Spintronics and Nanomagnetics

ECS 521/641

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Spin relaxation

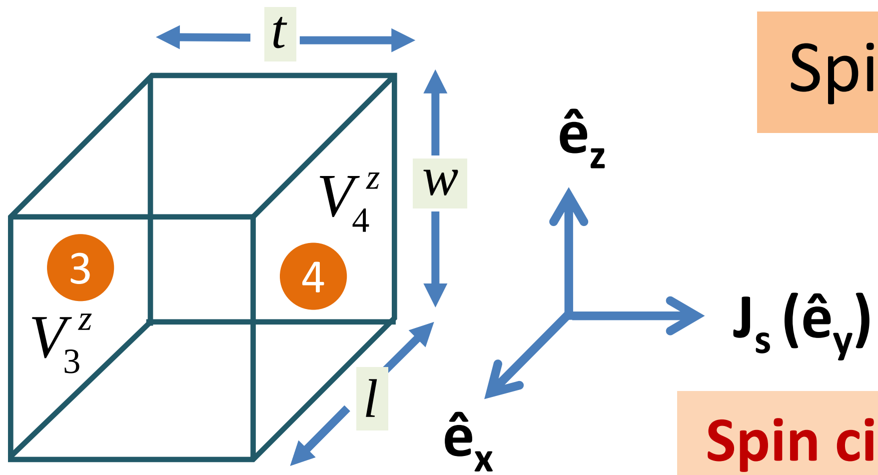
Magnetoresistance

Spin waves

Magnetic Force Microscopy

Spin relaxation

Spin relaxation

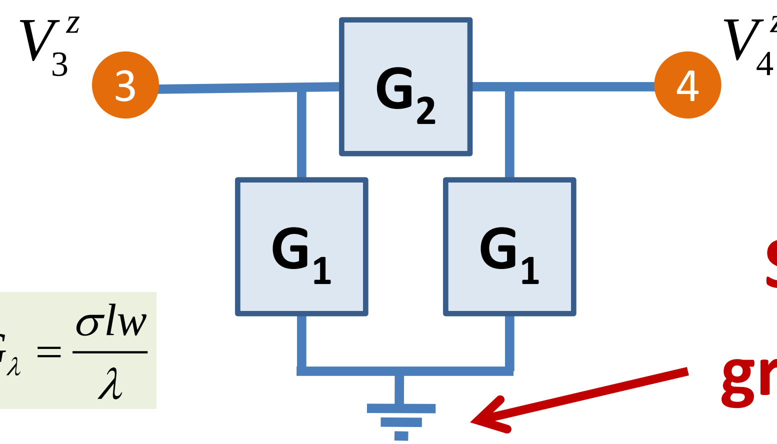


Spin relaxes due to spin diffusion

$$\frac{d^2V^z(y)}{dy^2} = \frac{V^z(y)}{\lambda^2}$$

λ: Spin diffusion length

Spin circuit

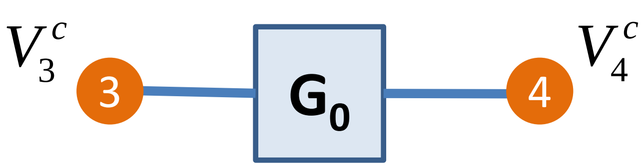


$$G_\lambda = \frac{\sigma l w}{\lambda}$$

Spin ground

$$G_1 = G_\lambda \tanh\left(\frac{t}{2\lambda}\right) \qquad G_2 = G_\lambda \,\mathrm{csch}\left(\frac{t}{\lambda}\right)$$

Charge circuit



$$G_0 = \frac{\sigma l w}{t}$$

No shunt elements

Dispersion relation: $B = 0, \nu = 0$

$$E_{\pm} = \frac{\hbar^2 (k_x^2 + k_z^2)}{2m^*} \pm \sqrt{\left(\frac{g\mu_B B_z}{2} + \eta k_x - \nu k_z\right)^2 + \left(\frac{g\mu_B B_x}{2} - \eta k_z + \nu k_x\right)^2}$$

$$E_{\pm} = \frac{\hbar^2 k^2}{2m^*} \pm \eta k$$

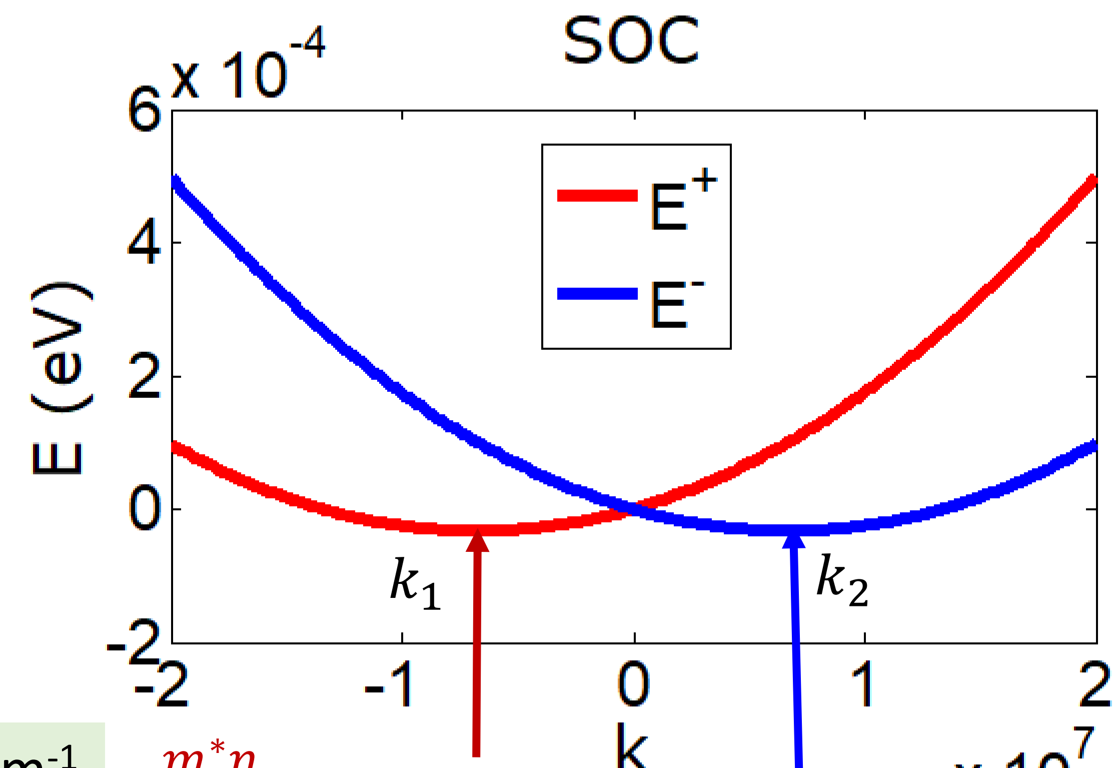
$$k_2 - k_1 = \frac{2m^*\eta}{\hbar^2}$$

$m^* = 0.05 m_0$

$\eta = 10^{-11} eV - m$

$\frac{\hbar^2}{2m^*} = 7.4566e - 19 \quad eV - m^2$

SOC splitting = 1.3411e+07 m^{-1}



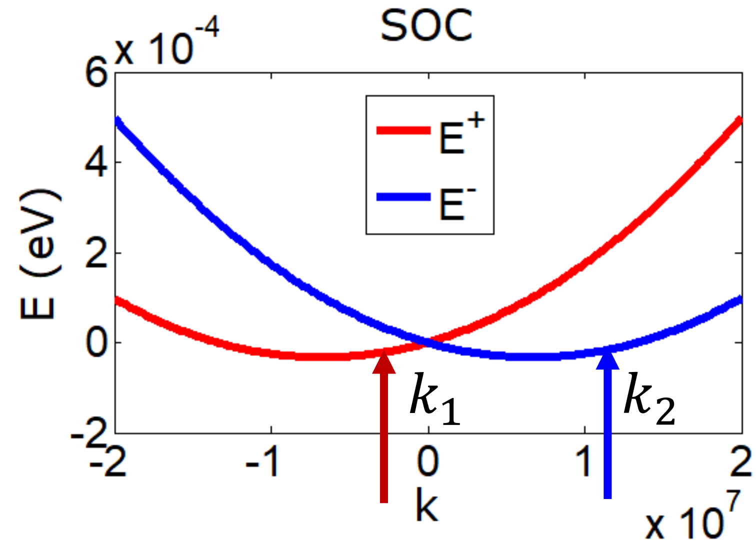
$-\frac{m^*\eta}{\hbar^2} = -6.7055e+06$

$\frac{m^*\eta}{\hbar^2} = 6.7055e+06$

Spin-orbit magnetic field

$$E_\pm = \frac{\hbar^2 k^2}{2m^*} \pm \eta k$$

Similarly for Dresselhaus SOC
$\boldsymbol{\nu \rightarrow \eta}$



$$k_2 - k_1 = \frac{2m^*\eta}{\hbar^2}$$

$$v_1(E) = \frac{1}{\hbar}\frac{\partial E_+}{\partial k} = \frac{\hbar k_1(E)}{m^*} + \frac{\eta}{\hbar}$$

$$v_2(E) = \frac{1}{\hbar}\frac{\partial E_-}{\partial k} = \frac{\hbar k_2(E)}{m^*} - \frac{\eta}{\hbar}$$

$$v_1(E) = v_2(E) = v(E)$$

Velocity is spin-independent

$$v(E) = \frac{v_1(E) + v_2(E)}{2} = \frac{\hbar}{m^*}\frac{k_1(E) + k_2(E)}{2} = \frac{\hbar k_{av}(E)}{m^*}$$

$$\boldsymbol{B}_{\boldsymbol{Rashba}} = \frac{2a_R}{g\mu_B}(\boldsymbol{E} \times \boldsymbol{k})$$

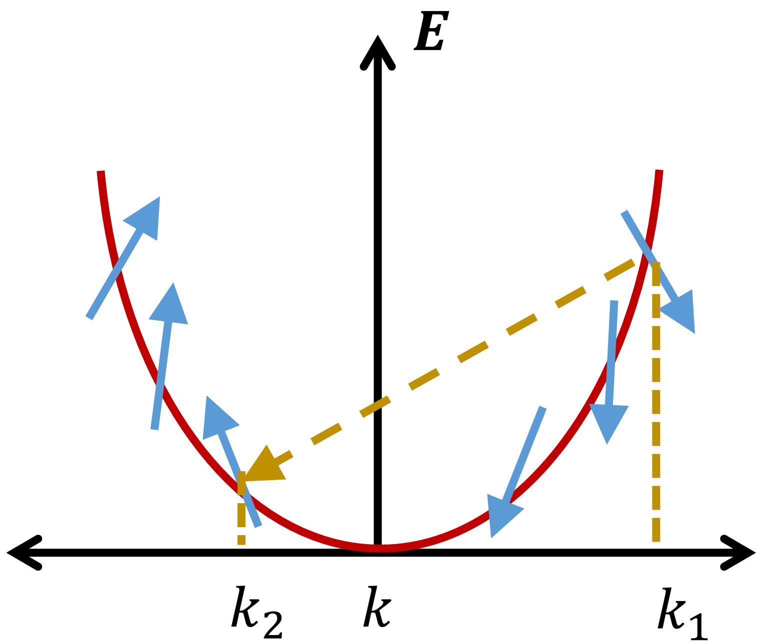
$$|\boldsymbol{B}_{\boldsymbol{Rashba}}| = \frac{2\eta}{g\mu_B}k_{av} = \frac{2\eta m^*}{g\mu_B \hbar}v = \frac{2^{3/2}\eta {m^*}^{1/2}}{g\mu_B \hbar}\sqrt{E}$$

Elliott-Yafet spin relaxation

In a crystal, the Bloch states may not be spin eigenstates

The actual polarization depends on the wavevectors

Each wavevector state still has two possible spin orientations that are mutually anti-parallel



A momentum changing collision event e.g., phonon scattering changes the wavevector k_1 to k_2

$$\tau_{EY} \propto \tau_m$$

- R. J. Elliott, Phys. Rev. 96, 266 (1954)
- Y. Yafet, Phys. Lett. A 98, 287 (1983)

D'yakonov Perel' spin relaxation

$$|\boldsymbol{B}_{\boldsymbol{Rashba}}| = \frac{2\eta}{g\mu_B}k = \frac{2\eta m^*}{g\mu_B\hbar}v$$

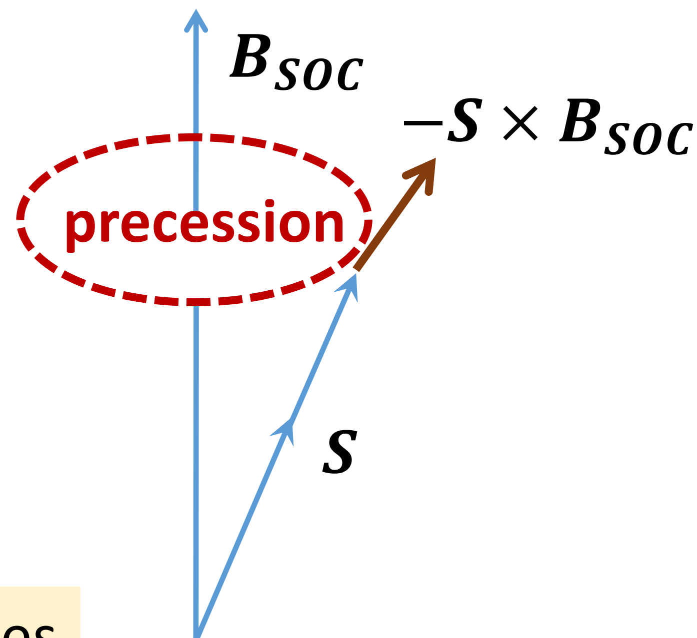
$$|\boldsymbol{B}_{\boldsymbol{Dresselhaus}}| = \frac{2\nu}{g\mu_B}k = \frac{2\nu m^*}{g\mu_B\hbar}v$$

If the velocity/wavevector changes **randomly owing to scattering**

The axis about which spin precesses changes

Frequency of precession changes

Frequent momentum relaxing collisions tend to slow down electrons and suppress DP spin relaxations



$$\frac{d\boldsymbol{S}}{dt} = -|\gamma|\boldsymbol{S} \times \boldsymbol{B}_{\boldsymbol{SOC}}$$

$$\tau_{DP} \propto \frac{1}{\tau_m}$$

- M. I. Dyakonov and V. I. Perel, Sov. Phys. Solid State 13, 3023 (1972)

Spin diffusion length

Drude model

$$\sigma = ne^2\tau_m/m^*$$

$$\lambda_{sf} = \sqrt{D\,\tau_{sf}}$$

D: Diffusions coefficient
D_{OS}: Density of states

$$D = \sigma/e^2 D_{OS}$$

$$\tau_{sf} = \left(\frac{\lambda_{sf}^2 m^*\ D_{OS}}{n}\right)\frac{1}{\tau_m}$$

EY spin relaxation

$$\tau_{EY} \propto \tau_m$$

$$\lambda_{sf} \propto \sigma$$

DP spin relaxation

$$\tau_{DP} \propto \frac{1}{\tau_m}$$

$$\lambda_{sf} = constant$$

Other spin relaxation mechanisms

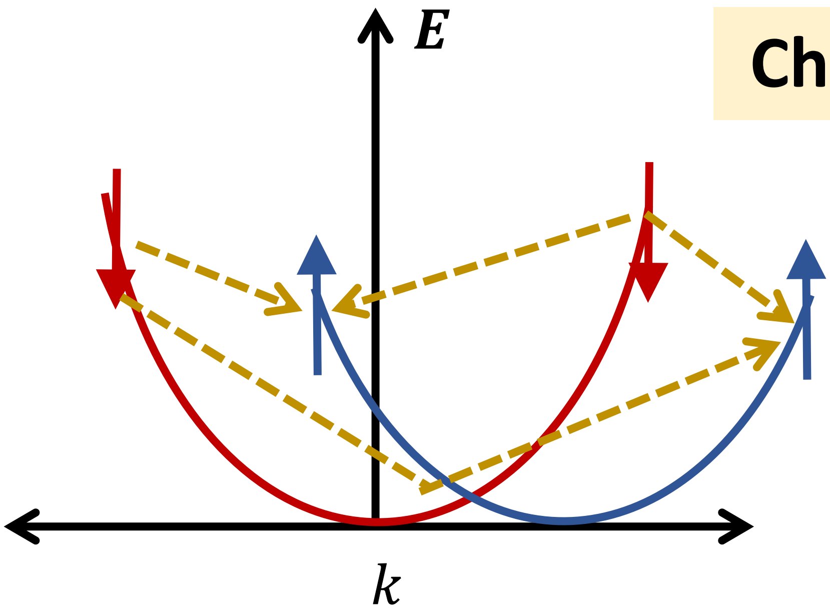
Bir-Arnov-Pikus spin relaxation

Spin relaxation in semiconductors when there is a significant concentration of both electrons and holes

Hyperfine interactions with nuclear spins

Nuclear spins generate a magnetic field which interacts with the electron spins via hyperfine interactions and can cause spin relaxation

Spin-galvanic effect



Charge current without a battery!

Spin-down band has higher energy

An electron from a filled state in the down-spin band to scatter to an empty state in the up-spin band

Asymmetric *k*-dependent scattering makes velocity asymmetric → current flow

No violation of energy conservation

Spin-polarized carrier population using circularly polarized light

- Ganichev et al, Spin-galvanic effect, Nature **417**, 153 (2002)

Magnetoresistance

Nobel Prize in Physics (2007)

The Nobel Prize in Physics 2007
Albert Fert, Peter Grünberg

The Nobel Prize in Physics 2007

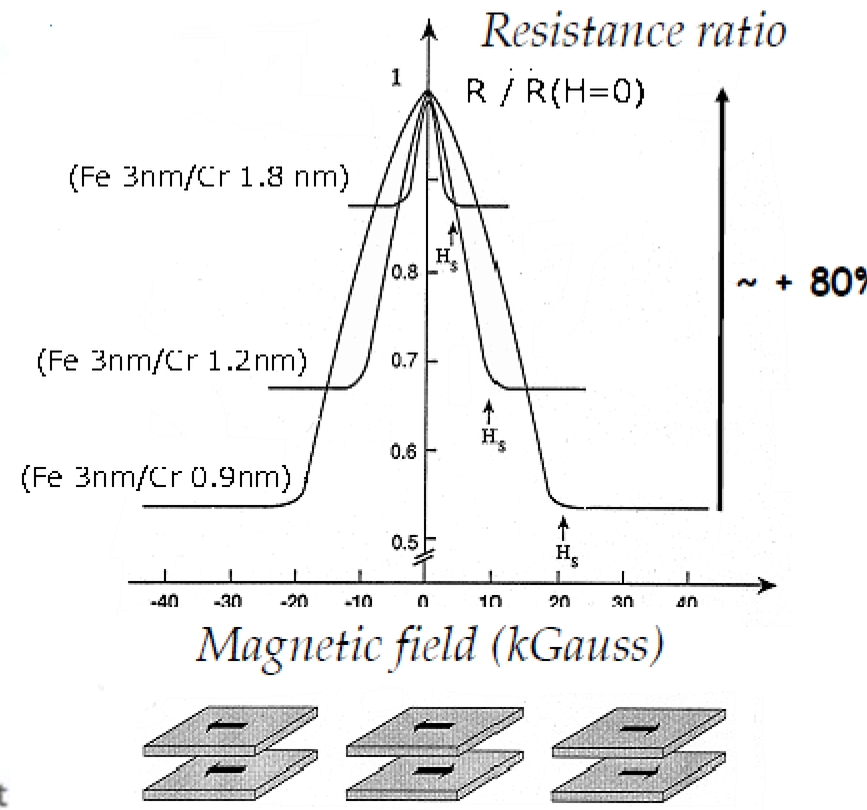
Photo: U. Montan
Albert Fert
Prize share: 1/2

Photo: U. Montan
Peter Grünberg
Prize share: 1/2

The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg *"for the discovery of Giant Magnetoresistance*

- **A. Fert**, M.N. Baibich et al., Phys. Rev. Lett. **61**, 2472 (1988)
- **P. Grunberg**, G. Binash et al., Phys. Rev. B **39**, 4828 (1989)

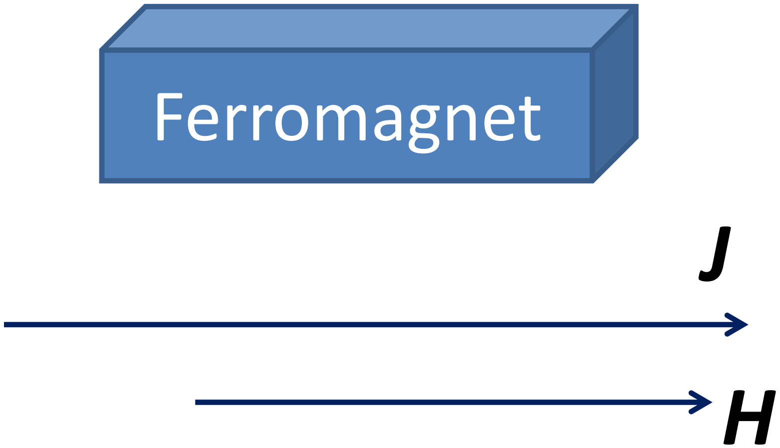
Giant Magneto-Resistance (GMR)



AP (AntiParallel) **P** (Parallel)

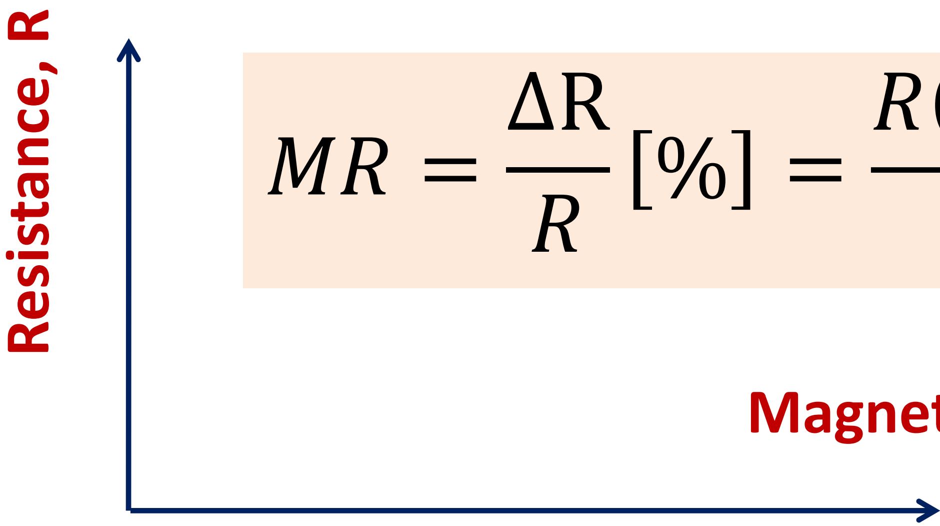
1988

Magneto-Resistance (MR)



$$\frac{\Delta\rho}{\rho} = a\left(\frac{H}{\rho}\right)^2$$

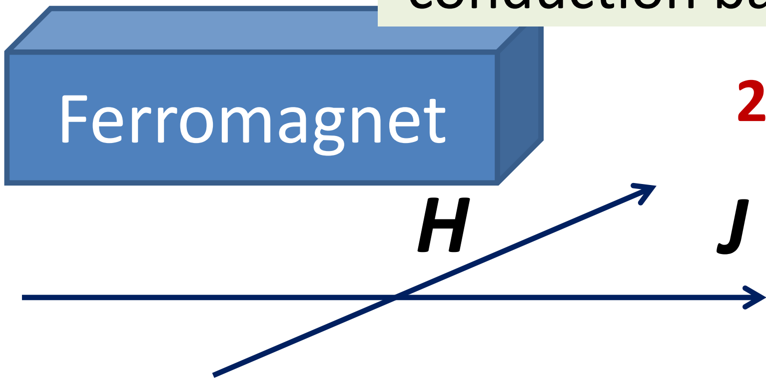
MR can be positive or negative



$$MR = \frac{\Delta \mathrm{R}}{R}[\%] = \frac{R(H) - R(0)}{R(0)} \times 100$$

Anisotropic Magneto-Resistance (AMR)

Anisotropic mixing of spin-up and spin-down conduction bands due to **spin-orbit coupling**



2-5% AMR

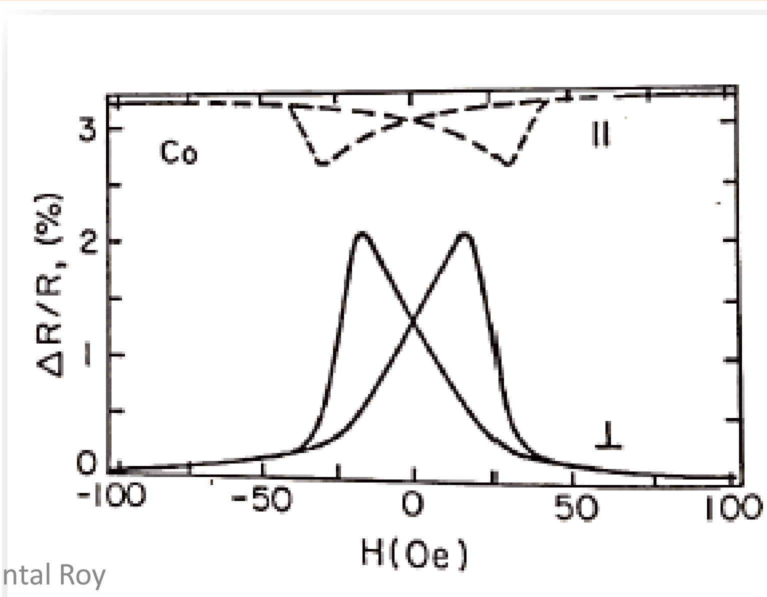
$$\frac{\Delta\rho}{\rho} \propto a\left(\frac{H}{\rho}\right)^2 + b\left(\frac{M}{\rho}\right)^2$$

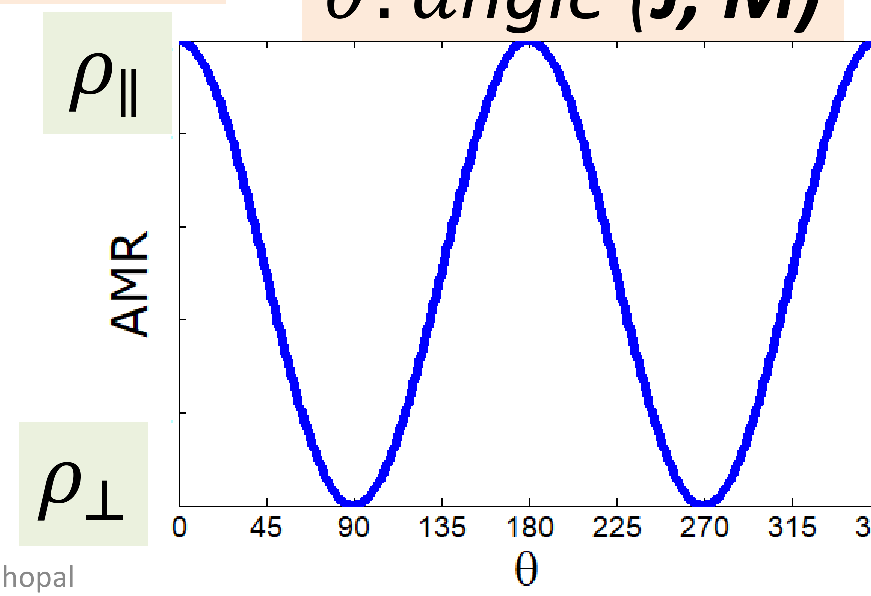
Ordinary Magnetoresistance

Anisotropic Magnetoresistance

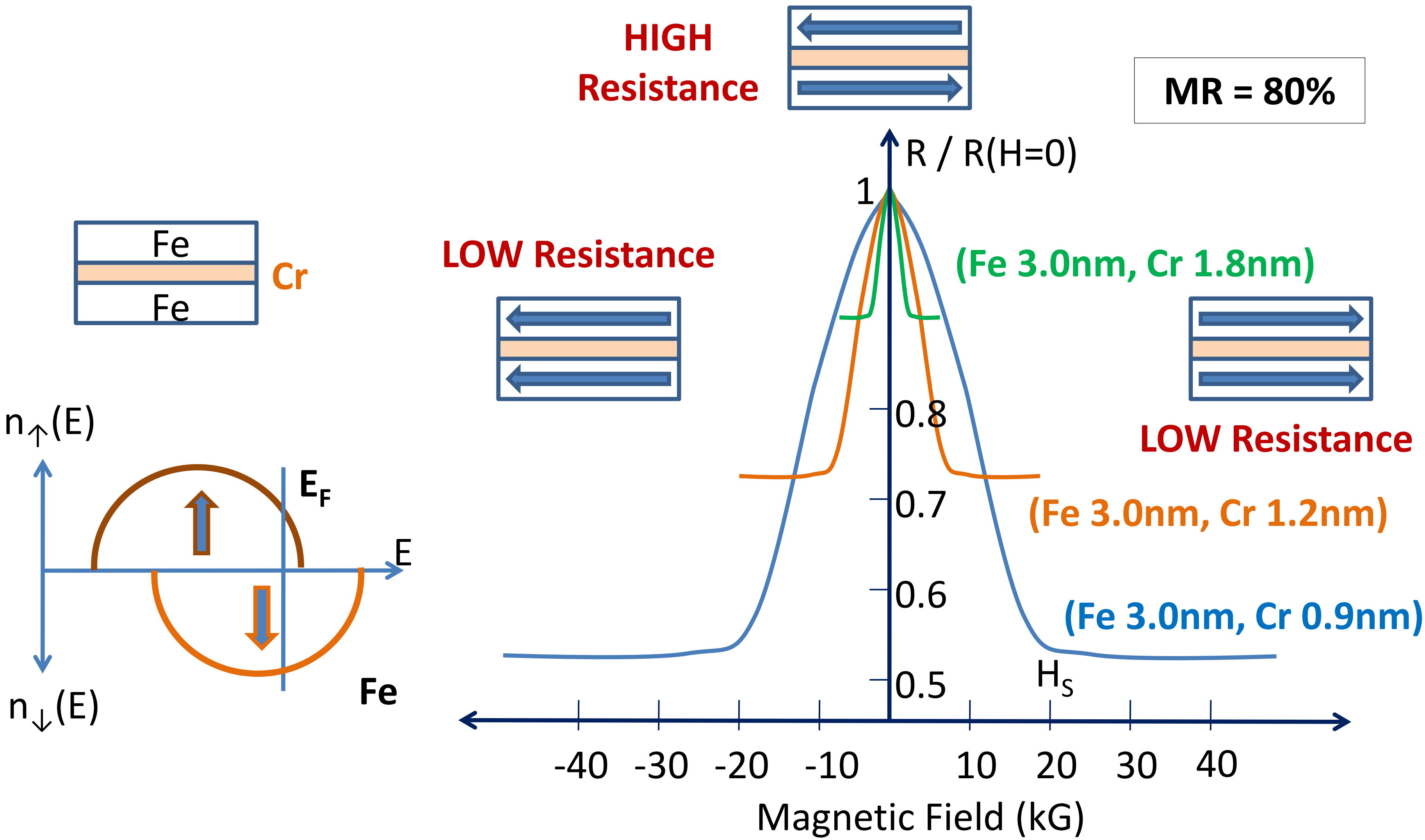
$$\rho(\theta) = \rho_\perp + (\rho_\parallel - \rho_\perp)\cos^2(\theta)$$

θ: *angle* ***(J, M)***



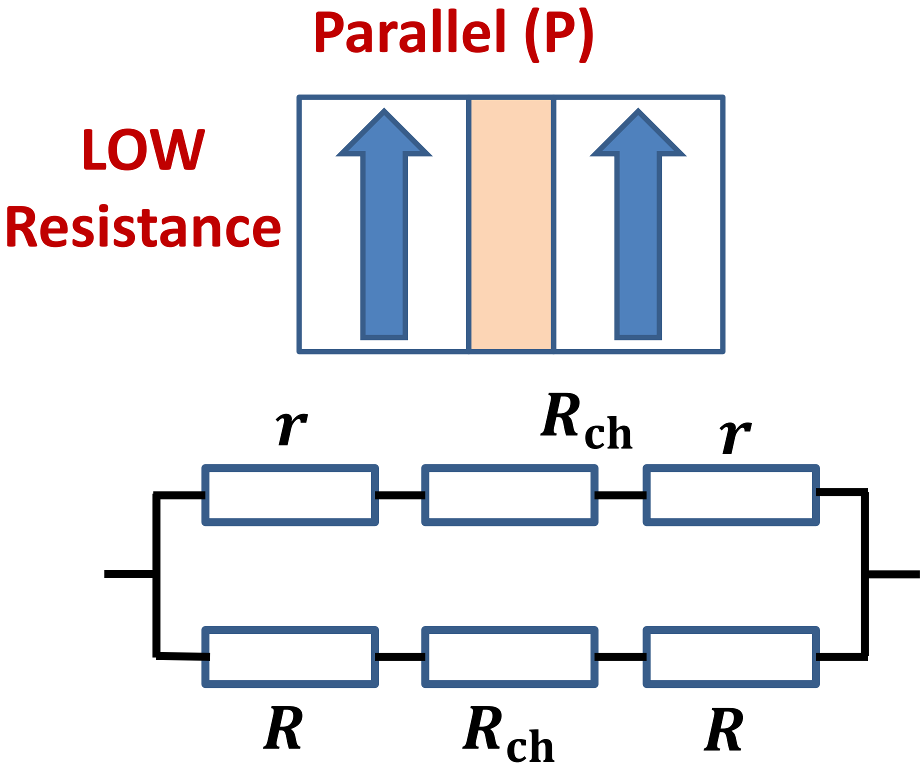


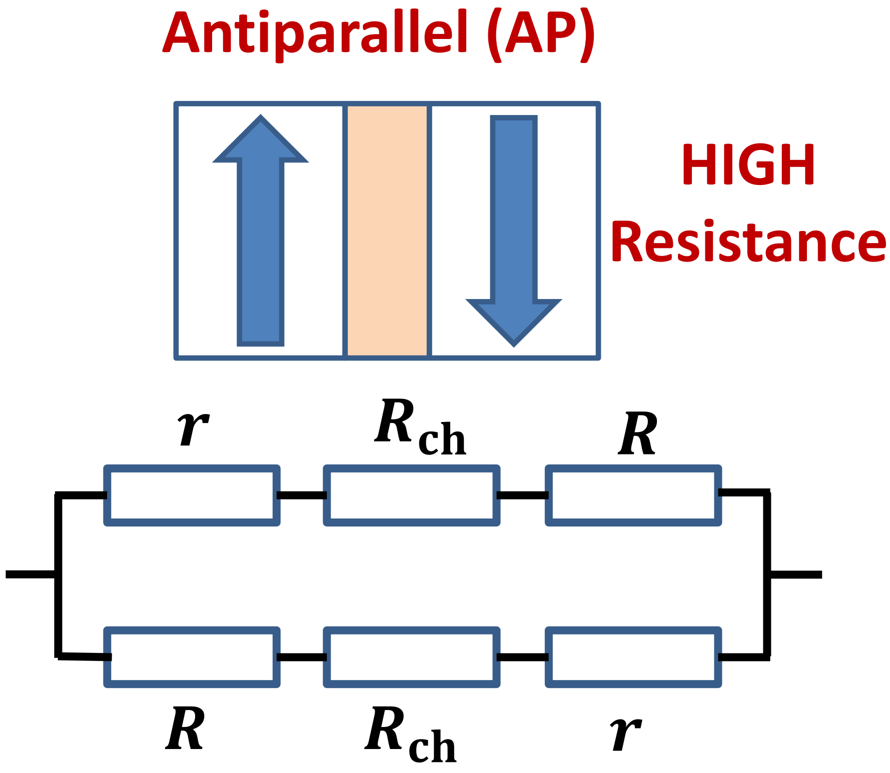
Giant Magneto-Resistance (GMR)



A. Fert, M.N. Baibich et al., Phys. Rev. Lett. **61**, 2472 (1988)

GMR: 2-current model





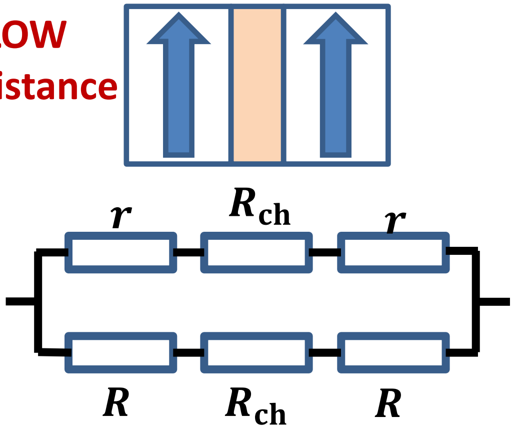
$$R_P = \left(\frac{1}{2r + R_{ch}} + \frac{1}{2R + R_{ch}} \right)^{-1}$$

$$R_{AP} = \frac{r + R + R_{ch}}{2}$$

GMR: 2-current model

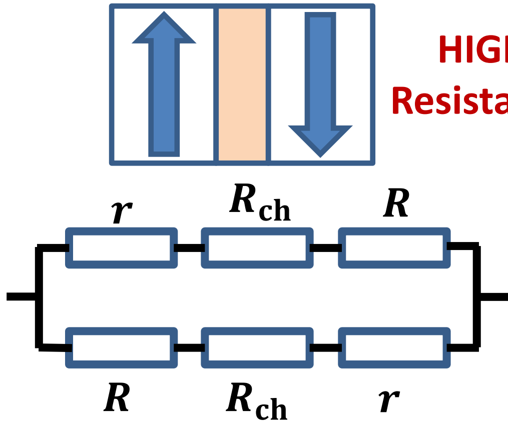
Parallel (P)

LOW Resistance



Antiparallel (AP)

HIGH Resistance



$$R_{AP} = \frac{r + R + R_{ch}}{2}$$

$$R_P = \left(\frac{1}{2r + R_{ch}} + \frac{1}{2R + R_{ch}} \right)^{-1}$$

$$MR = \frac{R_{AP} - R_P}{R_P} = \frac{(R - r)^2}{4rR}$$

$$R_{ch} \simeq 0$$

Polarization

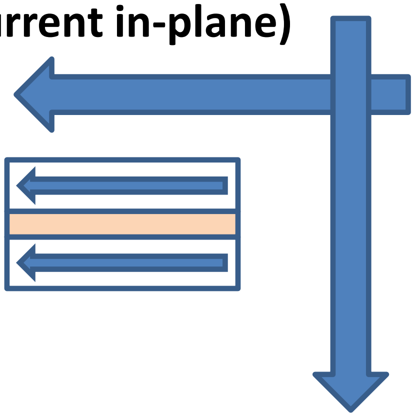
$$p = \frac{R - r}{R + r}$$

$$MR = \frac{p^2}{1 - p^2}$$

CIP and CPP geometry

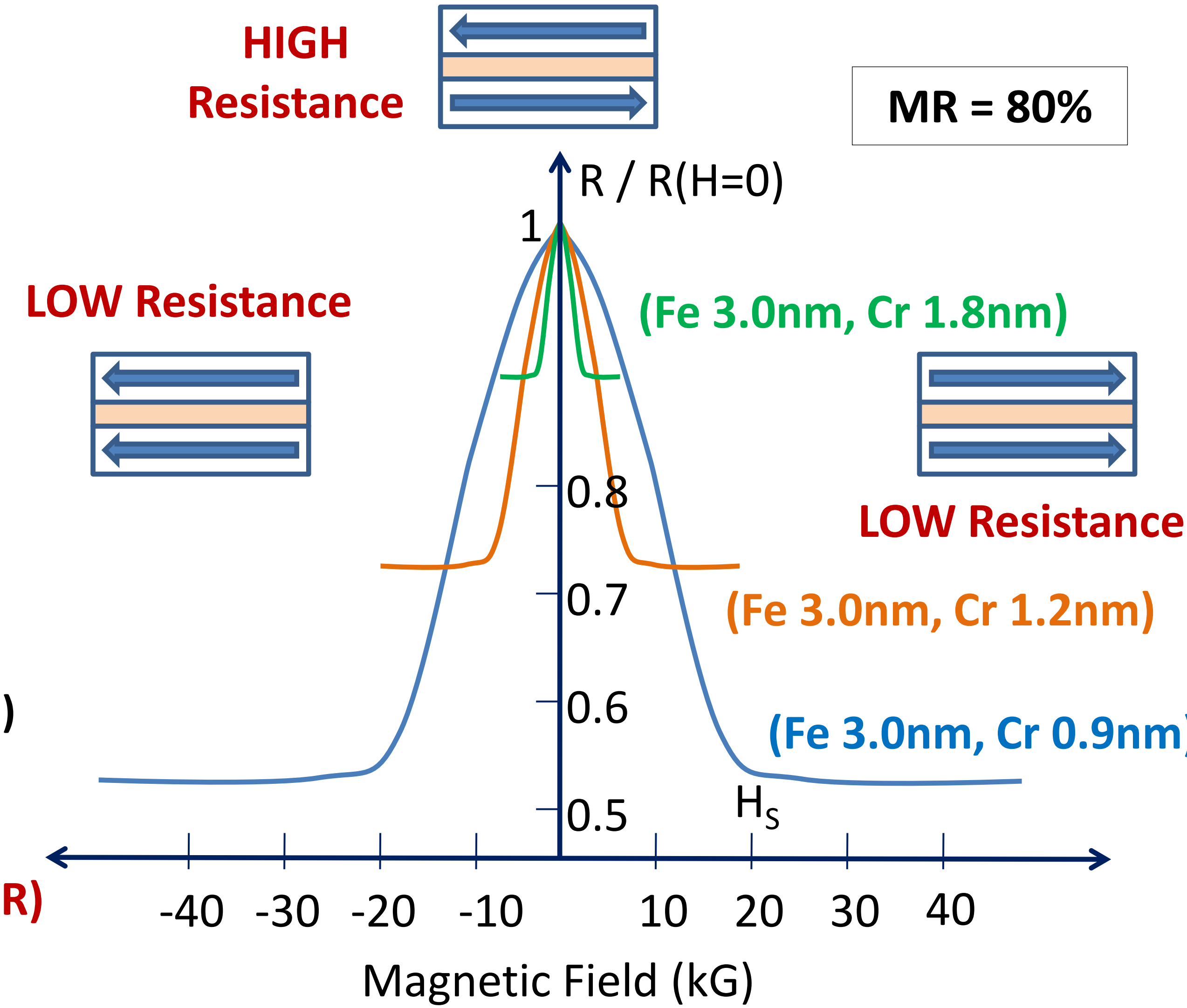
Nonlocal effect

CIP (Current in-plane)



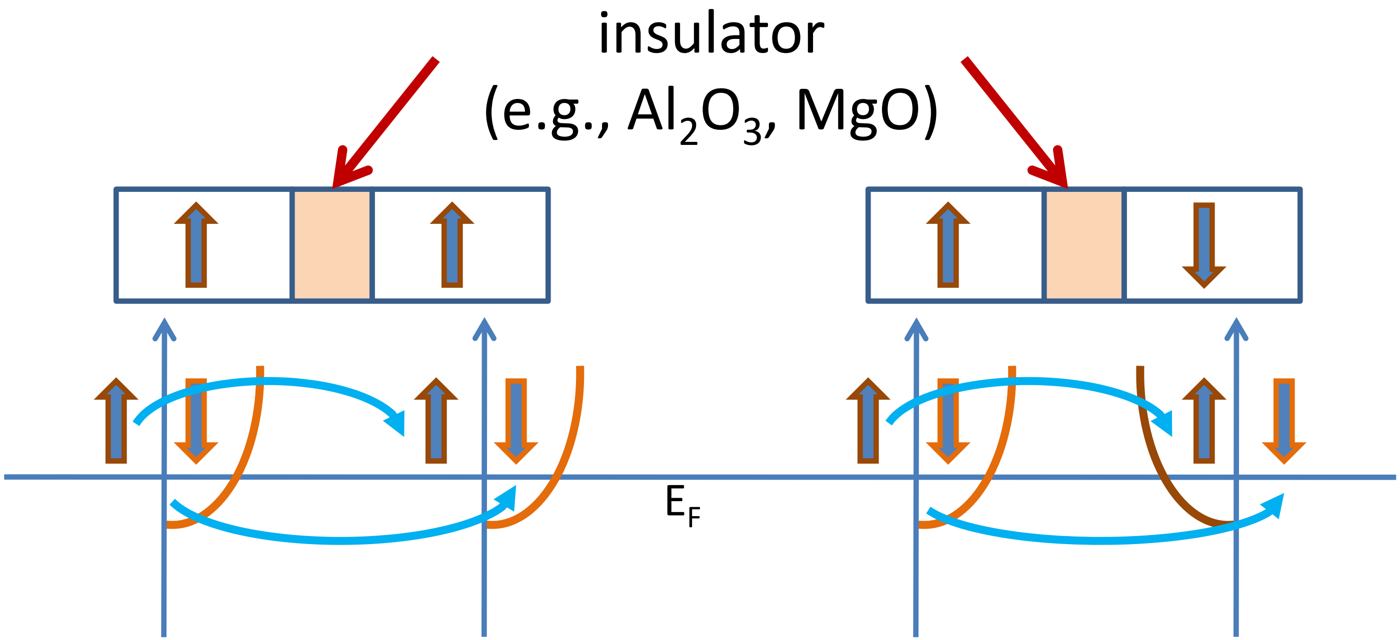
CPP (Current perpendicular to plane)

CPP is also used in tunneling magnetoresistance (TMR)
See next



A. Fert, M.N. Baibich et al., Phys. Rev. Lett. **61**, 2472 (1988)

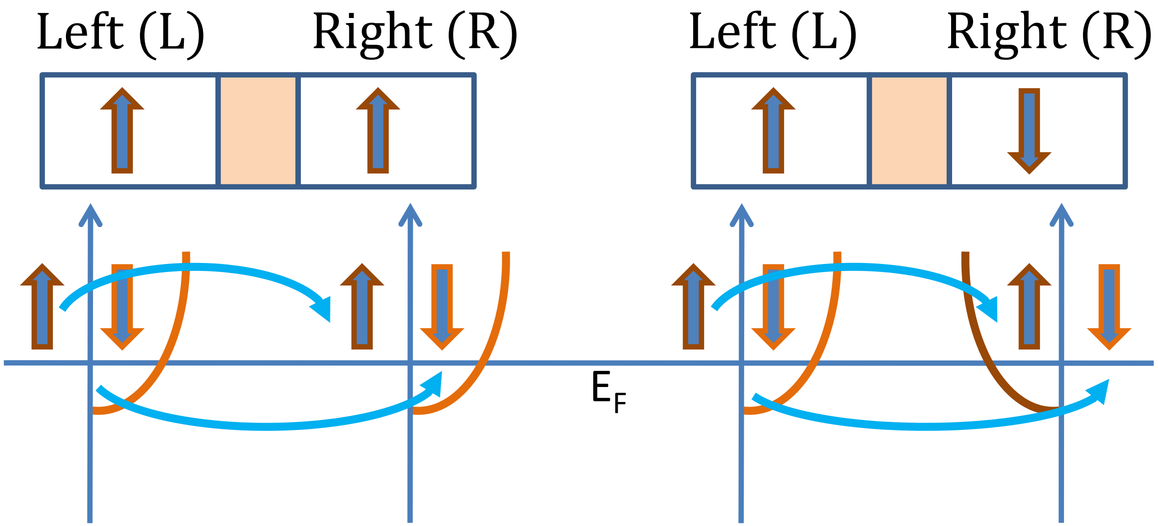
Tunneling Magneto-Resistance (TMR)



- Reported (1975) prior to GMR
- TMR >500% using MgO spacer

Julliere, M. Tunneling between ferromagnetic films. *Phys. Lett. A* **54,** 225–226 (1975)
Moodera, J. S. et al., *Phys. Rev. Lett.* **74,** 3273 (1995)
Mathon, J. et al., *Phys. Rev. B* **63,** 220403 (2001), Butler, W. et al., *Phys. Rev. B* **63,** 054416 (2001)
Yuasa, S. et al., *Nature Mater.* **3,** 868 (2004), Parkin, S. et al., *Nature Mater.* **3,** 862–867 (2004)

Tunneling Magneto-Resistance (TMR)



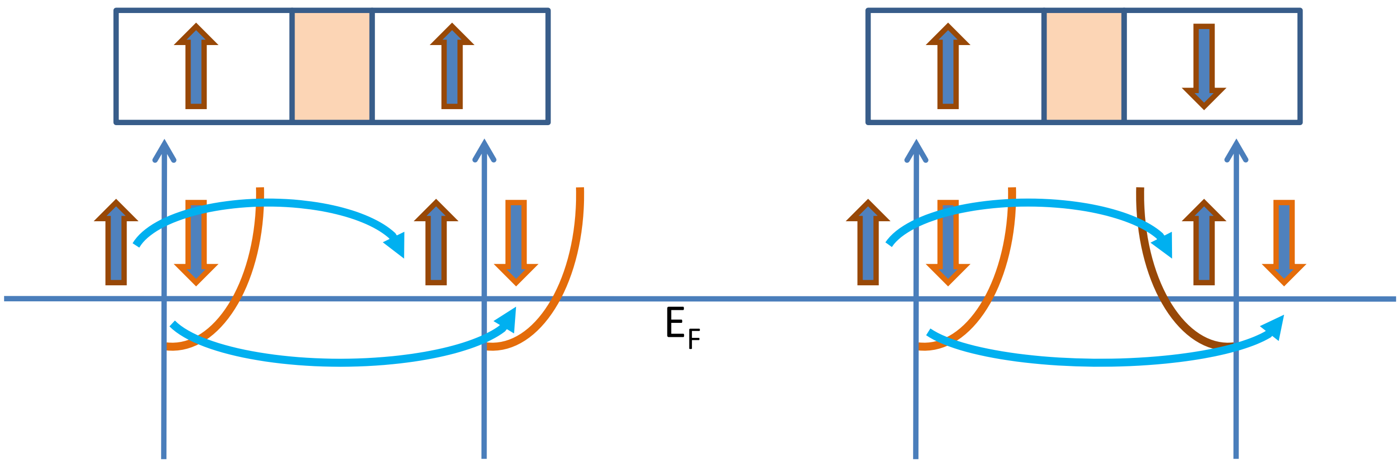
Conductance is proportional to the **density of states** $N_L^{\uparrow}, N_R^{\uparrow}, N_L^{\downarrow}, N_R^{\downarrow}$

$G^{\uparrow\uparrow} \propto N_L^{\uparrow} N_R^{\uparrow}$ $\quad$ $G^{\downarrow\downarrow} \propto N_L^{\downarrow} N_R^{\downarrow}$ $\quad$ $G^{\uparrow\downarrow} \propto N_L^{\uparrow} N_R^{\downarrow}$ $\quad$ $G^{\downarrow\uparrow} \propto N_L^{\downarrow} N_R^{\uparrow}$

$$TMR = \frac{G_P - G_{AP}}{G_{AP}} = \frac{N_L^{\uparrow} N_R^{\uparrow} + N_L^{\downarrow} N_R^{\downarrow} - N_L^{\uparrow} N_R^{\downarrow} - N_L^{\downarrow} N_R^{\uparrow}}{N_L^{\uparrow} N_R^{\downarrow} + N_L^{\downarrow} N_R^{\uparrow}}$$

$$= \frac{(N_L^{\uparrow} - N_L^{\downarrow})(N_R^{\uparrow} - N_R^{\downarrow})}{\frac{1}{2}\left[(N_L^{\uparrow} - N_L^{\downarrow})(N_R^{\uparrow} - N_R^{\downarrow}) - (N_L^{\uparrow} - N_L^{\downarrow})(N_R^{\uparrow} - N_R^{\downarrow})\right]}$$

Tunneling Magneto-Resistance (TMR)



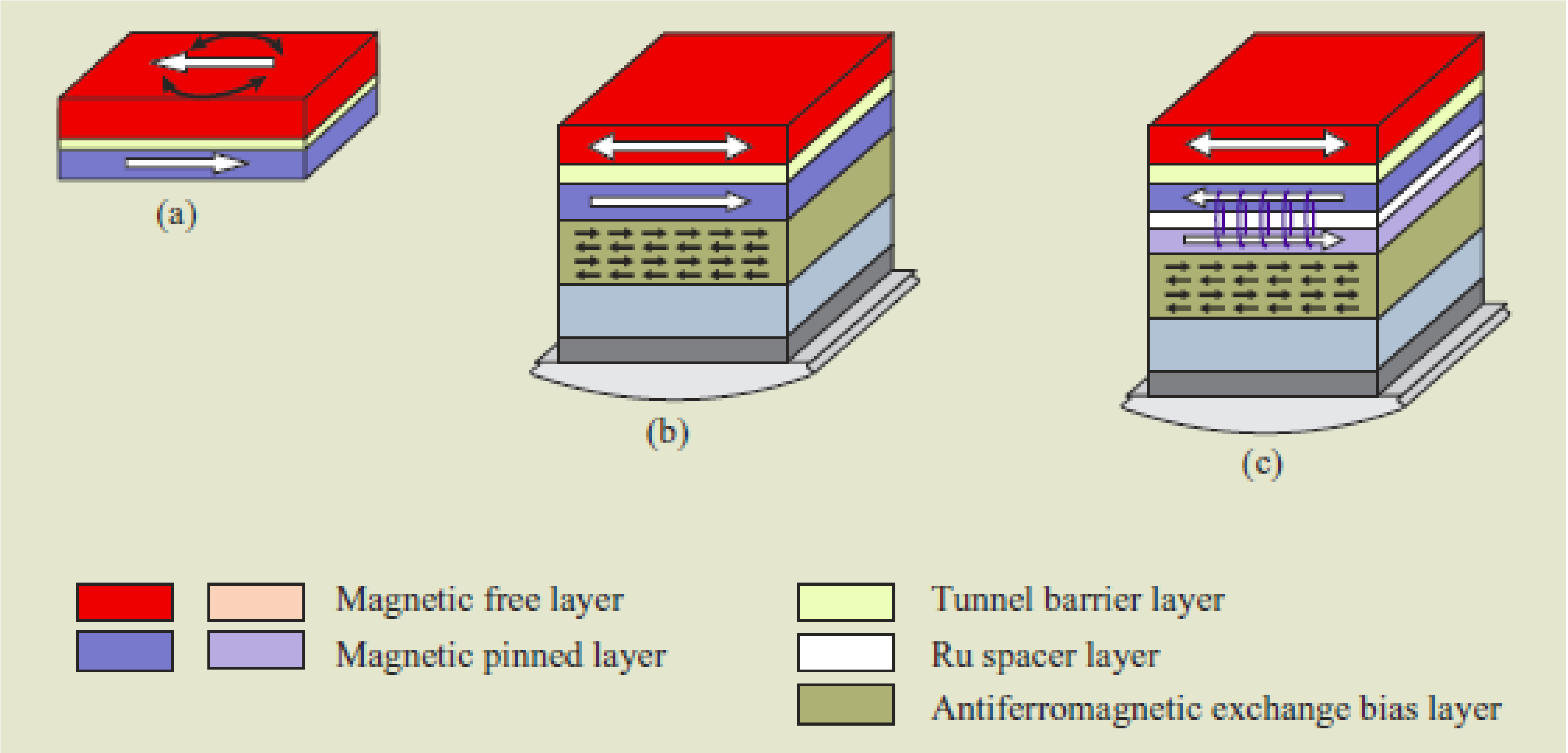
Conductance is proportional to the density of states

$$TMR = \frac{\left(N_L^{\uparrow} - N_L^{\downarrow}\right)\left(N_R^{\uparrow} - N_R^{\downarrow}\right)}{\frac{1}{2}\left[\left(N_L^{\uparrow} - N_L^{\downarrow}\right)\left(N_R^{\uparrow} - N_R^{\downarrow}\right) - \left(N_L^{\uparrow} - N_L^{\downarrow}\right)\left(N_R^{\uparrow} - N_R^{\downarrow}\right)\right]}$$

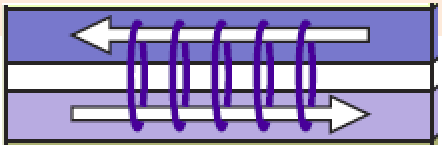
$$p_{L,R} = \frac{N_{L,R}^{\uparrow} - N_{L,R}^{\downarrow}}{N_{L,R}^{\uparrow} + N_{L,R}^{\downarrow}}$$

$$TMR = \frac{2p_L p_R}{1 - p_L p_R}$$

Magnetic Tunnel Junction (MTJ)



The magnetic offset caused by fields emanating from the pinned layer can be avoided by replacing a simple pinned layer with a **synthetic antiferromagnetic layer (SAF)**, a pair of ferromagnetic layers antiferromagnetically coupled through a **ruthenium (Ru) spacer layer**.



Gallagher, W. J. & Parkin, S. S. P., *IBM J. Res. Dev.* **50,** 5–23 (2006)

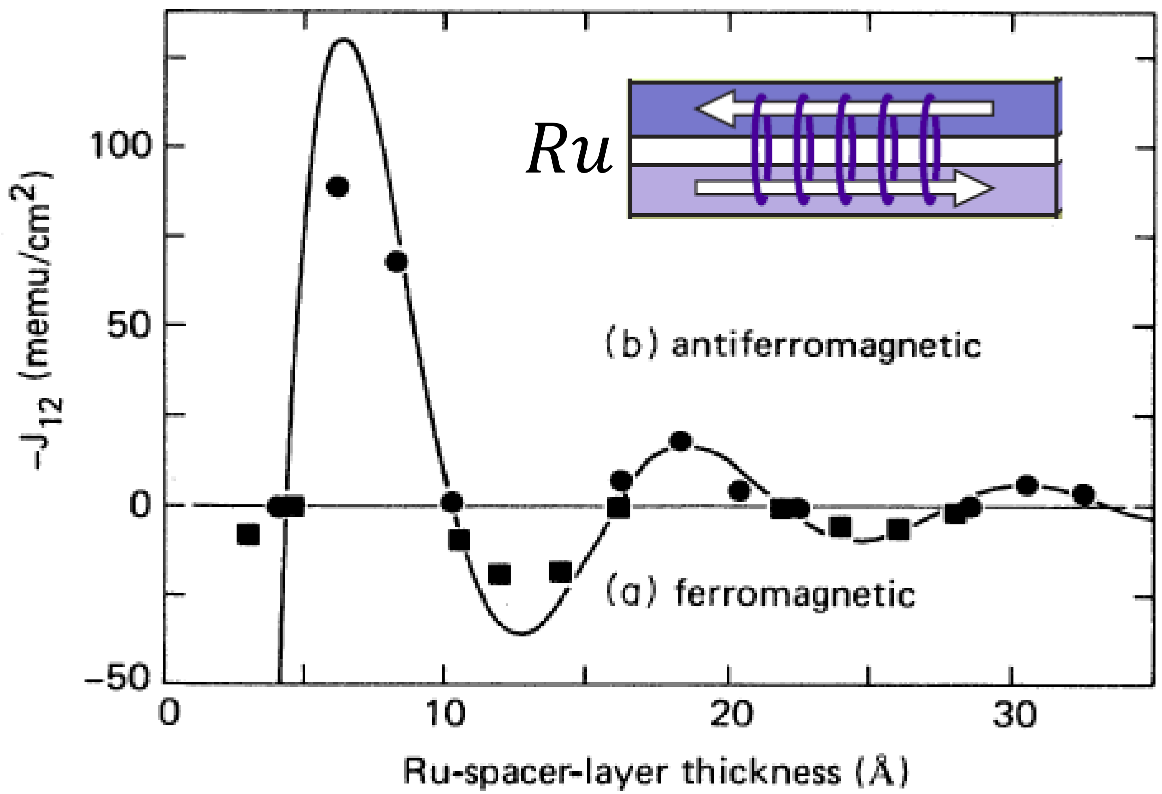
SAF: Interlayer exchange coupling

Ruderman–Kittel–Kasuya–Yosida

RKKY interaction

Indirect Exchange

Second-order perturbation theory



$$t_{Ru} = 0.8\,nm$$

$$J_{12} \propto \frac{\sin\left(\phi + \frac{2\pi t_{Ru}}{\lambda_F}\right)}{t_{Ru}^{p}}$$

$$\lambda_F = 11.5\ \dot{A}$$

$$p = 1.8$$

Parkin, S. S. P. et al, Phys. Rev. B (Rapid Comm.) **44,** 7131 (1991)

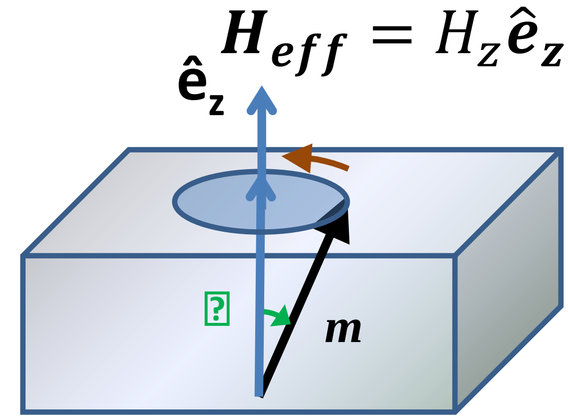
Spin waves and Magnons

Spin wave

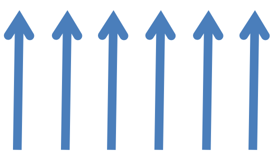
Ferromagnetic resonance

$$\frac{d\boldsymbol{M}}{dt} = -|\gamma|\boldsymbol{M} \times \boldsymbol{H}_{\boldsymbol{eff}}$$

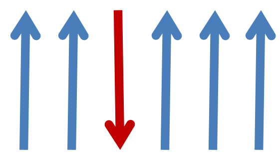
Neglecting damping



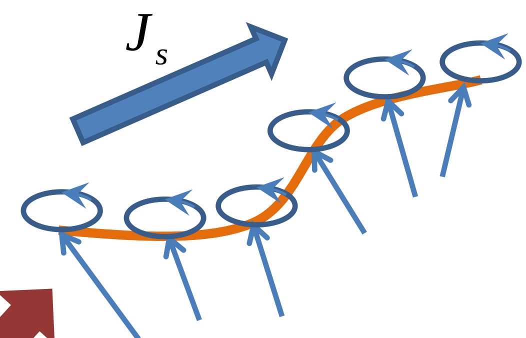
Precessing Magnetization



Ground state, U_0



An excited state, U_1



$$U = -2J \sum_{p=1}^{N} \boldsymbol{S}_{\boldsymbol{p}} \cdot \boldsymbol{S}_{\boldsymbol{p+1}}$$

$$\boldsymbol{S}_{\boldsymbol{p}} \cdot \boldsymbol{S}_{\boldsymbol{p+1}} = S^2$$

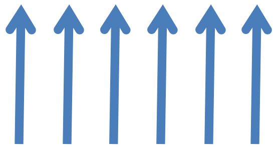
$$U_0 = -2JNS^2 \qquad U_1 = U_0 + 8JS^2$$

Excitation of much lower energy if all spins share the reversal

Spin-wave
spin current

Interconnect between devices

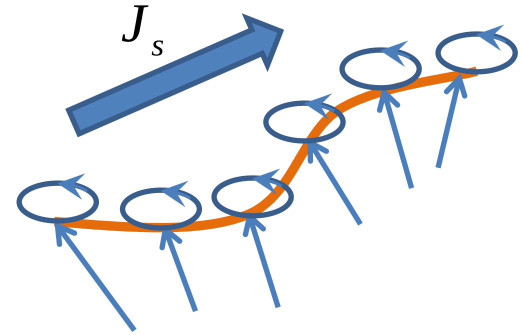
Spin wave dispersion relation



Ground state, U_0

$U_0 = -2JNS^2$

$$U = -2J \sum_{p=1}^{N} \boldsymbol{S_p} \cdot \boldsymbol{S_{p+1}}$$



Magnetic moment at site p

$$\boldsymbol{\mu_p} = -g\mu_B \boldsymbol{S_p}$$

Nearest neighbor exchange interaction

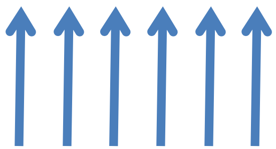
$$-2J\boldsymbol{S_p} \cdot \left(\boldsymbol{S_{p-1}} + \boldsymbol{S_{p+1}}\right) = -\boldsymbol{\mu_p} \cdot \boldsymbol{B_p}$$

$$\Rightarrow \boldsymbol{B_p} = (-2J/g\mu_B) \cdot \left(\boldsymbol{S_{p-1}} + \boldsymbol{S_{p+1}}\right)$$

$$\frac{d\boldsymbol{S_p}}{dt} = -|\gamma|\boldsymbol{S_p} \times \boldsymbol{B_p} = \frac{2J}{\hbar}\left(\boldsymbol{S_p} \times \boldsymbol{S_{p-1}} + \boldsymbol{S_p} \times \boldsymbol{S_{p+1}}\right)$$

$$S_p^z = S \qquad S_p^x, S_p^y \ll S$$

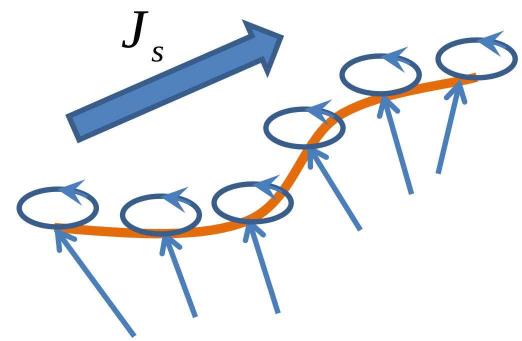
Spin wave dispersion relation



Ground state, U_0

$$U_0 = -2JNS^2$$

$$U = -2J\sum_{p=1}^{N} \boldsymbol{S_p} \cdot \boldsymbol{S_{p+1}}$$



$$S_p^z = S \qquad S_p^x, S_p^y \ll S$$

$$\frac{d\boldsymbol{S_p}}{dt} = -|\gamma|\boldsymbol{S_p} \times \boldsymbol{B_p} = \frac{2J}{\hbar}\left(\boldsymbol{S_p} \times \boldsymbol{S_{p-1}} + \boldsymbol{S_p} \times \boldsymbol{S_{p+1}}\right)$$

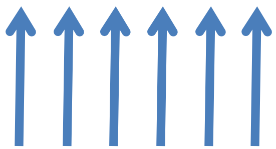
$$\frac{dS_p^x}{dt} = \frac{2J}{\hbar}\left[S_p^y\left(S_{p-1}^z + S_{p+1}^z\right) + S_p^z\left(S_{p-1}^y + S_{p+1}^y\right)\right]$$

$$\frac{dS_p^x}{dt} = \frac{2JS}{\hbar}\left[2S_p^y - S_{p-1}^y - S_{p+1}^y\right]$$

$$\frac{dS_p^z}{dt} = 0$$

$$\frac{dS_p^y}{dt} = -\frac{2JS}{\hbar}\left[2S_p^x - S_{p-1}^x - S_{p+1}^x\right]$$

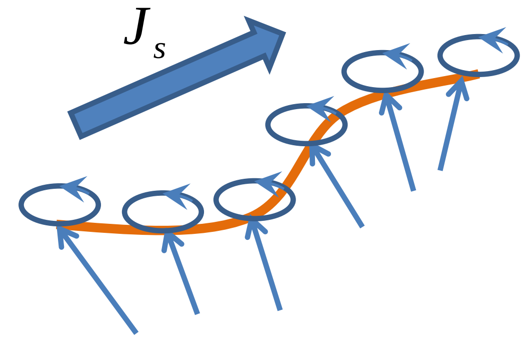
Spin wave dispersion relation



Ground state, U_0

$U_0 = -2JNS^2$

$$U = -2J\sum_{p=1}^{N} \boldsymbol{S_p}\cdot\boldsymbol{S_{p+1}}$$



a: lattice constant

$$S_p^x = ue^{i(pka-\omega t)}$$

$$S_p^y = ve^{i(pka-\omega t)}$$

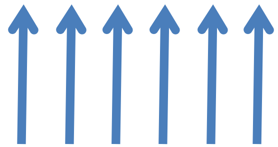
$$\frac{dS_p^x}{dt}$$

$$\frac{dS_p^y}{dt} = -\frac{2JS}{\hbar}\left[2S_p^x - S_{p-1}^x - S_{p+1}^x\right]$$

$$ue^{i(pka-\omega t)}(-i\omega) = \frac{2JS}{\hbar}\left[2ve^{i(pka-\omega t)} - ve^{i((p-1)ka-\omega t)} - ve^{i((p+1)ka-\omega t)}\right]$$

$$-i\omega u = \frac{2JS}{\hbar}\left[2 - e^{-ika} - e^{ika}\right]v = \frac{4JS}{\hbar}[1 - coska]v$$

Spin wave dispersion relation



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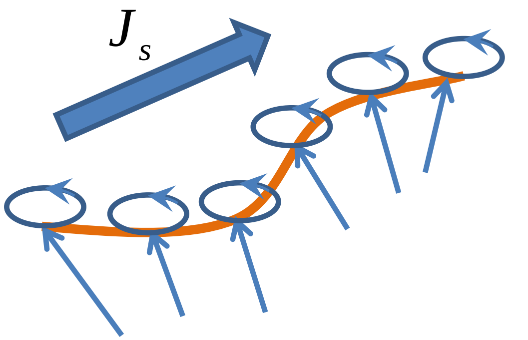

$$\frac{dS_p^x}{dt} = \frac{2JS}{\hbar}\left[2S_p^y - S_{p-1}^y - S_{p+1}^y\right]$$

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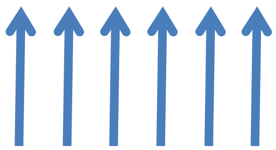
Spin wave dispersion relation



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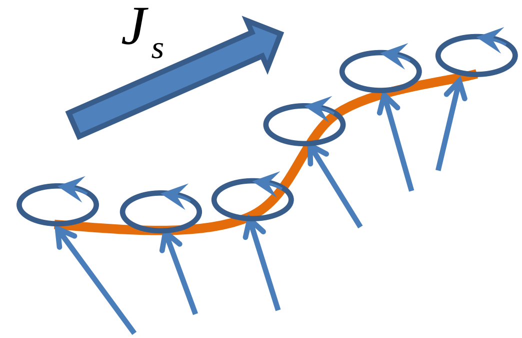


$$-i\omega u = \frac{2JS}{\hbar}\left[2 - e^{-ika} - e^{ika}\right]v = \frac{4JS}{\hbar}(1 - coska)v$$

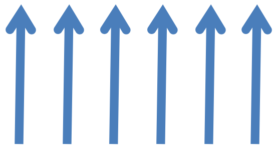
$$-i\omega v = -\frac{2JS}{\hbar}\left[2 - e^{-ika} - e^{ika}\right]u = -\frac{4JS}{\hbar}(1 - coska)u$$

$$\begin{vmatrix} i\omega & \frac{4JS}{\hbar}(1 - coska) \\ -\frac{4JS}{\hbar}(1 - coska) & i\omega \end{vmatrix} = 0$$

$$\omega = \frac{4JS}{\hbar}(1 - coska)$$

$$v = -iu$$

Spin wave dispersion relation



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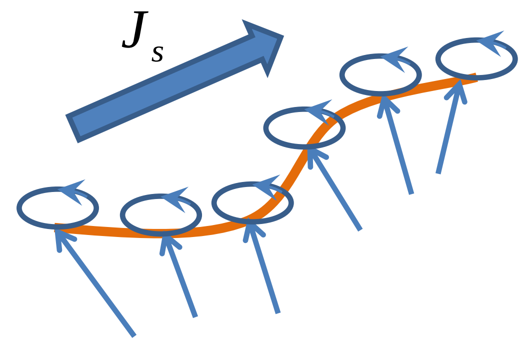


$$\omega = \frac{4JS}{\hbar}(1 - coska)$$

$$v = -iu$$

Taking real parts

$$S_p^x = u\, cos(pka - \omega t)$$

$$S_p^y = u\, sin(pka - \omega t)$$

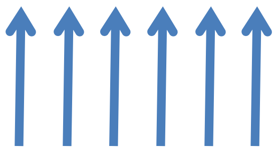
Circular precession about z-axis

$$ka \ll 1$$

$$\omega = \frac{4JSa^2}{\hbar}k^2 = Dk^2$$

D can be determined from spin-wave resonance

Magnon



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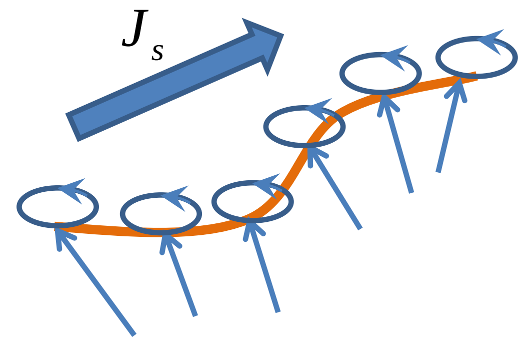

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Circular precession about *z*-axis

$$\omega = \frac{4JSa^2}{\hbar}k^2 = Dk^2$$

D can be determined from spin-wave resonance

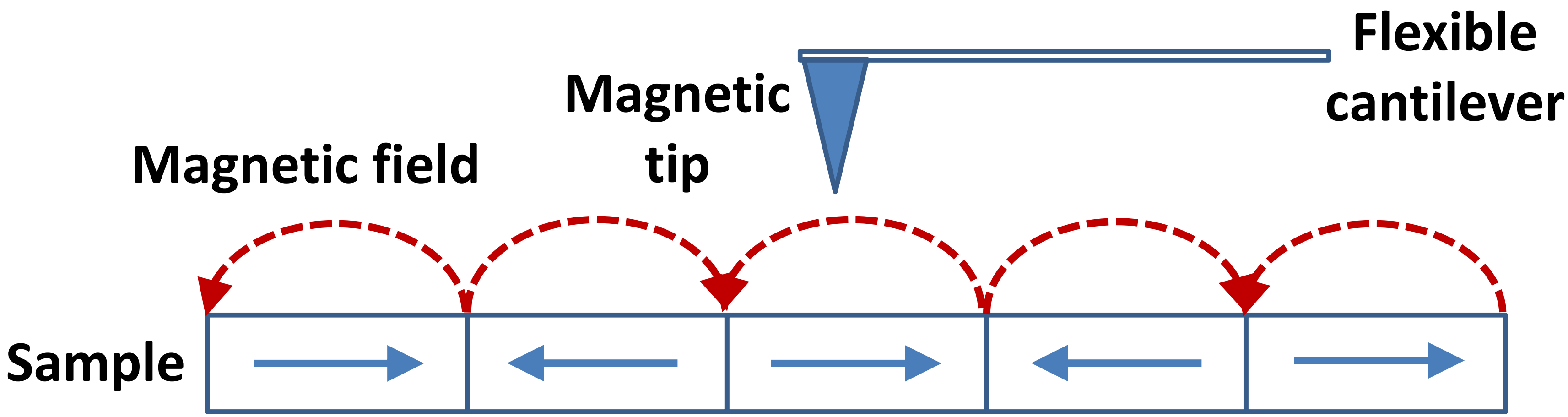
Magnon: Quantized spin waves

The energy of a mode of frequency ω_k with n_k magnons

$$\epsilon_k = \left(n_k + \frac{1}{2}\right)\hbar\omega_k$$

Magnetic Force Microscopy

Magnetic Force Microscopy (MFM)



Forces from the magnetic sample act on the tip and cause a deflection

An image is formed by scanning sample relative to the tip

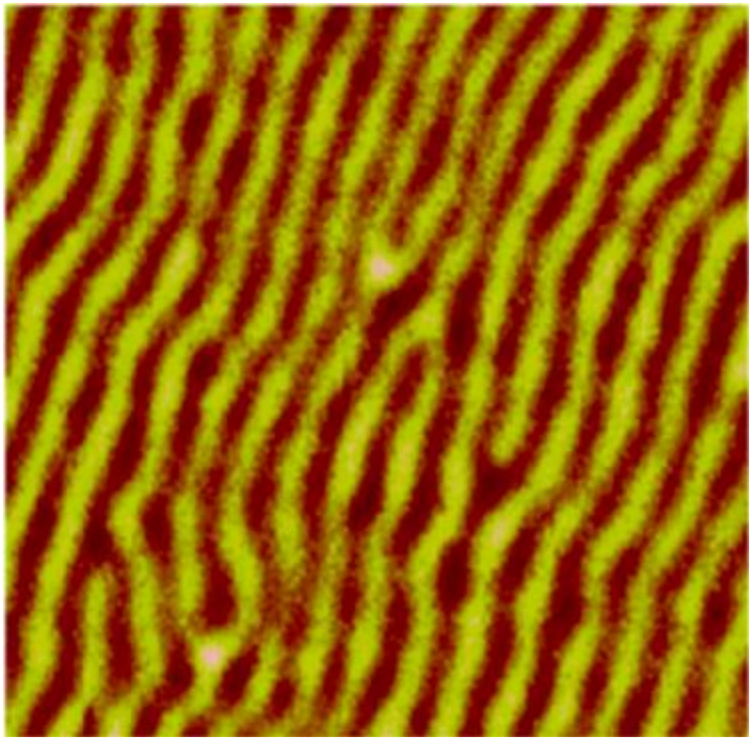
High resolution: ~10-100 nm

Contact mode: Tip is very near to sample (~0.1 nm)

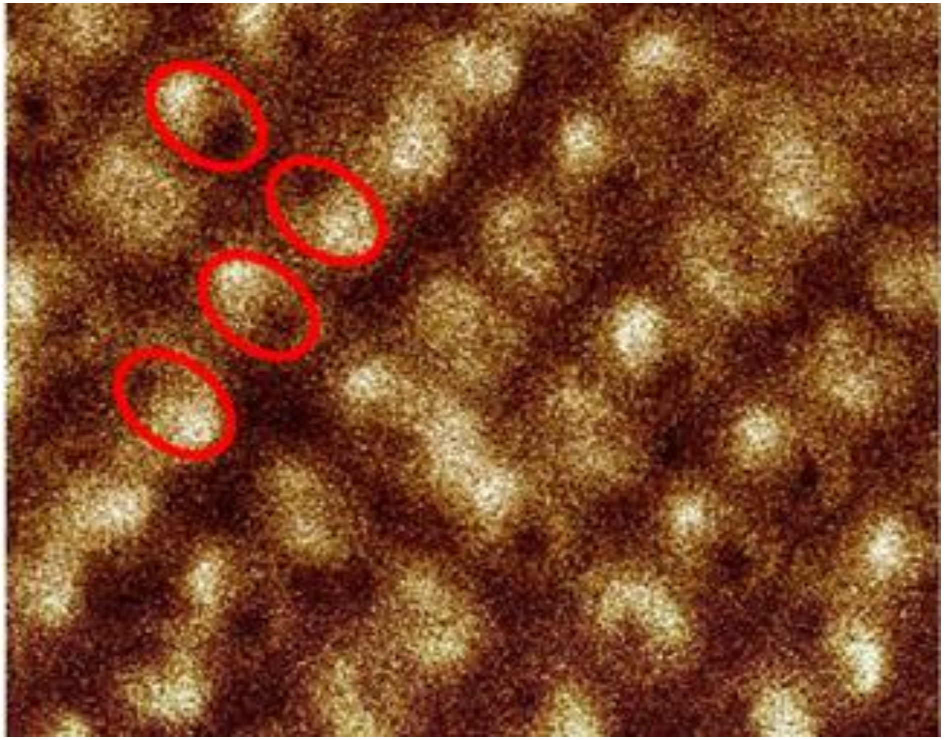
Tapping mode (AC): Probe comes near the sample momentarily to avoid damaging the sample and breaking of the tip that may happen in contact mode

Single-domain and Multi-domain

Multi-domain



Single-domain



Magnetic force microscopy (MFM) images