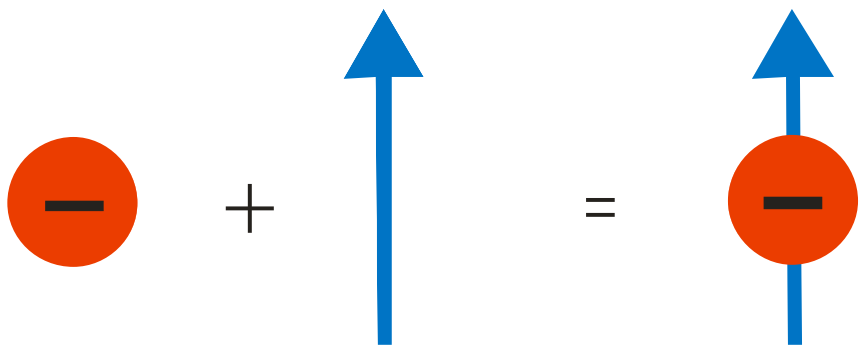
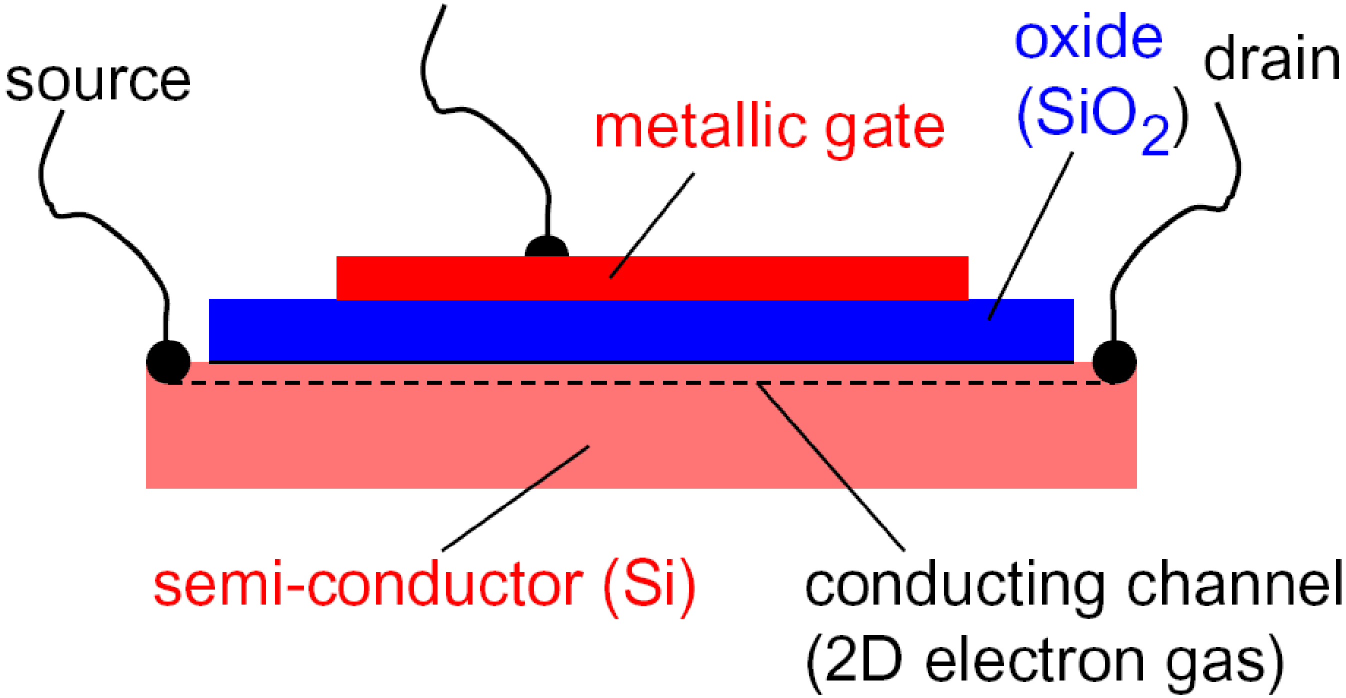
What is an electron?

electron = object with charge -e and spin ½



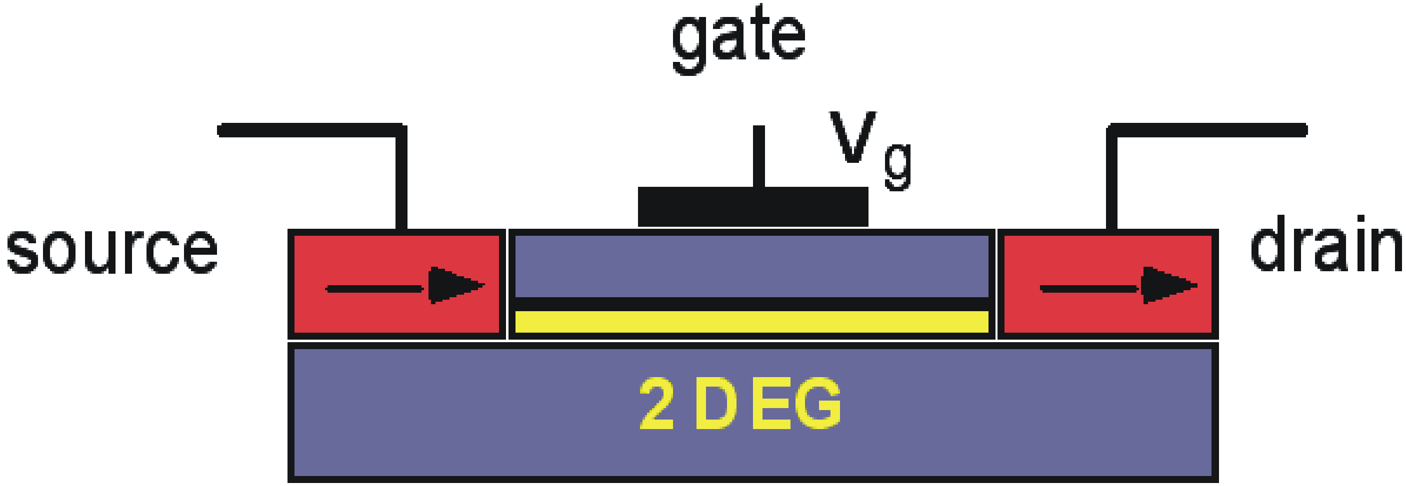
but so far, electronics has completely neglected the spin

“Normal” transistor (MOSFET)



- gate voltage controls the current between source and drain
- used as modulator / amplifier or switch

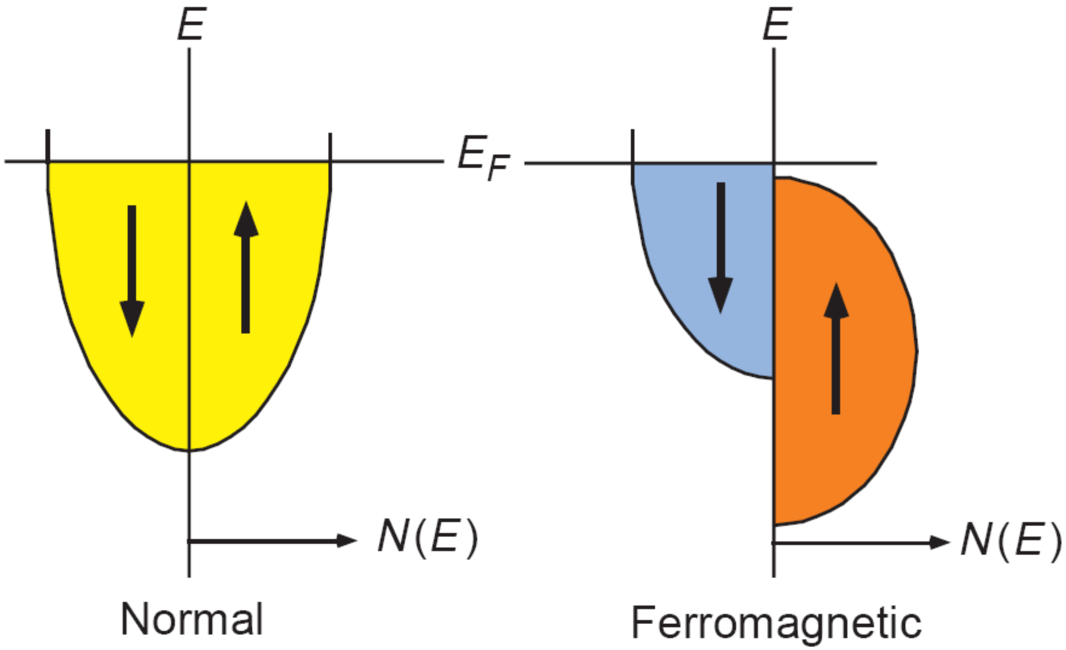
Spin transistor



- source and drain are ferromagnetic materials
- gate voltage changes the spin of the electrons to control the current – no external magnetic field

Spin-polarized transport

schematic DOS

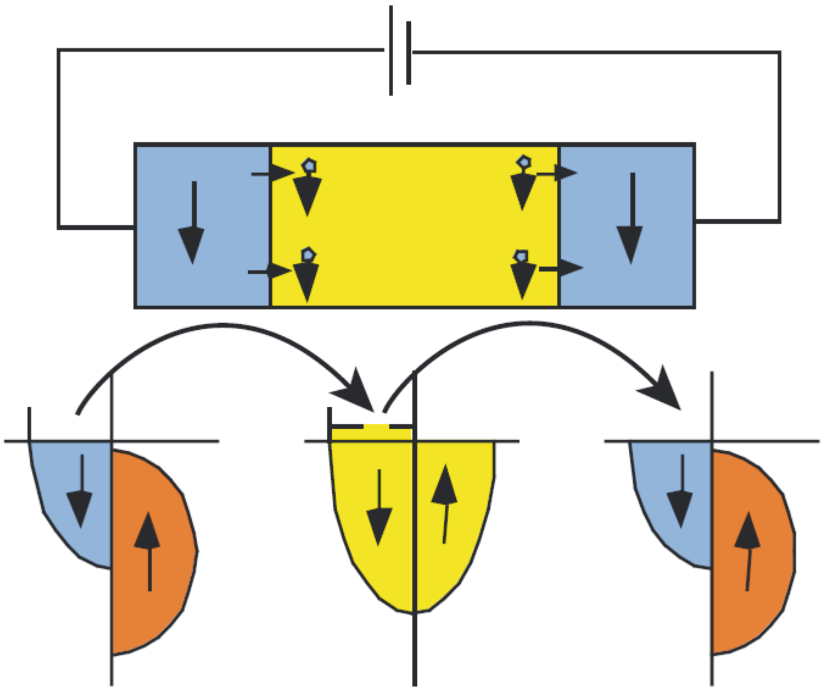


polarization:

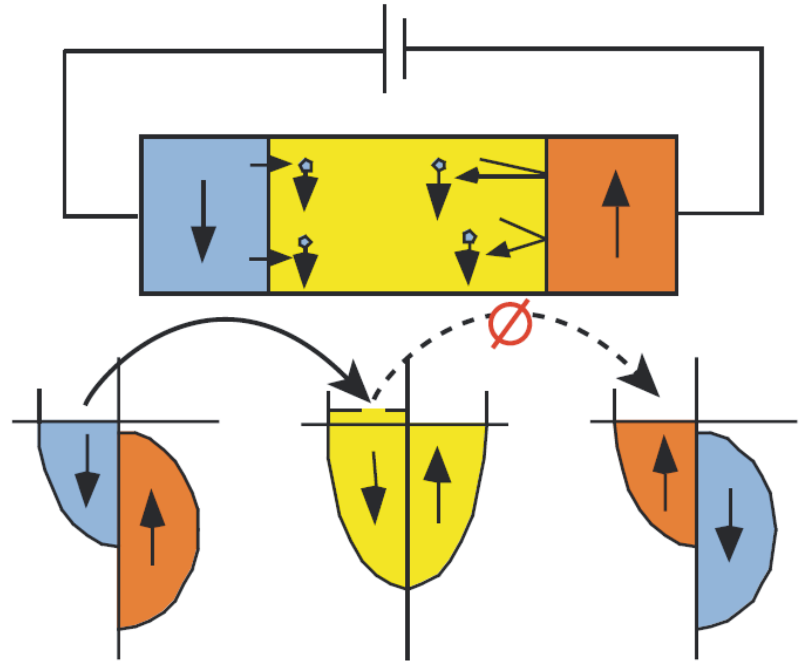
$$P = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow}$$

- imbalance of spin population at Fermi level leads naturally to spin-polarized transport
- commonly occurs in ferromagnetic metals (or alloys) with P up to 50 %

Spin valve



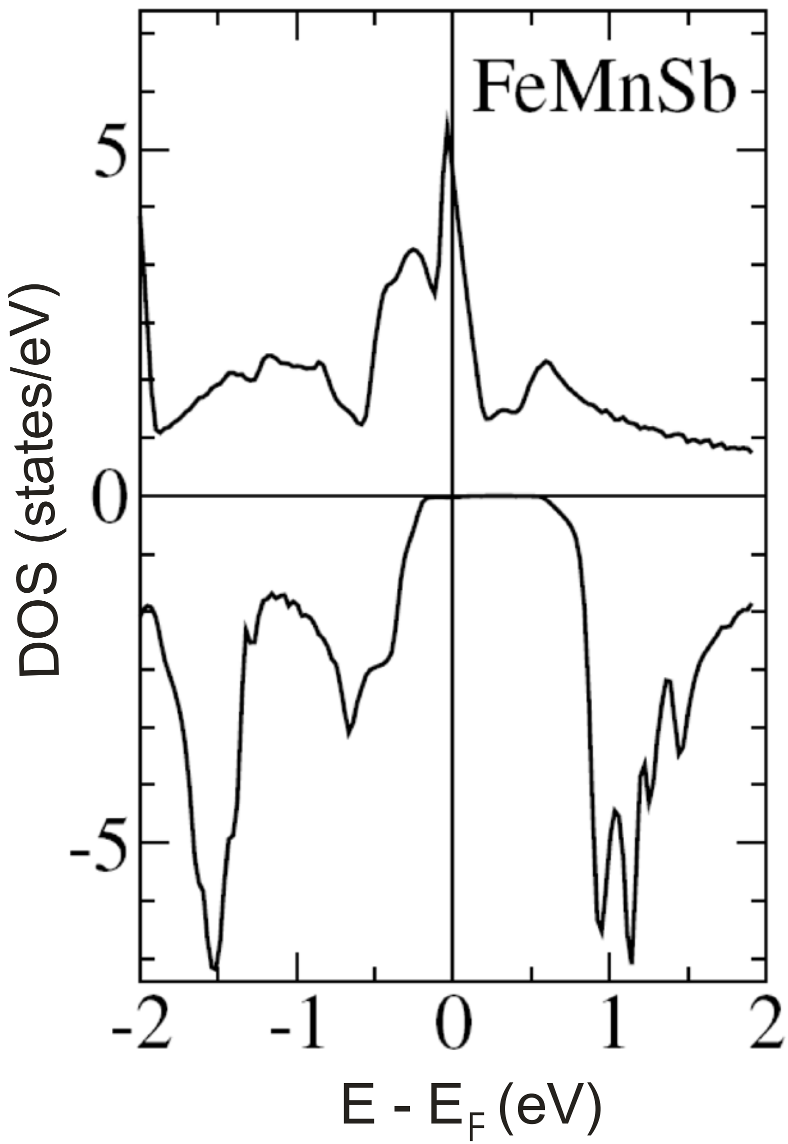
low resistance



high resistance

New materials

- Heusler alloys have a (theoretical) spin polarization of 100 %
- e.g. Co_2MnSi, FeMnSb



Mavropoulos *et al.*
J. Phys.: Condens. Matter **16** (2004)

Spin-orbit coupling

- an electron moving in an electric field experiences a magnetic field in its rest frame of reference

$$\vec{B} \propto \vec{v} \times \vec{E}$$

- non-relativistic limit of Dirac equation leads to the Schrödinger equation with an additional term that describes spin-orbit coupling (SOC)

$$\hat{H}_{SOC} = \frac{\hbar}{(2mc)^2} \nabla V \cdot (\hat{\sigma} \times \hat{k})$$

Symmetry considerations

- from time reversal symmetry (Kramer's theorem)

$$E(\vec{k},\uparrow) = E(-\vec{k},\downarrow)$$

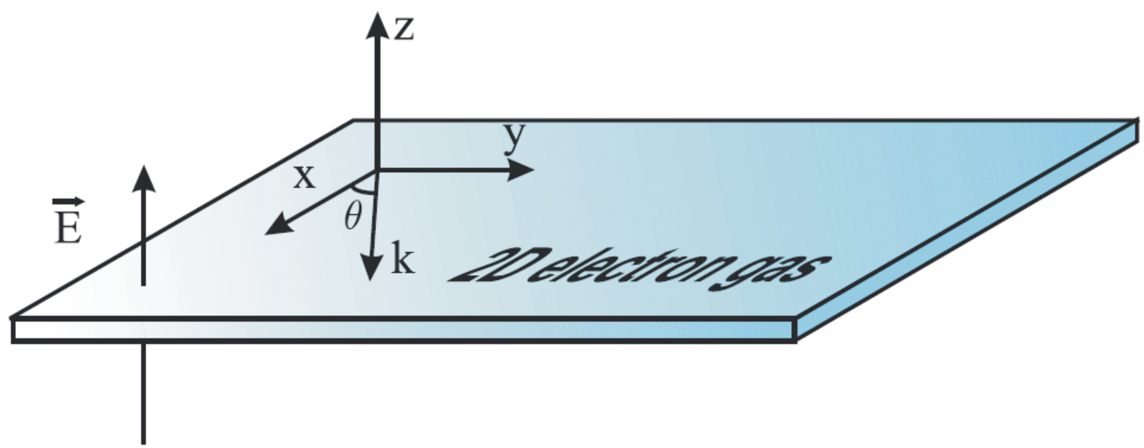
- from inversion symmetry

$$E(\vec{k},\uparrow) = E(-\vec{k},\uparrow)$$

- if both symmetries are fulfilled the bandstructure is doubly degenerated

$$E(\vec{k},\uparrow) = E(\vec{k},\downarrow)$$

quasi-2D free electron gas



on the surface of a solid or in heterostructures the inversion symmetry is broken and SOC can lift the degeneracy of the states

Rashba term

- spin-orbit Hamiltonian in 2D is so-called Rashba term

$$H_{SOC} = \alpha(\vec{\sigma} \times \vec{k})\vec{e}_z$$
$$= \alpha(\sigma_x k_y - \sigma_y k_x)$$

- coupling parameter α can be controlled by the electric field

$$\alpha \propto \nabla V$$

Ansatz

- full Hamiltonian of the 2DEG

$$H = \begin{pmatrix} \frac{1}{2m}(k_x^2 + k_y^2) & \alpha(k_y + ik_x) \\ \alpha(k_y - ik_x) & \frac{1}{2m}(k_x^2 + k_y^2) \end{pmatrix}$$

$$H\left|\psi\right\rangle = E\left|\psi\right\rangle$$

- commutator $\left[k, H\right]_- = 0$

- wave function $\left|\psi\right\rangle = e^{i(k_x x + k_y y)}\left(a\left|\uparrow\right\rangle + b\left|\downarrow\right\rangle\right)$

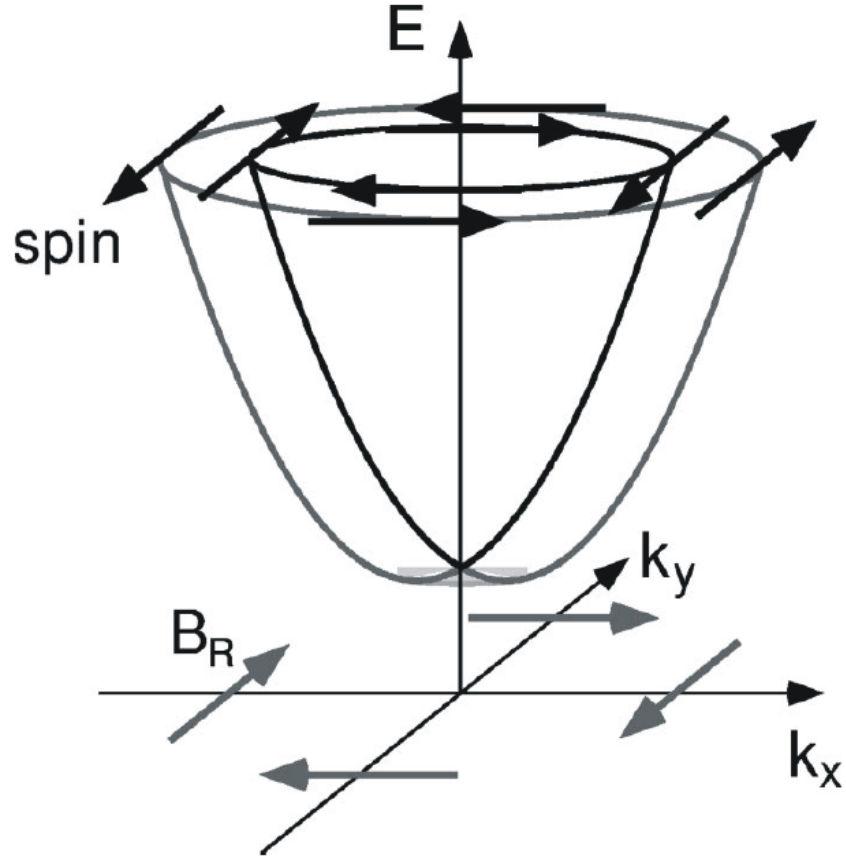
Eigenvalues and eigenstates

$$E_1(k,\uparrow) = \frac{k^2}{2m} + \alpha|k|$$

$$E_2(k,\downarrow) = \frac{k^2}{2m} - \alpha|k|$$

$$\psi_1(\vec{r}) = \tfrac{1}{\sqrt{2}} e^{i\vec{k}\vec{r}} \left(\left|\uparrow\right\rangle + ie^{i\Theta} \left|\downarrow\right\rangle \right)$$

$$\psi_2(\vec{r}) = \tfrac{1}{\sqrt{2}} e^{i\vec{k}\vec{r}} \left(ie^{-i\Theta} \left|\uparrow\right\rangle + \left|\downarrow\right\rangle \right)$$



Spin precession

- phase shift between two electrons with the same energy and different spin:

$$\Delta k = 2m\alpha$$

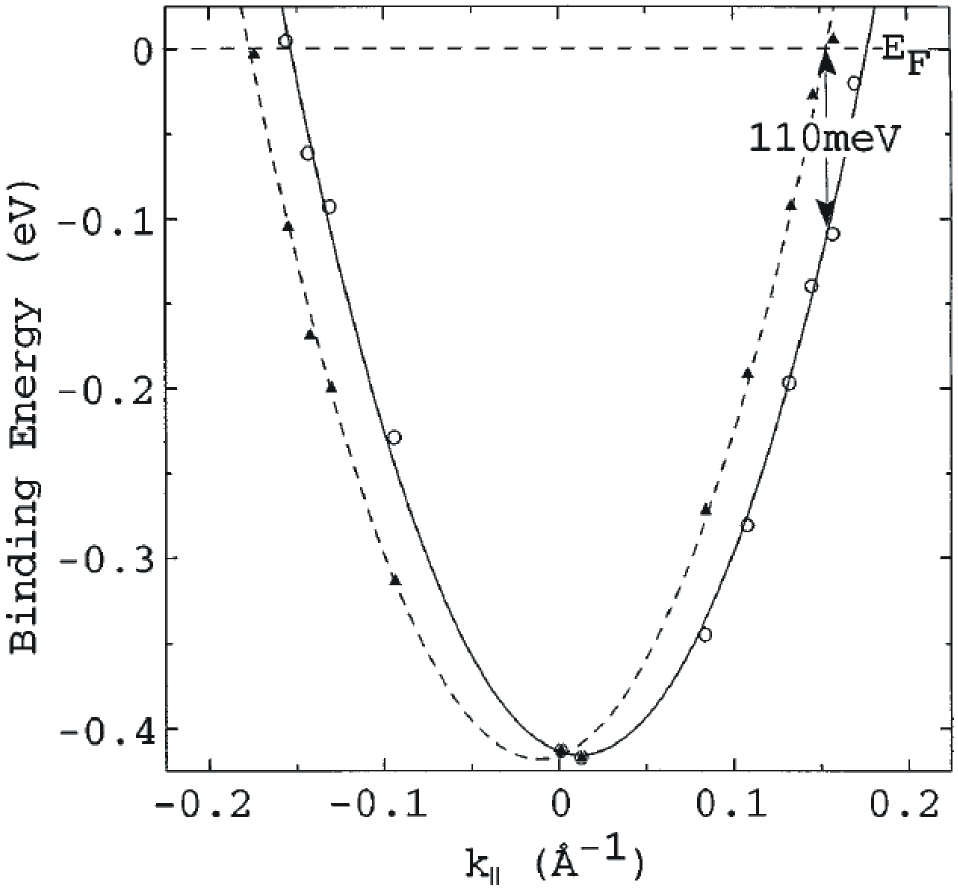
$$\Delta \theta = 2m\alpha L$$

- spin rotates analogue to Larmor precession with frequency

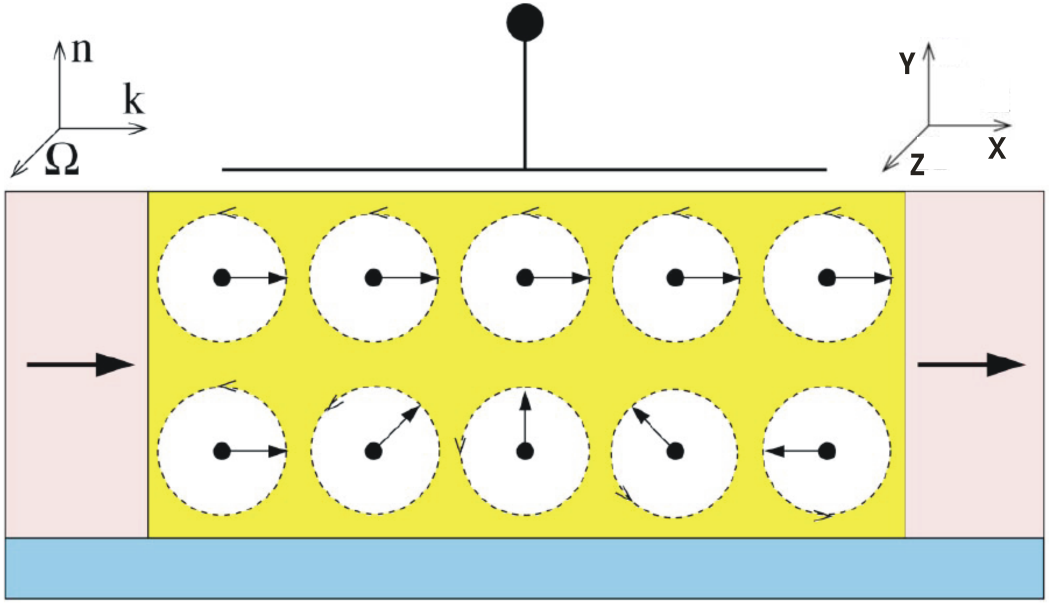
$$\Omega(\vec{k}) = \alpha(\vec{k} \times \vec{n})$$

Experimental results

spin splitting of Au(111) surface state
LaShell *et al.* PRL **77** (1996)



Spin transistor revisited



x-polarized spin is a superposition of spin-up and spin-down eigenstates along the z-axis

$$\begin{pmatrix}1\\1\end{pmatrix}=\begin{pmatrix}1\\0\end{pmatrix}+\begin{pmatrix}0\\1\end{pmatrix} \quad \leftrightarrow \quad |x\rangle=|\uparrow\rangle+|\downarrow\rangle$$