Controllable tuning of spin-singlet and spin-triplet currents in a Josephson spin-valve

Vladimir Krasnov

Experimental Condensed Matter Physics
Department of Physics, AlbaNova University Center,
Stockholm University, SE-10691 Stockholm, Sweden

Special thanks to:
Adrian Iovan and Taras Golod

2 september 2015, MISIS, Moscow

Outline:

Introduction: Spin-triplet and long-range proximity effect in S/F hybrids

How to distinguish wishful thinking from reality :
overview of technical difficulties and artifacts

How to make a decisive experiment :

- Need controllable tuning of the spin-triplet component
- Need mono-domain = nano-scale structure

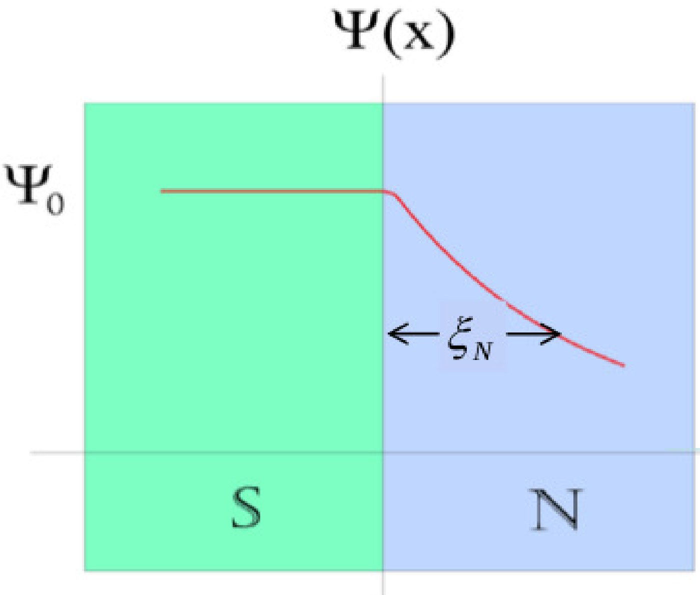
Experiment with a simplest possible case
a single asymmetric Josephson spin-valve $S/F_1/F_2/S$

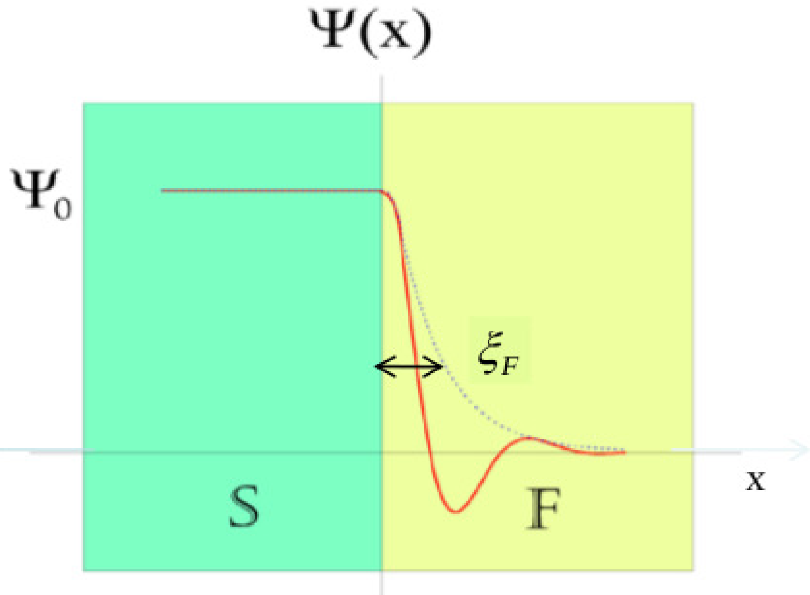
In-situ characterization using an ordinary spin-singlet current
and spin-valve MR

Deciphering the data using micromagnetic simulations

Evidence for controllable generation of a spin-triplet component

Proximity effect: S/N vs. S/F





$$\xi_N = \sqrt{\frac{\hbar D_N}{2\pi k_B T}} \approx few\ \mu m$$

$$\xi_F \sim \sqrt{\frac{\hbar D_F}{E_{ex}}} \approx few\ nm$$

$$\Psi(x) = \Psi_0 \exp(-x/\xi_N)$$

$$\Psi(x) = \Psi_0 \cos(x/\xi_F) \exp(-x/\xi_F)$$

A. I. Buzdin, Rev. Mod. Phys. **77**, 935 (2005).

F. S. Bergeret, A. F. Volkov, and K. B. Efetov, Rev. Mod. Phys. **77**, 1321 (2005).

Ya. V. Fominov, A. A. Golubov, and M. Yu. Kupriyanov, JETP Lett. **77**, 510 (2003).

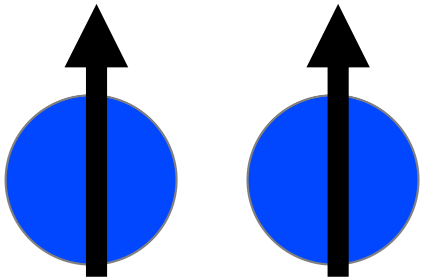
Ya. M. Blanter and F. W. J. Hekking, Phys. Rev. B **69**, 024525 (2004).

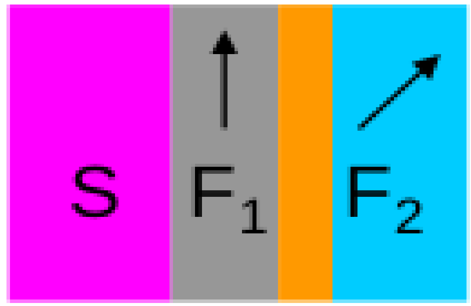
J. Kopu, M. Eschrig, J. C. Cuevas, and M. Fogelström, Phys. Rev. B **69**, 094501 (2004).

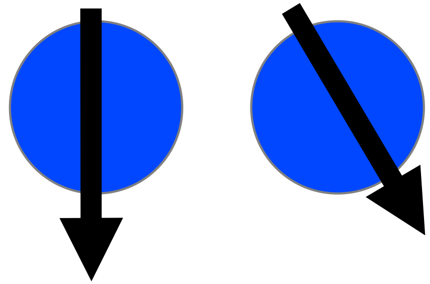
M. Houzet and A. I. Buzdin, Phys. Rev. B **76**, 060504 (2007).

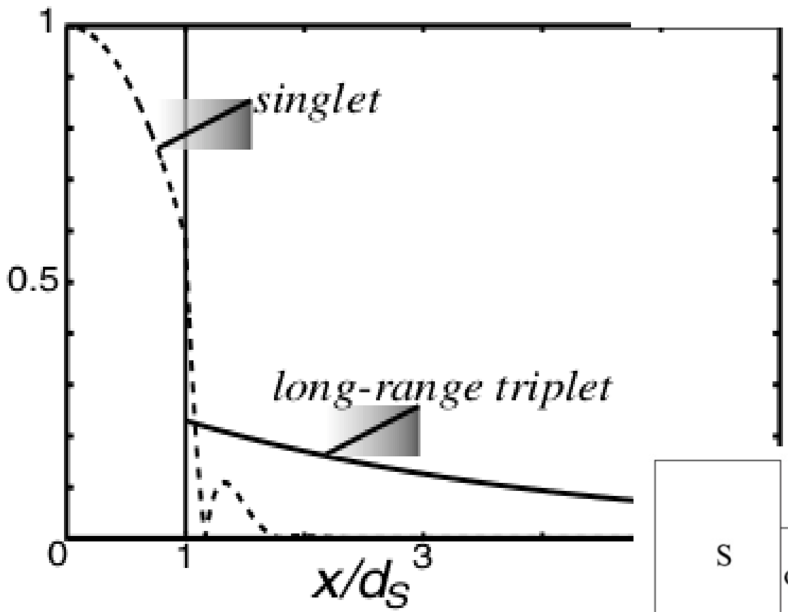
Y. Asano, Y. Sawa, Y. Tanaka, and A. A. Golubov, Phys. Rev. B **76**, 224525 (2007).

Generation of odd-frequency spin triplet component of superconducting condensate

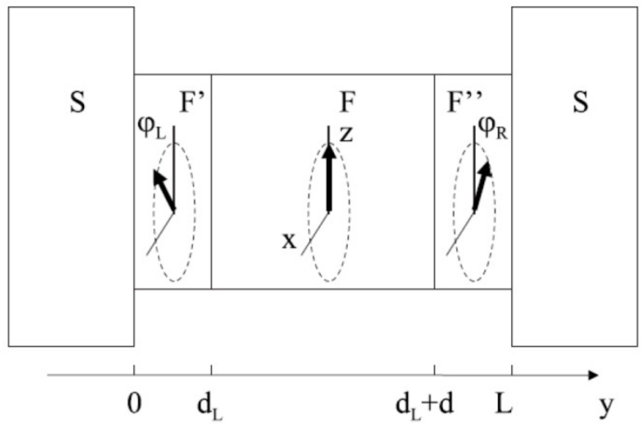




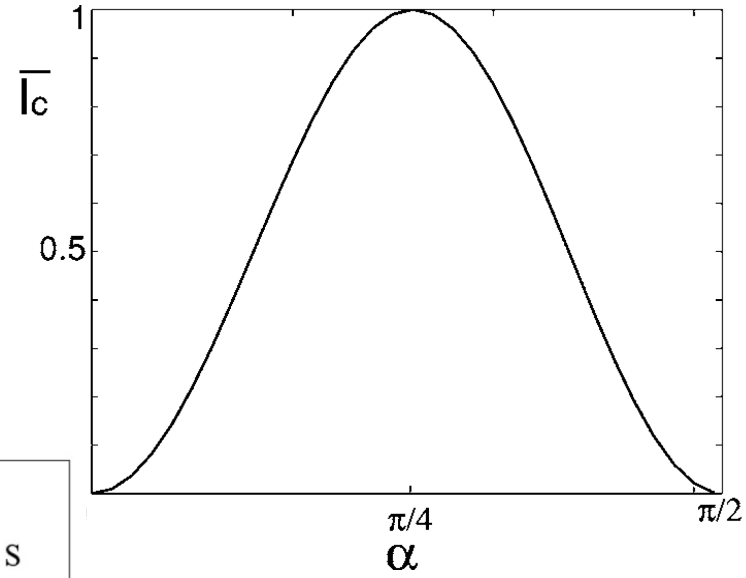




A. Kadigrobov, R. I. Shekhter, and M. Jonson, Europhys. Lett. **54**, 394 2001;
F. S. Bergeret, A. F. Volkov, and K. B. Efetov,
Phys. Rev. Lett. **86**, 4096 2001.



Houzet-Buzdin, PRB, 76, 060504 (2007)



A.F. Volkov, F.S. Bergeret and K.B. Efetov, PRL 90, 117006 (2003);
F. S. Bergeret, A. F. Volkov, and K. B. Efetov, Rev. Mod. Phys **77**, 1321 (2005).

Long-range proximity effect: is it an evidence of spin-triplet state?

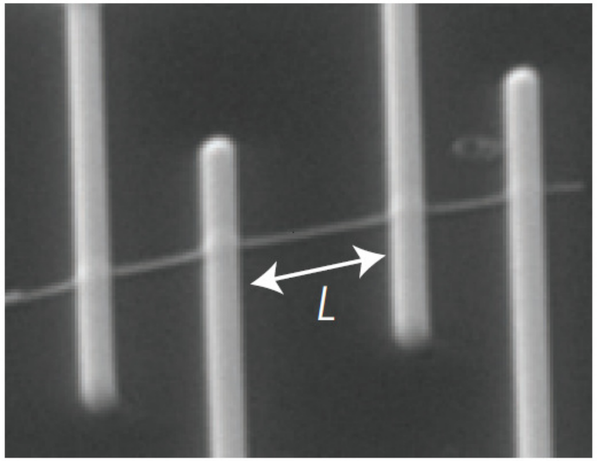
Could also be a singlet state (Clean case) A. S. Mel'nikov, et al., PRL **109**, 237006 (2012).

Experimental observations: **Strong Ferromagnets**

Ni / Al ~ 2000 nm !? V. T. Petrashov, et al., PRL **83**, 3281 (1999)

J. Aumentado and V. Chandrasekhar, PRB 64, 054505 (2001)

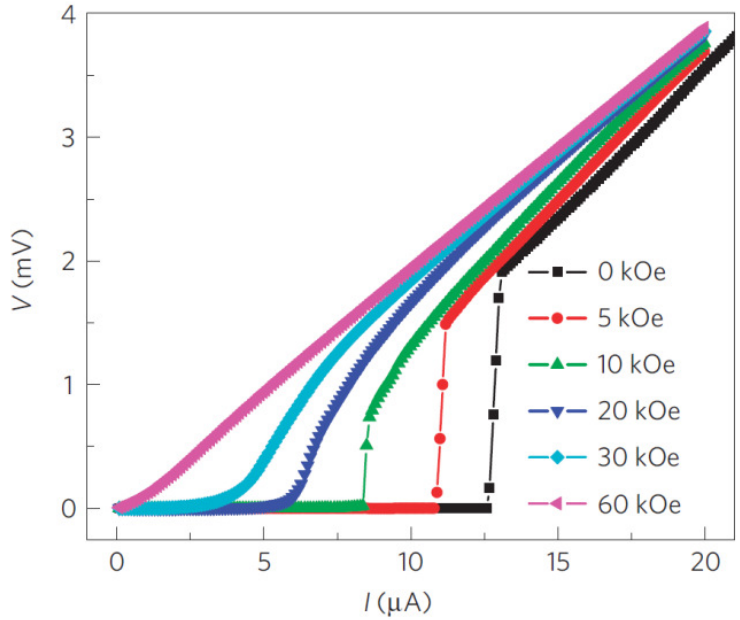
"The ferromagnet itself shows no appreciable superconducting proximity effect, but the ferromagnet/superconductor interface exhibits strong temperature, field, and current bias dependences. These effects are dependent on the local magnetic field distribution near the interface arising from the ferromagnet."



W / Co / W ~ 600 nm supercurrent

r = 20nm, $J_c \sim 10^6$ A/cm^2 !?

"The critical current (I_C) at zero field at 1.8 K is comparable to that observed in single-crystal 40-nm-diameter superconducting Sn nanowires."



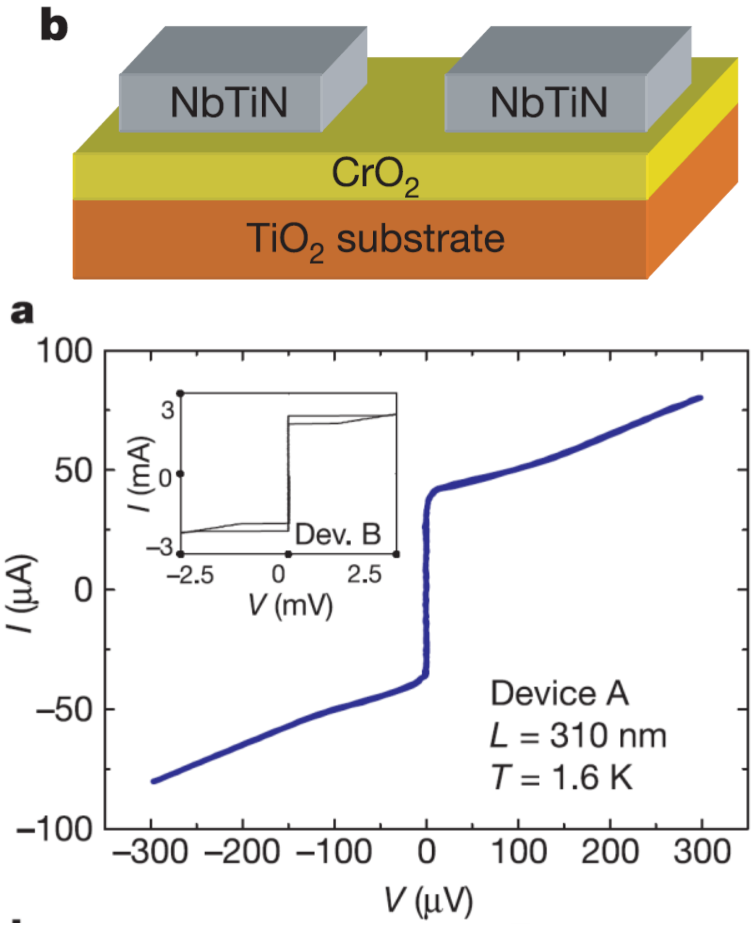
J. Wang *et al,* Nature Phys. 10, 389 (2010)

Ferromagnetic half-metals

NbTiN / CrO2 / NbTiN 240 - 1000 nm

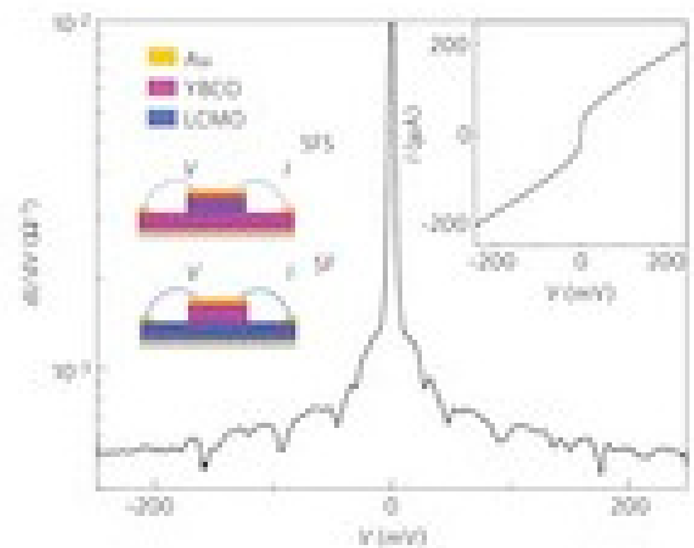
J_c=50 µA -2.5 mA / 2µm*100nm =
2.5x10^4 – 7.5x10^5 A/cm^2 !?

R.S. Keizer *et al,* Nature 439, 825 (2006)



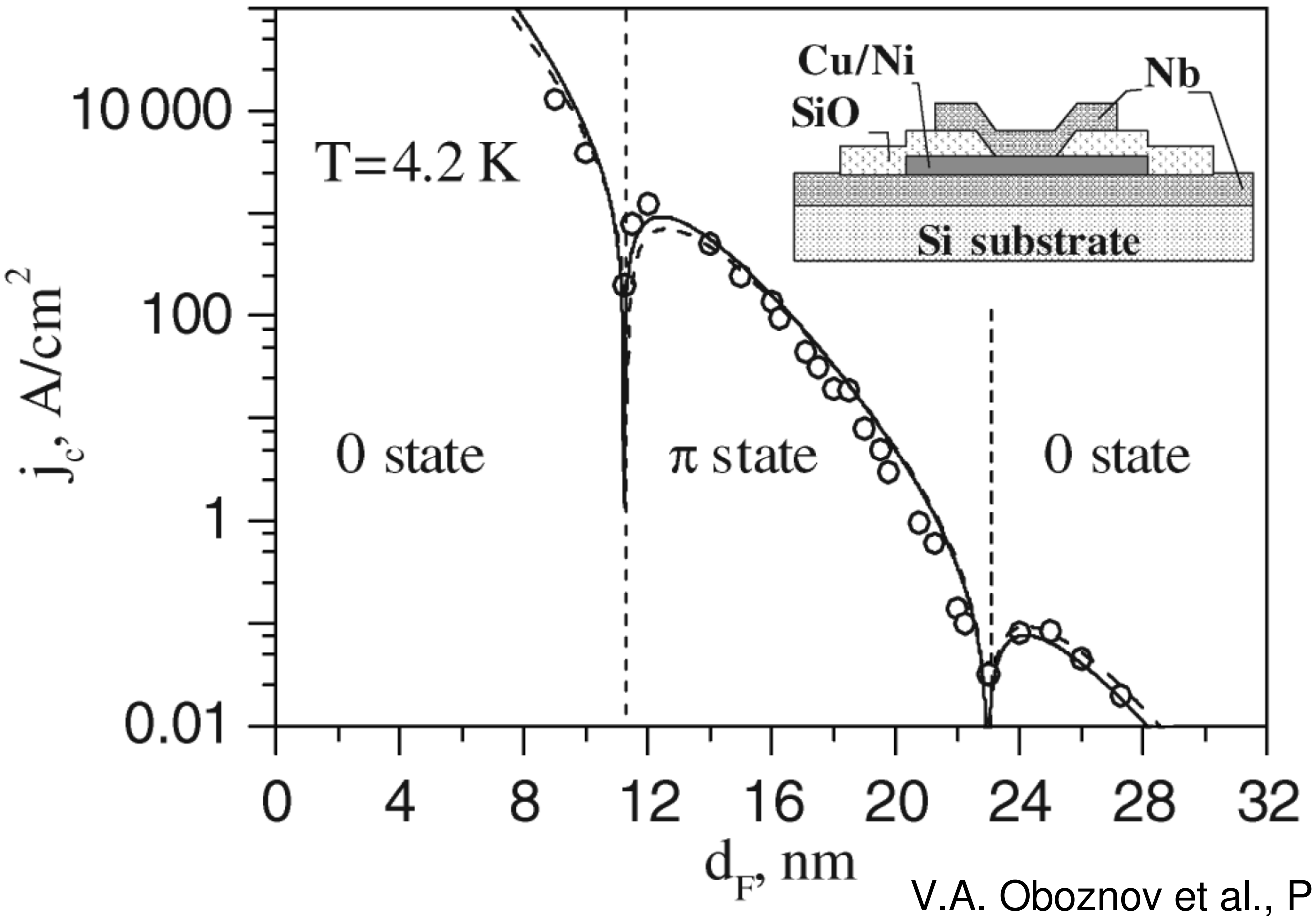
YBCO / LCMO / YBCO   ~ 20 nm

C. Visani, et al, Nat. Phys. **8**, 539 (2012).



Poster at M2S-2015: 200 nm huge J_c !?

Critical current density through a diluted ferromagnet $Cu_{0.47}Ni_{0.53}$



V.A. Oboznov et al., PRL 96, 197003 (2006)

Where from come J_c in excess of 10^5 in strong F and half metals with d > 100 nm ?

Is it indeed spin triplet or dead-layers (planar j's) or pin-holes (overlap j's)?

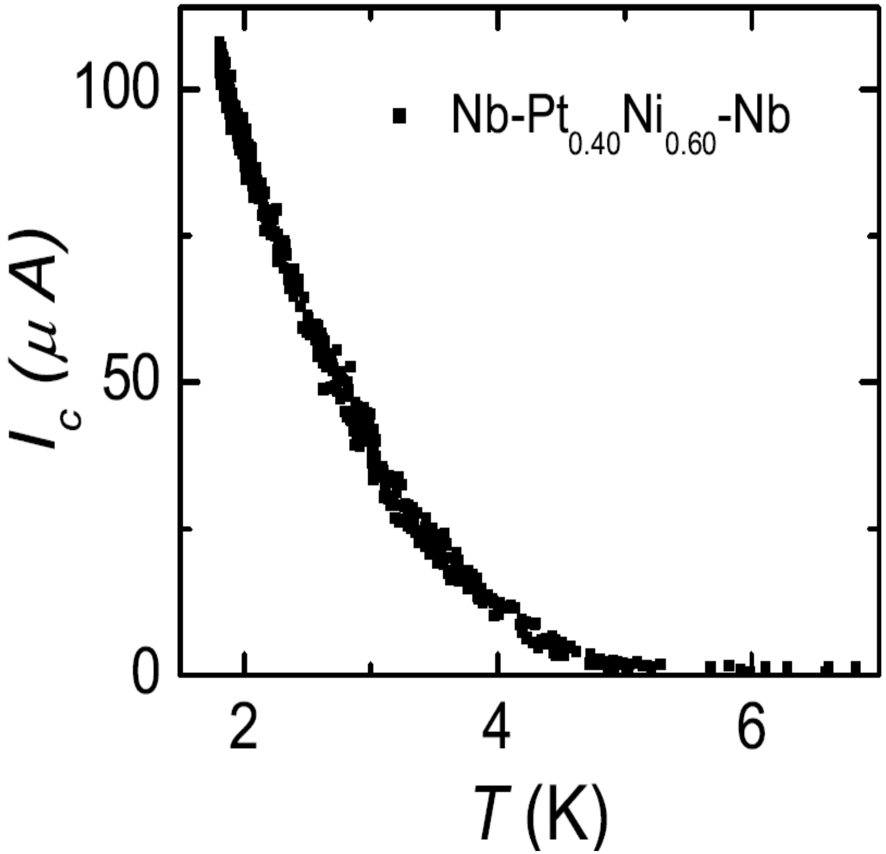
Where from comes non-collinear magnetization in a single F ?

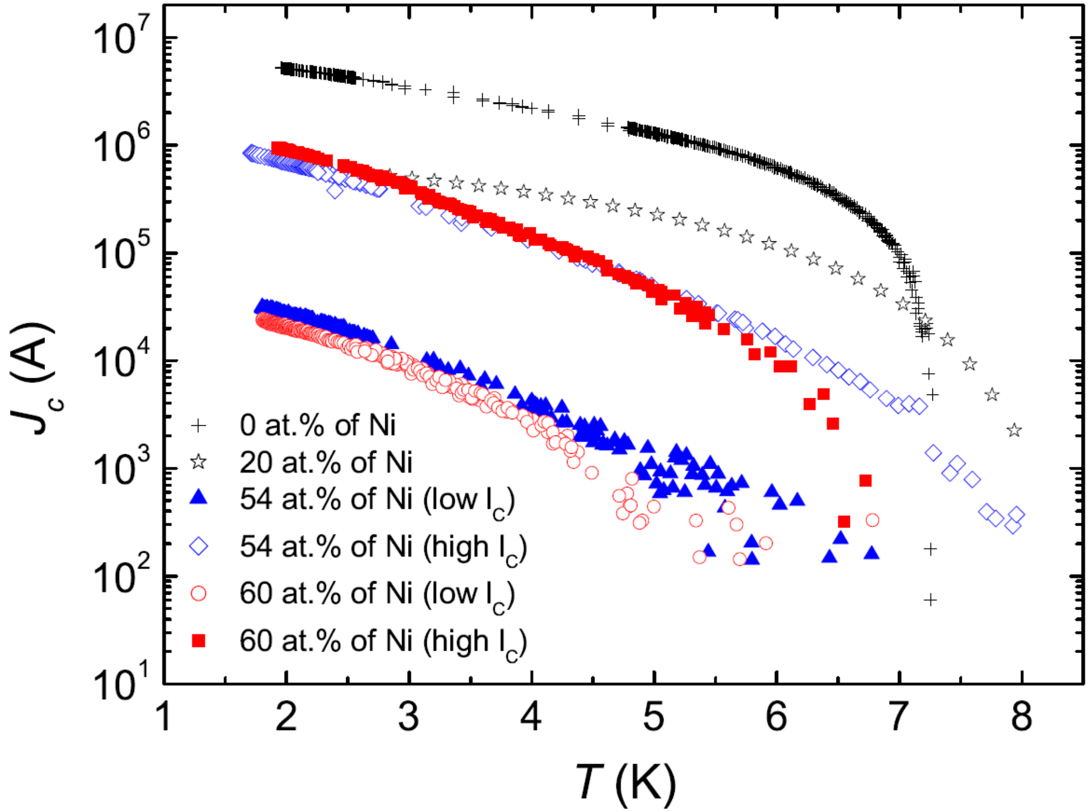
Strong temperature dependence of the critical current

$$J_c(T) \propto J_c(0) \exp\left(-\frac{t/2}{\xi_F(T)}\right)$$

$$\xi_N = \sqrt{\frac{D}{2\pi T}} \qquad \xi_F = \sqrt{\frac{D}{h}}$$

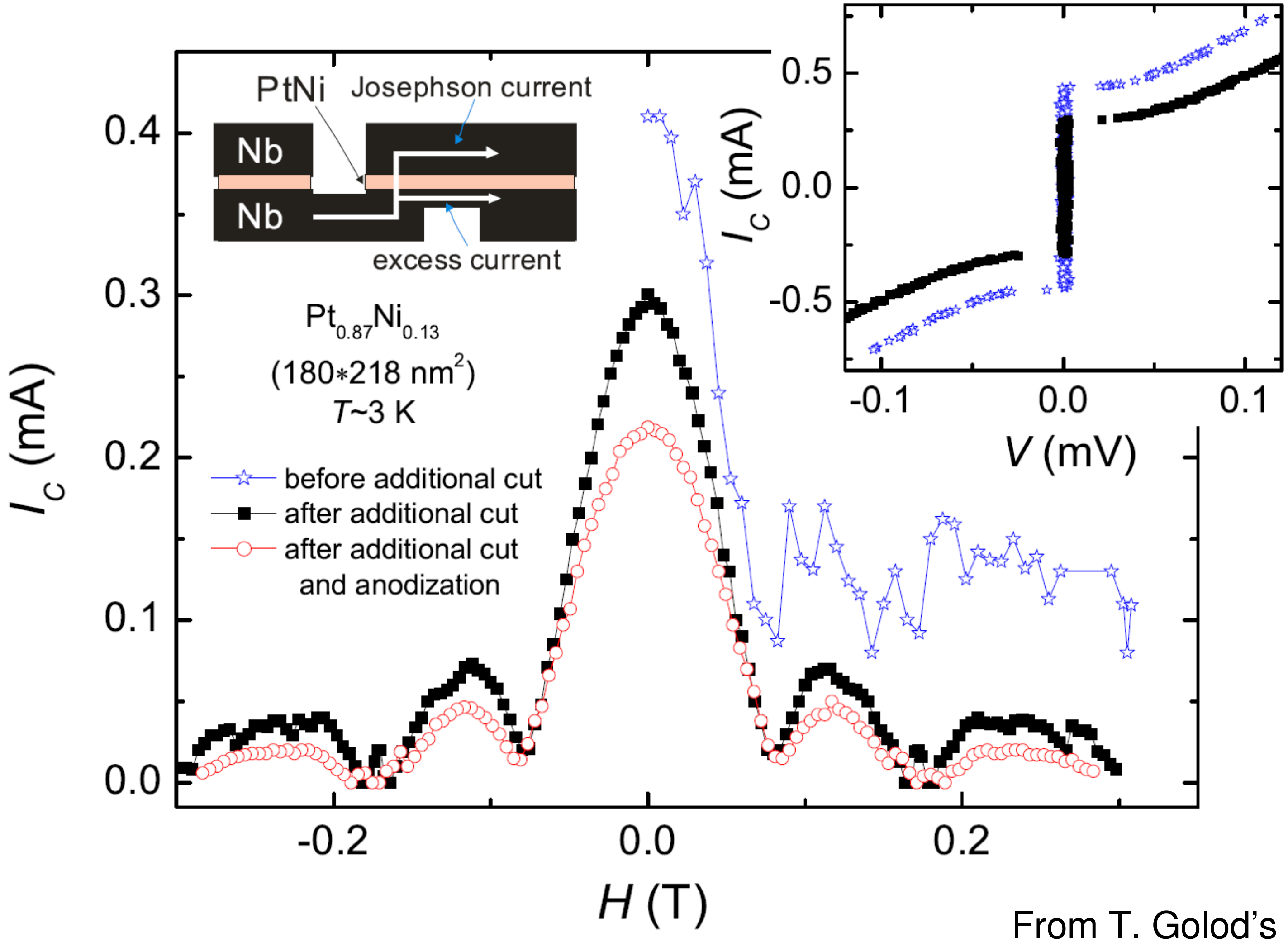
For N and spin-triplet F — For spin-singlet F





Dead (N) layers at interfaces (V.A. Oboznov et al., PRL 96, 197003 (2006))
or spin-triplet ?

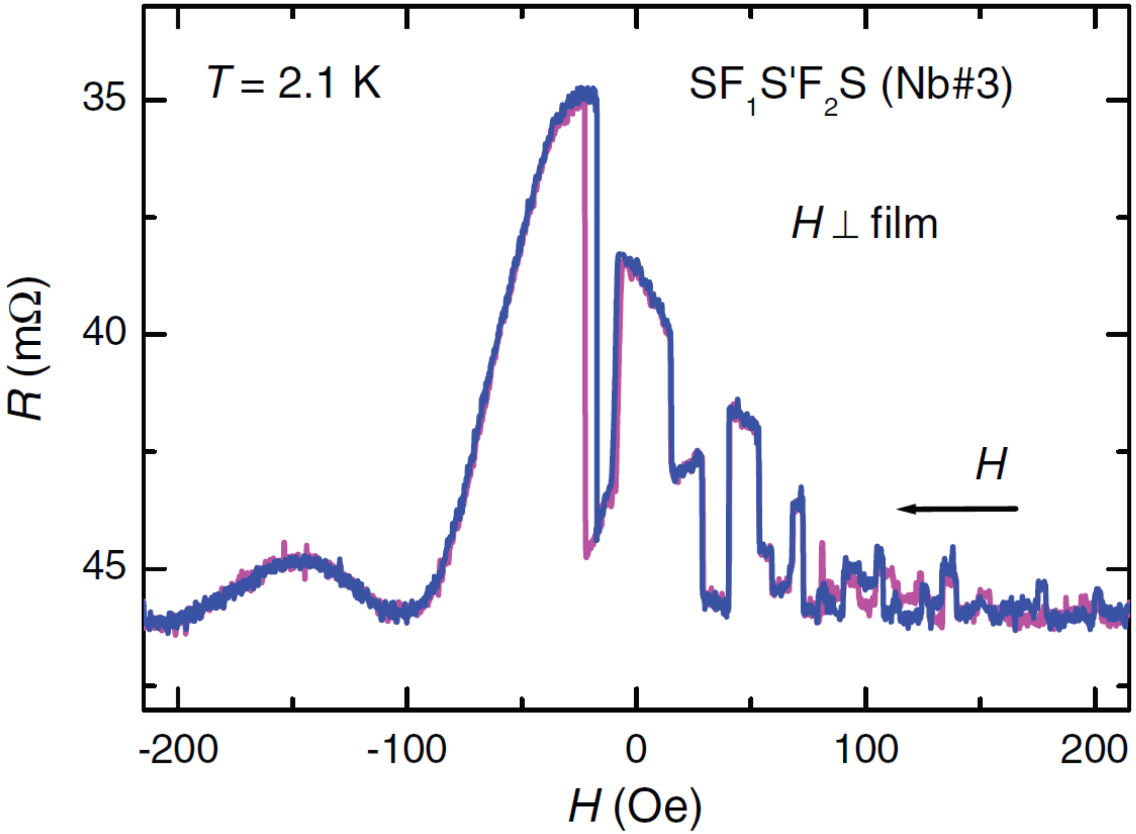
Inhomogeneities: identification of microshots



From T. Golod's PhD thesis

Inhomogeneities are clearly seen in Fraunhofer patterns

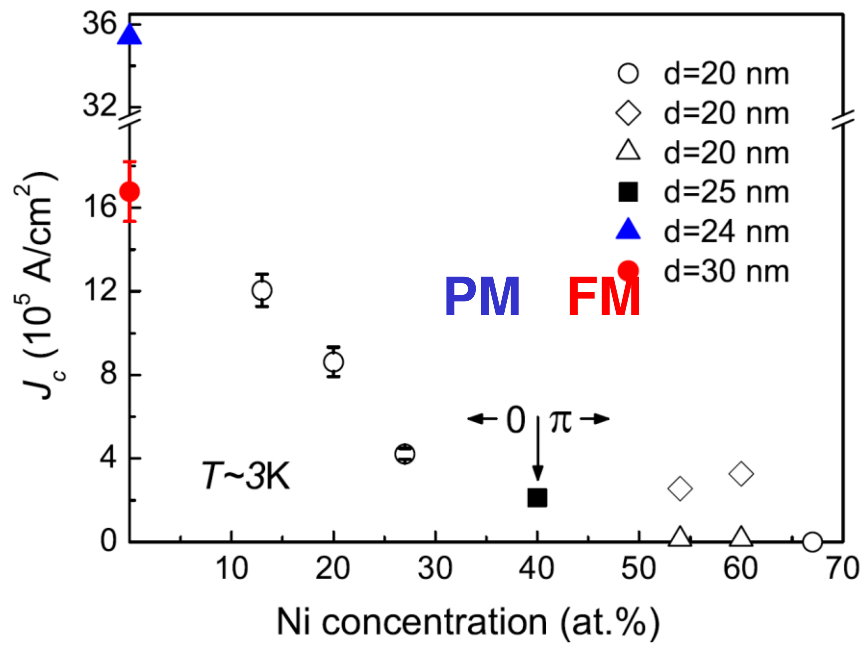
Inhomogeneities: detrimental role of domains



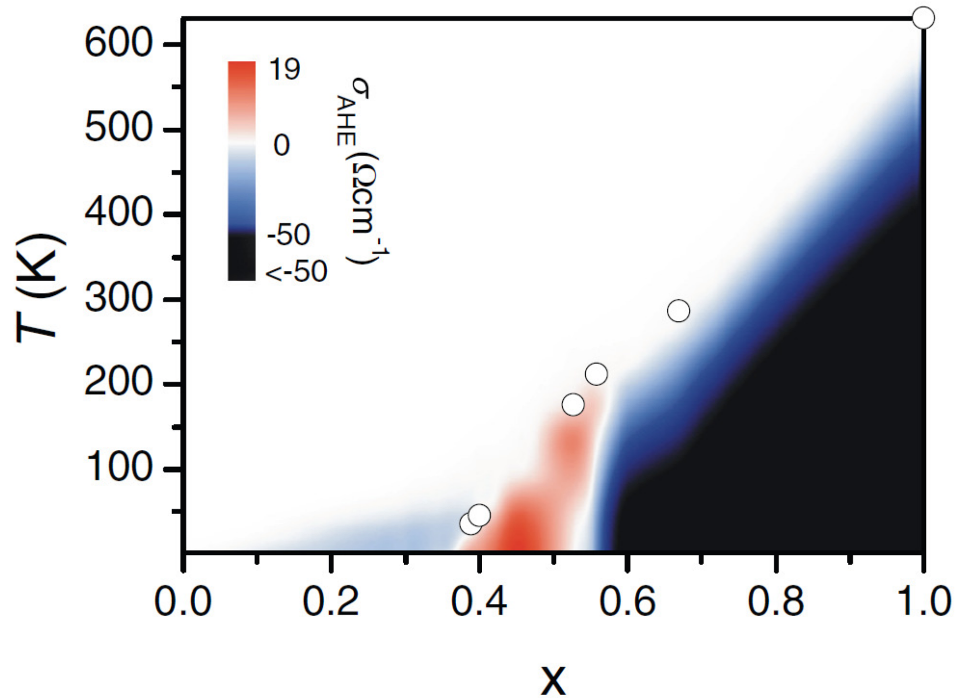
A. Iovan et al., PRB 90, 134514 (2014)

Need nano-scale monodomain structures

From SNS to SFS   Nb - PtNi - Nb



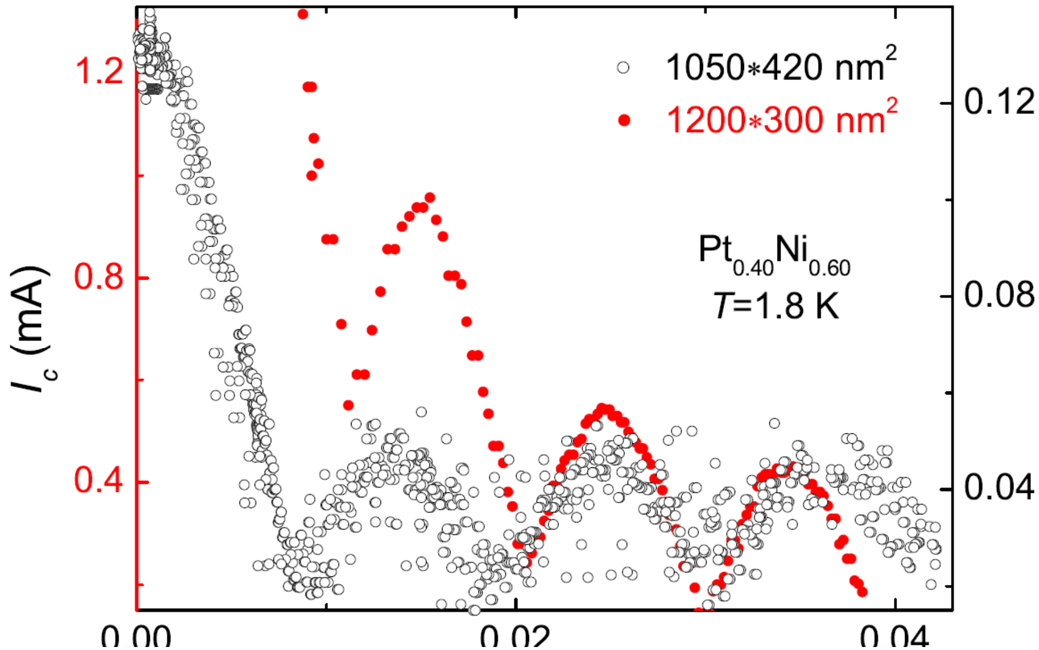
T. Golod et al.
Physica C
470, 890 (2010)



T. Golod, et al,
J. Appl. Phys.
110, 033909 (2011)

T. Golod, et al,
PRB **87**, 104407 (2013)

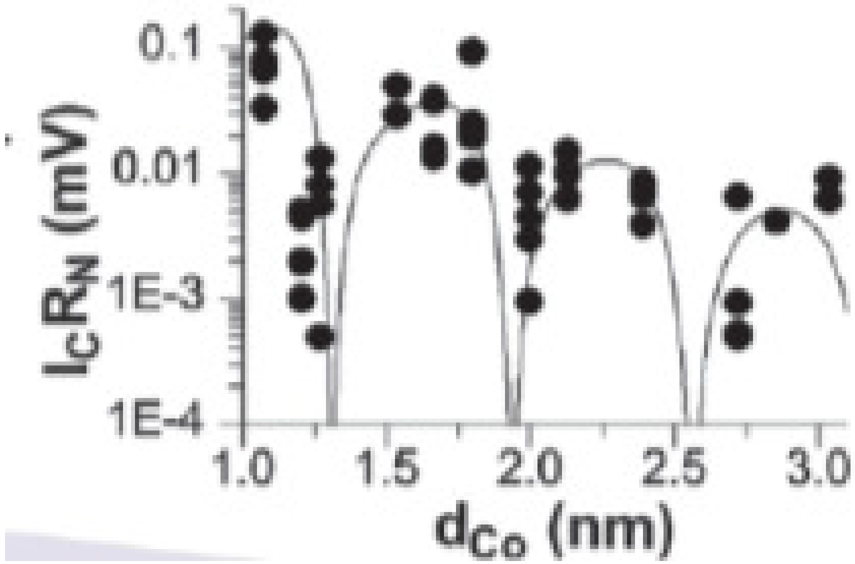
Large critical current variations in SFS junctions



Nb-PtNi-Nb

~20 times

From T. Golod's PhD thesis

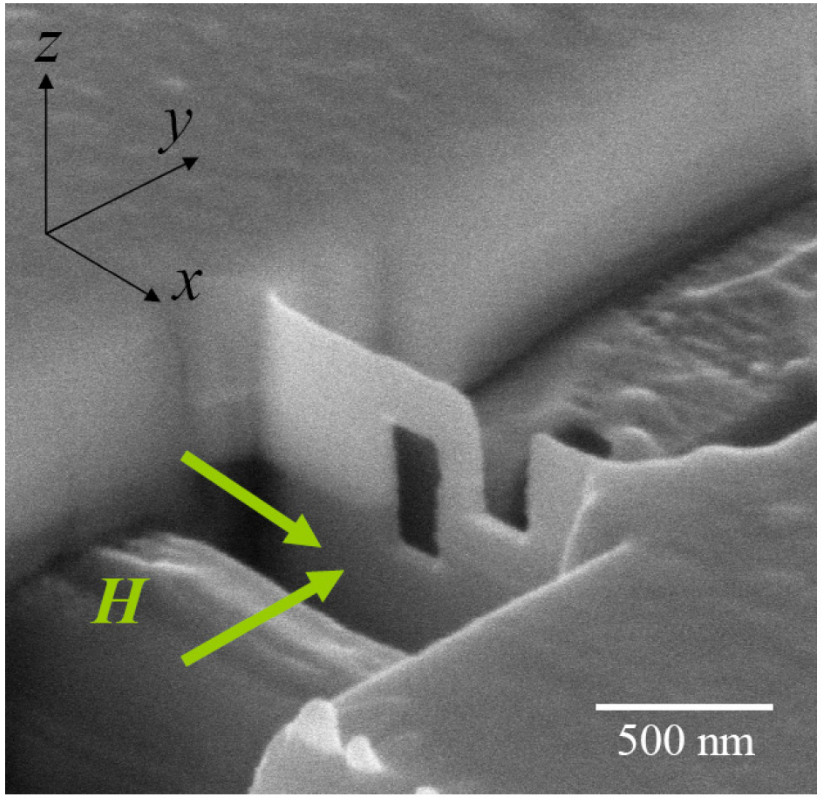


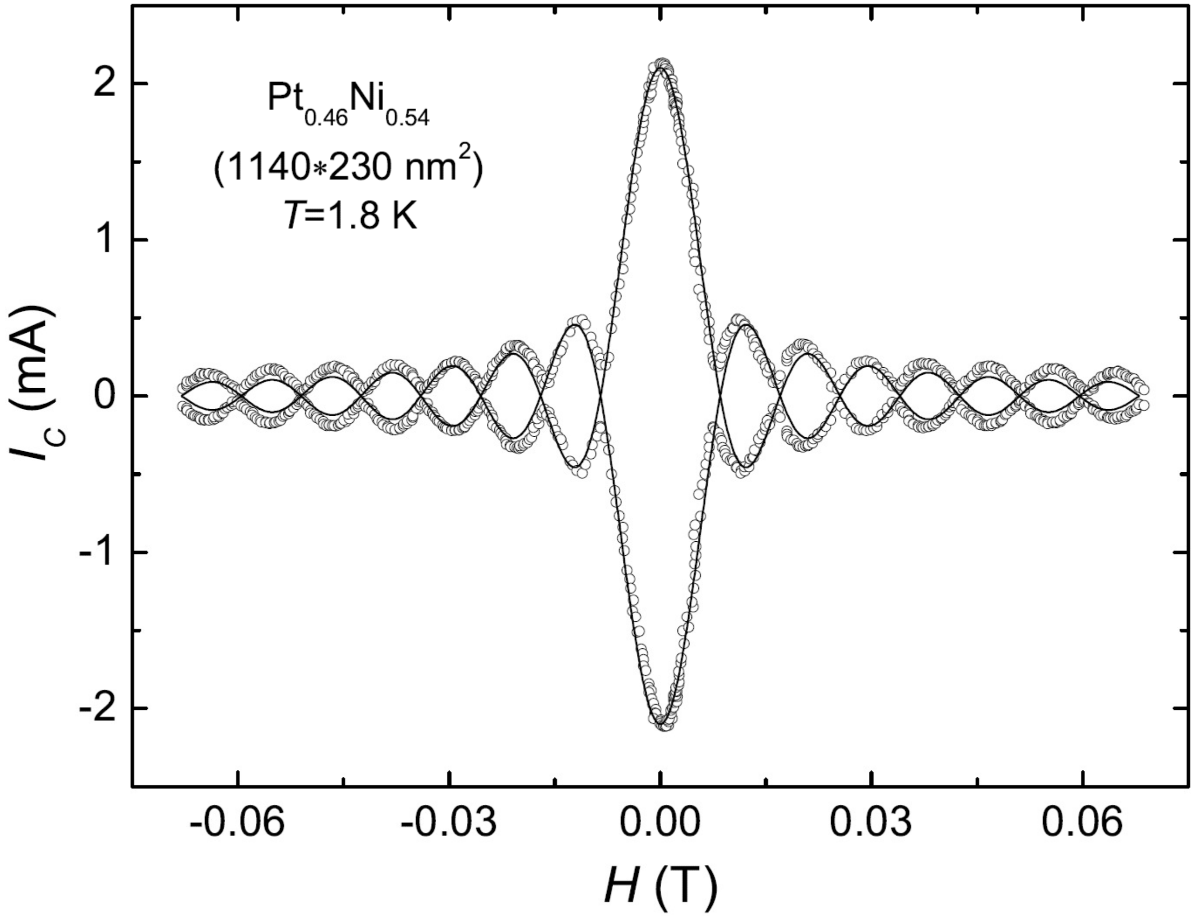
Nb-Co-Nb

Robinson et al.,
Science 329, 59 (2010)

Inhomogeneity or 0-pi transitions ?

Analysis of the high I_c state

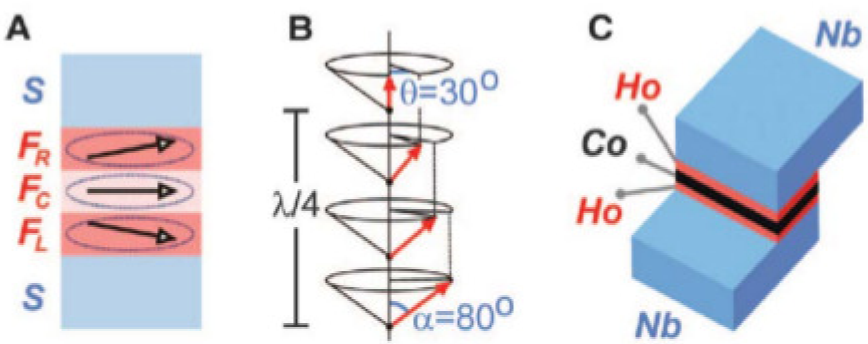


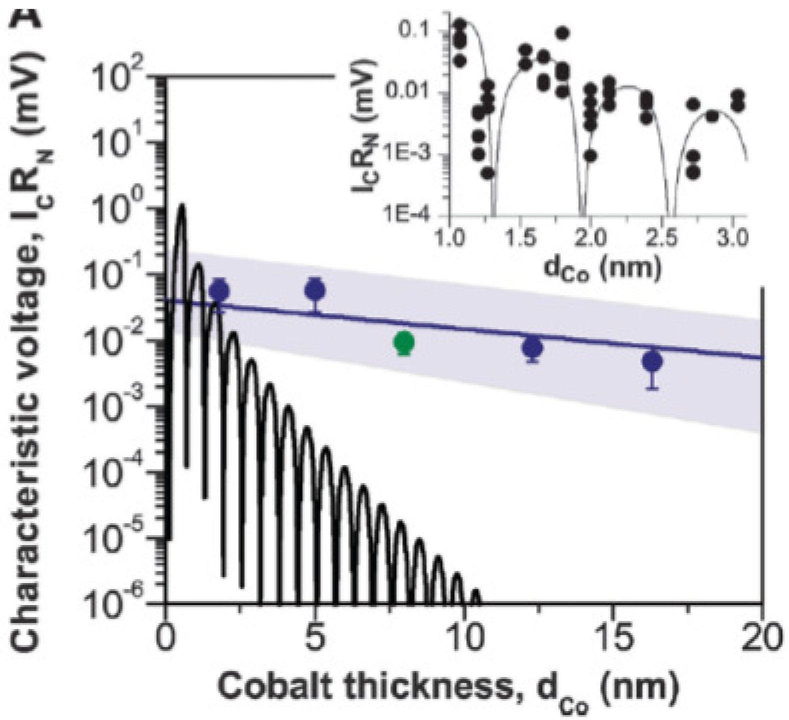


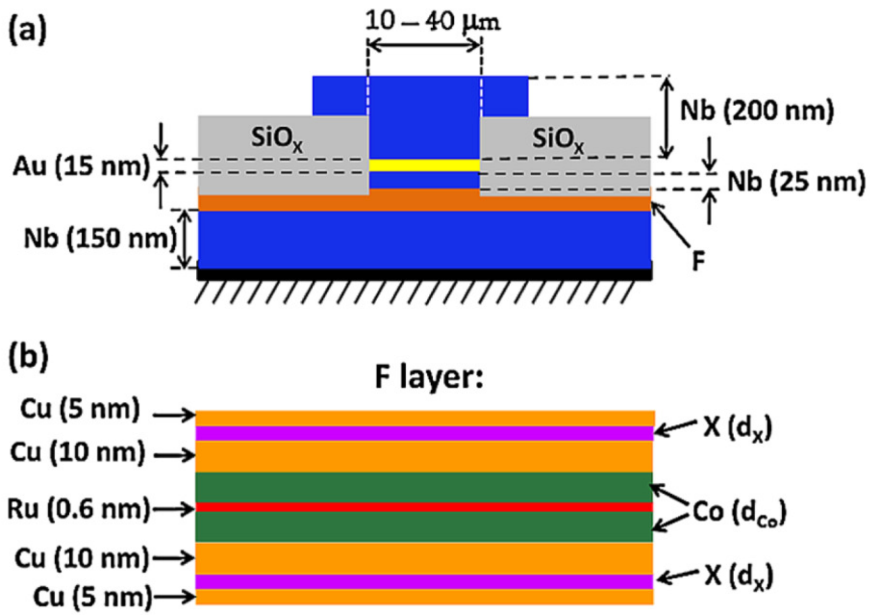
Looks remarkably homogeneous

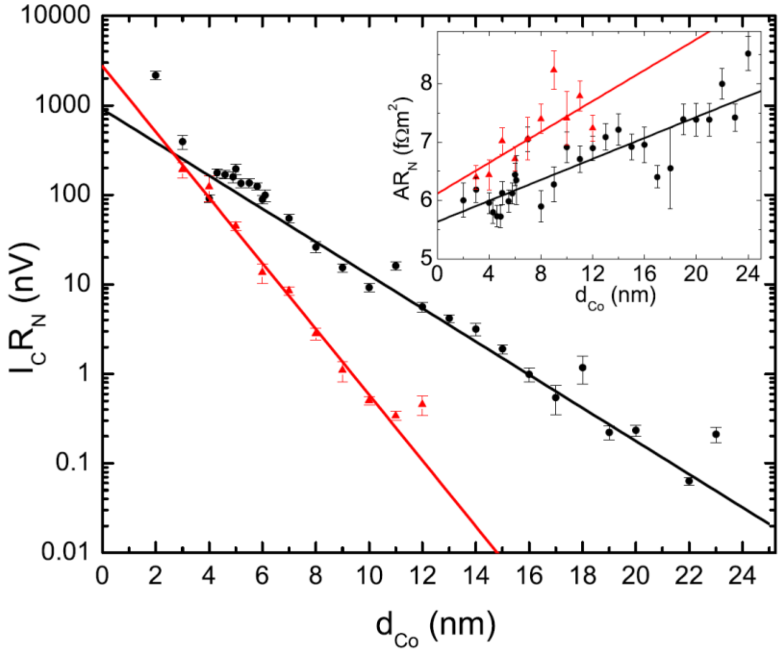
To prove the existence of spin-triplet – need to be able to control it

1. Robinson et al., Science 329, 59 (2010)









T. Khaire, et al., PRL 104, 137002 (2010)

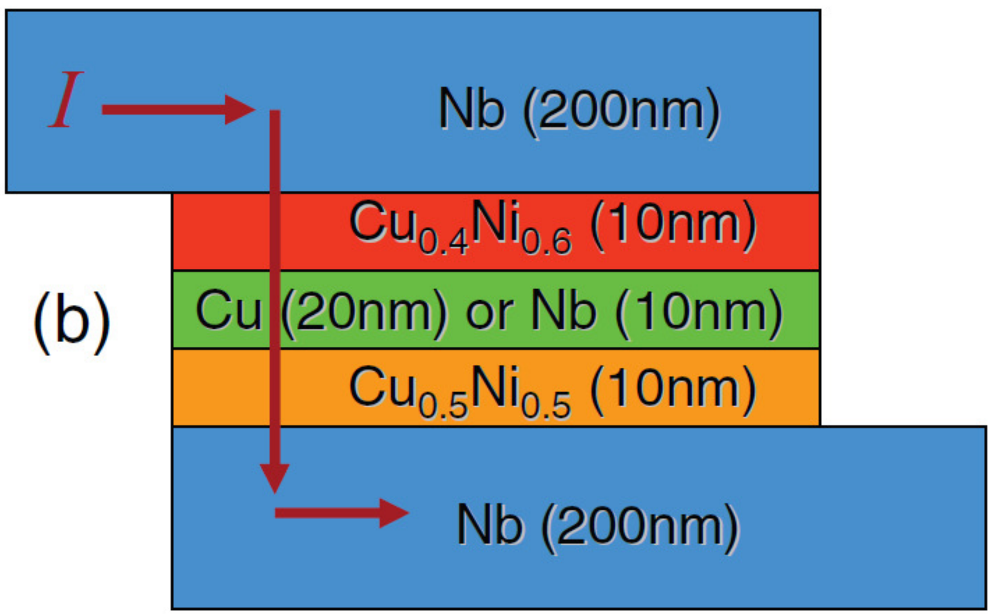
Motivation:

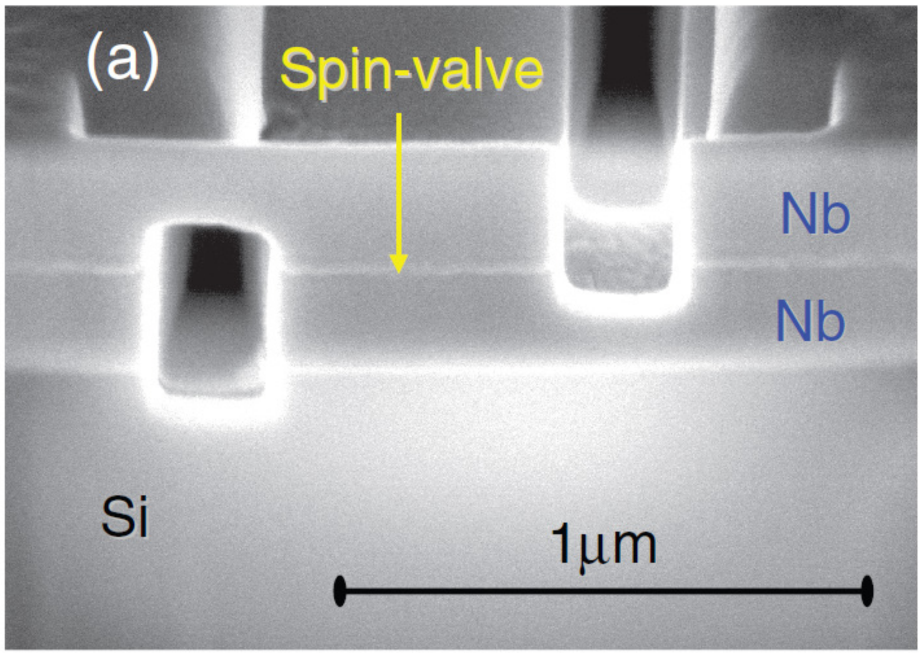
S F1 F2 S – the simplest (but non-optimal) structure for controllable generation of spin-triplet

Need different F1, F2 (L. Trifunovic, et al., PRB 84, 064511 (2011)) amplitude ~ F1-F2

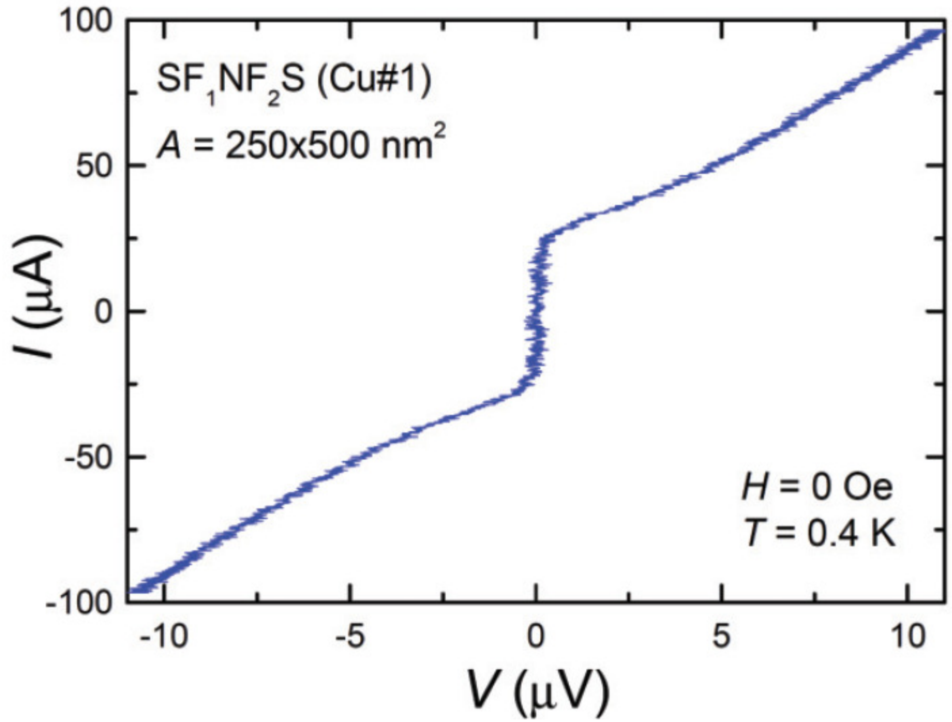
Need mono-domain nano-structures

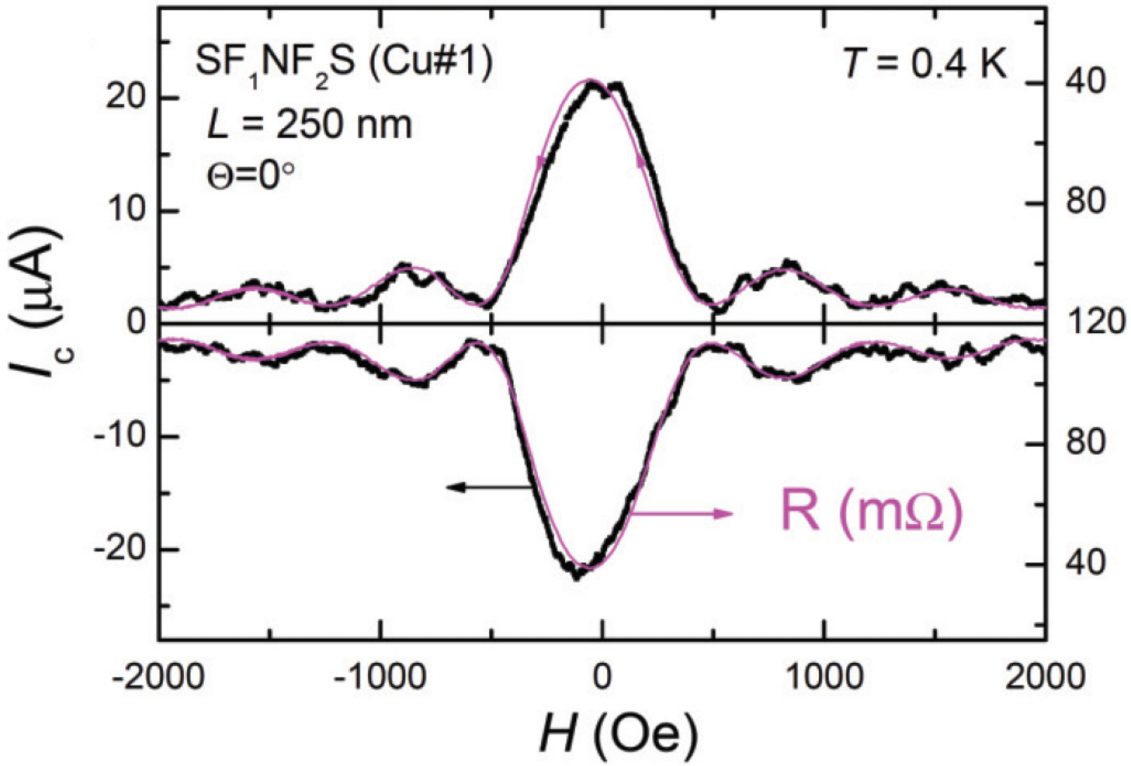
SF_1NF_2S or $SF_1S'F_2S$





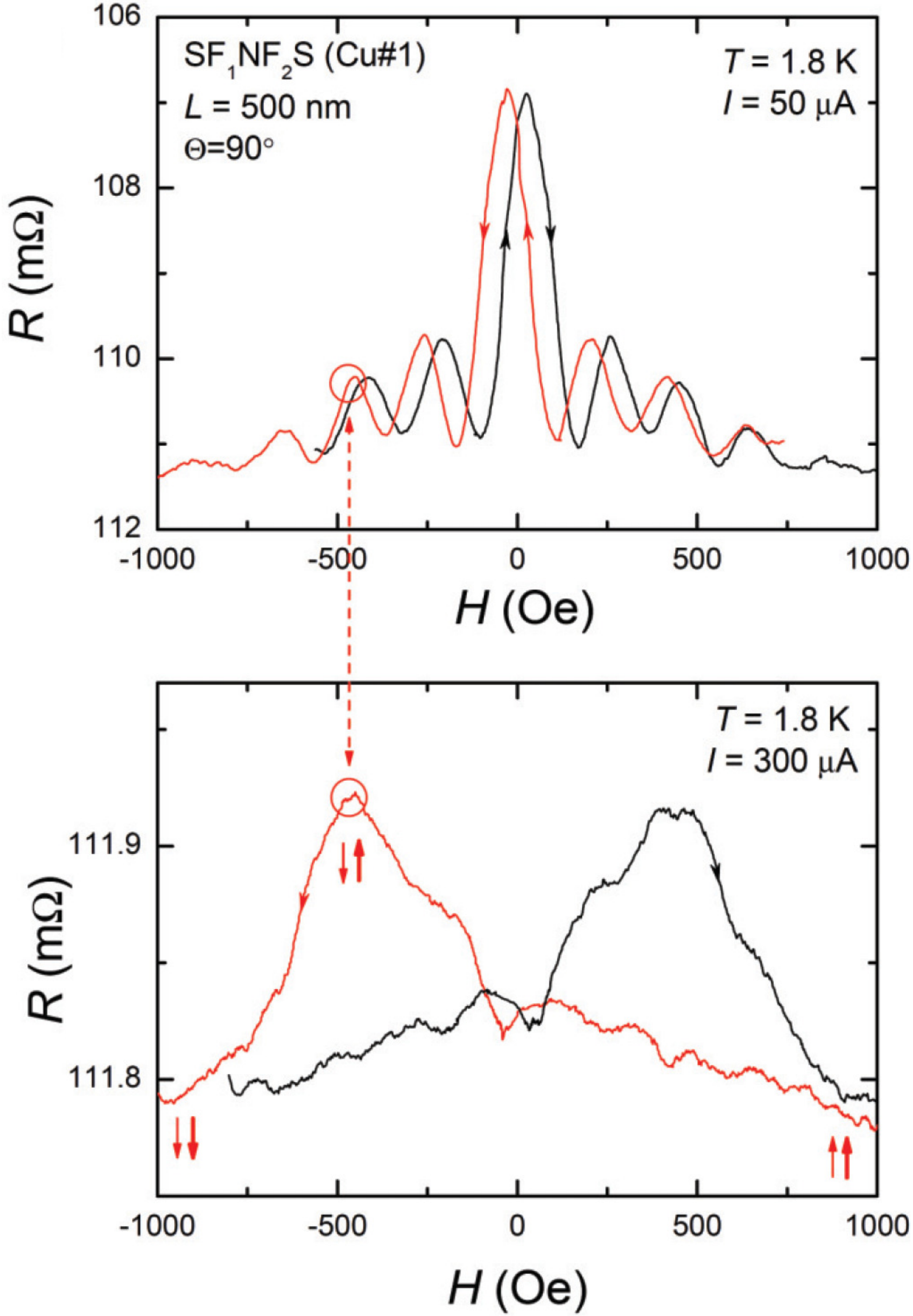
Nb
$Cu_{0.5}Ni_{0.5}$ (10nm)
Cu (10nm)
$Cu_{0.4}Ni_{0.6}$ (10nm)
Nb

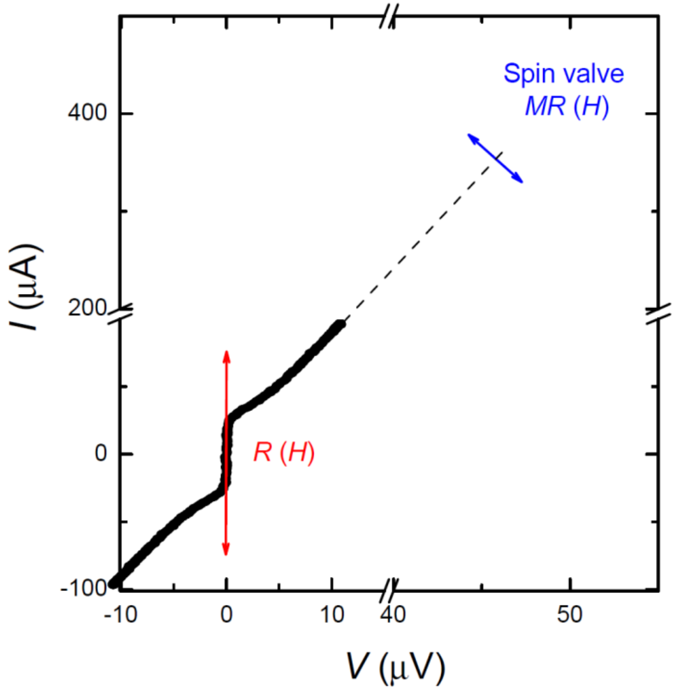




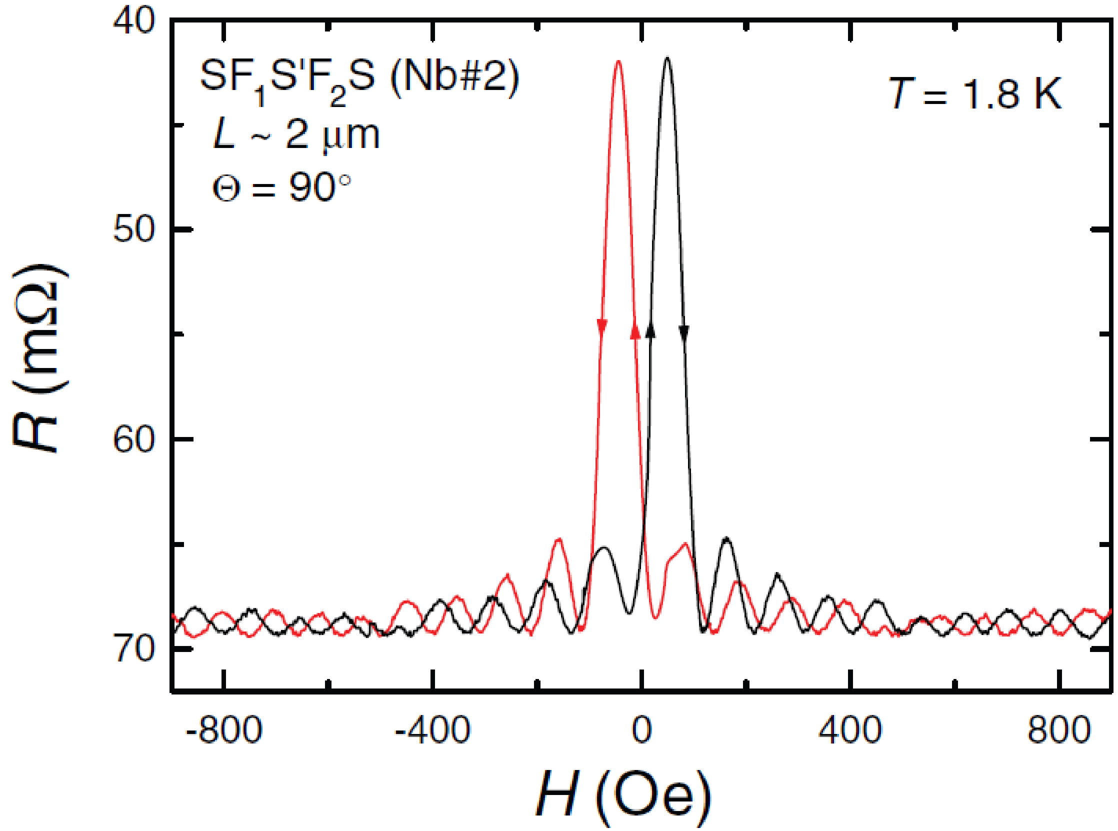
A. Iovan et al., PRB 90, 134514 (2014)

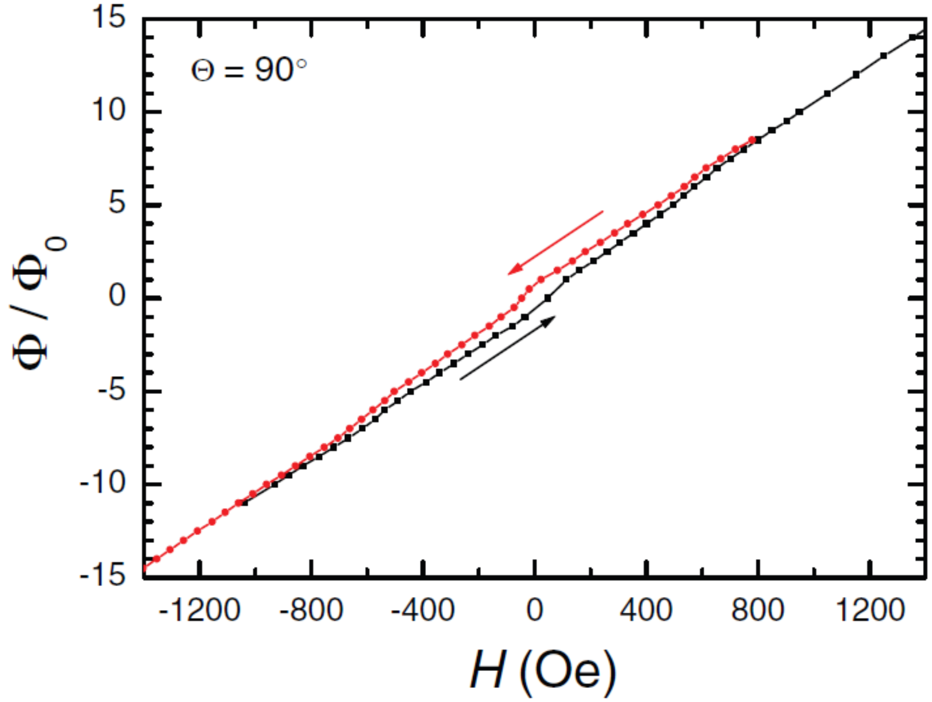
Simultaneous analysis of Josephson current and Spin-Valve MR

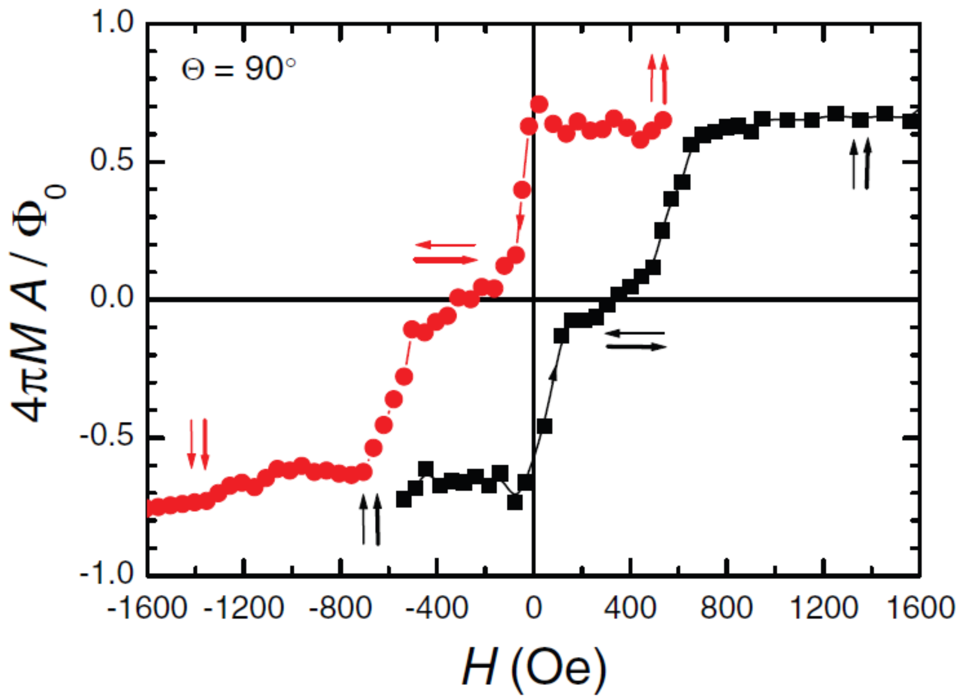




In-situ analysis of spin-valve magnetization : Absolute fluxometer



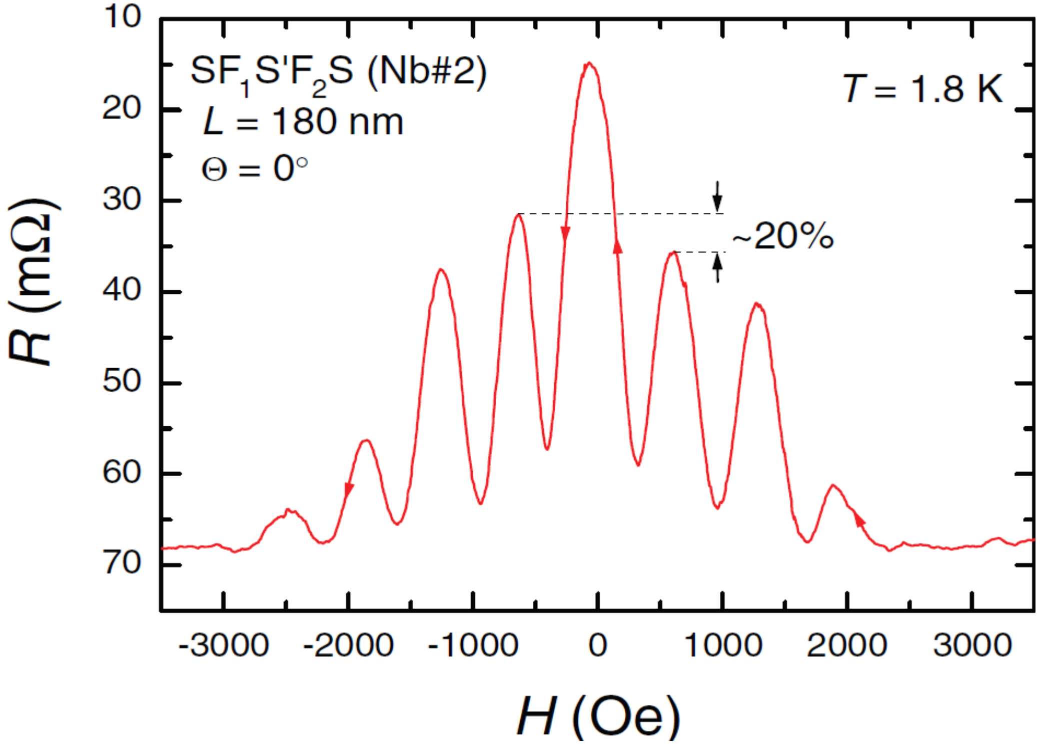


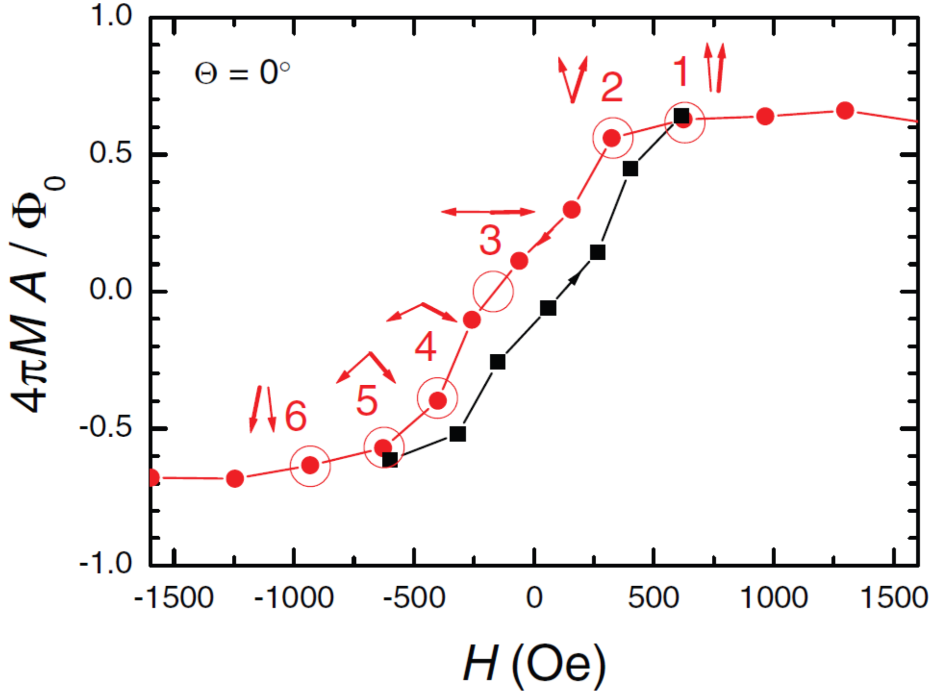


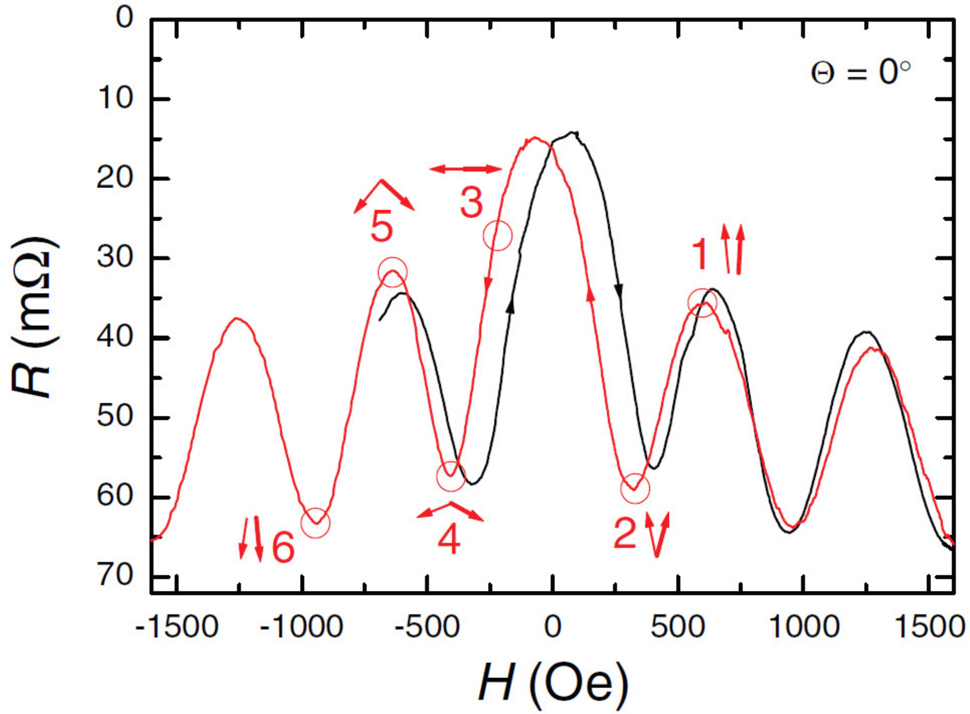
A. Iovan et al., PRB 90, 134514 (2014)

See also
V.V. Bol´ginov, et al., JETP Lett. 95, 366 (2012)

In-situ controlling of the spin-valve state



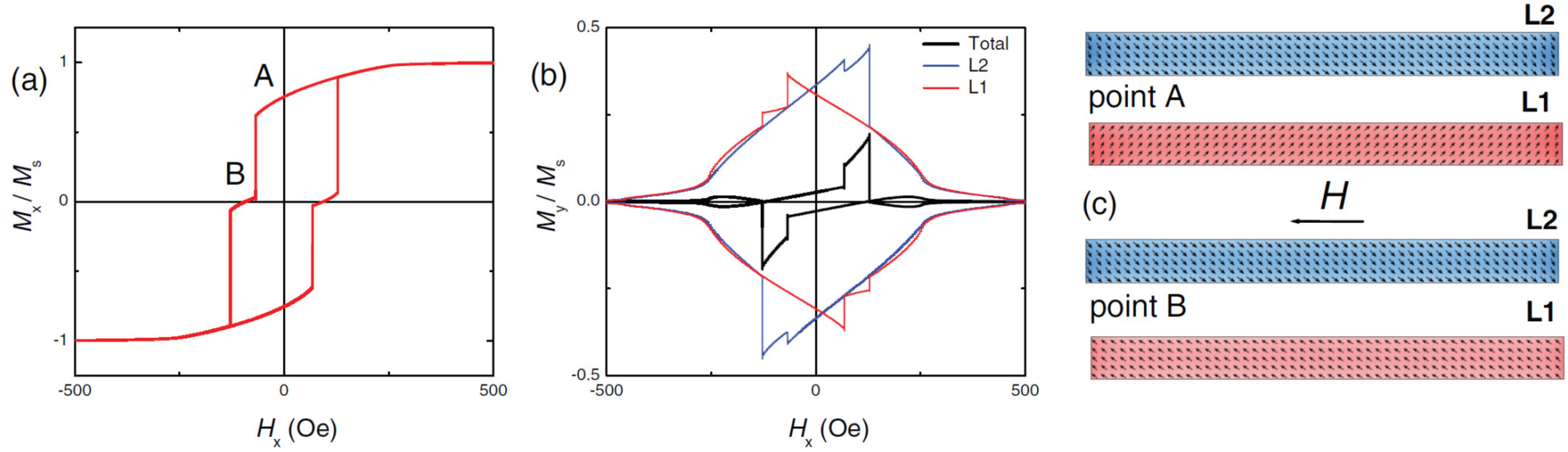




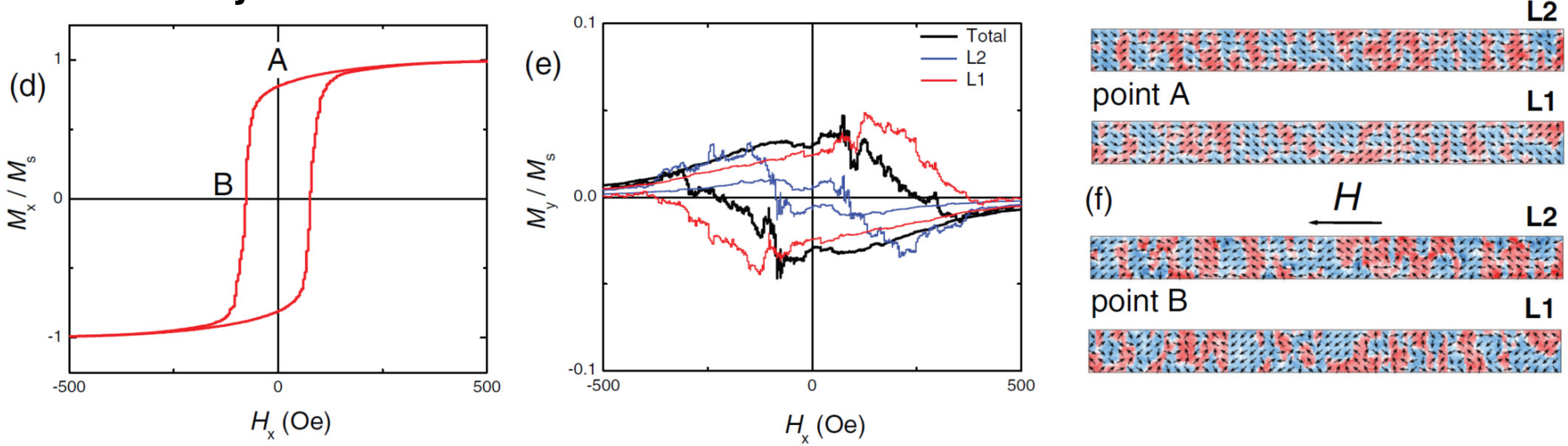
Enhancement of I_c in the non-collinear state of the SV

Micromagnetic calculations of spin-valve characteristics

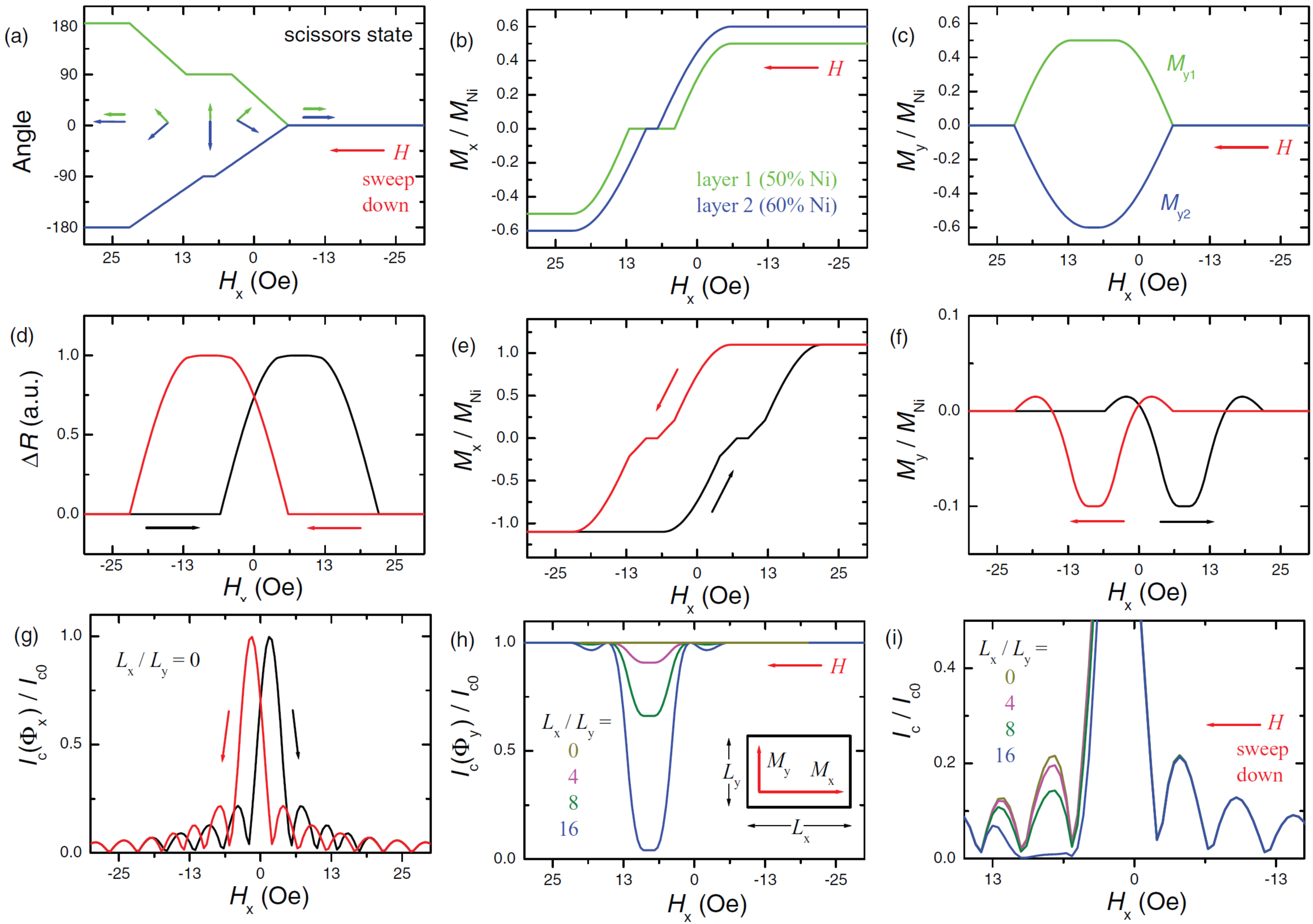
Mono-domain (scissors) case



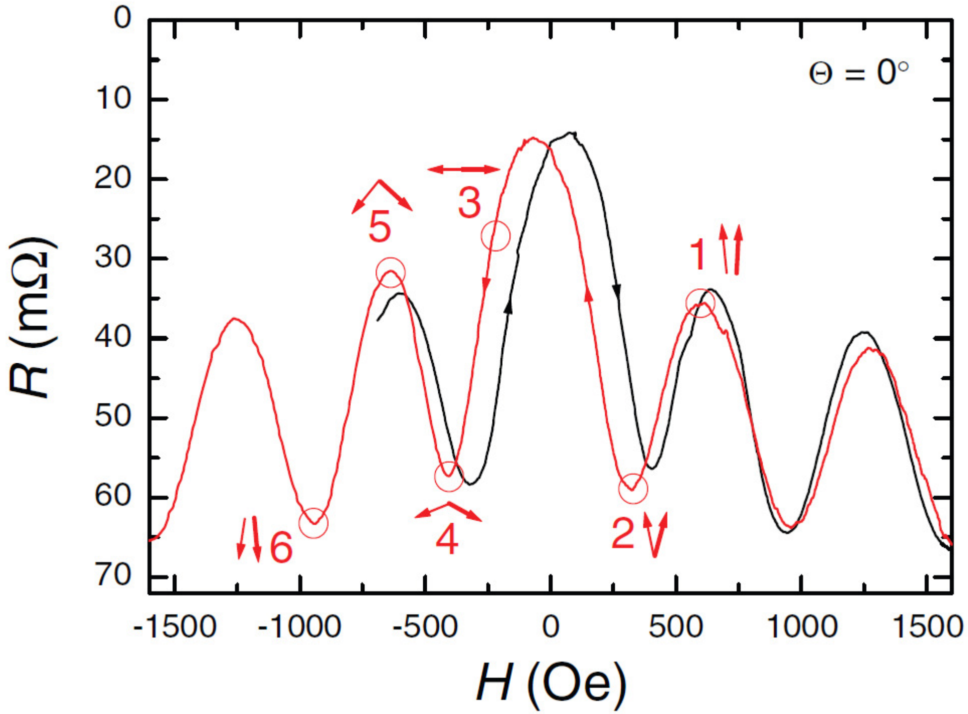
Poly-domain case

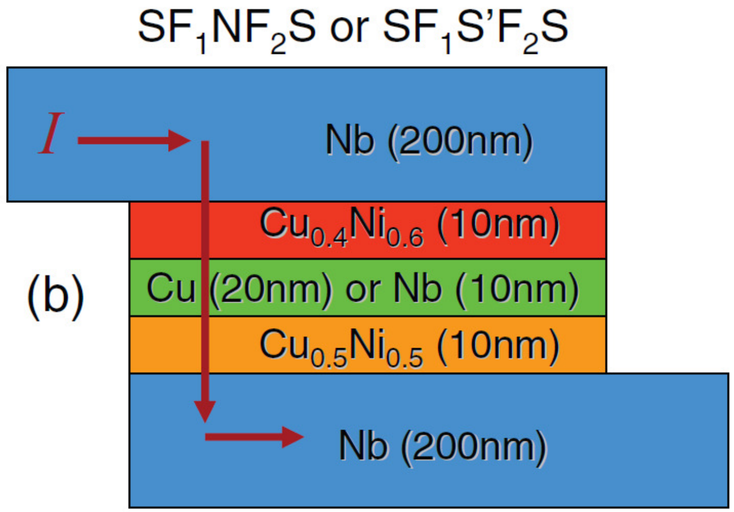


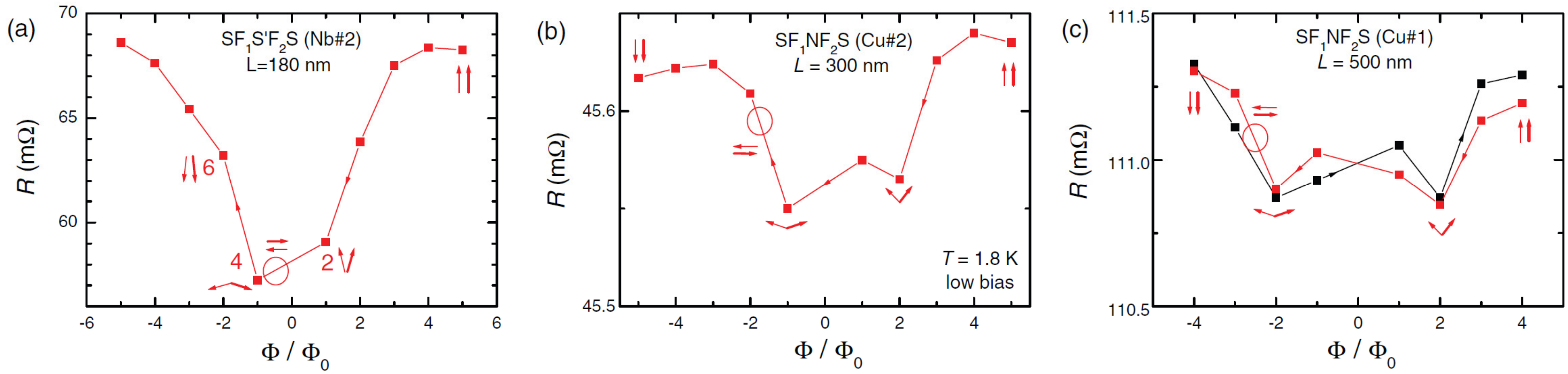
Influence of the orthogonal magnetization component (scissors case)



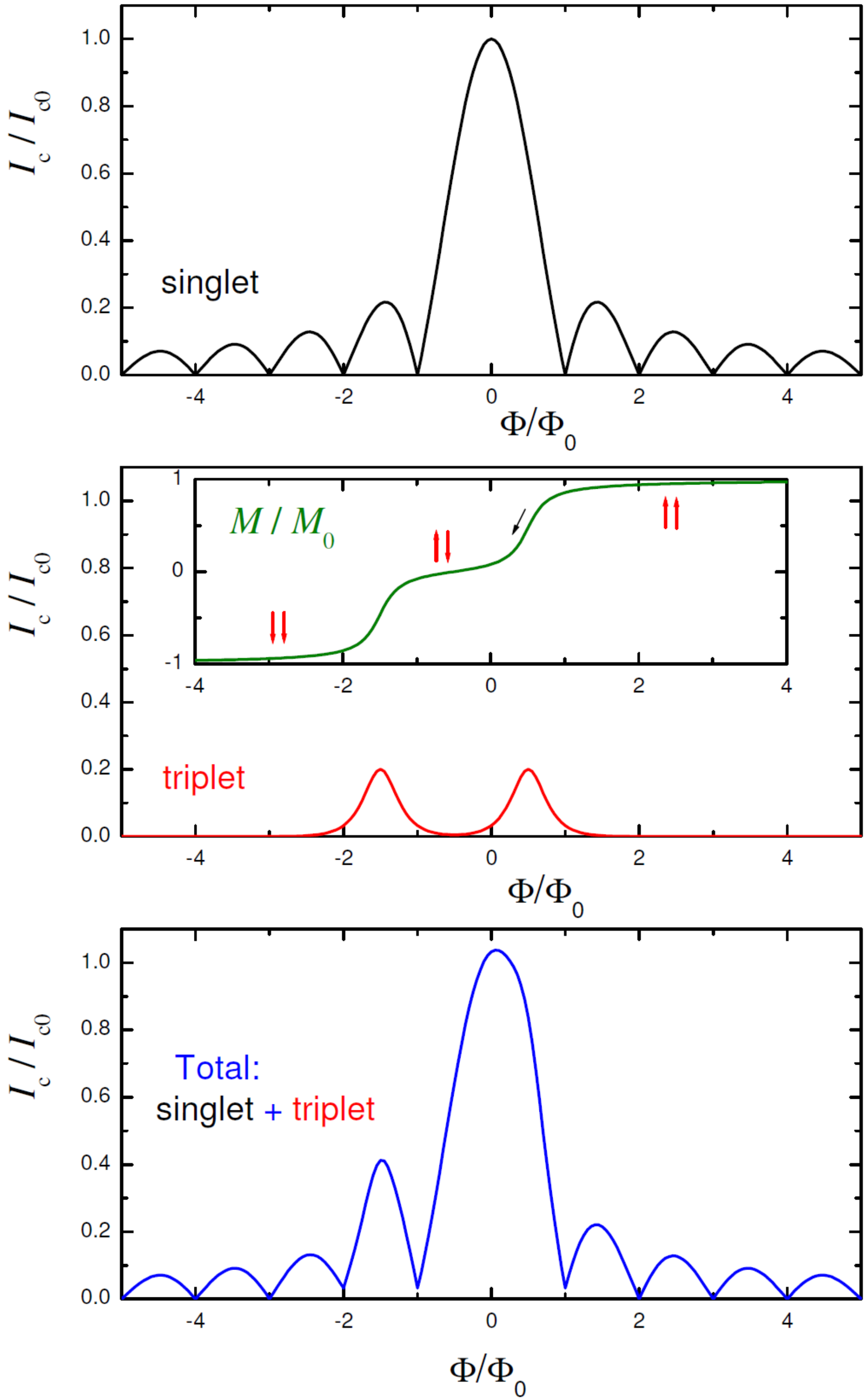
Search for a second non-collinear state
Proximity effect in a spacer layer





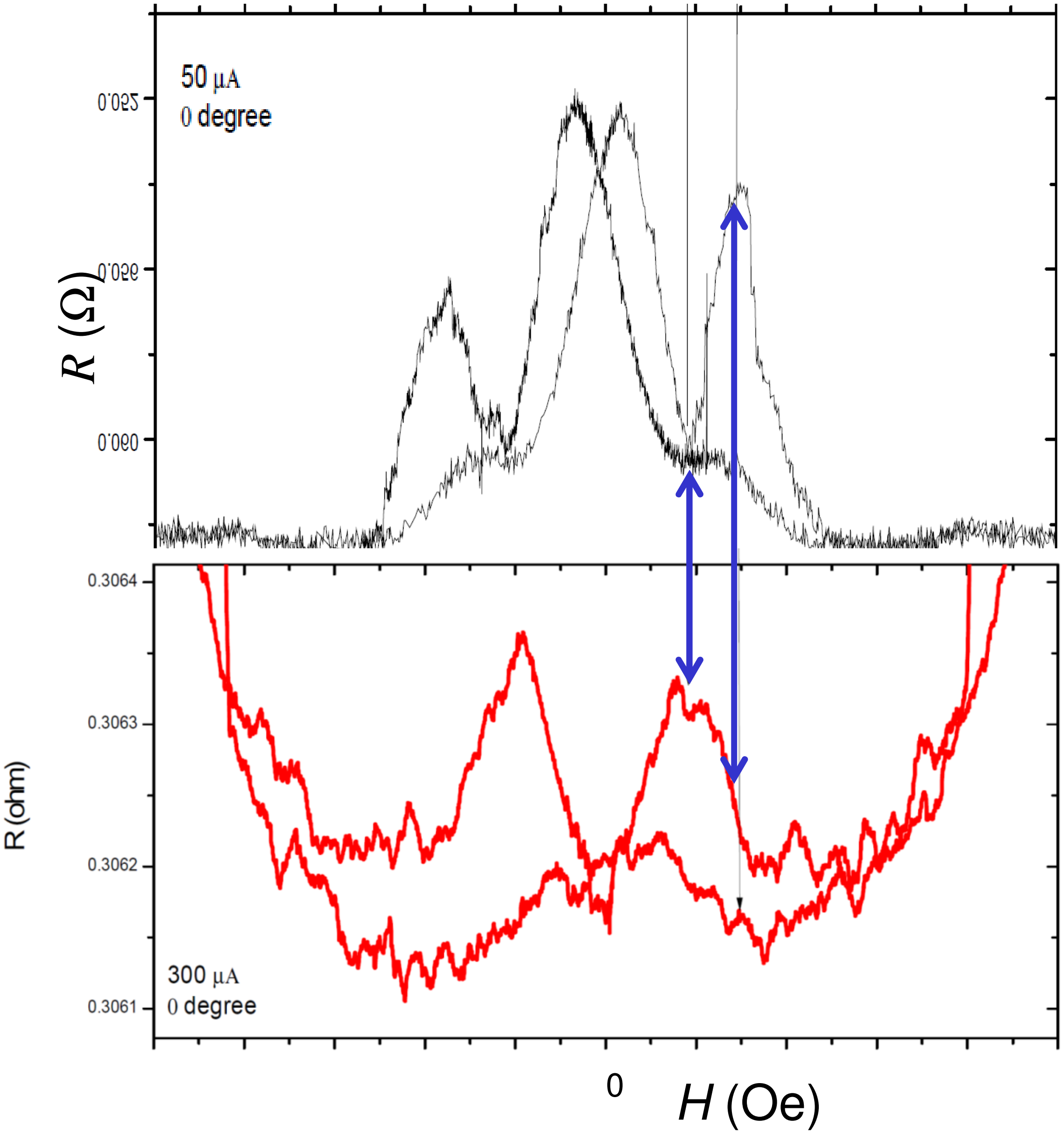


Origin of the observed asymmetry



A case of strong ferromagnets

Nb Ni (7nm) Cu (10nm) Ni (5nm) Nb



Summary:

Due to many technical difficulties and artifacts a decisive experiment :

- Need controllable tuning of the spin-triplet component
- Need mono-domain = nano-scale structure
- Deciphering the data using micromagnetic simulations

Experiment for the simplest case of a single asymmetric Josephson spin-valve S/F$_1$/F$_2$/S

In-situ characterization using an ordinary spin-singlet current and spin-valve MR

Evidence for controllable generation of a spin-triplet component