Chapter 4

Spin Valves

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2015年10月25日

Outline

1. Spin valves and spin injection

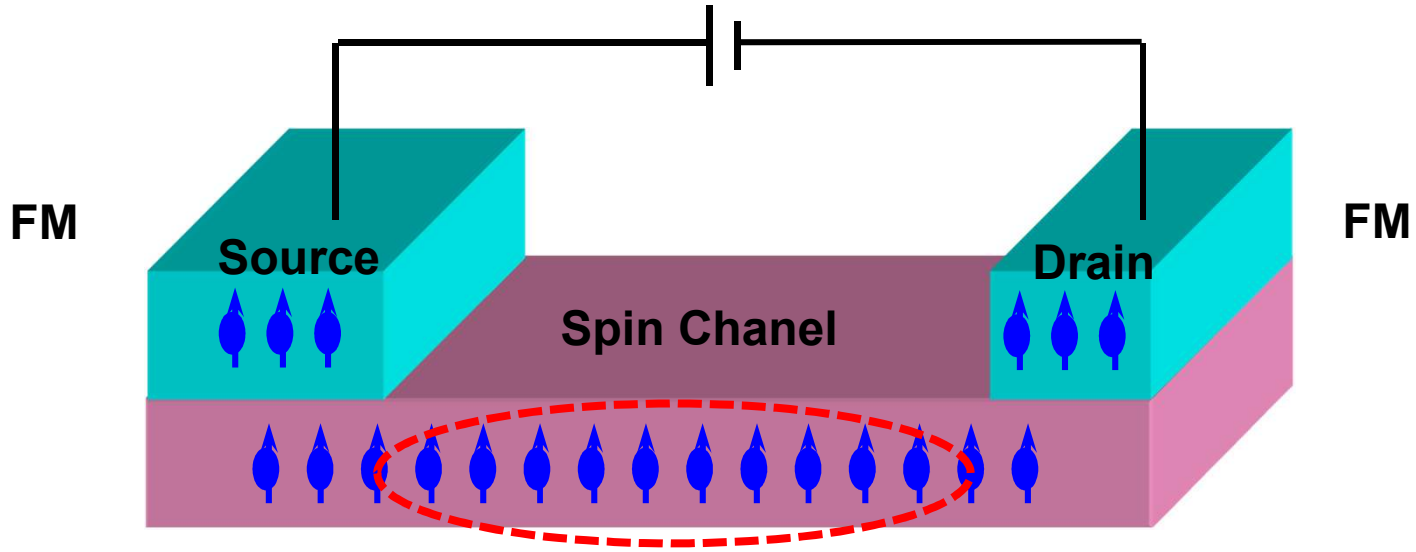
2. Spin valves based on Metal and Superconductor

3. Spin valves based on semiconductor and Quantum materials

Review of last class

Vertical Spin valves

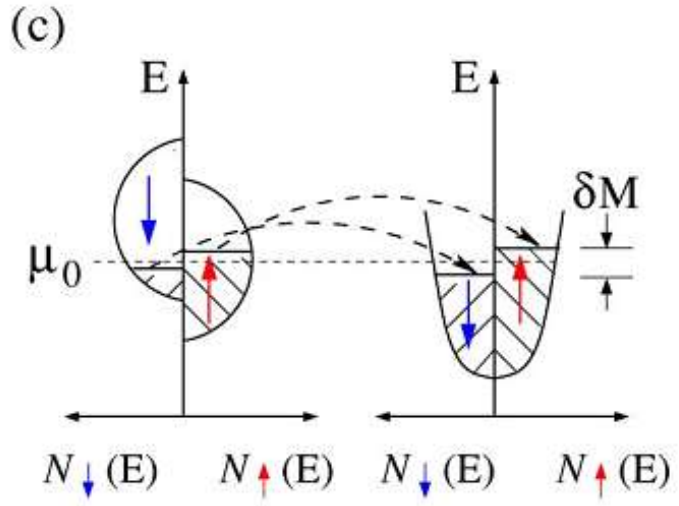
Lateral Spin valves



Spin manipulation

Spin injection

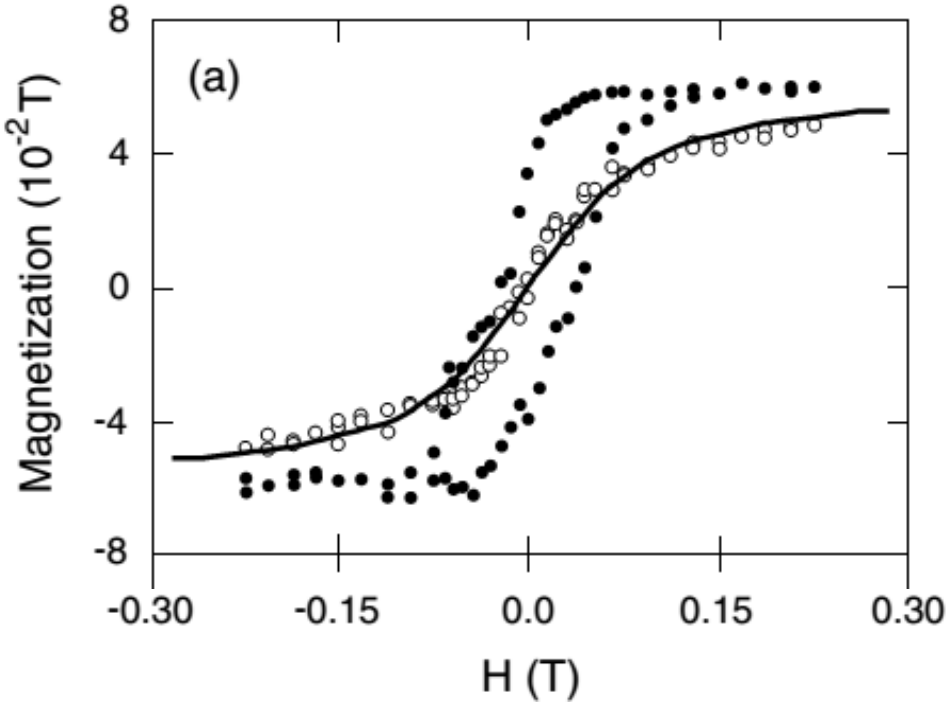
- **Electrical**



Review of last class

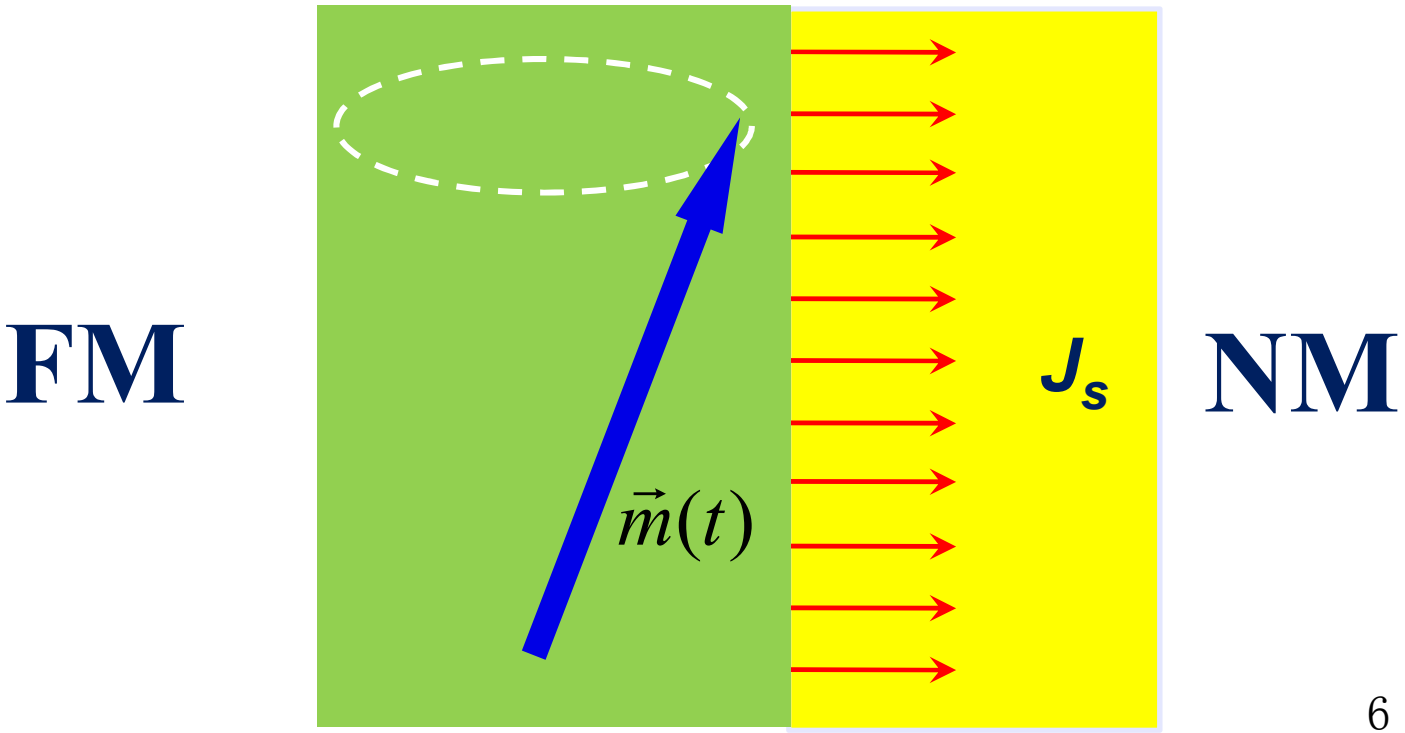
Spin injection

- **Optical**



Spin injection

- Dynamical



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

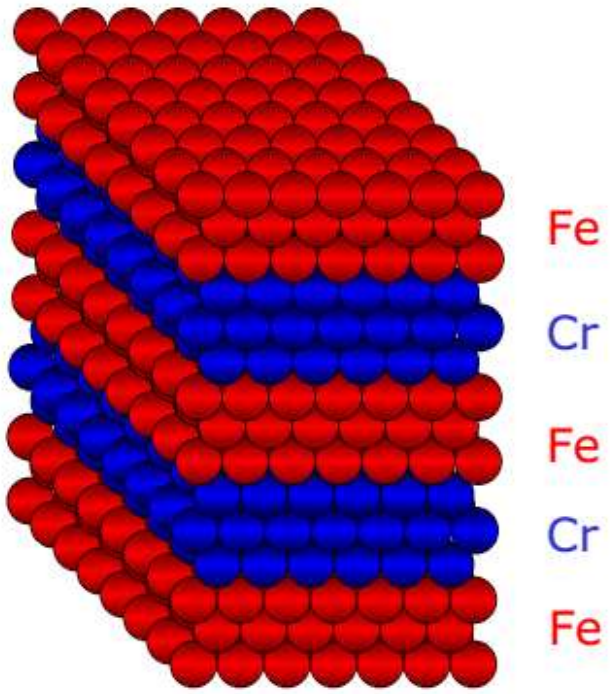
Nano devices (Thanks to cleanroom)

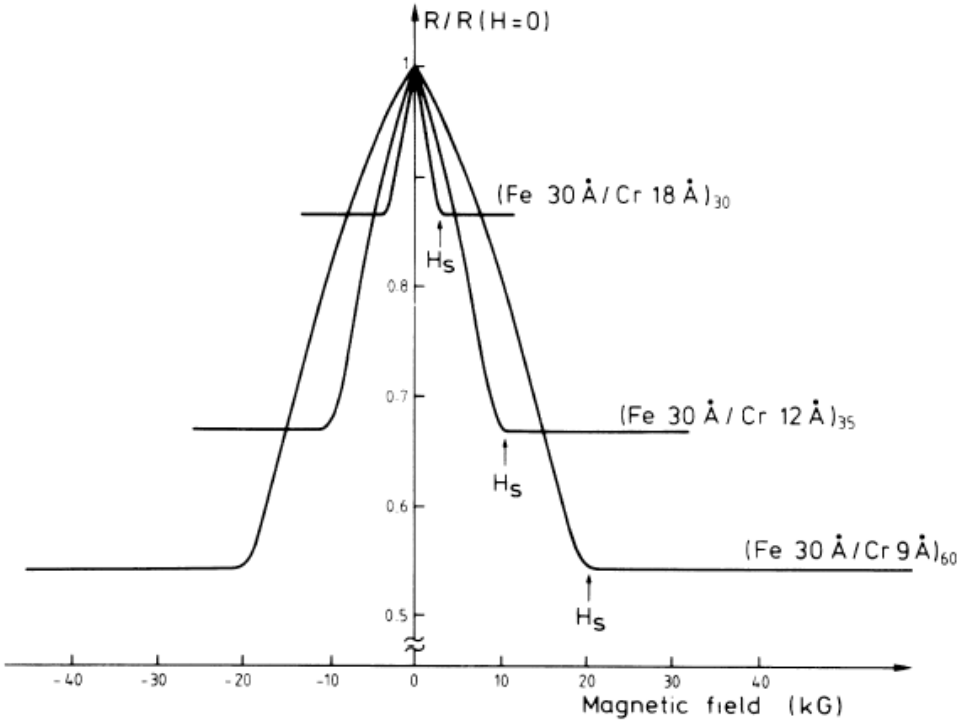
Spin injection efficiency

Spin relaxation in Metals: EY mechanism

GMR

Observation of GMR

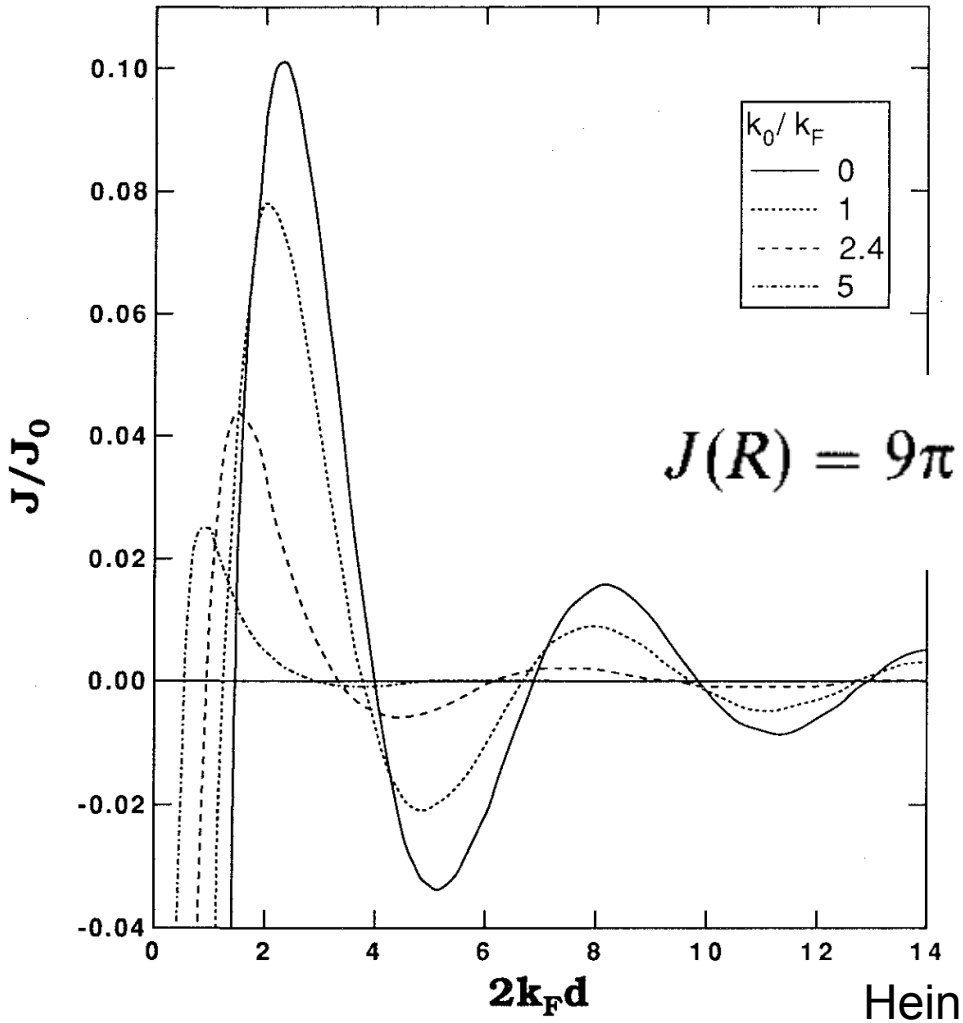




Baibich, et al, PRL (1988)
Fert, Rev. Mod. Phys. (2007)

GMR

GMR—RKKY coupling



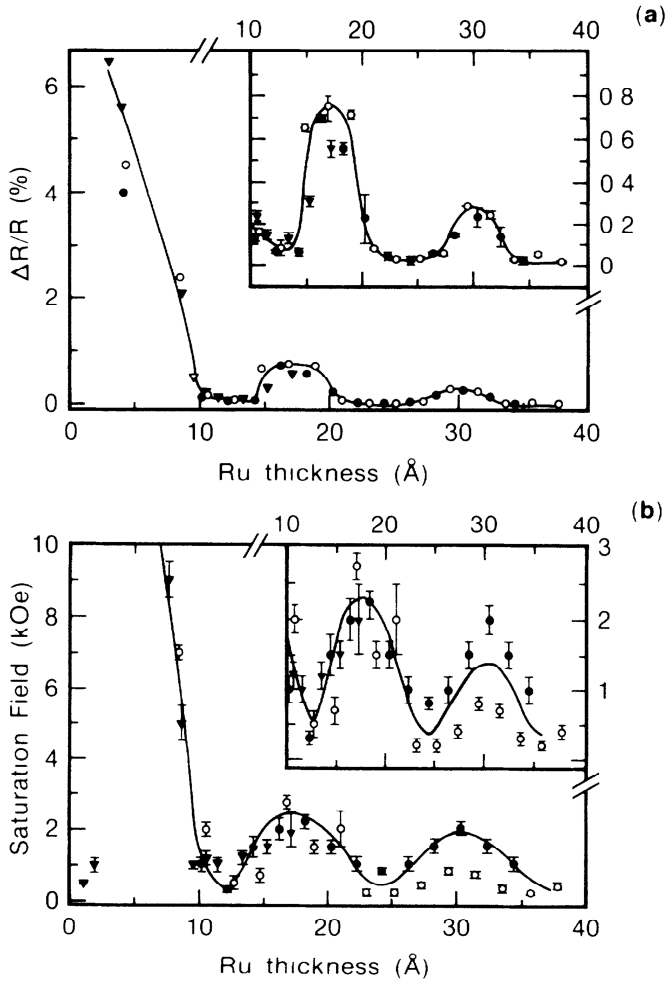
$$J(R) = 9\pi \frac{j}{\varepsilon_F}\left[\frac{\cos 2k_F R}{(2k_F R)^3} - \frac{\sin 2k_F R}{(2k_F R)^4}\right]$$

Heinrich, Book, chapter 2 (1994)

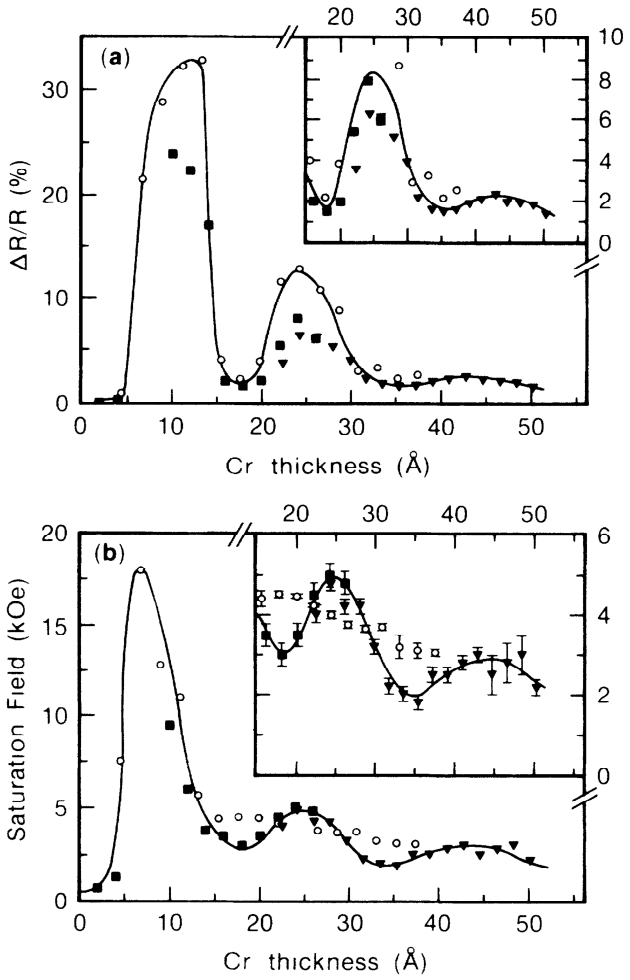
GMR

GMR—RKKY coupling

Ru



Cr

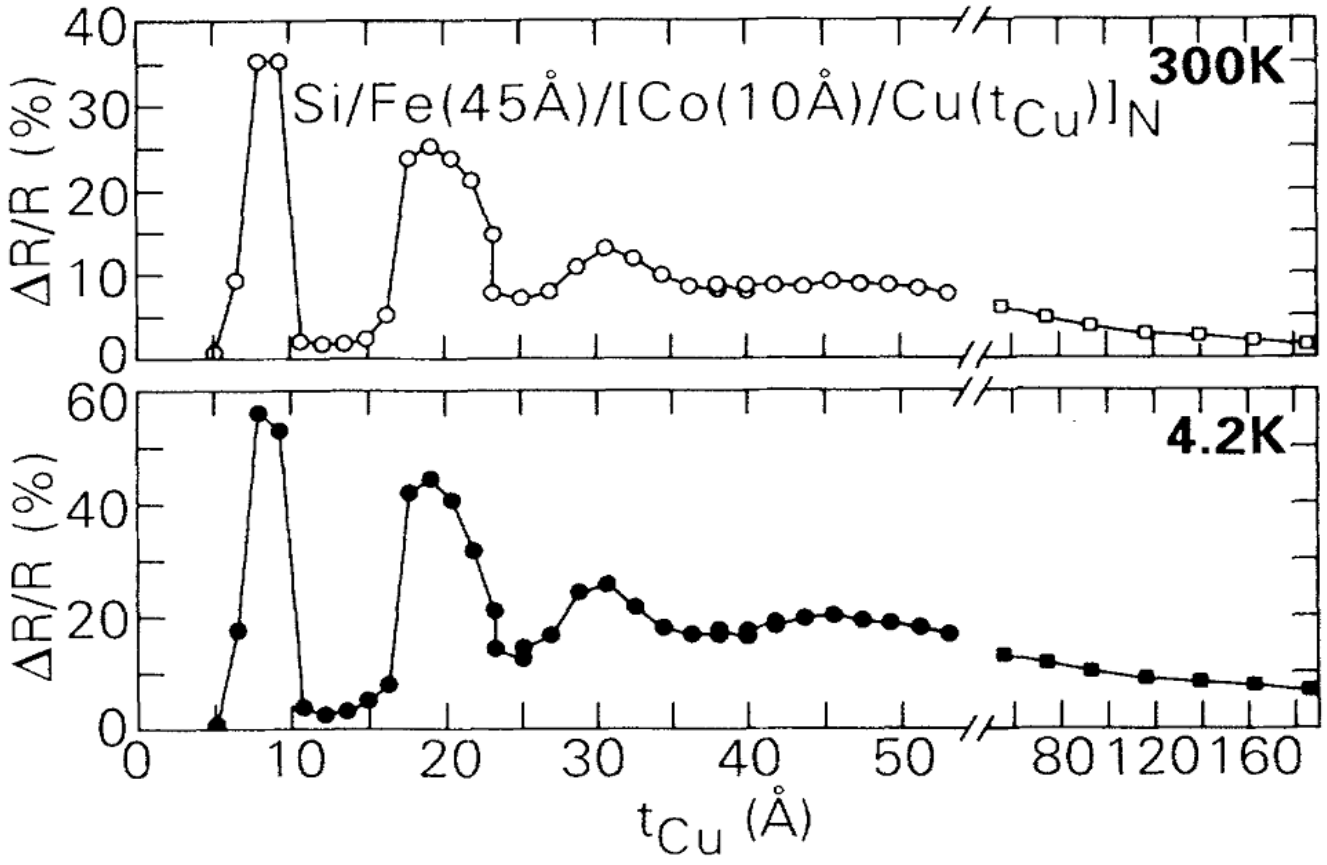


Parkin, et al, PRL (1990)

GMR

GMR—RKKY coupling

Cu



Parkin, et al, PRL (1991)

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, Universite 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**

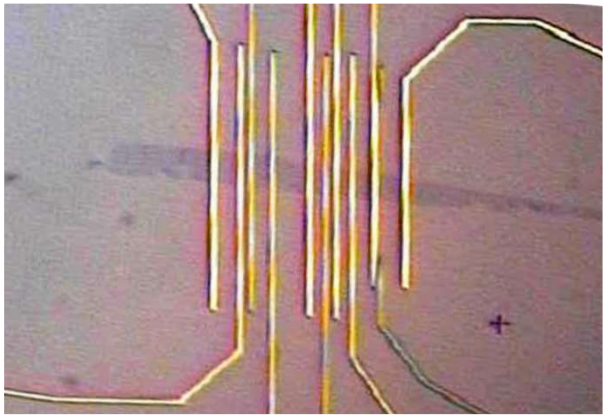
2) **Spin transfer torque**

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

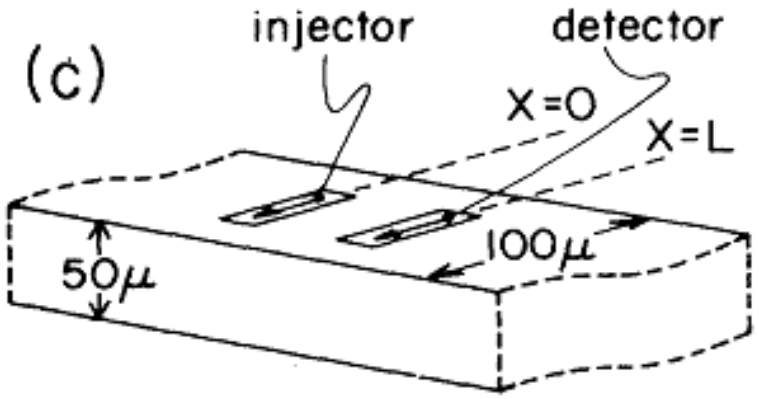
VOLUME 55, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 1985

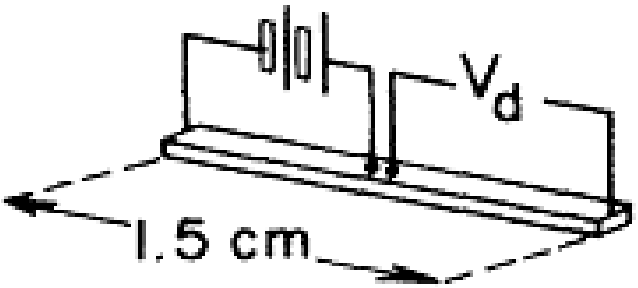
Interfacial Charge-Spin Coupling: Injection and Detection of Spin Magnetization in Metals

Mark Johnson and R. H. Silsbee
Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, New York 14853
(Received 1 July 1985)

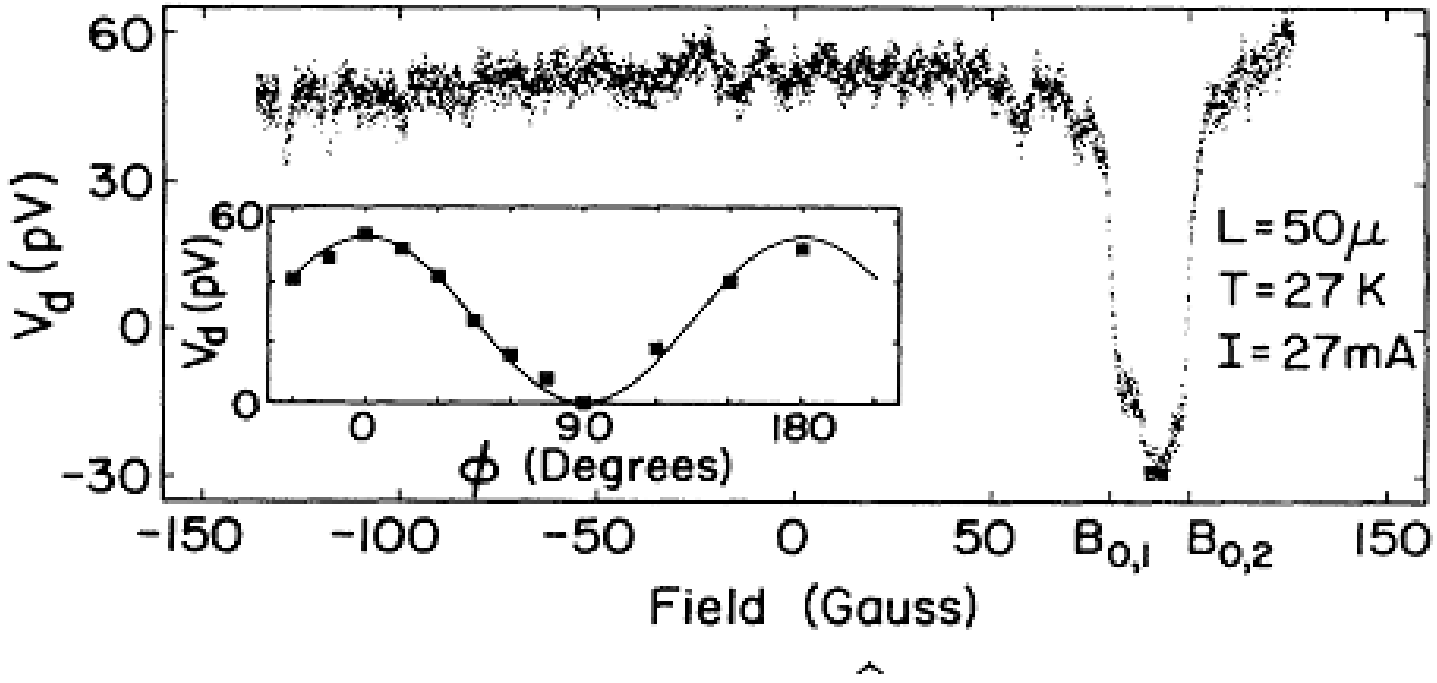
The strong inequivalence of spin-up and spin-down subbands in a ferromagnet causes a coupling between the charge and spin transport across the interface of a ferromagnetic and a contiguous paramagnetic metal. This allows the use of sensitive electronic measurements to probe spin transport. Application 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

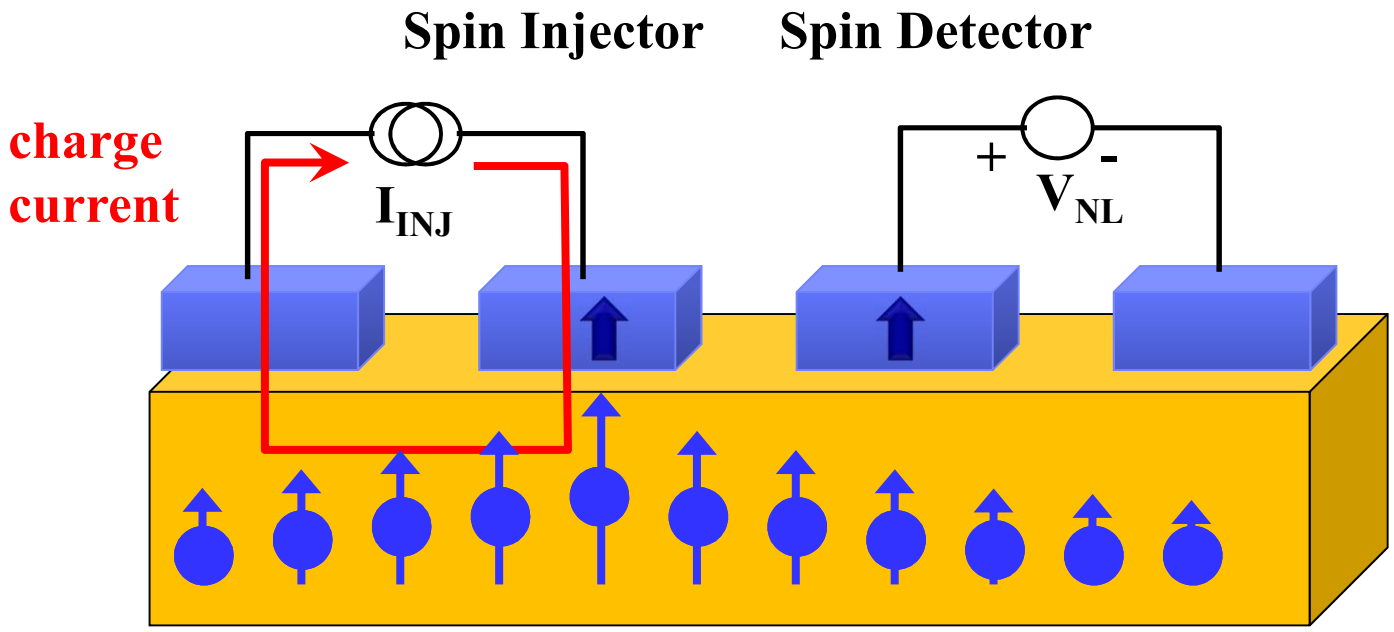




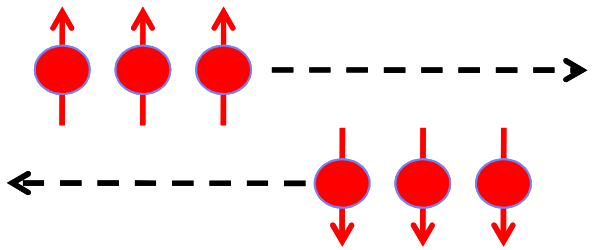
Nonlocal Metal spin valve



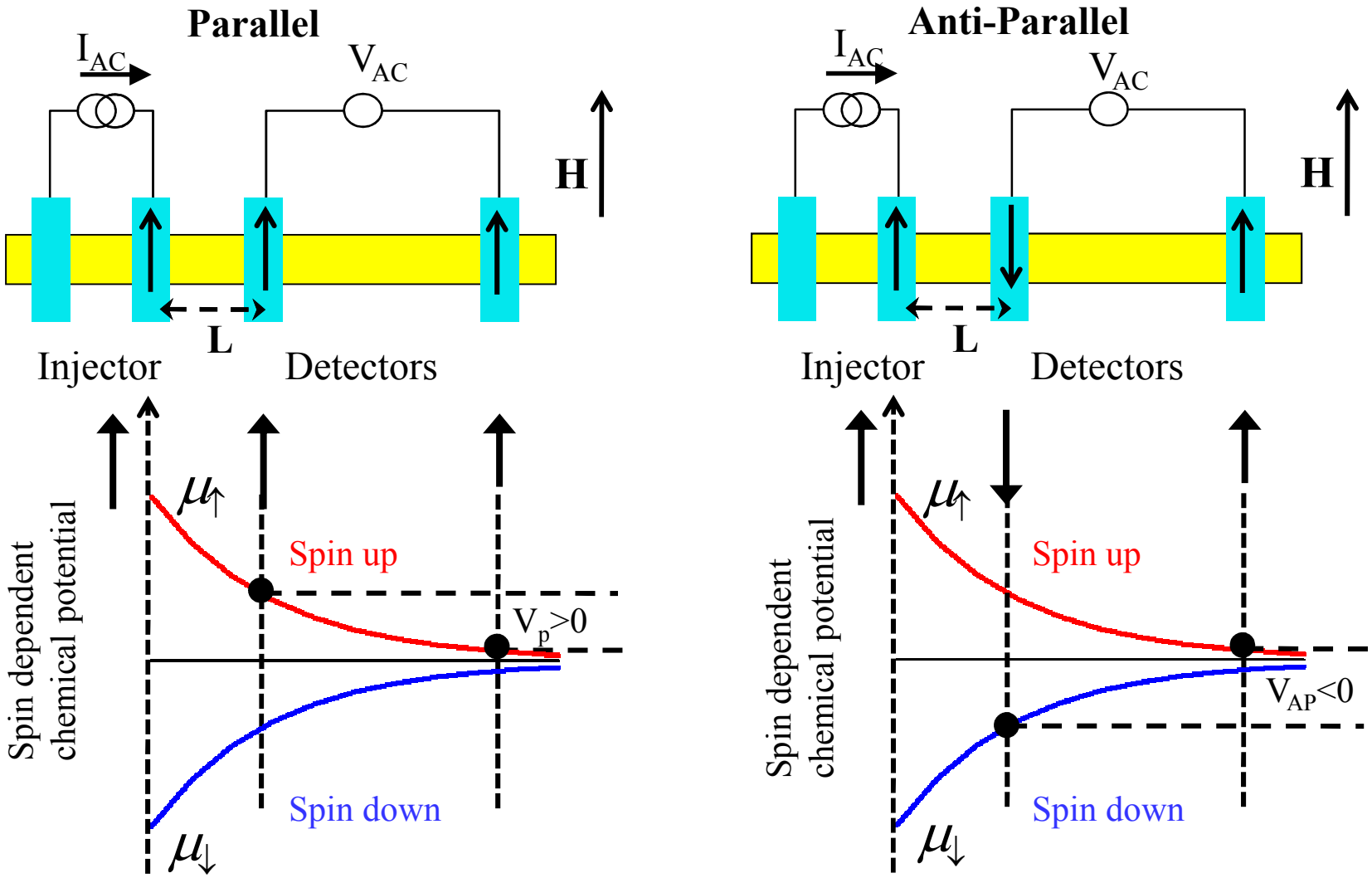
Nonlocal Metal spin valve



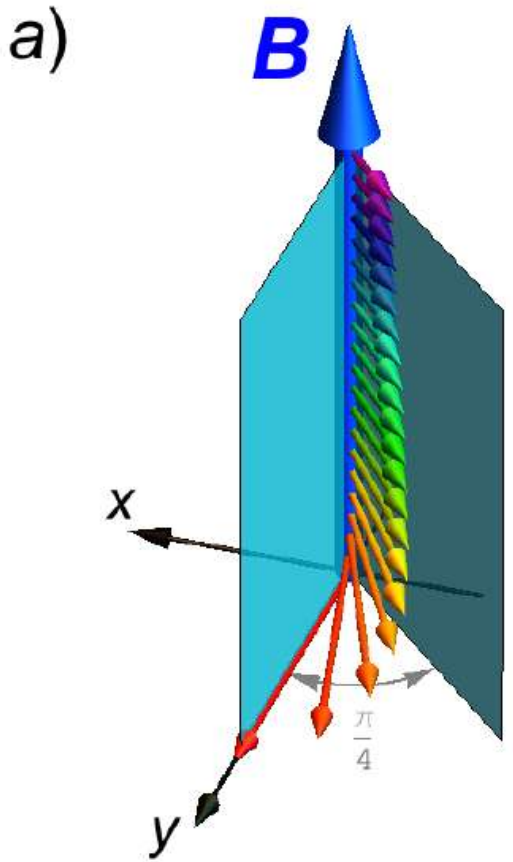
Pure spin current: Flow of spin without net flow of charge

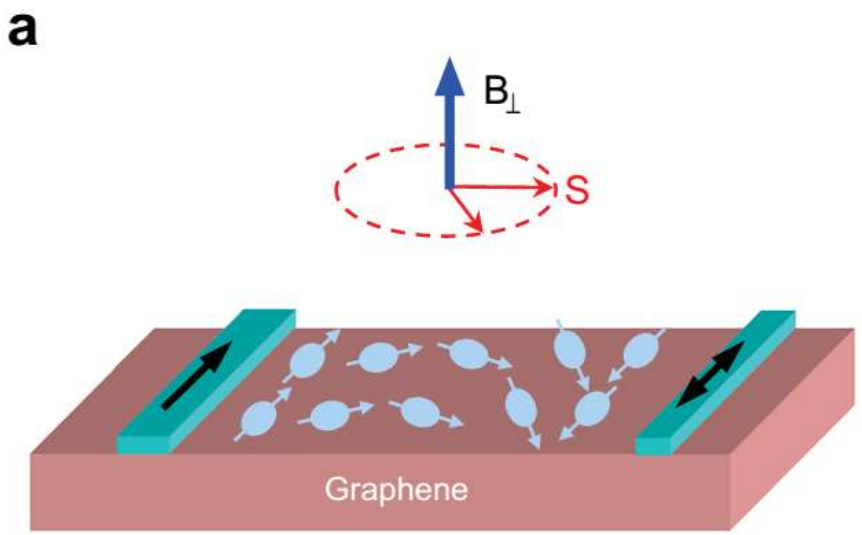


Nonlocal Metal spin valve

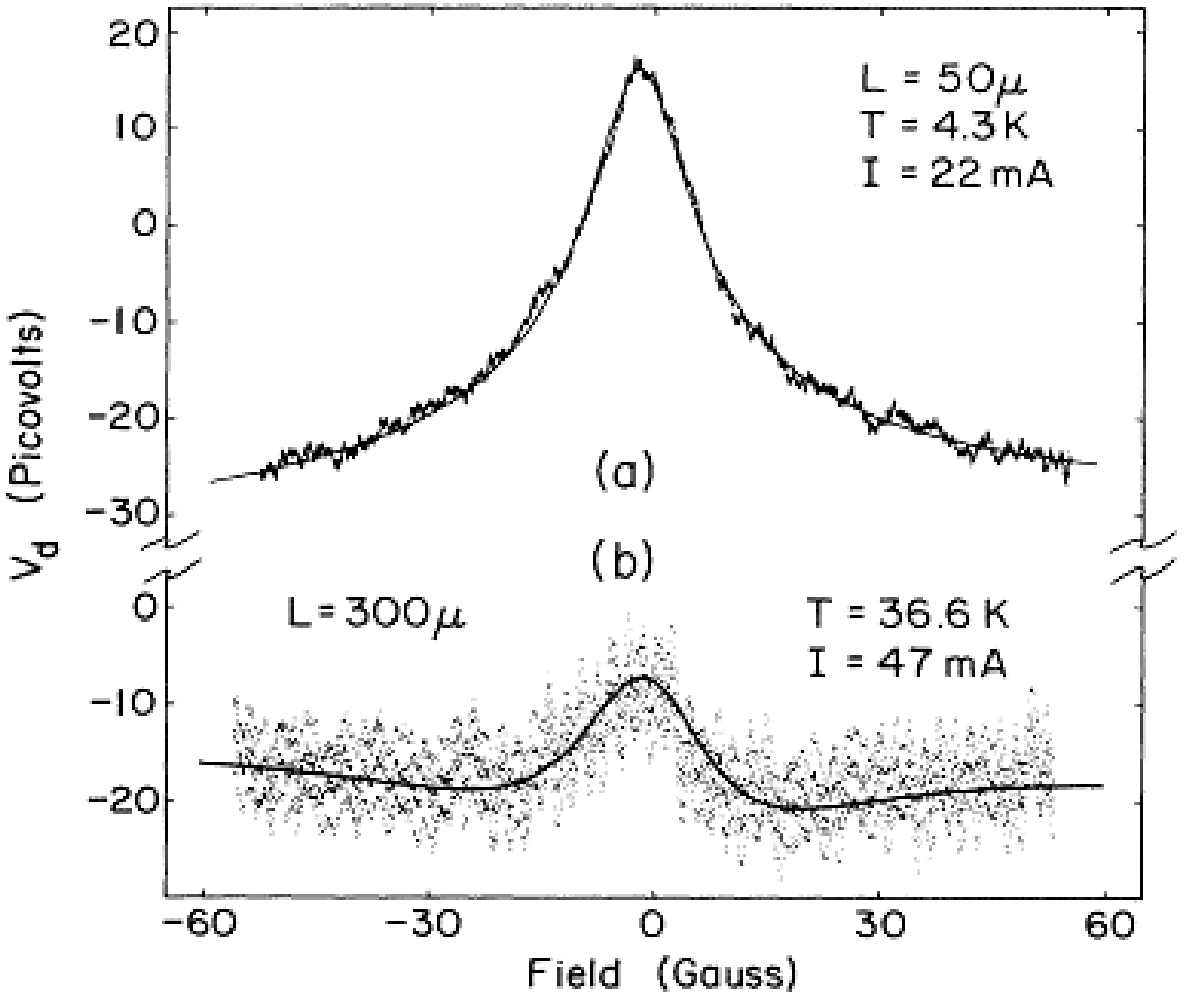


Nonlocal Metal spin valve





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

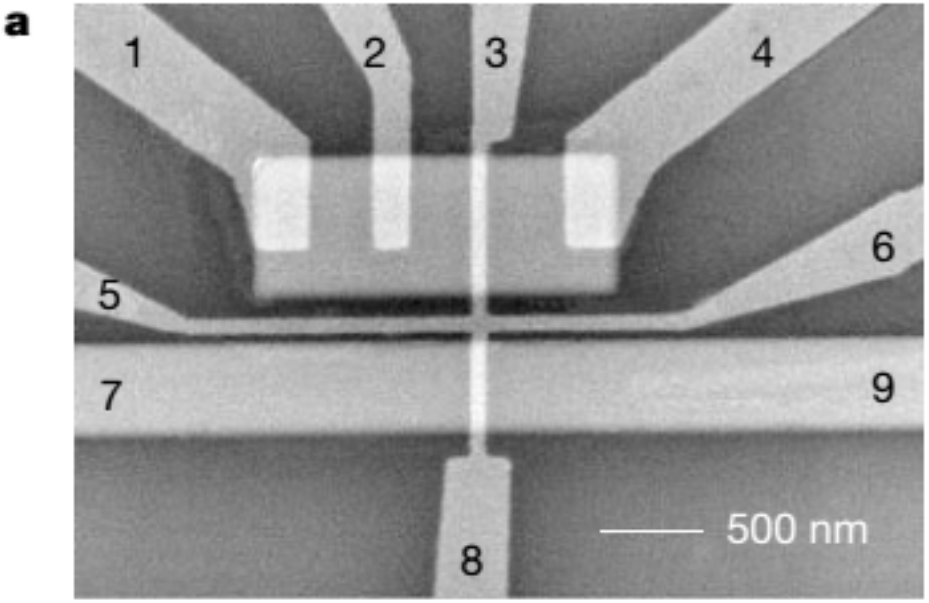
F. J. Jedema, A. T. Filip & B. J. van Wees

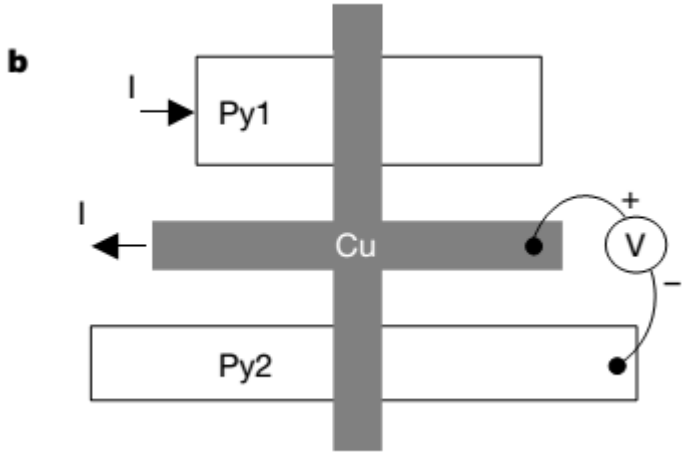
1. Department of Applied Physics and Materials Science Centre, University of Groningen, Nijenborgh 4.13, 9747 AG Groningen, The Netherlands

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

Nonlocal Metal spin valve

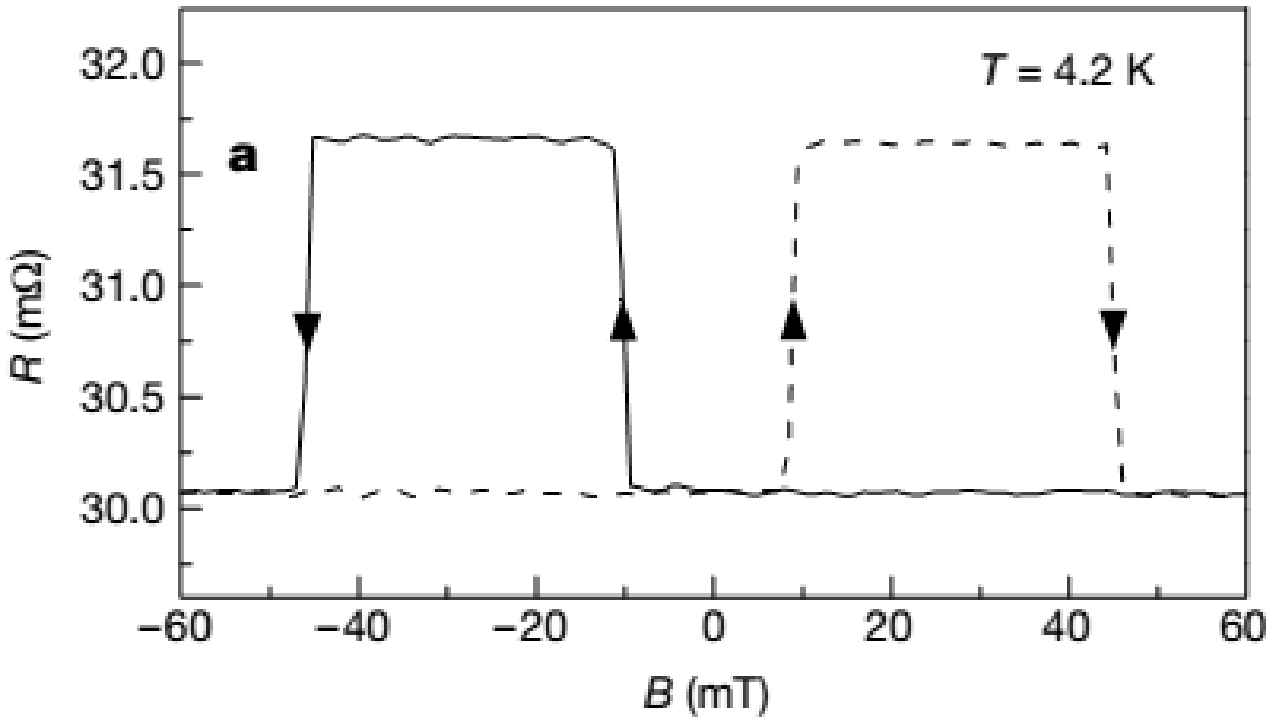
Small devices on Cu





Nonlocal Metal spin valve

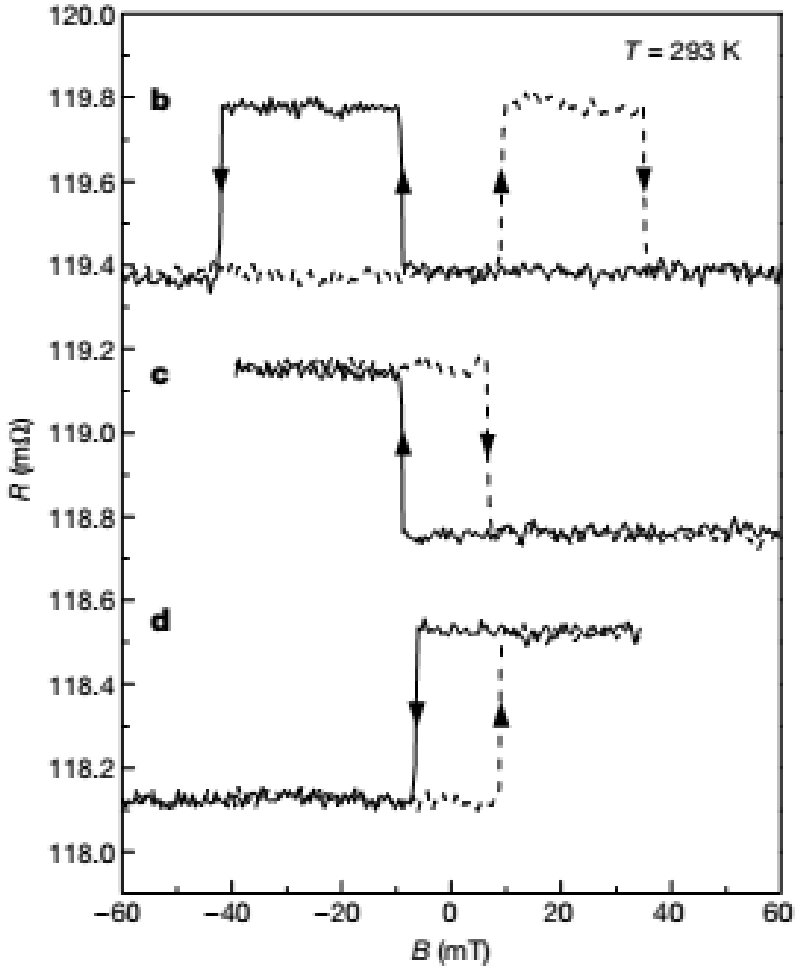
Small devices



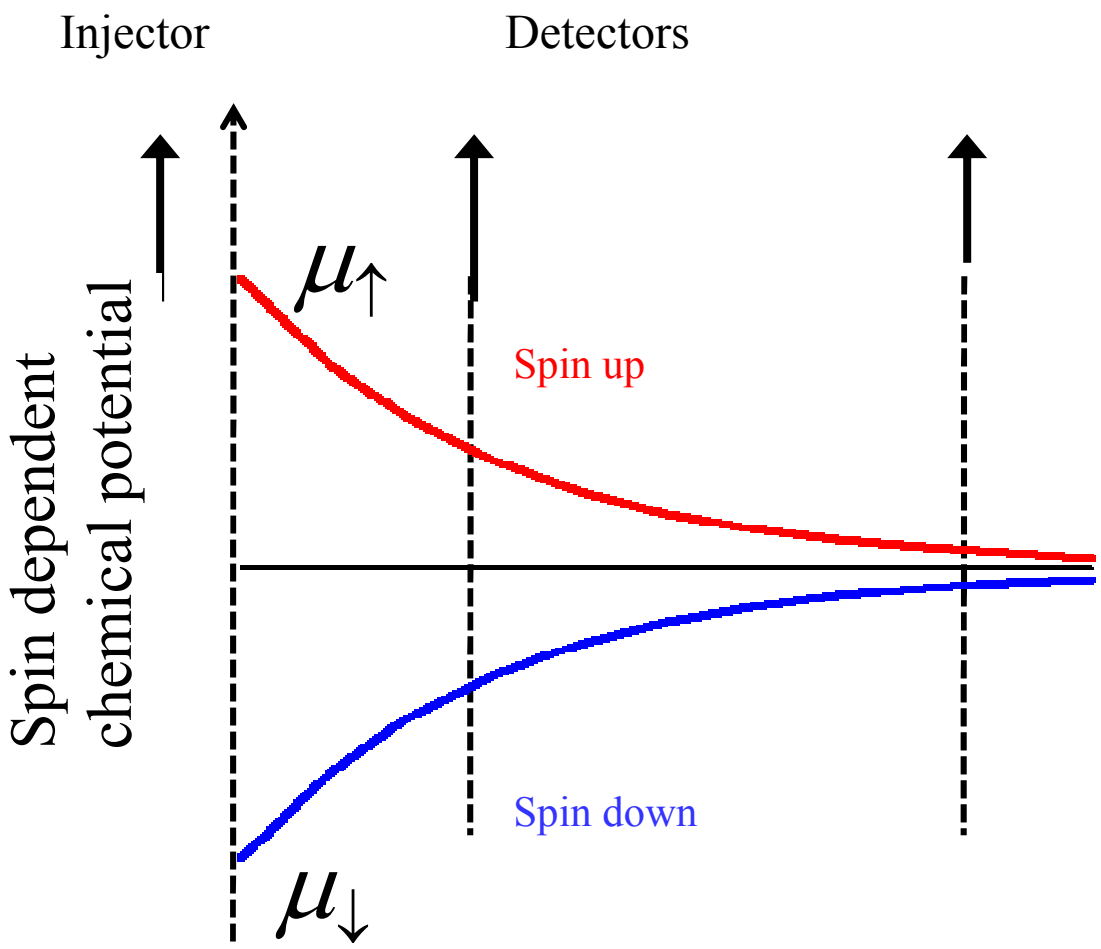
Jedema, et al, Nature (2001)

Nonlocal Metal spin valve

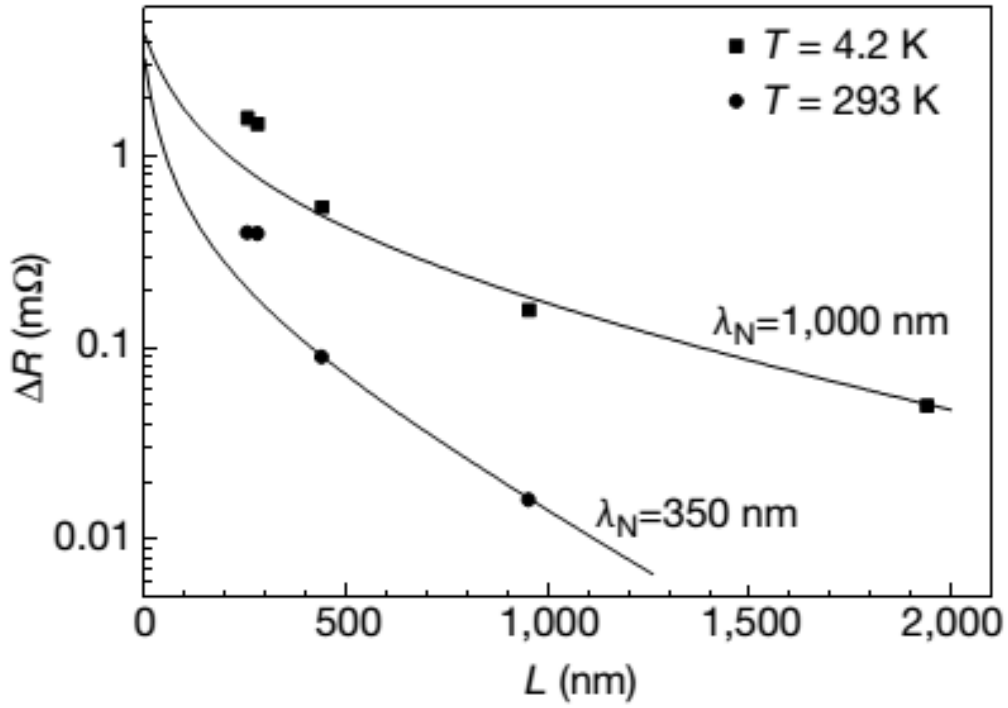
Small devices



Nonlocal Metal spin valve



Nonlocal Metal spin valve



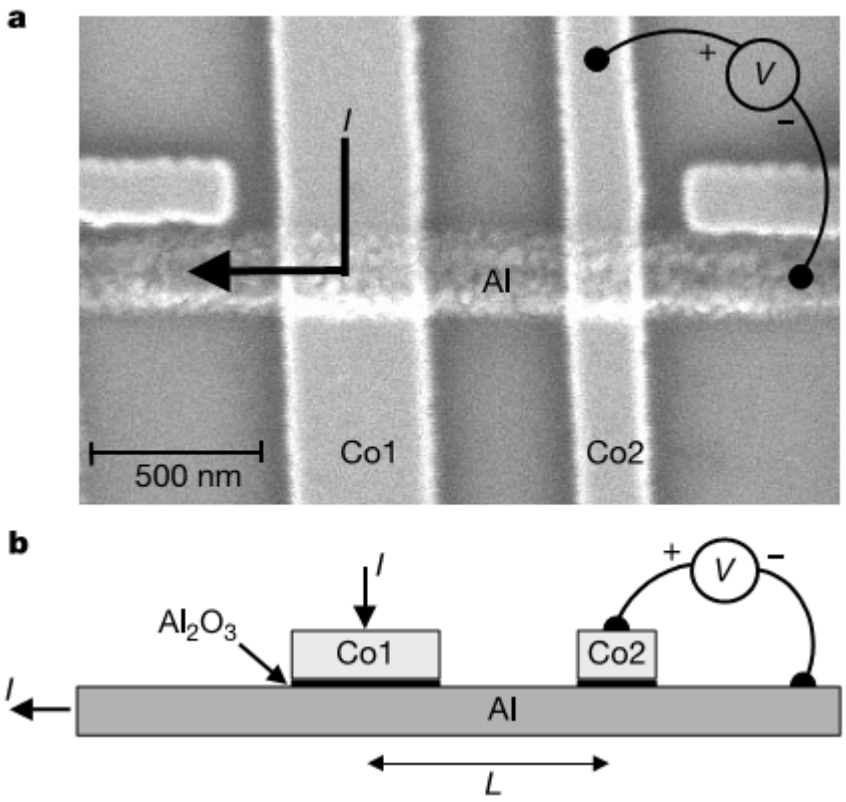
$$\Delta R = \frac{\alpha_F^2 \frac{\lambda_N}{\sigma_N A} e^{(-L/2\lambda_N)}}{(M+1)[M\sinh(L/2\lambda_N) + \cosh(L/2\lambda_N)]} \qquad (1)$$

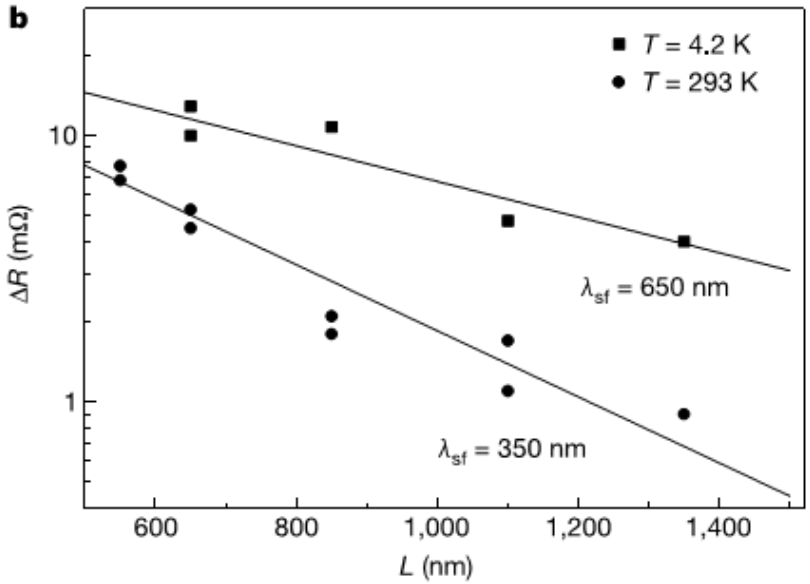
where $M = (\lambda_N \sigma_F / \lambda_F \sigma_N)(1 - \alpha_F^2)$, $\alpha_F = \sigma_\uparrow - \sigma_\downarrow / \sigma_\uparrow + \sigma_\downarrow$ is the bulk

Hanle spin precession

Small devices on Al

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

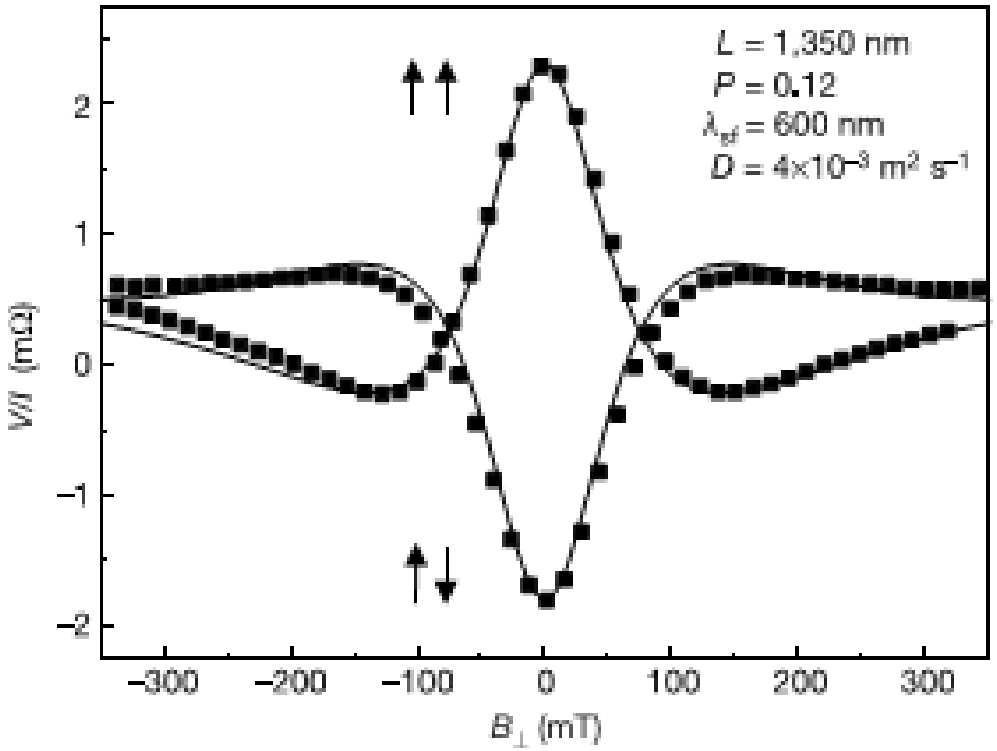




Jedema, et al, Nature (2002)

Hanle spin precession

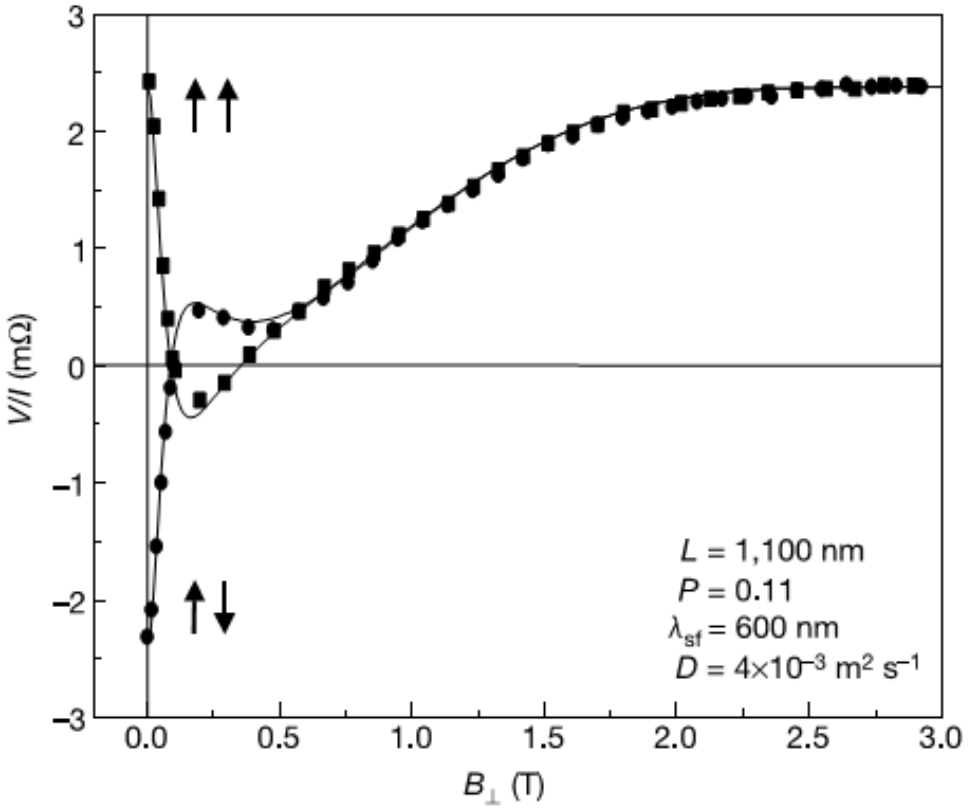
Small devices on Al



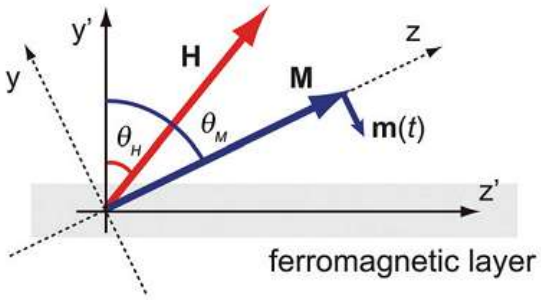
$$V(B_\perp) = \pm I \frac{P^2}{e^2 N_{\mathrm{Al}} A} \int_0^\infty P(t) \cos(\omega_{\mathrm{L}} t) \exp(-t/\tau_{\mathrm{sf}}) \mathrm{d}t$$

Hanle spin

Small devices on Al

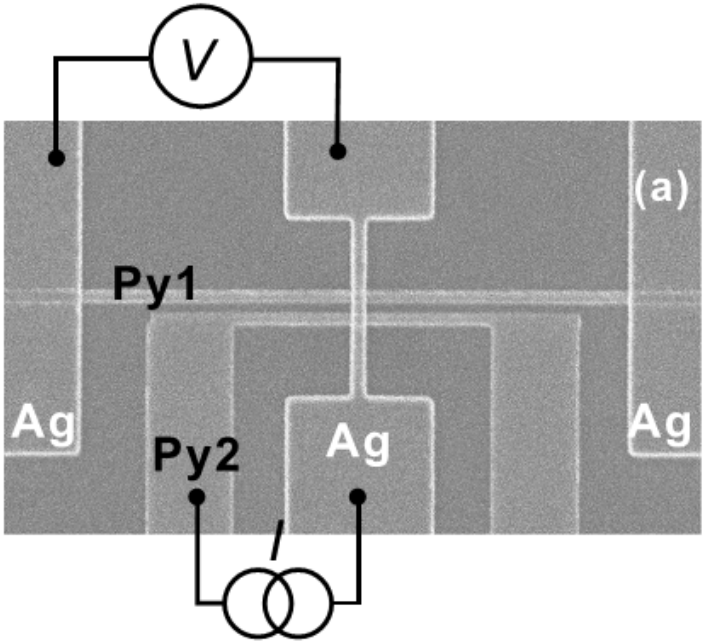


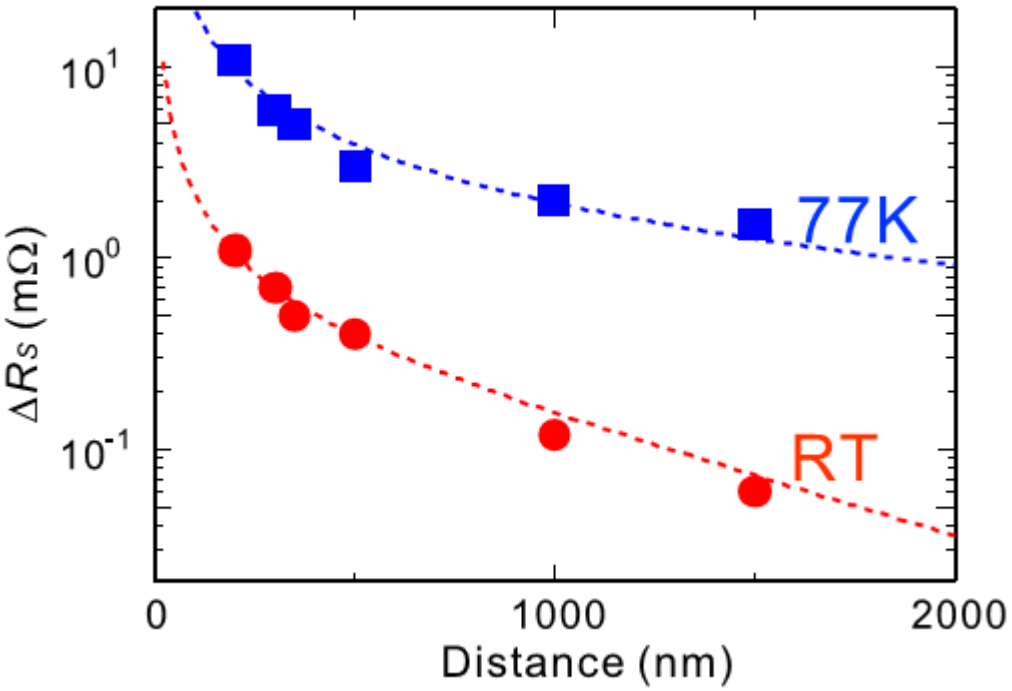
Magnetic anisotropy



Ag spin valves

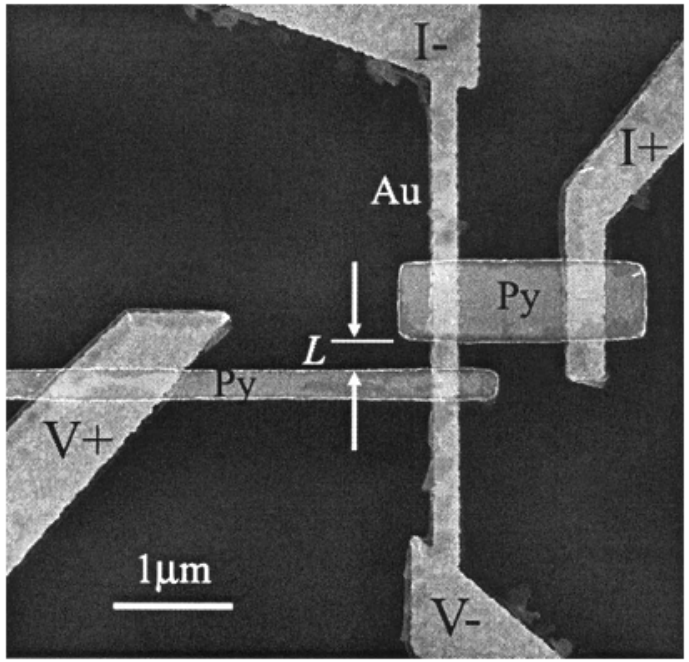
Small devices on Ag

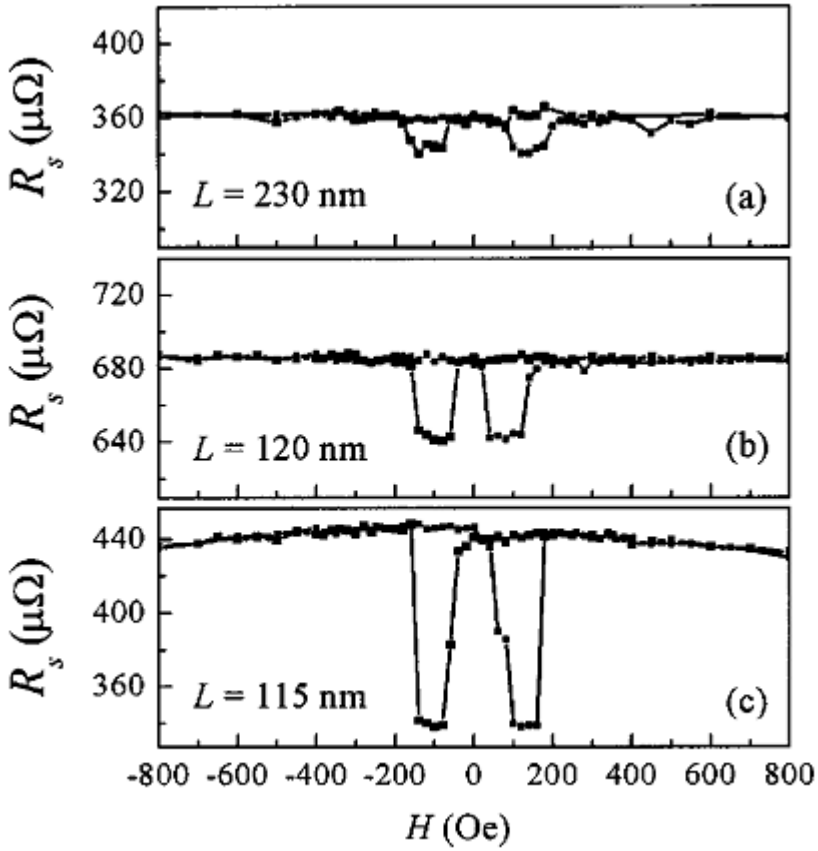




Kimura & Otani, et al, PRL (2007)

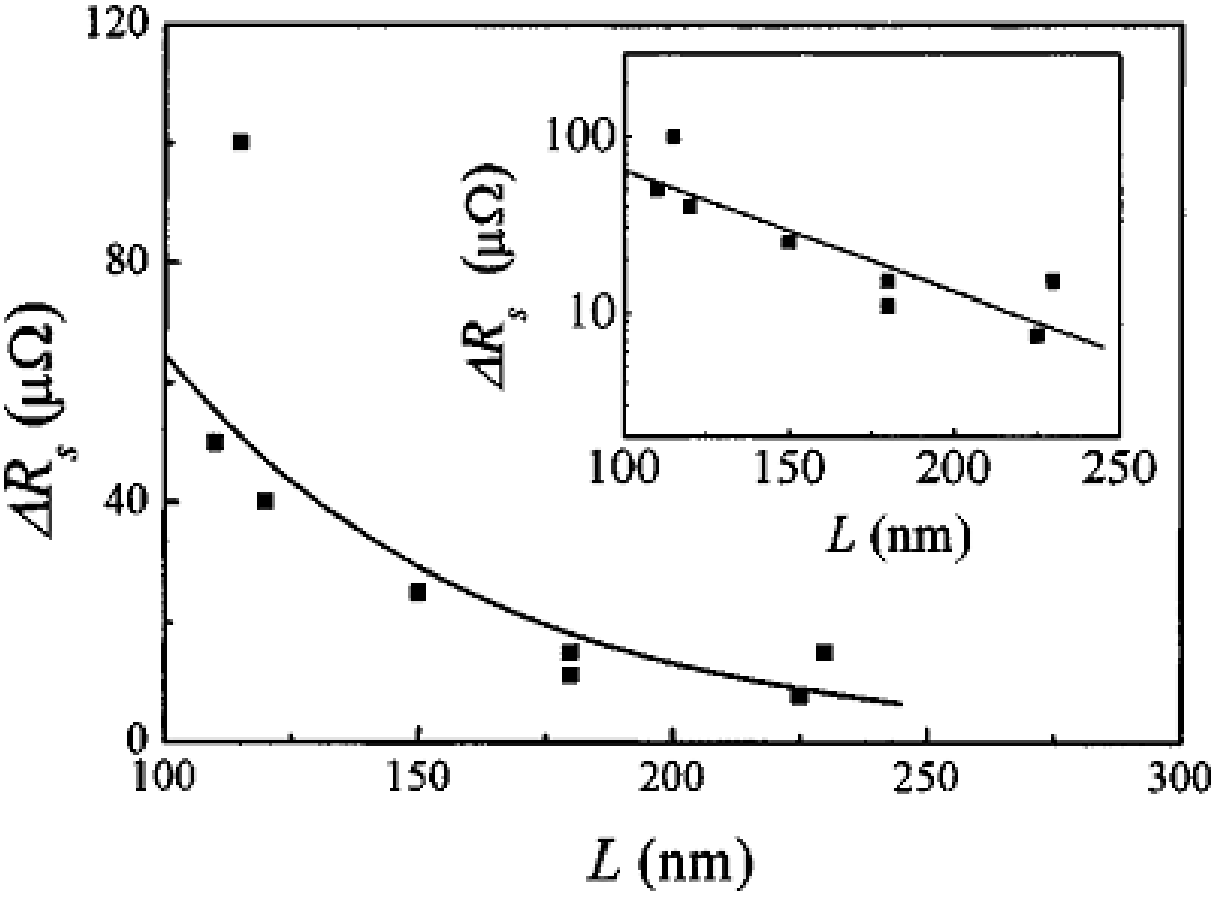
Au spin valves





Ji, et al, J. Physics D (2007)

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]

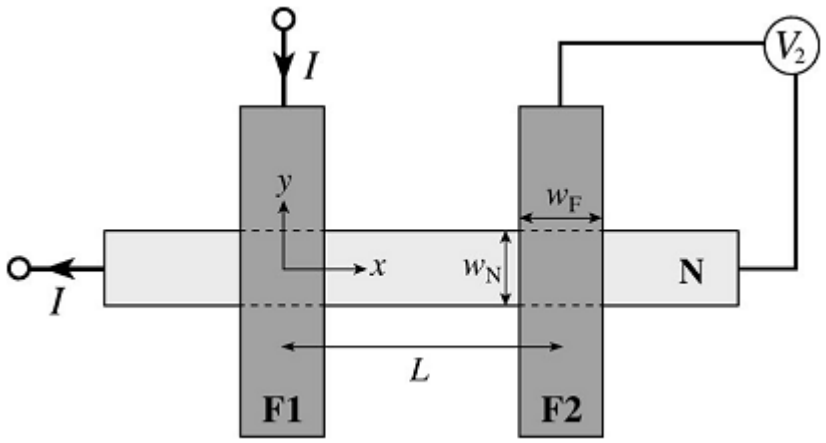
[a] These P values are obtained by using L defined as the centre-to-centre separation between the injector and the detector.

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)



Kimura, et al, PRB (2006)

Spin injection efficiency

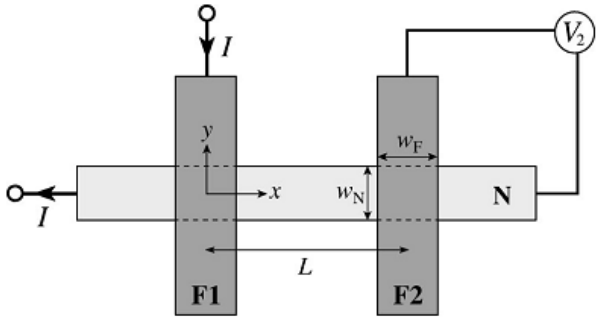
$$R_{NL} = 4R_N e^{-L/\lambda_N} \prod_{i=1}^{2} \left(\frac{P_J \frac{R_i}{R_N}}{1-P_J^{\,2}} + \frac{P_F \frac{R_F}{R_N}}{1-P_F^{\,2}}\right) \times \left[\prod_{i=1}^{2} \left(1 + \frac{2\frac{R_i}{R_N}}{1-P_J^{\,2}} + \frac{2\frac{R_F}{R_N}}{1-P_F^{\,2}}\right) - e^{-2L/\lambda_N}\right]^{-1}$$

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

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

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

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



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

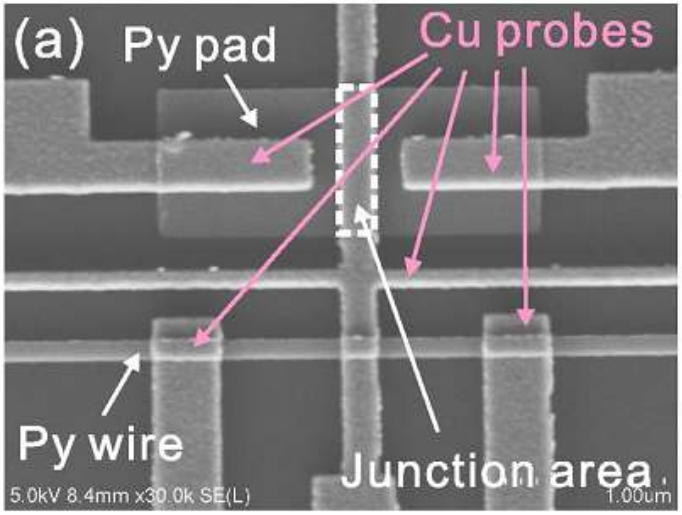
$$R_{NL} = 4R_N e^{-L/\lambda_N} \prod_{i=1}^{2} \left(\frac{P_J \frac{R_i}{R_N}}{1-P_J^2} + \frac{P_F \frac{R_F}{R_N}}{1-P_F^2} \right) \times \left[\prod_{i=1}^{2} \left(1 + \frac{2\frac{R_i}{R_N}}{1-P_J^2} + \frac{2\frac{R_F}{R_N}}{1-P_F^2} \right) - e^{-2L/\lambda_N} \right]^{-1}$$

$$R_s = P_J^2 \mathcal{R}_N e^{-L/\lambda_N}.$$

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

Spin injection efficiency

Junction size



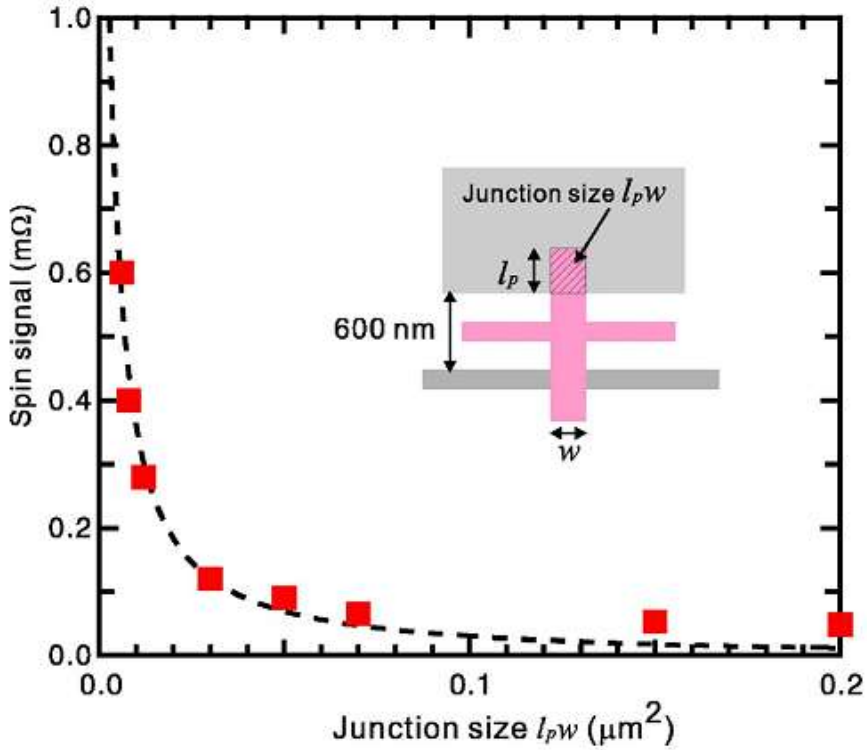
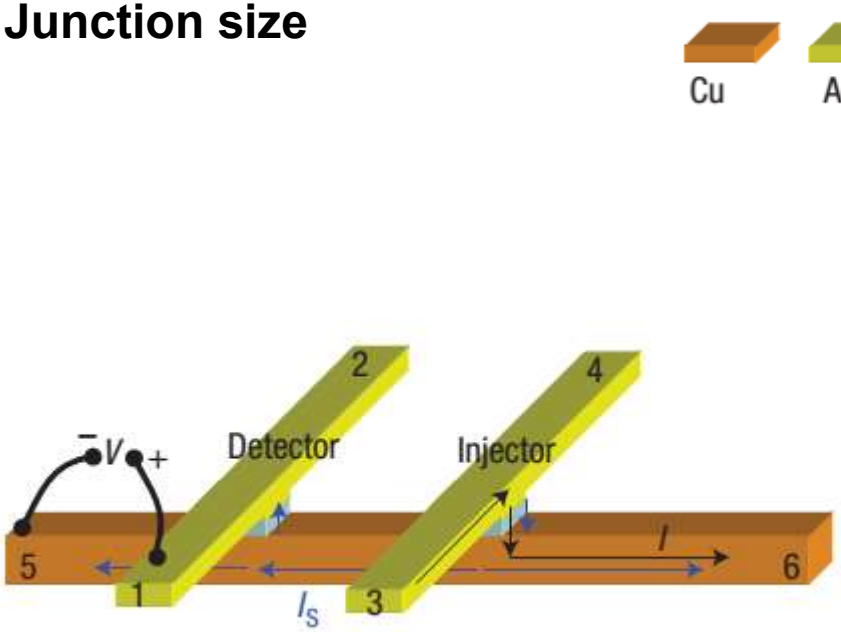


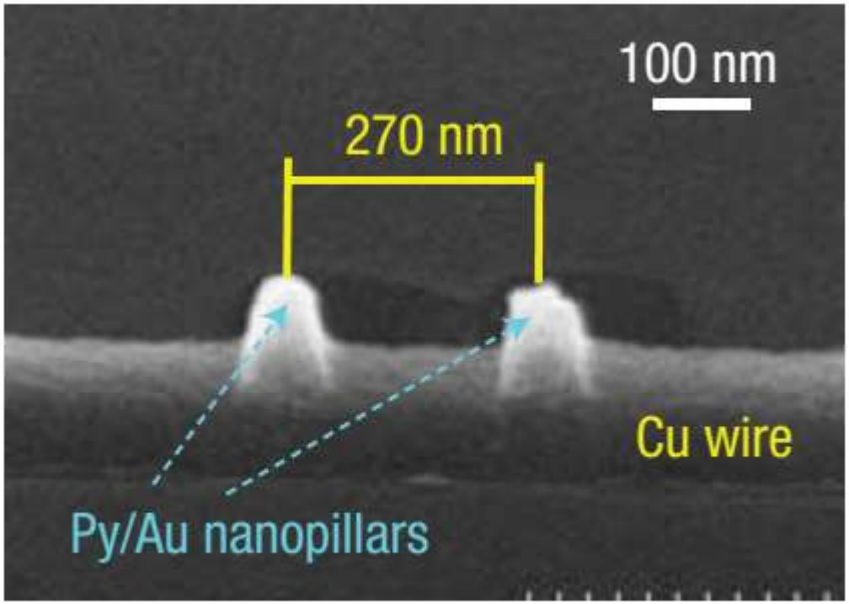
FIG. 4. (Color online) Spin signal in the NLSV measurement as a function of the junction size l_pw. The dotted curve is the best fitting to the data points using Eq. (2).

Kimura, et al, PRB (2006)

Spin injection efficiency

Junction size

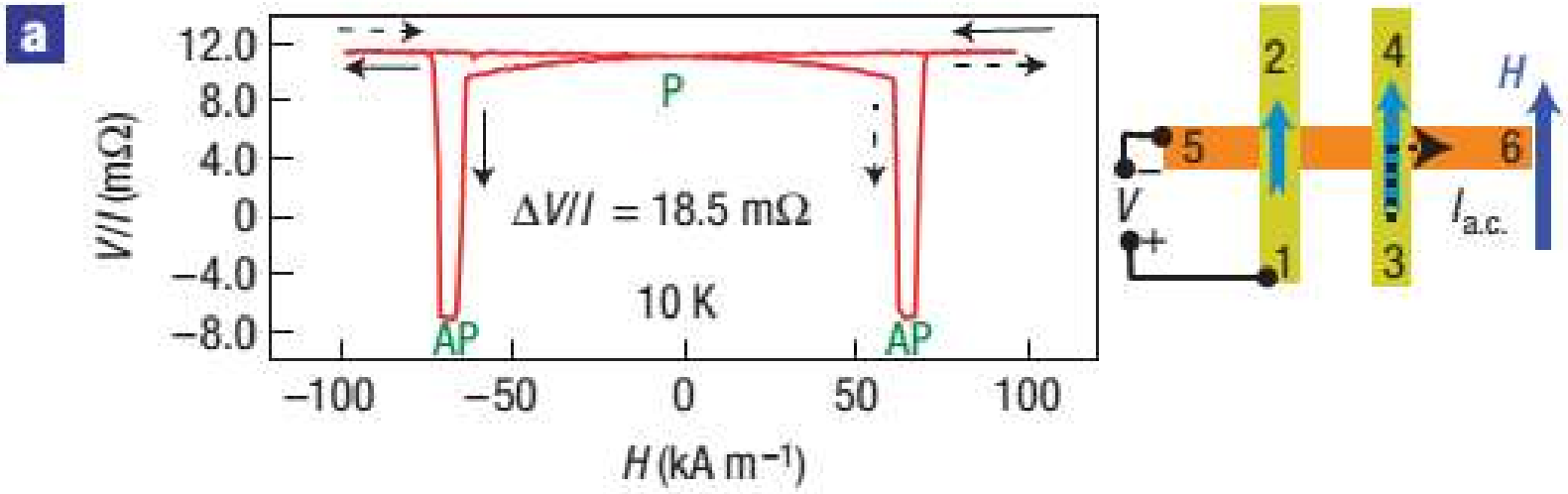




Yang, et al, Nature Physics (2008)

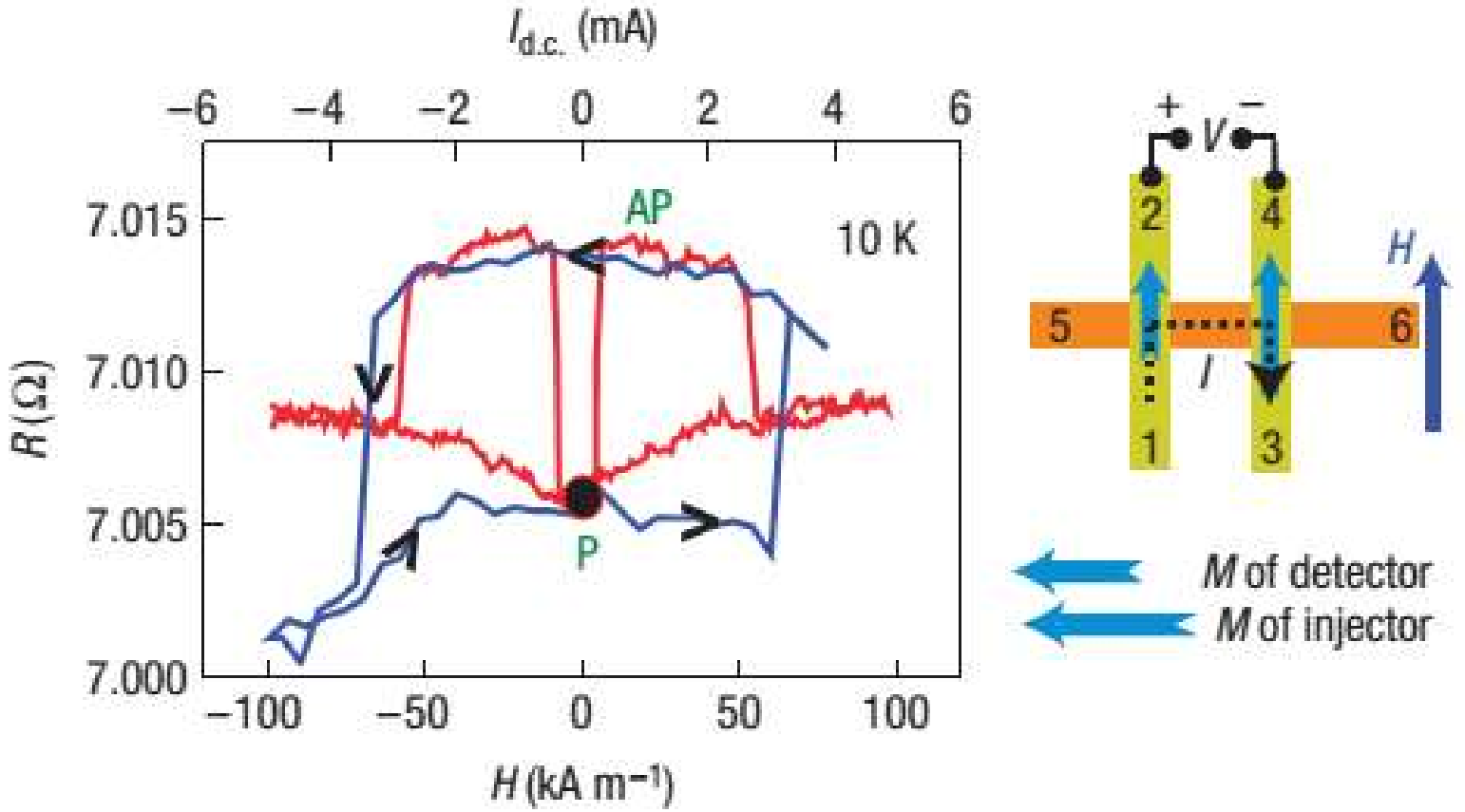
Spin injection efficiency

Junction size

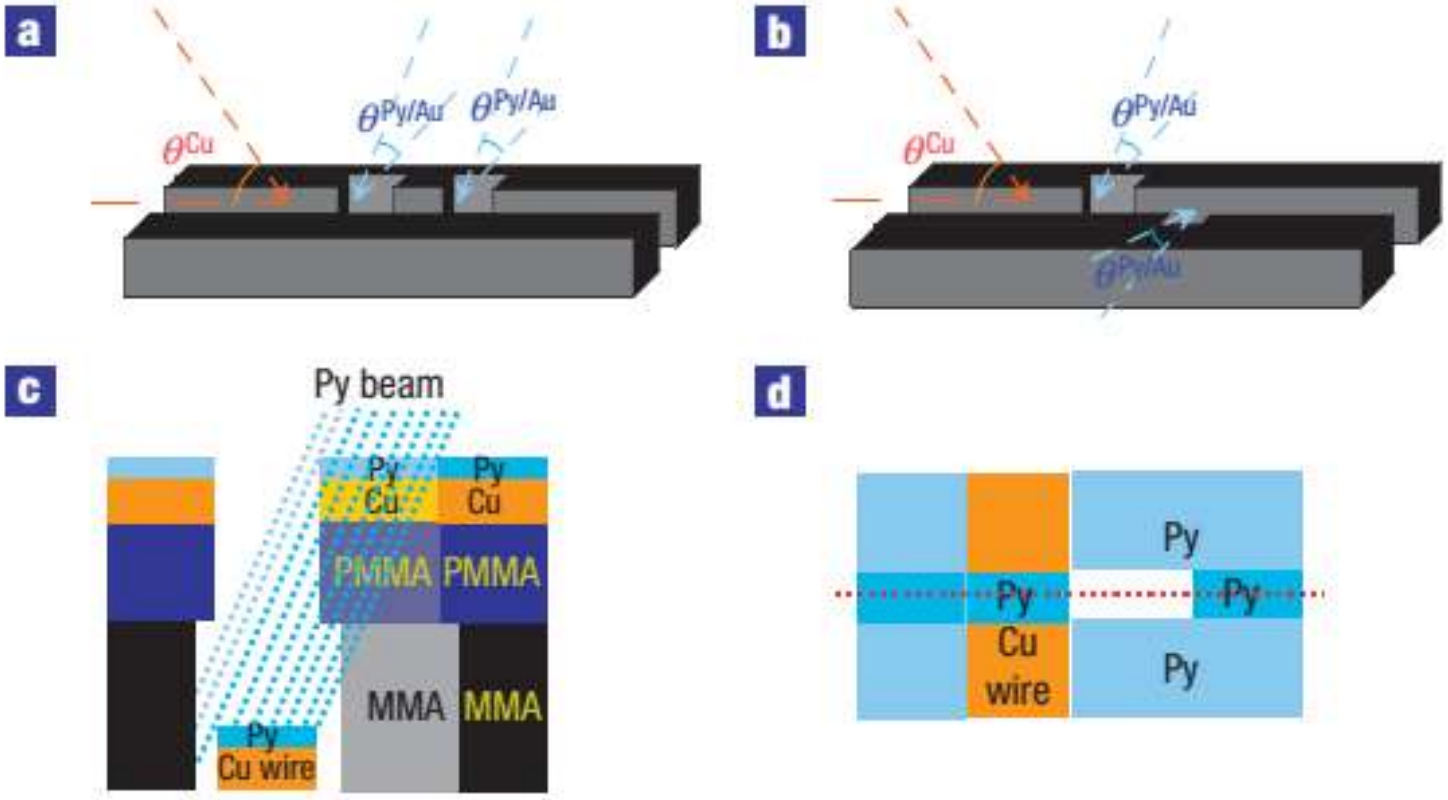


Spin injection efficiency

Junction size→ current switching

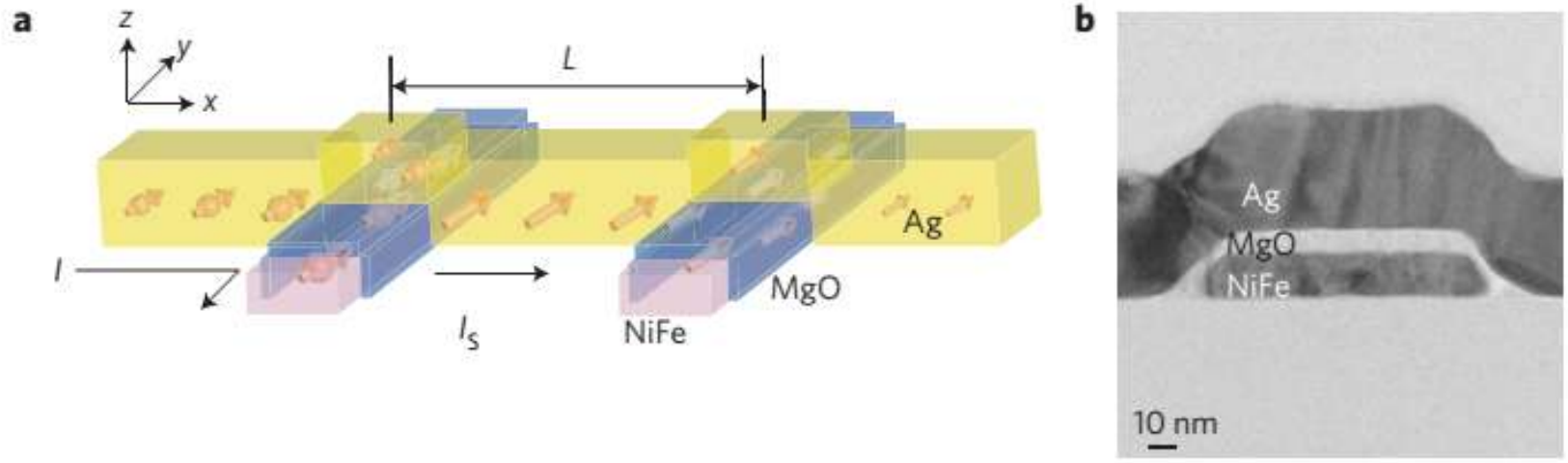


Angle deposition



Spin injection efficiency

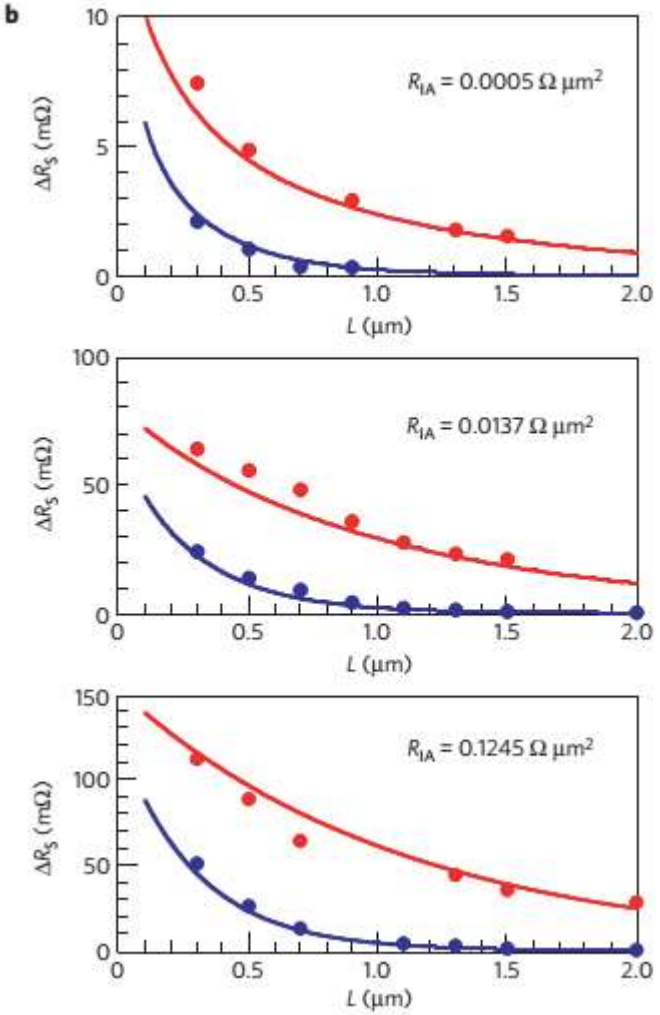
MgO tunnel barrier

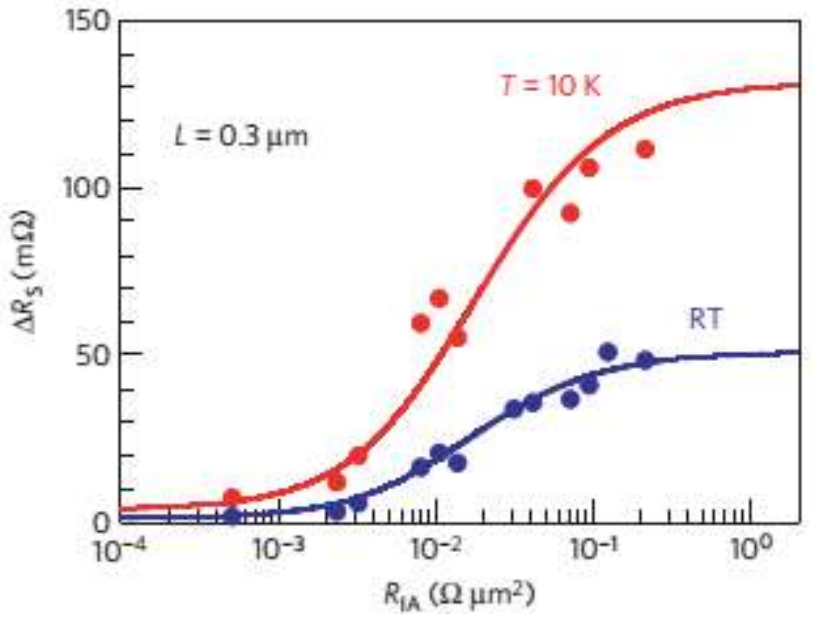


Fukuma, et al, Nature Materials (2011)

Spin injection efficiency

MgO tunnel barrier

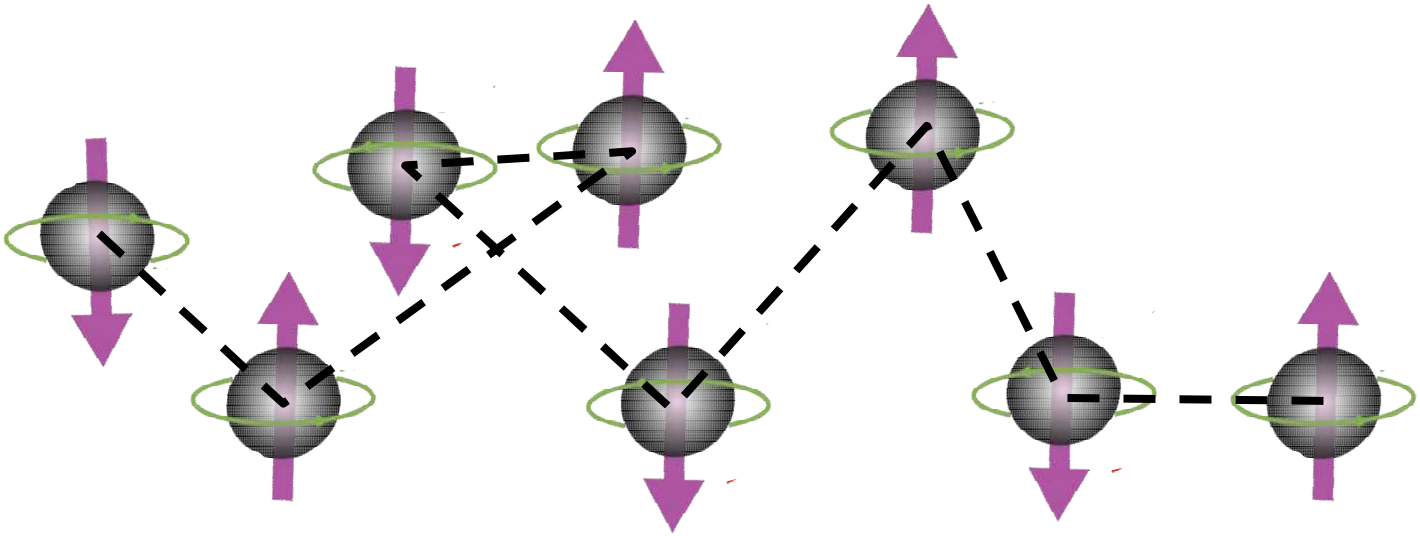




Fukuma, et al, Nature Materials (2011)

Spin relaxation

Elliot-Yafet spin relaxation

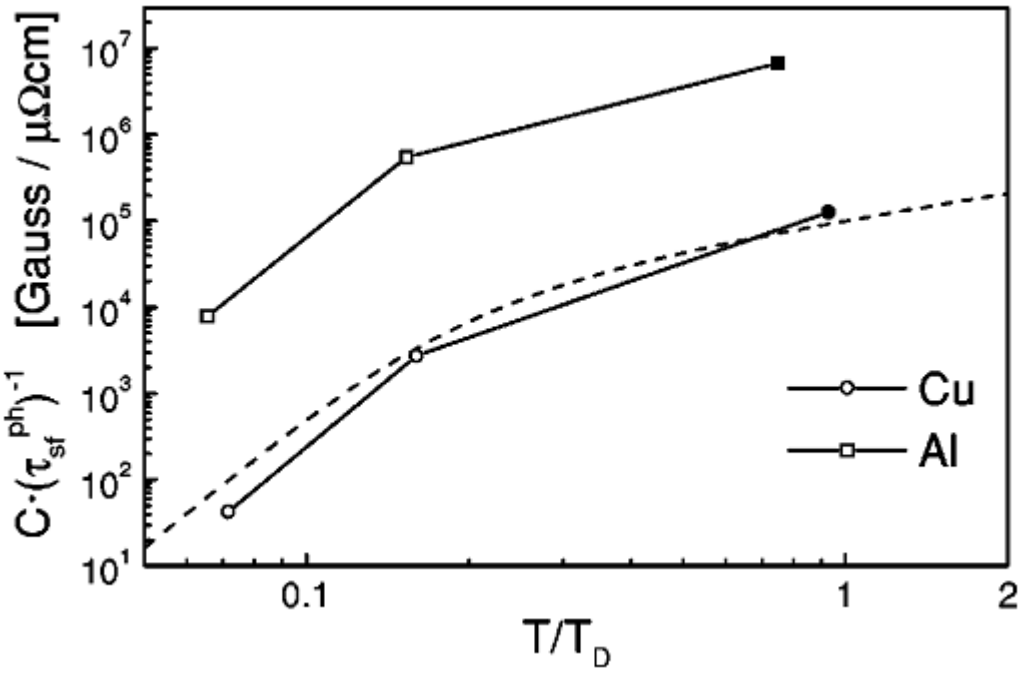


Spin flip during momentum scattering events:
More momentum scattering, more spin relaxation.

$\tau_s \sim \tau_p$ (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

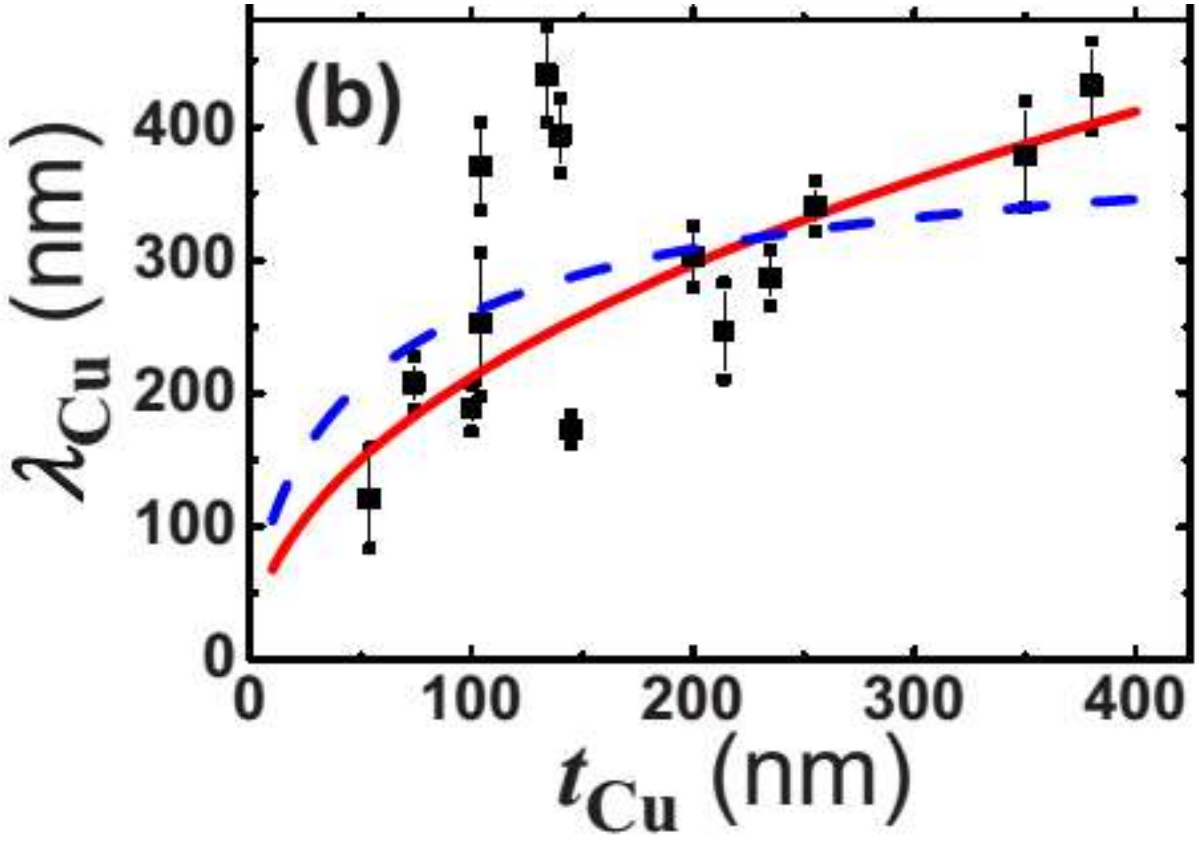
	T (K)	λ_s (nm)	P (%)	Reference
Fe/Al/Fe	1.8	500–1000	45[a]	[25]
Py/Ag/Py	79	180	22[a]	[15]
Py/Au/Py	10	63 ± 15	3	This work
	15	168	26[a]	[23]
Co/Cu/Co	10	200 ± 20	7	This work
Py/Cu/Py	300	350	2	[7]
		500	2–3	[22]
	4	1000	2	[7]

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

Ji, et al, J. Physics D (2007)

Spin relaxation

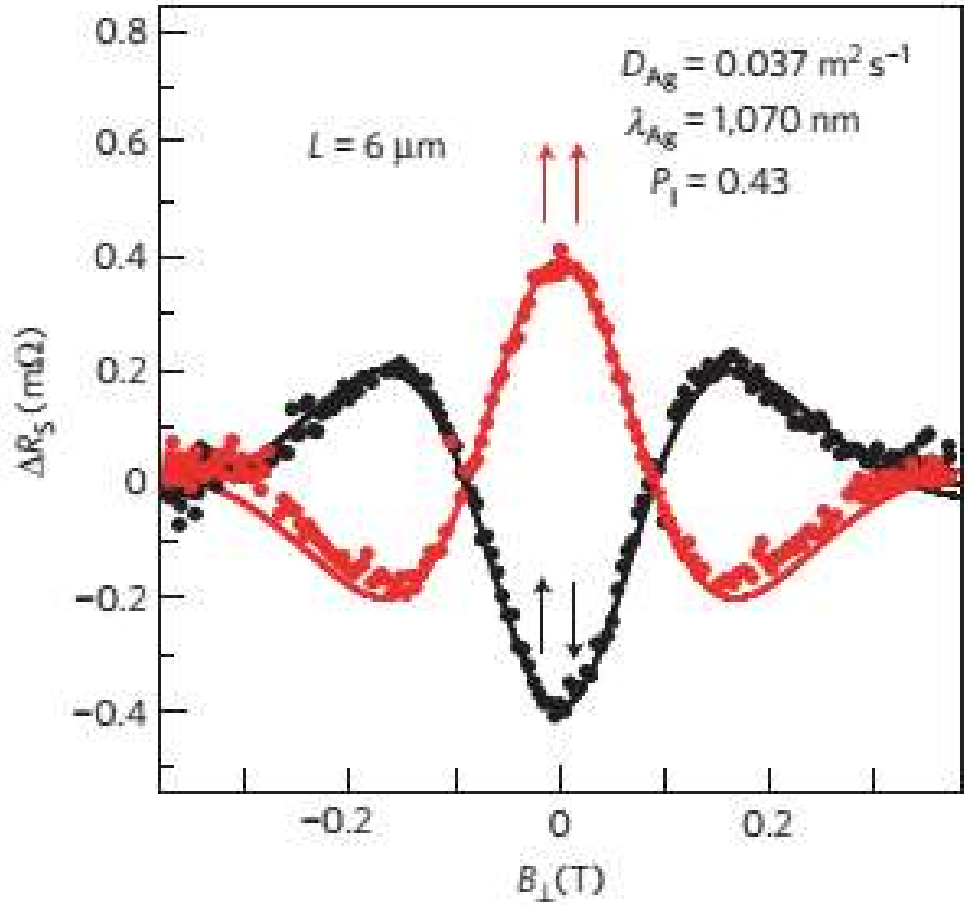
Surface impurity scattering



Erekhinsky, et al, APL (2010)

Spin relaxation

MgO tunnel barrier



Fukuma, et al, Nature Materials (2011)

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

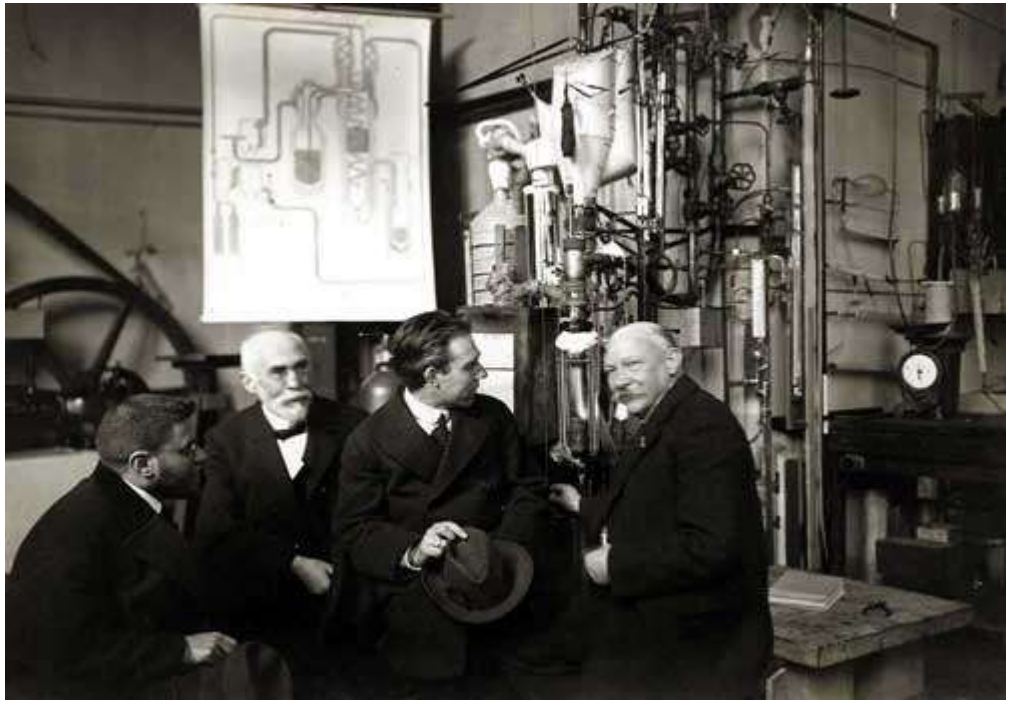
Large MR and control of T_C

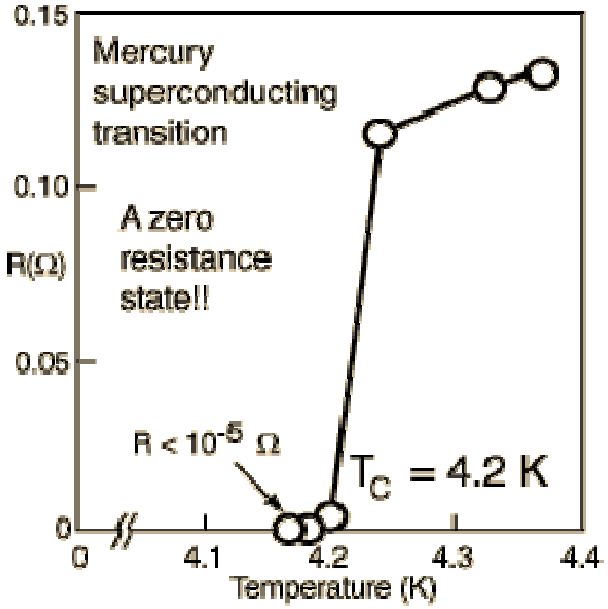
Josephson junction, Spin-triplet

Spin injection, Long spin lifetime

Large spin Hall

Superconductor



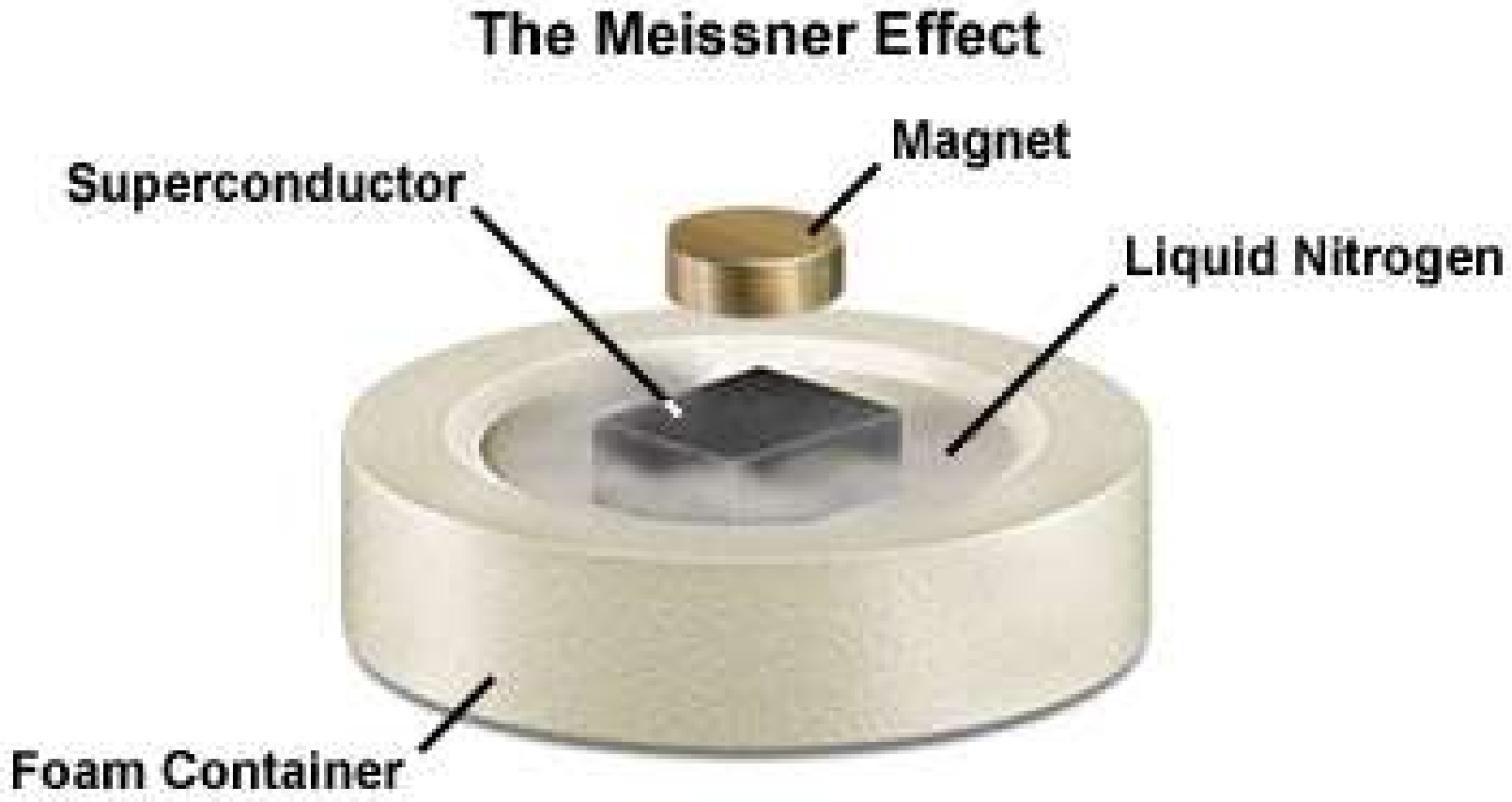


Onnes, Commun. Phys. Lab. (1911)

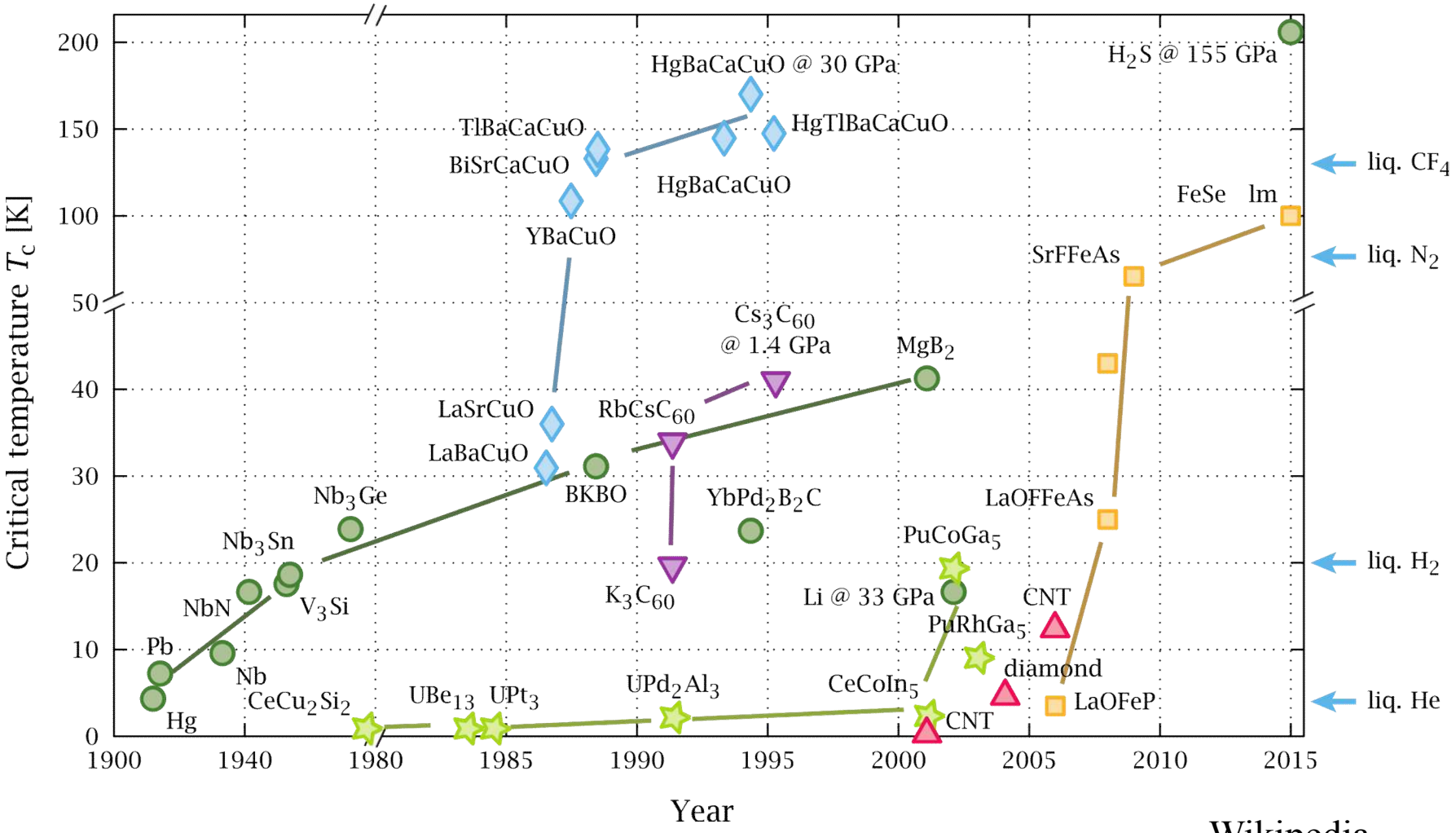
Superconductor

"Door meten tot weten"
(Knowledge through measurement)

Superconductor



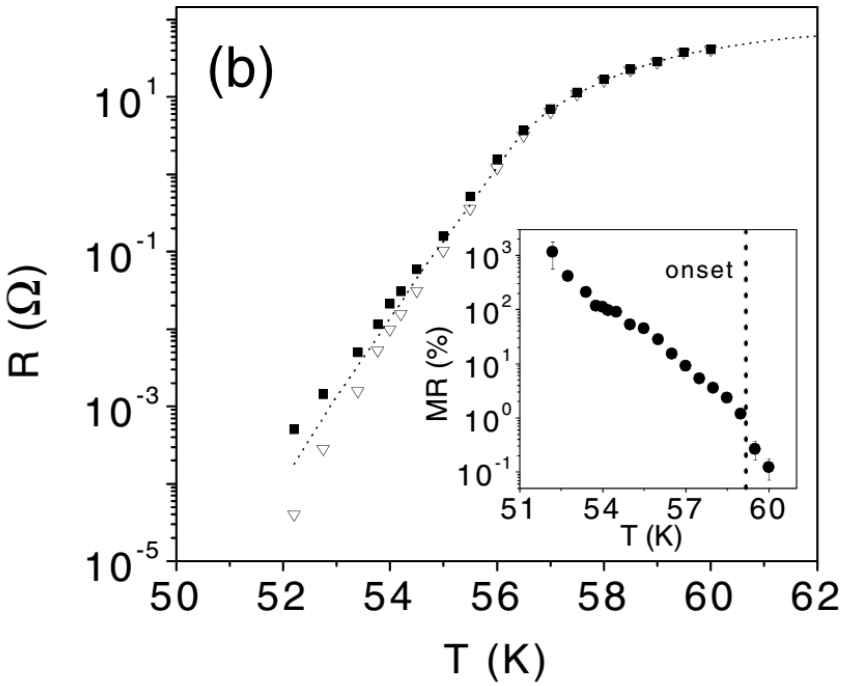
Superconductor

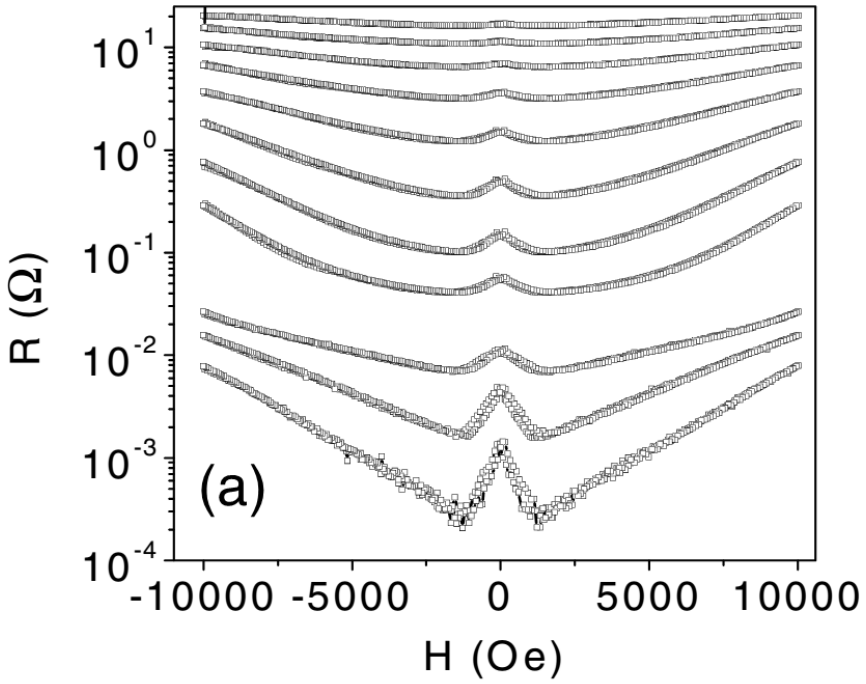


Wikipedia

Superconductor

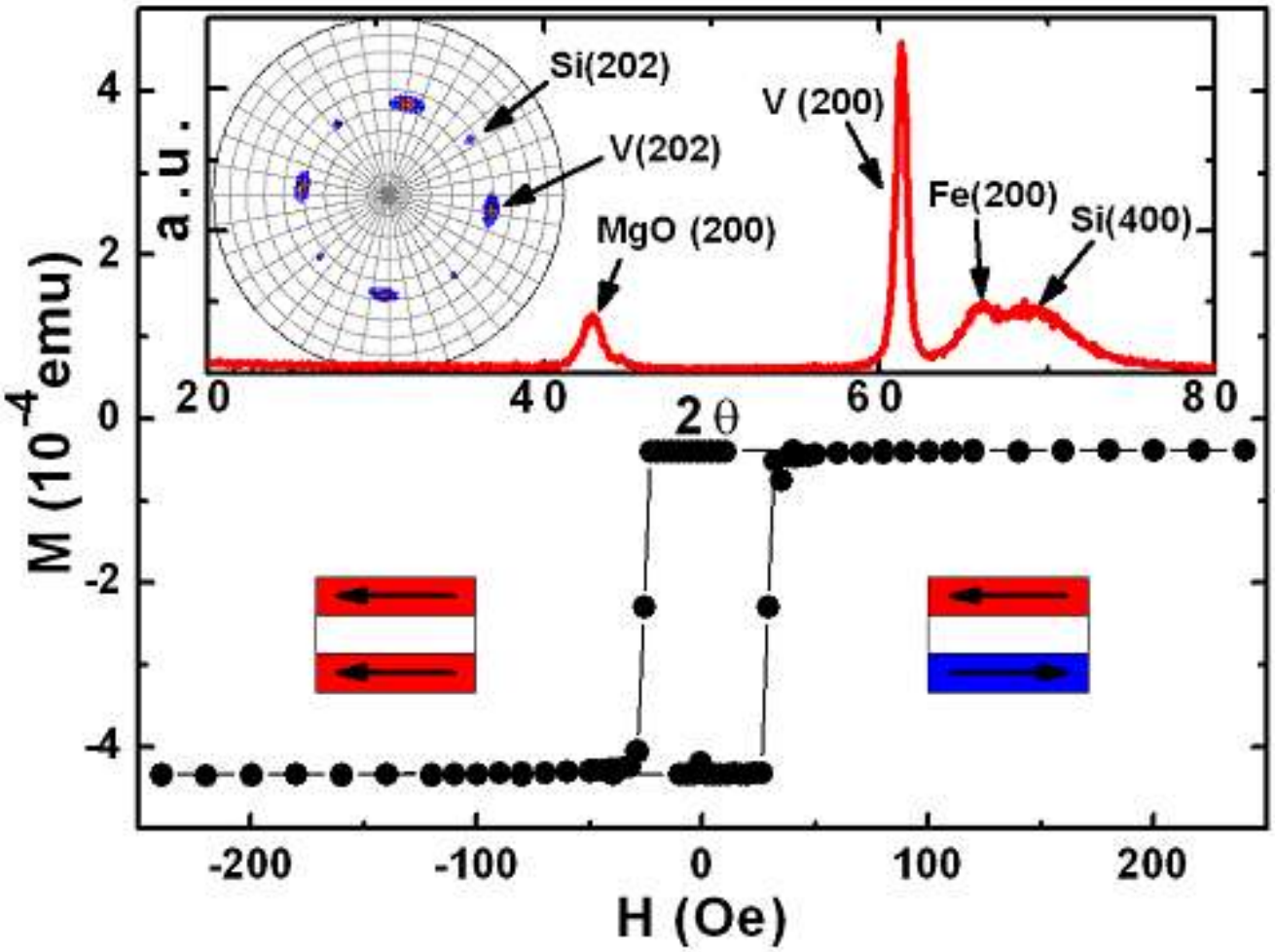
LaCaMnO—YBaCuO—LaCaMnO multilayers





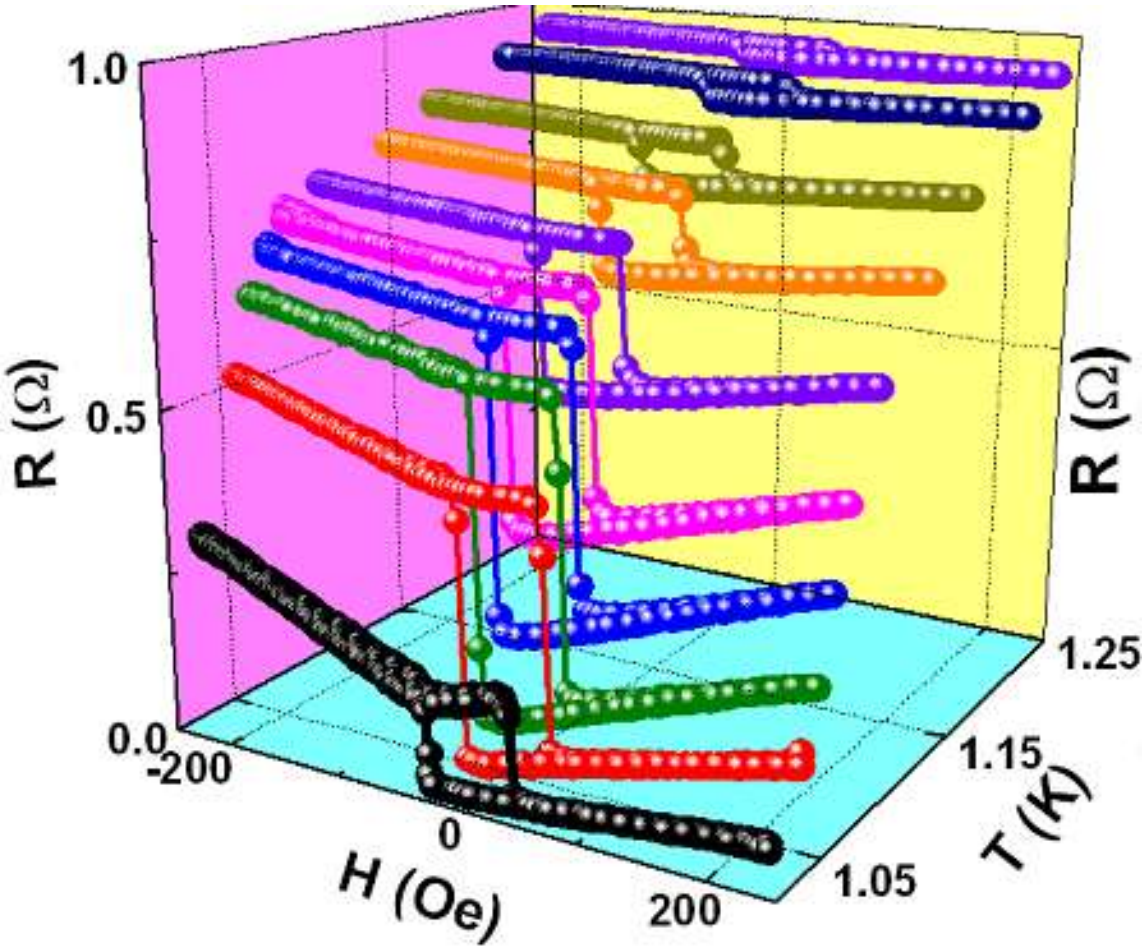
Pena, et al, PRL (2005)

Superconductor

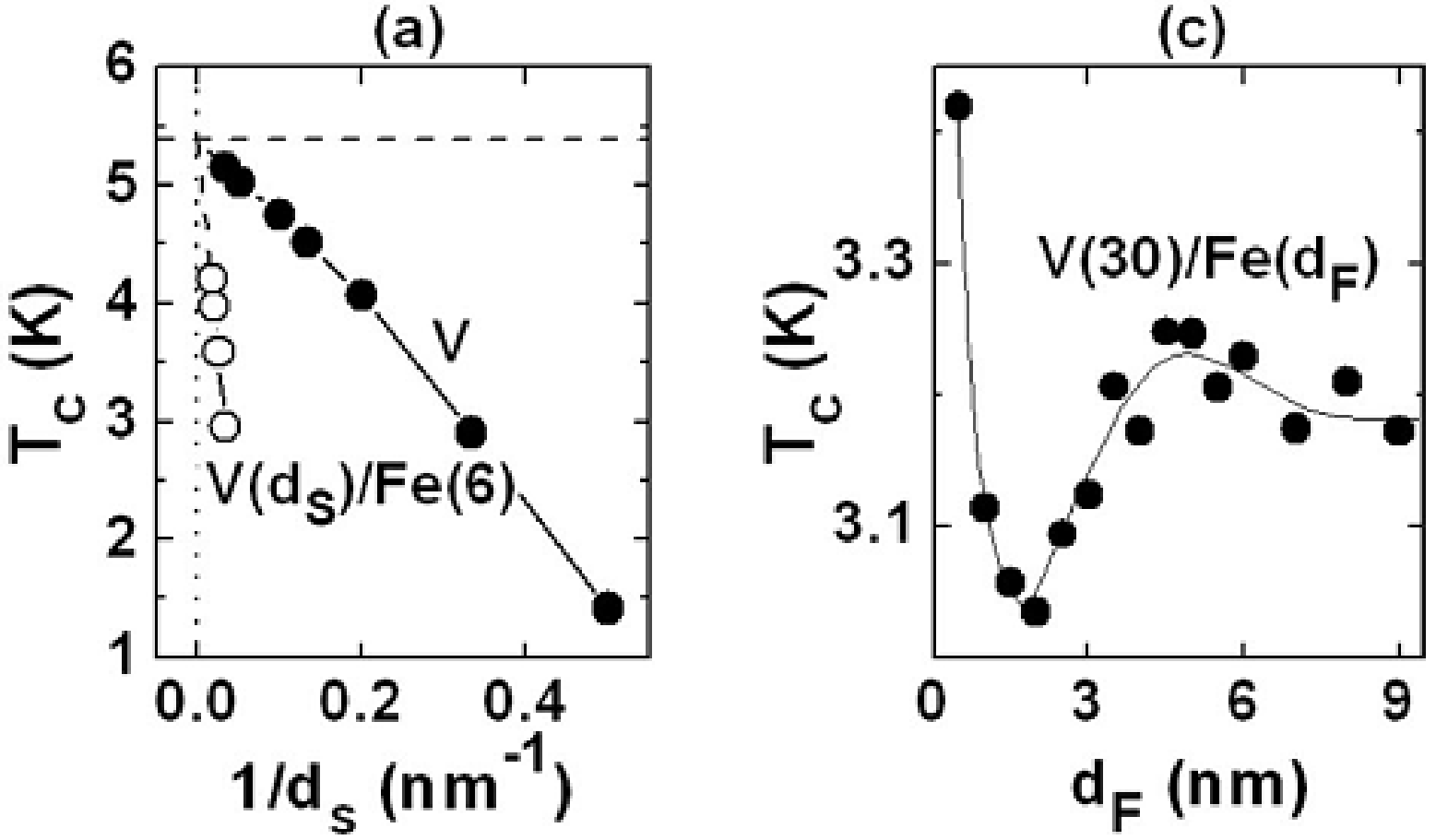


Miao, et al, PRL (2008)

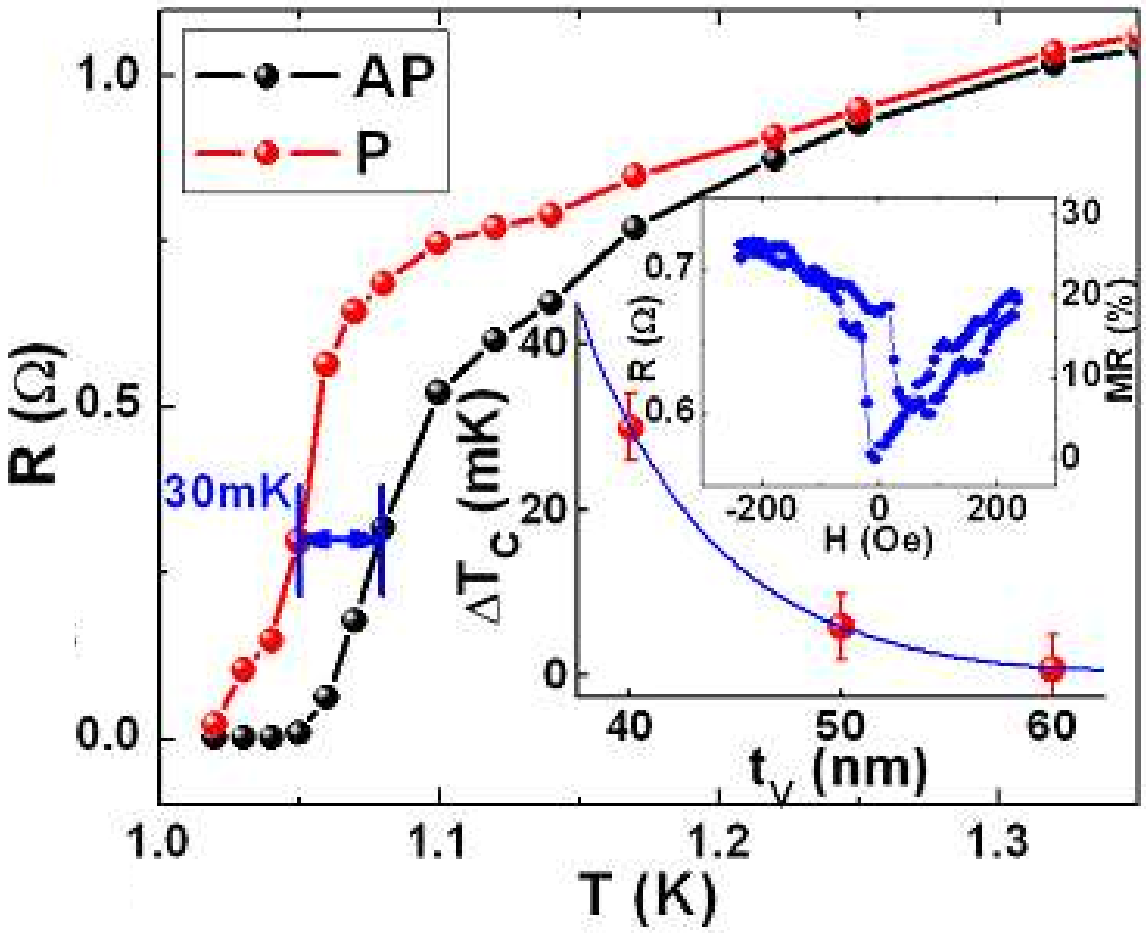
Superconductor



Superconductor

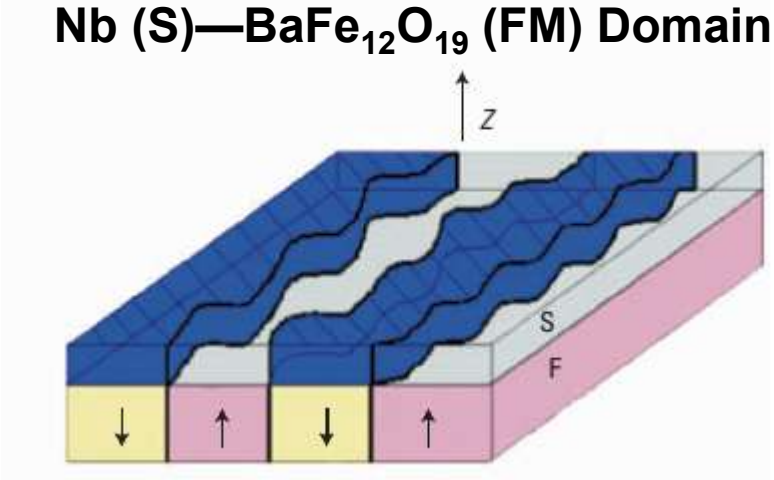


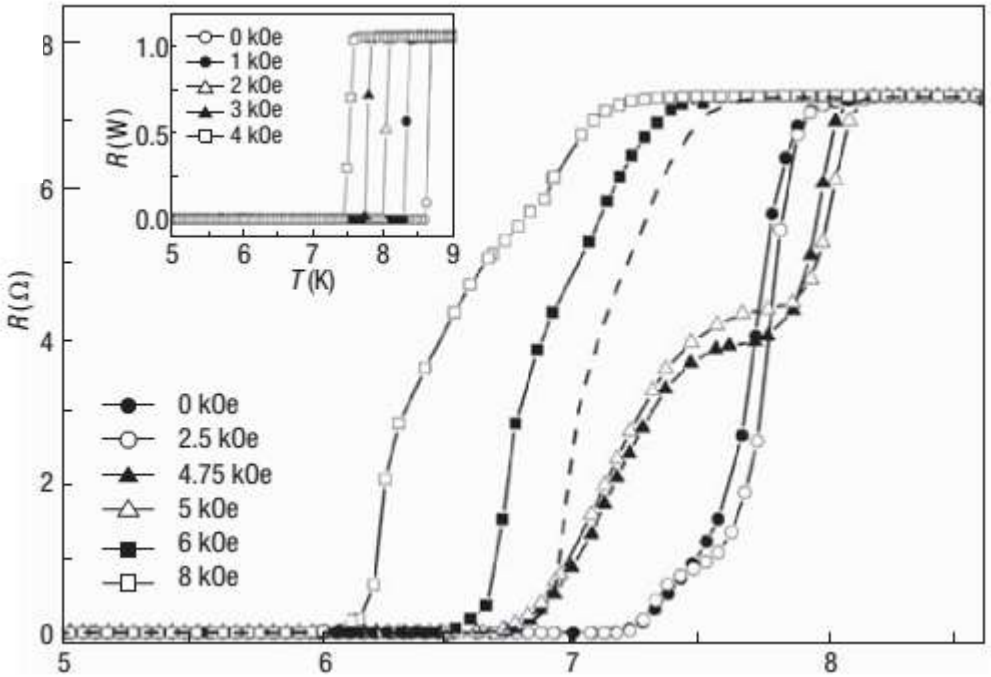
Superconductor



Superconductor

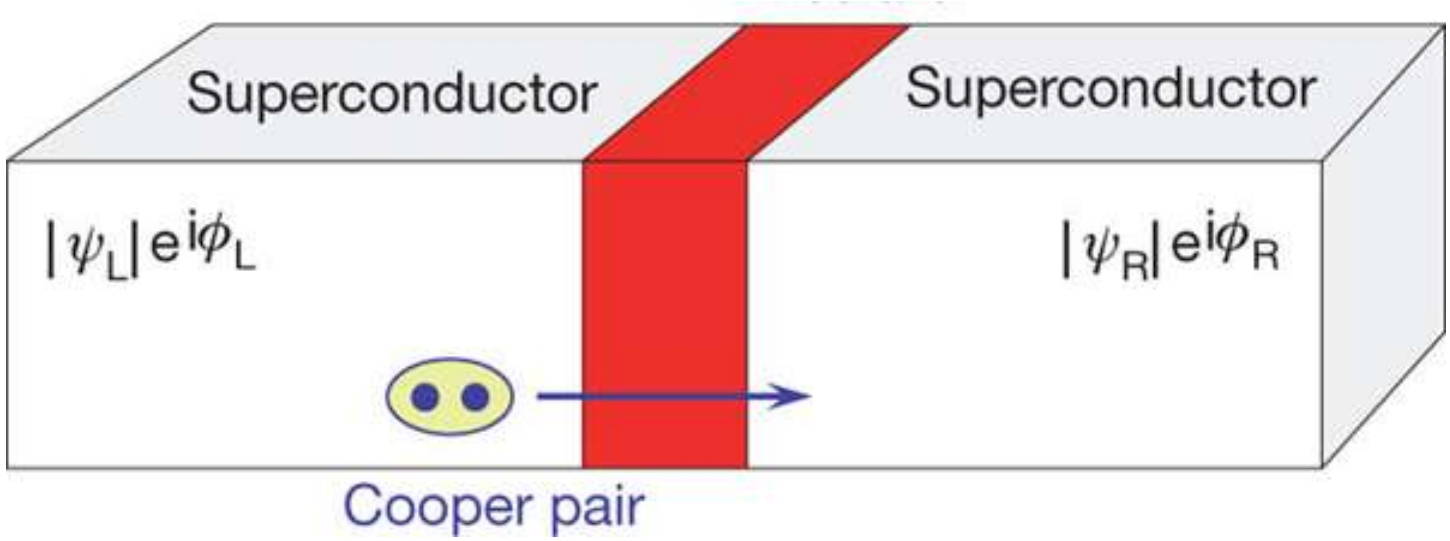
Nb (S)—$BaFe_{12}O_{19}$ (FM) Domain wall superconductivity



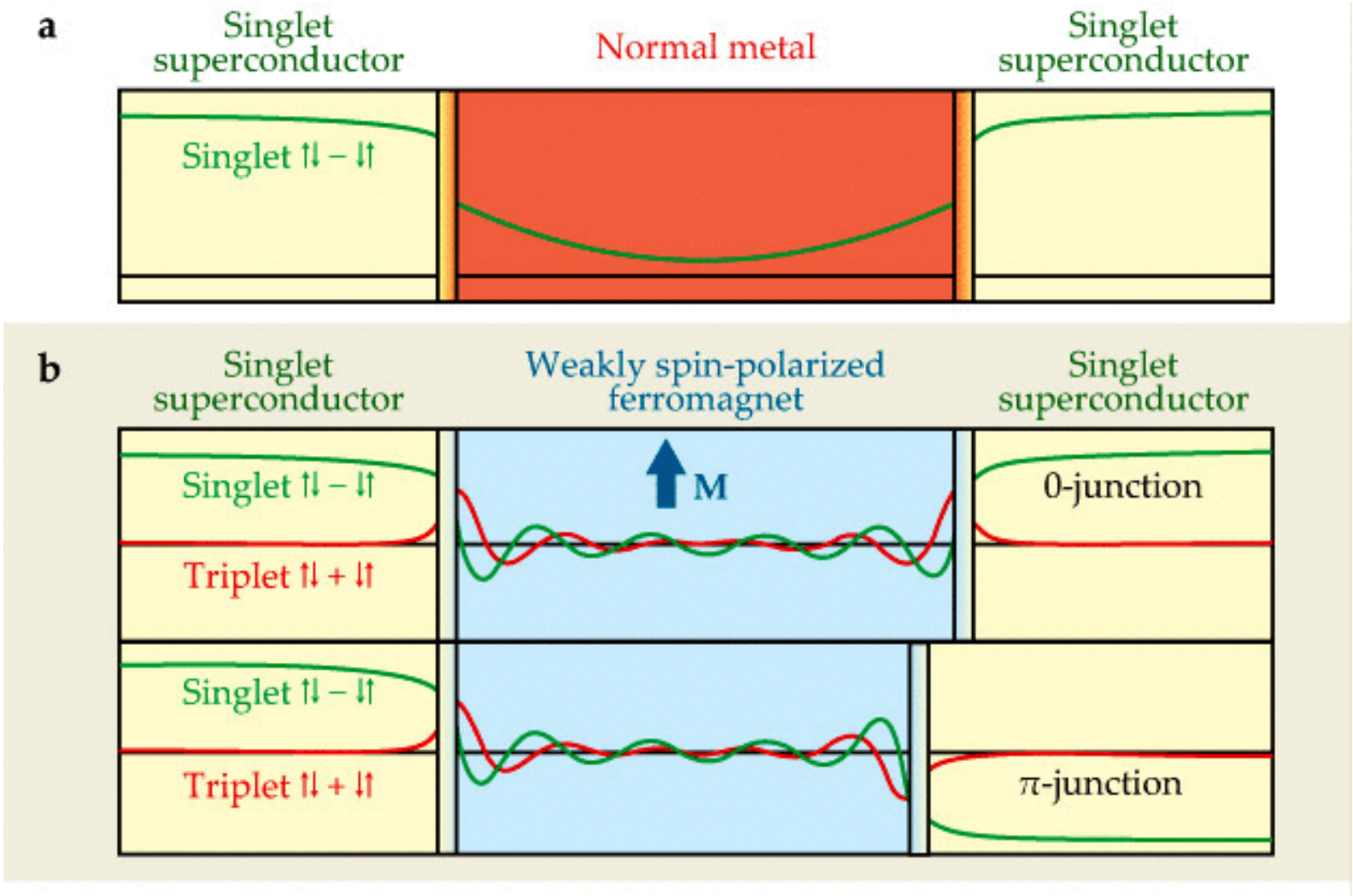


Yang, et al, Nature Phys. (2004)

Josephson junction



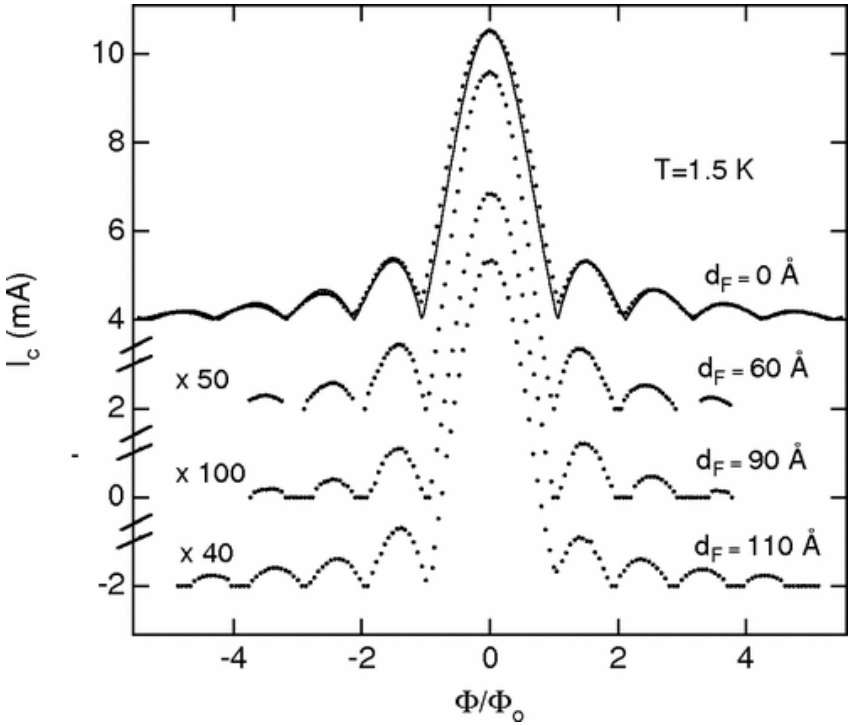
Josephson junction

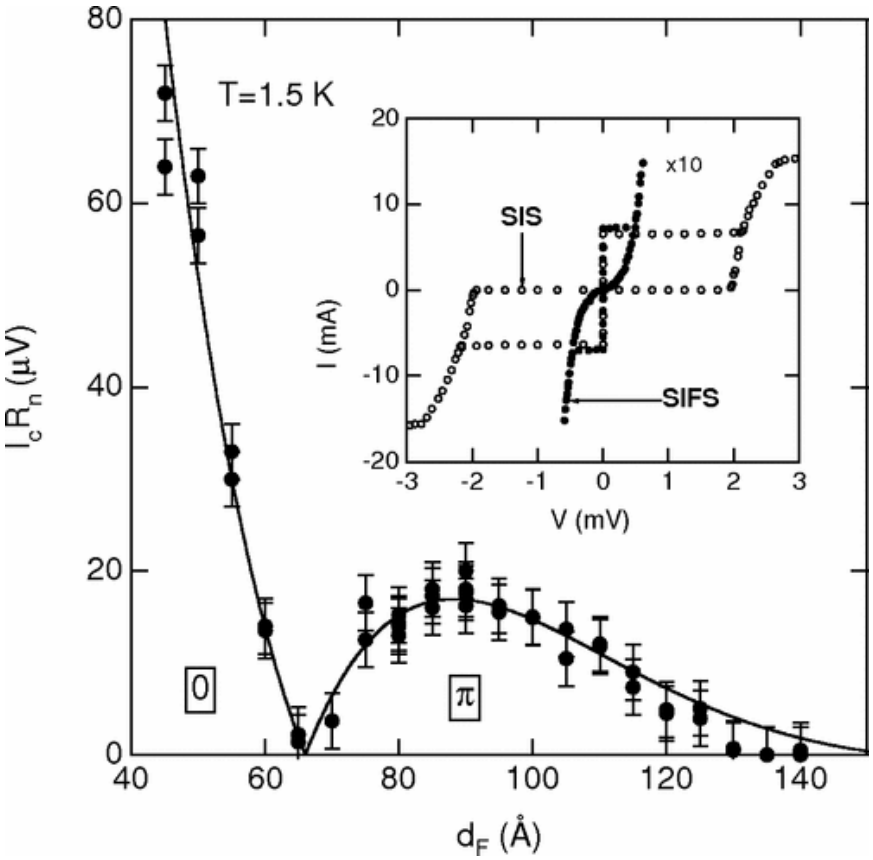


Matthias Eschrig, Physics Today (2011)

$\pi-$ Josephson junction

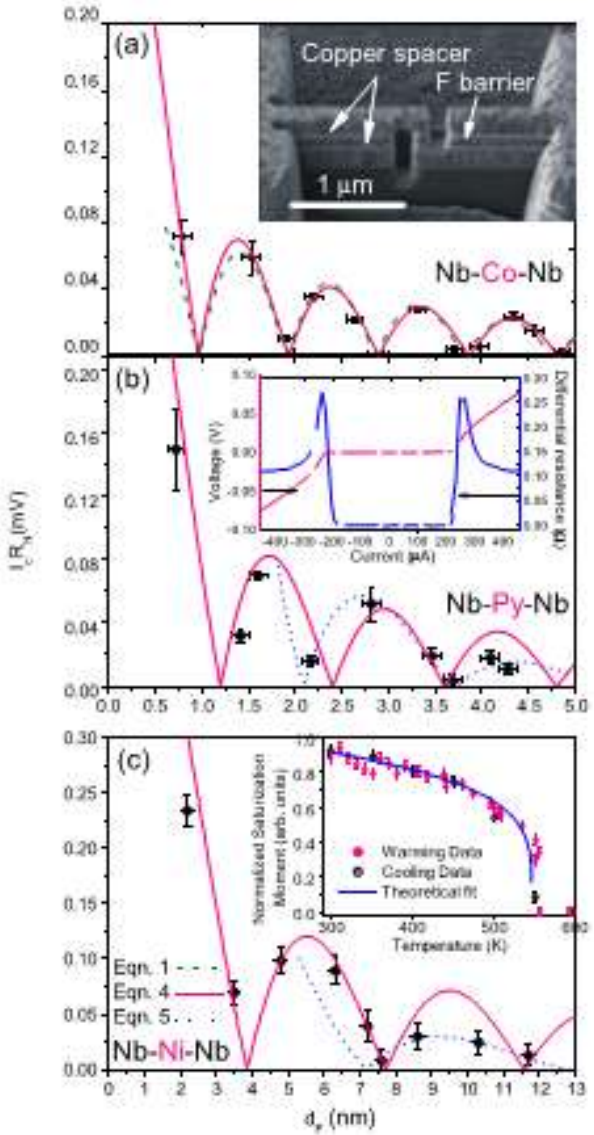
$Nb/Al/Al_2O_3/PdNi/Nb$





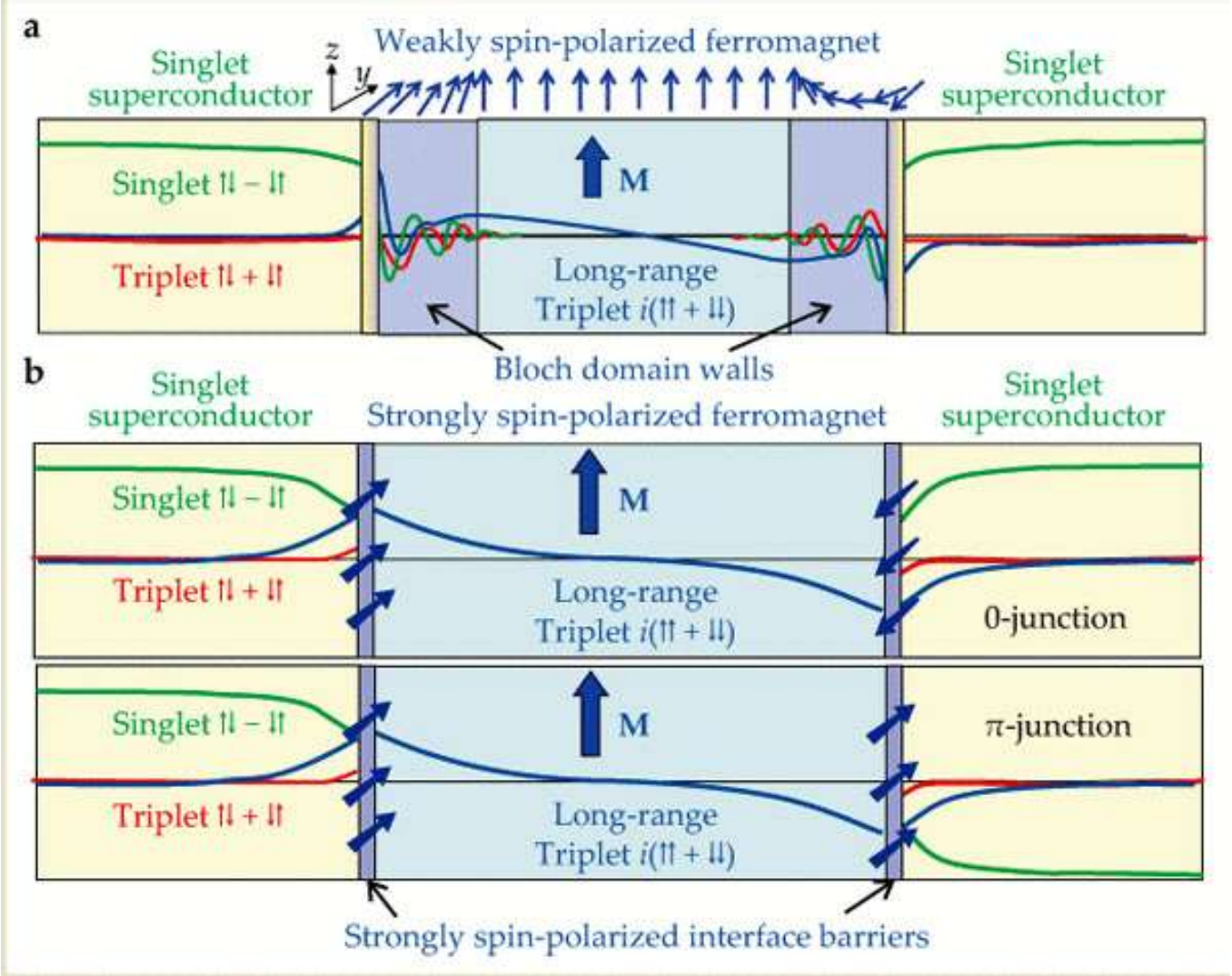
Kontos, et al, PRL (2002)

Pi Josephson junction

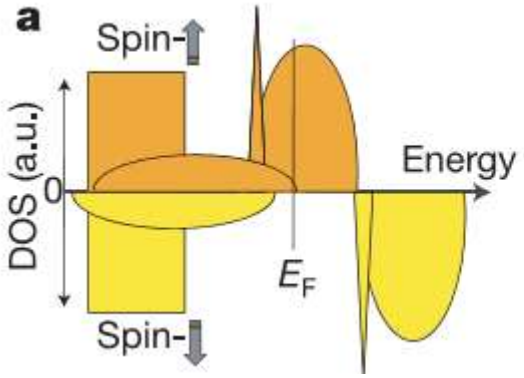


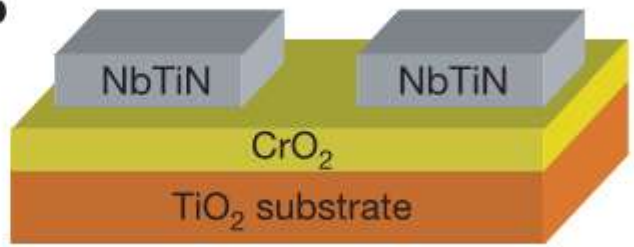
Robison, et al, PRL (2006)

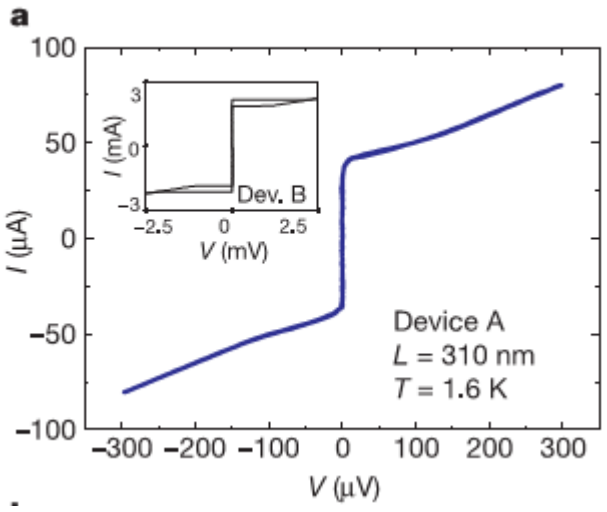
Spin triplet Josephson junction

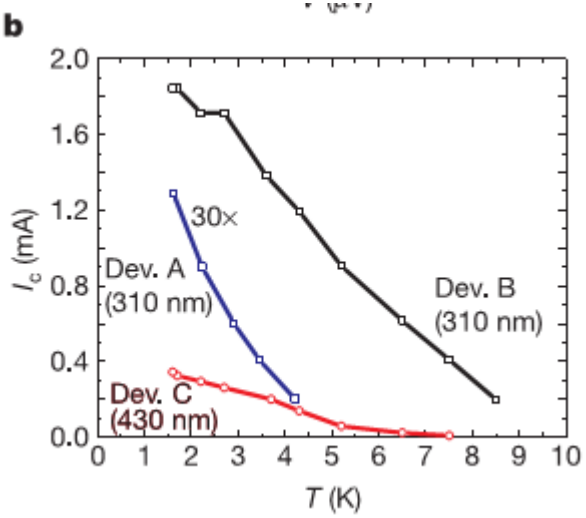


Spin triplet Josephson junction



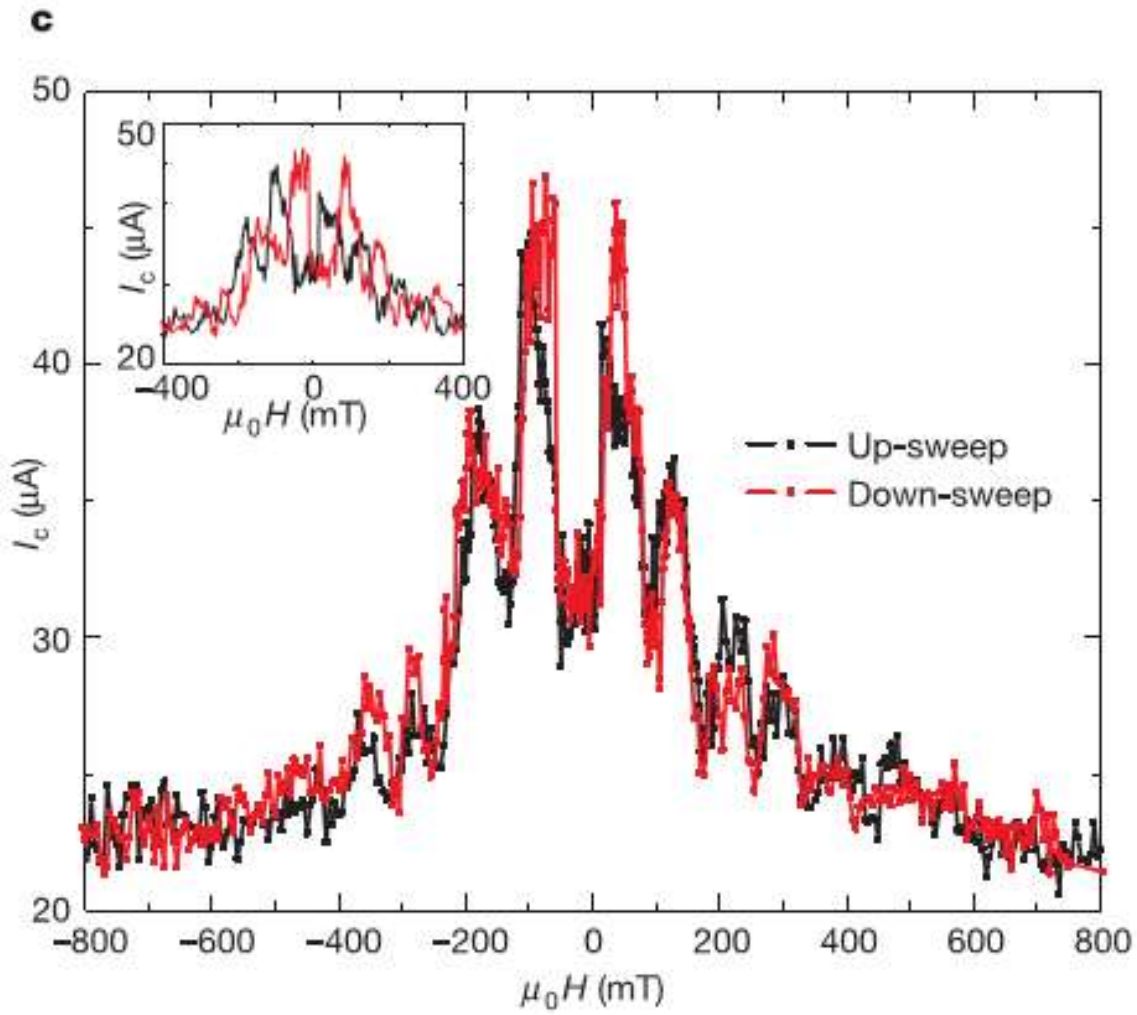




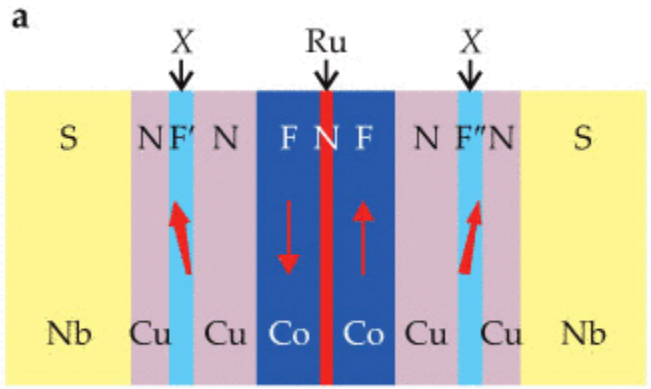


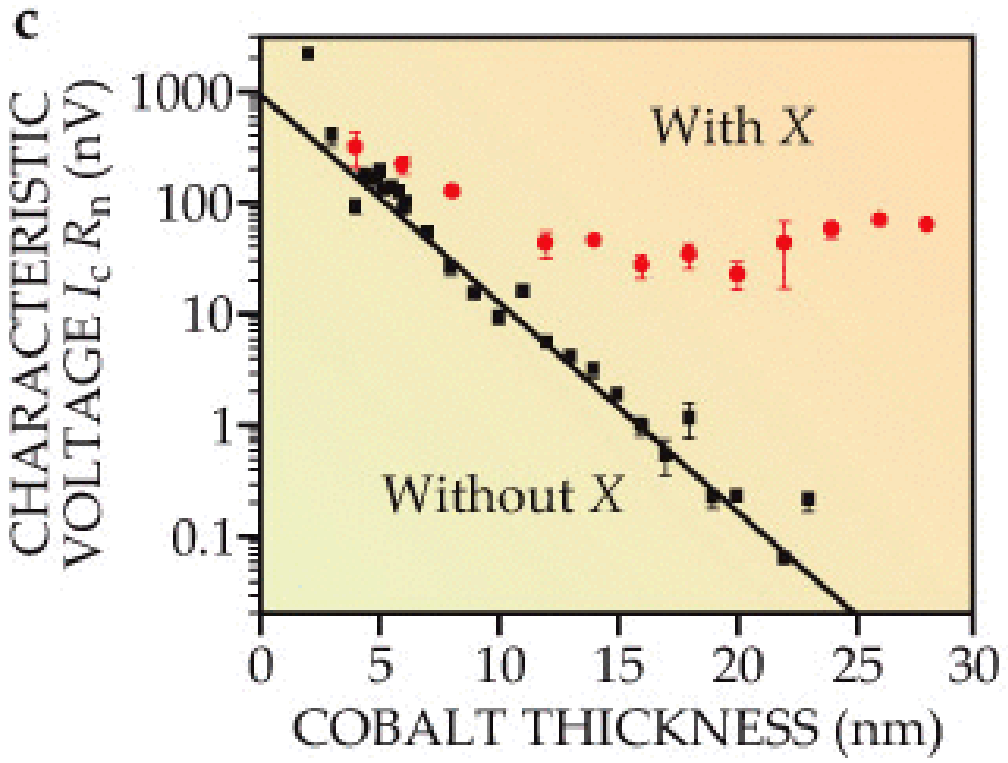
Kerizer, et al, Nature (2006)

Spin triplet Josephson junction



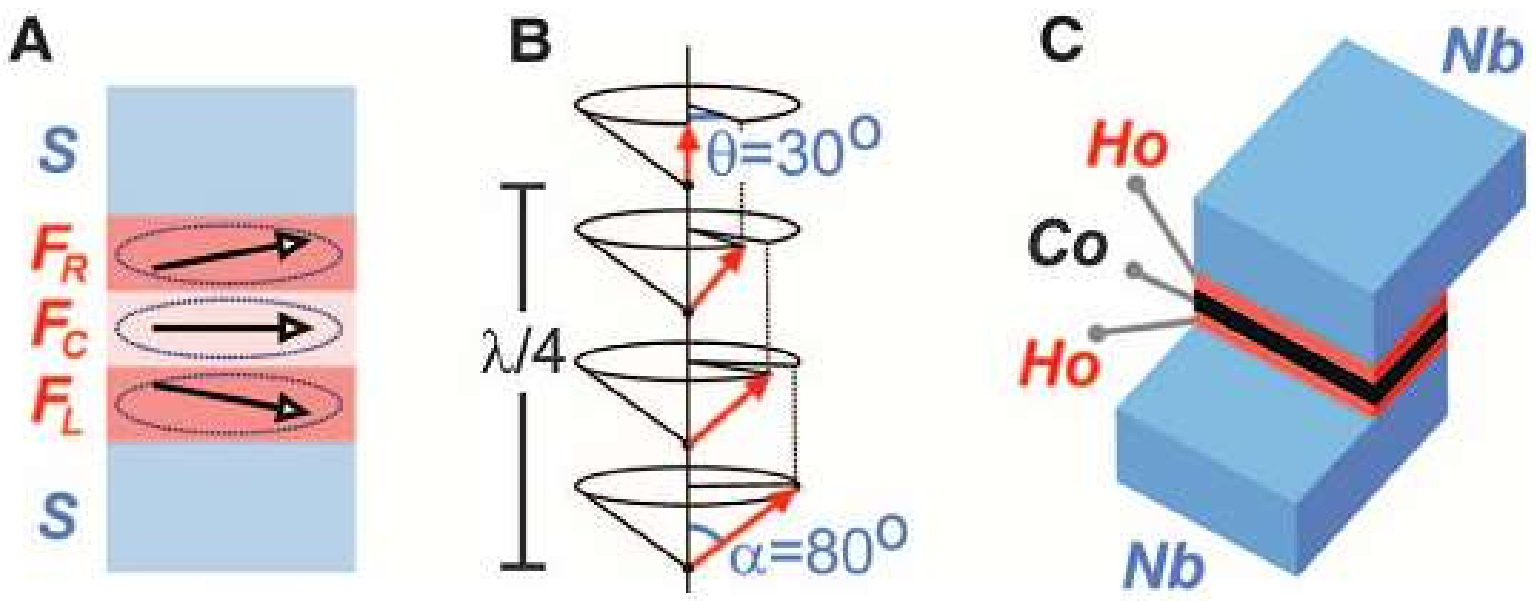
Spin triplet Josephson junction





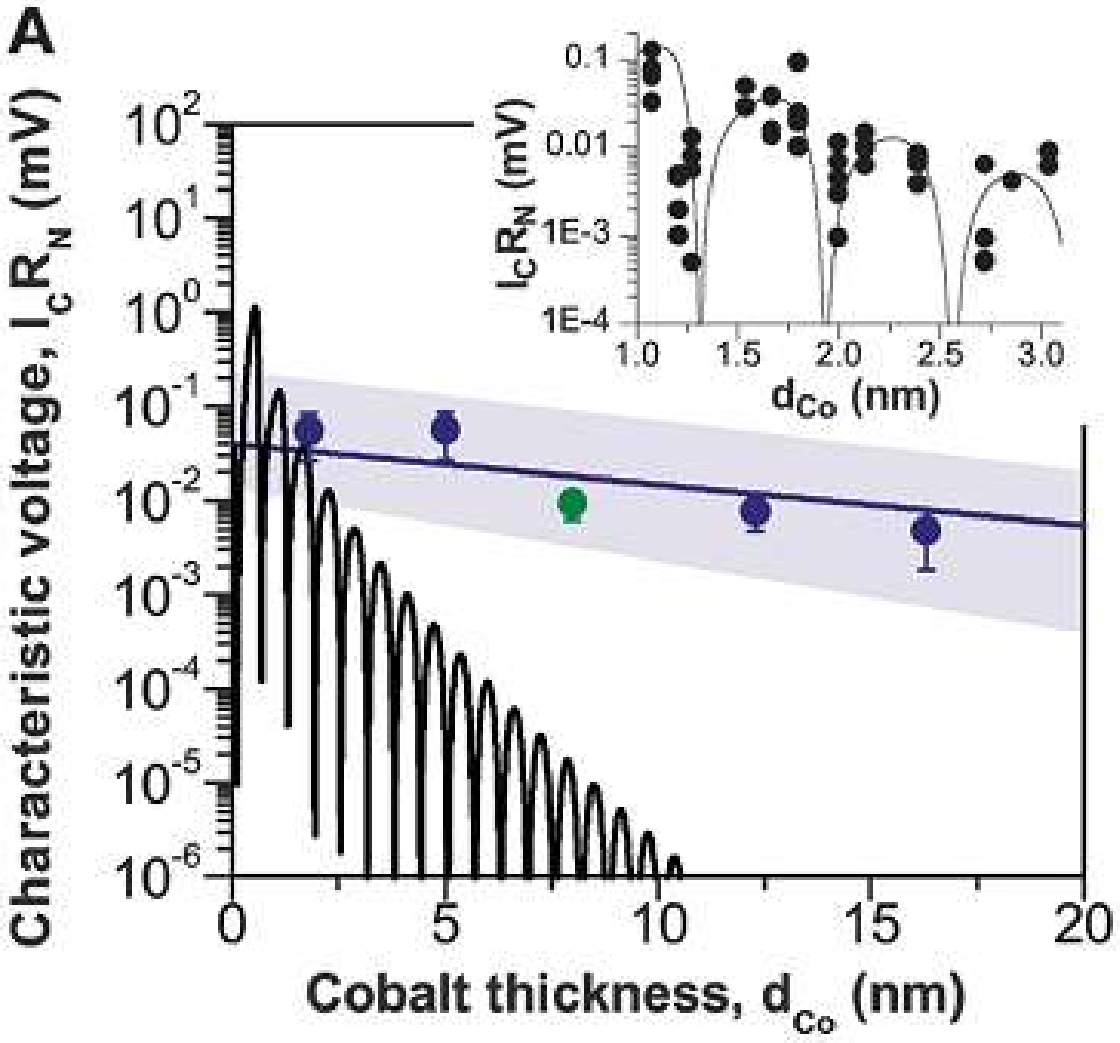
Khaire, et al, PRL (2010)

Spin triplet Josephson junction



Robinson, et al, Science (2010)

Spin triplet Josephson junction

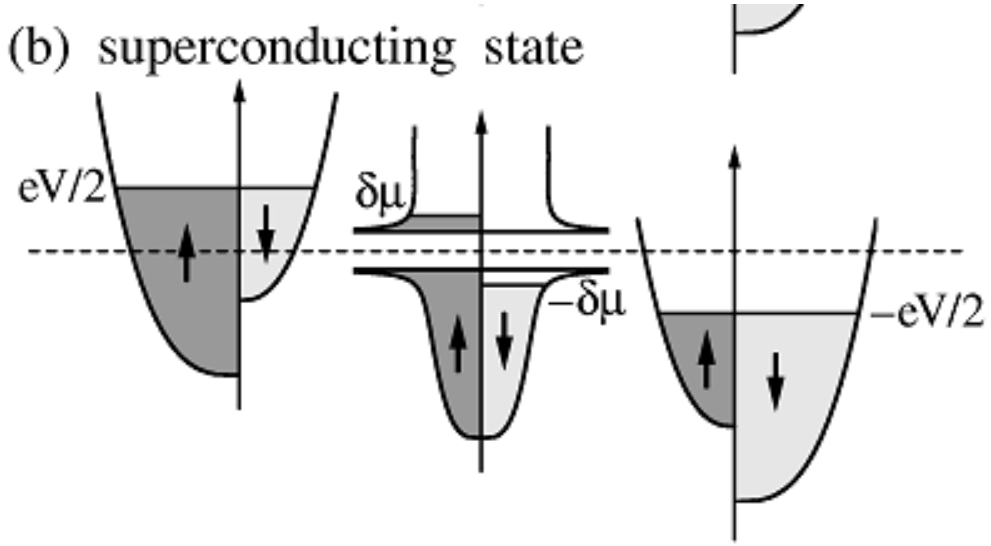


Spin injection into Superconductor

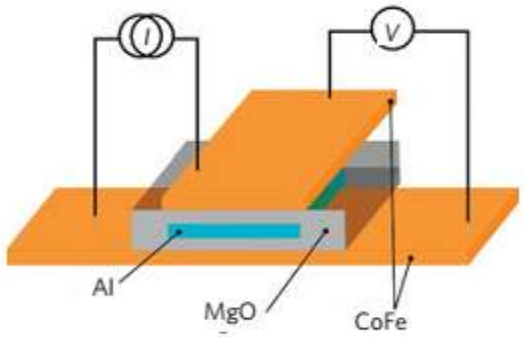
Spin Imbalance and Magnetoresistance in Ferromagnet/Superconductor/Ferromagnet Double Tunnel Junctions

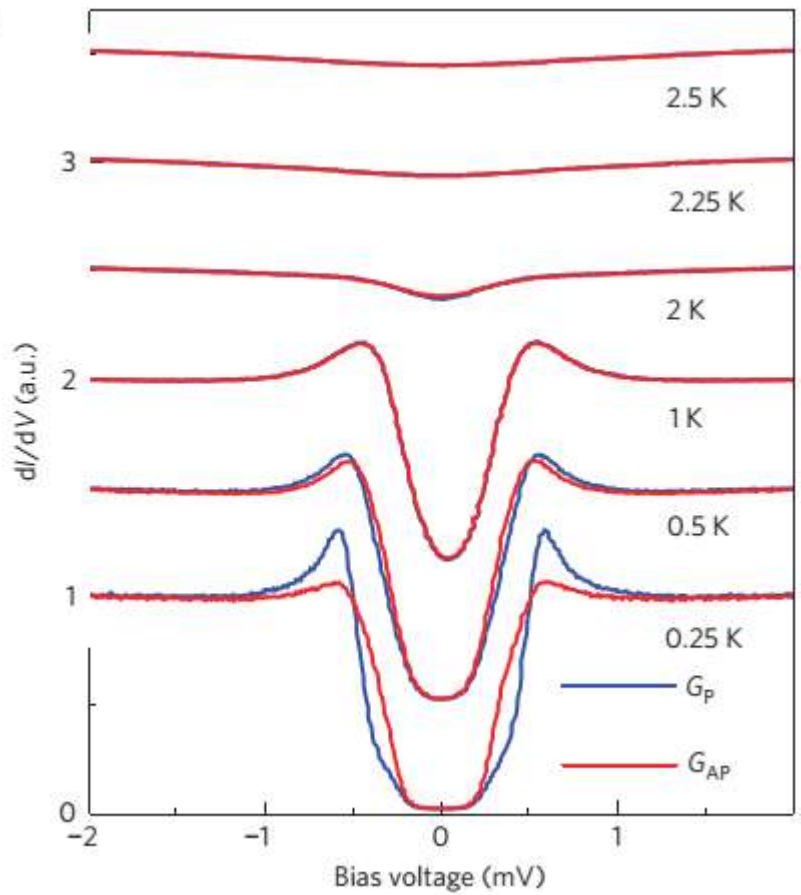
S. Takahashi,[1] H. Imamura,[2] and S. Maekawa[1]
[1]*Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
[2]*CREST and Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*
(Received 22 January 1999)

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.



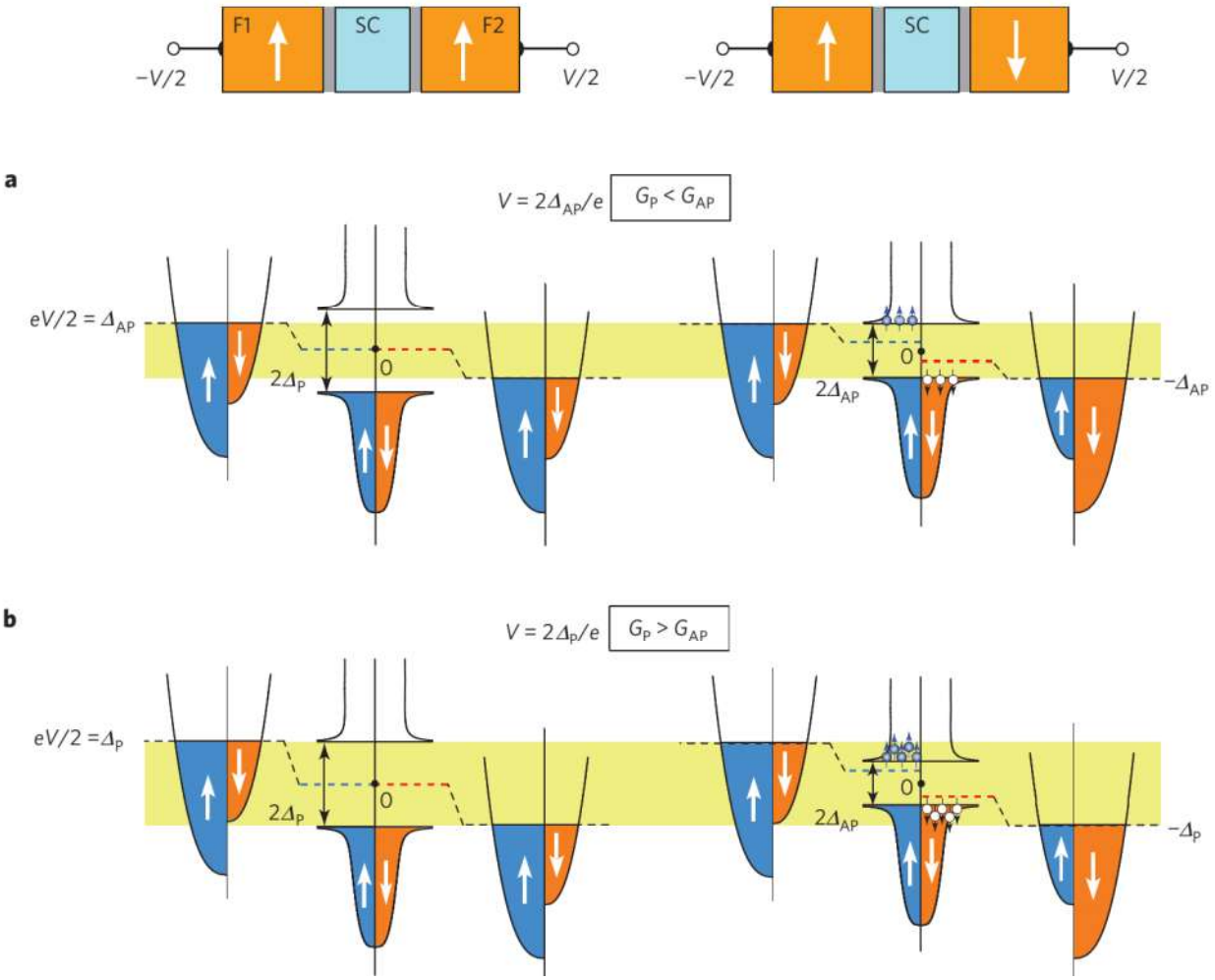
Spin injection into Superconductor





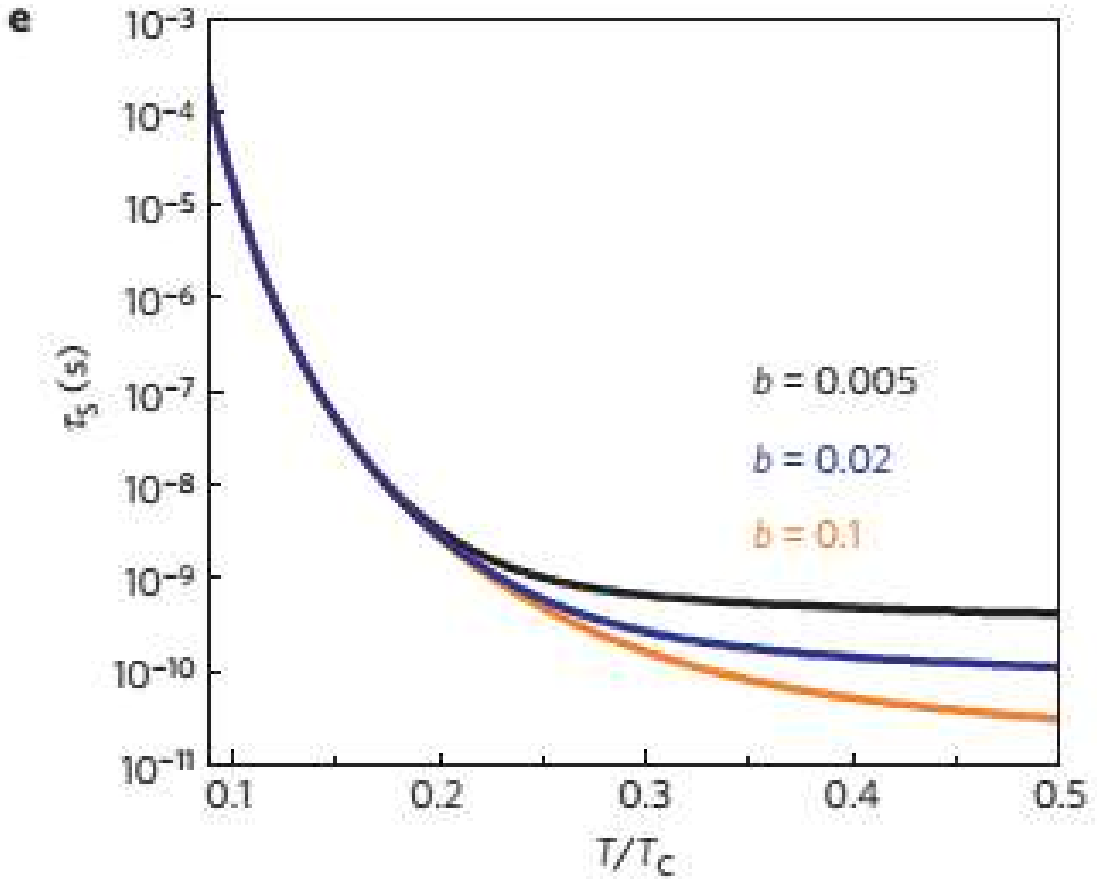
Yang, et al, Nature Materials (2010)

Spin injection into Superconductor

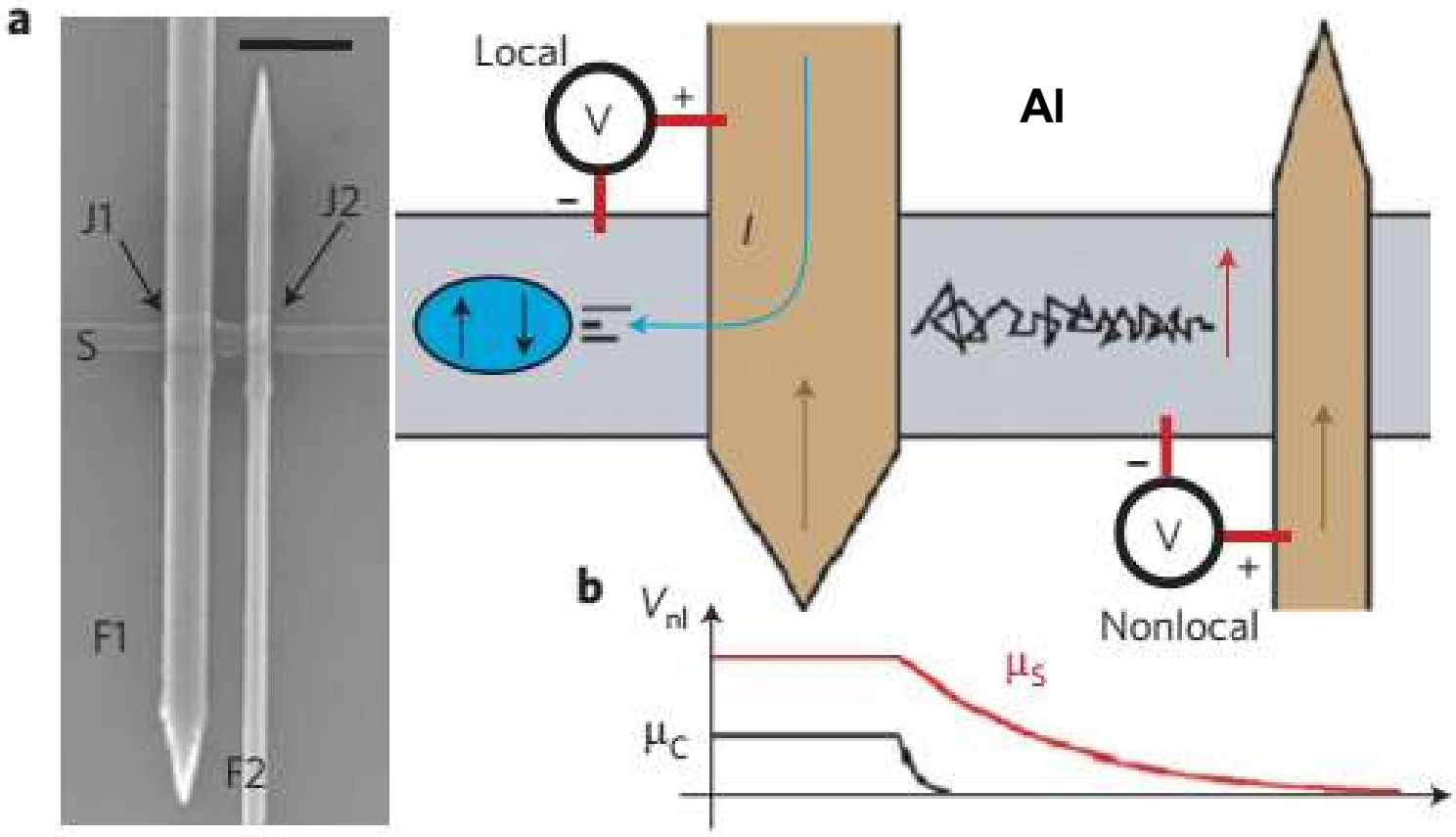


Spin injection into Superconductor

Long spin lifetime



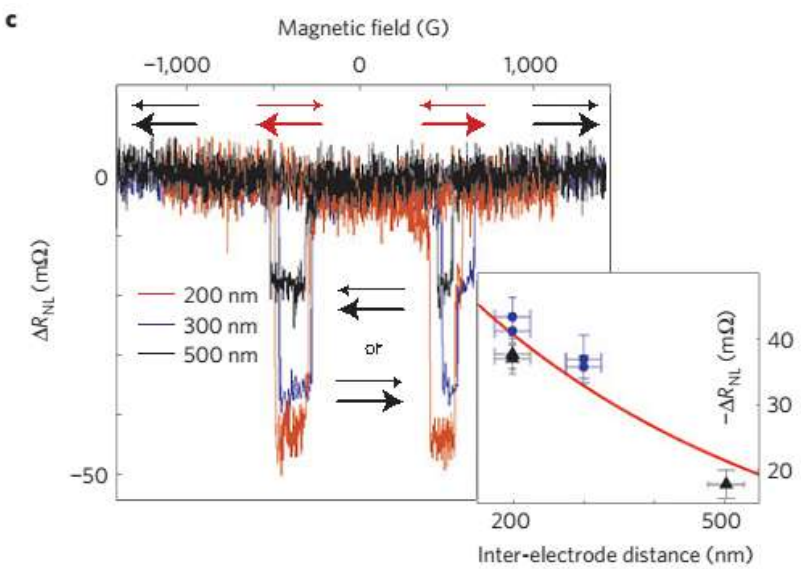
Spin injection into Superconductor

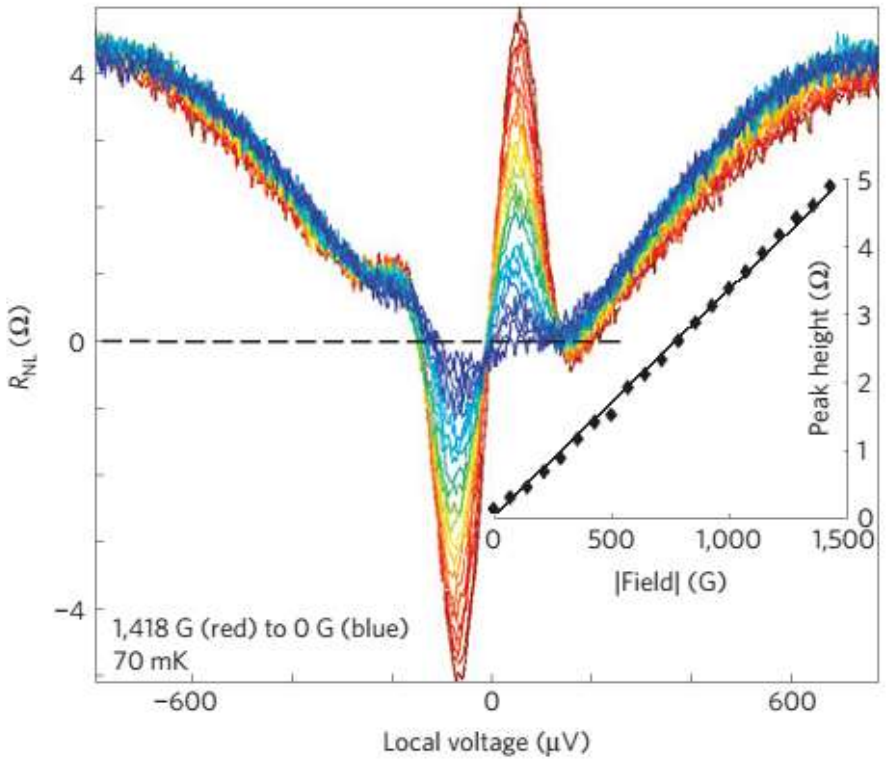


Quay, et al, Nature Physics (2013)

Spin injection into Superconductor

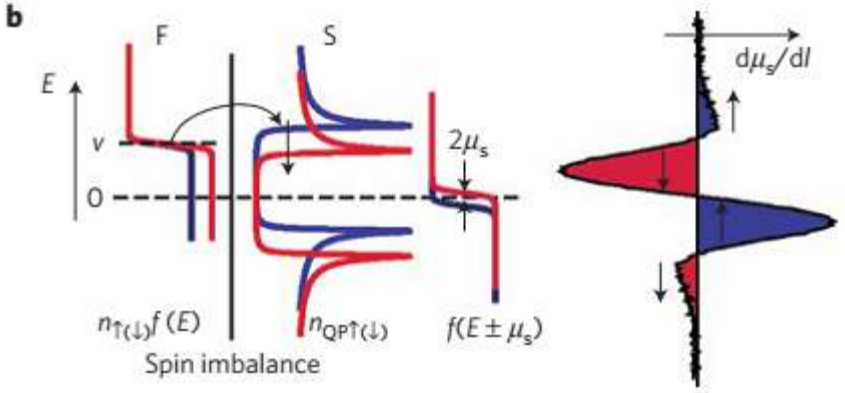
Transition from N→ S

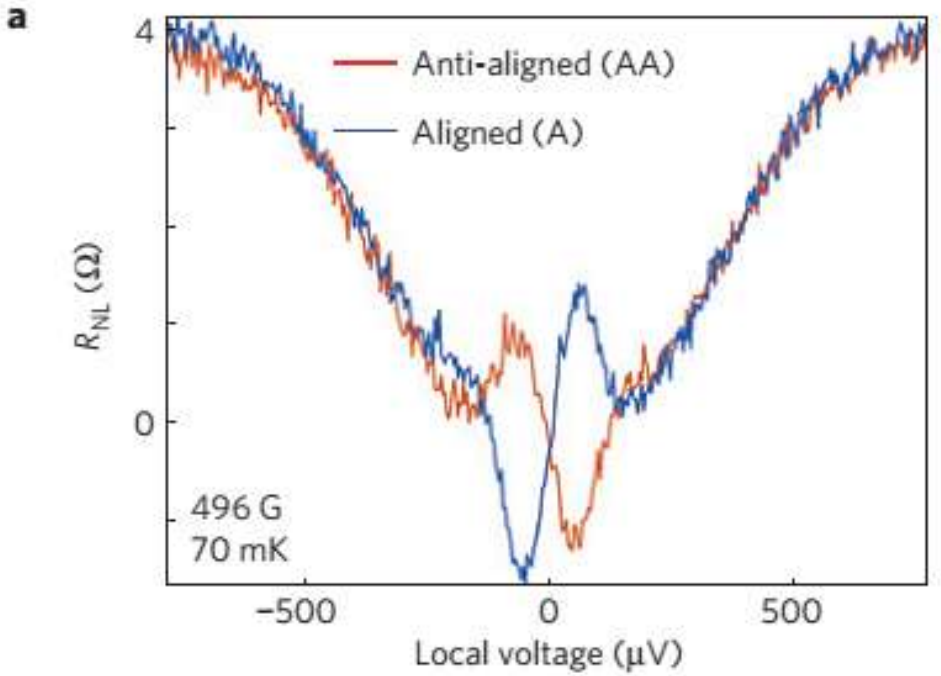




Spin injection into Superconductor

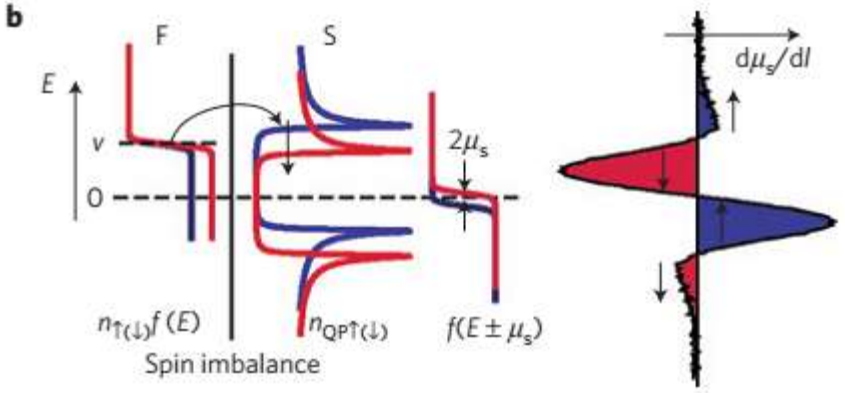
Transition from N→ S

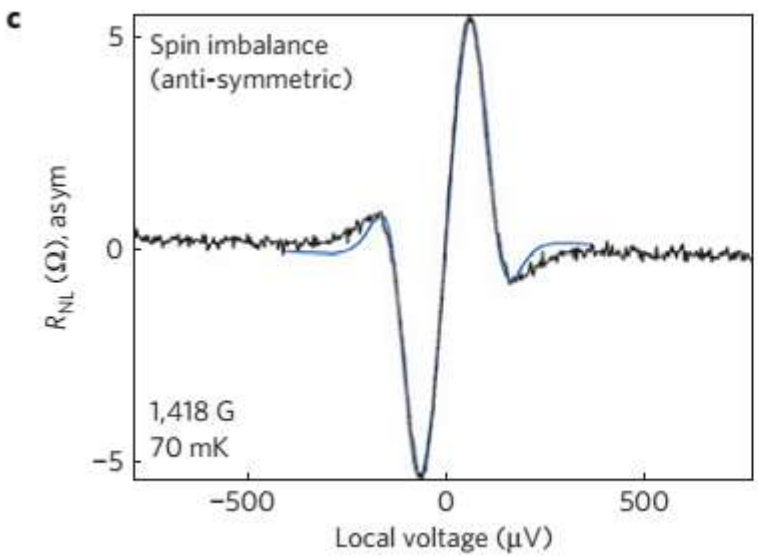


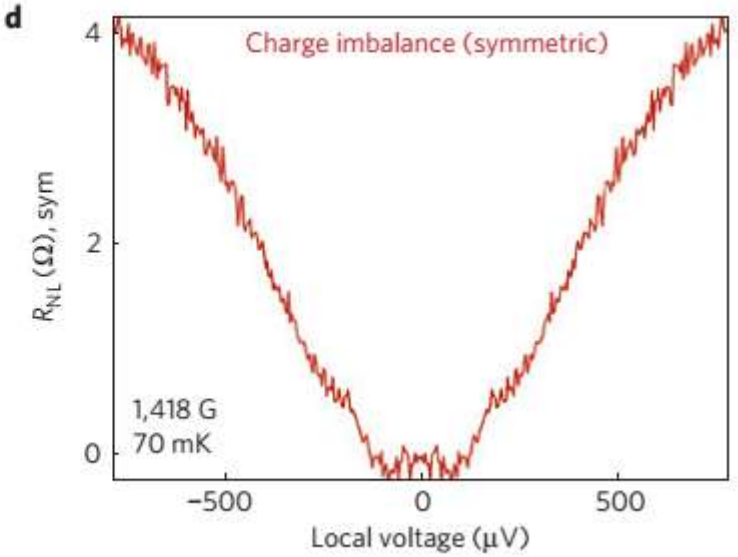


Spin injection into Superconductor

Transition from N→ S

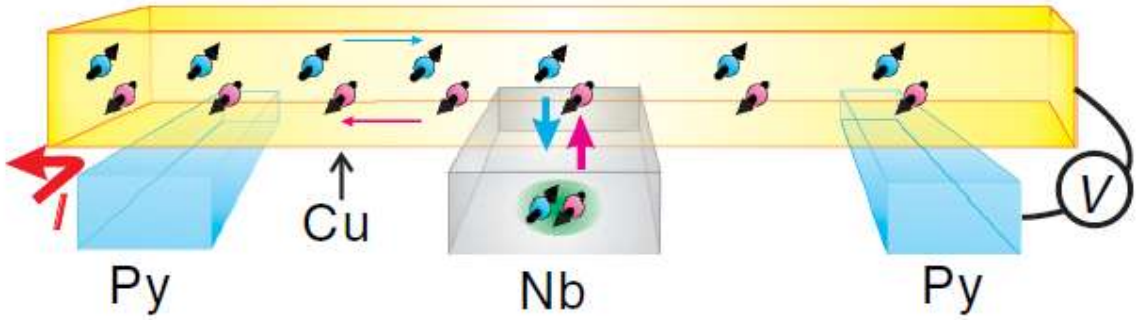


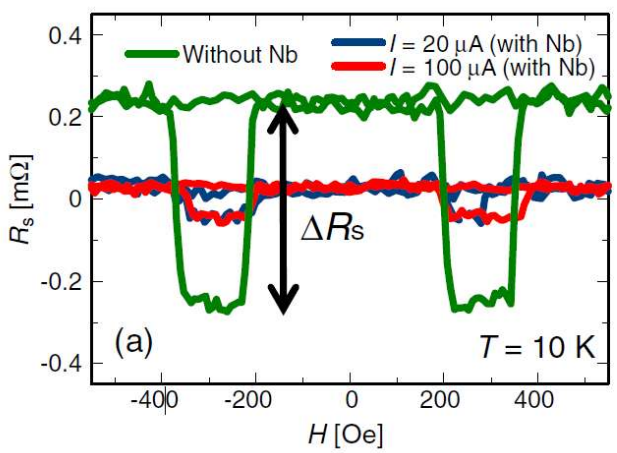


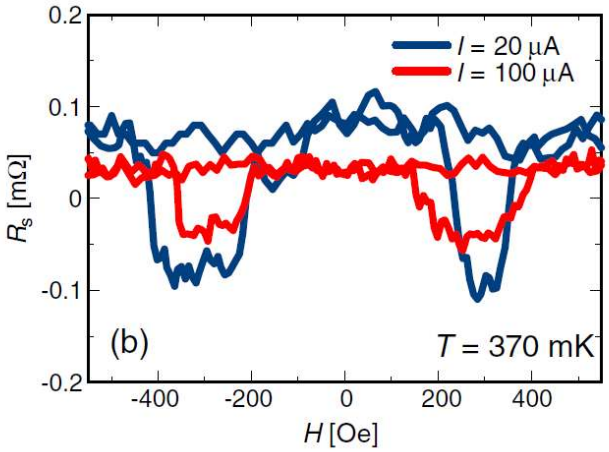


Spin injection into Superconductor

Spin absorption by Nb

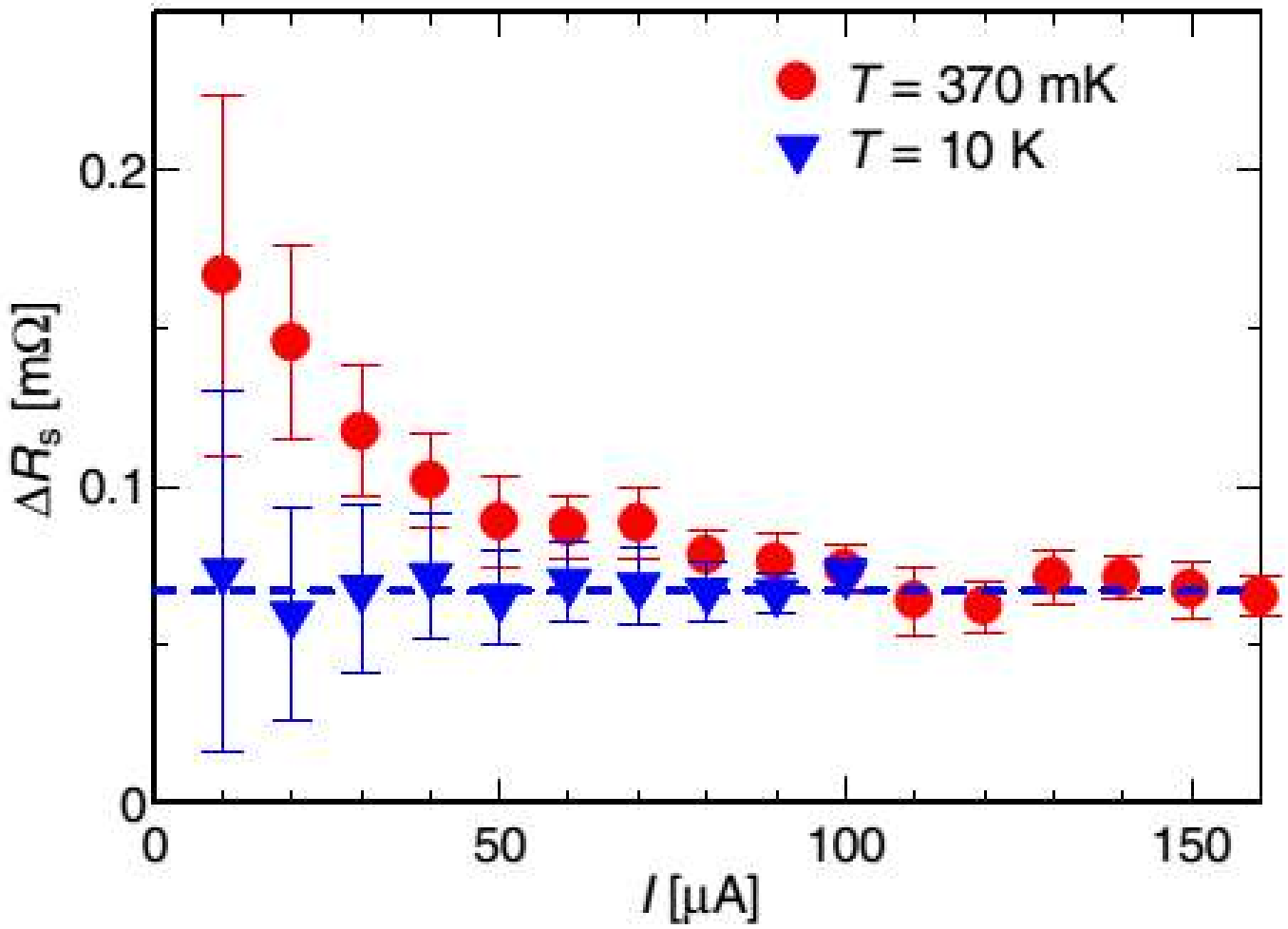




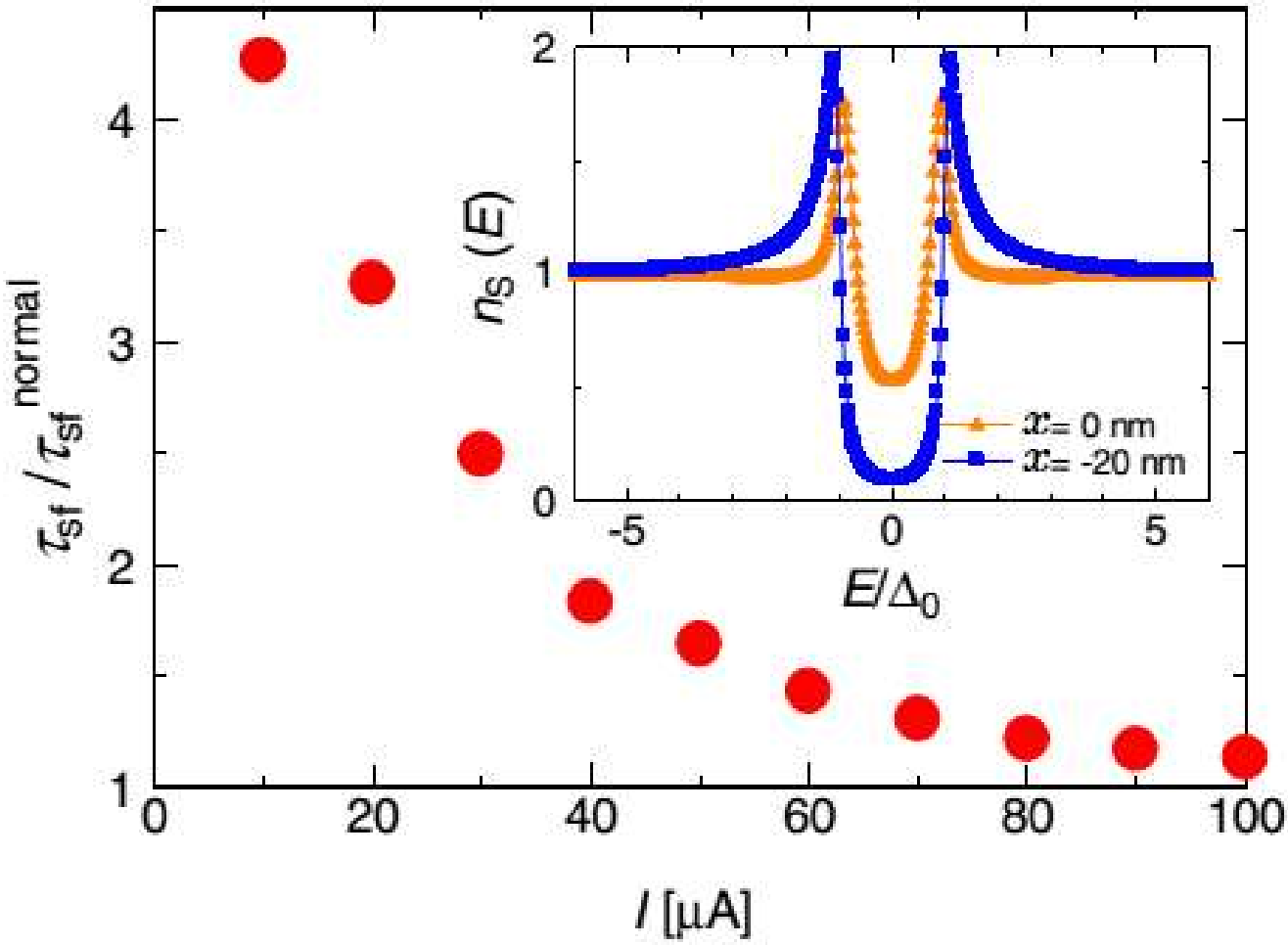


Wakamura, et al, PRL (2014)

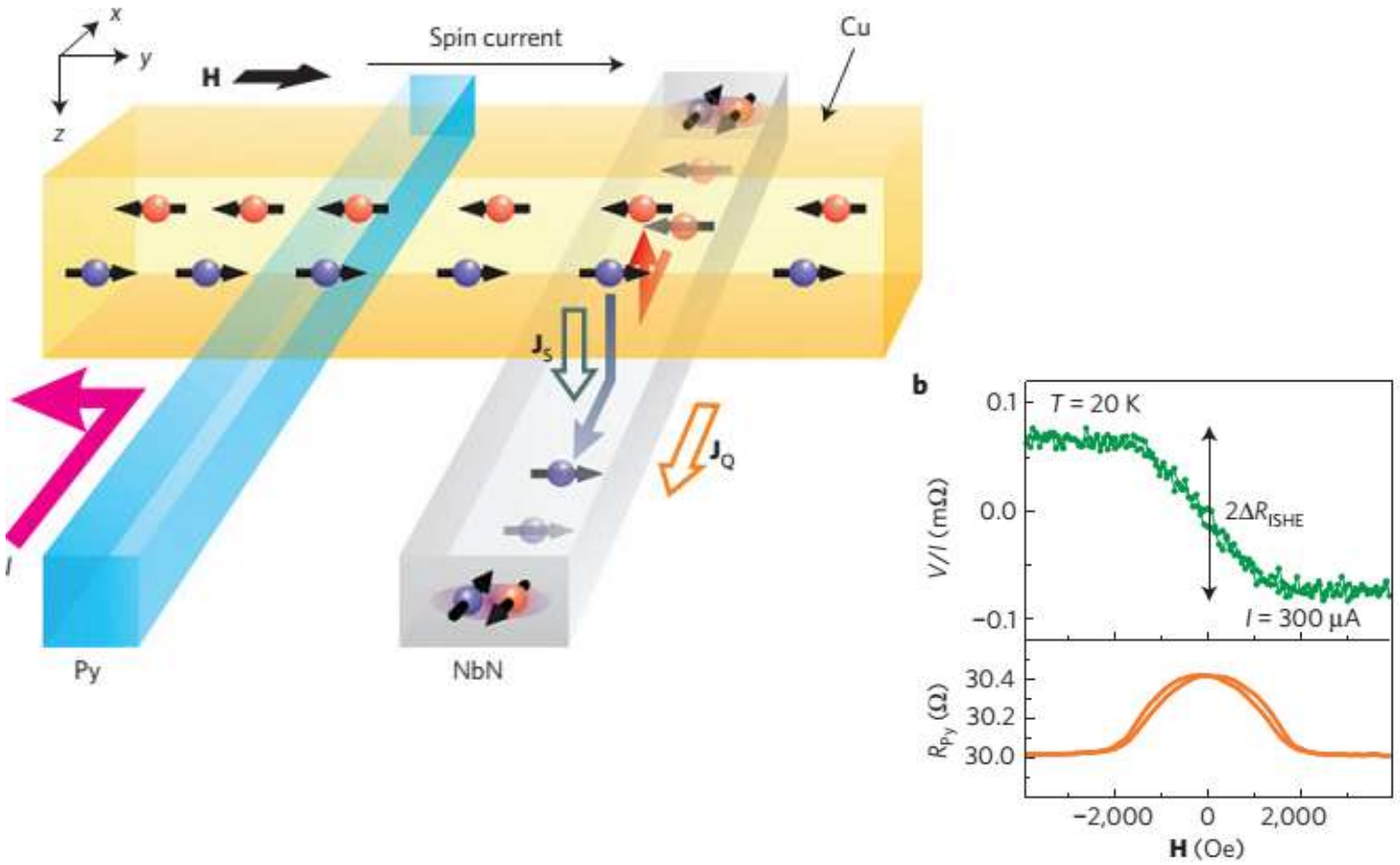
Spin injection into Superconductor



Spin injection into Superconductor

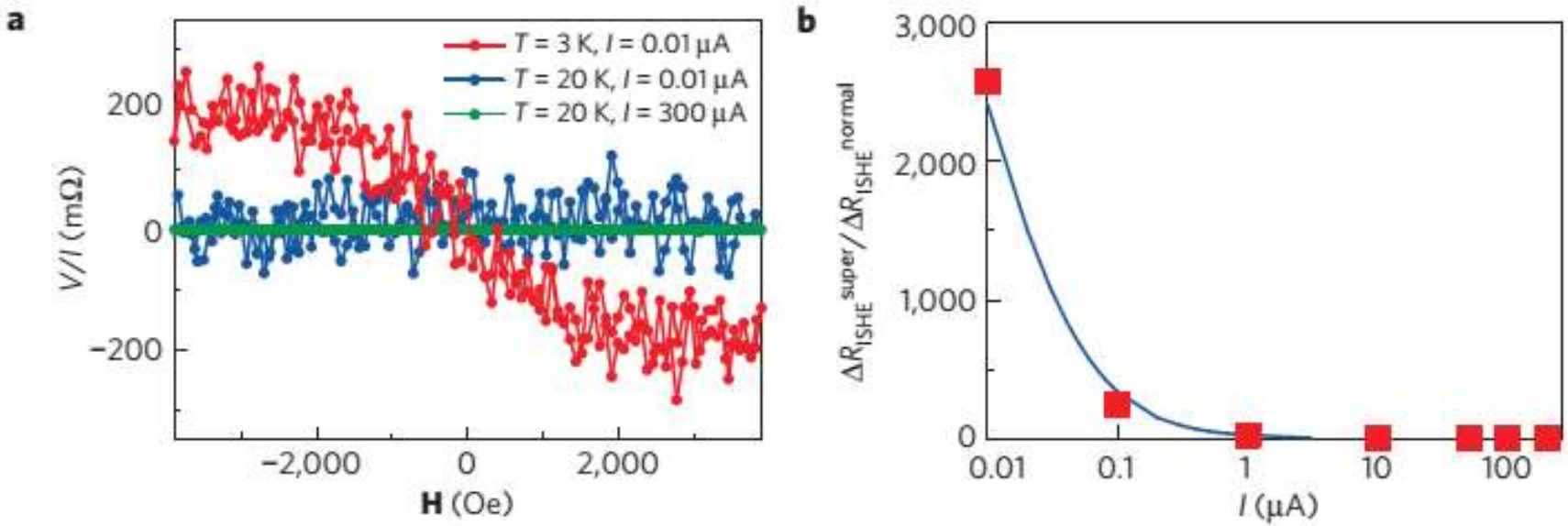


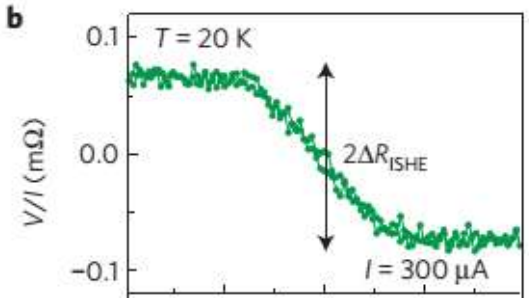
Spin Hall in Superconductor



Wakamura, et al, Nature Materials (2015)

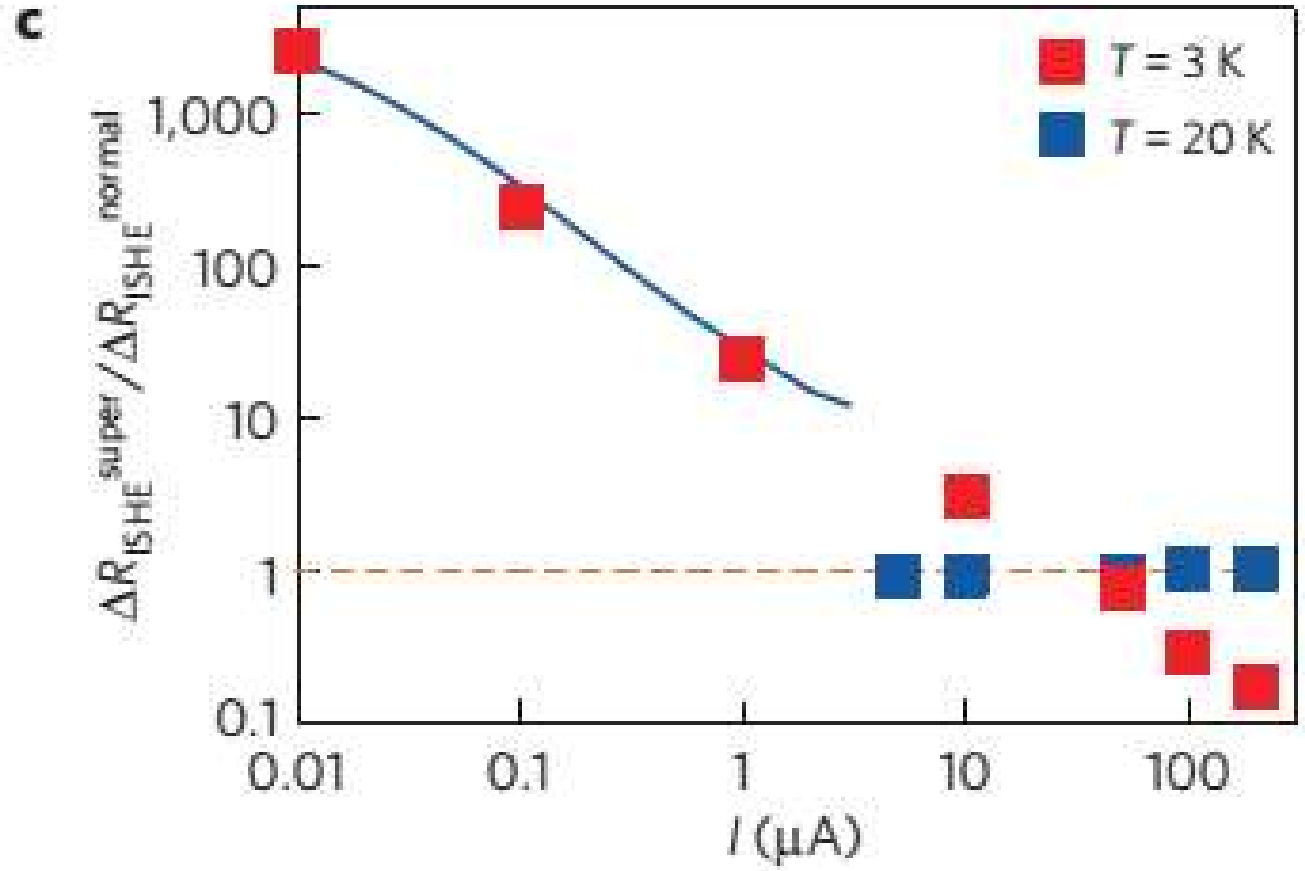
Spin Hall in Superconductor





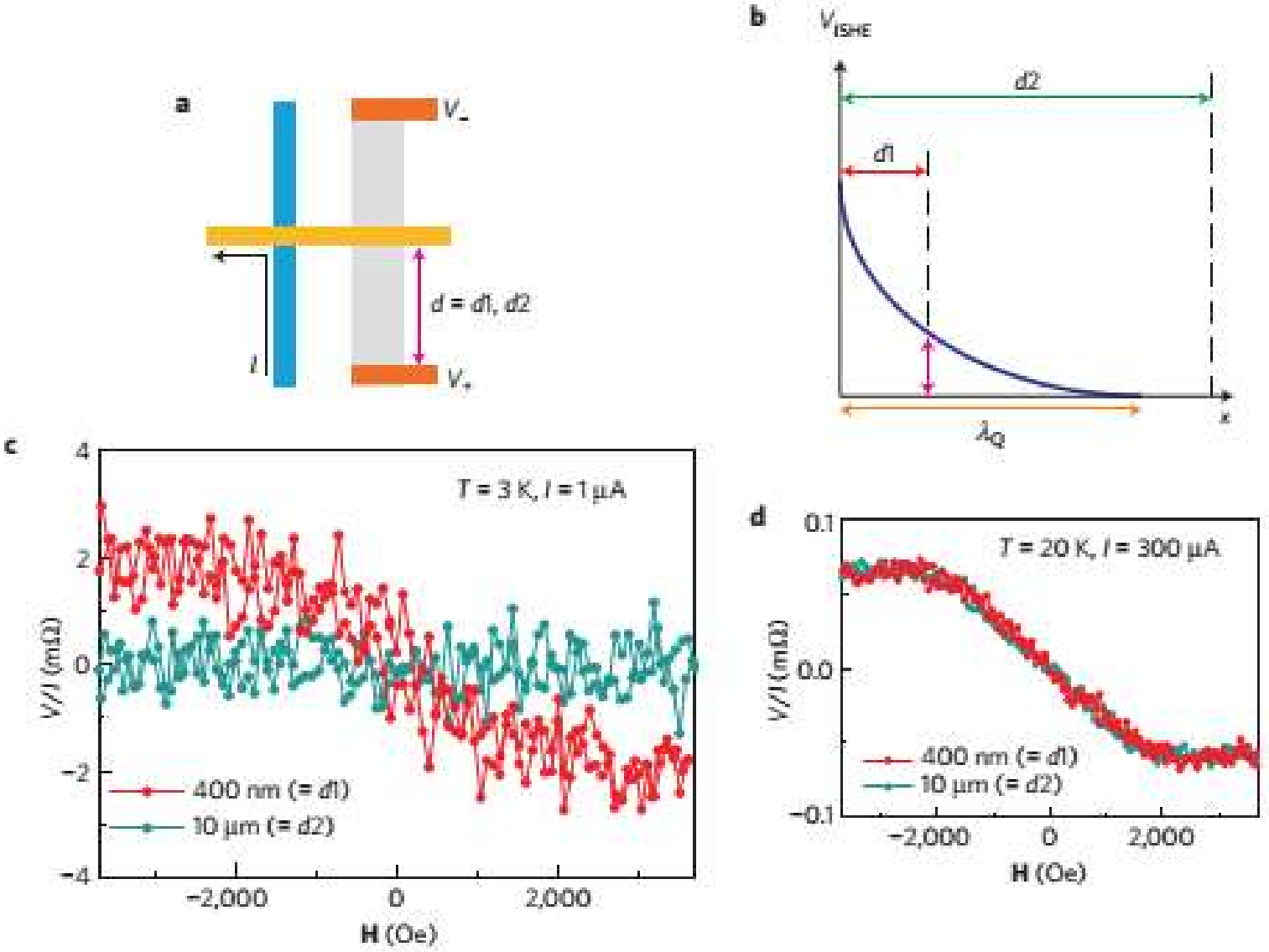
Wakamura, et al, Nature Materials (2015)

Spin Hall in Superconductor



Wakamura, et al, Nature Materials (2015)

Spin Hall in Superconductor



Review of last class

1. Metal Spin Valves

Local and Nonlocal spin valves

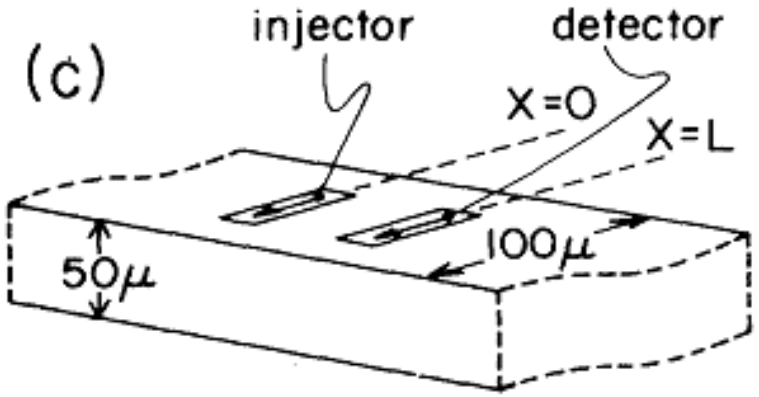
Hanle spin precession

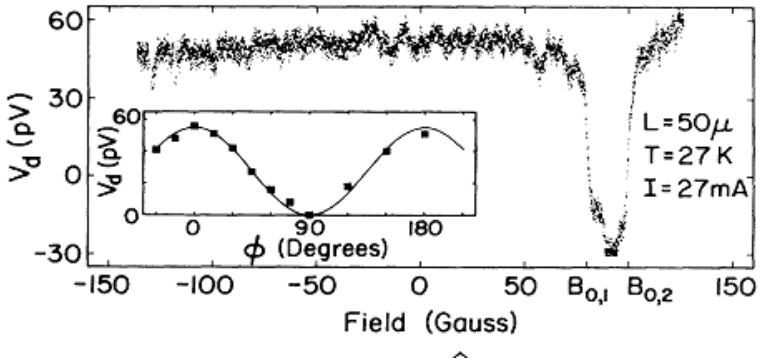
Nano devices (Thanks to cleanroom)

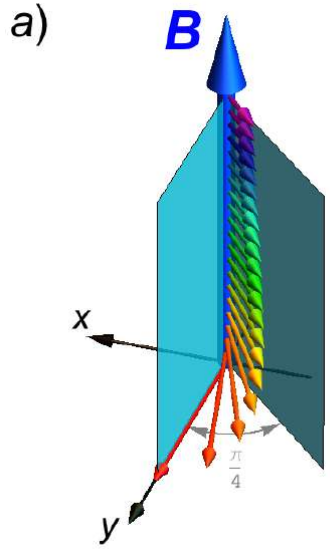
Spin injection efficiency

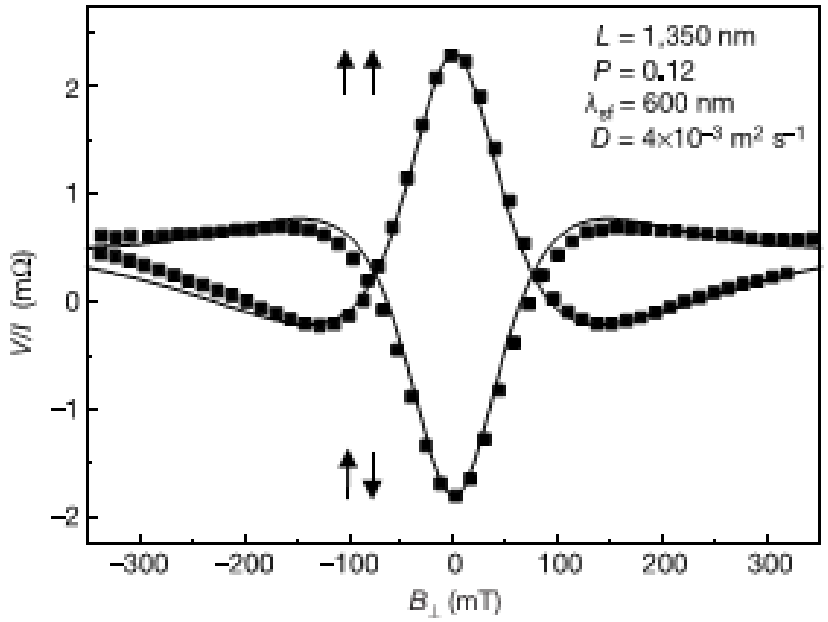
Spin relaxation in Metals: EY mechanism

Review of last class









Review of last class

Spin Injection efficiency

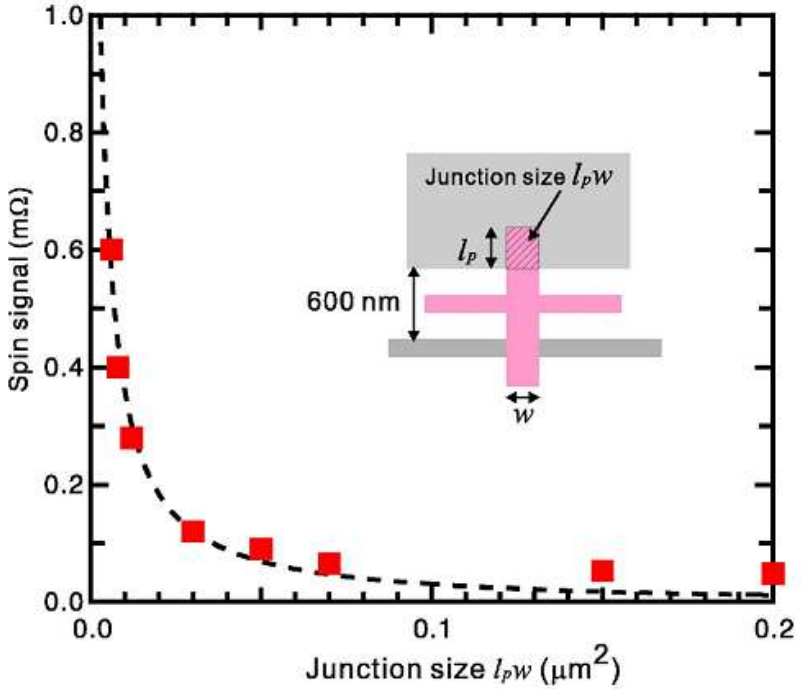
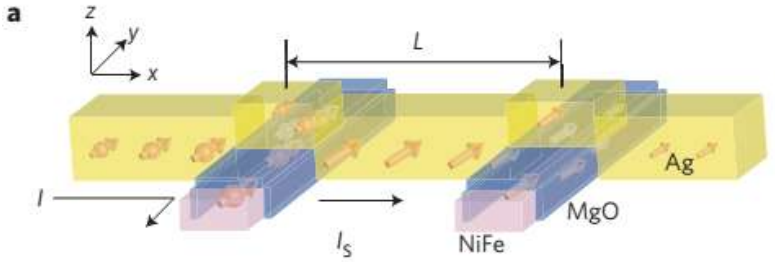
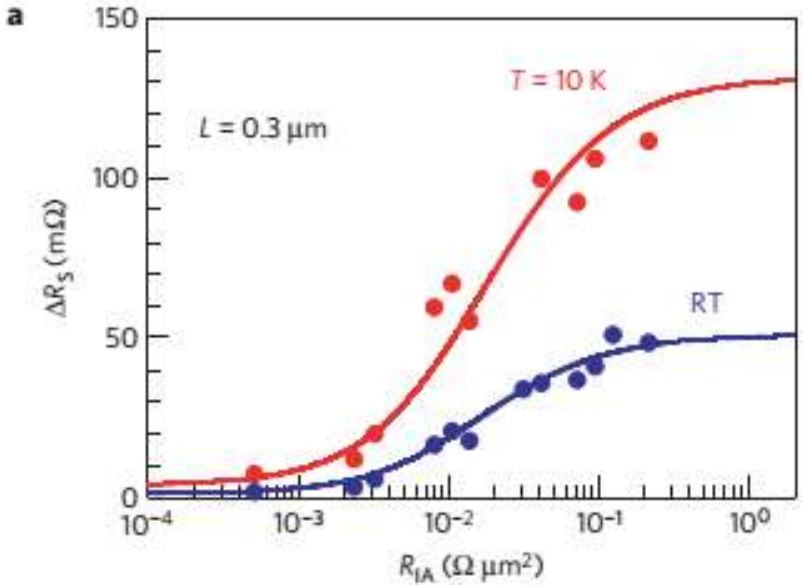
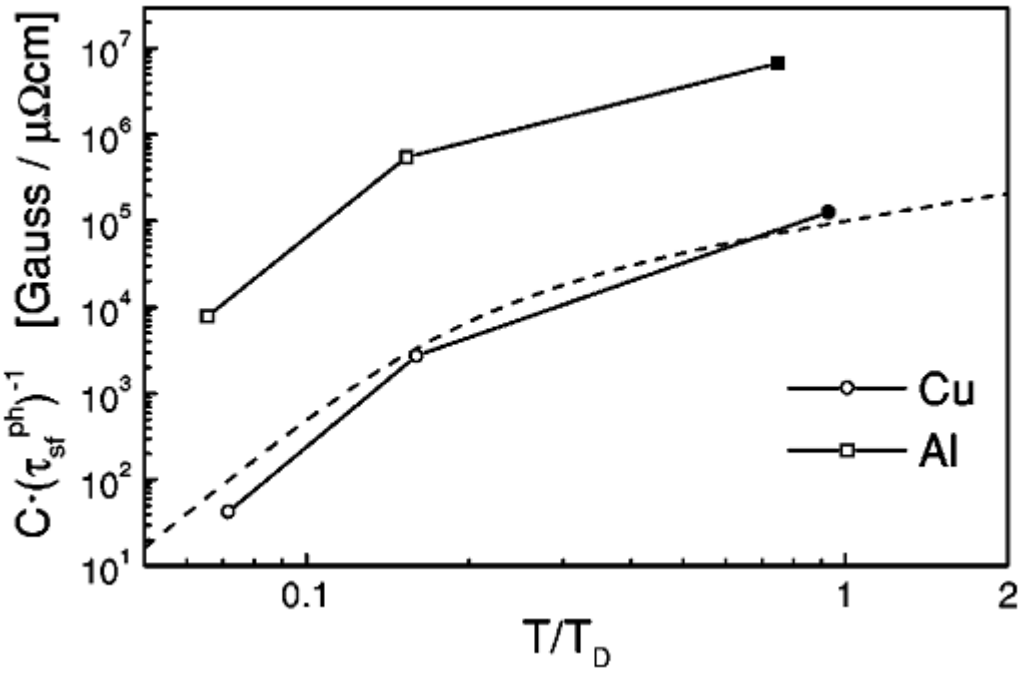


FIG. 4. (Color online) Spin signal in the NLSV measurement as a function of the junction size $l_p w$. The dotted curve is the best fitting to the data points using Eq. (2).





Review of last class



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

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

Review of last class

2. Superconductor Spin Valves

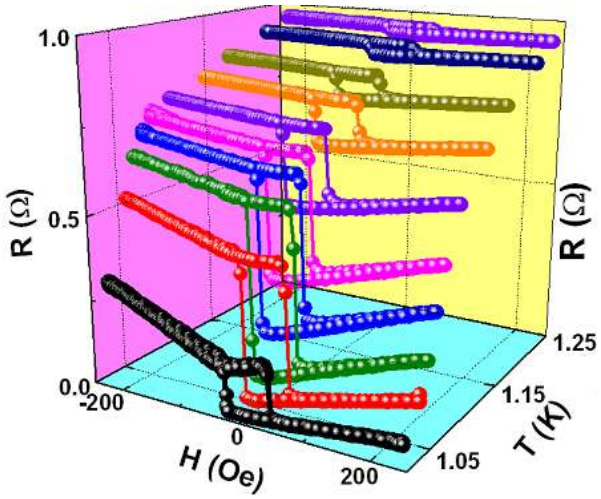
Large MR and control of T_C

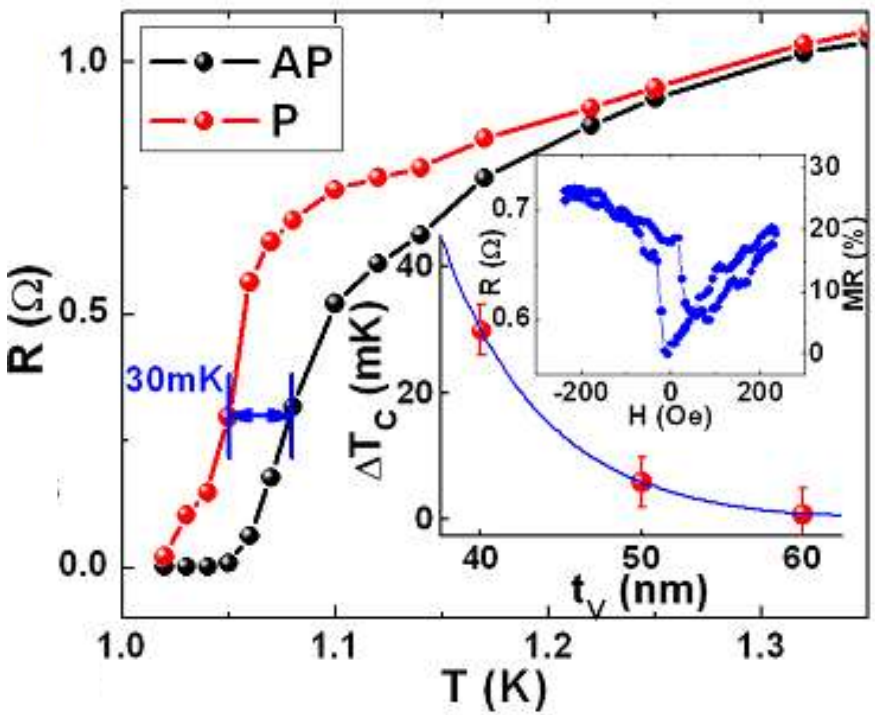
Josephson junction, Spin-triplet

Spin injection, Long spin lifetime

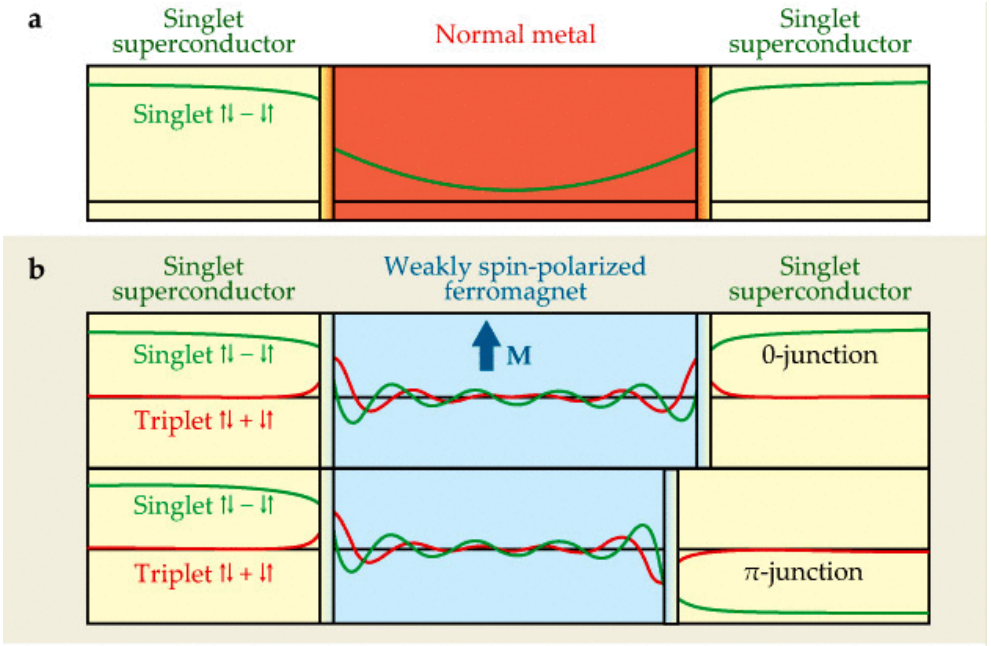
Large spin Hall

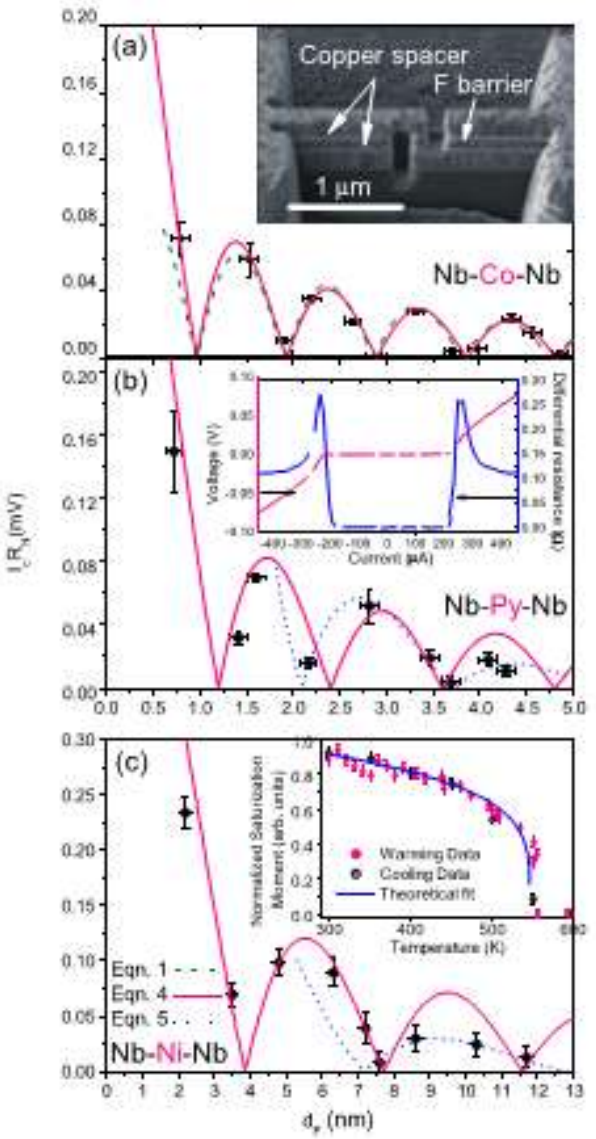
Review of last class





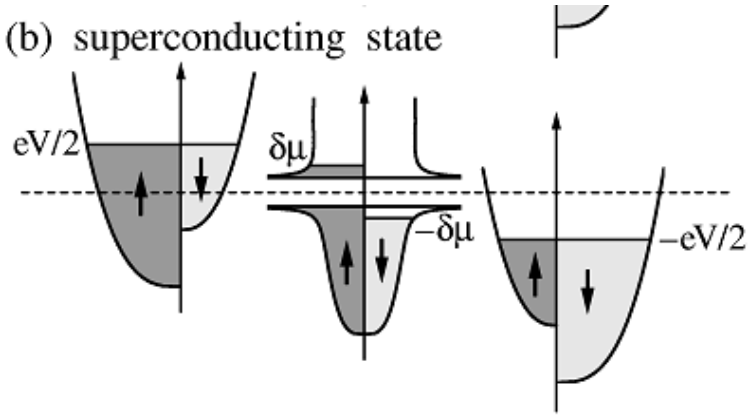
Review of last class



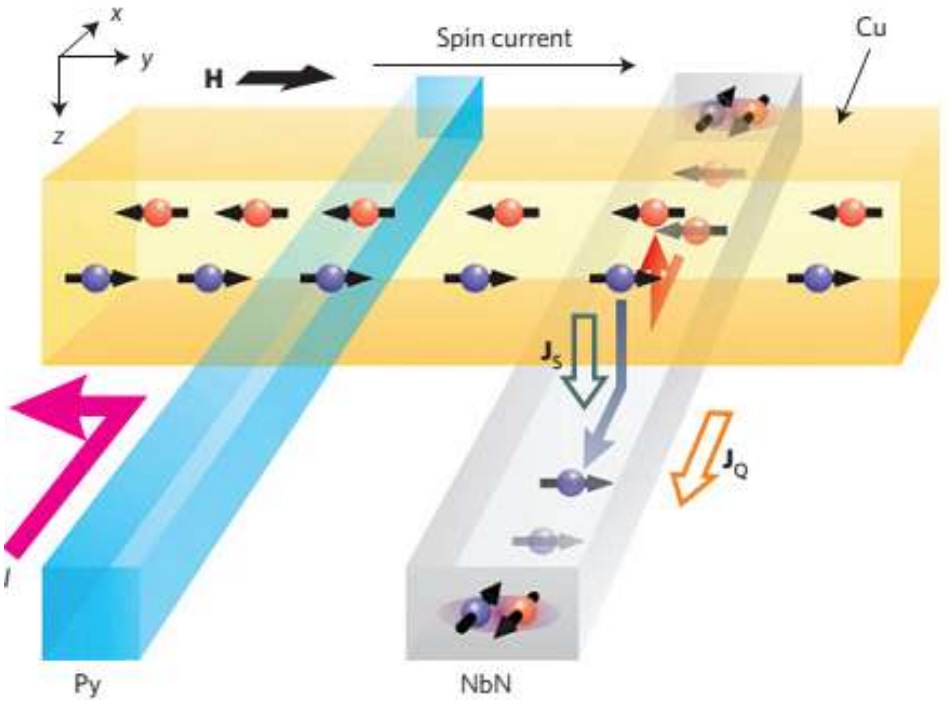


Review of last class

Spin injection



Spin Hall



下一节课: Nov. 1st

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！