Spintronics of Spin-Orbit coupled Systems: Achievements and Challenges

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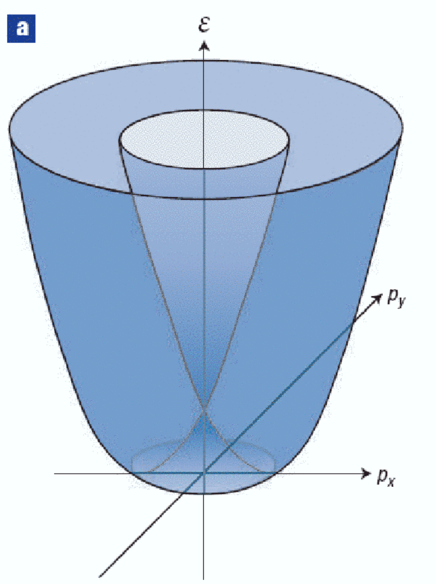
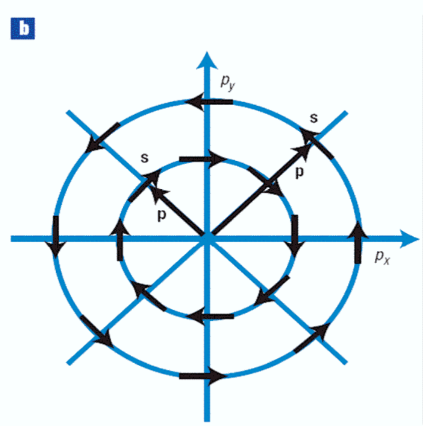
How spin-orbit coupling changes the spectrum of noncentrosymmetric systems?

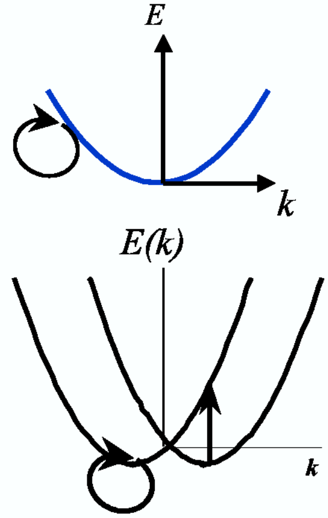


It splits the paraboloid $E(p)=p^2/2m$ into two sheets



SO coupling establishes a strict connection between the direction of the momentum $\boldsymbol{p}$ and the direction of the spin $\boldsymbol{s}$

Where Spin Coupling to Electric Field comes from?



Oscillator strength for a free electron in a parabolic band:

$$f = m_0 / m$$

m - electron effective mass

m_0 - electron vacuum mass

Simplest spin-orbit coupling in non-centrosymmetric uniaxial crystals and in quantum wells

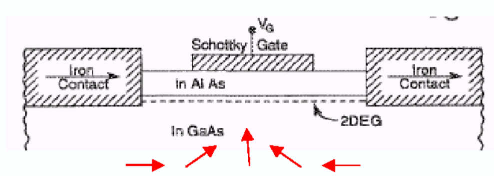
$$H_\alpha = \alpha(\boldsymbol{\sigma} \times \mathbf{k}) \cdot \hat{\mathbf{z}} = \alpha(\sigma_x k_y - \sigma_y k_x)$$

It splits spectrum into two spin branches

Near the spectrum bottom the oscillator strength is divided equally between the intra- and interbranch transitions

f_{inter} **results in spin coupling to *ac* electric field, and in EDSR (electric dipole spin resonance) in a strong magnetic field**

Spin transistor: Ideas encoded

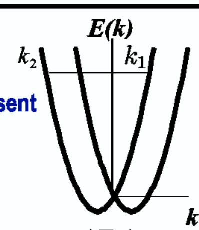


$$H_\alpha = g(\boldsymbol{\sigma} \cdot \mathbf{B}_{in})/2, \ \mathbf{B}_{in} = 2\alpha(\mathbf{k} \times \hat{\mathbf{z}})/g$$

2. electron spin $\mathbf{s} \,||\, \mathbf{k}$ precesses in the effective magnetic field $\mathbf{B}_{in}(\mathbf{k})$

Two equivalent pictures:

$$H_\alpha = \alpha(\sigma_x k_y - \sigma_y k_x)$$



1. two Fermi momenta represent two beams that interfere

$$P = \cos^2[(k_1 - k_2)L/2]$$

Gate controlled birefringence $\alpha = \alpha(E_g)$

Basic ideas underlying the device:

(i) Spin injection from ferromagnetic electrodes,

(ii) Gate control of electron spin (SO),

(iii) Spin precession in internal magnetic field (SO),

(iv) Spin interference (SO).

Spintronics without magnetic elements:

generating nonequilibrium spin populations electrically *via* SO coupling

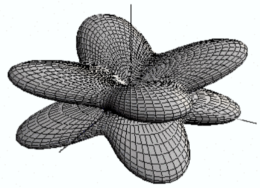
EDSR – Electric Dipole Spin Resonance

$$H_{so} = H_1(\mathbf{k},\boldsymbol{\sigma}) + H_2(\mathbf{r},\boldsymbol{\sigma}), \quad g\mu_B B >> \alpha k_F$$

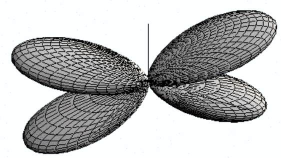
$H_1(\boldsymbol{k},\sigma)$ mechanism well known in 3D:

Bell (1962), McCombe et al. (1967), Dobrowolska et al. (1984)

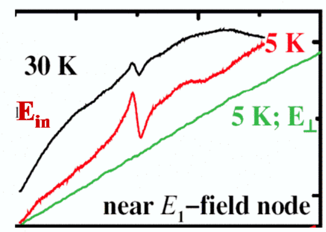
$$H_1(\mathbf{k},\boldsymbol{\sigma}): H_\alpha = \alpha(\sigma_x k_y - \sigma_y k_x) \text{ SIA, } H_\beta = \beta(\sigma_x k_x - \sigma_y k_y) \text{ BIA}$$



SIA $\tilde{\mathbf{E}} \parallel \hat{\mathbf{z}}$



BIA and SIA $\tilde{\mathbf{E}} \parallel \hat{\mathbf{z}}$



Schulte et al. (2005) AlAs

In narrow QWs, EDSR with in-plane *E* dominates

$$I_{EDSR} \approx 10^4 I_{EPR}$$

Ratio of matrix elements : $\ell_\perp / \ell_\parallel \approx \omega_c \omega_s / \omega_0^2$

$$H_2(\mathbf{r},\boldsymbol{\sigma}) = \mu_B(\boldsymbol{\sigma}\hat{\mathbf{g}}(\mathbf{r})\mathbf{B}(\mathbf{r}))/2$$

With $g \approx 0$, the mechanism proved to be efficient in AlGaAs QWs with $\mathbf{E} \parallel \mathbf{z}$

Kato et al. (2003)

Charge Transport *vs* Spin Transport

Maxwellian equations include:

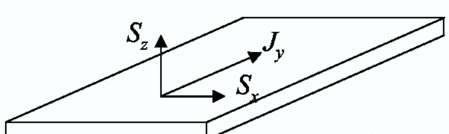
E, *D*, ρ, and *J* for electric charge and current

B and *H*, or *M*=(*B*-*H*)/4π for magnetization

Spin magnetization *S* is the only observable quantity.

There is no magnetic charges and currents.

Spin nonconservation makes theory highly sophisticated, cf. AHE

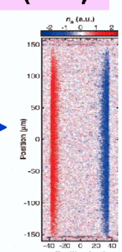


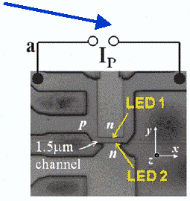
Observing S_x: Kato et al. (2004), Silov et al. (2004), Ganichev et al. (2004)

Observing S_z by optical techniques:

in *n*-GaAs by Kerr rotation (Kato et al. 2004)

in *p*-GaAs by polarized emission (Wunderlich et al. 2005)

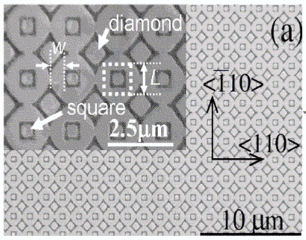


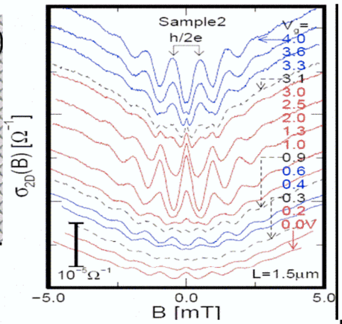


All these observations: generating spin magnetization by electric current due to central symmetry violation

(irrespective of detailed mechanisms)

Spin interference in transport experiments



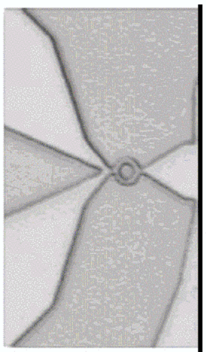


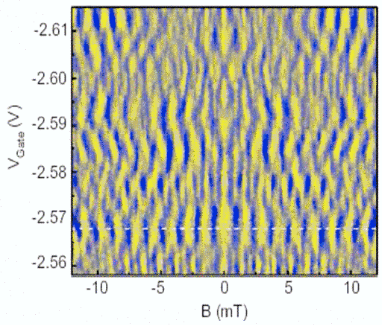
Spin interferometer with square loop array

(follow *B*=0 vertical)

InGaAs

Koga et al. (2005)





Conductance of a ring

controlled by gate voltage

(follow vertical sections)

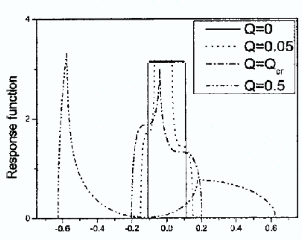
←α=0 HgTe/HgCdTe

Koenig et al. (2005)

Formalism, spatial scales, and spin currents

Two analytical models: (I) ballistic transport in rings and (ii) diffusive transport

Both result in characteristic length $\ell_\alpha = \hbar^2 / m\alpha \approx L_{\rm sd}, k_\alpha = m\alpha/\hbar^2$

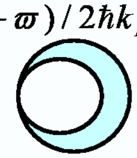


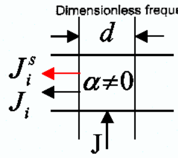
Response of $\sigma_x(\mathbf{q},\omega)$ to $\mathbf{E}(\mathbf{r},t) = E\exp[i(\mathbf{qr}-\omega t)]$

$Q = q/2k_\alpha, \varpi = 2v_F k_\alpha, \Omega = m(\omega-\varpi)/2\hbar k_F k_\alpha$

Response diverges for $q \to 2k_\alpha$

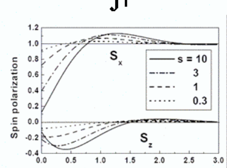
(breakdown when two Fermi surfaces touch)





$\alpha \neq 0$ island as spin emitter into $\alpha = 0$ leads; maximum effect at $d \approx \ell_\alpha$

Such spin currents are well defined because they are conserved in α=0 regions



Spin currents in $\alpha \neq 0$ regions

$j_i^l = \frac{1}{2}\langle \sigma_l v_i + v_i \sigma_l \rangle$ or $j_i^l = \langle \frac{d}{dt}\sigma_l x_i \rangle$

A beautiful playground for different SO coupling mechanisms, but they physical meaning and relation to spin accumulation remain obscure yet

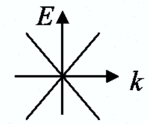
In systems with $j_i^z = 0$, $S_z \neq 0$ develops when spin leak at or across the edge

Conjecture: spin currents with $q \approx ik_\alpha$ seem more relevant than $q=0$ currents

Nontraditional systems: from graphene to metal surfaces

Dispersion law and magnetic quantization in graphene:

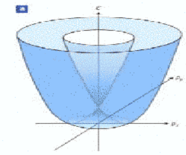
$$E(k)=\hbar v_F k,\ E_n=\mathrm{sign}\{n\}\sqrt{2\hbar v_F^2 B|n|/c},\ -\infty<n<\infty$$



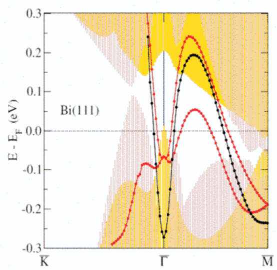
Magnetic quantization with *k*-linear SO term:

$$E_0=\hbar\omega_c\delta,\ E_n^{\pm}=\hbar\omega_c(n\pm\sqrt{\delta^2+2(k_\alpha\ell_B)^2 n}),\ n\leq 1$$

$$\omega_c=eB/\hbar c,\ \delta=(1-gm/2m_0)/2,\ k_\alpha=m\alpha/\hbar^2,\ \ell_B^2=c\hbar/eB$$

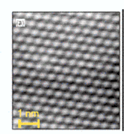


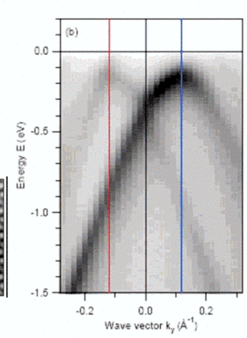
Giant SO coupling near surfaces of semimetals and metals



Surface states Bi (111)
Black: without SO coupling
Red: with SO coupling
Koroteev et al. (2004)

Bi/Ag(111) monolayer alloy





Large SO results in ultra-short spin precession lengths

Conclusions:

1. Effect of SO on energy spectrum
2. Ideas underlying SO devices,
3. EDSR in 2D,
4. Electrical generation of spin populations,
5. Discovery of spin interference,
6. Theory: status, characteristic scales, challenges,
7. Nontraditional systems and surfaces