

Chapter 4

Spin Valves

韩伟

量子材料科学中心

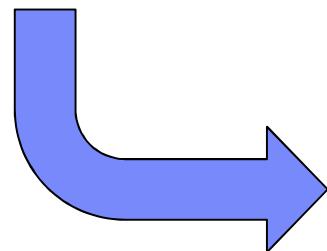
2017年10月27日

Outline

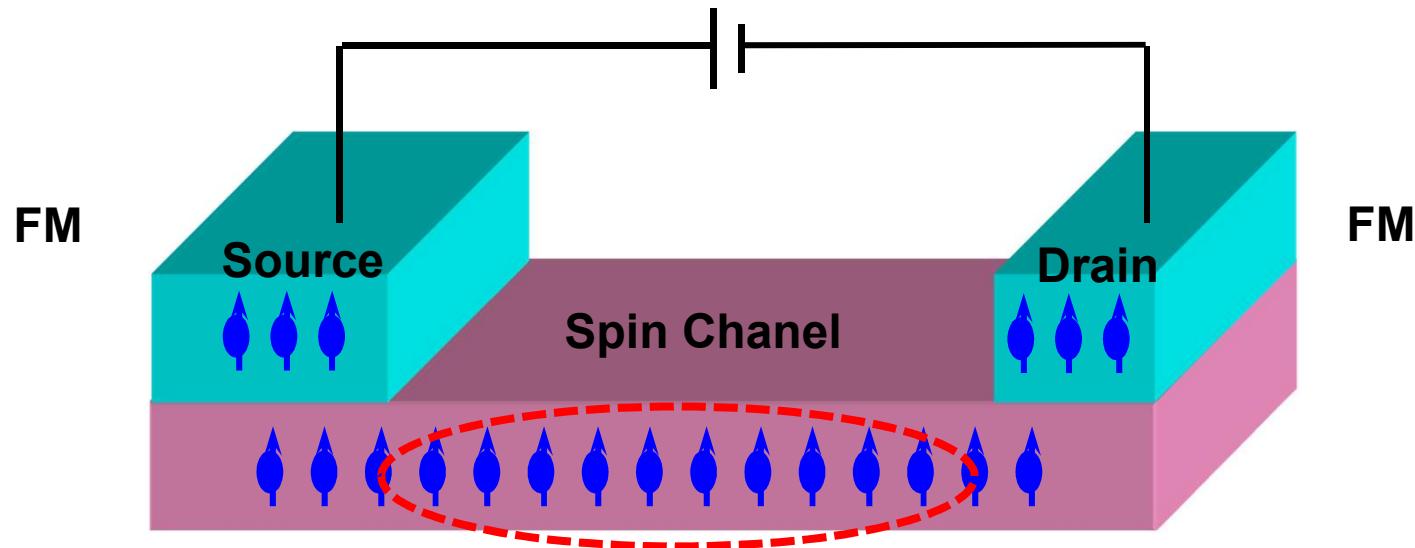
- 1. Spin valves and spin injection**
- 2. Spin valves based on Metal and Superconductor**
- 3. Spin valves based on semiconductor and Quantum materials**

Review of last class

Vertical Spin valves



Lateral Spin valves

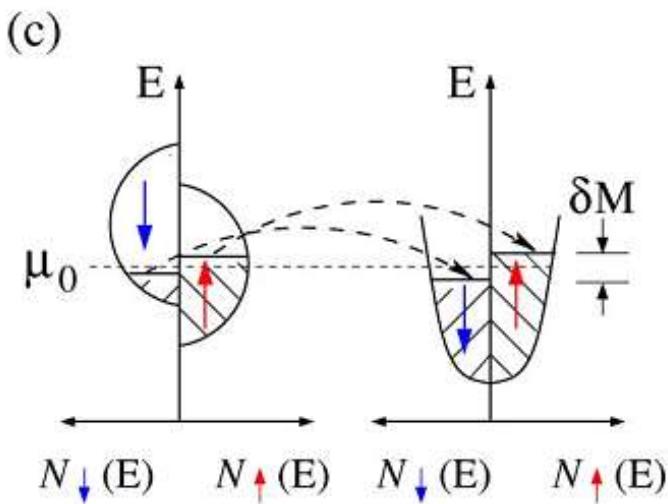


Spin manipulation

Review of last class

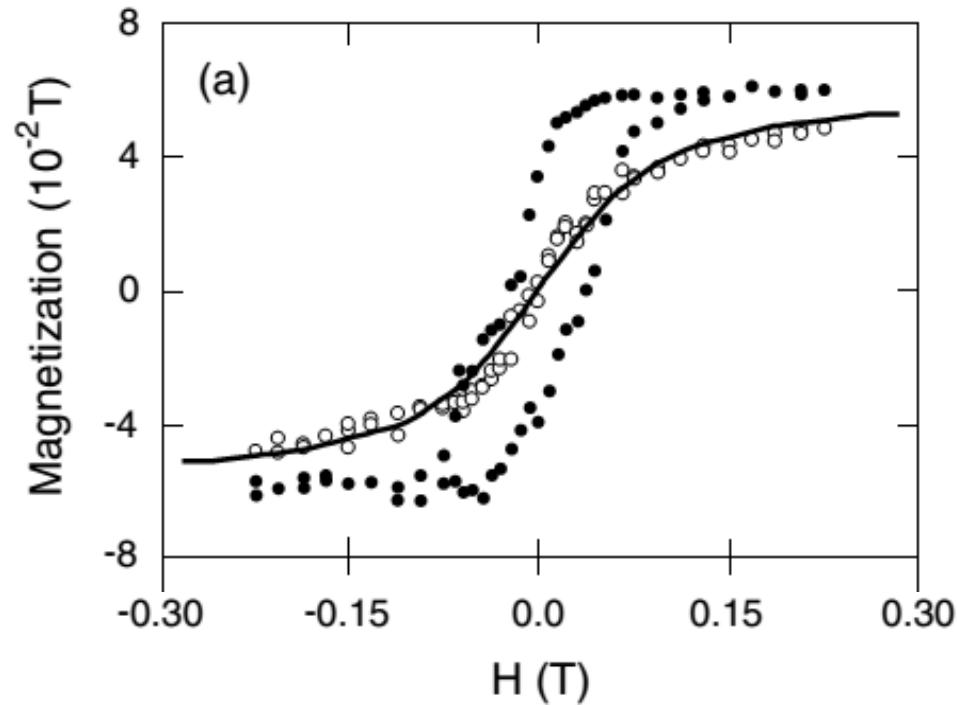
Spin injection

□ Electrical



Spin injection

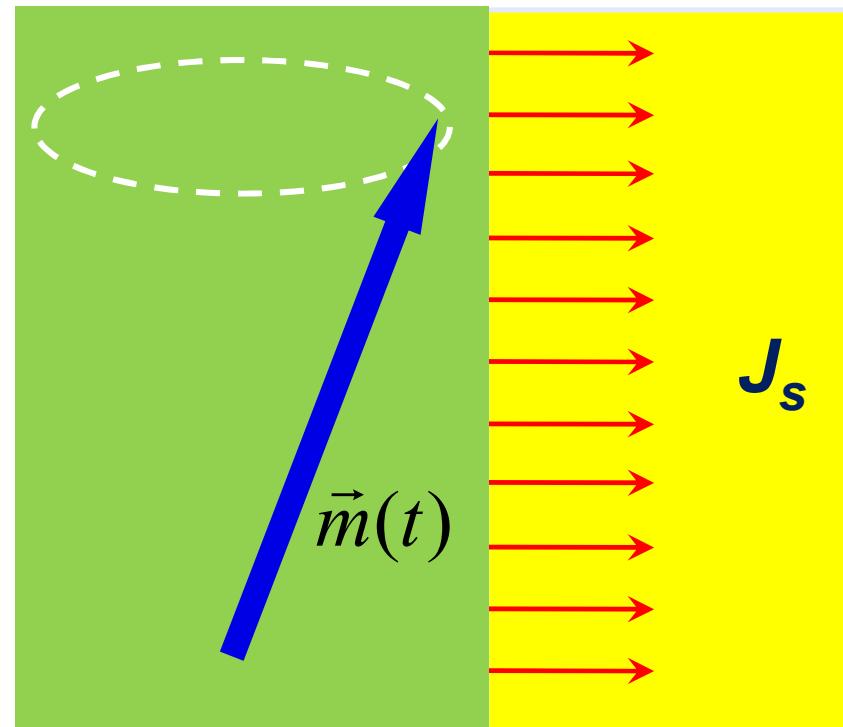
□ Optical



Spin injection

□ Dynamical

FM



NM

This Class

2. Spin valves based on Metal and Superconductor

Outline

1. Metal spin valves

2. Superconducting spin valves

Outline

1. Metal Spin Valves

Local and Nonlocal spin valves

Hanle spin precession

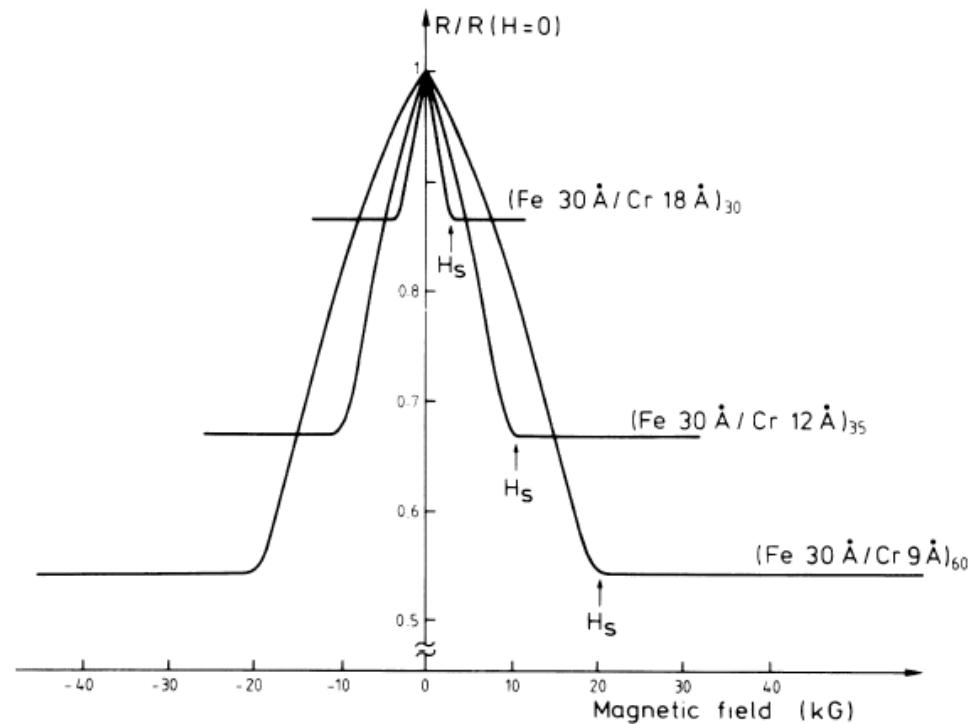
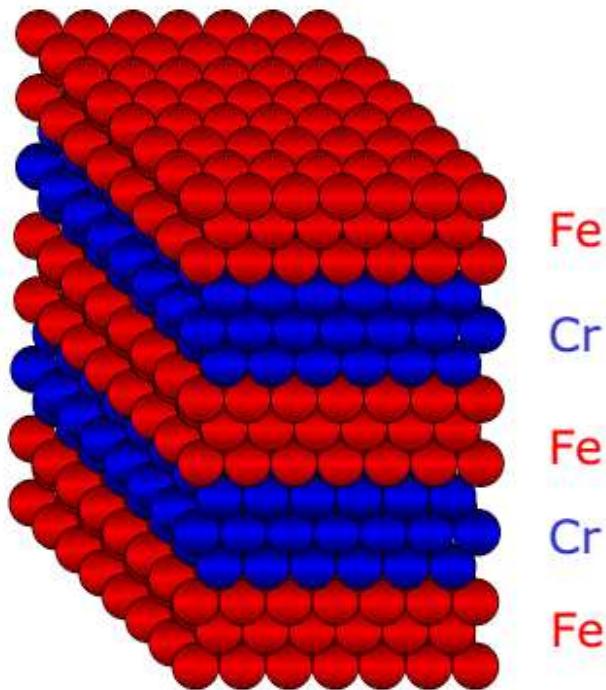
Nano devices (Thanks to cleanroom)

Spin injection efficiency

Spin relaxation in Metals: EY mechanism

GMR

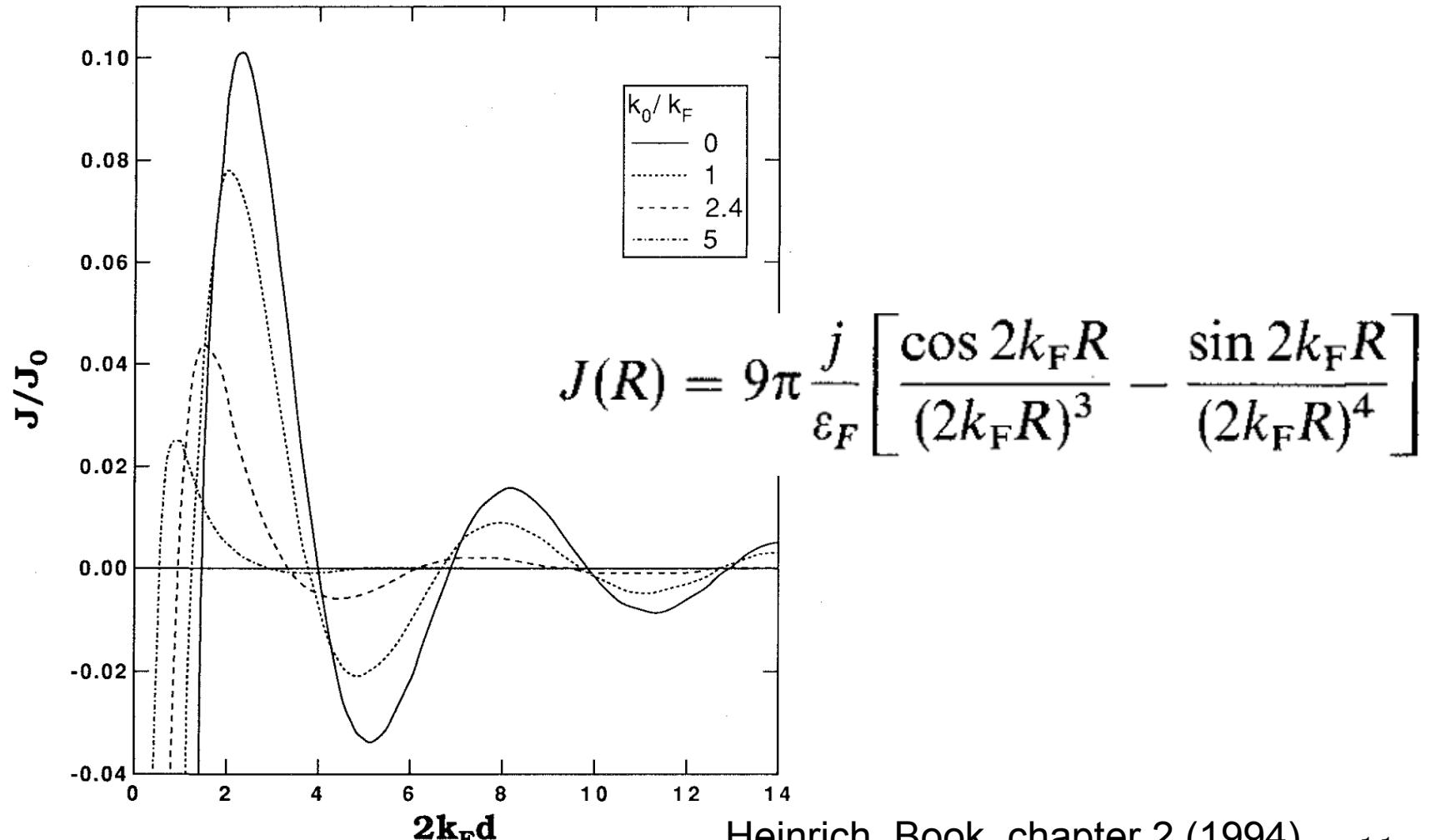
Observation of GMR



Baibich, et al, PRL (1988)
Fert, Rev. Mod. Phys. (2007)

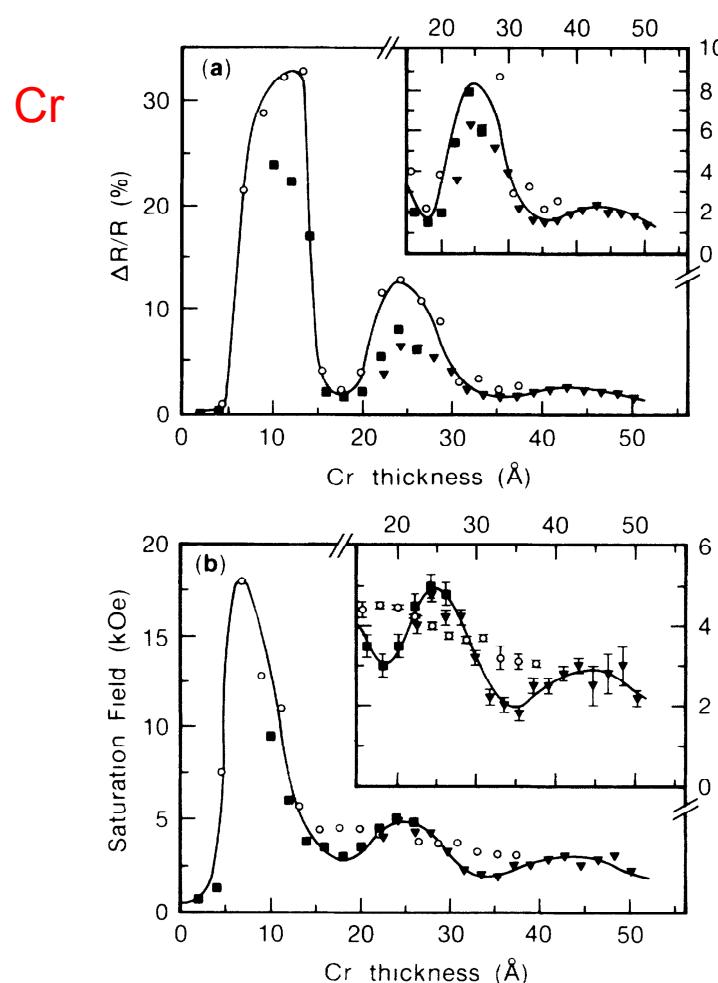
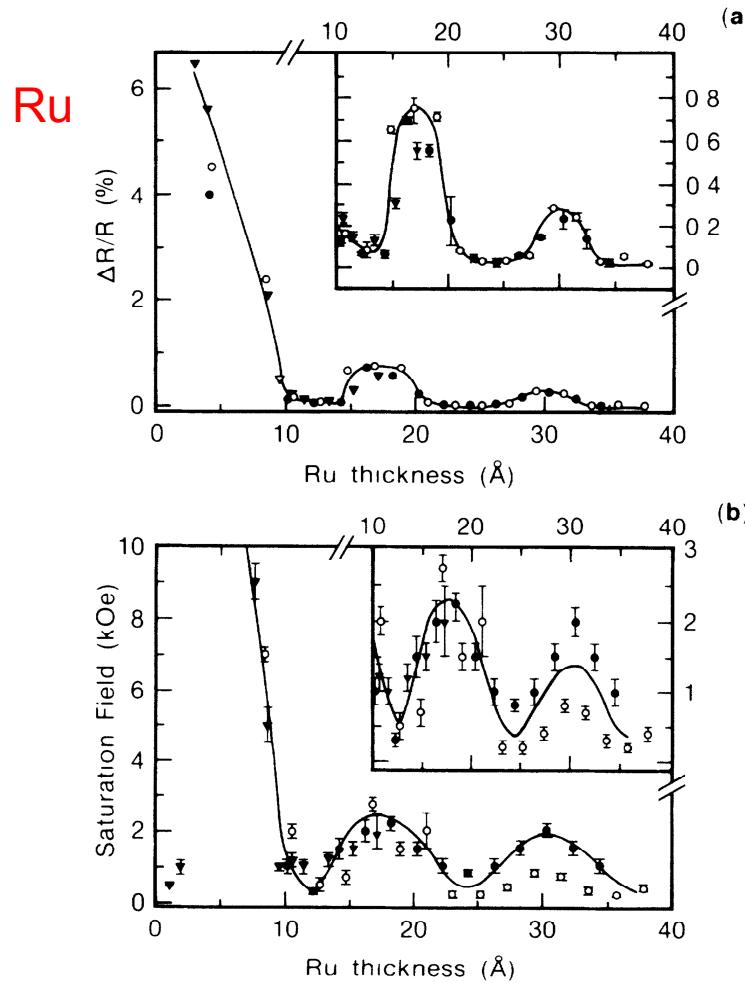
GMR

GMR—RKKY coupling



GMR

GMR—RKKY coupling

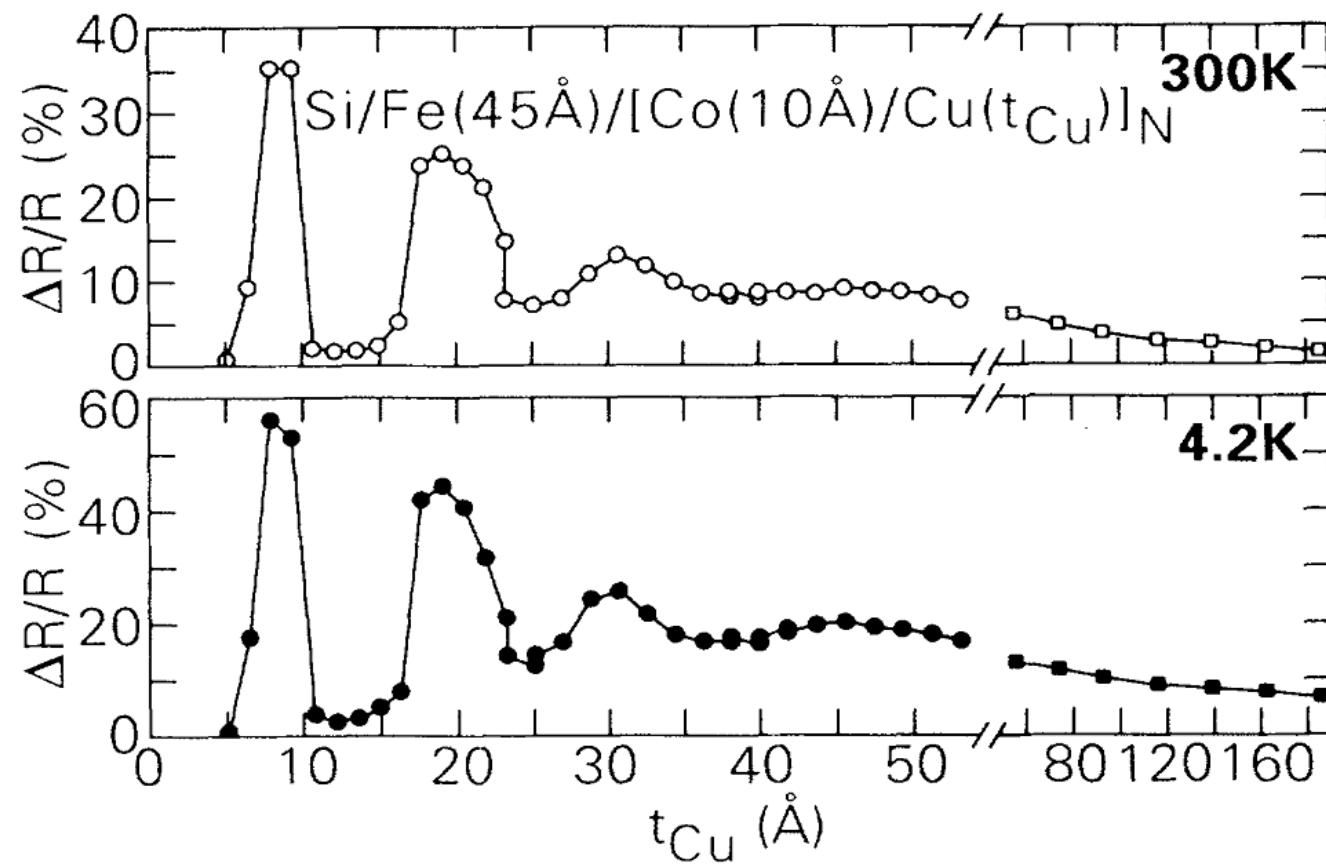


Parkin, et al, PRL (1990)

GMR

GMR—RKKY coupling

Cu



Nonlocal Metal spin valve

PHYSICAL REVIEW B

VOLUME 19, NUMBER 9

1 MAY 1979

Coupling between ferromagnetic and conduction-spin-resonance modes at a ferromagnetic–normal-metal interface

R. H. Silsbee,* A. Janossy,[†] and P. Monod

Laboratoire de Physique des Solides, Université Paris-Sud, 91405, Orsay, France

(Received 1 November 1978)

The transmission-electron-spin resonance (TESR) is measured on copper foils with ferromagnetic films of permalloy, iron, and nickel deposited on one surface. The greatly enhanced TESR resulting from the presence of the ferromagnetic film is studied as a function of orientation of the magnetic field which tunes the relative resonance frequencies of the ferromagnetic resonance (FMR) mode and the pure-copper TESR modes over a wide range. A phenomenological theory is developed from appropriate Bloch equations for the copper and for the ferromagnetic film, coupled by the transport of magnetization by the diffusion of electrons across the interface between the two metals. This theory describes well a number of distinct features of the experimental results.

R. Silsbee

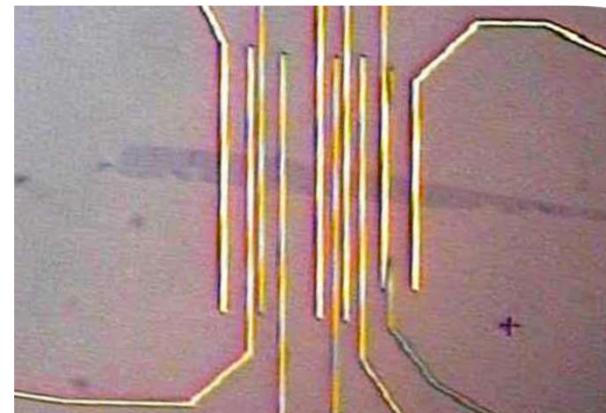
- 1) Spin pumping**
- 2) Spin transfer torque**

Nonlocal Metal spin valve

R. Silsbee and Mark Johnson (PhD)

1980

A Major obstacle: No cleanroom for the fabrication of small devices



Nonlocal Metal spin valve

VOLUME 55, NUMBER 17

PHYSICAL REVIEW LETTERS

21 OCTOBER 1985

Interfacial Charge-Spin Coupling: Injection and Detection of Spin Magnetization in Metals

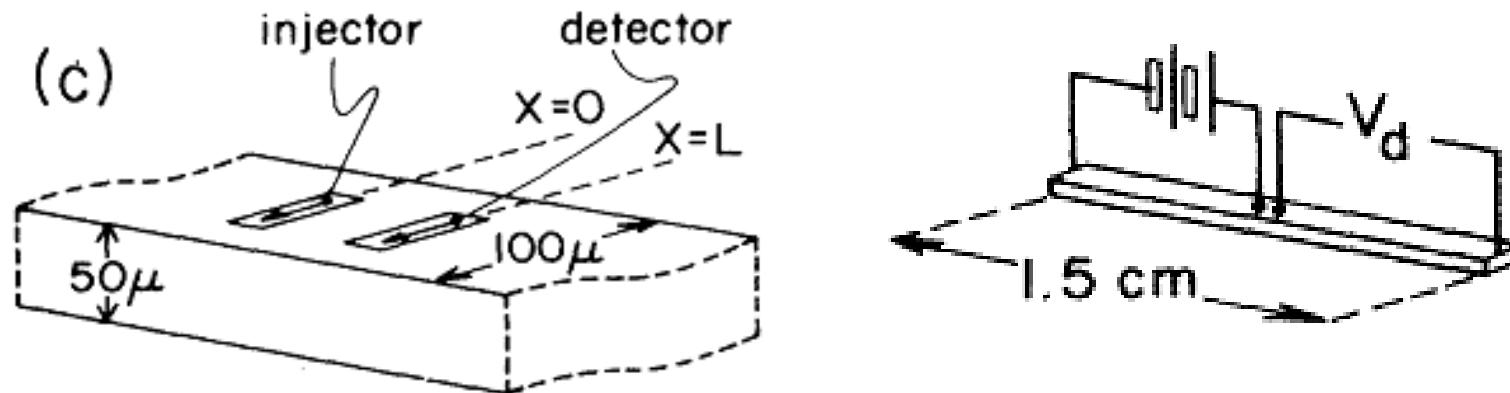
Mark Johnson and R. H. Silsbee

Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853

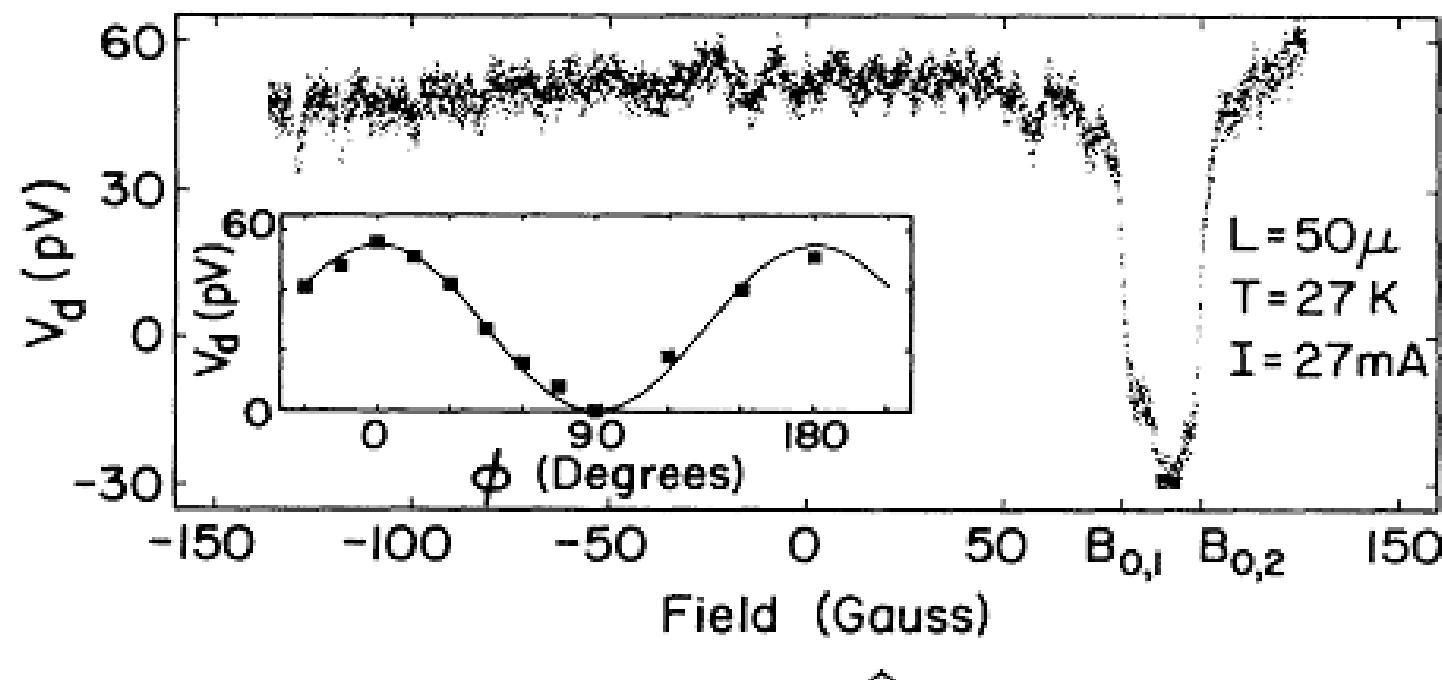
(Received 1 July 1985)

The strong inequivalence of spin-up and spin-down subbands in a ferromagnet causes a coupling between the charge and spin transport across the interface of a ferromagnetic and a contiguous paramagnetic metal. This allows the use of sensitive electronic measurements to probe spin transport. Application of small static magnetic fields results in a Hanle effect which permits determination of the spin-relaxation time T_2 . The unique features of the method should make it applicable to a wide range of studies.

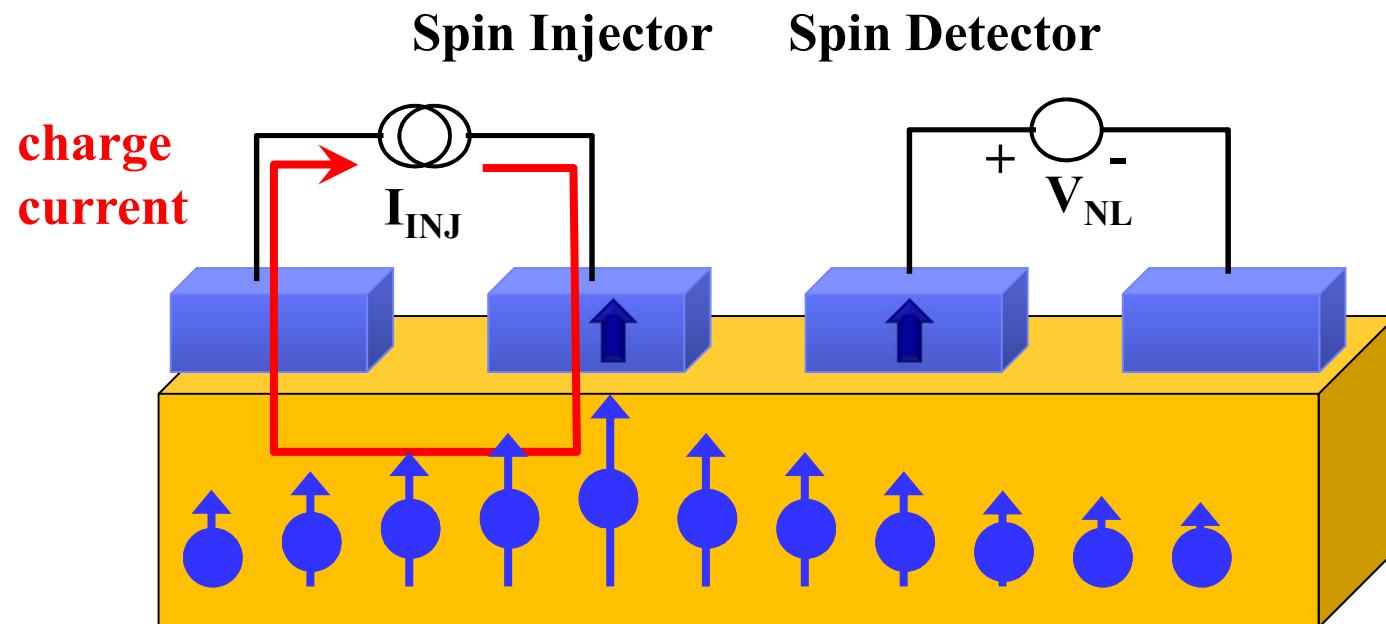
PACS numbers: 07.58. + g, 72.15.-v, 73.40.-c



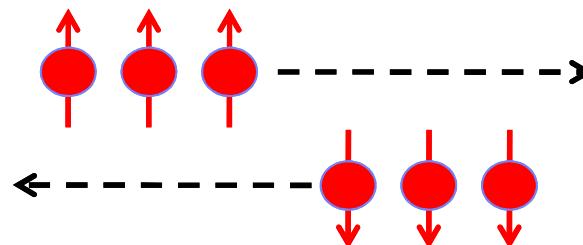
Nonlocal Metal spin valve



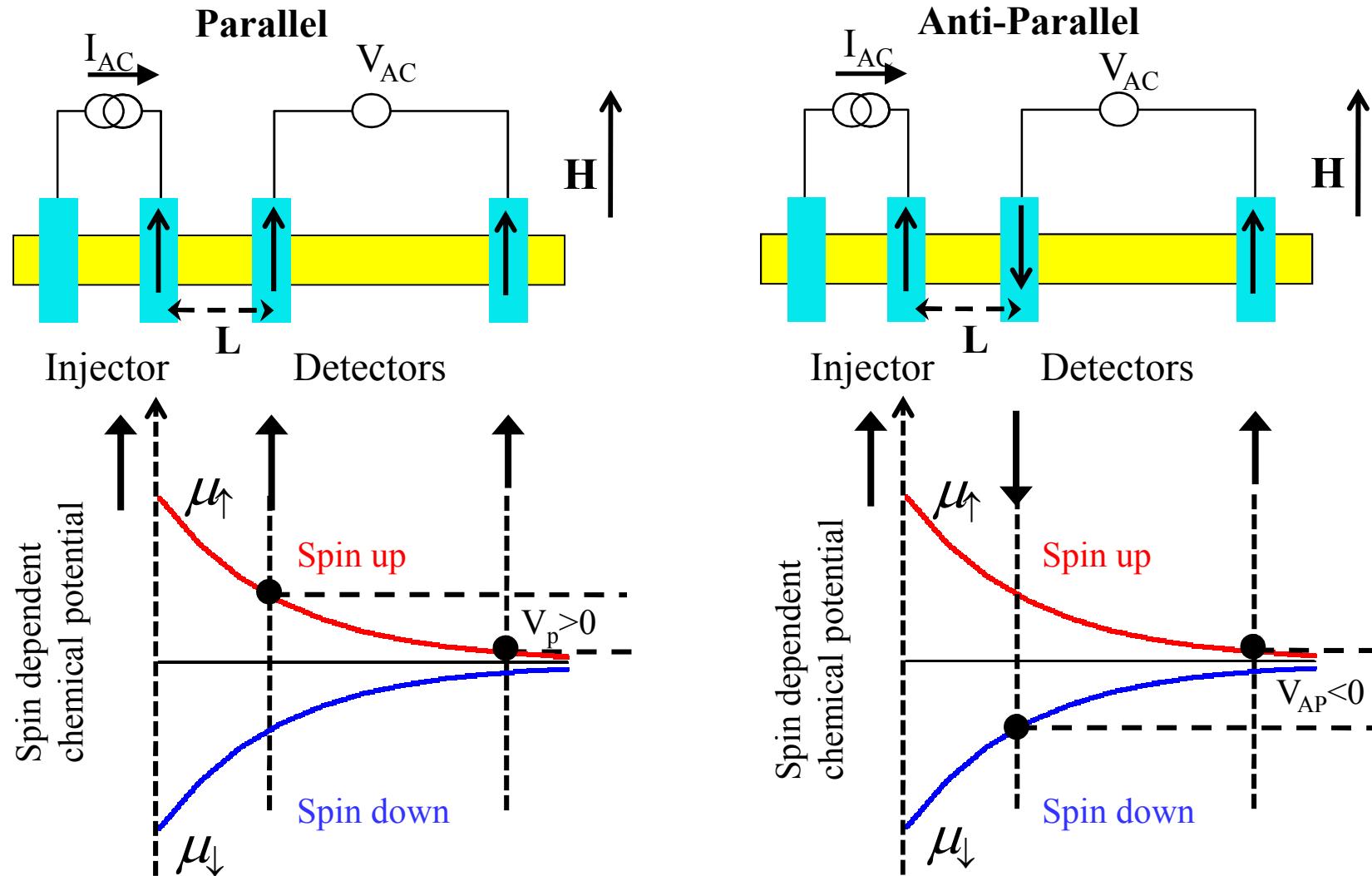
Nonlocal Metal spin valve



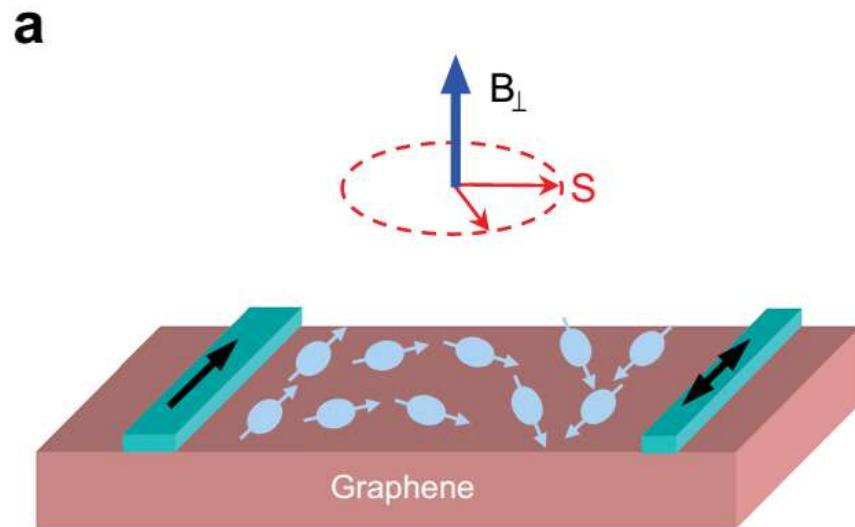
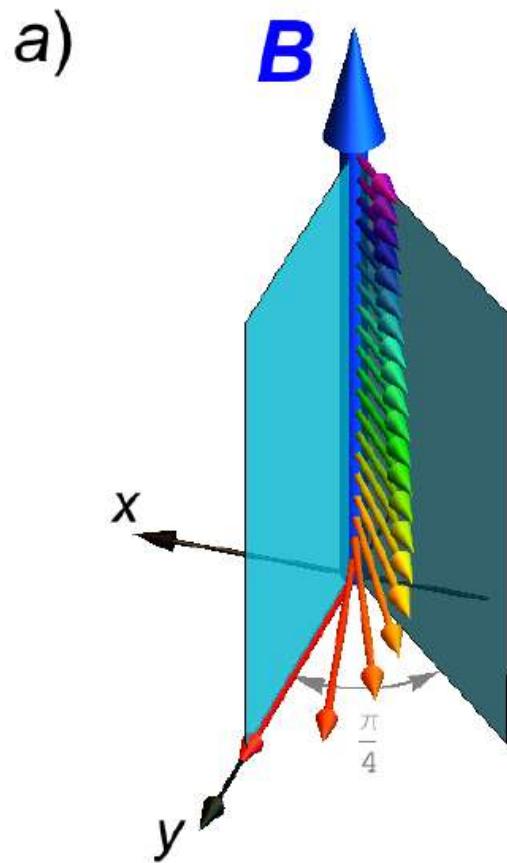
Pure spin current: Flow of spin without net flow of charge



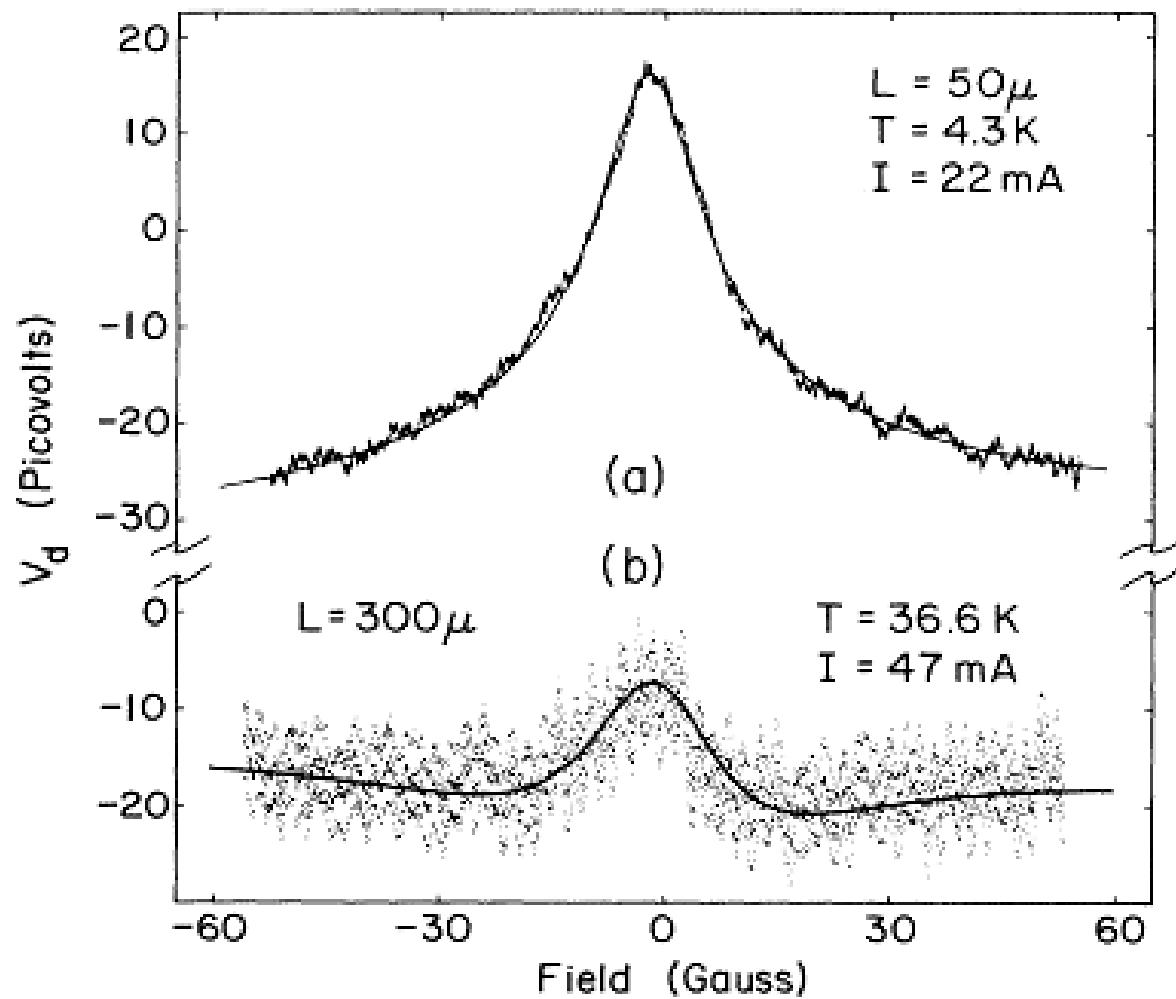
Nonlocal Metal spin valve



Nonlocal Metal spin valve



Nonlocal Metal spin valve



Nonlocal Metal spin valve

Small devices



Letters to Nature

Nature **410**, 345-348 (15 March 2001) | doi:10.1038/35066533; Received 3 November 2000;
Accepted 2 January 2001

Electrical spin injection and accumulation at room temperature in an all-metal mesoscopic spin valve

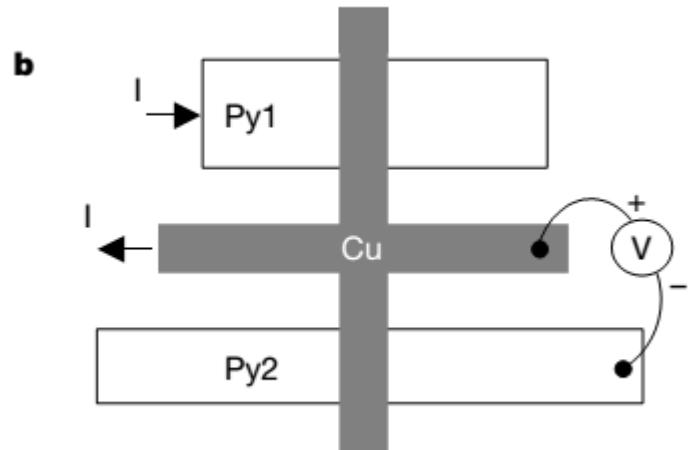
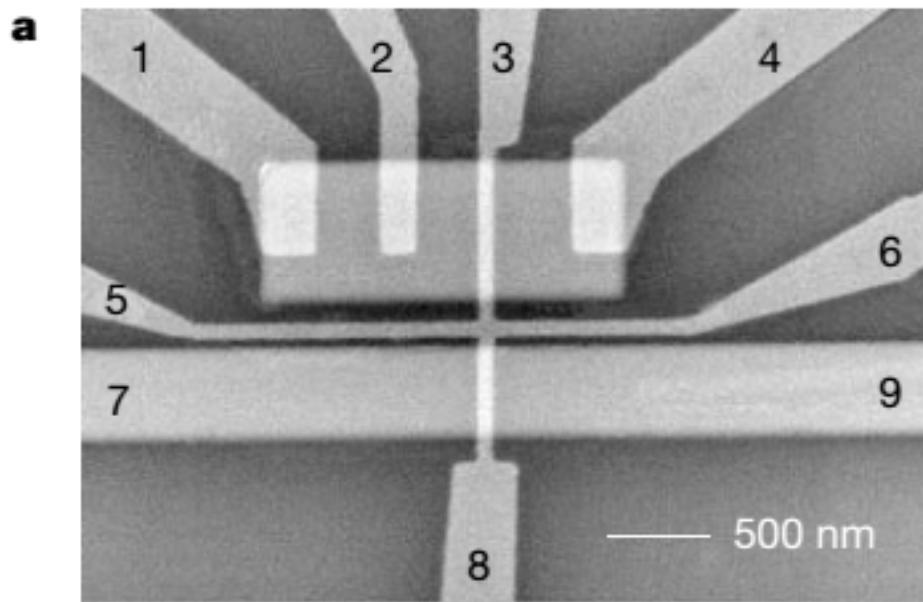
F. J. Jedema, A. T. Filip & B. J. van Wees

1. Department of Applied Physics and Materials Science Centre, University of Groningen,
Nijenborgh 4.13, 9747 AG Groningen, The Netherlands

Correspondence to: Correspondence should be addressed to F.J.J. (e-mail:
Email: jedema@phys.rug.nl).

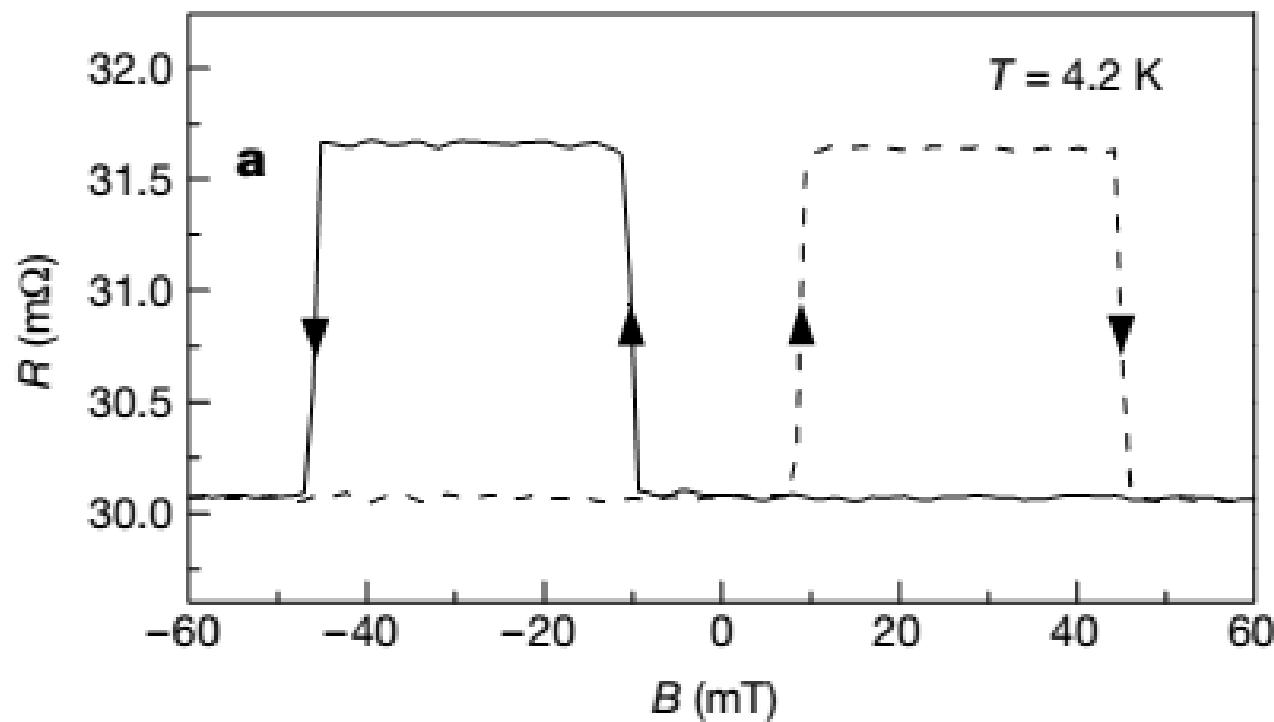
Nonlocal Metal spin valve

Small devices on Cu



Nonlocal Metal spin valve

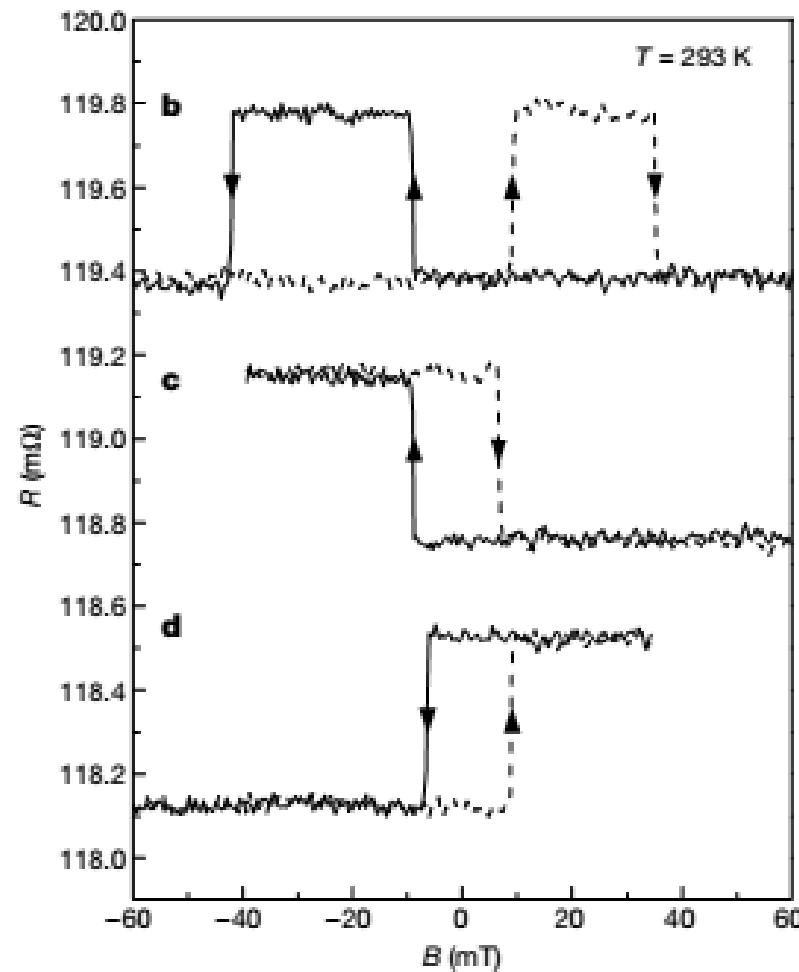
Small devices



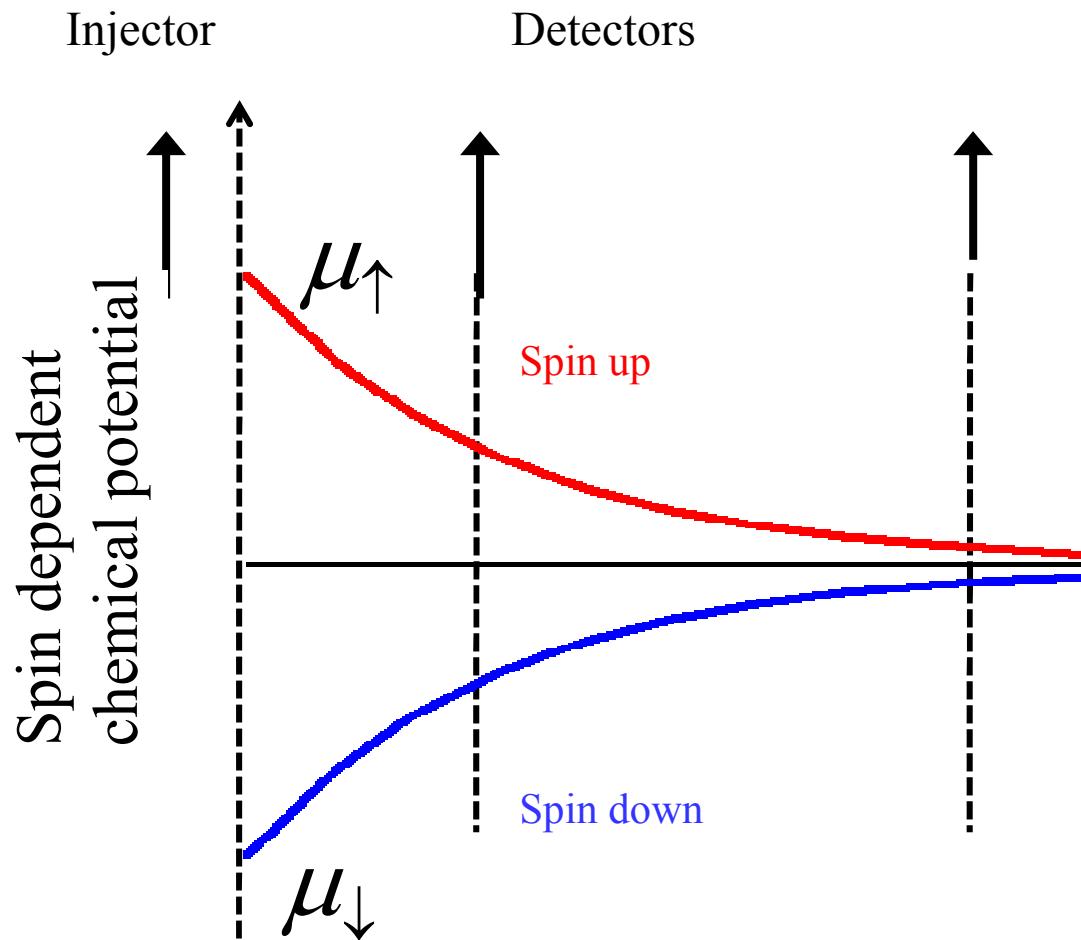
Jedema, et al, Nature (2001)

Nonlocal Metal spin valve

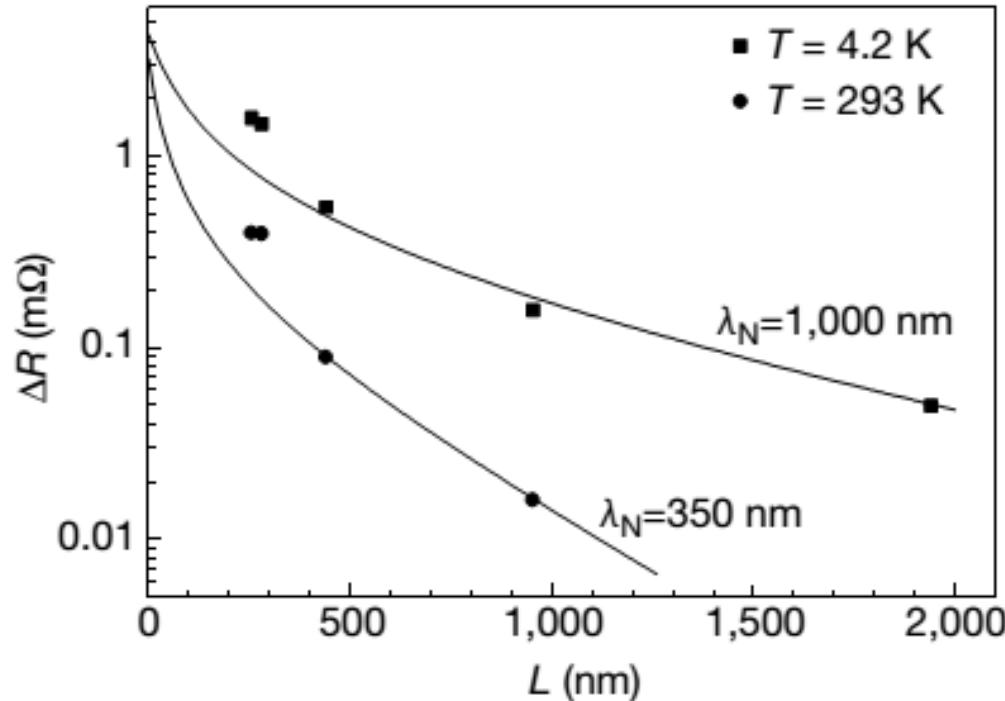
Small devices



Nonlocal Metal spin valve



Nonlocal Metal spin valve



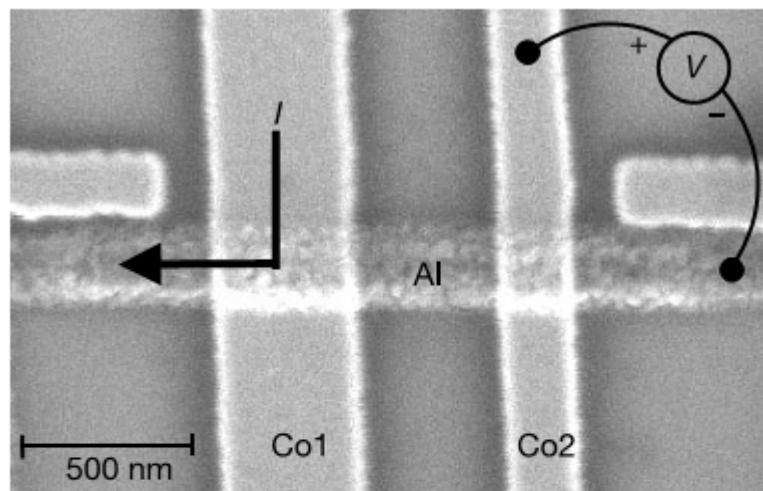
$$\Delta R = \frac{\alpha_F^2 \frac{\lambda_N}{\sigma_N A} e^{(-L/2\lambda_N)}}{(M + 1)[M \sinh(L/2\lambda_N) + \cosh(L/2\lambda_N)]} \quad (1)$$

where $M = (\lambda_N \sigma_F / \lambda_F \sigma_N)(1 - \alpha_F^2)$, $\alpha_F = \sigma_{\uparrow} - \sigma_{\downarrow}/\sigma_{\uparrow} + \sigma_{\downarrow}$ is the bulk

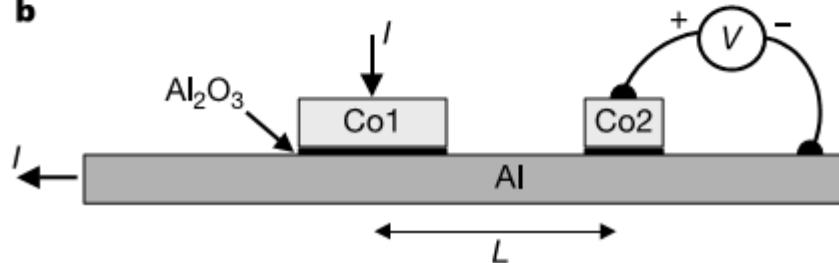
Hanle spin precession

Small devices on Al

a

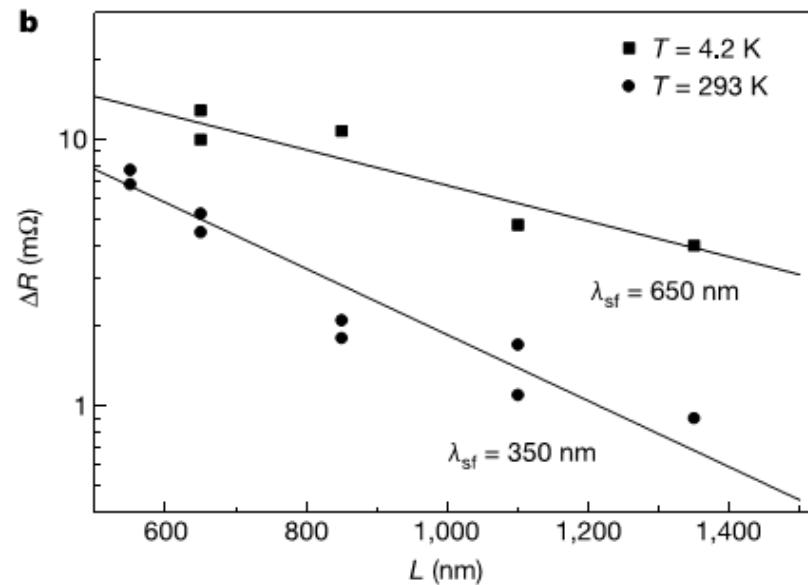


b



$$\frac{V}{I} = \pm \frac{1}{2} P^2 \frac{\lambda_{sf}}{\sigma_{Al} A} \exp(-L/\lambda_{sf})$$

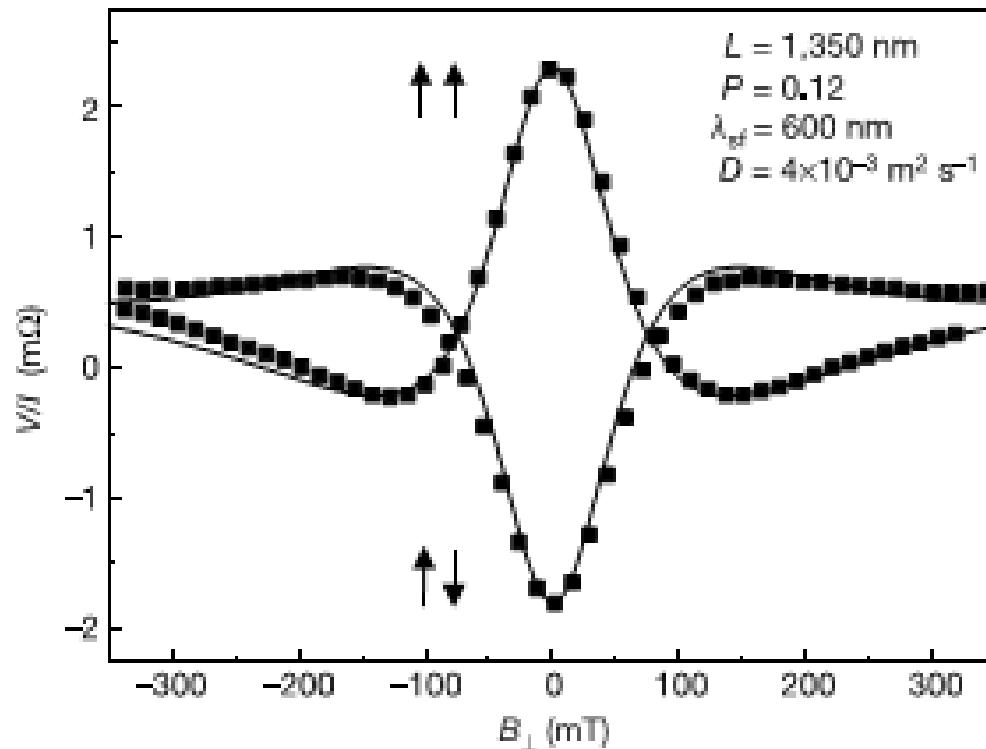
b



Jedema, et al, Nature (2002)

Hanle spin precession

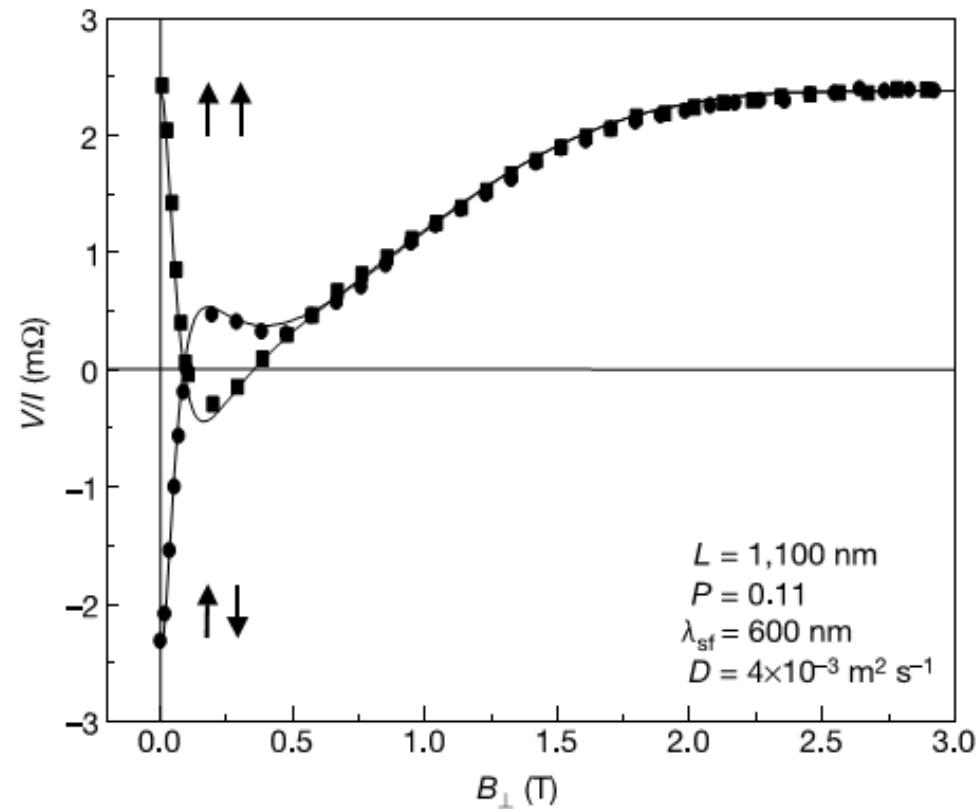
Small devices on Al



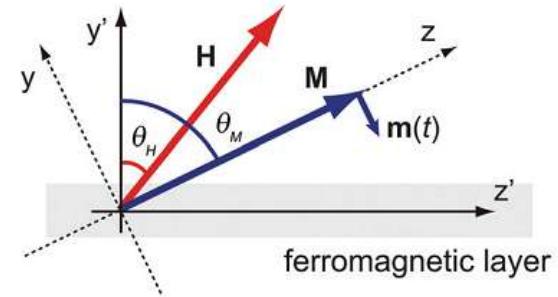
$$V(B_{\perp}) = \pm I \frac{P^2}{e^2 N_{Al} A} \int_0^{\infty} P(t) \cos(\omega_L t) \exp(-t/\tau_{sf}) dt$$

Hanle spin

Small devices on Al

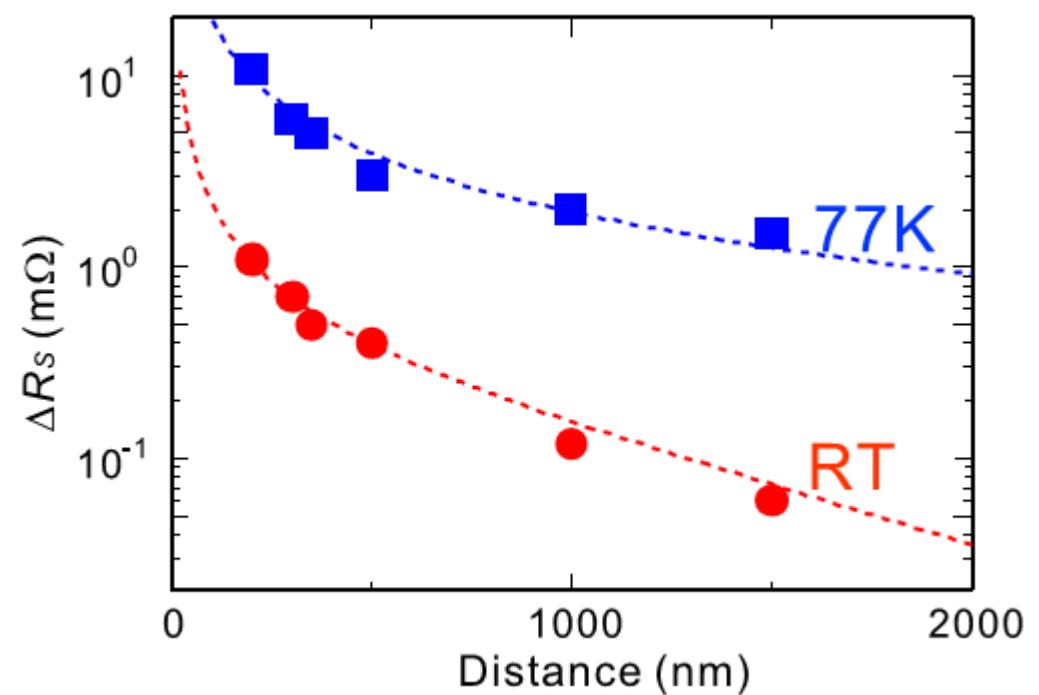
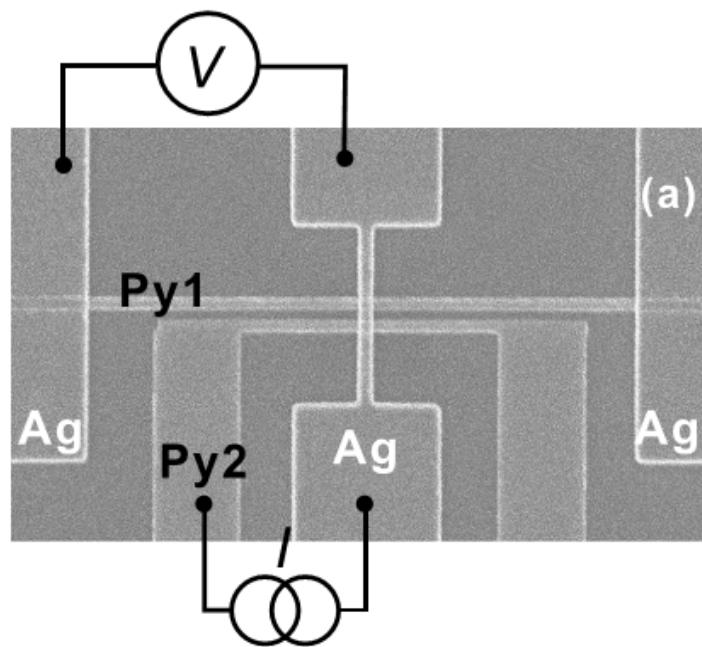


Magnetic anisotropy



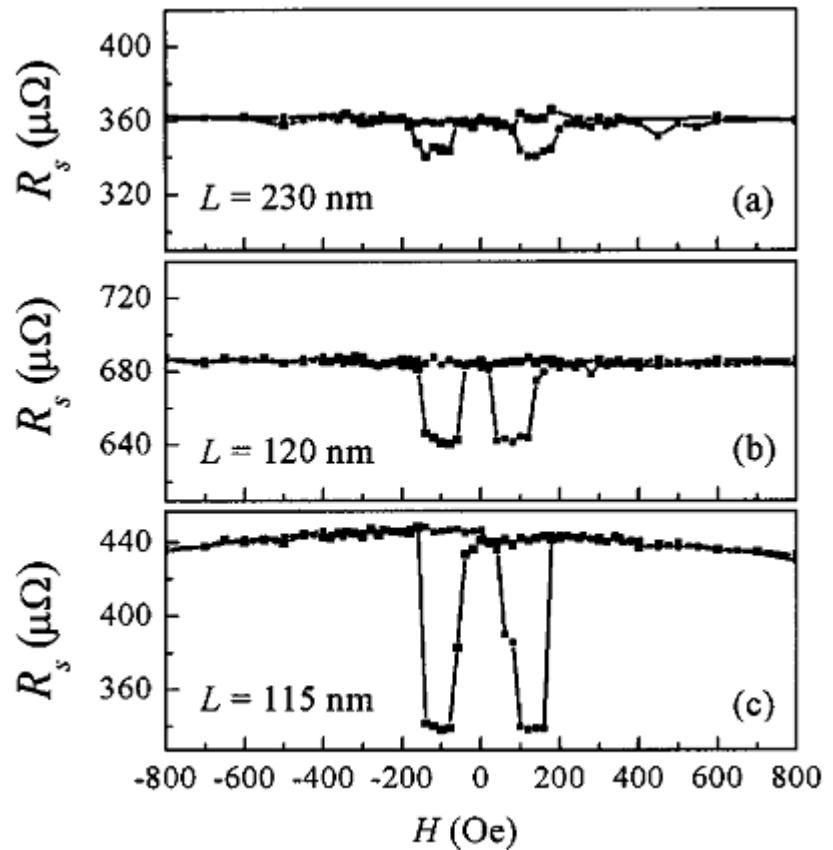
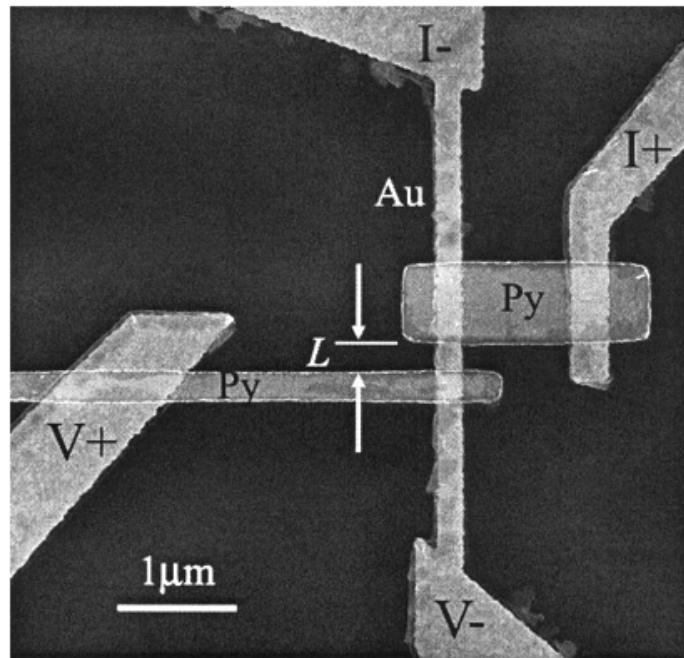
Ag spin valves

Small devices on Ag

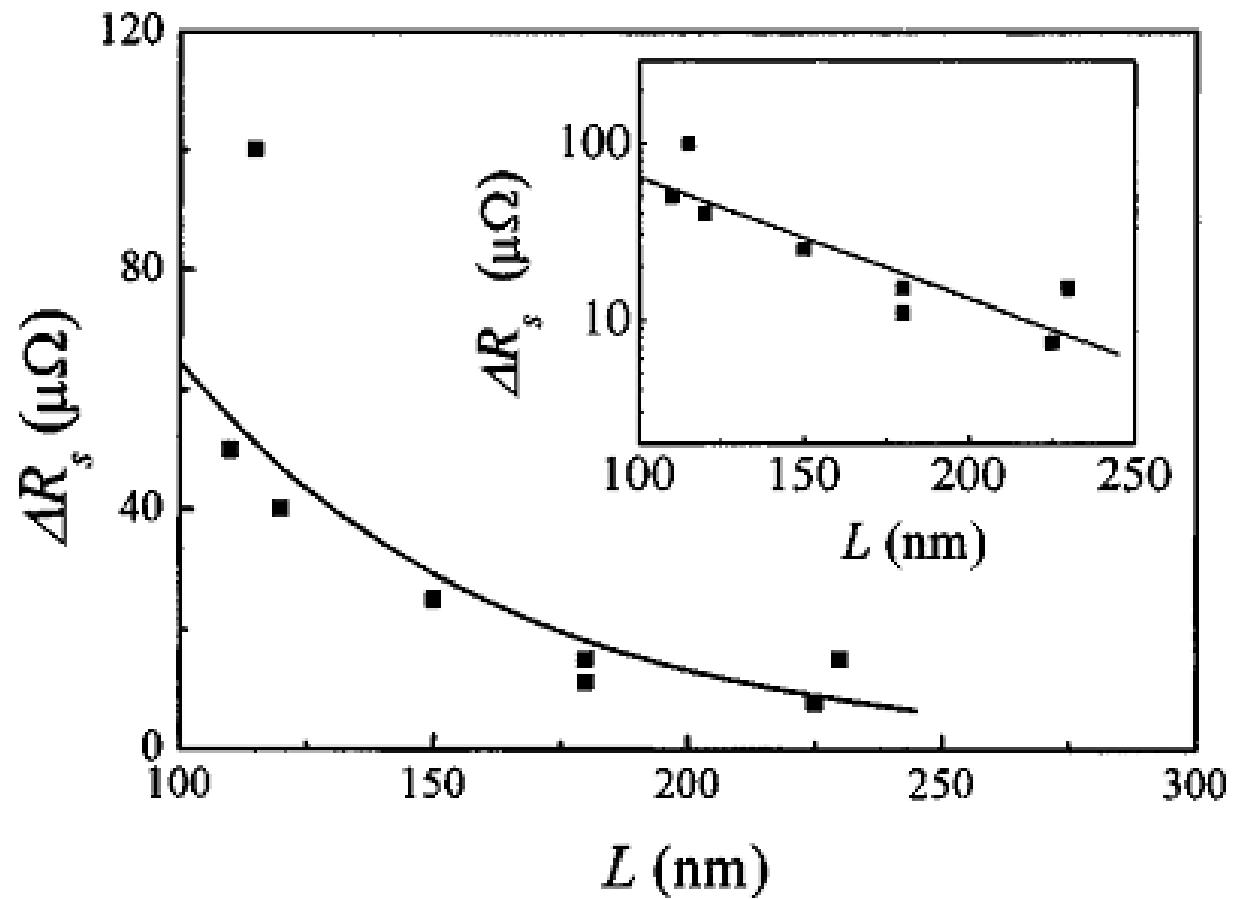


Kimura & Otani, et al, PRL (2007)

Au spin valves



Au spin valves



Metal spin valves

	T (K)	λ_s (nm)	P (%)	Reference
Fe/Al/Fe	1.8	500–1000	45 ^a	[25]
Py/Ag/Py	79	180	22 ^a	[15]
Py/Au/Py	10	63 ± 15	3	This work
	15	168	26 ^a	[23]
Co/Cu/Co	10	200 ± 20	7	This work
Py/Cu/Py	300	350	2	[7]
		500	2–3	[22]
	4	1000	2	[7]

^a These P values are obtained by using L defined as the centre-to-centre separation between the injector and the detector.

Spin injection efficiency

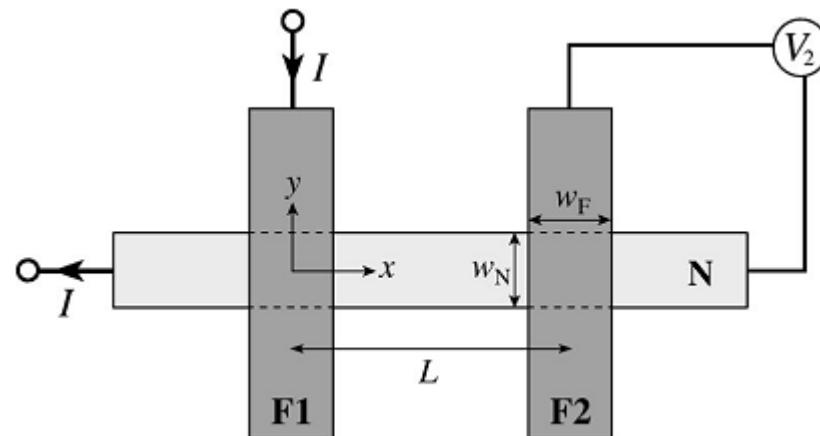
PHYSICAL REVIEW B **67**, 052409 (2003)

Spin injection and detection in magnetic nanostructures

S. Takahashi and S. Maekawa

Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan

(Received 5 November 2002; published 28 February 2003)



Spin injection efficiency

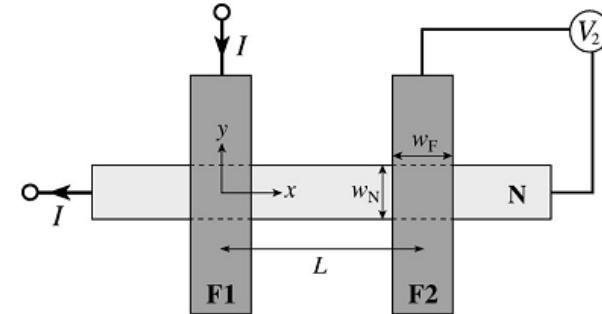
$$R_{NL} = 4R_N e^{-L/\lambda_N} \prod_{i=1}^2 \left(\frac{P_J \frac{R_i}{R_N}}{1 - P_J^2} + \frac{P_F \frac{R_F}{R_N}}{1 - P_F^2} \right) \times \left[\prod_{i=1}^2 \left(1 + \frac{2 \frac{R_i}{R_N}}{1 - P_J^2} + \frac{2 \frac{R_F}{R_N}}{1 - P_F^2} \right) - e^{-2L/\lambda_N} \right]^{-1}$$

$$P_F = (\sigma_F^\uparrow - \sigma_F^\downarrow) / (\sigma_F^\uparrow + \sigma_F^\downarrow)$$

$$P_J = (G_i^\uparrow - G_i^\downarrow) / (G_i^\uparrow + G_i^\downarrow)$$

$$R_N = \rho_N \lambda_N / A_N$$

$$R_F = \rho_F \lambda_F / A_J$$



R_i (R_1, R_2) interfacial resistances between
FM (injector, detector) and nonmagnetic material

Spin injection efficiency

For ohmic contact junction

$$R_{NL} = 4R_N e^{-L/\lambda_N} \prod_{i=1}^2 \left(\frac{P_J \frac{R_i}{R_N}}{1 - P_J^2} + \frac{P_F \frac{R_F}{R_N}}{1 - P_F^2} \right) \times \left[\prod_{i=1}^2 \left(1 + \frac{2 \frac{R_i}{R_N}}{1 - P_J^2} + \frac{2 \frac{R_F}{R_N}}{1 - P_F^2} \right) - e^{-2L/\lambda_N} \right]^{-1}$$

$$R_{NL} = \frac{4p_F^2}{(1-p_F^2)^2} R_N \left(\frac{R_F}{R_N} \right)^2 \frac{e^{-L/\lambda_G}}{1 - e^{-2L/\lambda_G}} = \frac{4p_F^2}{(1-p_F^2)^2} \frac{R_F^2}{R_N} \frac{e^{-L/\lambda_G}}{1 - e^{-2L/\lambda_G}}$$

$$P^2 = \frac{4p_F^2}{(1-p_F^2)^2} \left(\frac{R_F}{R_N} \right)^2$$

$$R_F = \rho_F \lambda_F / A_J$$

Spin injection efficiency

For tunneling contact junction

$$R_{NL} = 4R_N e^{-L/\lambda_N} \prod_{i=1}^2 \left(\frac{P_J \frac{R_i}{R_N}}{1 - P_J^2} + \frac{P_F \frac{R_F}{R_N}}{1 - P_F^2} \right) \times \left[\prod_{i=1}^2 \left(1 + \frac{2 \frac{R_i}{R_N}}{1 - P_J^2} + \frac{2 \frac{R_F}{R_N}}{1 - P_F^2} \right) - e^{-2L/\lambda_N} \right]^{-1}$$

$$R_s = P_J^2 R_N e^{-L/\lambda_N}$$

$$P_J = (G_i^\uparrow - G_i^\downarrow) / (G_i^\uparrow + G_i^\downarrow)$$

Spin injection efficiency

Junction size

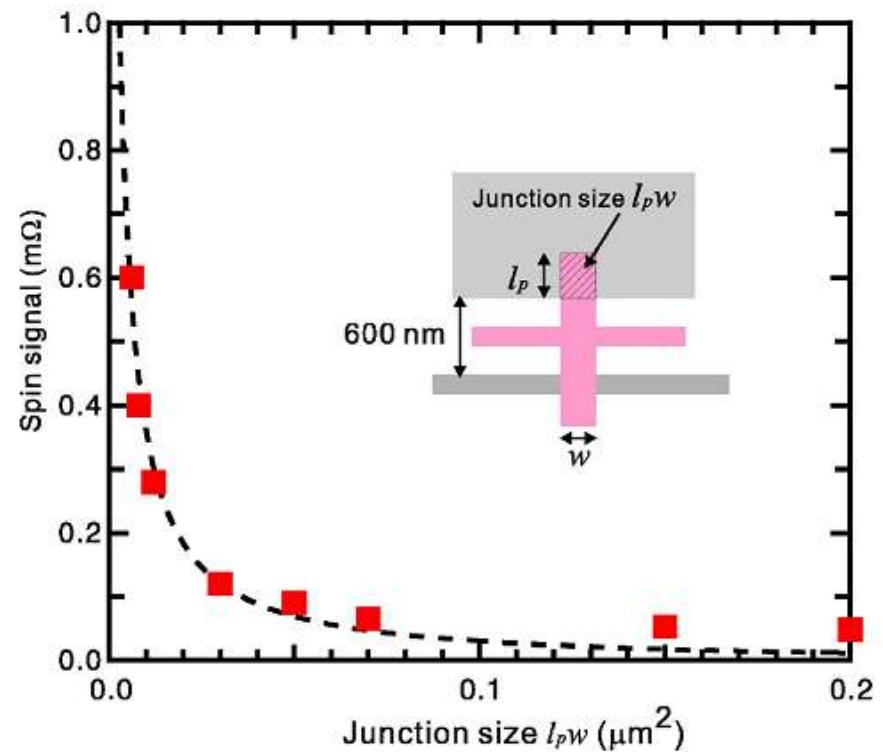
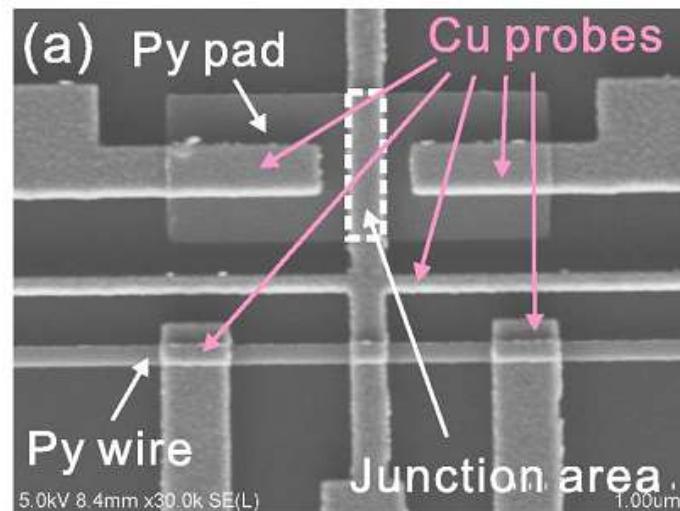
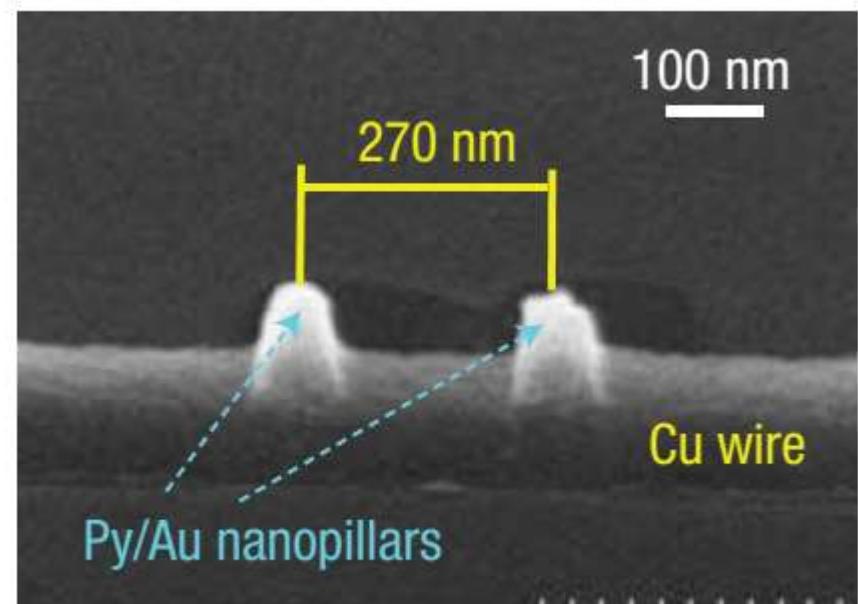
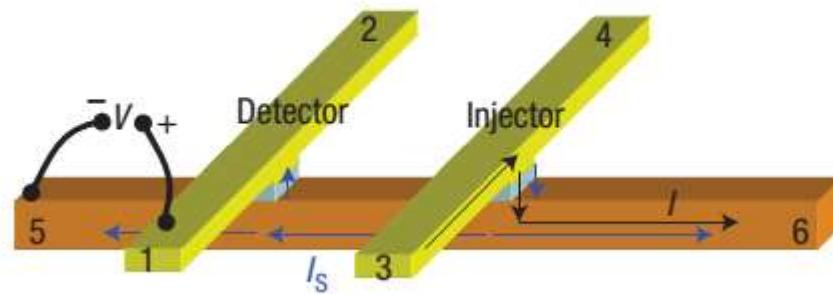


FIG. 4. (Color online) Spin signal in the NLSV measurement as a function of the junction size $l_p w$. The dotted curve is the best fitting to the data points using Eq. (2).

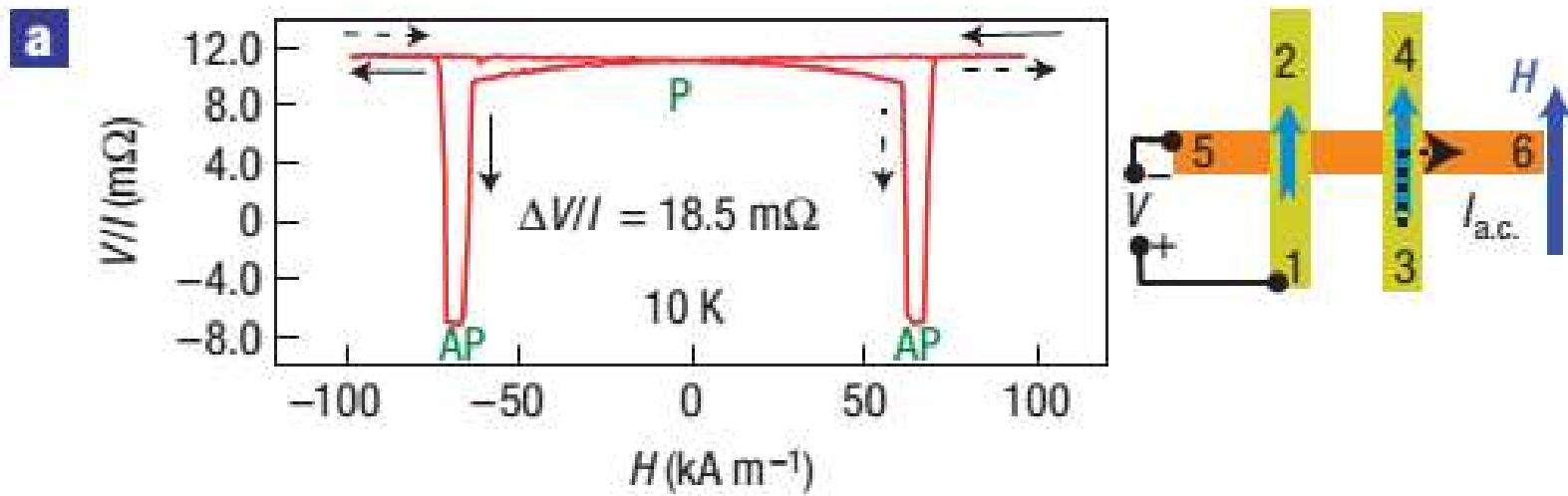
Spin injection efficiency

Junction size



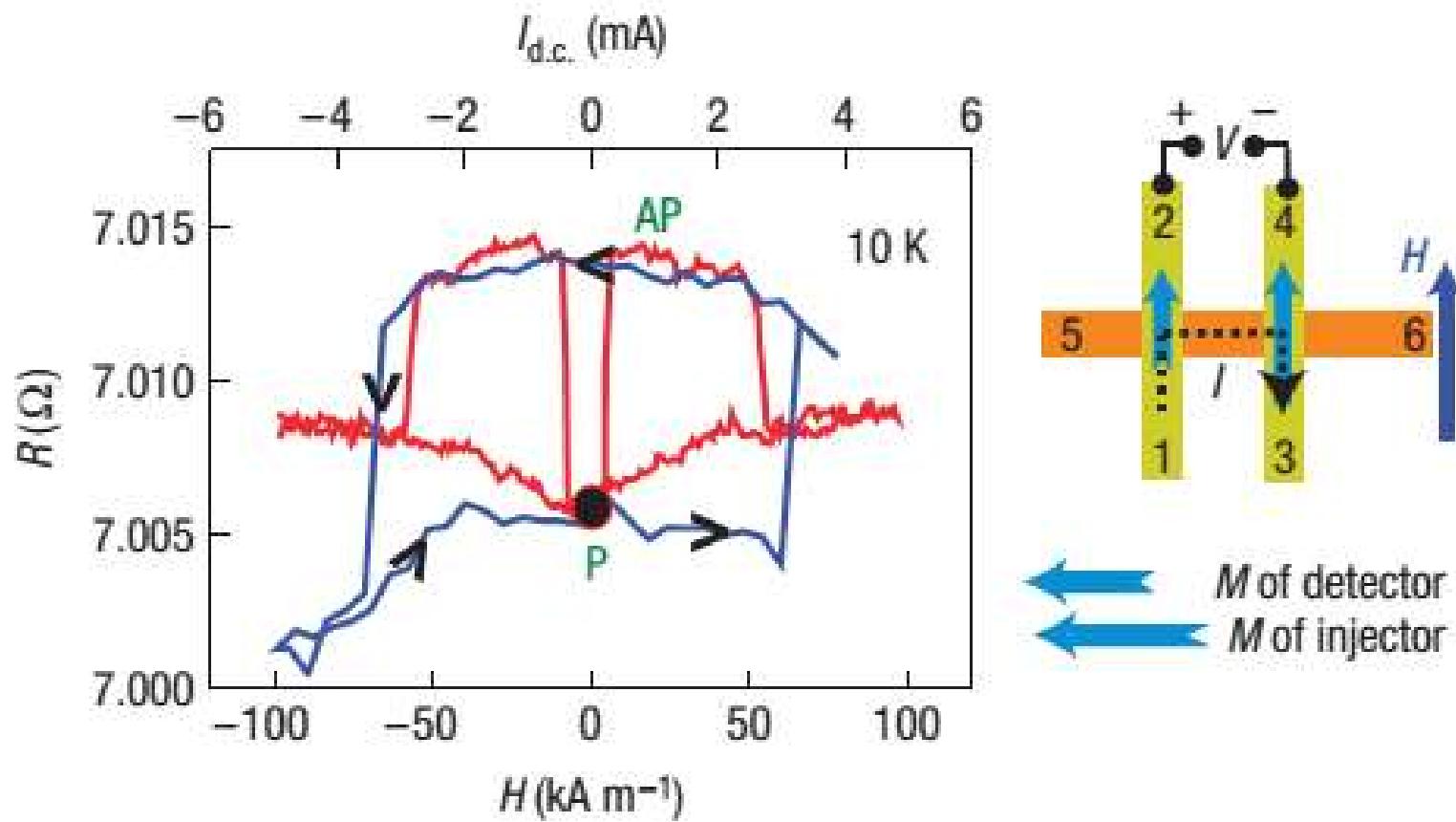
Spin injection efficiency

Junction size

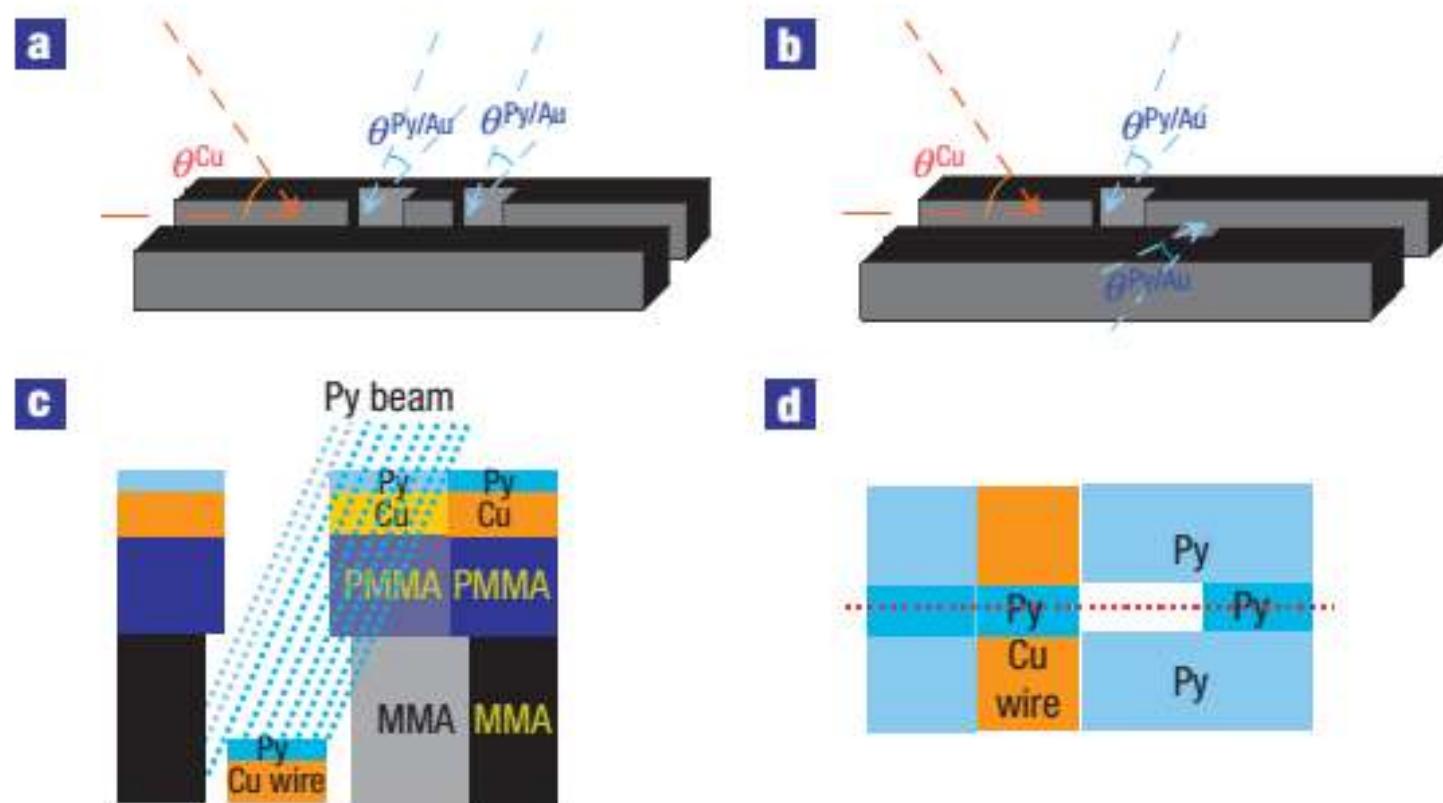


Spin injection efficiency

Junction size → current switching

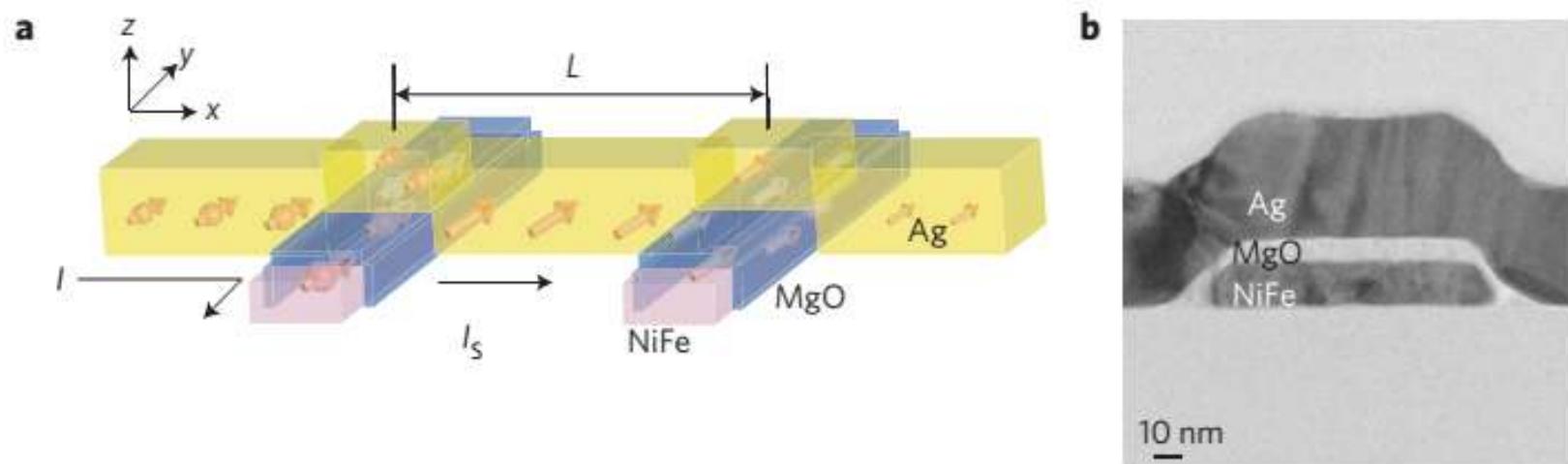


Angle deposition



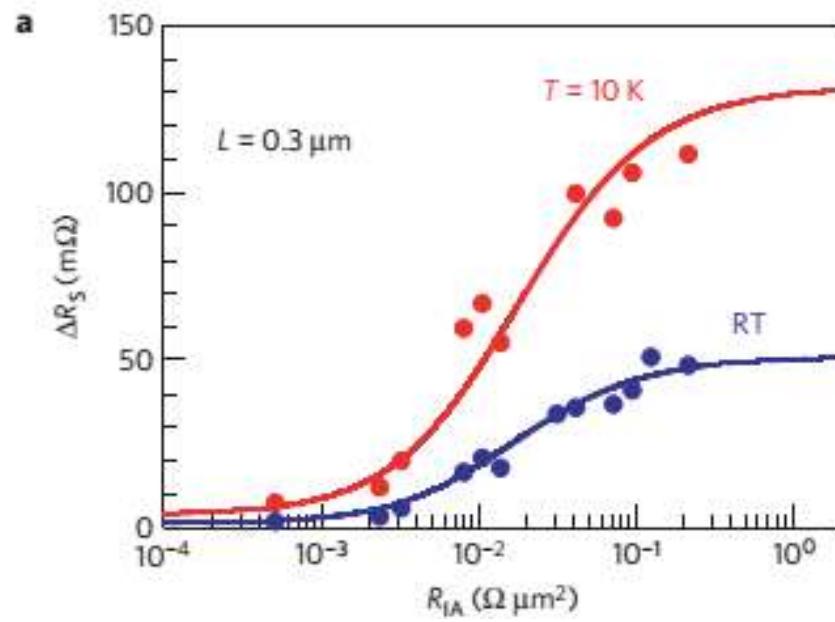
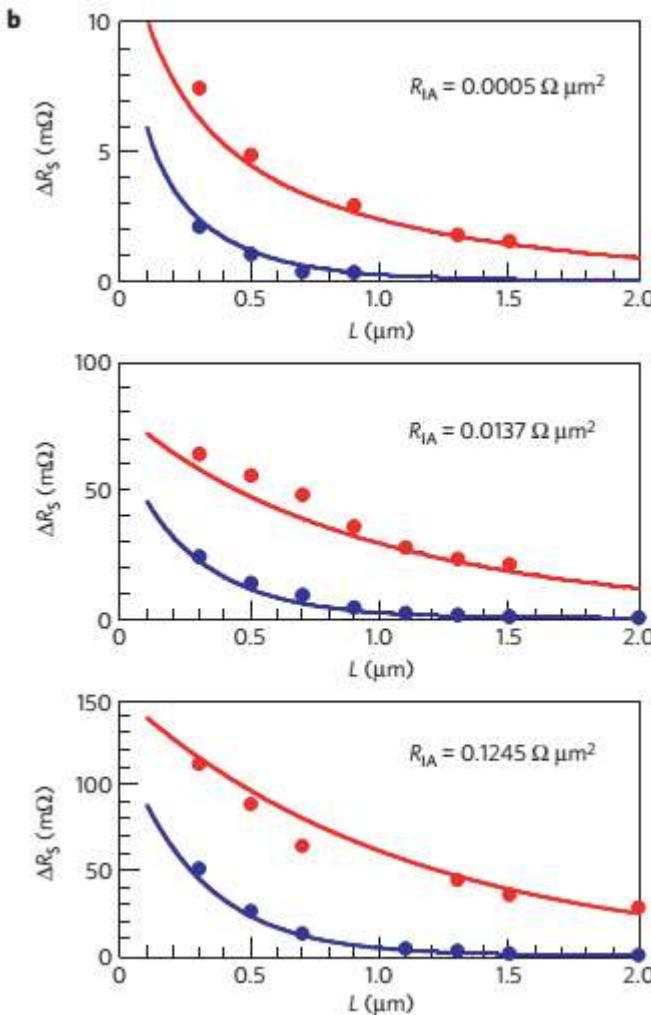
Spin injection efficiency

MgO tunnel barrier



Spin injection efficiency

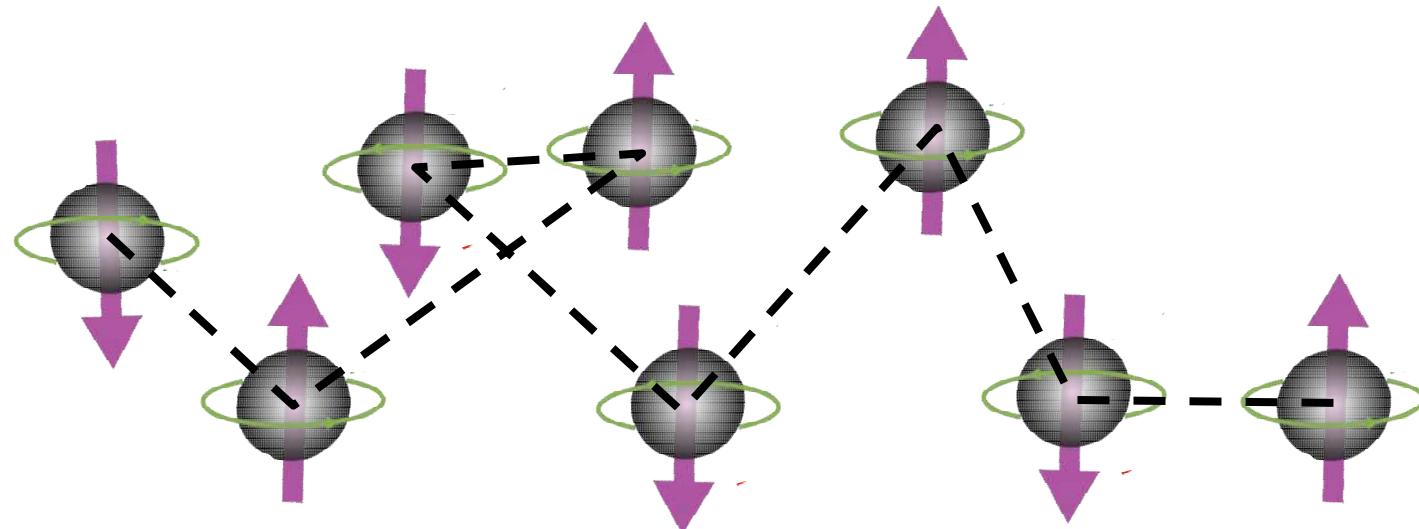
MgO tunnel barrier



Fukuma, et al, Nature Materials (2011)

Spin relaxation

Elliot-Yafet spin relaxation

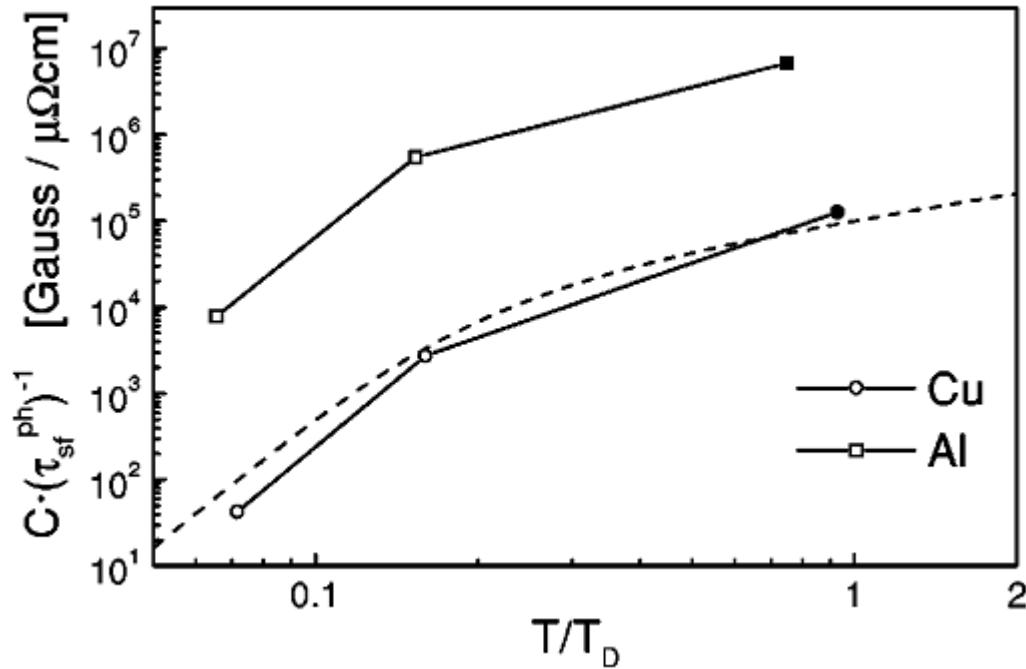


**Spin flip during momentum scattering events:
More momentum scattering, more spin relaxation.**

$$\tau_s \sim \tau_p (D)$$

- J. Fabian, et al, Acta Phys. Slovaca (2007)
R.J. Elliott, Phys. Rev. (1954)
F. Meier and B.P. Zachachrenya, Optical Orientation, (1984).
Josza, et al, Phys. Rev. B (2009)

Spin relaxation



$$\frac{\tau_e}{\tau_{sf}} = a \propto \left(\frac{\lambda}{\Delta E} \right)^2$$

Jedema, et al, PRB (2003)
Fabian & Das Sarma, PRL (1998)

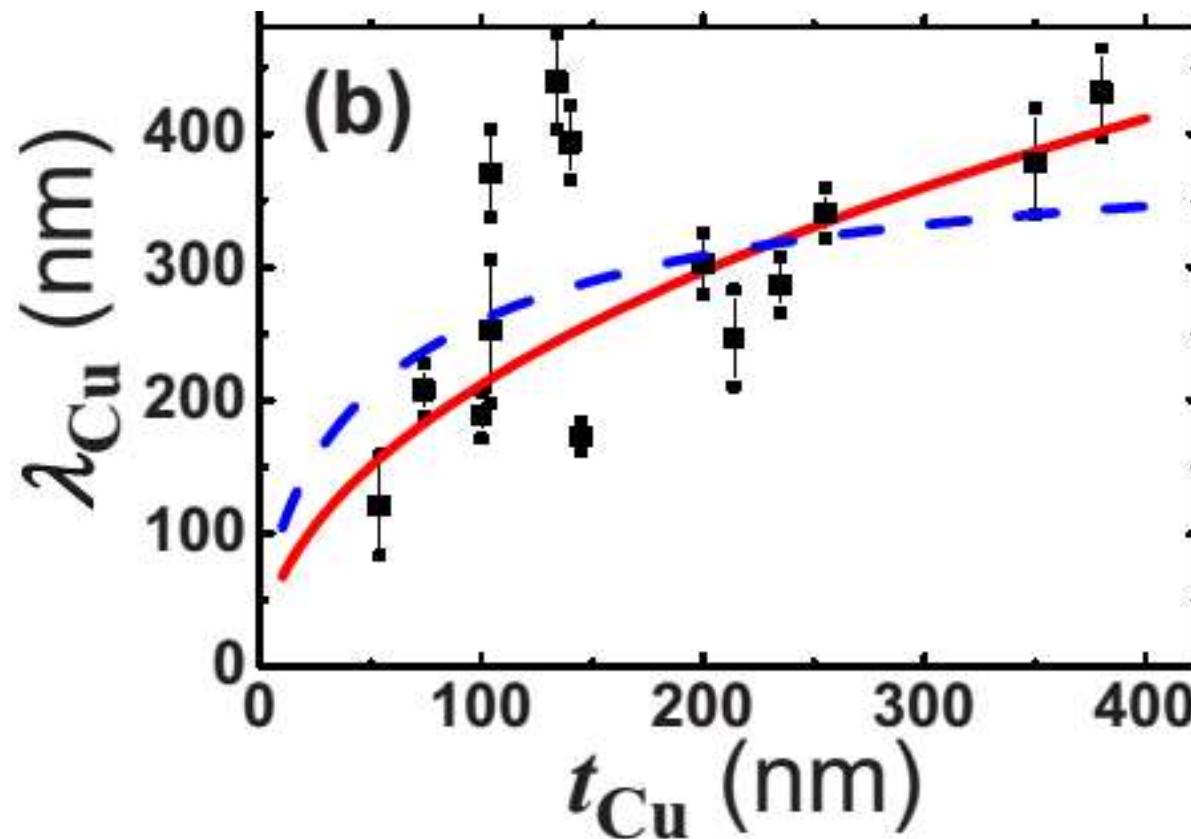
Spin relaxation

	T (K)	λ_s (nm)	P (%)	Reference
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Py/Ag/Py	79	180	22 ^a	[15]
Py/Au/Py	10	63 ± 15	3	This work
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^a These P values are obtained by using L defined as the centre-to-centre separation between the injector and the detector.

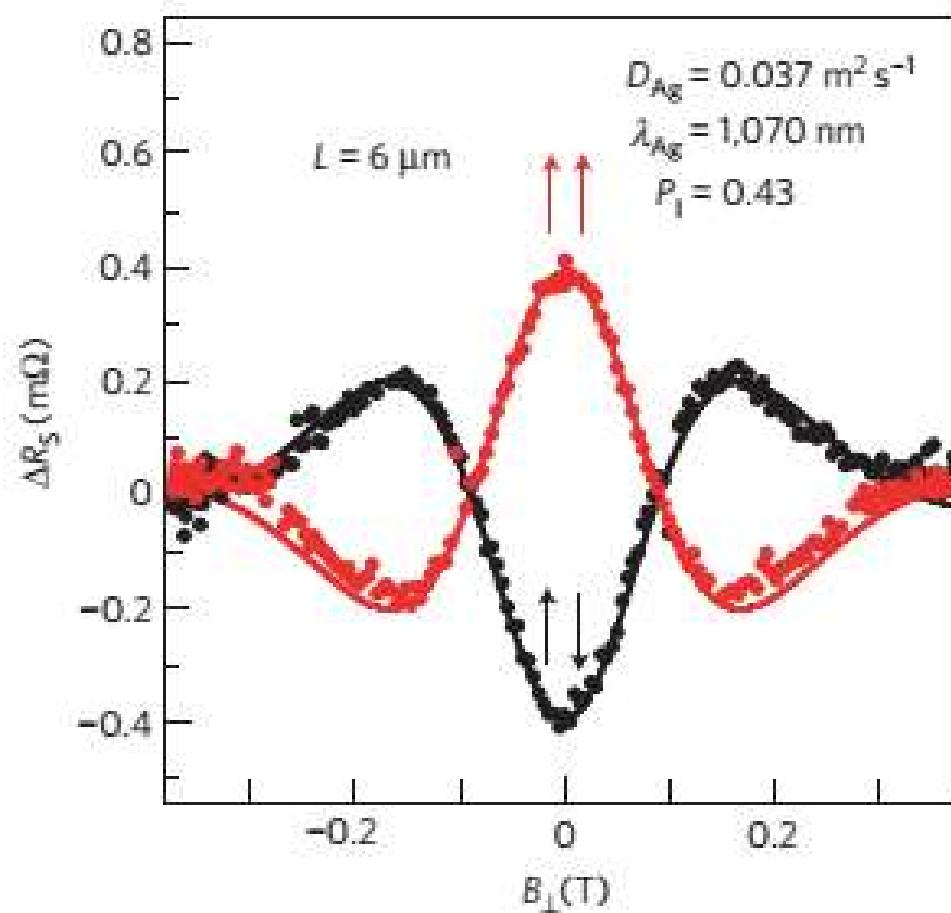
Spin relaxation

Surface impurity scattering



Spin relaxation

MgO tunnel barrier



Summary

1. Metal Spin Valves

Local and Nonlocal spin valves

Hanle spin precession

Nano devices (Thanks to cleanroom)

Spin injection efficiency

Spin relaxation in Metals: EY mechanism

休息10分钟

Outline

2. Superconductor Spin Valves

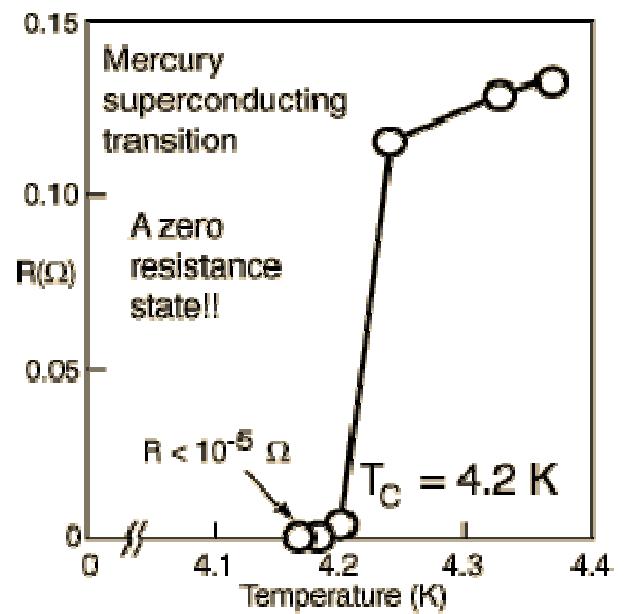
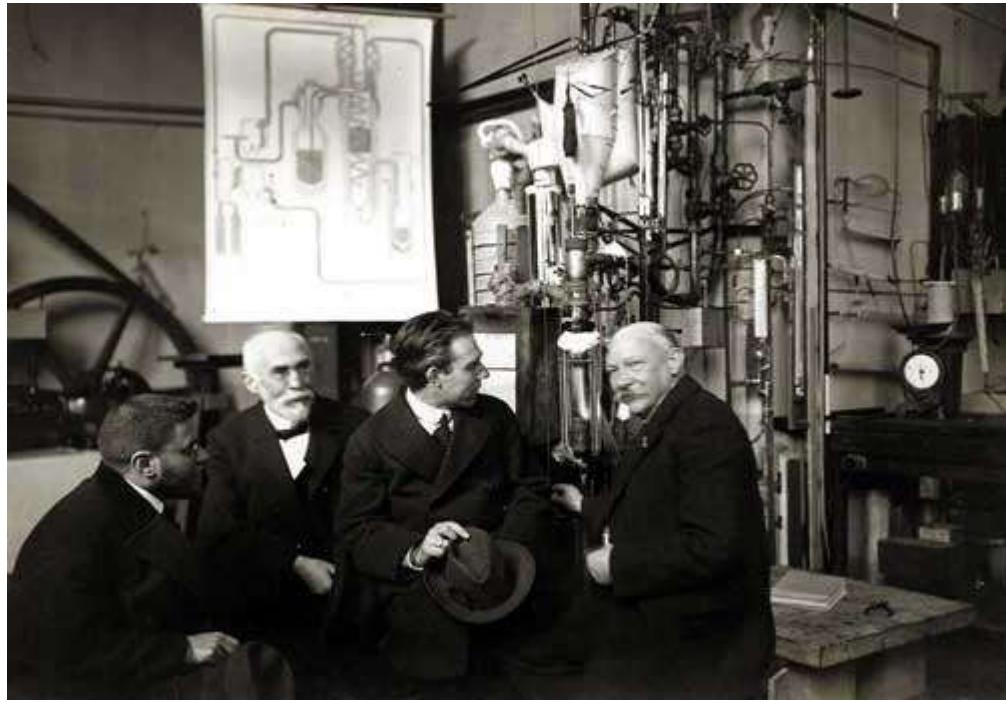
Large MR and control of T_C

Josephson junction, Spin-triplet

Spin injection, Long spin lifetime

Large spin Hall

Superconductor



Onnes, Commun. Phys. Lab. (1911)

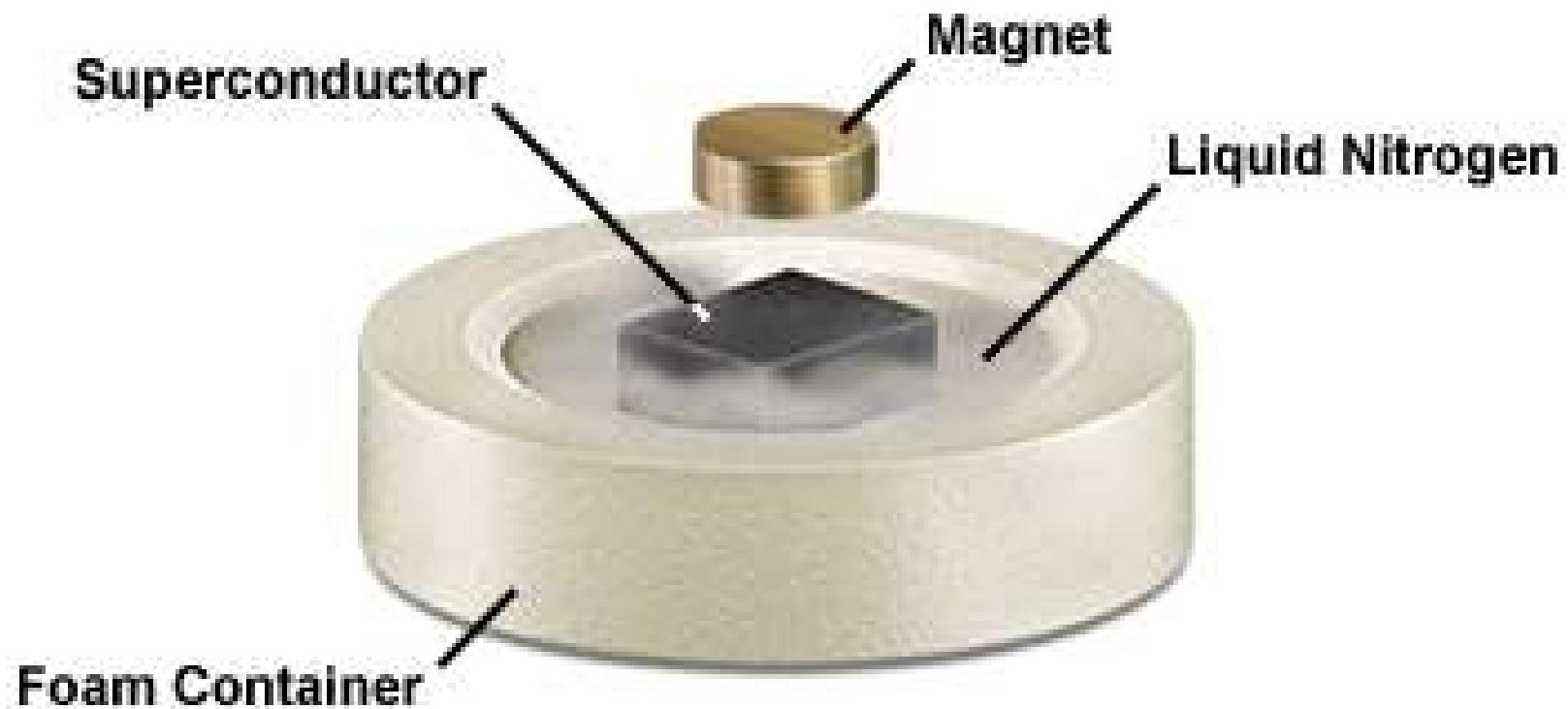
Superconductor

"Door meten tot weten"
(Knowledge through measurement)

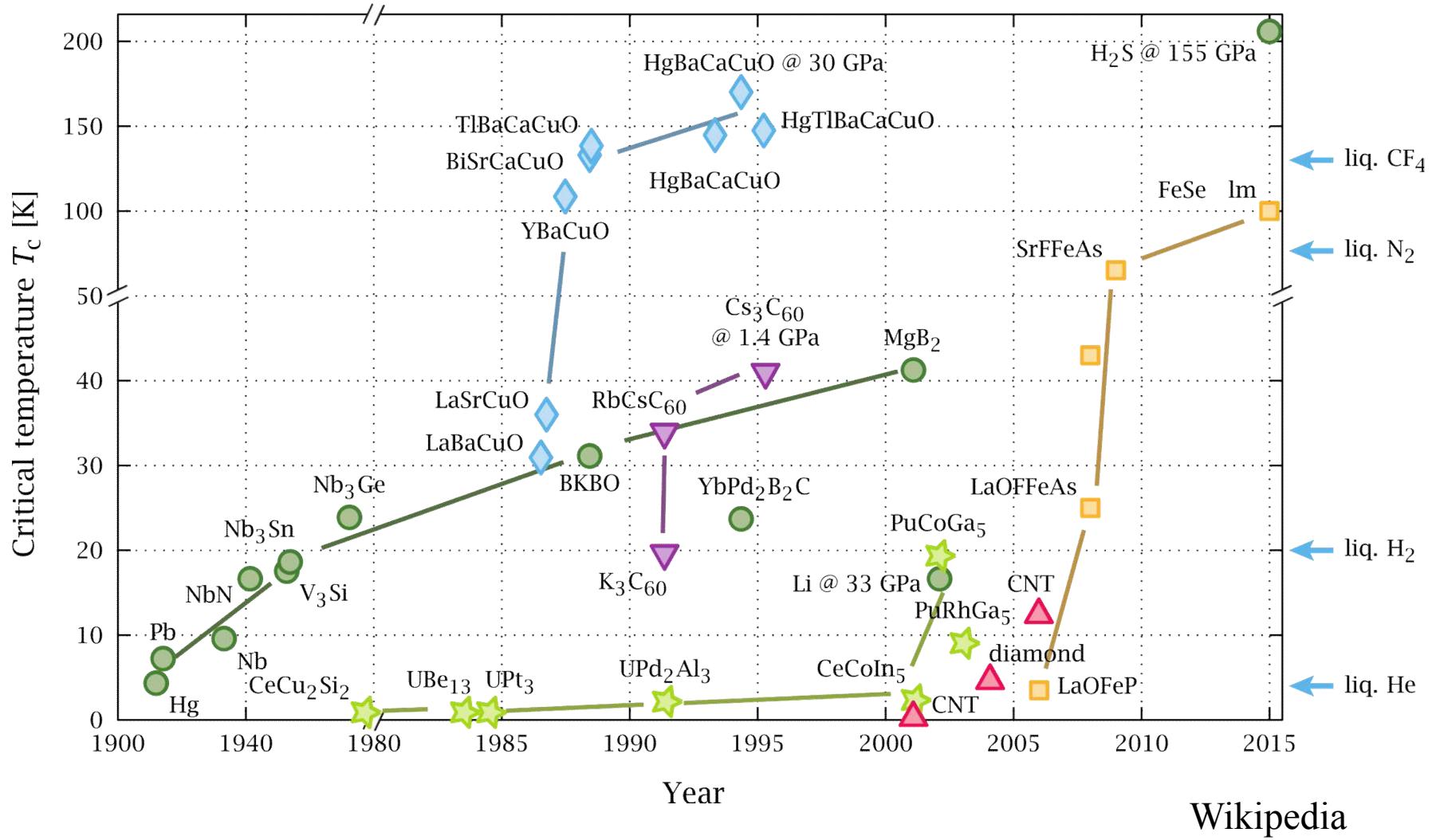


Superconductor

The Meissner Effect



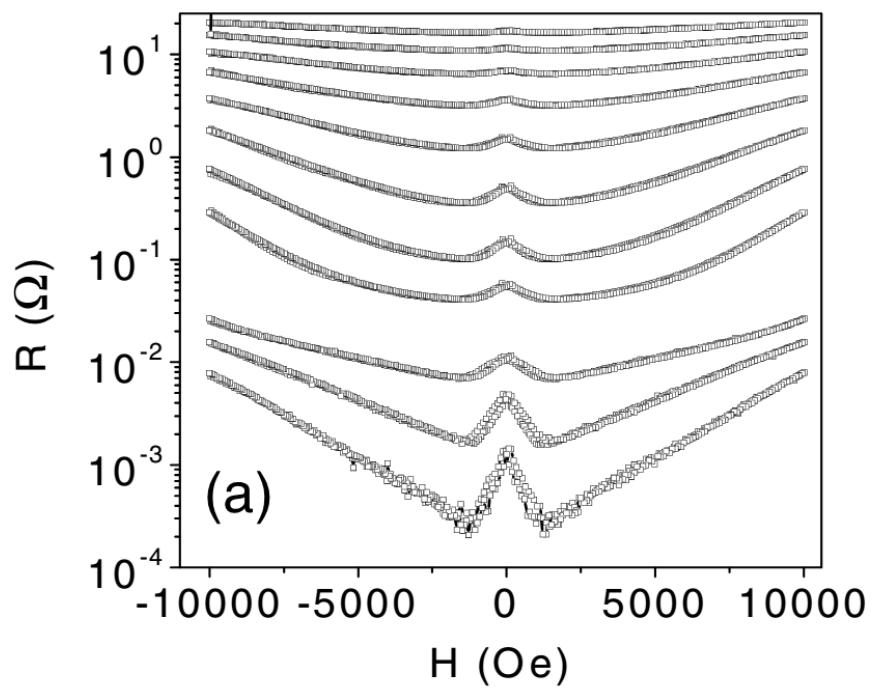
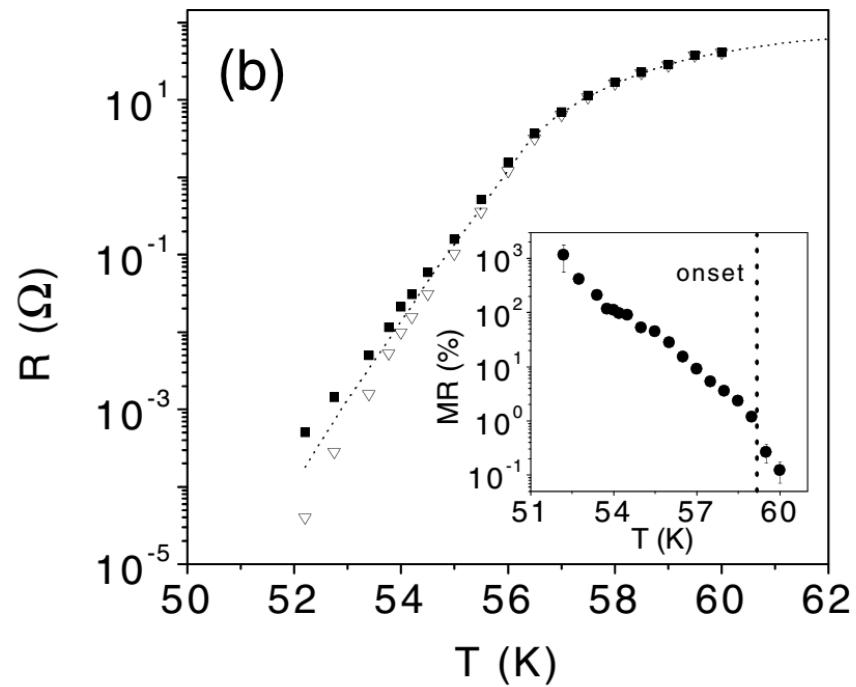
Superconductor



Wikipedia

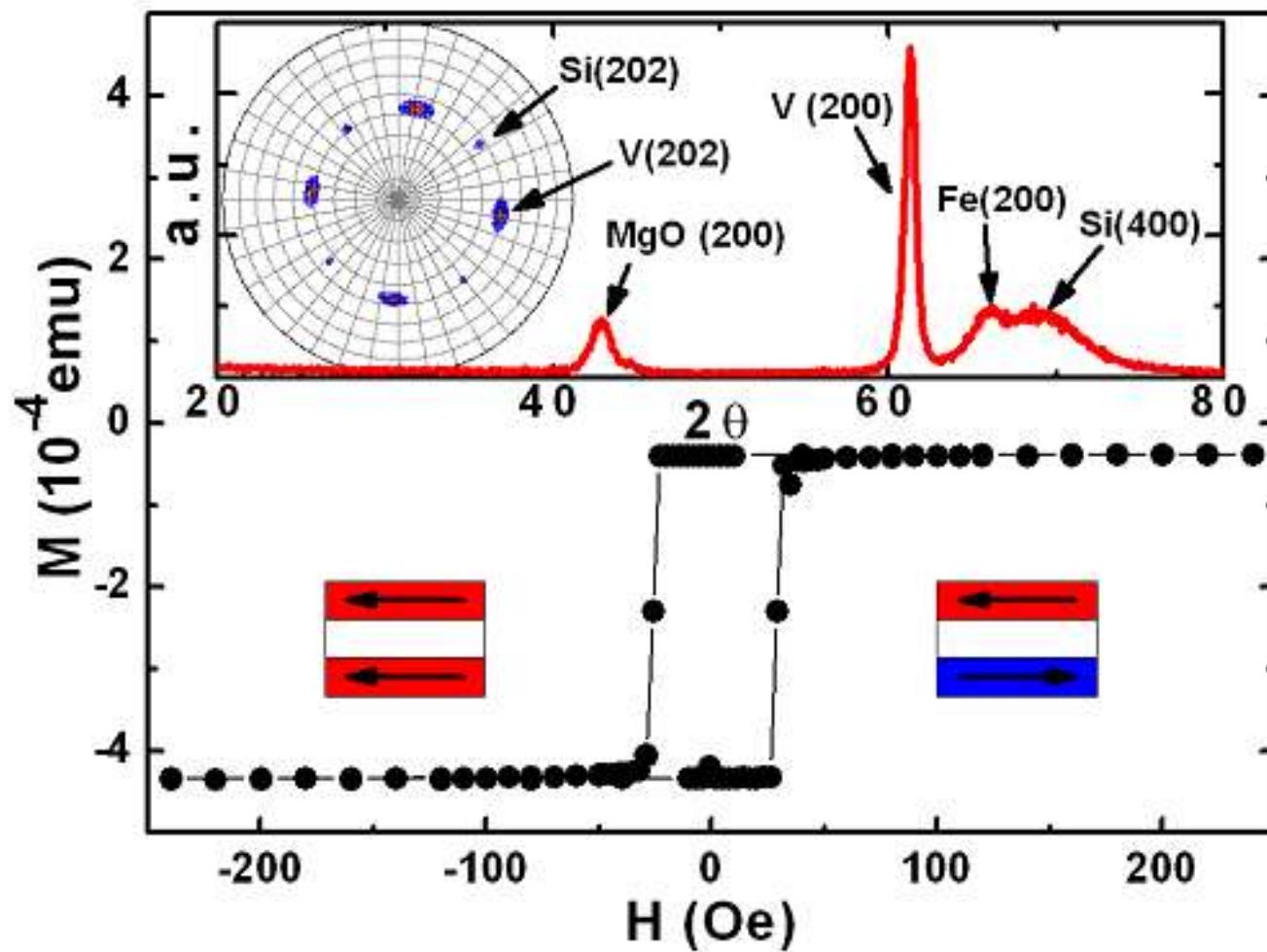
Superconductor

LaCaMnO—YBaCuO—LaCaMnO multilayers



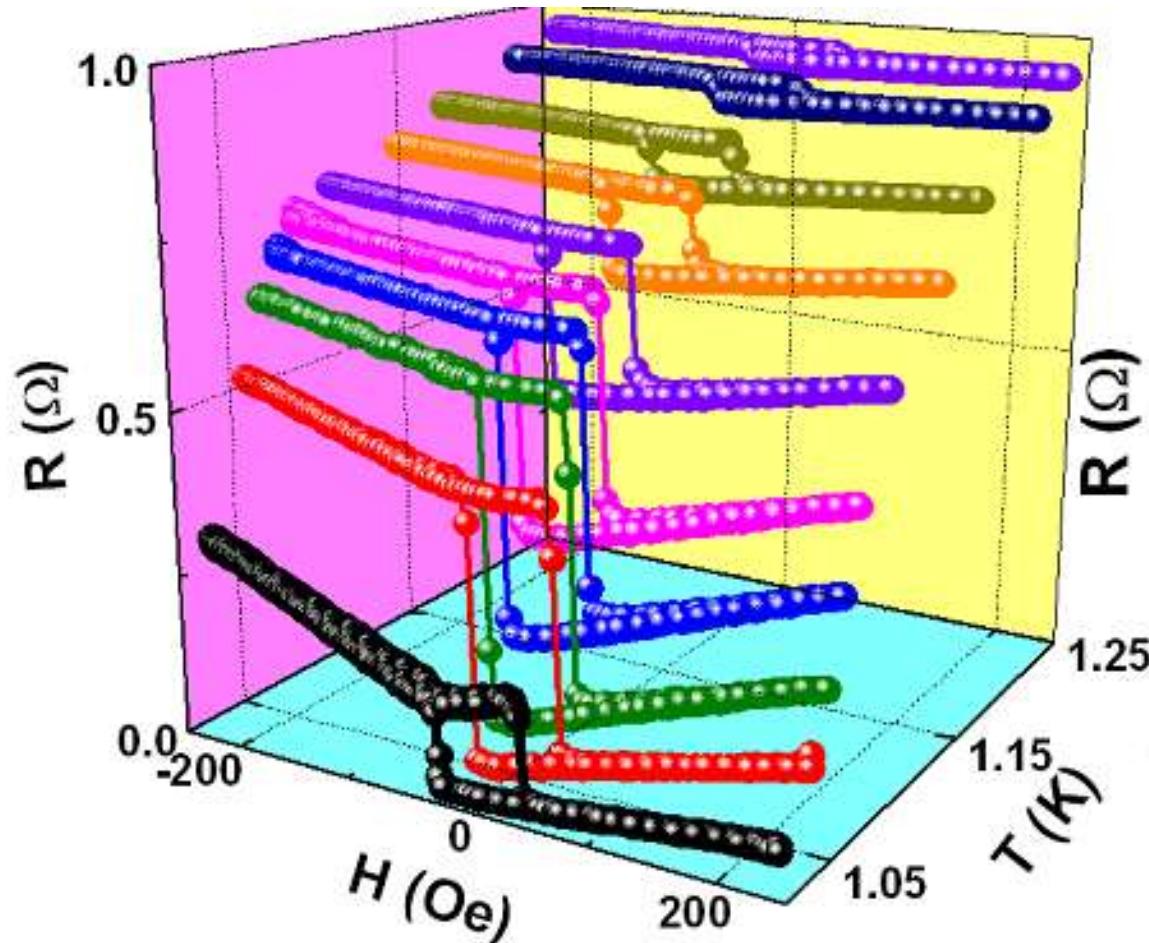
Pena, et al, PRL (2005)

Superconductor

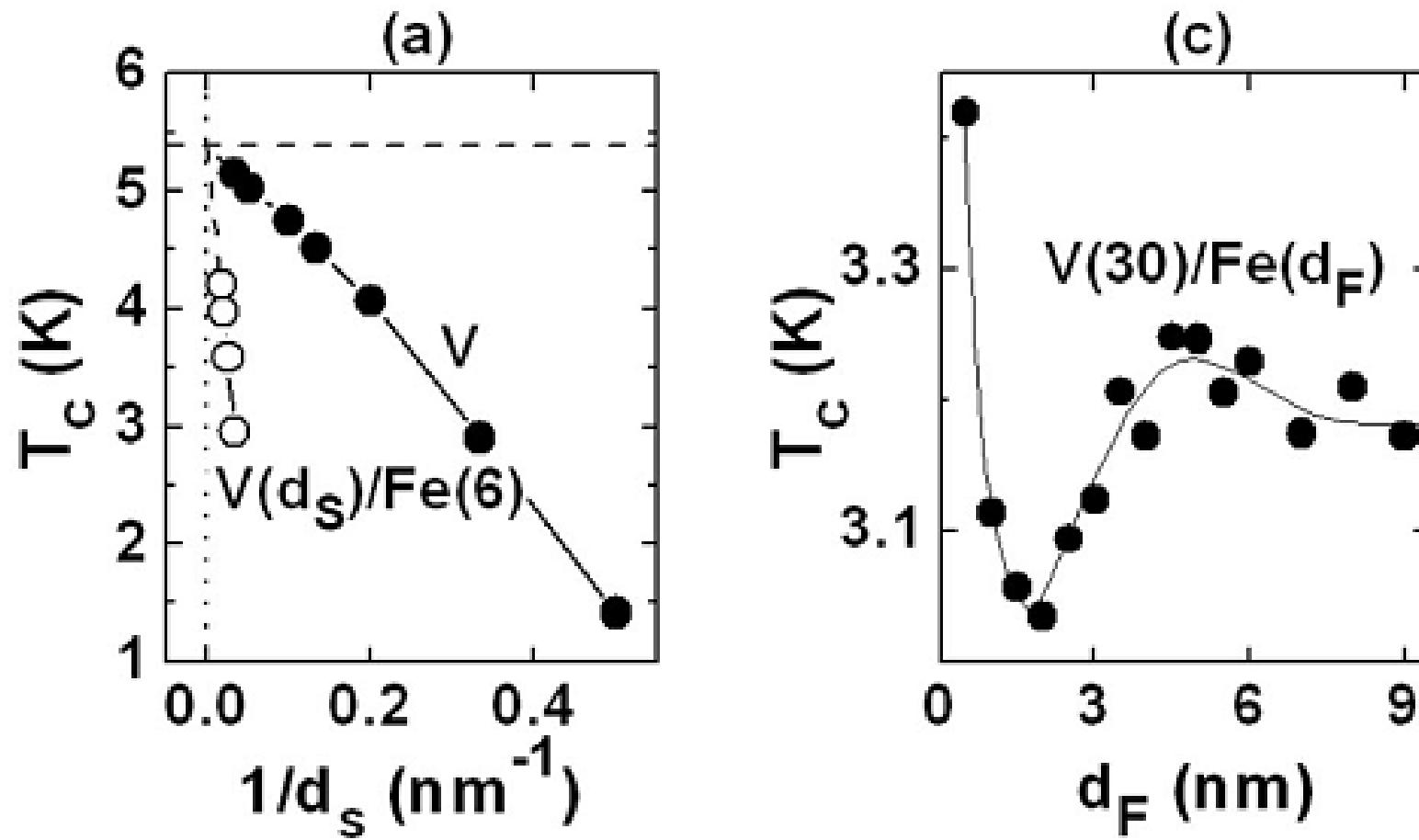


Miao, et al, PRL (2008)

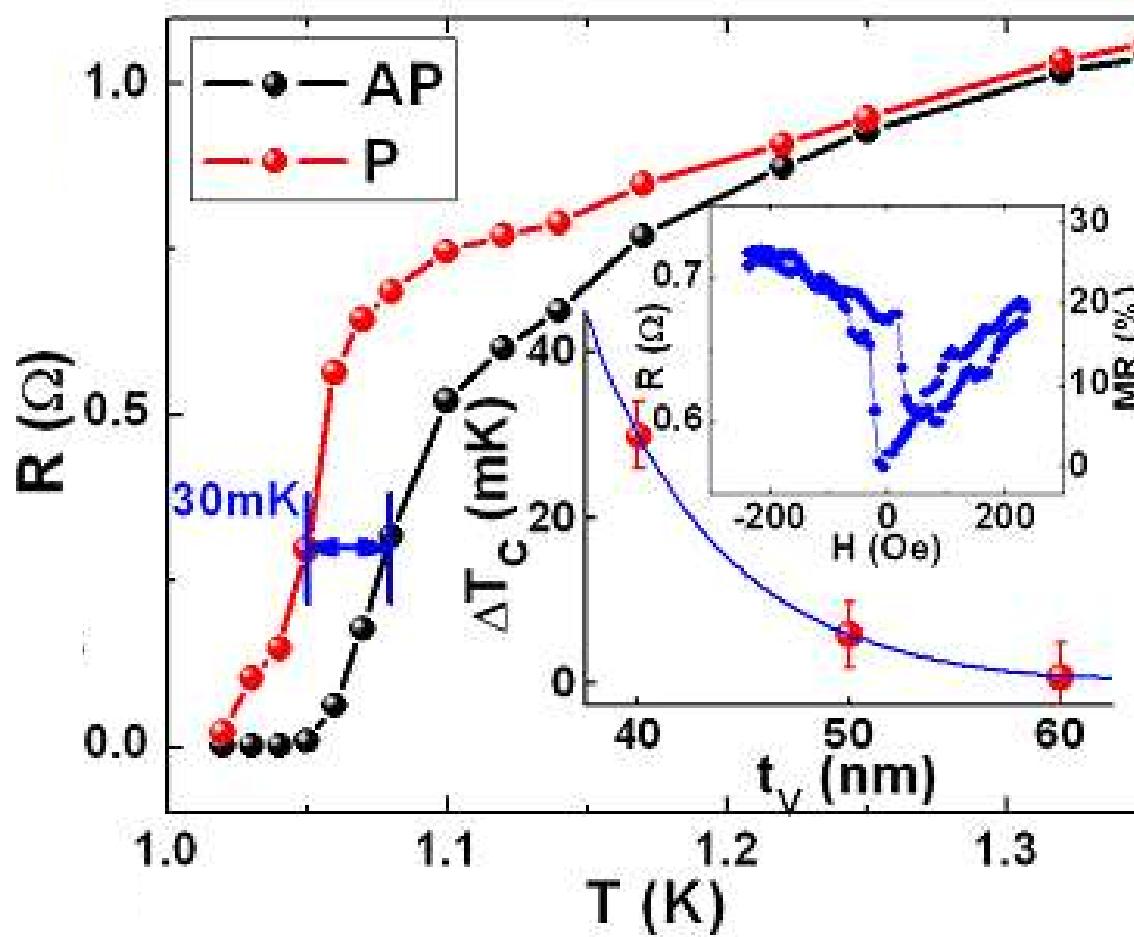
Superconductor



Superconductor

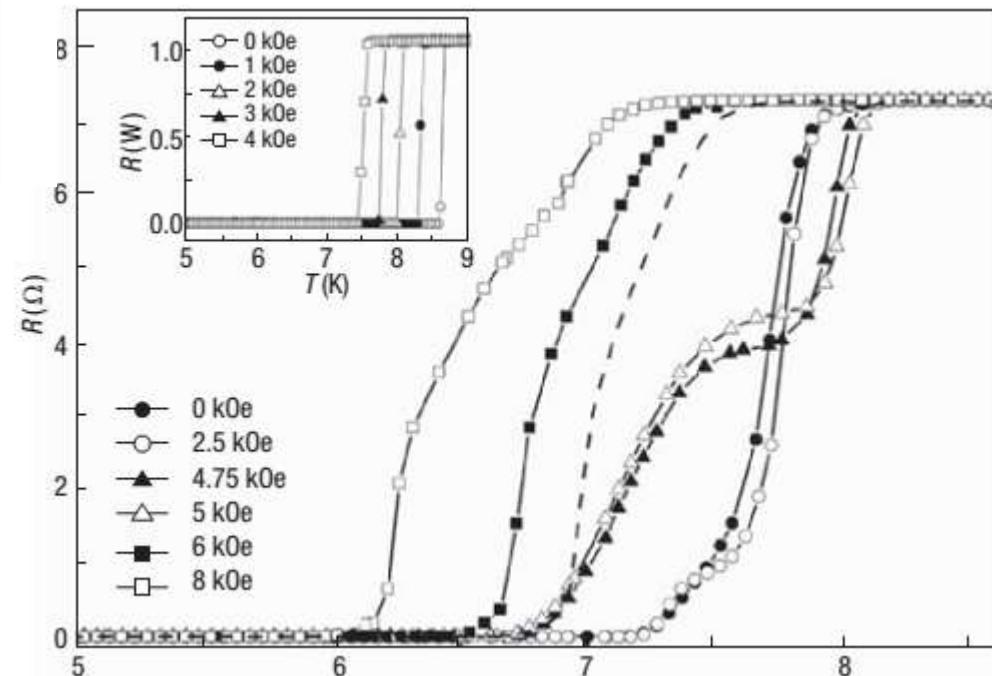
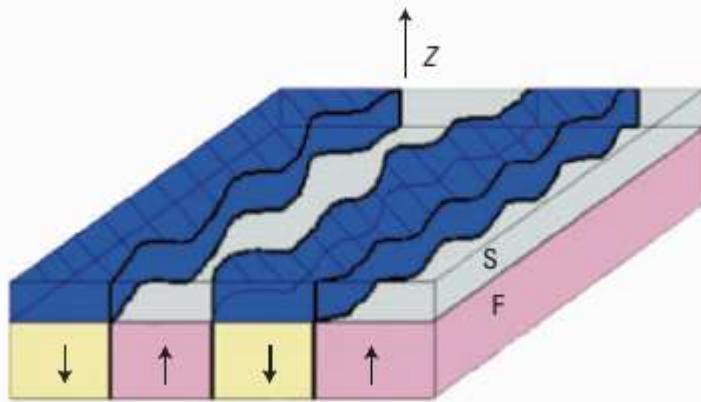


Superconductor



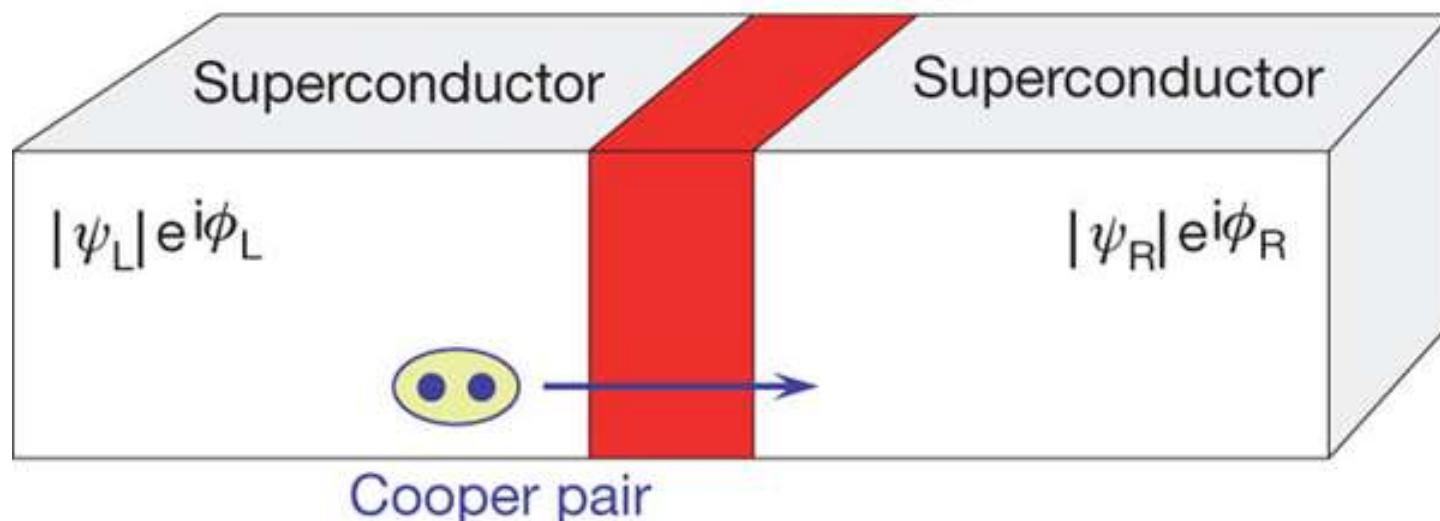
Superconductor

Nb (S)—BaFe₁₂O₁₉ (FM) Domain wall superconductivity



Yang, et al, Nature Phys. (2004)

Josephson junction

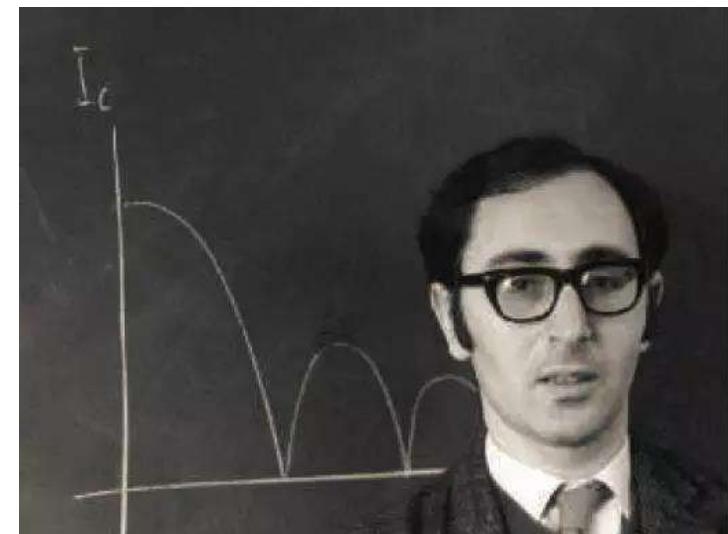


Single electron tunneling?

Tunneling as a pair?

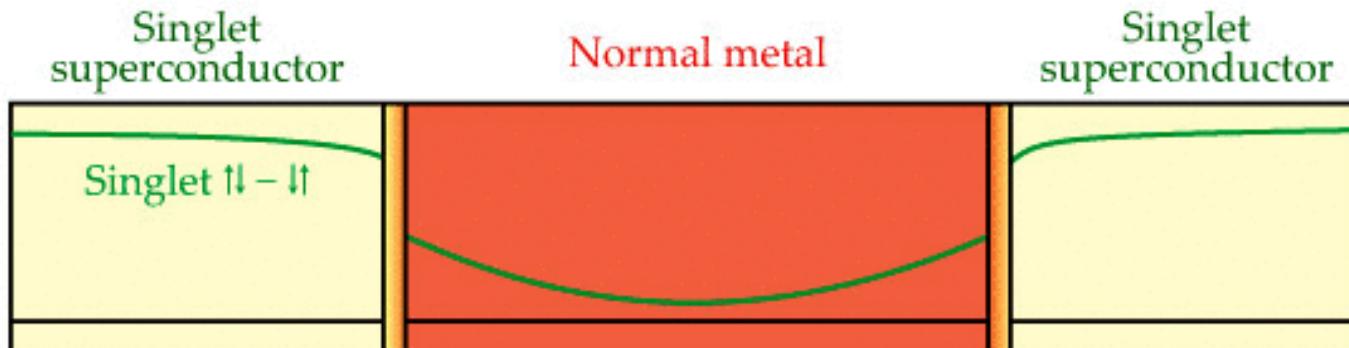


vs

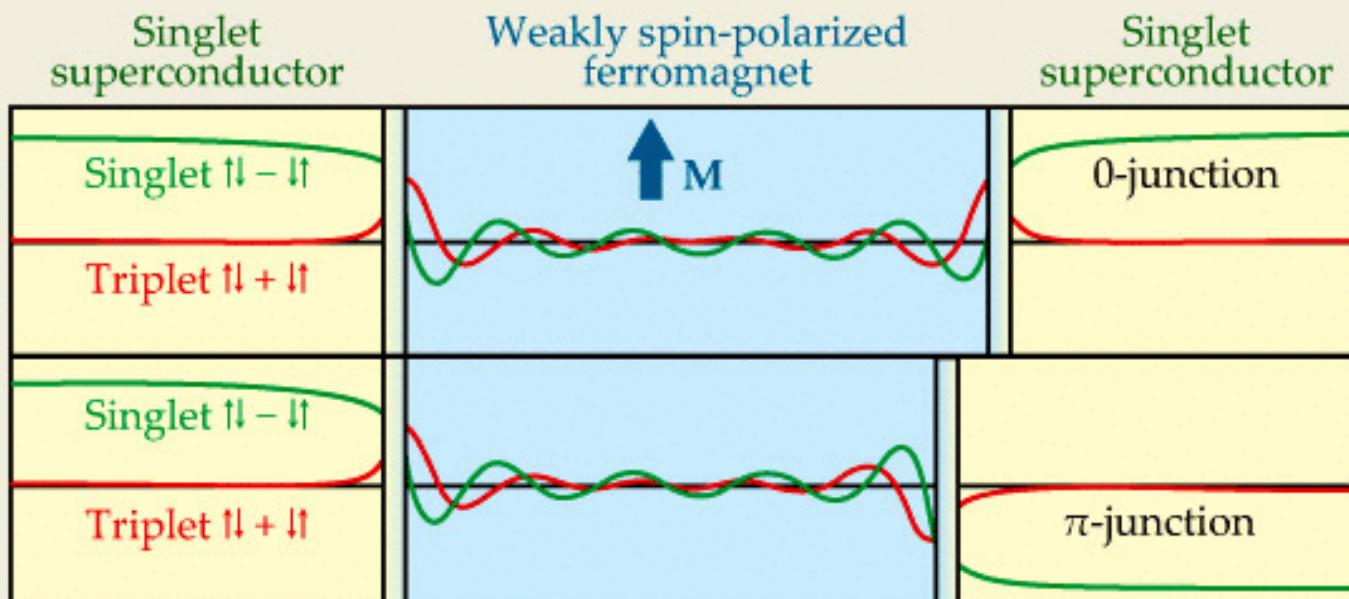


Josephson junction

a

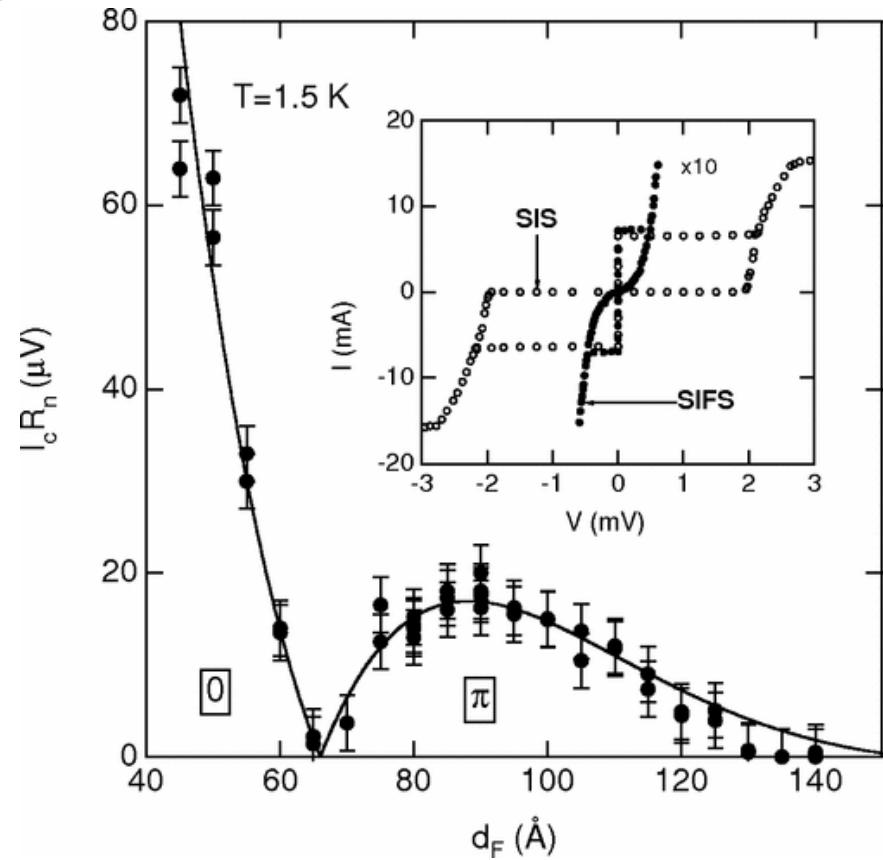
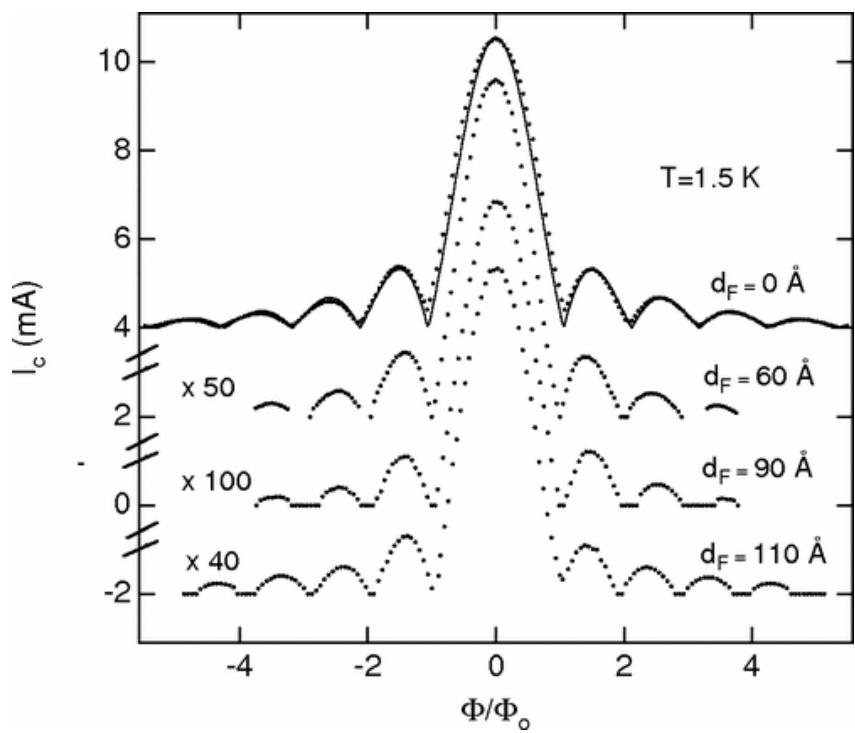


b



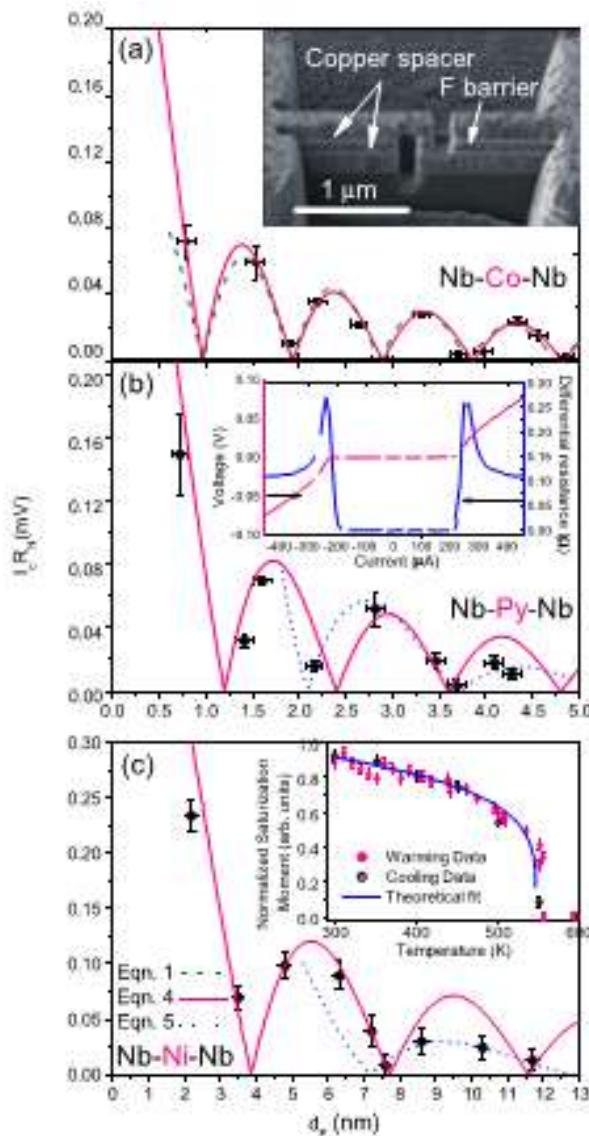
π - Josephson junction

Nb/Al/Al₂O₃/PdNi/Nb



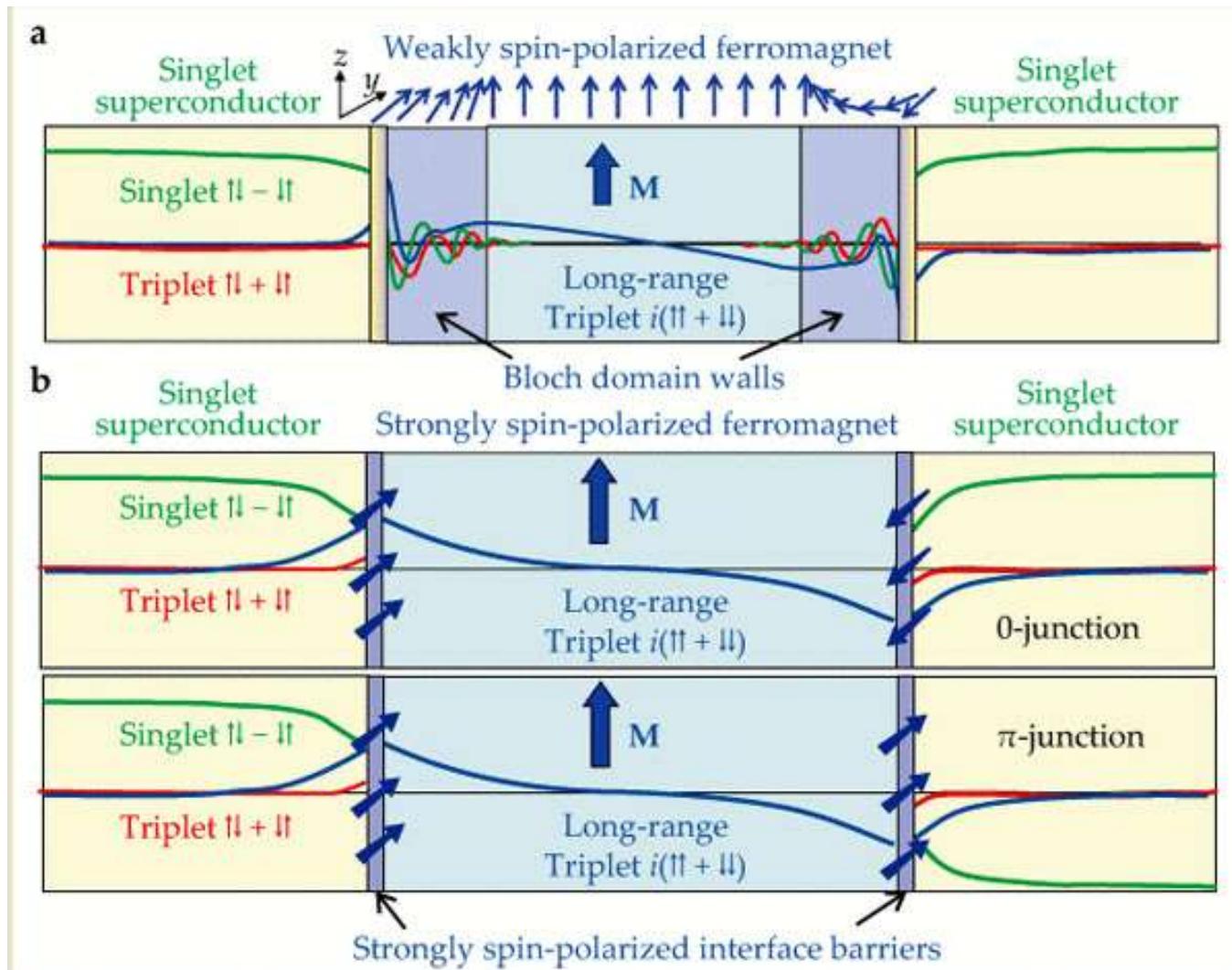
Kontos, et al, PRL (2002)

Pi Josephson junction

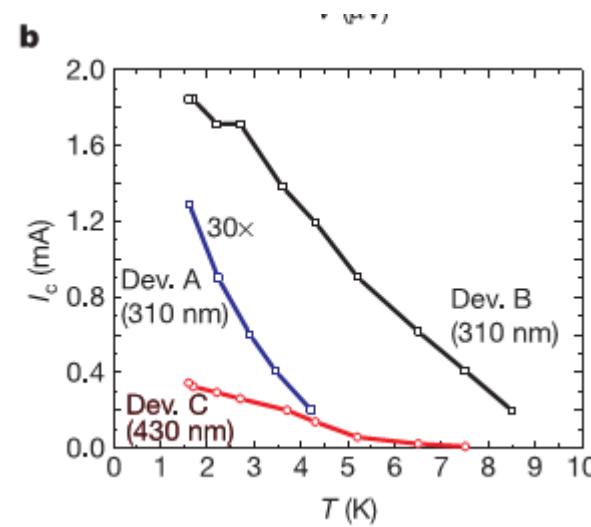
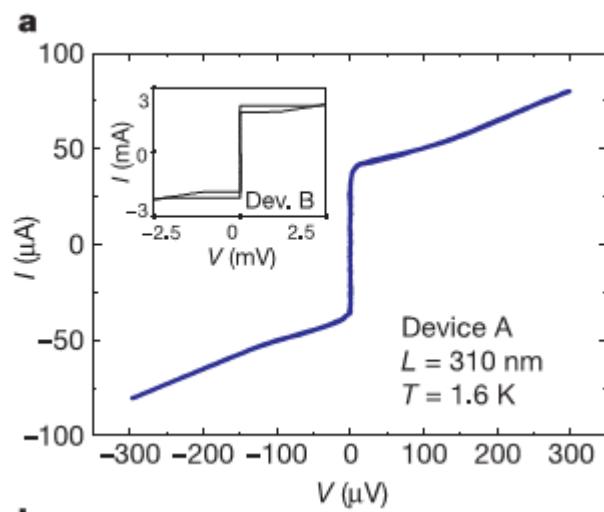
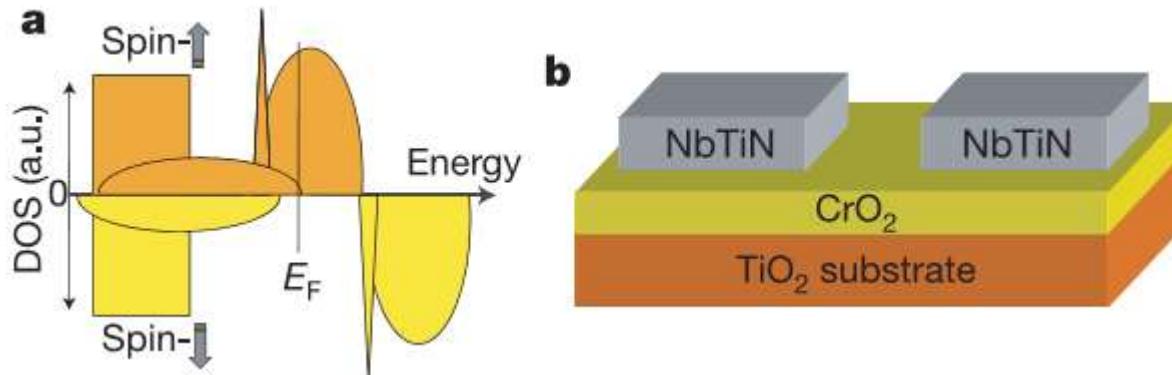


Robison, et al, PRL (2006)

Spin triplet Josephson junction

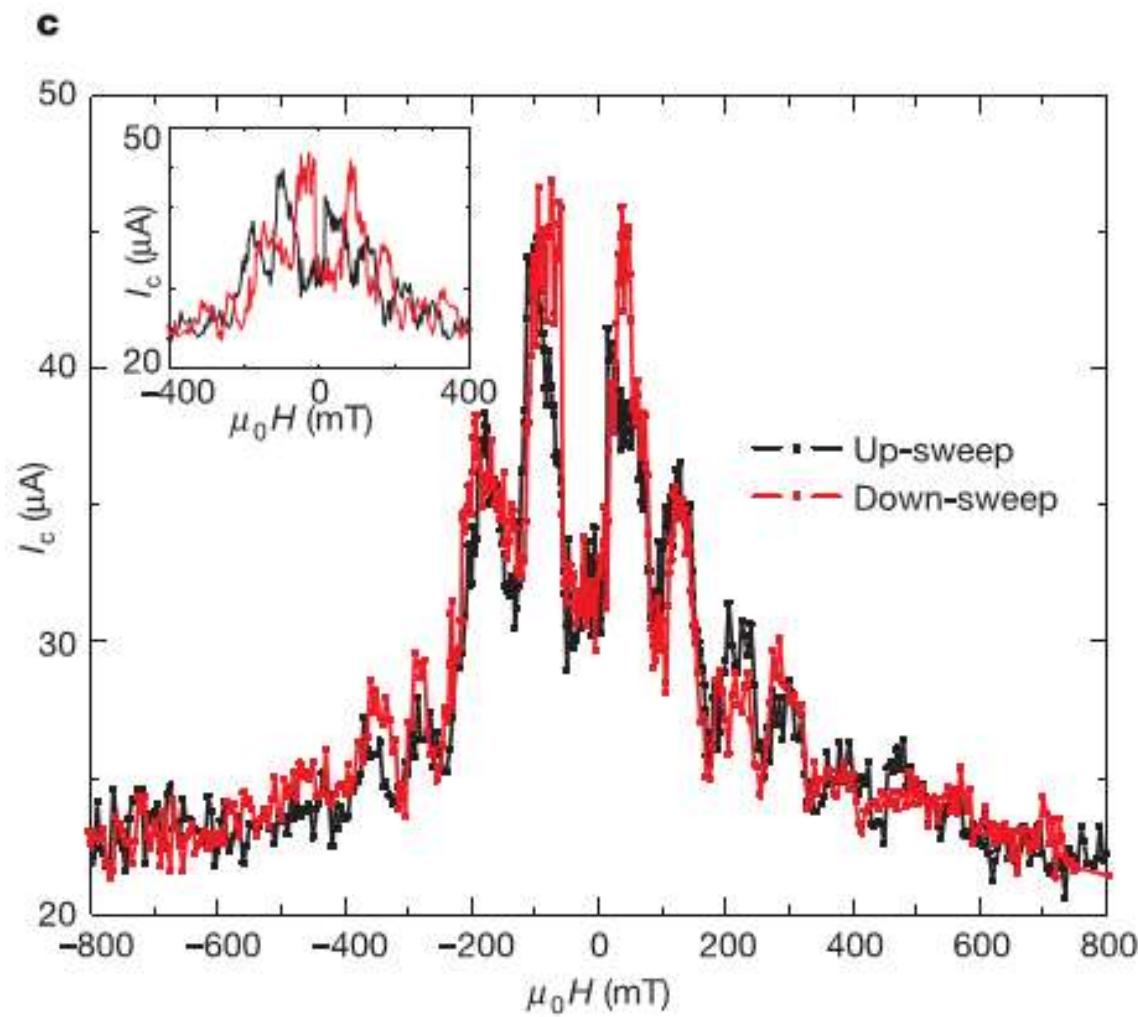


Spin triplet Josephson junction

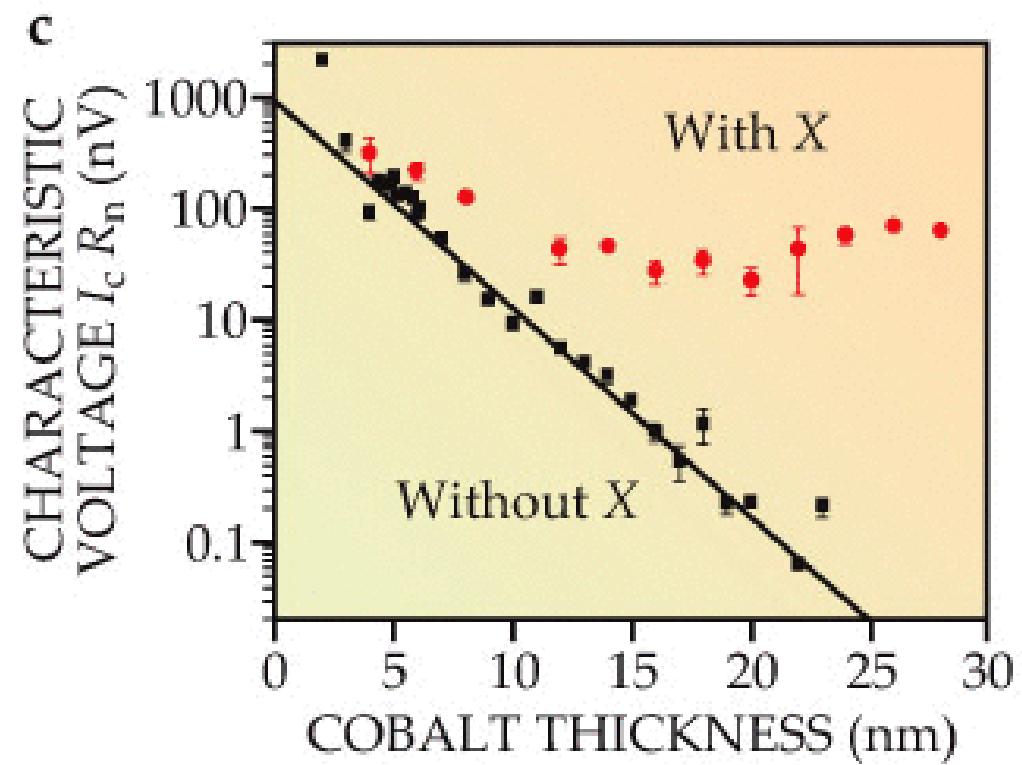
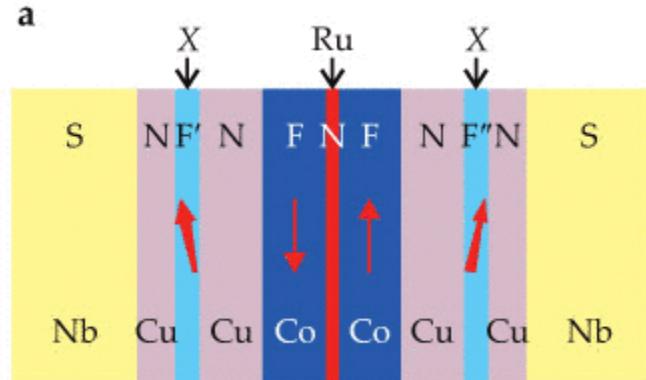


Kerizer, et al, Nature (2006)

Spin triplet Josephson junction

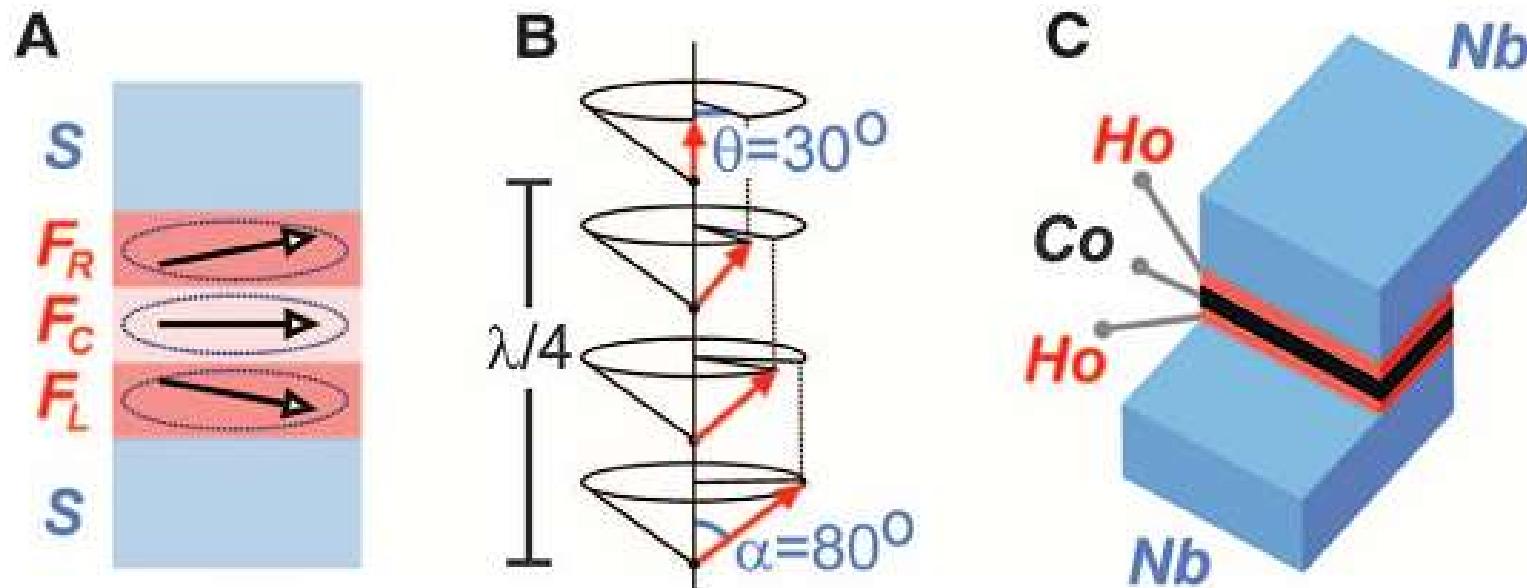


Spin triplet Josephson junction



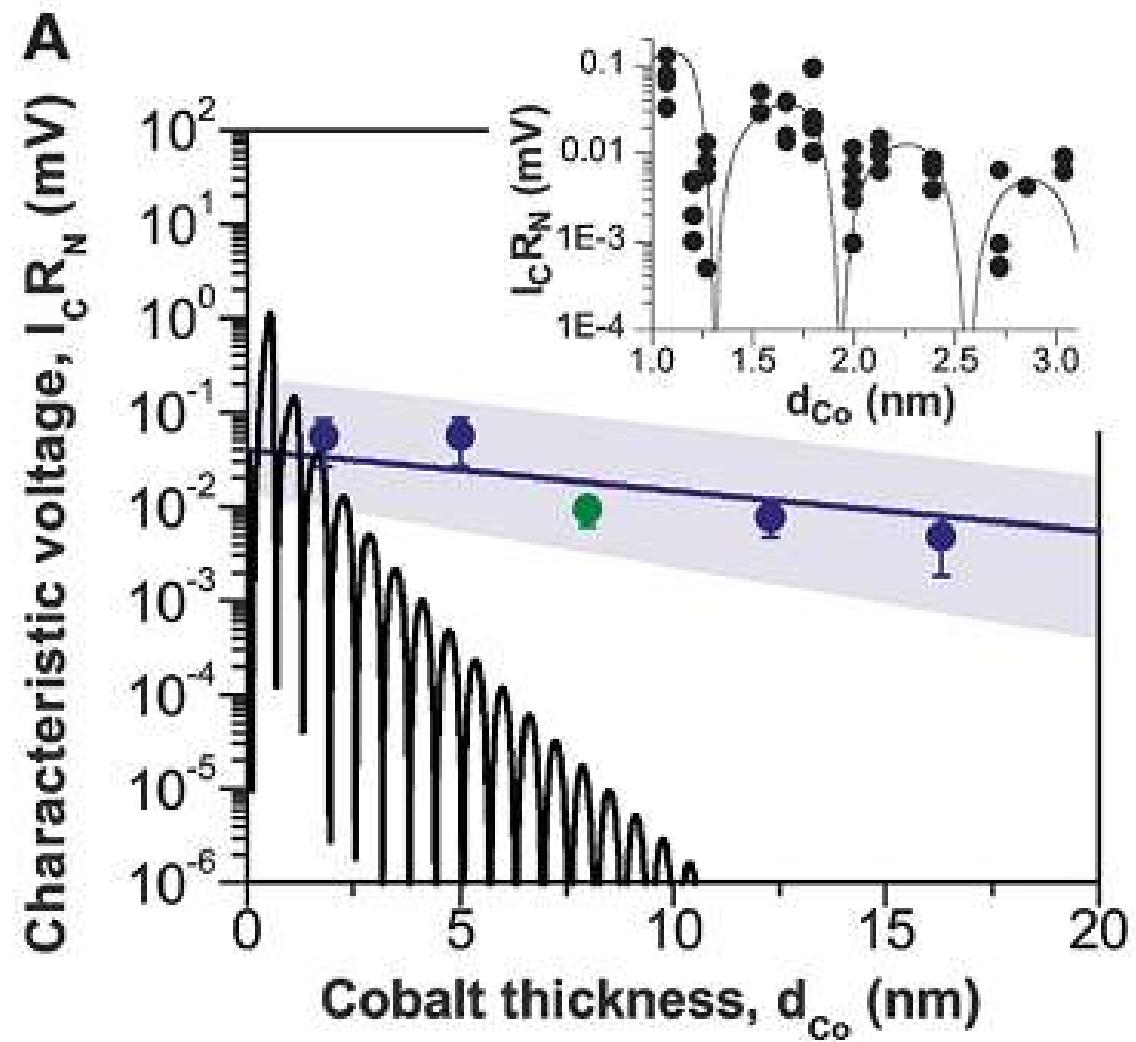
Khaire, et al, PRL (2010)

Spin triplet Josephson junction

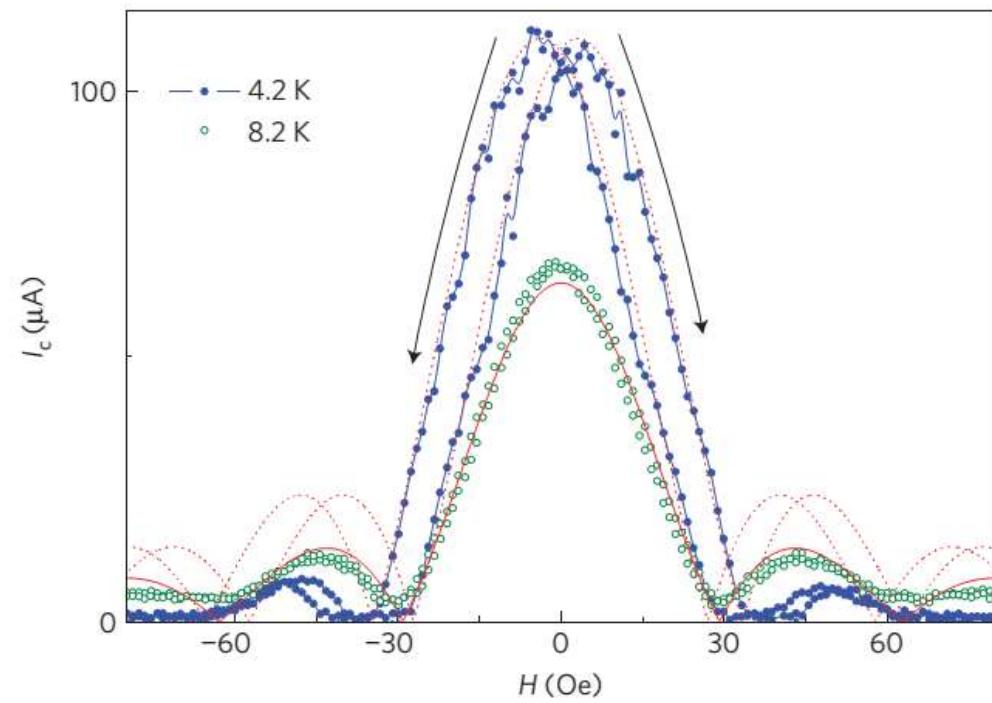
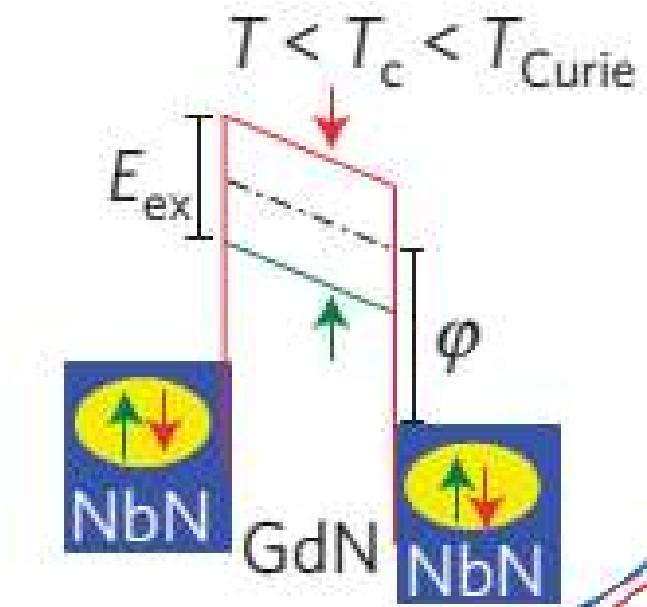


Robinson, et al, Science (2010)

Spin triplet Josephson junction

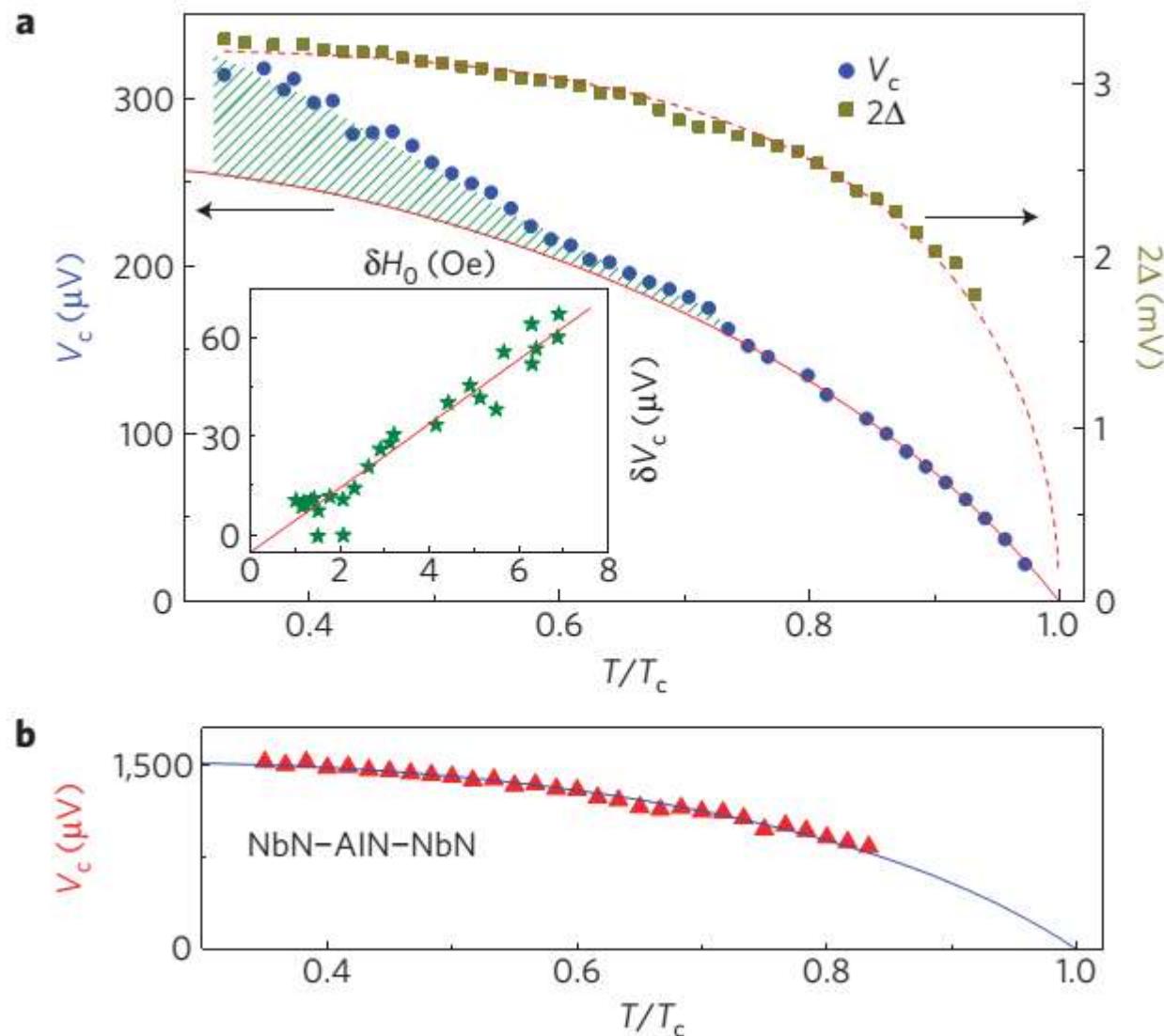


Spin filter Josephson junction



Senapati, et al, Nature Materials (2011)

Spin filter Josephson junction



Spin injection into Superconductor

Spin Imbalance and Magnetoresistance in Ferromagnet/Superconductor/Ferromagnet Double Tunnel Junctions

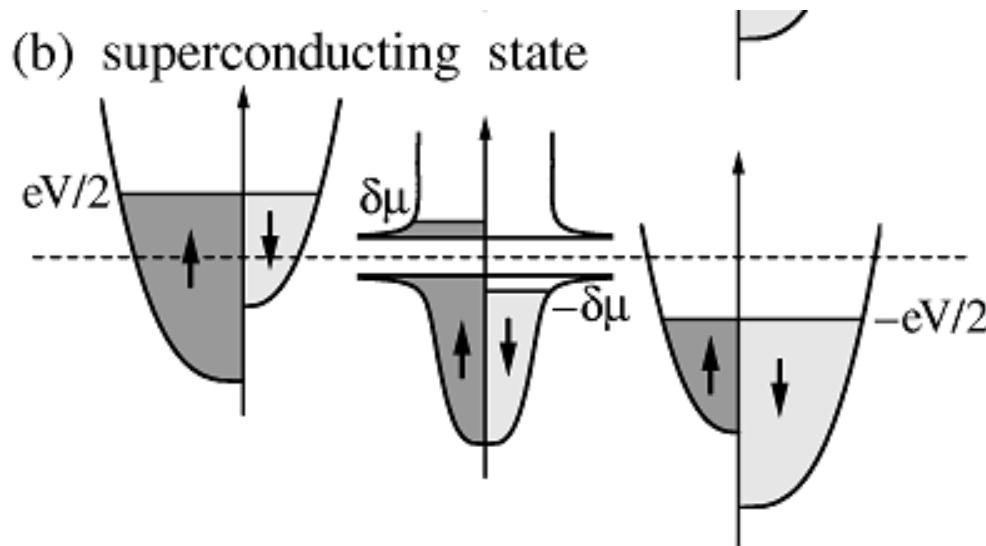
S. Takahashi,¹ H. Imamura,² and S. Maekawa¹

¹*Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*

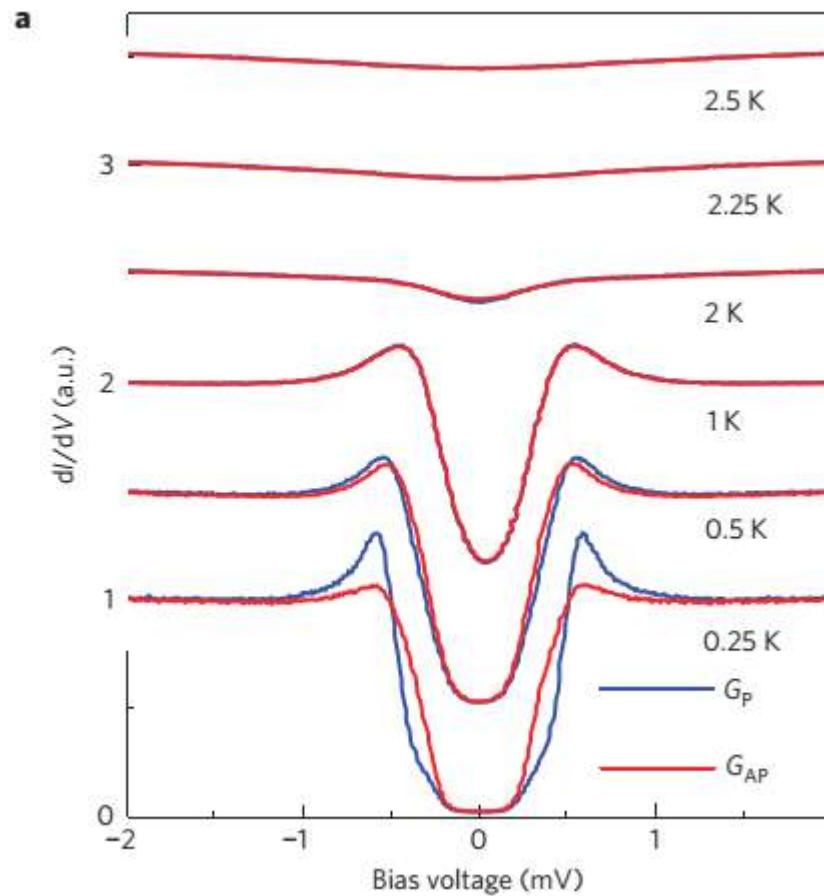
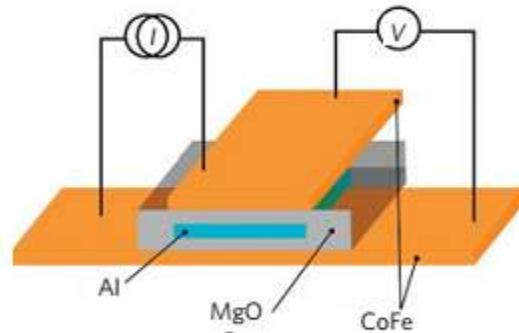
²*CREST and Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*

(Received 22 January 1999)

We theoretically study the spin-dependent transport in a ferromagnet/superconductor/ferromagnet double tunnel junction. The tunneling current in the antiferromagnetic alignment of the magnetizations gives rise to a spin imbalance in the superconductor. The resulting nonequilibrium spin density strongly suppresses the superconductivity with increase of bias voltage and destroys it at a critical voltage V_c . The results provide a new method not only for measuring the spin polarization of ferromagnets but also for controlling superconductivity and tunnel magnetoresistance by applying a bias voltage.

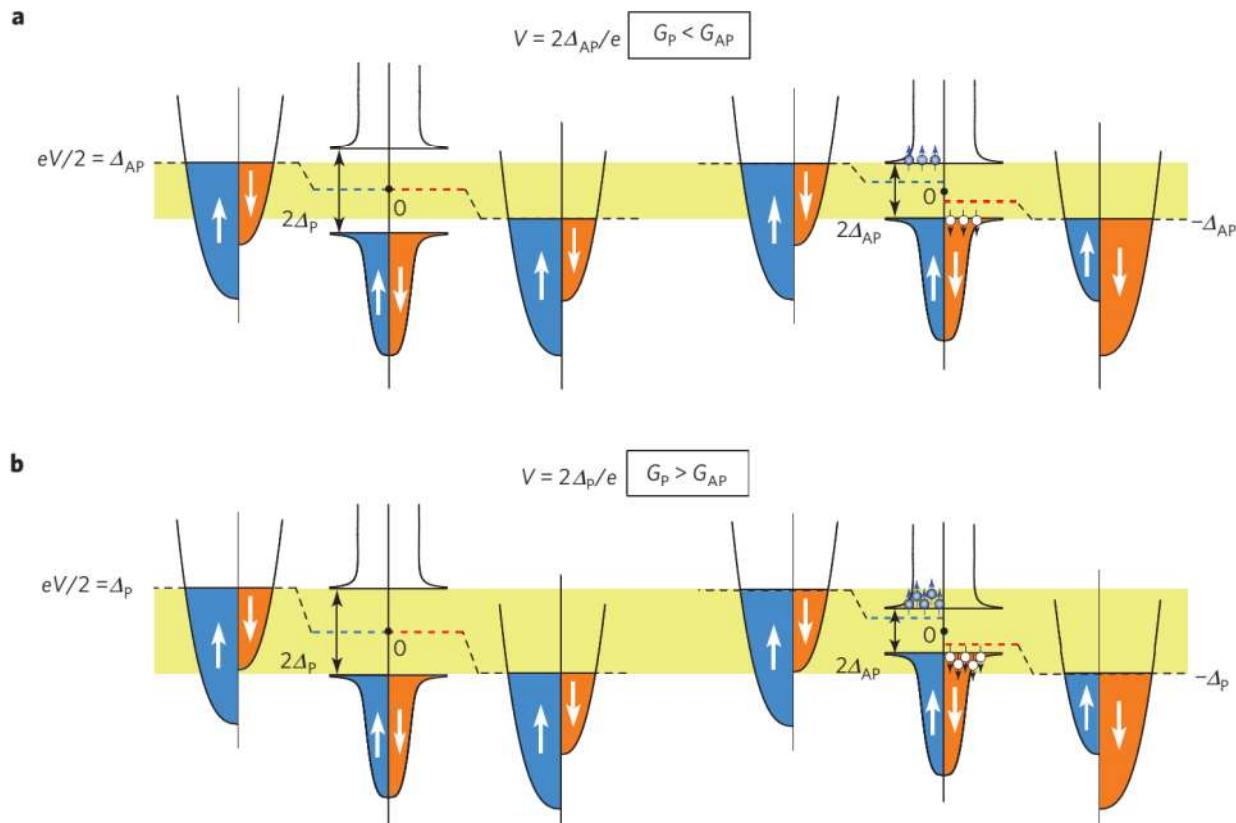


Spin injection into Superconductor



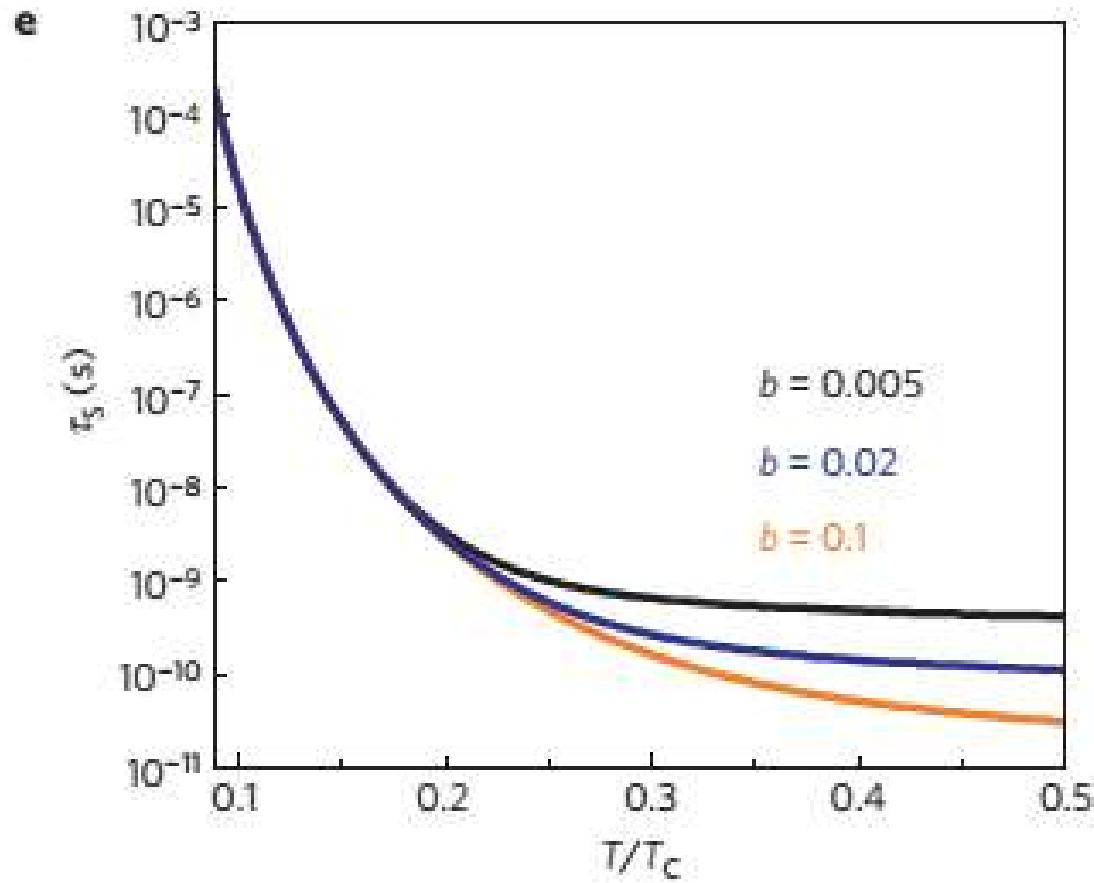
Yang, et al, Nature Materials (2010)

Spin injection into Superconductor

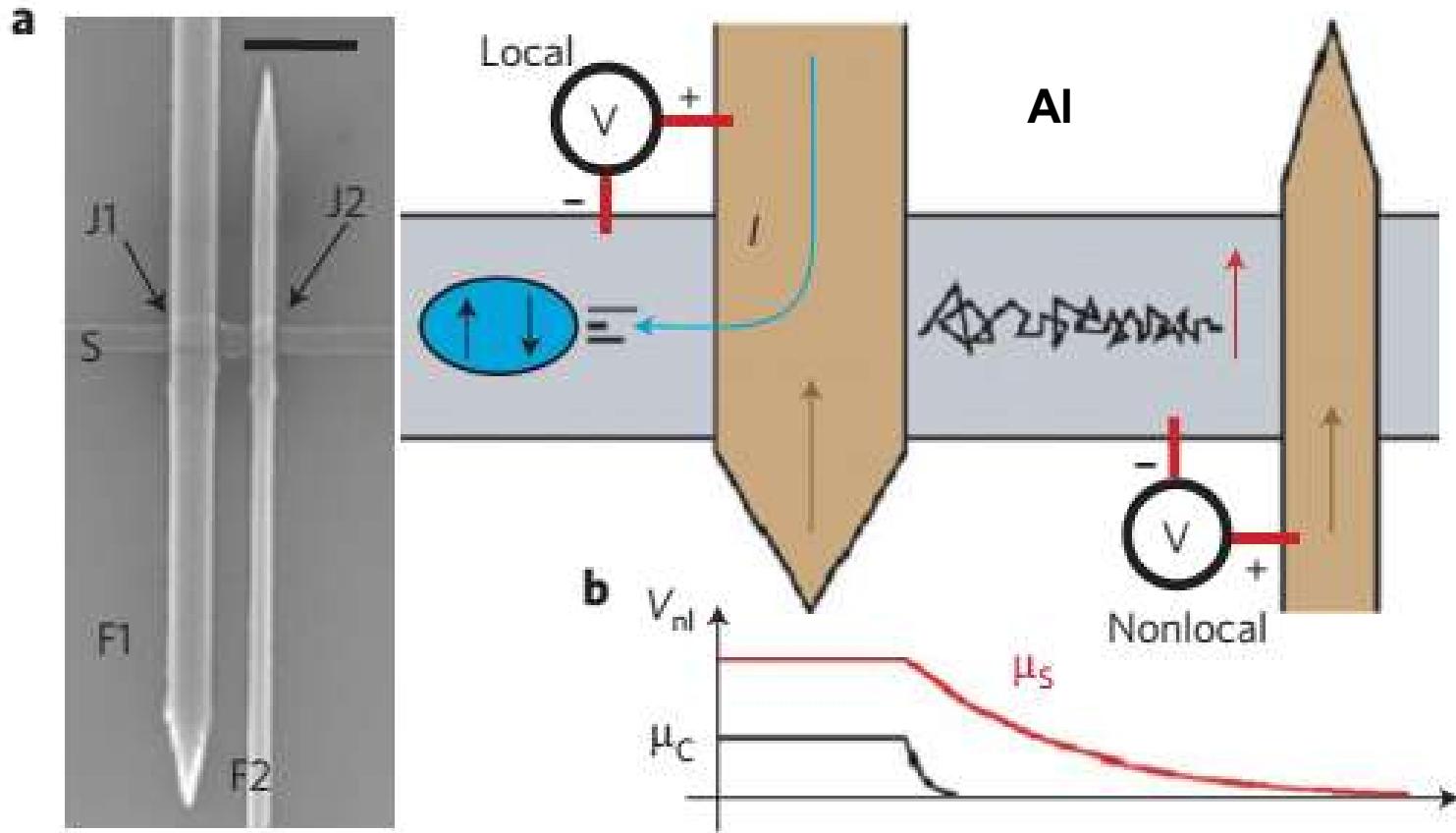


Spin injection into Superconductor

Long spin lifetime



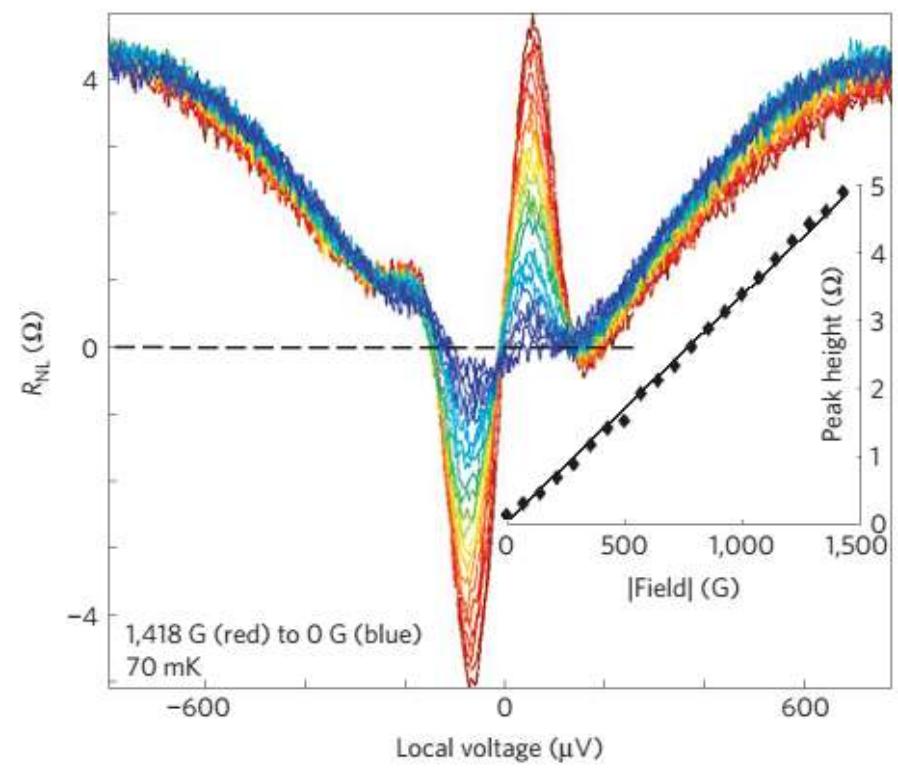
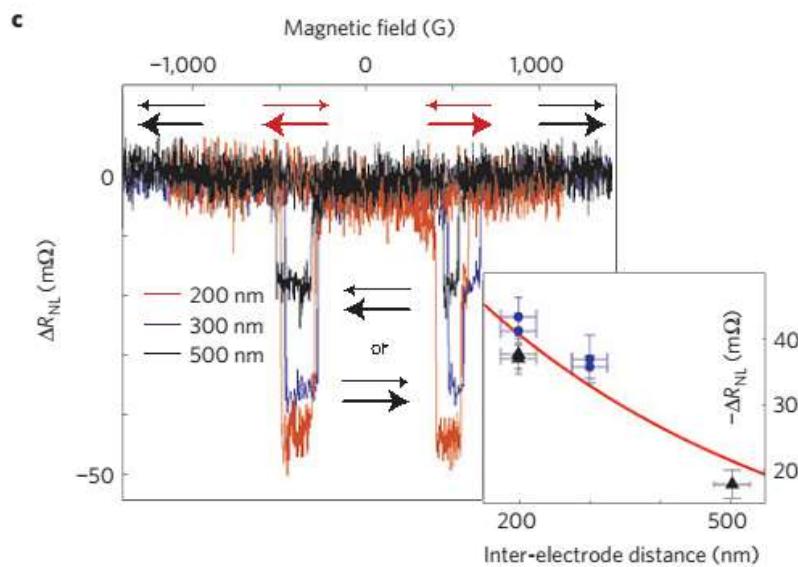
Spin injection into Superconductor



Quay, et al, Nature Physics (2013)

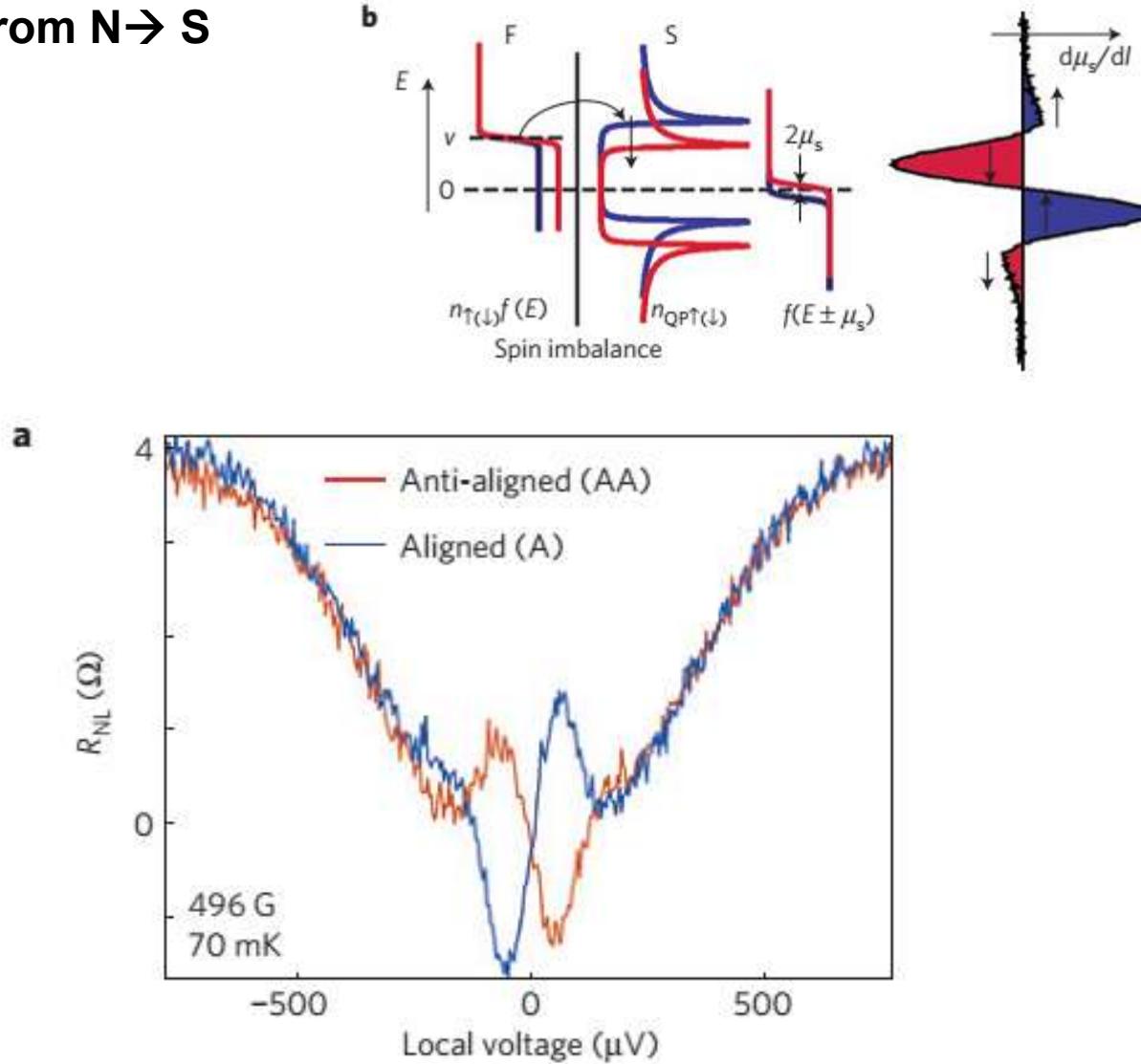
Spin injection into Superconductor

Transition from N \rightarrow S



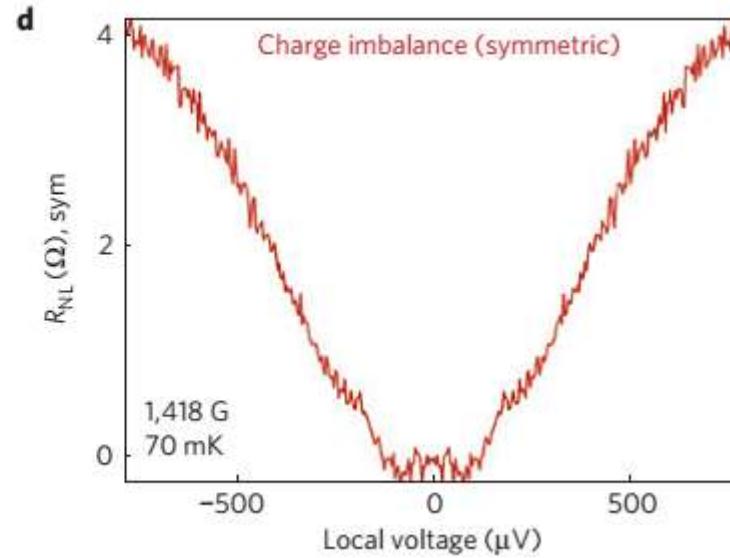
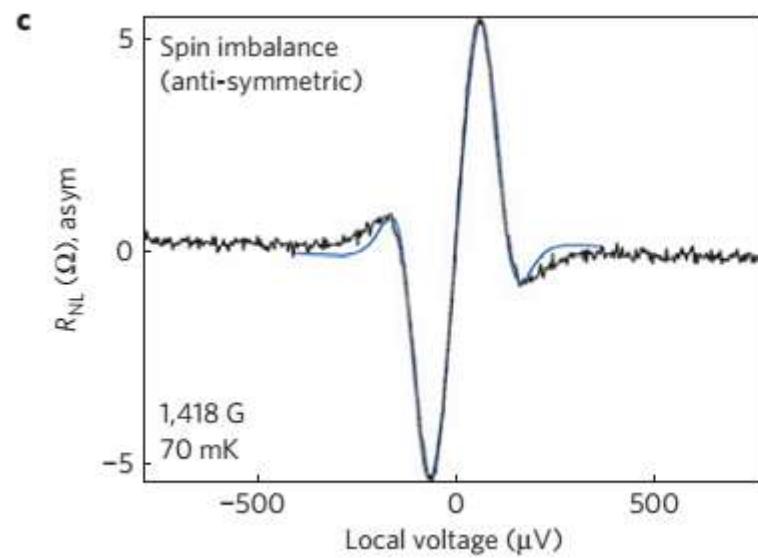
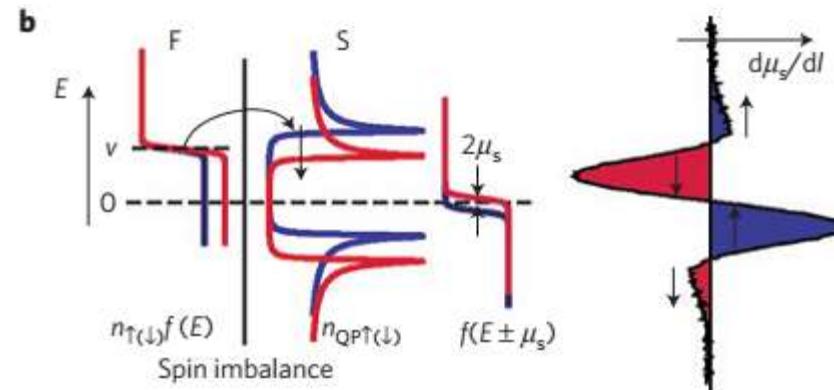
Spin injection into Superconductor

Transition from N \rightarrow S



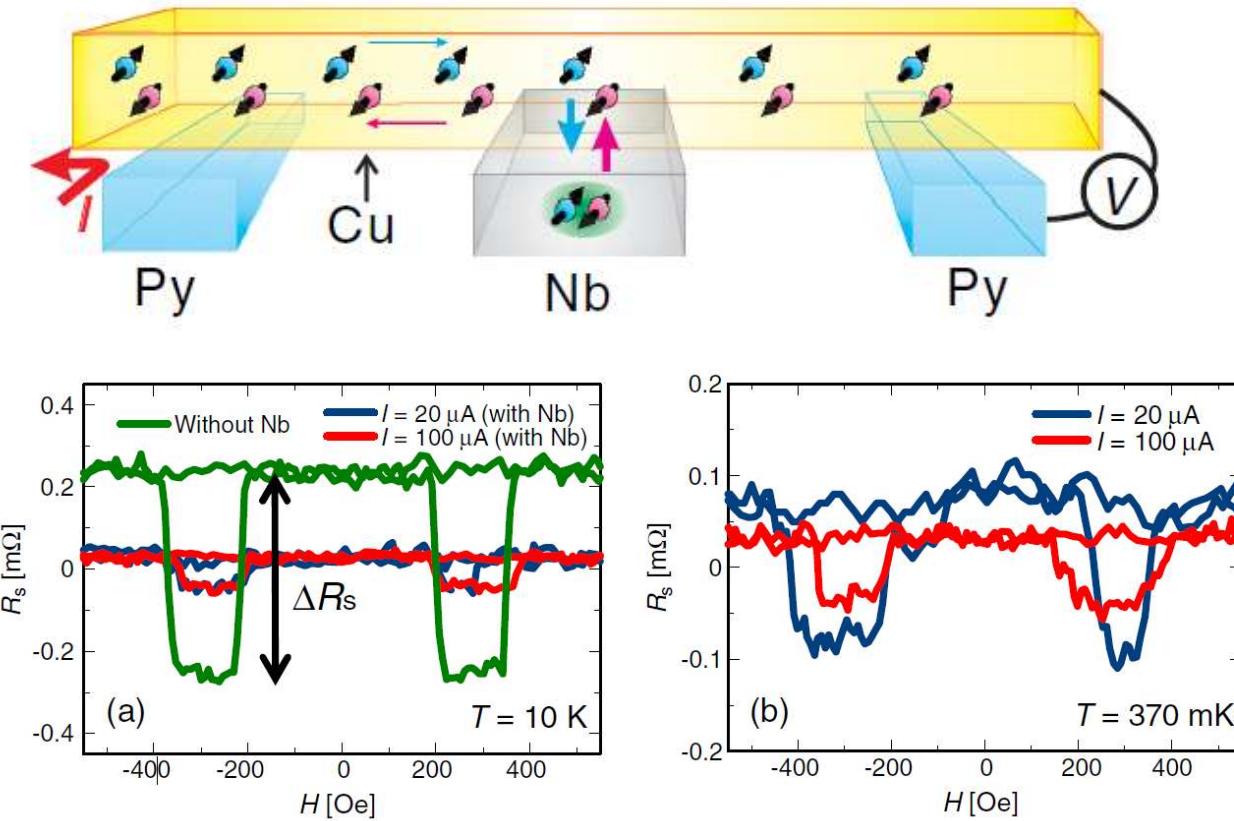
Spin injection into Superconductor

Transition from N \rightarrow S



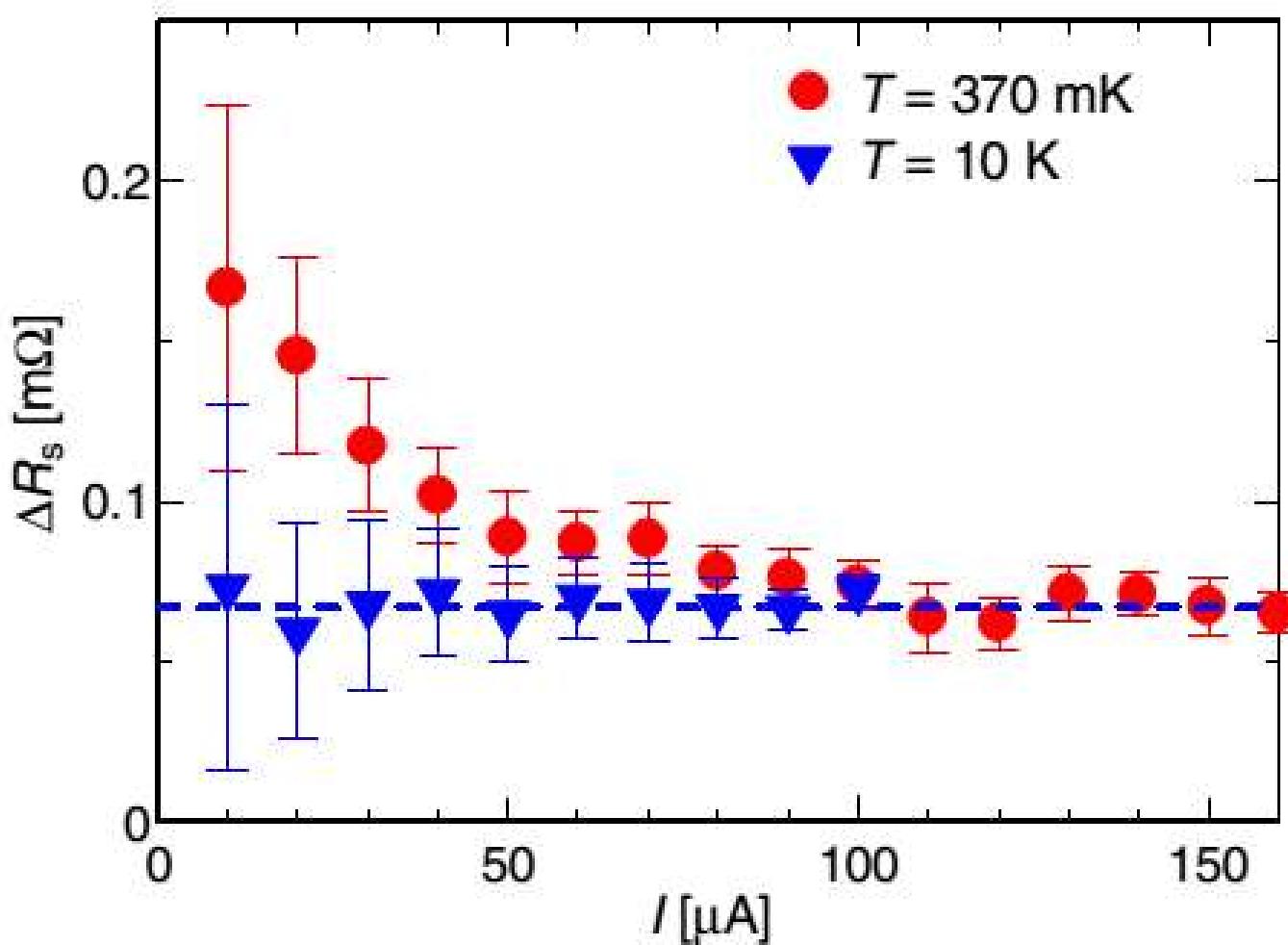
Spin injection into Superconductor

Spin absorption by Nb

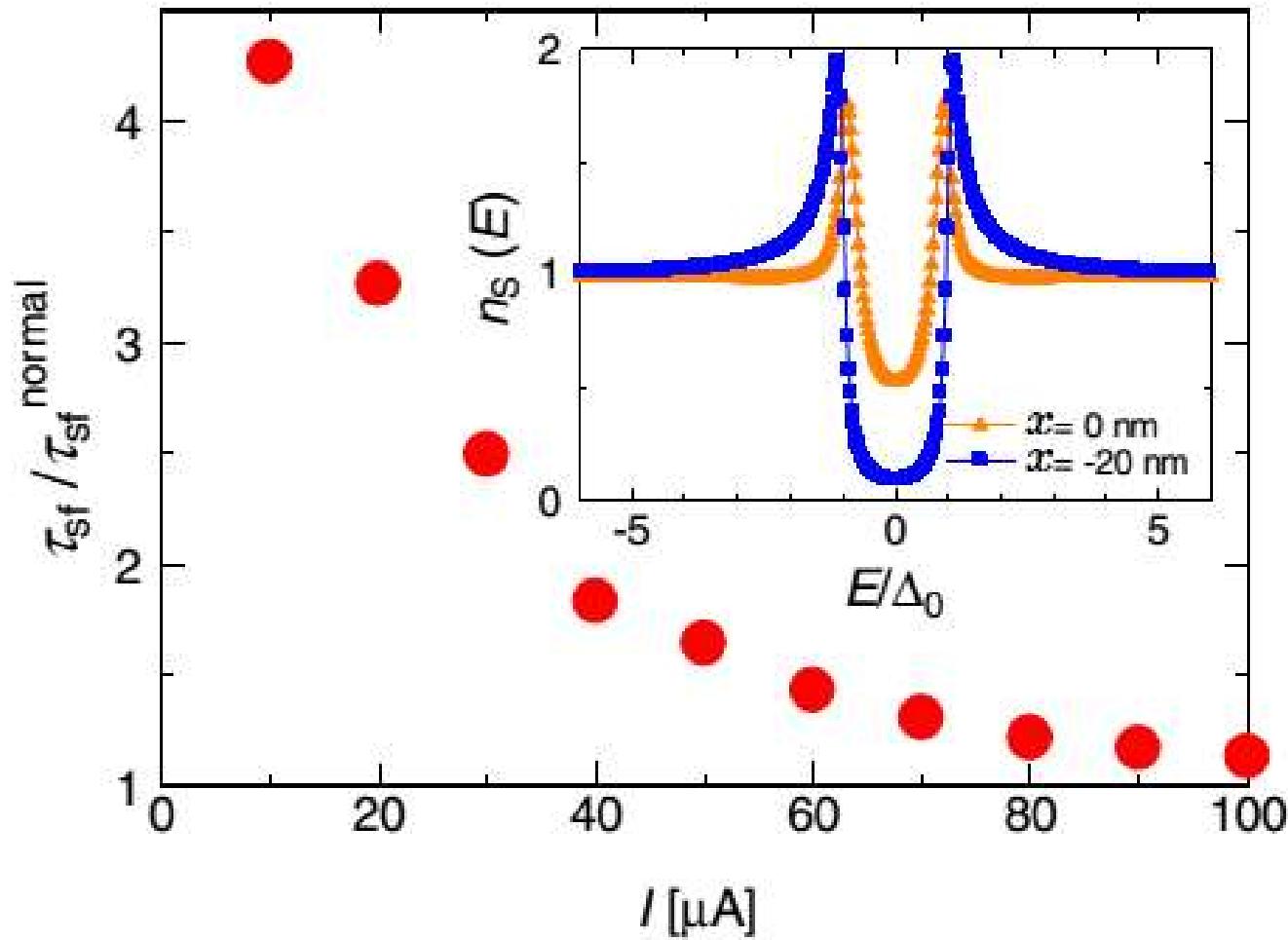


Wakamura, et al, PRL (2014)

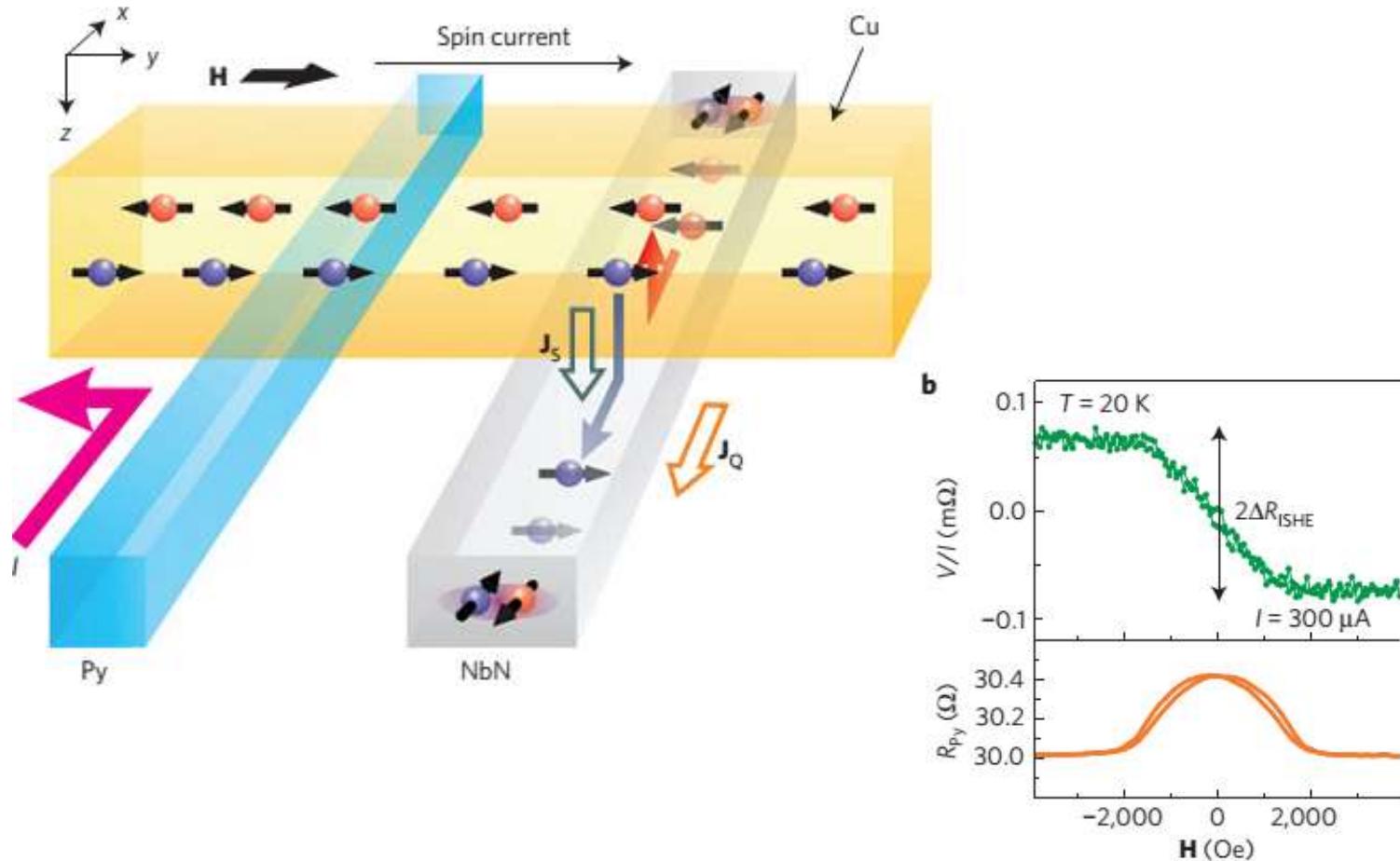
Spin injection into Superconductor



Spin injection into Superconductor

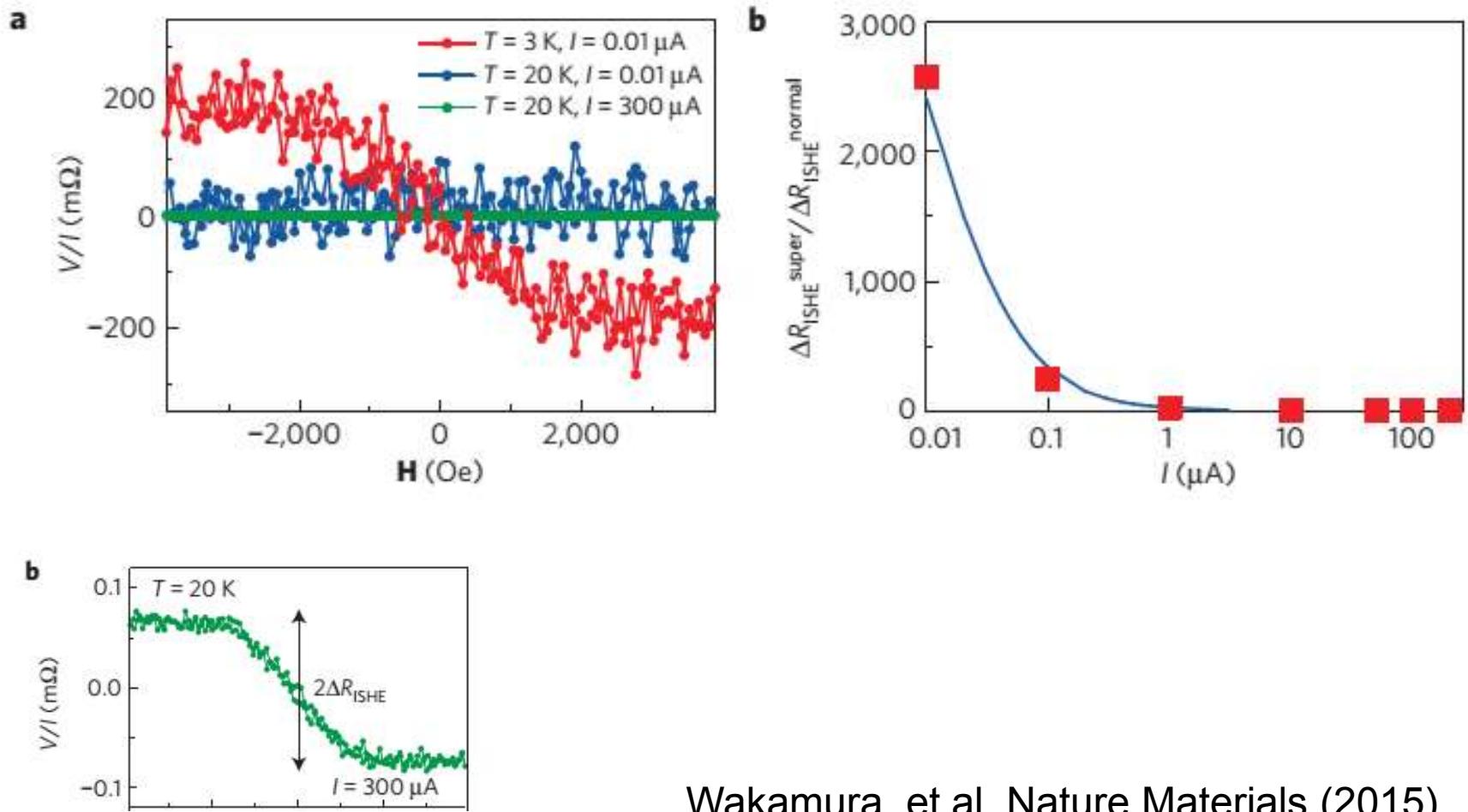


Spin Hall in Superconductor



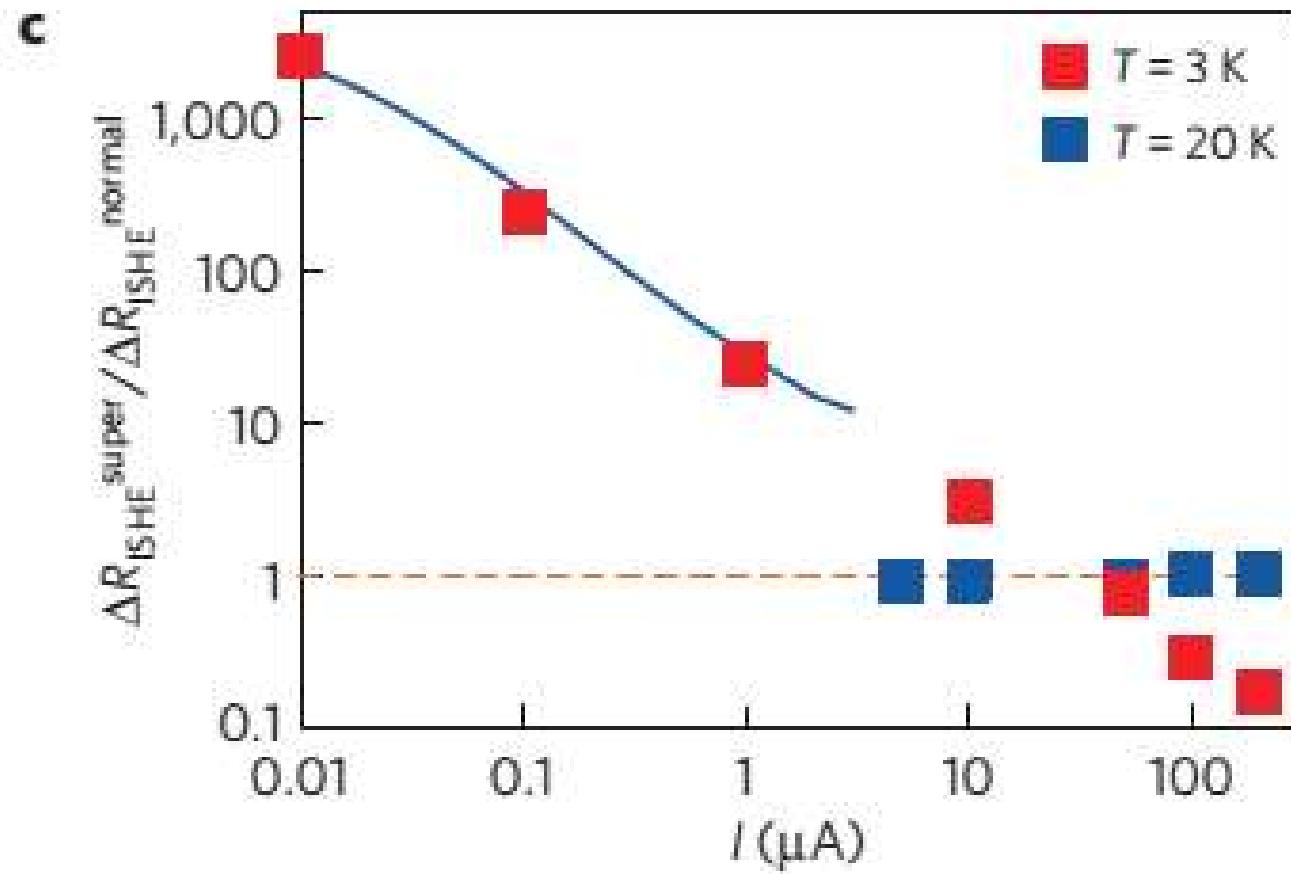
Wakamura, et al, Nature Materials (2015)

Spin Hall in Superconductor



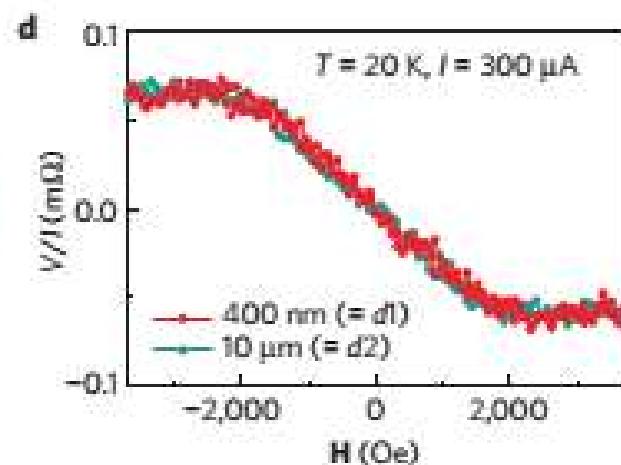
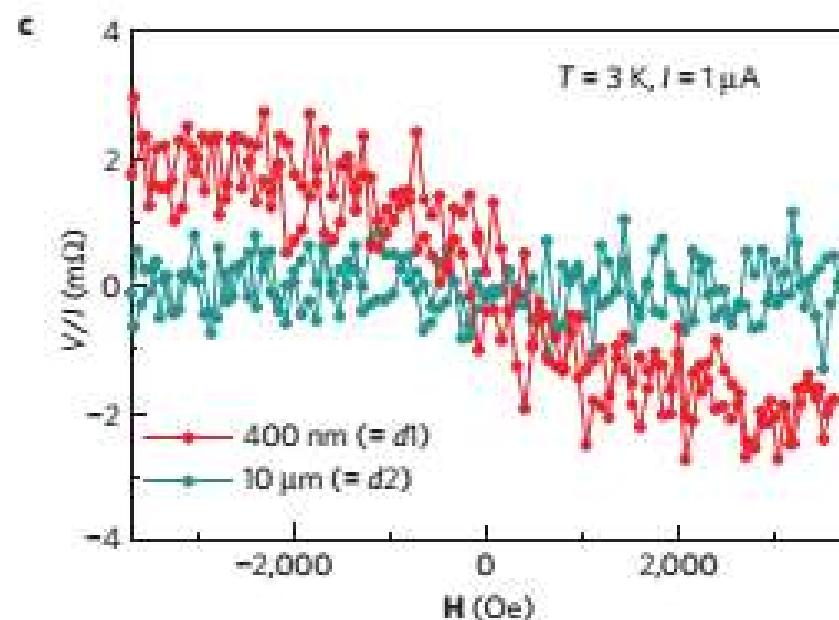
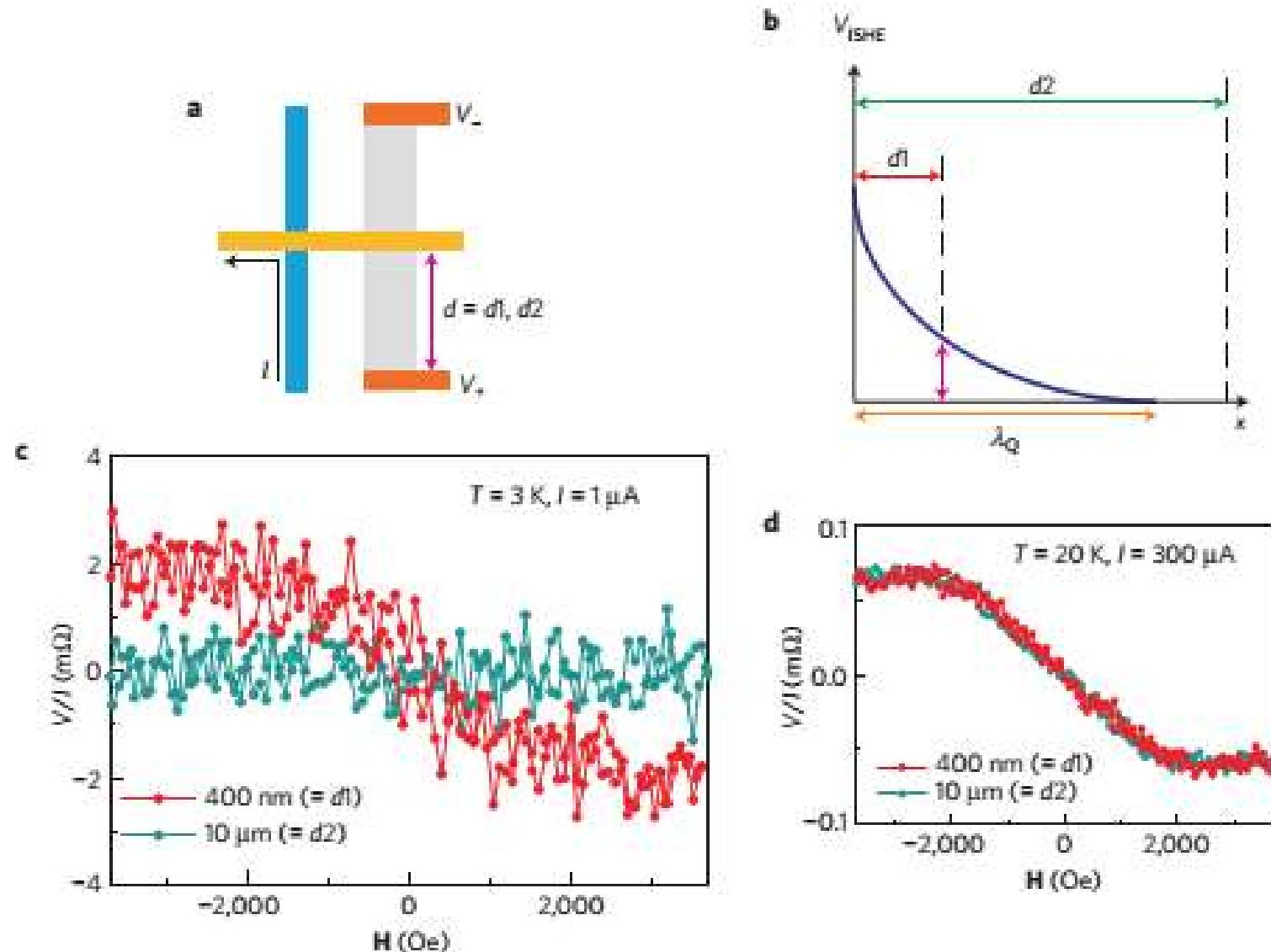
Wakamura, et al, Nature Materials (2015)

Spin Hall in Superconductor



Wakamura, et al, Nature Materials (2015)

Spin Hall in Superconductor



Review of this class

1. Metal Spin Valves

Local and Nonlocal spin valves

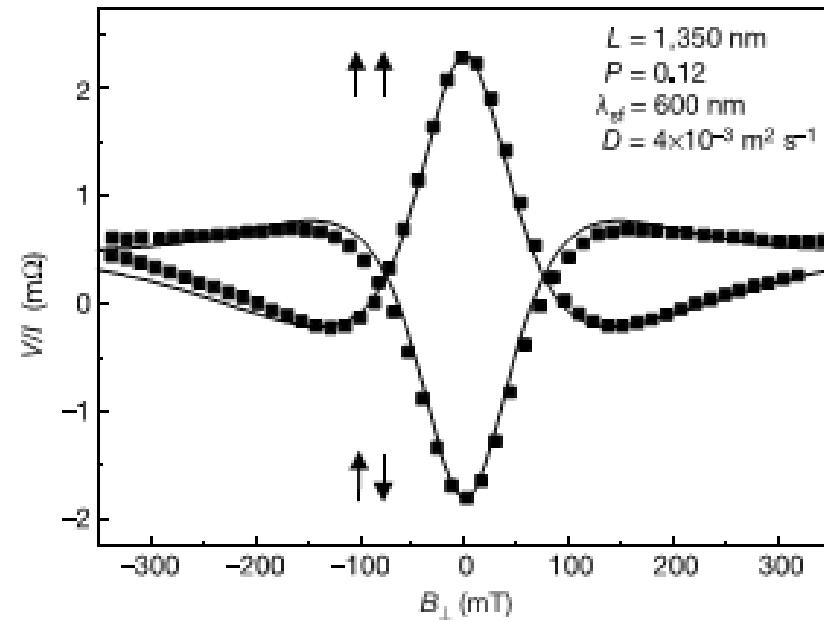
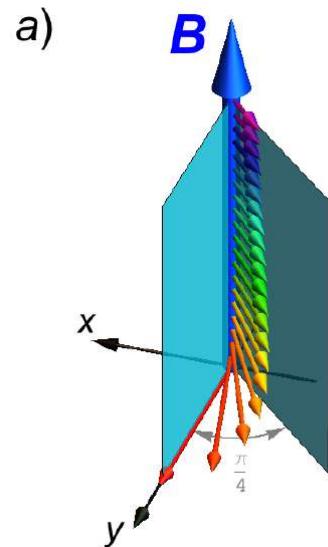
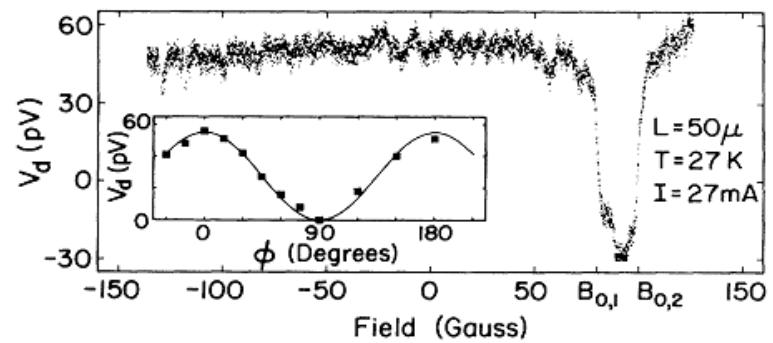
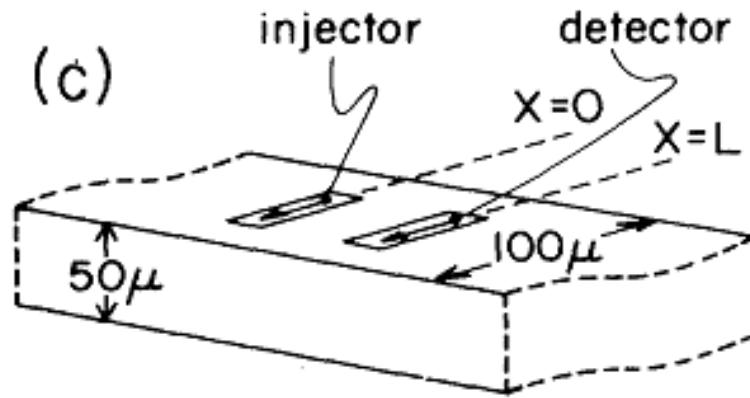
Hanle spin precession

Nano devices (Thanks to cleanroom)

Spin injection efficiency

Spin relaxation in Metals: EY mechanism

Review of this class



Review of this class

Spin Injection efficiency

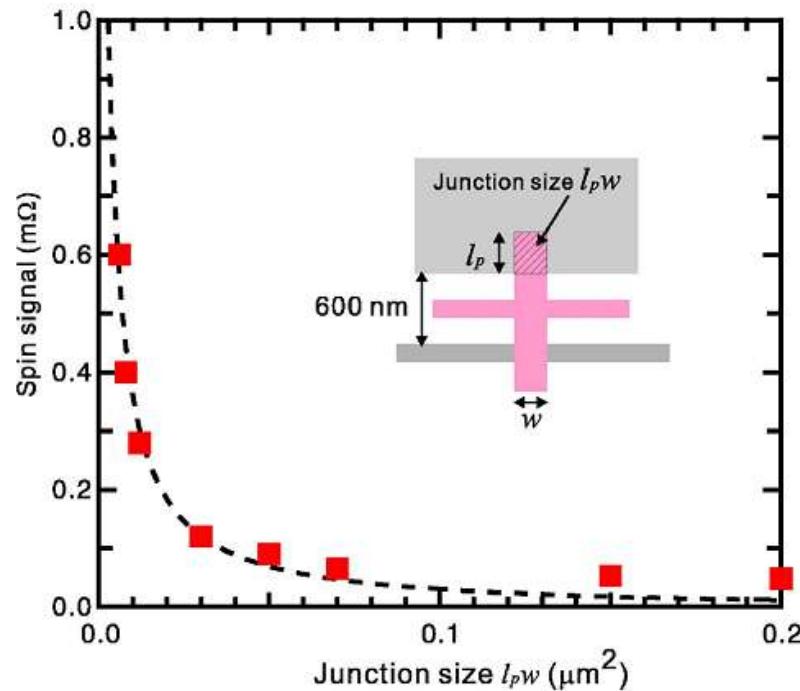
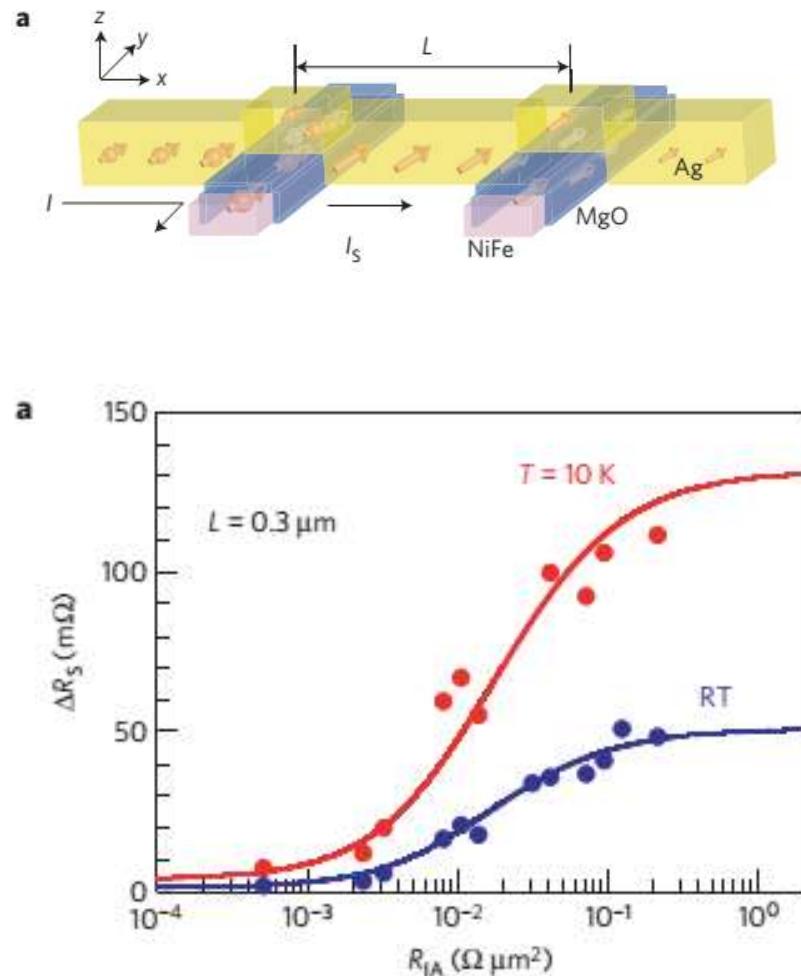


FIG. 4. (Color online) Spin signal in the NLSV measurement as a function of the junction size $l_p w$. The dotted curve is the best fitting to the data points using Eq. (2).



Review of this class

2. Superconductor Spin Valves

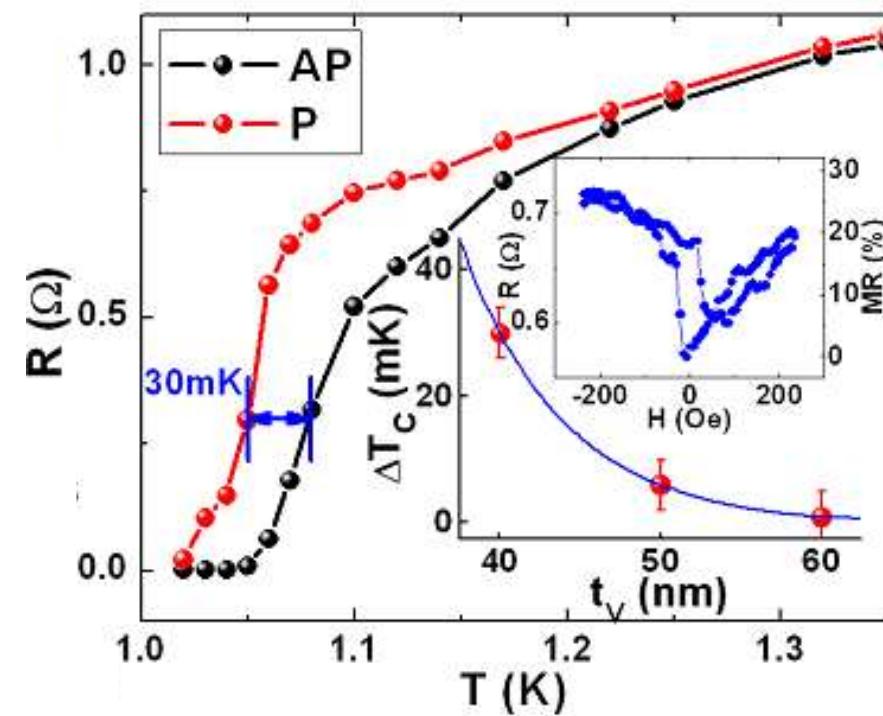
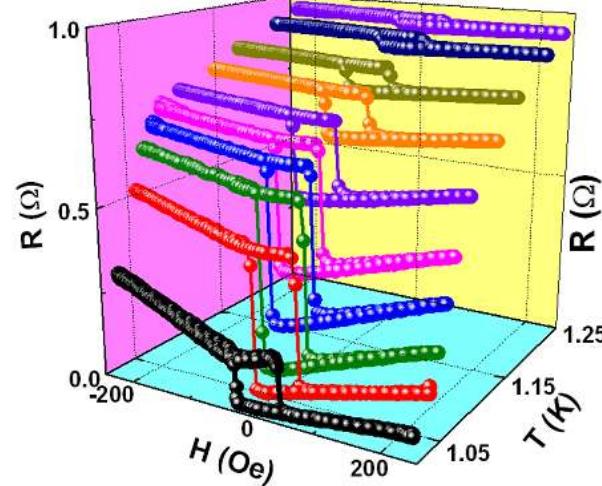
Large MR and control of T_C

Josephson junction, Spin-triplet

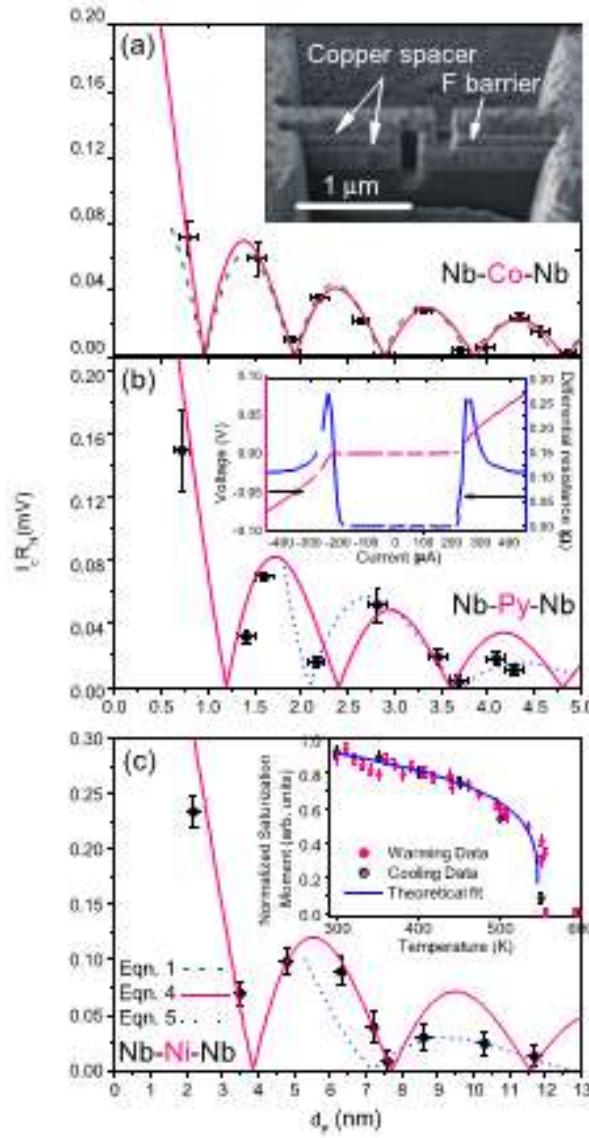
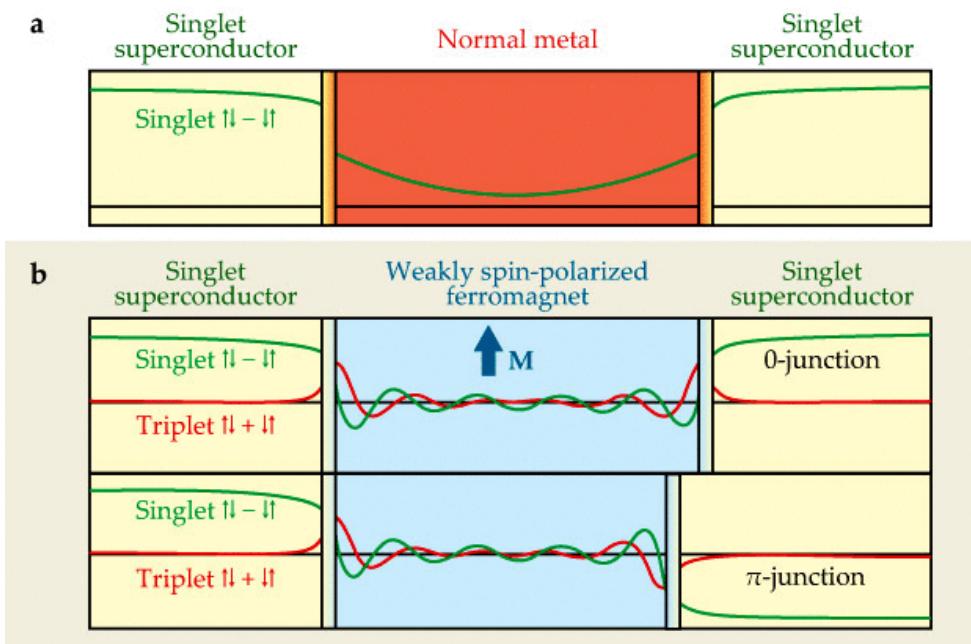
Spin injection, Long spin lifetime

Large spin Hall

Review of this class

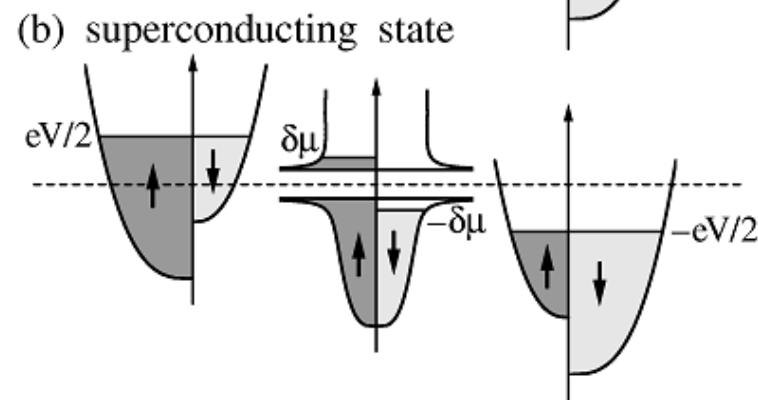


Review of this class

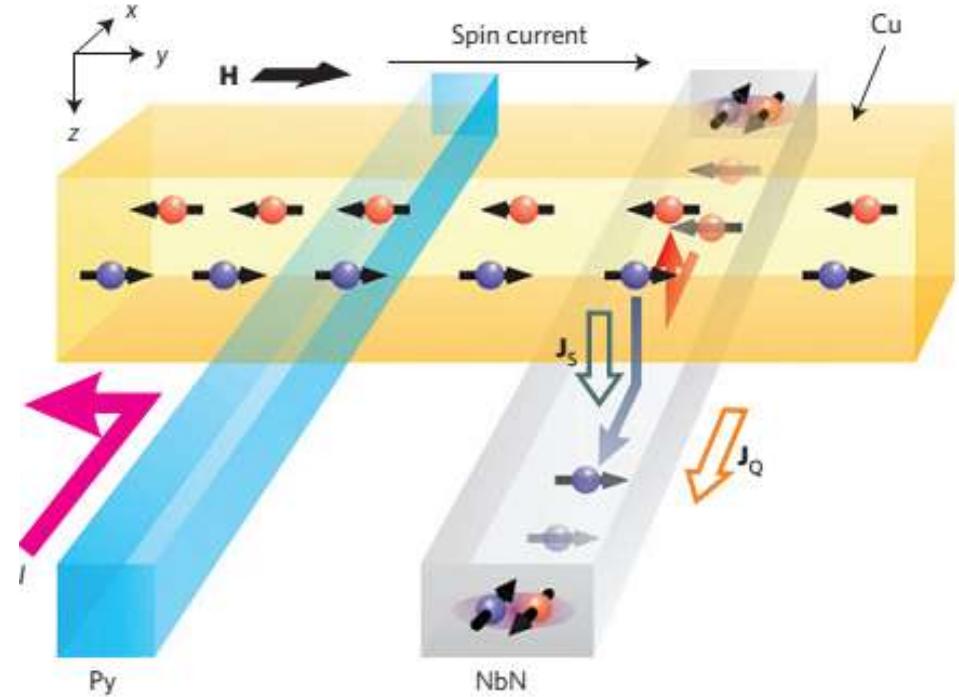


Review of this class

Spin injection



Spin Hall



下一节课: Nov. 3rd

Chapter 4: Spin Valves

3. Spin valves based on semiconductor and Quantum materials

课件下载：

<http://www.phy.pku.edu.cn/~LabSpin/teaching.html>

谢谢！