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Superconducting spin valves and exchange coupling

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www.superspintronics.org

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singlet

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- Jacob Linder (Trondheim)

triplet

Metallic singlet spin valves

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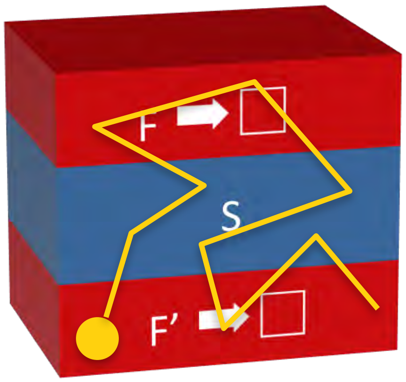
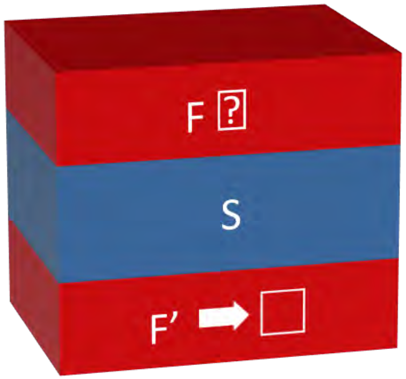
P state – exchange field in both F layers adds and suppresses T_c

P



AP state – exchange field in F layers (partially) cancels and reduces suppression of T_c

AP



But – proximity effect suppresses T_c in both cases

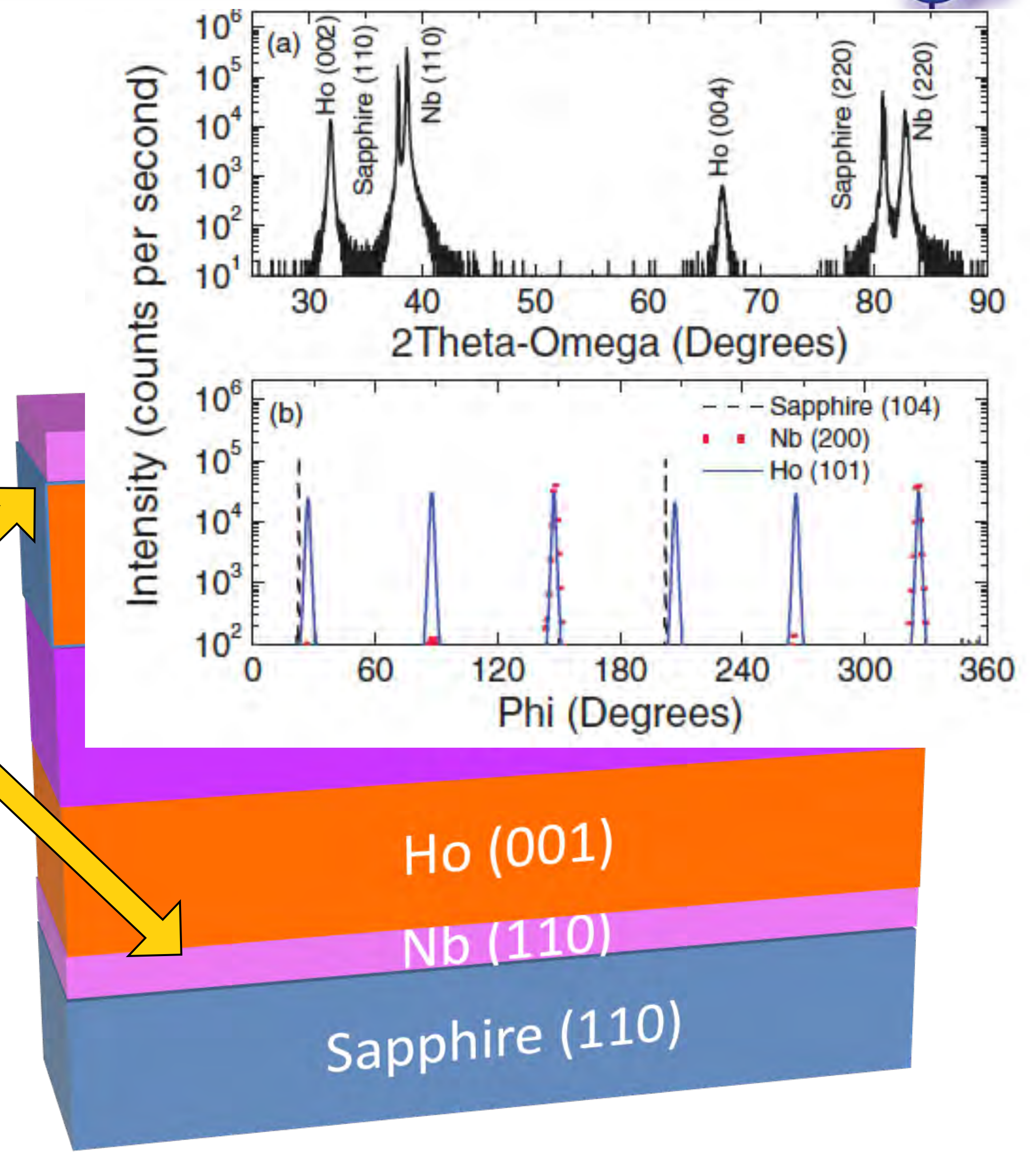
How about rare-earth ferromagnets??

Epitaxial growth of Nb/Ho heterostructures

- To test role of spin spiral need epitaxial films

- Growth at 650-860 °C
- Nb (110) seed layer on a-plane sapphire
- Ho (001) on Nb
- etc….
- Nb capping layer to prevent Ho oxidation

- Comparison non-epi samples grown at RT



Ho magnetic properties

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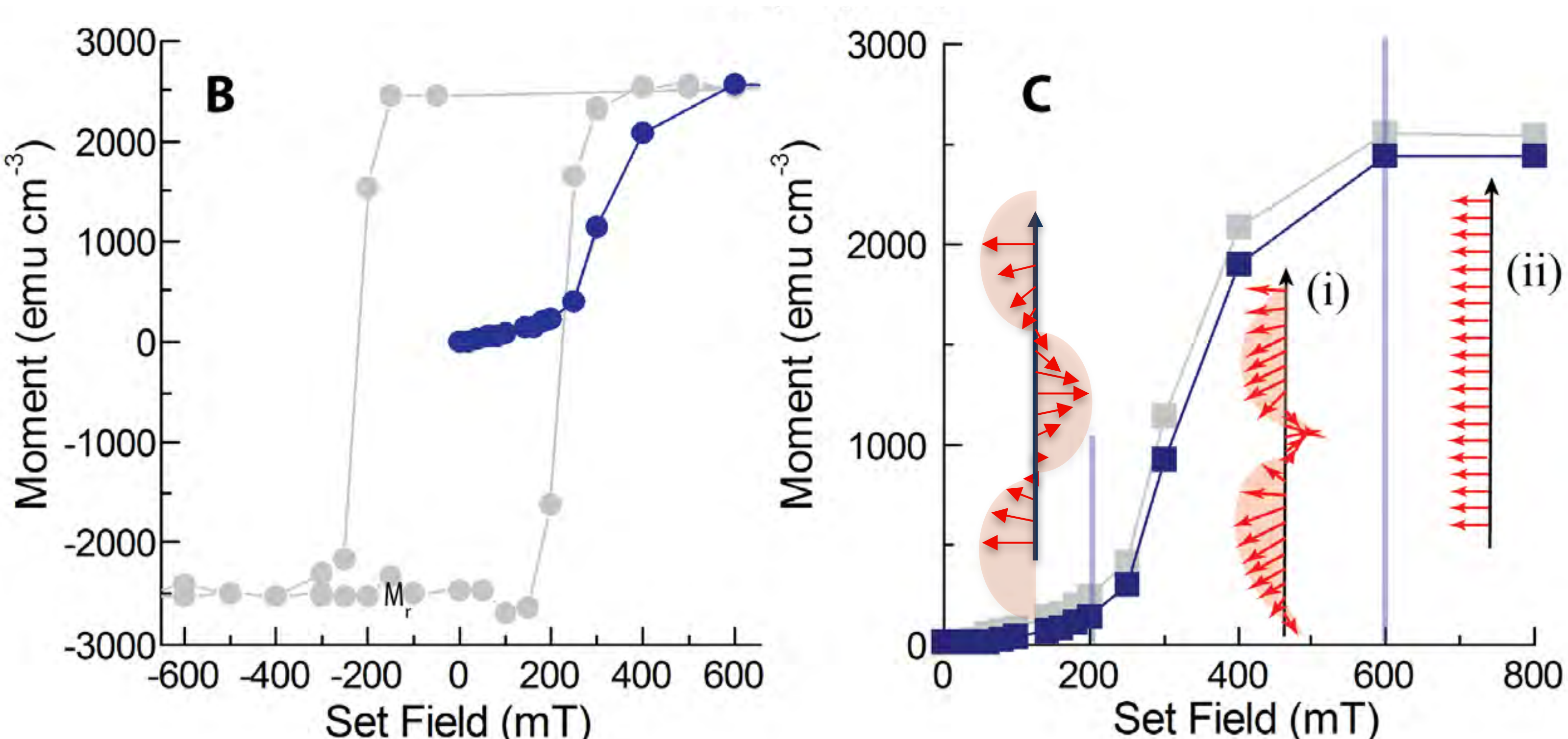
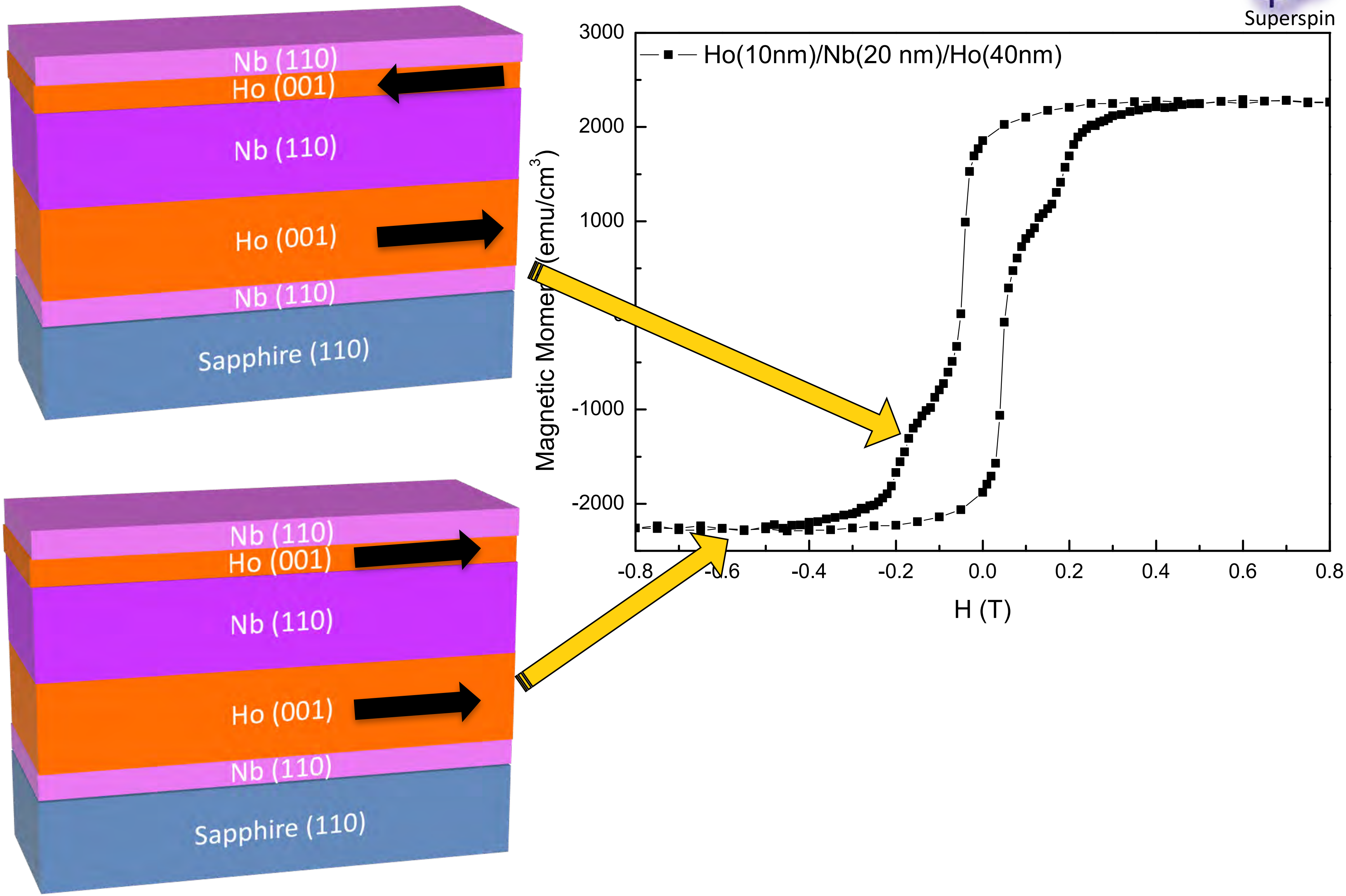
- As-cooled spin spiral antiferromagnetic state ($M_{rem} = 0$)
- Field-induced irreversible metamagnetic transition to ferromagnetic state ($M_{rem} = M_{sat}$)
- Stable square hysteresis loop in FM state



Ho/Nb/Ho trilayers



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T_c dependence on magnetic state

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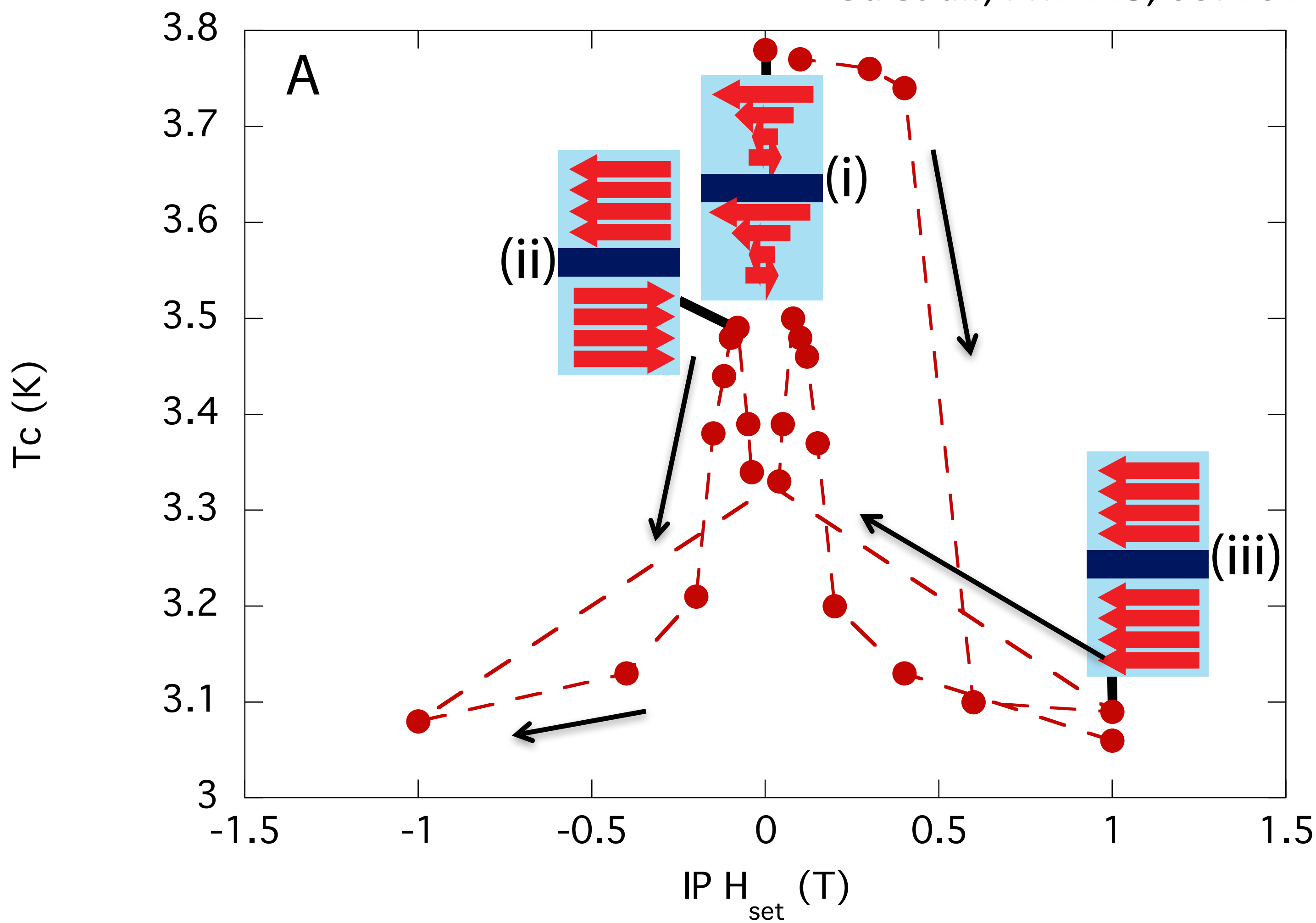
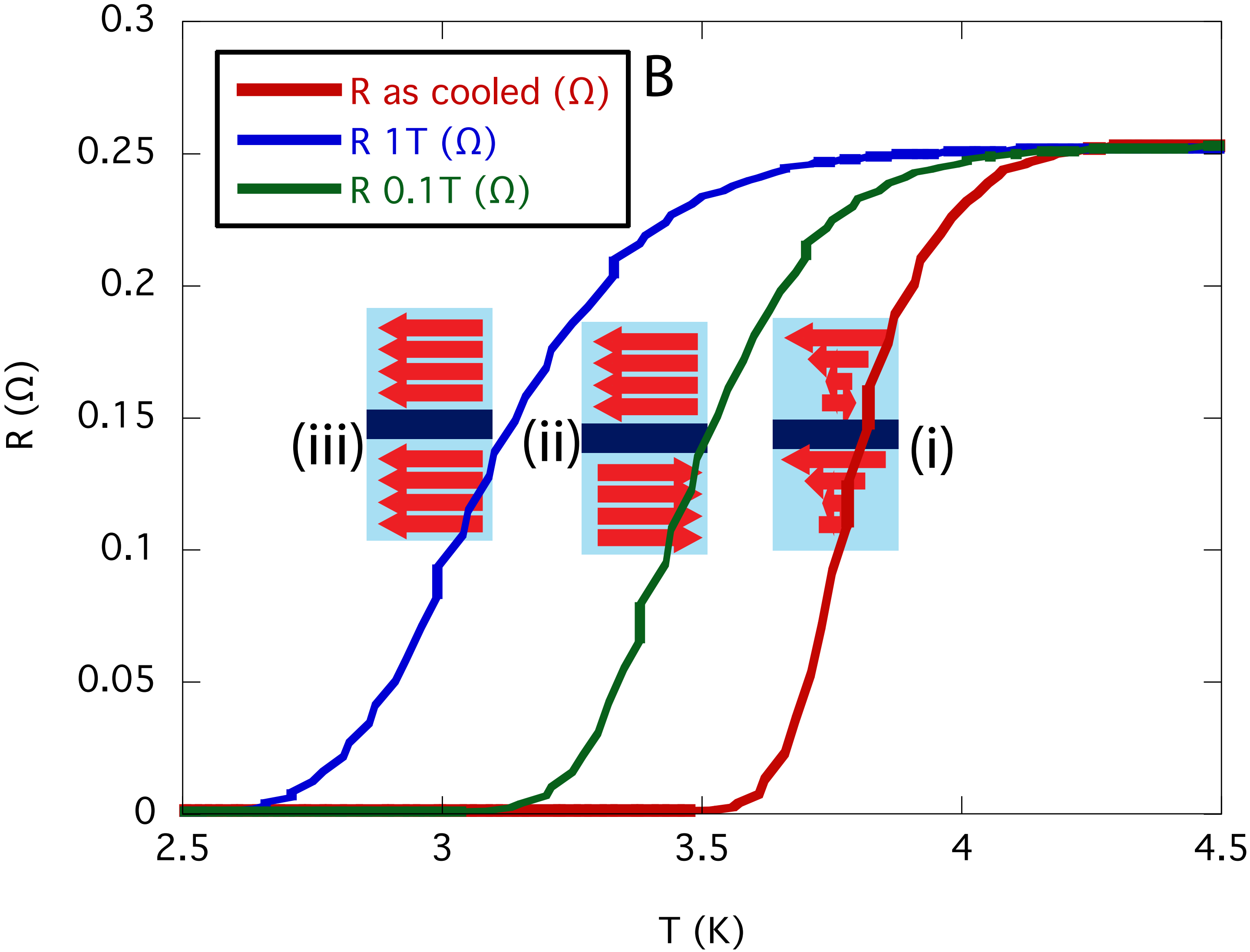
- Apply H_{set} to set magnetic state and then measure at H = 0
- Repeated for increasing and decreasing H_{set}

Gu *et al.*, PRL **115**, 067201 (2015)



T_c dependence on magnetic state



Gu *et al.*, PRL **115**, 067201 (2015)

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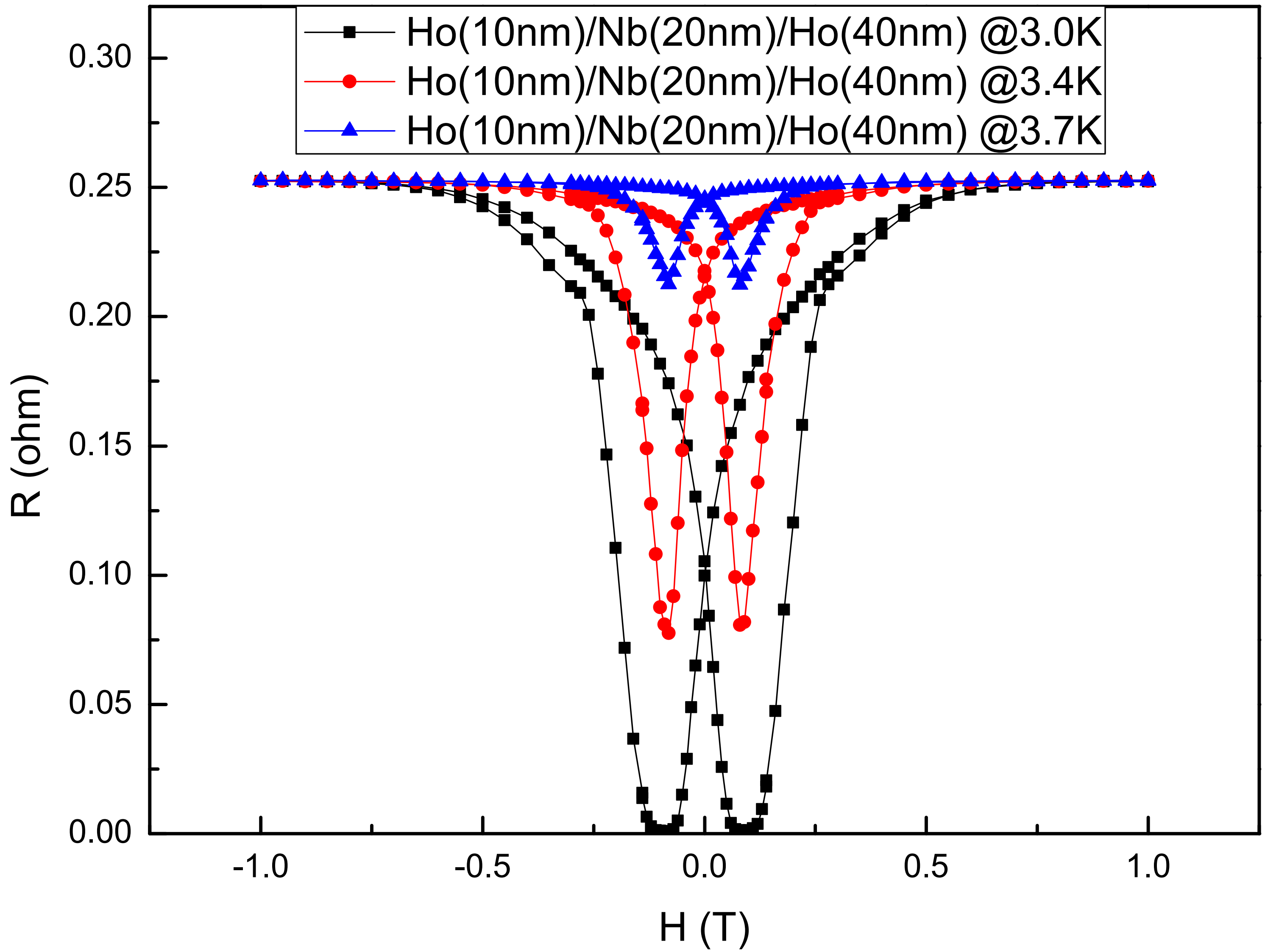
Infinite magnetoresistance

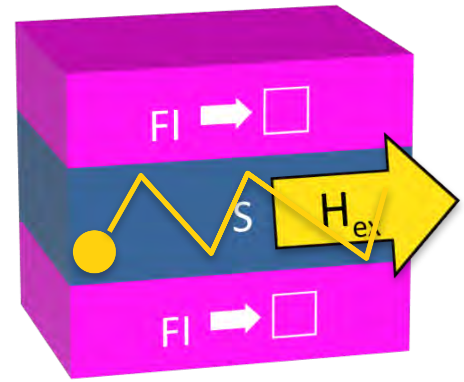


Gu *et al.*, PRL **115**, 067201 (2015)

FI/S/FI spin valves

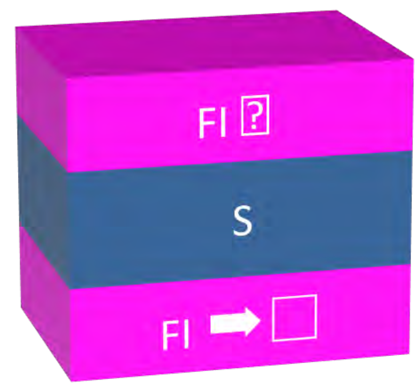
P state – exchange field from FIs in S layers adds and suppresses T_c

P



AP state – exchange field from FI in S layers cancels and reduces suppression of T_c

AP



No proximity effect

FI/S/FI spin valve

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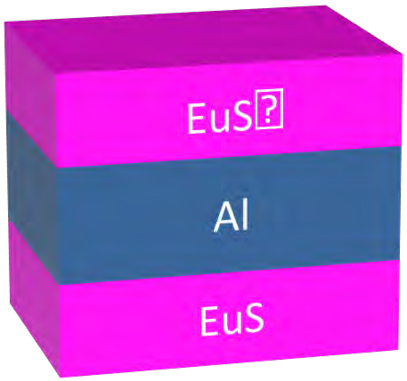
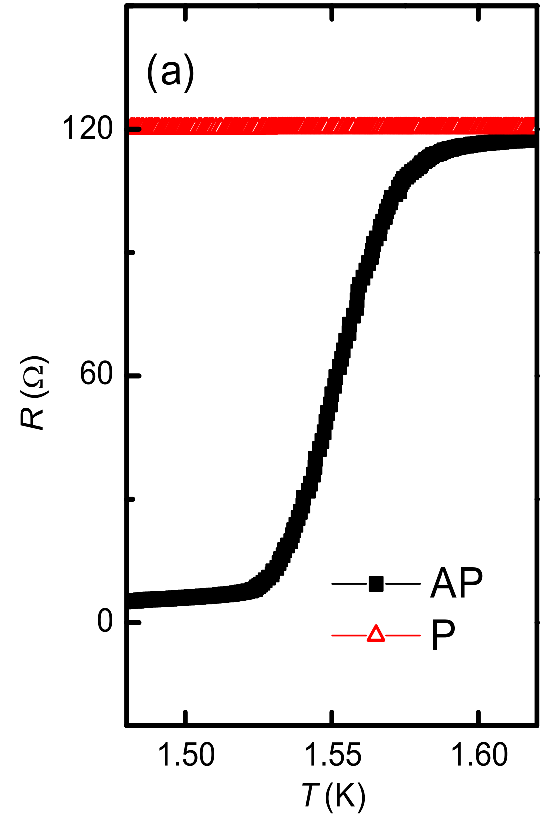
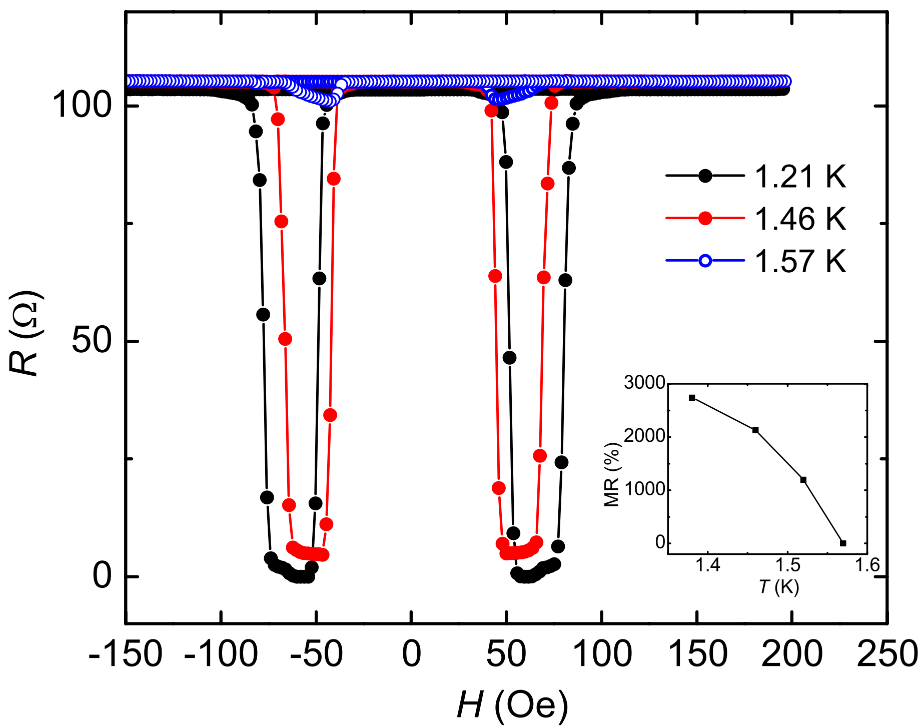


Large ΔT_c



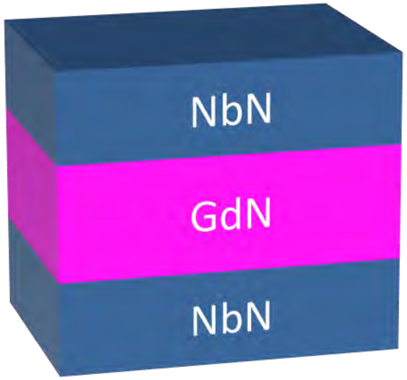


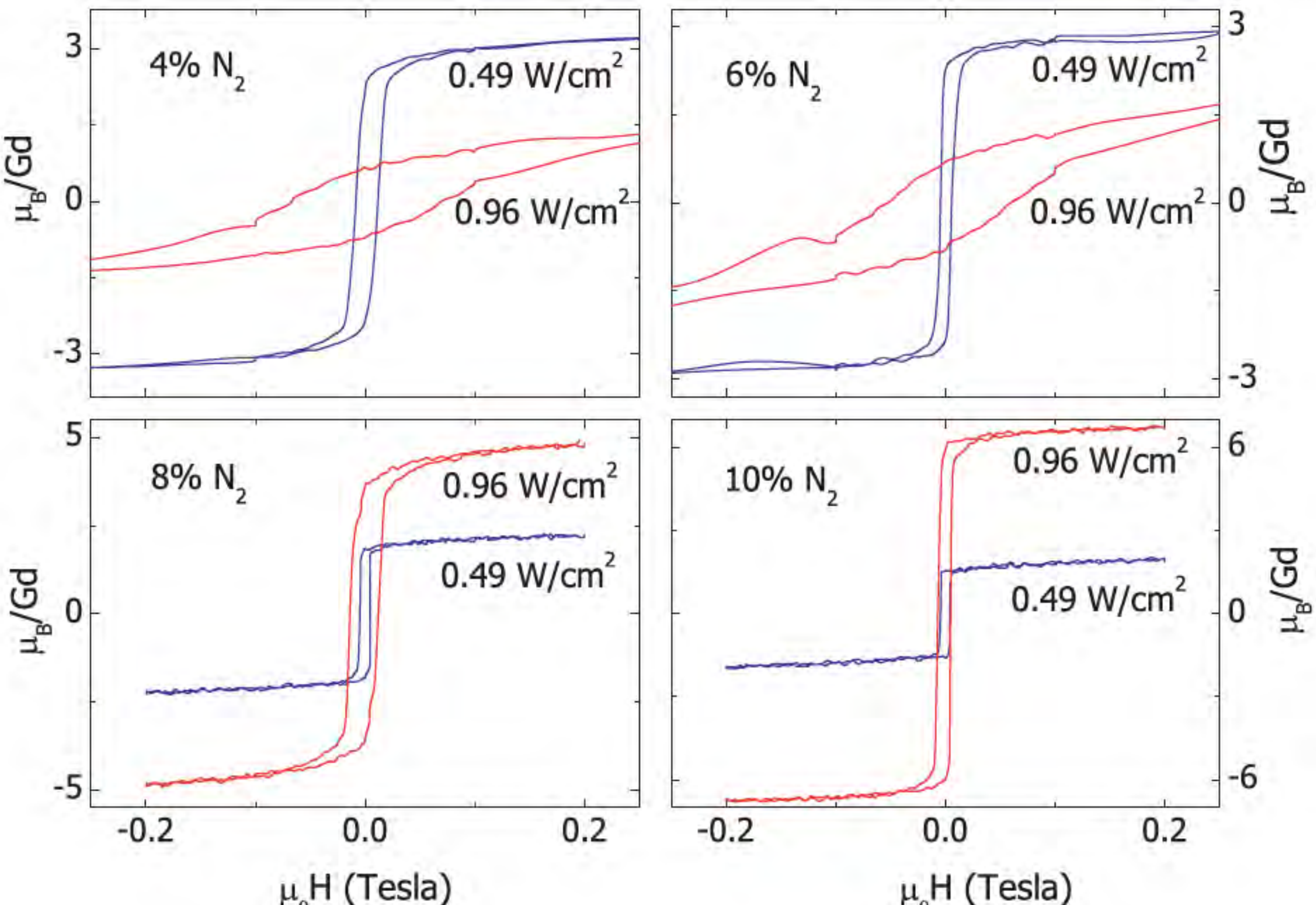
Infinite magnetoresistance

Li *et al.*, PRL **110**, 097001 (2013)

GdN

- A magnetic semiconductor / insulator
- Reactive sputtering from Nb & Gd targets
- Magnetic properties depend strongly on stoichimetry





Senapati *et al.*, PRB **83,** 014403 (2011).

GdN tunnel barriers

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nature materials

LETTERS

PUBLISHED ONLINE: 11 SEPTEMBER 2011 | DOI: 10.1038/NMAT3116

Spin-filter Josephson junctions

Kartik Senapati*†, Mark G. Blamire and Zoe H. Barber

Josephson junctions with ferromagnetic barriers have been intensively investigated in recent years[1]. Of particular interest has been the realization of so called π-junctions with a built-in phase difference[2], and induced triplet pairing[3,4]. Such experiments have so far been limited to systems containing metallic ferromagnets. Although junctions incorporating a ferromagnetic insulator (I_F) have been predicted to show a range of unique properties including π-shifts with intrinsically low dissipation[5,6] and an unconventional temperature dependence[7] of the critical current I_c, difficulties with the few known I_F materials have prevented experimental tests. Here we report supercurrents through magnetic GdN barriers and show that the field and temperature dependence of I_c is strongly modified by the I_F. In particular we show that the strong suppression of Cooper pair tunnelling by the spin filtering of the I_F barrier can be modified by magnetic inhomogeneity in the barrier.

Superconductor/ferromagnet/superconductor (S/F/S) junctions based on diffusive ferromagnetic barriers are now well understood.

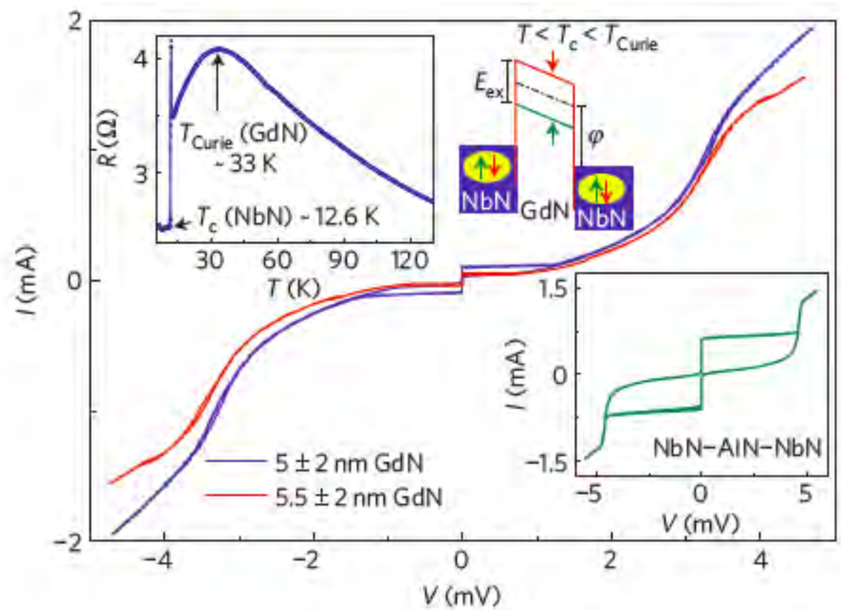

Figure 1 | Spin filtering and Josephson effect in NbN-GdN-NbN junctions.

GdN/Nb/GdN SSV

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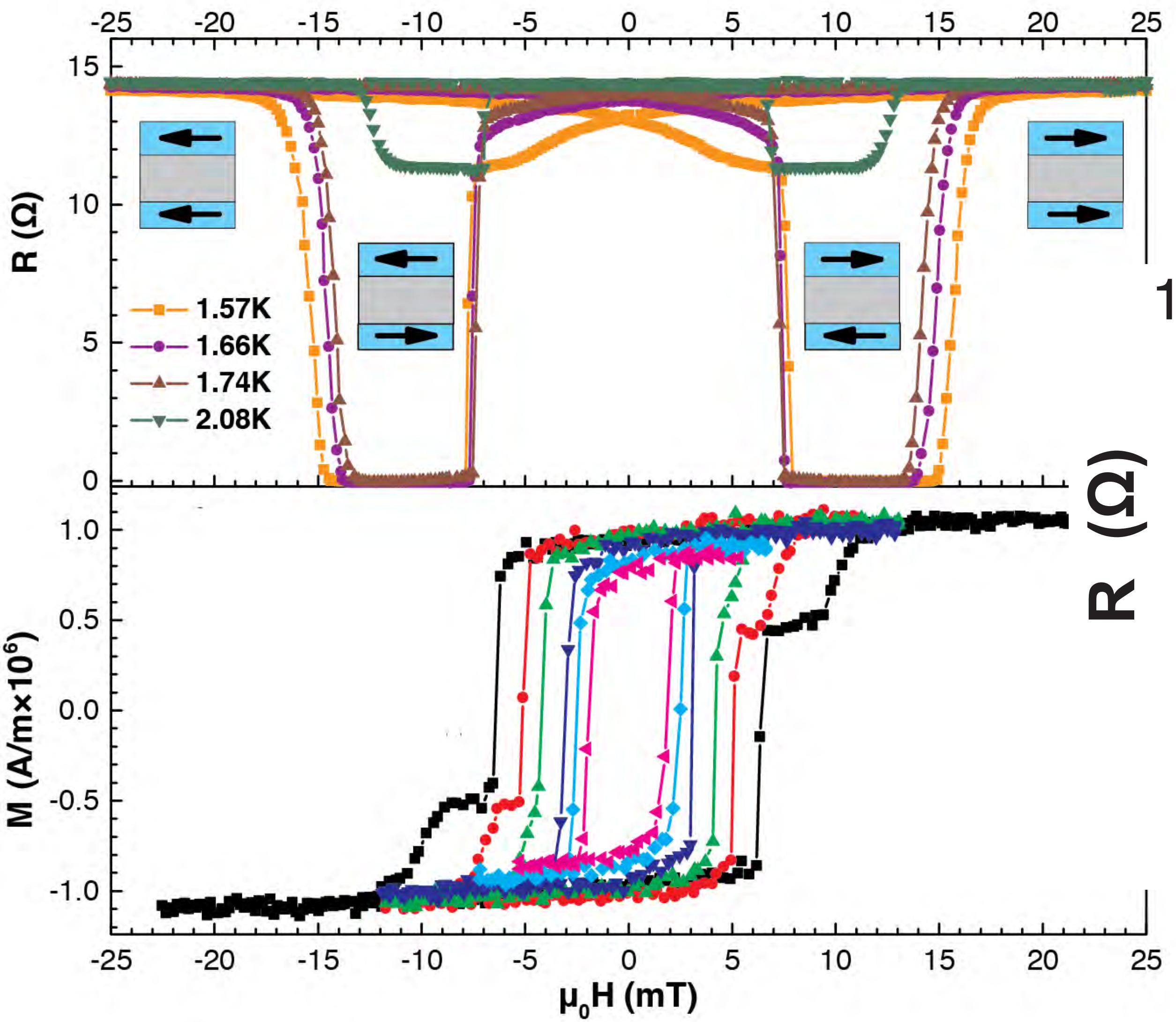

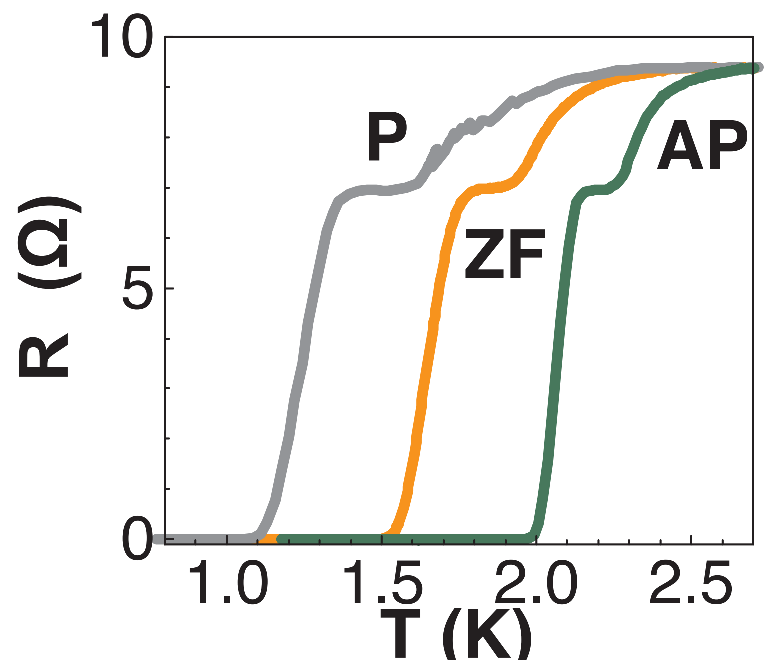

Coupling of magnetism and superconductivity

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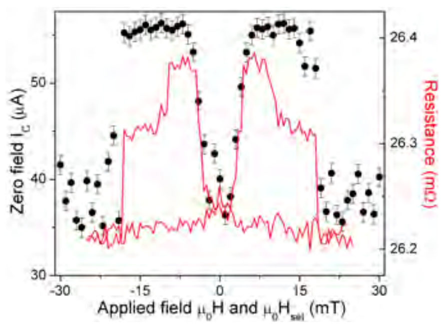
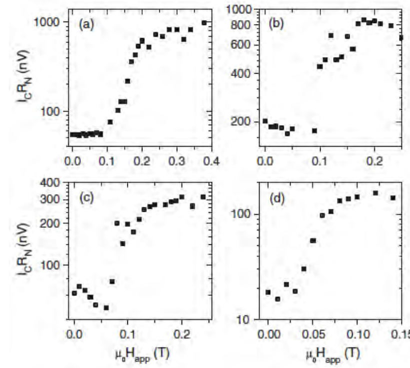
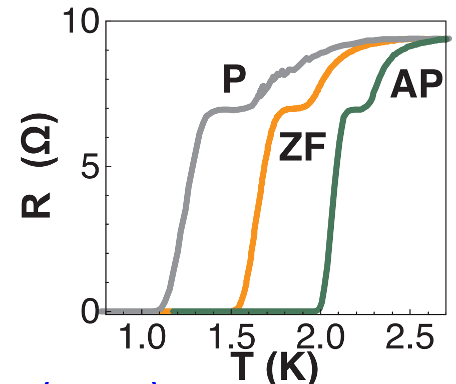
- Control of superconductivity by magnetism – using magnetic fields

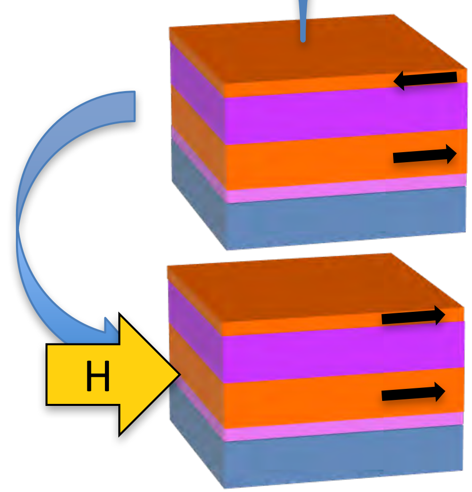






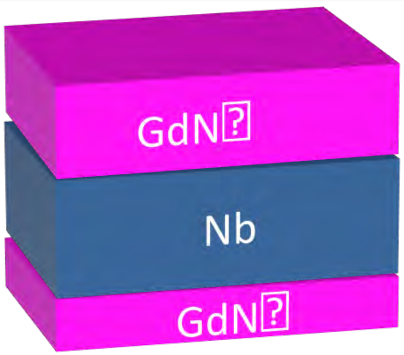
Bell *et al.*, APL **84**, 1153 (2004) Klose *et al.*, PRL **108**, 127002 (2012)

- Control of magnetism by superconductivity??

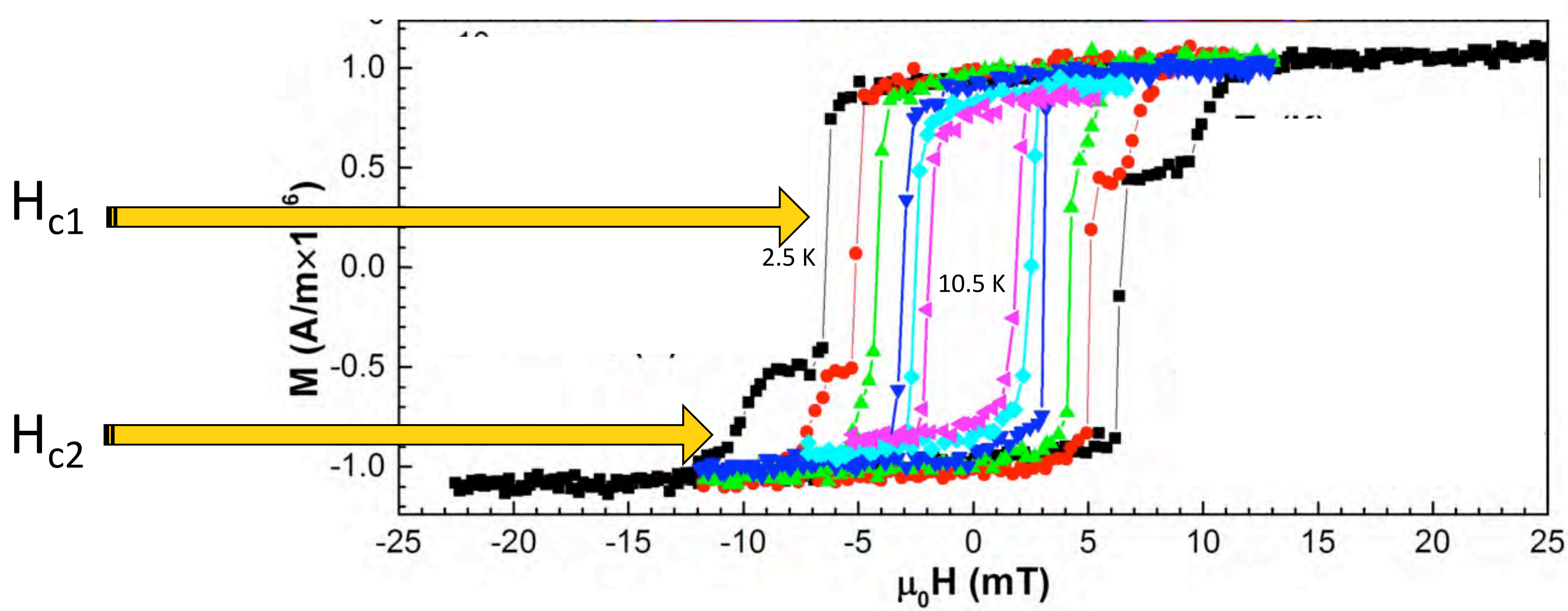


FI/S/FI spin valves

in



H_{c2} H_{c1}



GdN/Nb(x nm)/GdN

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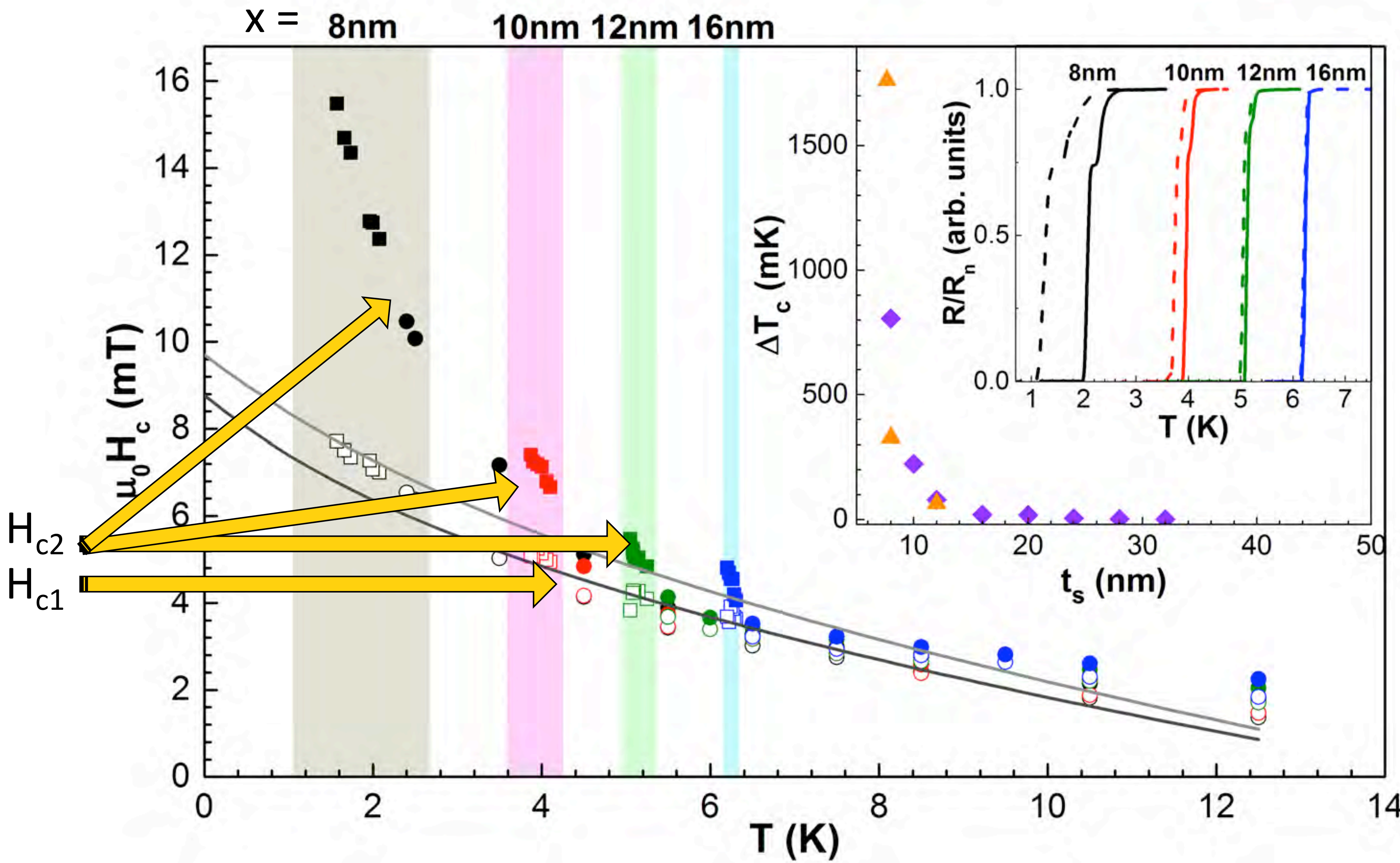

Superconducting exchange coupling

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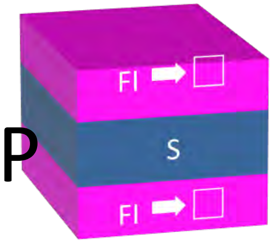
de Gennes, Phys. Lett. **23**, 10 (1966)

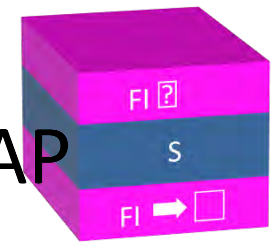
- Net exchange field, and hence T_c, dependent on angle between FI layers
- Condensation energy $E_c = \frac{1}{2} t_S N(0) \Delta^2$
- Energy gap $\Delta(T,\theta) \simeq 3.2 k_B T_c(\theta) \sqrt{1 - \frac{T}{T_c(\theta)}}$

P



Low E_c

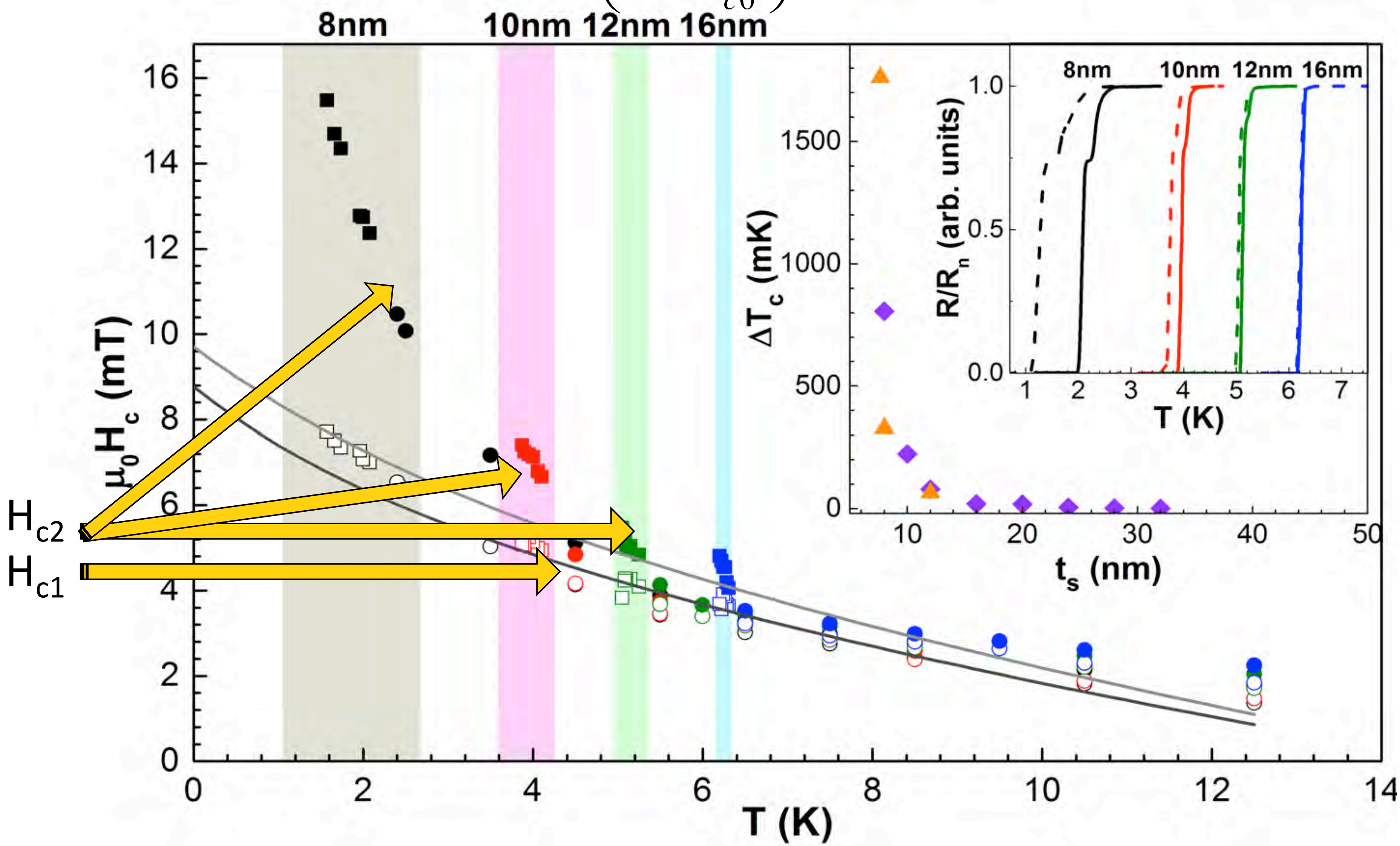
AP



High E_c

Superconducting exchange coupling

$$E_{exS}(T) = \frac{3.2^2}{2} k_B{}^2 d_s N(0) T_{c0}\left(1 - \frac{T}{T_{c0}}\right) = \frac{3.2^2}{2} k_B{}^2 d_s N(0) \Delta T_c$$

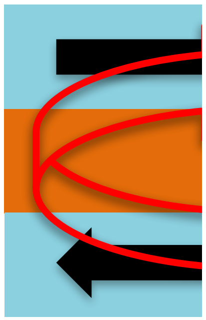


Another form of exchange coupling

- Exchange bias

nature materials | LETTERS
PUBLISHED ONLINE: 19 SEPTEMBER 2016 | DOI: 10.1038/NMAT4753

- RKKY



Superconducting exchange coupling between ferromagnets

Yi Zhu, Avradeep Pal, Mark G. Blamire* and Zoe H. Barber

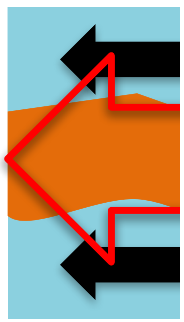
Recent discoveries from superconductor (S)/ferromagnet (FM) heterostructures include π-junctions[1], triplet pairing[2,3], critical temperature (T_c) control in FM/S/FM superconducting spin valves (SSVs)[4–7] and critical current control in S/FM/N/FM/S spin valve Josephson junctions[8,9] (N: normal metal). In all cases, the magnetic state of the device, generally set by the applied field, controls the superconducting response. We report here the observation of the converse effect, that is, direct superconducting control of the magnetic state in GdN/Nb/GdN SSVs. A model[10] for an antiferromagnetic effective exchange interaction based on the coupling of the superconducting condensation energy to the magnetic state can explain the Nb thickness and temperature dependence of this effect. This superconducting exchange interaction is fundamentally different in origin from the various exchange coupling phenomena that underlie conventional spin electronics (spintronics), and provides a mechanism for the active control of the magnetic state in superconducting spintronics[11].

fields, $H_{c1,2}$, corresponding to the switching of the 5 nm and 3 nm GdN layers, respectively. This is evident in low-T magnetization versus field ($M(H)$) loops (Fig. 1b). For temperatures well above T_c, there is little evidence of separate switching of the two GdN layers despite their different thicknesses.

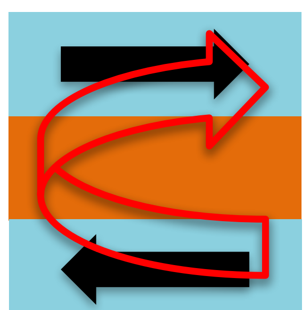
Figure 2 shows the temperature dependence of $H_{c1,2}$ for several t_S; in the normal state, $H_{c1,2}$ are similar to each other and between samples. However, for each t_S, below T_c, H_{c2} increases rapidly with decreasing temperature, suggesting the onset of a pronounced AF exchange coupling in the superconducting state. Our results provide the first experimental evidence for a superconducting exchange coupling (SEC), originally proposed by de Gennes[10], mediated by the dependence of the superconductivity on the angle between the ferromagnetic insulator (FI) magnetizations in a SSV.

In order to distinguish this effect from other temperature-induced changes to H_c, we plot, in Fig. 2, H_c from 5 and 3 nm-thick plain GdN films (that is, corresponding respectively to H_{c1} and H_{c2} in the SSV samples). The SSV H_{c2} data increase above the

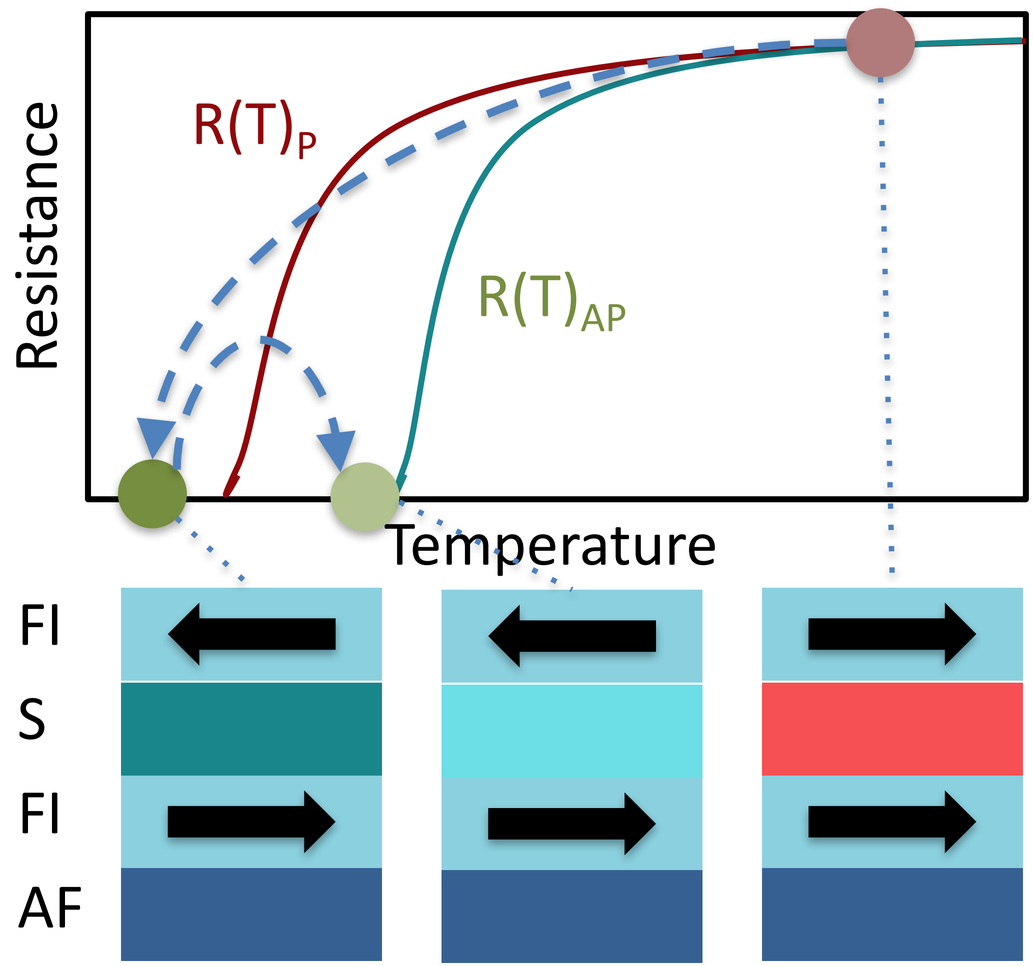
- Néel



- Superconducting exchange coupling

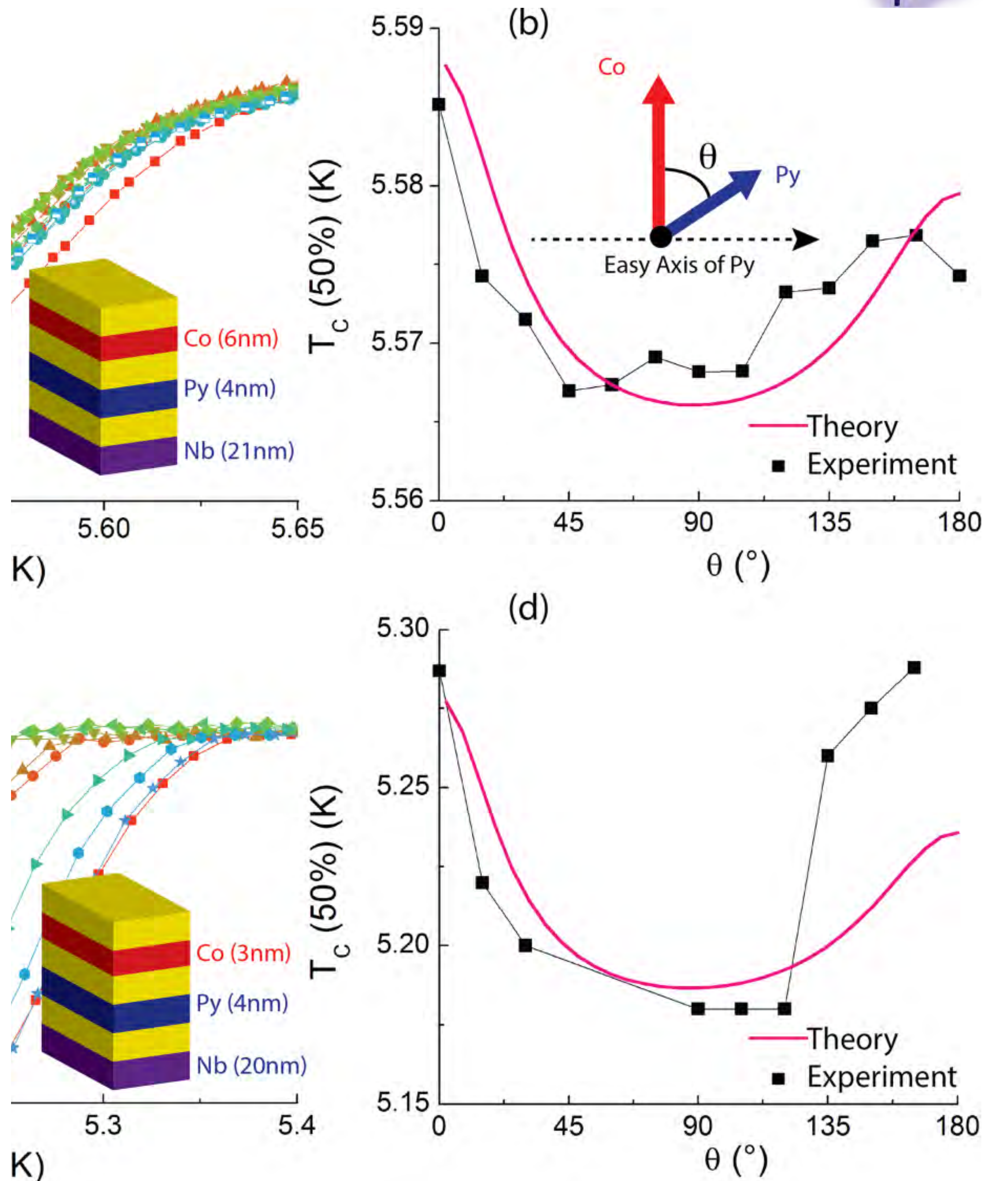


But (potentially) controllable

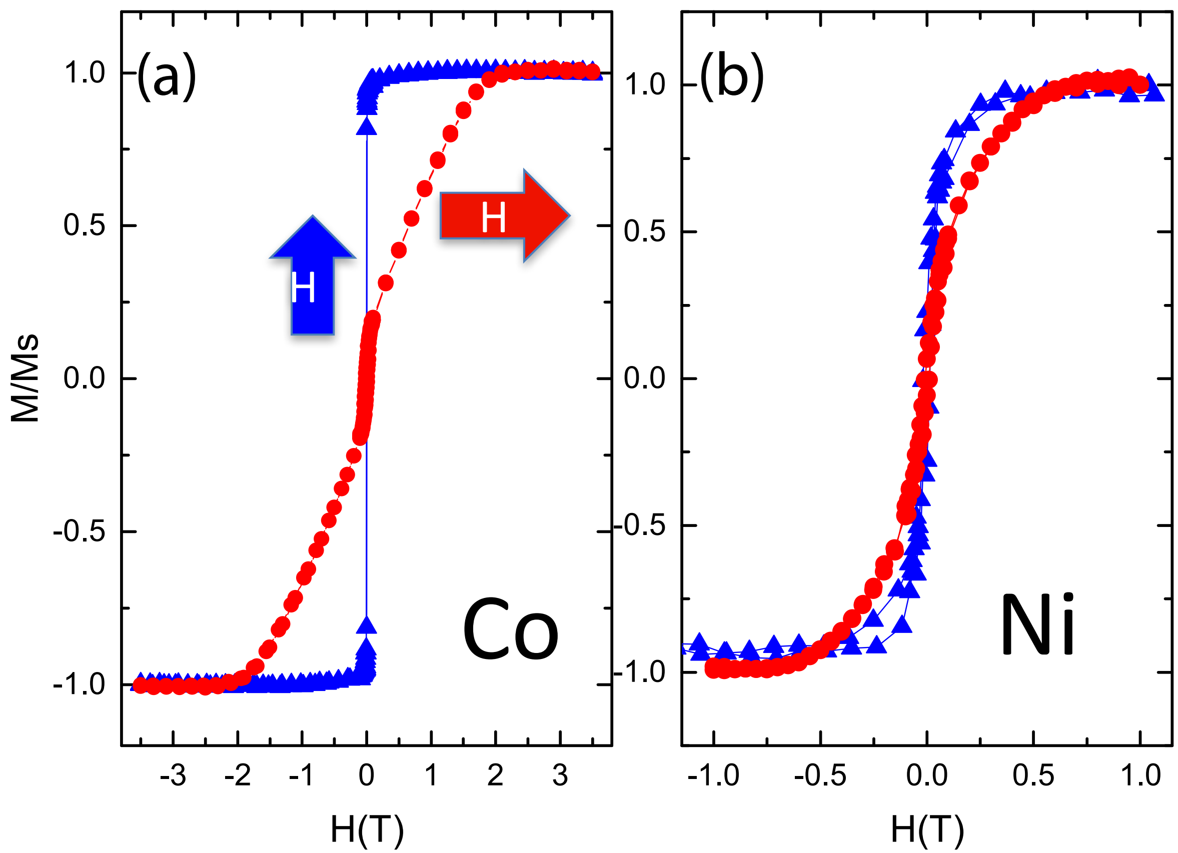


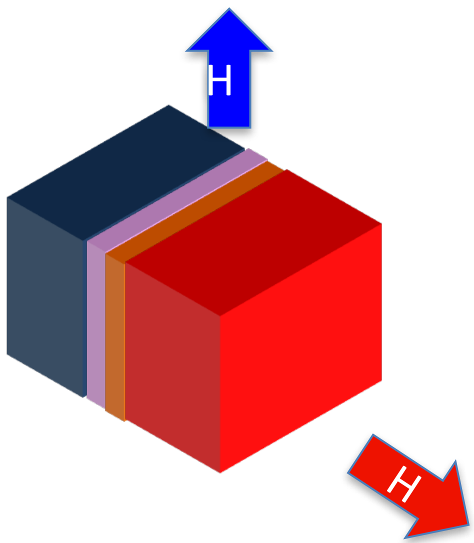
Triplet spin valve

- Orthogonal F layers create triplet proximity channel into thick F layer and lower T_c
- In-plane field rotation produces ΔT_c
  - Wang *et al.*, PRB **89**, 140508(R) (2014)



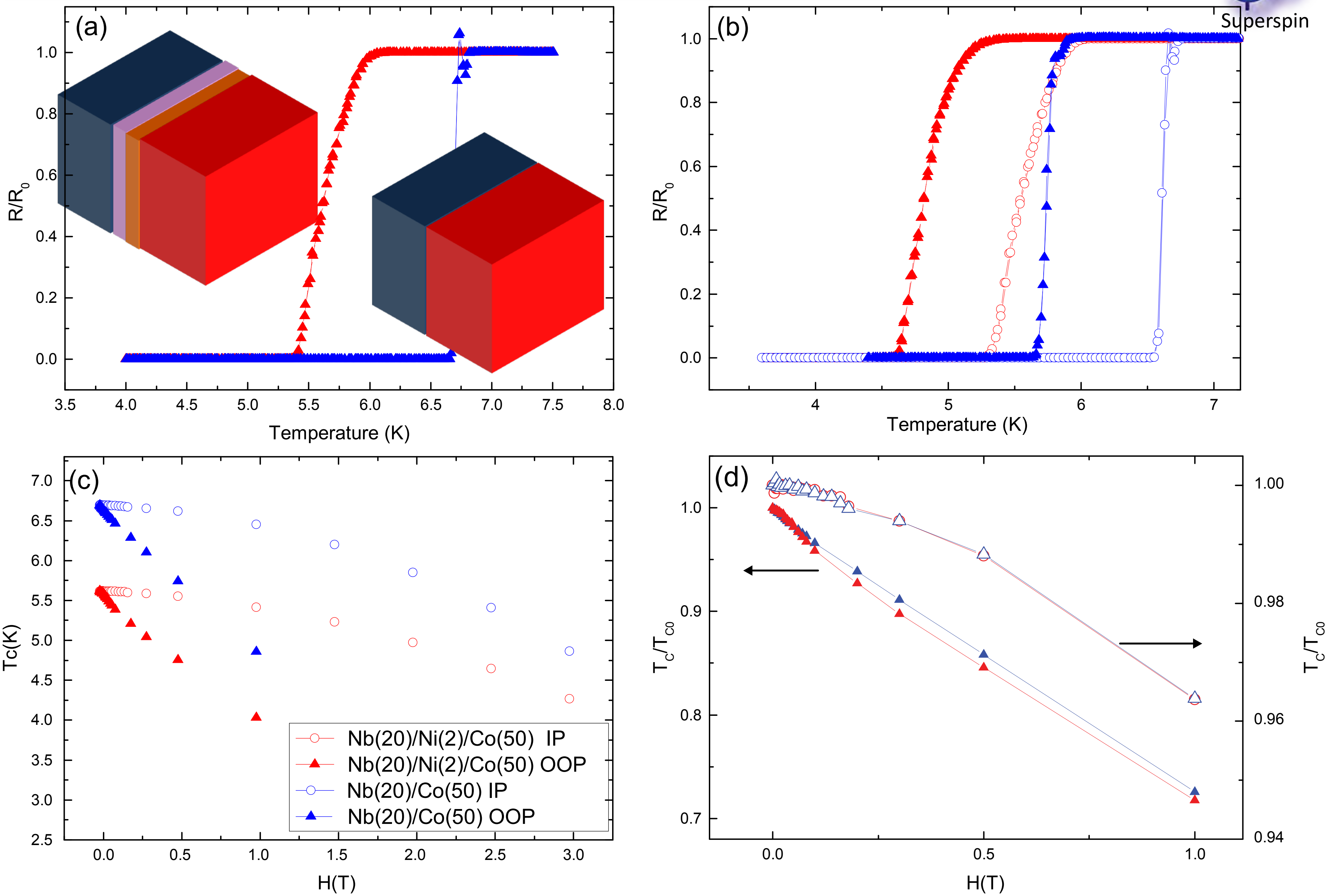
Out of plane triplet spin valve



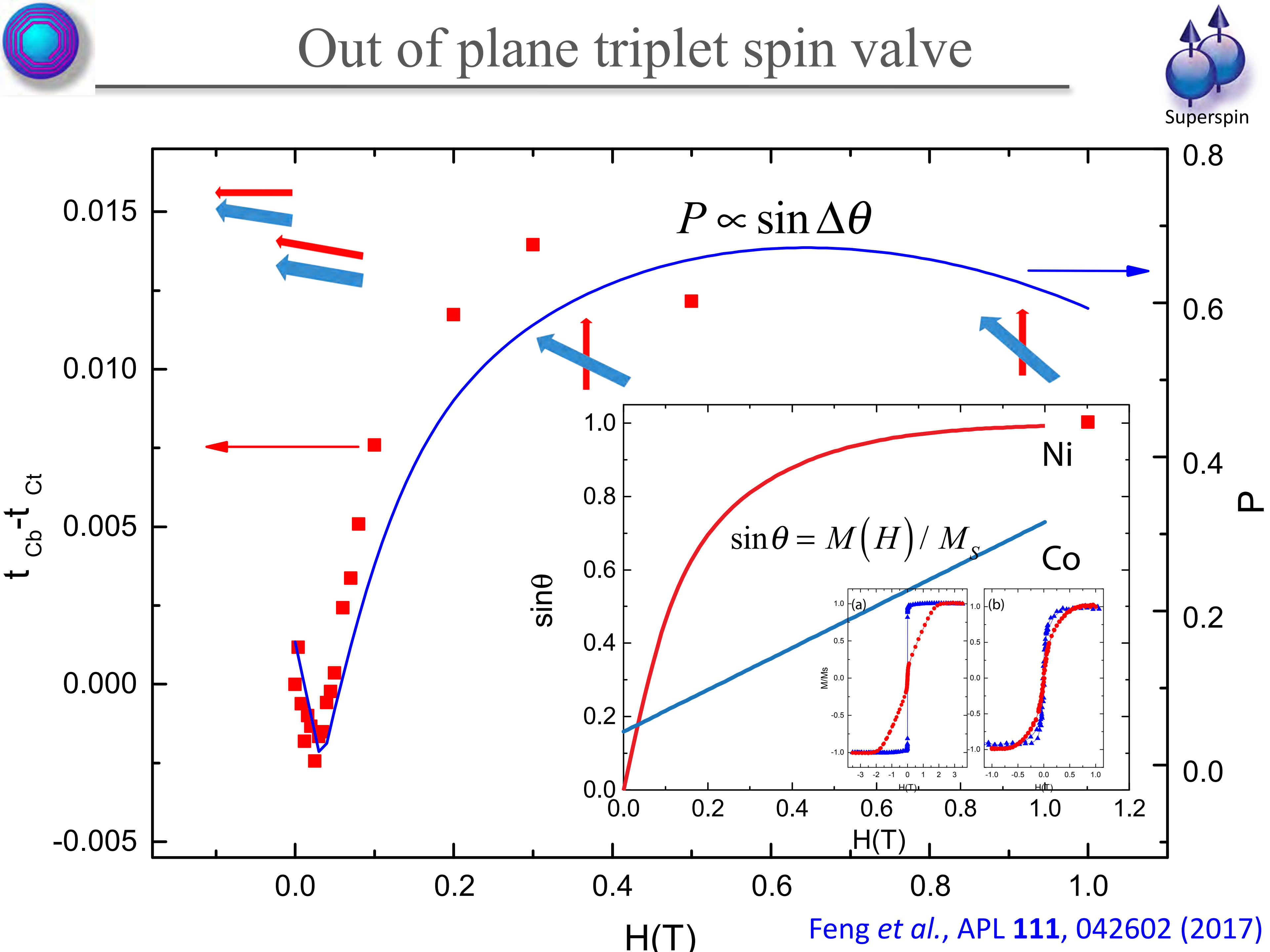


- MoGe/Ni/Cu/CrO_2
  - Singh *et al.*, PRX **5**, 021019 (2015)
- Nb/Ni/Cu/Co
  - Feng *et al.*, APL **111**, 042602 (2017)

Out of plane triplet spin valve

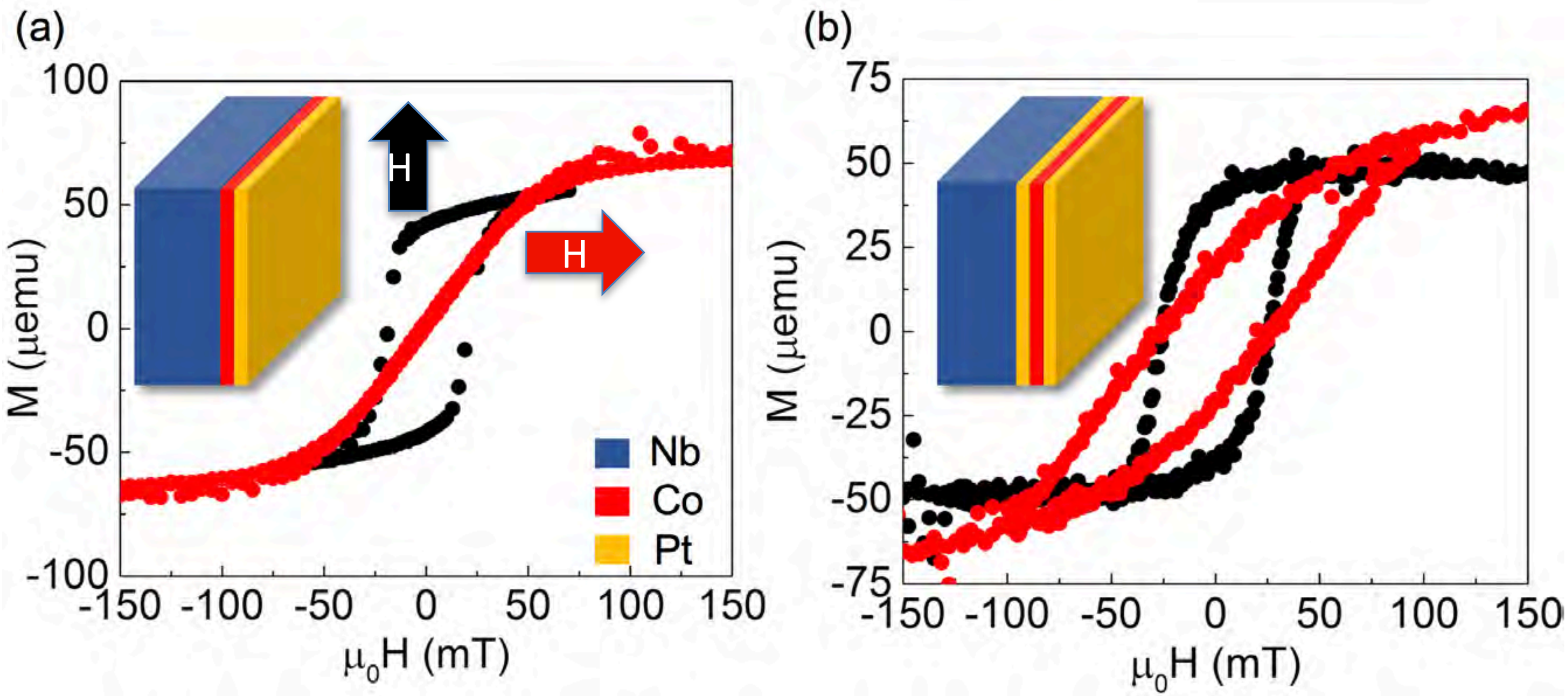


Out of plane triplet spin valve



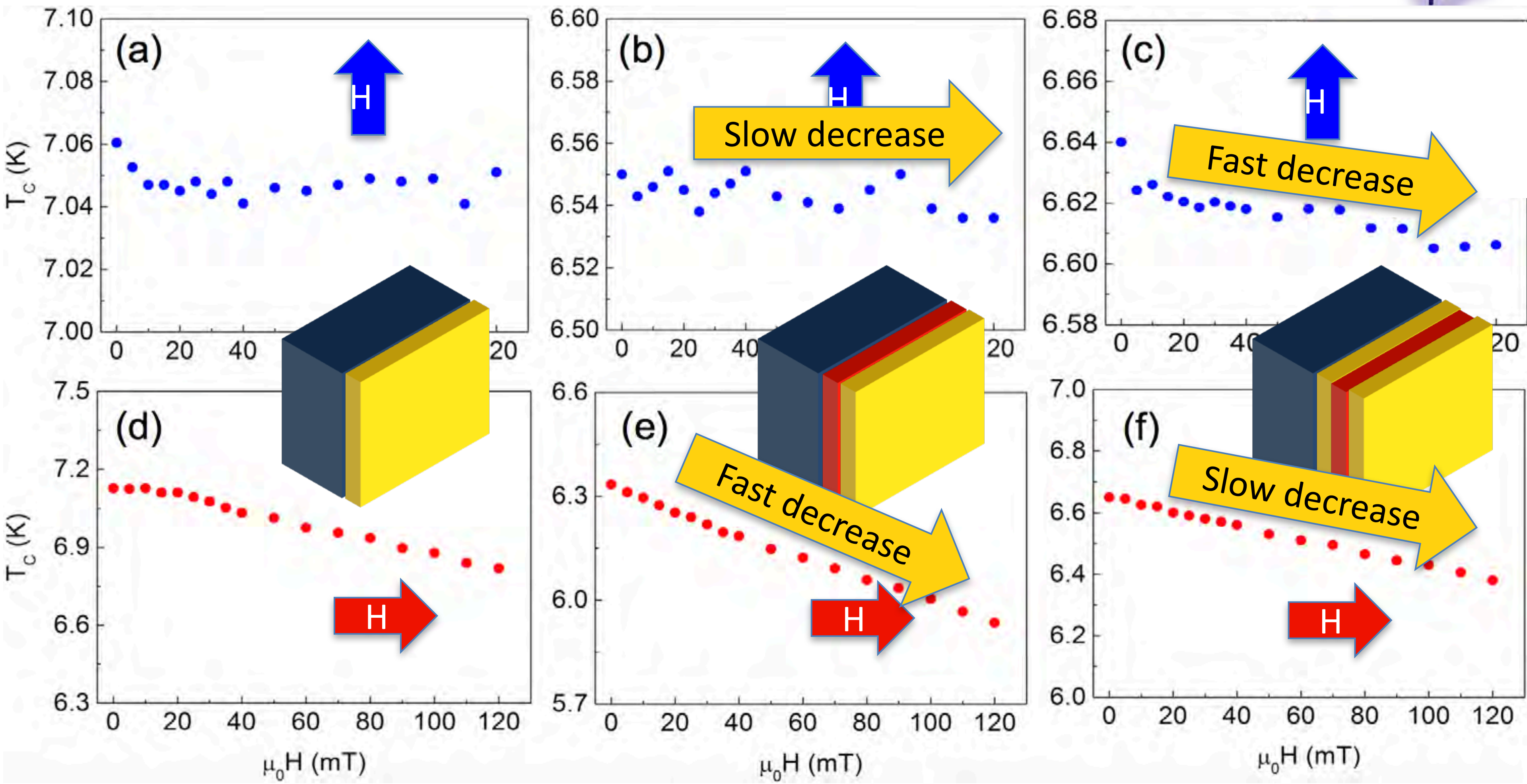
Feng *et al.*, APL **111**, 042602 (2017)

Spin-orbit spin valve



- Nb/(Pt)/Co/Pt
- One magnetic layer
- Change magnetisation angle with respect to spin-orbit.

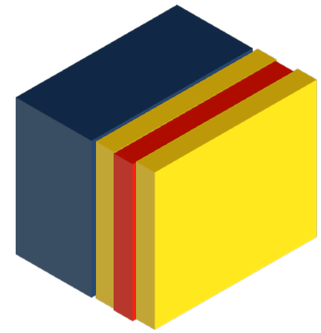
$T_c(H)$



- Co flux injected for OOP field for Nb/Co/Pt and Nb/Pt/Co/Pt
- Pt spacer layer changes behaviour

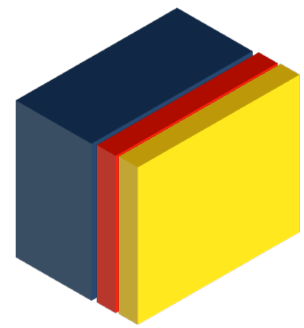
$\Delta T_c(H)$

- Structural inversion symmetry of Pt/Co/Pt gives rise to spin-orbit coupling



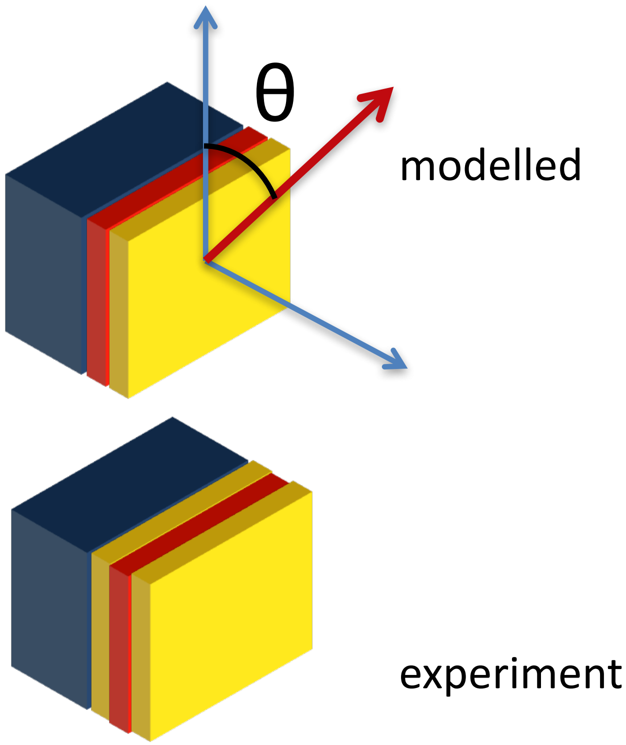
SOC

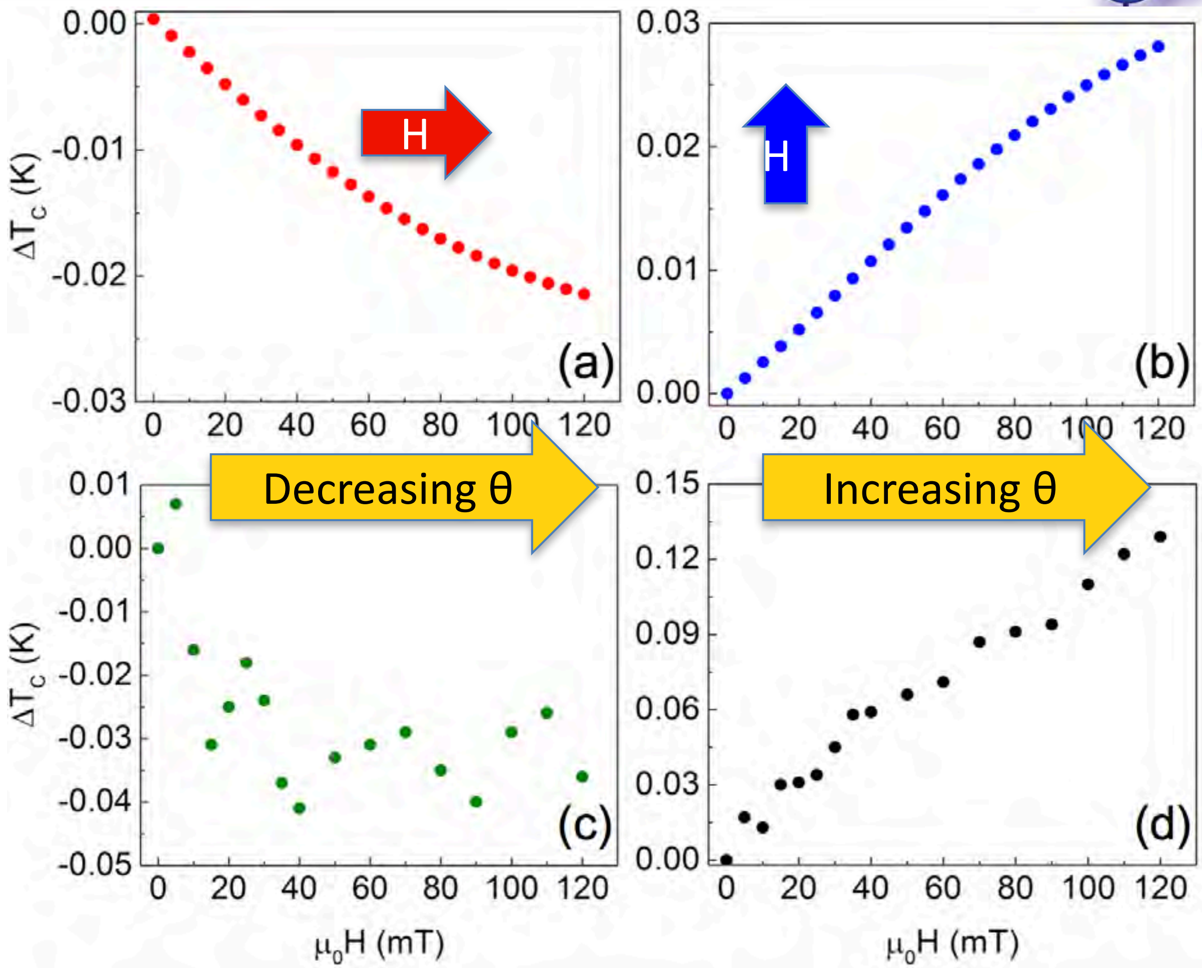
- Triplet pairing components appear due to spin rotation of the Cooper pair due to SOC .



No SOC

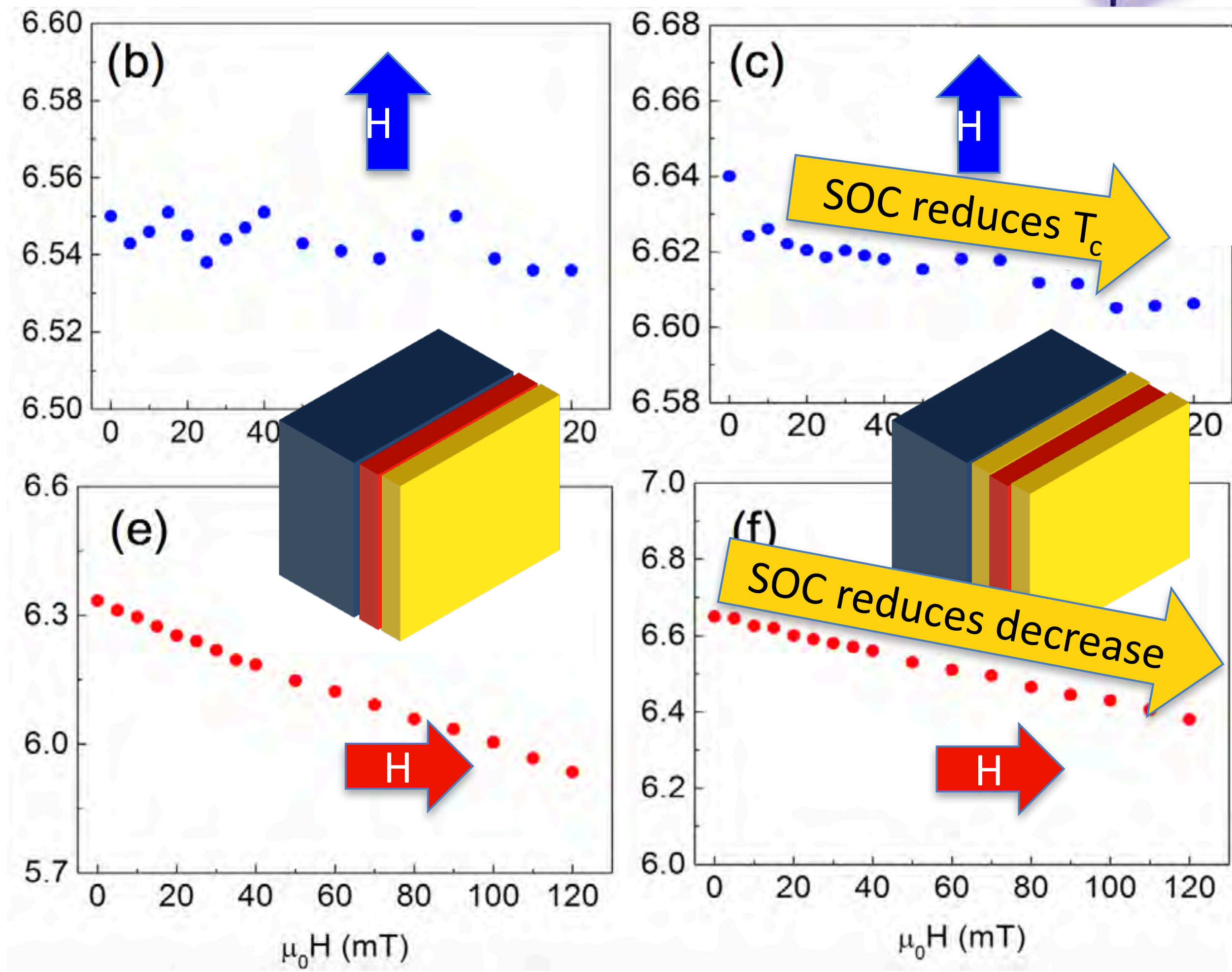
$\Delta T_c(H)$





- Difference between $T_c(H)$ for Nb/Co/Pt and Nb/Pt/Co/Pt
- Depairing energy of short-range triplets increases with θ
- Closing the triplet proximity channel with increasing θ results in fewer Cooper pairs leaking from superconductor - increasing T_c

Triplet proximity effect controlled with one magnet



- Co flux injected for OOP field for Nb/Co/Pt and Nb/Pt/Co/Pt
- Pt spacer layer changes behaviour

Superspintronics

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- Infinite magnetoresistance in Ho/Nb/Ho spin valves
- Very large ΔT_c (> 1.5 K) in GdN/Nb/GdN spin valves
- Superconducting control of the magnetic state
  - A key ingredient for superconducting spintronics
  - www.superspintronics.org
- Demonstration of triplet proximity ef
- Superconducting spin currents