

Spin-orbit effects in low-dimensional systems

Spin-orbit interaction in semiconductor layers

- Hamiltonian:
$$H = \frac{\mathbf{p}^2}{2m^*} + V(\mathbf{r}) + H_{\text{SO}}$$

- Spin-orbit interaction:
$$H_{\text{SO}} = \mathbf{k} \mathbf{A} \boldsymbol{\sigma}$$
 Linear in an electron momentum

Effect of crystal inversion asymmetry (Dresselhaus term):

G. Dresselhaus, Phys. Rev. **100**, 580 1955.

3D
$$H_{D_3D} = \alpha_{\Gamma} \left\{ \sigma_x k_x (k_y^2 - k_z^2) + \sigma_y k_y (k_z^2 - k_x^2) + \sigma_z k_z (k_x^2 - k_y^2) \right\}$$



Strong z-confinement

2D
$$H_{D_2D} = \alpha_{\Gamma} \langle k_z^2 \rangle \left\{ \sigma_y k_y - \sigma_x k_x \right\}$$

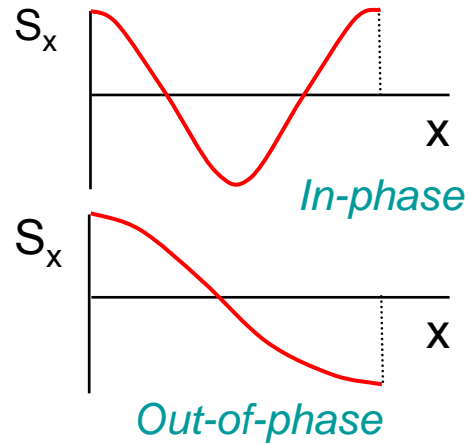
Asymmetry of confining potential (Bychkov-Rashba term), strain effects, asymmetry of heterostructure interface:

$$H_R = \eta (k_y \sigma_x - k_x \sigma_y)$$

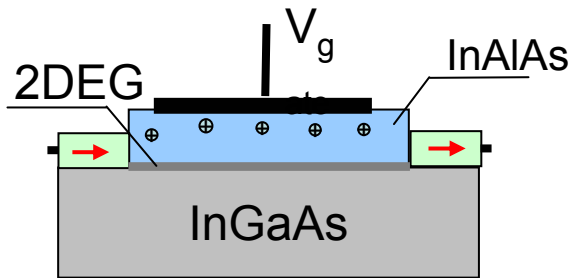
Spin precession

Ideal precession

$$H_R = \eta(k_y \sigma_x - k_x \sigma_y) \quad v_j = \frac{1}{\hbar} \frac{\partial H}{\partial k_j}$$

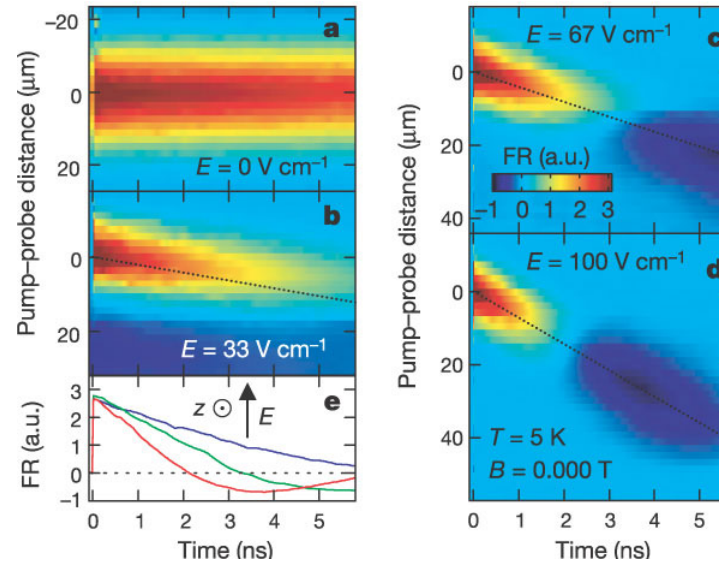


Spin-FET



S. Datta, B. Das,
Appl. Phys. Lett., **56**, 665 (1990)

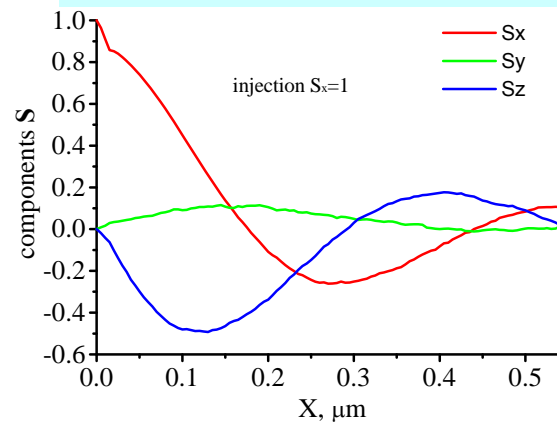
Experiment, low field, low T



Strain effect

Y. Kato, *et. al.*, *Nature* **427**, 50 (2004)

Model, high field, room T



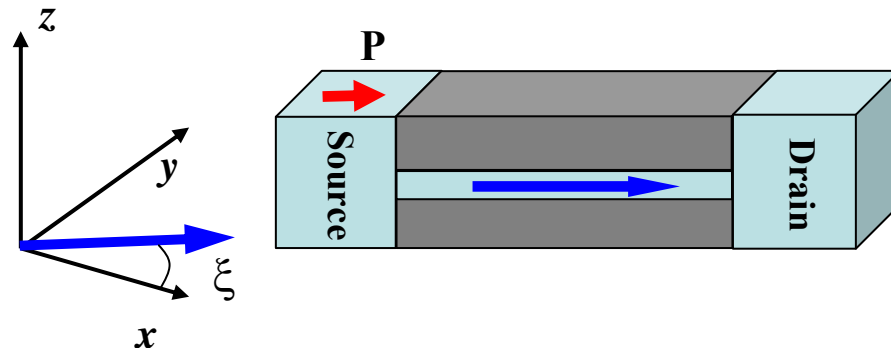
S. Saikin, *et. al.*,
J. Appl. Phys. **94**,
1769 (2003)

Anisotropy of spin scattering

Non-ballistic Spin-FET

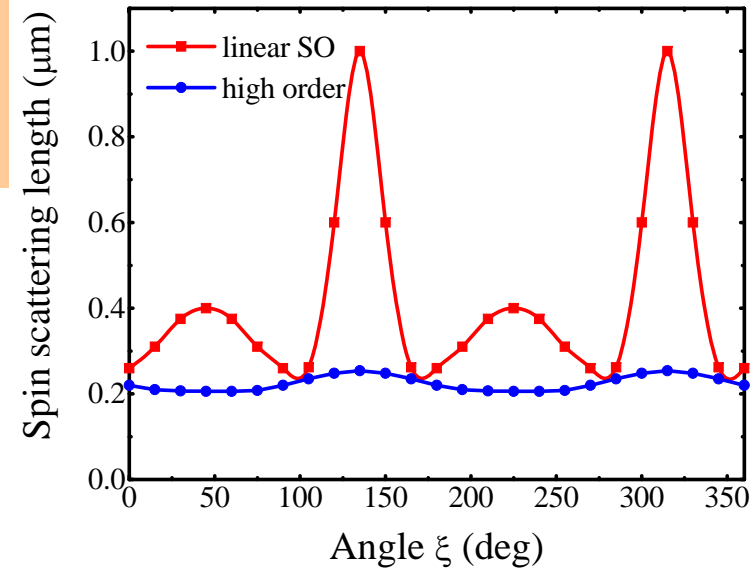
Control spin-relaxation by an electric gate:

- $V_g = 0$ spin is conserved
- $V_g \neq 0$ spin relaxes



J. Schliemann, et. al., *Phys. Rev. Lett.* **90**, 146 801, 2003.

Simulations

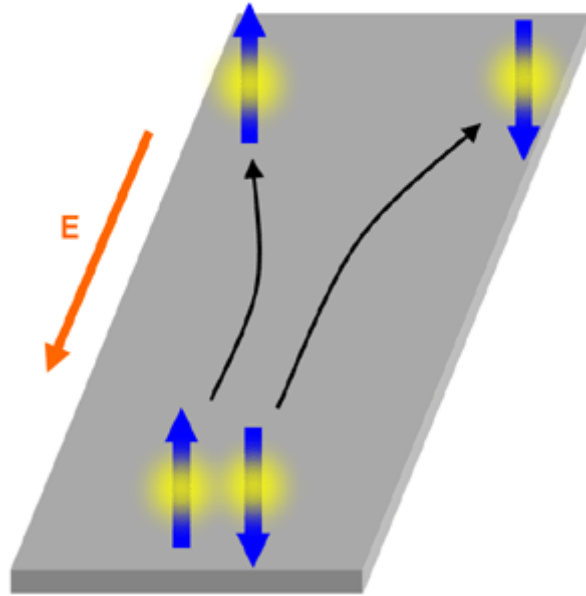


S. Saikin, et. al., *IEEE Trans. Nanotechnol.* **3**, 173 (2004)

Dresselhaus term: $H_{D_{2D}} = \alpha_{\Gamma} \langle k_z^2 \rangle ((k_y \sigma_y - k_x \sigma_x) \cos 2\xi + (k_y \sigma_x + k_x \sigma_y) \sin 2\xi)$

Bychkov-Rashba term: $H_R = \eta (k_y \sigma_x - k_x \sigma_y)$

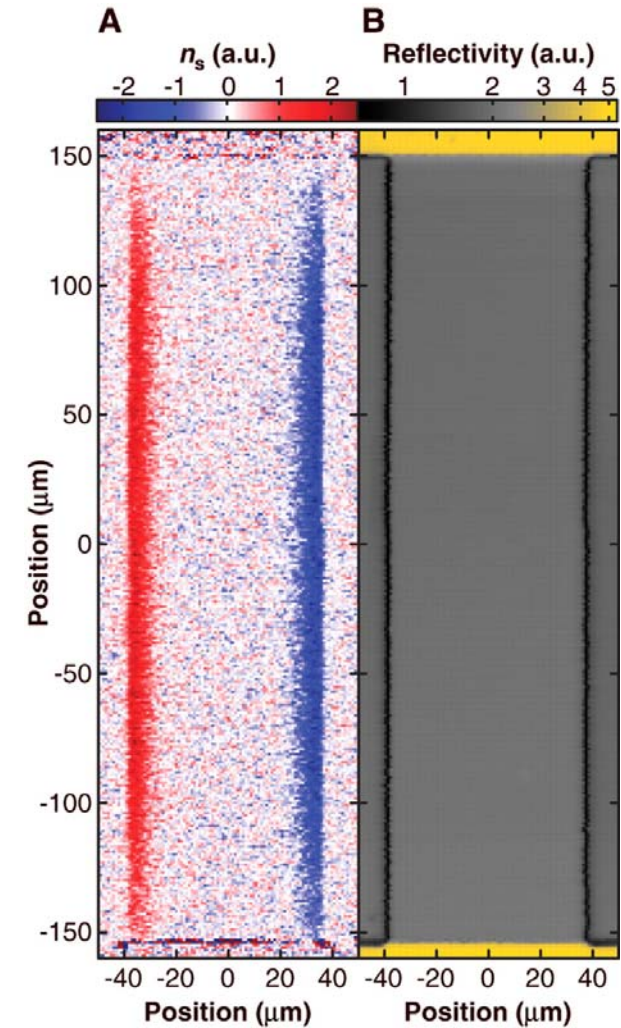
Intrinsic spin Hall effect



Spin Hall effect

Predicted:

M. I. D'yakonov and V. I. Perel', JETP Lett. **13**, 467 (1971)



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