Spin Hall effect

Egy kis spintronika

Spin-pálya kölcsönhatás
Miért nem szeretjük a spin-pálya kölcsönhatást?
Miért szeretjük mégis?
A spin-injektálás buktatói

Spin Hall effect: a kezdetek

Dyakonov – Perel 1971
Hirsch 1999
SOI és aszimmetrikus szórás: skew scattering, side jump
Extrinsic vs. intrinsic origin
Méréstechnikai buktatók

Spin Hall effect: kísérleti igazolás

Optika: Awschalom 2004, Wunderlich 2005
Nem-lokális transzport: Valenzuela & Tinkham 2006

Spin Hall effect: elméleti kitekintés

SHE, AHE, OHE...

Spin mágneses térben (Zeeman effektus)

Spin operátor $$\mathbf{S} = \frac{1}{2}\boldsymbol{\sigma}$$

Pauli mátrixok $$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Mágneses momentum $$\boldsymbol{\mu} = -\frac{1}{2} g \mu_{\mathrm{B}} \boldsymbol{\sigma}$$

$$\mu_{\mathrm{B}} = |e|\hbar/2m_{\mathrm{e}}$$

$$g = 2.0023$$

A spinre ható forgatónyomaték
homogén mágneses térben $$\mathbf{M} = \boldsymbol{\mu} \times \mathbf{B}$$

Hamilton operátor $$H = -\boldsymbol{\mu}\mathbf{B} = \frac{1}{2} g \mu_{\mathrm{B}} \boldsymbol{\sigma}\mathbf{B}$$

Energia sajátértékek $$\boxed{E_{\pm} = \pm\frac{1}{2} g \mu_{\mathrm{B}} B}$$

Zeeman felhasadás

Spin elektromos térben (Spin-pálya kölcsönhatás)

Külső elektromos térben mozgó elektron a vele mozgó vonatkoztatási rendszerben egy mágneses teret is érez (Lorentz trf.):

$$\mathbf{B}' = -\frac{1}{c^2}\mathbf{v}\times\mathbf{E}$$

A mágneses momentum v/c rendben nem változik.

Naivan: $$H'_{SO} = g\mu_\mathrm{B}\mathbf{B}'\mathbf{S}' = -g\mu_\mathrm{B}\frac{1}{c^2}(\mathbf{v}\times\mathbf{E})\,\mathbf{S} = H_\mathrm{SO}$$

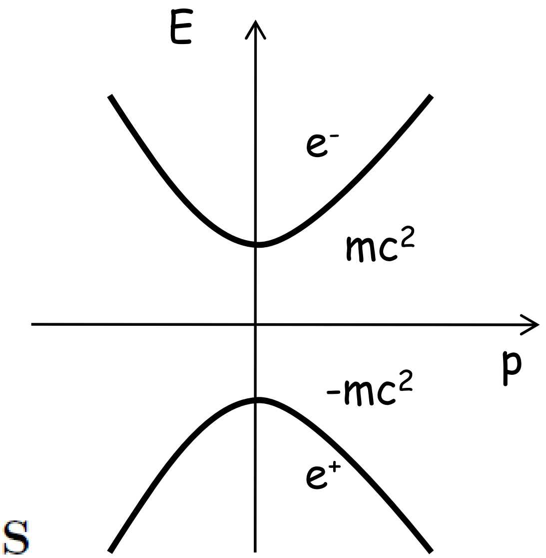
Precízebben: Dirac egyenlet nem-relativisztikus sorfejtésével

$$\begin{pmatrix} E-mc^2 & -c\boldsymbol{\sigma\pi} \\ -c\boldsymbol{\sigma\pi} & E+mc^2 \end{pmatrix}\boldsymbol{\Psi} = 0 \qquad E = \pm\sqrt{c^2p^2+m^2c^4}$$

$$\boxed{H = mc^2 + V + \frac{p^2}{2m} - \frac{p^4}{8m^3c^2} - \frac{\hbar e}{4mc^2}(\boldsymbol{\sigma p E}) + \frac{\hbar^2}{8m^2c^2}\triangle V}$$

Spin-pálya

$$H_\mathrm{SO} = -\frac{g\mu_\mathrm{B}}{2}\frac{1}{c^2}(\mathbf{v}\times\mathbf{E})\,\mathbf{S} = \frac{g\hbar}{4c^2m_\mathrm{e}^2}(\nabla V(\mathbf{r})\times\mathbf{p})\,\mathbf{S}$$



Erős félvezetős analógia!

SOI hatása a sávszerkezetre

- Nehezebb elemek – erősebb gradiens az atomi potenciálokban – erősebb SOI
  kristályokban is igaz (Si < Ge < GaAs)

- SOI csökkenti a szimmetriát – további degenerációk oldódnak fel (SO split-off band)

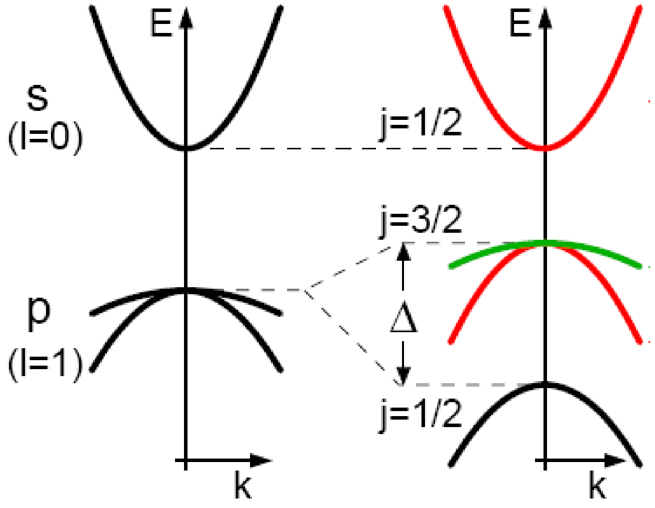
Inverziós szimmetria
Időtükrözési szimmetria } $\mathbf{k} \rightarrow -\mathbf{k}$ $S_z \rightarrow -S_z$ $E_{\uparrow}(\mathbf{k}) = E_{\downarrow}(\mathbf{k})$

inverzió szimmetria nélküli zinc blende félvezetők (GaAs, InAs, InSb):

Bulk Inversion Asymmetry Dresselhaus SOI $E_{+}(\mathbf{k}) = E_{-}(-\mathbf{k})$

2DEG aszimmetrikus kvantumgödörben:
Structure Inversion Asymmetry, Rashba SOI

„beépített" elektromos tér a háromszög potenciál miatt, hasonlóan mint a Datta-Das tranzisztornál



Spin-orbit interaction in 2DEGs

$$H = H_0 + \alpha_{\mathrm{R}}(\sigma_x k_y - \sigma_y k_x) + \beta_{\mathrm{D}}(\sigma_x k_x - \sigma_y k_y)$$

SIA

BIA

$$\alpha_{\mathrm{R}} = \alpha \langle E_z \rangle,$$

$$\beta_{\mathrm{D}} = \beta \langle k_z^2 \rangle$$

Built in and external electric fields

Band structure and QW width

k-dependent spin-orbit induced magnetic field:

$$\mathbf{B}_{\mathrm{SO}}(\mathbf{k}) = \frac{2}{g\mu_{\mathrm{B}}} \begin{pmatrix} \alpha_{\mathrm{R}} k_y + \beta_{\mathrm{D}} k_x \\ -\alpha_{\mathrm{R}} k_x - \beta_{\mathrm{D}} k_y \\ 0 \end{pmatrix}$$

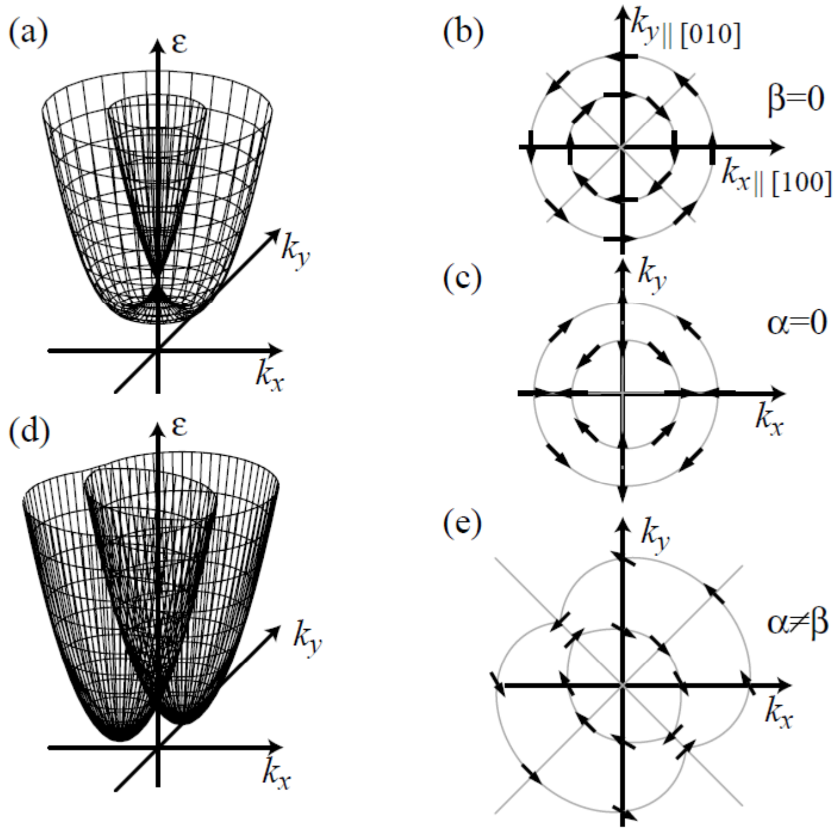
$$g\mu_{\mathrm{B}} \mathbf{B}_{\mathrm{SO}}(\mathbf{k}) \boldsymbol{\sigma} / 2.$$

$$E_{\pm} = \frac{\hbar^2 k_{\|}^2}{2m^\star} \pm \alpha_{\mathrm{R}} k_{\|} \qquad k_{\|} = \sqrt{k_x^2 + k_y^2}.$$

Parabolae shifted in **k** by $\pm m^\star \alpha_{\mathrm{R}} / \hbar^2.$

Same for the Dresselhaus term

$$\frac{\Delta E_{\mathrm{SO}}}{E_{\mathrm{F}}} = \frac{4\alpha_{\mathrm{R/D}} m^\star}{\hbar^2 k_{\mathrm{F}}}$$



Spin-pálya kölcsönhatás (SOI) vs. Spintronika

Miért nem szeretjük?

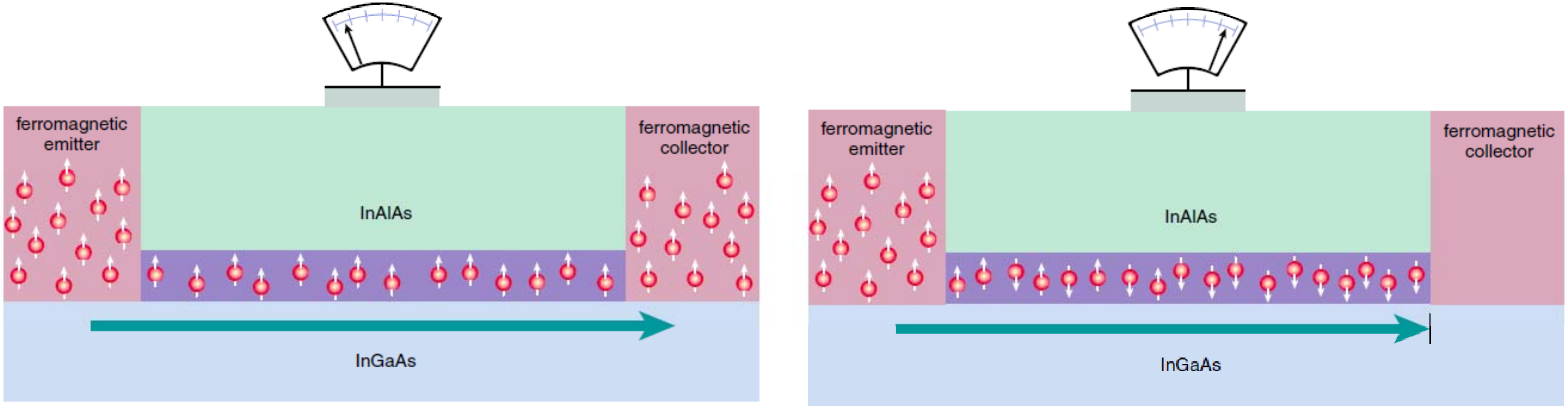
Preferált spin irányok minden egyes **k** irányhoz → a momentum szórások spin szórással járnak együtt → gyors spinrelaxáció (információ vesztés)

Miért szeretjük mégis?

Alacsonyabb dimenziókban a **k** -tér erősen redukált → a momentum szórások kisebb hányada jár spin szórással → hosszabb spinrelaxációs idők

A spin csatolódik a töltéshez és a momentumhoz → spin manipuláció mágneses tér nélkül, tisztán kapufeszültségekkel! – gyors, leskálázható

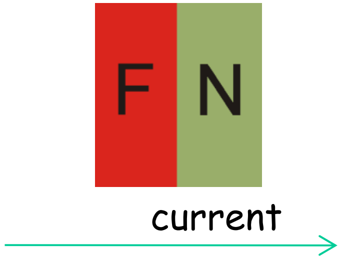
Datta-Das transistor



S. Datta and B. Das, APL **56**, 665 (1990).

Spin injection and detection

FM-NM interface

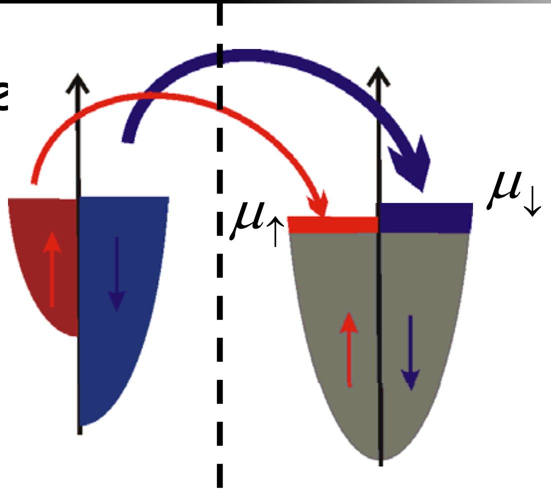


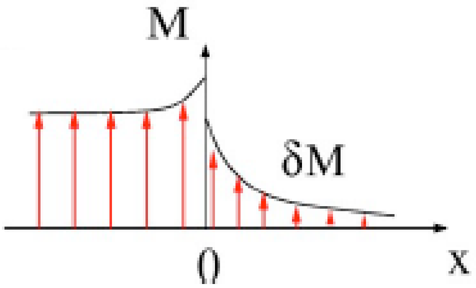
Proper handling is the Valet-Fert model, i. e. Boltzmann equation for two subbands

very low efficiency for semiconductors

$$\boxed{\frac{\beta^2}{1-\beta^2}\,\frac{\lambda_{\mathrm{fm}}^2}{\sigma_{\mathrm{fm}}^2}\,\frac{\sigma_{\mathrm{sc}}^2}{x_0^2}\,\frac{4}{\left(2\frac{\lambda_{\mathrm{fm}}\sigma_{\mathrm{sc}}}{x_0\sigma_{\mathrm{fm}}}+1\right)^2-\beta^2}}$$

G. Schmidt *et al.*, PRB **62**, R4790 (2000).





interface spin loss

$\delta_{F/N}$

spin imbalance of the current results in a different chemical potential for the two subbands, which decays in bulk

This is detected in the GMR experiment

diffusive spin transport

associated lifetime t_s and length scale l_s

$\ell_S = \sqrt{D\tau_S}$ with $\tau_m << \tau_S$

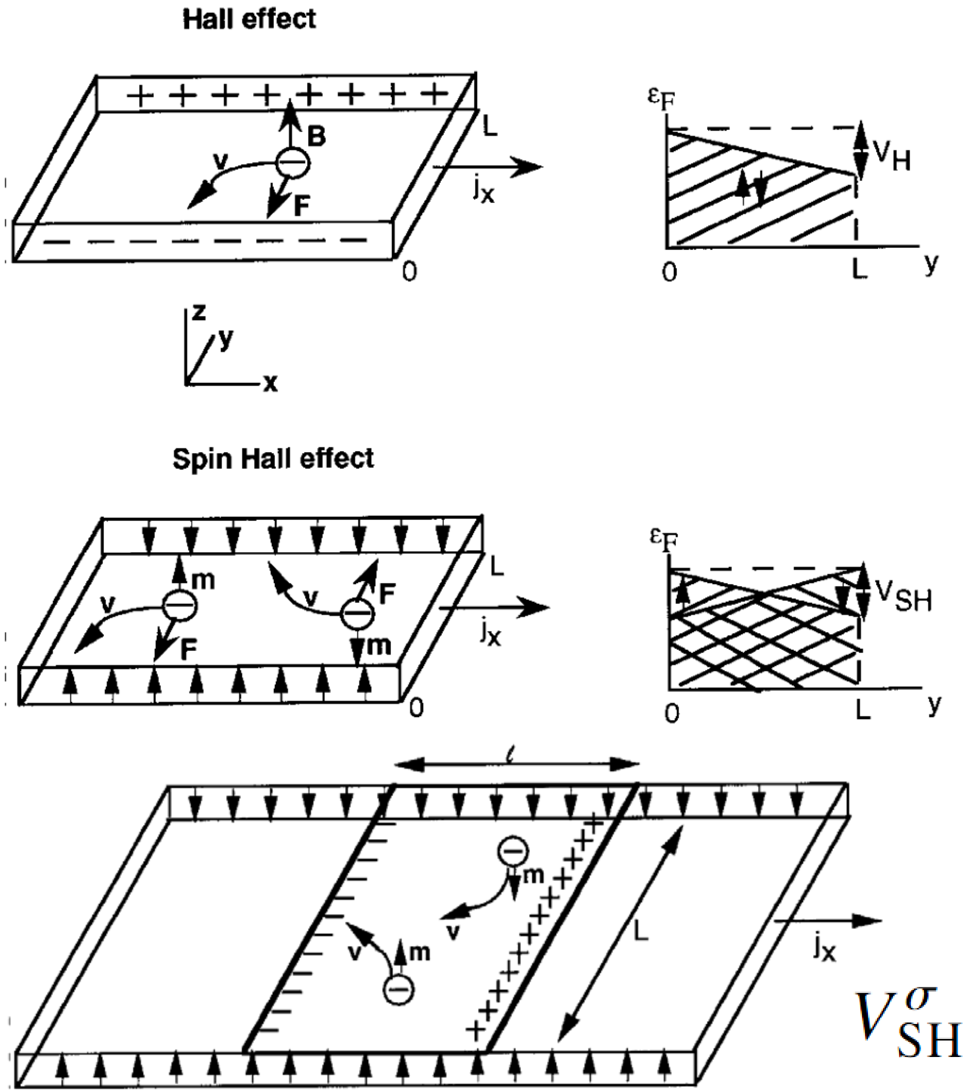
$$D = \frac{1}{3} v_F l_m$$

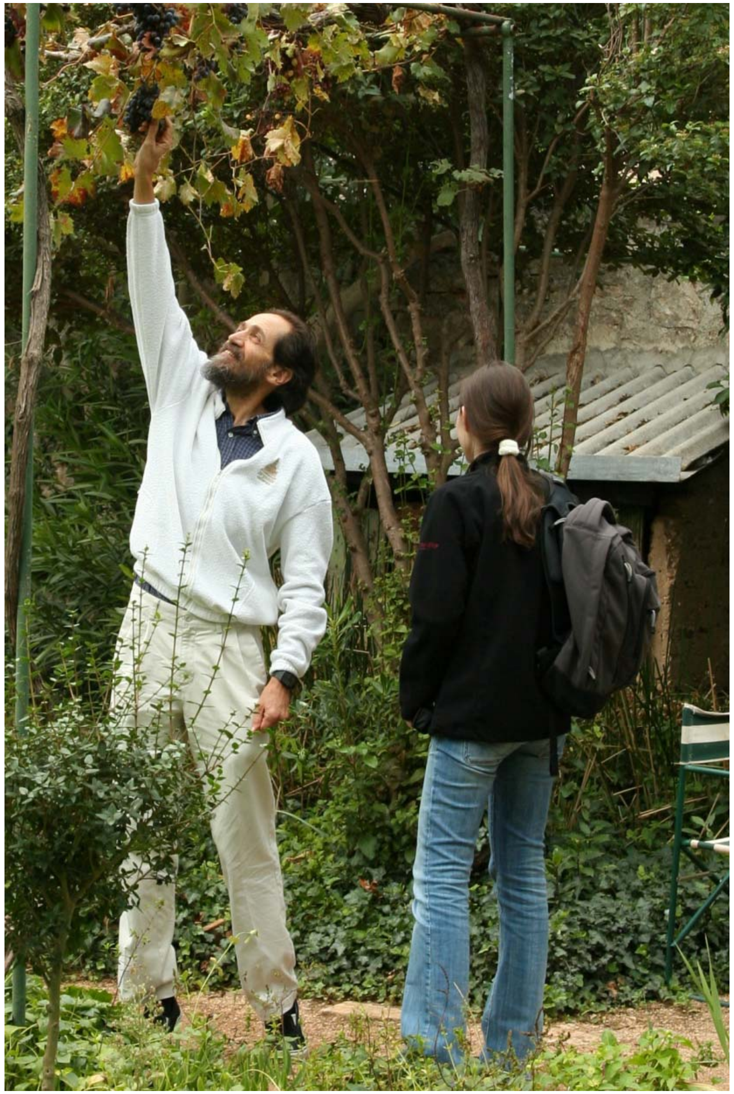
J. Bass and W. P. Pratt Jr, J. Phys.: Condens. Matter 19, 183201 (2007)

Spin Hall effect: J. E. Hirsch, 1999

M. I. Dyakonov and V. I. Perel, Phys. Lett. **35A**, 459 (1971).

J. E. Hirsch, PRL **83**, 1834 (1999).



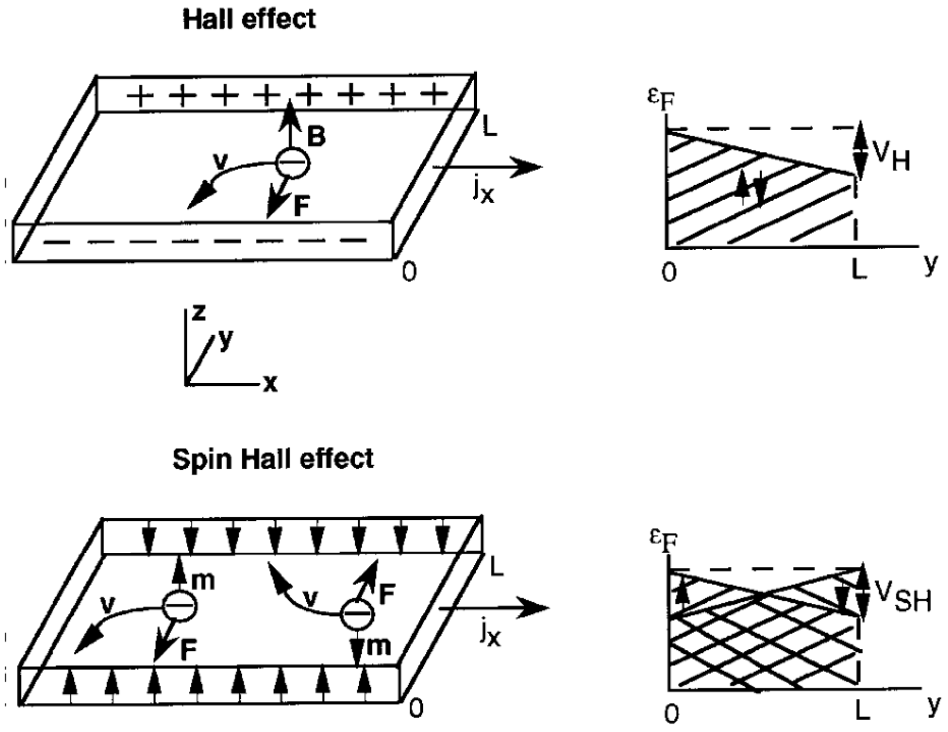


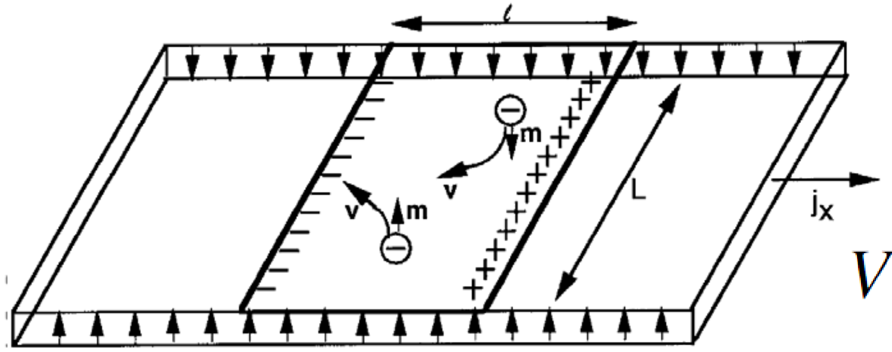
$$V^{\sigma}_{\mathrm{SH}} = 4\pi R_s l j_\sigma n_\sigma \mu_B$$ ~50 nV

Spin Hall effect: J. E. Hirsch, 1999

M. I. Dyakonov and V. I. Perel, Phys. Lett. **35A**, 459 (1971).

J. E. Hirsch, PRL **83**, 1834 (1999).





Kísérleti nehézségek

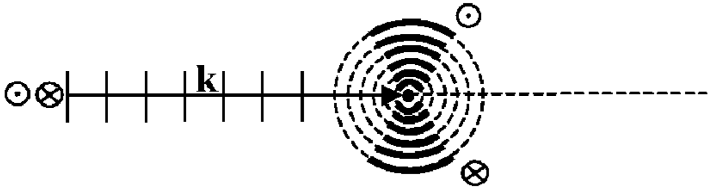
- Áram mágneses tere
- FM elektródák anizotróp mágneses ellenállása
- Hagyományos Hall effektus, AHE

$$V_{\mathrm{SH}}^{\sigma} = 4\pi R_s l j_\sigma n_\sigma \mu_B$$ ~50 nV

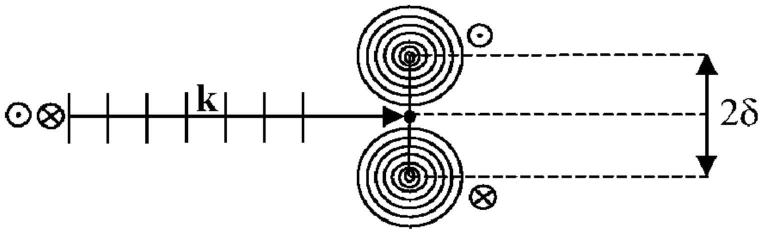
Spin Hall effect: SOI and asymmetric spin scattering

A. Crépieux and P. Bruno, PRB **64**, 014416 (2001).

Skew scattering



Side-jump



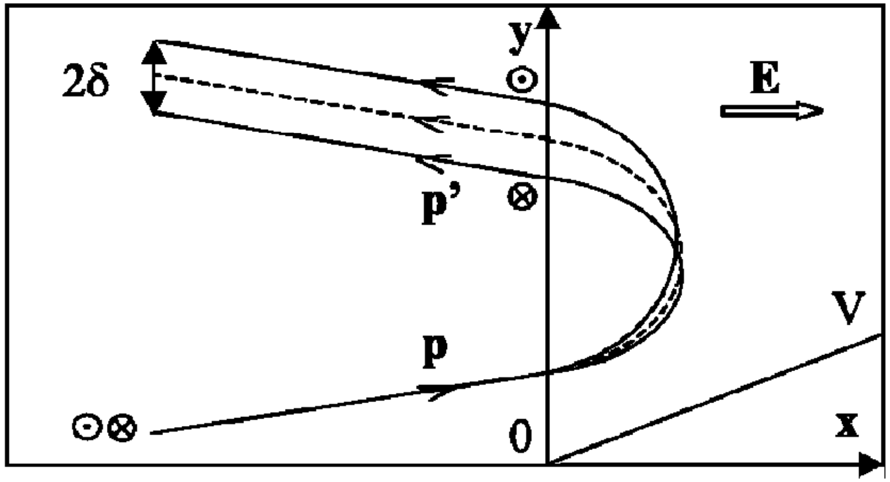
Kvázi-klasszikus magyarázat

$$H=\frac{p^2}{2m}-\mu_B(\boldsymbol{\sigma}\cdot\mathbf{B}_{\text{eff}})+V+\frac{\hbar}{4m^2c^2}(\boldsymbol{\sigma}\times\boldsymbol{\nabla}V)\cdot\mathbf{p}$$

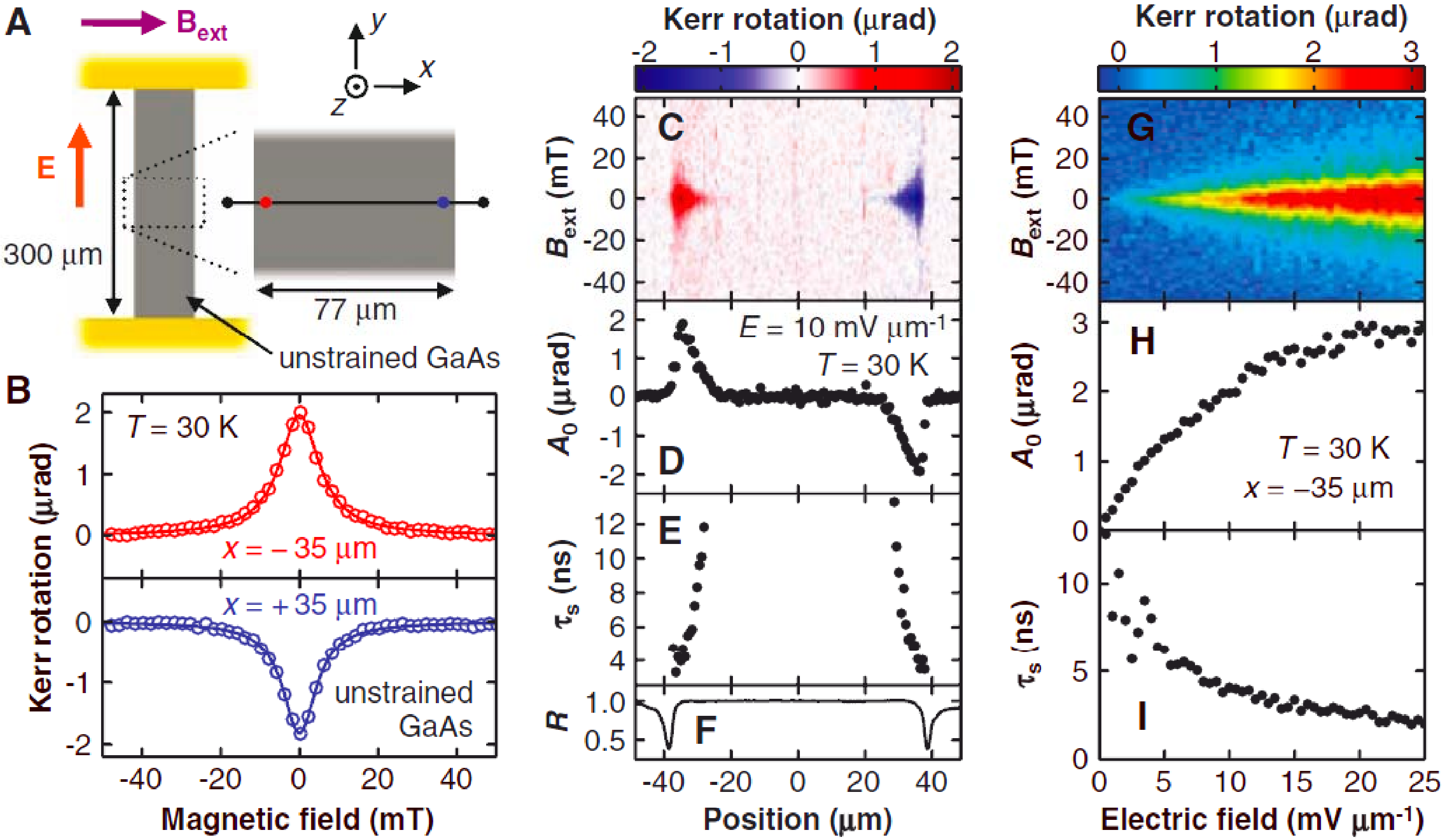
$$\mathbf{v}=\frac{\partial H}{\partial\mathbf{p}}=\frac{\mathbf{p}}{m}-\frac{e\hbar}{4m^2c^2}(\boldsymbol{\sigma}\times\mathbf{E})$$

$$\boldsymbol{\delta}=\int_{-\infty}^{+\infty}\mathbf{v}_a\,dt=-\int_{-\infty}^{+\infty}\frac{e\hbar}{4m^2c^2}(\boldsymbol{\sigma}\times\mathbf{E})\,dt$$

$$\boldsymbol{\delta}=-\frac{\hbar\boldsymbol{\sigma}}{4m^2c^2}\times\int_{-\infty}^{+\infty}d\mathbf{p}=\frac{\lambda^2\boldsymbol{\sigma}}{4\hbar}\times(\mathbf{p}-\mathbf{p}')$$

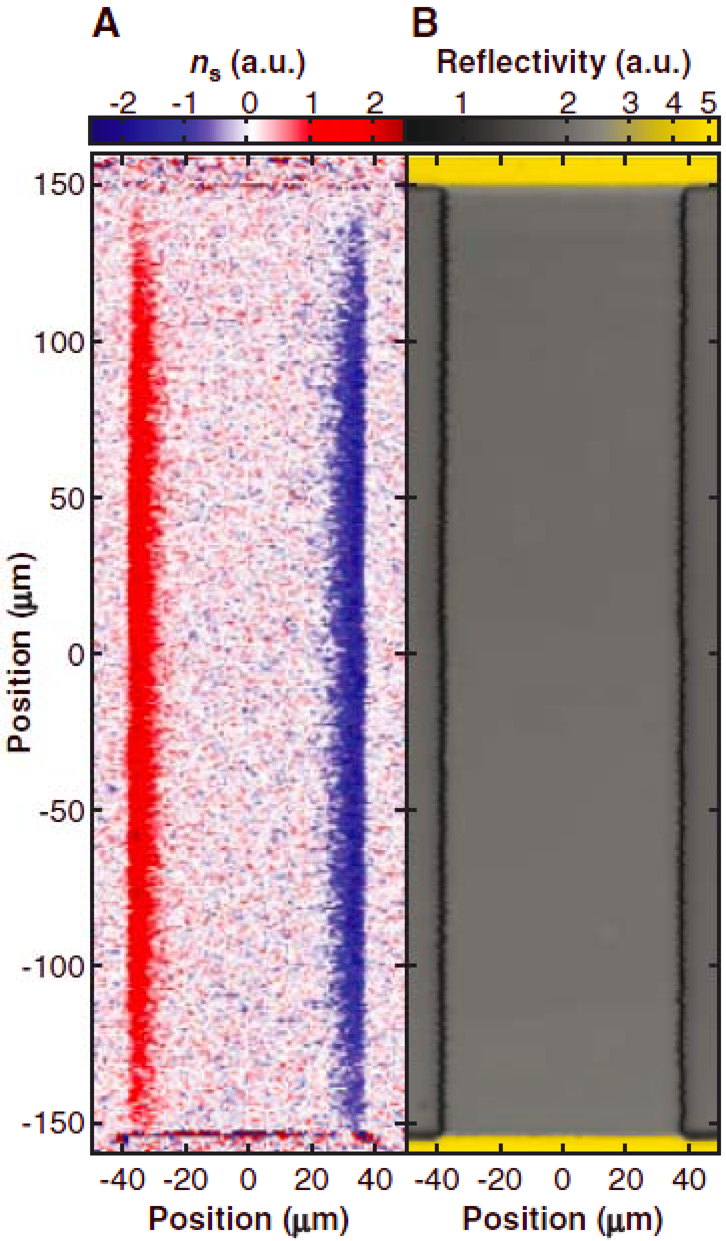


Spin Hall effect: experimental evidence 1



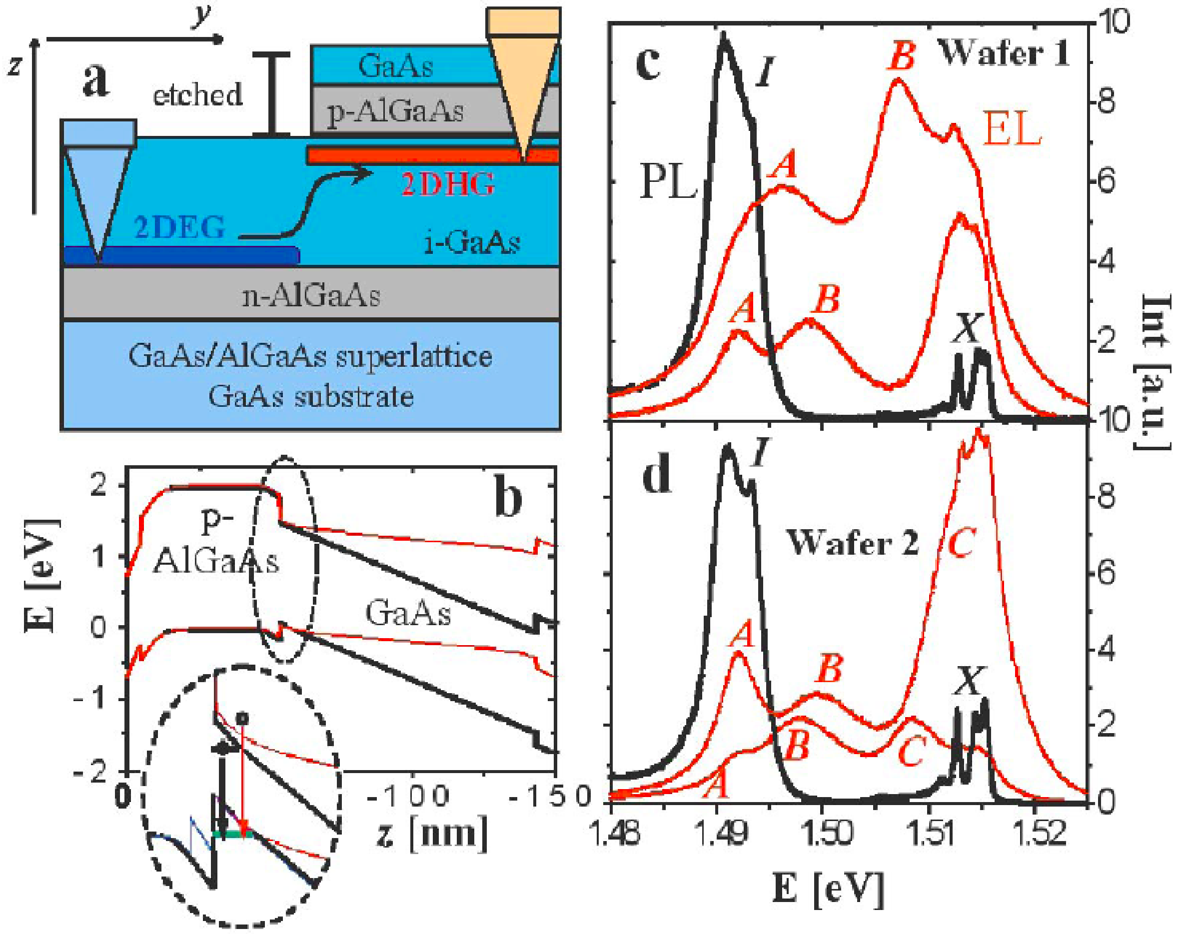
Y. K. Kato *et al.*, Science **306**, 1910 (2004).

Spin Hall effect: experimental evidence 1



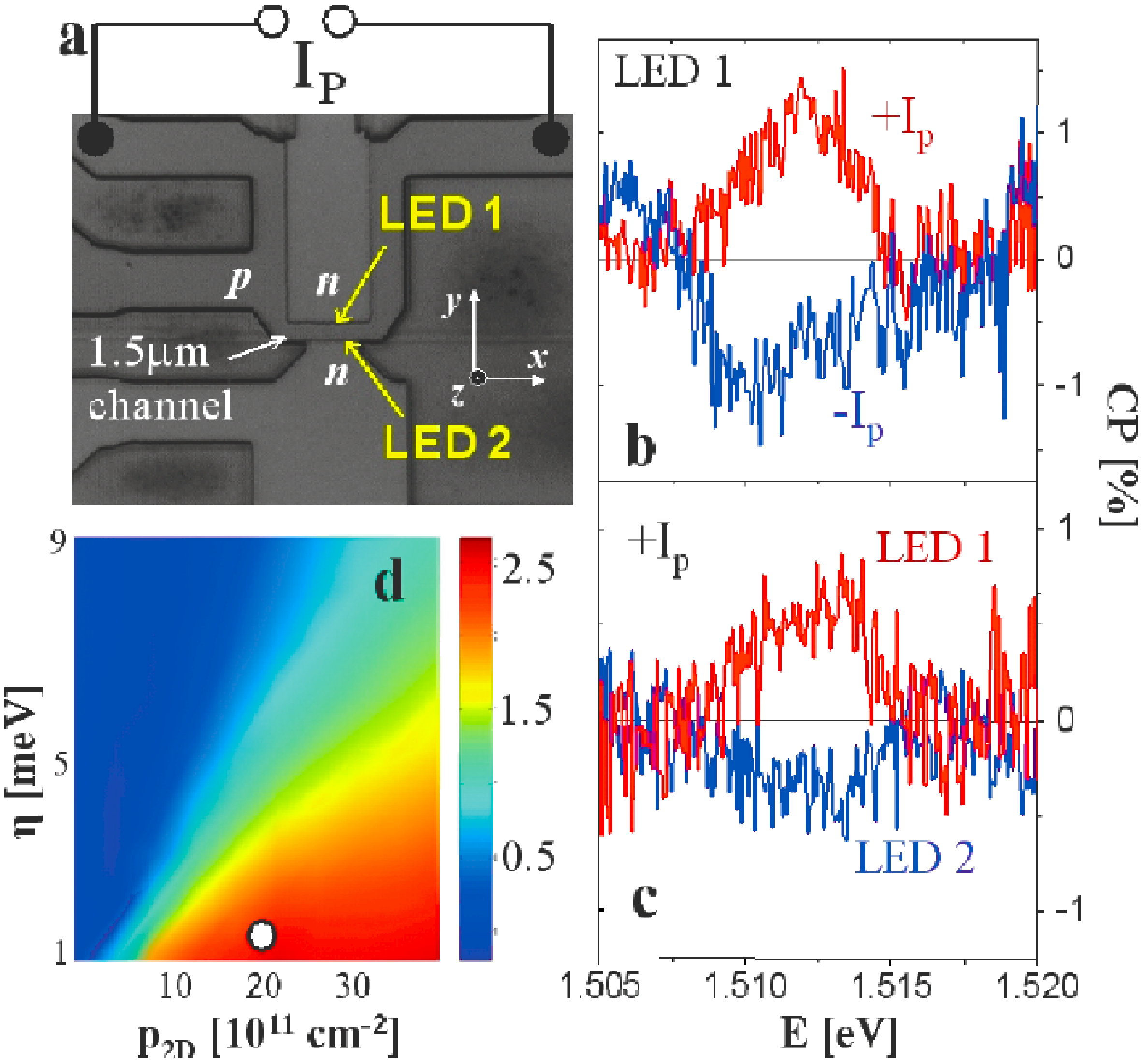
Y. K. Kato *et al.*, Science **306**, 1910 (2004).

Spin Hall effect: experimental evidence 2



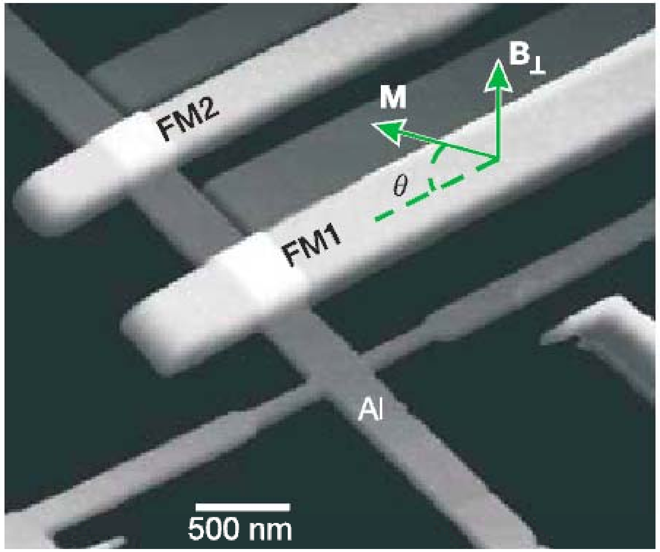
J. Wunderlich *et al.*, PRL **94**, 047204 (2005).

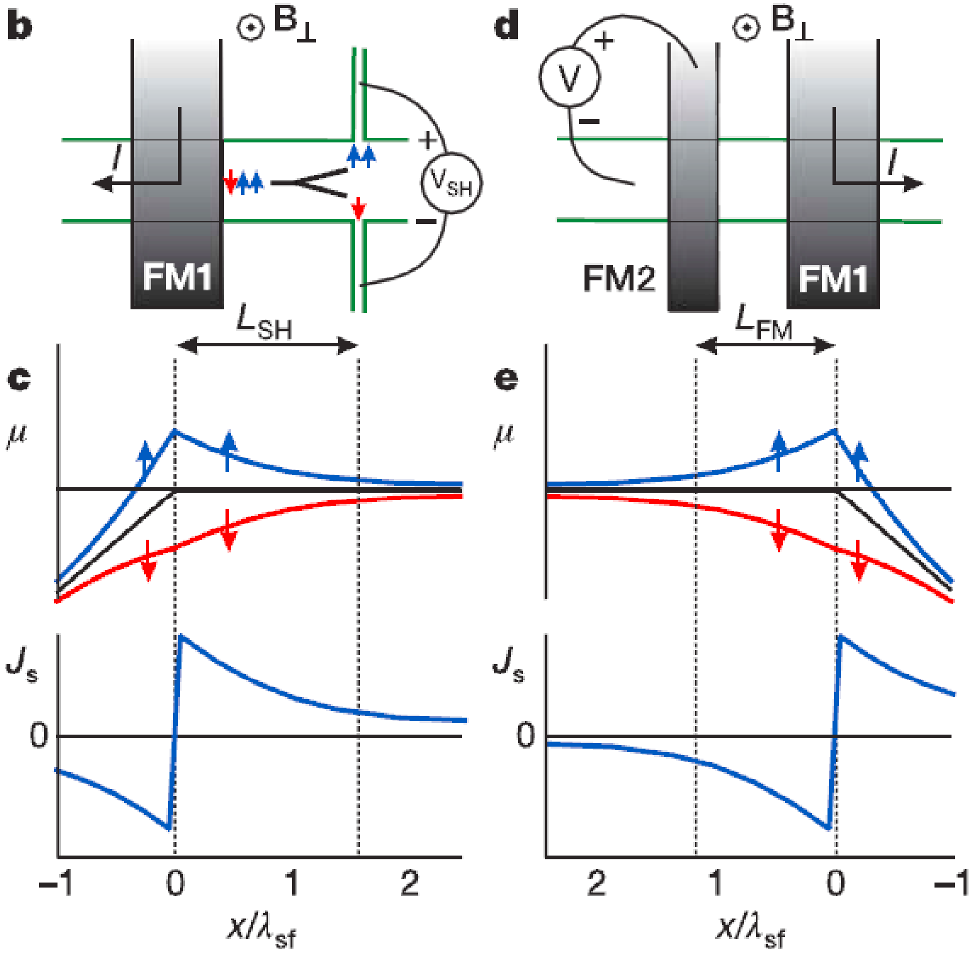
Spin Hall effect: experimental evidence 2



J. Wunderlich *et al.*, PRL **94**, 047204 (2005).

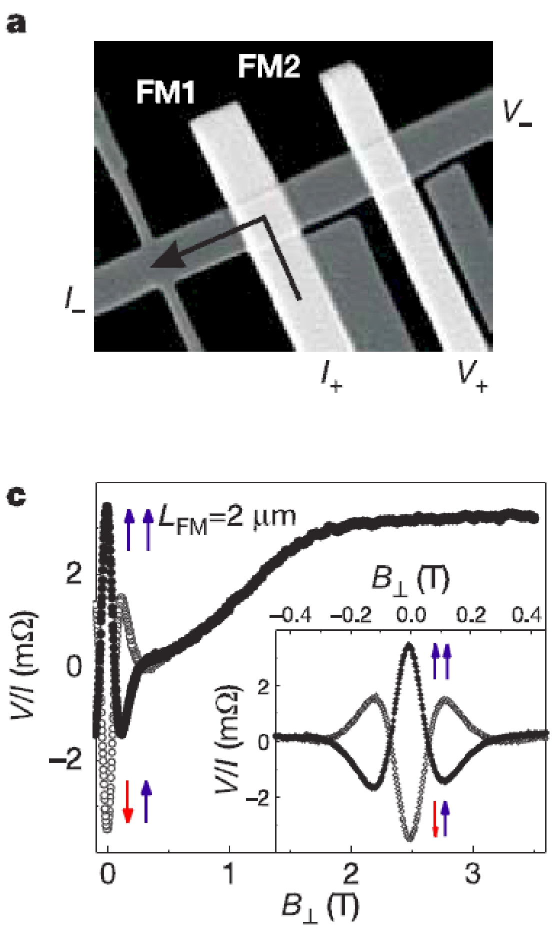
Spin Hall effect: experimental evidence 3

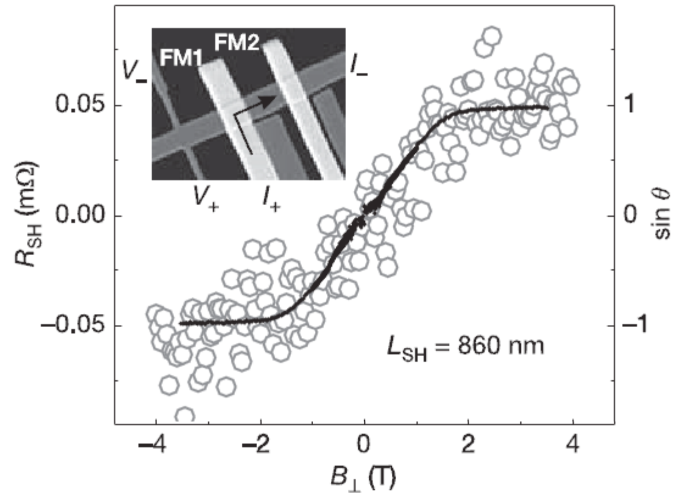


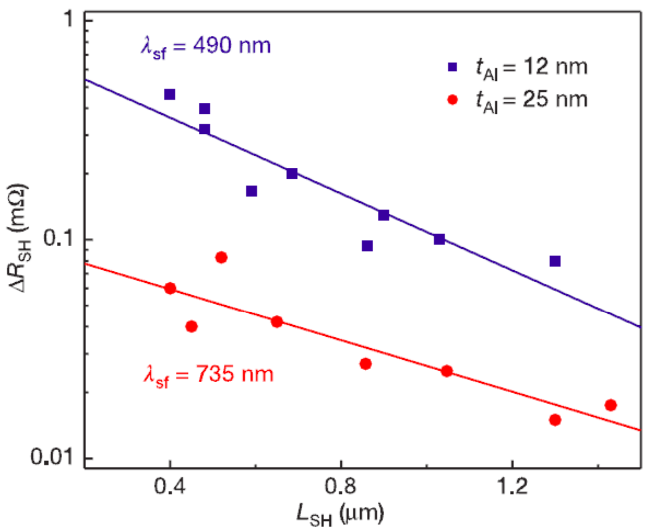


S. O. Valenzuela and M. Tinkham, Nature **442**, 176 (2006).

Spin Hall effect: experimental evidence 3

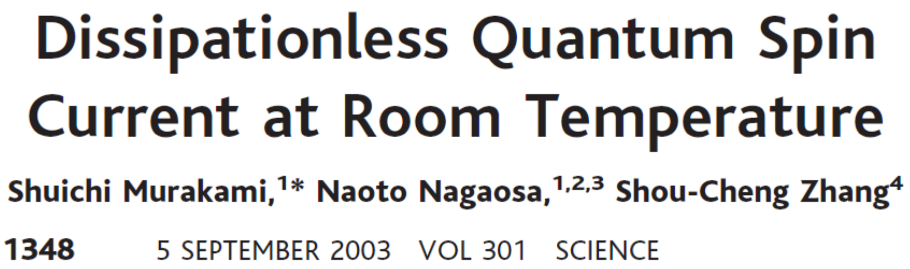






S. O. Valenzuela and M. Tinkham, Nature **442**, 176 (2006).

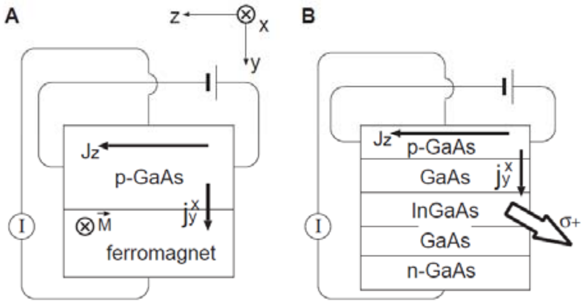
Spin Hall effect: theory outlook



Dissipationless Quantum Spin Current at Room Temperature

Shuichi Murakami,[1*] Naoto Nagaosa,[1,2,3] Shou-Cheng Zhang[4]

1348 5 SEPTEMBER 2003 VOL 301 SCIENCE

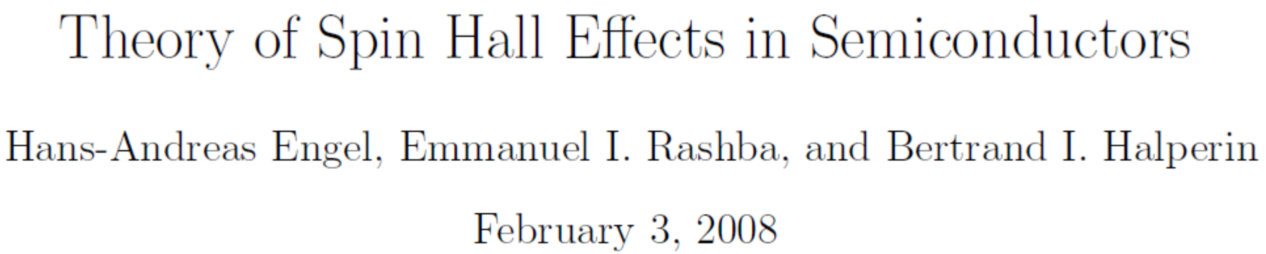


PRL **102,** 016601 (2009) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2009

Giant Orbital Hall Effect in Transition Metals: Origin of Large Spin and Anomalous Hall Effects

H. Kontani,[1] T. Tanaka,[1] D. S. Hirashima,[1] K. Yamada,[2] and J. Inoue[3]

Recent review (cond-mat):



Theory of Spin Hall Effects in Semiconductors

Hans-Andreas Engel, Emmanuel I. Rashba, and Bertrand I. Halperin

February 3, 2008