Spin Transport in 6.1 Å Semiconductors

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We investigate theoretically spin-polarized transport and relaxation in III-V semiconductors including the 6.1-Å materials, and explore the possibility of its manipulation in practical nanoscale devices.

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What do we want?

- New (effective) approach to represent information
  - Digital / Analog
  - Scalar / Vector
  - Classical / Quantum
  - ??? / ???
- Implementation
  - What ever information we have should be preserved until read-out
  - Strong enough handles to manipulate information during its life-time

Maybe Spintronics?

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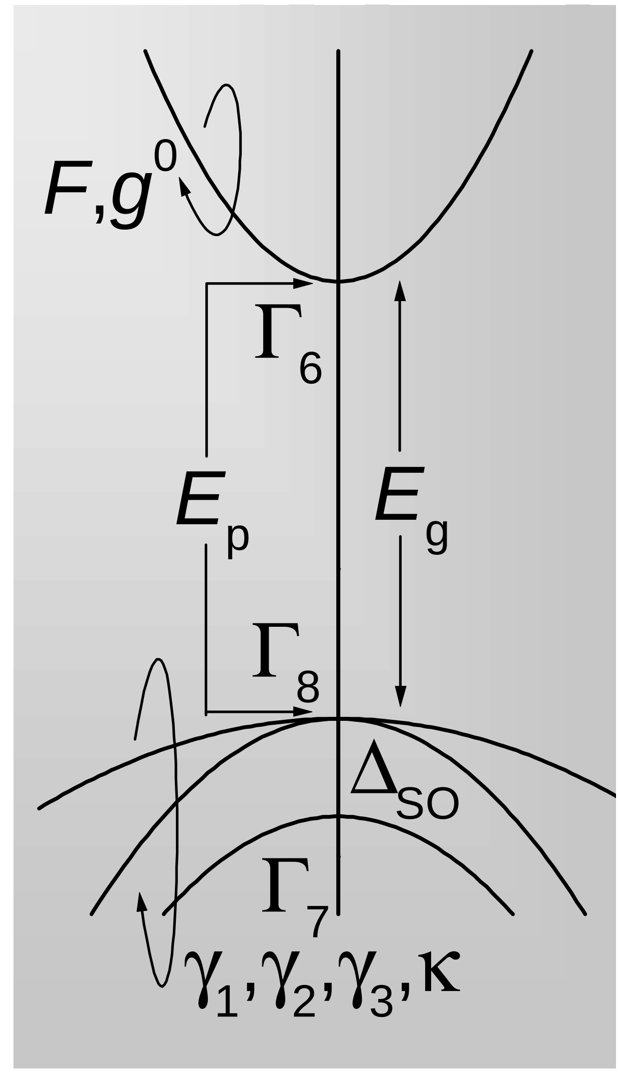
Cons and Pros of 6.1 Å materials

- Typical III-V materials
- Small band gap
  - small electron effective mass
- Large ratio of spin-orbit (SO) splitting to band gap
  - large value of g factor
  - large structure-asymmetry induced SO (Bychkov-Rashba) splittings
- "Weird" relative band alignment in some heteropairs
- Semimagnetic semiconductors



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Outline

- Mechanisms of spin relaxation in III-V semiconductors
- Taking spin relaxation under control: D'yakonov-Perel' mechanism in narrow channels*
- 2D ballistic nanostructures with control electrodes for spintronics
  - Three-terminal T-shaped structure**
  - Ring with two terminals***

*) A.A. Kiselev and K.W. Kim, Phys. Rev. B **61**, 13115 (2000).
) A.A. Kiselev and K.W. Kim, Appl. Phys. Lett. **78, 775 (2001).
***) A.A. Kiselev and K.W. Kim, to be published.

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Mechanisms of spin relaxation*

- D'yakonov-Perel' (DP) mechanism: spin splitting of the conduction band at finite wave vectors is equivalent to effective magnetic field that causes electron spin to precess. It is random due to scattering in real space.
- Bir-Aronov-Pikus processes involve a simultaneous flip of electron and hole spins due to electron-hole exchange coupling.
- Spin relaxation due to momentum relaxation directly through spin-orbit coupling (Elliot-Yafet process).
- Spin relaxation due to carrier spin --- nuclear momentum interactions.

*) G. E. Pikus and A. N. Titkov, in *Optical Orientation*, edited by F. Meier and B. P. Zakharchenya (Elsevier, 1994), p. 73.

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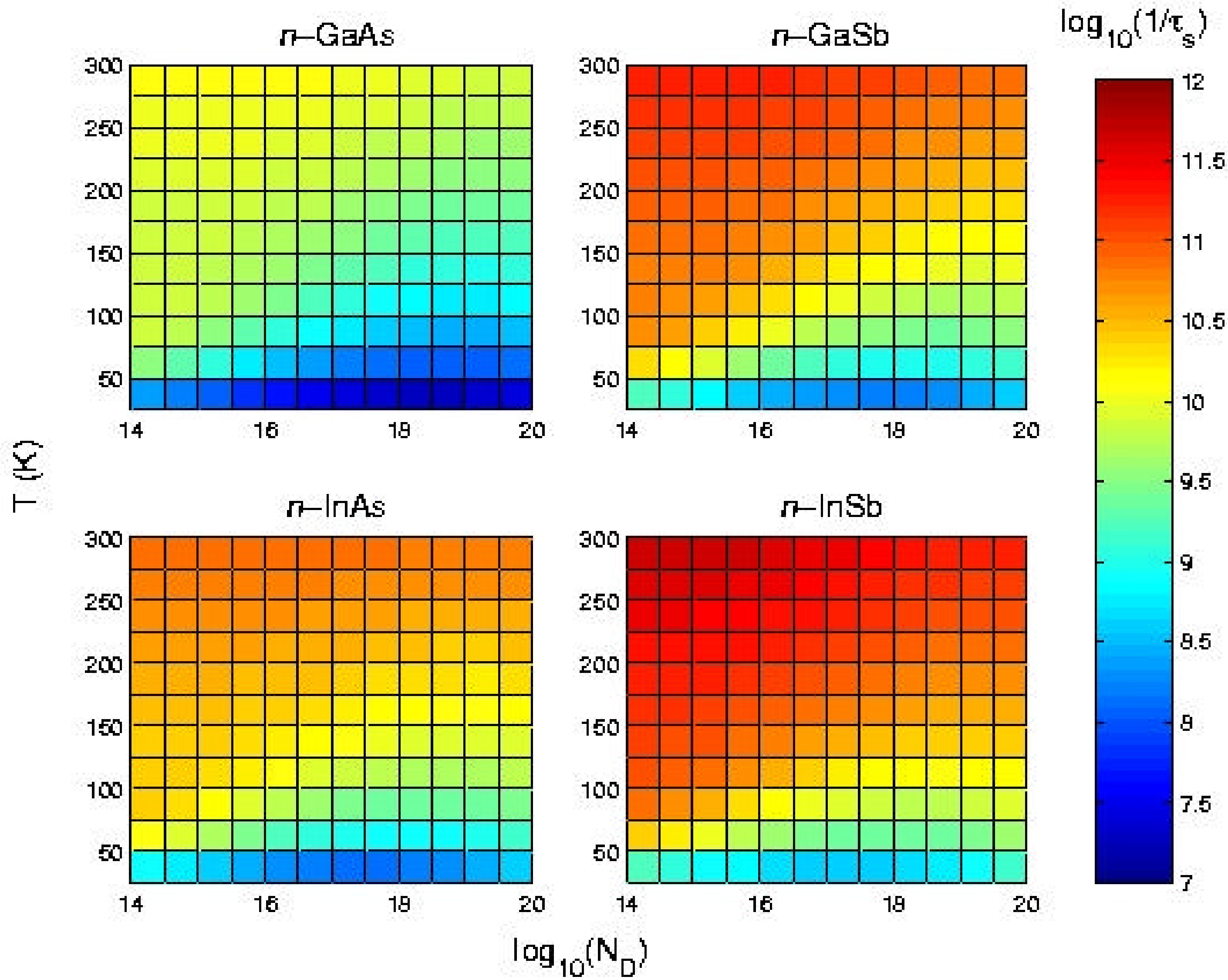
n-Doped bulk semiconductors



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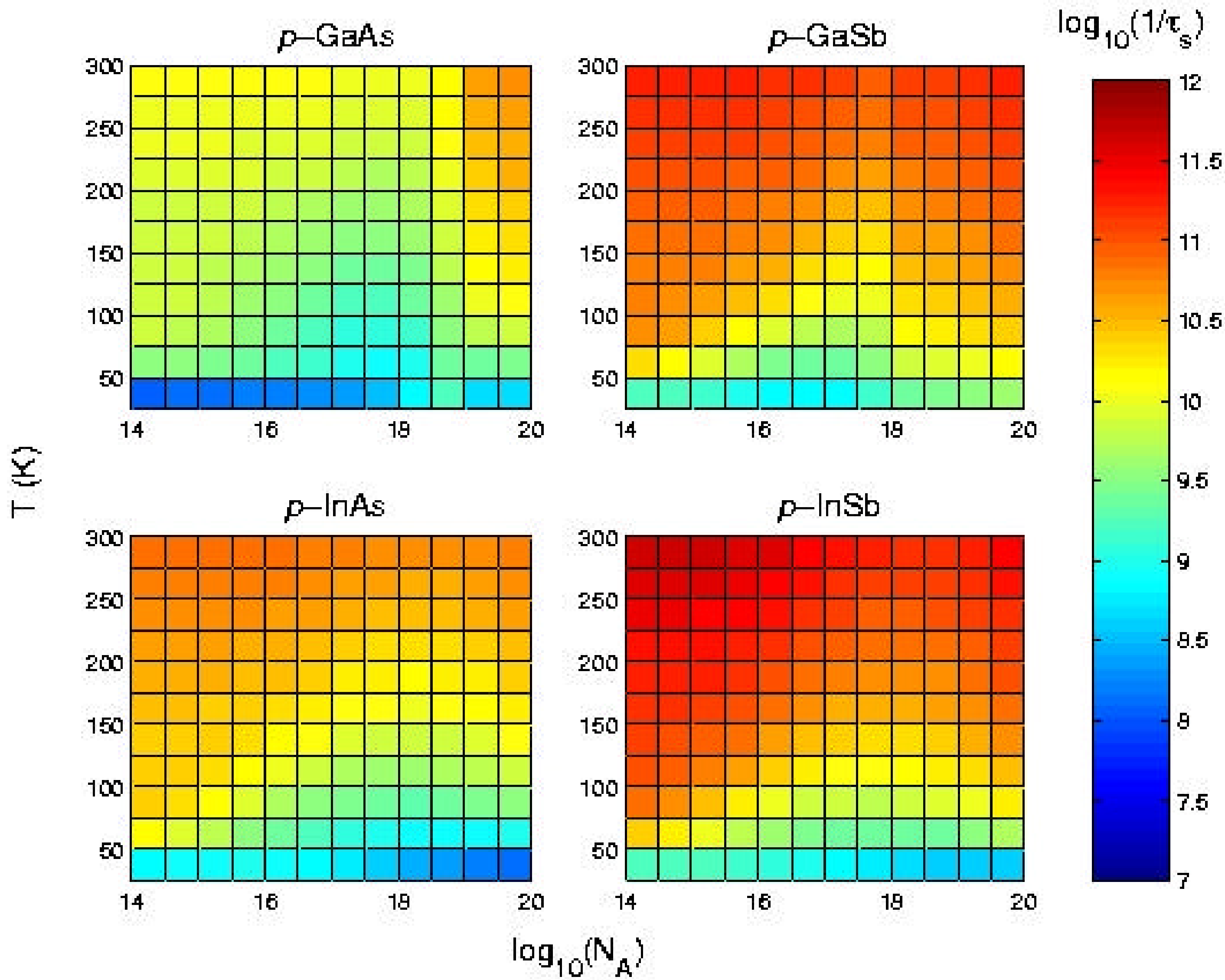
p-Doped bulk semiconductors



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Relevant spin-relaxation mechanisms

- *n*-type

  Mostly, the DP mechanism dominates except of InSb, which is governed by the EY-mechanism in low T (T < ~5 K) and at small doping concentrations (N_D < ~10^{18} cm^{-3}).

Analysis shows that the D'yakonov-Perel' mechanism is most relevant.

- *p*-type
  - GaAs and GaSb: The DP and BAP mechanisms compete; the DP is dominant in high T and at small doping concentrations.
  - InSb: The DP is dominating.
  - InAs: There is a competition between the DP and the BAP for Δ_{exc} > 1 μeV and the DP is dominating for Δ_{exc} < 1 μeV

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Spin splitting of conduction electrons for DP mechanism

Bulk zinc-blende semiconductors - 2 x 2 conduction band Hamiltonian

$$H = \frac{\hbar^2 k^2}{2m_e} + \tilde{ç}'\left[ó_x k_x \left(k_y^2 - k_z^2\right) + cycl.perm.\right]$$

The constant $\tilde{ç}'$ reflects the strength of the spin splitting in the conduction band and it is defined by the details of the semiconductor band structure.

The second (spin-dependent) term is equivalent to the presence of an effective magnetic field that causes electron spin to precess.

2D (001) heterostructures --- bulk Hamiltonian terms with k_z^2 will dominate due to strong spatial confinement. This reorients the effective magnetic field into the plane of the 2D electron gas (xy plane).

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Bulk- vs. structure-asymmetry-induced spin splittings in 2D systems

In addition to the **bulk-induced terms** in the effective Hamiltonian

$(\hbar / 2)\, ç' (ó_x$ [redacted] $- ó_x$ [redacted] $)$, where h' is derived from $\tilde{h}'$,

new (Bychkov-Rashba*) terms appear in asymmetric 2D heterostructures $(\hbar / 2)\, ç_{\mathrm{DP}} (ó_x$ [redacted] $- ó_y$ [redacted] $)$.

Constant h_{DP} is defined by degree of the structure asymmetry and can be manipulated, i.e., by external electric field.

Both types of terms individually have the same effect on the spin relaxation in heterostructures. We (arbitrarily) use Bychkov-Rashba term in our analysis.

*) Yu. A. Bychkov and E. I. Rashba, Sov. Phys. JETP Lett. **39**, 78 (1984).

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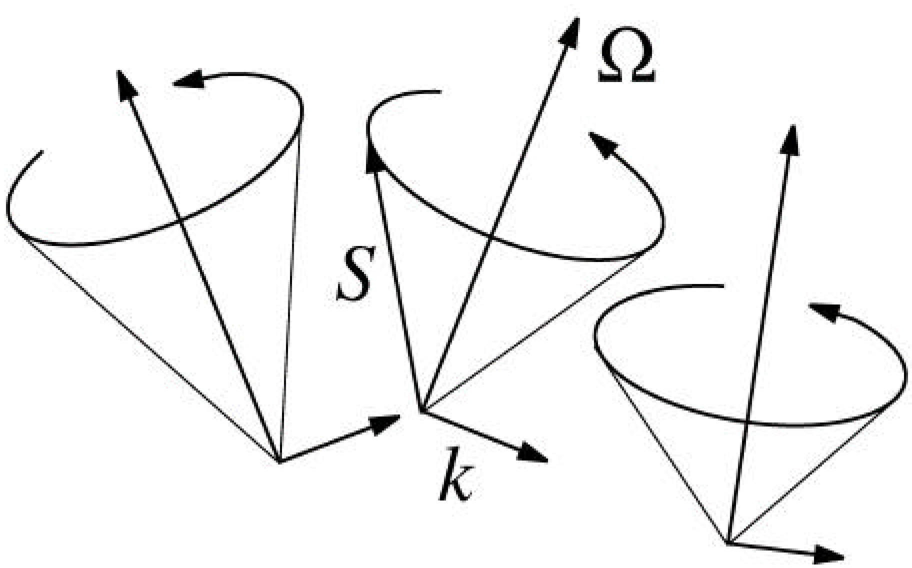
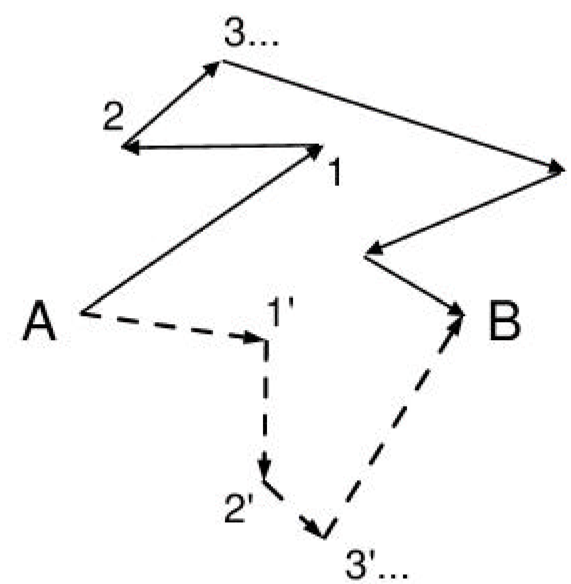
D’yakonov-Perel’ mechanism in 2D

2×2 Hamiltonian in 2D structures with $\boldsymbol{z}$ = (0,0,1) defines spin precession in the effective magnetic field (that is random in the presence of electron scattering).

$$H_S = \frac{\hbar}{2}\sigma\cdot\Omega_{eff}, \quad \frac{dS}{dt} = \Omega_{eff}\times S, \quad \Omega_{eff} \equiv h_{DP}\boldsymbol{n}\times\boldsymbol{z}, \quad \boxed{t_S^{-1} \approx t_p\left\langle \Omega_{eff}^2 \right\rangle}$$

Random elementary rotations **do not commute** in 2D (and 3D).





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Possibilities to manipulate spin relaxation

Regime of motional narrowing --- Since $t_s^{-1} \sim t_p\langle\Omega_{eff}^2\rangle$, reduction of momentum relaxation time, t_p, leads to the suppression of spin relaxation.

Structure orientation --- Spin splitting is absent (small) for structures with principal axis along (011).

External magnetic field --- Additional spin splitting, which is independent of electron wave vector will fix precession axis. Good candidate is the external magnetic field.

Narrow channels of 2DEG --- DP spin relaxation in true 1D systems is absent, the question is --- How narrow the channel should be?

Compensation of spin splittings --- Bulk- and structure-asymmetry-induced spin terms in the Hamiltonian are additive. By manipulating structure asymmetry (i.e., by electric field), it is possible to tune combined splitting.

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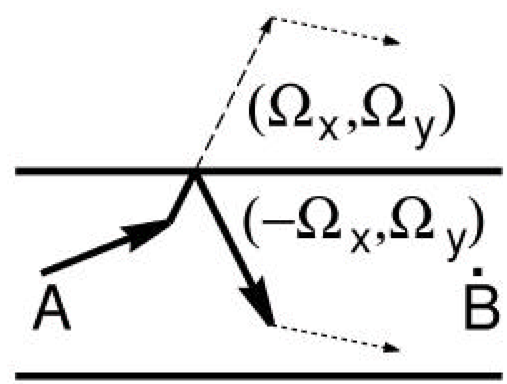
Monte Carlo model of quasi-1D electron spin transport

- Classical real-space movement. All particles have the same velocity $|\boldsymbol{v}|$.
- Scattering is elastic and isotropic: no correlation between velocity directions before and after scattering events.
- Electron-electron interaction is neglected, all electrons are independent.
- Momentum relaxation time is t_p, distribution of times between scattering events is exponential (no correlation). Mean-free path is $L_p = |\boldsymbol{v}|\, t_p$
- Spin-rotating Hamiltonian is

$$H_S = \frac{\hbar}{2}\boldsymbol{\sigma}\cdot\boldsymbol{\Omega}_{eff} = \frac{\hbar}{2}\varsigma_{\mathrm{DP}}\left(ó_x í_y - ó_y í_x\right)$$

- Reflecting channel boundaries



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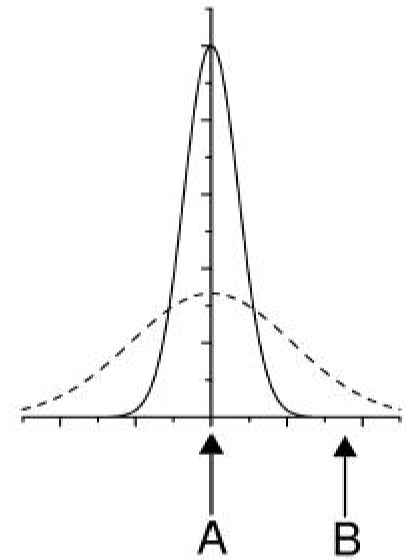
Types of experiments

Particles are inserted at point A with spin $\boldsymbol{S}$ and experience multiple scattering.

Diffusive pattern of motion, $\langle r \rangle \sim L_p (t/t_p)^{1/2}$



- Average spin $\langle \boldsymbol{S} \rangle$ is measured at time t at point B (correlation function, most informative --- our choice).
- At time t average $\langle \boldsymbol{S} \rangle$ is calculated for the whole ensemble, real-space position is not important (optical experiments).
- Particle, reaching point B is immediately removed from the system, $\langle \boldsymbol{S} \rangle$ is calculated as a function of distance r_{AB} (spin-sensitive electric measurements).

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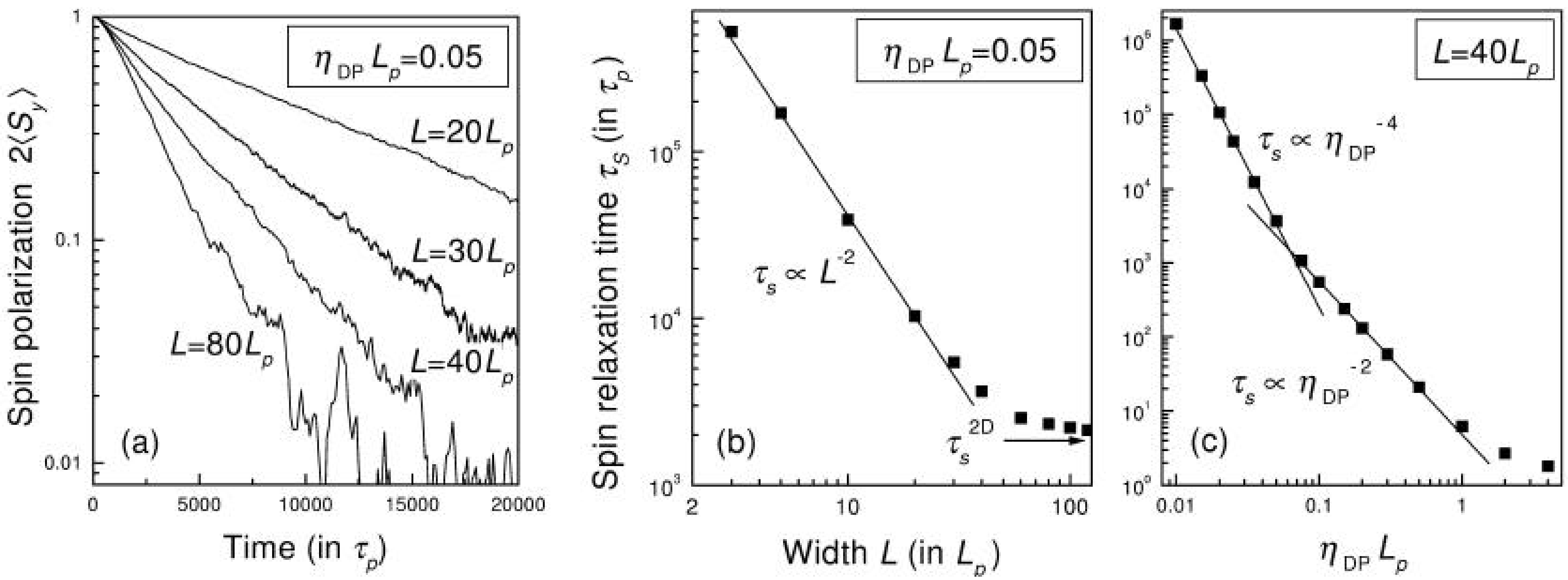
Spin relaxation in a channel



Apart from position-dependent spin rotation by angle $f = h_{\mathrm{DP}}\, \boldsymbol{r}_{\mathrm{AB}}\times \boldsymbol{z}$, spin relaxation dependencies are essentially the same for all points.

a) Decay of spin polarization is approximately exponential, so one can introduce spin relaxation time of electrons in the channel;

b,c) Power-law scaling of t_s with L and h_{DP}.

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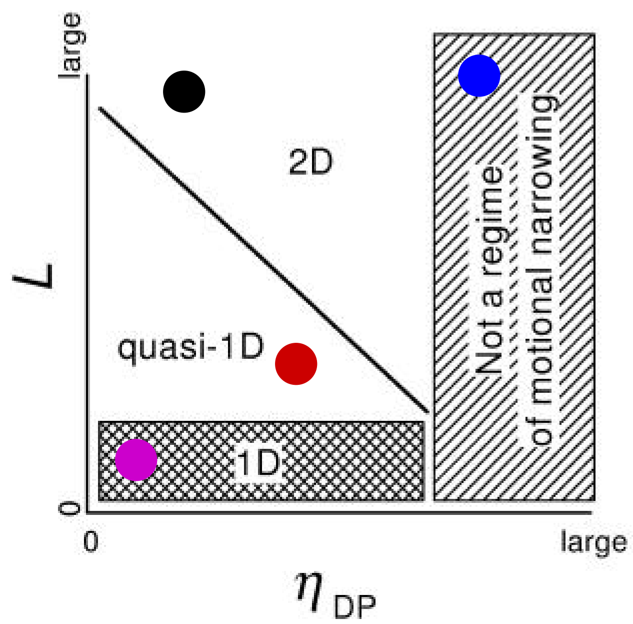
Regimes of spin relaxation in a channel



- $h_{DP} L_p \sim 1$ --- elementary rotations during free flights are not small, $t_s \sim t_p$
- $h_{DP} L_p \ll 1$, $h_{DP} L \sim 1$ --- 2D spin relaxation, $t_s^{2D} \sim \tau_p (h_{DP} L_p)^{-2}$
- $h_{DP} L \ll 1$ --- suppression of spin relaxation, quasi-1D regime, $t_s \sim t_s^{2D} (h_{DP} L)^{-2}$
- $L \sim L_p$ --- L starts to act as L_p, quantum mechanical quantization in the channel, intersubband scattering

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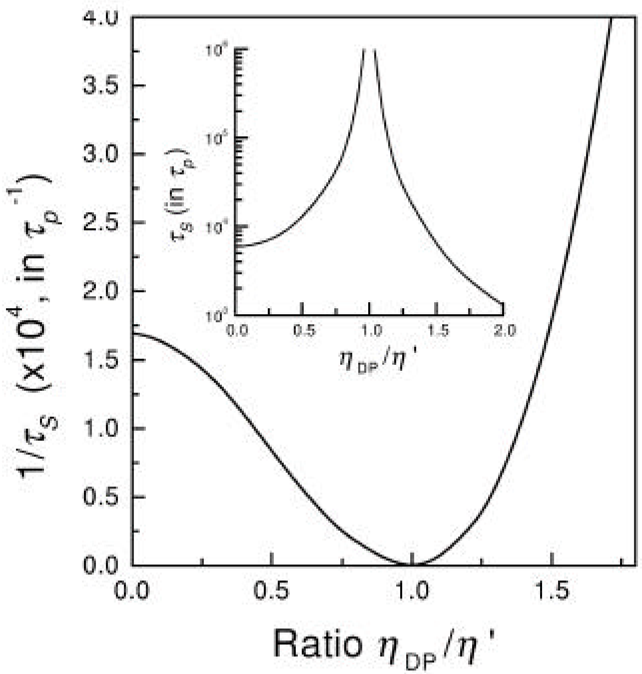
Compensation of bulk- and structure-induced splittings



- The bulk-asymmetry- (h') and structure-asymmetry-induced (h_{DP}) spin terms are additive

- They are both linear-in-k and have similar but different form

- It is possible to tune h_{DP} splitting to some desired value (say, $h_{DP} = \pm h'$), manipulating external electric field

- This allows to fix the axis of the effective magnetic field and suppress spin relaxation, as it happens in the pure 1D case.

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Now ballistic devices...
Idea 1

- In spintronic* devices one needs to manipulate spin
- Conventional approach --- by external magnetic field
  - micromagnets, ferromagnetic films, additional extensive circuitry, external magnets :-(
- Possible alternative --- *intrinsic effect* provided by spin-orbit (SO) interaction.** SO interaction *by definition* couples spin and orbit degrees of freedom

*) G. A. Prinz, Physics Today **48(4)**, 58 (1995); Science **282**, 1660 (1998).
) S. Datta and B. Das, Appl. Phys. Lett. **56, 665 (1990); Bulgakov, K. N. Pichugin, A. F. Sadreev, P. Streba, and P. Seba, Phys. Rev. Lett. **83**, 376 (1999).

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Idea 2

- Due to typically large difference in energy scales for spin and orbital motion, it is common to consider influence of SO term only on the spin coordinate (spin precession in the effective magnetic field).
- **Spin cannot influence electron trajectory**
- For any initial spin orientation, by the end of trajectory each spin will rotate by the same total angle
- Isotropic distribution of spins will convert into isotropic distribution.

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Idea 3

- *Reciprocal effect* can be made important in the vicinity of resonances where relevant orbital energy scale is *drastically* reduced up to the resonance width

- **Completely different trajectories for different spin orientations**

- Initial isotropic distribution of spins can be split into two or more with $\langle S \rangle \neq 0$. One can achieve spin filtering

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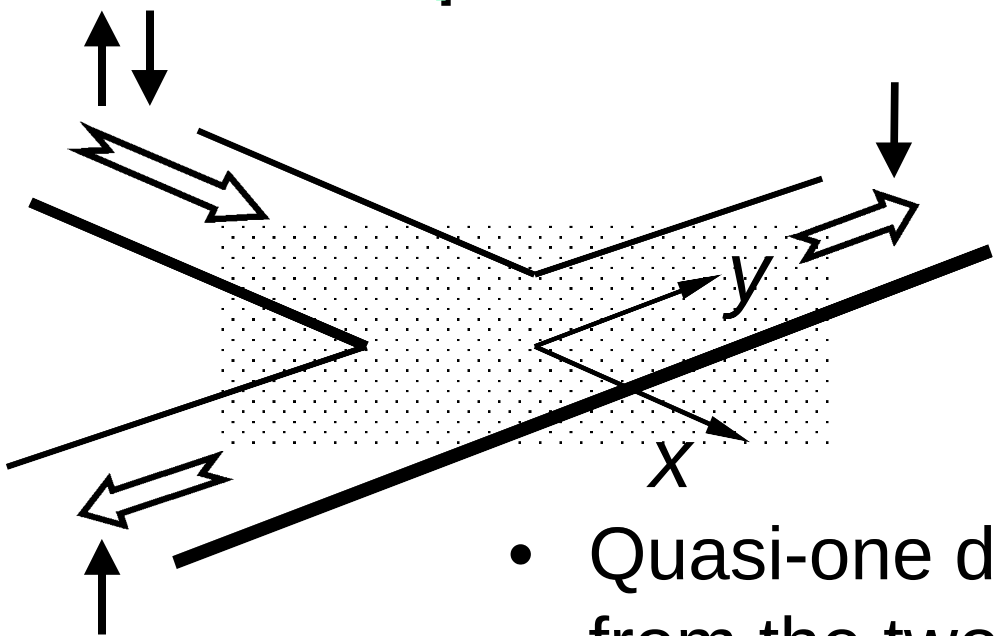
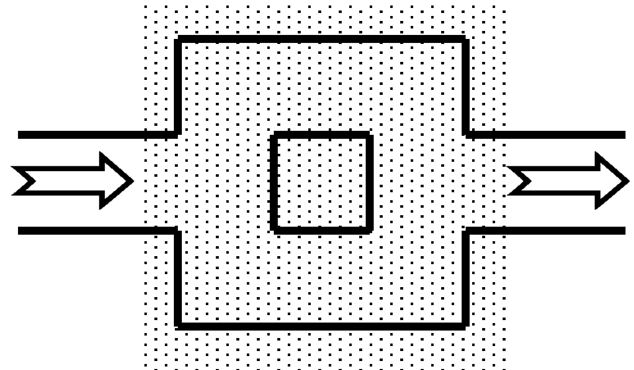
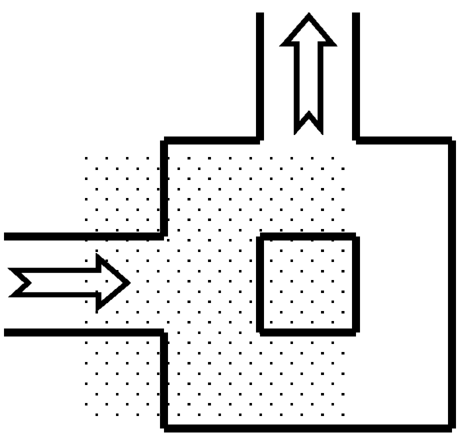
T-shaped 2D structure and others...







- Quasi-one dimensional channels formed from the two-dimensional electron gas (2DEG) using, e.g., electrostatic split-gate technique
- Special control electrode(s) are located over/under the structure (back and front gates) to manipulate SO interaction

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Hamiltonian and other formulae

- 2D electron Hamiltonian (including spin part)

$$\hat{H} = \frac{\hbar^2 k^2}{2m} + V(x,y) + \left\{ \text{ç}(x,y) \left(\hat{\hat{o}}_x k_y - \hat{\hat{o}}_y k_x \right) \right\}$$

- Channels are formed by hard walls (with boundary conditions $\hat{u}_S \equiv 0$) or alternatively can be defined by the potential profile $V(x,y)$ (soft walls)

- The third dimension (i.e. $\boldsymbol{z}$ coordinate) is quantized.

- ç reflects strength of the structure- or bulk-asymmetry-induced spin-orbit (SO) interaction*

*) Yu. A. Bychkov and E. I. Rashba, Sov. Phys. JETP Lett. **39**, 78 (1984); G. Lommer, F. Malcher, and U. Rössler, Phys. Rev. B **32**, 6965 (1985).

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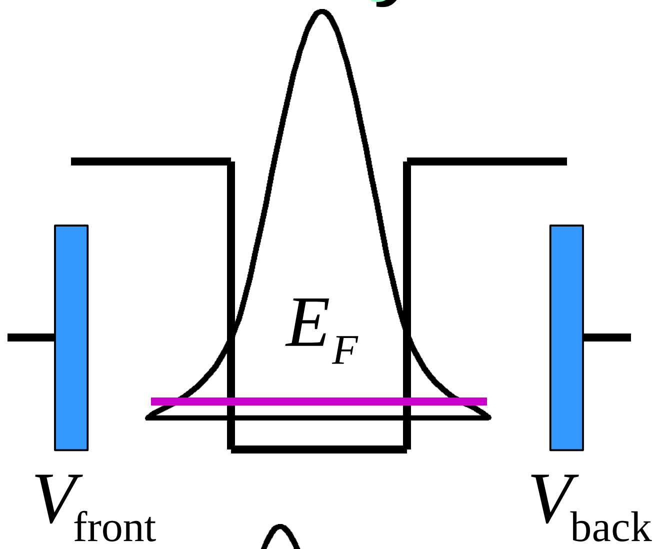
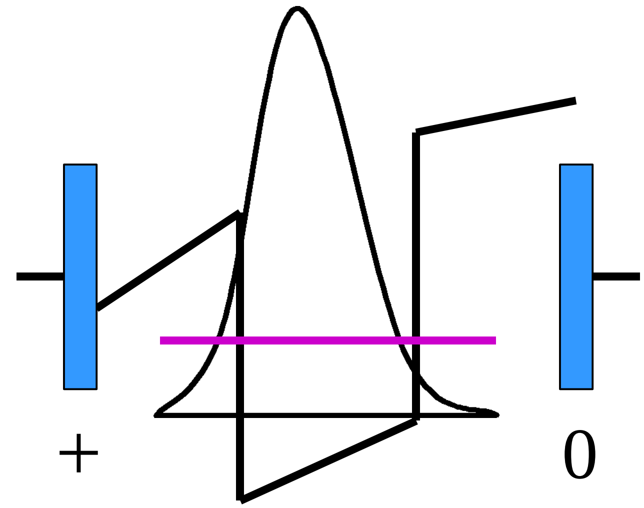
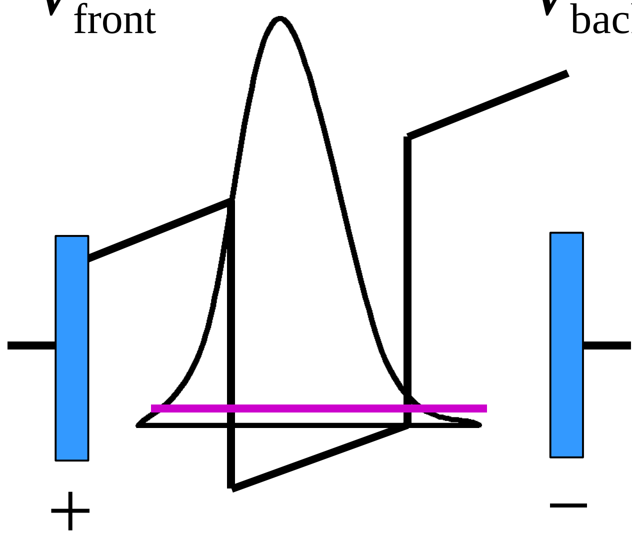
Manipulation of SO term by front/back gates







Independent variables:

$$V \approx \frac{1}{2}\left(V_{\text{front}} + V_{\text{back}}\right)$$

[redacted] $$\propto \frac{1}{2}\left(V_{\text{front}} - V_{\text{back}}\right)$$

D. Grundler, Phys. Rev. Lett. **84**, 6074 (2000).

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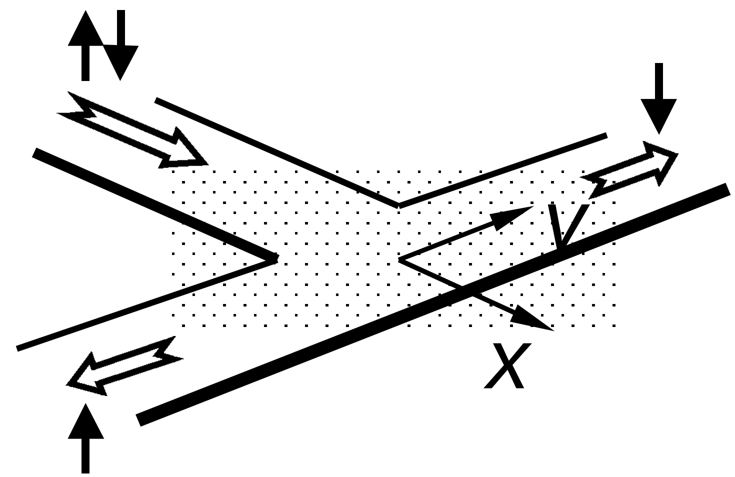
Model variables

- Incident electron energy
- Gate-induced potential

$$V \approx \frac{1}{2}\left(V_{\text{front}} + V_{\text{back}}\right)$$

- SO interaction coefficient

$$\varsigma \propto \frac{1}{2}\left(V_{\text{front}} - V_{\text{back}}\right)$$



Small front and back electrodes at the intersection:

$$V(r), \varsigma(r):\;\; X(r) = \frac{X_0}{1 + e^{(r-r_0)/\Delta r}}$$

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Real-life structure parameters

- Channel width

$$w = 1000 \text{ Å}$$

- Electron effective mass (InAs)

$$m = 0.023 m_0$$

- Quantization energy

$$E_0 = 1.6 \text{ meV}$$

- SO term parameter

$$\varsigma_0 = 180 \text{ meV} \cdot \text{Å}$$

(that is equal to $0.11 \times E_0 w$)

- Electrode radius

$$r_0 = 2000 \text{ Å}$$

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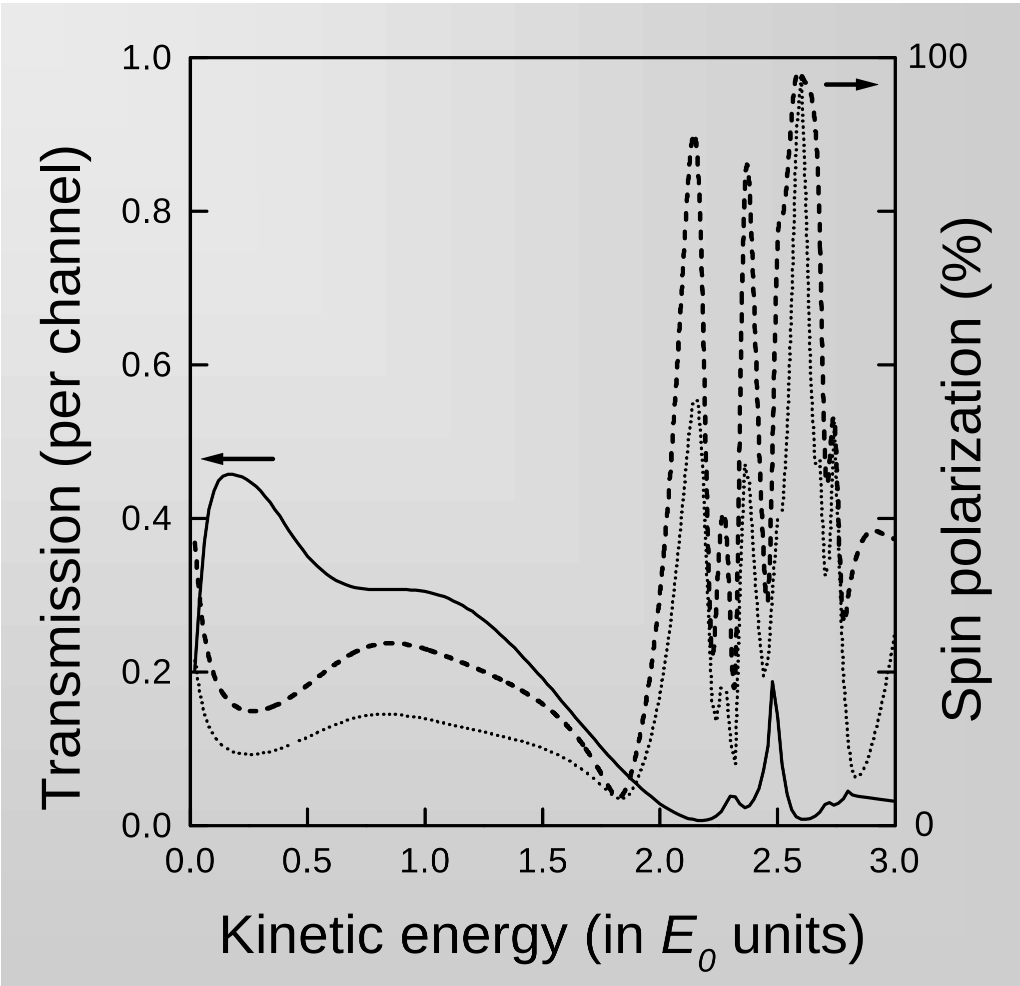
Polarization of the transmitted flux



- Dashed line --- total polarization $|\boldsymbol{P}|$
- Dotted --- difference between flux polarization in the $+y$ and $-y$ channels $\left(P_x^2 + P_z^2\right)^{1/2}$
- Solid --- total transmission

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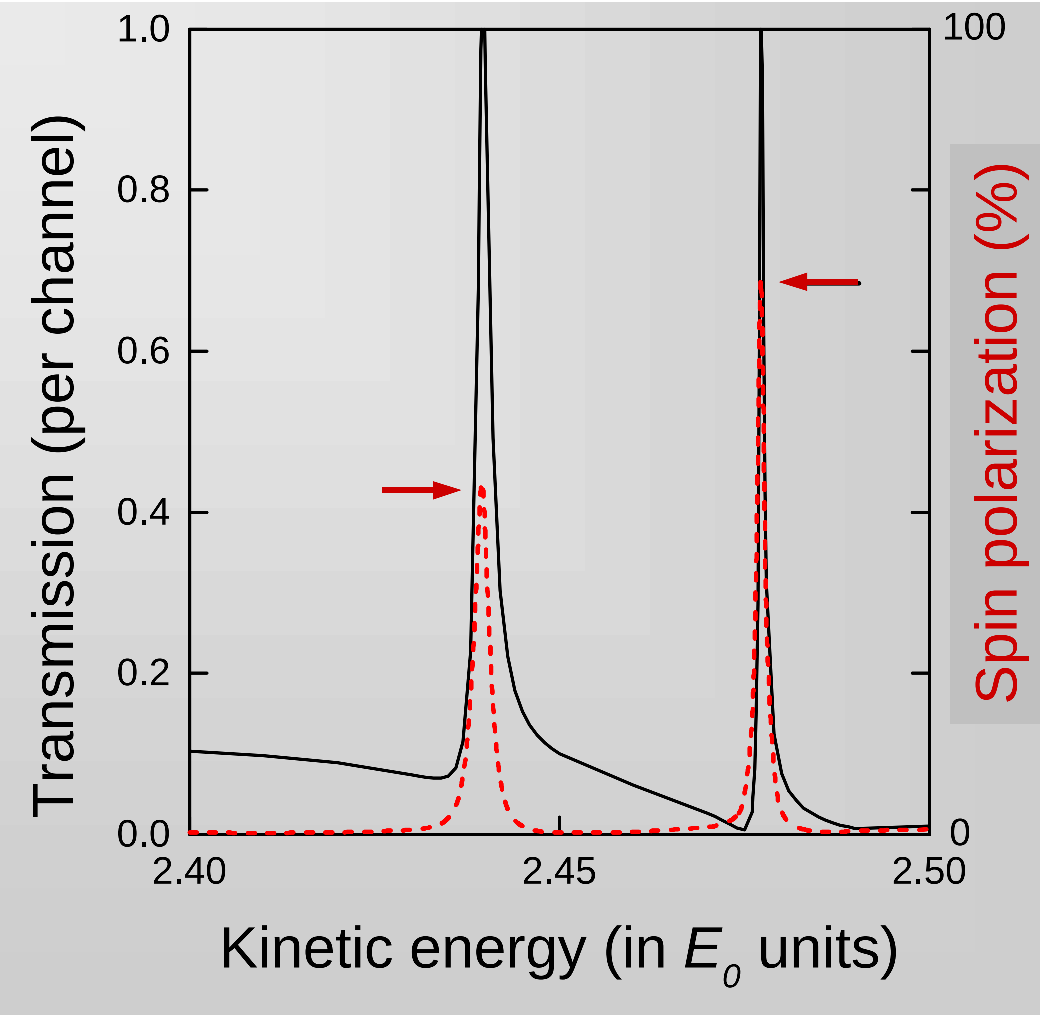
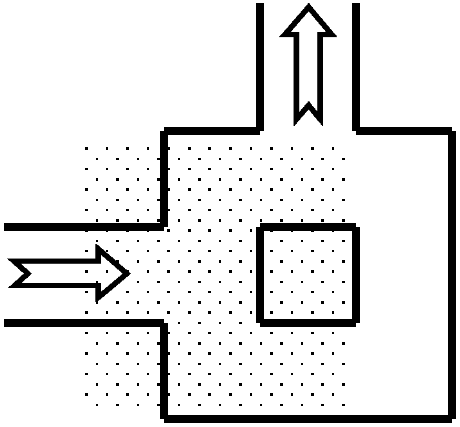
Modified structure: “Asymmetric square ring”





We have achieved simultaneously high transmission and high spin polarization of the transmitted flux.

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Conclusion

- We have identified different regimes of the D'yakonov-Perel' spin relaxation and analyzed dependencies of the spin relaxation time on the channel width L and DP parameter (inverse spin-rotation length) h_{DP}. The most attractive for the future spintronic applications is a regime of the suppressed spin relaxation with the relaxation time, t_s, scaling as L_{DP}^{-2} in narrow channels

- Functional ballistic spin devices can be designed that are based on the *internal* SO effect, modulated by control electrodes, that feature simultaneously high transmission efficiency and strong spin-dependent phenomena, including spin filtering and directional multiplexing

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