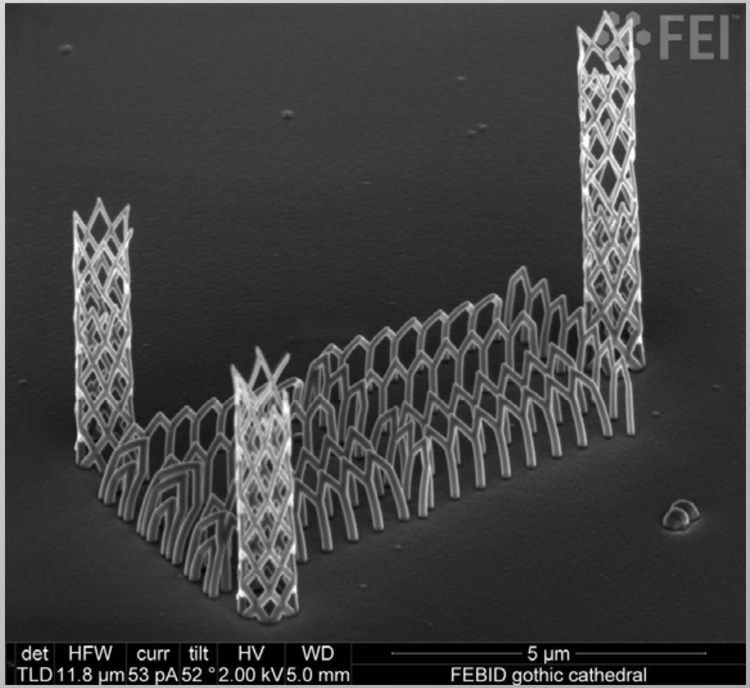
Focused **I**on **B**eam **I**nduced **P**rocessing applied to **Nanosuperconductivity**

Rosa Córdoba Castillo

rocorcas@unizar.es



UNIVERSIDAD AUTONOMA DE MADRID

icma Instituto de Ciencia de Materiales de Aragón

Summer School in Basics and Applications of Nanolithography, Jaca, Spain. July 16th-18th, 2018

Outline

1) **Introduction to the Superconductivity**

2) **Focused Ion Beam Induced Processing (FIBIP)**

   - Nanolithography: FIB Induced Milling

   - Nanofabrication: FIB Induced Deposition

3) **Focused Ion Beam Induced Processing (FIBIP) applied to the nanosuperconductivity**

   - Nanolithography: FIB Induced Milling applied to the nanosuperconductivity

   - Nanofabrication: FIB Induced Deposition applied to the nanosuperconductivity

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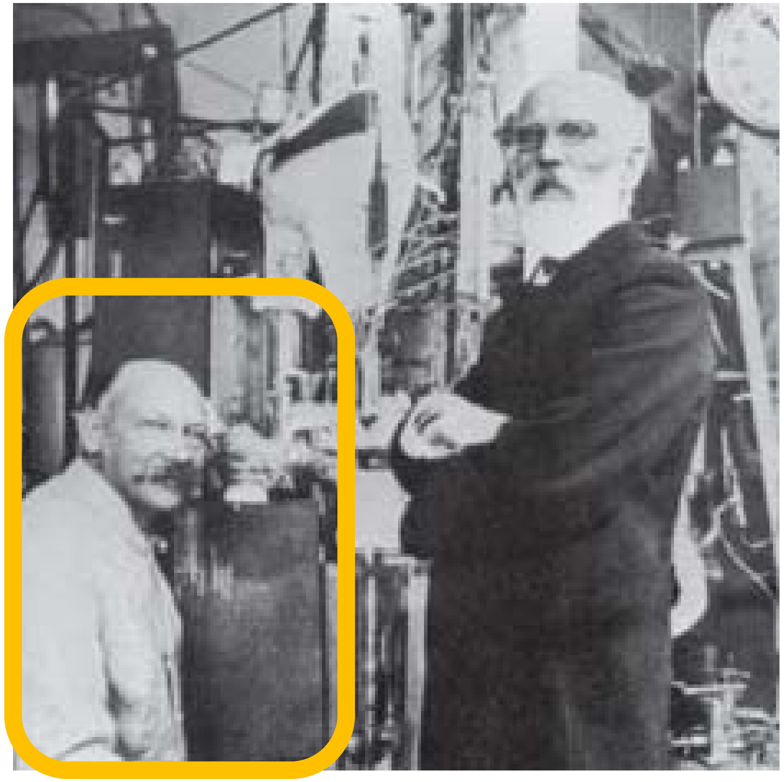
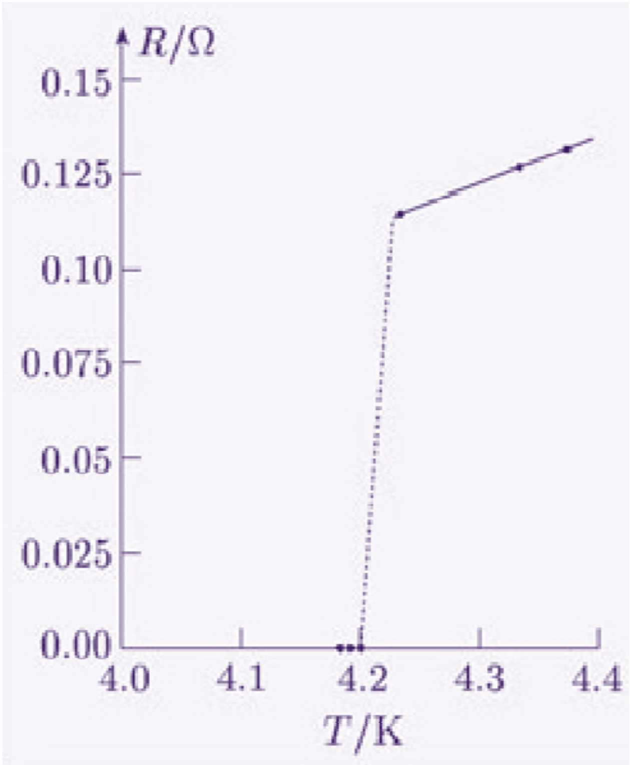
Introduction to the Superconductivity

Superconducting materials - strengths



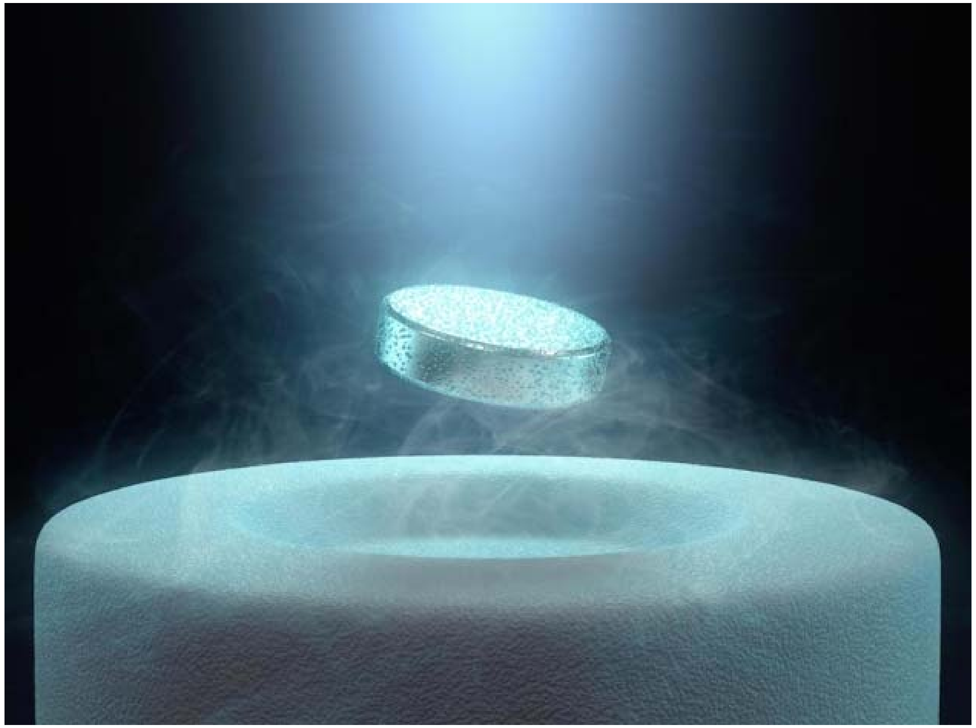
H. Kamerlingh Onnes, 1911

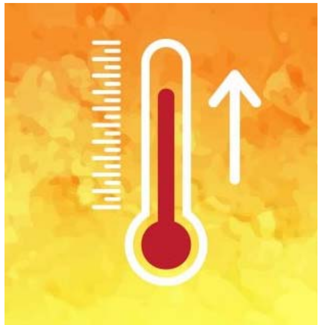


Perfect conductor

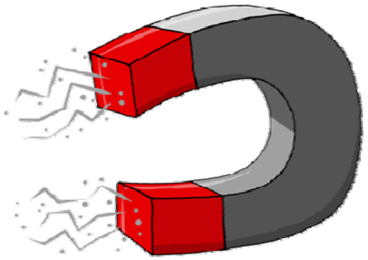
Introduction to the Superconductivity

Superconducting materials - weaknesses

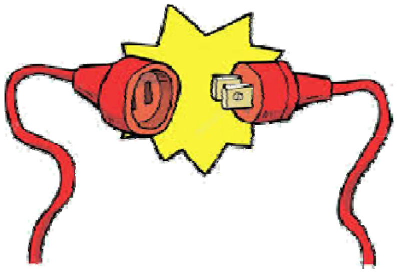




Temperature



Magnetic field



Current

Introduction to the Superconductivity

Superconducting materials - applications

• High energy physics

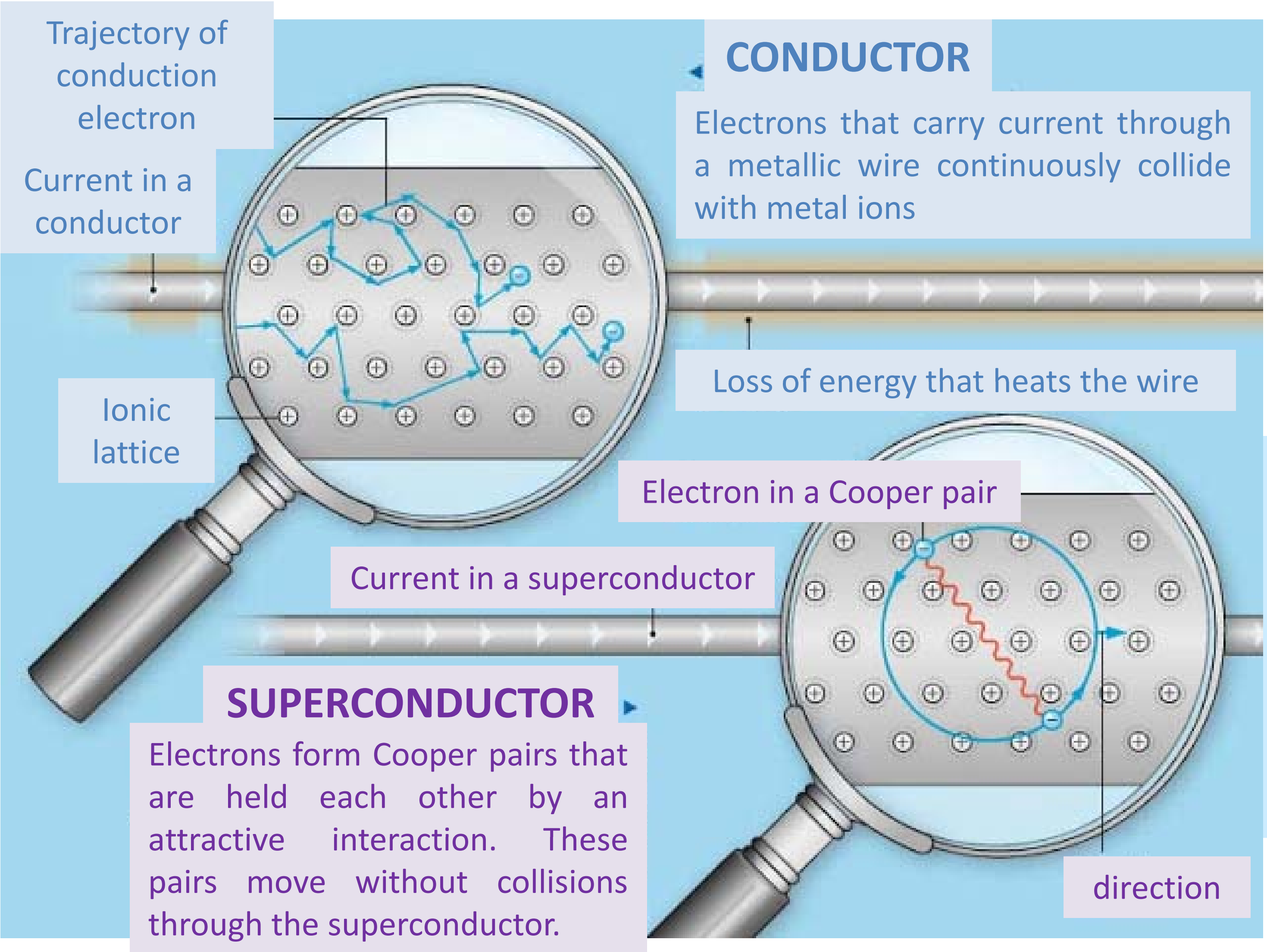
• Medical field

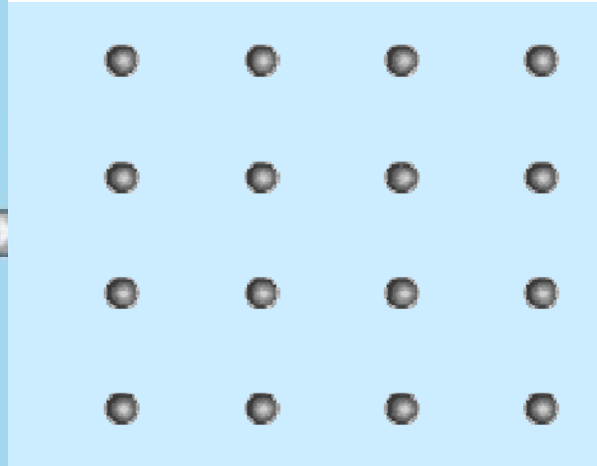
• Power generation

• Power quality and storage

• Transportation

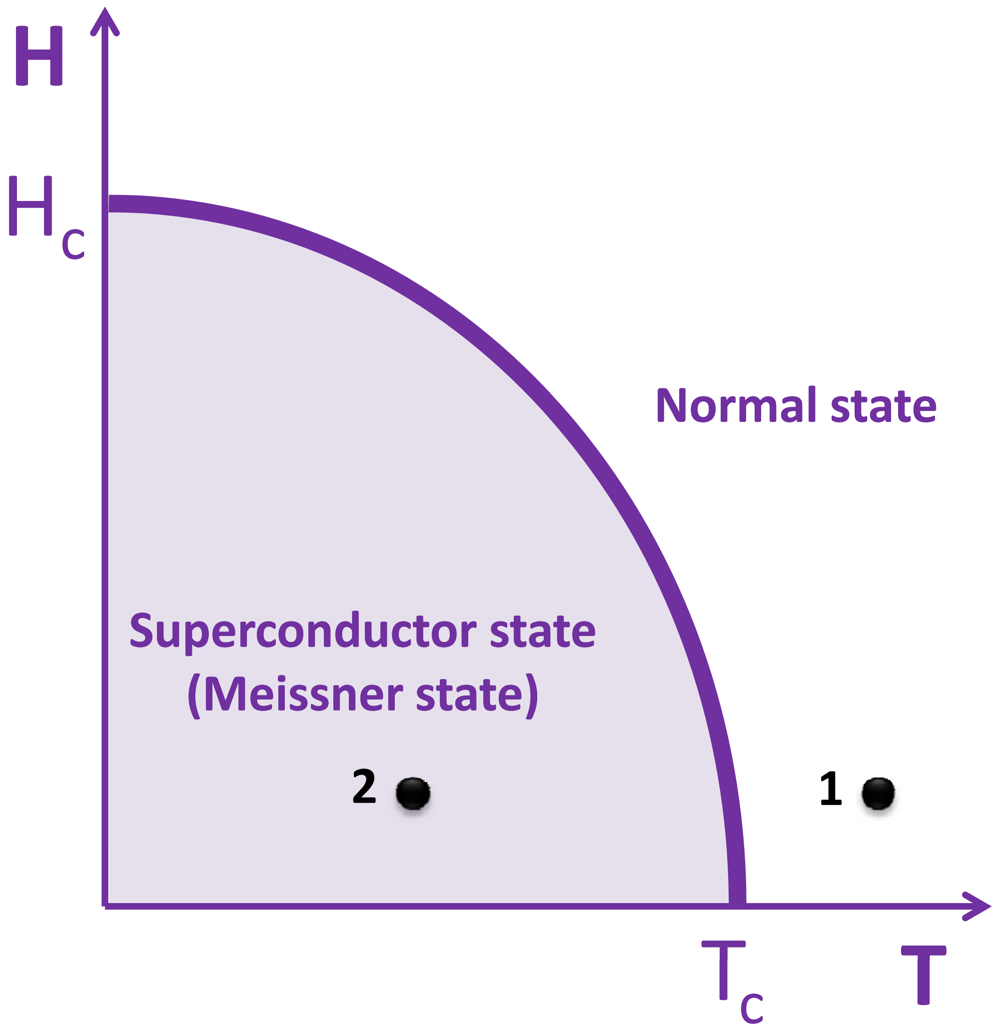
Superconducting materials - origin

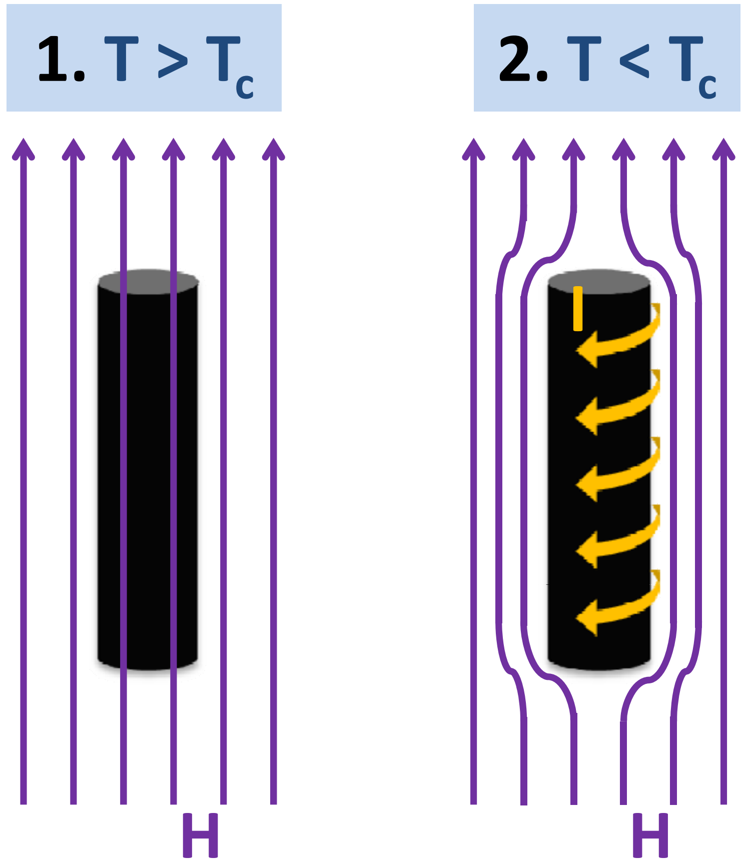




Superconductivity – Phase diagram

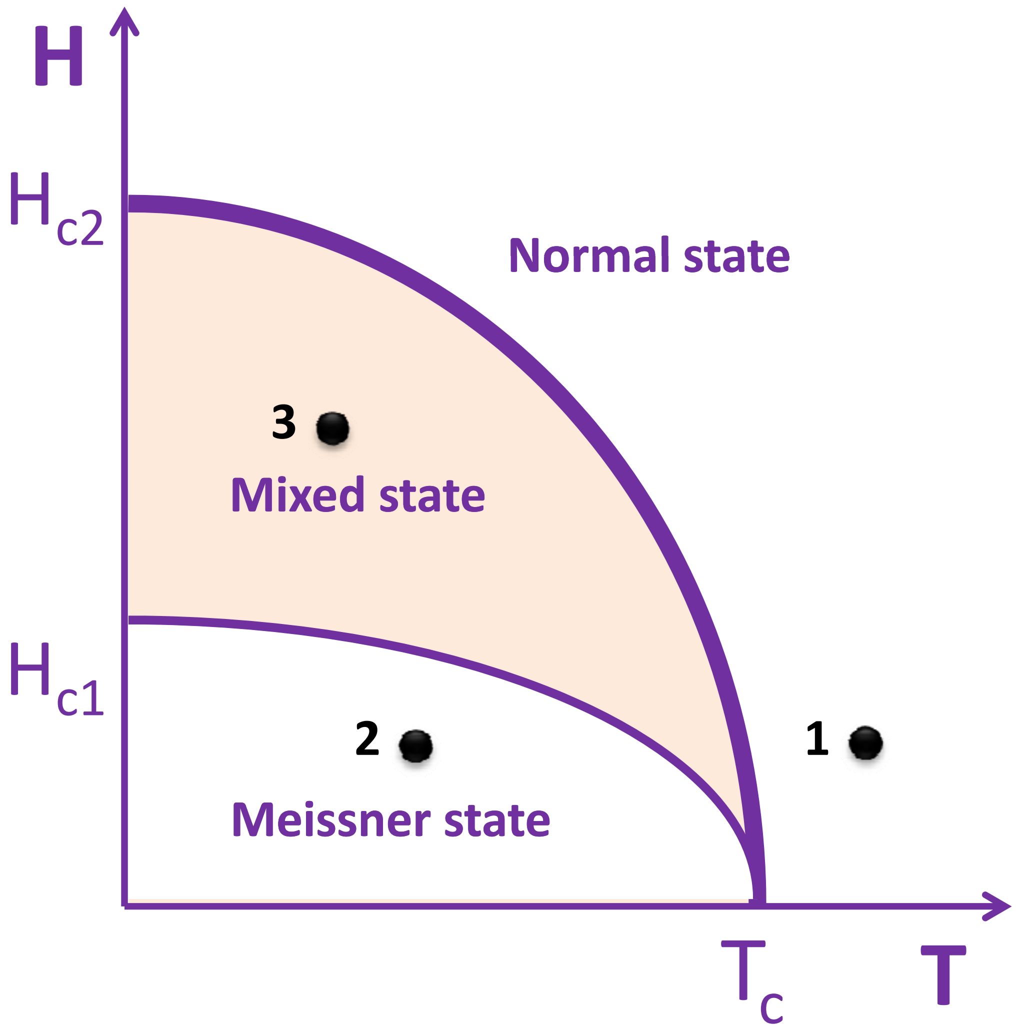
Superconductor Type I

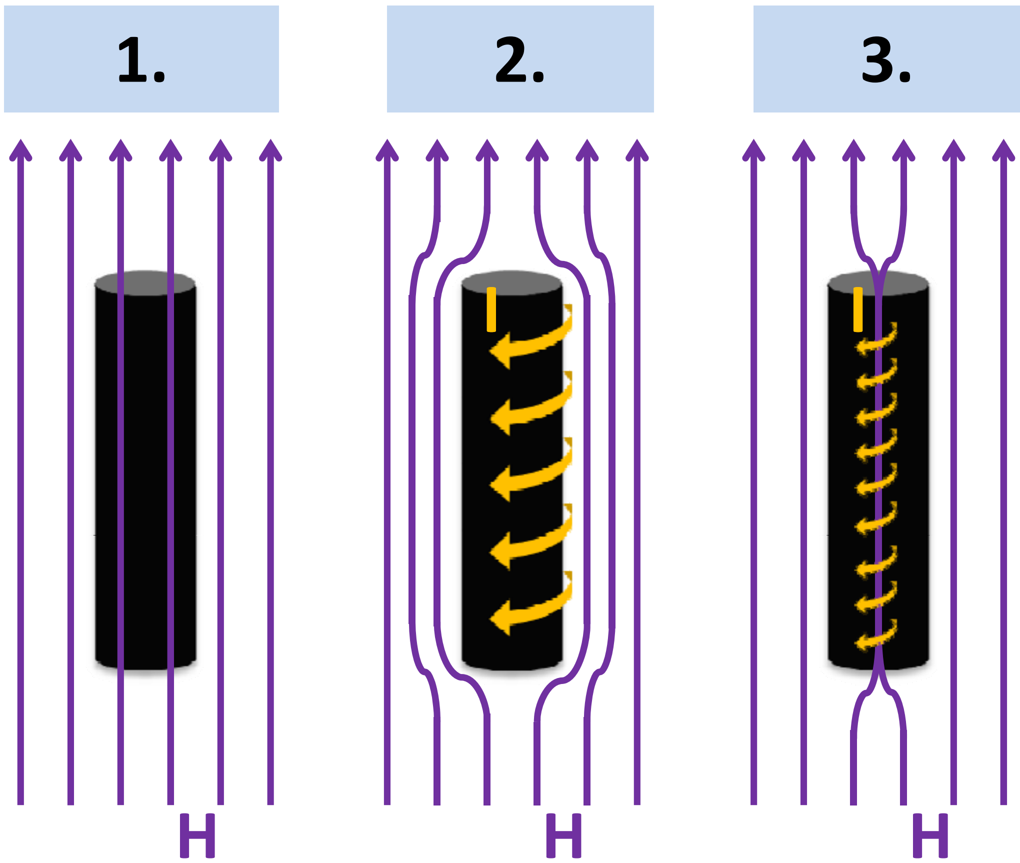




Superconductivity – Phase diagram

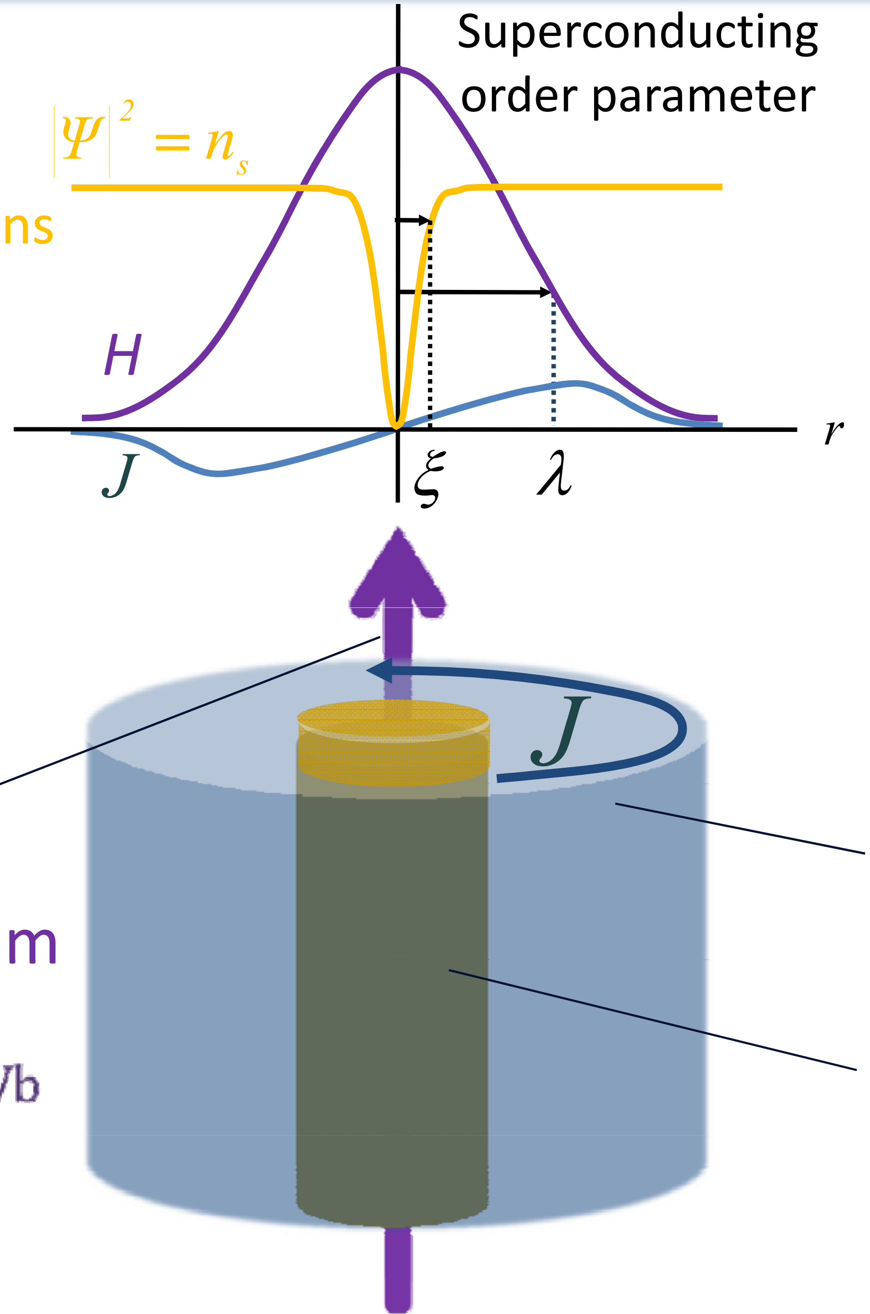
Superconductor Type II





Type II Superconductor – SC vortex

density of superconducting electrons



ξ: superconducting coherence length

λ: penetration length

Screening supercurrent

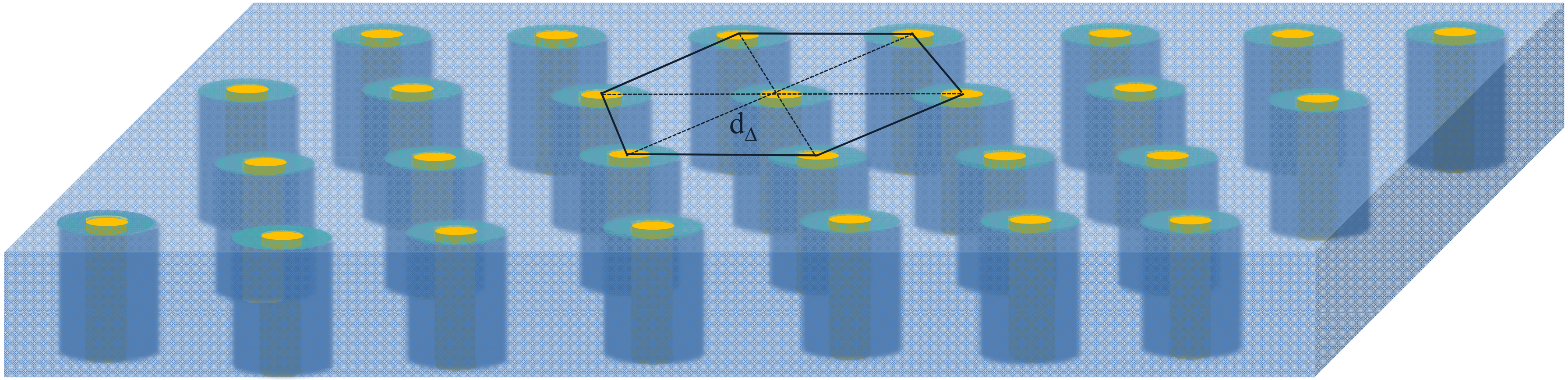
Magnetic flux quantum

$$\Phi_0 = \frac{h}{2e} \approx 2.07 \cdot 10^{-15}\ \mathrm{Wb}$$

Normal core

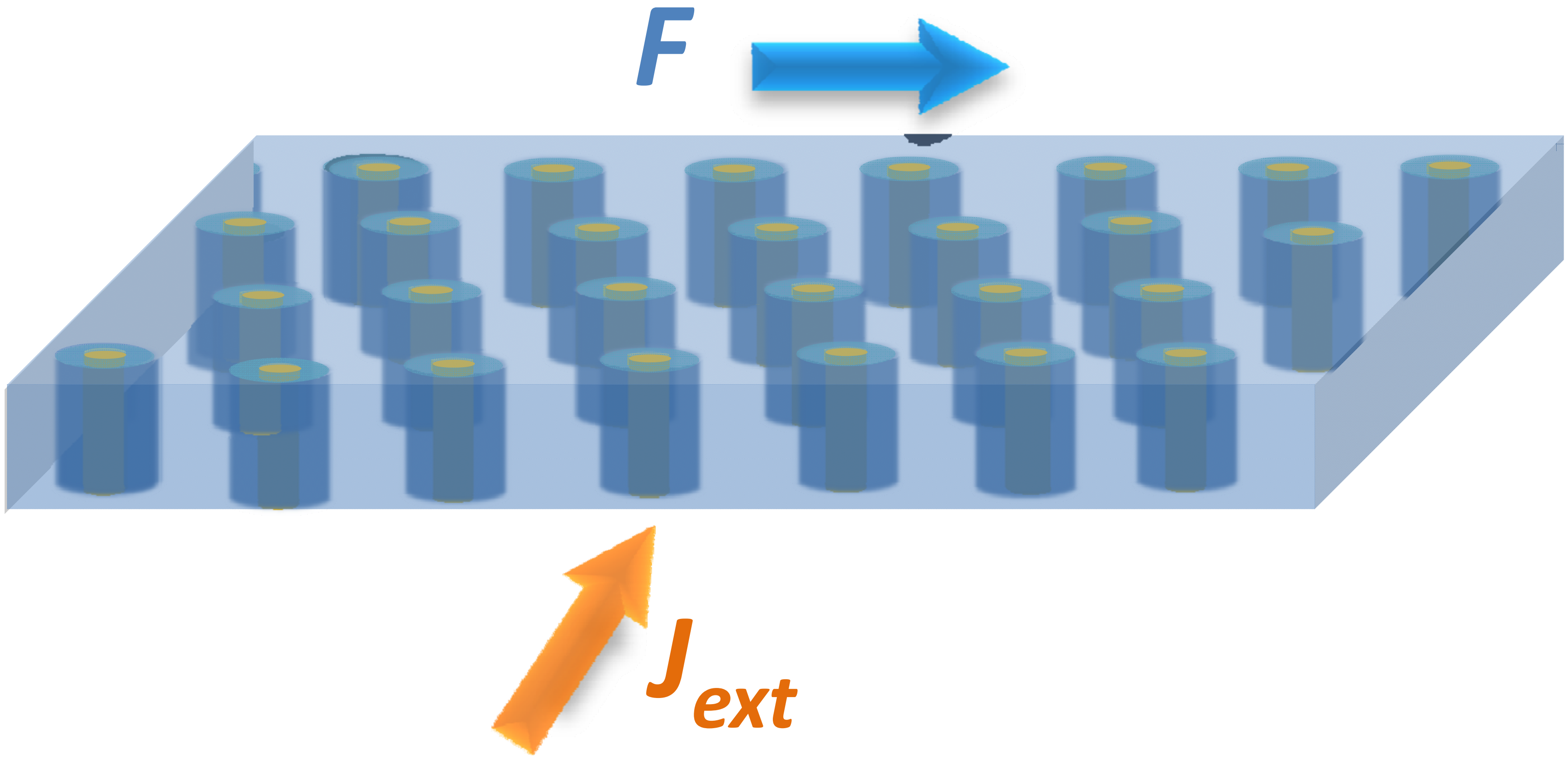
Type II Superconductor – vortex lattice

Abrikosov vortex lattice



$$d_\Delta = \left(\frac{4}{3}\right)^{1/4} \left(\frac{\phi_0}{B}\right)^{1/2}$$

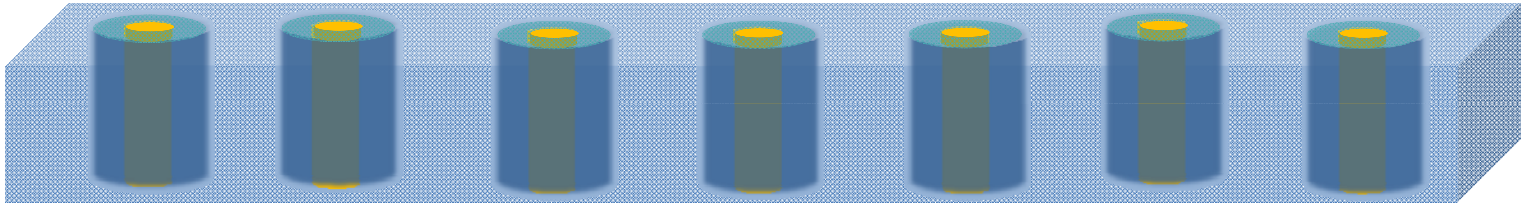
Type II Superconductor – vortex dynamics



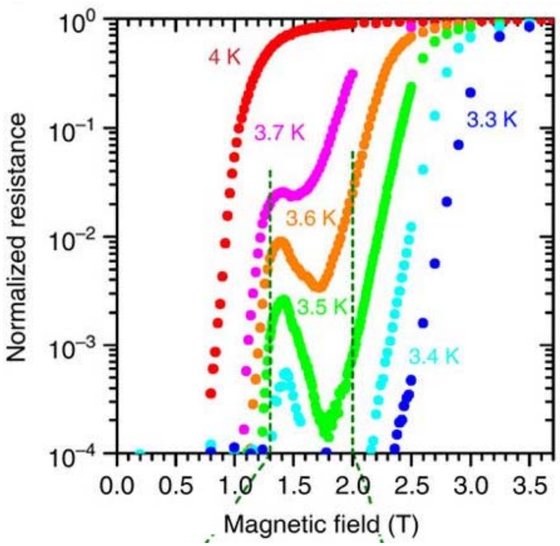
$$\boldsymbol{F} = \boldsymbol{J}_{ext} \times \phi_0 \qquad \boldsymbol{E} = \nabla \mathbf{V} = \mathbf{B} \times \mathbf{v}_{\boldsymbol{\phi}}$$

Nanosuperconductivity

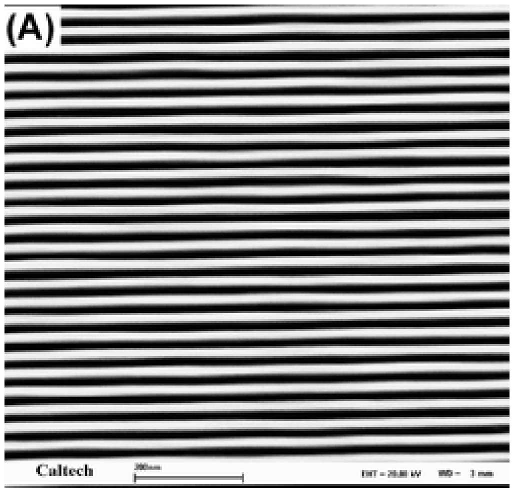
ξ: superconducting coherence length



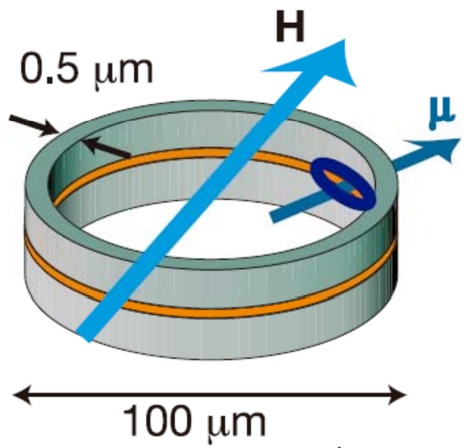
- **Dissipation-free energy state**
- **Quasi 1D SC nanowire arrays**
- **Quantum dynamics of a single vortex**



R. Córdoba et al., Nature Comm. (2013)



K. Xu et al., Nano Letters (2008)



A. Wallraff et al., Nature (2005)

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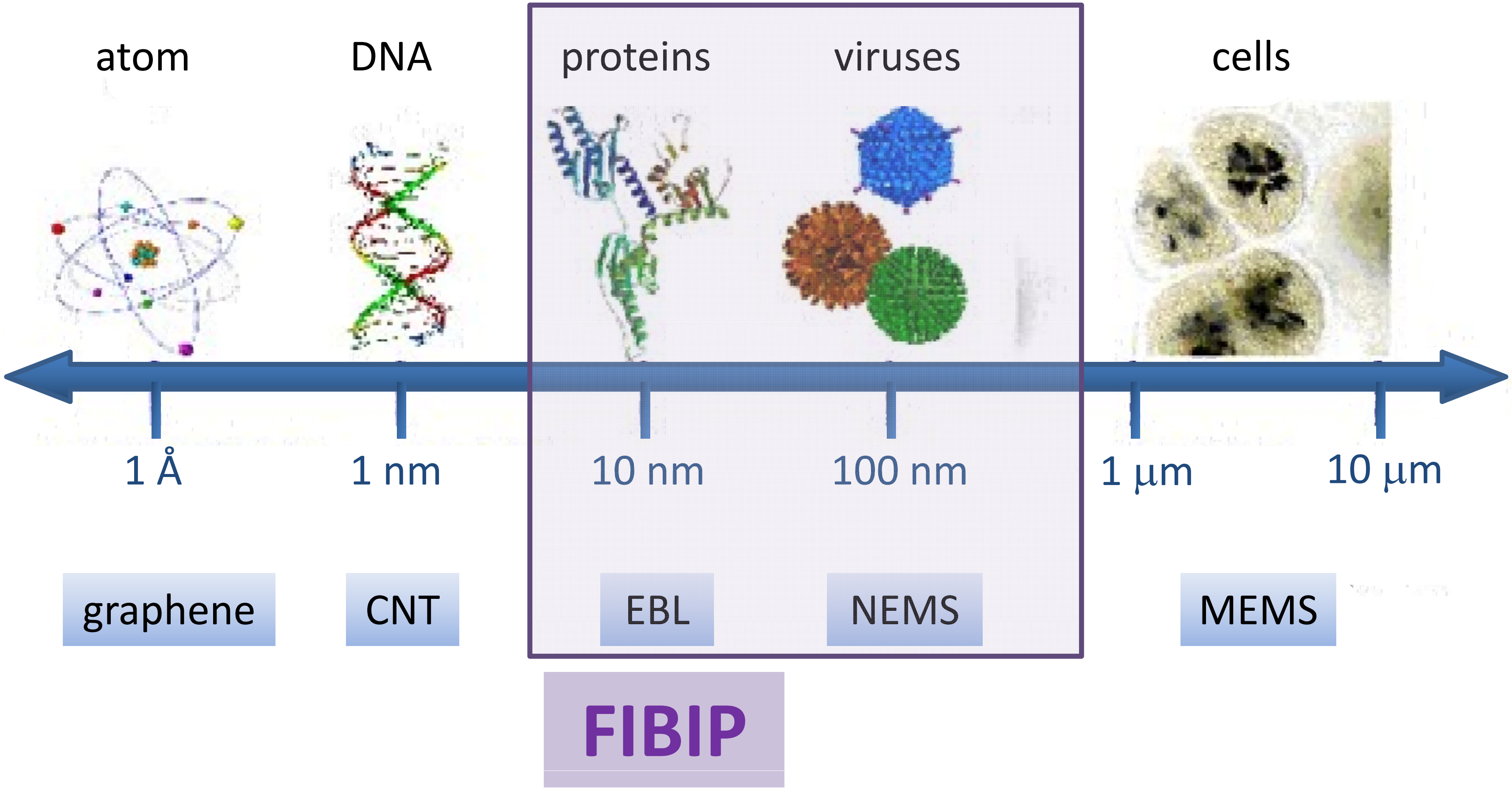
Focused Ion Beam Induced Processing (FIBIP)

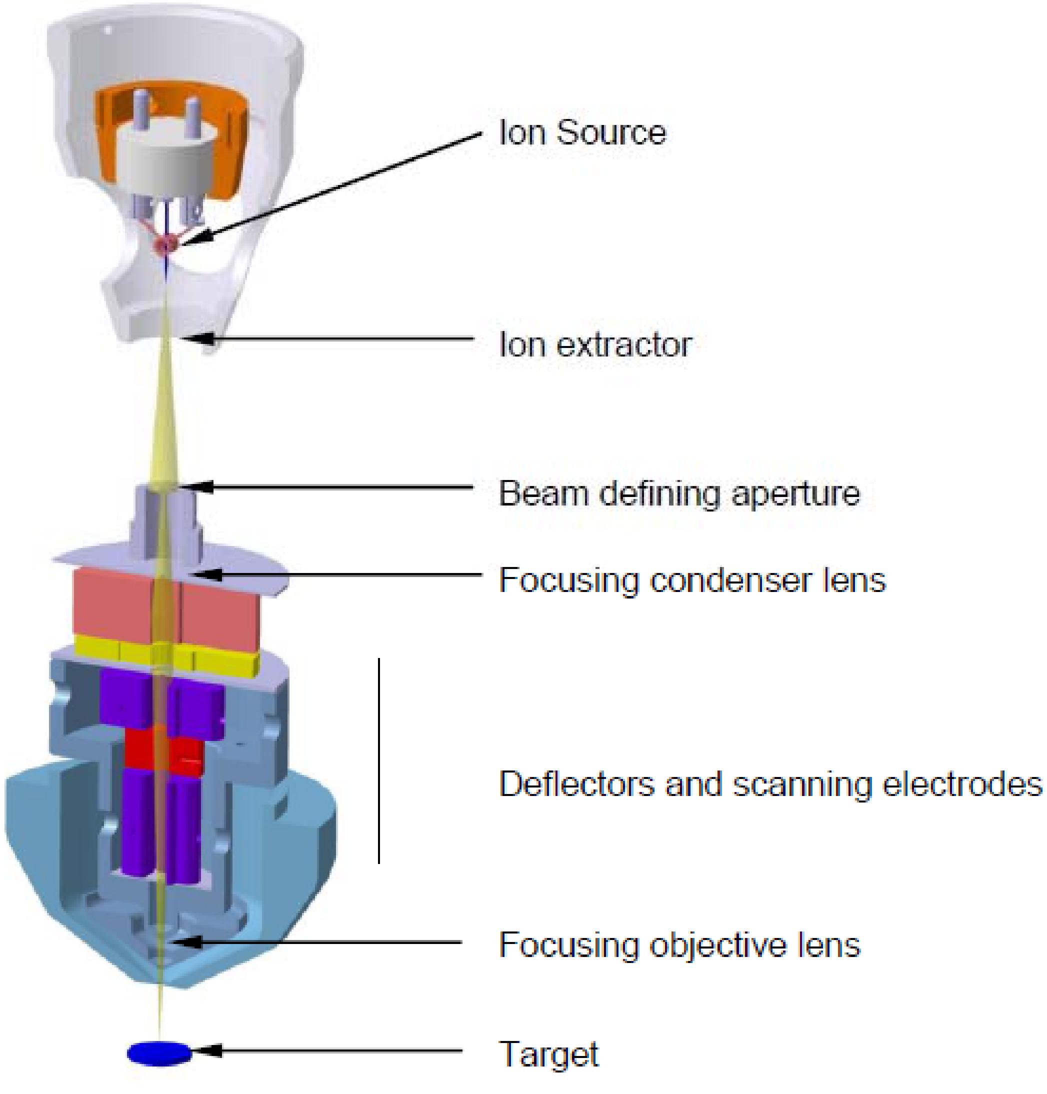
Nanoscience and Nanotechnology



Focused Ion Beam Induced Processing (FIBIP)

EBL	FIBIP
~nm size in plane substrate	from ~10 nm to ~100 µm)
5 steps	1 step
1D, 2D nanostructures	any kind of substrate
	1D, 2D, 3D nanostructures

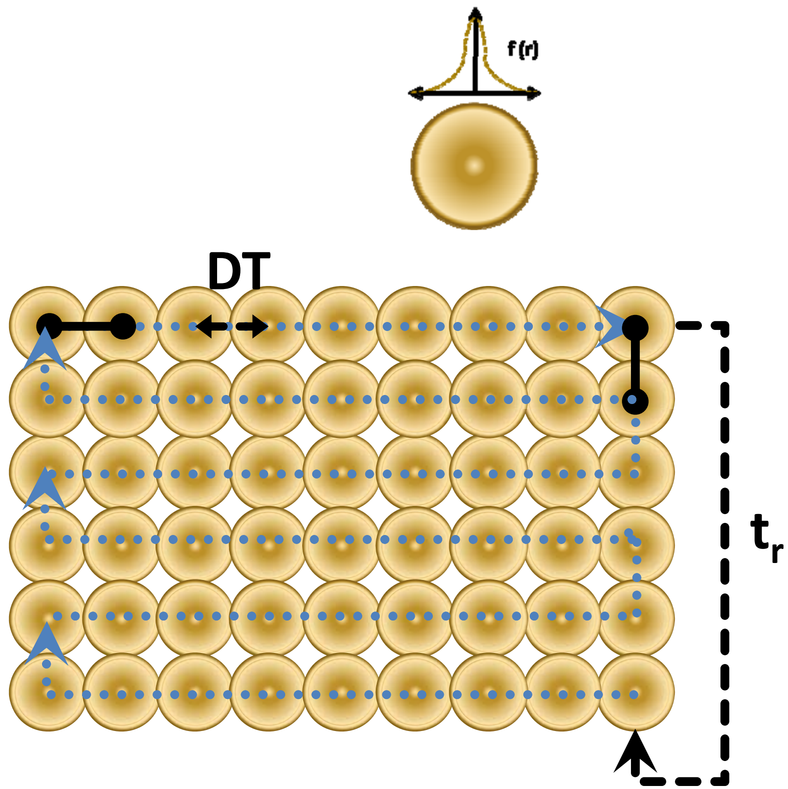
Focused ion beam (FIB)



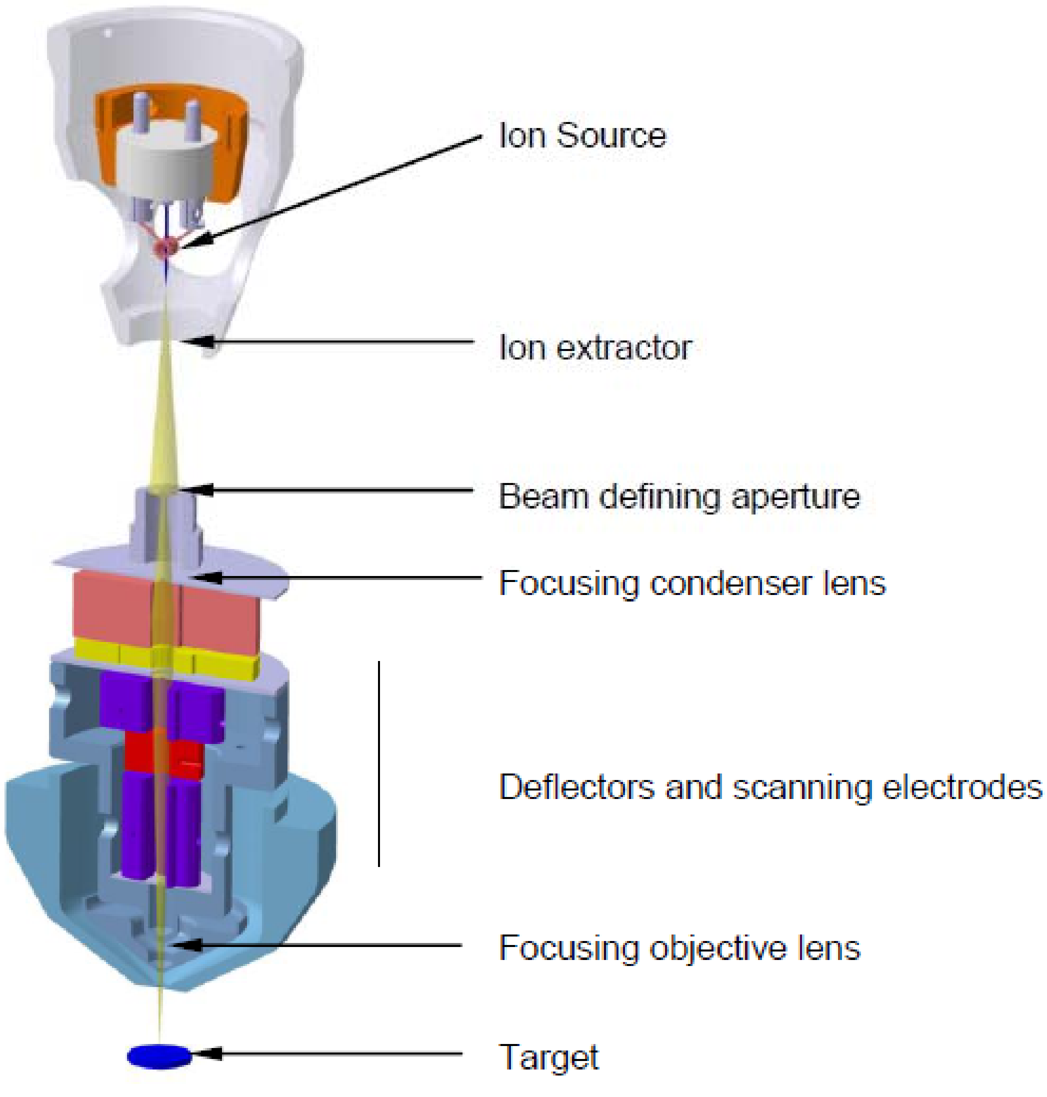
J. Gierak, Nanofabrication 1 (2014) 35

UNDERLYING IDEA:

$\lambda \sim$ **h/mv**, short λ (< 1 nm), accelerating the ions under high voltage (up to 50 kV).



Focused ion beam (FIB)



J. Gierak, Nanofabrication 1 (2014) 35

UNDERLYING IDEA:

$\lambda \sim$ **h/mv**, short λ (< 1 nm), accelerating the ions under high voltage (up to 50 kV).

CONFIGURATIONS:

-Imaging and Analysis

-Nanolithography:

FIB Induced Milling

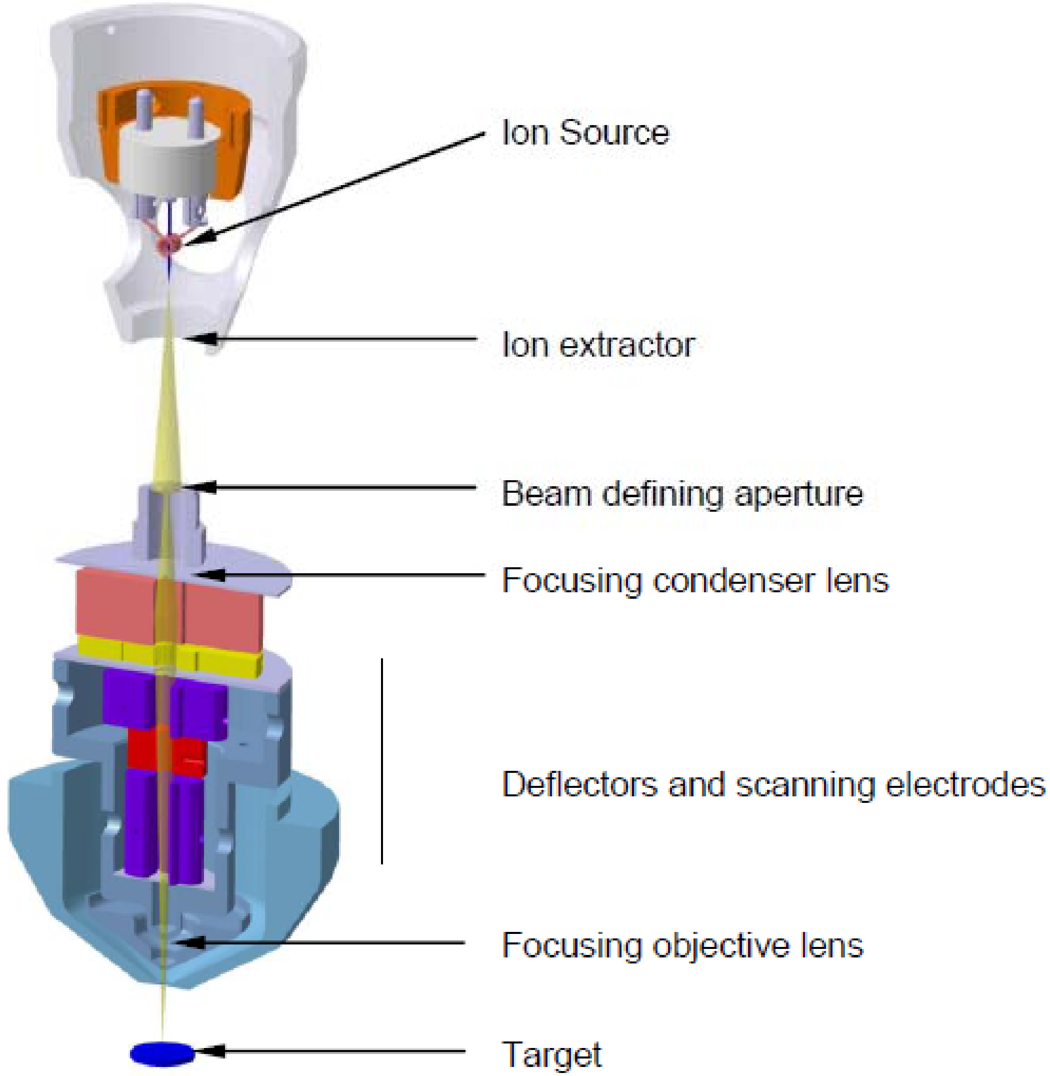
-Nanofabrication:

FIB Induced Deposition

FIBIP

Ga^+ focused ion beam column

- Voltage: 0.5-50 kV
- Beam current: 1pA-20nA
- Condenser lens
- Deflection lens
- Objective lens
- Apertures and stigmators
- “Beam blanker”



J. Gierak, Nanofabrication 1 (2014) 35

Ga$^+$ focused ion beam column

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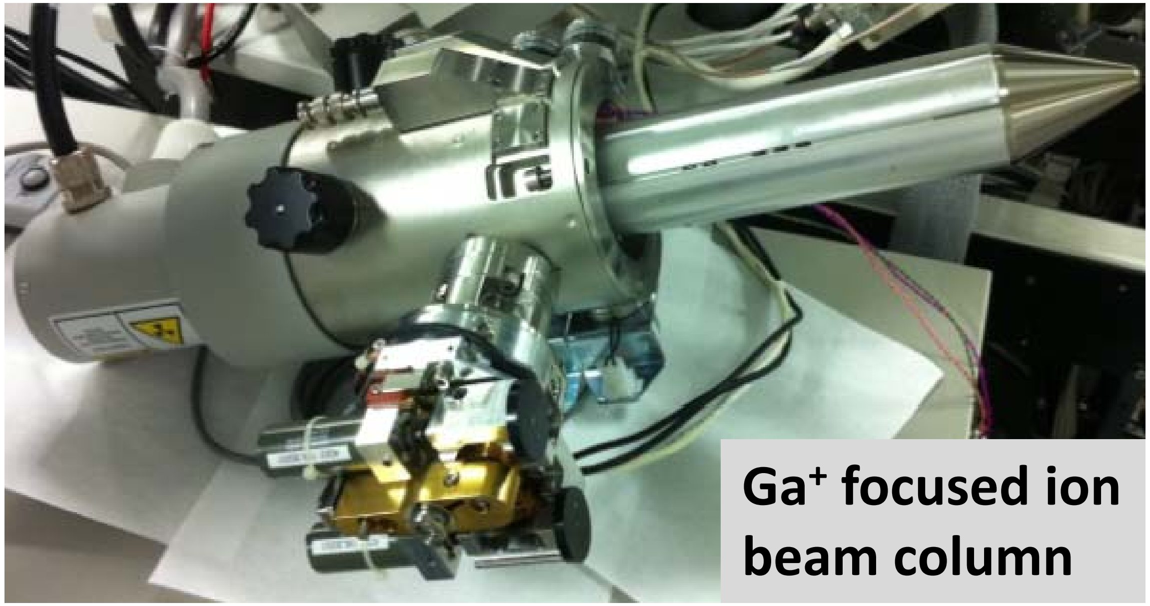
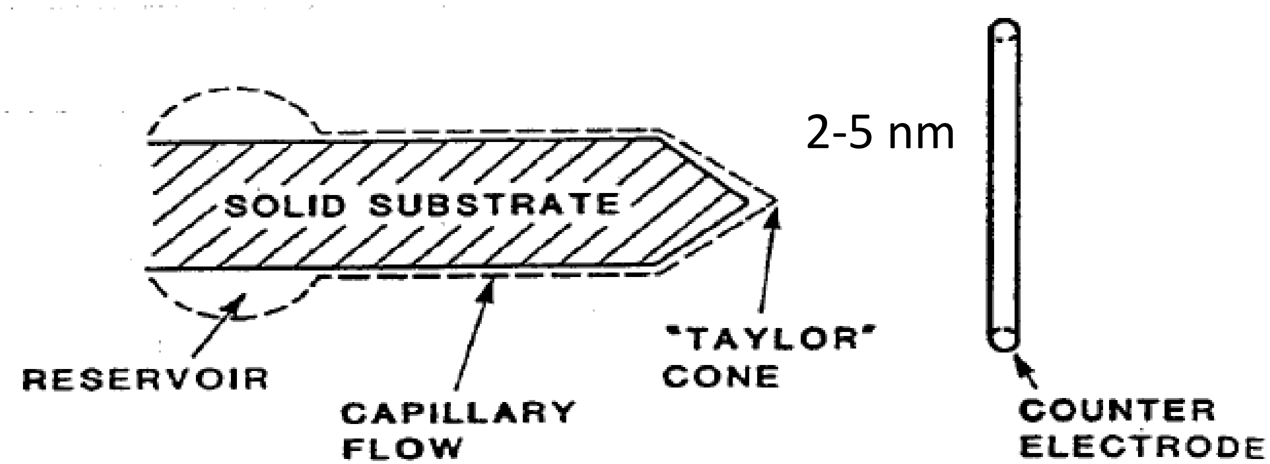


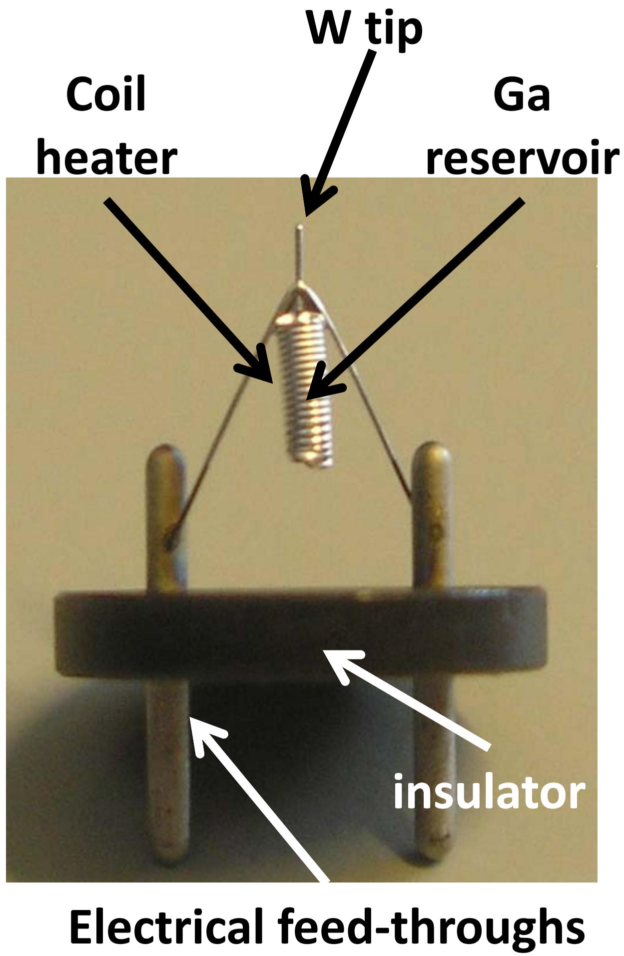
Ga$^+$ focused ion beam column

Focused ion beam sources

1. Liquid metal ion source (LMIS):

- generally based on gallium, with resolution of 5 nm
- low melting point and vapour pressure
- long life time: 1500 hours
- viscous behaviour on a W tip
- source brightness: 10^8 A/cm^2

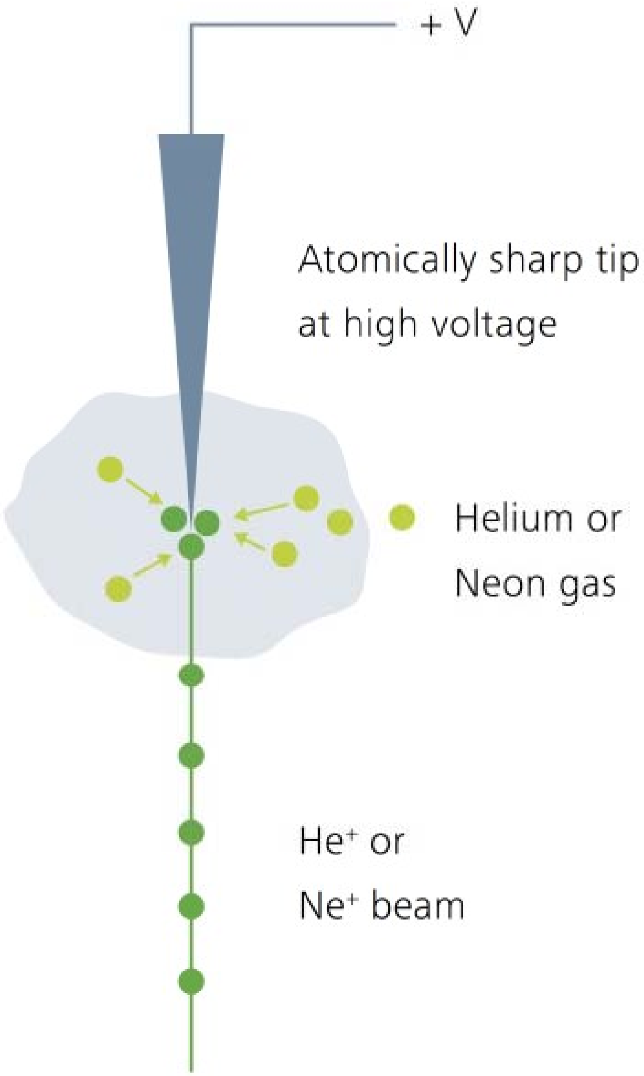




Focused ion beam sources

2. Gas ion source (GIS):

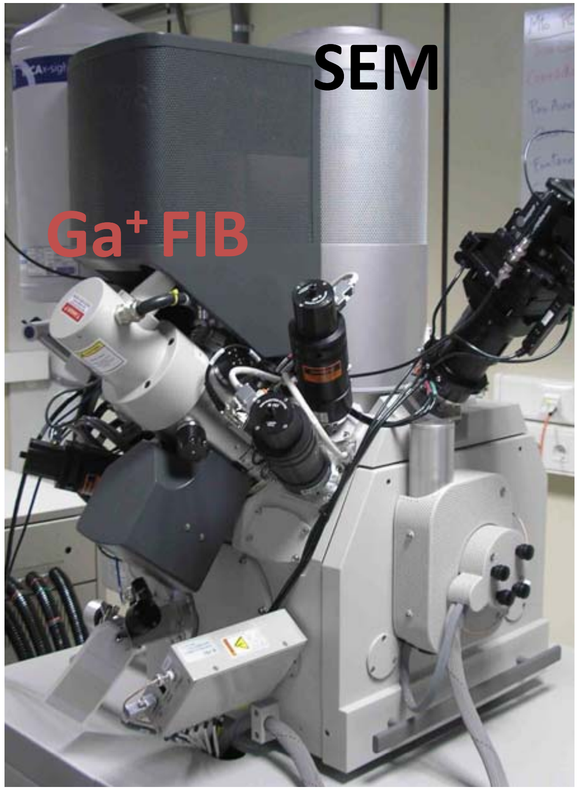
- based on He and Neon
- probe size≈ 0.3 nm
- source brightness: 10^9 A/cm^2 (30 times better than the Schottky FEG electron source and 500 times better than LMIS)



Commercial FIB configurations

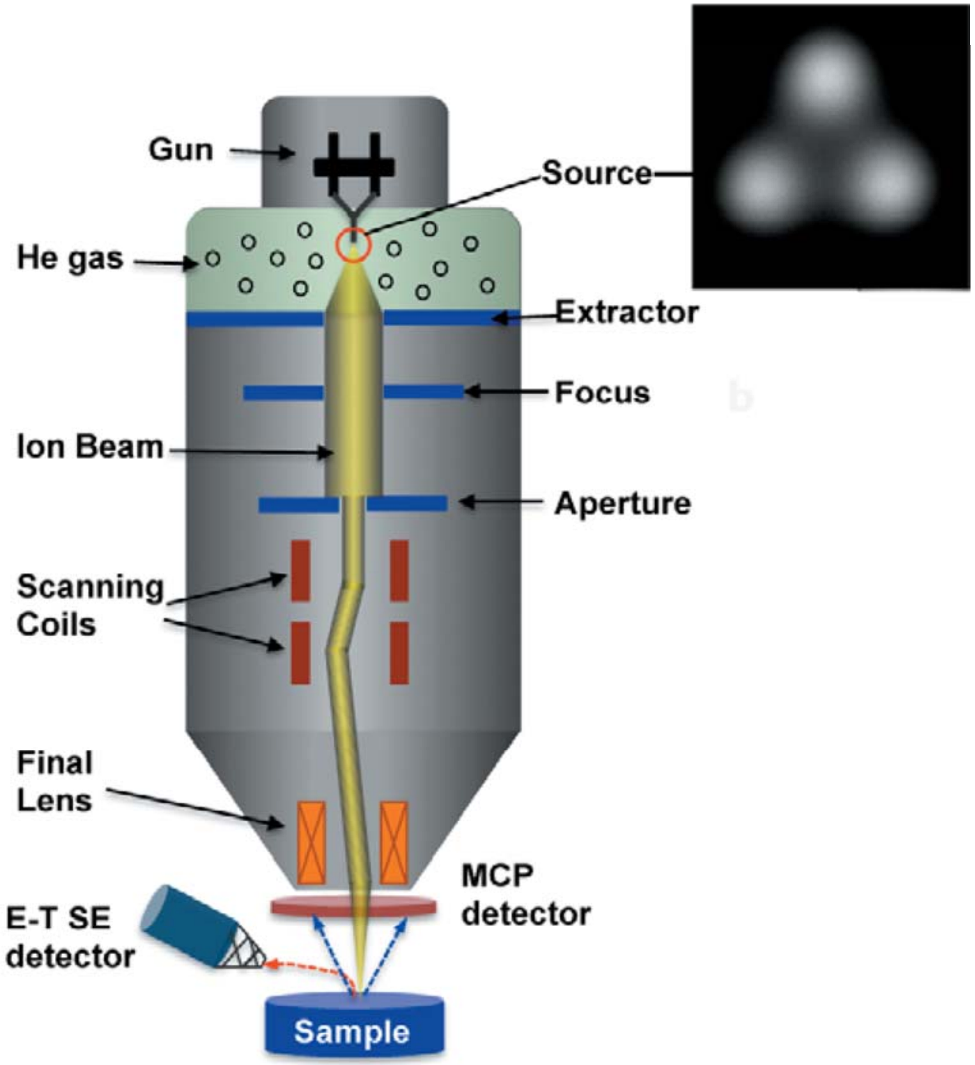
One single FIB

FIB + SEM = Dual Beam



Three FIBs = Multi FIB

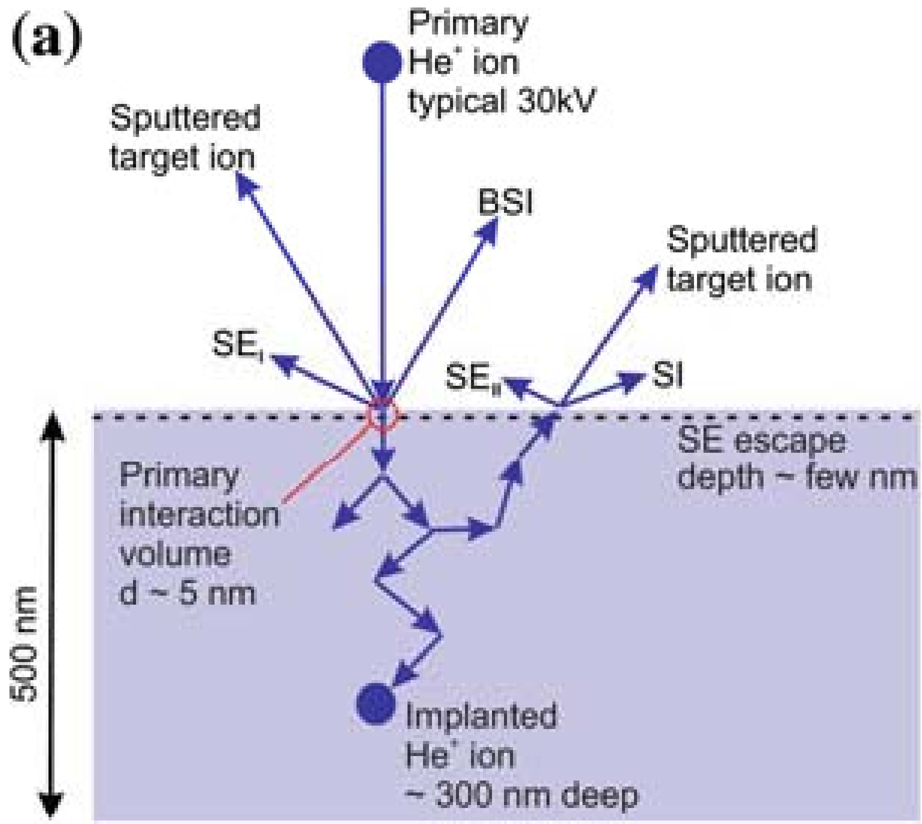
He$^+$/Ne$^+$ focused ion beam column



- **Advantages:**

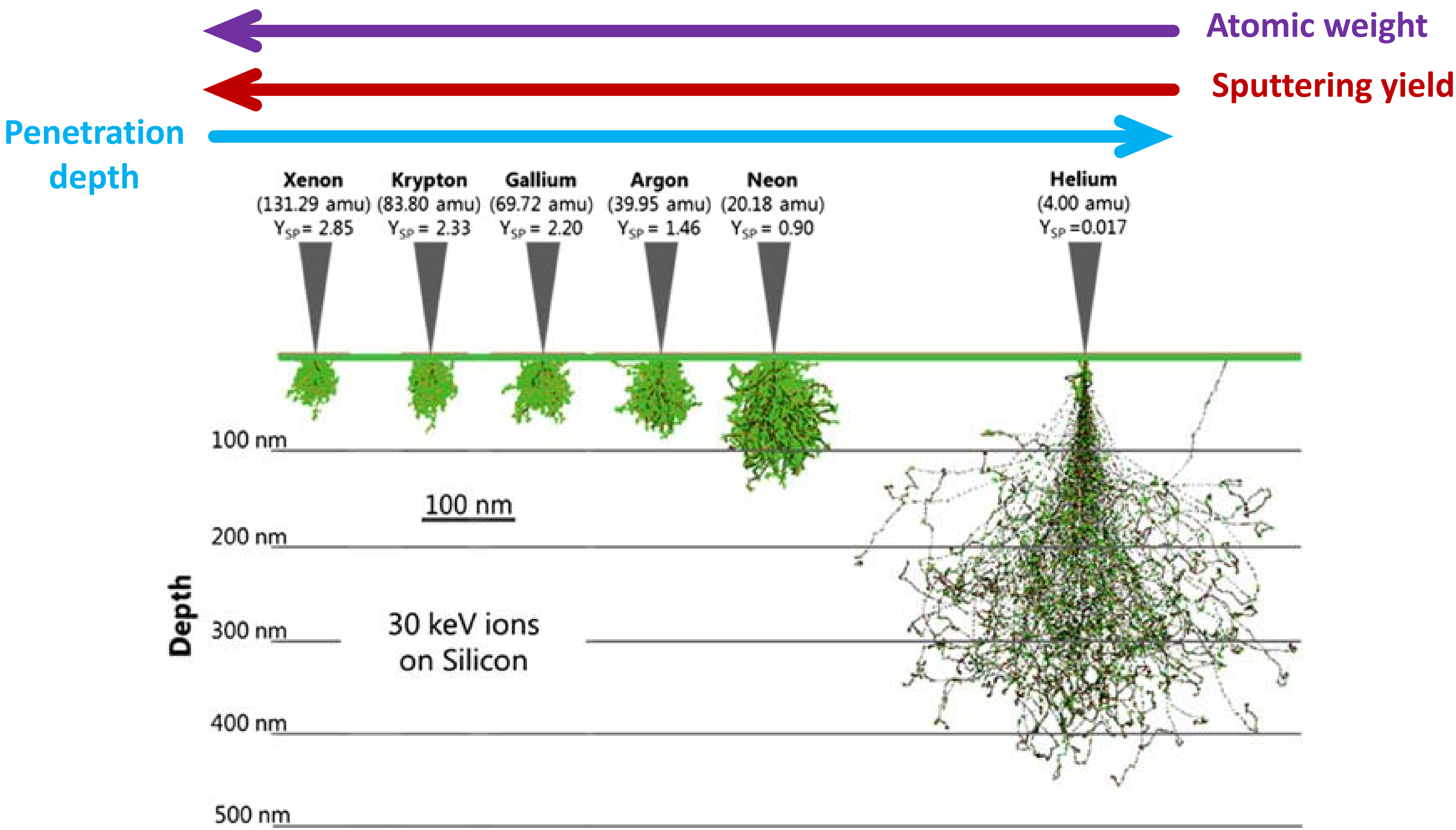
- higher resolution imaging, 2 nm
- lower proximity effect
- higher sensitivity
- milling of sub-10 nm structures
- growth of sub-10 nm structures

Interaction of ions with solid materials



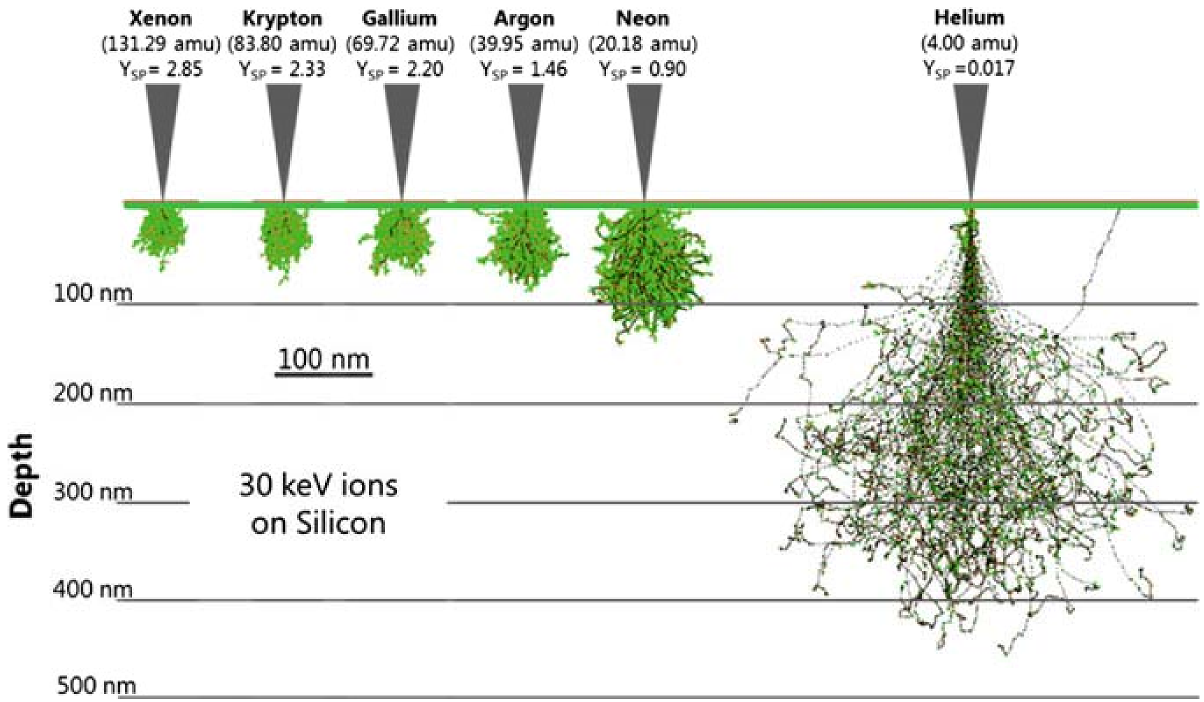
Shorubalko, book chapter in "Helium Ion Microscopy", Springer 2016

Interaction of ions with solid materials

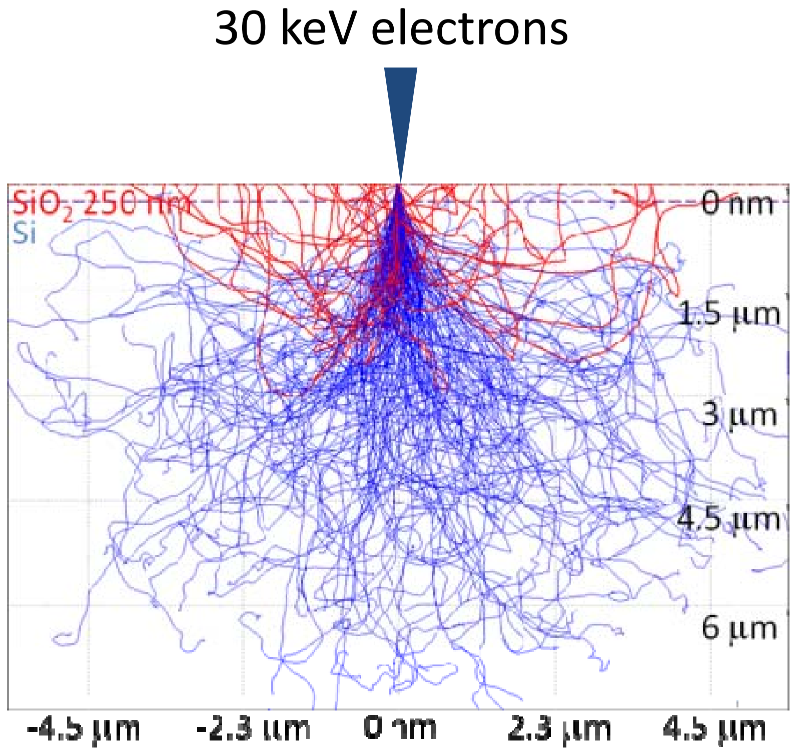


Shorubalko, book chapter in "Helium Ion Microscopy", Springer 2016

Interaction of ions vs. electrons with solid materials



Shorubalko, book chapter in "Helium Ion Microscopy", Springer 2016



The interaction of ions with matter is much shorter than in the case of electrons, thus being confined closer to the surface.

Focused Ion Beam Induced Processing (FIBIP)

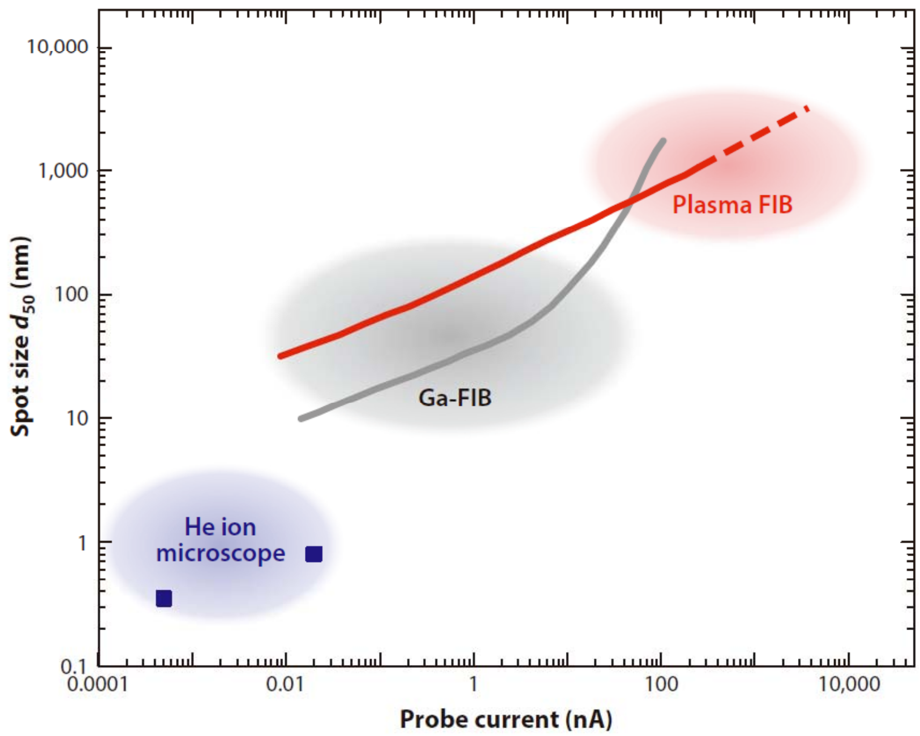
FIBIP:

- ***Nanolithography:***

FIB Induced Milling

- ***Nanofabrication:***

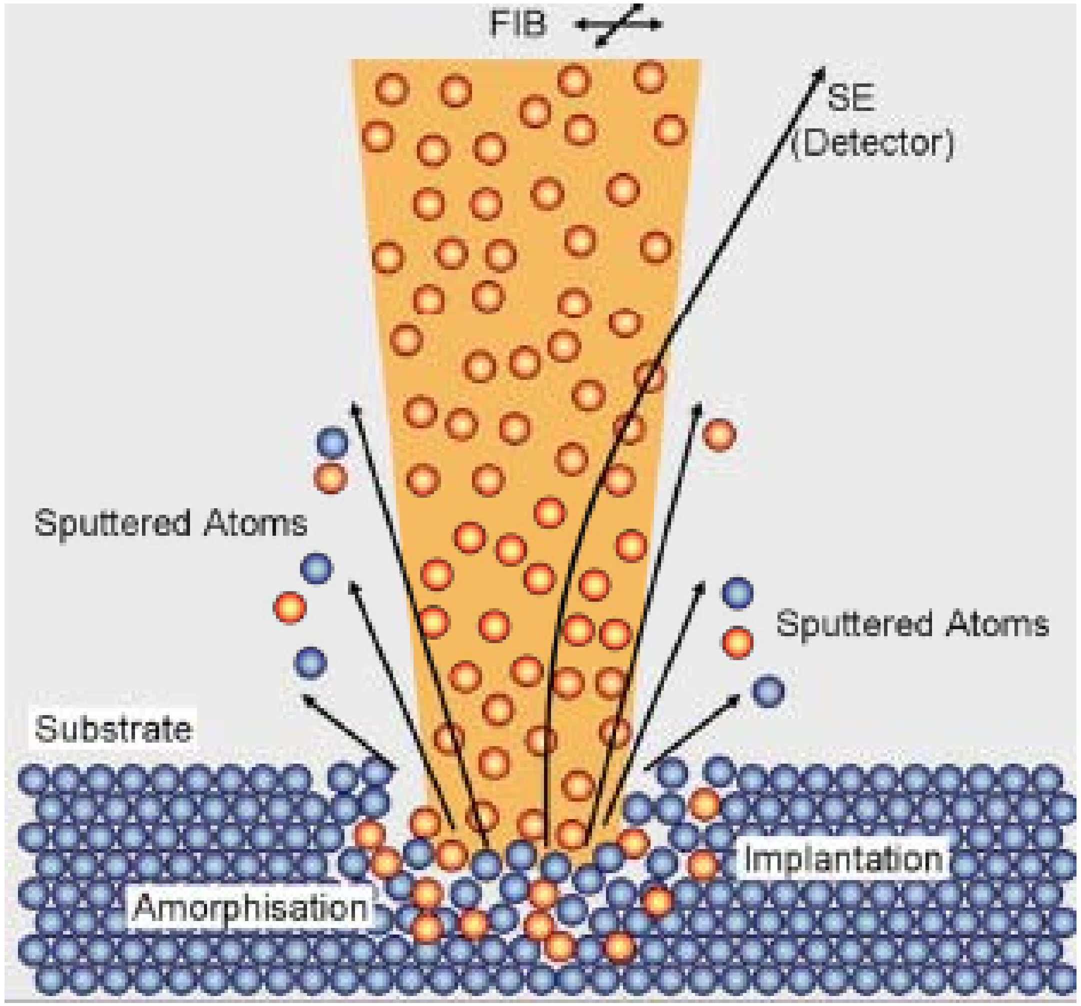
FIB Induced Deposition



Philip J.W. Moll , Annual Review of Condensed Matter Physics 2017

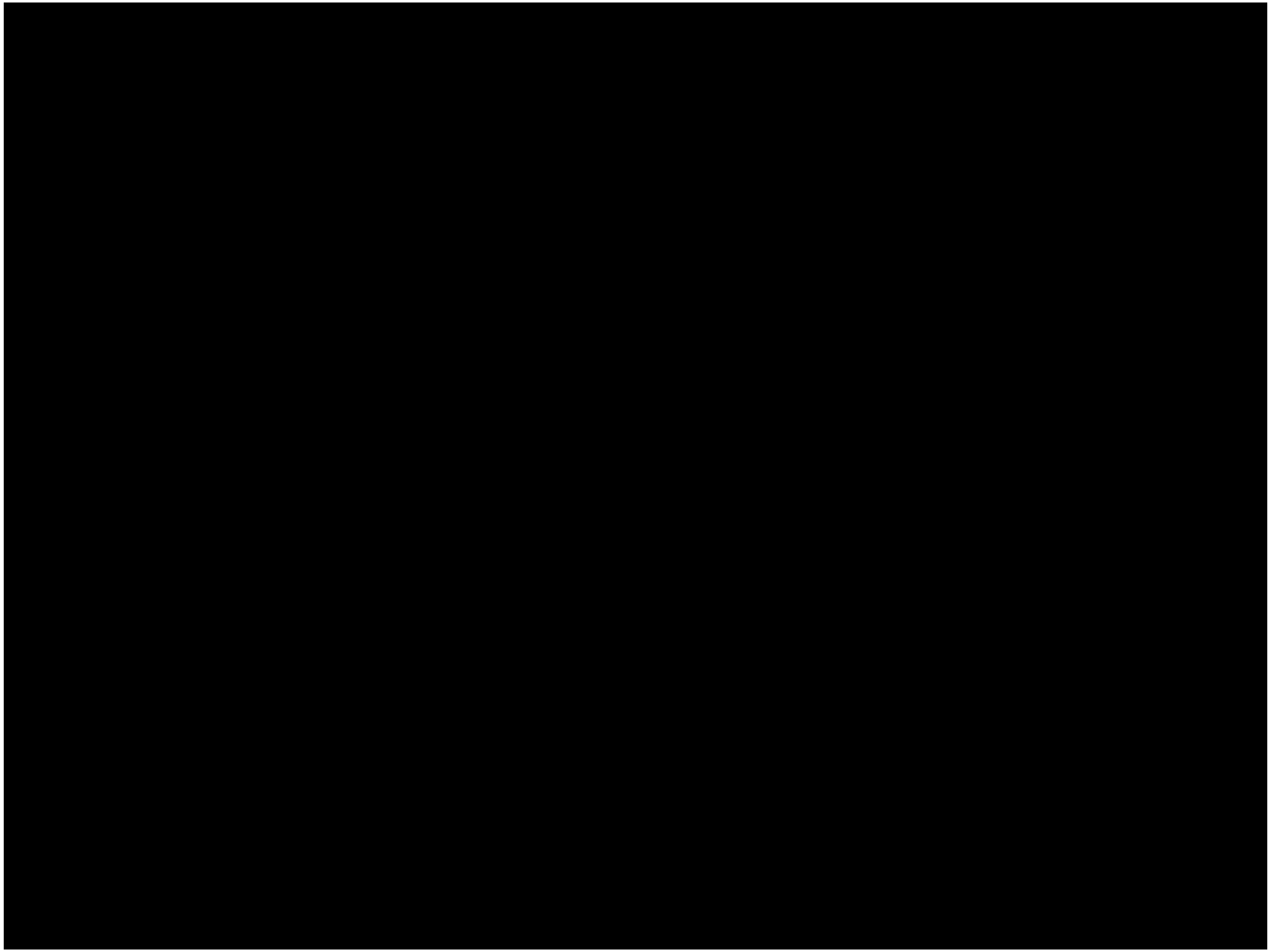
Nanolithography: *FIB induced milling*

Physical process: transfering momentum



Utke, JVSTB 2008

Nanolithography: ***FIB induced milling***



Nanofabrication: *FIB Induced Deposition*

APRIL 1, 1934 PHYSICAL REVIEW VOLUME 45

Insulating Films Formed Under Electron and Ion Bombardment

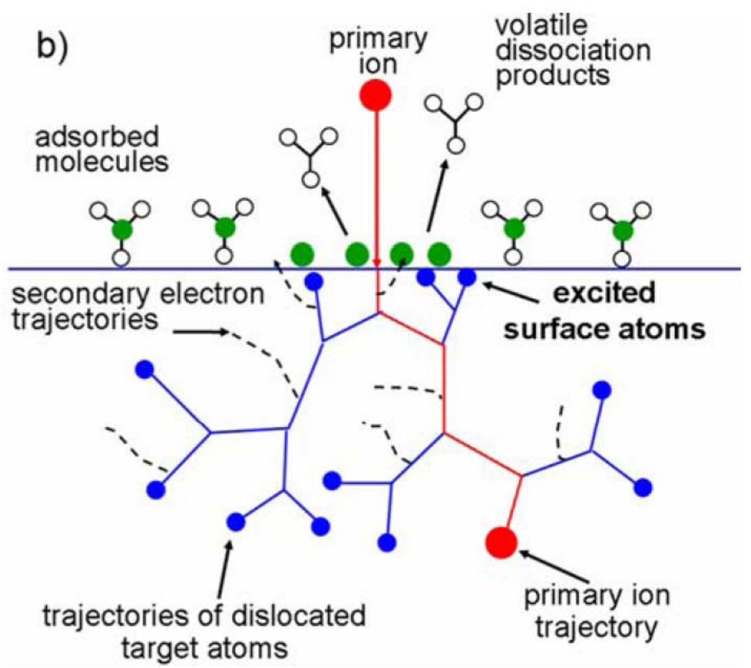
R. LARIVIERE STEWART, *Ryerson Physical Laboratory, University of Chicago*

(Received December 18, 1933)

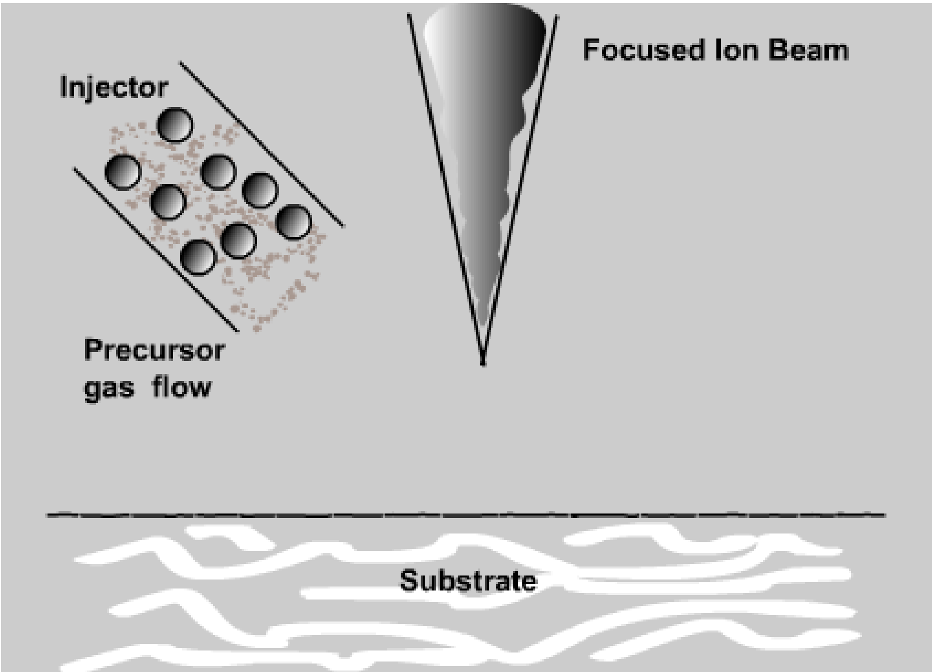
In an evacuated tube in which the slightest traces of organic vapors may occur, even with liquid air cooling, insulating layers are formed on surfaces subject to electron or canal-ray bombardment. These layers may be attributed to carbon compounds, and their formation is related to the polymerization of organic vapors by electrical discharges, α-particles, and ultraviolet light. The simple ion-deposition theory is inadequate as the layers are formed only at the point of impact of the rays on the surface. Electrical resistances and break-down potentials were observed for several films. The importance of these deposits in general experimental practice, such as the photometry of mass-spectra, is pointed out, and, amongst others, cases are cited of their influence producing contact potentials, pseudo high vacua, erroneous photographic recording and differential condensation of vapors upon previously bombarded surfaces.

Nanofabrication: *FIB Induced Deposition*

Focused ion beam induced deposition (FIBID)



Utke, J. Vac. Sci. Technol. B, 2008

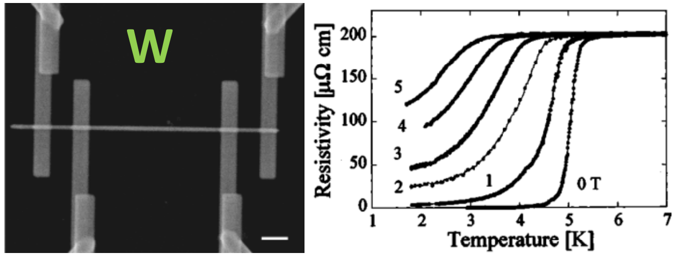


Ga^+ FIBID

APPLICATIONS: integrated circuit modification (circuit edit), mask repair, fabrication of small electrical contacts… Although generally the metallic content is not high enough (at. % 40-80) impairing the applications of the technique.

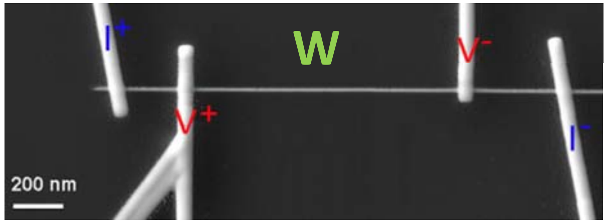
Nanofabrication: *FIB Induced Deposition*

Focused ion beam induced deposition (FIBID)



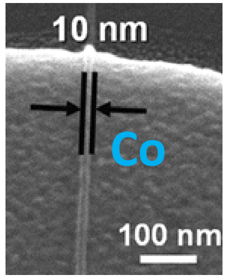
Sadki, APL 2004

Ga⁺ FIBID lateral resolution: ***19 nm***

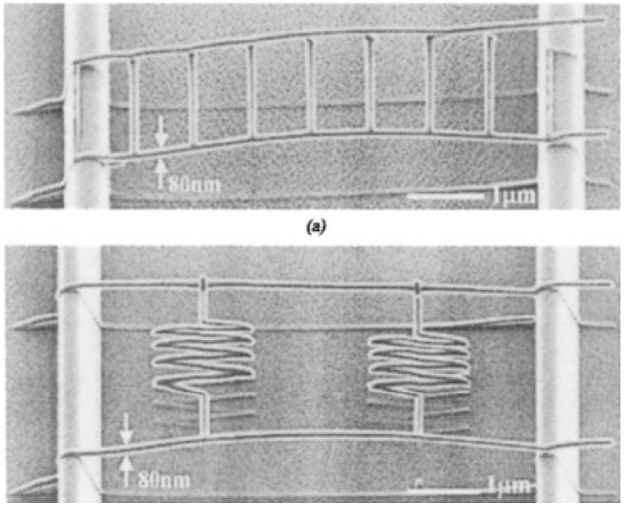


W. Li, Micr. Eng. 2011

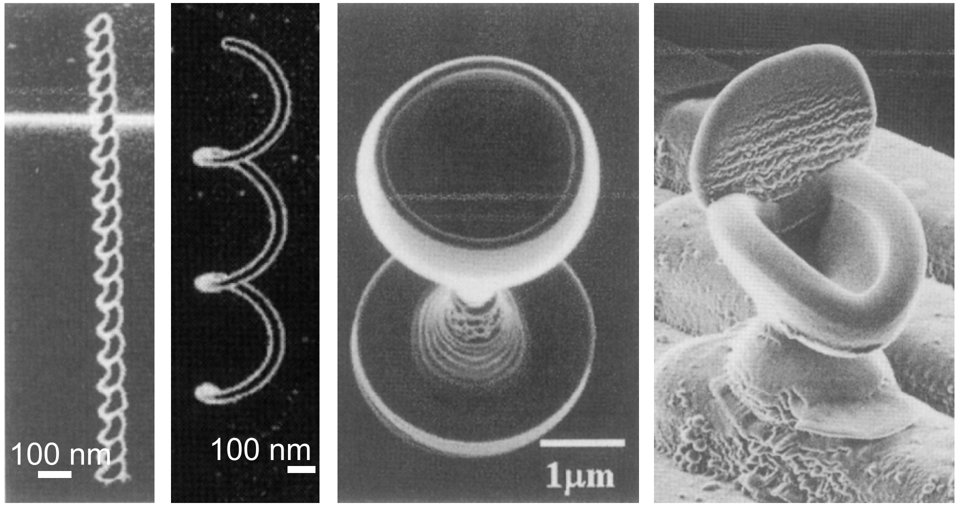
He⁺ FIBID lateral resolution: ***10 nm***



H. Wu, J. Mat. Sci. 2014



Morita et al. 2003



Giannuzzi et al. 2005

W, Pt, Co, Pd, C,… metals, ferromagnets, superconductors

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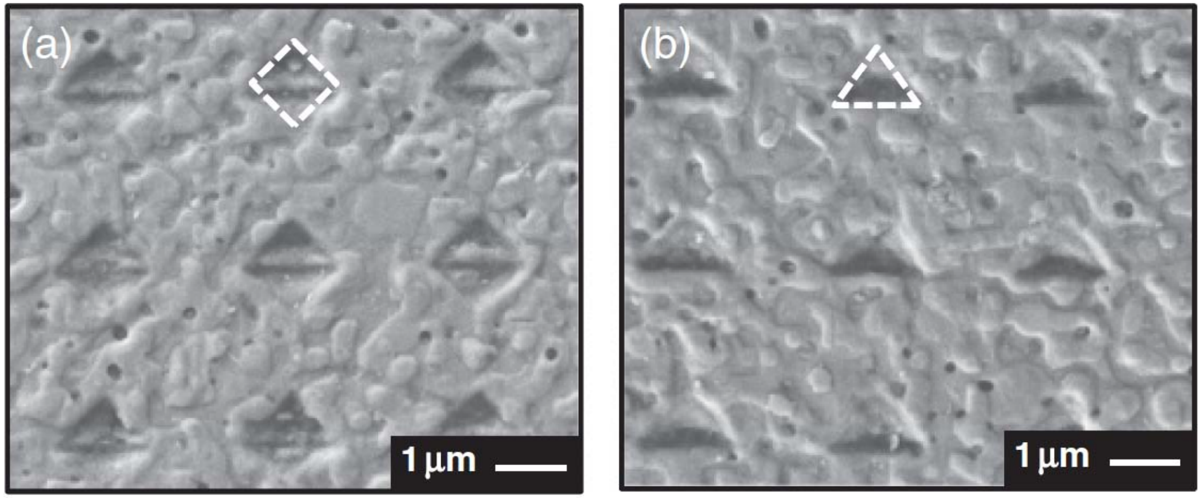
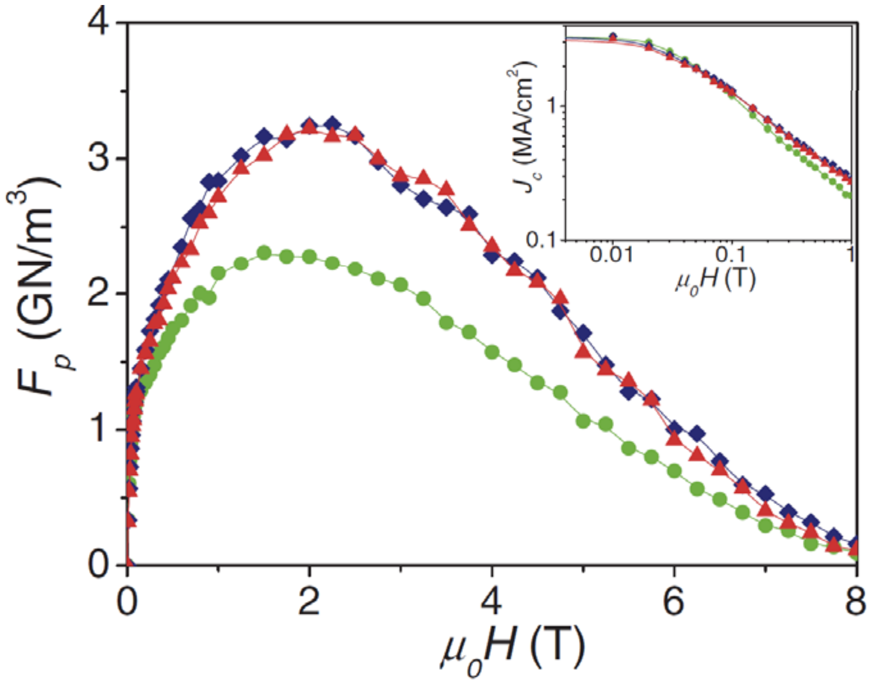
Nanolithography: ***FIB Induced Milling*** applied to nanosuperconductivity

Example of vortex pinning in high-temperature $YBa_2Cu_3O_7$ thin films patterned with an array of antidots

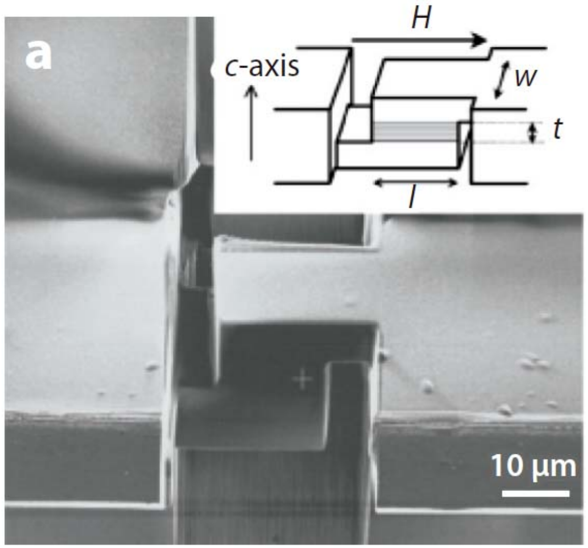




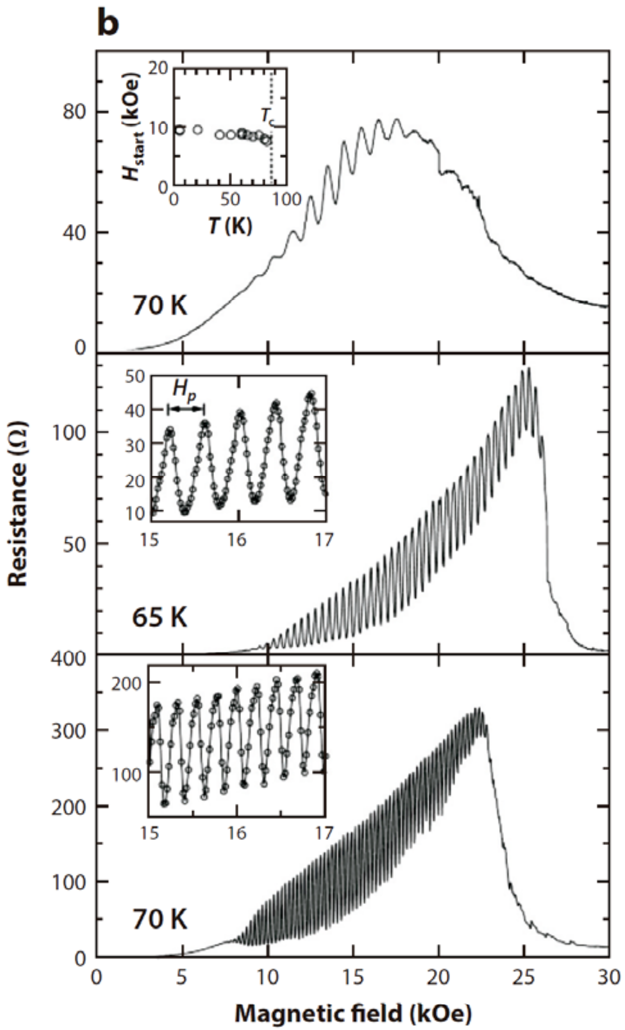
A. Palau et al. PHYSICAL REVIEW B 85, 012502 (2012)

Nanolithography: *FIB Induced Milling* applied to nanosuperconductivity

Example of structures for intrinsic Josephson physics



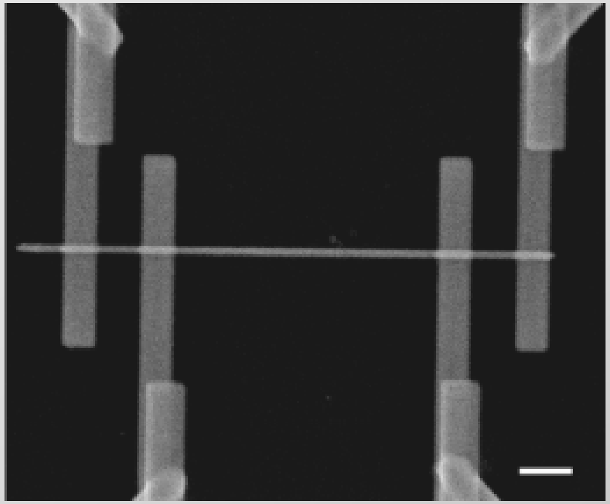
Bi2Sr2CaCu2O8+*y*

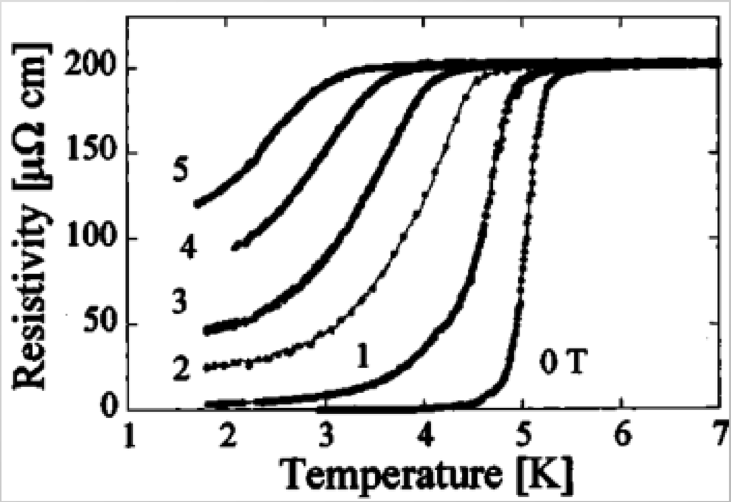


S. Ooi et al. Phys. Rev. Lett. 2002

Nanofabrication: *FIB Induced Deposition* applied to nanosuperconductivity

- **Superconducting deposits grown by Ga^+ FIBID**



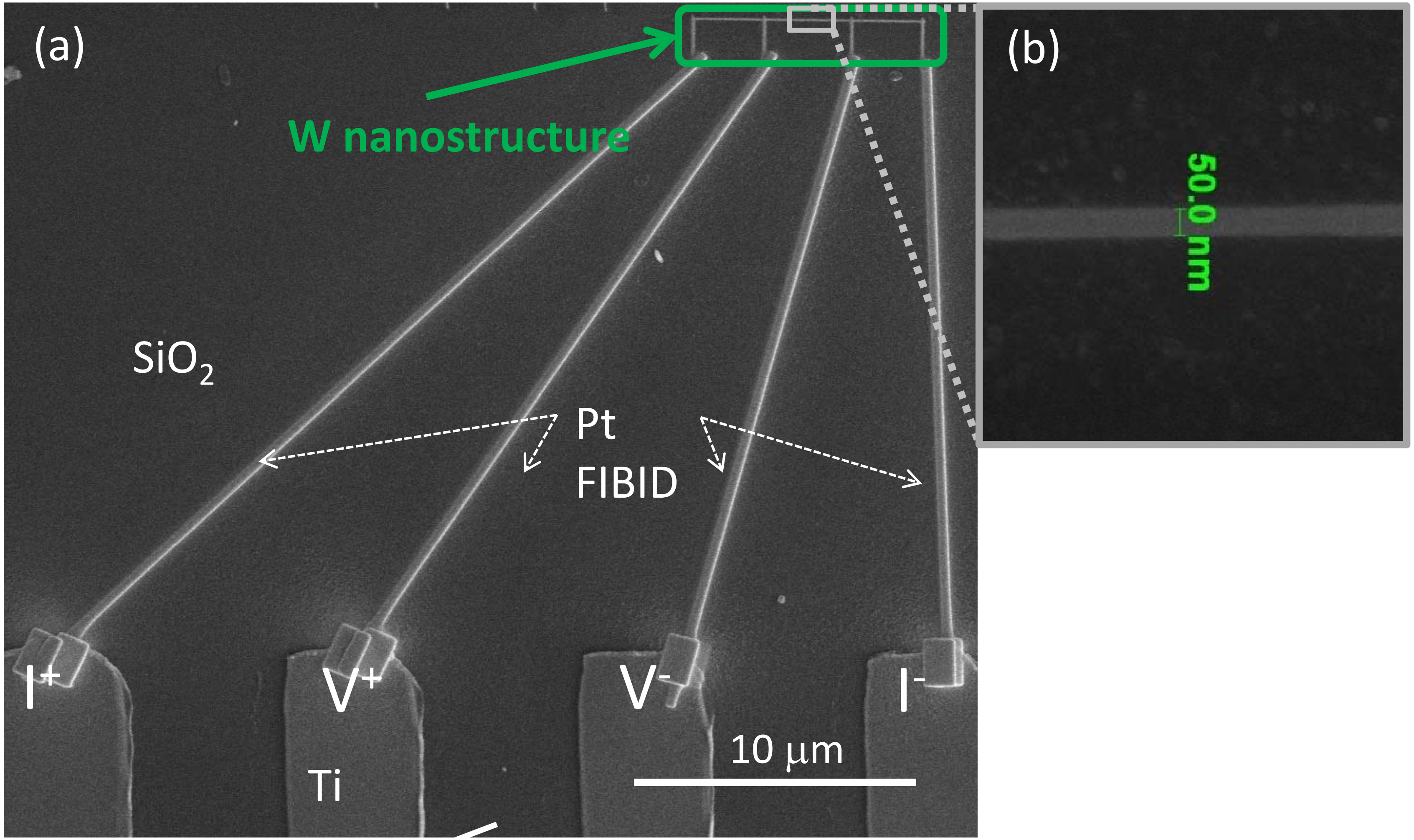


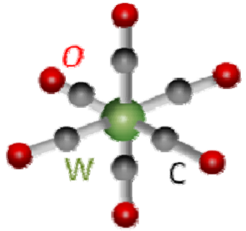
Sadki, APL 2004

- Type II superconductor
- $T_c \sim 5$ K
- B_{c2} (0K) > 9 T

Nanofabrication: ***FIB Induced Deposition*** applied to nanosuperconductivity

Example of <u>superconducting</u> nanowires: WC Ga^+ FIBID

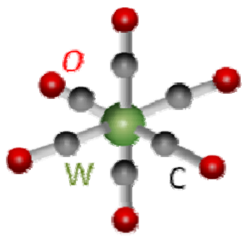




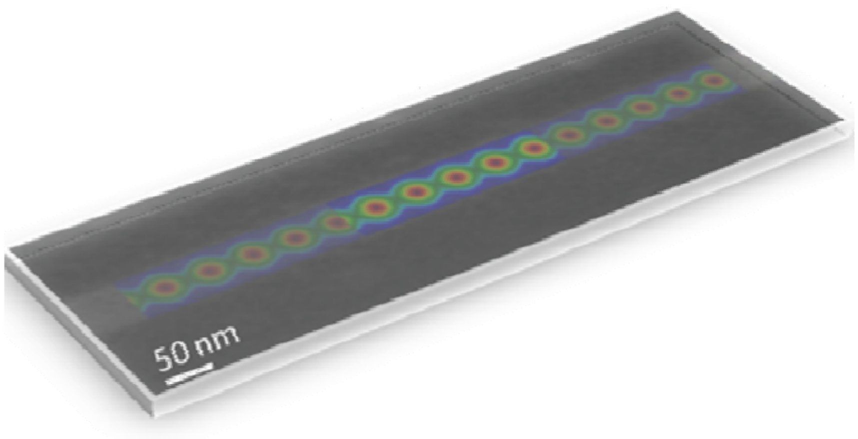
R. Córdoba et al., Nature Comm. 2013

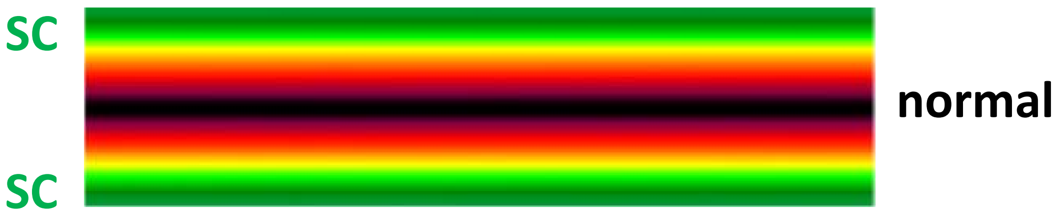
Nanofabrication: *FIB Induced Deposition* applied to nanosuperconductivity

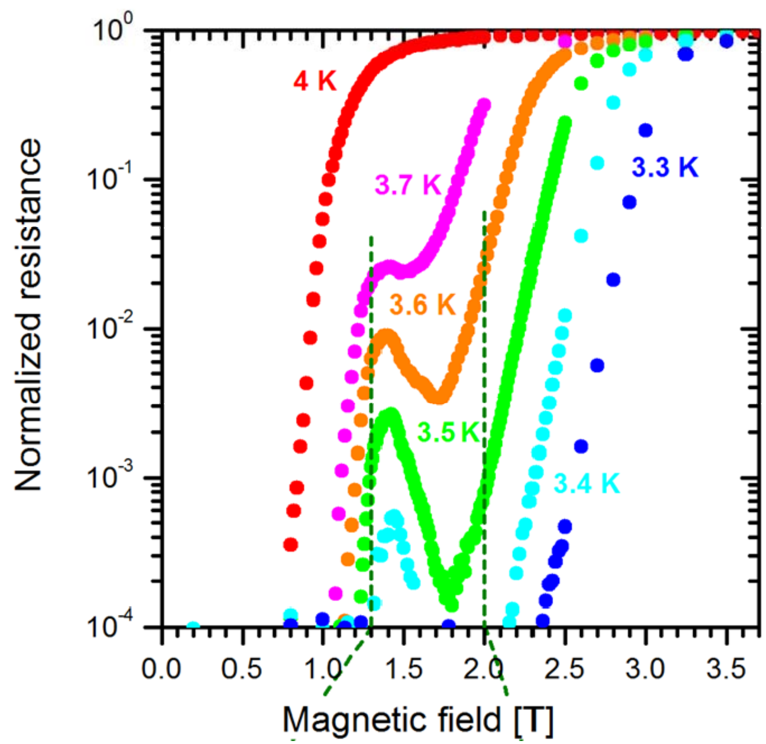
Example of superconducting nanowires: WC Ga^+ FIBID



Re-entrance of the superconductivity



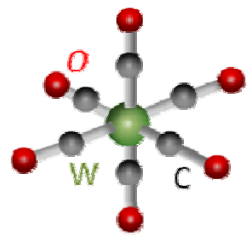




R. Córdoba et al., Nature Comm. (2013)

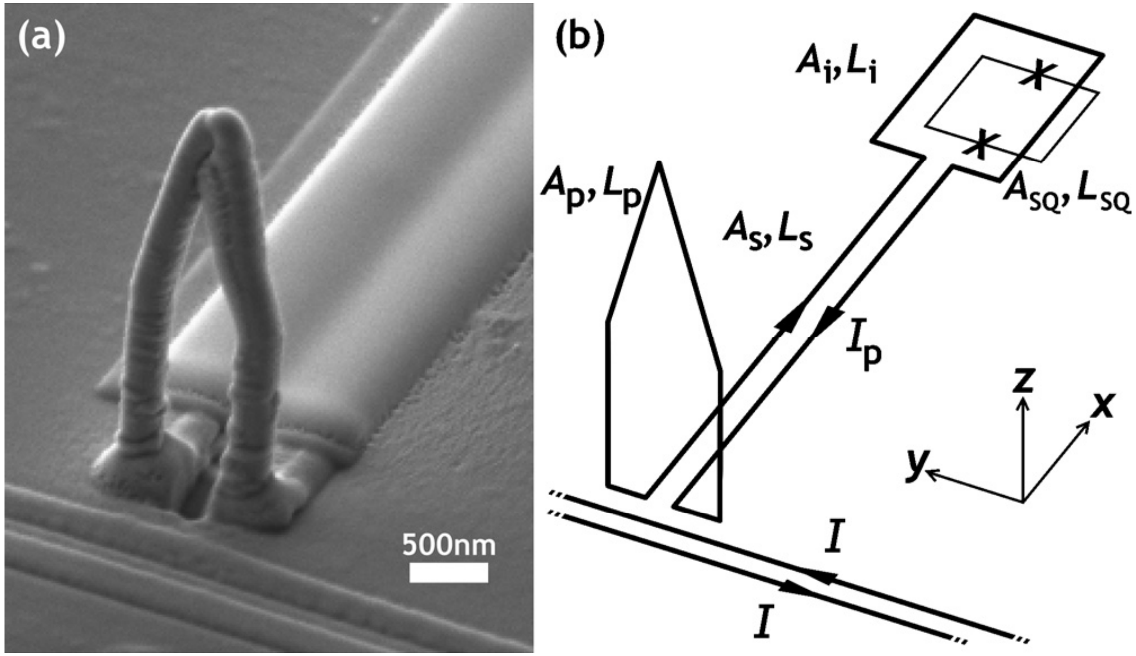
Nanofabrication: *FIB Induced Deposition* applied to nanosuperconductivity

Example of 3D SC quantum interference device (SQUID) pickup loops: WC Ga^+ FIBID



W-C NWs grown by **Ga^+ FIBID**:

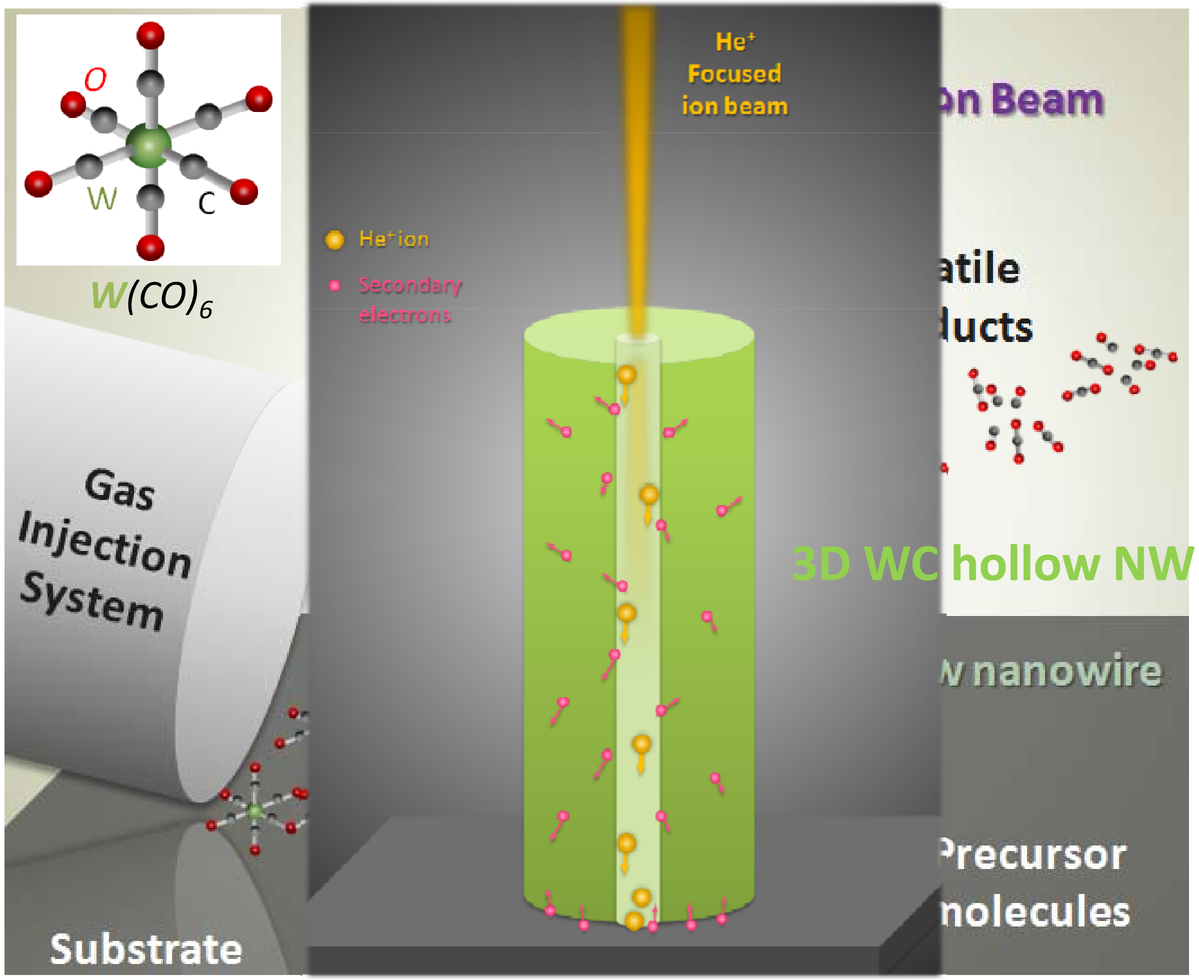
T_c~ 5.4 K, J_c(4.2K)~ 0.4 MA/cm^2



Romans et al., Appl. Phys. Lett. 97, 222506 (2010)

Nanolithography and Nanofabrication: ***FIBIP*** applied to nanosuperconductivity

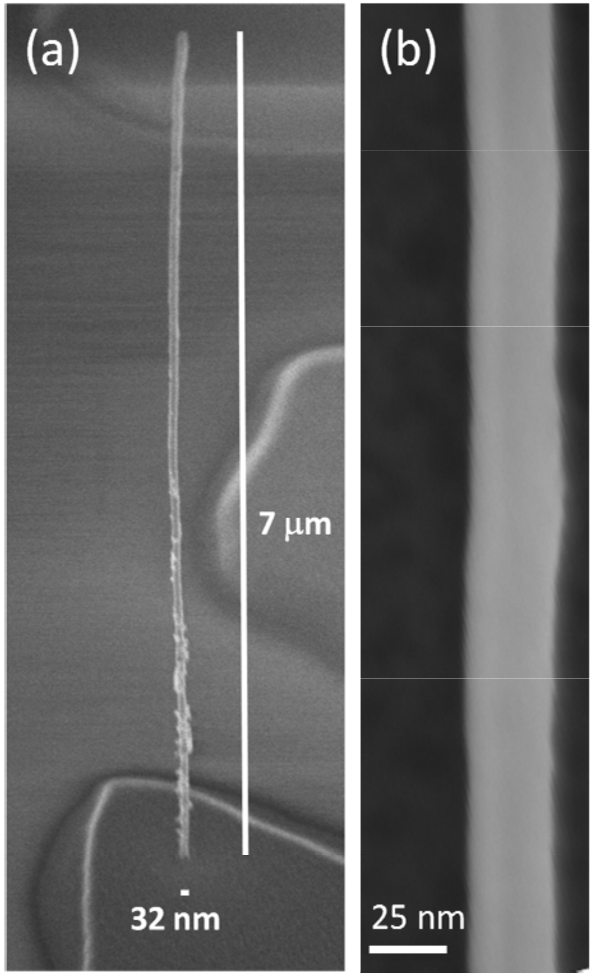
Example of 3D superconducting hollow nanowires: WC He^+ FIBID



R. Córdoba et al., Nano Letters 2018

Nanolithography and Nanofabrication: ***FIBIP*** applied to nanosuperconductivity

Example of 3D superconducting hollow nanowires: WC He^+ FIBID



30 kV	
1.15 pA	1.34 pA
32 nm	70 nm
21.2 nm/s	6.4 nm/s
0.015 $\mu m^3/nC$	0.018 $\mu m^3/nC$

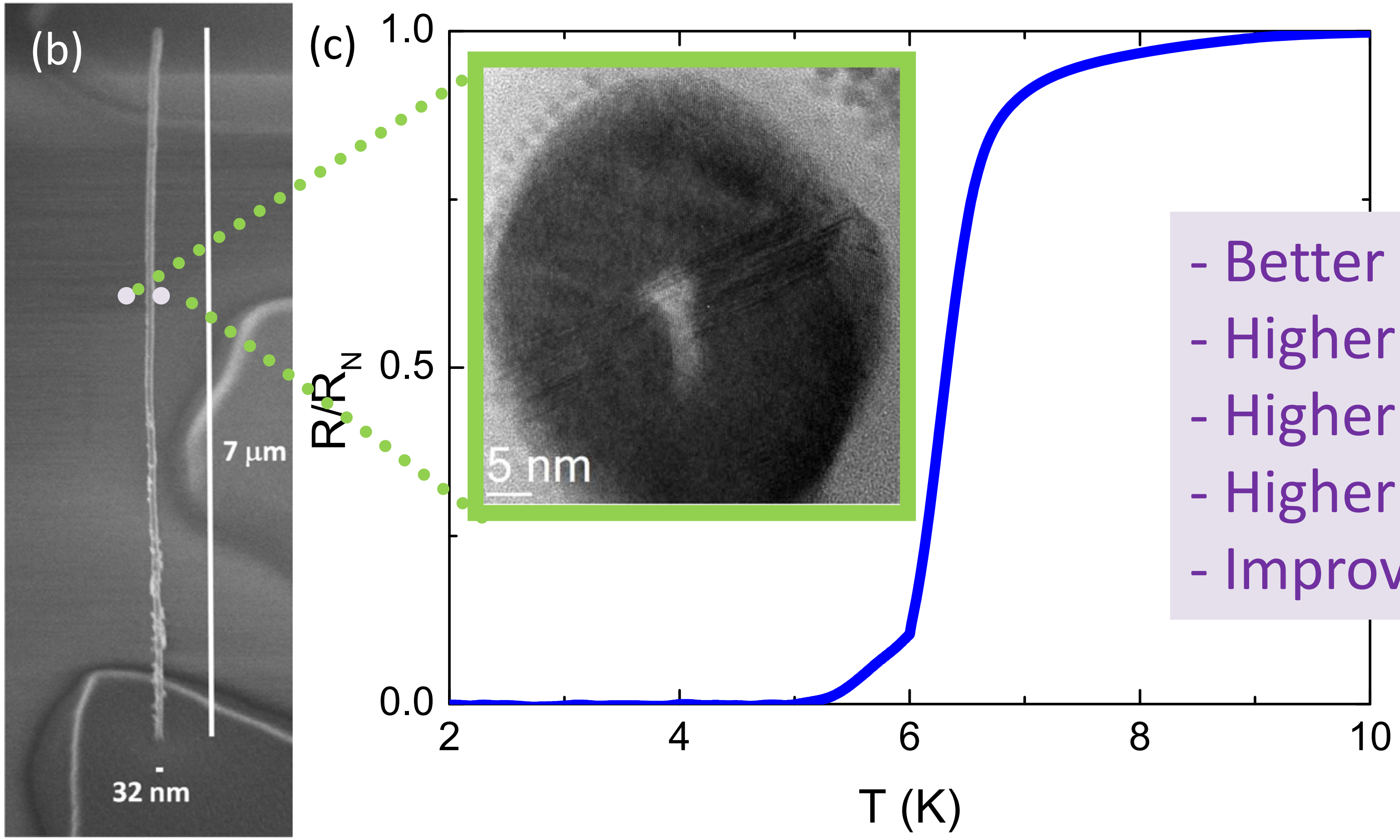
3D WC nanowires:
- *d* down to **32 nm**
- AR (***l/d***)≈ **200**

Volume per dose:
- similar to Ga^+ FIBID.
- **10^3** times **higher** than FEBID

Smallest hollow nanowire has been fabricated so far.

Nanolithography and Nanofabrication: ***FIBIP*** applied to nanosuperconductivity

Example of 3D <u>superconducting</u> hollow nanowires: WC He^{+} FIBID



- Better resolution
- Higher aspect ratio
- Higher crystallinity
- Higher purity
- Improved SC properties

R. Córdoba et al., Nano Letters 2018

Cathedral-Basilica of Our Lady of the Pillar
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Thank you very much for your attention