

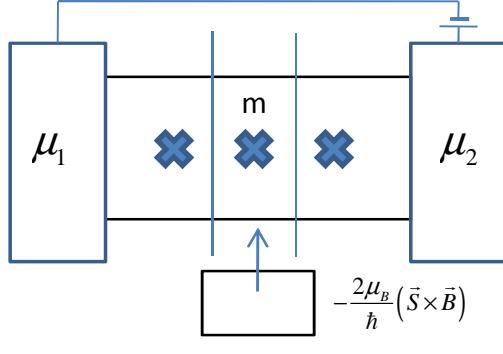
ECE 659 Quantum Transport: Atom to Transistor

Lecture 32: Spin Torque/Pseudo spin

Supriyo Datta

Spring 2009

Notes prepared by Samiran Ganguly



$$i\hbar I_{op} = (HG^n - G^n H) + (\Sigma G^n - G^n \Sigma^+) + (\Sigma^{in} G^+ - G \Sigma^{in})$$

$$G^n \sim \psi\psi^+$$

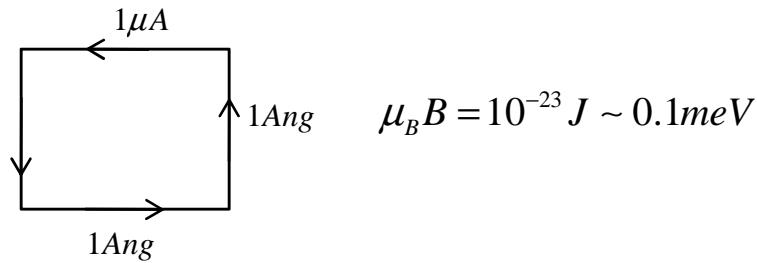
$$i\hbar \frac{\partial \psi}{\partial t} = H\psi + \Sigma\psi + s$$

$$I_{op} \rightarrow i\hbar \frac{\partial}{\partial t}(\psi\psi^+)$$

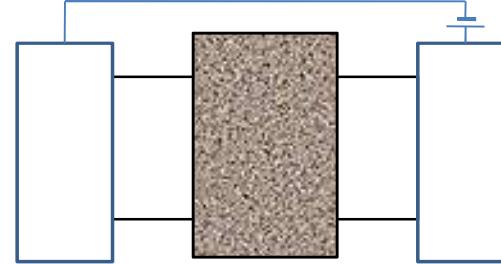
$$(I_{op})_{m,m} = H_{m,m-1}G_{m-1,m}^n + H_{m,m}G_{m,m}^n + H_{m,m+1}G_{m+1,m}^n$$

Spin torque: $\frac{1}{i\hbar} \text{Trace}(\vec{\sigma} H_{m,m} G_{m,m}^n) \Rightarrow -\frac{2\mu_B}{\hbar}(\vec{S} \times \vec{B})$

With a usual magnet we get $B=1T$

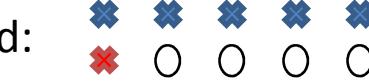


We can increase the field by including the magnet in the channel

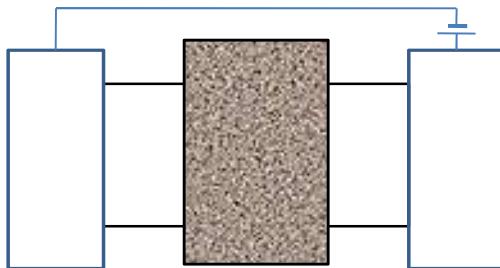


This can give rise to 1 eV splitting : 10^4 T due to exchange interaction

$$Fe^{26} = \underbrace{1s^2 2s^2 2p^6 3s^2 3p^6}_{18} 4s^2 3d^6$$

d:  4 unpaired electrons

$$4\mu_B$$



Moving electrons

$$\frac{d\vec{S}}{dt} = -g \frac{\mu_B}{\hbar} (\vec{S} \times \vec{B})$$

$$\frac{d\vec{m}}{dt} = +g \frac{\mu_B}{\hbar} (\vec{m} \times \vec{B})$$

Magnet

A thin magnet (a few monolayers) can be flipped by this force

If: $\vec{B} = k\vec{m}$

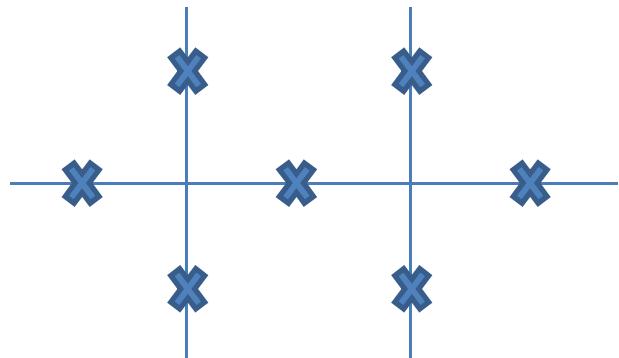
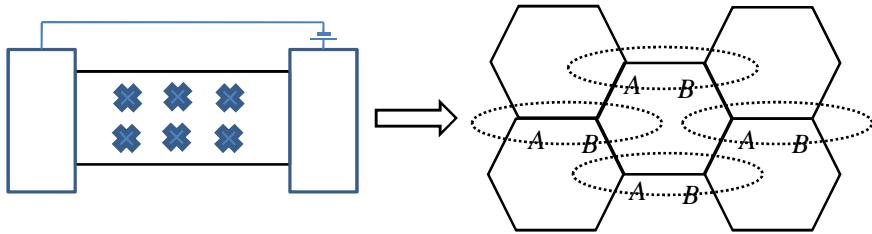
$$\frac{10^4 T}{\mu_B / \text{unit cell}}$$

$$\begin{aligned} \frac{d\vec{m}}{dt} &= g \frac{\mu_B}{\hbar} (\vec{S} \times k\vec{m}) && \xrightarrow{\frac{10^{-5} \mu_B}{\text{unit cell}}} \\ &= -g \frac{\mu_B}{\hbar} (\vec{m} \times k\vec{S}) \end{aligned}$$

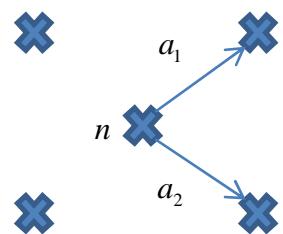
$$k\vec{S} \rightarrow 0.1 T \text{ enough to flip a magnet}$$

This torque, however is applicable only on the surface monolayers because electrons start to align themselves in the direction of magnetic field inside the magnet, thereby decreasing the torque. So this effect is applicable only on thin magnets

Pseudo spin:



The graphene can now be handled using mathematical tools developed to handle spins



$$H_{n,n} = t \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \rightarrow t\sigma_x$$

$$H_{n,m} = t \begin{bmatrix} 0 & 0 \\ 1 & 0 \end{bmatrix} \rightarrow t \frac{\sigma_x - i\sigma_y}{2} \quad \text{Right}$$

$$H_{n,m} = t \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix} \rightarrow t \frac{\sigma_x + i\sigma_y}{2} \quad \text{Left}$$

$$E\{\psi_n\} = \sum_m H_{nm} \{\psi_m\}$$

$$\{\psi_n\} = \{\phi\} e^{i\vec{k} \cdot \vec{d}_n}$$

$$E\{\phi\} = \underbrace{\sum_m H_{nm} e^{i\vec{k} \cdot \vec{d}_n}}_{h(\vec{k})} \{\phi\}$$

$$h(\vec{k}) = t \left[\begin{array}{c} \sigma_x - i\sigma_y (e^{i\vec{k} \cdot \vec{a}_1} + e^{i\vec{k} \cdot \vec{a}_2}) \\ \hline \sigma_x + \frac{\sigma_x - i\sigma_y (e^{i\vec{k} \cdot \vec{a}_1} + e^{i\vec{k} \cdot \vec{a}_2})}{2} \\ \hline \sigma_x + i\sigma_y (e^{i\vec{k} \cdot \vec{a}_1} + e^{i\vec{k} \cdot \vec{a}_2}) \\ \hline \frac{\sigma_x + i\sigma_y (e^{i\vec{k} \cdot \vec{a}_1} + e^{i\vec{k} \cdot \vec{a}_2})}{2} \end{array} \right]$$

$$= t \left[\sigma_x \underbrace{B_x}_{k_x, k_y} + \sigma_y B_y \right]$$