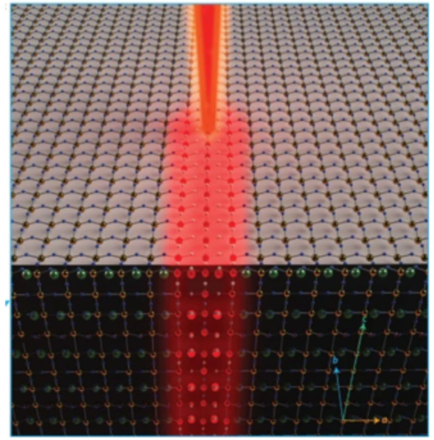
Cuprate superconductor YBCO offers nanoSQUID operation up to much higher temperature and magnetic field

Extremely challenging fabrication

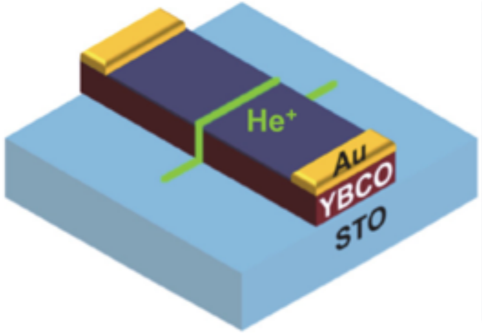
High-T_c cuprate superconductors, such as YBCO have very small and anisotropic values of **ξ** ∽ 0.1 – 1 nm

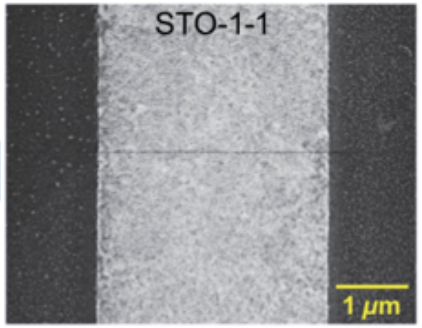
➡ The electrical properties of JJs are very sensitive to chemical variations and structural defects on atomic length scales

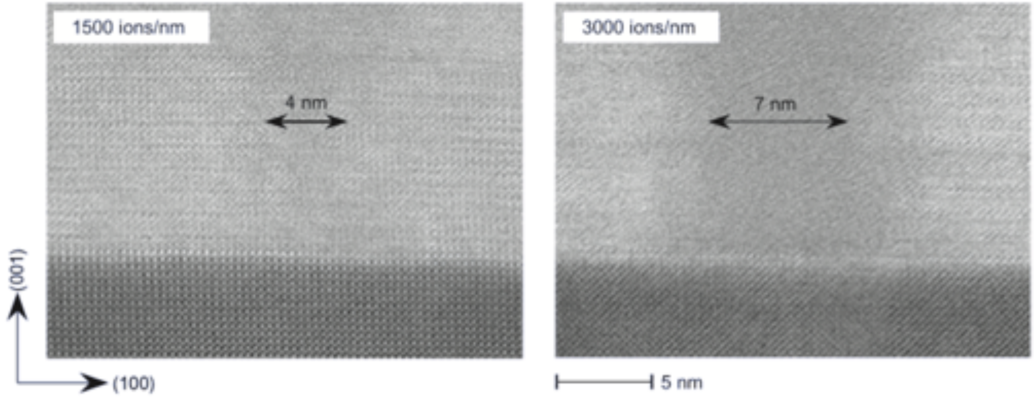
Josephson Junctions patterned Focused Helium Ion Beam



- Sharply He-FIB (0.5-nm diameter) can be used to directly write tunnel barriers
- Barrier properties can be continuously controlled by varying the irradiation dose







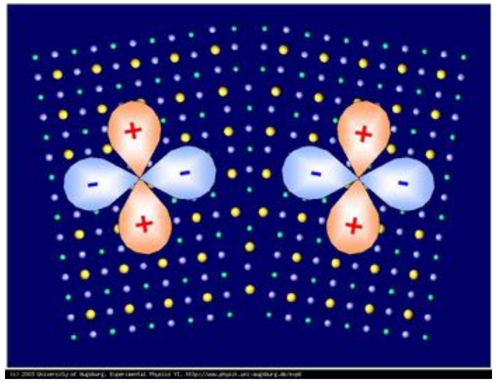
Cybart et al, Nat. Nanotech. 10, 598 (2015), Müller et al PR Appl. 11, 044082 (2019)

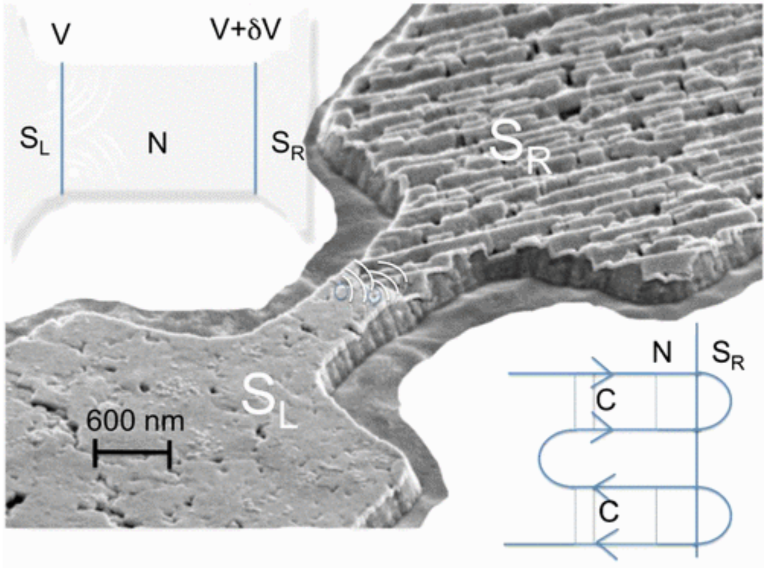
Grain Boundary Josephson Junctions

High-T_c cuprate superconductors, such as YBCO have very small and anisotropic values of **ξ** ∽ 0.1 – 1 nm making the fabrication of Josephson Junctions extremely challenging

Grain Boundary Josephson Junctions

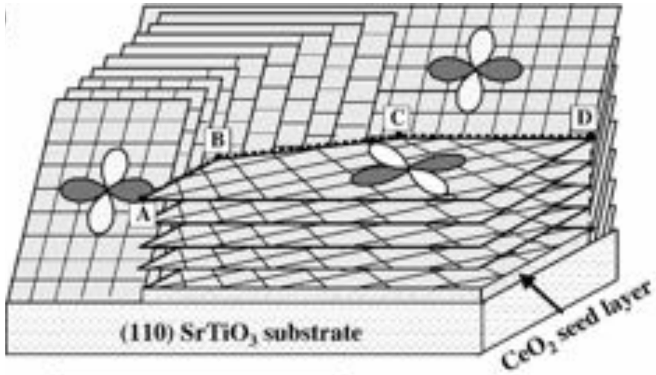
Grain boundaries are excellent Josephson junctions and have been exploited very successfully as research devices.





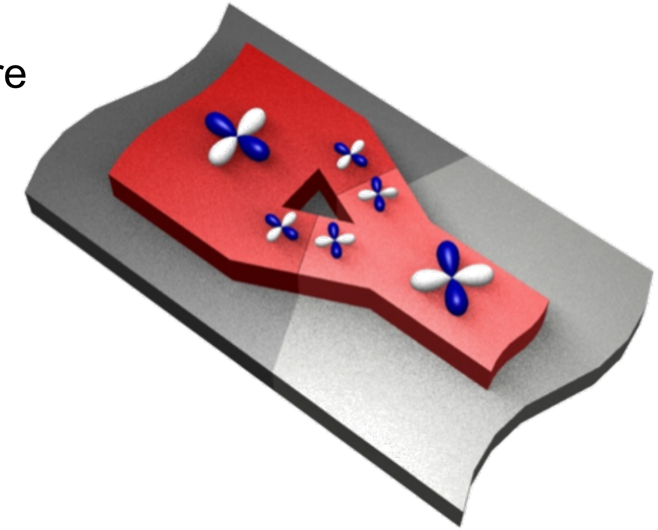
Grain boundary JJ in a YBCO film. (103) & (001) growth

By using bi-crystalline substrates or buffer layers one can change the GB angle and thus control the properties of the junctions



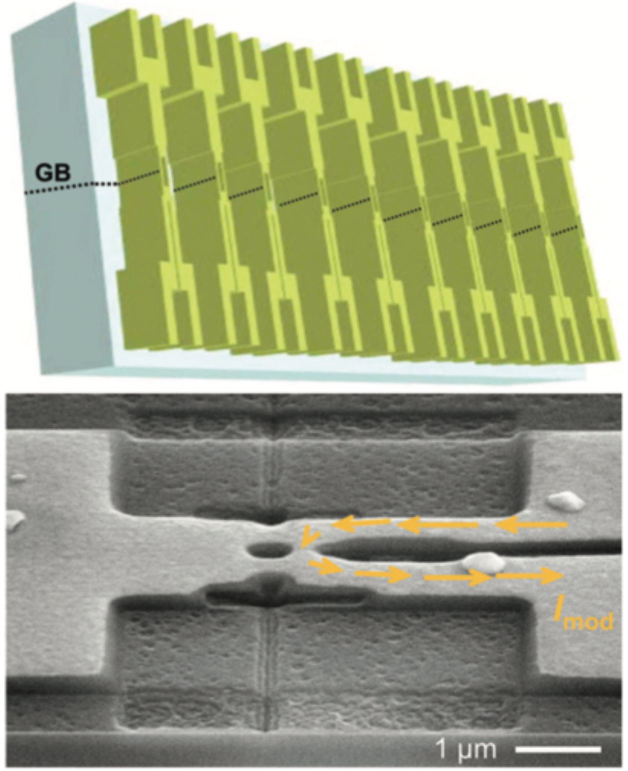
Lucignano et al. PRL, 105, 147001 (2010),

NanoSQUIDS Based on Cuprate Superconductors



Cuprate superconductor YBCO offers nanoSQUID operation up to much higher temperature and magnetic field

SQUIDS based on Grain Boundary Josephson Junctions



YBCO nanoSQUIDs on MgO bicrystal substrates fabricated by Ga FIB milling.

Although micrometric SQUIDs based on GBJs have been successfully produced the miniaturization of high-quality GBJs is challenging, because of degradation of the material due to oxygen loss during nanopatterning

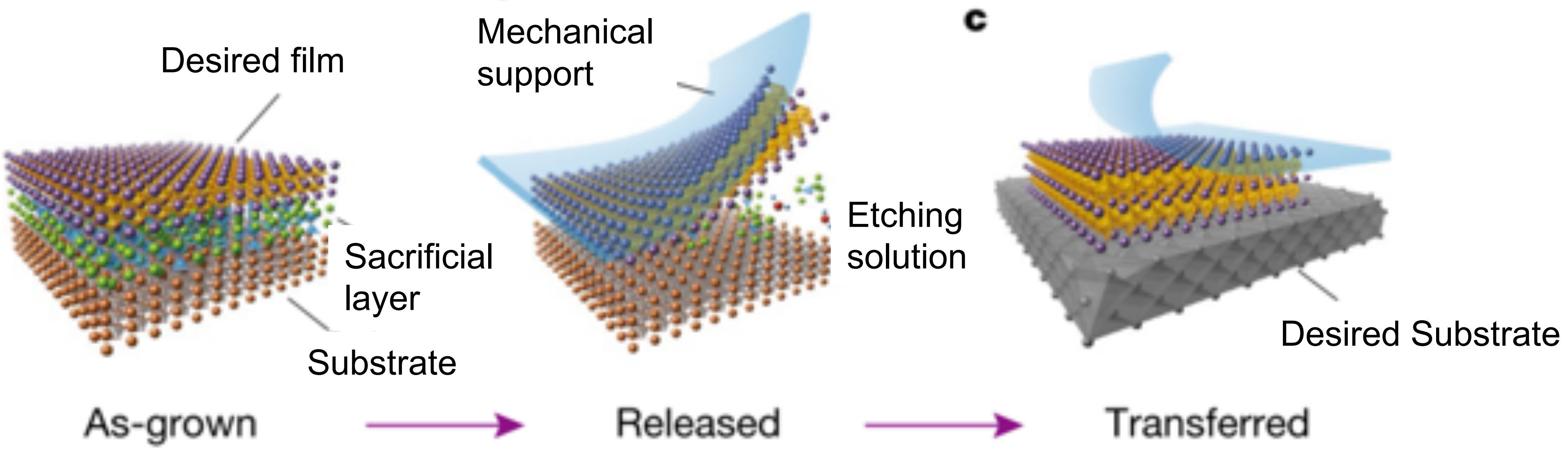
- Milling conditions have to be carefully tuned
- An Au protective layer on top of YBCO may be used for the protection of devices

Lin et al, Nanoscale, 12, 5658 (2020)

Integration onto Targeted Substrates

Single crystal functional oxides: Multifunctional materials that can be adopted for next generation electronics → Major challenges lies in the direct integration of epitaxial layers onto targeted substrates (Si / Flexible)

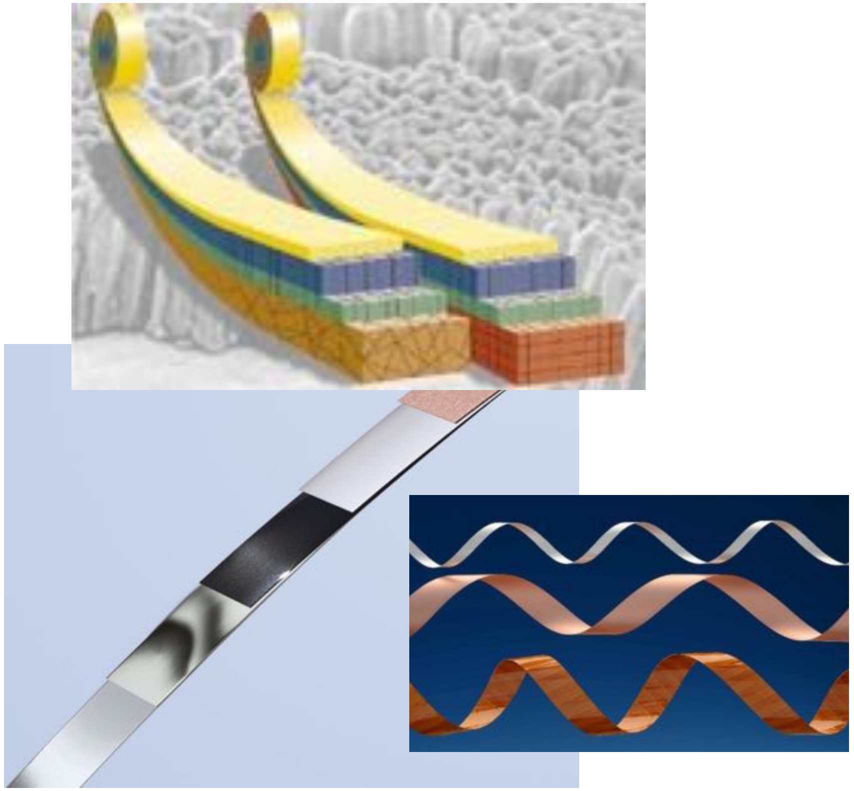
Freestanding crystalline oxide perovskites with high crystalline quality using a **sacrificial buffer layer**



Bakaul et al. Nat. Com. 7, 10547 (2016), Ji et al. Nature, 6, 570 (2019), Chen et al PRB 3, 060801 (2019)

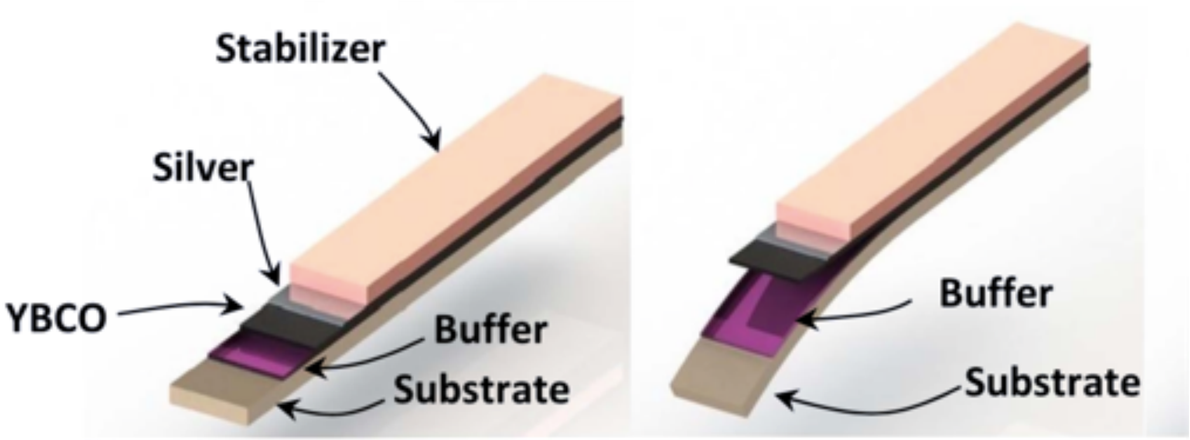
Integration onto Targeted Substrates

Single crystal functional oxides: Multifunctional materials that can be adopted for next generation electronics → Major challenges lies in the direct integration of epitaxial layers onto targeted substrates (Si / Flexible)



Commercially available textured metallic tapes

Textured YBCO film exfoliated from a metallic substrate that can be transferred onto the desired substrate



Exfoliation by mechanically stretching the flexible metallic tape

Solovyov et al. SUST, 30, 014006 (2017)

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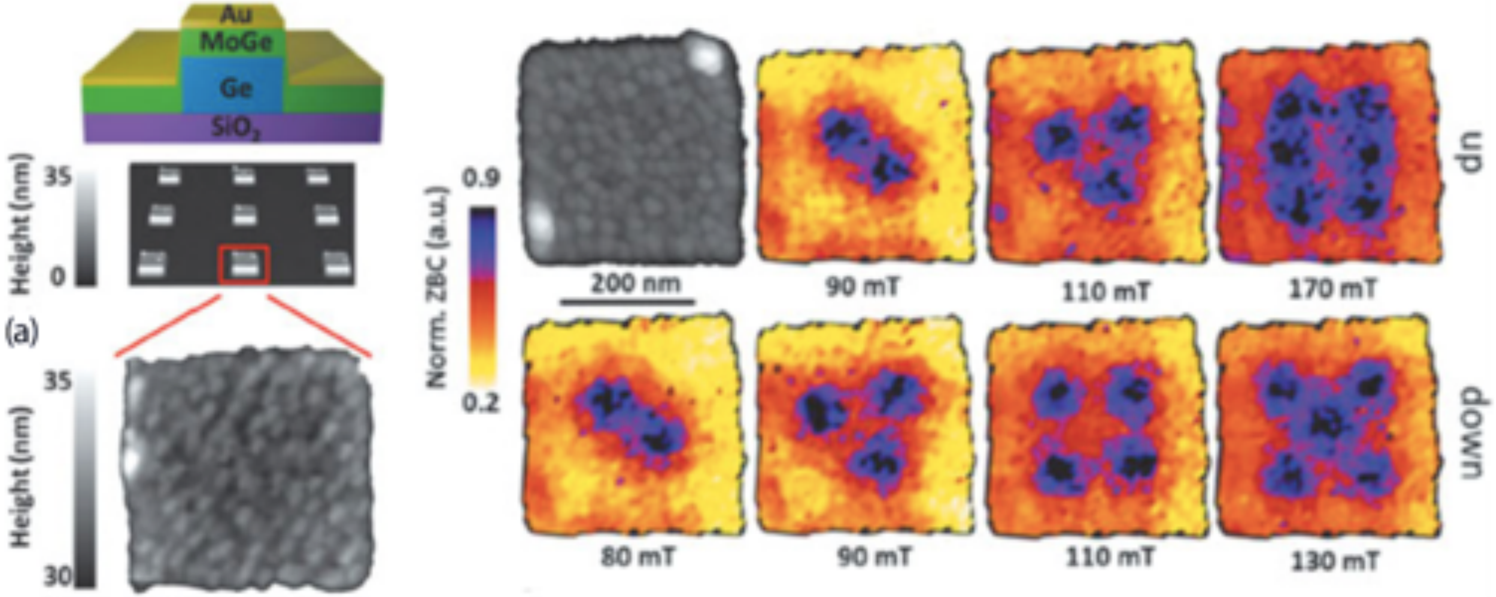
    - Hybrid SC / FM Systems: Spintronic Devices

Nanoscale Confinement of Superconductors

What happens when the size of a superconductor is decreased to the nanoscale?

Confinement effects occur as soon as one of the dimension of a superconducting sample becomes comparable to one of its characteristic length scales, ξ and λ



Confinement of vortices in MoGe nanosquares.

Vortex states in mesoscopic samples are determined by the interplay between the inter-vortex interaction which is modified due to the presence of boundaries and the confinement $\rightarrow$ vortex patterns display strong features of the sample shape and may differ strongly from a triangular lattice.

Timmermans et al, PRB, 93, 054514 (2016)

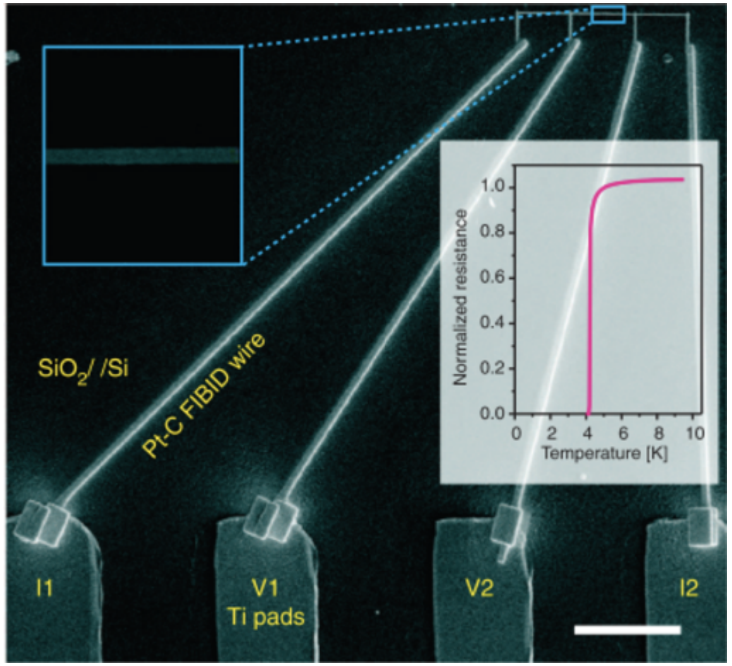
Superconducting Nano-wires

Mesoscopic length scales → Both the supercurrent distribution and the properties of vortex matter are strongly influenced by the sample topology and size

Geometry constrains are known to be responsible for **vortex exclusion and rearrangement processes**

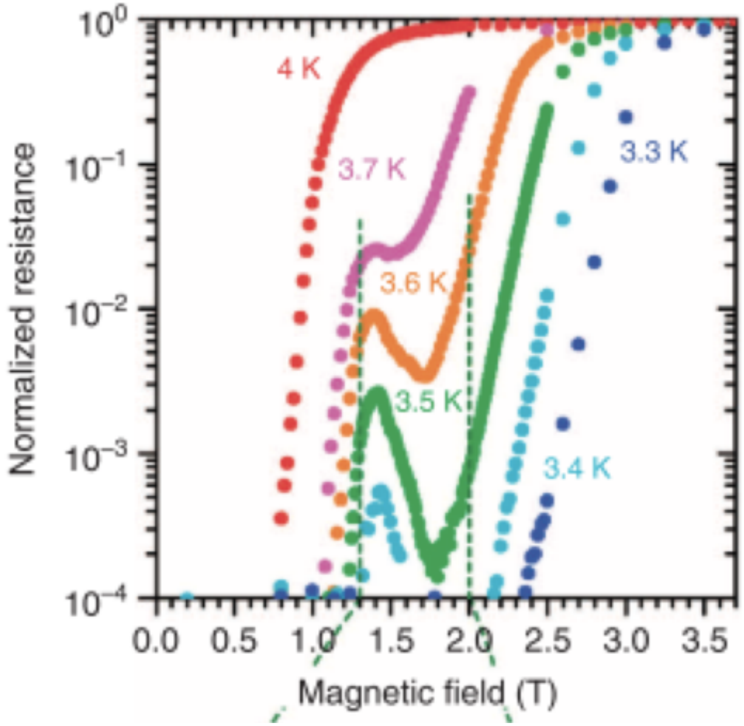
Vortices completely expelled from a thin SC strip

$B_0 \sim 1/W^2$



W-based nanowire (50nm) grown by FIBID

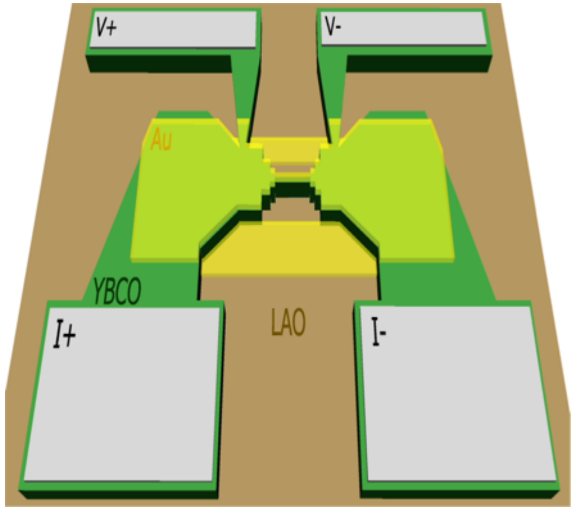
Vortices penetration
$B_0 \sim 1/W^2 \sim 1T$



Cordoba et al. Nat. Commun. (2013), Likharev, Sov. Radiophys. (1972), Stan et al. PRL (2004), Kuit et al. PRB (2008)

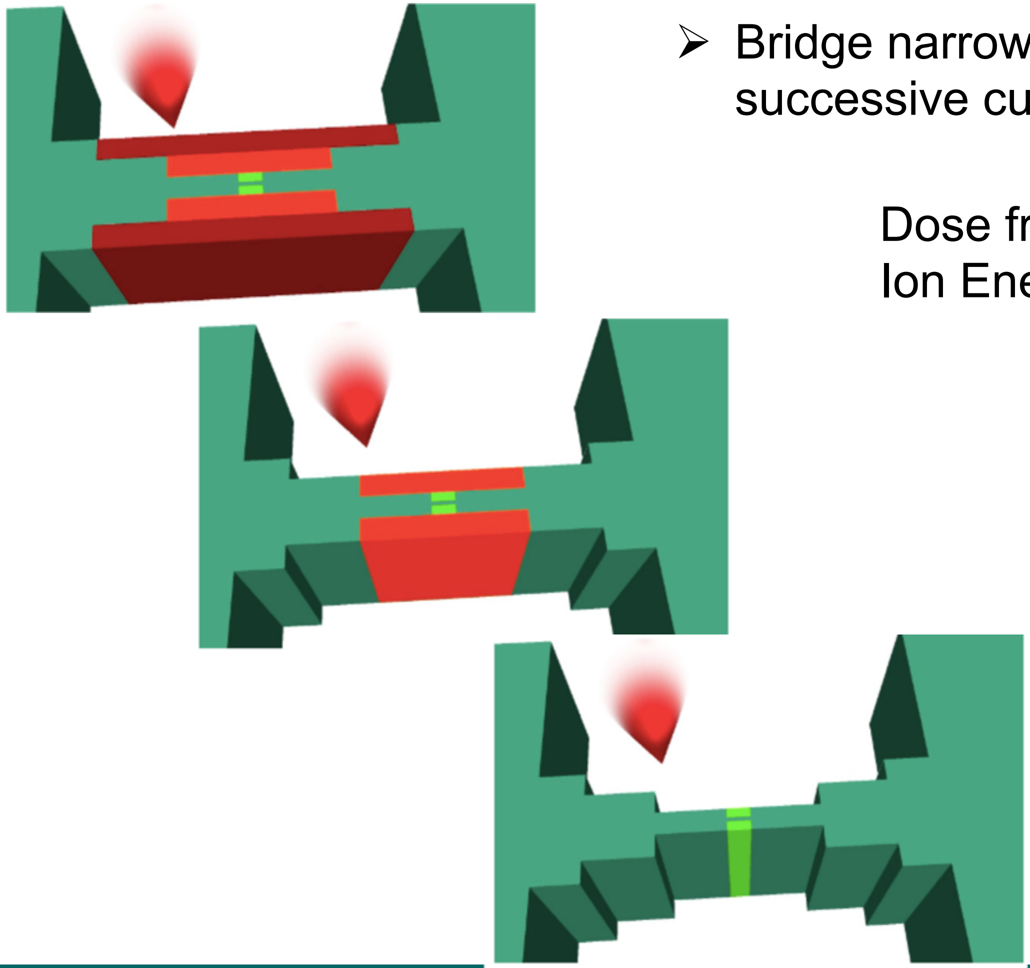
High-Temperature YBCO Superconducting Nanowires

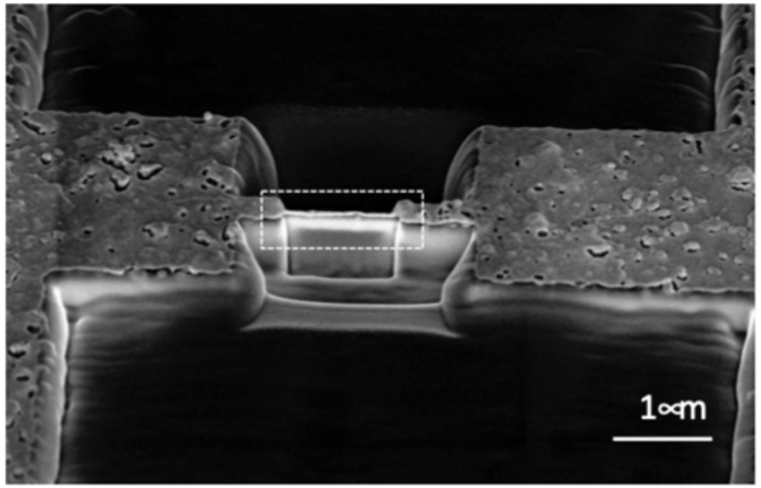
$YBa_2Cu_3O_{7-d}$ (YBCO) film



- YBCO micro-bridges in a four-point configuration patterned by standard photolithography
- Protecting Au capping layer (50nm)
- Bridge narrowing by performing several steps with successive cuts by FIB

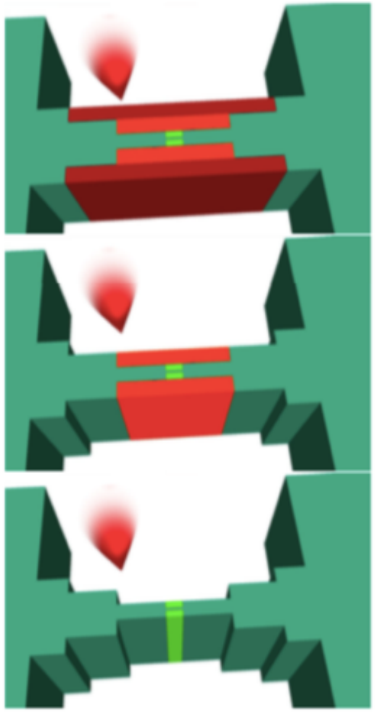
Dose from 200pA to 10pA
Ion Energy = 30KeV

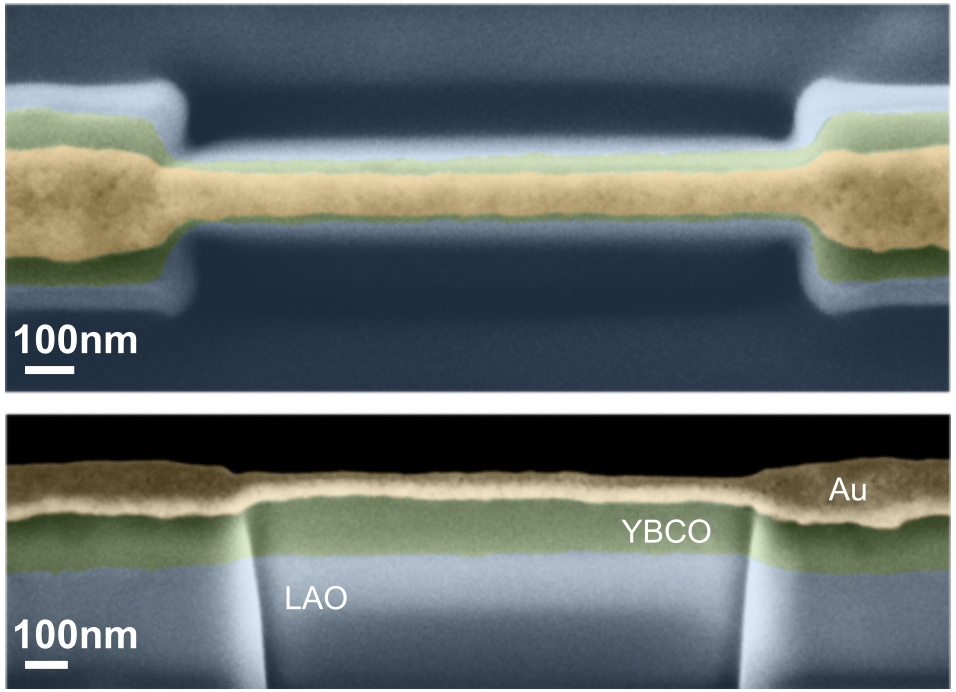


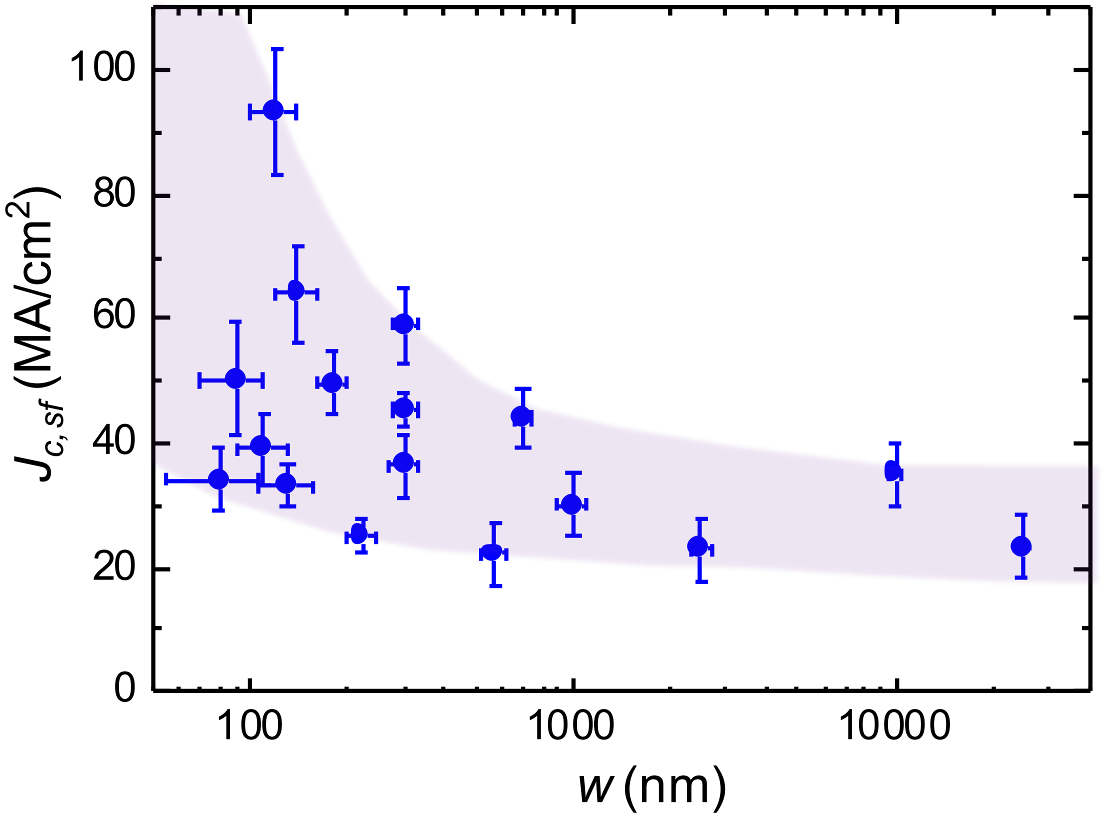


Rouco et al. Materials, 11, 211 (2018)
Rouco et al. Nano Lett. 19, 4174 (2019)

Self-Field J_c in YBCO Nanowires

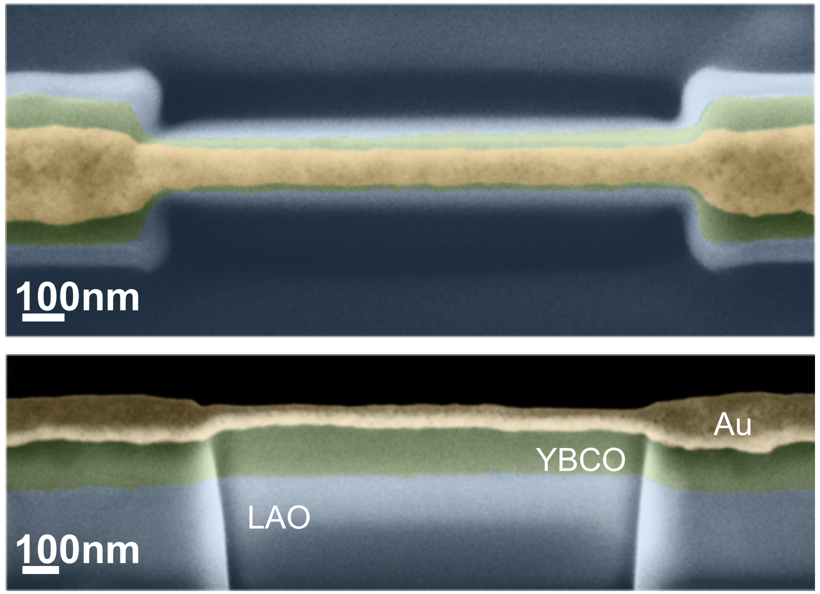


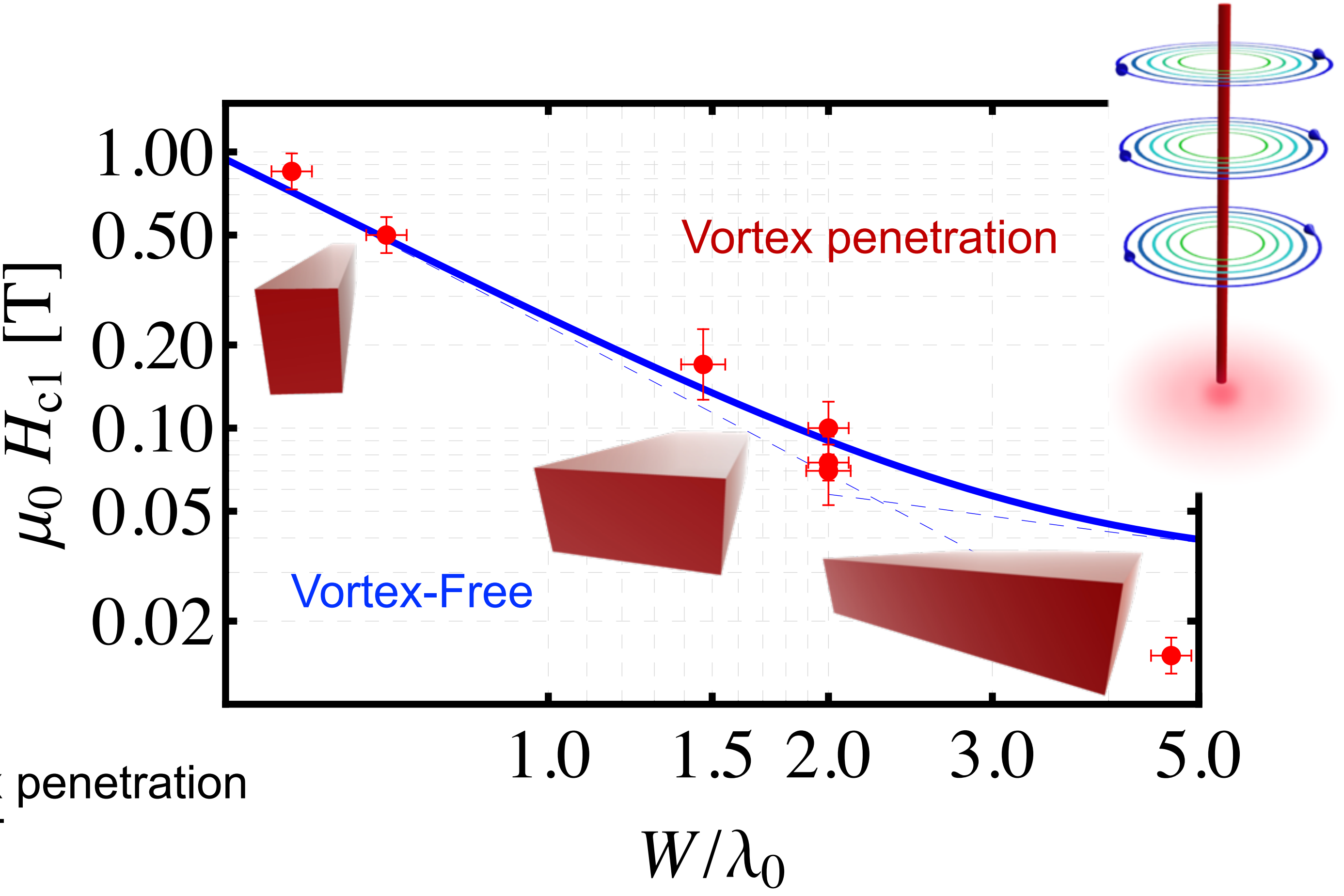




Systematic enhancement of $J_{c,sf}$ when reducing W → Values approaching the Ginzburg-Landau depairing current in the limit W < $2\lambda_0$

Magnetic Field Penetration in YBCO Nanowires

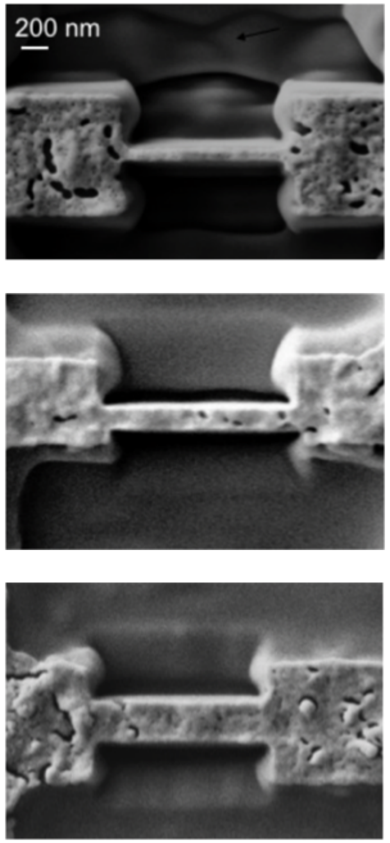


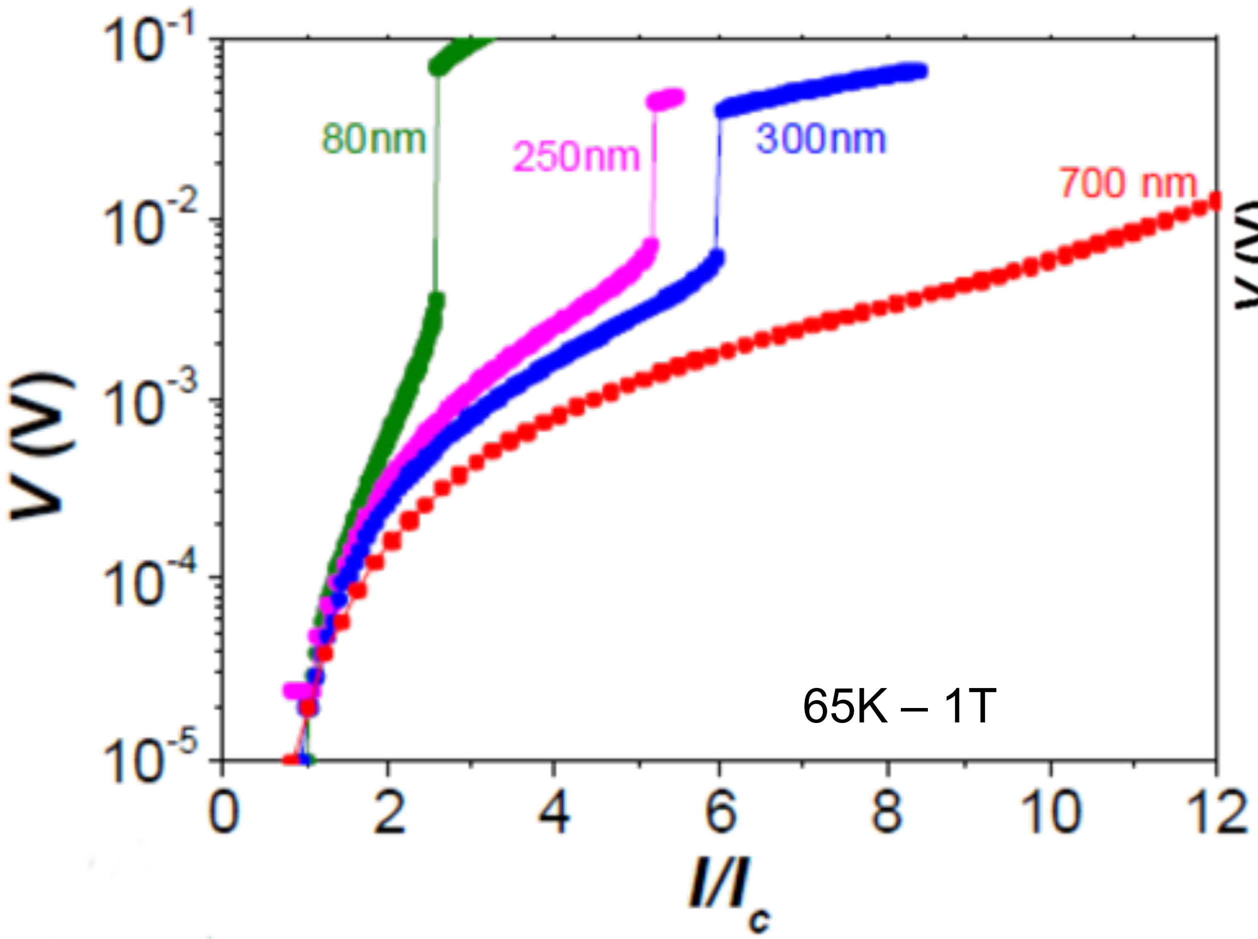


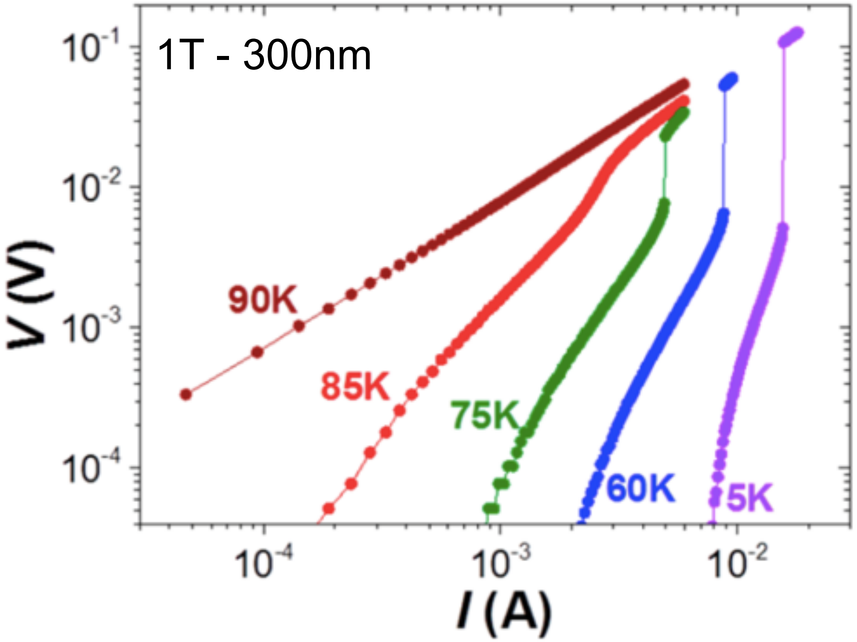
For widths W much smaller than λ vortex penetration field can reach values on the order of 1 T

Tailoring the geometry down to the nanoscale allows us to expand the vortex-free region to very high fields → <u>Excellent candidates for noise-sensitive devices</u>

Superconducting Properties of YBCO Nanowires



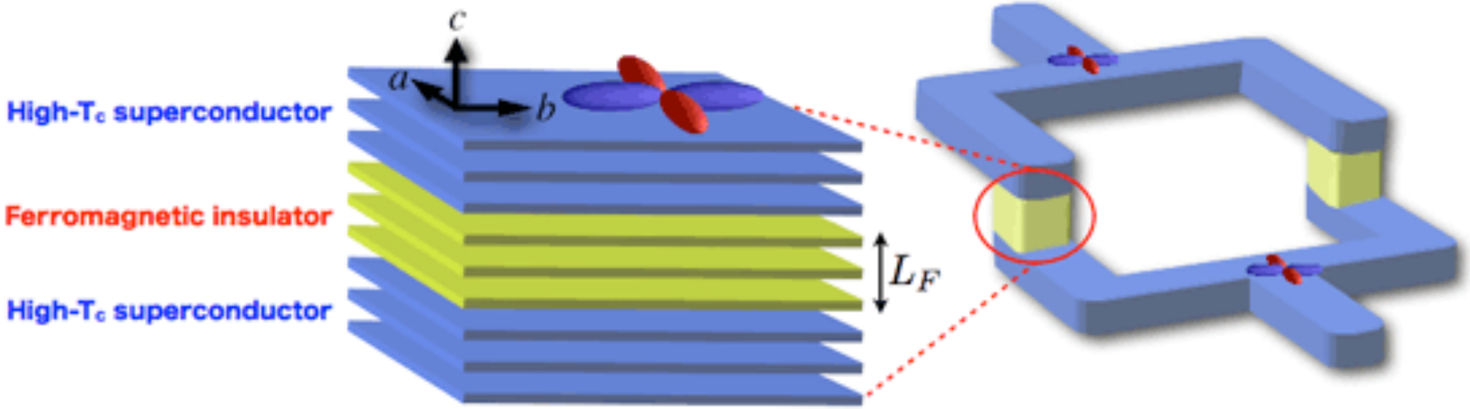




Flux-flow penetration induces very sharp voltage transitions from the superconducting to the normal state → Potential for detector applications

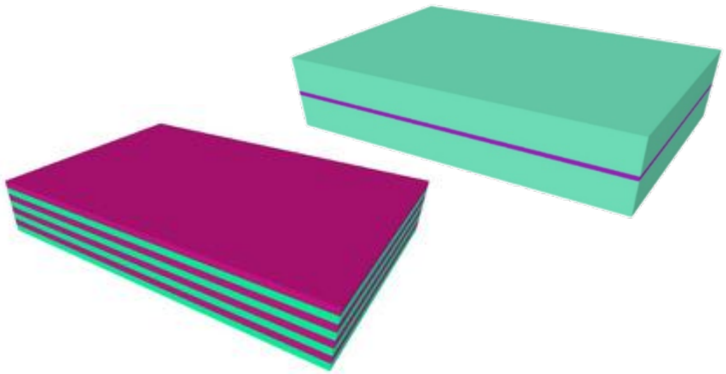
3D Nano-Patterning

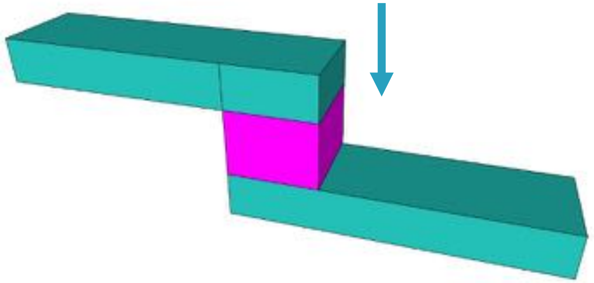
Complex Oxide heteroestructures → vertical tunnel Junctions

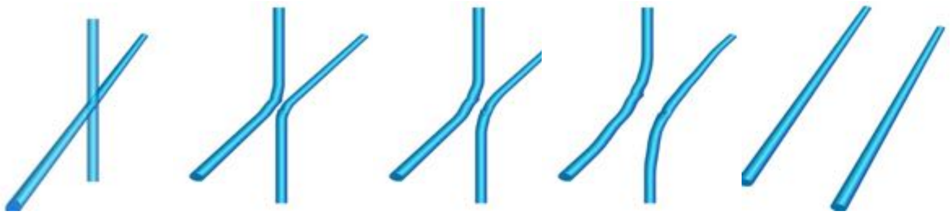


Hetero-structures
Multilayers with different pinning behavior

Vortex motion along layers with different pinning →
Vortex entanglement, crossing of lattices

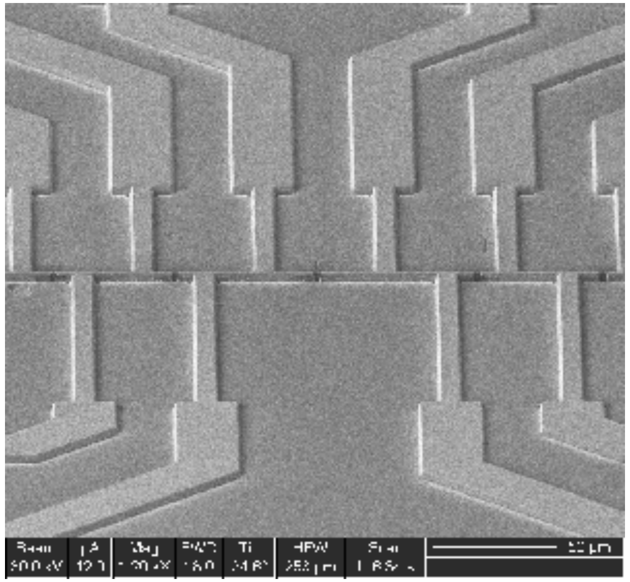




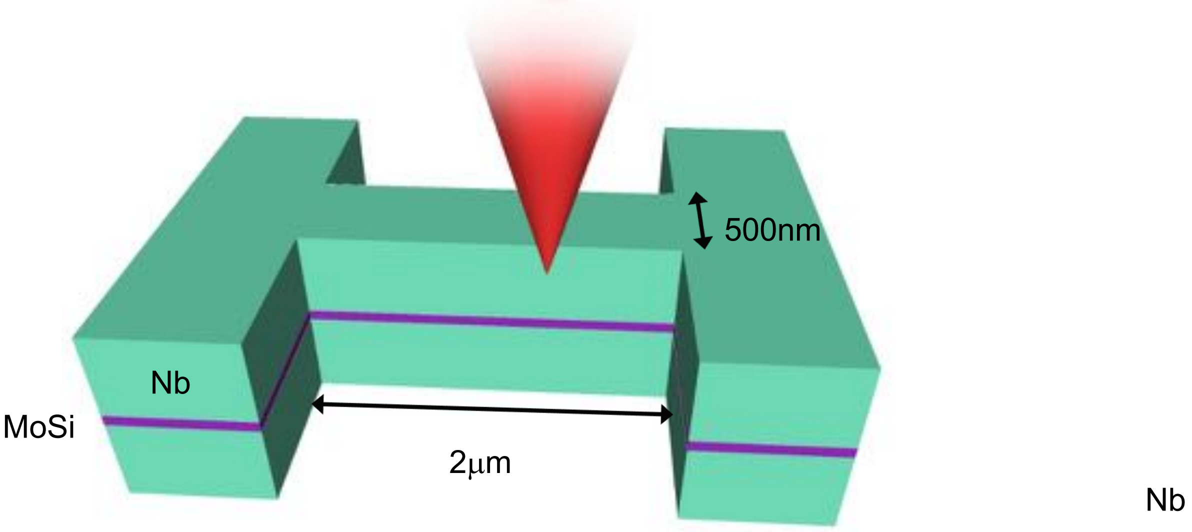


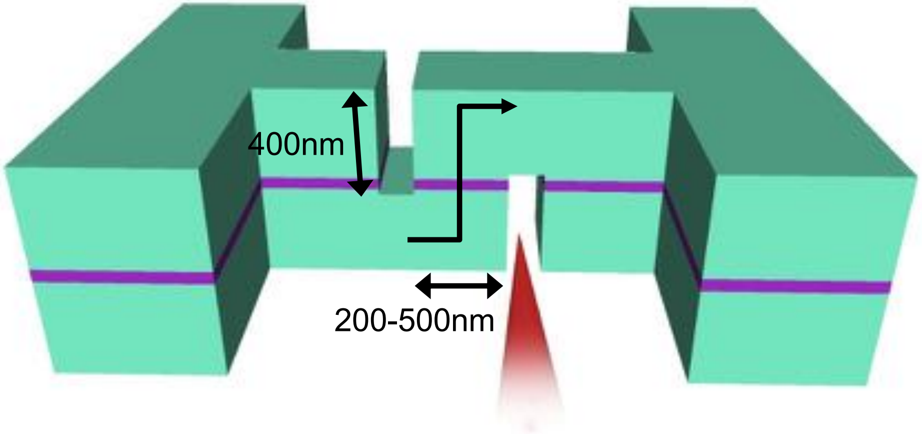
3D Nano-Patterning

6μ - 10μ wide current tracks defined by standard photolithography
Nb/MoSi/Nb tri-layers



Current track narrowed with FIB to ~ 500nm



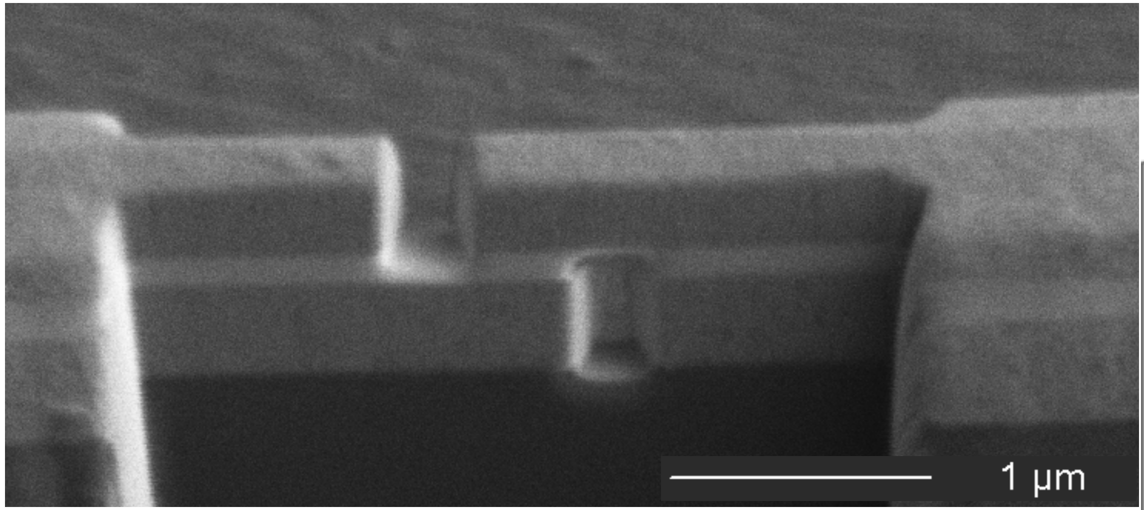


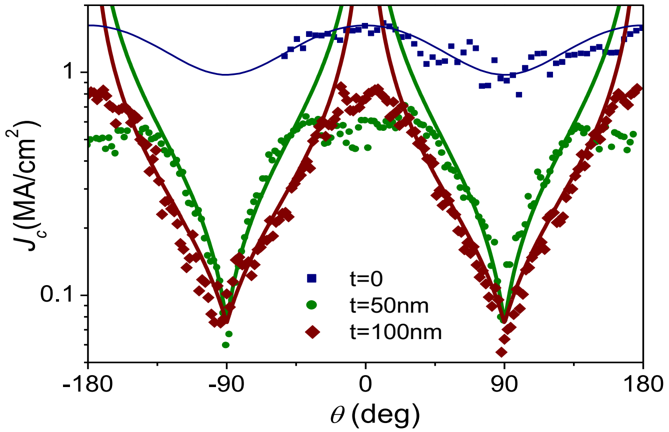
Nano- devices with dimensions in the range 100-500nm in which the current is constrained to flow along the *vertical* axis → transport properties in very confined areas

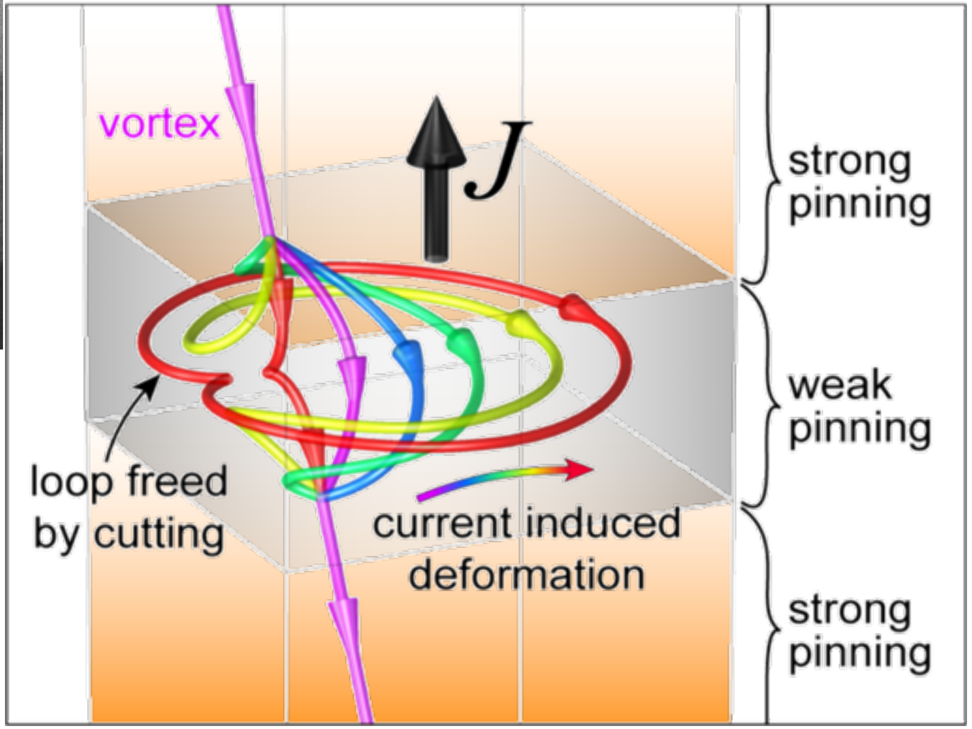
Palau et al. PRL 101, 097002 (2008)

Vortex Breaking – Cutting & Channelling

Structures in which a weak pinning layer is sandwiched between two strongly pinning layers

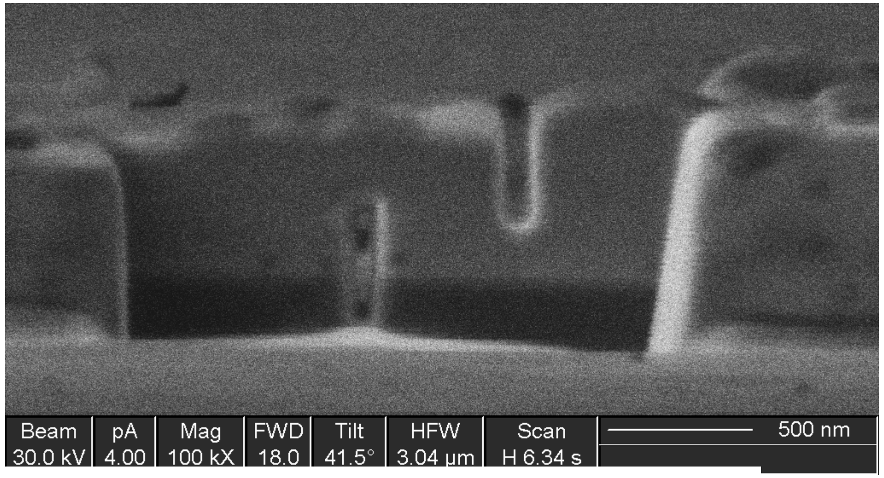


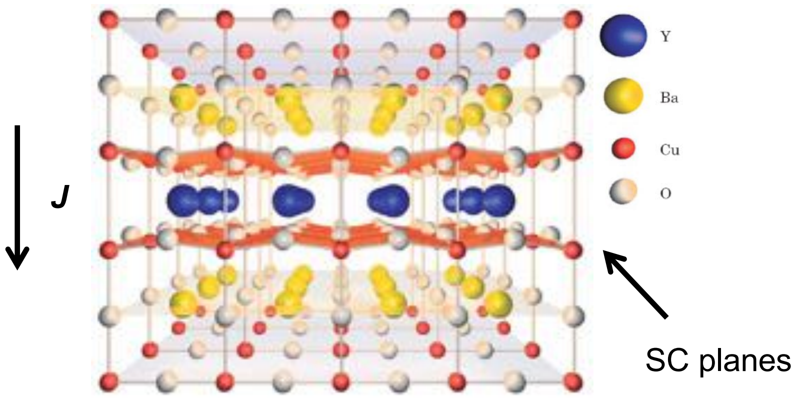


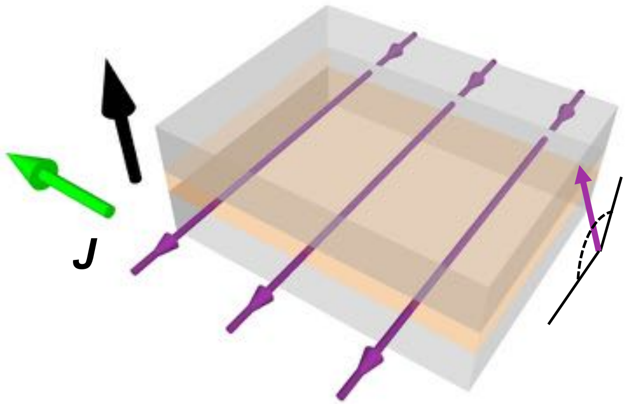


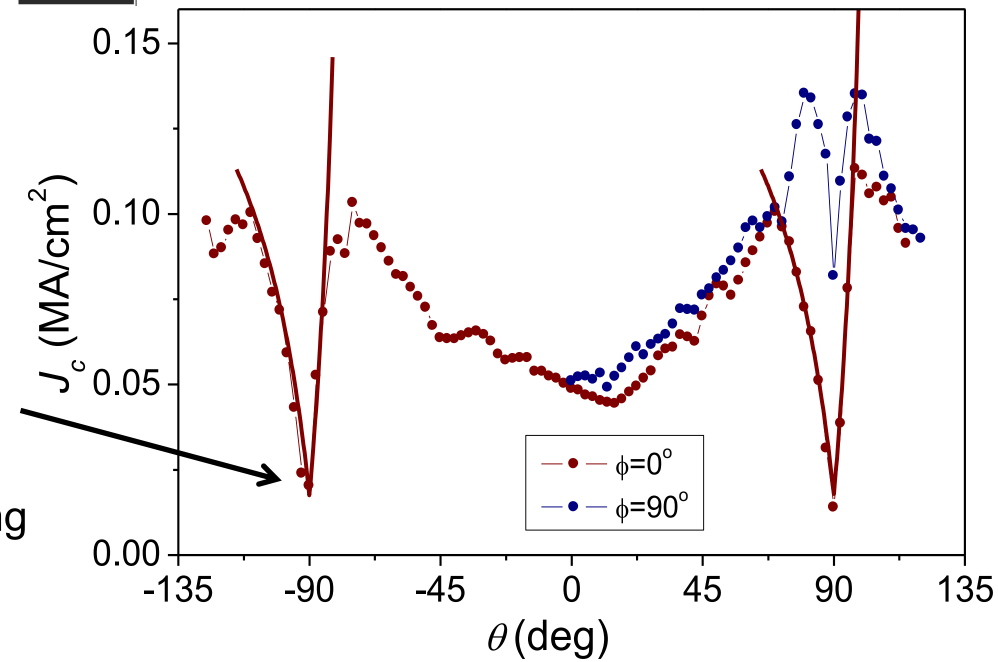
Well-controlled weak pinning channels → Quantitative analysis of flux cutting and channeling

Channelling along Superconducting planes









Easy vortex flow along the *ab* – planes→ vortex cutting and channeling

Palau et al. PRL 97, 257002 (2006)
Gutierrez, Palau, et al. 79, 064526 (2009)

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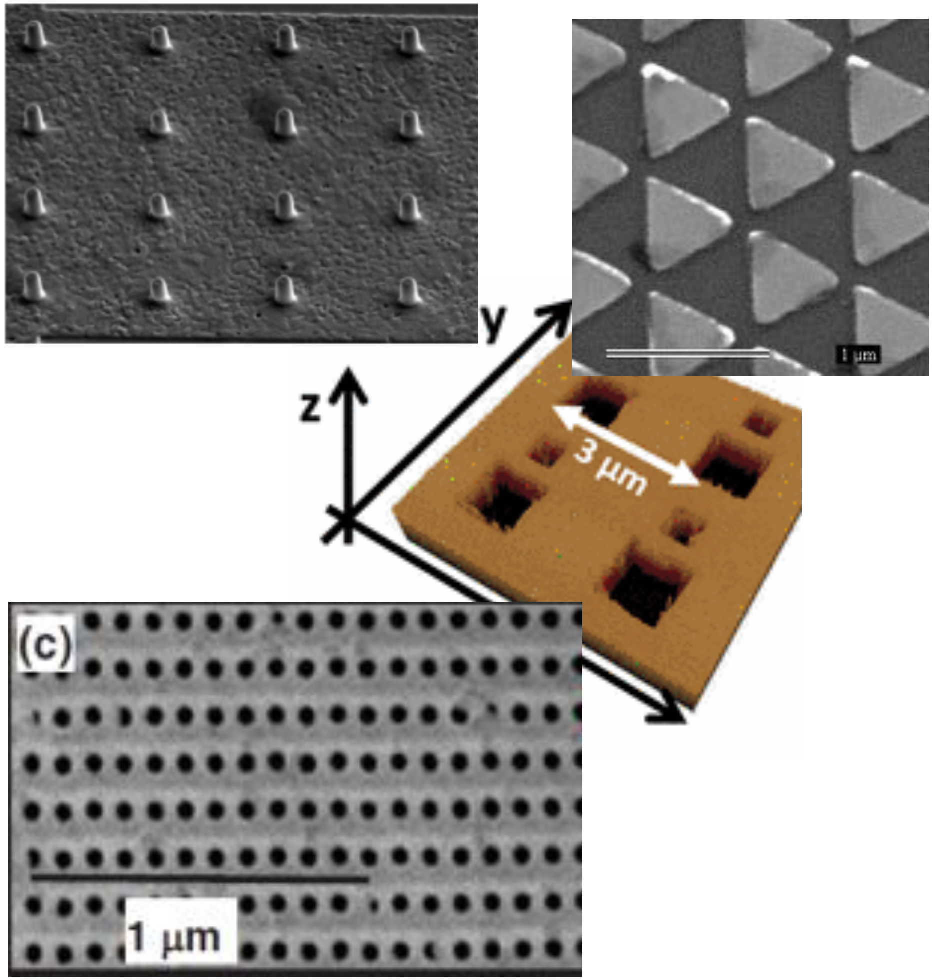
Vortex Manipulation via Artificial Nano-Structures

Engineered vortex energy Landscape



Vortex pinning

Ordered distributions of sub-micrometric structures

- holes (antidots / blind antidots)
- nano-particles (insulating, magnetic…)
- Nano-regions with suppressed SC

controlled pinning energy landscapes → manipulate vortices

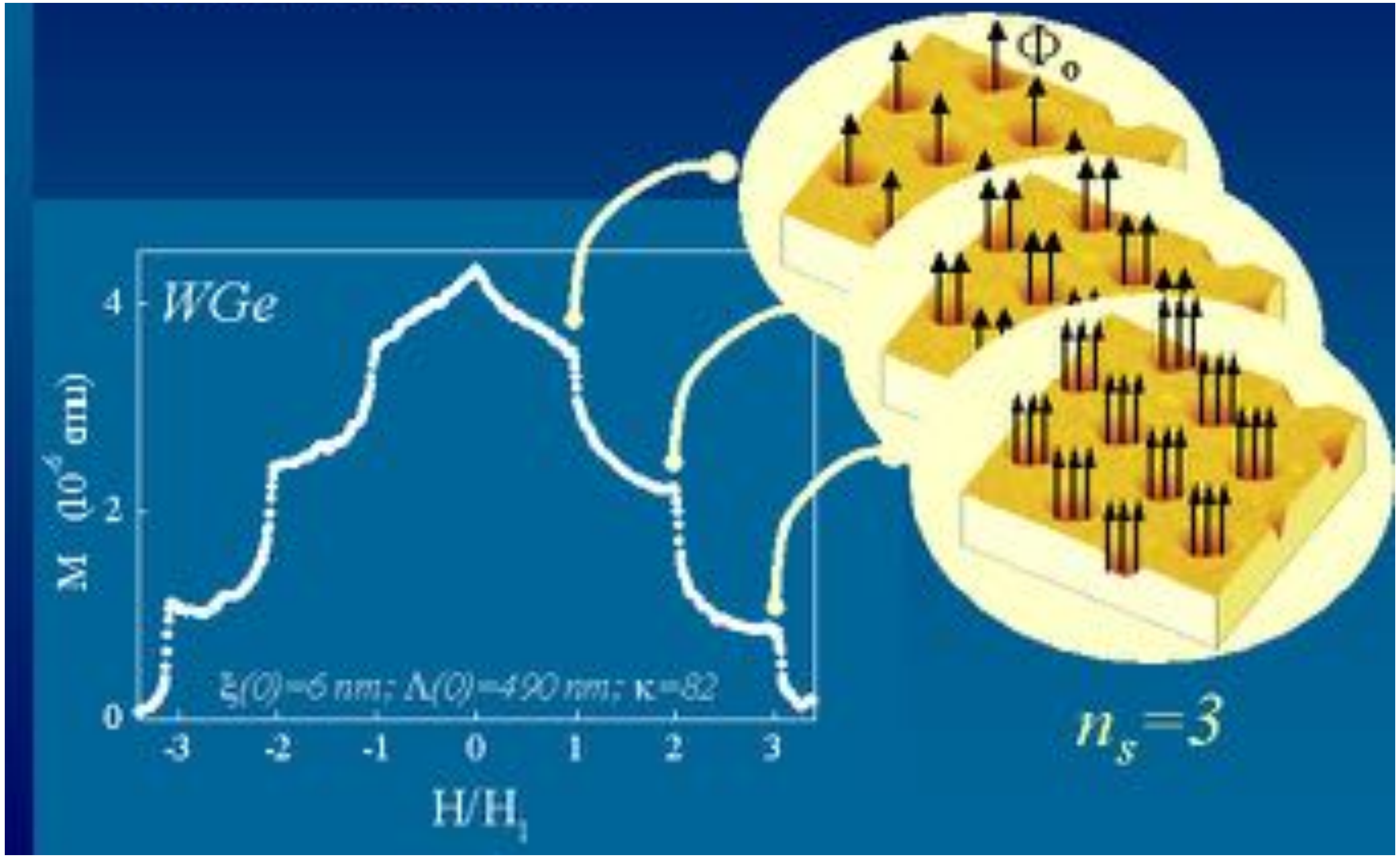
- vortex confinement
- vortex guidance
- Vortex rectification

→ **Fluxonic Devices**

Commensurability Effects – Matching Field Effects

Interaction between vortex lattice and a regular defect lattice → Matching effect

Stable vortex configuration at the matching fields → Maximum J_c values



Pb(500Å) film with regular antidot lattice

matching field → number of vortices matches the number of defects

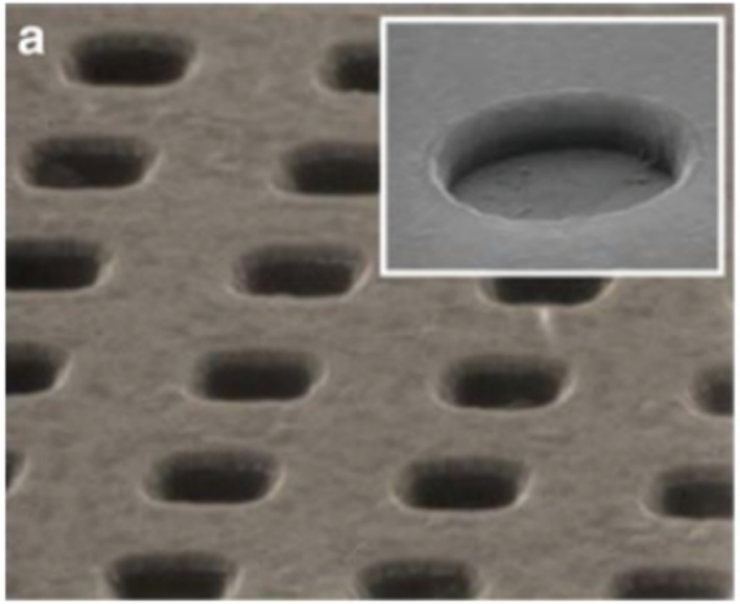
$B = n\,\Phi_0$ and $n \sim 1/a_0^2$

$a_0 = \sqrt{\Phi_0/B}$

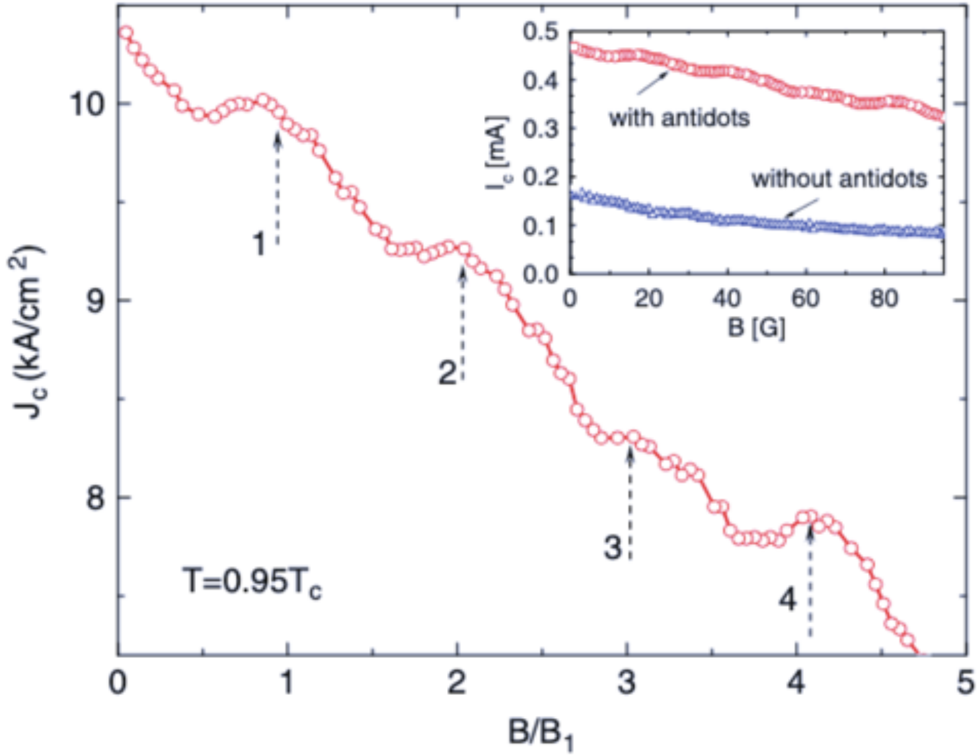
Moshchalkov, PRB, 57 (1998), Superconductors at the Nanoscale-De Gruyter book (2017)

Matching Effects in HTS

Strong thermal fluctuations, anisotropy effects, larger applied magnetic fields → Richer Phenomenology



YBCO film
Square lattice fabricated by EBL & Ion milling
periodicity = 1μm, radius= 220nm



Strong intrinsic pinning reduces the impact of artificial ordered energy landscape created by ordered antidots

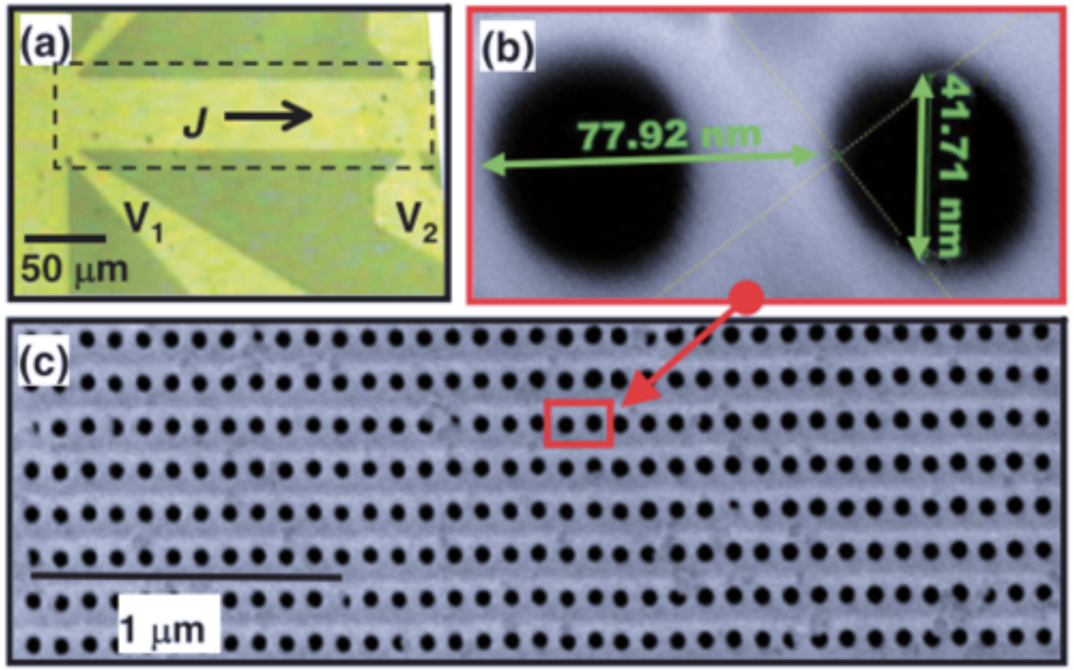
→ Soft matching effects observed

Minimum distance without too much damaging ∼ 1μm → First matching ∼ 2mT

Superconductors at the Nanoscale-De Gruyter book (2017)

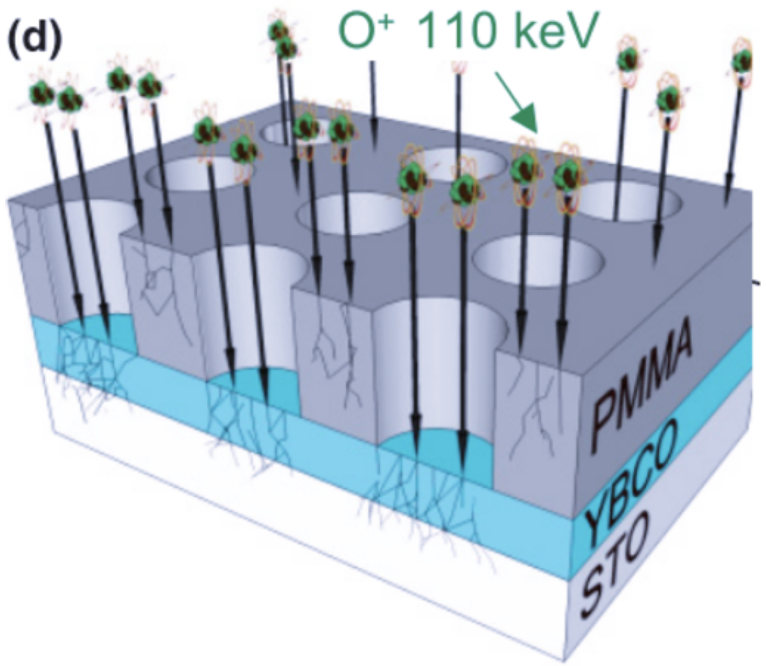
Matching Effects in HTS

Artificial ordered defects created by **masked ion irradiation**



Holes of D∼ 40nm with inter-hole distance d ∼ 120 nm

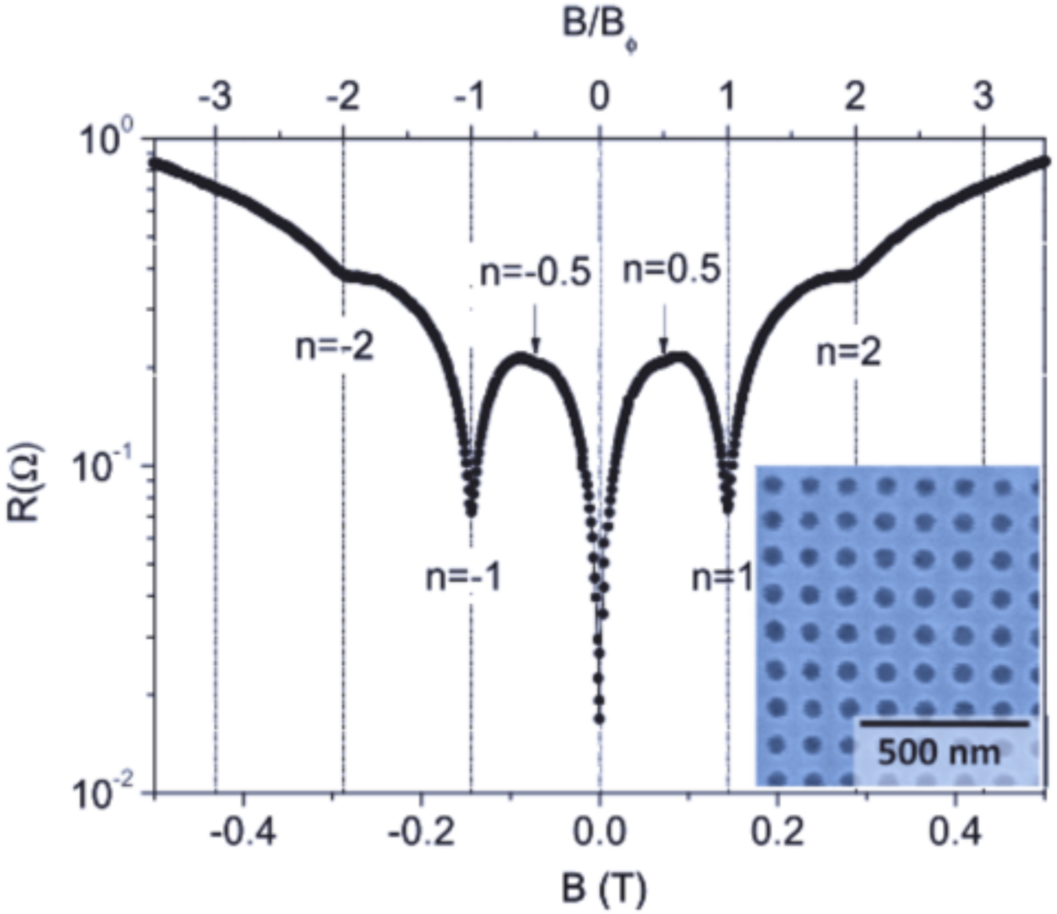
- PMMA (800nm)
- EBL to created a nanoperforated PMMA mask
- O+ irradiation (E= 110KeV, f = 10^{13} – 10^{14} cm^{-2})

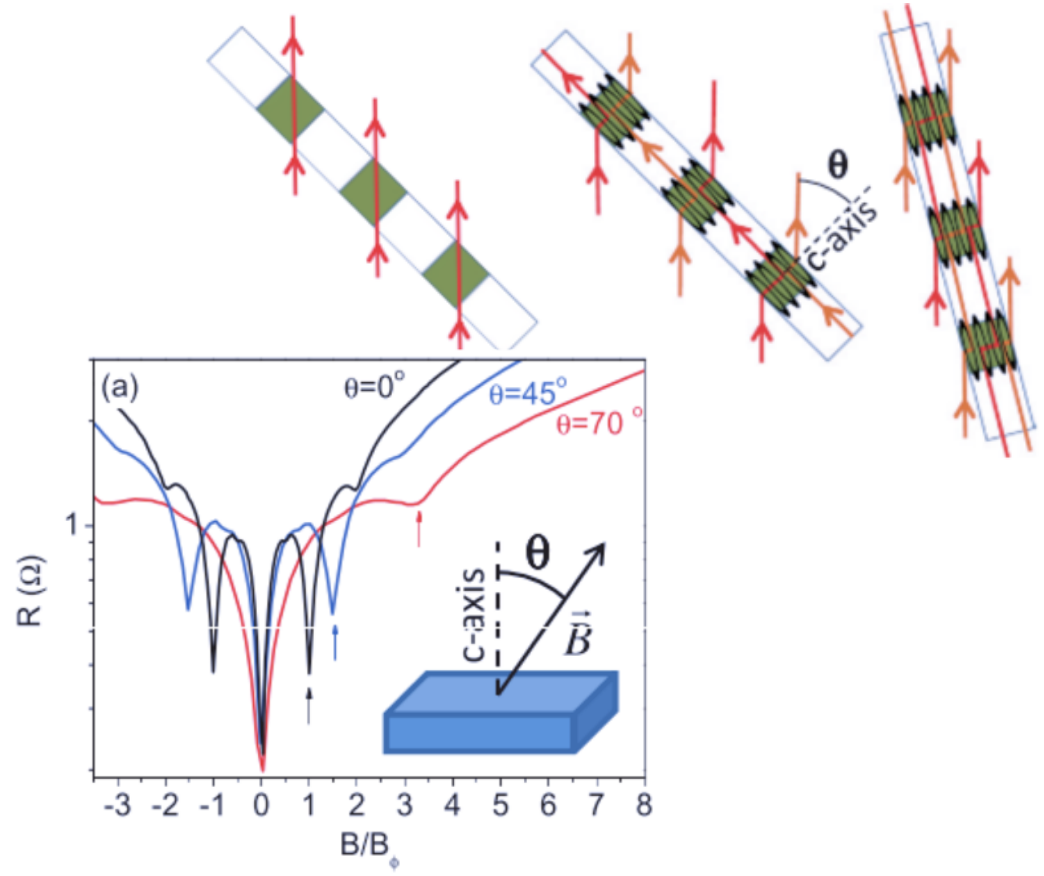


O+ ions through the mask induces disorder (oxygen vacancies and interstitials) → T_c is locally depressed in the hole areas

Swiecicki et al. PRB 85, 224502 (2012), J. Trastoy et al. NJP 15, 103022 (2013)

Matching Effects in HTS





Nanometric distances → vortex manipulation in very high magnetic fields (up to two orders of magnitude higher than with other techniques)

Study the interplay of anisotropy, random disorder and nanoscale periodic pinning

Especially relevant for fluxtronic devices → higher fields imply greater data storage capacity

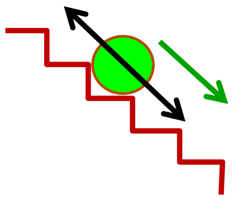
Guided Vortex Motion - Ratchets

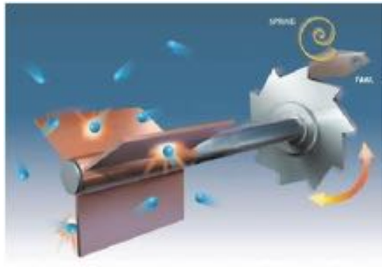
Ratchet physics → active topic of research extensively studied in a wide spectrum of fields in physics.

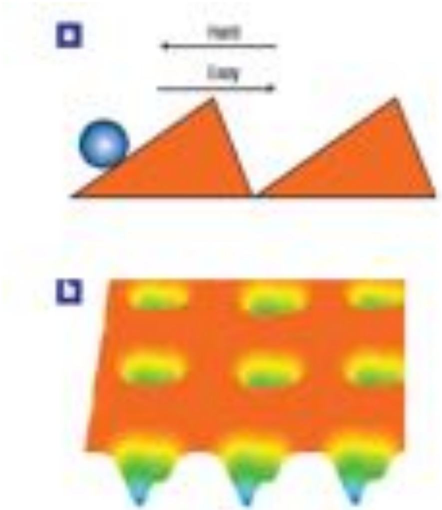
Ex: bio-membranes in two drift regimes: diluted (single particles) and concentrated (interacting particles))

"ratchet effect"

A single particle in an asymmetric potential shows a ratchet effect, biasing or rectifying their motion, when subjected to non-equilibrium fluctuations







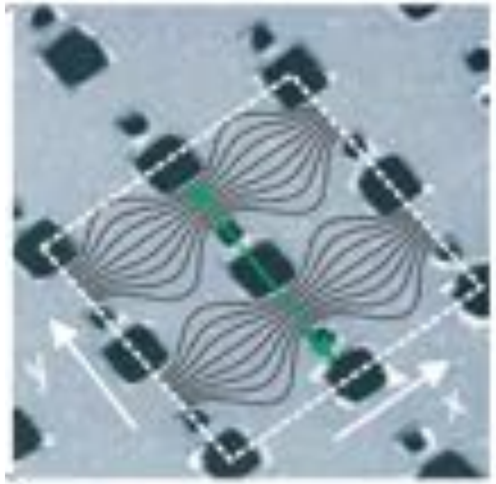
Ratchet effects in superconducting systems → size and quantity of particles (vortices) can be finely tuned with two external parameters (*T* and *H*)

Controlled vortex motion → Net transport of matter at the nanoscale

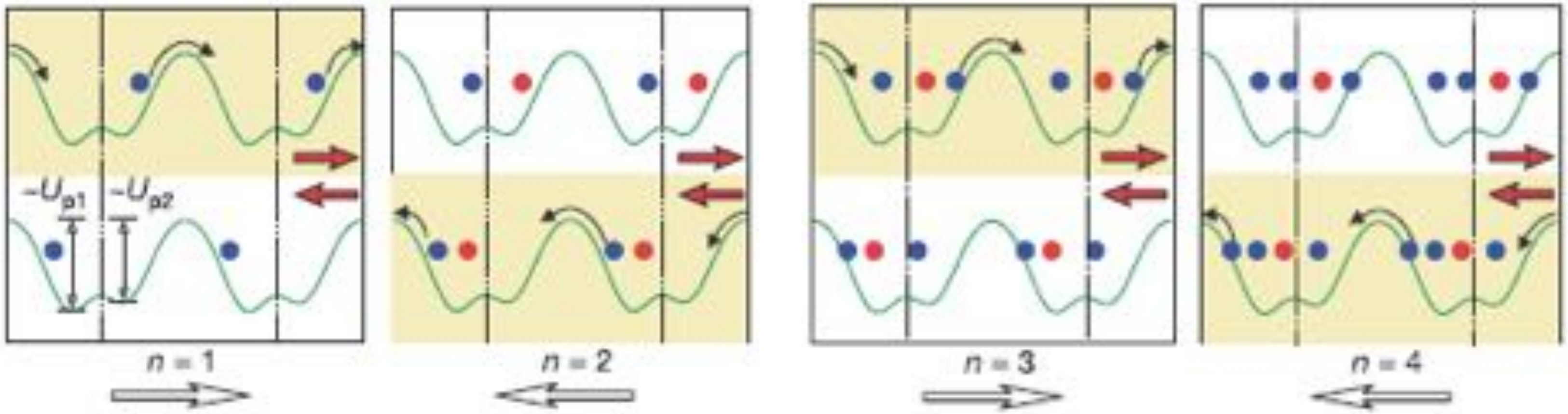
Model systems for understanding similar ratchet phenomena
Electronic devices in superconductors:
rectify ac driving forces
field dependence reversible vortex diodes

Asymmetric Pinning Potentials in LTS

Al films patterned with square arrays of submicron antidots by EBL



Double antidot array → asymmetric pinning potential



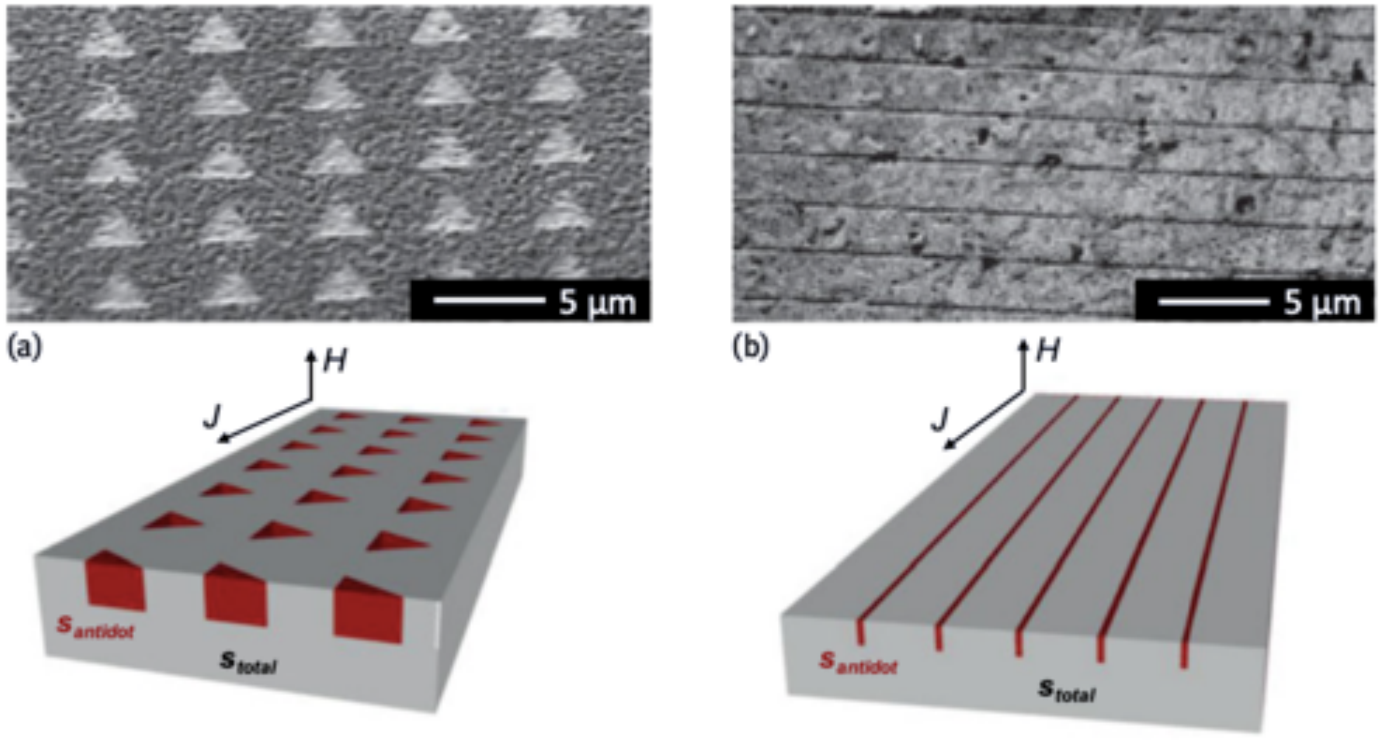
- Net motion of vortices versus the ac Lorentz force → ratchet effect
- Direction of the vortex drift does undergo multiple reversals as the vortex density is increased

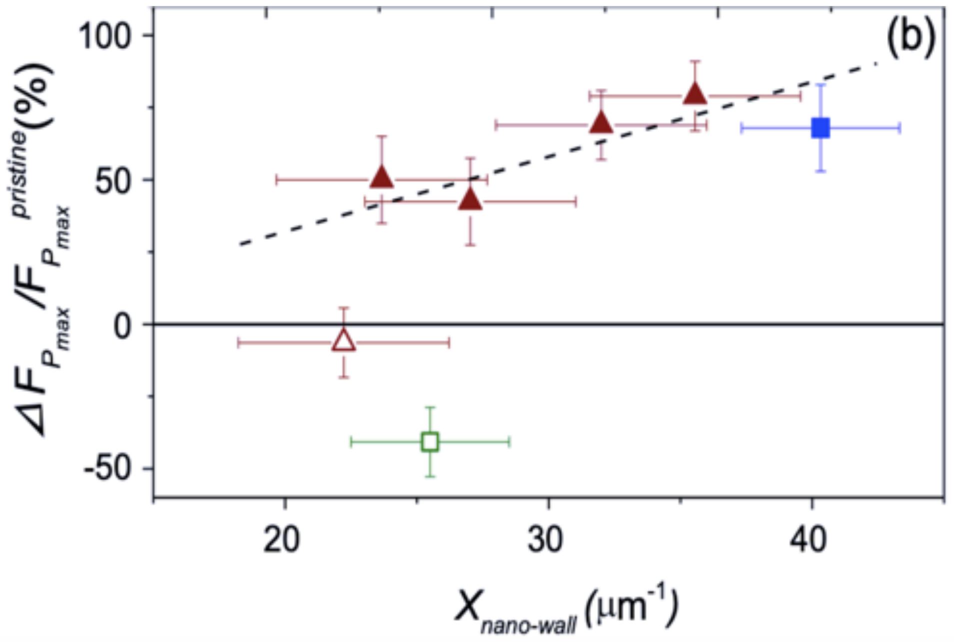
Villegas et al. Science, 302 (2003), Clecio et al, Nature 440 (2006)

Effective anisotropic pinning sites in HTS - Nanowall Pinning

Antidot lattices to modify the pinning landscape of YBCO Films

YBCO films patterned by FIB / EBL, with blind trenches and anti- dots using a slow-enough milling rate to properly define the desired structures without damaging the surrounding area.



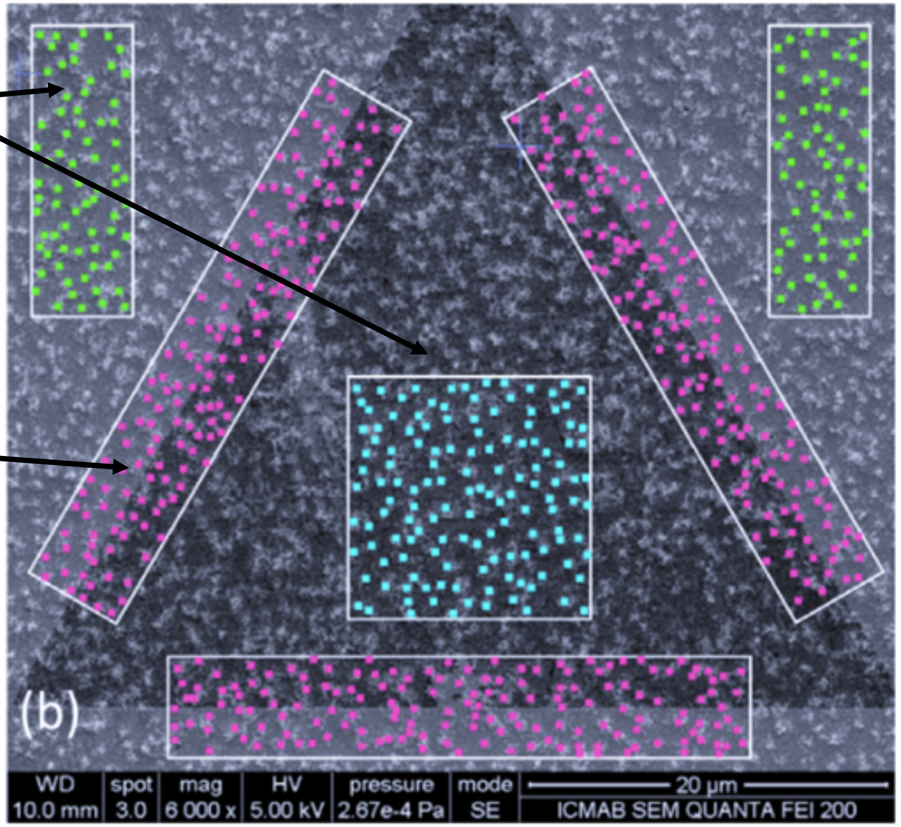


The variation of the pinning force correlate with the patterned nanowall length

Effective anisotropic pinning sites in HTS - Nanowall Pinning

$\rho_{in} \sim \rho_{out} \sim 0.75$ vortex /μm^2

$\rho_{wall} \sim 0.85$ vortex /μm^2 (13% higher)



SEM image of magnetic Bitter decoration (4.5K, 1.5mT)

Nanowalls are acting as very effective pinning sites → Reduction of the order parameter near the nanowalls by localized deoxygenation or amorphization of the YBCO structure

A. Palau et al. / Physica C 506 (2014) 178–183, Chapt. 6- Superconductors at the Nanoscale-De Gruyter book (2017)

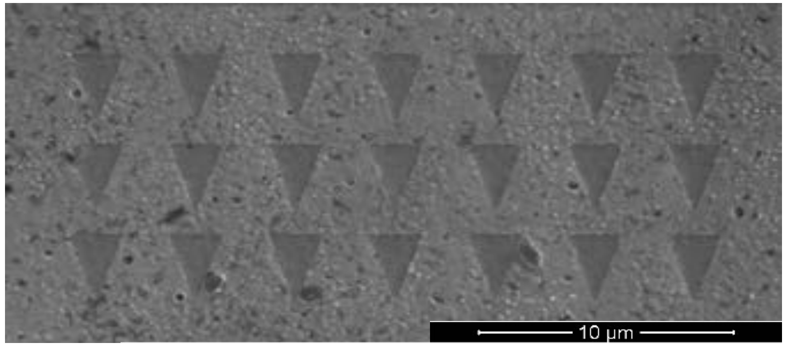
Asymmetric Pinning Potentials in HTS

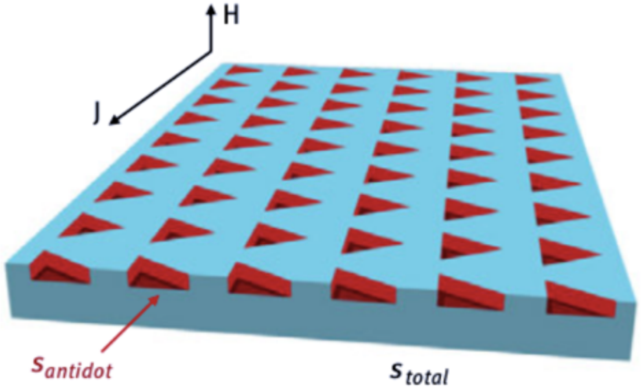
Ratchet system based on a nanostructured HTS (very rich H-T vortex phase diagram) → Study the physics of rectified motion of a large number of particles.

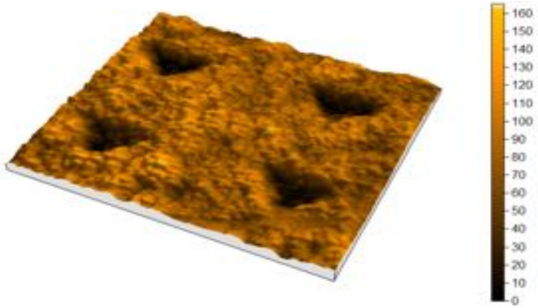
<u>Controlled vortex motion in HTS</u> thin films quite complicated due to the strong influence of thermal fluctuations and high intrinsic pinning.

Triangular array of blind antidots fabricated by FIB and EBL

Size ~ 0.5-5 μm
depth ~ 50-150 nm
Shape, distance, distribution



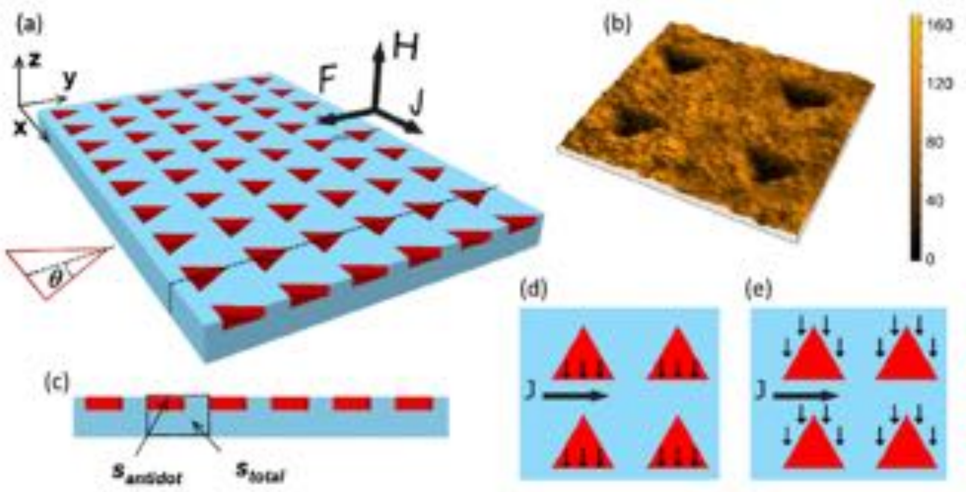


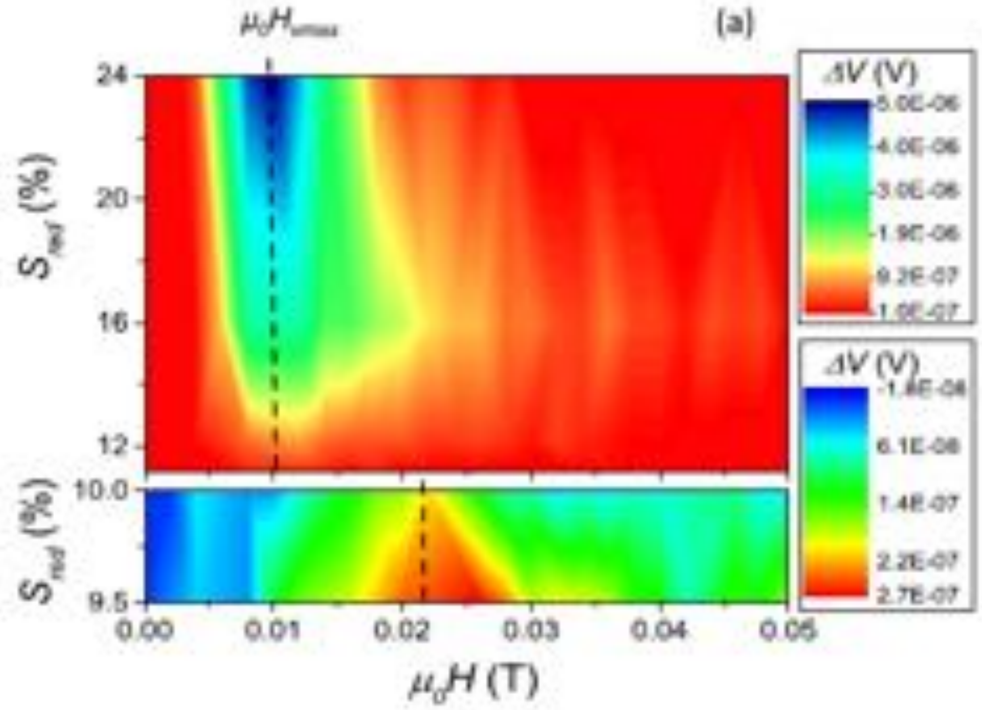


Palau et al. PRB 85 (2002), Rouco et al. NJP 17 (2015)

Guided Vortex Motion in HTS

YBCO film with asymmetric blind antidots fabricated by FIB or EBL





Rectified flux motion arising from the <u>collective effect of many interacting vortices</u> is obtained in a specially designed superconducting device.

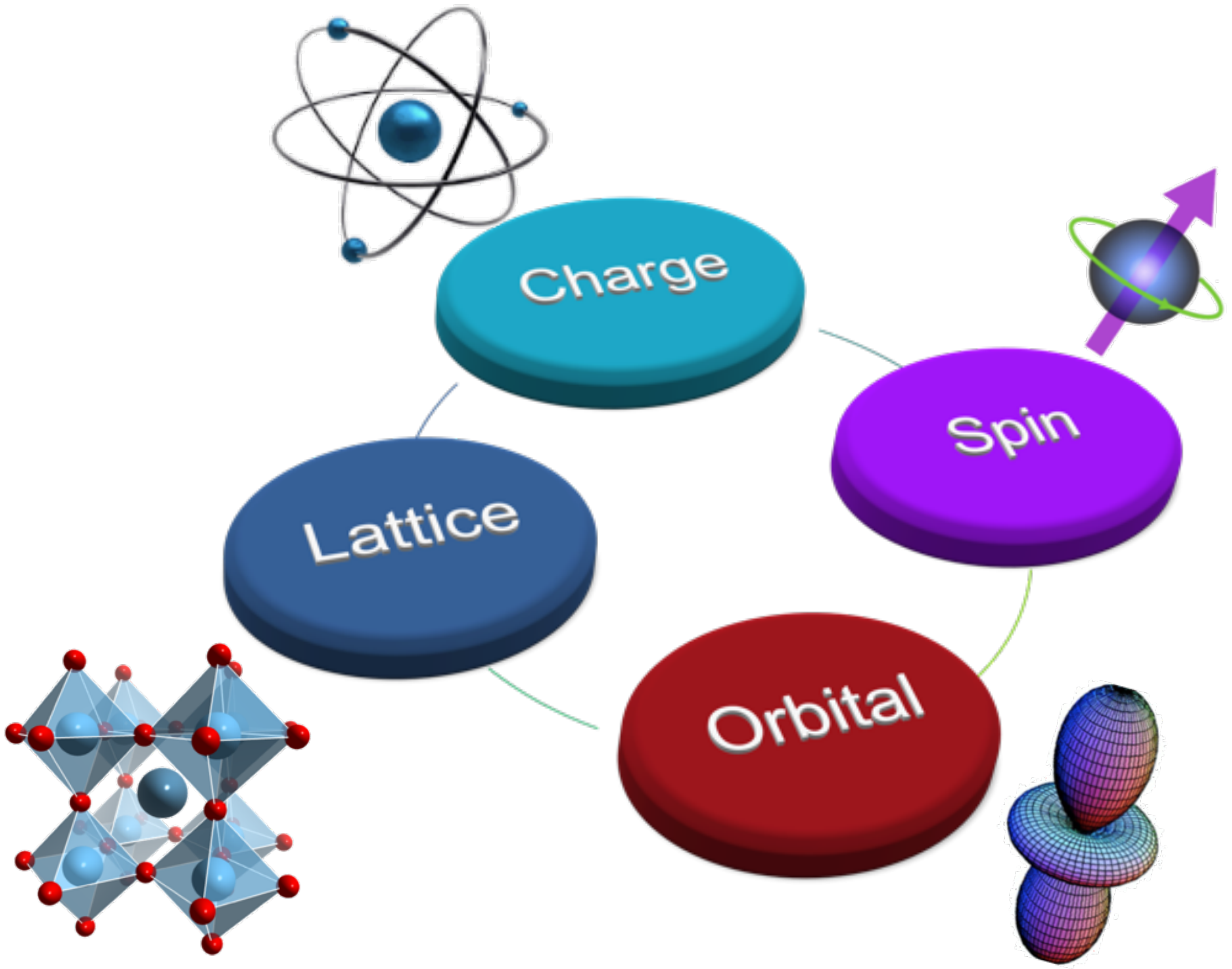
The amplitude and sign of the rectified vortex motion can be finely tuned with the pattern geometry.

Using a system based on a <u>high-temperature superconductor</u> → explore the physics of ratchet systems with many <u>interacting particles of different sizes</u>

Outline

- Outstanding Properties of Superconductors
- High Temperature Superconductors – Nano-Fabrication Challenges
- HTS for Next Generation Advanced Electronic Devices
  - Confined Geometries: Mesoscopic Effects / 3D vortex Dynamics
  - Engineered Pinning Landscapes: Fluxonic devices
  - Carrier Density Modulation: Mottronic Devices
  - Hybrid SC / FM Systems: Spintronic Devices

Strongly Correlated Oxides



Complex interactions between degrees of freedom

Broad spectrum of functional properties

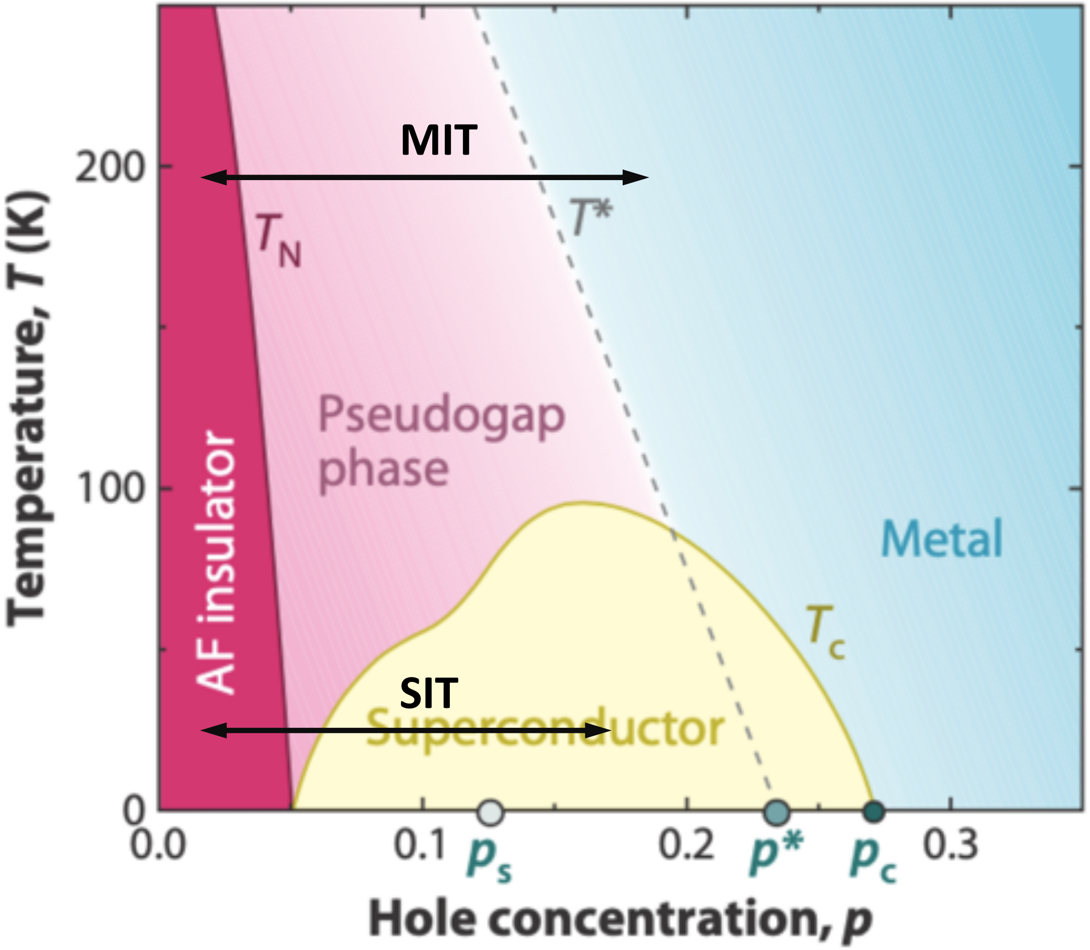
- High-temperature Superconductivity
- Colossal magnetoresistance
- Ferroelectricity
- Ferromagnetism

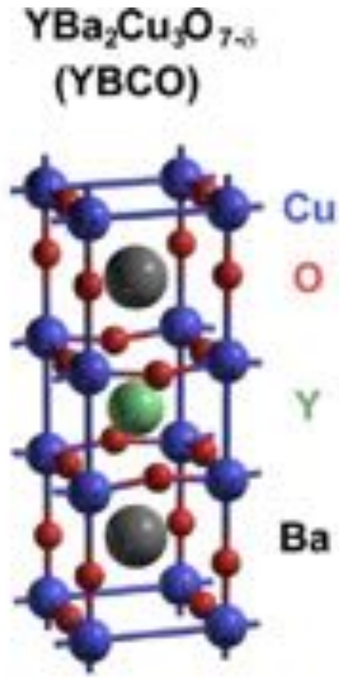
Transitions between competing phases may be induced by different external perturbations

- Light
- Temperature
- Pressure
- Strain
- Electric field

Phase Diagram of Strongly Correlated Cuprates

Non volatile Reversible Metal (Superconductor) - Insulator transitions through an optimal modulation of their carrier concentration



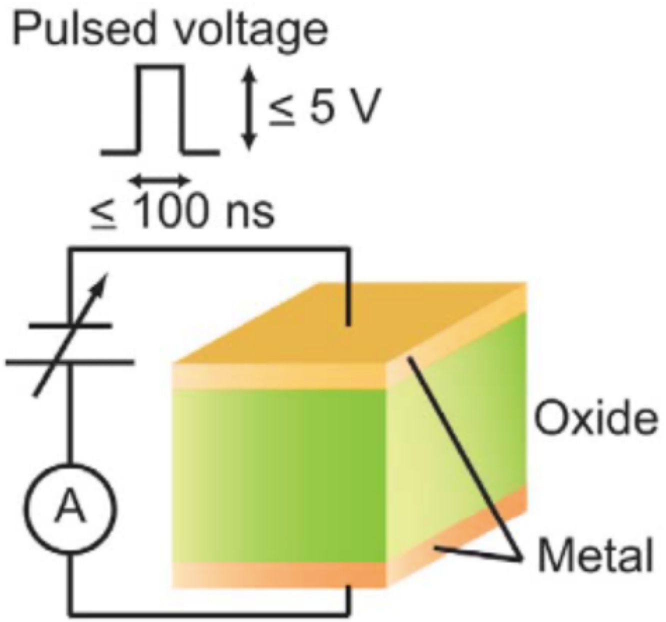


Oxyen doping is a crucial parameter that governs the electronic properties of these systems

Taillefer , Annu. Rev. Condens. Matter Phys. 1, 51–70 (2010)

Resistive Switching in Strongly Correlated Oxides

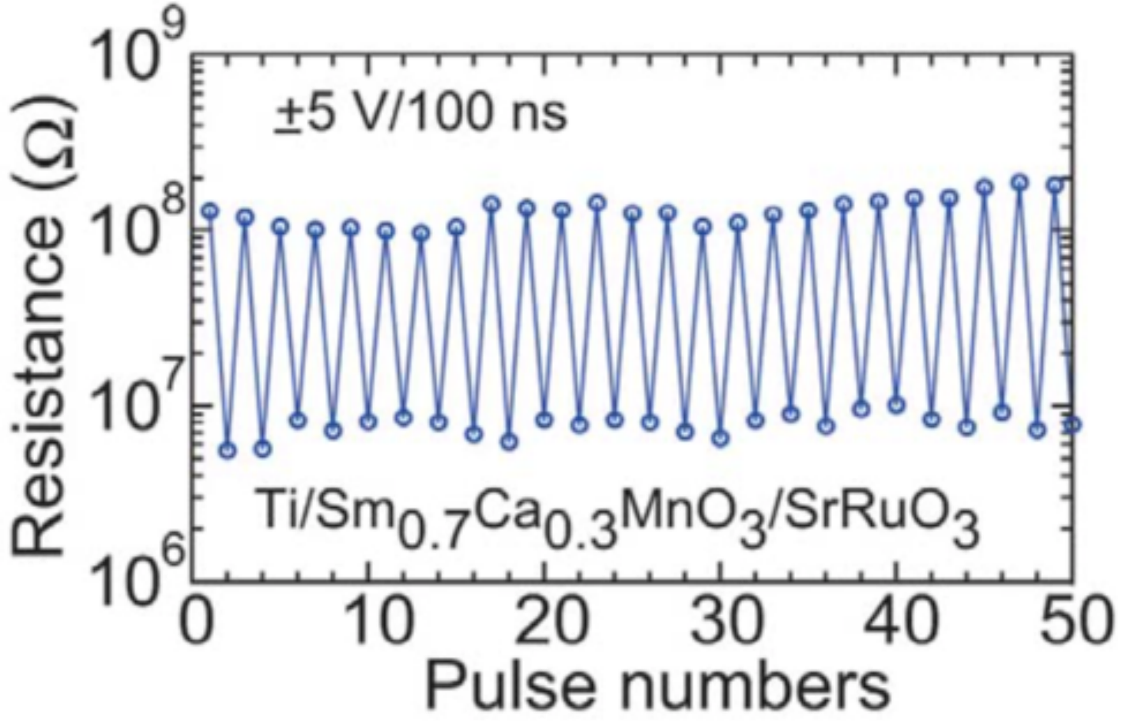
The resistance of a device is controlled by an electric field



capacitor-like structure

insulating or semiconducting transition metal oxides

TiO_2, HfO_2, WO_3, Nb_2O_5, Va_2O_5, $Pr_{0.7}Ca_{0.3}MnO_3$, $SrTiO_3$, $BaTiO_3$, ….



large change in resistance (>1000%) on applying pulsed voltages

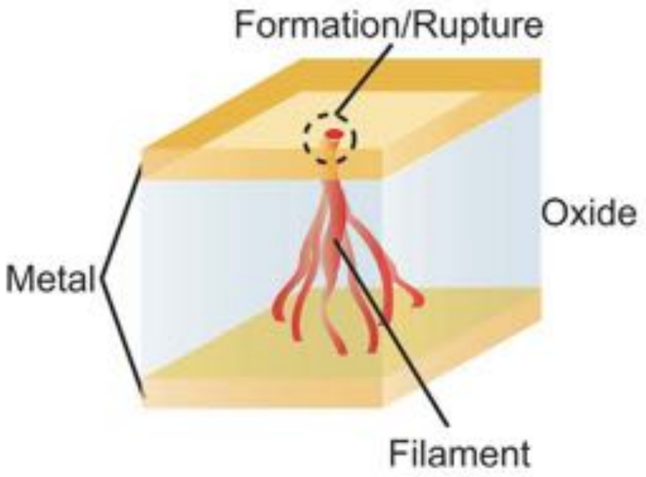
Sawa, Materials Today, 11, 6 (2008)

Resistive Switching in Strongly Correlated Oxides

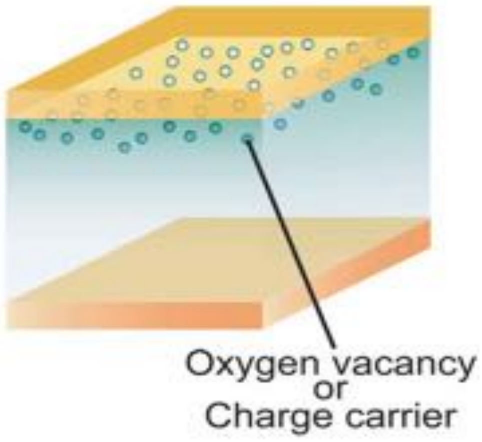
Devices based on Insulator to-Metal transitions

Mechanism behind the switching phenomena → **local migration of oxygen vacancies**

Filamentary-type



Interface-type



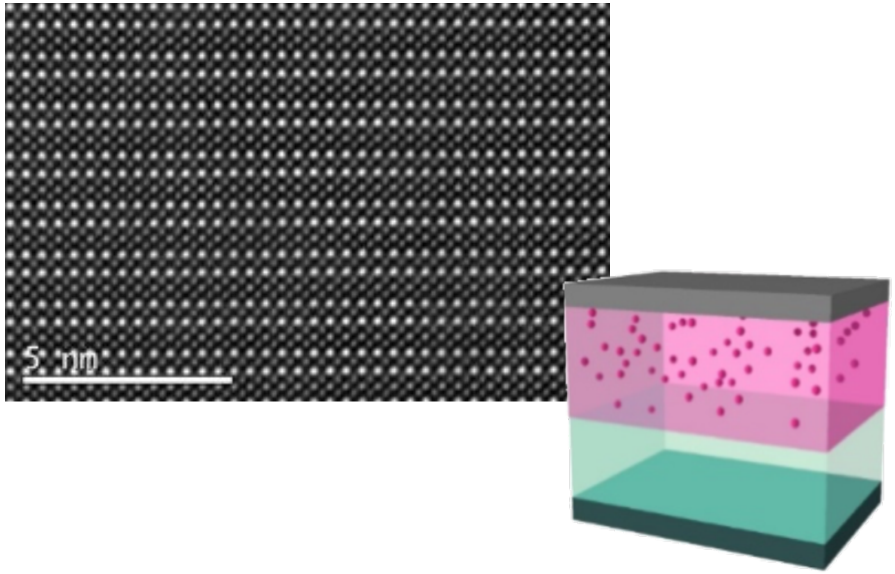
Promising features for memory applications and Neuromorphic computing

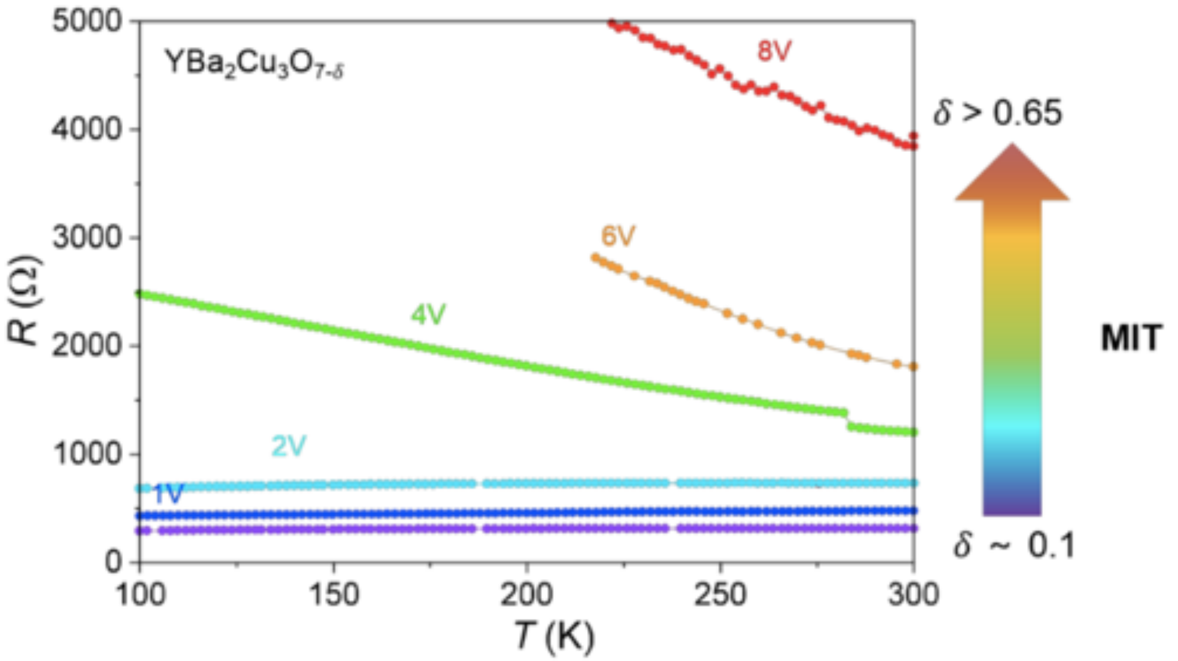
- Highly scalable simple structure
- Large change in resistance (R_{off}/R_{on} exceeding 10^3) with moderate pulsed voltages
- Large endurance (more than 65000 RS cycles), retention time (>10 y) and writing speed (< 100ns)
- Multi level states by applying the appropriate voltage pulse

Sawa, Materials Today, 11, 6 (2008), Janod et al. Adv. Funct. Mater. 2015, 25, 2687

Feld Induced Metal (SC) - Insulating Transitions in Cuprates

Robust volume-phase transitions



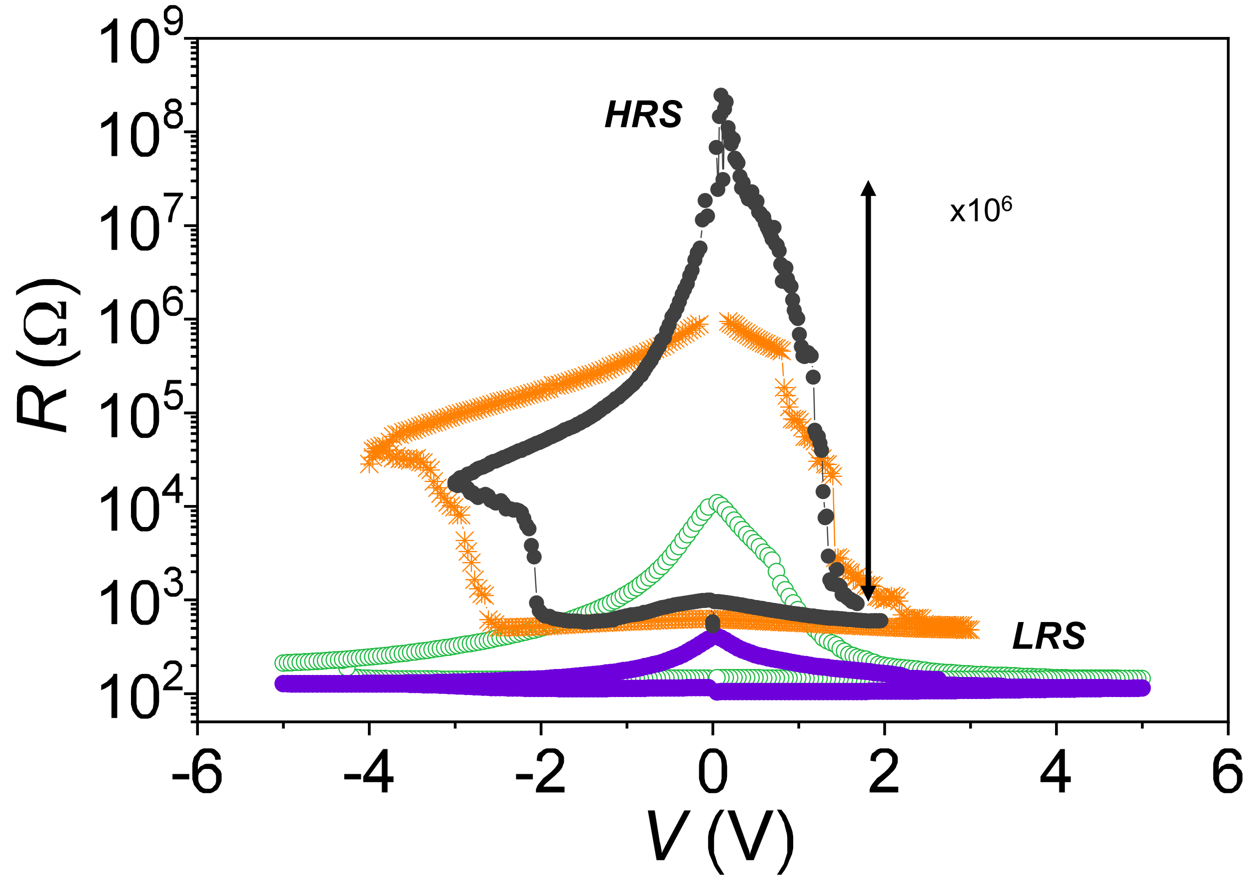


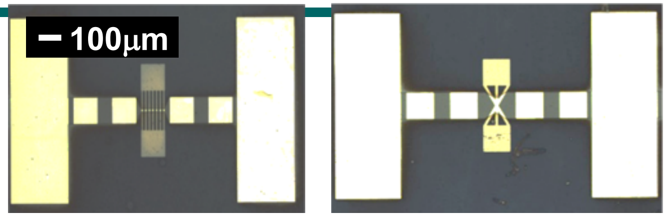
Field-induced reversible robust volume Metallic to Insulator Transition (MIT) through oxygen doping:

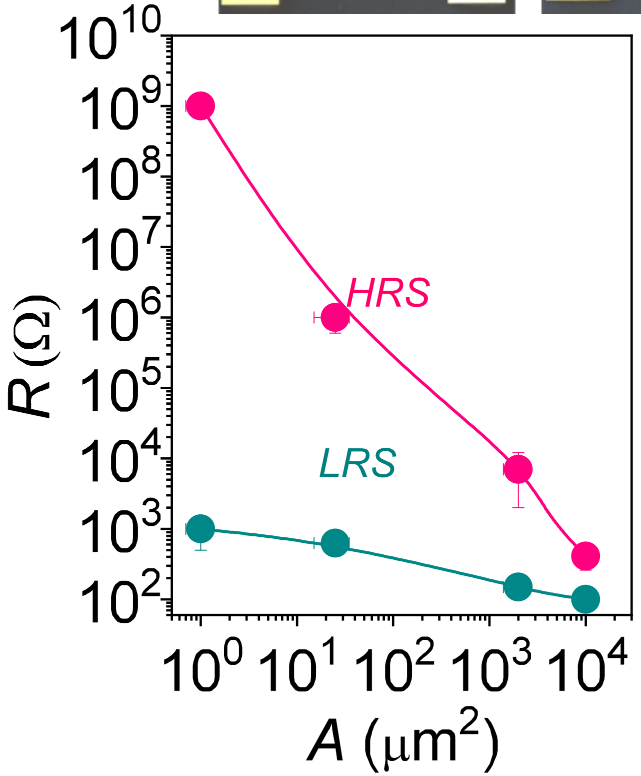
- Homogeneous and robust switching performance → Reduce device-to-device and cycle-to-cycle variability
- Highly spatial control of the switching event → Unprecedent flexibility to design transistor-like devices
- Devices operating at RT or below T_c

Gonzalez-Rosillo et al. Small 2001307 (2020), Gonzalez-Rosillo et al. Adv. Electron. Mater. 1800629 (2019), Palau et al. ACS Mat. & Interf. 10, 30522 (2018), Gonzalez-Rosillo et al. J Electroceram 39,185 (2017)

Large Switching Ratios using micro- / nano- metric contacts

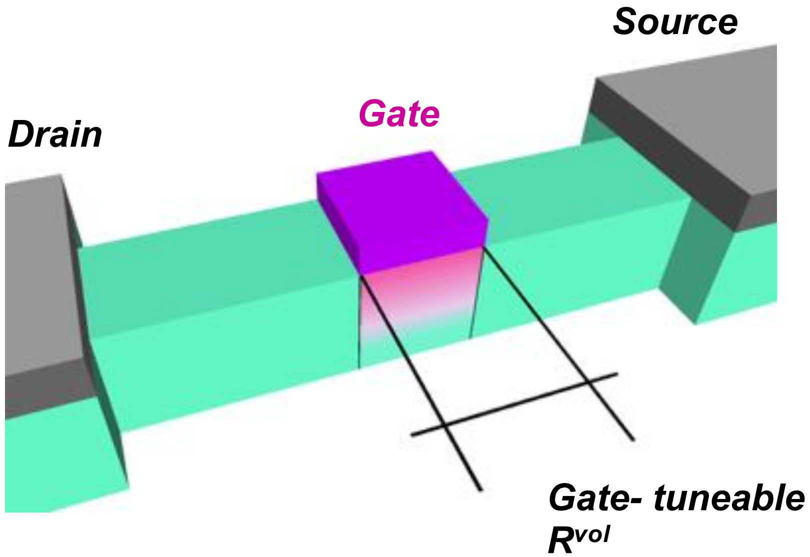






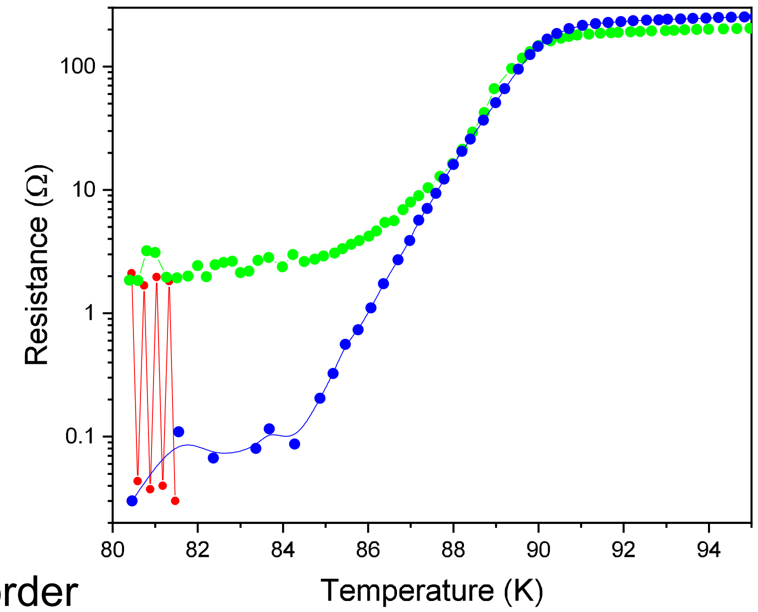
- **Area dependent resistance values** consistent with a switching effect homogeneously distributed underneath the electrode
- Very large switching ratios obtained with moderate low V pulses by using micrometric contacts

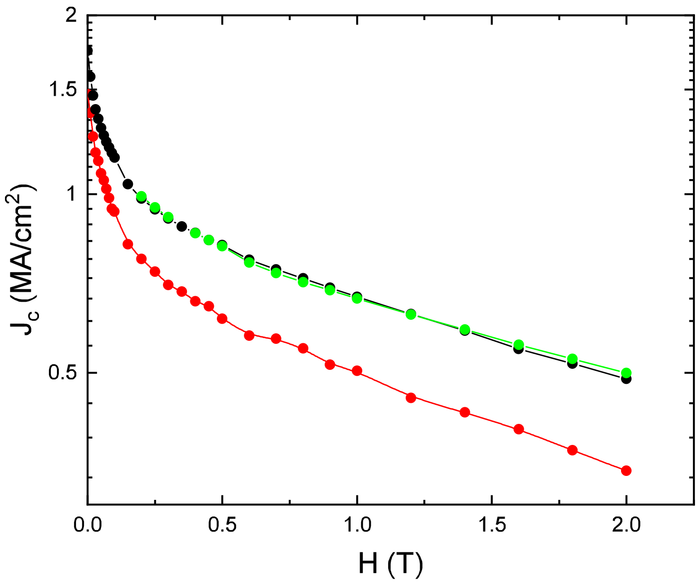
Transistor-like devices with SC Drain-Source Channel



Reversible modulation of the superconducting order parameter in localized volumes (10 - 100 nm)

Transistor like devices with a free-resistance drain-source SC channel

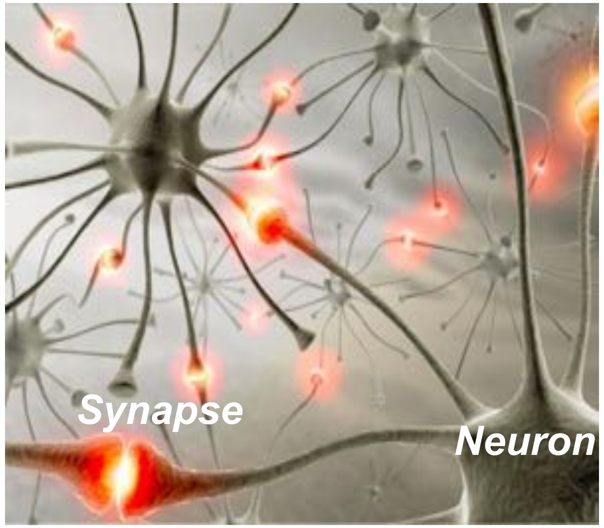


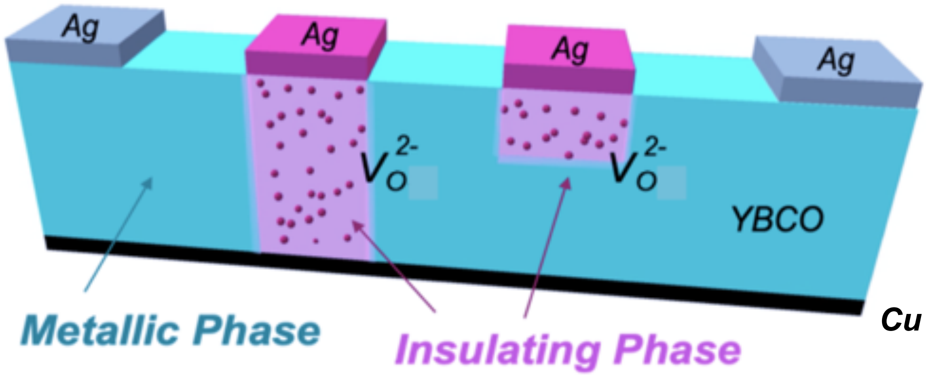


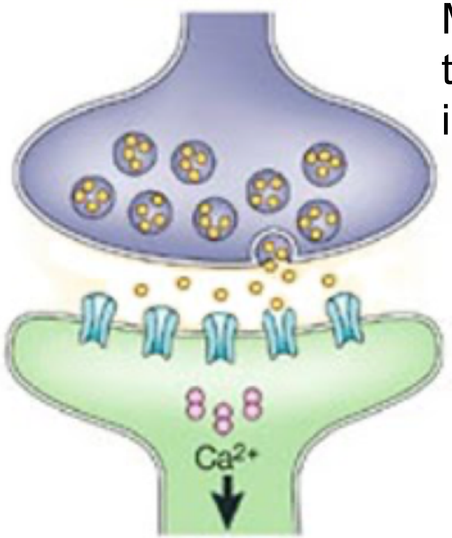
- **Homogenously and reversibly tune a superconducting channel ON and OFF** by means of an electric field as the external control parameter.

- Reversible artificial pinning centres

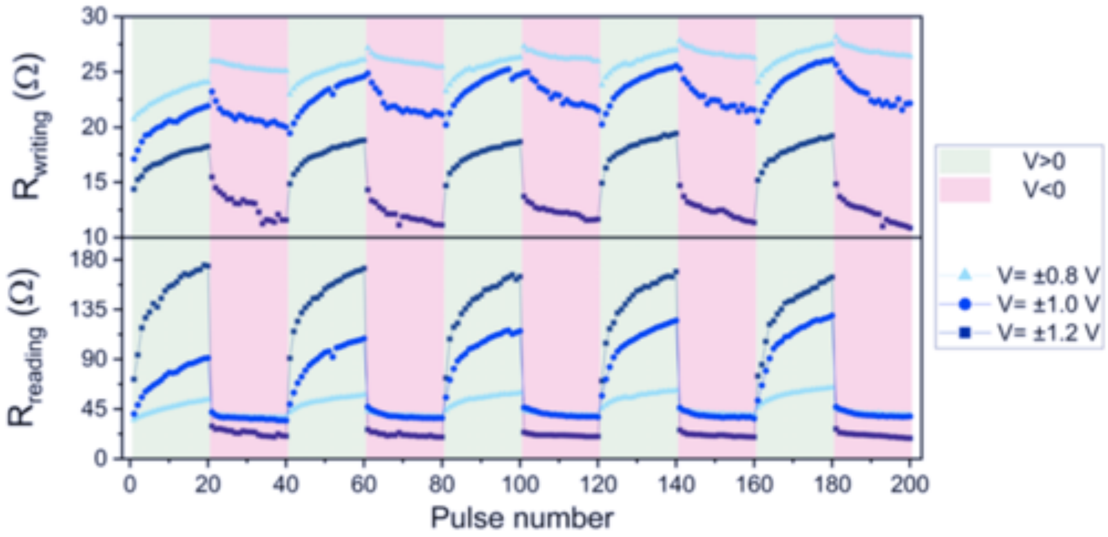
Neuromorphic Functionalities at Room Temperature







Movement of oxygen ions can mimic the flux of sodium and potassium ions in neurons.



Transistor-like synaptic devices, being able to realize <u>signal transmission and synapse learning functions simultaneously</u>, offer a promising solution for efficient synapse simulation

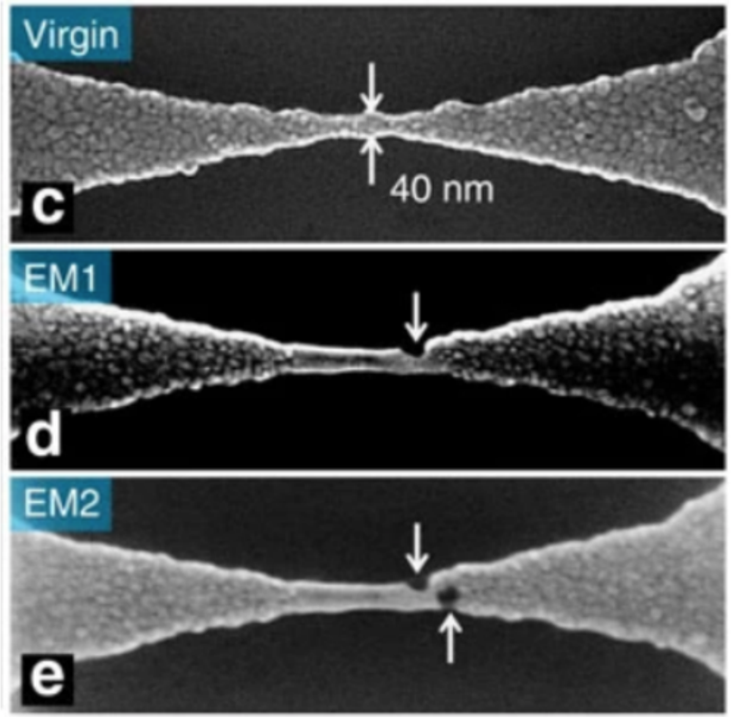
Fernández-Rodríguez et al. Materials, 13, 281 (2020)

Electromigration effects to narrow down SC constrictions

Current-Induced Atom Migration → capability to move atoms one by one when properly controlled

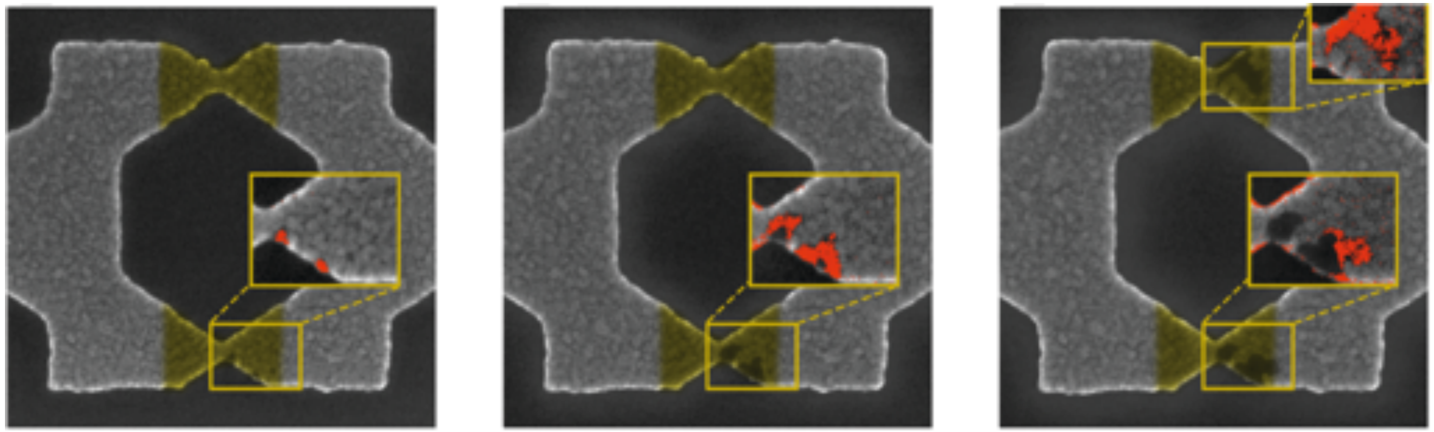
Tune the cross section of monoatomic compounds with ultimate resolution

Targeted atom displacement reducing the size of the constriction



Al nanowires

Nano-SQUIDs with controllable weak links

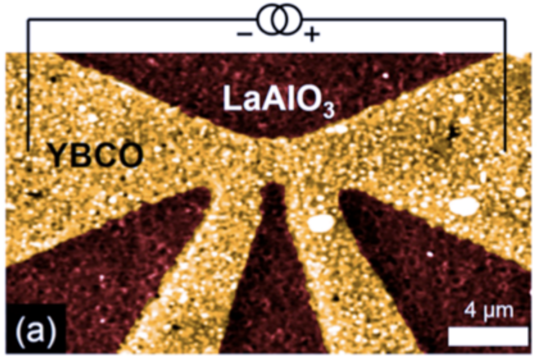


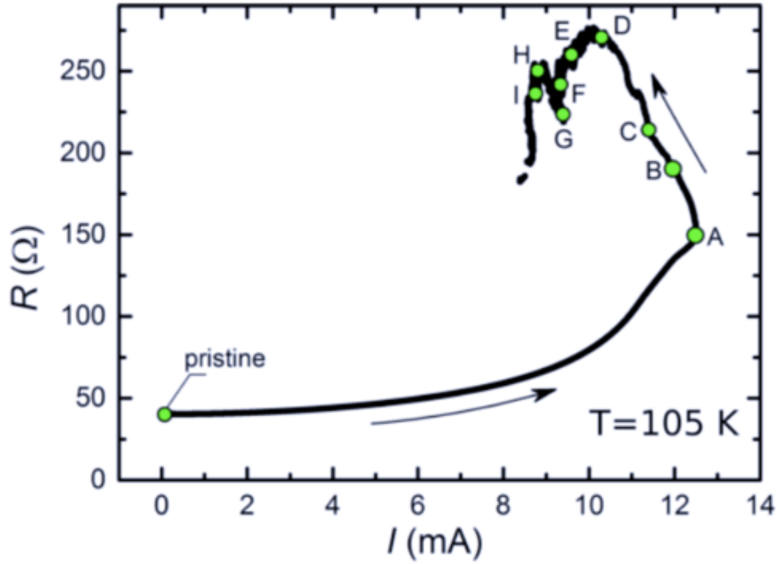
Shrinking of the constriction due to subsequent electromigration processes

S. Collienne et al. Phys. Rev. Appl. 15, 034016 (2021); Keijers et al. Nanoscale, 10, 21475 (2018); X.D.A. Baumans et al. Nat. Commun, 7, 105660 (2016)

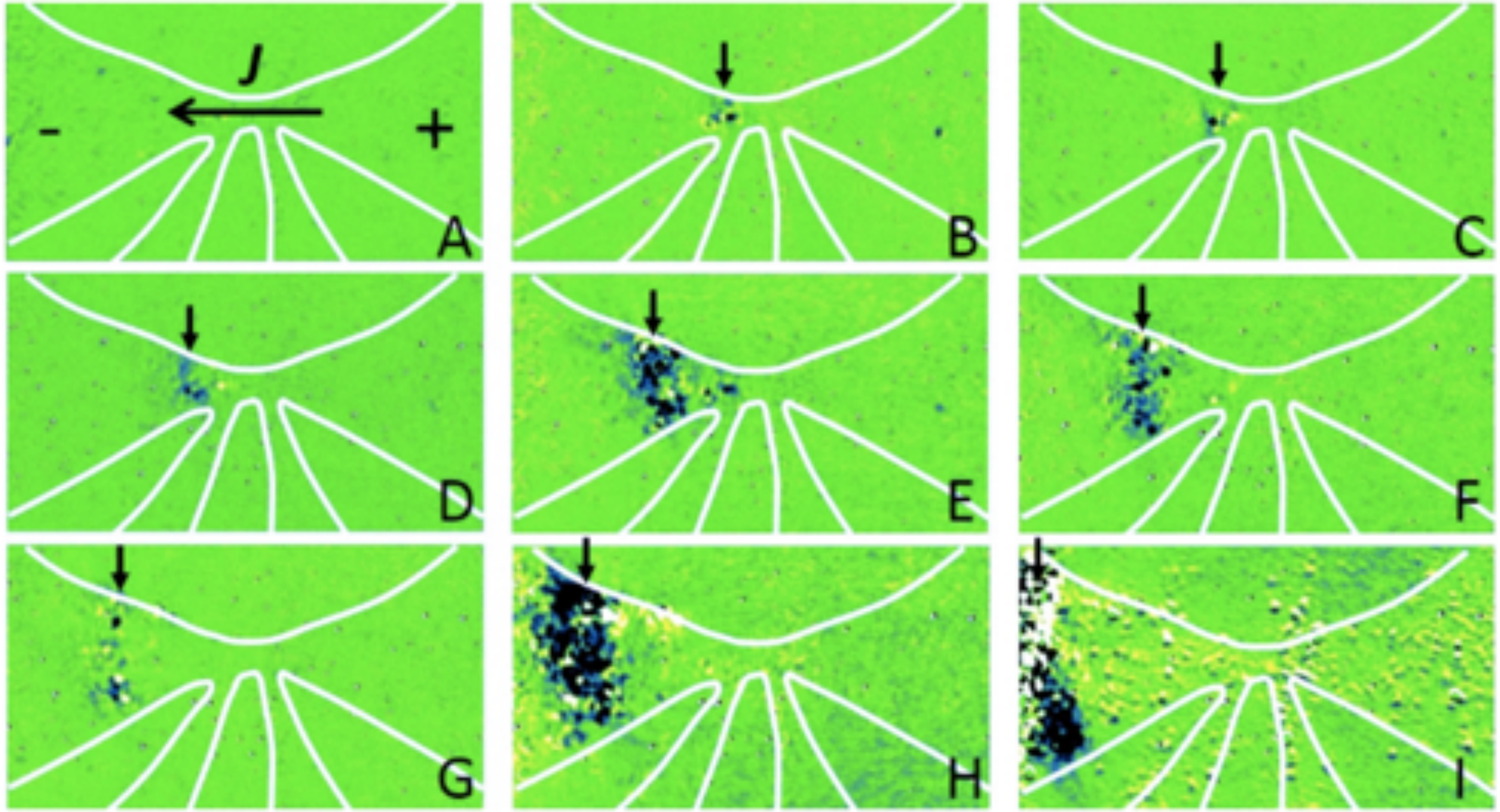
Electromigration in YBCO

Change on the stoichiometry with the same atomic precision





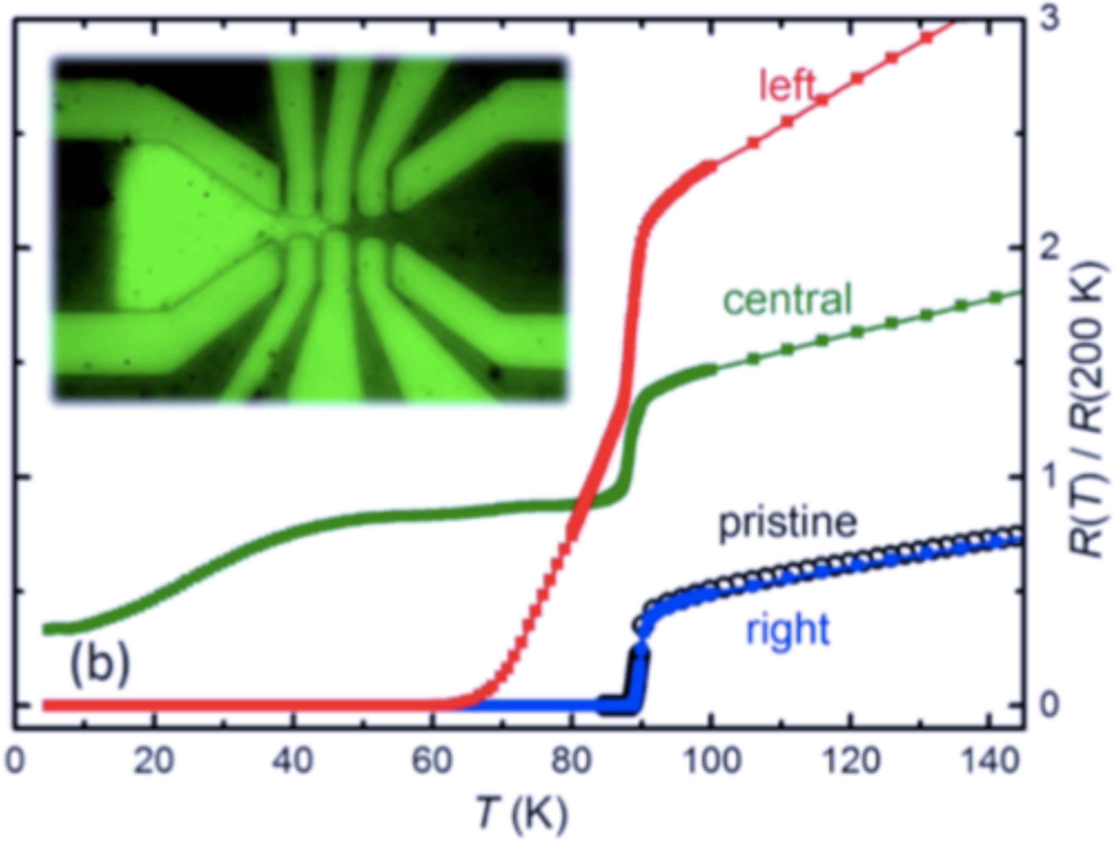
Oxygen diffusion induced current-stimulated oxygen migration

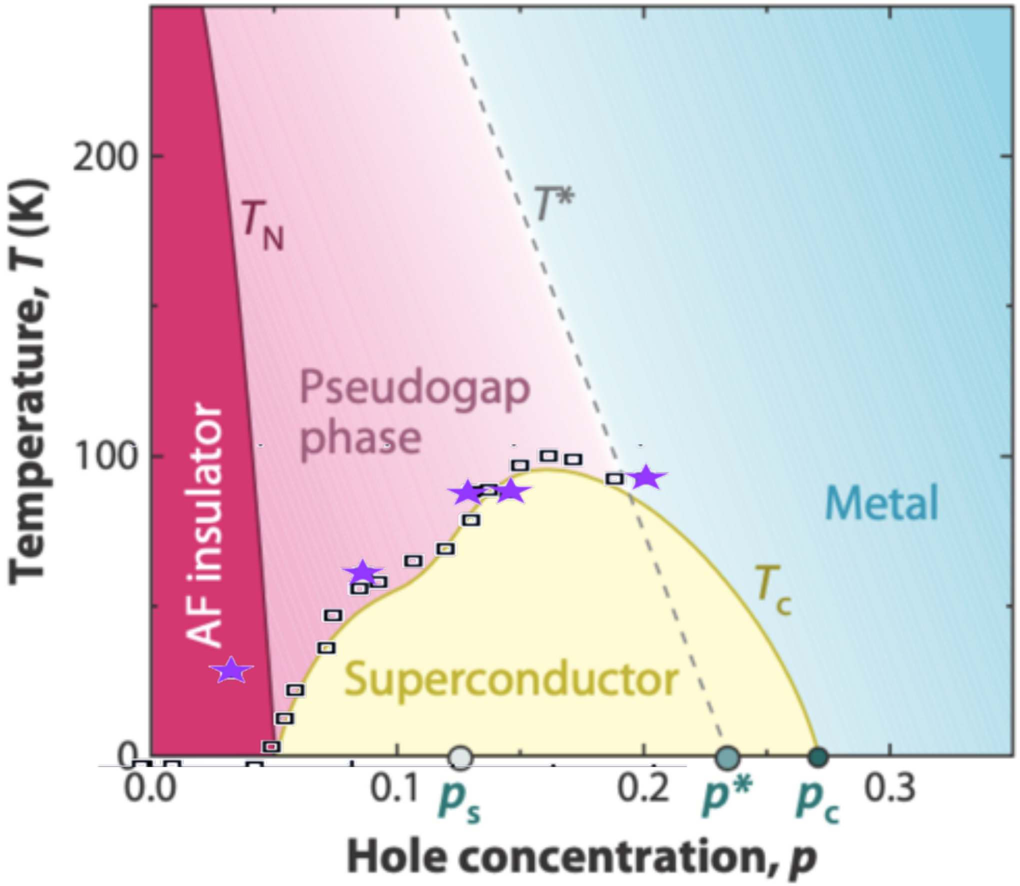


Oxygen vacancy displacement towards the cathode (−) visible by optical microscopy

Marinkovic et al. ACS Nano 14, 9, 11765–11774 (2020), Palau et al. ACS Mat. & Interf. 10, 30522−30531 (2018)

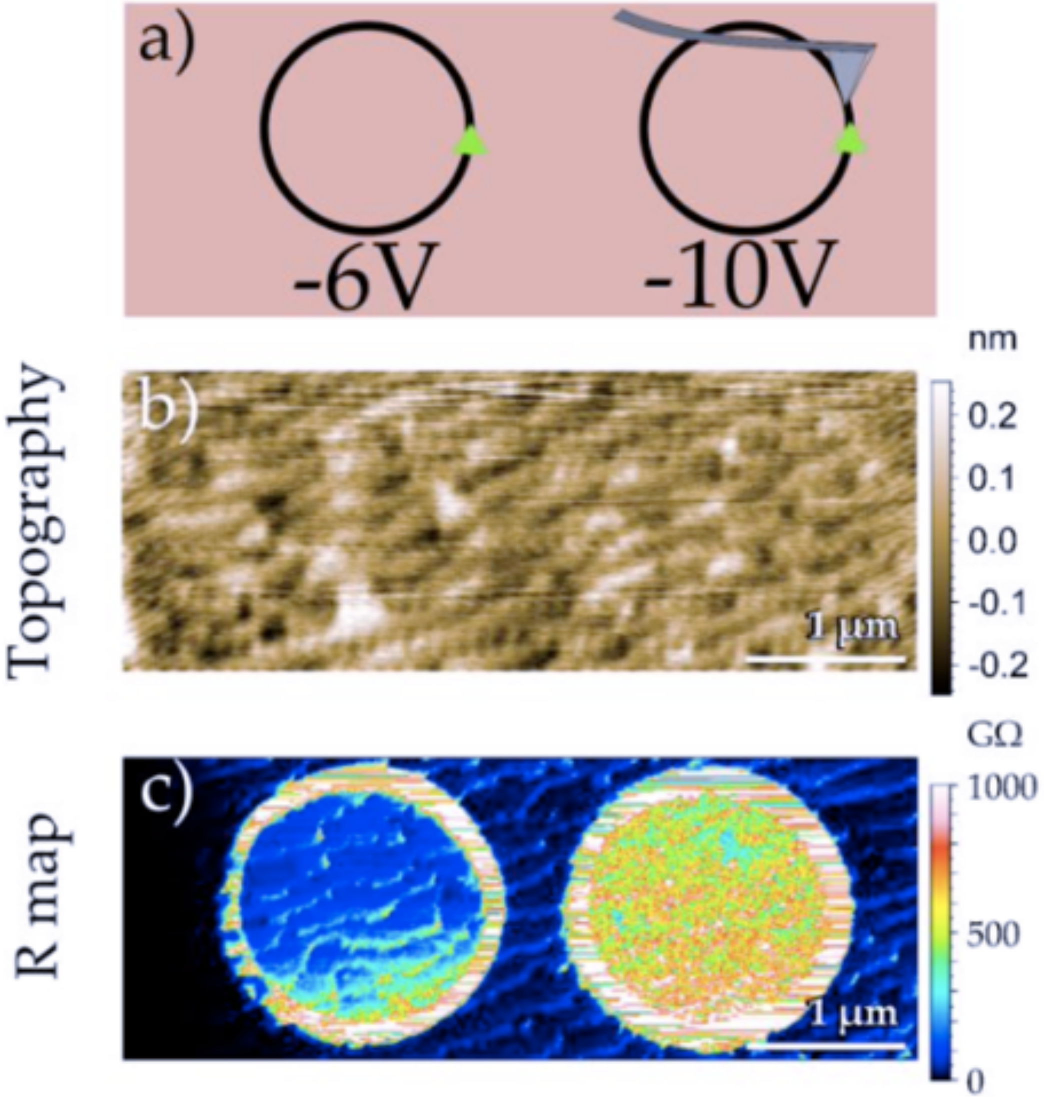
Fine Tuning of Oxygen Doping by Electromigration





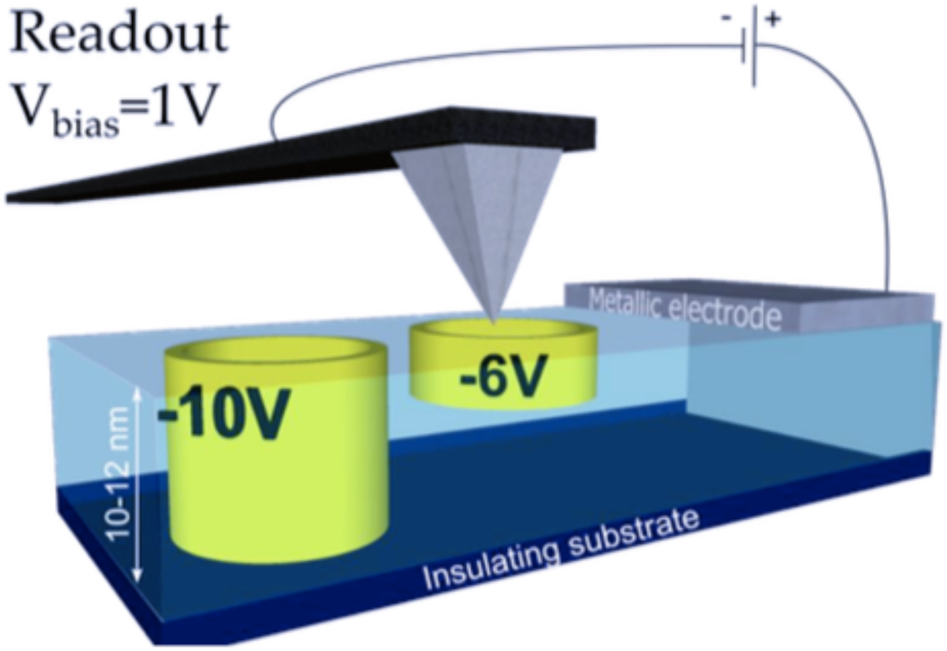
- Area with oxygen vacancies clearly visible as a bright region in microscope images
- Clear modulation of T_c at different regions of the YBCO constriction
- Appealing approach to study the electronic phases in cuprates

current-AFM: Tuning the oxygen doping at nanoscale

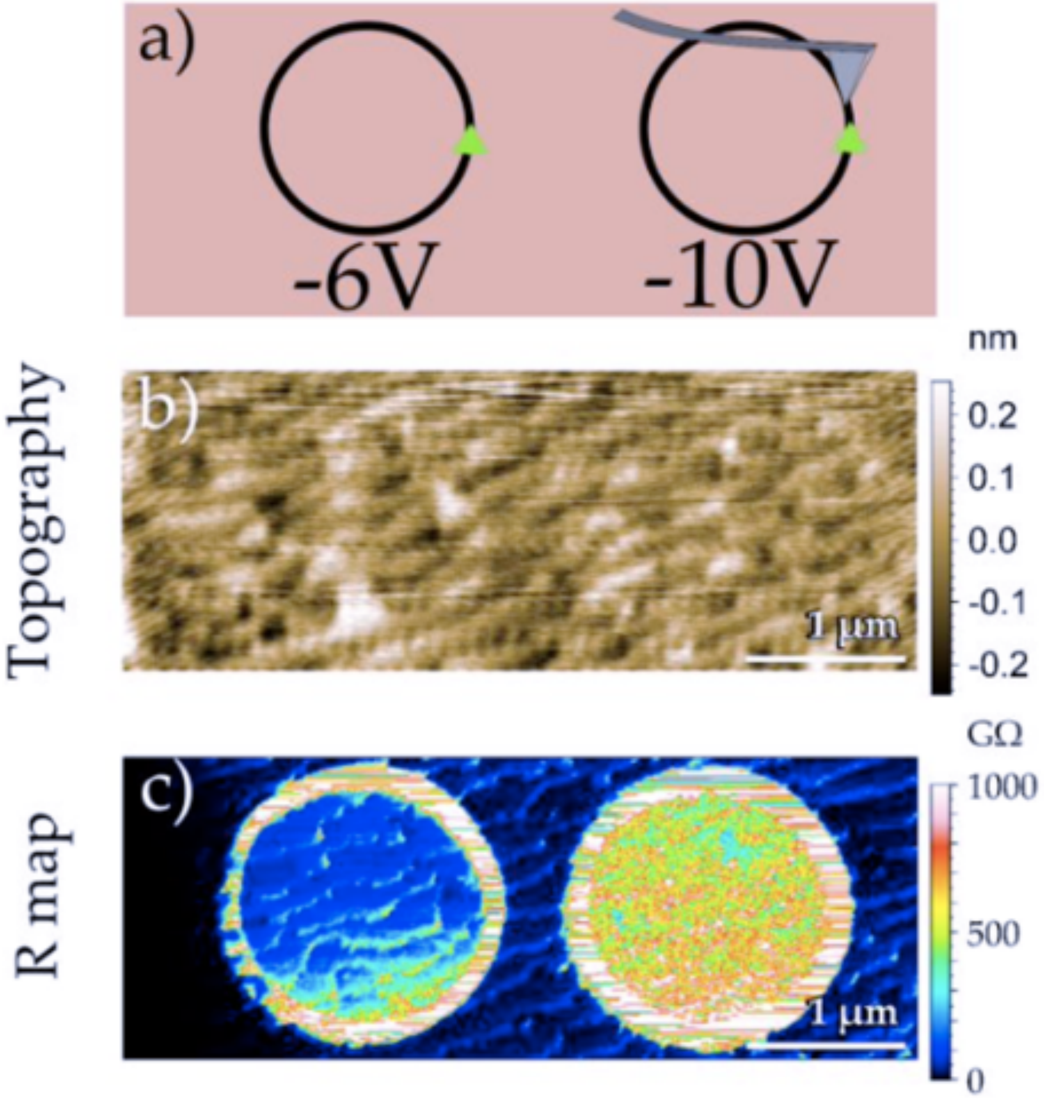


Conducting AFM → control over the metal-insulator transition at nanometric scales

Nanoscale insulating regions can be created and erased using voltages applied by a conducting AFM probe



current-AFM: Tuning the oxygen doping at nanoscale



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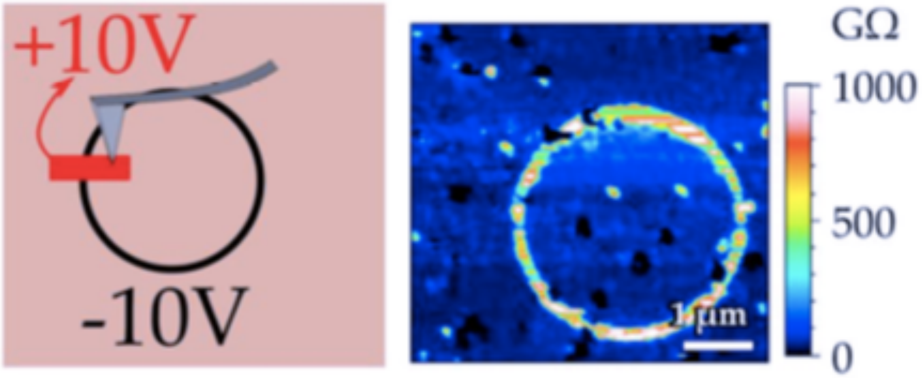


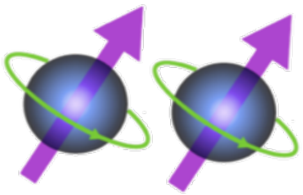
Outline

- Outstanding Properties of Superconductors
- High Temperature Superconductors – Nano-Fabrication Challenges
- HTS for Next Generation Advanced Electronic Devices
    - Confined Geometries: Mesoscopic Effects / 3D vortex Dynamics
    - Engineered Pinning Landscapes: Fluxonic devices
    - Carrier Density Modulation: Mottronic Devices
    - Hybrid SC / FM Systems: Spintronic Devices

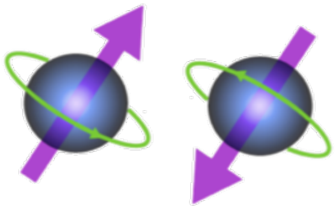
Hybrid Superconducting – Ferromagnetic Systems

The interplay between these two **antagonistic long-range order phenomena**, gives rise to **rich physical properties and unusual behaviours**

FM

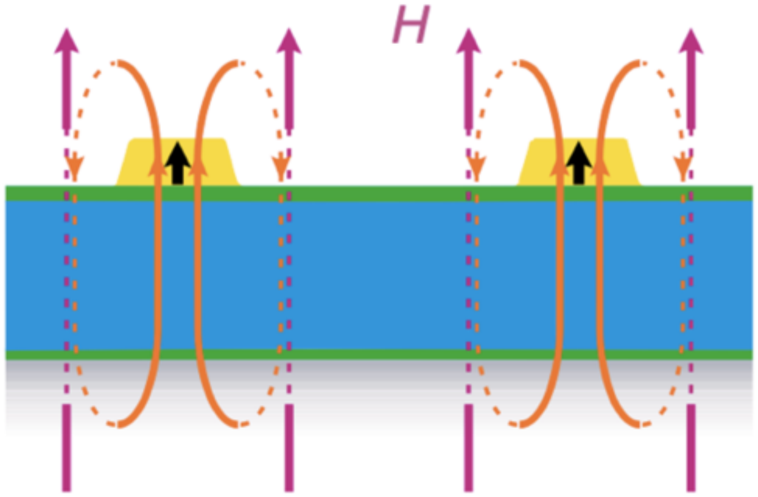


SC

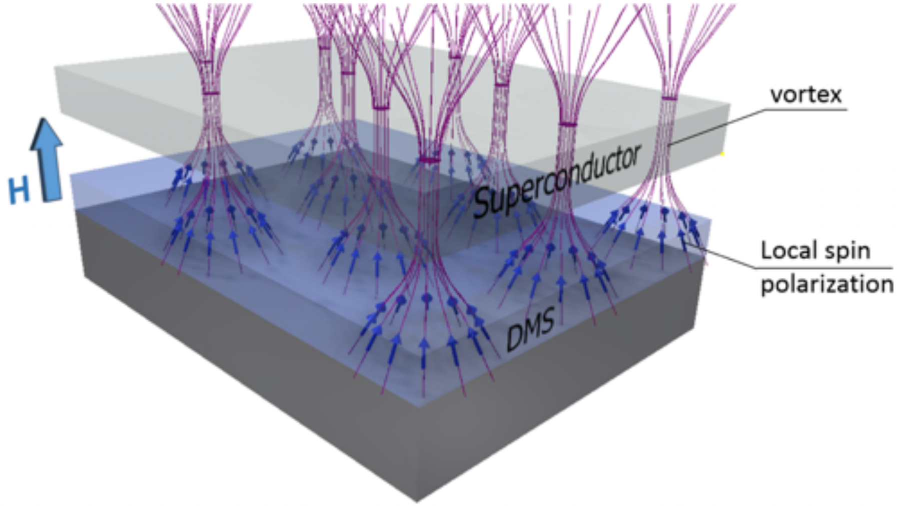


- **proximity effects**
- **stray-magnetic field manipulation**
- **Magnetic pinning**
- **vortex guidance**
- **spin-injection phenomena**

Magnetic stray fields may change the superconducting state



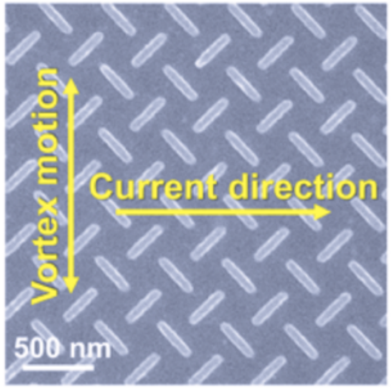
Superconducting Vortices may act as tiny Magnetic Tweezers to modify magnetic spins

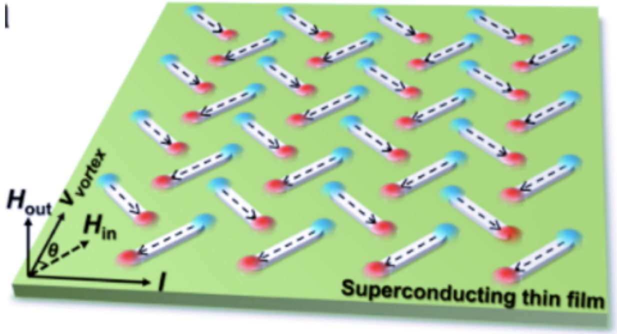


Shaw et al. Metals 2019, 9, 1022, Velez et al. JMMM. 320, 2547 (2008)

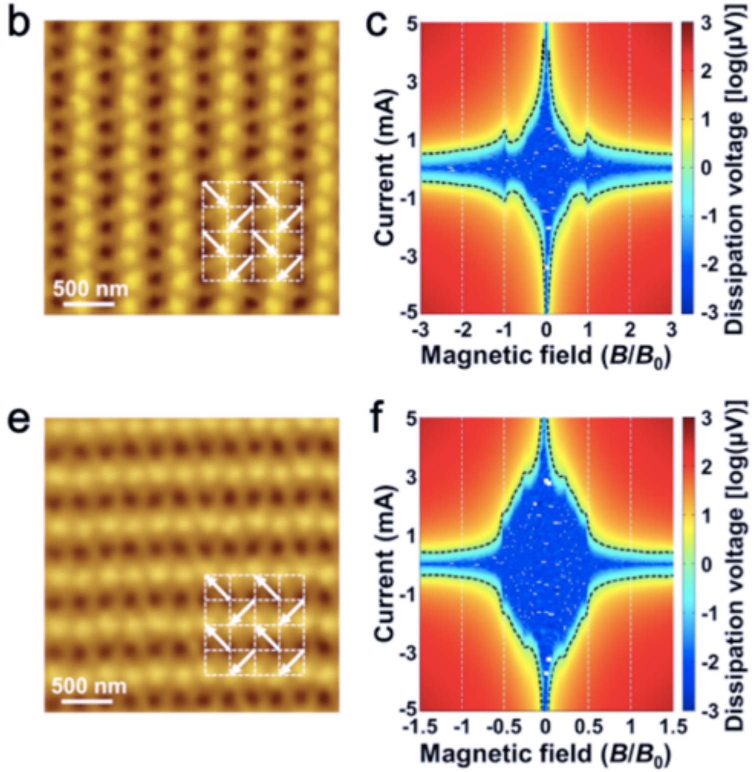
Artificial Ice Systems: Switchable pinning potentials

<u>Spin ice</u> is a magnet with frustrated interactions from which we observe emergent magnetic textures tuneable with the applied magnetic field





MoGe / Permalloy



→ pairs of spins can minimize their energy by adopting a head-to-tail configuration **<u>monopoles</u>**

The tuneable magnetic charges in the artificial-spin-ice strongly interact with the flux quanta in the superconductor

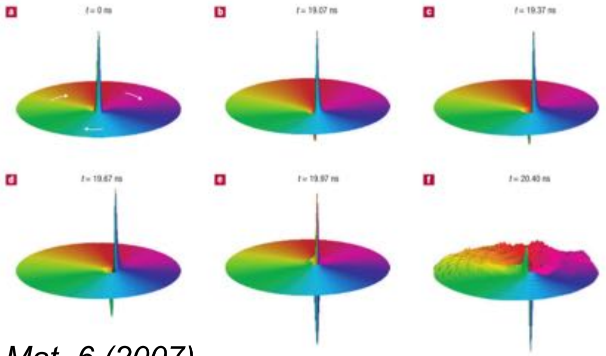
→ The different states have measurable effects on the superconducting critical current profile, which can be reconfigured by precise selection of the spin-ice magnetic state through the application of an external magnetic field

Lyu et al. Nano Lett. 2020, 20, 8933−8939, Wang et al. Nat. Nanotech. 13, 560 (2018)

Spin Textures in Magnetic Materials

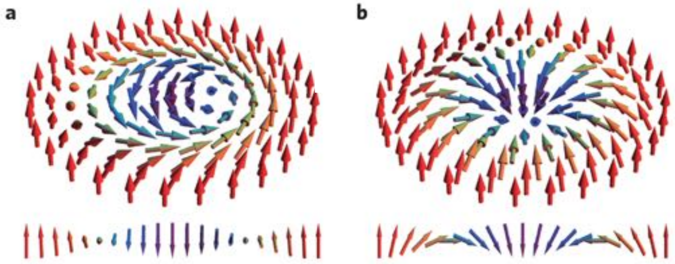
The emergence of **non-trivial magnetic states** such as **vortices, skyrmions, and monopoles** has extended the boundaries of magnetism because their **extraordinary stability**.

Magnetization with a moving vortex structure

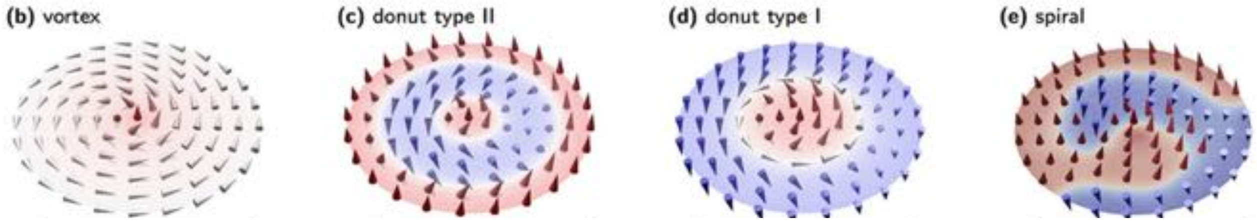


Yamada et al. Nat. Mat. 6 (2007)

Bloch- and Néel-type skyrmions



Kézsmárki et al. Nat. Mat. 14 (2015)



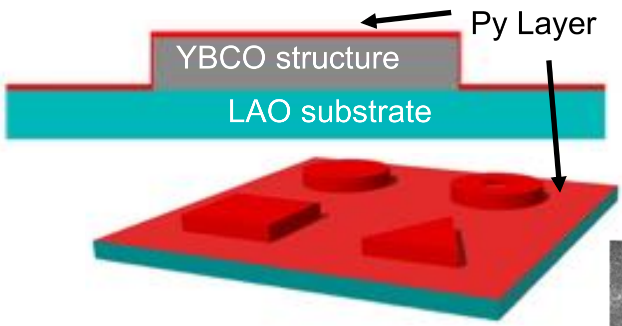
Robert Streubel et al. Scient. Rep. 5 (2015)

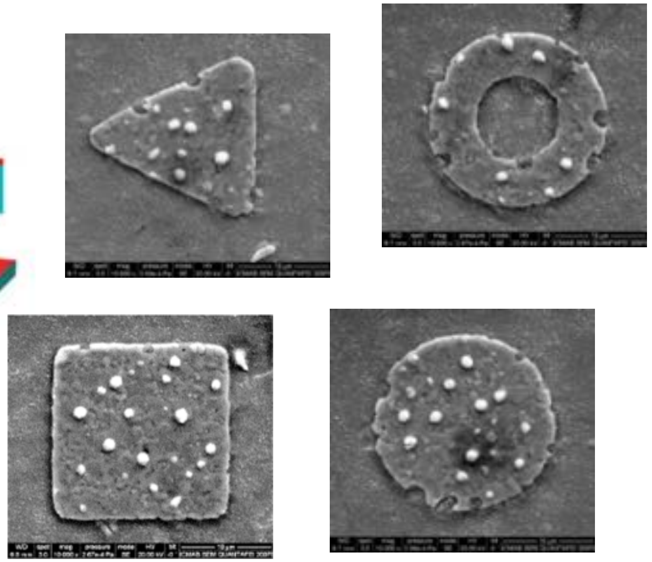
Control of **complex spin states** and **magnetic domain walls** and is a major research theme in spintronics as it can offer a very effective way to **transmit and store information in a non-volatile way**.

The **main bottleneck** limiting the use of magnetic states as information bits remains on the **valance between thermal stability and operation power**.

Hybrid System: FM Layer / High-Temperature SC Dots

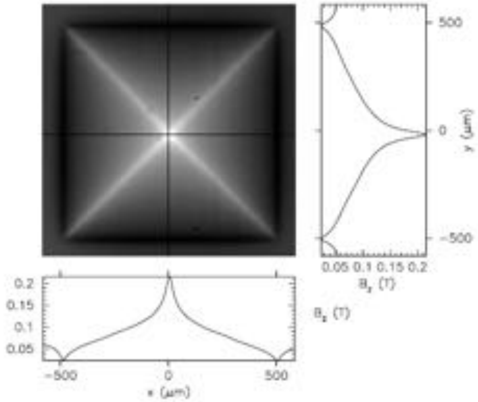
YBCO-CSD film patterned with SC dots (20µm x 20 µm) of different shapes + 4 nm Soft ferromagnetic layer ($Fe_{20}Ni_{80}$)



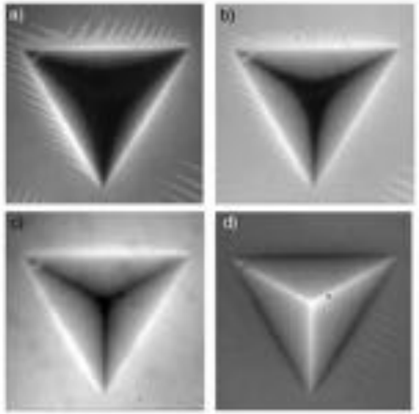


→ Flux penetration / distribution completely depends on the **sample geometry**

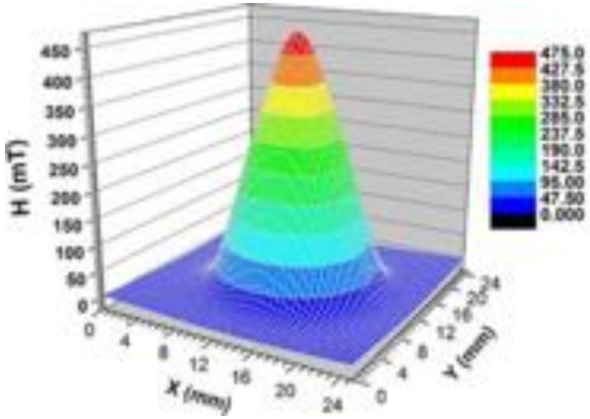
Squared SC thin film



Triangular SC thin film



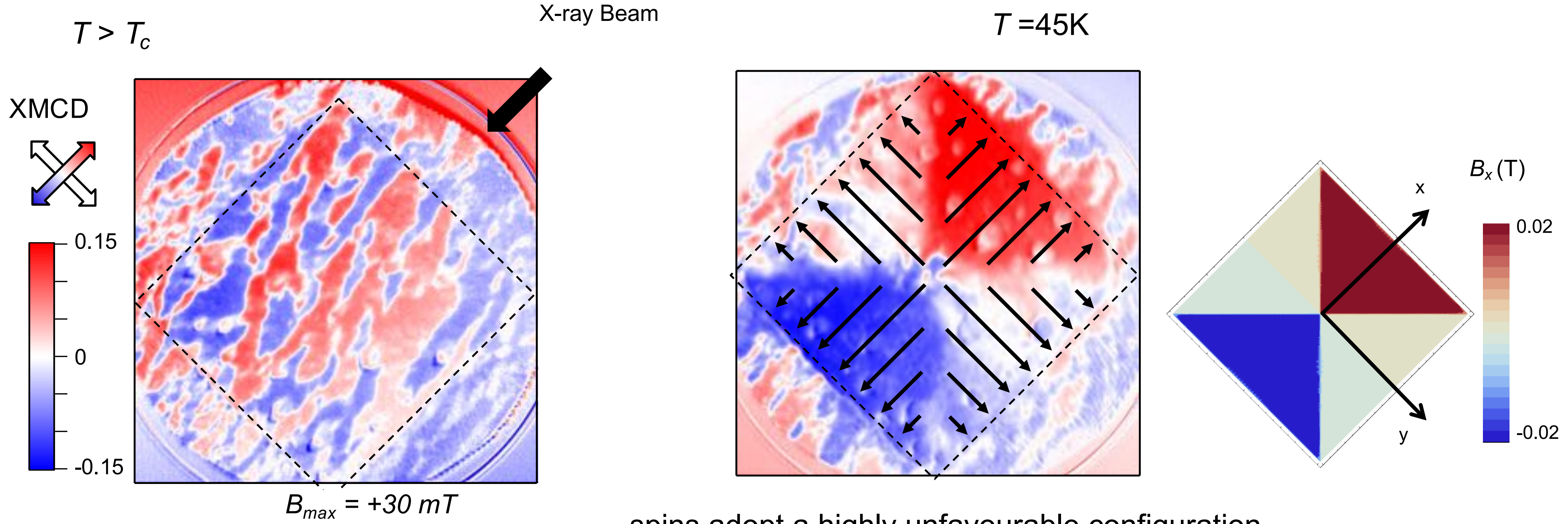
Disk-shape SC thin film



Jooss et al RPP ***65*** *(2002)*

FM / SC Hybrid Systems

In-plane magnetic domain configurations of the Py Layer (X-PEEM / XMCD)



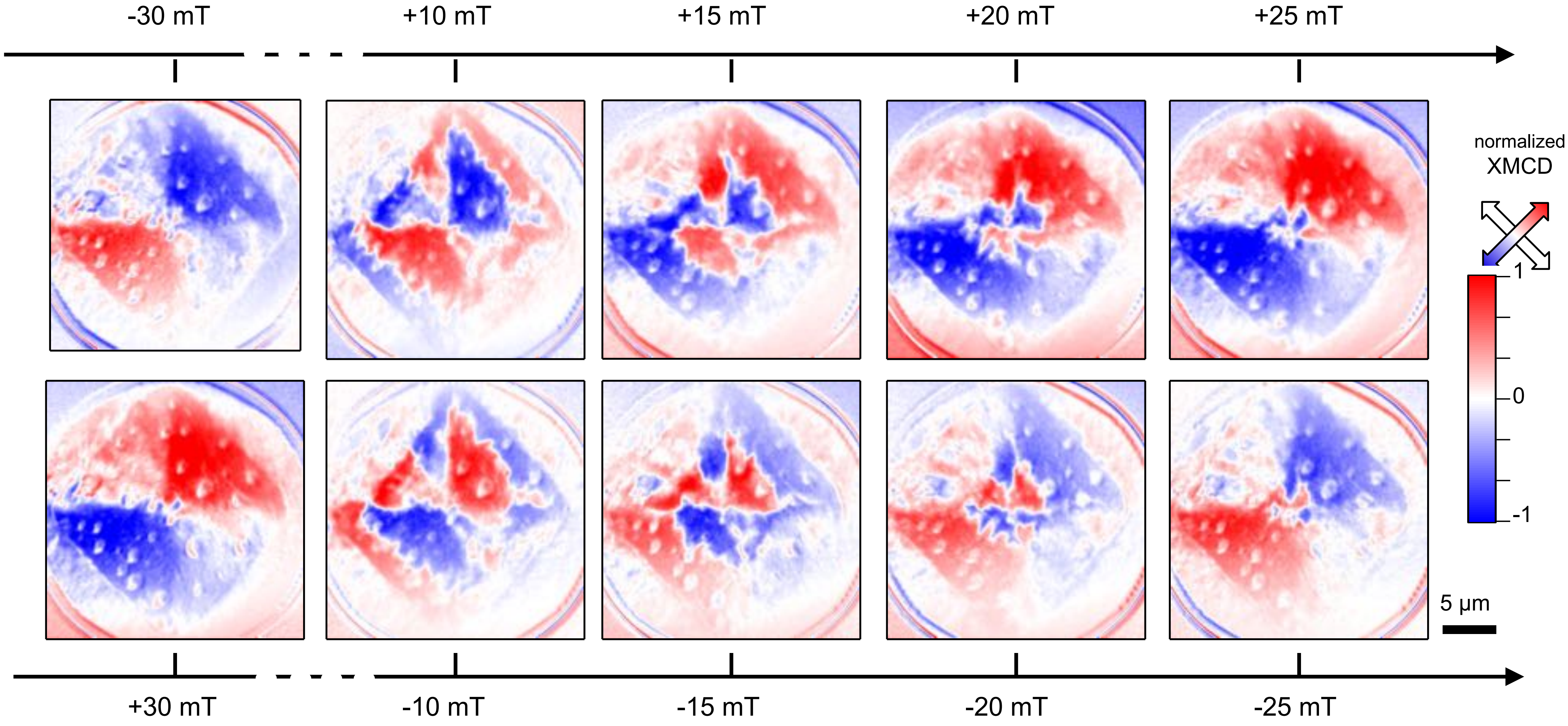
spins adopt a highly unfavourable configuration

Singular Py spin configuration in which **four tail-to-tail domain walls** emerging from the diagonals are formed and stabilized at zero applied field.

Palau et al. Advanced Science (2016) 1600207

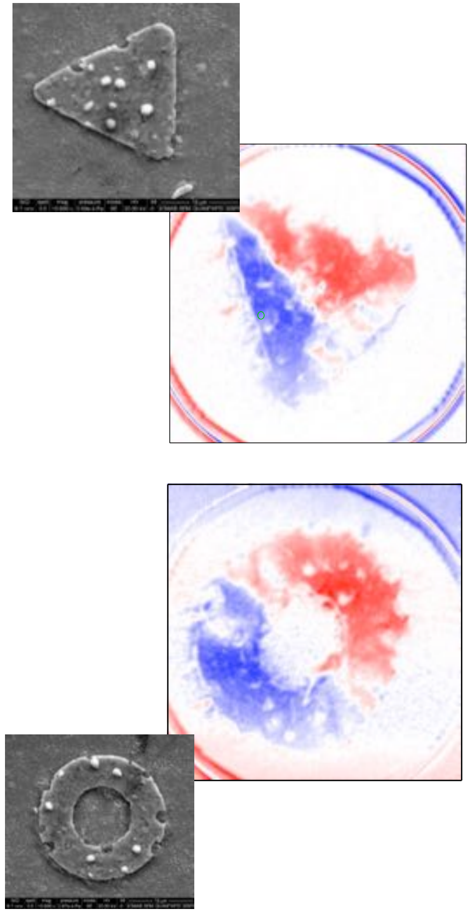
Imprinted Magnetic States Stable at Zero Field

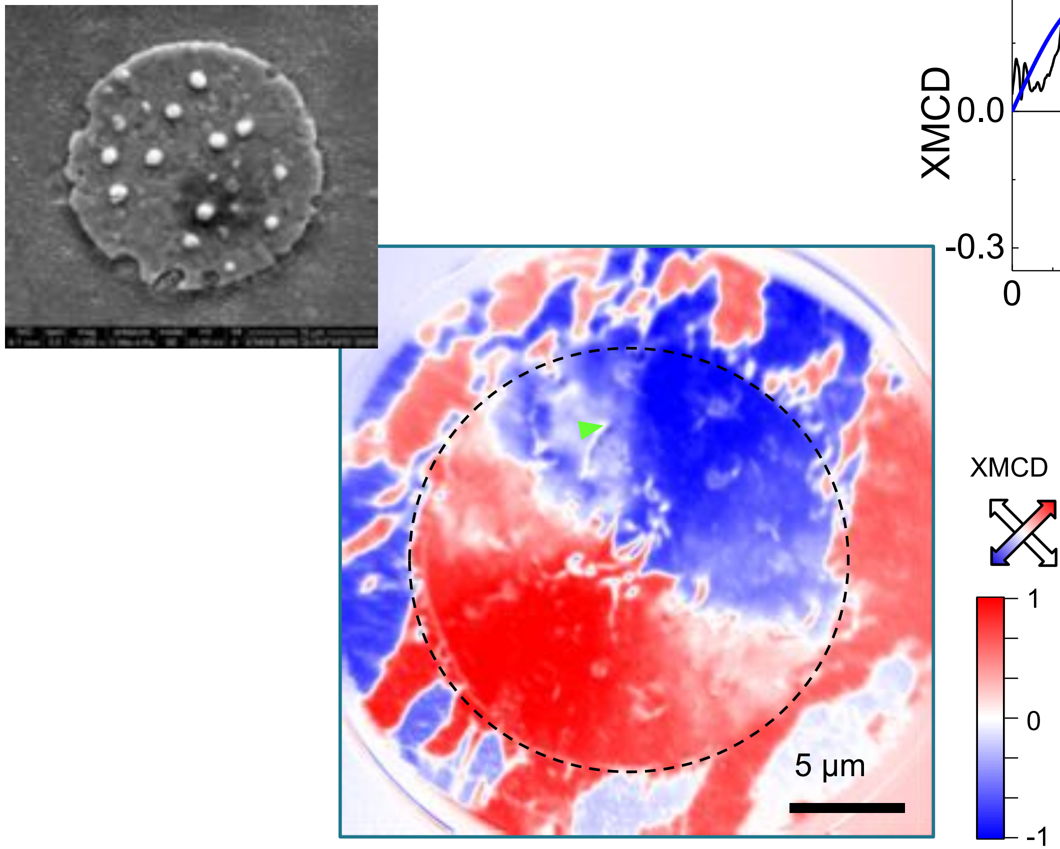
The **magnetic pattern imprinted** in the FM layer can be **controlled by the magnetic history** experienced by the SC dot

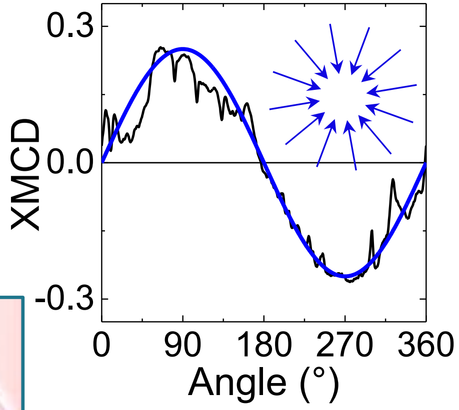


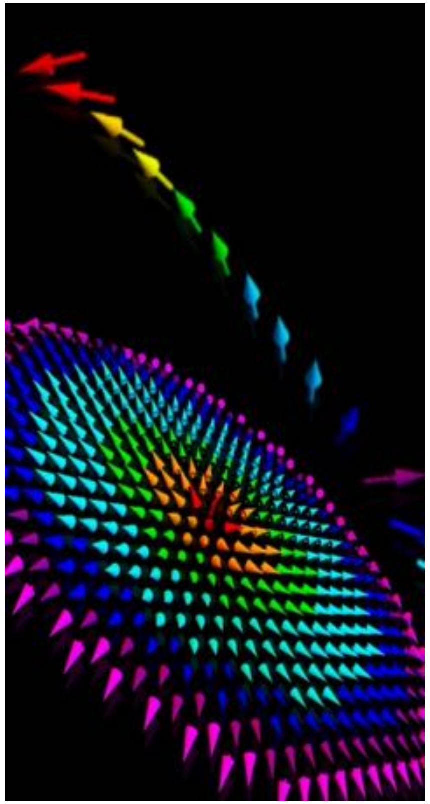
Large Manifold of Non-Trivial Spin Textures

Many different singular magnetic states can induced in the Py layer by changing the SC trapped field (shape of the dot).









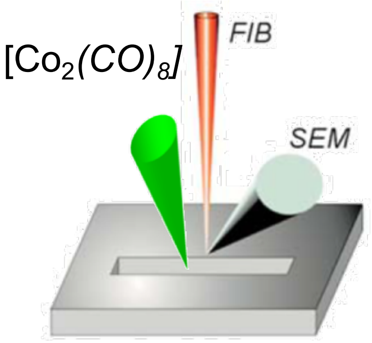
2D monopole-like spin texture configuration, whose magnetic charge can be easily switched from +1 to -1 by changing the sign of B_{max}

Palau et al. Advanced Science (2016) 1600207, Alcalà et al. Book Chapter, Springer (In Press)

Hybrid system: FM Nanostructures / SC Film

Prof. J.M. De Teresa, Dr. R. Cordoba
Instituto de Nanociencia de Aragón

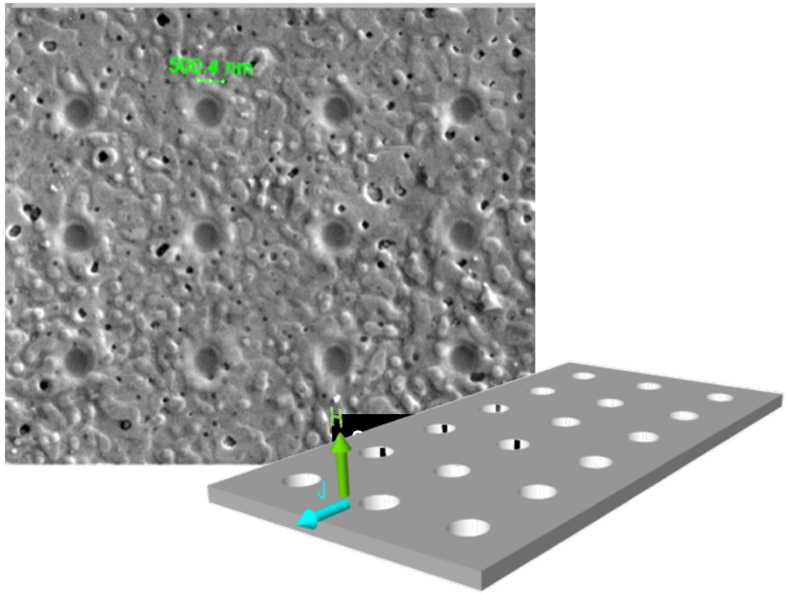
Possibility combine SC with 3D spin textures that could provide a third dimension in controlling magnetic states at the nanoscale



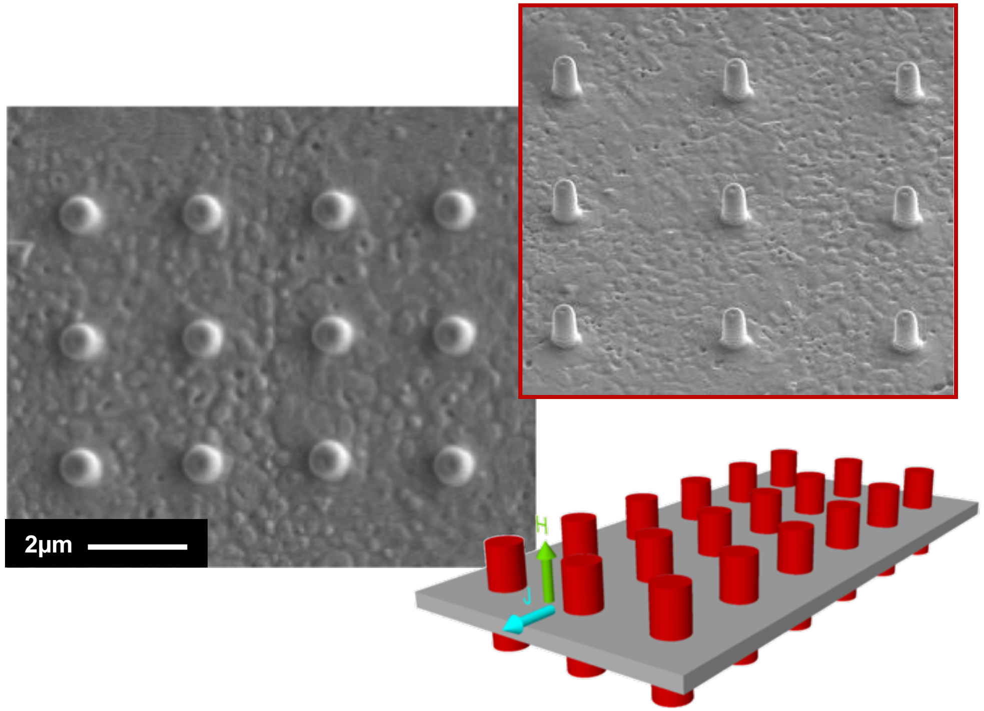
Focused Ion Milling (FIB) +
Focused Electron Beam Induced Deposition (FEBID)

Local deposition → No damage of the SC properties

Antidots

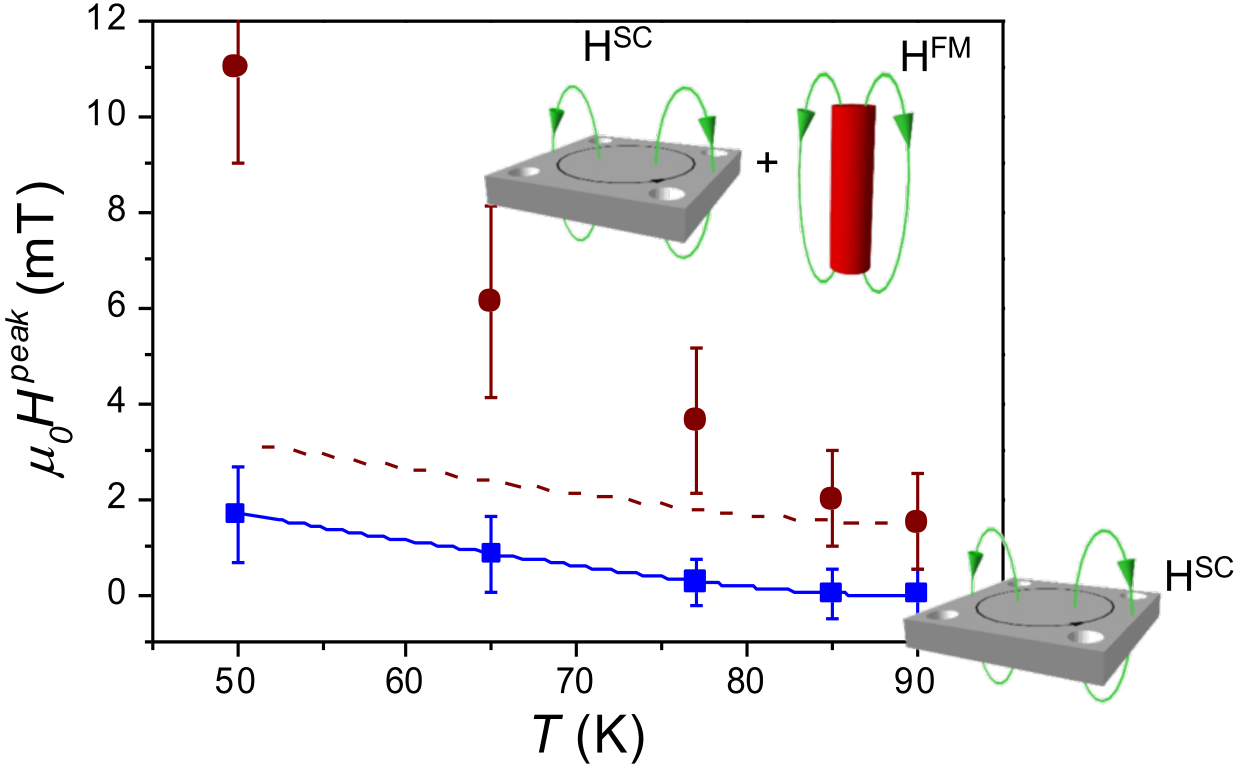


Co rods

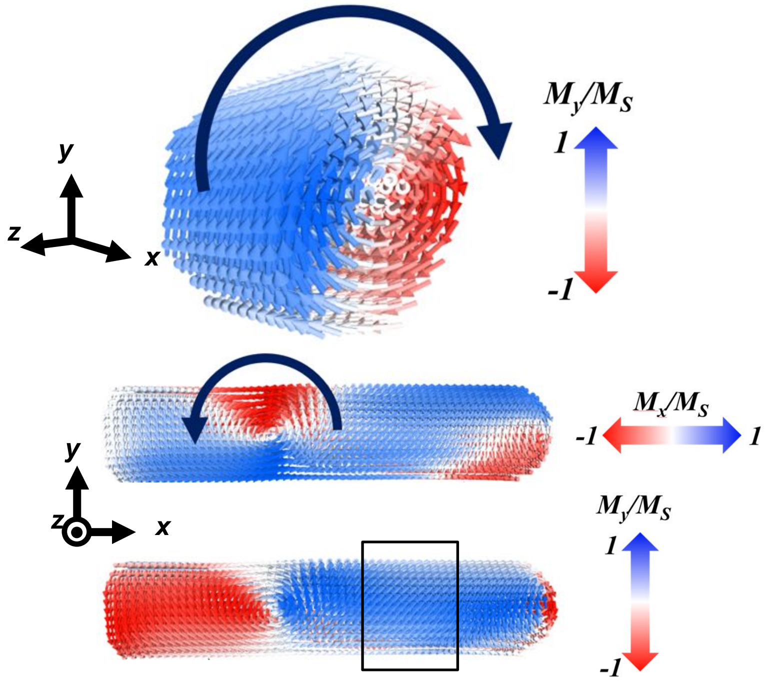


HTS film, patterned with antidots, and with FM nano-rods grown inside them

Remanent Magnetic Structure of Nano-Rods



micromagnetic simulations



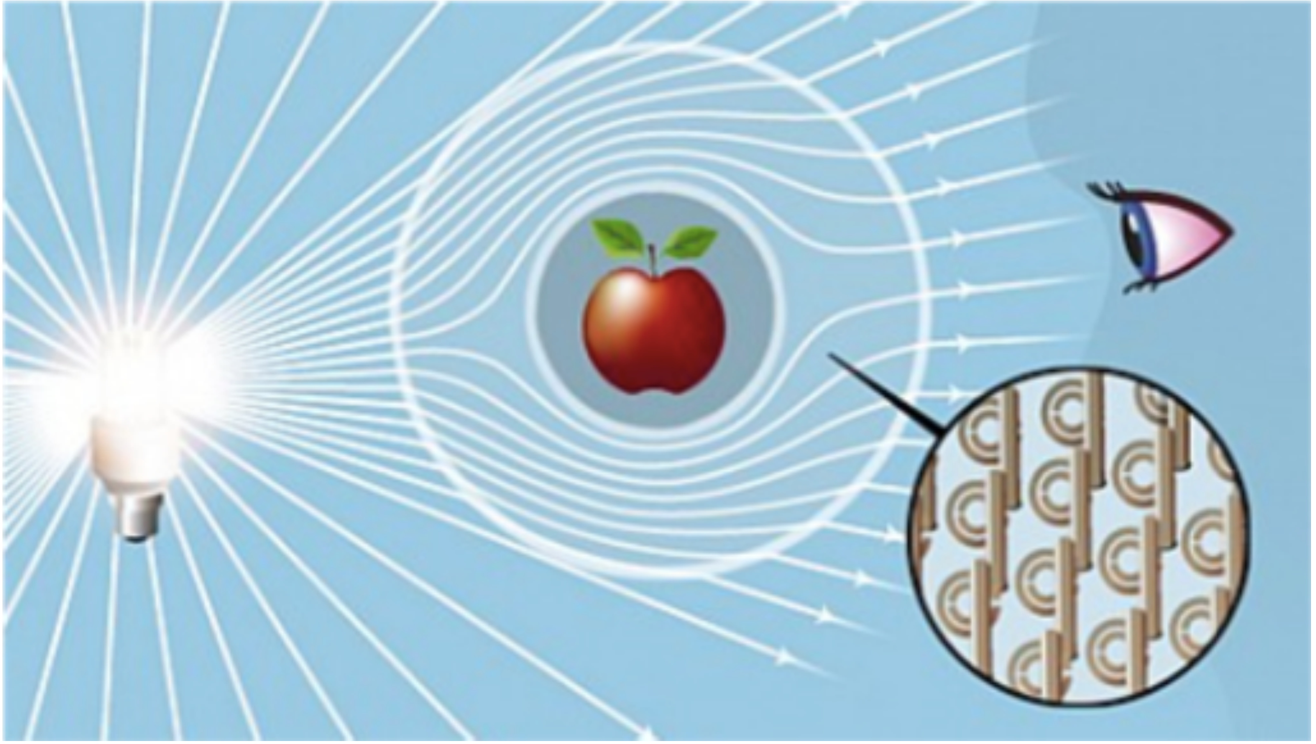
<u>SC properties</u> of the film and <u>3D nanometric magnetic structure</u> of the Co nano-rods tuned by **cooperative non homogenous SC-FM stray fields.**

Proper choice of the SC sample geometry (current loops) → **controllable 3D magnetic textures and vortex states at the nanometric scale with loss-free supercurrents.**

Rouco et al Sci. Rep. 7, 5663 (2017)

Ferromagnetic/Superconducting Metamaterials

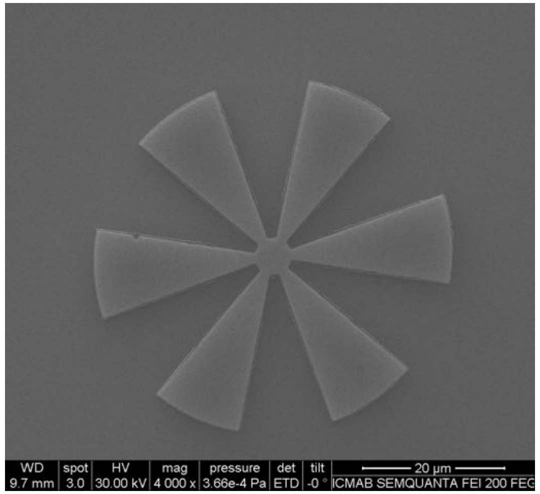
Metamaterials: artificial materials structured on the subwavelength scale with unique electromagnetic properties that simply do not occur in nature

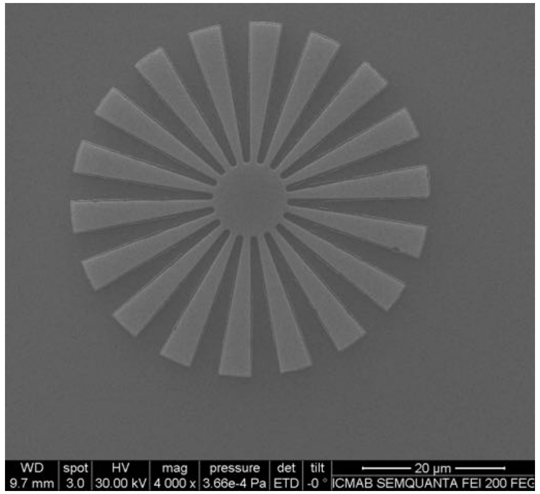


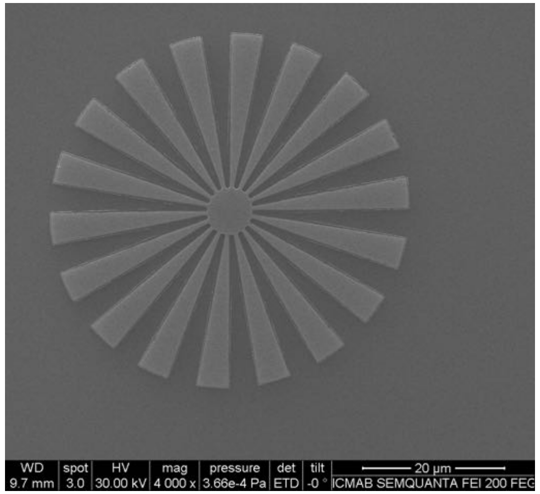
Optical metamaterials

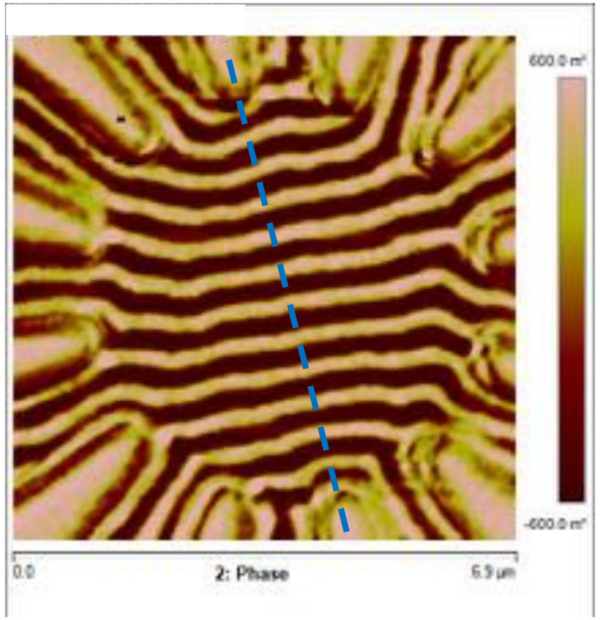
Ferromagnetic/Superconducting Metamaterials

FM / Air Metasurfaces

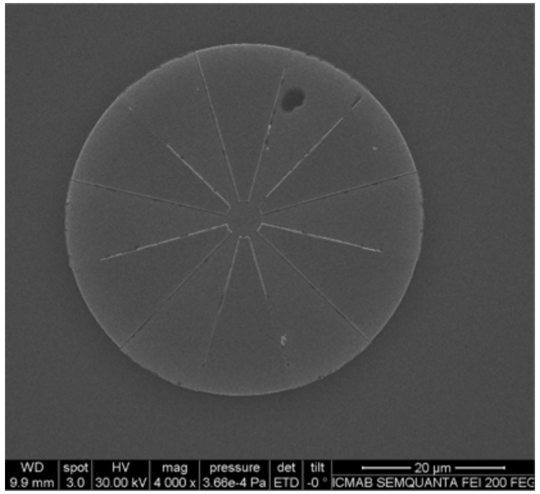


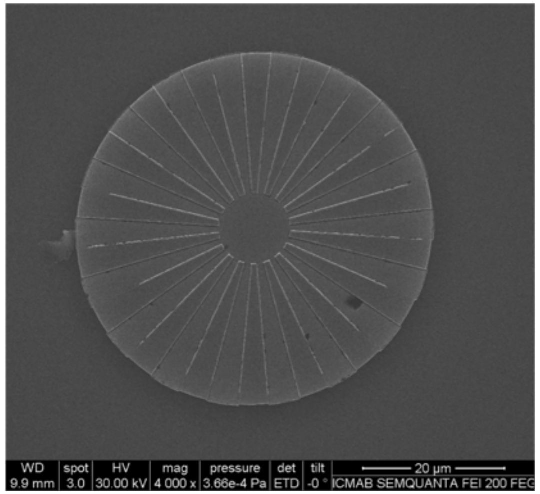


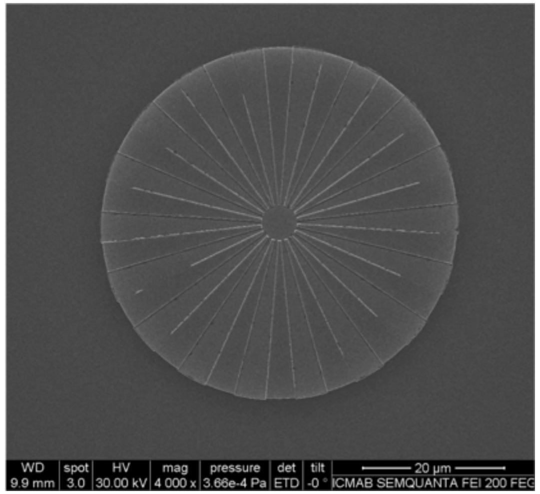


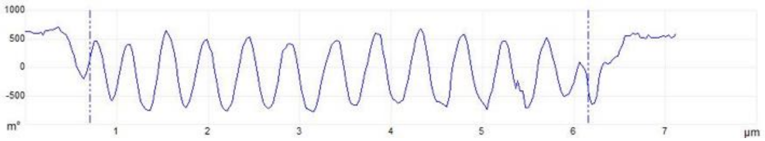


FM / SC Metasurfaces







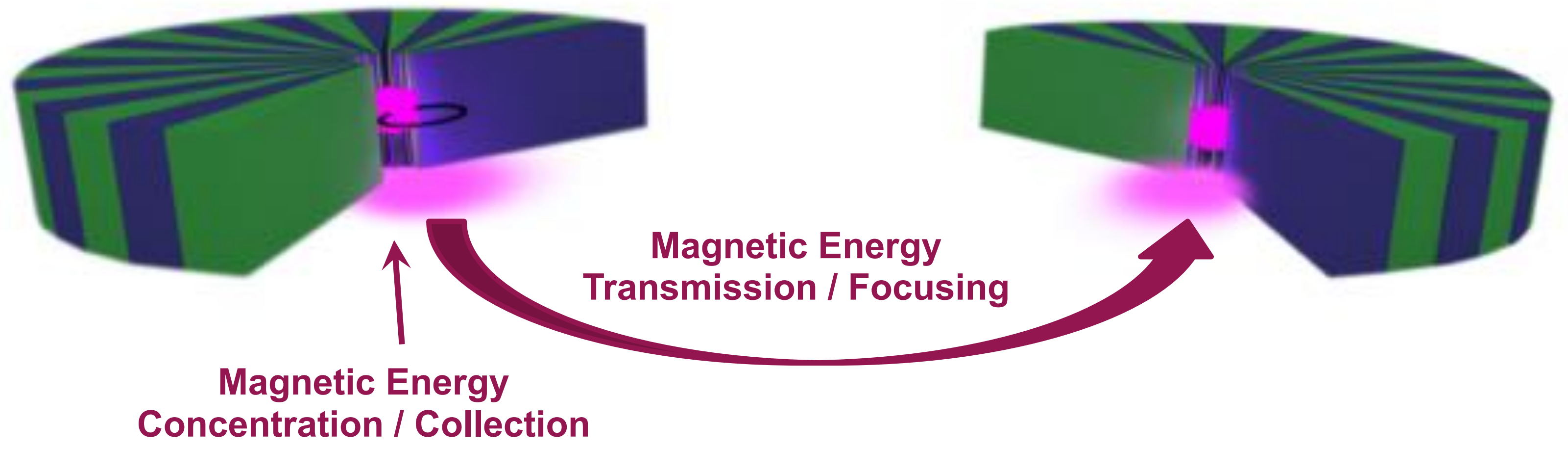


The magnetic field inside the metasurface can be tuned with the size / number of petals

Ferromagnetic/Superconducting Metamaterials

Metamaterials: artificial materials structured on the subwavelength scale with unique electromagnetic properties that simply do not occur in nature

FS/SC metasurfaces

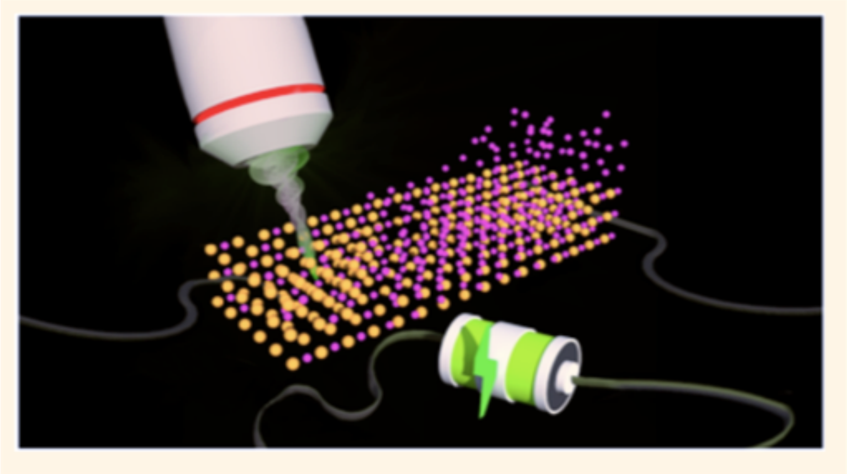


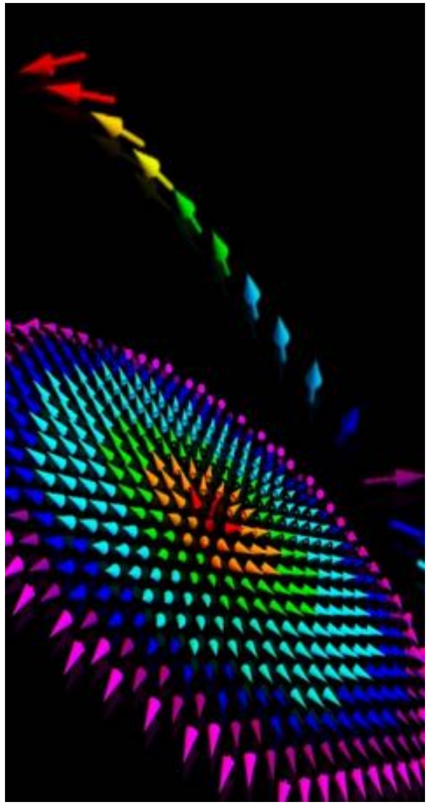
Use metamaterial shells composed of concentric pieces made of FM-SC **for guiding, concentrating, harvesting, and transferring static and low- frequency magnetic fields, at micro- / nano-scale**

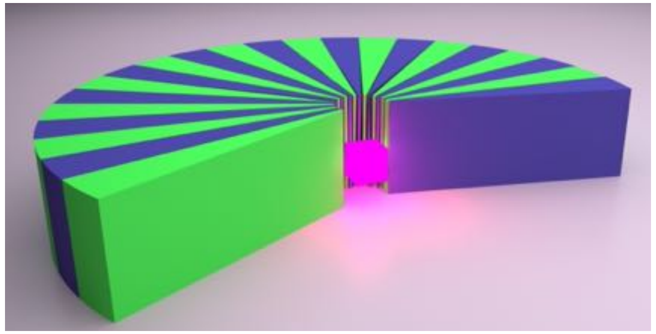
- To enhance sensitivity and performance of magnetic sensors
- To achieve feasible magnetic harvesters for autonomous electronic devices
- To effectively transmit magnetic energy for wireless devices

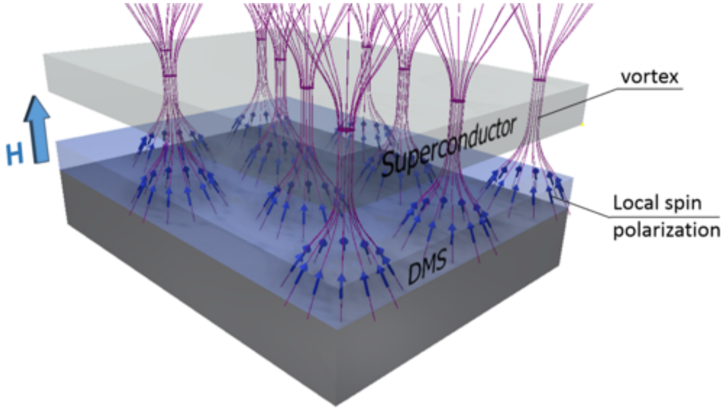
High-Temperature Superconducting Functional Devices

High-temperature cuprate superconductors very complex materials with huge technological potential for energy-efficient functional devices









Nanolithography of HTS is a challenging task essential for practical applications

High-Temperature Superconducting Functional Devices

High-temperature cuprate superconductors very complex materials with huge technological potential for energy-efficient functional devices

Superconducting Materials and Large Scale Nanostructures (SUMAN) @ ICMAB-CSIC

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