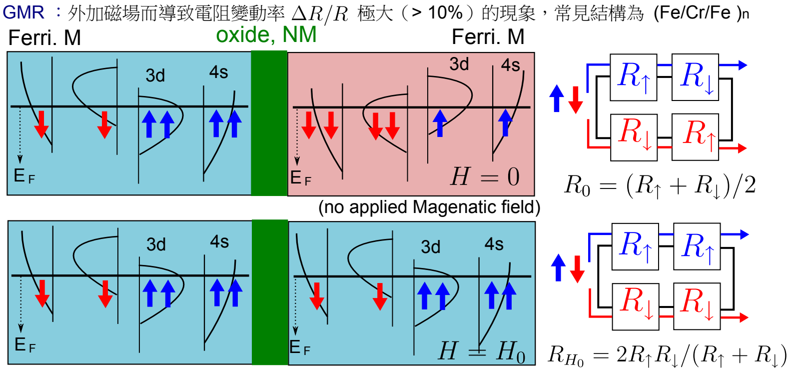
Spintronics ：To create a revolutionary new class of electronics based on the spin degree of freedom in additional to, or in the place of, the charge degree of freedom.

Catagories of spintronics: Ferromagnetic metal based devices:read head (GMR), MRAM Spin transport in semiconductors ultrafast switches, fully programmable all-spintronics microprocessors, Manipulation of quantum spin states of individual electrons, nuclear spin and magnetic clusters: quantum logic gates,. Devices based on spin current in semiconductor spin transistor, ...

GMR ：外加磁場而導致電阻變動率 $\Delta R/R$ 極大（> 10%）的現象，常見結構為 (Fe/Cr/Fe)n



(no applied Magenatic field)

$$R_0 = (R_\uparrow + R_\downarrow)/2$$

(with applied Magenatic field)

$$R_{H_0} = 2R_\uparrow R_\downarrow/(R_\uparrow + R_\downarrow)$$

$$\Delta R = R(H=H_0) - R(H=0) = -(R_\uparrow - R_\downarrow)^2/(2R_\uparrow R_\downarrow)$$

Synchronization of Spin torque nano-oscillators from an induced corrugated attractor

$$\frac{d\vec{n}_i}{d\tau} = -(\nabla_{\vec{n}_i}\boxed{w_i}), \quad u_i \equiv U(4\pi M_s\gamma)^{-1} = 0, \ \alpha = 0,$$ dimensionless LLG

magnetic energy dencity $w \equiv W(4\pi M_s\gamma)t, \quad \tau \equiv (4\pi M_s\gamma)t,$

$$\boxed{w(\theta_1,\theta_2,\phi_1,\phi_2)} = \boxed{w_{dem}(\theta_1,\theta_2)} + \boxed{w_r(\theta_1,\theta_2,\phi_1,\phi_2)} \qquad \vec{n} \equiv \vec{M}/M_s$$

$$\boxed{w_{dem}(\theta_1,\theta_2) = (\cos\theta_1^2 + \cos^2\theta_2)/2}$$

demagnetization energy density
residue energy density including in-plane
uniaxial anisotropic energy density

$$\boxed{\begin{aligned} w_r(\theta_1,\theta_2,\phi_1,\phi_2) &= w_{u1}(\theta_1,\phi_1) + w_{u2}(\theta_2,\phi_2) + A(\theta_1,\theta_2,\phi_1,\phi_2) \\ &= k(\sin^2\theta_1\sin^2\phi_1 + \sin^2\theta_2\sin^2\phi_2)/2 + A(r)[\sin\theta_1\sin\theta_2\cos(\phi_1-\phi_2) \\ &\quad -2\cos\theta_1\cos\theta_2] \qquad A(r) = V/(4\pi r^3) \end{aligned}}$$

dipolar interaction energy density

$$\boxed{\frac{d\theta_i}{dt} = -\frac{1}{\sin\theta_i}\frac{\partial w}{\partial\phi_i}, \quad \frac{d\phi_i}{dt} = -\frac{1}{\sin\theta_i}\frac{\partial w}{\partial\theta_i}, \ (i=1,2)}$$

subtituted in θ_i

diameter of the free layer >> d and $A \sim k$: $(\theta_i,\phi_i) = (\boxed{\pi/2 + \delta\theta_i(\tau)}, \phi_i(\tau)) \quad |\delta\theta_i| \ll 1$

for the low energy orbit in which the total magnetic energy density $|w|$ is always near to $w_r \sim 2k$ the orbit can be written as equation above. These orbits will obey the energy conservation law:

$$w_0(\pi/2,\pi/2,\phi_{01},\phi_{02}) = w_1(\pi/2+\delta\theta_1,\pi/2+\delta\theta_2,\phi_{11},\phi_{12})$$

└ initial state final state ┘

thus the order of magnitude of $|\delta\theta_i| \sim \sqrt{k}$

$$\boxed{\frac{d(\delta\theta_i)}{dt} = -\frac{\partial w}{\partial\phi_i}, \quad \frac{d\phi_i}{dt} = -\frac{\partial w}{\partial(\delta\phi_i)}} \rightarrow \boxed{\frac{d(\delta\theta_i)}{dt} = -\frac{\partial H}{\partial\phi_i}, \quad \frac{d\phi_i}{dt} = -\frac{\partial H}{\partial(\delta\phi_i)}}$$

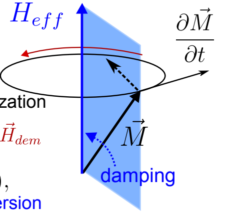
$$w(\delta\theta_1,\delta\theta_2,\phi_1,\phi_2) = (\delta\theta_1^2 + \delta\theta_2^2)/2 + k(\sin^2\phi_1 + \sin^2\phi_2)/2 + A(r)\cos(\phi_1-\phi_2)$$

$$H(\delta\theta_1,\delta\theta_2,\phi_1,\phi_2) = w(\delta\theta_1,\delta\theta_2,\phi_1,\phi_2)$$

$$L(\delta\theta_1,\delta\theta_2,\phi_1,\phi_2) = \sum_{i=1}^{2}\frac{d\phi_i}{dt}\delta\theta_i - H = \frac{1}{2}\sum_{i=1}^{2}\left(\frac{d\phi}{dt}\right)^2 - \left(\frac{k}{2}\sum_{i=1}^{2}\sin^2\phi_i + A(r)\cos(\phi_1-\phi_2)\right)$$

LLG (Landau-Lifshitz-Gilbert) equation

$$\frac{\partial\vec{M}}{\partial t} = -|\gamma|(\vec{M}\times\vec{H}_{eff}) + \frac{\alpha}{M_s}\left(\vec{M}\times\frac{\partial\vec{M}}{\partial t}\right)$$



α damping constant γ giromagnetic ratio M_s saturation magnetization

$\vec{H}_{eff}$ effective magnetic filed $\vec{H}_{eff} = \vec{H}_{exc} + \vec{H}_{anis} + \vec{H}_{zeeman} + \vec{H}_{dem}$

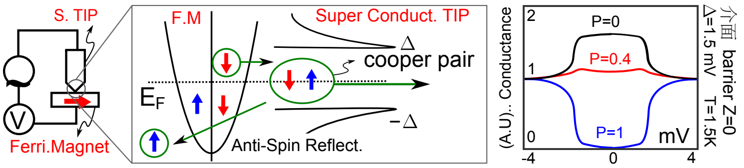
$$\frac{M}{\partial t} = -\frac{|\gamma|}{1+\alpha^2}\vec{M}\times\vec{H}_{eff} - \frac{\gamma\alpha}{(1+\alpha^2)M_s}\vec{M}(\vec{M}\times\vec{H}_{eff}),$$

LL version

Spin Polarization: $P_N = (N_\uparrow - N_\downarrow)/(N_\uparrow + N_\downarrow)$ **S.P. of current:** $P = (I_\uparrow - I_\downarrow)/(I_\uparrow + I_\downarrow)$

$P_N = 1 \rightarrow \text{normal metal} \qquad P_N = 0 \sim 1 \rightarrow \text{ferromegnet} \qquad P_N = 1 \rightarrow \text{half-metal ferromegnet}$

Spin Polarization detecting: Point Contact Andreev Reflection F.M, - S.C tip Junction



Ballistic Transport Assumed: negligible electrical resistivitydue to scattering

Modified BTK model G(0)/G(∞)=2(1-P), G (conductance), G(∞)=G(bias >> Δ)

Thermal process in magnetization

$\langle x(t)\rangle = 0, \ \langle x^2(t)\rangle = 2Dt \quad D \propto T$, Brownian motion

$\langle w(t)\rangle = 0, \ dx/dt = 2Dw(t), \ \langle w(t)w(s)\rangle = \delta(t-s)$ Wiener process

$\langle x^2(t)\rangle = \int_0^t ds_1 \int_0^t ds_2 \langle w(s_1)w(s_2)\rangle = 2D(t)$ Langevin equation

$\frac{dx_i}{dt} = A_i(\vec{x},t) + \sqrt{D}B_{ij}(\vec{x},t)\frac{dw_j(t)}{dt}$ Fockker Plank equation (Strtonovich & Ito ver.)

$$\frac{\partial P}{\partial t} = -\frac{\partial}{\partial x_i}(A_iP) + \frac{D}{2}\frac{\partial}{\partial x_i}\left\{B_{ik}\frac{\partial}{\partial x_j}(B_{jk}P)\right\} \qquad \frac{\partial P}{\partial t} = -\frac{\partial}{\partial x_i}(A_iP) + \frac{D}{2}\frac{\partial^2}{\partial x_i\partial x_j}[(BB^T)_{ij}P]$$

$\frac{d^2x}{dt^2} + \eta\frac{dx}{dt} + V'(x) = \sqrt{2\eta T}w(t)$ Dissipation fluctuation theorem, F-P equation is satisfied by $P(x) = N\exp(-E_{total}/T)$, Bolzman distribution P

All initial states are mapped onto thermal equillibrium!

Colored noise

$$\boxed{dy/dt = -\eta\int_0^t \phi(t-s)y(s)ds + V'(x) + \xi(t), \qquad y = dx/dt, \quad \langle\xi(t)\xi(t')\rangle = 2\eta T\phi(t-t')}$$

$$\frac{d\vec{M}}{dt} = -\gamma\vec{M}\left\{\vec{H}_{det} + \lambda\int_0^t \phi(t-t')\frac{d\vec{M}}{dt}dt' + \vec{\xi}\right\} \qquad \langle\xi(t\xi(t'))\rangle = \lambda T\phi(t-t')\delta_{ij}$$

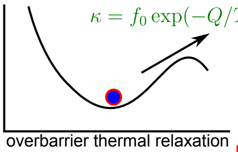
$\phi(t) = \alpha\exp(-\alpha t)$ so far we can deal with

In ultrafst processes, the white noise approx. is no longer exist -> colored noise

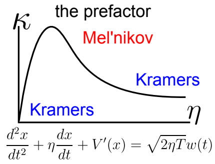
Stoner-Wohlfarth model: Superparamagnetic particle

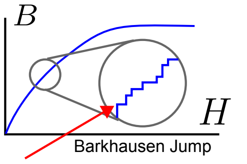
$E/KV = 1 - kx^2 + 2hx, \ \Delta E = KV(1-h)^2$ uniaxial system, axial symmetry

dynamic of thermal relaxation $dn/dt = n_0\exp(-\kappa t), \ \kappa = f_0\exp(-\Delta E/k_BT)$



overbarrier thermal relaxation





Barkhausen Jump

horizontal step decrease in mean lengh if temporature is increased

$$\dot{\mathbf{M}} = \gamma[\mathbf{M}\times\mathbf{H}_{eff}] + \frac{\alpha_{||}}{M^2}(\mathbf{M}\cdot(\mathbf{H}_{eff}+\zeta_{||}))\mathbf{M} - \frac{\alpha_\perp}{M^2}[\mathbf{M}\times[\mathbf{M}\times(\mathbf{H}_{eff}+\zeta_\perp)]]$$

Landau-Lifshitz-Bloch equation by Garanin

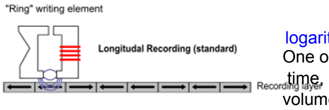
magnetisation (which absolute value is not conserved and is fluctuating) and H
ms of susceptibilities:

The Fokker-Planck equation known, but there is no known algorithm to simulate the equation.

Magnetization vector not conserved – elevated temperatures

$$\mathbf{H}_{eff} = -\frac{\partial F}{\partial\mathbf{M}} = \mathbf{H} - \frac{1}{\chi_\perp}(\mathbf{M}_x + \mathbf{M}_y) - \frac{1}{\chi_{||}}\left(\frac{M^2}{M_e^2} - 1\right)\mathbf{M}$$

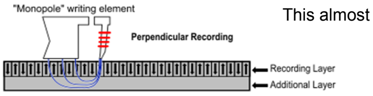
Most common application of nanoparticles in computer memories – huge research and development. Magnetization held in place by magnetic anisotropy. Thermal effects can cause it to overcome the barrier and reverse direction – memory is lost!The smaller the particle size the easier the thermal re[illegible] limit on recording density Standard commercial thermal stability is 10 years.



logarithmic decay

One observes a large number of particle at the same time, and each one is different.Average over activation volumes:

$$\langle\exp(-\kappa(V)t)\rangle \propto -\ln t$$



This almost always seen in experiments

半金屬(half-metal)：強鐵磁性之極端狀況, 全 3d 軌域與 sp 軌域未超過費米級之 up(down)-spin 帶被極化, 故對up(down)-spin 電流像 insulator, 對 down(up)-spin 電流像 conductor

半金屬特性; 飽和磁化 (Saturation magnetization) 由於某自旋方向電子有能隙, 導致磁矩量子化，即淨磁矩為 Bohr magneton 的整數倍。零磁化率 (Zero Susceptibility) 如果要使全滿能帶中自旋向下的電子跳到費米能附近自旋向上的半填滿能帶，或者是從費米能附近自旋向上的半填滿能帶，跳到自旋向下的能帶，需要額外的能量。當均勻的外場施加於單自旋金屬時, 系統的狀態不會有任何改變, 磁化率為磁化對外加場的導數故為零 完全極化(Fully Polarization) 在費米能附近的傳導電子極化率100%

Application of Half-metal (a) Magneto-optical effects Large Kerr rotation in PtMnSb (b)Magneto-resistance applications Spin-valve, pick-up head MRAM (c)Spin electronics spin transistor, spin injection, spin accumulation,spin detection, spin current 應用在自旋電子元件之優點 高自旋極化率與自旋選擇傳導可以大量提高自旋相關的傳輸效率(如 magnetic tunnel junction) 。由磁性單自旋金屬氧化物及適當的絕緣氧化物勢壘所構成的磁性穿隧結及其元件預期會在室溫、低場下具有高磁阻的反應 half-metal 形成高自旋電流應用 注入一般金屬中可以研究此金屬的自旋擴散長度, 自旋極化電流將會破壞 cooper pair，實驗上將自旋極化電流注入 YBaCuO 會使超導電流極具的下降 應用在STM探針 可用來解析樣品表面的磁性結構,而不像傳統的磁性針頭會同時影響磁化結構

Topological insulator A topological insulator is a material conducting on its boundary but behaves as an insulator in its bulk. The conducting channel(s) are guaranteed by time-reversal symmetry, topologically protected, will not be affected by local impurities etc, and thus robust.

How to become a topological insulator? Spin-orbit effect, Lattice constant adjustment,To get inversion states and Dirac cone on the boundary.

charge current: electric current with random spin $J_c = -e(j_\uparrow + j_\downarrow)$

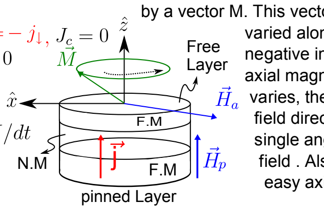
spin current: pure spin current without electric current $J_s = \hbar(j_\uparrow - j_\downarrow)/2$, $j_\uparrow = -j_\downarrow$, $J_c = 0$

spin polarized current: electric current with polarized spin $j_\uparrow = 0$ or $j_\downarrow = 0$ $J_c \neq 0$

modified LLG equation with perpendicular polarizer an in-plane applied field

$$\vec{M}' = -\gamma(\vec{M}\times\vec{H}) + (\alpha/M_s)\vec{M}\times\vec{M}' + (\gamma a_J/M_s)\vec{M}\times(\vec{M}\times\hat{z}), \quad \vec{M}' = d\vec{M}/dt$$

$$\vec{H} = H_KM_x/M_s\hat{x} - 4\pi M_z\hat{z} + \vec{H}_a, \quad \vec{H}_a = H_a\cos\beta\hat{x} + H_a\sin\beta\hat{y}$$



Hall effect: 當固體導體有電流通過，在導體上外加與電流方向垂直的磁場，會使得導線中的電子與電洞受到不同方向的洛倫茲力而往不同方向上聚集，在聚集起來的電子與電洞之間會產生電場，此一電場將會使後來的電子電洞受到電力作用而平衡掉磁場造成的洛倫茲力，使得後來的電子電洞能順利通過不會偏移，此稱為霍爾效應。而產生的內建電壓稱為霍爾電壓。

Quantum hall effect: 在外加強磁場的低溫二維電子系統中（如 MOSFET），霍爾電壓量子化的現象。

Spin hall effect: 自旋方向相反的電子由於 spin-orbit interaction 的關係會在方向相反的導體表面累積，此效應無外部磁場時成立，若外部磁場夠強，則會因為自旋進動的影響使 SHE 減弱或者消失。

Inverse Spin Hall Effect: 注入特定極化之自旋電流而產生一般電流

Quantum spin Hall effect: 在二維低溫，具有強 spin-orbit 耦合的 quantum well 結構 (如 HgTe)，在無外加磁場（零磁場）的情況下可觀查到霍爾電壓量子化

Anomalous Hall effect: 在鐵磁（或有外加磁場順磁）材料，霍爾電壓包含 hall effect 以外因磁化貢獻的分量，又稱為 extraordinary Hall effect。spin hall effect 即 AHE 的一種。

$$\boxed{\sigma = \nu\,\mathrm{e}^2/h} \qquad \nu = 1,2,3\ldots \qquad \nu = 1/2, 2/5, 3/7\ldots$$

hall conductivity

quantum hall effect

fractional quantum hall effect (including elctron-electron interaction)

single domain particle: A magnetic particle that stays in a single domain state for all magnetic fields

Stoner−Wohlfarth model the magnetization does not vary within the ferromagnet and it is represented by a vector M. This vector rotates as the magnetic field H changes. The magnetic field is only varied along a single axis; its scalar value h is positive in one direction and negative in the opposite direction. The ferromagnet is assumed to have a uni-axial magnetic anisotropy with anisotropy parameter Ku. As the magnetic field varies, the magnetization is restricted to the plane containing the magnetic field direction and the easy axis. It can therefore be represented by a single angle φ, the angle between the magnetization and the field . Also specified is the angle θ between the field and the easy axis.