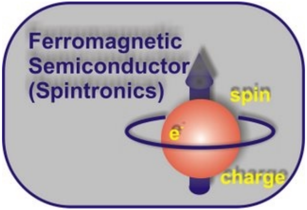
SPINTRONICS



Waltraud Buchenberg

Faculty of Physics

Albert-Ludwigs-University Freiburg

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WHAT IS SPINTRONICS?

OVERVIEW - SPINTRONICS

microelectronic devices that function by exploiting the spin of electrons

→ active control and manipulation of spin degrees of freedom in solid-state-systems

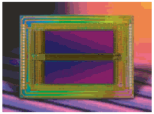
→ own new functionalities not feasible or ineffective with conventional electronics

→ common use today: magnetic read head in computer hard drives

Goal of spintronics:

→ understanding the interaction between a particle spin and its solid-state environments

→ creating useful devices
e.g. SFET, nonvolatile MRAM



Motorola 256-kb MRAM device

TERM DECLARATION

Spin:

- spin of a single electron with magnetic moment $\mu_e = -g\mu_B\vec{s}$
- average spin of an ensemble of electrons, manifested by magnetization

Control of spin:

- coherent spin manipulation of a single or a few-spin system
- control of the population and the phase of the spin of an ensemble of particles

FUNDAMENTAL STUDIES OF SPINTRONICS

Investigations of:

- $\rightarrow$ spin transport in electronic materials
- $\rightarrow$ spin dynamics
- $\rightarrow$ spin relaxation (mostly involving spin-orbit coupling)

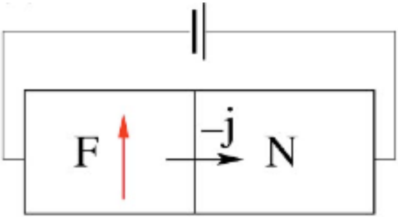
spintronic applications:

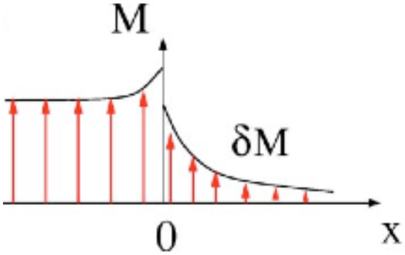
- $\rightarrow$ typically require current flow and/or manipulation of the non-equilibrium spin (spin polarization)

HOW TO GENERATE SPIN POLARIZATION?

Creating a non-equilibrium spin population:

- electrical spin injection: more desirable for device applications
  - $\rightarrow$ magnetic electrode connected to sample
  - $\rightarrow$ current drives spin-polarized electrons from electrode to sample
  - $\rightarrow$ non-equilibrium spin (or magnetization δM) accumulates in the sample (dependent on spin relaxation)





(I. Žutić et. al. Rev. Mod. Phys. **76**, p. 328, 2004)

SPIN-POLARIZED TRANSPORT

Two-current model (Mott 1936):

- looking for explanation of unusual behavior of resistance in ferromagnetic metals
- at sufficiently low temperatures:

  → electrons of majority and minority spin (magnetic moment parallel and anti-parallel to the magnetization of a ferromagnet, respectively) do not mix in the scattering processes

  → conductivity can be expressed as the sum of two *independent* and *unequal* parts for two different spin projections

  → **current in ferromagnets is spin polarized**

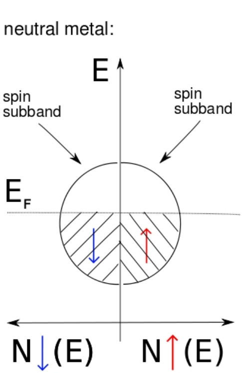
- various magneto-resistive phenomena can be explained by this model when further extented

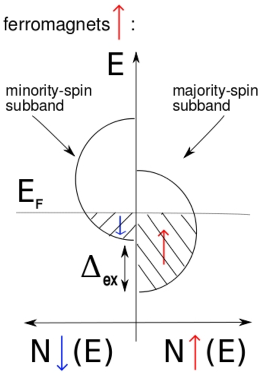
MAGNETO-RESISTANCE

STONER MODEL

→ accounts for metallic ferromagnets

→ qualitatively explains the properties of excitations in the spin polarized states





spin-resolved density of d states in neutral and ferromagnetic metals (Δ_{ex}: exchange spin splitting)

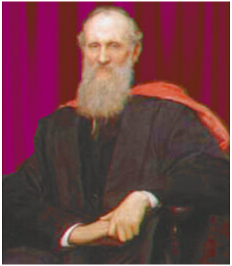
ANISOTROPIC MAGNETO-RESISTANCE IN BULK FERROMAGNETS

→ discovered by Lord Kelvin (Thomson, 1857)

→ electrical resistance depends on the angle between the direction of electrical current and orientation of magnetic field

"When you can measure what you are speaking about and express it in numbers, you know something about it."

Lecture to the Institution of Civil Engineers, 3 May 1883

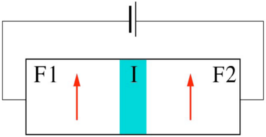


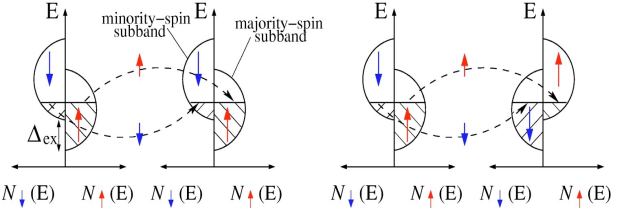
Lord Kelvin

(www.todayinsci.com/K/Kelvin_Lord/Kelvin_Lord.htm)

F/I/F MAGNETIC TUNNEL JUNCTION

Model for a change of conductance G between magnetization M (↑↑) and M (↑↓) in two ferromagnetic regions (F):





electron tunneling in F/I/F tunnel junctions:

parallel orientation of magnetizations — *anti-parallel orientation of magnetizations*

(M. Jullière, Phys. Lett. **54A**, 225, 1975)

SPIN-VALVE EFFECT

Tunneling and Giant Magneto Resistance (TMR and GMR):

$$\text{TMR} = \frac{\Delta R}{R_{\uparrow\uparrow}} = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}} = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}} \qquad \text{with} \qquad R = \frac{1}{G}$$

in terms of polarization P_j ($j = 1, 2$):

$$P_j = \frac{N_{\text{M}j} - N_{\text{m}j}}{N_{\text{M}j} + N_{\text{m}j}}$$

$N_{\text{M}j}, N_{\text{m}j}$: spin-resolved density of states for majority, minority spin in ferromagnet F_j

$$G_{\uparrow\uparrow} \sim N_{\text{M}1} N_{\text{M}2} + N_{\text{m}1} N_{\text{m}2}$$

$$G_{\uparrow\downarrow} \sim N_{\text{M}1} N_{\text{m}2} + N_{\text{m}1} N_{\text{M}2}$$

$$\Longrightarrow \text{TMR} = \frac{2 P_1 P_2}{1 - P_1 P_2}$$

discovery of large temperature TMR:

- renewed interest in studying magnetic tunnel junctions
  basis for several magnetic RAM-prototypes

MAGNETO-RESISTANCE APPLICATIONS

ability to control the relative orientation of M_1 and M_2 is of major importance!

realized by:

- small magnetic field
- high switching speeds
- using the phenomenon: *spin-transfer torque*

  $\rightarrow$ spin-polarized current transfers angular momentum from carriers to ferromagnet
  $\Longrightarrow$ altering the orientation of the corresponding magnetization

  (even without an applied magnetic field)

  [in GMR or TMR structures: relative orientation of magnetizations affects the flow of spin-polarized current]

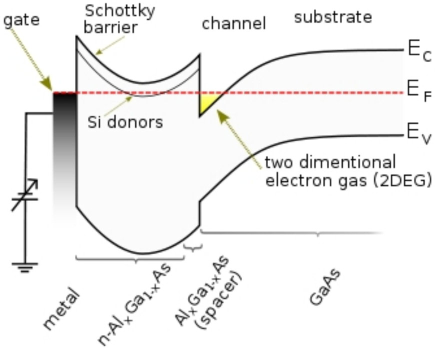
- optically and electrically (ferromagnetic semiconductors)

SPIN FIELD EFFECT TRANSISTOR (SPIN-FET)

2D ELECTRON GAS (2DEG)

- → free electrons in 2 dimensions
- → electrons are confined symmetrically or asymmetrically in the third dimension

  ⟹ quantized energy levels



Band structure in GaAs/AlGaAs heterojunction based High-electron-mobility-transistor (HEMT)

http://en.wikipedia.org/wiki/High_electron_mobility_transistor

SPIN-ORBIT (SO) COUPLING

$\Longrightarrow$ it is an interaction coupling the particle's spin with its orbital motion

example:

$\rightarrow$ Atoms: LS-coupling

SO coupling in 2DEG:

- Dresselhaus effect (bulk inversion asymmetry)
- Rashba effect (structure inversion asymmetry):
  - $\rightarrow$ investigated to create an electronic analog of the electro-optic modulator (Spin-FET)
  - $\rightarrow$ depends on:
    - confining potential shape (SO-coupling constant α):

      changeable by using an external electric field

RASHBA EFFECT IN 2DEG

SO Hamiltonian:

$$H_{SO} = \frac{\alpha}{\hbar}(\vec{\sigma} x \vec{p}) \cdot \hat{e} \qquad [1]$$

$\vec{\sigma}$: Pauli matrices

α: SO coupling constant

$\hat{e}$: unity vector perpendicular to the 2DEG

Total Hamiltonian H of a 2DEG in plane (x, y):

$$H = \frac{\vec{p}^2}{2m^*} + \frac{\alpha}{\hbar}(\vec{\sigma} x \vec{p}) \cdot \hat{e}_z \quad \text{with} \quad \vec{p} \equiv (p_x, p_y, 0)$$

([1] Yu. A. Bychkov and E. I. Rashba, JETP Lett. **39**, 78, 1984)

TOTAL HAMILTONIAN H

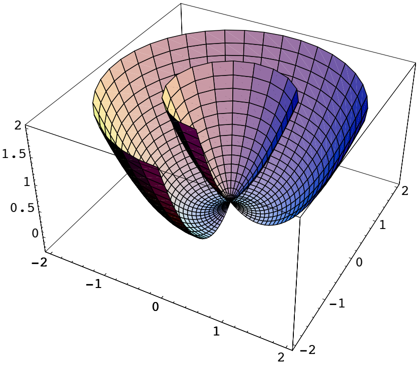
eigenvalues:

$$E_\pm(\vec{k}) = \frac{\hbar^2 k^2}{2m^*} \pm \alpha k = \frac{\hbar^2}{2m^*}(k \pm k_{SO})^2 - \Delta_{SO}$$

$$k = \sqrt{k_x^2 + k_y^2}$$

$$k_{SO} = \frac{\alpha m^*}{\hbar^2}$$

$$\Delta_{SO} = \left(\frac{\alpha m^*}{\hbar}\right)^2$$



energy spectrum of H

TOTAL HAMILTONIAN H

eigenvectors:

$$\Psi_+(x,y) = \quad e^{i(k_x x + k_y y)} \; \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ ie^{-i\Theta} \end{pmatrix} \qquad \text{with} \quad \Theta = arctan\left(\frac{k_y}{k_x}\right)$$

$$\Psi_-(x,y) = \quad e^{i(k_x x + k_y y)} \; \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ -ie^{-i\Theta} \end{pmatrix}$$

Θ : angle between $\vec{p}$ and k_x axis

Properties:

$\rightarrow$ always $\Psi_+ \perp \Psi_-$

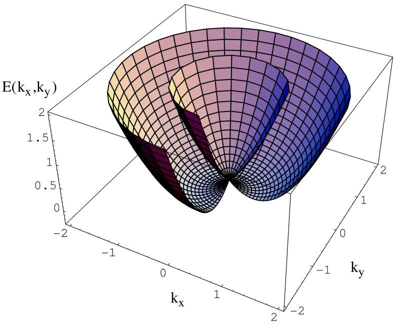
$\rightarrow$ electron moves along x:

$$\Psi_+(x,y) \sim \begin{pmatrix} 1 \\ i \end{pmatrix} \quad \text{and} \quad \Psi_-(x,y) \sim \begin{pmatrix} 1 \\ -i \end{pmatrix}$$

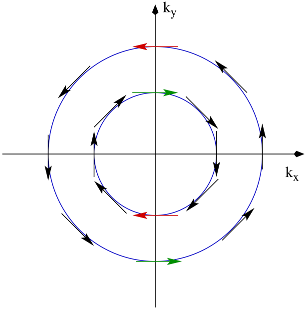
$\rightarrow$ electron moves along y:

$$\Psi_+(x,y) \sim \begin{pmatrix} 1 \\ 1 \end{pmatrix} \quad \text{and} \quad \Psi_-(x,y) \sim \begin{pmatrix} 1 \\ -1 \end{pmatrix}$$

ENERGY SPECTRUM AND FERMI CONTOURS



energy spectrum of H

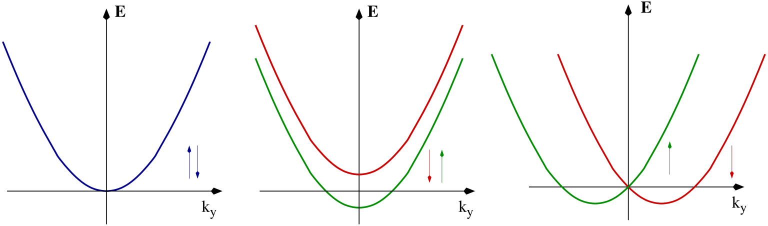


Fermi contours

Parametrization:

$$\vec{k} = k(\cos\varphi, \sin\varphi) \qquad k_{\pm}^{F}(\varphi, E_F) = \mp\frac{\alpha m^*}{\hbar^2} + \sqrt{\left(\frac{\alpha m^*}{\hbar^2}\right)^2 + \frac{2m^*}{\hbar^2}E_F}$$

ENERGY SPECTRA



free electron — *electron in external magnetic field* — *electron in presence of Rashba SO interaction*

electron:

LEFT : free: spin degeneracy!

CENTER : in external magnetic field: Zeeman splitting
($gap = g^* \mu_B B$; g^*: effective gyro-magnetic ratio)

RIGHT : with structure inversion asymmetry: degeneracy removed without gaining a gap except for $\vec{k}$=0

SPIN FIELD EFFECT TRANSISTOR (SPIN-FET)

→ proposed by Datta and Das [1]

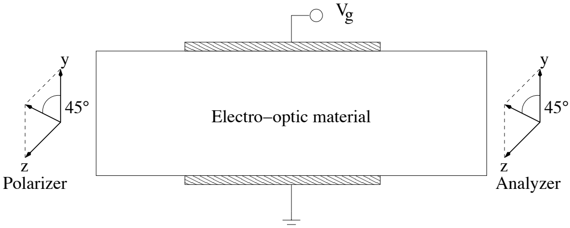
→ using Rashba SO interaction:

$$H_{SO} = \frac{\alpha}{\hbar}(\vec{\sigma} x \vec{p}) \cdot \hat{e}$$

→ basic effect understandable through analogy to electro-optic light modulator

([1] S. Datta and B. Das, Appl. Phys. Lett, **56**, 665-667, 1990)

ELECTRO-OPTIC LIGHT MODULATOR



electro-optic light modulator

→ input of polarized light in y-z-plane: $\begin{pmatrix} 1 \\ 1 \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \begin{pmatrix} 0 \\ 1 \end{pmatrix}$

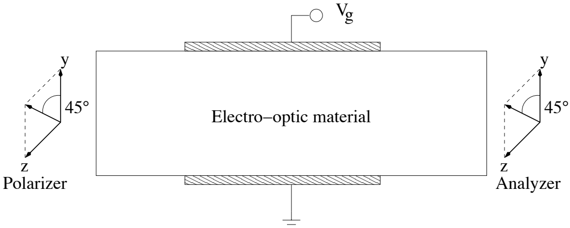
(45° pol.) (z pol.) (y pol.)

→ electro-optic effect (dielectric constant $\epsilon_{zz} \neq \epsilon_{yy}$)

$\Longrightarrow$ two polarizations gain different phase shifts ($k_1 L$ and $k_2 L$)

→ emerging light polarization: $\begin{pmatrix} e^{ik_1 L} \\ e^{ik_2 L} \end{pmatrix}$

ELECTRO-OPTIC LIGHT MODULATOR



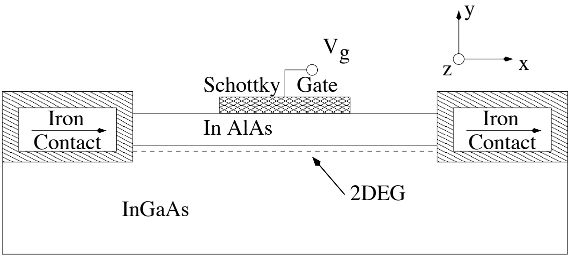
electro-optic light modulator

→ output along $\begin{pmatrix} 1 \\ 1 \end{pmatrix}$ can pass the analyzer

→ output power:
$$P_0 \propto \left| \begin{pmatrix} 1 & 1 \end{pmatrix} \begin{pmatrix} e^{ik_1 L} \\ e^{ik_2 L} \end{pmatrix} \right| = 4\cos^2\left(\frac{(k_1 - k_2)L}{2}\right)$$

→ gate voltage:
controls phase shift difference $(k_1 - k_2)L$

SPIN FIELD EFFECT TRANSISTOR (SPIN-FET)

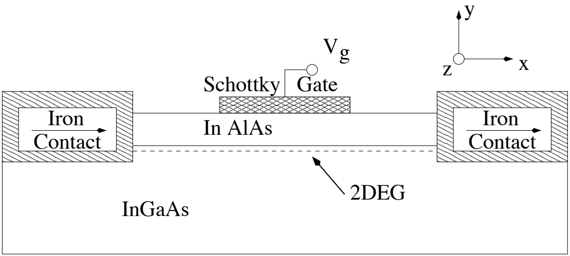


Spin-FET (Datta and Das)

→ polarizer and analyzer:

- implemented by using ferromagnetic material contacts (iron)
- at the Fermi energy:
  density of states for electrons with one spin ≫ density of states for electrons with other spin (Stoner-Model)
- electron injection and detection occurs preferentially with a particular spin by the contact

SPIN-FET

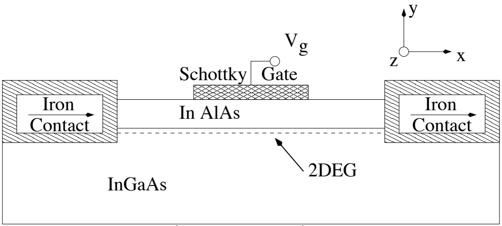


Spin-FET (Datta and Das)

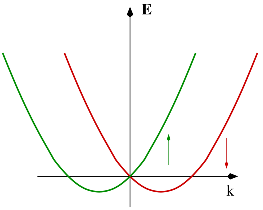
$\rightarrow$ contact magnetized in x direction:

- preferentially injects and detects electrons spin polarized along positive x direction
- represented by: $\underset{(+x \text{ pol.})}{\begin{pmatrix} 1 \\ 1 \end{pmatrix}} = \underset{(+z \text{ pol.})}{\begin{pmatrix} 1 \\ 0 \end{pmatrix}} + \underset{(-z \text{ pol.})}{\begin{pmatrix} 0 \\ 1 \end{pmatrix}}$

SPIN-FET



Spin-FET (Datta and Das)



energy spectrum
(Rashba-spin-orbit interaction)

→ narrow-gap semicondutors with Rashba SO coupling:

- provide the analog of an electro-optic material (phase shift!)
- existence of energy splitting between spin up and spin down electrons in 2DEG's even with no external magnetic field
- +z polarized and -z polarized electrons with the same energy have different wave vectors k_1 and k_2

SPIN-FET

Assumption: 2DEG in the x-z plane

1D-case:

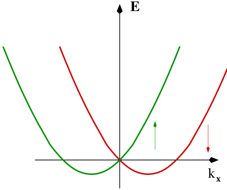
electron is traveling in the x direction: $k_x \neq 0,\ k_z = 0,\ H_R = \frac{\alpha}{\hbar}(\sigma_z \cdot p_x)$

$$H = H_0 + H_R = \begin{pmatrix} \frac{\hbar^2 k_x^2}{2m^*} + \alpha k_x & 0 \\ 0 & \frac{\hbar^2 k_x^2}{2m^*} - \alpha k_x \end{pmatrix}$$

$$E(z\ pol./spin \uparrow) = \frac{\hbar^2 k_x^2}{2m^*} - \alpha k_x$$

$$E(-z\ pol./spin \downarrow) = \frac{\hbar^2 k_x^2}{2m^*} + \alpha k_x$$

eigenstates: $\begin{pmatrix} 1 \\ 0 \end{pmatrix} ; \begin{pmatrix} 0 \\ 1 \end{pmatrix}$



energy spectrum (Rashba-spin-orbit interaction)

$\Longrightarrow$ incoming electron beam $\begin{pmatrix} 1 \\ 1 \end{pmatrix}$ splits equally between them!

1D-case:

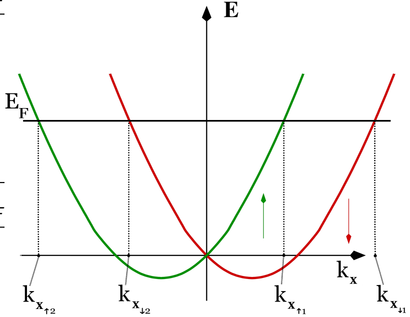
$$E(z\ pol./spin\uparrow) = \frac{\hbar^2 k_x^2}{2m^*} - \alpha k_x = E_F\ \text{(Fermi energy)}$$

$$k_{x_{\uparrow(1/2)}} = \frac{m^*\alpha}{\hbar^2} \pm \sqrt{\left(\frac{m^*\alpha}{\hbar^2}\right)^2 + \frac{2m^* E_F}{\hbar^2}}$$

$$E(-z\ pol./spin\downarrow) = \frac{\hbar^2 k_x^2}{2m^*} + \alpha k_x = E_F$$

$$k_{x_{\downarrow(1/2)}} = -\frac{m^*\alpha}{\hbar^2} \pm \sqrt{\left(\frac{m^*\alpha}{\hbar^2}\right)^2 + \frac{2m^* E_F}{\hbar^2}}$$

$$\Longrightarrow \quad \boxed{k_{x_{\uparrow(1)}} - k_{x_{\downarrow(1)}} = \frac{2m^*\alpha}{\hbar^2}}$$



energy spectrum (Rashba-spin-orbit interaction)

SPIN-FET

1D-case:

output power:

$$P_0 \propto \left| \begin{pmatrix} 1 & 1 \end{pmatrix} \begin{pmatrix} e^{ik_{x_{\uparrow(1)}} L} \\ e^{ik_{x_{\downarrow(1)}} L} \end{pmatrix} \right| = 4\cos^2\left(\frac{(k_{x_{\uparrow(1)}} - k_{x_{\downarrow(1)}})L}{2}\right)$$

differential phase shift:

$$\Delta\Theta = (k_{x_{\uparrow(1)}} - k_{x_{\downarrow(1)}})L = \frac{2m^* \alpha L}{\hbar^2}$$

$\Delta\Theta$:

$\rightarrow$ $\propto$ spin-orbit coefficient α (gate-voltage-controlled)

$\rightarrow$ $\propto$ length of the semiconductor L

phase difference of π is achievable within a mean free path

SPIN-FET

Additional confining potential V(z) (Quasi-1D-case):

$\rightarrow$ used to confine electrons in a wave guide

$\rightarrow$ it restricts the angular spectrum of the electrons

$\Longrightarrow$ larger overall current modulation

$$H = \begin{pmatrix} \frac{p_x^2+p_z^2}{2m^*} + V(z) + \frac{\alpha}{\hbar} p_x & -\frac{\alpha}{\hbar} p_z \\ -\frac{\alpha}{\hbar} p_z & \frac{p_x^2+p_z^2}{2m^*} + V(z) - \frac{\alpha}{\hbar} p_x \end{pmatrix}$$

$$= \begin{pmatrix} \frac{p_x^2}{2m^*} + \frac{\alpha}{\hbar} p_x & 0 \\ 0 & \frac{p_x^2}{2m^*} - \frac{\alpha}{\hbar} p_x \end{pmatrix}$$

$$+ \begin{pmatrix} \frac{p_z^2}{2m^*} + V(z) & -\frac{\alpha}{\hbar} p_z \\ -\frac{\alpha}{\hbar} p_z & \frac{p_z^2}{2m^*} + V(z) \end{pmatrix} = H_x + H_z$$

SPIN-FET

Quasi-1D-case with $V(z) = \begin{cases} 0 & -\frac{L}{2} \leq z \leq \frac{L}{2} \\ \infty & \text{otherwise} \end{cases}$

finding eigenstates of H:

$\rightarrow$ use **unperturbed** (α=0) eigenstates as a basis set:

$$\Phi_m(x,z) = const \cdot e^{ik_x x} \cdot \cos(k_z(m) \cdot z) \Longrightarrow |m, k_x\rangle$$

with $\langle m`, k_x` | m, k_x\rangle = \delta_{m`,m} \, \delta_{k_x`,k_x}$; m: subband index

energy eigenvalues: $H(\alpha = 0)|m, k_x\rangle = E_{m,k_x}|m, k_x\rangle$

$$E_{m,k_x} = \epsilon_m + \frac{\hbar^2 k_x^2}{2m^*}$$

$$\left(-\frac{\hbar^2(\frac{\partial^2}{\partial z^2})}{2m^*} + V(z)\right)\Phi_m(z) = \epsilon_m \Phi_m(z)$$

The two spins, $|+\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$ and $|-\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$, are degenerated!

SPIN-FET

Quasi-1D-case

The Rashba term $\mathrm{H}_R = \frac{\alpha}{\hbar}(\sigma_z p_x - \sigma_x p_z)$ couples the eigenstates of $\mathrm{H}(\alpha = 0)$:

$$\langle m`, k_x`, i | H_x + H_z | m, k_x, j\rangle \quad \text{with} \quad i, j \in [+, -]$$

non zero matrix elements when $\alpha \neq 0$:

$$\langle m`, k_x`, + | H_x | m, k_x, + \rangle = \langle m`, k_x`, + | \frac{p_x^2}{2m^*} + \frac{\alpha}{\hbar}\sigma_z p_x | m, k_x, + \rangle$$
$$= \left(\frac{\hbar^2 k_x^2}{2m^*} + \alpha k_x \right) \ \delta_{m`,m} \ \delta_{k_x`,k_x}$$

$$\langle m`, k_x`, - | H_x | m, k_x, - \rangle = \langle m`, k_x`, - | \frac{p_x^2}{2m^*} + \frac{\alpha}{\hbar}\sigma_z p_x | m, k_x, - \rangle$$
$$= \left(\frac{\hbar^2 k_x^2}{2m^*} - \alpha k_x \right) \ \delta_{m`,m} \ \delta_{k_x`,k_x}$$

SPIN-FET

Quasi-1D-case

$$\langle m`, k_x`, \pm | H_z | m, k_x, \mp \rangle = \langle m`, k_x`, \pm | \frac{p_z^2}{2m^*} + V(z) - \frac{\alpha}{\hbar}\sigma_x p_z | m, k_x, \mp \rangle$$
$$= \frac{\alpha}{\hbar}\langle m` | p_z | m \rangle \ \delta_{k_x`, k_x} = \frac{\alpha}{\hbar} \ \delta_{m`, m\pm 1} \ \delta_{k_x`, k_x}$$

- Eigenstates of H:

  $\rightarrow$ involve linear combinations of different subbands

- subbands are sufficiently far apart in energy:
  - neglect subband mixing

$\rightarrow$ width of the confining potential well:

  $\rightarrow$ responsible for distance between subbands

  $\rightarrow$ has to be technically feasible

SPIN-FET

Quasi-1D-case

$\rightarrow$ Neglecting intersubband mixing

$\Longrightarrow$ main effect of H_R is to split the degeneracy between the two spins:

- $E_{m,k,s} \simeq \epsilon_m + \frac{\hbar^2 k_x^2}{2m^*} + \alpha k_x s$ $\qquad$ $s = -1$ (spin up)

  $s = \ 1$ (spin down)

- wave vectors k_1 and k_2 corresponding to the **same** energy E for the two spins differ by:

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

  (same result as discussed earlier for plane unguided waves)

- differential phase shift $\Delta\Theta = \frac{2m^* \alpha L}{\hbar^2}$

  $\Longrightarrow$ **independence of m,**k_x**!**

SPIN-FET

Quasi-1D-case

independence of m,k_x for the differential phase shift $\Delta\Theta$!

$\Longrightarrow$ important advantage for device applications:

$\rightarrow$ normally, quantum interference devices:

- single moded in order to obtain large effects
- low temperature
- low voltages

$\rightarrow$ here:

- $\Delta\Theta$ between the two spins is the same for all energies and mode numbers and controlled by spin-orbit coupling coefficient α
- large percentage modulation of the current in multimoded devices operated at high temperatures and large applied bias may be possible

CONCLUSIONS

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★ TMR/GMR:

→ construction of nonvolatile RAM devices

★ STONER MODEL

★ CONTROL AND MANIPULATION OF SPIN VIA RASHBA EFFECT

★ SPIN-FET