A microscopic approach to spin dynamics: about the meaning of spin relaxation times

Christian Lechner

christian.lechner@physik.uni-regensburg.de

Institut für Theoretische Physik, Universität Regensburg

20.04.2005

Outline

- Motivation
- Spin relaxation in semiconductors
- The concept of Bloch equations
- The spin-dependent Bloch equations
  - An extension of the optical Bloch equations
  - Comparison with experimental observables
- Conclusion

Motivation

- Reaching limits of conventional semiconductor technologies (e.g. transistors)
  $\longrightarrow$ leakage currents
  $\longrightarrow$ heat

Motivation

- Reaching limits of conventional semiconductor technologies (e.g. transistors)
  $\longrightarrow$ leakage currents
  $\longrightarrow$ heat
- Possible solution: Spintronics
  $\Rightarrow$ *Usage of the spin degree-of-freedom of carriers*
  (not only electronic devices, also optical devices)

Motivation

- Reaching limits of conventional semiconductor technologies (e.g. transistors)
  $\longrightarrow$ leakage currents
  $\longrightarrow$ heat
- Possible solution: Spintronics
  $\Rightarrow$ *Usage of the spin degree-of-freedom of carriers*
  (not only electronic devices, also optical devices)
- Limits of spintronics:
  $\longrightarrow$ spin injection
  $\Rightarrow$ **spin relaxation and spin dephasing**

Spin relaxation DP

D'yakonov Perel' (DP) mechanism

- Origin: spin-orbit (SO) interaction in systems without inversion-symmetry
  $\longrightarrow$ band splitting: $E_\uparrow(\mathbf{k}) \neq E_\downarrow(\mathbf{k})$

  Structure of SO interaction: $\mathcal{H}_{SO} \sim \sigma \cdot \mathbf{B}(\mathbf{k})$
  $\longrightarrow$ splitting corresponds to an effective $\mathbf{k}$-dependent magnetic field $\mathbf{B}(\mathbf{k})$
  $\Rightarrow$ precession of the spins around $\mathbf{B}(\mathbf{k})$

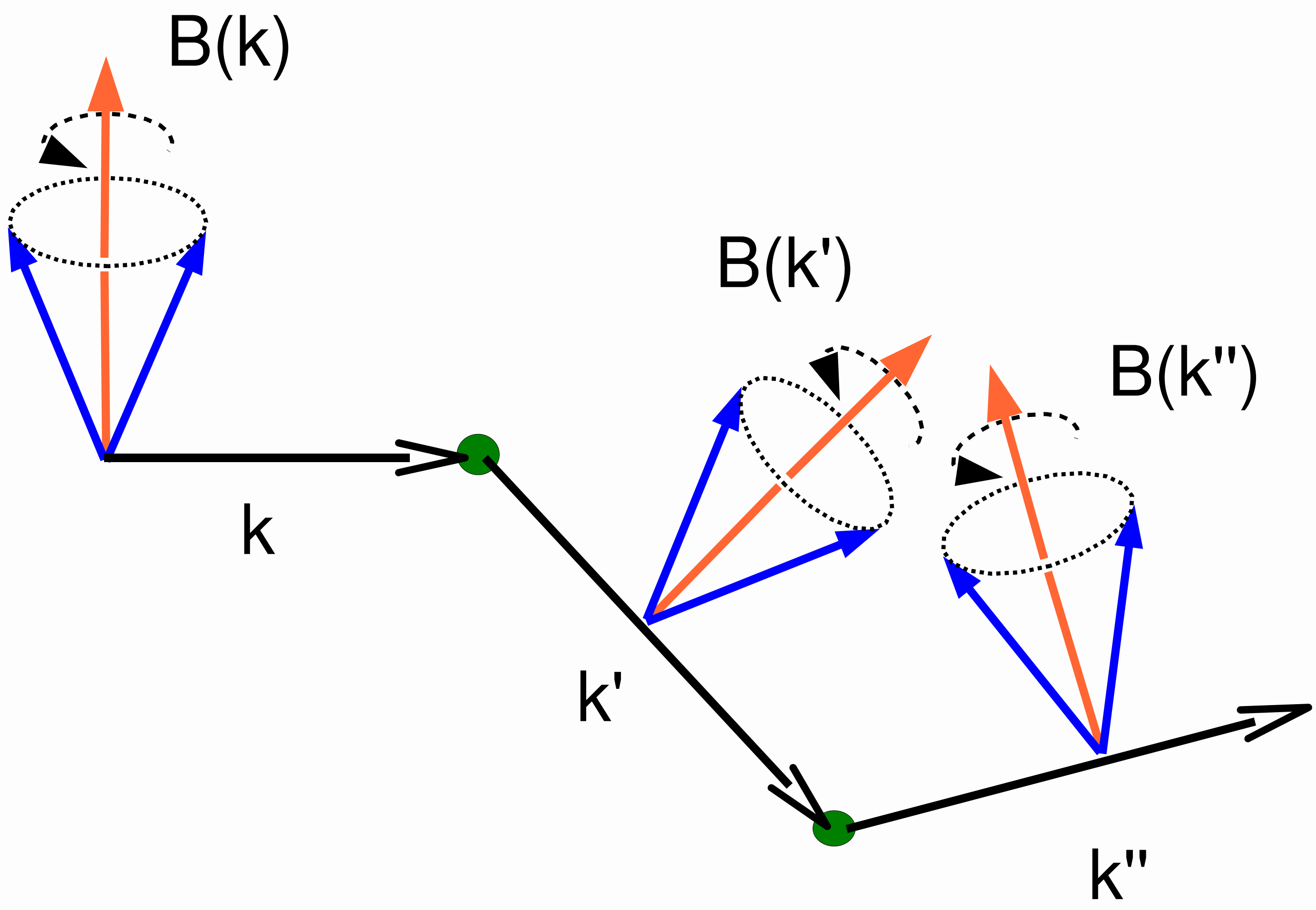
Spin relaxation DP

D'yakonov Perel' (DP) mechanism

- Origin: spin-orbit (SO) interaction in systems without inversion-symmetry
  $\rightarrow$ band splitting: $E_{\uparrow}(\mathbf{k}) \neq E_{\downarrow}(\mathbf{k})$

  Structure of SO interaction: $\mathcal{H}_{SO} \sim \sigma \cdot \mathbf{B}(\mathbf{k})$
  $\rightarrow$ splitting corresponds to an effective $\mathbf{k}$-dependent magnetic field $\mathbf{B}(\mathbf{k})$
  $\Rightarrow$ precession of the spins around $\mathbf{B}(\mathbf{k})$
- In addition: scattering
  $\rightarrow$ change of the $\mathbf{k}$-vector of the electrons
  $\rightarrow$ change of the magnetic field $\mathbf{B}(\mathbf{k})$

Spin relaxation DP II



Spin relaxation DP III

⇒ **Spin relaxation**

Spin relaxation DP III

⇒ Spin relaxation

- Characteristics:
  spin relaxation time $\leftrightarrow$ scattering time
  (*motional narrowing*)

$$\tau_s \sim \tau_p^{-1}$$

Spin relaxation DP III

⇒ **Spin relaxation**

- Characteristics:
  spin relaxation time ↔ scattering time
  (*motional narrowing*)

$$\tau_s \sim \tau_p^{-1}$$

- Sources of inversions-asymmetry:
  bulk inversion-asymmetry (BIA/Dresselhaus)

$$\mathbf{B}(\mathbf{k}) \sim \mathbf{k}^3$$

  structure inversion-asymmetry (SIA/Rashba)

$$\mathbf{B}(\mathbf{k}) \sim \mathbf{k}$$

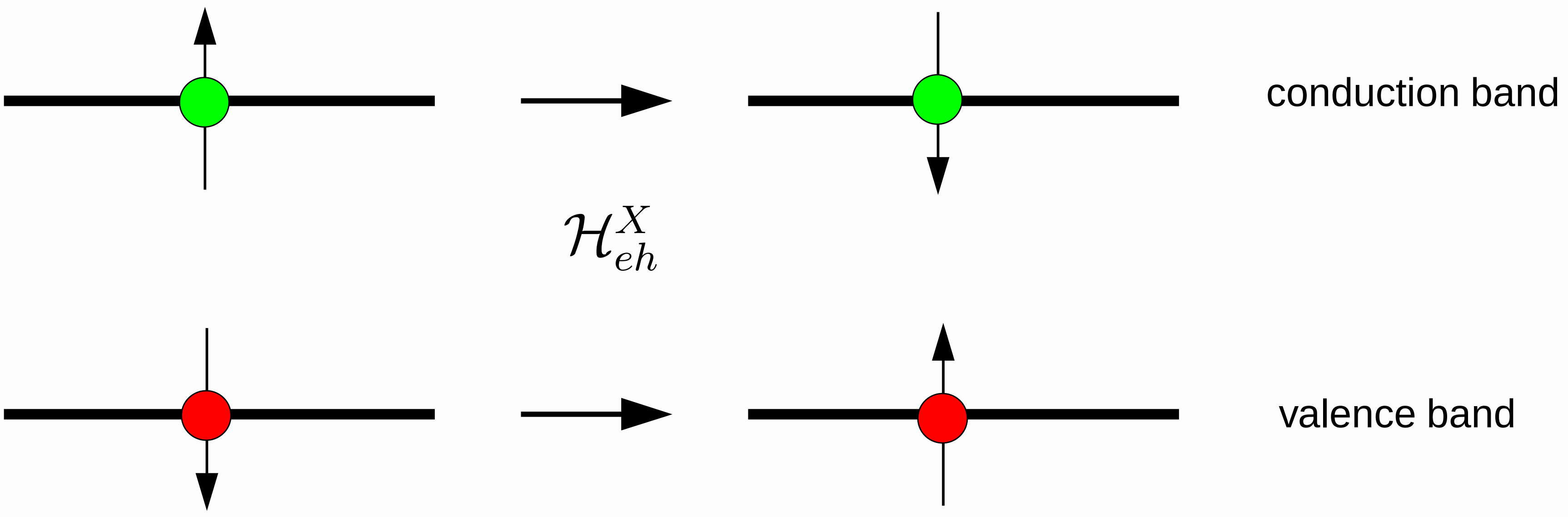
Spin relaxation BAP

Bir Aronov Pikus (BAP) mechanism

- Scattering of electrons and holes due to Coulomb-exchange interaction possible

$\longrightarrow$ simultaneous spin-flip of electrons and holes

$\Rightarrow$ restriction on electron system: spin relaxation


$\mathcal{H}_{eh}^{X}$
conduction band
valence band

Spin relaxation EY

Elliott Yafet (EY) mechanism

- SO interaction leads to admixture of hole states in the valence band to electron states in the conduction band with opposite spin
  $\longrightarrow$ no pure states
  $\Rightarrow$ direct spin flip scattering possible
- Characteristics:
  spin relaxation time $\leftrightarrow$ scattering time

$$\tau_s \sim \tau_p$$

- What is one of the best methods to describe dynamics in optically excited semiconductors?

Universität Regensburg

Bloch equations I

- What is one of the best methods to describe dynamics in optically excited semiconductors?

Bloch equations

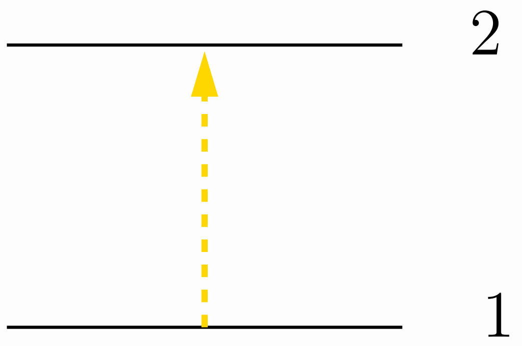
Universität Regensburg

Bloch equations I

- What is one of the best methods to describe dynamics in optically excited semiconductors?

Bloch equations

- Example: optically driven two-level system

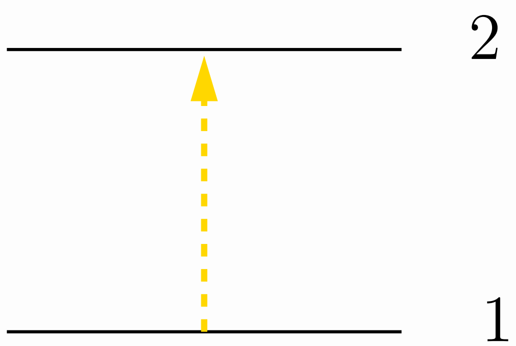


Bloch equations I

- What is one of the best methods to describe dynamics in optically excited semiconductors?

Bloch equations

- Example: optically driven two-level system



Dynamical variables of the system:

occupation difference

coherence

Bloch equations II

- Description by 2×2 density matrix:

$$\varrho_{i\,j} := \langle c_i^\dagger\, c_j \rangle = \begin{cases} i = j & \text{occupation number} \\ i \neq j & \text{coherence} \end{cases}$$

- Equations of motion (EOM) given by *Liouville equation*

$$i\,\hbar\,\partial_t \varrho = [\mathcal{H}, \varrho]_-$$

- Decay of the components:
  - occupation number T_1 ($\longrightarrow$ diagonal entries)
  - coherence T_2 ($\longrightarrow$ offdiagonal entries)

Universität Regensburg

Spindynamics I

- Possibility 1: classification of the spin states with respect to a fixed quantization axis (e.g. growth direction of a QW)

Universität Regensburg

Spindynamics I

- Possibility 1: classification of the spin states with respect to a fixed quantization axis (e.g. growth direction of a QW)
- spin-up and spin-down electrons in the conduction band define two-level system (coupling via SO interaction)

$$\varrho(\mathbf{k}) := \begin{pmatrix} \varrho_{\uparrow\uparrow}(\mathbf{k}) & \varrho_{\uparrow\downarrow}(\mathbf{k}) \\ \varrho_{\downarrow\uparrow}(\mathbf{k}) & \varrho_{\downarrow\downarrow}(\mathbf{k}) \end{pmatrix}$$

Hamiltonian:

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{light} + \mathcal{H}_{scatt}$$

Spindynamics II

- Hamiltonian for a QW system with SO interaction

$$\mathcal{H}_0 = \sum_{\substack{\sigma\,\sigma' \\ \mathbf{k}'}} \left\{ \epsilon(\mathbf{k}') + \mathbf{h}(\mathbf{k}')\,\frac{\sigma_{\sigma\,\sigma'}}{\mathbf{2}} \right\} c^\dagger_\sigma(\mathbf{k}')\, c_{\sigma'}(\mathbf{k}')$$

SO interaction: $\mathbf{h}(\mathbf{k}) = \Big(h_x(\mathbf{k}),\ h_y(\mathbf{k}),\ 0\Big)$

Spindynamics II

- Hamiltonian for a QW system with SO interaction

$$\mathcal{H}_0 = \sum_{\substack{\sigma\,\sigma' \\ \mathbf{k}'}} \left\{ \epsilon(\mathbf{k}') + \mathbf{h}(\mathbf{k}')\,\frac{\sigma_{\sigma\,\sigma'}}{\mathbf{2}} \right\} c^\dagger_\sigma(\mathbf{k}')\,c_{\sigma'}(\mathbf{k}')$$

SO interaction: $\mathbf{h}(\mathbf{k}) = \Big(h_x(\mathbf{k}),\, h_y(\mathbf{k}),\, 0\Big)$

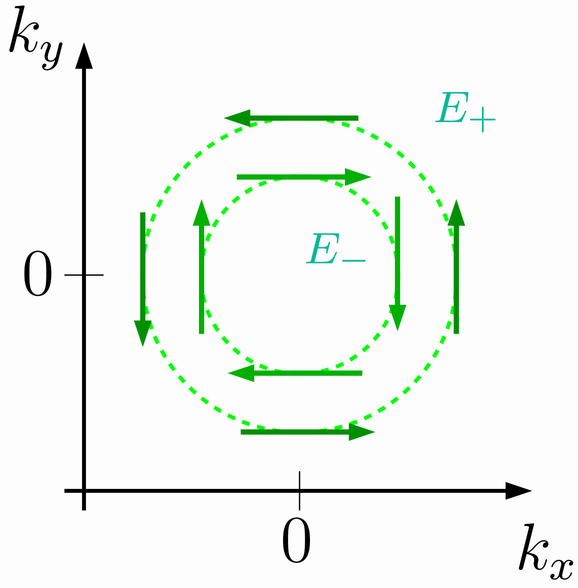
- EOM:

$$\begin{aligned}
\partial_t \varrho_{\uparrow\uparrow}(\mathbf{k}) &= -\frac{1}{\hbar}\Big(h_x(\mathbf{k})\,\Im\{\varrho_{\uparrow\downarrow}(\mathbf{k})\} - h_y(\mathbf{k})\,\Re\{\varrho_{\uparrow\downarrow}(\mathbf{k})\}\Big) \\
\partial_t \varrho_{\downarrow\downarrow}(\mathbf{k}) &= \frac{1}{\hbar}\Big(h_x(\mathbf{k})\,\Im\{\varrho_{\uparrow\downarrow}(\mathbf{k})\} - h_y(\mathbf{k})\,\Re\{\varrho_{\uparrow\downarrow}(\mathbf{k})\}\Big) \\
\partial_t \varrho_{\uparrow\downarrow}(\mathbf{k}) &= \frac{1}{2\,\hbar}\Big(i\,h_x(\mathbf{k}) - h_y(\mathbf{k})\Big)\Big(\varrho_{\uparrow\uparrow}(\mathbf{k}) - \varrho_{\downarrow\downarrow}(\mathbf{k})\Big)
\end{aligned}$$

[↻]

Bloch equations with spin

- Aim: microscopic theory of spin relaxation based on the **Bloch equations**
- Formulation with diagonal kinetic part of Hamiltonian
  $\longrightarrow$ Eigenstates
  $\Rightarrow$ Spin ($\pm\mathbf{m_c}$) depends on wavevector $\mathbf{k}$



Bloch equations with spin II

- scattering described in the density matrix formalism
  $\longrightarrow$ restriction on electron-phonon scattering

$\Rightarrow$ **Extension of the *optical* Bloch equations**

- Starting point: six-level system

- Spin polarization is controlled by excitation with circularly polarized light

Bloch equations with spin III

- Hamiltonian:

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{light} + \mathcal{H}_{phonon}$$

Bloch equations with spin III

- Hamiltonian:

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{light} + \mathcal{H}_{phonon}$$

- Kinetic contribution:

$$\mathcal{H}_0 = \sum_{\mathbf{k}'\, m_c'} \epsilon_{m_c'}(\mathbf{k}')\, c^{\dagger}_{m_c'}(\mathbf{k}')\, c_{m_c'}(\mathbf{k}') + \sum_{\mathbf{k}'\, m_v'} \epsilon_{m_v'}(\mathbf{k}')\, v_{m_v'}(\mathbf{k}')\, v^{\dagger}_{m_v'}(\mathbf{k}')$$

Bloch equations with spin III

- Hamiltonian:

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{light} + \mathcal{H}_{phonon}$$

- Kinetic contribution:

$$\mathcal{H}_0 = \sum_{\mathbf{k}'\, m'_c} \epsilon_{m'_c}(\mathbf{k}')\, c^\dagger_{m'_c}(\mathbf{k}')\, c_{m'_c}(\mathbf{k}') + \sum_{\mathbf{k}'\, m'_v} \epsilon_{m'_v}(\mathbf{k}')\, v_{m'_v}(\mathbf{k}')\, v^\dagger_{m'_v}(\mathbf{k}')$$

- Hamiltonian is diagonal
$\longrightarrow$ spin precession contained in eigenenergies $\epsilon_{m_i}(\mathbf{k})$
[↻]

Bloch equations with spin III

- Hamiltonian:

$$\mathcal{H} = \mathcal{H}_0 + \mathcal{H}_{light} + \mathcal{H}_{phonon}$$

- Kinetic contribution:

$$\mathcal{H}_0 = \sum_{\mathbf{k}'\, m_c'} \epsilon_{m_c'}(\mathbf{k}')\, c^\dagger_{m_c'}(\mathbf{k}')\, c_{m_c'}(\mathbf{k}') + \sum_{\mathbf{k}'\, m_v'} \epsilon_{m_v'}(\mathbf{k}')\, v_{m_v'}(\mathbf{k}')\, v^\dagger_{m_v'}(\mathbf{k}')$$

- Hamiltonian is diagonal
  $\rightarrow$ spin precession contained in eigenenergies $\epsilon_{m_i}(\mathbf{k})$
  [$\circlearrowright$]

- Interaction with the light field:

$$\mathcal{H}_{light} = -\sum_{\substack{m_c'\, m_v' \\ \mathbf{k}'}} \left\{ \mathbf{E}(t) \cdot \mathbf{d}^{cv}_{m_c'\, m_v'}(\mathbf{k}')\, c^\dagger_{m_c'}(\mathbf{k}')\, v^\dagger_{m_v'}(\mathbf{k}') + \text{h.c.} \right\}$$

Bloch equations with spin VI

- Electron-phonon interaction $\mathcal{H}_{phonon}$:

$$\mathcal{H}_{phonon} \quad =$$

Bloch equations with spin VI

- Electron-phonon interaction $\mathcal{H}_{phonon}$:

$$\mathcal{H}_{phonon} = \boxed{\sum_{\mathbf{q}} \hbar\,\omega(\mathbf{q})\, b^\dagger(\mathbf{q})\, b(\mathbf{q})}$$

Bloch equations with spin VI

- Electron-phonon interaction $\mathcal{H}_{phonon}$:

$$\mathcal{H}_{phonon} = \sum_{\mathbf{q}} \hbar\,\omega(\mathbf{q})\, b^\dagger(\mathbf{q})\, b(\mathbf{q})$$

$$+ \sum_{\mathbf{k}'\,\mathbf{q}} \Big\{ \sum_{m_c'\,m_c''} \Big(g^e_{m_c'\,m_c''}(\mathbf{q})\, c^\dagger_{m_c''}(\mathbf{k}'+\mathbf{q})\, b(\mathbf{q})\, c_{m_c'}(\mathbf{k}')$$

$$+\,\text{h.c.}\Big)$$

Bloch equations with spin VI

- Electron-phonon interaction $\mathcal{H}_{phonon}$:

$$\mathcal{H}_{phonon} = \sum_{\mathbf{q}} \hbar\,\omega(\mathbf{q})\, b^\dagger(\mathbf{q})\, b(\mathbf{q})$$
$$+ \sum_{\mathbf{k}'\,\mathbf{q}} \Big\{ \sum_{m_c'\,m_c''} \Big(g^e_{m_c'\,m_c''}(\mathbf{q})\, c^\dagger_{m_c''}(\mathbf{k}'+\mathbf{q})\, b(\mathbf{q})\, c_{m_c'}(\mathbf{k}') + \text{h.c.}\Big)$$
$$+ \sum_{m_v'\,m_v''} \Big(g^h_{m_v'\,m_v''}(\mathbf{q})\, v^\dagger_{m_v''}(\mathbf{k}'+\mathbf{q})\, b(\mathbf{q})\, v_{m_v'}(\mathbf{k}') + \text{h.c.}\Big)$$

Universität Regensburg

Bloch equations with spin V

- Restriction to conduction band
  $\rightarrow 2 \times 2$ density matrix:

$$\boldsymbol{\varrho}^{(m_c\,\bar{m}_c)}(\mathbf{k}) = \begin{pmatrix} \varrho_{m_c\,m_c}(\mathbf{k}) & \varrho_{m_c\,-m_c}(\mathbf{k}) \\ \varrho_{-m_c\,m_c}(\mathbf{k}) & \varrho_{-m_c\,-m_c}(\mathbf{k}) \end{pmatrix}$$

- Scattering treated in 2^{nd} order Born approximation

Bloch equations with spin VI

- EOM of $\varrho_{m_c\,m_c}(\mathbf{k})$:

$$
\begin{aligned}
i\hbar\partial_t\,\varrho_{m_c\,m_c}(\mathbf{k}) \;=\;& \sum_{m_v}\left\{\mathbf{E}(t)\cdot\mathbf{d}^{cv}_{m_c\,m_v}(\mathbf{k})\,P_{m_c\,m_v}(\mathbf{k}) - \text{h.c.}\right\}\\
&+\sum_{\mathbf{q}\,m_c'}\Big\{g^{e}_{m_c'\,m_c}(\mathbf{q})\langle c^\dagger_{m_c'}(\mathbf{k}+\mathbf{q})\,b(\mathbf{q})\,c_{m_c}(\mathbf{k})\rangle\\
&\quad - g^{e}_{m_c\,m_c'}(\mathbf{q})\langle c^\dagger_{m_c}(\mathbf{k})\,b(\mathbf{q})\,c_{m_c'}(\mathbf{k}-\mathbf{q})\rangle\\
&\quad + g^{e\,*}_{m_c\,m_c'}(\mathbf{q})\langle c^\dagger_{m_c'}(\mathbf{k}-\mathbf{q})\,b^\dagger(\mathbf{q})\,c_{m_c}(\mathbf{k})\rangle\\
&\quad - g^{e\,*}_{m_c'\,m_c}(\mathbf{q})\langle c^\dagger_{m_c}(\mathbf{k})\,b^\dagger(\mathbf{q})\,c_{m_c'}(\mathbf{k}+\mathbf{q})\rangle\Big\}
\end{aligned}
$$

Bloch equations with spin VI

Universität Regensburg

- EOM of $\varrho_{m_c\, m_c}(\mathbf{k})$:

$$
\begin{aligned}
i\hbar\partial_t\, \varrho_{m_c\, m_c}(\mathbf{k}) \;&=\; \sum_{m_v} \left\{ \mathbf{E}(t)\cdot \mathbf{d}^{cv}_{m_c\, m_v}(\mathbf{k})\, P_{m_c\, m_v}(\mathbf{k}) - \text{h.c.} \right\} \\
&+ \sum_{\mathbf{q}\, m_c'} \Big\{ g^{e}_{m_c'\, m_c}(\mathbf{q}) \langle c^\dagger_{m_c'}(\mathbf{k}+\mathbf{q})\, b(\mathbf{q})\, c_{m_c}(\mathbf{k})\rangle \\
&\qquad - g^{e}_{m_c\, m_c'}(\mathbf{q}) \langle c^\dagger_{m_c}(\mathbf{k})\, b(\mathbf{q})\, c_{m_c'}(\mathbf{k}-\mathbf{q})\rangle \\
&\qquad + g^{e\,*}_{m_c\, m_c'}(\mathbf{q}) \langle c^\dagger_{m_c'}(\mathbf{k}-\mathbf{q})\, b^\dagger(\mathbf{q})\, c_{m_c}(\mathbf{k})\rangle \\
&\qquad - g^{e\,*}_{m_c'\, m_c}(\mathbf{q}) \langle c^\dagger_{m_c}(\mathbf{k})\, b^\dagger(\mathbf{q})\, c_{m_c'}(\mathbf{k}+\mathbf{q})\rangle \Big\}
\end{aligned}
$$

- Hierarchy problem due to *phonon-assisted* density matrices

Bloch equations with spin VII

Solution: truncation of the hierarchy

1. Derive EOM of the phonon-assisted density matrices
2. Factorize the expectation values into their macroscopic parts
3. Take only those which lead to a absolute squared value of the interaction matrix element
4. Integrate and apply the *Markov* and *adiabatic* approximation
5. Insert result into initial EOM

$\longrightarrow$ Boltzmann limit

Results

- Diagonal entry:

$$\partial_t\, \varrho_{m_c\, m_c}(\mathbf{k})\big|_{phonon} = -\Gamma^{out}_{m_c\, m_c}(\mathbf{k})\, \varrho_{m_c\, m_c}(\mathbf{k}) + \Gamma^{in}_{m_c\, m_c}(\mathbf{k})(1 - \varrho_{m_c\, m_c}(\mathbf{k}))$$

- with:

$$\Gamma^{out}_{m_c\, m_c}(\mathbf{k}) = \frac{\pi}{\hbar} \sum_{\mathbf{q}, m_c'} |g_{m_c'\, m_c}(\mathbf{q})|^2 \times \Big\{ \delta\left(\epsilon_{m_c'}(\mathbf{k}+\mathbf{q}) - \epsilon_{m_c}(\mathbf{k}) - \hbar\omega(\mathbf{q})\right) \left(1 - \varrho_{m_c'\, m_c'}(\mathbf{k}+\mathbf{q})\right) \beta(\mathbf{q}) + \delta\left(\epsilon_{m_c'}(\mathbf{k}-\mathbf{q}) - \epsilon_{m_c}(\mathbf{k}) + \hbar\omega(\mathbf{q})\right) \left(1 - \varrho_{m_c'\, m_c'}(\mathbf{k}-\mathbf{q})\right) \times (1 + \beta(\mathbf{q})) \Big\}$$

Results II

- Offdiagonal entry:

$$\partial_t \, \varrho_{m_c\,-m_c}(\mathbf{k})\big|_{phonon} = \frac{1}{i\hbar}\,\Sigma^{e-p}_{m_c\,-m_c}(\mathbf{k})\;\varrho_{m_c\,-m_c}(\mathbf{k})$$

- Self-energy

$$\Sigma^{e-p}_{m_c\,-m_c}(\mathbf{k}) = \hbar\left(\Omega^{e-p}_{m_c\,-m_c}(\mathbf{k}) - i\,\Gamma^{e-p}_{m_c\,-m_c}(\mathbf{k})\right)$$

- real and imaginary part are connected via *Kramers-Kronig relation*

Results III

Imaginary part of the self-energy

$$\Gamma^{e-p}_{m_c\,-m_c}(\mathbf{k}) =$$

$$\frac{\pi}{\hbar}\sum_{\mathbf{q}\,m_c'}\Big\{|g^{e}_{m_c'\,m_c}(\mathbf{q})|^2\,\delta\left(\epsilon_{m_c'}(\mathbf{k}+\mathbf{q})-\epsilon_{-m_c}(\mathbf{k})-\hbar\omega(\mathbf{q})\right)\,\times$$

$$\left[\left(1-\varrho_{m_c'\,m_c'}(\mathbf{k}+\mathbf{q})\right)\,\beta(\mathbf{q})+\varrho_{m_c'\,m_c'}(\mathbf{k}+\mathbf{q})\,(1+\beta(\mathbf{q}))\right]$$

$$+|g^{e}_{m_c'\,m_c}(\mathbf{q})|^2\,\delta\left(\epsilon_{m_c'}(\mathbf{k}-\mathbf{q})-\epsilon_{-m_c}(\mathbf{k})+\hbar\omega(\mathbf{q})\right)\,\times$$

$$\left[\left(1-\varrho_{m_c'\,m_c'}(\mathbf{k}-\mathbf{q})\right)\,(1+\beta(\mathbf{q}))+\varrho_{m_c'\,m_c'}(\mathbf{k}-\mathbf{q})\,\beta(\mathbf{q})\right]$$

$$+|g^{e}_{m_c'\,-m_c}(\mathbf{q})|^2\,\delta\left(\epsilon_{m_c}(\mathbf{k})-\epsilon_{m_c'}(\mathbf{k}-\mathbf{q})-\hbar\omega(\mathbf{q})\right)\,\times$$

$$\left[\left(1-\varrho_{m_c'\,m_c'}(\mathbf{k}-\mathbf{q})\right)\,(1+\beta(\mathbf{q}))+\varrho_{m_c'\,m_c'}(\mathbf{k}-\mathbf{q})\,\beta(\mathbf{q})\right]$$

$$+|g^{e}_{m_c'\,-m_c}(\mathbf{q})|^2\,\delta\left(\epsilon_{m_c}(\mathbf{k})-\epsilon_{m_c'}(\mathbf{k}+\mathbf{q})+\hbar\omega(\mathbf{q})\right)\,\times$$

$$\left[\left(1-\varrho_{m_c'\,m_c'}(\mathbf{k}+\mathbf{q})\right)\,\beta(\mathbf{q})+\varrho_{m_c'\,m_c'}(\mathbf{k}+\mathbf{q})\,\left(1+\beta(\mathbf{q})\right)\right]\Big\}$$

Result IV

- Offdiagonal-entry: scattering contributions *beyond* the Boltzmann limit
  (different truncation rules, but still 2^{nd} order Born approximation)

$$\partial_t\, \varrho_{m_c\,-m_c}(\mathbf{k}) = -\frac{1}{i\hbar} \sum_{\mathbf{q}\, m_c'} \bar{\Sigma}^{e-p}_{m_c'\,-m_c'}(\mathbf{q})\, \varrho_{m_c'\,-m_c'}(\mathbf{k}+\mathbf{q})$$

- self-energy

$$\bar{\Sigma}^{e-p}_{m_c'\,-m_c'}(\mathbf{q}) = \hbar \left(\bar{\Omega}^{e-p}_{m_c'\,-m_c'}(\mathbf{q}) - i\, \bar{\Gamma}^{e-p}_{m_c'\,-m_c'}(\mathbf{q}) \right)$$

- contributions are **not** connected via *Kramers-Kronig relation*

Universität Regensburg

Summary of results

- Typical form of EOM in 2^{nd} order Born approximation (compared with carrier dynamics)

Summary of results

- Typical form of EOM in 2^{nd} order Born approximation (compared with carrier dynamics)

- **But**: Explicit inclusion of spin degree-of-freedom

Summary of results

- Typical form of EOM in 2^{nd} order Born approximation (compared with carrier dynamics)
- **But**: Explicit inclusion of spin degree-of-freedom

$\Rightarrow$ **spin dependent optical Bloch equations**

Universität Regensburg

Summary of results

- Typical form of EOM in 2^{nd} order Born approximation (compared with carrier dynamics)

- **But**: Explicit inclusion of spin degree-of-freedom

$\Rightarrow$ **spin dependent optical Bloch equations**

$\Rightarrow$ Decay times

Decay times

- Formal definition of decay times:

$$\frac{1}{T_{1,\mathbf{k}}} = \sum_{m_c'} \left(\Gamma^{in}_{m_c' \, m_c'}(\mathbf{k}) + \Gamma^{out}_{m_c' \, m_c'}(\mathbf{k}) \right)$$

$$\frac{1}{T_{2,\mathbf{k}}} = \Gamma^{e-p}_{m_c \, -m_c}(\mathbf{k})$$

- Result for small spin splitting:

$$T_{1,\mathbf{k}} \simeq T_{2,\mathbf{k}}$$

- Result for spin degenerate:

$$T_{1,\mathbf{k}} = T_{2,\mathbf{k}}$$

$\Rightarrow$ Experimental observables

Observables

- Experimental observables:

Spin polarization S ($\rightarrow$ spin relaxation):

$$S = \sum_{\mathbf{k}} \left(\varrho_{\uparrow\uparrow}(\mathbf{k}) - \varrho_{\downarrow\downarrow}(\mathbf{k}) \right)$$

Spin coherence C ($\rightarrow$ spin dephasing):

$$C = \sum_{\mathbf{k}} |\varrho_{\uparrow\downarrow}(\mathbf{k})|$$

Observables

- Experimental observables:

Spin polarization S ($\rightarrow$ spin relaxation):

$$S = \sum_{\mathbf{k}} \left(\varrho_{\uparrow\uparrow}(\mathbf{k}) - \varrho_{\downarrow\downarrow}(\mathbf{k}) \right)$$

Spin coherence C ($\rightarrow$ spin dephasing):

$$C = \sum_{\mathbf{k}} |\varrho_{\uparrow\downarrow}(\mathbf{k})|$$

$\Rightarrow$ **Unitary transformation**

Universität Regensburg

Transformation

- Transformed density matrix (*Rashba SO interaction*)

$$\varrho^{(\uparrow\downarrow)}(\mathbf{k})\big|_{\text{Rashba}} =$$

$$\frac{1}{2}\begin{pmatrix} d_+ + 2\Im\{\varrho_{m_c\,-m_c}(\mathbf{k})\,\mathrm{e}^{i\varphi}\} & d_- + 2i\,\Re\{\varrho_{m_c\,-m_c}(\mathbf{k})\,\mathrm{e}^{i\varphi}\} \\ d_- - 2i\,\Re\{\varrho_{m_c\,-m_c}(\mathbf{k})\,\mathrm{e}^{i\varphi}\} & d_+ - 2\Im\{\varrho_{m_c\,-m_c}(\mathbf{k})\,\mathrm{e}^{i\varphi}\} \end{pmatrix}$$

with

$$d_\pm = \varrho_{m_c\,m_c}(\mathbf{k}) \pm \varrho_{-m_c\,-m_c}(\mathbf{k})$$

and

$$\varphi = \sphericalangle(k_x,\,k_y)$$

Transformation II

- Observables:

$$S = \sum_{\mathbf{k}} 4\Re\left\{-i\,\mathrm{e}^{-i\varphi}\,\varrho_{m_c\,-m_c}(\mathbf{k})\right\}$$

$$C = \sum_{\mathbf{k}} \sqrt{d_{-}^{2} + 4\Im\left\{-i\,\mathrm{e}^{-i\varphi}\,\varrho_{m_c\,-m_c}(\mathbf{k})\right\}}$$

- Spin relaxation is ruled by $T_{2,\mathbf{k}}$ of the Bloch equations
- Spin dephasing is ruled by a *combination* of $T_{1,\mathbf{k}}$ and $T_{2,\mathbf{k}}$ of the Bloch equations
- Connection discussed by M.E. Flatté et al.in *Semiconductor Spintronics and Quantum Computation* **but here**: microscopic theory

- Concept of Bloch equations:

Extension towards spin dynamics

Conclusion

- Concept of Bloch equations:

  Extension towards spin dynamics

- Microscopic description of spin dynamics:
  optical Bloch equations with spin
  $\longrightarrow$ electron-phonon scattering

Conclusion

- Concept of Bloch equations:

  Extension towards spin dynamics

- Microscopic description of spin dynamics:
  optical Bloch equations with spin
  $\longrightarrow$ electron-phonon scattering

- Formal definition of T_1 and T_2 times

Conclusion

- Concept of Bloch equations:

  Extension towards spin dynamics

- Microscopic description of spin dynamics:
  optical Bloch equations with spin
  $\longrightarrow$ electron-phonon scattering
- Formal definition of T_1 and T_2 times
- Connection between decay times of Bloch equations and spin relaxation/dephasing times

Outlook

- Extension of semiconductor Bloch equations
  $\longrightarrow$ inclusion of many-particle effects (already done)
- Numerical evaluation of equations (work in progress)

- **More information: cond-mat/0412370**

Universität Regensburg

THANKS

- J. Kainz, U. Rössler (University of Regensburg)
- R. Winkler (University of Hannover)

- Financial support:
  DFG-Förderprojekt FOG 370/2-1
  Forschergruppe Ferromagnet-Halbleiter-Nanostrukturen

THANK YOU FOR YOUR ATTENTION!