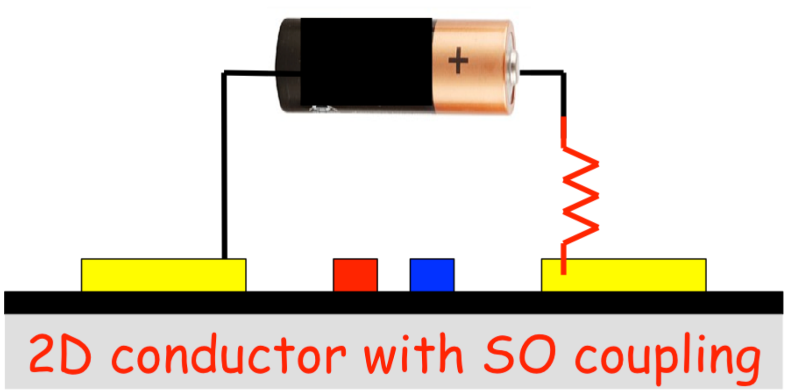
A Different Perspective

Inspired by *Mesoscopic Physics*

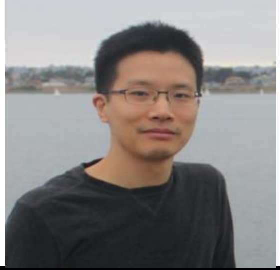
Spin - Charge Conversion



Spin Diffusion Equation with
Four Electrochemical Potentials

(2012) PRB **86**, 085131
(2015) Sci. Rep. **5**, 10571
(2016) Sci. Rep. **6**, 20325

Dr. Seokmin Hong (INTEL)



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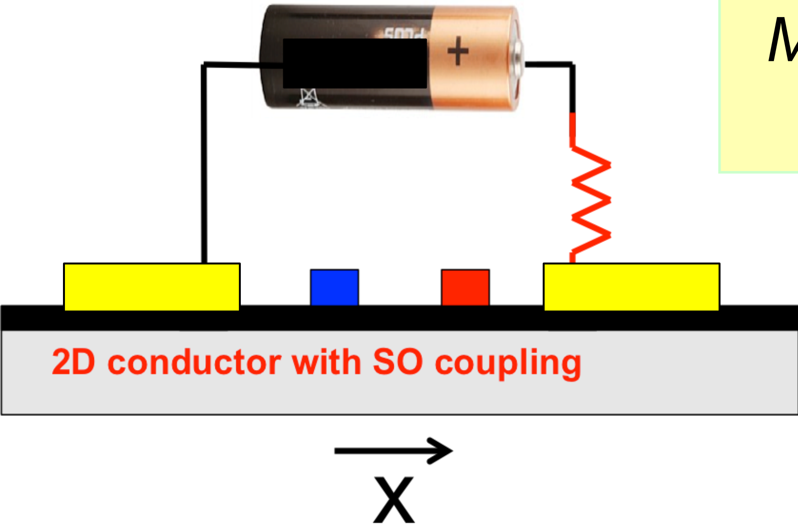
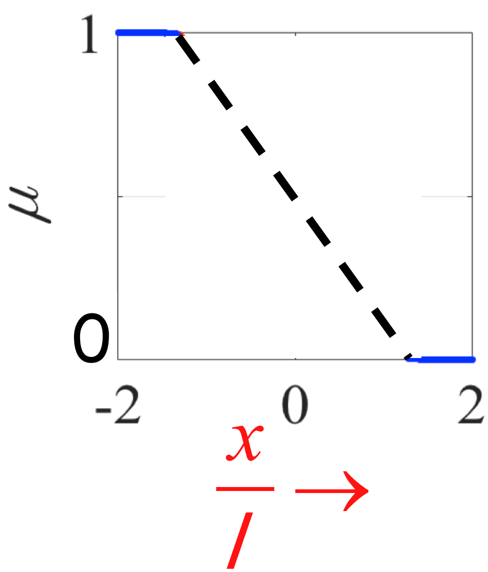
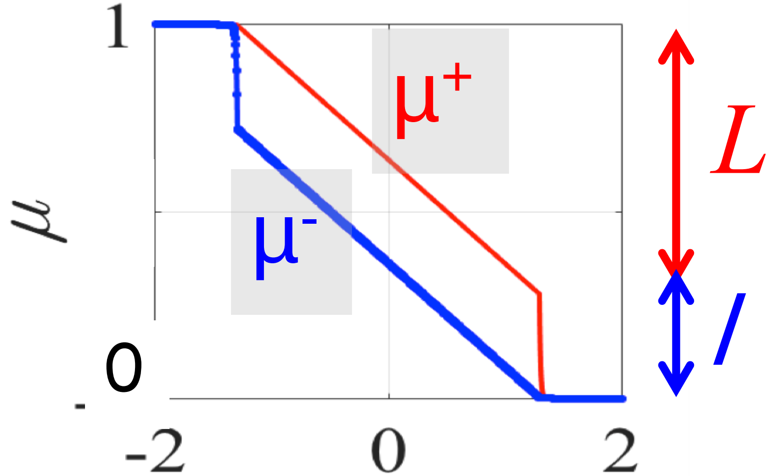
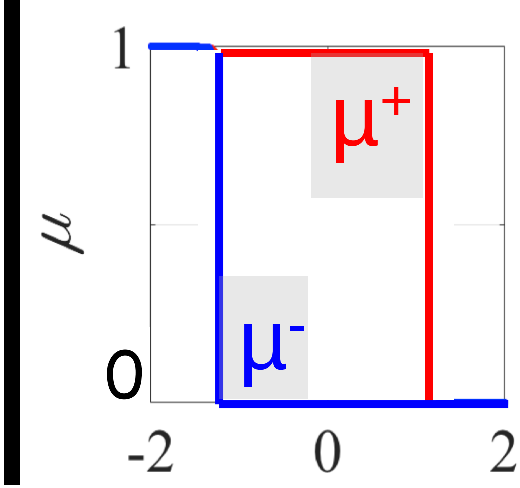
Mesoscopic Physics: Any Conductor



$$I = \left(\mu^{+} - \mu^{-}\right) \overbrace{\frac{q}{h} M}^{G_B / q}$$

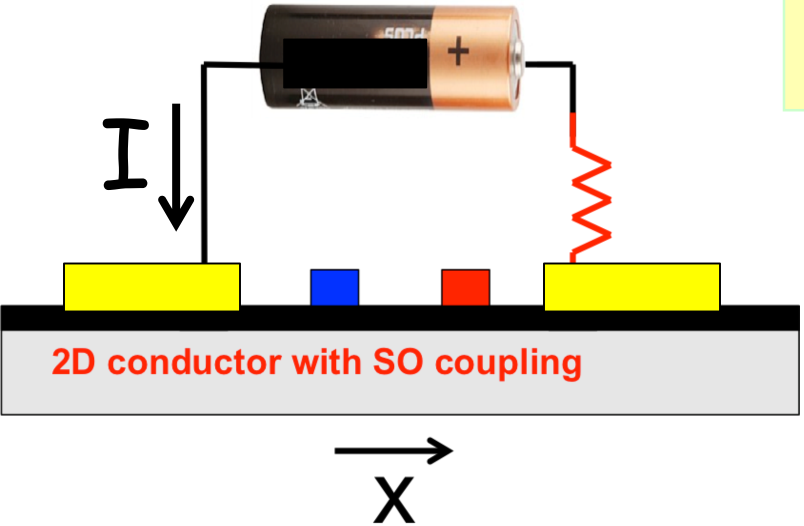






Diffusive $l \sim$ *mean free path (mfp)*

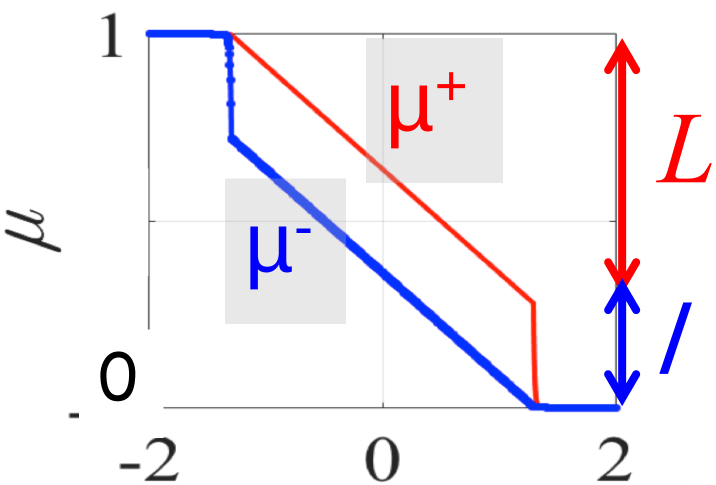
Ballistic



Number of Modes

$$I = \left(\mu^+ - \mu^-\right) \overbrace{\frac{q}{h} M}^{\frac{G_B}{q}} \qquad M \leftarrow \frac{k_F W}{\pi}$$

$$= \left(\mu_1 - \mu_2\right) \frac{\lambda}{L+\lambda} \frac{G_B}{q}$$



$$G = \underbrace{\frac{G_B}{W} \lambda}_{\downarrow} \frac{W}{L}$$

$$\sigma \sim \frac{M}{W} \lambda \rightarrow D\upsilon\lambda$$

Einstein Relation

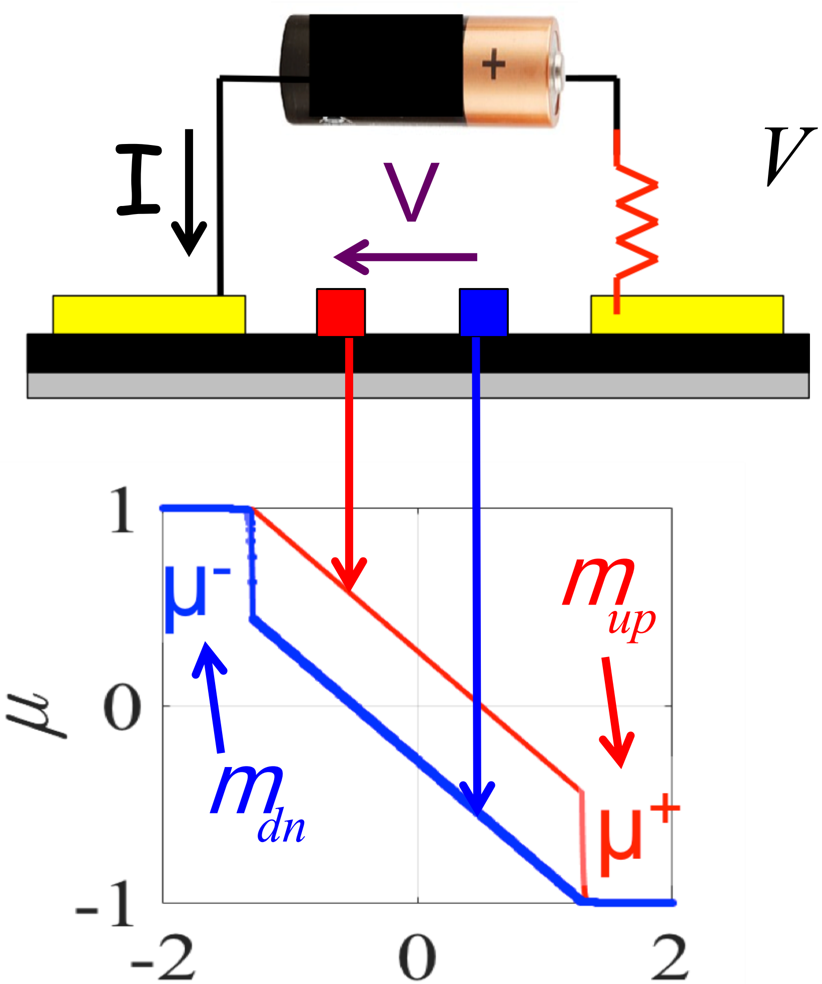
$\lambda \sim$ *mean free path (mfp)*

FM

NM

Spin voltage

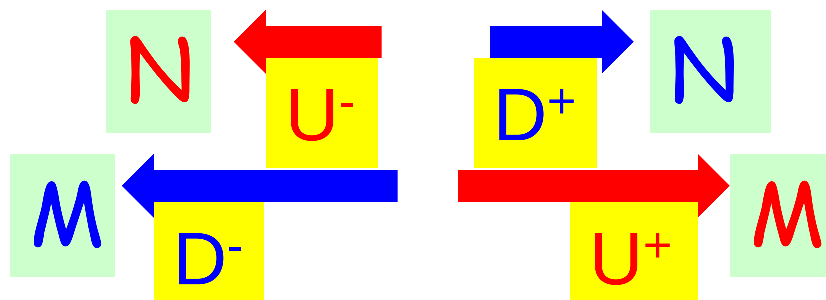
$$\mu^+ - \mu^- = qI / G_B$$

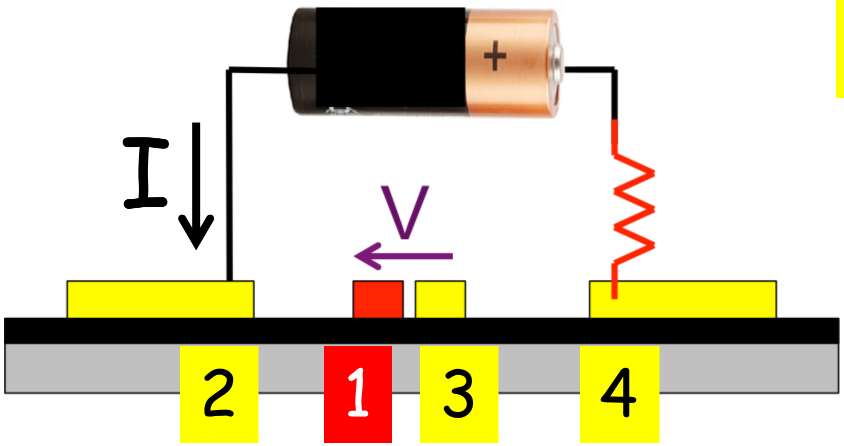


$$V = V_0 + \frac{I}{G_B} * \frac{2}{\pi} * p \times P_{magnet}$$

$$M, N \approx \frac{k_F W}{\pi} \rightarrow p \equiv \frac{M - N}{M + N}$$

$$G_B = \frac{q^2}{h}(M + N)$$





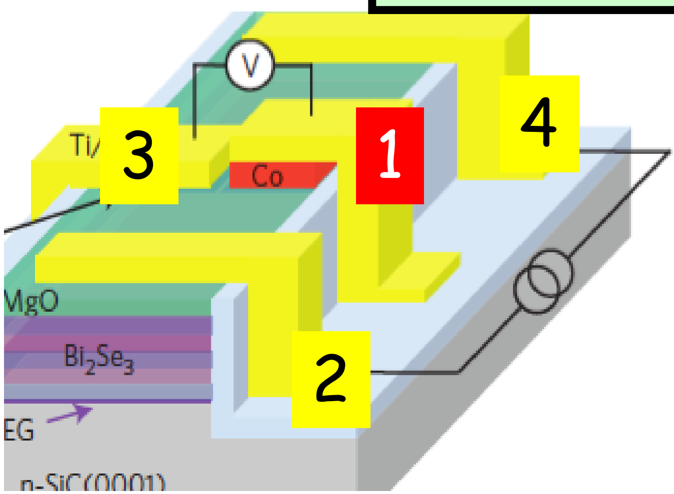
Hong et al. (2012) PRB 86 085131

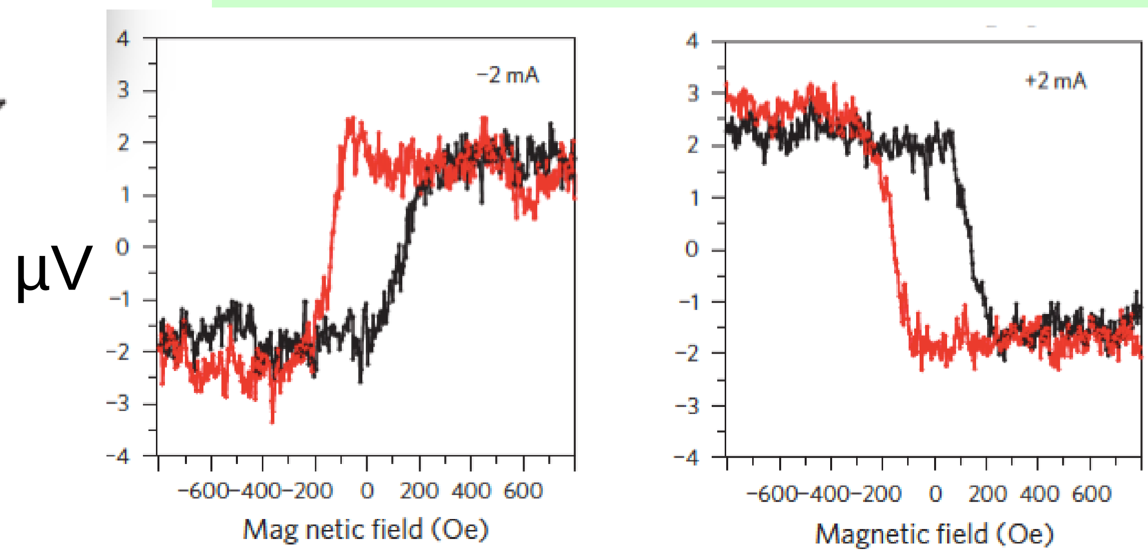
$$V = \cancel{V_0} + \frac{I}{2G_B} * \frac{2p'}{p} P_{magnet}$$

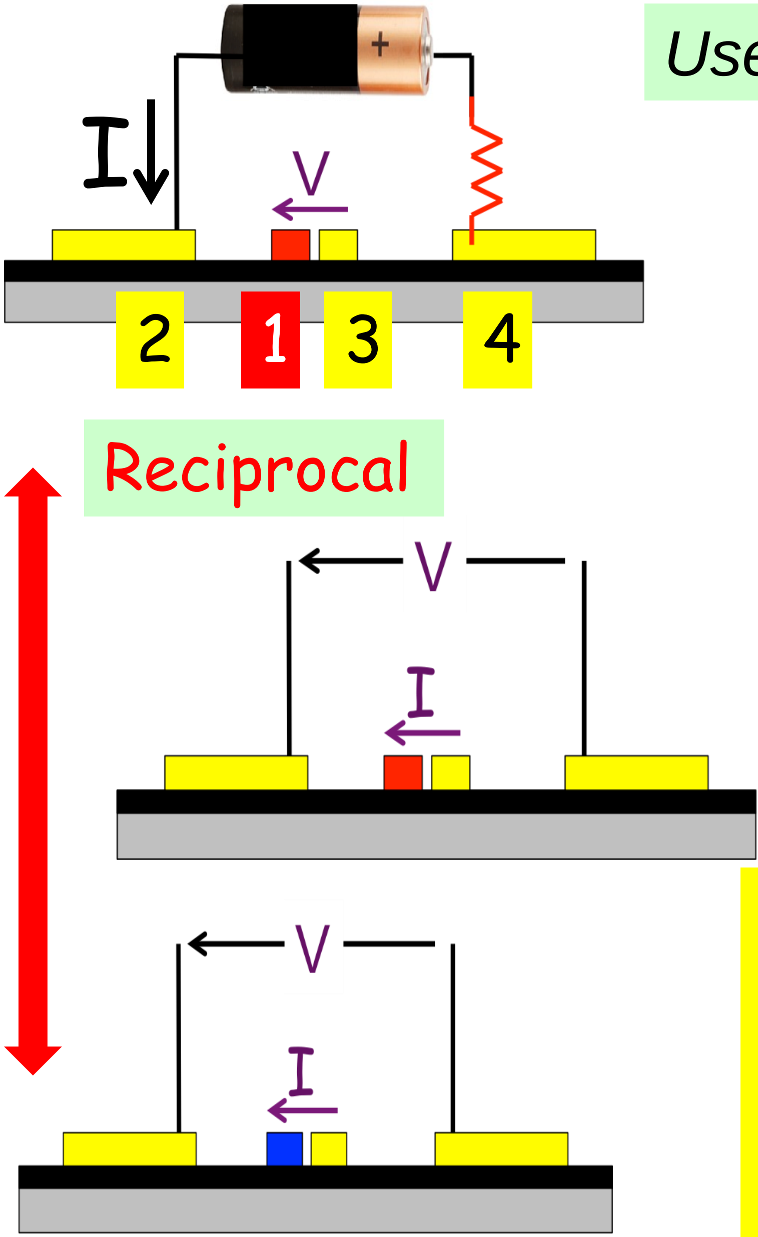
- Tang *et al.* Nano Lett. **14** , 5423 (2014)
- Tian *et al.*, Sci. Rep. **5**, 14293 (2015)
- Liu *et al.*, Phys. Rev. **B91**, 235437 (2015)
- deVries *et al.* Phys.Rev. **B92**, 201102R (2015)
- Dankert *et al.* Nano Lett, **15**, 7976 (2015)

Experiment

Li et al. (2014)
Nat. Nano 9, 218







Used by Büttiker (1986)

Reciprocity

$$R_{ij,kl}(+B,+M) = R_{kl,ij}(-B,-M)$$

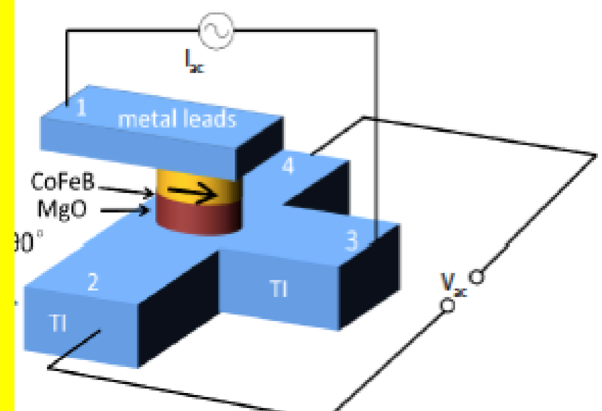
$$V = \pm \frac{I}{2G_B} * \frac{2p}{p} \times P_{magnet}$$

R(+M)=R(-M) if voltage and current terminals are the same

(Linear Response)

Reciprocity has been demonstrated experimentally

- Liu *et al.*, Phys. Rev. B91, 235437 (2015)



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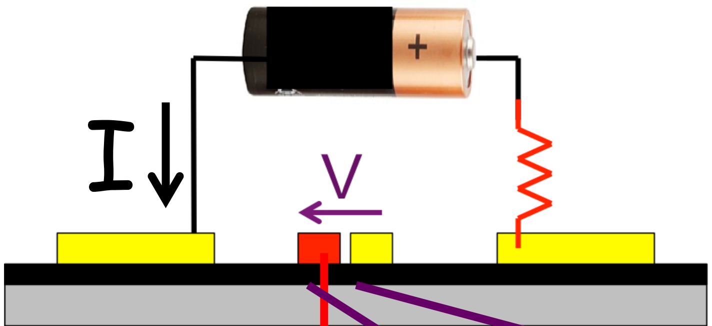
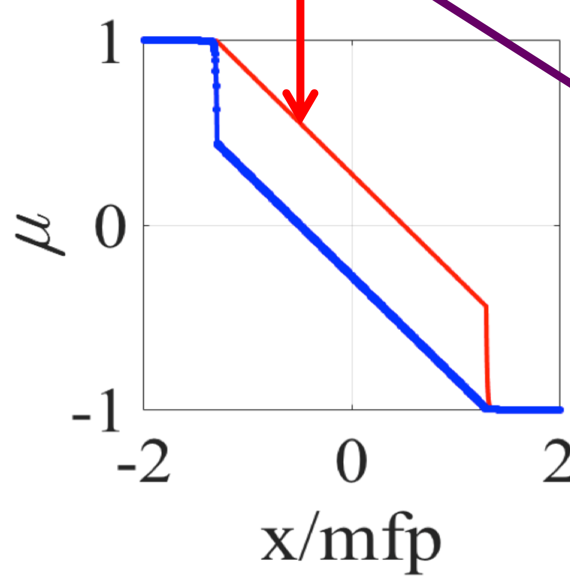
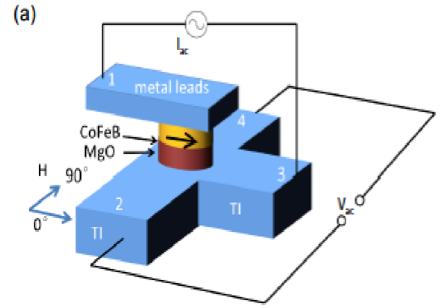
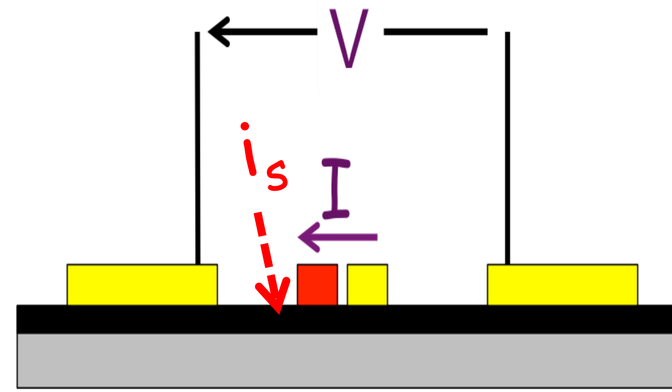
$$V = \pm \frac{qI}{2G_B} * \frac{2p}{p}\,{}^{\prime}\; P_{magnet}$$

Can we use Low Resistance Magnet Interface?









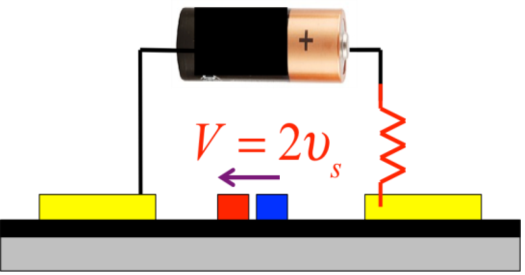
Magnet interface should have large minority spin resistance

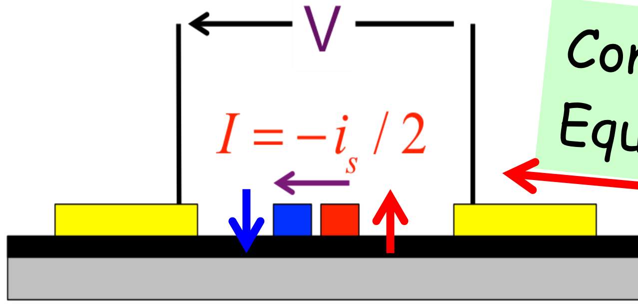
Injection by Spin Pumping

FM

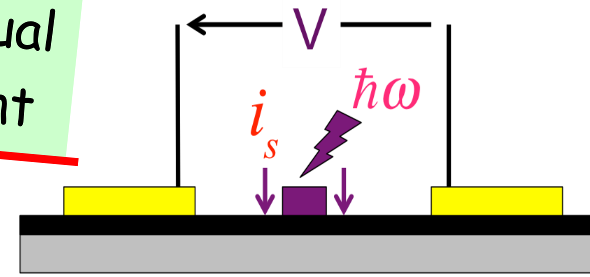
NM

$$"P_{magnet}" = 1$$





Conceptual Equivalent



$$\frac{I_{SC}}{G} = V = \frac{2p}{p} \frac{-i_s/2}{G_B}$$

$$\frac{k_1 - k_2}{k_1 + k_2} \approx \frac{M - N}{M + N} = p$$

$$\lambda_{IREE} = \left| \frac{I_{SC}}{i_s / L} \right| = \frac{p\lambda}{p}$$

$$p \approx \frac{\alpha_R}{\hbar \upsilon_F}$$

Rojas Sanchez et al. Nat. Comm. 4, 2944 (2013)

$$H = \frac{\hbar^2 k^2}{2m} I + \alpha_R \vec{\sigma} \times \vec{k}$$

$0.3\,nm$

$\lambda \approx u_F t_s$

$p \approx 0.05$

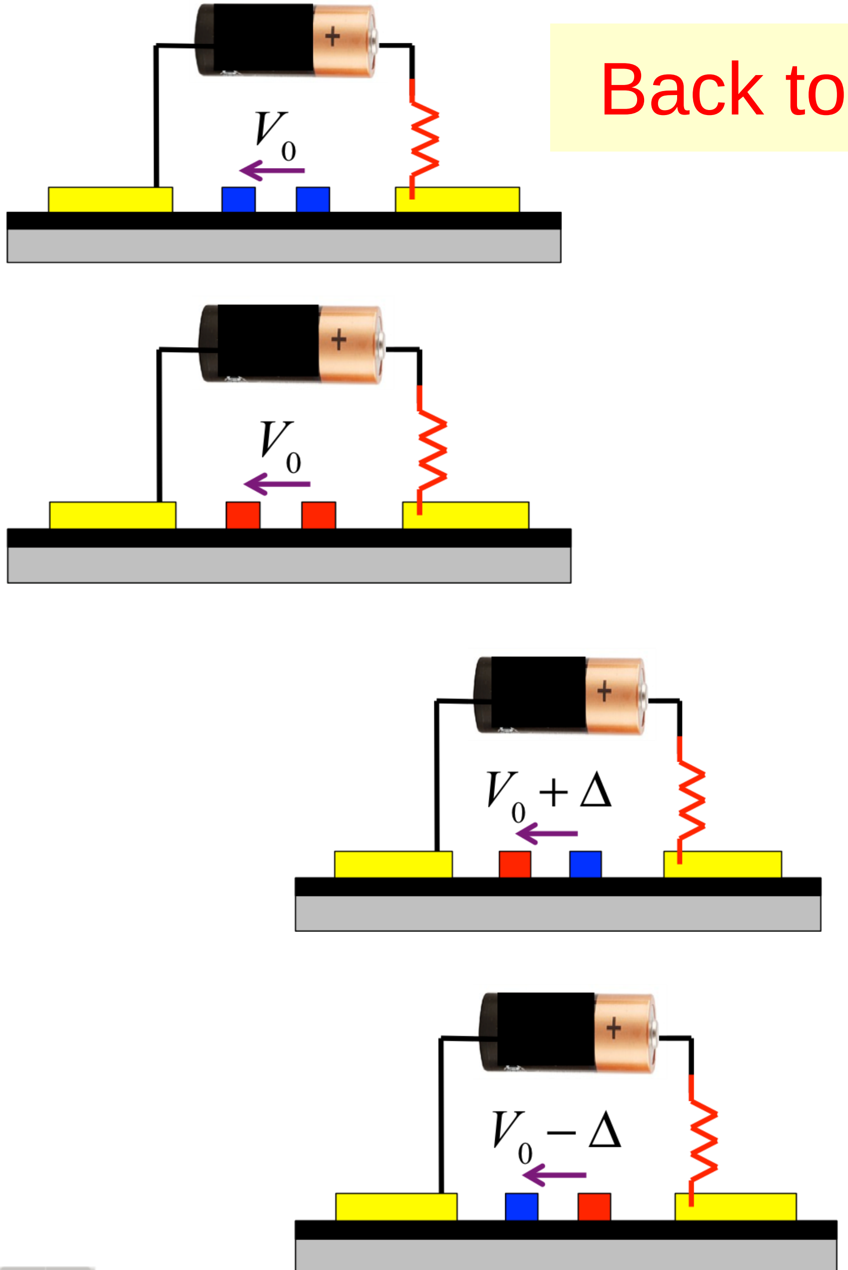
$\lambda \approx 20nm$

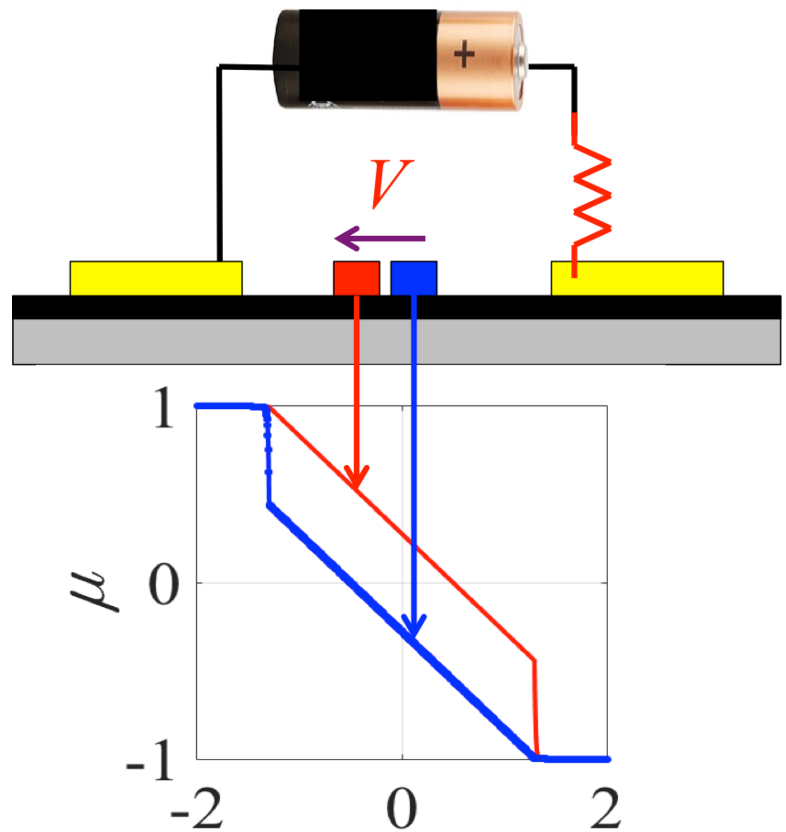
$$\frac{\alpha_R \tau_s}{\hbar} = \frac{I_{SC}}{i_s / L} = \lambda_{IREE}$$

Back to Regular Contacts

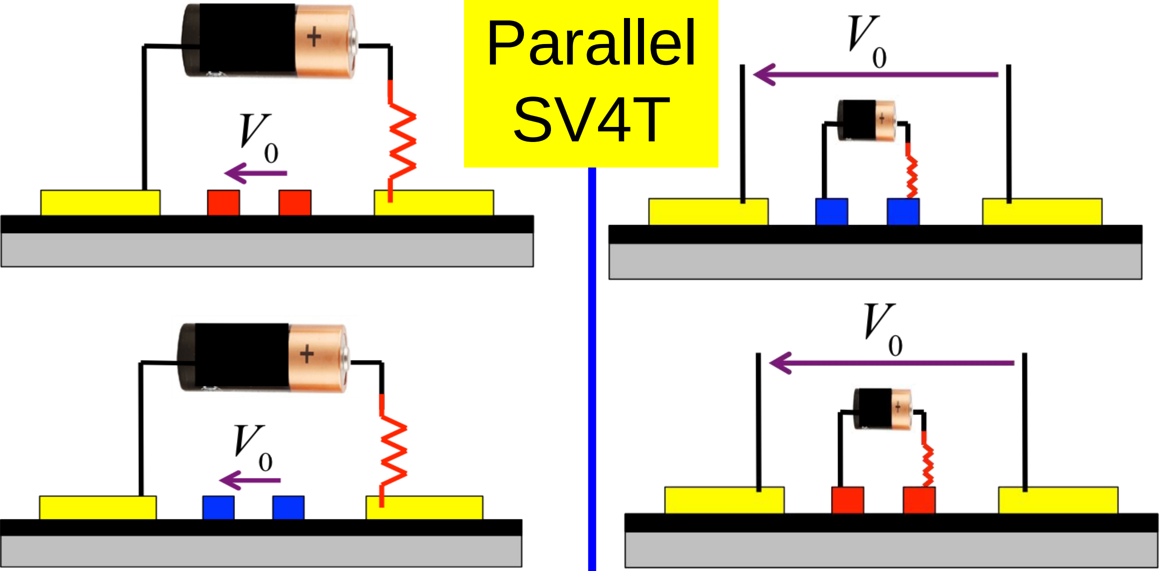
FM

NM

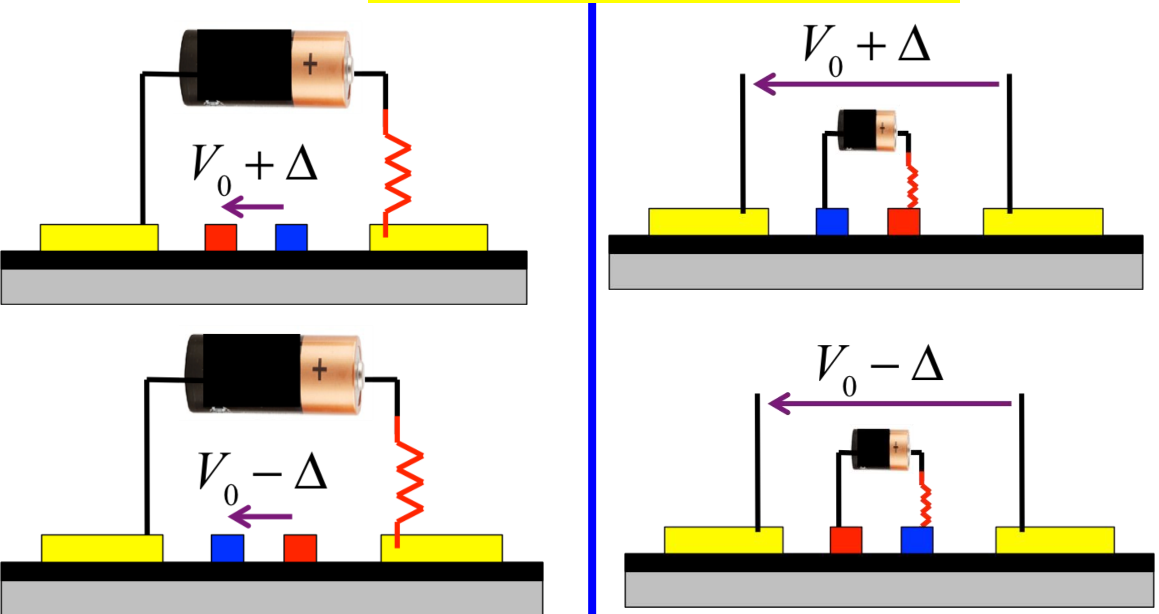




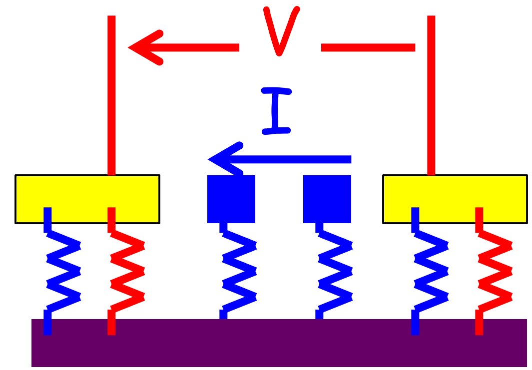
Parallel SV4T

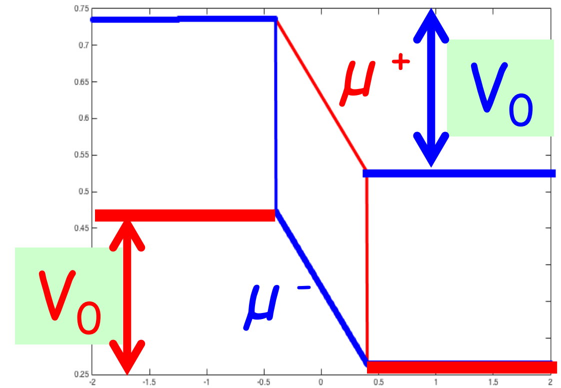


Anti-Parallel SV4T



Reciprocal Structures





Linear Response
R(+M)=R(-M) if V & I terminals are the same

Supriyo Datta

Spin Diffusion Equation with Four Potentials

Diffusion Equation

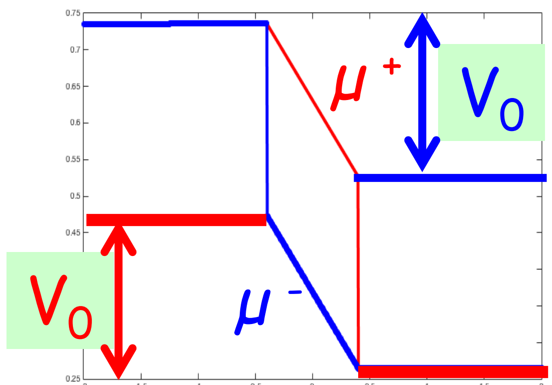
$$\frac{d}{dx} m = -\frac{J}{s}$$

Valet - Fert Equation

$$\frac{d}{dx} m_{up} = -\frac{m_{up} - m_{dn}}{l_{sf}} = -\frac{d}{dx} m_{dn}$$

Hong et al.
Sci. Rep. **6**,
20325 (2016)

$$\frac{d}{dx}\begin{Bmatrix} M\,\tilde{\mu}(U^+) \\ -M\,\tilde{\mu}(D^-) \\ -N\,\tilde{\mu}(U^-) \\ N\,\tilde{\mu}(D^+) \end{Bmatrix} = \begin{bmatrix} -u_1 & r_{s1} & r & t_s \\ r_{s1} & -u_1 & t_s & r \\ r & t_s & -u_2 & r_{s2} \\ t_s & r & r_{s2} & -u_2 \end{bmatrix} \begin{Bmatrix} \tilde{\mu}(U^+) \\ \tilde{\mu}(D^-) \\ \tilde{\mu}(U^-) \\ \tilde{\mu}(D^+) \end{Bmatrix}$$



$$\frac{d}{dx} m^+ = -\frac{m^+ - m^-}{l} = \frac{d}{dx} m^+$$

Mesoscopic Physics

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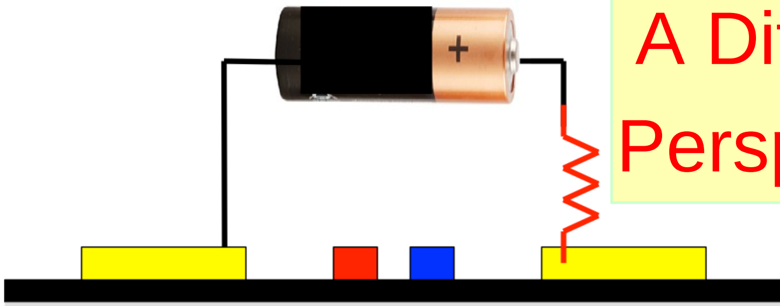
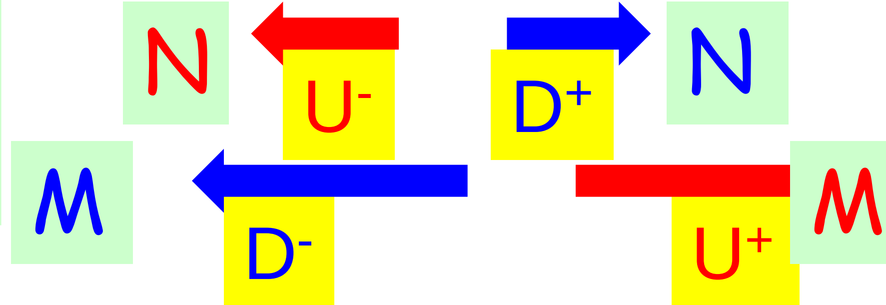


A Different Perspective



… What might be of modern interest is the "channel" concept which is so important in localization theory. The transport properties at low frequencies can be reduced to a sum over one-dimensional "channels"…

P. W. Anderson, *50 Years of Anderson Localization (2010)*

$$M, N \sim \frac{k_F W}{\pi}$$

$$\rightarrow p \equiv \frac{M - N}{M + N}$$

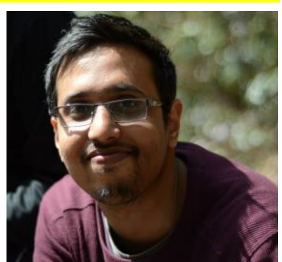
$$G_B = \frac{q^2}{h}(M + N)$$

$$G = G_B \frac{\lambda}{L}$$

Thanks!

Dr. Seokmin Hong (INTEL)

Shehrin Sayed



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