Poster 2
31

Conserved Spin Quantity in Strained Hole Systems with Rashba and Dresselhaus Spin-Orbit Coupling

Paul Wenk, Michael Kammermeier, John Schliemann

Institute for Theoretical Physics, University Regensburg, 93040 Regensburg

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Motivation

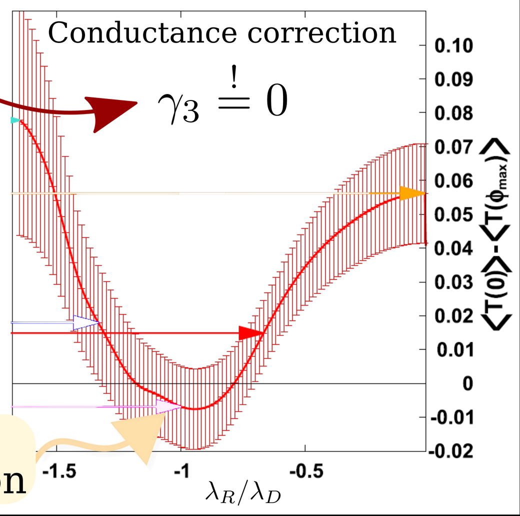
The critical challenge for spintronic devices: control of the carrier spin lifetime, which is limited by the *spin relaxation* and dephasing processes in semiconductors, here of *Dyakonov-Perel type*.

Goal: Following the idea of a non-ballistic spin-field-effect transistor in 2D electron gases [1], find the spin-preserving symmetries to extend the application of spintronic devices to the *non-ballistic/diffusive* regime (with spin-independent scattering) in 2D hole gases (2DHG) in a zincblende type semiconductor hetero-structure, including both Rashba (SIA) and Dresselhaus (BIA) spin-orbit coupling (SOC).
What are the optimal material parameters? Is it sufficient to tune Rashba/Dresselhaus SOC? What are the persistent spin states (PSS)?

Problems: Reducing the Rashba contribution [2] in a hole system $\mathcal{H}^{r}_{8v8v} = r^{8v8v}_{41}((k_y\mathcal{E}_z - k_z\mathcal{E}_y)J_x + \text{c.p.})$

to a 2D system: r^{8v8v}_{41} is due to the band-gap splitting, $\implies$ has to be re-calculated including the effect of subband splitting!

- In general, we have $\gamma_3 > \gamma_2$, however, for PSS in 2DHG with BIA+SIA [2]
- In 2DHG with SIA+strain [3]: $\gamma_3 \overset{!}{=} 0$. One finds a PSS only for $\gamma_2 = -\gamma_3$
- A correct application of Loewdin perturbation is non-trivial.



System

Starting point is an effective 4x4 Hamiltonain

$$\mathcal{H} = \mathcal{H}_{\rm L} + \mathcal{H}_{\rm BIA} + \mathcal{H}_{\rm S} + V,$$

with the *Luttinger Hamiltonian* for III-V semiconductors in three dimensions (total angular momentum j=3/2)

$$\mathcal{H}_{\rm L} = -\frac{\hbar^2}{2m_0}\left(\gamma_1\mathbf{k}^2 - 2\gamma_2\left[\left(J_x^2 - \frac{1}{3}\mathbf{J}^2\right)k_x^2 + \text{c.p.}\right] - 4\gamma_3\left[\{J_x, J_y\}\{k_x, k_y\} + \text{c.p.}\right]\right),$$

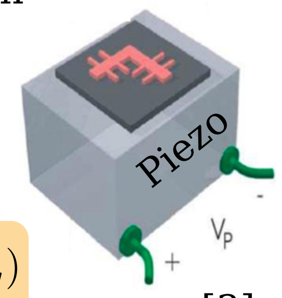
due to bulk inversion asymmetry (BIA)

$$\mathcal{H}_{\rm BIA} = \frac{2}{\sqrt{3}}C_k\left(k_x\{J_x, J_y^2 - J_z^2\} + \text{c.p.}\right) + \left(\begin{array}{c}\text{other } relativistic \text{ terms}\\ \sim b^{8v8v}_{42}, b^{8v8v}_{51}, b^{8v8v}_{52}\end{array}\right) + b^{8v8v}_{41}\left(\{k_x, k_y^2 - k_z^2\}J_x + \text{c.p.}\right)$$

and the *Bir-Pikus Hamiltonian* to include strain

$$\mathcal{H}_{\rm S} = \sum_i\left(a\,\epsilon_{ii} + b\,\epsilon_{ii}J_i^2 + d\sum_{j,\,j\neq i}\epsilon_{ij}\{J_i, J_j\}\right)$$

$$\beta^2 e^{2i\theta} := \frac{m_0}{\hbar^2\gamma_3}\left(b\left(\epsilon_{xx} - \epsilon_{yy}\right) + 2id\epsilon_{xy}\right)$$



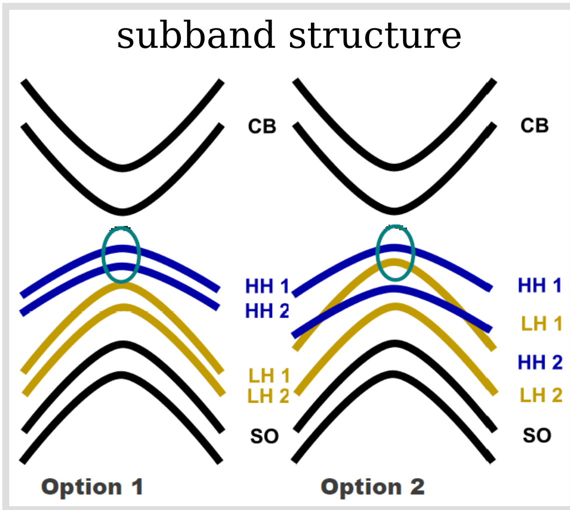
[3]

The structure IA (SIA) contribution is calculated explicitly by including

$$V_{\rm E}(z) = \mathbb{1}_{4\times4}\cdot e\mathcal{E}_z z$$

The lateral confinement,

$$V_{\rm c}(z) = \mathbb{1}_{4\times4}\cdot\begin{cases}0 & \text{for } z\in[0, L],\\ \infty & \text{otherwise.}\end{cases}$$

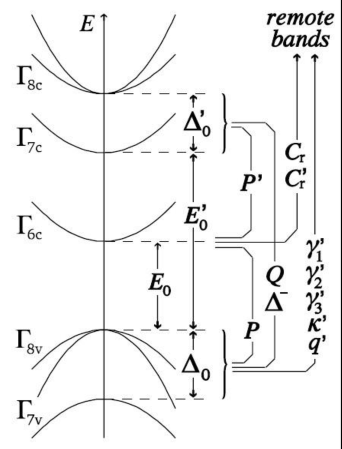


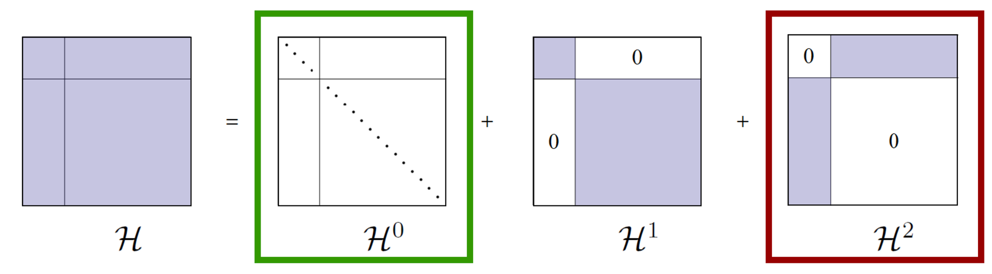
Model

The confinement in [001]-direction allows for a simplification of

$$\mathcal{H} = \begin{pmatrix}\mathcal{H}_{\rm HH} & \mathcal{H}_{\rm HH\text{-}LH}\\ \mathcal{H}_{\rm LH\text{-}HH} & \mathcal{H}_{\rm LH}\end{pmatrix}$$

to an effective HH/LH 2x2 Hamiltonian using quasi-degenerate perturbation theory, **Loewdin's partitioning**

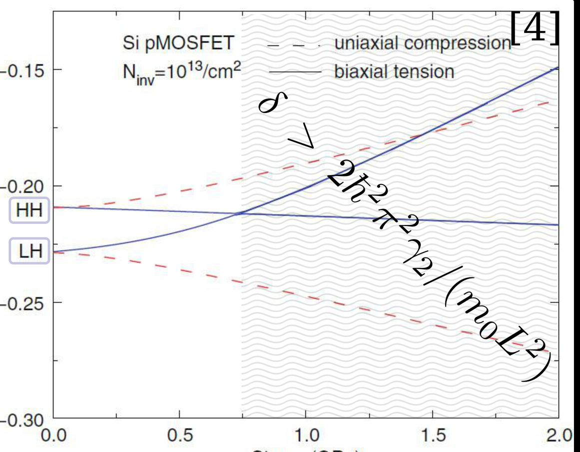




Small parameter in perturb.: subband splitting

spatial confinement

strain $\delta = b\left(\epsilon_{xx} + \epsilon_{yy} - 2\epsilon_{zz}\right)$



If the non-commutativity of the momentum operator k_z and the position operator z is used to derive a finite Rashba coefficient the **energy splitting** $\Delta_{\rm hl}$ **cannot be the one coming from the subband quantization**, which is a result of the confinement in z-direction. The splitting has to have another source, e.g., **strain**.
Given a HH(LH) like ground state it is necessary to include, in addition to the first LH(HH) like subband, also the **second HH(LH) like subband**.

Effective SO Field

Assuming the ground state being HH/LH like and applying third order Loewdin perturbation theory,

$$\mathcal{H}^{\rm eff} \approx \sum_{i=0}^{3}\left(E^{(i)}_{\rm kin} + V^{(i)}_{\rm eff}\right)\cdot\mathbb{1}_{2\times2} + \mathbf{\Omega}^{(i)}\cdot\boldsymbol{\sigma}$$

we get for the SO field

$$\mathbf{\Omega}_{\rm HH} = \mathbf{\Omega}_+$$
$$\mathbf{\Omega}_{\rm LH} = \mathbf{\Omega}_- + \mathbf{\Omega}_b$$
$$\mathbf{\Omega}_b = b^{8v8v}_{41}\left\{k_xk_y^2, -k_x^2k_y, 0\right\}^\top$$

$$\Omega_{x,\pm} = \lambda_{\rm D,\pm}\Big\{k_xk_y^2\left(\gamma_2 \mp 2\gamma_3\right) - k_x^3\gamma_2 + \eta_\pm k_x + \beta^2\gamma_3\Big[\pm k_y\left(\frac{k_x^2}{\langle k_z^2\rangle} - 1\right)\sin(2\theta) + k_x\left(\frac{k_y^2}{\langle k_z^2\rangle} - 1\right)\cos(2\theta)\Big]\Big\}$$
$$+ \lambda_{\rm R,\pm}\left[\pm\left(\gamma_2 \pm 2\gamma_3\right)k_x^2k_y \mp \gamma_2k_y^3 + \beta^2\gamma_3\left(\pm k_y\cos(2\theta) + k_x\sin(2\theta)\right)\right],$$

dependence on shear strain ϵ_{xy} and deformation potential d

$$\Omega_{y,\pm} = \lambda_{\rm D,\pm}\Big\{\pm k_x^2k_y\left(\gamma_2 \mp 2\gamma_3\right) \mp k_y^3\gamma_2 \pm \eta_\pm k_y + \beta^2\gamma_3\Big[k_x\left(\frac{k_y^2}{\langle k_z^2\rangle} - 1\right)\sin(2\theta) \mp k_y\left(\frac{k_x^2}{\langle k_z^2\rangle} - 1\right)\cos(2\theta)\Big]\Big\}$$
$$\pm \lambda_{\rm R,\pm}\left[\pm\left(\gamma_2 \pm 2\gamma_3\right)k_xk_y^2 \mp \gamma_2k_x^3 + \beta^2\gamma_3\left(k_y\sin(2\theta) \mp k_x\cos(2\theta)\right)\right]$$

$\eta_+ \sim \eta_0(C_k, b^{8v8v}_{42}, b^{8v8v}_{51})$ — small *relativistic* Dresselhaus SOC terms --> ***linear*** in k contribution!

$$\lambda_{\rm D,\pm} = \pm\frac{3\hbar^2}{2m_0\Delta_{\rm h1,l1}}b^{8v8v}_{41}\langle k_z^2\rangle,$$

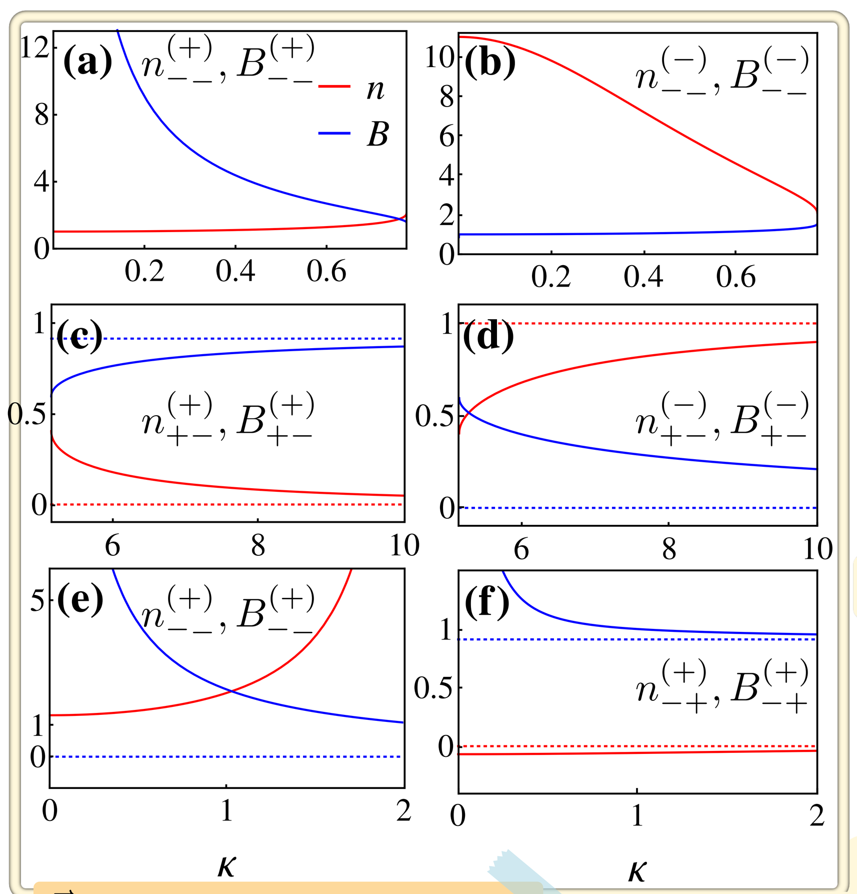
2nd order contribution due to Dresselhaus SOC

$$\lambda_{\rm R,+} = \frac{128\hbar^4 e\mathcal{E}_z\gamma_3}{9\pi^2m_0^2\Delta_{\rm h1,l1}\Delta_{\rm h1,h2}},$$
$$\lambda_{\rm R,-} = \frac{128\hbar^4 e\mathcal{E}_z\gamma_3}{9\pi^2m_0^2\Delta_{\rm l1,h1}\Delta_{\rm l1,l2}}.$$

3rd order contribution due to Rashba SOC, prop. to γ_3 !

The contribution comming from $\mathcal{H}^r_{8v8v} = r^{8v8v}_{41}((k_y\mathcal{E}_z - k_z\mathcal{E}_y)J_x + \text{c.p.})$ is of **higher than 3rd order**!

Conditions for a Conserved Spin in a 2DHG



Following the analysis of Ref. [2], our goal is to identify a conserved quantity Σ which is directly connected with k-independent eigenspinors. The general ansatz is

$$[\Sigma, \mathcal{H}_{\rm eff}] = 0 \quad \text{with} \quad \Sigma = s_0\mathbb{1}_{2\times2} + \mathbf{s}\cdot\boldsymbol{\sigma}$$

$$\Sigma_\xi = \sum_{\mathbf{k},k=k_{\parallel F}}\sum_{\alpha\beta}c^\dagger_{\mathbf{k}\alpha}(\sigma_x + \xi\sigma_y)_{\alpha\beta}c_{\mathbf{k}\beta},\qquad \Sigma_\pm$$

$$\theta = \pm\tfrac{\pi}{4} \equiv \chi\tfrac{\pi}{4} \longleftrightarrow \epsilon_{xx} = \epsilon_{yy} \wedge \epsilon_{xy} \neq 0 \;\vee\; \beta = 0,\quad \text{fixed } k_{\parallel F} = \sqrt{\eta_+(\Gamma+1)/(2\gamma_2\lambda_{D,+}\Gamma)}$$

However, this is limited to a specific relation between

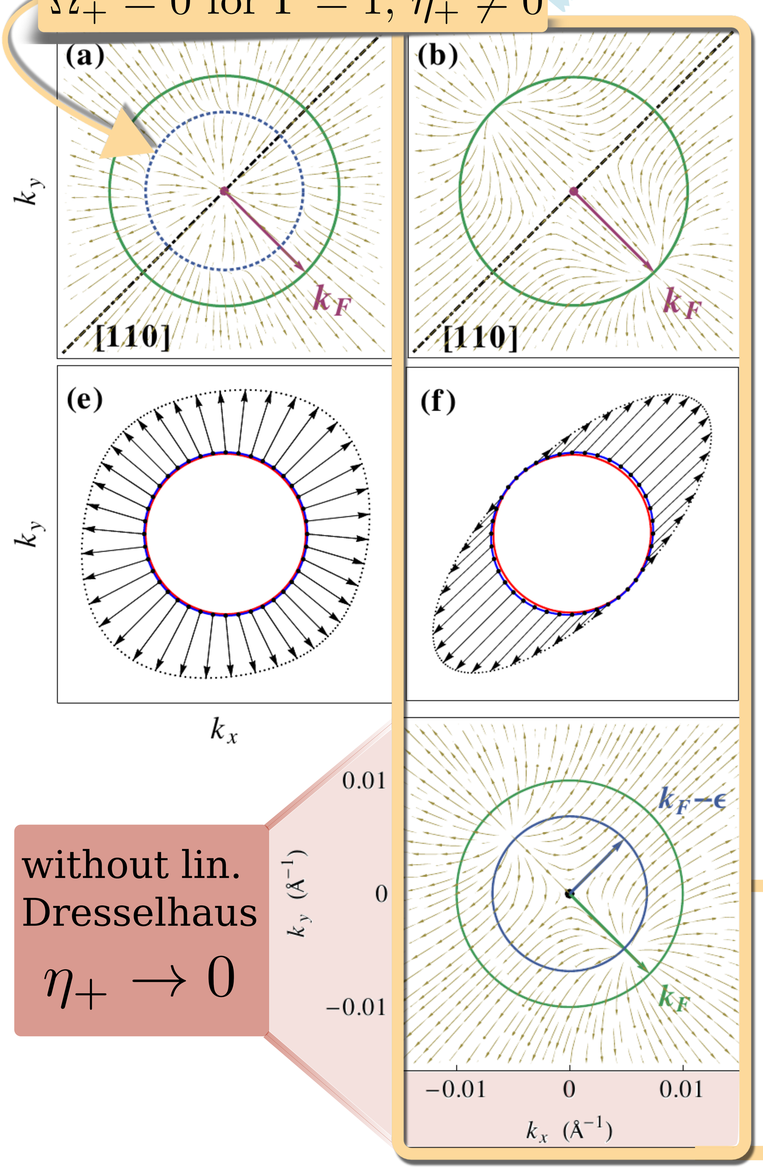
- Rashba and Dresselhaus SOC
- Luttinger parameters
- strain amplitude:

(a)-(d): optimal parameter condition for HH like ground state, (e),(f): LH like

$$n^{(\pm)}_{\xi,\chi} = \xi\frac{2\left(1+\Gamma\right)}{2\left(1-\Gamma\right) - (\xi\chi)\Gamma\kappa^2\left(B^{(\pm)}_{\xi,\chi}\right)^2},$$
$$B^{(\pm)}_{\xi,\chi} = \sqrt{\frac{\xi\chi\left(4-\kappa^2\right) \pm \mathcal{W}}{2\Gamma\kappa^2}},$$
$$\mathcal{W} = \sqrt{\kappa^4 + 8\left(1+\Gamma\right)\eta_0 - 8\left(1+2\Gamma\right)\kappa^2 + 16}.$$

$$\lambda_{\rm D,\pm} = n\lambda_{\rm R\,\pm},\quad \gamma_3 = \Gamma\gamma_2,\quad \beta = Bk_{\parallel F},\quad \langle k_z^2\rangle = \left(\frac{k_{\parallel F}}{\kappa}\right)^2$$

$\vec{\Omega}_+ = 0$ for $\Gamma = 1$, $\eta_+ \neq 0$



p-doped InSb: SO field without (left column) and with applied strain.

Limitation: Only on the averaged E_F contour (rot. symmetric) we find (here for a HH like ground state) a collinear SO field:

$$\mathbf{\Omega}_{\rm HH} = (k_x + \xi k_y)\varphi^{(\pm)}(k_x, k_y)\begin{pmatrix}\xi\\1\\0\end{pmatrix}\Bigg|_{k_x^2+k_y^2=k_{\parallel F}^2}.$$

We have shown that for the **existence of a conserved spin quantity** in semiconductors, which are accessible for experiments, the **interplay between Dresselhaus SOC, Rashba SOC and strain is crucial. We do not find a conserved spin-quantity for realistic band parameters and unconstrained $\mathbf{E_F}$ if one of these constituents is missing.**

Outlook

- Analysis of long lived spin states in 2DHGs with other growth directions.
- Calculation of weak (anti)localization.
- Dependence of Rashba SOC coefficient on the filling.

References

[1] Schliemann *et al.*, PRL **90**, 146801 (2003)
[2] Dollinger *et al.*, PRB **90**, 115306 (2014)
[3] Sacksteder *et al.*, PRB **89**, 161307 (2014)
[4] Sun et al., Strain Effects in Semiconductors: Theory and Device Applications, Springer (2010)

Poster results: PRB **93, 115312 (2016)**