Freie Universität Berlin

Spin Coulomb drag in presence of spin-orbit coupling

Matthias Lüffe

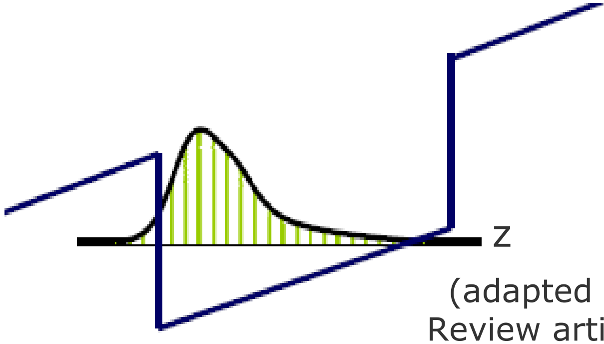
FU Berlin

Deutsche Forschungsgemeinschaft DFG

SPP 1285

Spin-orbit interactions (SOI)

In QW with structure inversion asymmetry,



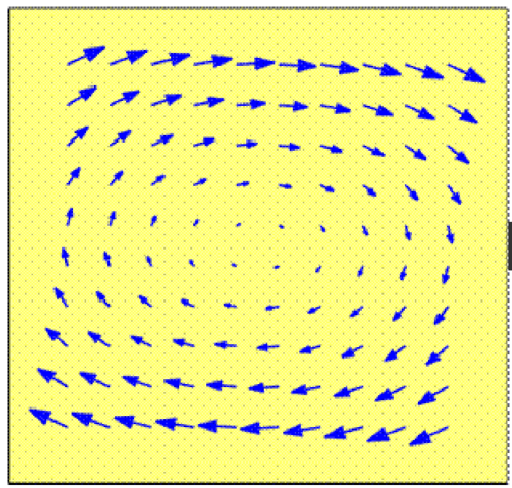
(adapted from Review article by Fabian et al.)

$$H_{SO} = \alpha(\sigma \times \mathbf{k}) \cdot \hat{\mathbf{z}} + \gamma\,(\sigma_x\, k_x - \sigma_y\, k_y)\,.$$

Written as k-dependent Zeeman field:

$$H = \frac{\mathbf{p}^2}{2m} - \frac{1}{2}\mathbf{b}(\mathbf{k}) \cdot \sigma$$

w/, e.g., $\mathbf{b}(\mathbf{k}) = \alpha(\mathbf{k} \times \hat{\mathbf{z}})$ (Rashba)



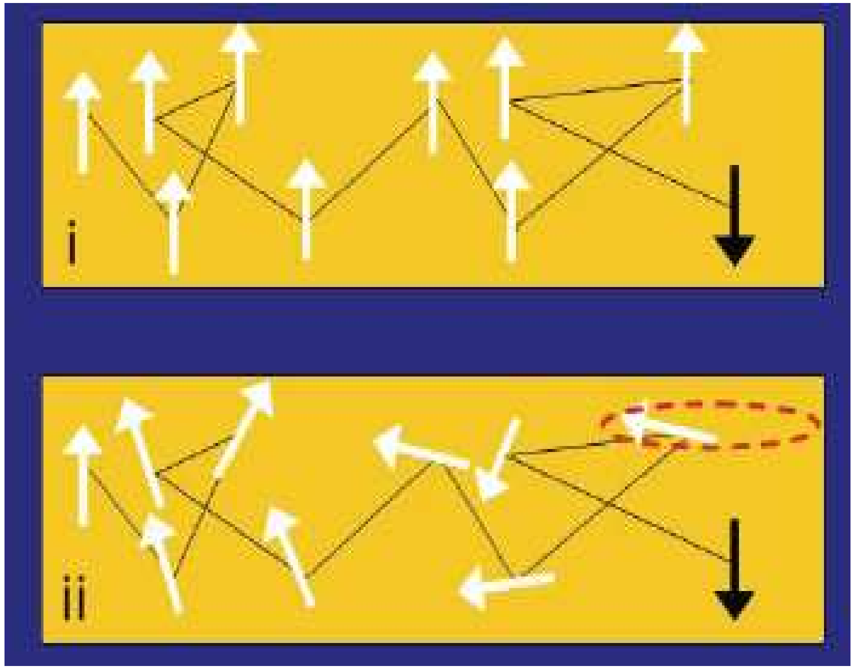
Spin relaxation

Spin relaxation due to SO-coupling+disorder:

i. Elliott-Yafet
   (silicon)

ii. Dyakonov-Perel
   (zinc-blende)

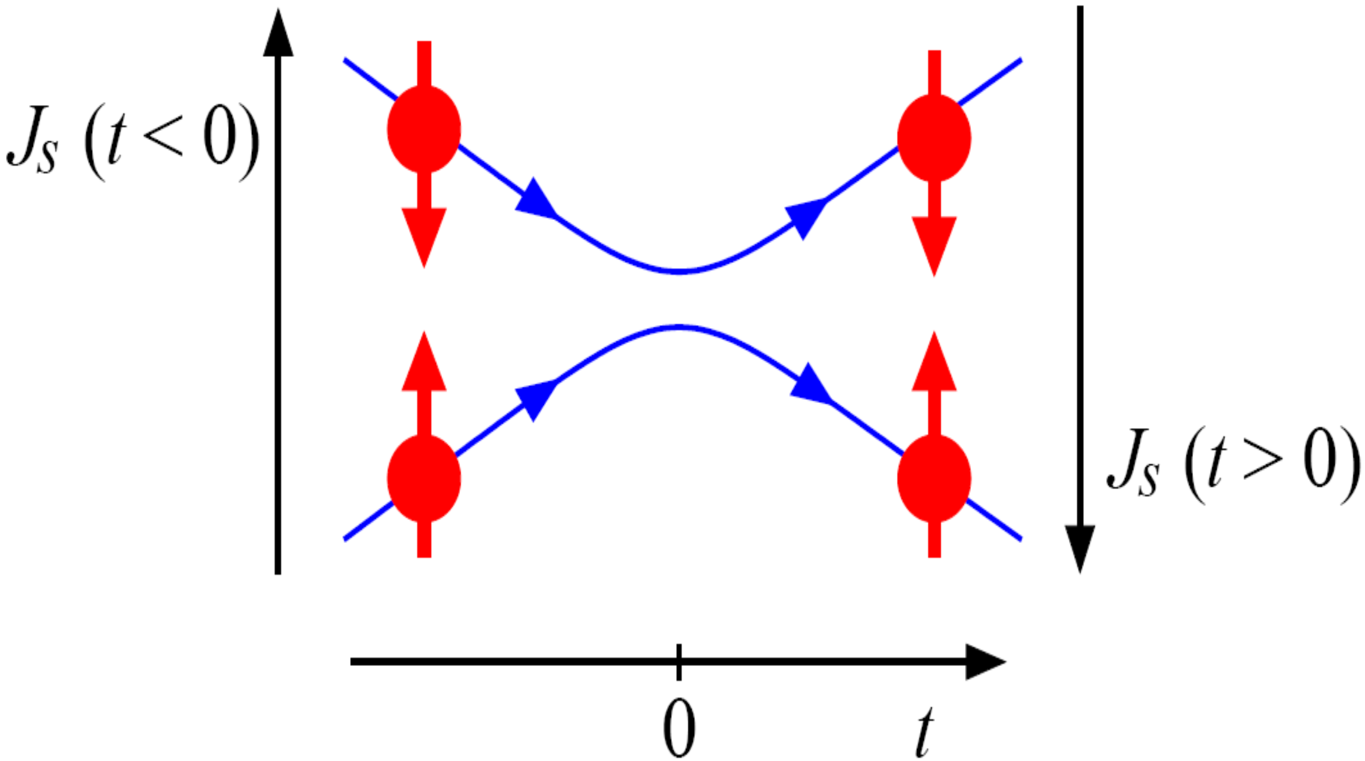
$$1/\tau_s \sim \Omega^2\,\tau$$



(reproduced from Review article by Fabian et al.)

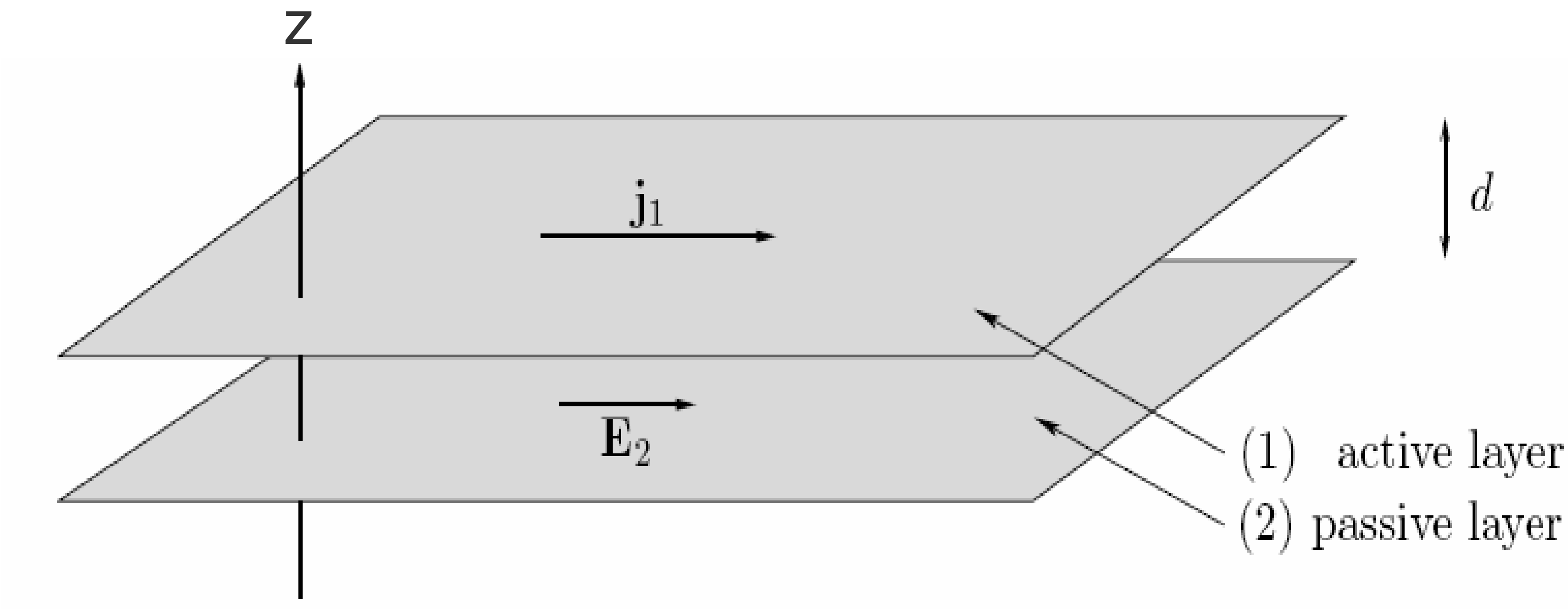
intrinsic mechanism: Spin Coulomb drag

Non-conservation of spin currents due to e-e-scattering:



(Reproduced from R. Winkler, cond-mat/0605390v1)

(charge) Coulomb drag



-Pair of parallel 2DEG´s, e.g. GaAs/AlGaAs quantum wells

-Current in layer 1 induces response in layer 2

-Transresistivity:

$$\rho_{21} = E_2/j_1; \quad j_2 = 0$$

(charge) Coulomb drag

Viable theoretical approaches:

-Boltzmann Equation

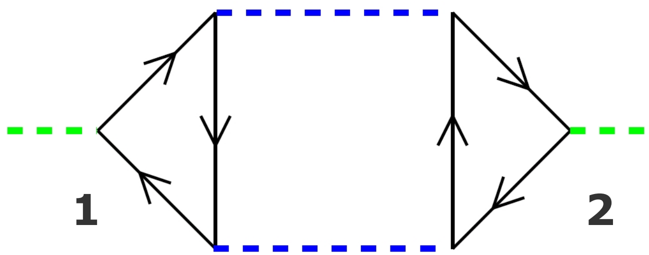
A-P. Jauho & H. Smith,
PRB 47 4420 (1993)

-Memory function formalism

L. Zheng & A.H. MacDonald,
PRB 48 8203 (1993)

-Diagrammatic Linear response theory

$$\sigma_{21} = j_2/E_1; \quad E_2 = 0$$



K. Flensberg, B. Y-K. Hu and J.M. Kinaret, PRB 52 14761 (1995);

A. Kamenev & Y. Oreg,
PRB 52 7516 (1995)

Spin Coulomb drag

Freie Universität Berlin

D´Amico & Vignale, PRB 62 4853 (2001):

“Spin Coulomb drag“ (SCD)

$$\rho_{\uparrow\downarrow} = E_{\uparrow}/J_{\downarrow};\ J_{\uparrow} = 0$$

[See also: Flensberg et al., PRB 64 245308 (2001)]

Same principle as in charge Coulomb drag, BUT:

- Only one layer
- SOI *should* be part of the unperturbed problem

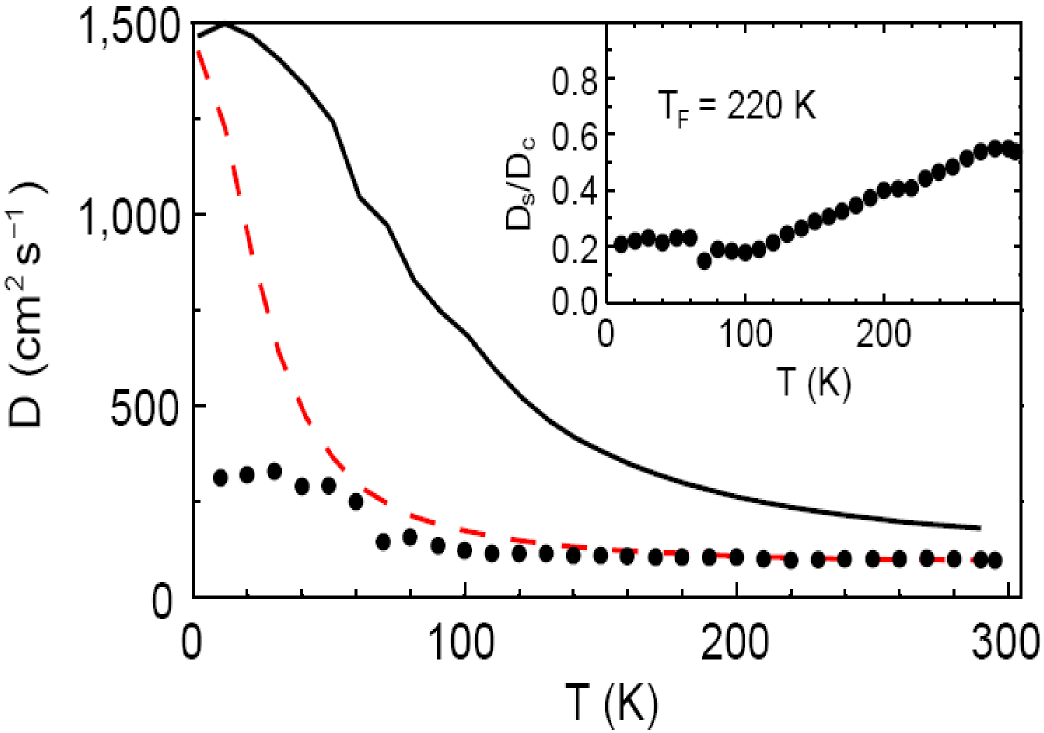
Spin Coulomb drag

Freie Universität Berlin

-SCD causes reduction of the spin diffusion coefficient (w/ respect to the charge diffusion coefficient) by a factor:

$$\frac{1}{1+\frac{|\rho_{\uparrow\downarrow}|}{\rho}}$$

-verified in spin-grating experiment, Weber et al. (2005)!



Weber et al., Nature 437 (2005)

Freie Universität Berlin

Transient spin grating setup:

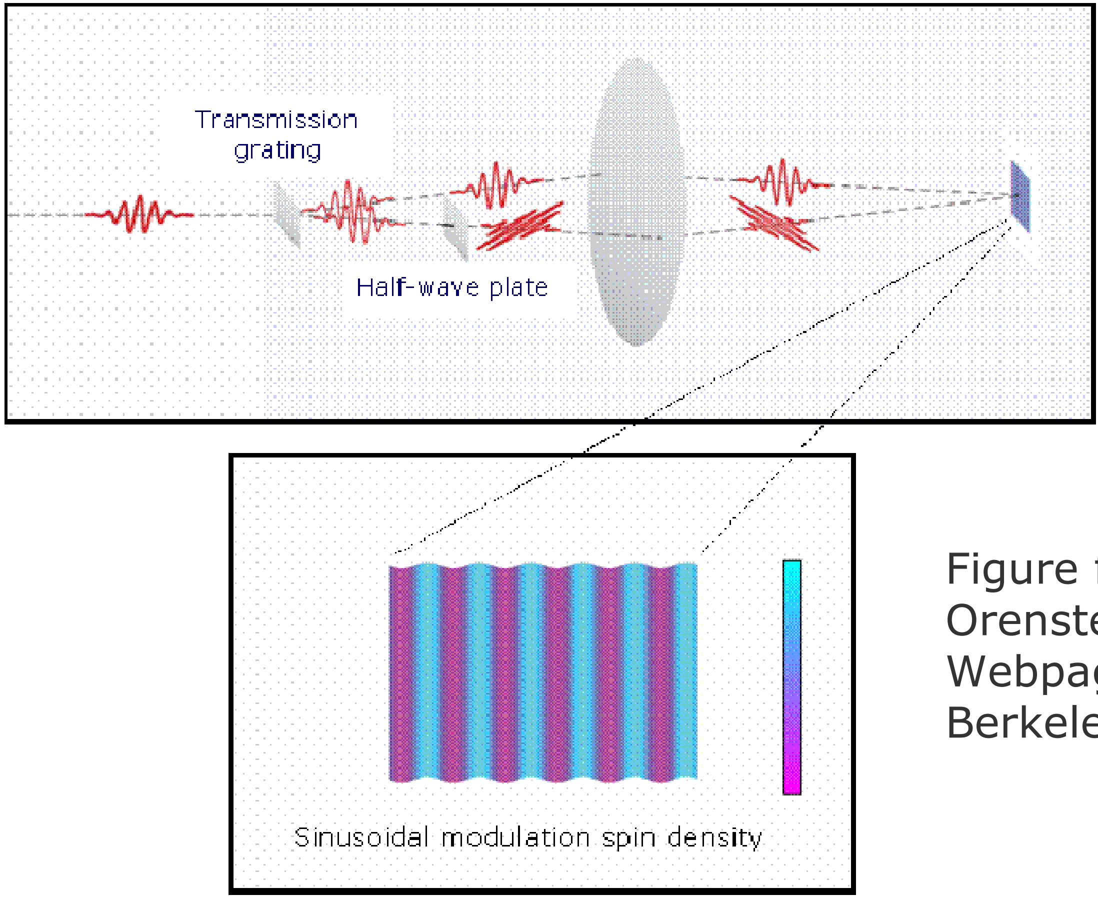


Figure from Orenstein`s Webpage at Berkeley

How is SCD affected by SO-coupling?

- Tse & Sarma, PRB 75, 045333 (2007)
  Diagrammatic approach; Rashba SO coupling enhances transresistivity by a factor

$$\sim \left[1 + \left(\frac{\alpha}{v_F}\right)^2\right].$$

- Our aim: Description of SCD within the framework of a kinetic equation for the density *matrix (in spin space)*

Nonequil. statistical operator

Freie Universität Berlin

(cf. textbook by Zubarev, Statistical Mechanics of Nonequibrium Processes)

Idea:

-*Reduced* description based on chosen set of observables and corresponding timescales.

-Construct the nonequilibrium density matrix starting from a quasi-equilibrium density matrix

-Derive closed system of generalized kinetic Equations for the relevant variables

-weak interactions → Born approximation

Nonequil. statistical operator

Freie Universität Berlin

Generalized kinetic equation for the relevant variable:

$$\frac{\partial \langle P_{\mathbf{p}} \rangle}{\partial t} = i \sum_{\mathbf{q}} \omega_{\mathbf{pq}} \langle P_{\mathbf{q}} \rangle + \mathcal{J}_{\mathbf{p}}^{(1)} + \mathcal{J}_{\mathbf{p}}^{(2)}$$

$$\mathcal{J}_{\mathbf{p}}^{(1)} = i \langle [\mathcal{H}_{\text{int}}, P_{\mathbf{p}}] \rangle_{\text{q}}$$

$$\mathcal{J}_{\mathbf{p}}^{(2)} = \lim_{\varepsilon \to +0} \int_{-\infty}^{0} e^{\varepsilon t} dt \left\langle \left[\mathcal{H}_{\text{int}}(t), [P_{\mathbf{p}}, \mathcal{H}_{\text{int}}] + i \sum_{\mathbf{l}} \frac{\delta \mathcal{J}_{\mathbf{p}}^{(1)}}{\delta \langle P_{\mathbf{l}} \rangle} P_{\mathbf{l}} \right] \right\rangle$$

(valid in Born approx. + Markovian approx.)

Nonequil. statistical operator

Freie Universität Berlin

Relevant variable:

$$\langle P_m \rangle = n_{\sigma\sigma'}(\mathbf{k}) = \langle a^\dagger_{\mathbf{k}\sigma'} a_{\mathbf{k}\sigma} \rangle$$

$$\hat{n} = f\,\sigma_0 + \mathbf{\Phi} \cdot \sigma$$

With static & uniform electric field,

Lhs:

$$\frac{\partial f}{\partial t} + e\mathbf{E} \cdot \frac{\partial n^0}{\partial \mathbf{k}} \quad = \quad \ldots$$

$$\frac{\partial \mathbf{\Phi}}{\partial t} + e\mathbf{E} \cdot \frac{\partial \mathbf{\Phi}^0}{\partial \mathbf{k}} + \mathbf{b} \times \Phi \quad = \quad \ldots$$

Rhs: ... (vast expression due to SO-coupling in H_0)

Program

-Solve kinetic equation

-Comparison with diagrammatic perturbation theory

-Add spin-flip scattering (→negative transresistivity?)

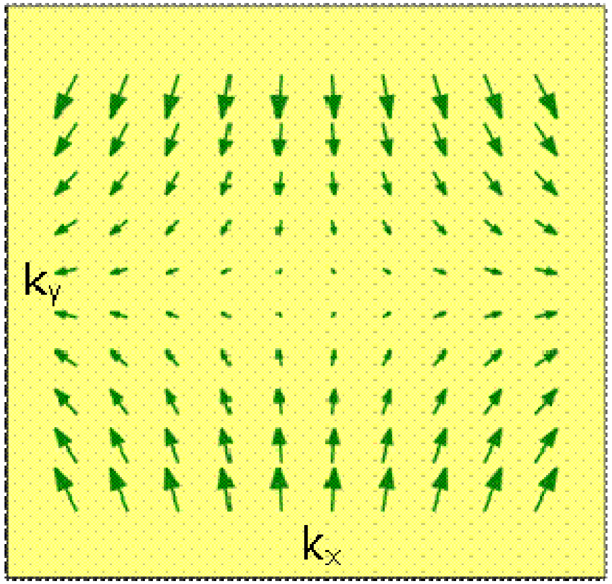
-Inclusion of correlated disorder scattering (within diagrammatic perturbation theory)

-SHE and AHE with SCD

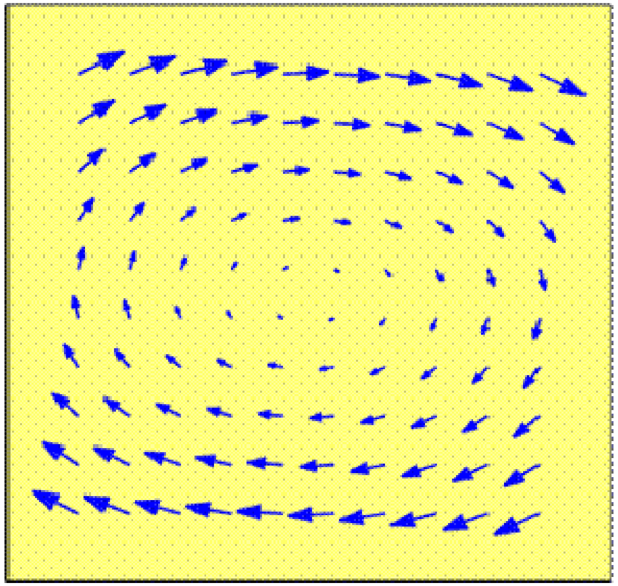
Thanks for your attention!

Spin-orbit coupling

Dresselhaus



Rashba



Coulomb drag

Trans-*conductivity* $\sigma_{21} = j_2/E_1; \quad E_2 = 0$

[for weak coupling: $\rho_{21} = \sigma_{21}/(\sigma_{11} + \sigma_{22})$]

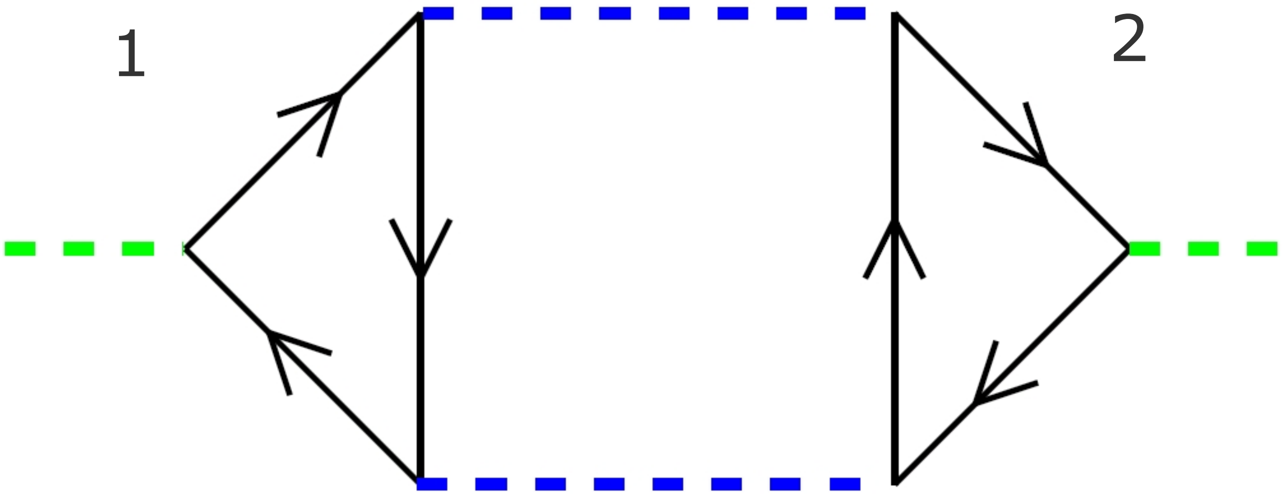
Calculated from Kubo-formula:

$$\sigma_{21}^{\alpha\beta}(\mathbf{r}, \mathbf{r}'; \omega) = \frac{i}{\omega}\Pi_{21}^{\alpha\beta,R}(\mathbf{r} - \mathbf{r}'; \omega)$$

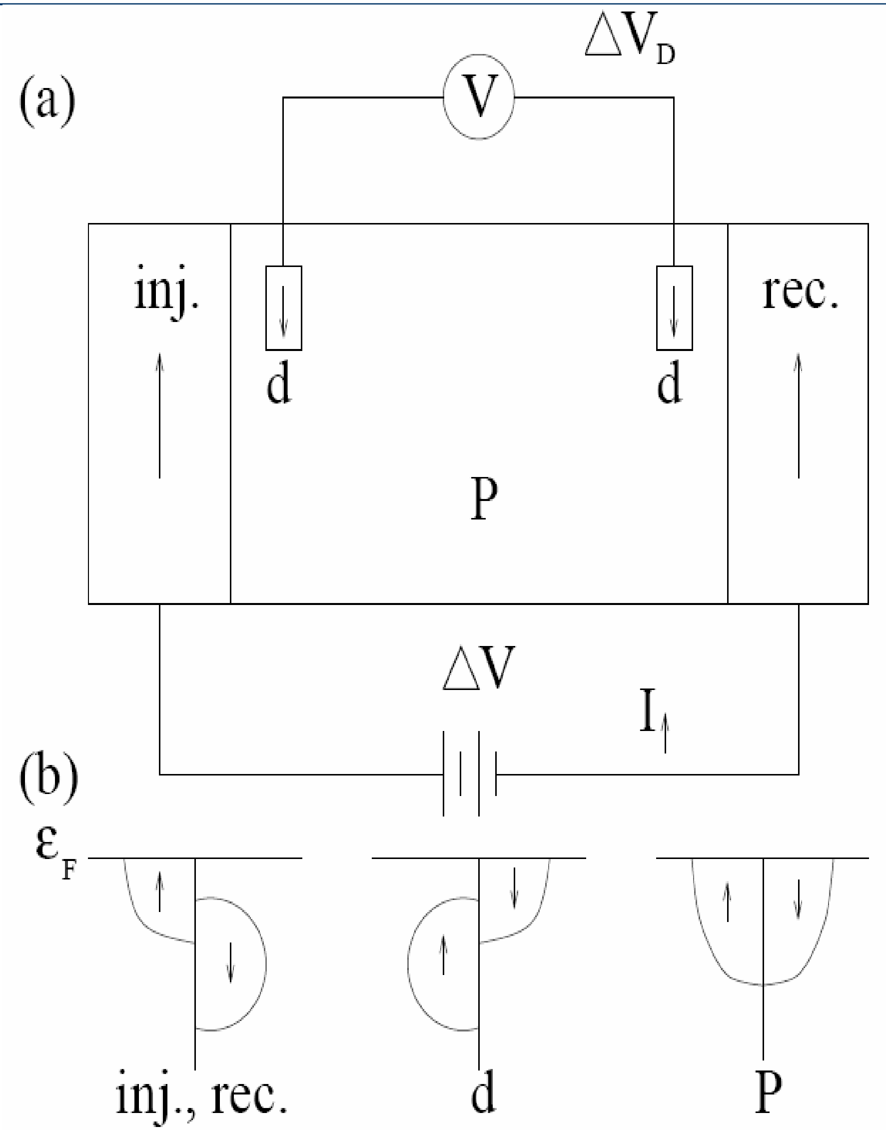
with

$$\Pi_{21}^{\alpha\beta,R}(\mathbf{r} - \mathbf{r}'; t - t') \equiv -i\Theta(t - t')\left\langle [j_{\alpha,2}(\mathbf{r}, t), j_{\beta,1}(\mathbf{r}', t')]_- \right\rangle$$

(charge) Coulomb drag



$$\sigma_{21}^{\alpha\beta} = \int \frac{\omega}{2\pi} \sum_{\mathbf{q}} \frac{|U(\mathbf{q},\omega)|^2}{8T\sinh^2(\omega/2T)} \Gamma_2^{\alpha}(\mathbf{q},\omega)\, \Gamma_1^{\beta}(\mathbf{q},\omega)$$



ΔV_D
(a)
V
inj.
d
d
rec.
P
ΔV
I
(b)
ε_F
inj., rec.
d
P