Electrical detection of spin precession in a metallic mesoscopic spin valve

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Content

1. Motivation: Spintronics

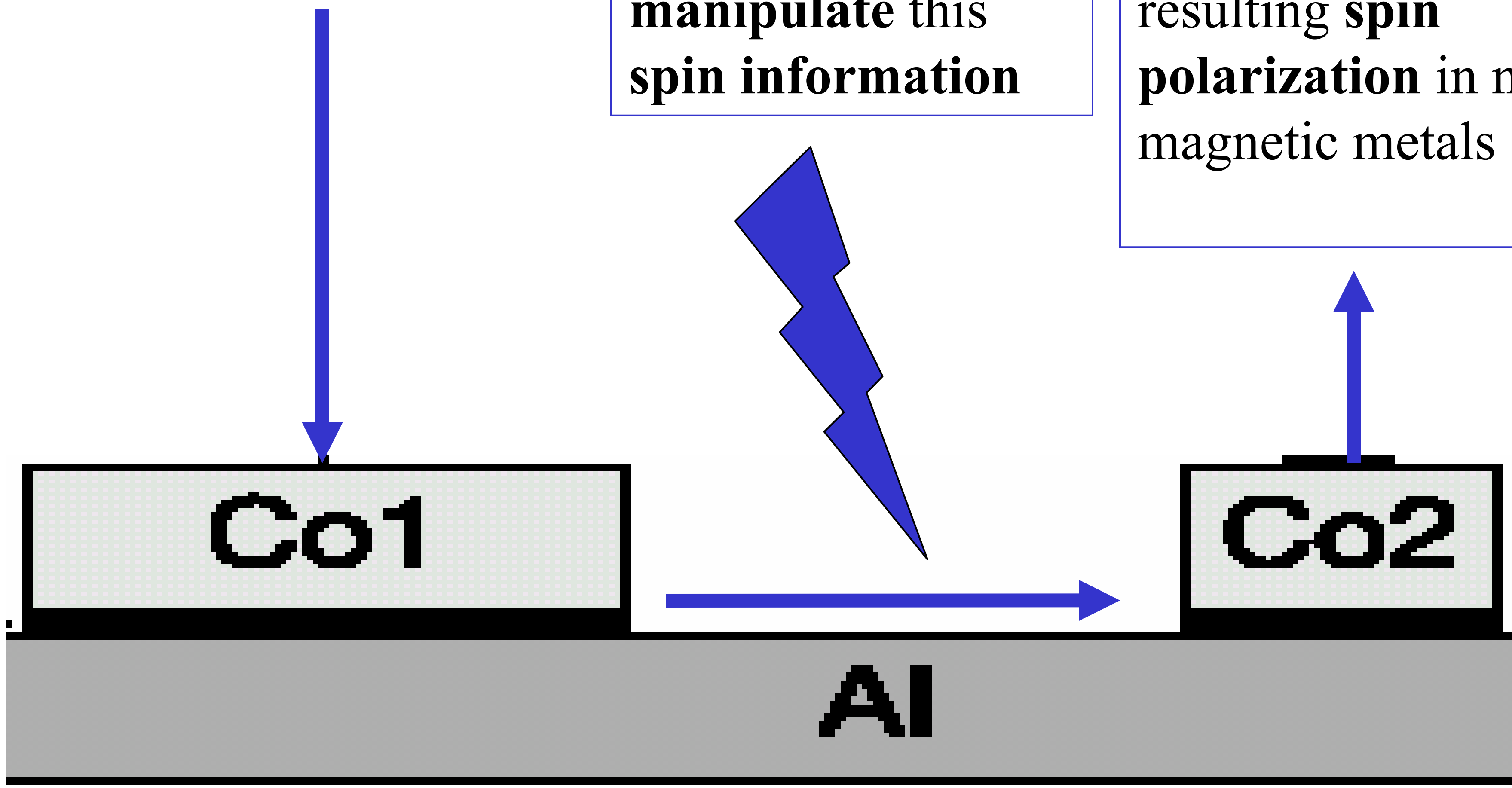
Want to use **spin DOF** for information processing, i.e.

…

to **inject** a **spin current**

to **transfer** and **manipulate** this **spin information**

to **detect** the resulting **spin polarization** in non-magnetic metals



Idea of the Experiment

Co-Al-Co-spin-valve: FNF-tunnel-junction

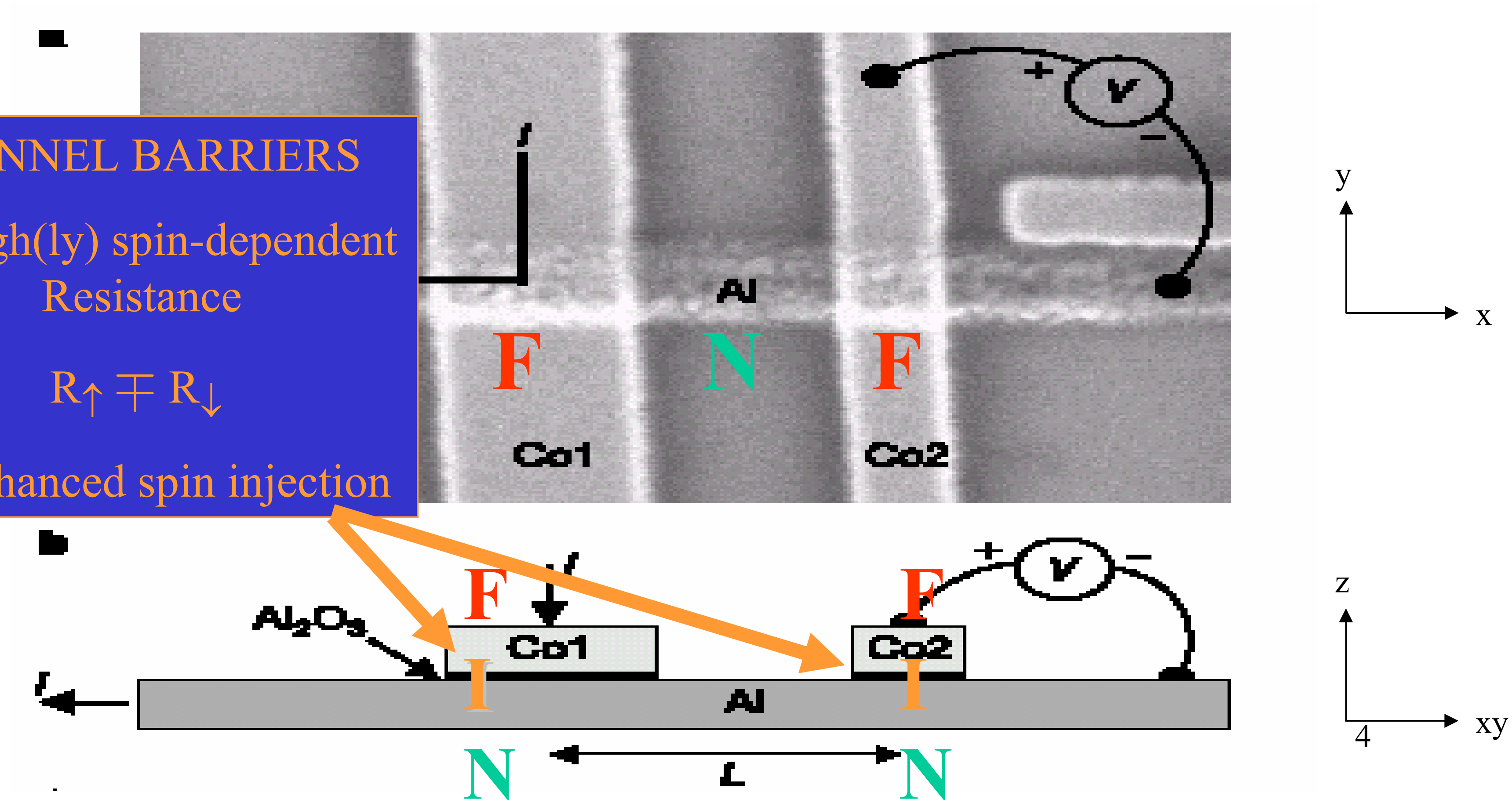
(more precisely a F-I-N-I-F Junction)

TUNNEL BARRIERS

=> high(ly) spin-dependent Resistance

$R_\uparrow \mp R_\downarrow$

=> enhanced spin injection



spin injection and detection

of hot electrons (1eV) above Fermi level

Apply current I

Co1:Injector

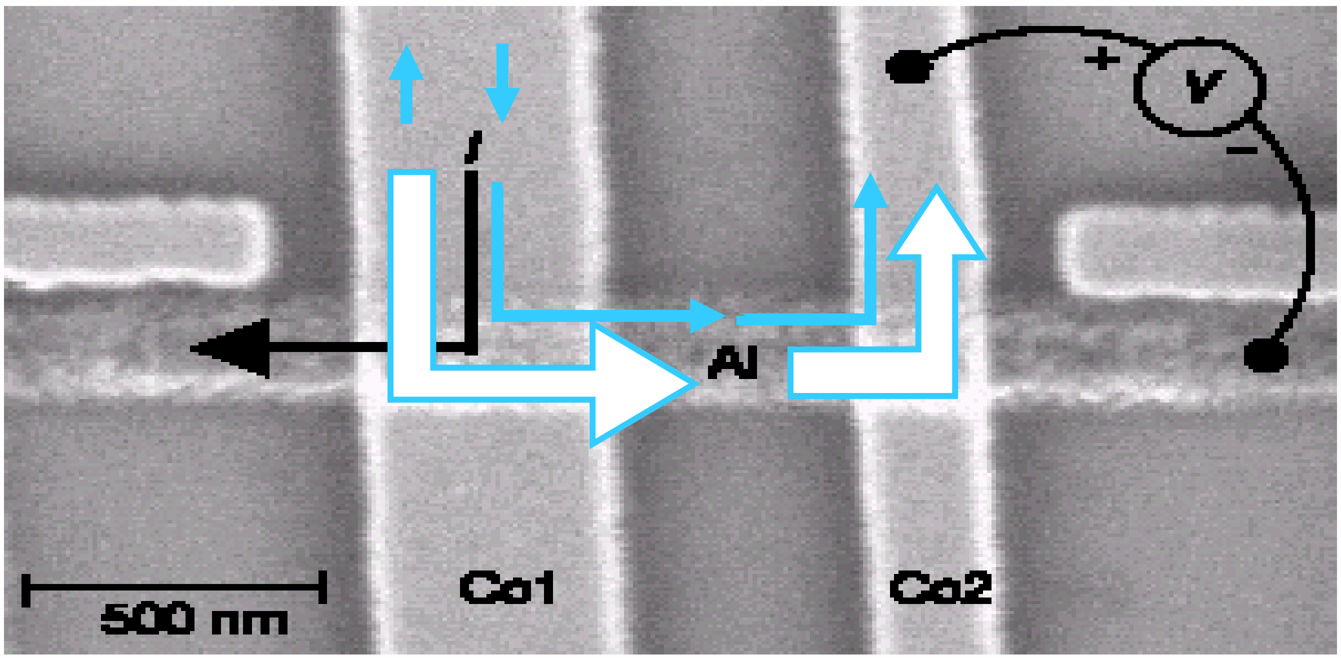
$\underline{\mathbf{M}}_{Co1}$ ↑

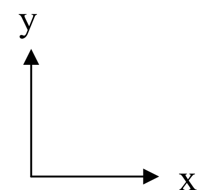
Co2: Detector

$\underline{\mathbf{M}}_{Co2}$ ↑

Measure voltage V

Electron spins





↑ "majority spins" || $\underline{\mathbf{M}}_{Co1}$

↓ "minority spins" ∦ $\underline{\mathbf{M}}_{Co1}$

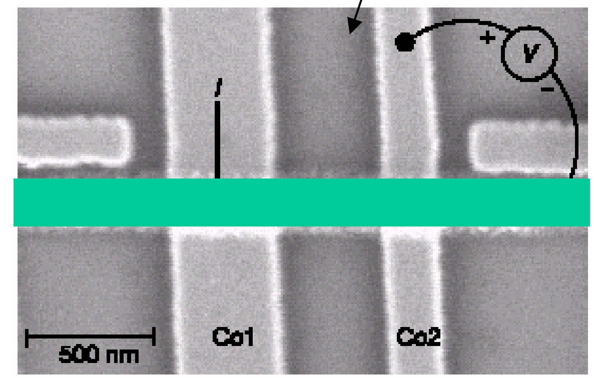
=> non-zero spin polarization P (10%)
in non-magnetic Al!

1.1 Fabrication

suspended shadow mask evaporation

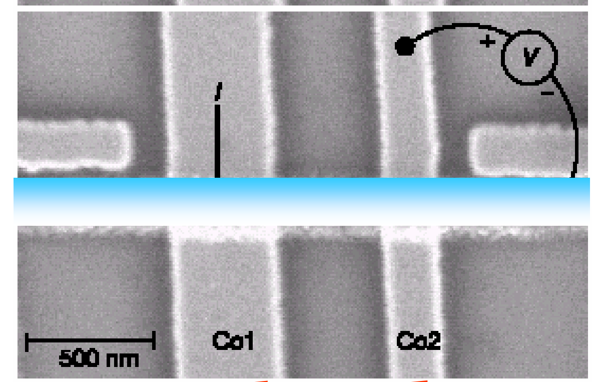
Step 1: Pattering with EBL

Evaporate **Al strip 50x250 nm^2**



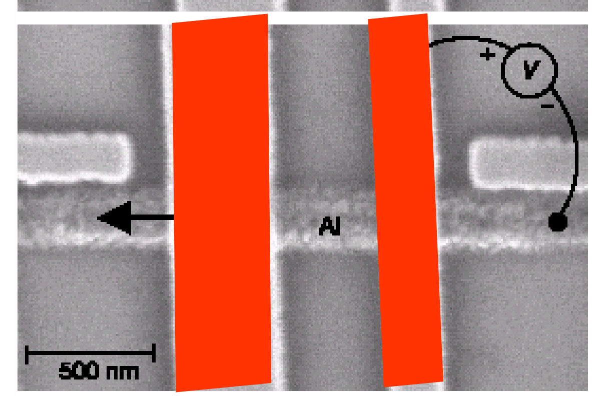
Step 2: $2Al + {}^3/_2\, O_2$ ⌫ Al_2O_3

at 5 x 10-3 bar for 10 minutes



Step 3: Evaporate two Co electrodes

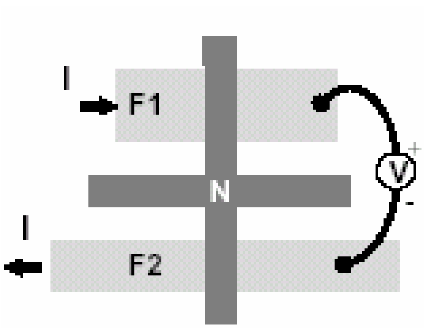
Co1: 0.4 x 4 💻m^2 and Co2 0.2 x 12 💻m^2



1.2 Measurement Geometry

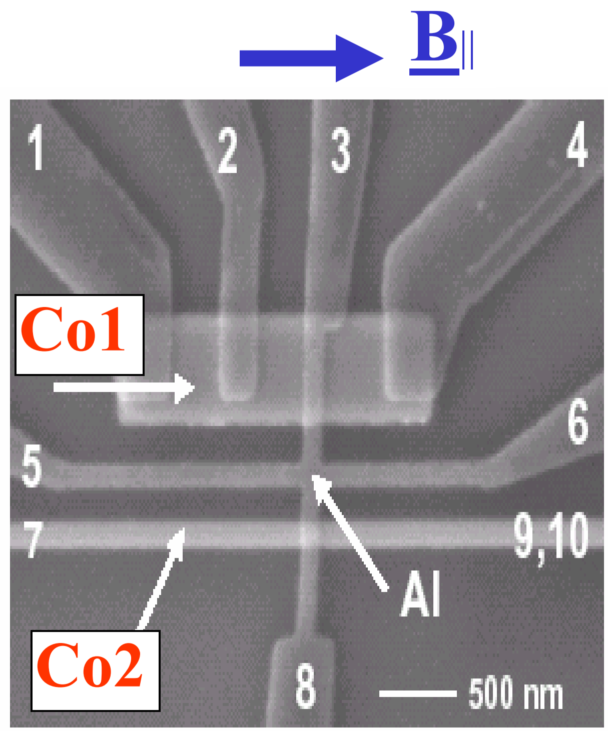
Goal: Device resistance R = V/I sensitive to the spin DOF only!

- conventional

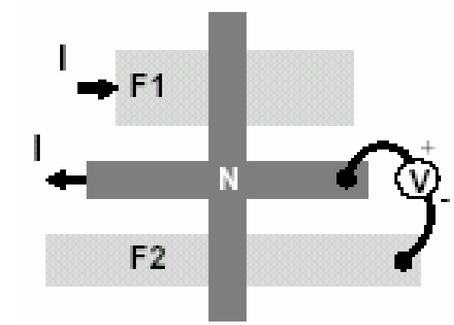


$R_{background} >> R_{\uparrow}, R_{\downarrow}$

- AMR contributions
- Hall effects
- spin flips



☎ non-local geometry



- ~~AMR contributions~~
- ~~Hall effects~~
- spin flips

2.1 Transport in a Ferromagnet

Spin-dependent ...

...DOS at E_F

$\mathbf{N_\uparrow}$

$\mathbf{N_\downarrow}$

...diffusion constants

$$D_\uparrow = \frac{1}{3} v_{F\uparrow} l_{e\uparrow}$$
$$D_\downarrow = \frac{1}{3} v_{F\downarrow} l_{e\downarrow}$$

...conductivities

$$\sigma_\uparrow = N_\uparrow e^2 D_\uparrow$$
$$\sigma_\downarrow = N_\downarrow e^2 D_\downarrow$$

Current I distributed over **two spin channels** (due to $\sigma_\uparrow \mp \sigma_\downarrow$)

$$j_\uparrow = \frac{\sigma_\uparrow}{e} \frac{\partial \mu_\uparrow}{\partial x}$$
$$j_\downarrow = \frac{\sigma_\downarrow}{e} \frac{\partial \mu_\downarrow}{\partial x}$$

Spin polarization p of ferromagnet

$$p = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

$$\langle p \rangle_{\text{weighted}} = p^2$$

Spin flip time ☺$_{\uparrow\downarrow}$, ☺$_{\downarrow\uparrow}$

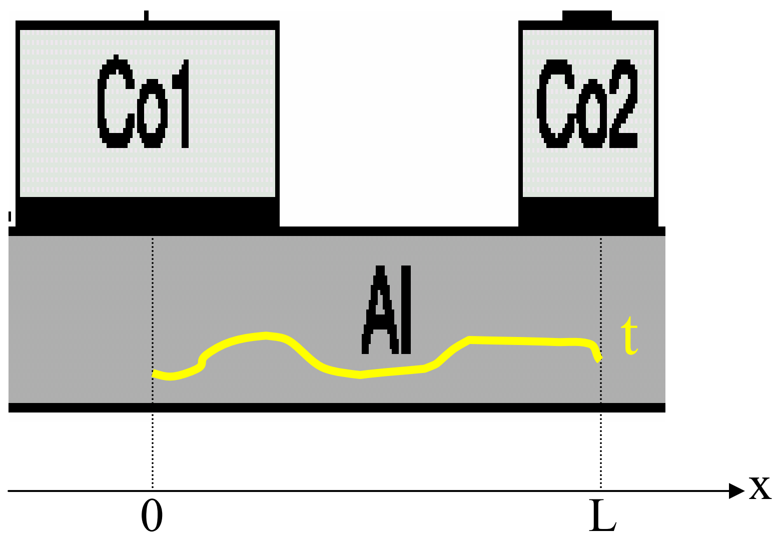
$$1/\tau_{sf} = 1/\tau_{\uparrow\downarrow} + 1/\tau_{\downarrow\uparrow}$$

Momentum scattering time ☺$_e$ = l_e /v_F < ☺$_{sf}$ => diffusive regime

2.2 Diffusive Regime

Diffusive regime

t > ☺$_{sf}$



- t 'flight time' from Co1-Co2
- **🖰$_{sf}$ = (D ☺$_{sf}$)$^{1/2}$** spin relaxation length

  typically 🖰$_{sf}$ ≈1 💻m
- D diffusion constant (of e in Al)
- L = d(Co1, Co2) ≈ 550-1350 nm

Diffusive Transport Regime

Def: Electrochemical potential (at B=0)

$$\mu = \mu_{ch} - eV$$

μ_{ch} = n/N(E_F) = (excess electron density) / (DOS at E_F)

In the linear response regime (small deviations from equilibrium, i.e. $|eV| < k_B T$)

Electron transport through a diffusive channel is due to a $\Delta\mu$ of two connected electron reservoirs

A driving force of electron transport, a gradient of μ, can result from either

$\mathbf{E} = -\nabla V$

Drift picture

$E \neq 0$

$$\sigma = e^2 N(E_F)\, D$$

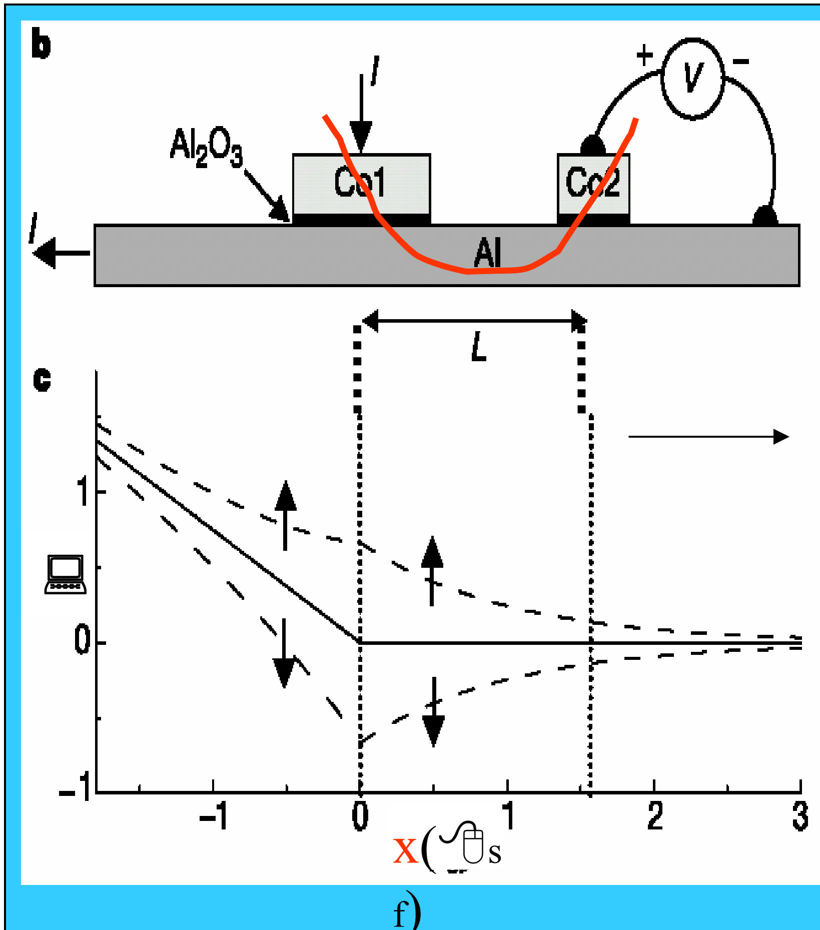
Einstein relation

∇n

Diffusion picture

$E = 0, \nabla n \neq 0$

Diffusion equation



—— μ without spin injection

– – – μ↑ and μ↓ with spin injection

Thus, (1D) spin-coupled diffusion eq. in Al describing the effect of the spin flip processes:

$$D\frac{\partial^2(\mu_\uparrow - \mu_\downarrow)}{\partial x^2} = \frac{(\mu_\uparrow - \mu_\downarrow)}{\tau_{sf}} \quad \Longleftrightarrow \quad \Delta\mu'' = 1/\lambda_{sf}^{\,2}\,\Delta\mu$$

i.e. Non-equilibrium spin accumulation $\Delta\mu$ decays over timescale τ_{sf}.

=> Solution (1):

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

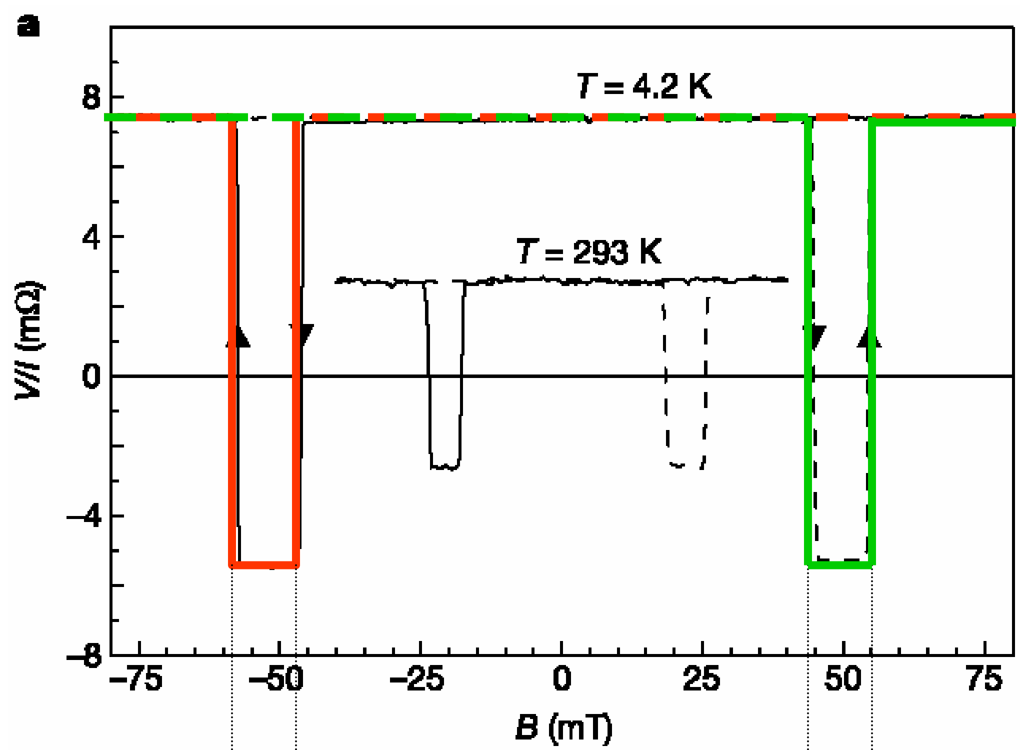
A cross sectional area

3. Experimental Results
3.1 Control relative Magnetization of Co1 and Co2 via $\underline{B}_{||}$

Choose different aspect ratios for Co1 and Co2
in order to control

$\underline{M}_{Co1}$ - $\underline{M}_{Co2}$ ∈ {⇉, ⇄}

=> different coercive fields $B_{||}$



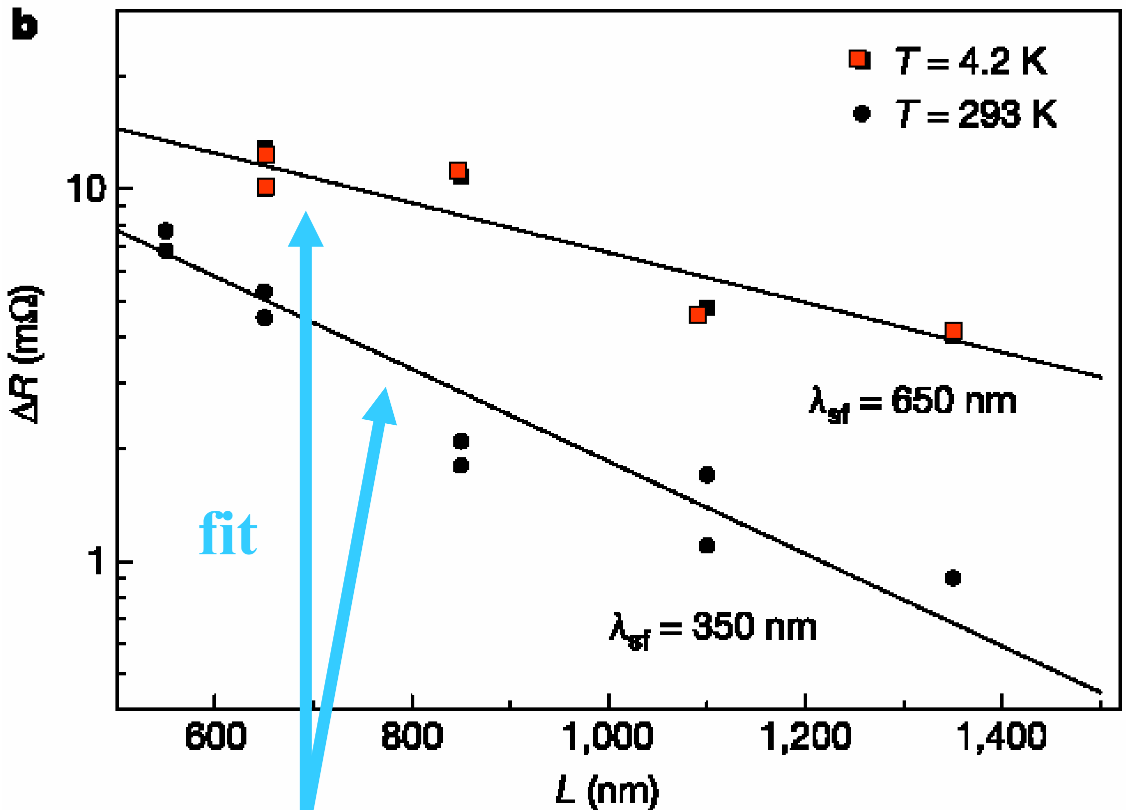
From symmetry:

R = V/I indeed sensitive to spin DOF only!

Sweep - ⌫ + ⇄ ⇉ ⇇

Sweep + ⌫ - ⇉ ⇄ ⇇

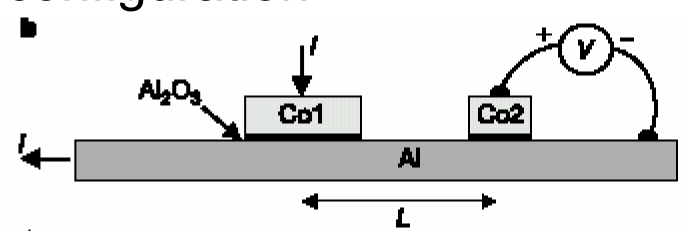
3.2 Spacing L from Injector Co1 to Detector Co2



spin dependent resistance

ΔR = ΔR(L) = ΔV/I

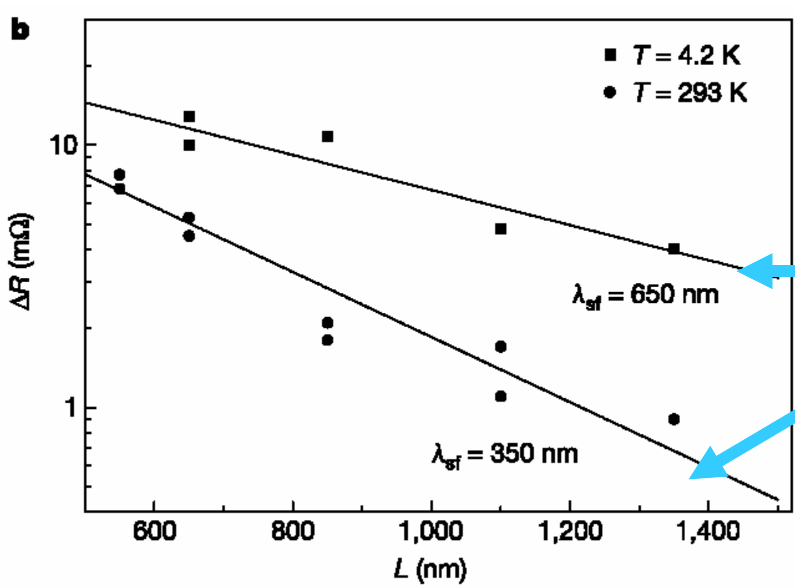
where ΔV is the output voltage difference between parallel and antiparallel configuration



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

$e^{-L/\lambda_{sf}}$ describes effect of spin scattering/ flips

3.1 Retrieve λ_{sf}, D and τ_{sf} from $\Delta R(L)$



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

From fit : **P** (T=4.2K) = **P** (T=293K) = 0.11 ± 0.02

λ_{sf} (T=4.2K) = 650 ± 100nm λ_{sf} (T=293K) = 350 ± 50

nm

From Einstein relation $\sigma = e^2 N_{Al}(E_F)\,D$ with $N_{Al} = 2.4\text{x}10^{22}$ states/cm^3:

D (T=4.2K) = 4.3x10^{-3} m^2/s **D** (T=293K) = 2.7x10^{-3} m^2/s

From $\lambda_{sf} = (\tau_{sf} D)^{1/2}$:

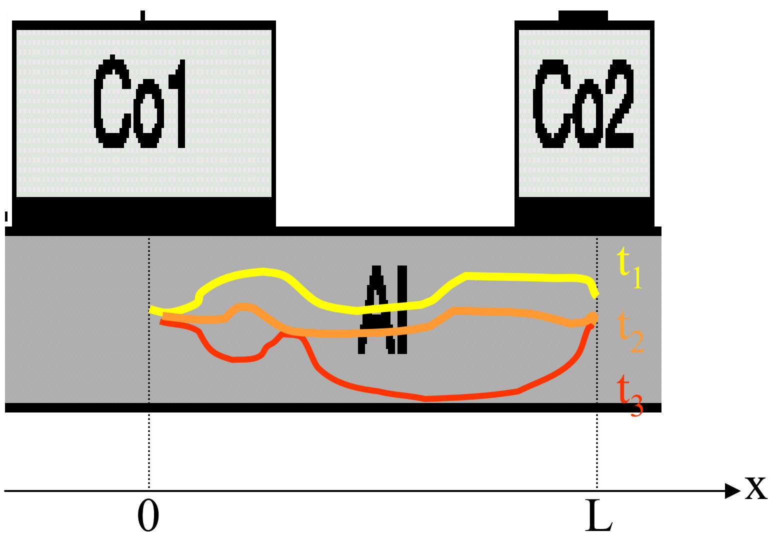
τ_{sf} (T=4.2K) = 100 ps τ_{sf} (T=293K) = 45 ps

Diffusive Regime Correction

Have many different paths/flight times t in the Al strip from Co1 to Co2

=> broad distribution over diffusion times t

$$P(t) = [1/\sqrt{4\pi Dt}]\exp[-L^2/(4Dt)]$$

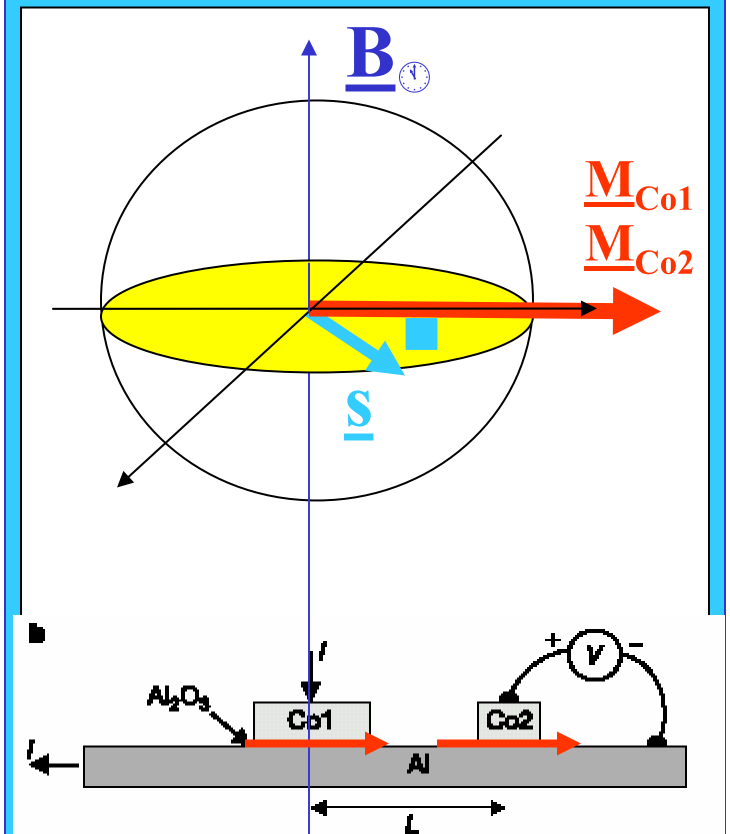


<u>CORRECTION to output voltage V:</u>

Sum contributions of e^--spin over all diffusion times t

$$V \propto \int_0^\infty P(t)\ dt$$

3.3 Diffusion eq. Solution with B🕚



Diffusion time from Co1-Co2 $t = L^2/D$

spins precess around B🕚 direction with

❄$_{Larmor}$ = g_{Al}💻$_B$B🕚 $/\hbar$

=> spin direction altered by ■ = ❄$_L$ t

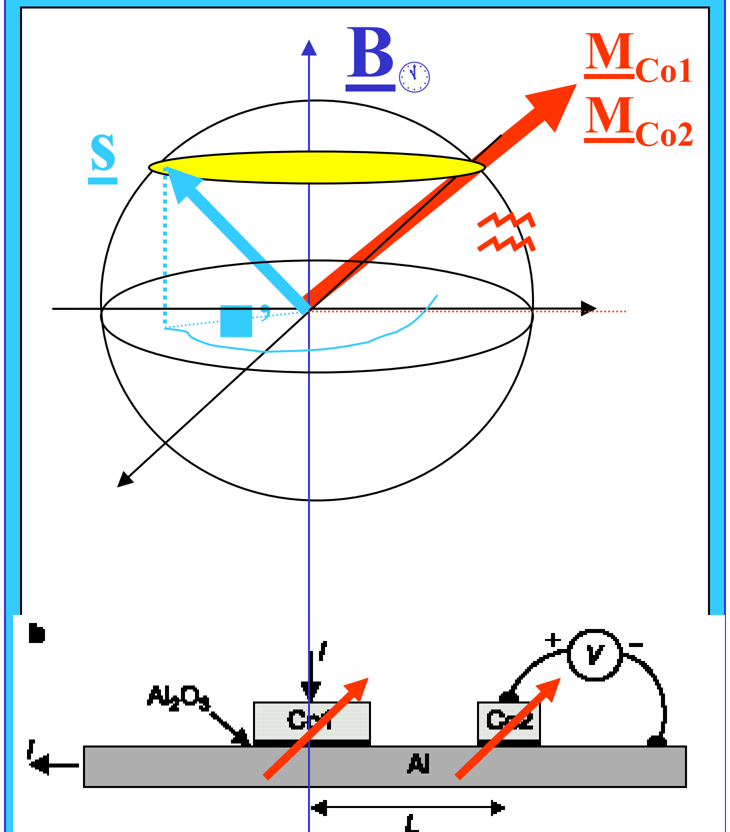
=> Co2 electrode detects projection of spin onto M_{Co2} direction ϵ {0, 👌}

=> contribution of an e^- to V is ~ ±cos(■)

=> Solution (2):

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

Diffusion eq. Solution at large $B_{\perp}$



Diffusion time from Co1-Co2 $t = L^2/D$

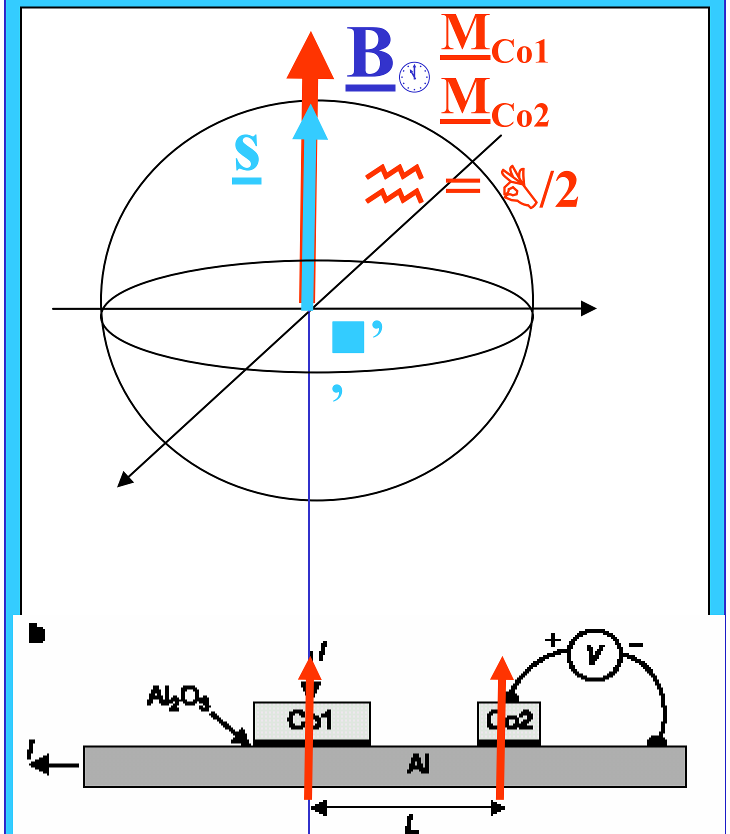
At large $\mathbf{B}_{\perp}$, the Co2 detector electrode magnetization $\mathbf{M}_{Co2}$ is tilted out of the Al plane by an angle $\vartheta \in [0, \pi/2]$

=> Solution (3):

$$V(B_{\perp}, \vartheta) = V(B_{\perp})\cos^2(\vartheta) + |V(B_{\perp} = 0)|\sin^2(\vartheta) \quad (3)$$

precession **background**

Limits for very...



Diffusion time from Co1-Co2

$t = L^2/D$

... large B⊙

♒=👌/2

(3) $V(B_\perp,\vartheta) = V(B_\perp)\cos^2(\vartheta) + |V(B_\perp = 0)|\sin^2(\vartheta)$

1

precession

background

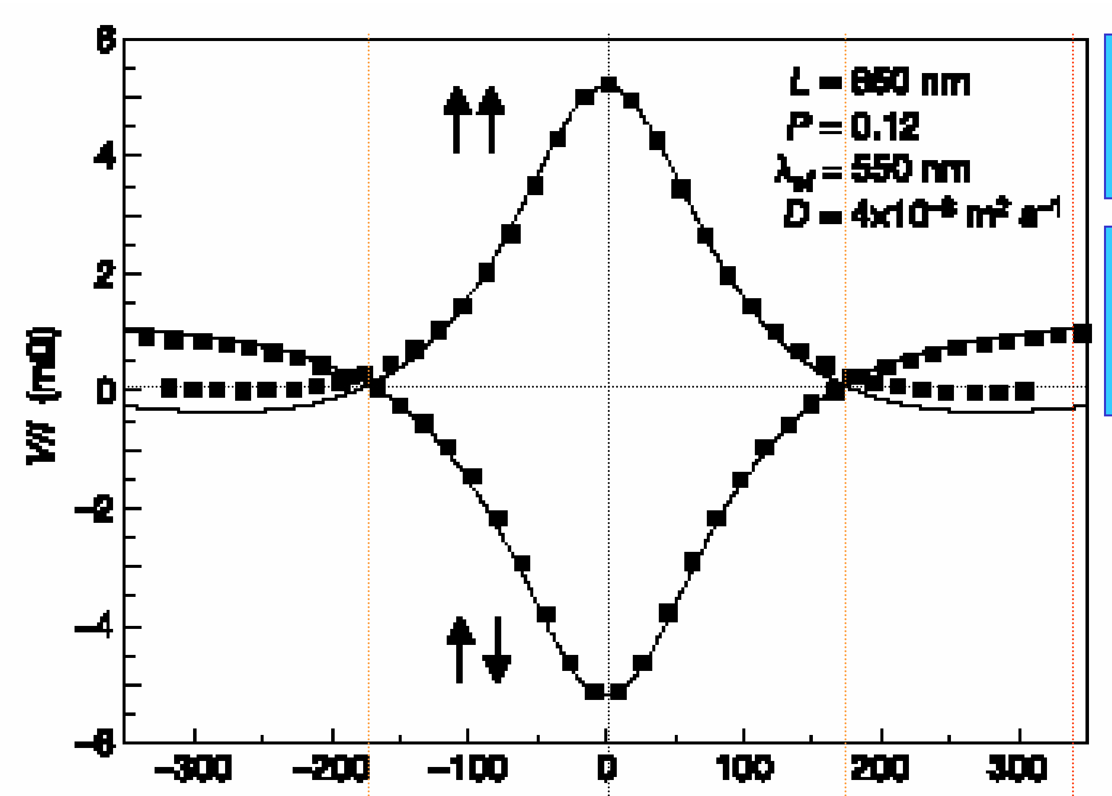
(3) $V(B_\perp,\vartheta) = V(B_\perp)\cos^2(\vartheta) + |V(B_\perp = 0)|\sin^2(\vartheta)$

1

... small B⊙

♒=0 ⁝

V/I as a function of (B🕓, ♒) at T=4.2 K and L=650nm



B🕓

♒ = -👌/2 ♒ = 0 ♒ = 👌/2 ♒ = 👌

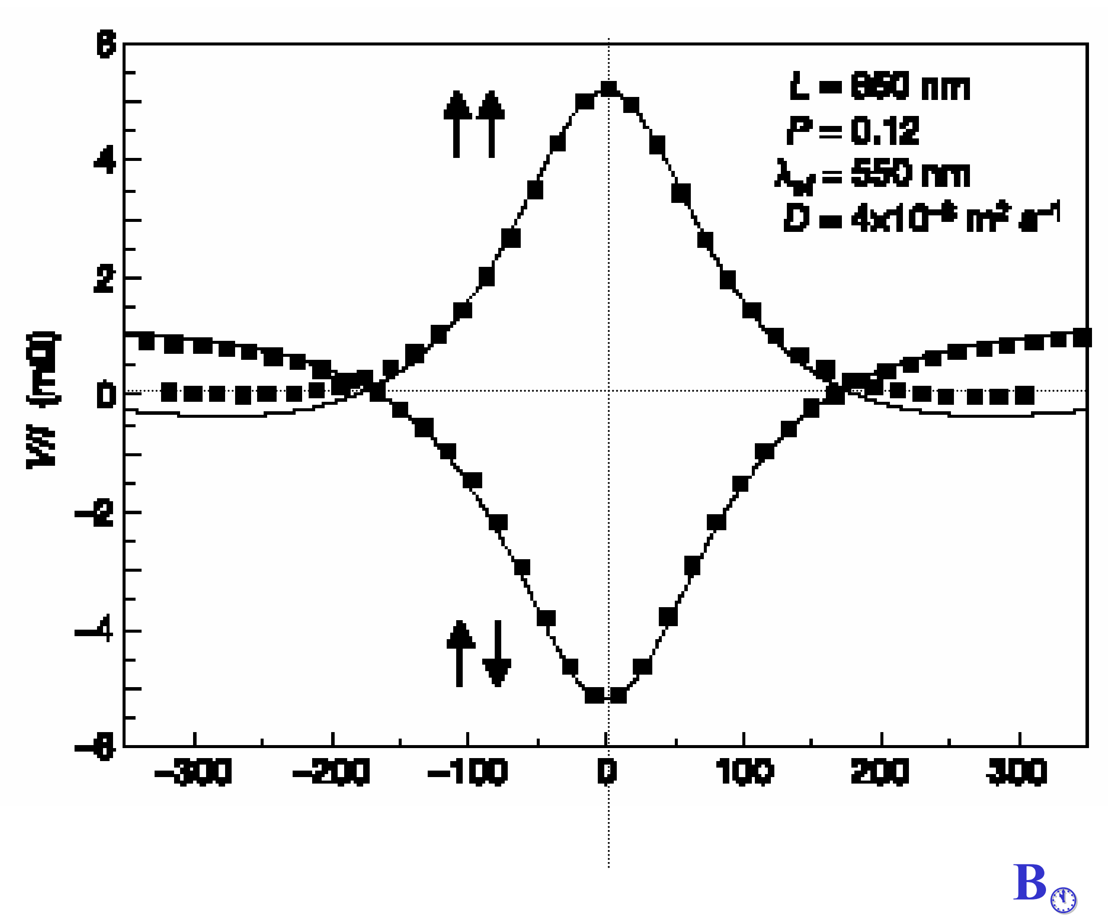
(2) $V(B_\perp) = \pm I \frac{P^2}{e^2 N_{Al} A} \int_0^\infty P(t)\cos(\omega_L t)\exp(-t/\tau_{sf})\mathrm{d}t$

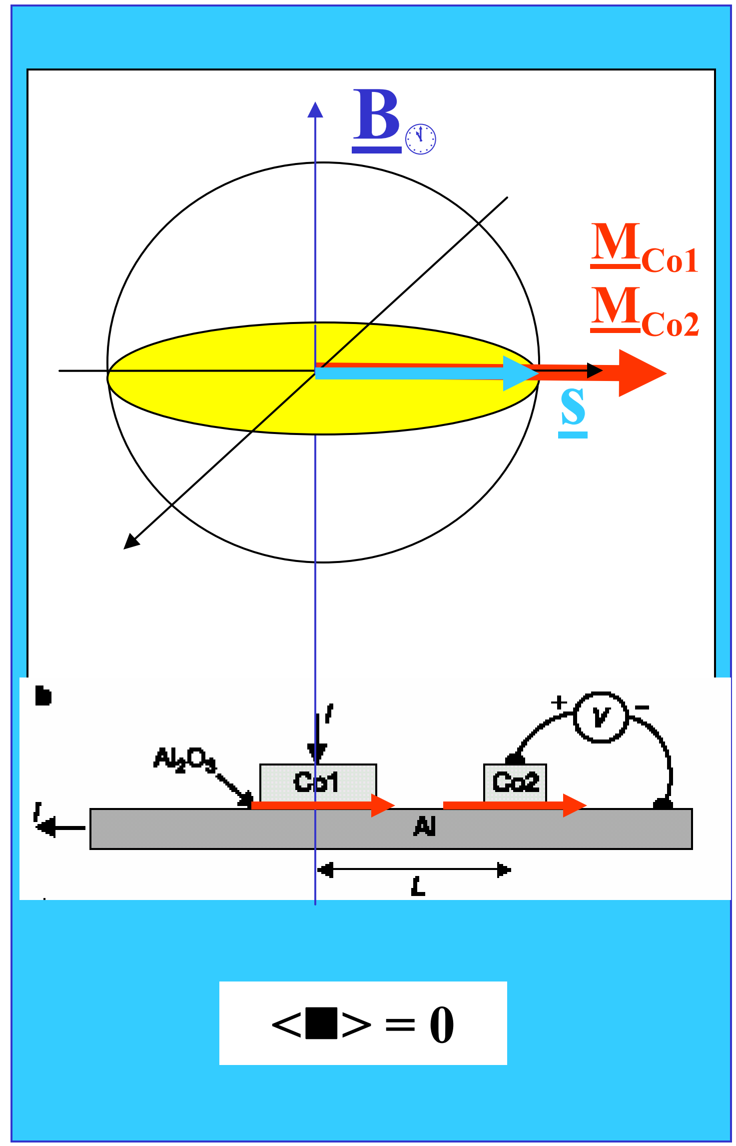
(3) $V(B_\perp, \vartheta) = V(B_\perp)\cos^2(\vartheta) + |V(B_\perp = 0)|\sin^2(\vartheta)$

♒ = ♒(**B**🕓) independently from measurement of the anisotropic magnetoresistance of the Co electrodes

Effectively converting spin-up to spin-down population et v.v.

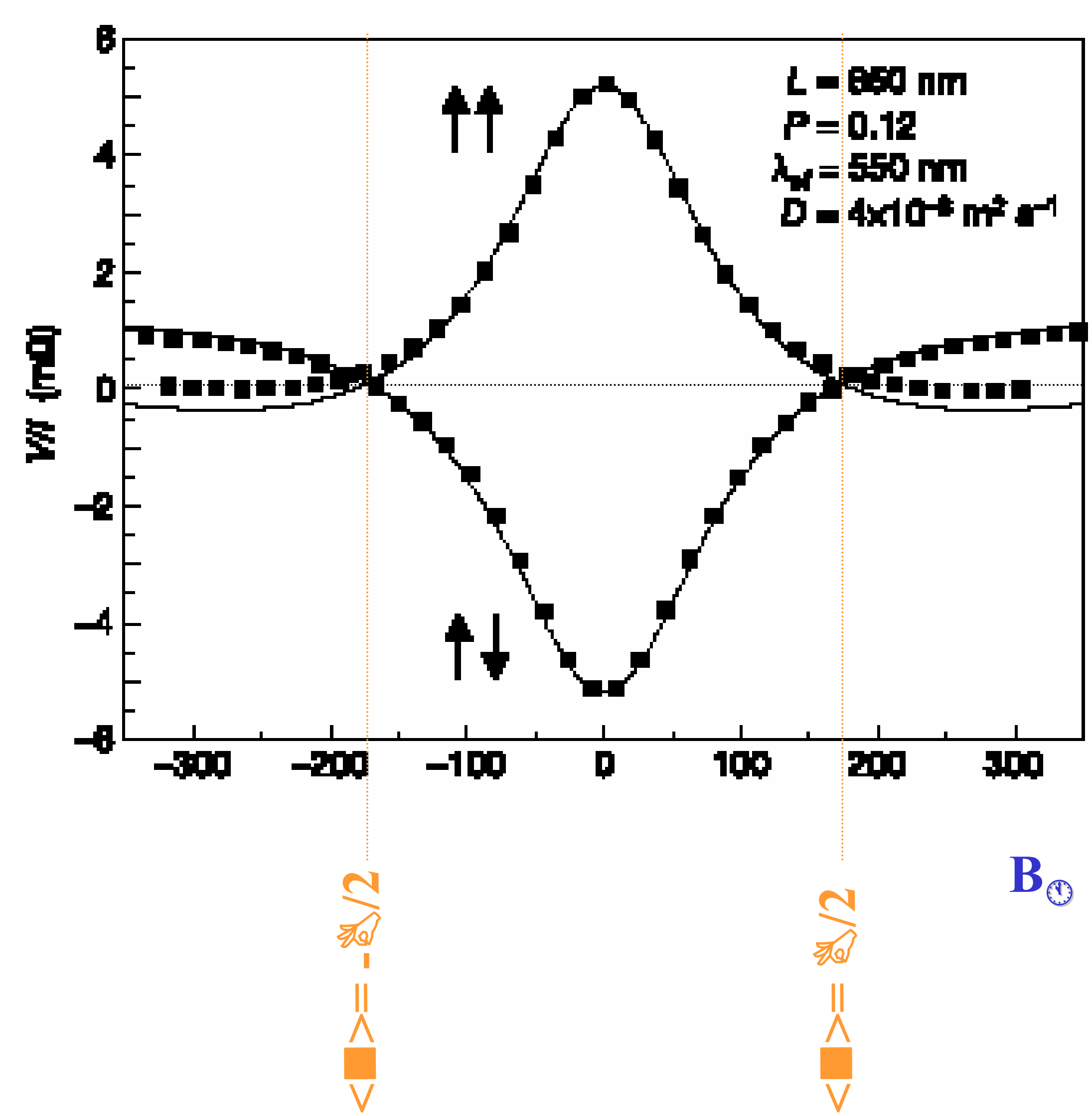
V/I as a function of ($B_{\odot}$, ♒) at T=4.2 K and L=650nm

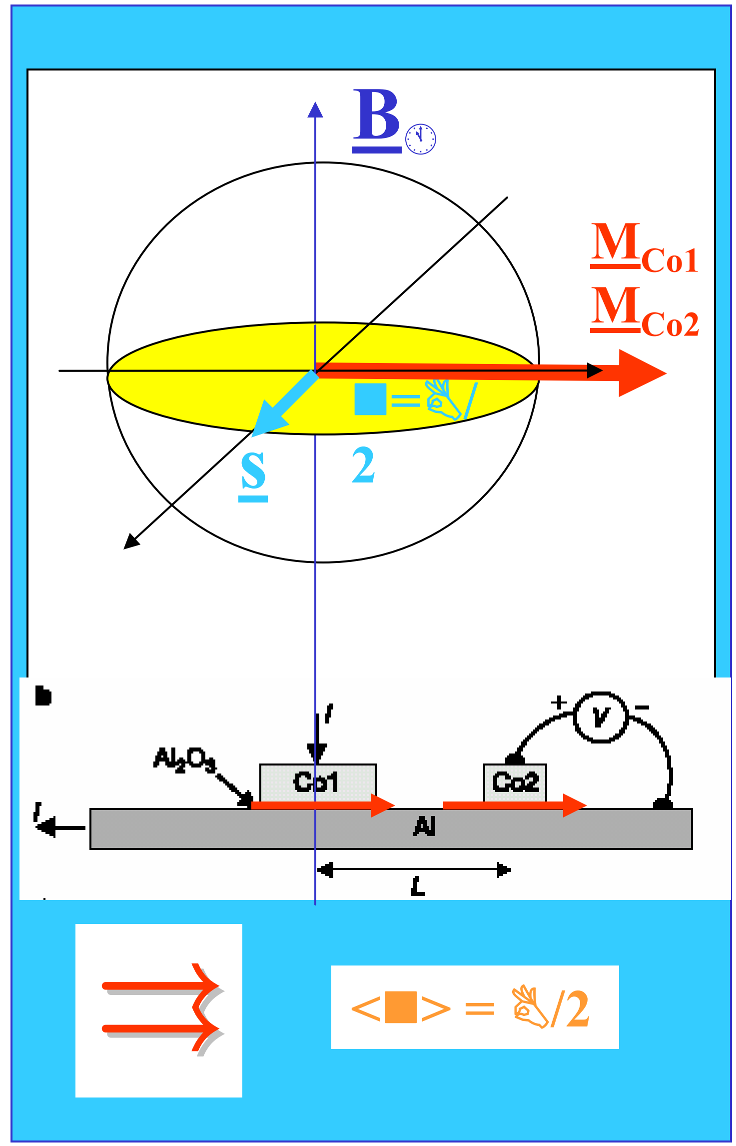




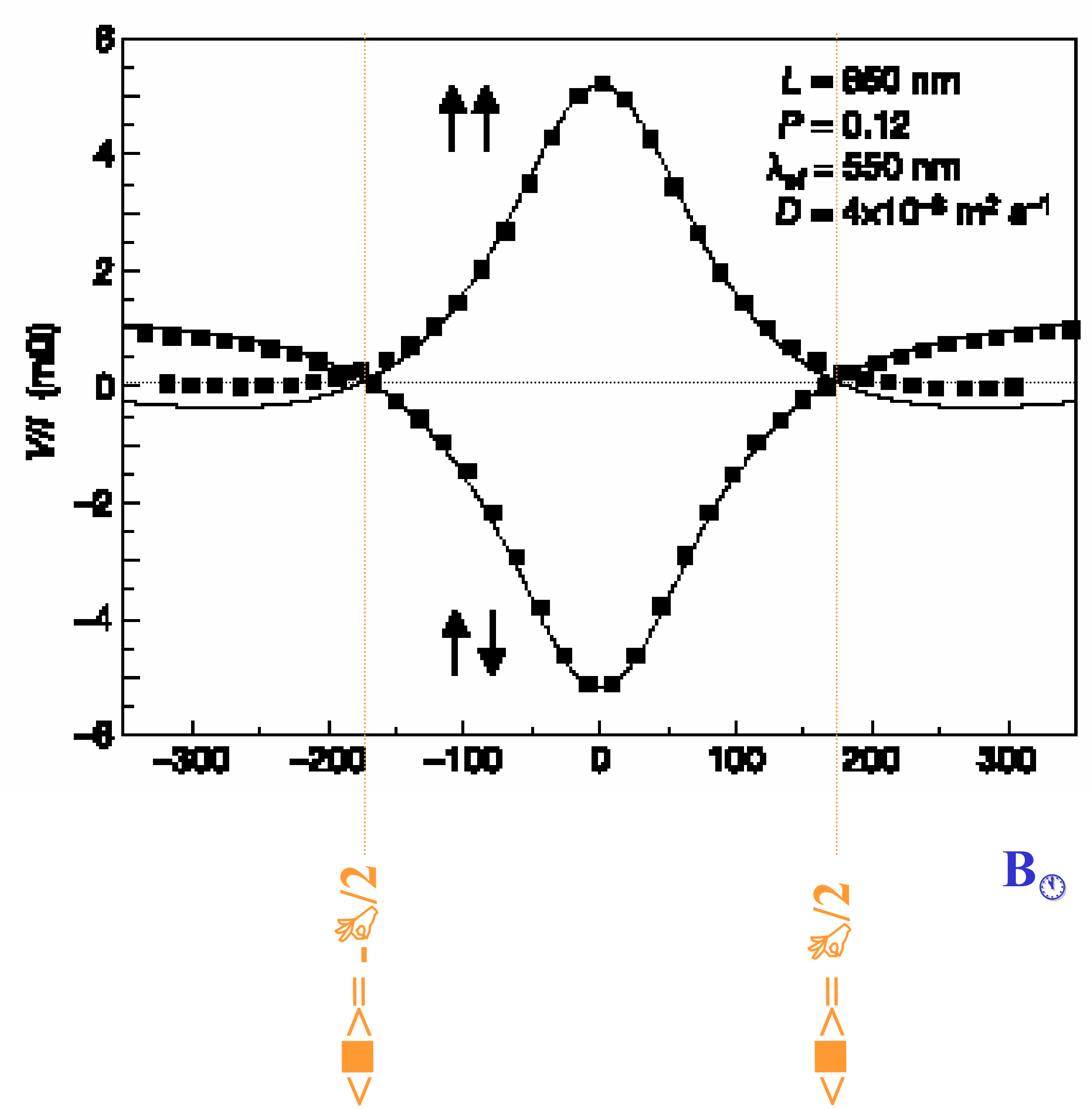
<■> = 0

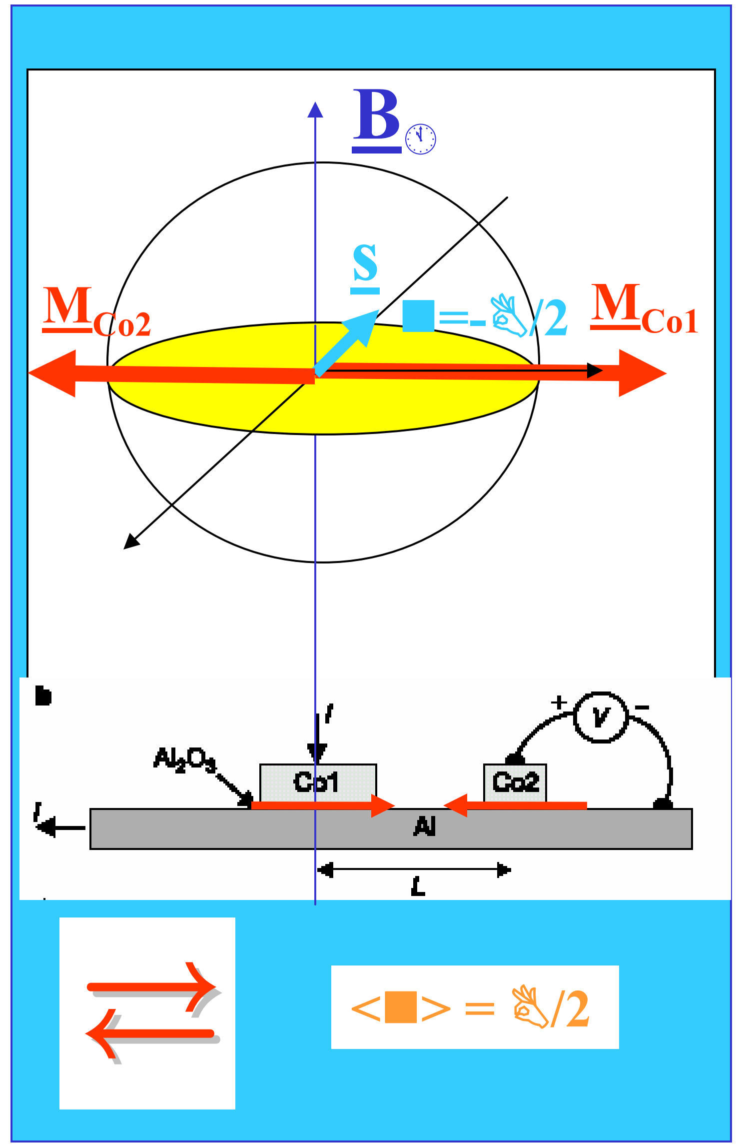
V/I as a function of (B🕔, ♒) at T=4.2 K and L=650nm



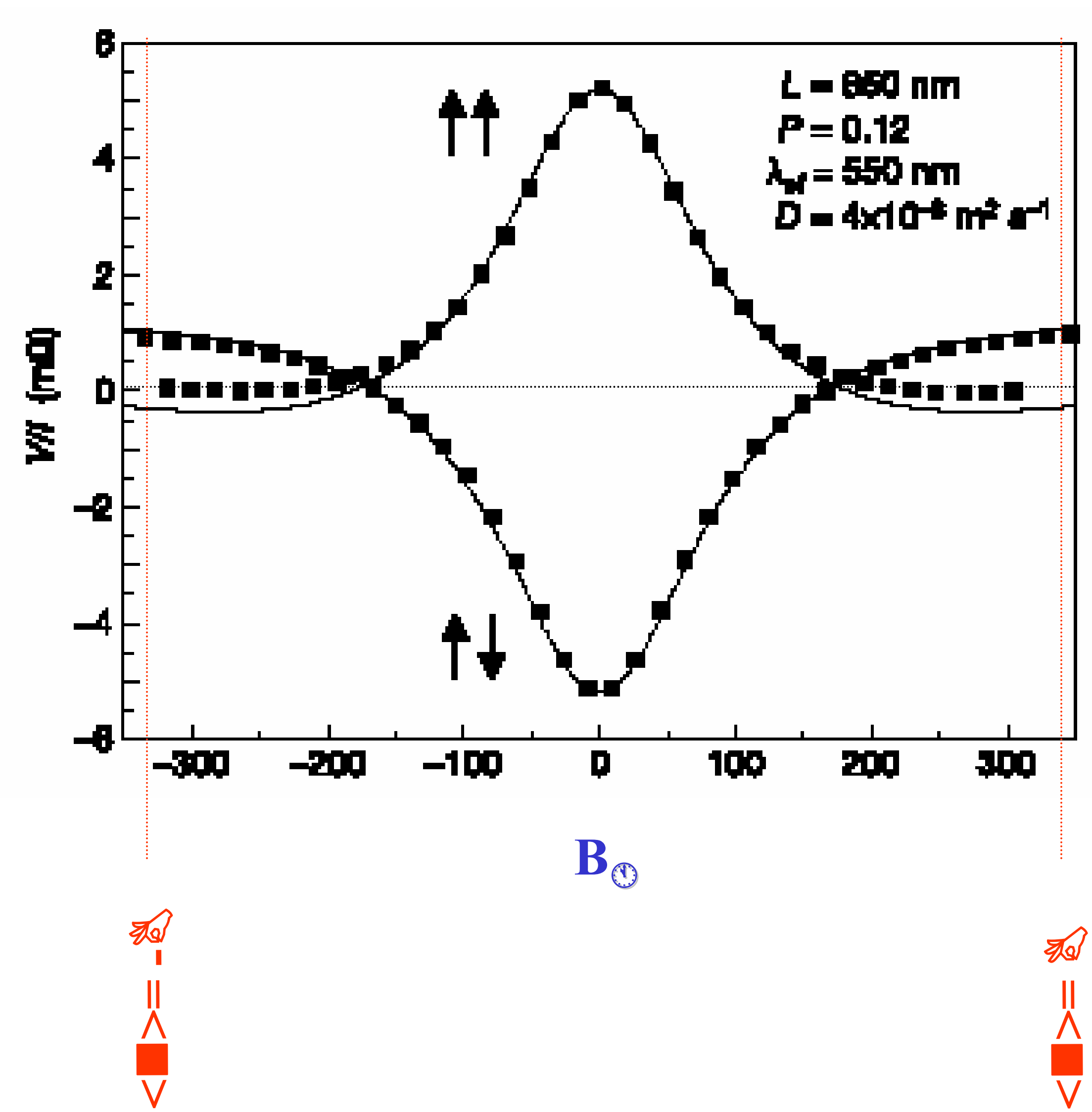


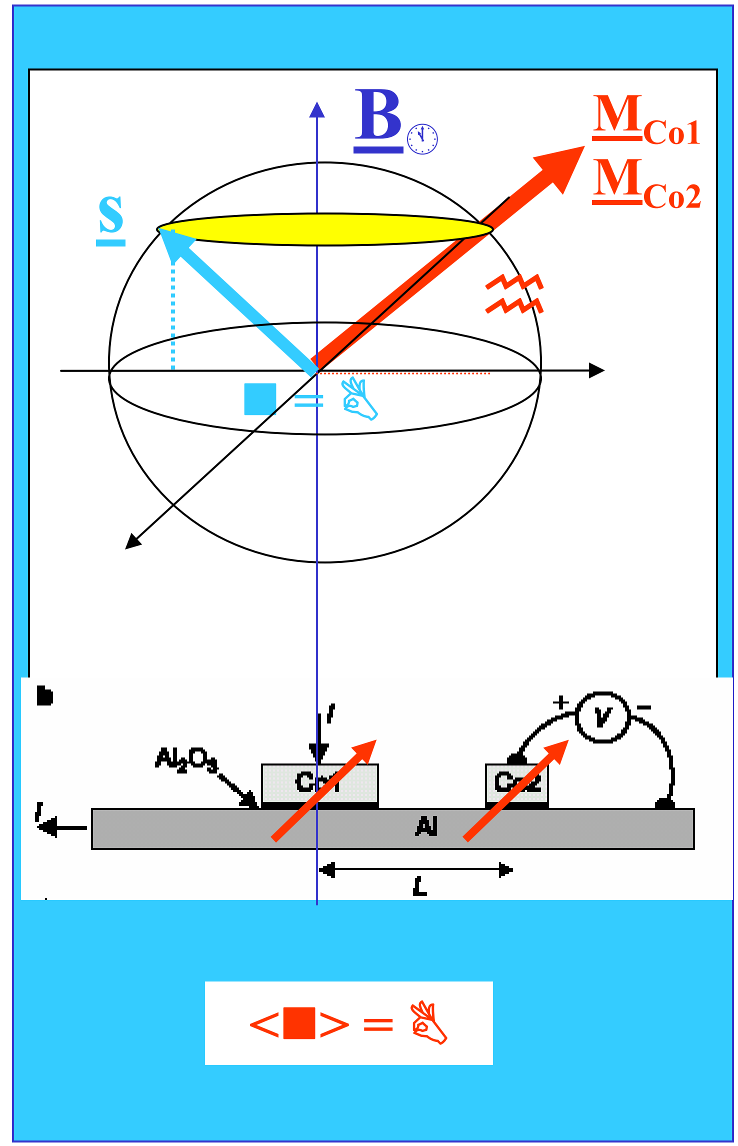
V/I as a function of (B,) at T=4.2 K and L=650nm





V/I as a function of (B🕐, ♒) at T=4.2 K and L=650 nm





4. Facit

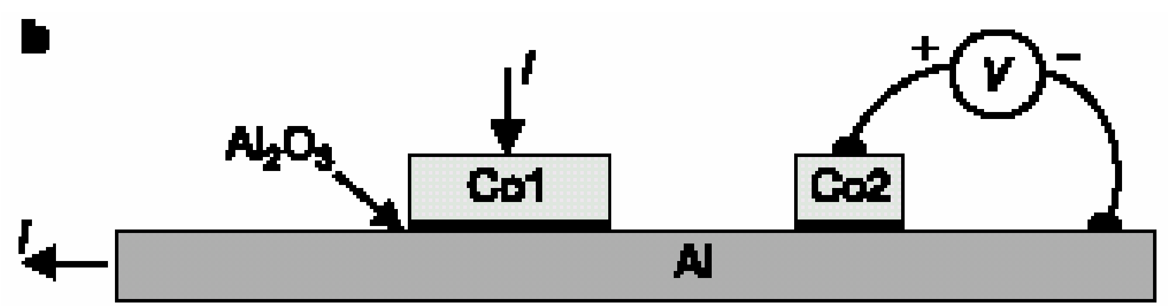
The device is such that...

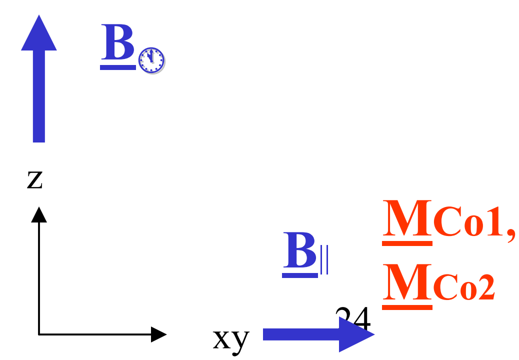
- the output voltage V is sensitive to the spin DOF only
- can control sgn(V) via...

  1. the **relative magnetization** $\mathbf{M}_{Co1}$ **-** $\mathbf{M}_{Co2}$ via $\mathbf{B}_{\parallel}$

  2. **coherent spin precession** via $\mathbf{B}_{\odot}$
     inducing an average precession angle $\langle\varphi\rangle=\pi$

- works also at room temperature
- in good agreement with theoretical predictions

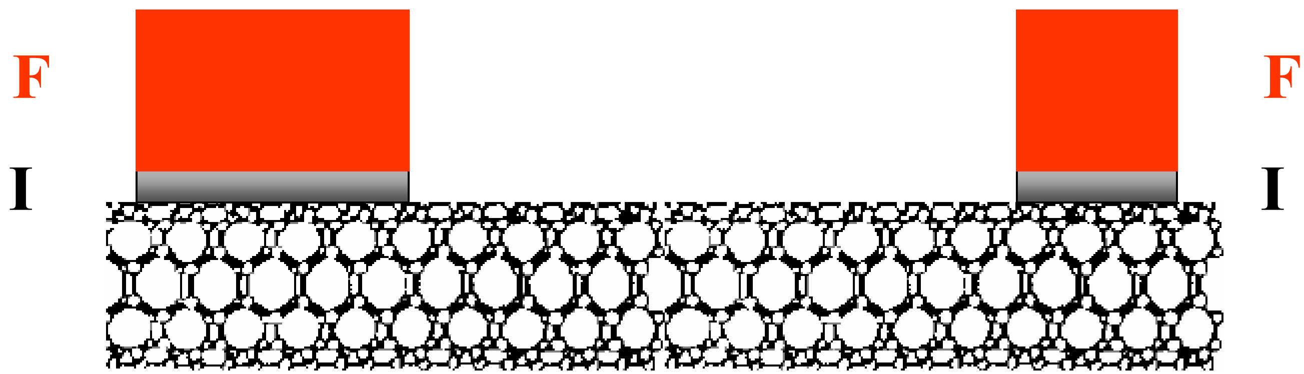




substrate plane

5. Outlook:

Al ⟶ Carbon Nanotubes



☎ ballistic transport in metallic (single wall) CNT
=> increased length of spin transmission channel
lesser loss of detection signal when manipulating spin

Fuel for Discussion:

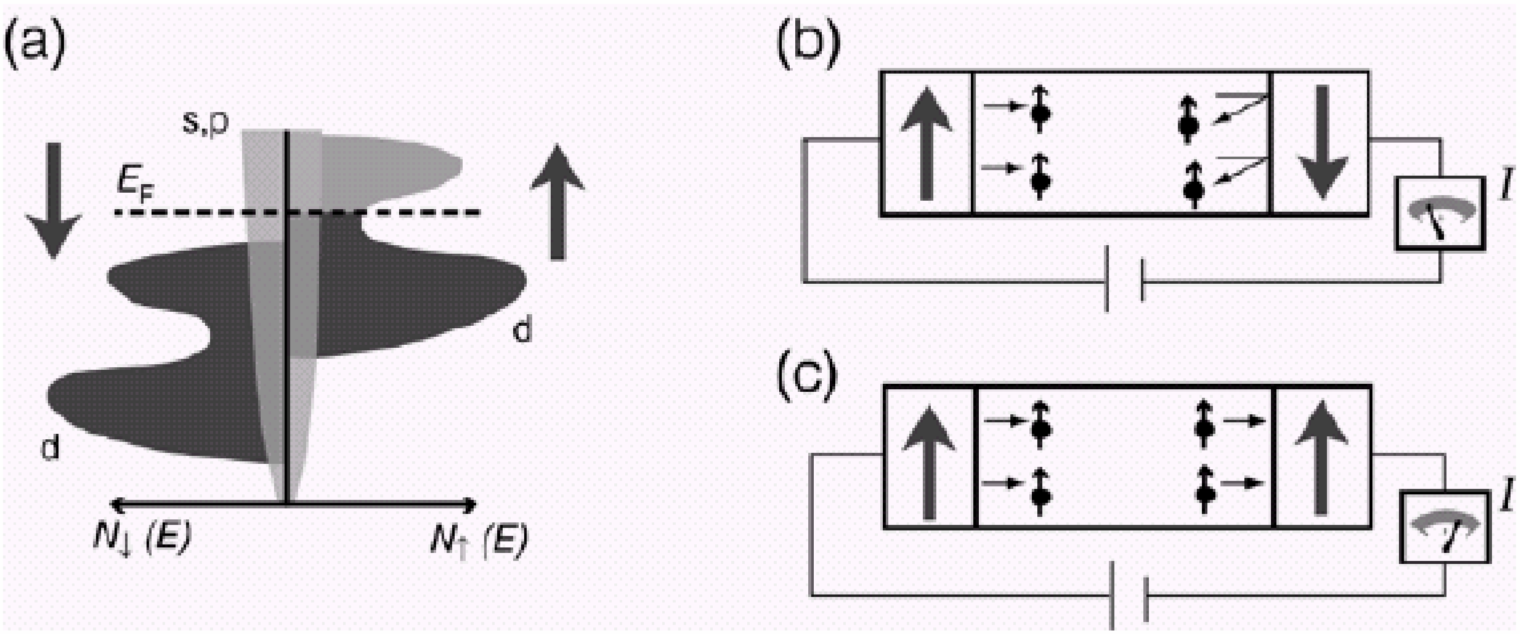


Fig. 1(a) Band structure for a ferromagnetic material showing the imbalance in the density of states at the Fermi energy. **(b)** Schematic representation of a F/N/F spin-electronic device in the anti-parallel and **(c)** parallel configurations (after Ref. 3).

Diffusion eq. In Al with boundary condtions

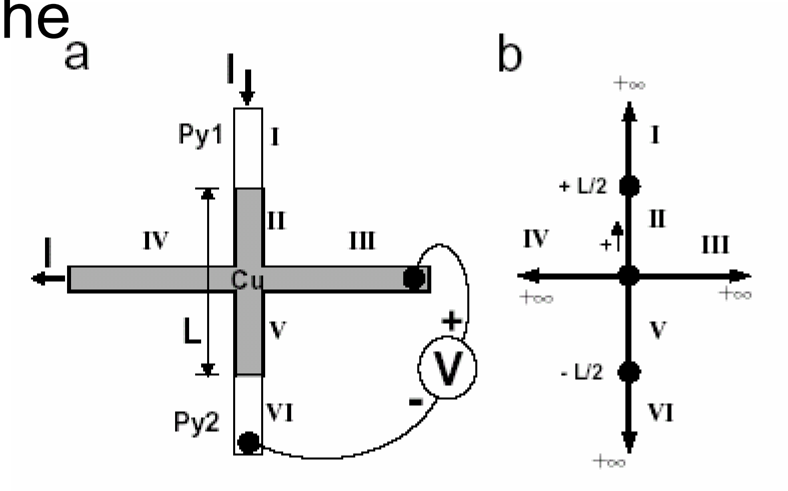
general solution for a uniform ferromagnet or nonmagnetic wire (using current conservation)

$$\mu_\uparrow = A + Bx + \frac{C}{\sigma_\uparrow} exp(-x/\lambda_{sf}) + \frac{D}{\sigma_\uparrow} exp(x/\lambda_{sf})$$

$$\mu_\downarrow = A + Bx - \frac{C}{\sigma_\downarrow} exp(-x/\lambda_{sf}) - \frac{D}{\sigma_\downarrow} exp(x/\lambda_{sf})$$

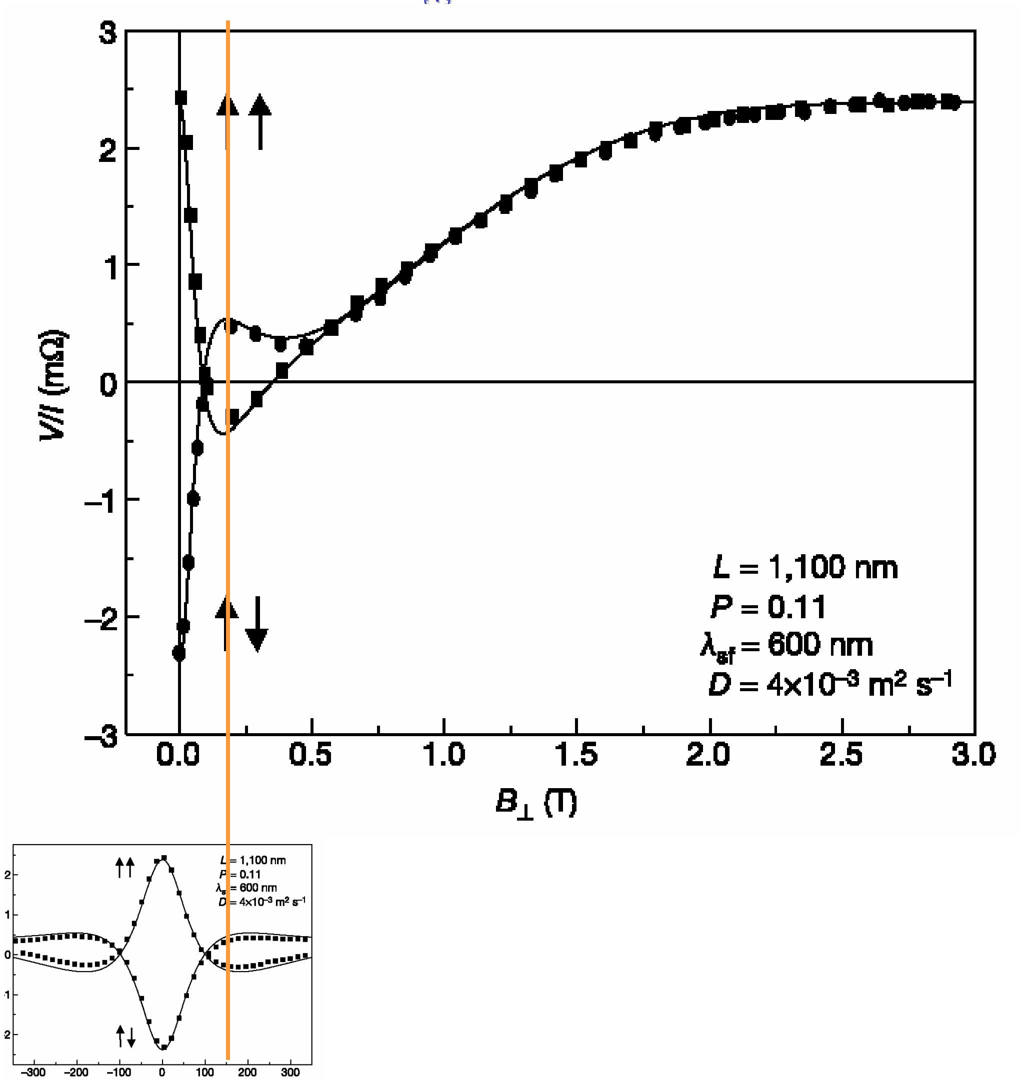
Coefficients A, B, C, D fixed by b.c.

solutions in each of the six regions of the

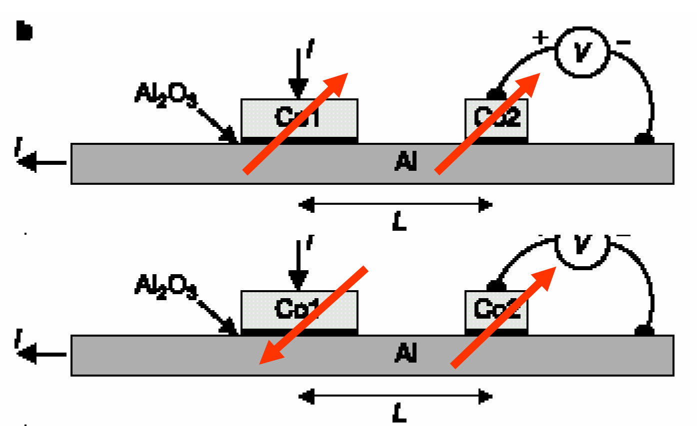


Asymmetry between ⇉ and ⇄ in theV/I curves

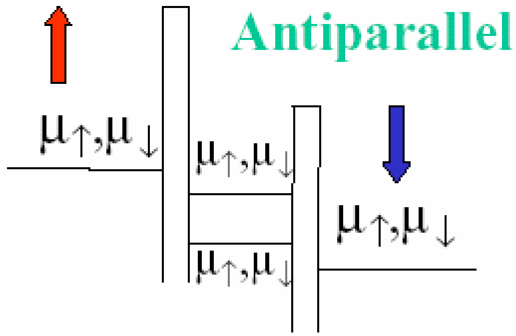
... for $\mathbf{B}_{\perp}$ > 200 mT

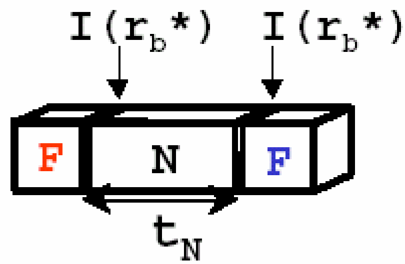


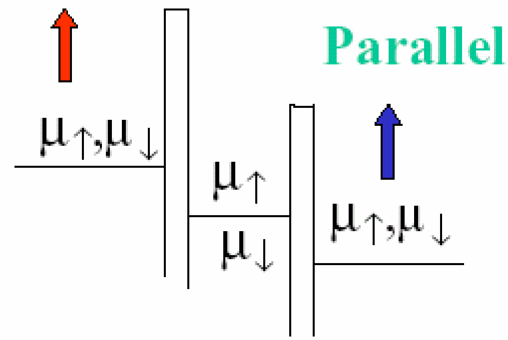
<= Co electrodes tilted out of substrate plane (AL strip)

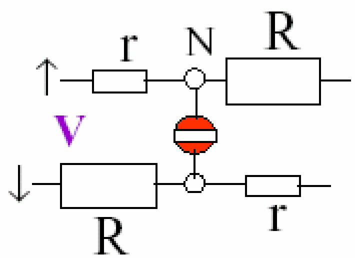


Experimental evidence : Spin transmission through a F/I/N/I/F double tunnel junction



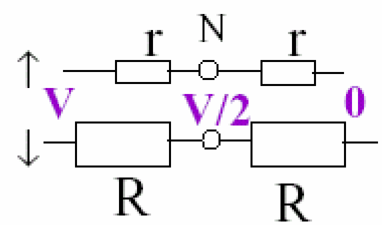






$$R^{ap} = \frac{r+R}{2}$$

$$R^{p} = \frac{rR}{r+R}$$



Condition for large TMR ≡ condition for negligible spin transfer between ↑ and ↓ in N $\Rightarrow$ $t_N \ll \frac{(l_{sf}^N)^2}{en\upsilon r_b^*}$

Possible for N = SC (small n),
Impossible for N = metal (large n)

A. Fert, H. Jaffrès,
Phys. Rev. B, 64, 184420 (2001)