Magnetic control over spin-triplet supercurrents

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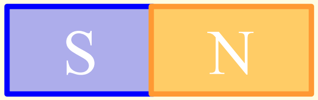
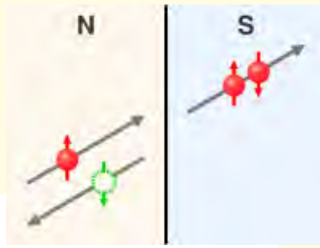
- Long-range spin-triplet supercurrents exist, generated by magnetic inhomogeneities
- Control **supercurrent** = control **generator**

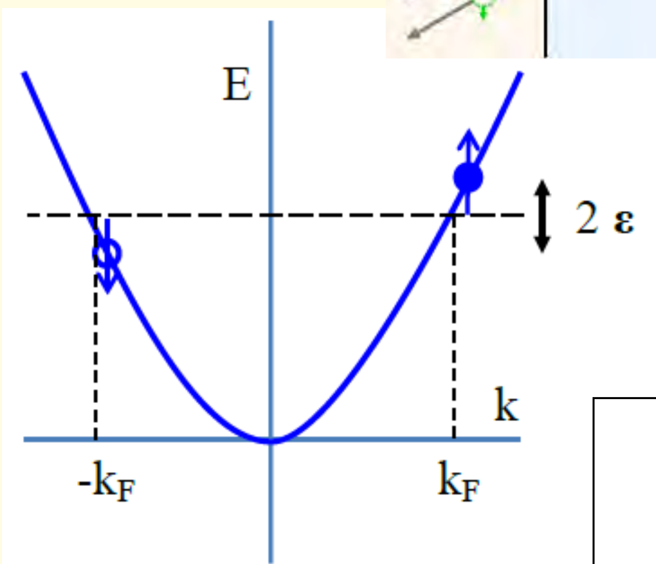
1. **CrO_2** (HFM) : devices based on **wires**
   with ***Amrita Singh***
2. **Co** (FM) : device based on a **disk**
   with ***Kaveh Lahabi*** (Leiden) , *Paul Alkemade* (Delft) , and *Morten Amundsen, Ali Ouassou* , *Jacob Linder* (Trondheim)

and on good interfaces

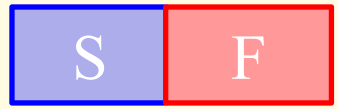
From normal current to supercurrent : Andreev reflections

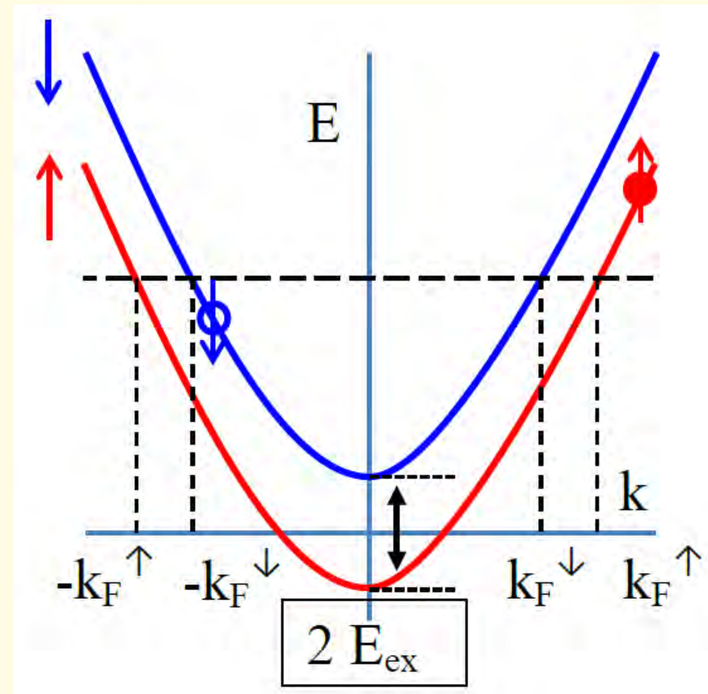






$\tau = \hbar / 2\varepsilon$





$k_F^{\uparrow} - k_F^{\downarrow} \equiv Q = 2E_{ex} / \hbar v_F$

Electron-hole decoherence in N, F

$$\xi_N = \sqrt{D_N \tau} = \sqrt{\frac{\hbar D_N}{2\pi k_B T}}$$

diffusive

$$= \sqrt{\frac{\hbar D_F}{2E_{ex}}}$$

So, ***singlet pairs in F :*** $E_{ex} \approx 1\ eV\ (Ni) \rightarrow \xi_F \approx 1\ nm$

The Long Range effects: **odd-frequency triplets**

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Symmetry of the ***pair correlation function*** $F(r_1 - r_2 ; s_1 ; s_2 ; t_1 - t_2)$:

F is **odd** under exchange of **space, spin,** $\boxed{\textit{time}}$ (Berezinskii, 1974)

$\Rightarrow$ ‘Pauli’ can be circumvented with negative **time**/ **frequency**

Spin	Orbit	ω	occurs
odd, $\uparrow\downarrow - \downarrow\uparrow$	**even,** 	**even**	**Nb, YBCO**
even, $\uparrow\uparrow \quad \downarrow\downarrow$	**odd,** 	**even**	**^3He, Sr_2RuO_4**
even, $\uparrow\uparrow \quad \downarrow\downarrow$	**even,** 	**odd,**	**s-wave triplet in F is possible !**

Triplet pair in F not broken by exchange : $\xi_F^{triplet} \propto \sqrt{D_F / k_B T}$ **!**

(Bergeret, 2001
Kadigrobov, 2001)

How to make it ?

With ‘spin-active’ interface

Make triplets; requires inhomogeneous magnetization

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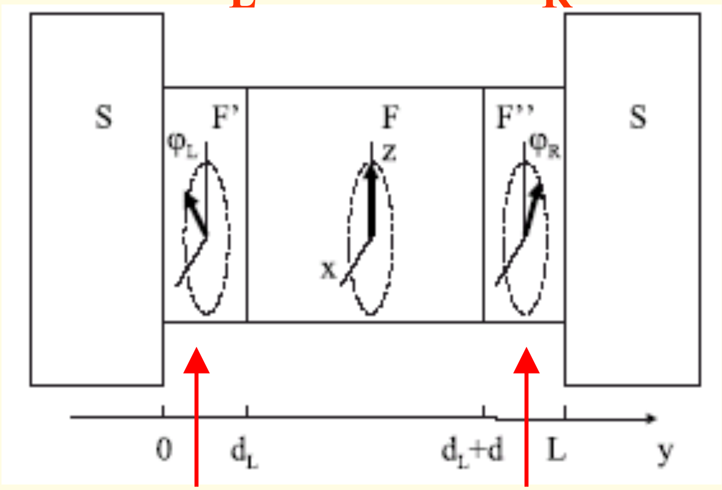
Spin mixing by spin-dependent scattering

Rotation of the quantization axis

singlet $|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$ $\rightarrow$ **m=0 triplet** $|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$ $\rightarrow$ **m=1 triplet** $|\uparrow\uparrow\rangle$, $|\downarrow\downarrow\rangle$

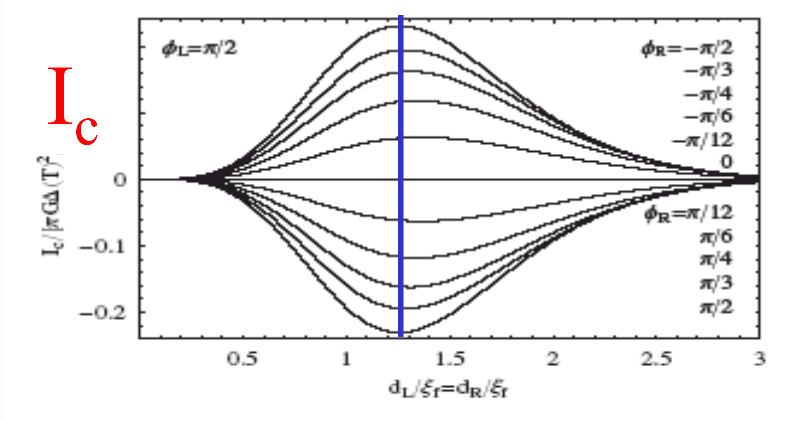
- Bergeret (2001) : mix / rotate in domain wall
- Houzet / Buzdin : mix / rotate with different F's ; 0- or π-junction

S / F_L / F / F_R / S



φ_L φ_R

optimum $d_{L,R}$

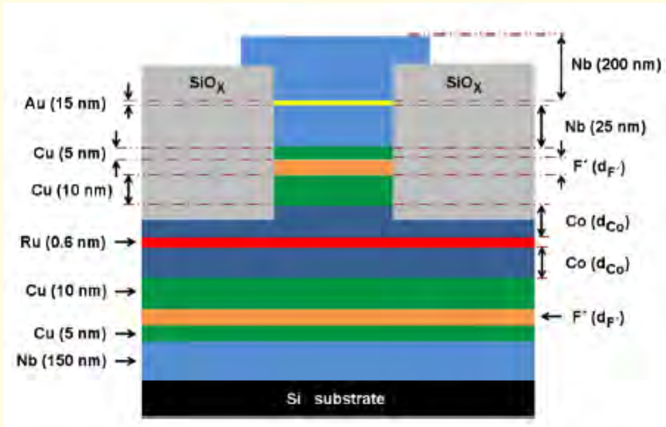


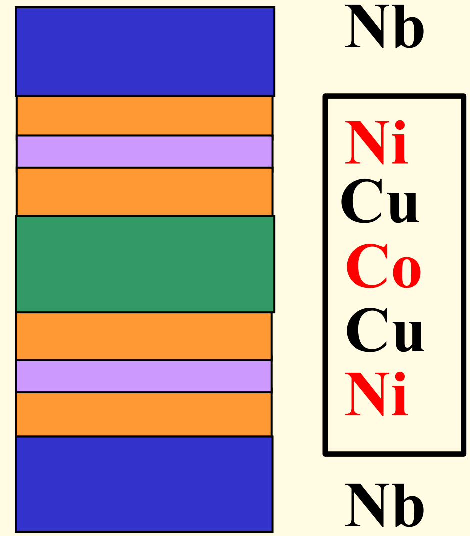
$\varphi_L = +\pi/2$; $\varphi_R = -\pi/2 .. +\pi/2$

Implement the inhomogeneity : **triplets in Co**

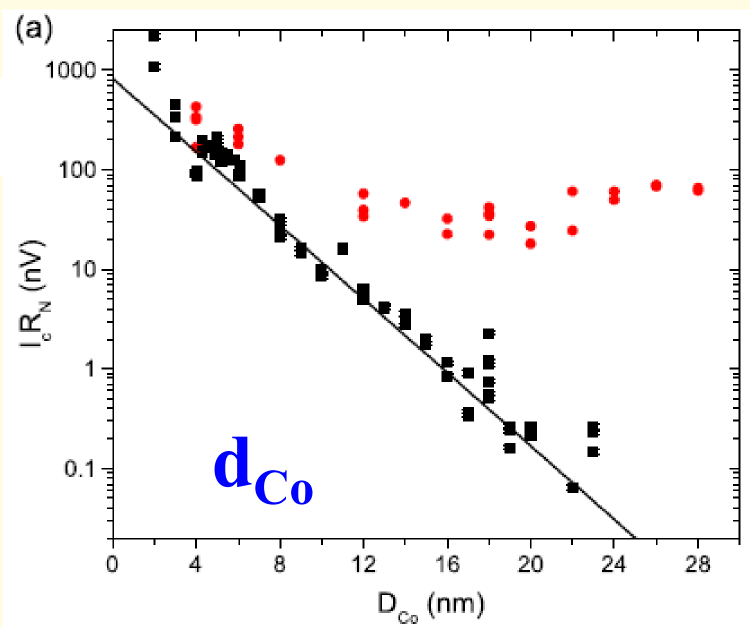
Stacked junctions

Khaire et al., PRL 2010
Klose et al., PRB 2012





I_cR_N



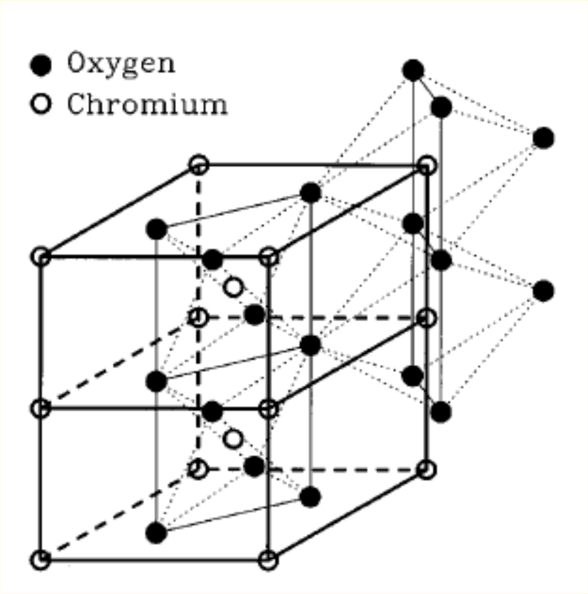
Junction length d_{Co} > 30 nm !

‘Leiden triplets’

Material of choice : CrO_2

P = 100 %

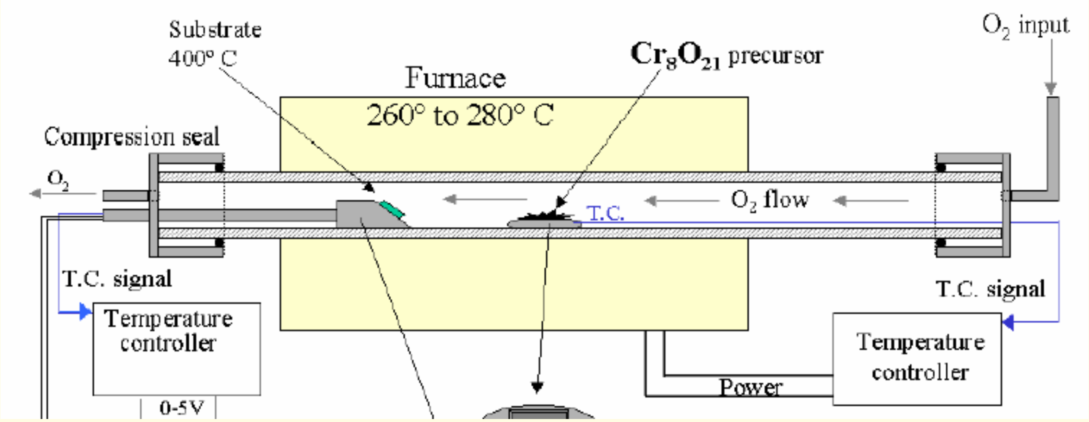
- CrO_2 , Cr^{4+} : $4d^2$, S = 1
- **$T_C \approx 390$ K,**
- **$M_S = 2\ \mu_B$ / Cr**



tetragonal rutile structure

Metastable oxide

fabricate : *only CVD, **best on TiO_2***

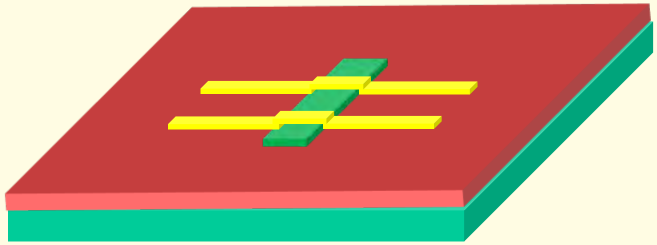


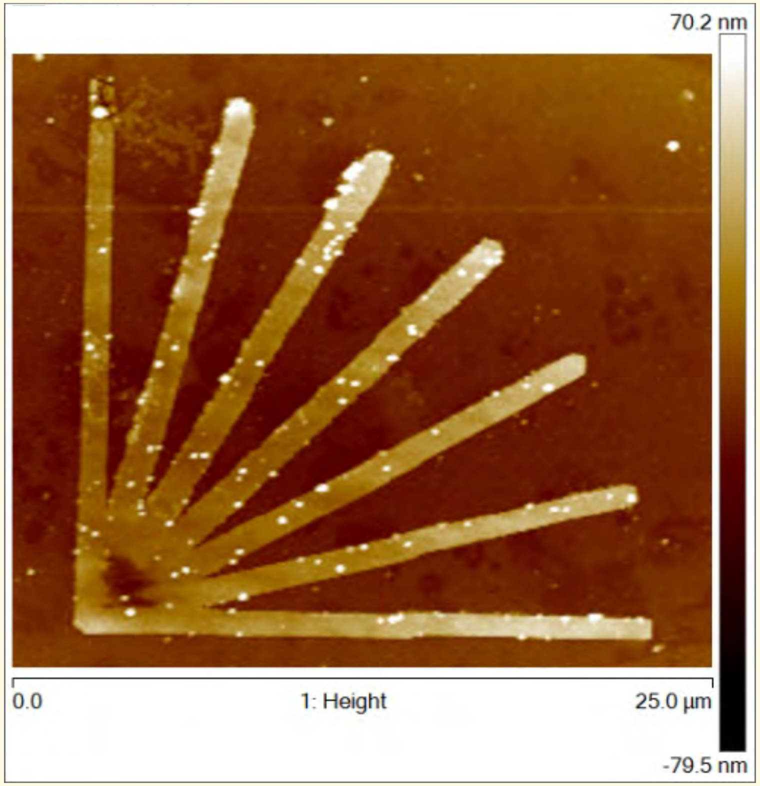
$\xi_{F,singlet} \approx 1\ nm$

- S contacts are **not** grown in-situ

Full films of CrO_2 is a (device) hindrance

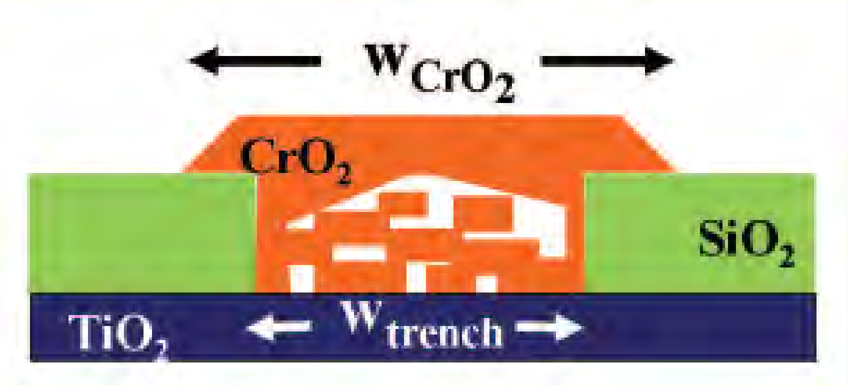
Solution : ***selective area growth***



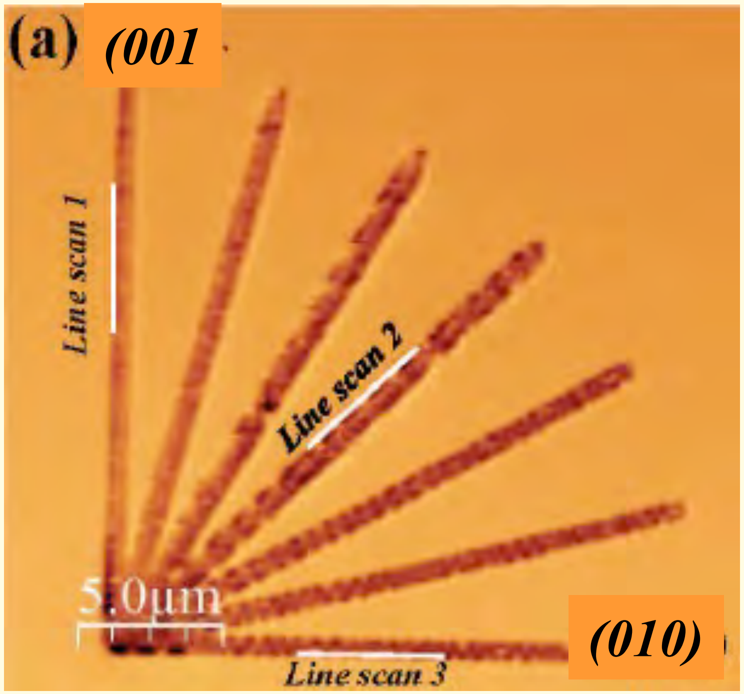


grow in different directions

Growth = ‘overgrowth’: gives very clean surfaces

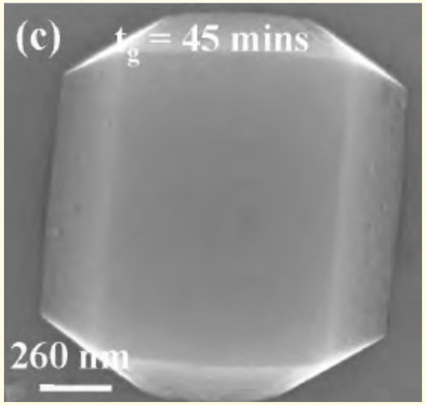


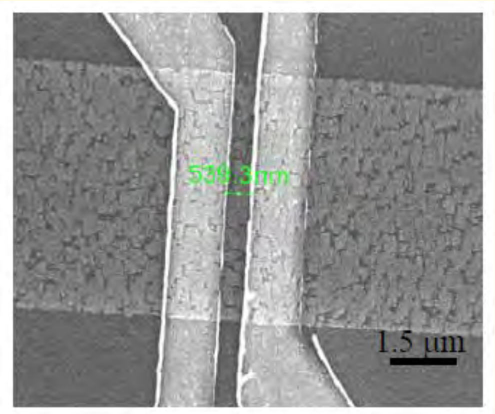
easy axis or
hard axis



high crystallinity

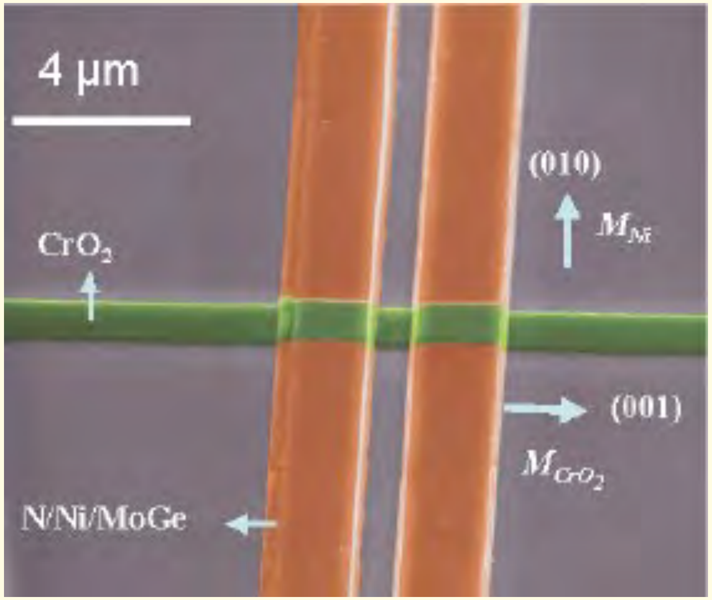
better than
etched films

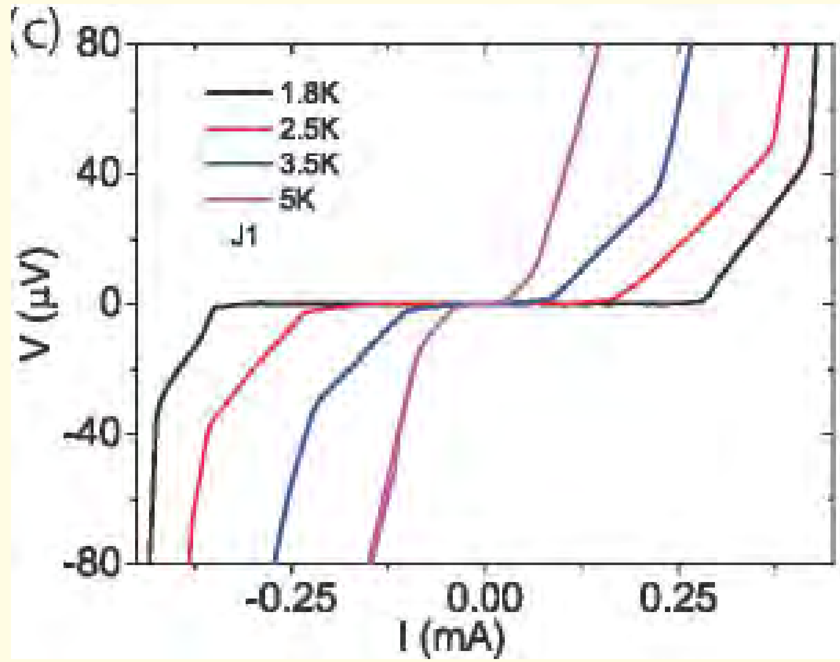




A wire-based device :

1 μm wide, gap : 600 nm
contacts Cu/Ni/MoGe





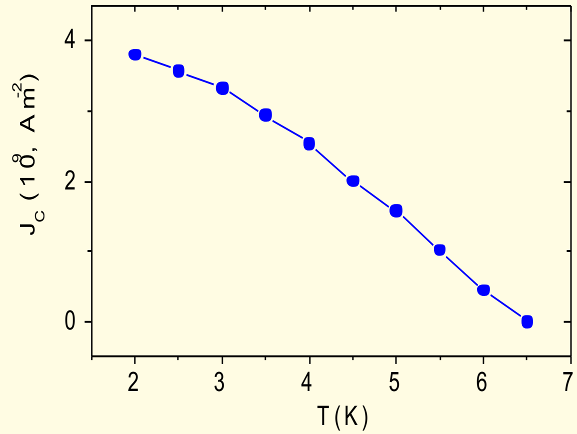
- wire along easy axis
- built-in perpendicular magnetizations between wire and contacts.
- π - junction ?

$J_c > 10^9$ A/m^2 @ 4 K
record-large
(over 600 nm)

Singh *et al, PR X6, 2016*

Magnetic control

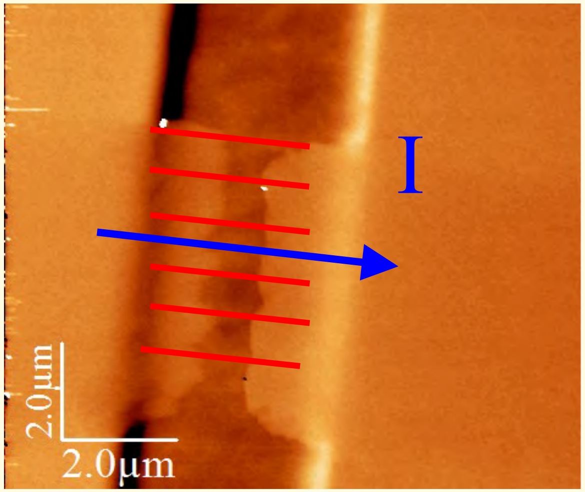
transverse junction on
a hard-axis (010) wire ;
stack is CrO_2 / Cu / MoGe

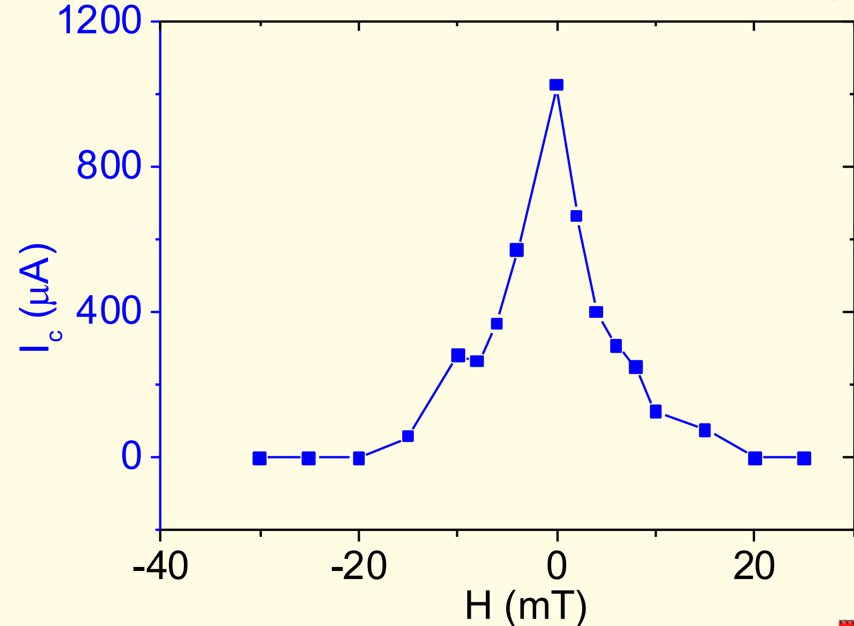


Clear I_c

sensitive to a
small field

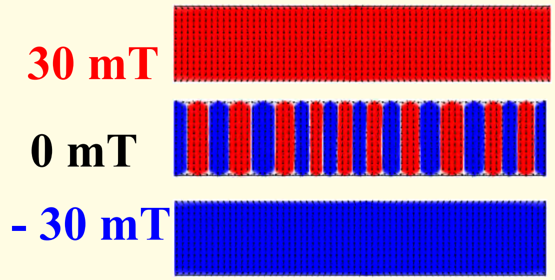
No **Ni !**





1 μ - sized domains

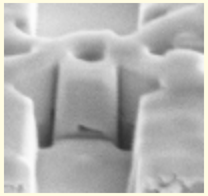
simulation



The supercurrent is
generated and **switched**
by the domain structure

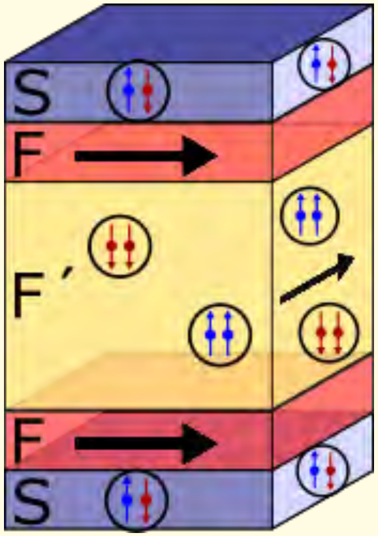
A Co-based planar triplet device

Kaveh Lahabi



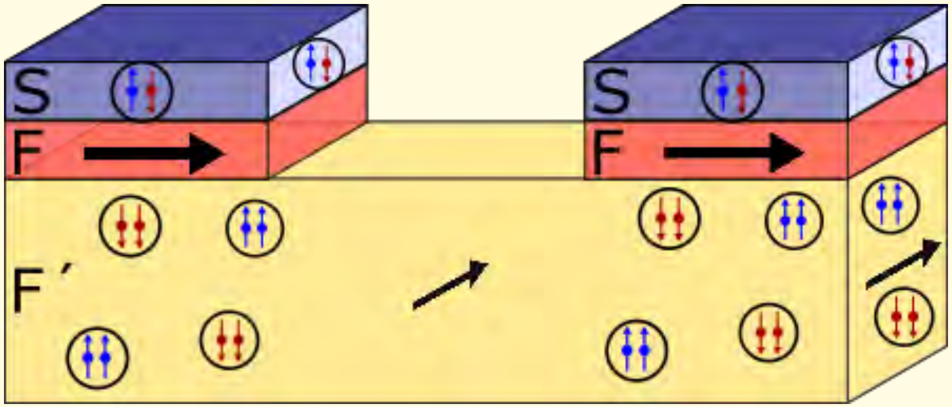
Sr_2RuO_4

Stacks



Difficult to have
F-layer control

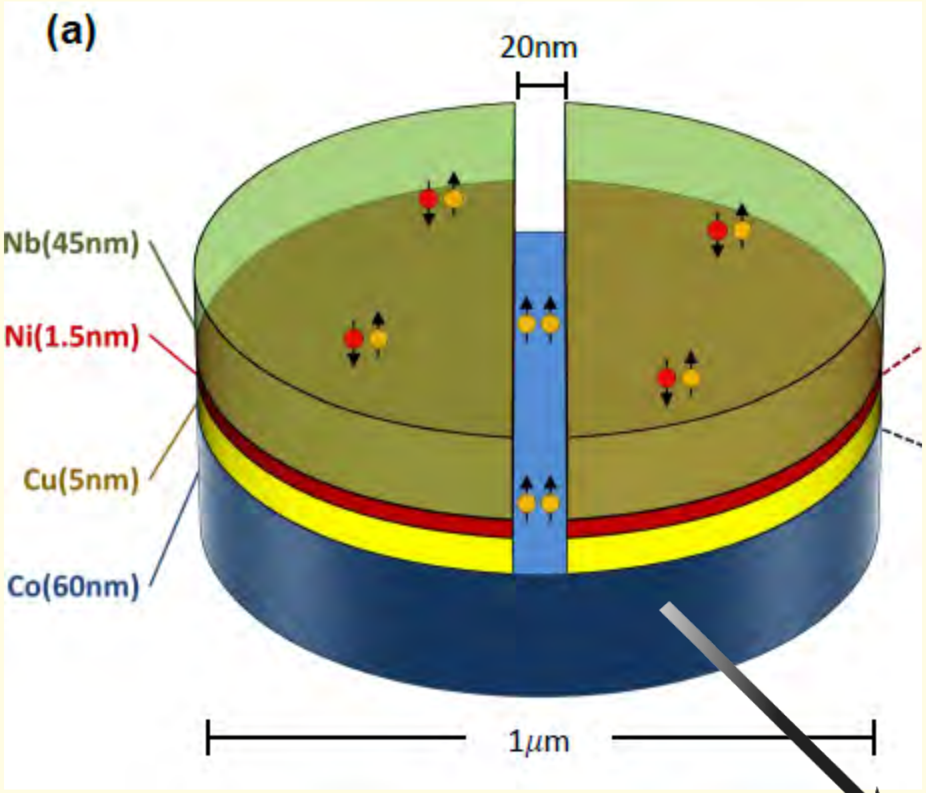
Planar devices

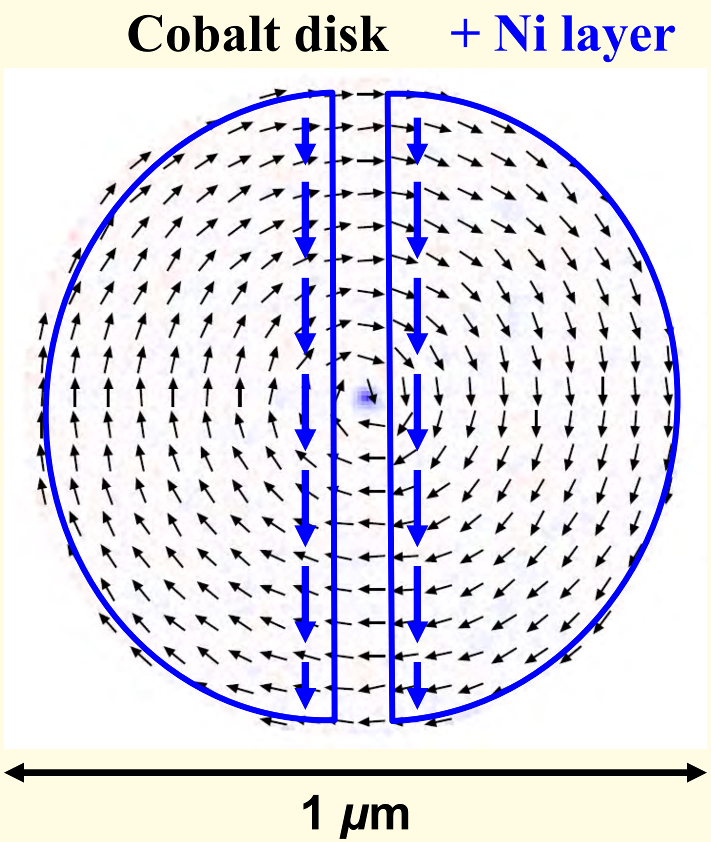


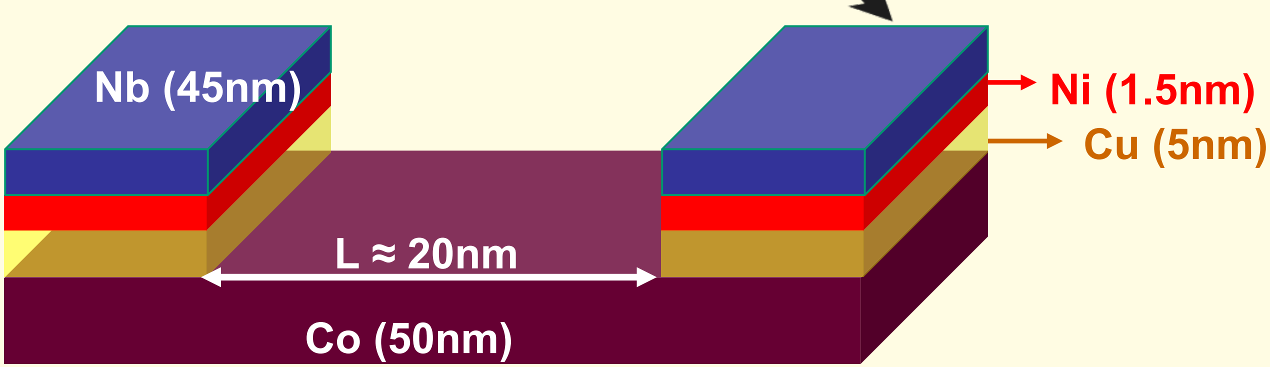
So far limited to CrO_2

General problem : stray field coupling

Use a multilayer disk

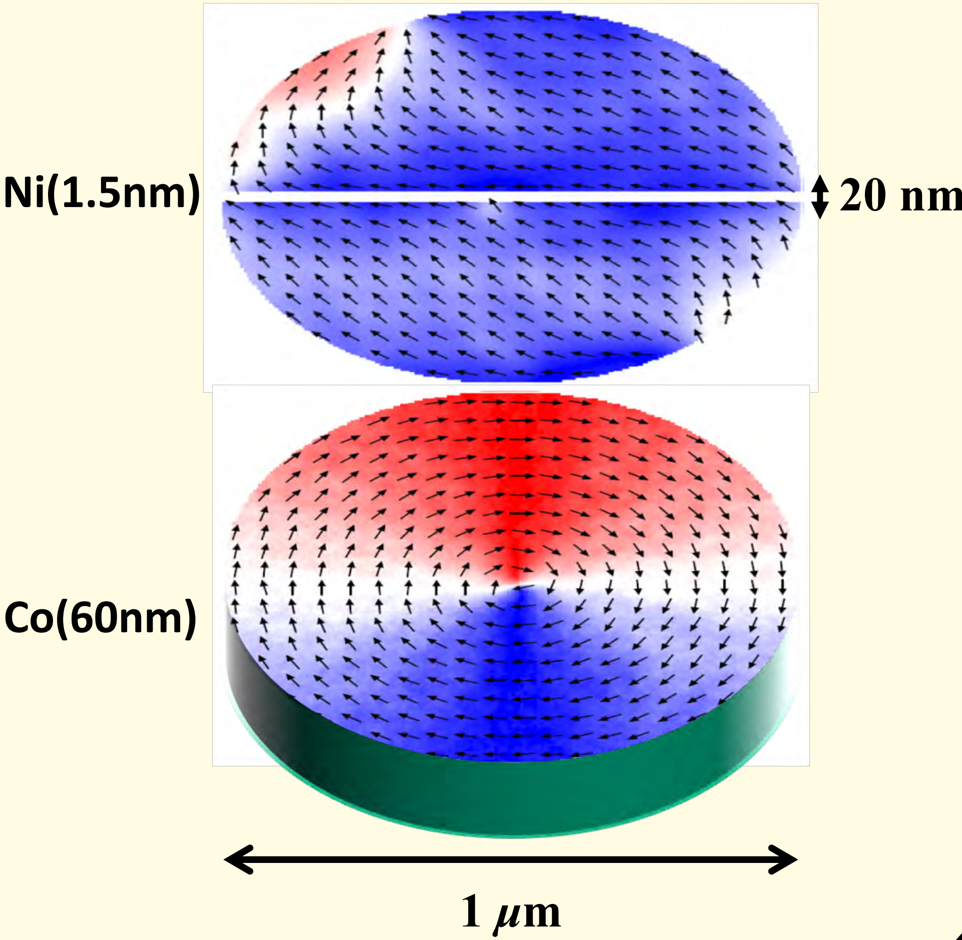


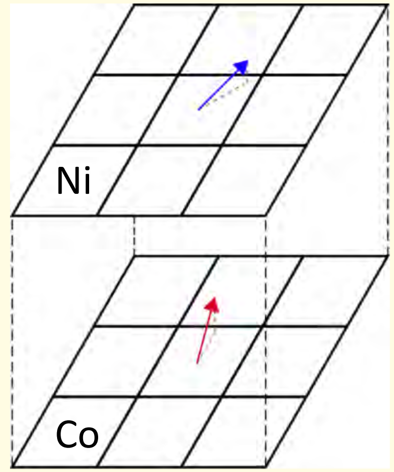


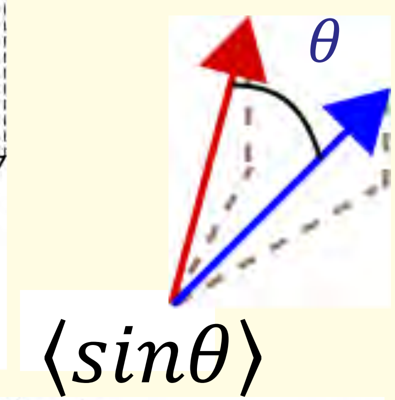


Note the vortex in the center

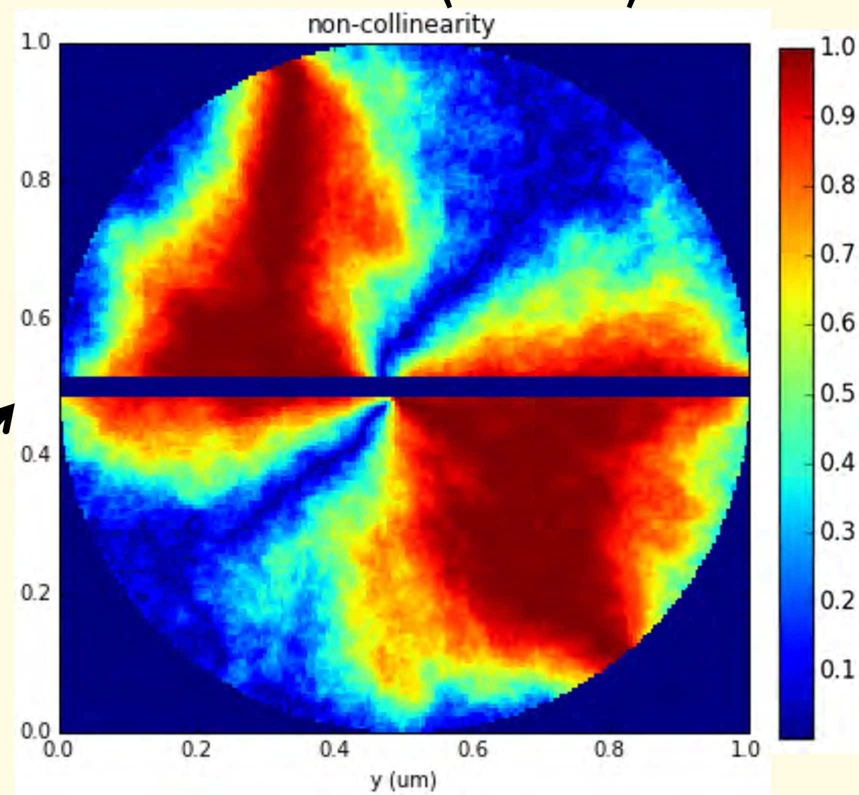
Non-collinearity : Micromagnetic simulations (OOMMF)



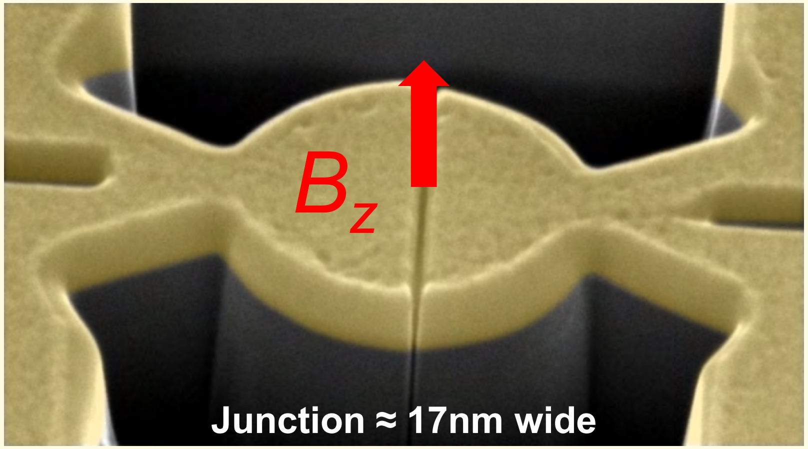




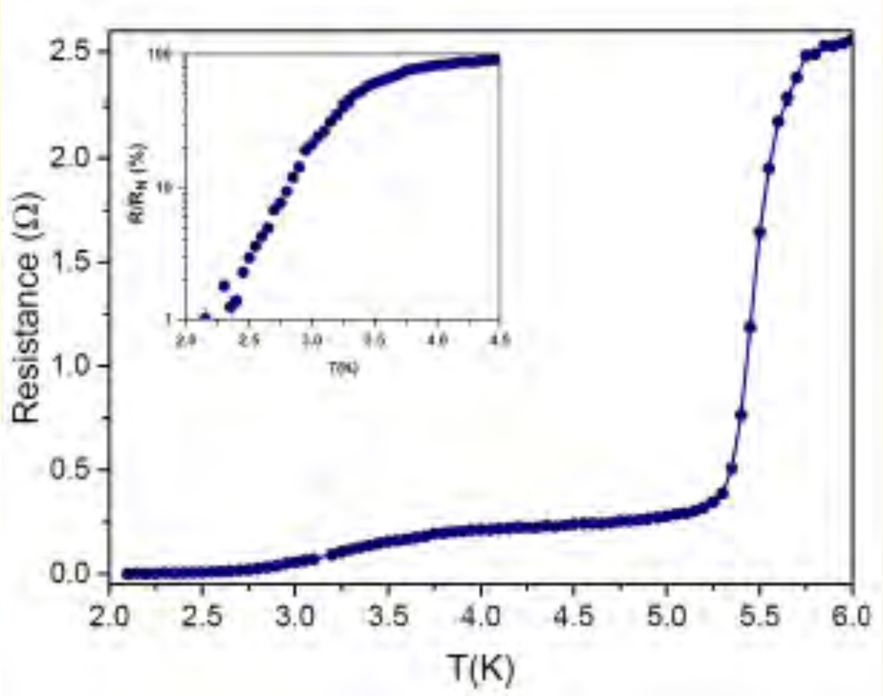
Spatial variation of the non-collinearity between Co and Ni

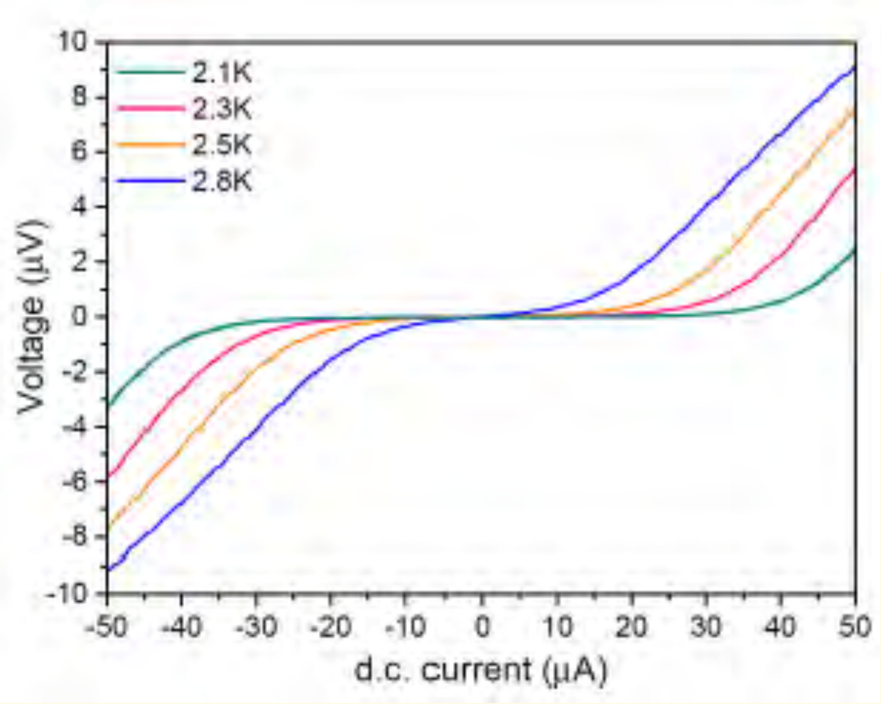


Device by FIB



Characterize R(T), j_c

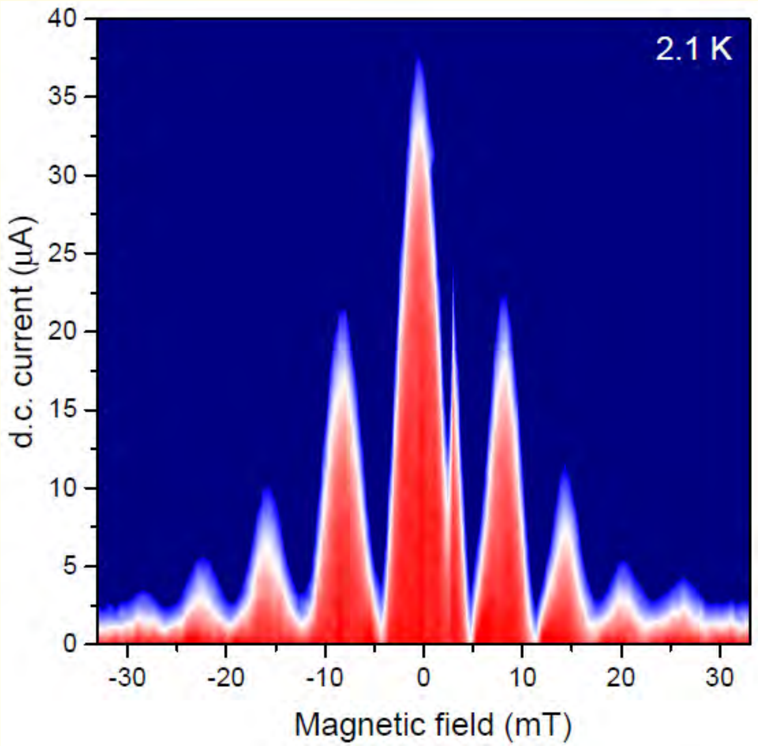


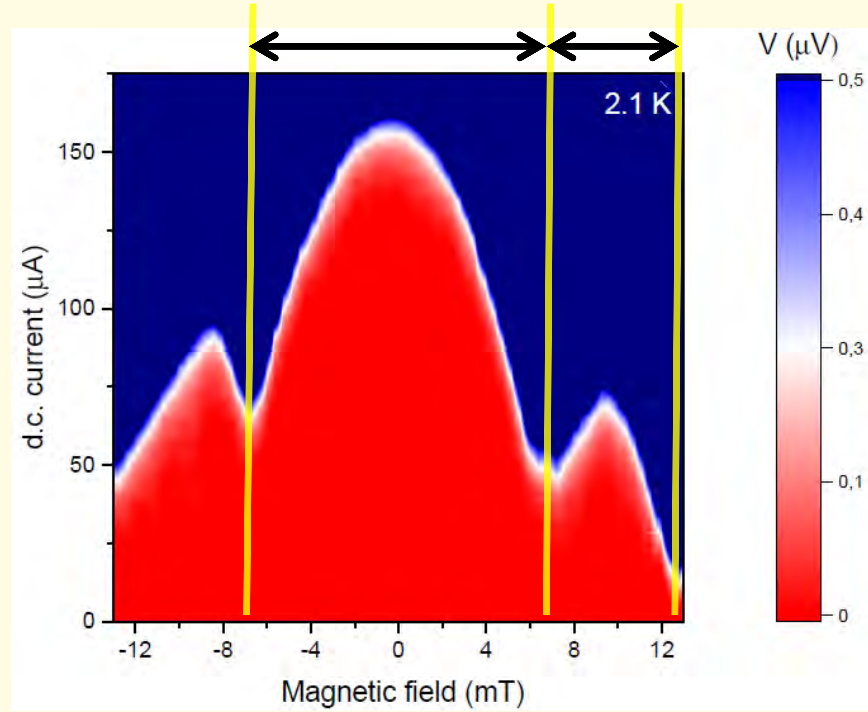


A triplet junction

Field out-of-plane

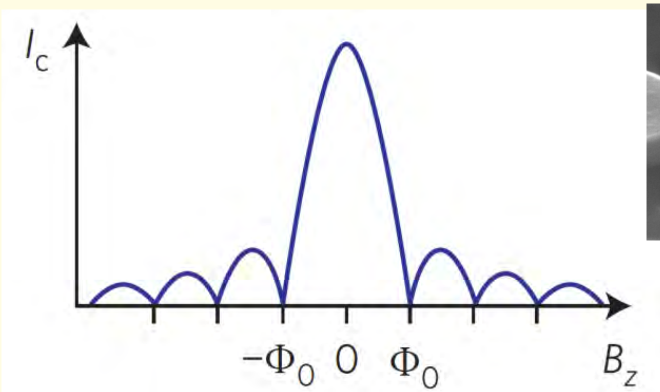
Compare “shallow” gap

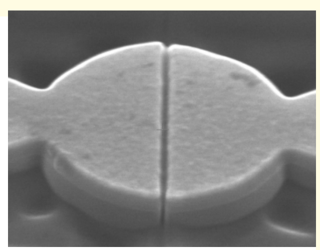




Not Fraunhofer

Fraunhofer





central lobe $2\Phi_0$

Supercurrent distribution: Fourier transform

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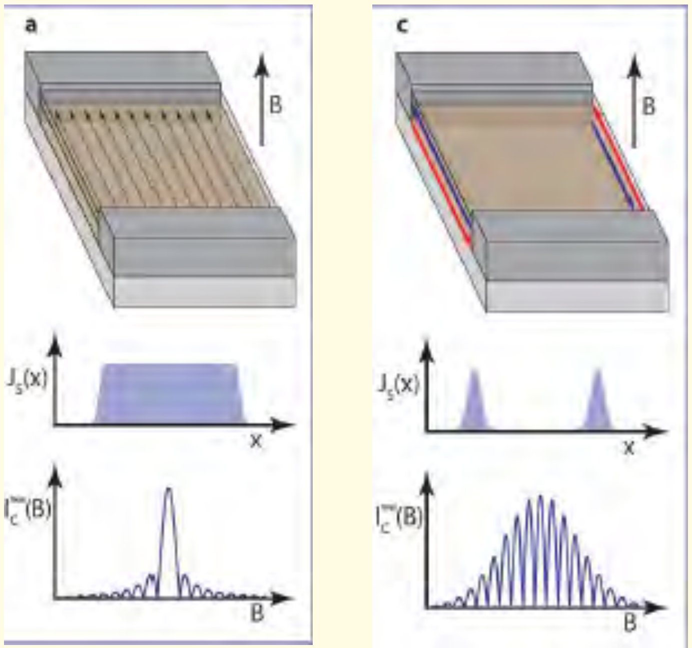
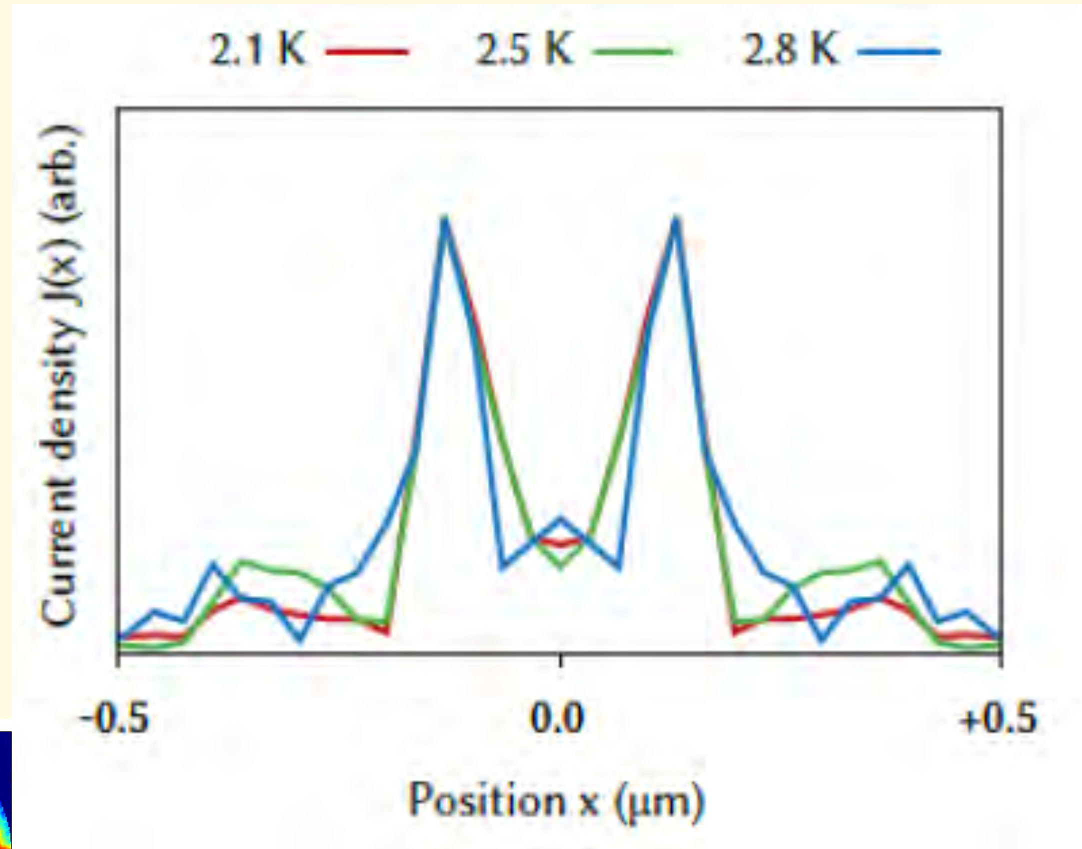
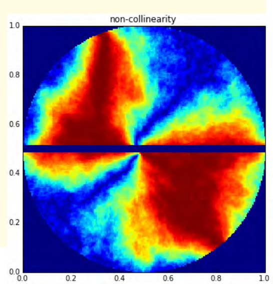
PHYSICAL REVIEW B VOLUME 3, NUMBER 9 1 MAY 1971

Supercurrent Density Distribution in Josephson Junctions

R. C. Dynes and T. A. Fulton
Bell Telephone Laboratories, Murray Hill, New Jersey 07974
(Received 19 November 1970)



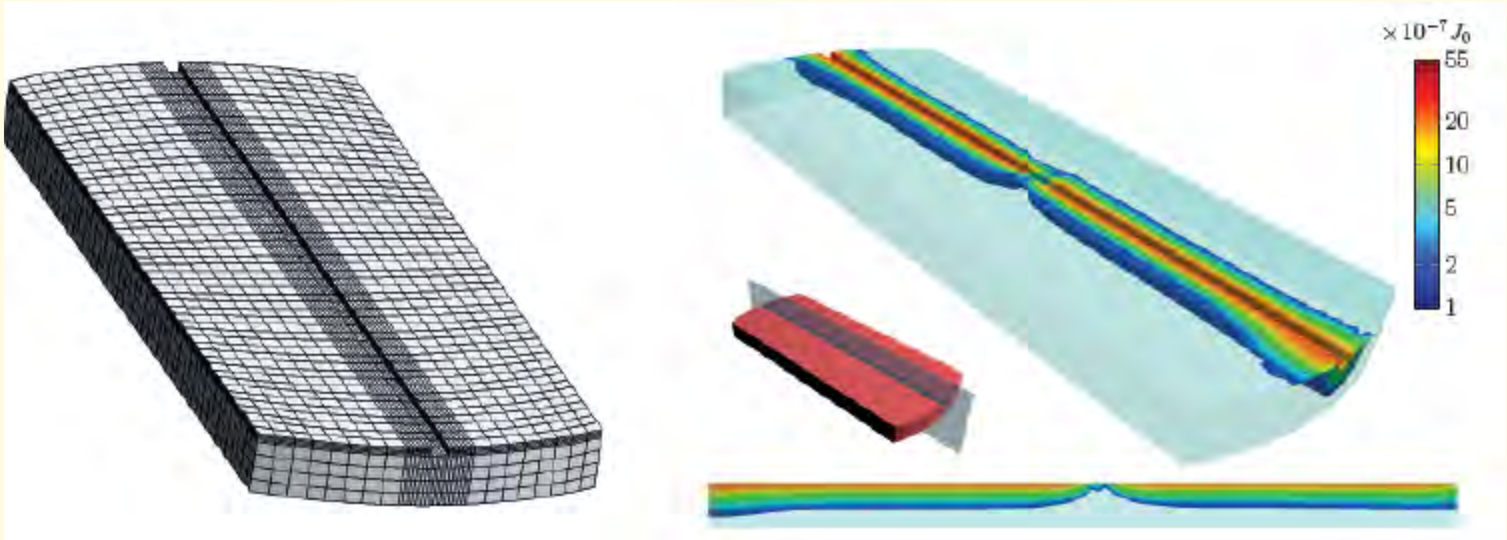


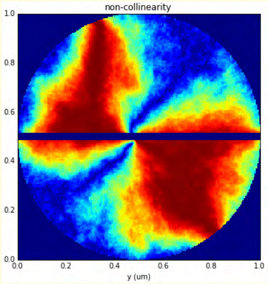


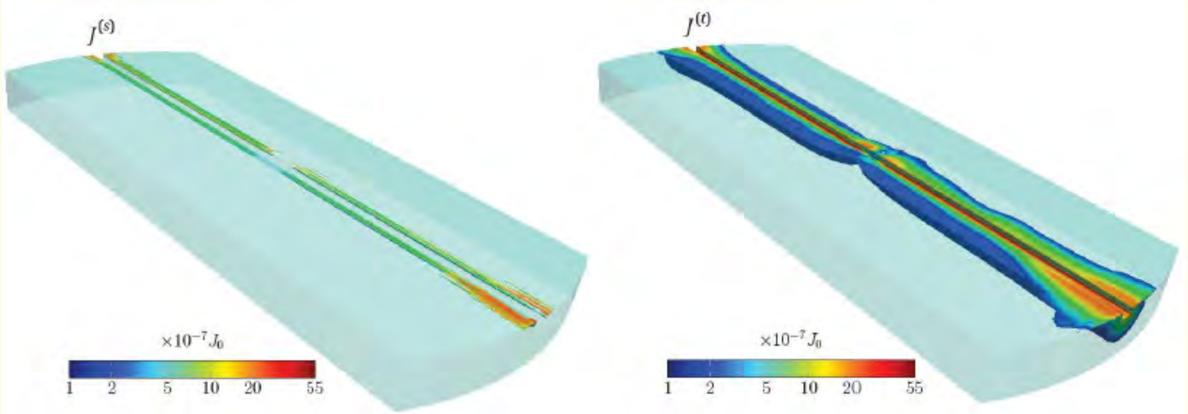
Two channels around the vortex

Supercurrent simulations *(Amundsen, Ouassou, Linder)*

Use μmagnetics + Usadel on a mesh

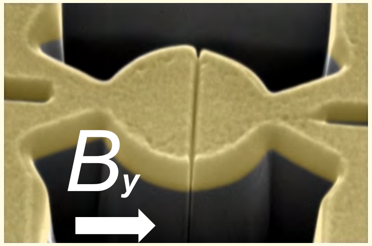


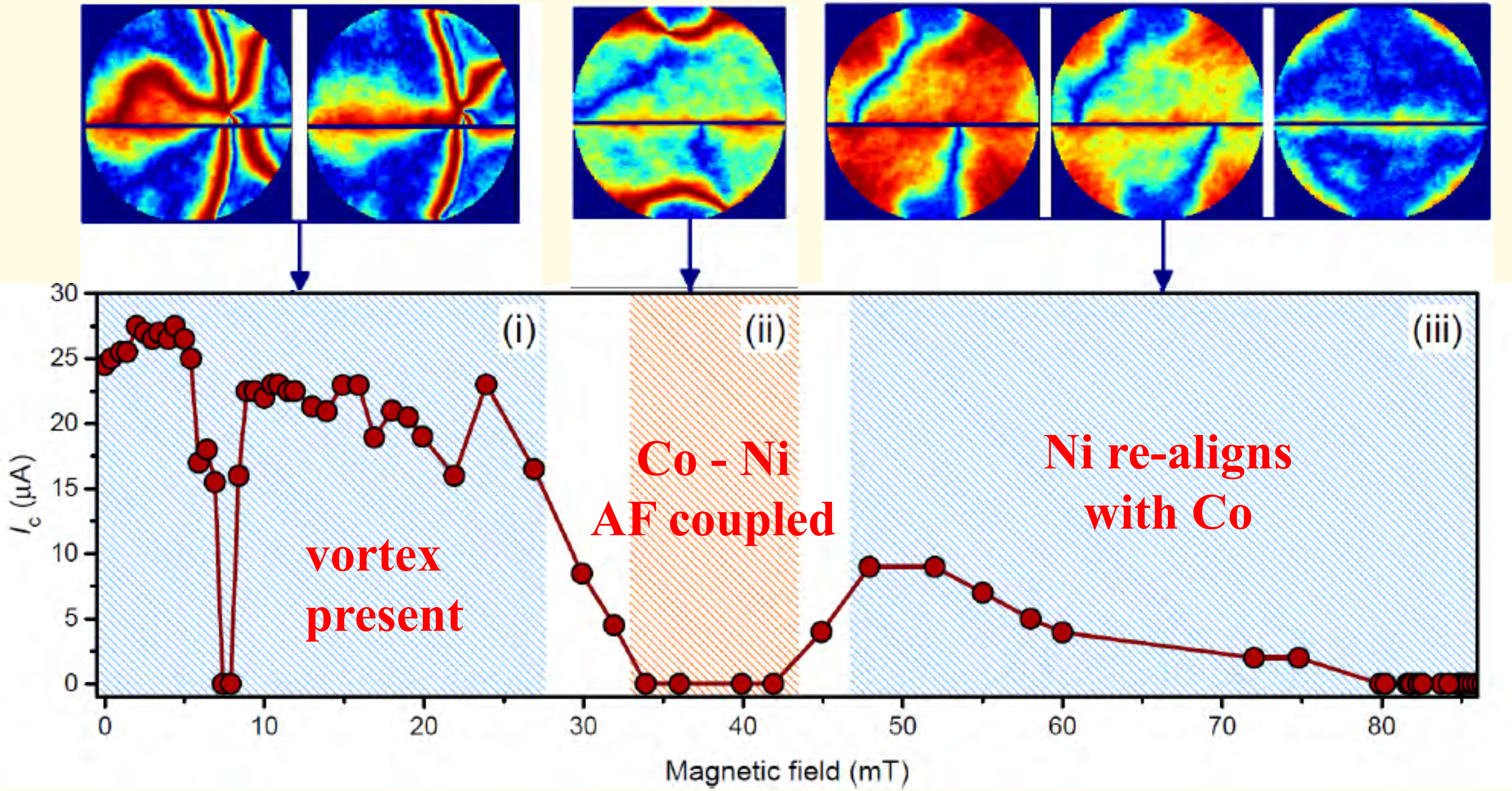




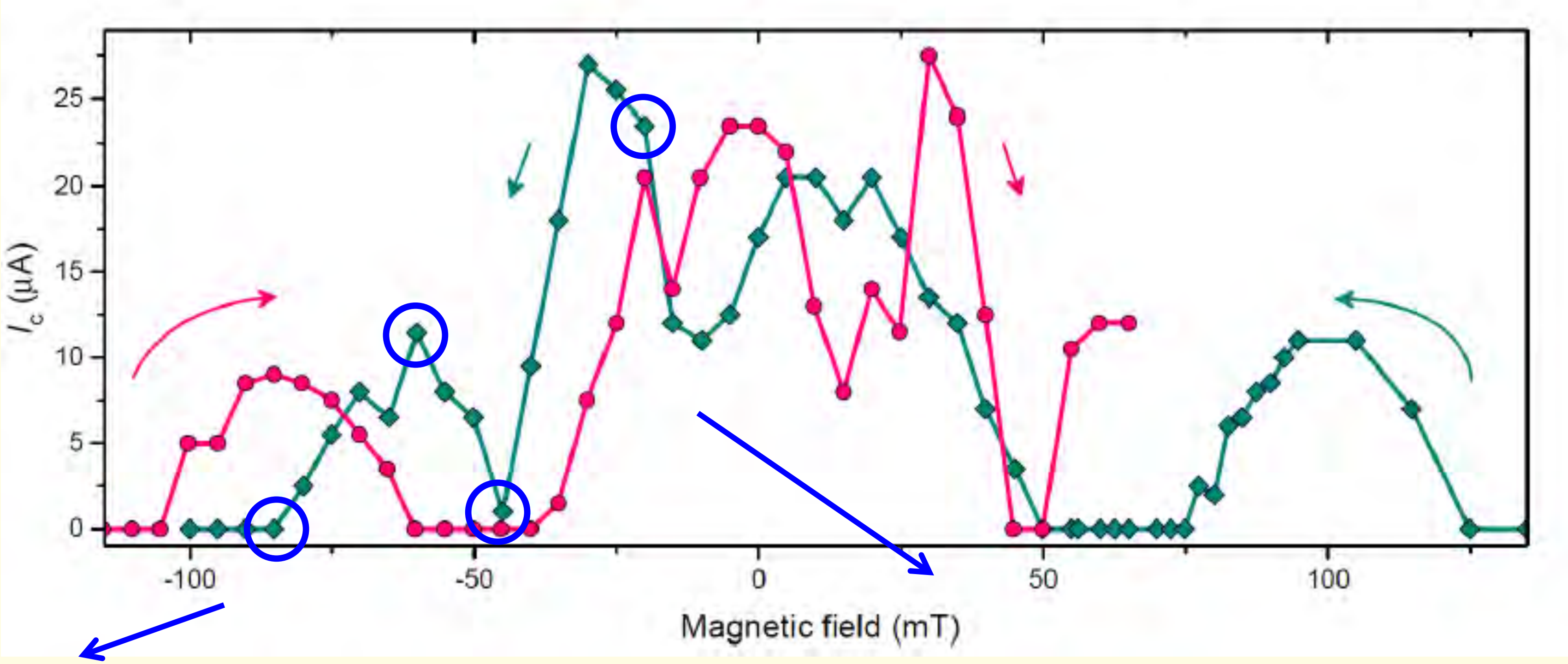
No singlets, only triplet

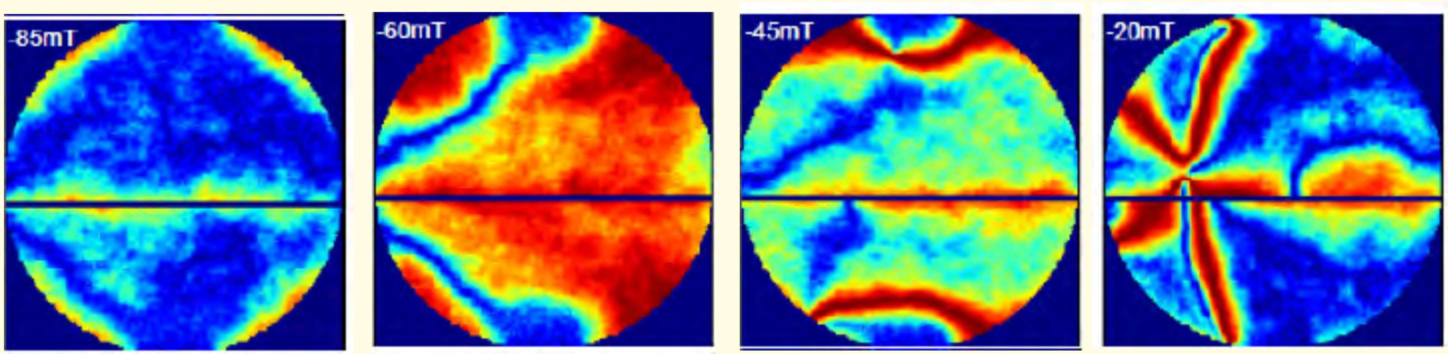
In-plane field : change in I_c by pushing the vortex along the trench





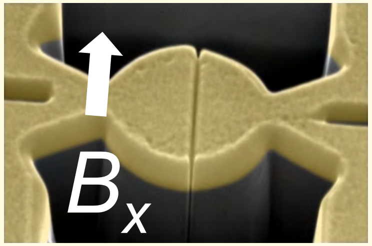
Field reversal - hysteresis

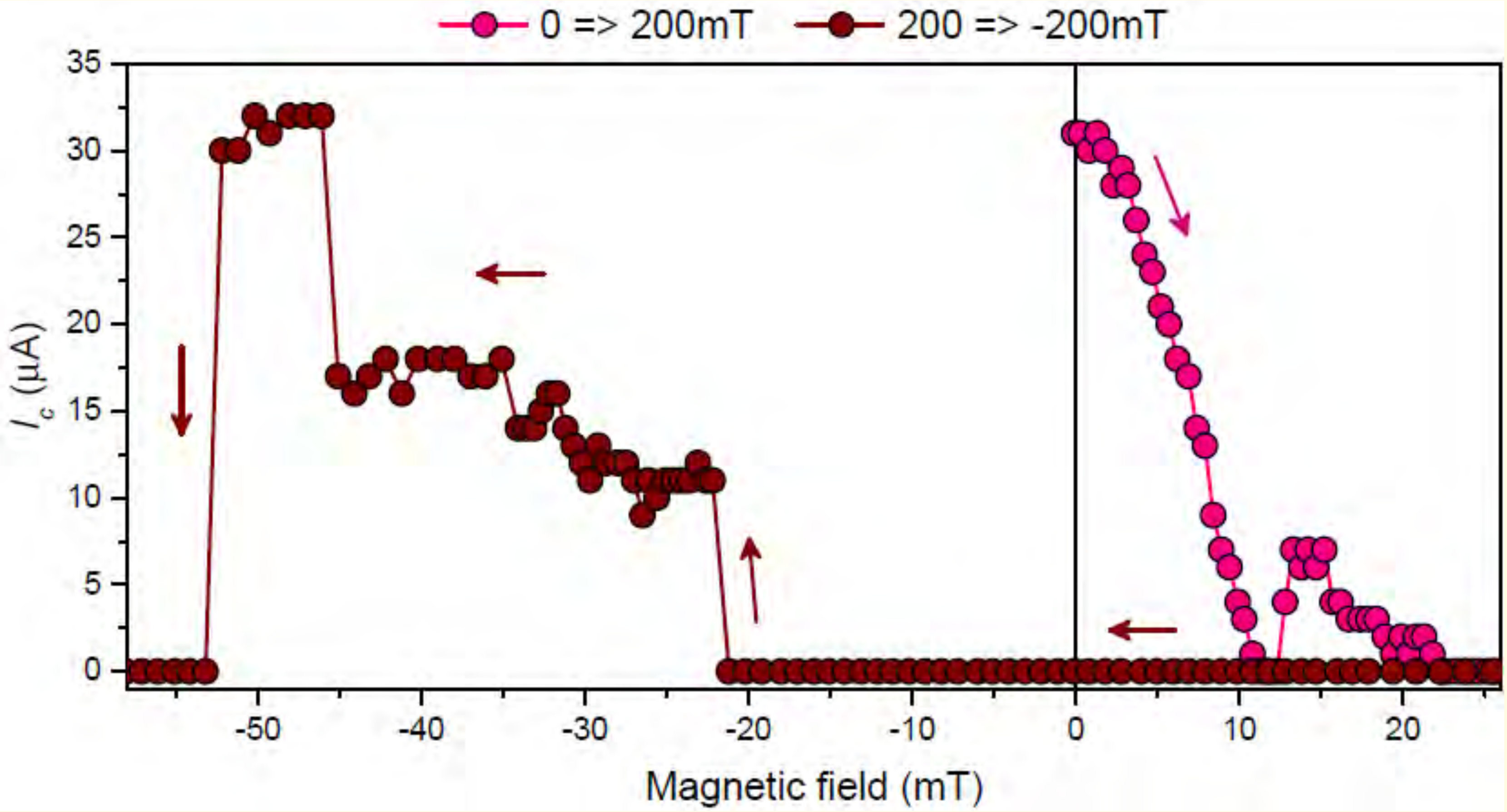




-85 mT **-60 mT** **-45 mT** **-20 mT**

Behavior can be explained with micromagnetics pushing the vortex ⊥ the trench

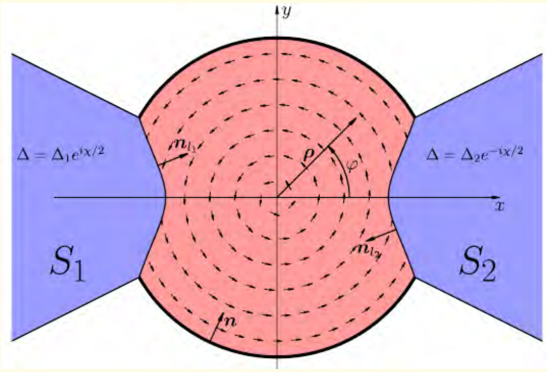




very different - vortex reconstitutes differently

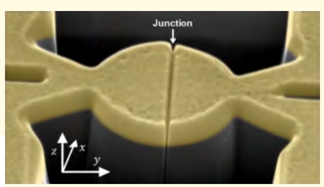
Do without Ni ?

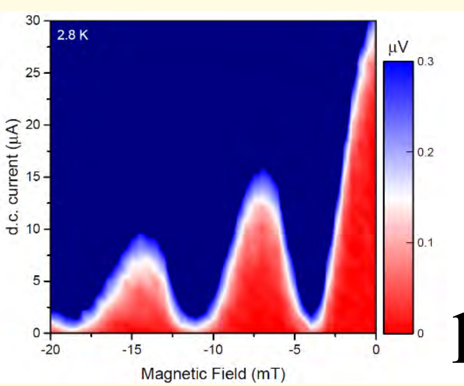
Triplets from exchange field gradients



Kalenkov-Zaikin-Petrashov, PRL '11

Co/Cu/Nb

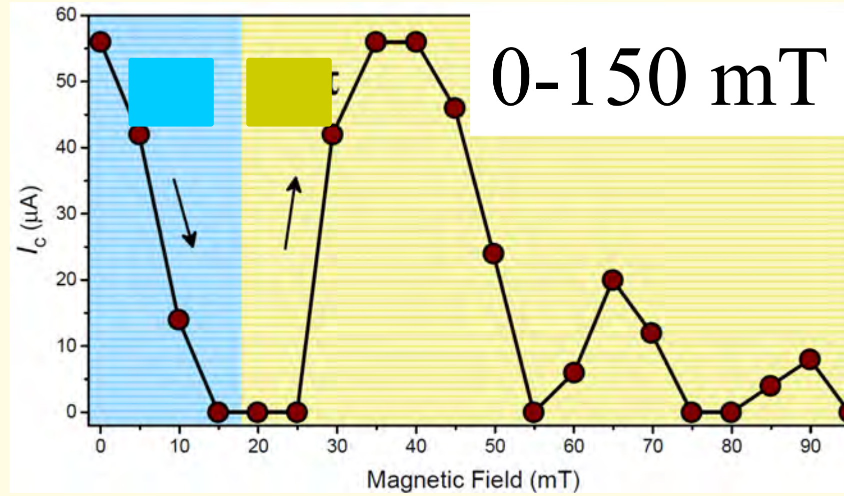




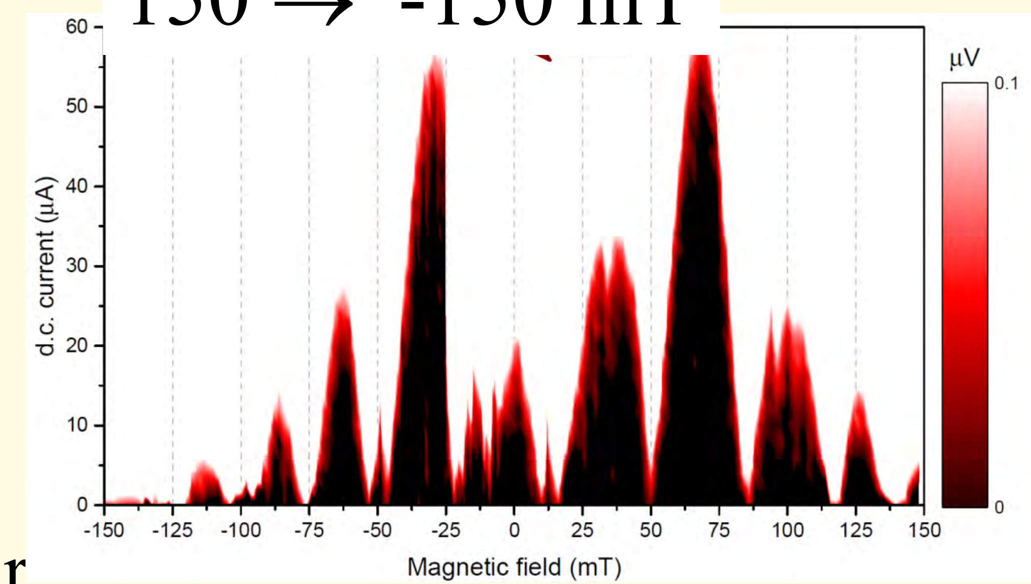
Interference pattern similar

In-plane field : very different

0-150 mT



150 → -150 mT



Conclusion

Getting closer to superspintronics

- Demonstrated a **CrO_2 wire** where **triplet** supercurrents are switched by domain walls
- Demonstrated a **lateral disk-shaped Co-junction** , which carries a **triplet** supercurrent,
- A **magnetic vortex** determines the current distribution which can be changed with an **in-plane** field
- Micromagnetic and supercurrent **simulations** are beginning to allow for accurate **device design**