All optical control of electron spins in quantum dot ensembles

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Experimentelle Physik II
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JST-DFG workshop, Aachen, 05.-07.03.2008
Acknowledgements

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A. Shabaev and A. Efros 
Naval Research Laboratory, Washington DC, USA

D. Reuter and A. Wieck
Ruhr-University of Bochum, Germany
Acknowledgements

Research group: „Quantum Optics in Semiconductor Nanostructures“

Borussia Dortmund
Fußball heißt das Spiel, Borussia seine Seele!
Quantum information processing

Potential of quantum information processing:
- Increase of computational power
- Realization of new functionalities for communication
- Reduction of complexity

Demand:
- Long living coherence

Prerequisite
- Availability of high quality quantum hardware: Quantum dots!

\[ \alpha |0\rangle + \beta |1\rangle \text{ mit } \alpha, \beta = \text{const.} \]
Qubit-candidates in QDs

2-level systems

Spin is efficiently protected by confinement against efficient relaxation mechanisms in higher-dim. systems.
Experiments on QD ensembles!!

Single electron per QD!

Relaxation times $T_1$

in high magnetic field:

- TU Delft: gated QDs
  $T_1 \sim 10 \text{ ms}$

- TU Munich: self-assembled QDs
  $T_1 \sim 10 \text{ ms}$

at zero magnetic field:

- Dortmund: self-assembled QDs
  PRL 98, 107401 (2007)
  $T_1 \sim 0.3 \text{ s}$
Single spin vs spin ensembles

**Single spin**

**Pro:**
- avoid inhomogeneities

**Con:**
- fragile
- weak spectroscopic signal

**Spin ensemble**

**Pro:**
- robustness
- strong spectroscopic signal

**Con:**
- inhomogeneities
Outline

1. Introduction
2. Faraday rotation with time resolution
3. Generation of spin coherence
4. Mode-locking of spin coherence
5. Tailoring of mode-locking
6. Electron spin focussing by nuclei
7. Current work
Quantum dot samples

Self-assembled quantum dots

• 20 layers of InGaAs/GaAs QDs with density $\sim 10^{10}$ cm$^{-2}$ per layer
• n-doped 20nm below QD layer - dopant density $\sim$ dot density
• thermal annealing ($T>900^\circ C$ for 30s) to use Si-based detectors

Non-annealed QD geometry:
  - dome-shaped
  - $\sim 25$ nm diameter
  - $\sim 5$ nm height
  - large oscillator strength!
Experiment

pump - probe Faraday rotation

\[ \theta_F \propto \vec{M} \cdot \vec{k}_{\text{probe}} \propto M_z \]

\[ B = 3 \text{T} \]

\[ \theta_F \propto \exp\left(-\frac{\Delta t}{T_2^*}\right) \cos(\omega \Delta t) \]

Delay time, \( \Delta t \) (ps)
Spin relaxation

characteristic quantities:
- $T_1$: relaxation
  - longitudinal relaxation time
- $T_2$: decoherence
  - transverse relaxation time
- $T_2^*$: dephasing

ensemble effects (inhomogeneities, measurement variations etc)

longitudinal ($T_1$) → $\uparrow \longrightarrow \downarrow$

transverse ($T_2$) → $\uparrow \longrightarrow \downarrow$

$B$

$\left(\uparrow \rangle + \downarrow \rangle\right)/\sqrt{2}$

$\left(\uparrow \rangle + e^{i\phi} \downarrow \rangle\right)/\sqrt{2}$
Precession about magnetic field

\[ \hbar \omega = g_e \mu_B B_x \]

 Electron g-factor tensor

Considerable variation of g-factor

Precession about magnetic field

\[ \hbar \omega_e = g_e \mu_B B_x \]

Analysis of FR data

FR amplitude

$$\propto \exp\left(-\frac{t}{T^*_2}\right) \cdot \cos(\Omega_e t)$$

$$\hbar \Omega_e = g_e \mu_B B$$

$$|g_e| = 0.574$$

$$\Delta g_e \Rightarrow \hbar \Delta \Omega_e = \Delta g_e \mu_B B \Rightarrow \Delta g_e = 0.004 \equiv 0.7\%$$

$$T^*_2(B=0) > 6\text{ns} \quad \text{dephasing in random nuclear magnetic field}$$

Long lasting spin coherence

$T^*_2 < 5\text{ns}$

coherence outlasts pulse repetition period & dephasing time.

A. Greilich et al., Science 313, 341 (2006)

Dephasing time $T^*_2$ (ns)

Magnetic Field (T)
Spin mode locking

QD ensemble offers broad distribution of g-factors

Further selection:

\[ \omega_e = \frac{g_e \mu_B B}{\hbar} = N \cdot \frac{2\pi}{T_R} = N \cdot \Omega_R \]

Laser pulse separation: 
\[ T_R = 13.2 \text{ns} \]

Phase synchronization of spin subsets by laser
Spin synchronization scheme

Phase synchronization condition:

$$\omega_e = N \cdot \frac{2\pi}{T_R}$$

Precession frequency:

$$\pi \cdot 2 \cdot \omega \cdot N = \pi \cdot 2 \cdot \omega \cdot (N+1)$$

Mode out of phase:
Spin mode locking

A. Greilich et al., Science 313, 341 (2006)

\[ \Theta = 0.4\pi \]

\[ \Theta = \pi \]

\[ \Theta = 1.6\pi \]

\[ T_2 = 3.0 \mu s \]

\[ \omega_e = N \cdot \frac{2\pi}{T_R} \]
Transverse spin relaxation time

The decay time gives single dot coherence time $T_2 = 3.0 \mu s$, four orders of magnitude longer than ensemble dephasing $T_2^* = 0.4 ns$ at $B=6T$!

A. Greilich et al., Science 313, 341 (2006)

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Decay time gives single dot coherence time $T_2 = 3.0 \mu s$

Laser repetition period $T_R$ varied by pulse-picker from 13.2 to 990 ns

B = 6 T

$T_R = 13.2 \text{ ns}$

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Faraday rotation amplitude vs. time (ps)

B = 6 T

Faraday rotation amplitude vs. pulse repetition period, $T_R (\mu s)$

B = 6 T
T = 2 K

$T_2 = 3.0 \mu s$
Clocking of spin modes

only first pump is on

B=6T

two-pulse experiment: pump-pulse split into two beams with variable time delay in between
Clocking of spin modes

FR amplitude (arb. units)

Only first pump is on

Only second pump is on

$T_D = 1.8\text{ns}$

$T_R / T_D = 7$

B = 6T

A. Greilich et al., Science 313, 341 (2006)
Clocking of spin modes

-1 burst

only first pump is on

only second pump is on

+1 burst

both pumps are on

$T_R / T_D = 7$

$T_D = 1.8 \text{ns}$

B = 6T

A. Greilich et al., Science 313, 341 (2006)
Clocking of spin modes

\[ \omega_e = N \cdot K \cdot \frac{2\pi}{T_D} \]

\[ \omega_e = N \cdot L \cdot \frac{2\pi}{T_R - T_D} \]

⇒ spins echoes every \( T_D \)

redistribution of precession frequencies
Spin mode locking

A. Greilich et al., Science 313, 341 (2006)

\[
\omega_e = N \cdot \frac{2\pi}{T_R}
\]

\(T_2 = 3.0 \mu s\)

\(\Theta = 0.4\pi\)

\(\Theta = \pi\)

\(\Theta = 1.6\pi\)
Negative delay FR amplitude

Explanation for similar FR amplitudes before and after pump pulse arrival:

\[ \omega_e = \frac{2 \pi N}{T_R} = g_e \mu_B (B + B_N) / \hbar \]

Nuclei create magnetic field such that all electron spins in the ensemble contribute to mode-locking.

Electron-nuclei spin flip-flop

how do electrons and nuclei communicate?

**hyperfine interaction**

\[ V^\alpha = v_0 A^\alpha \left( \vec{I}^\alpha \cdot \vec{S} \right) \phi \left( \vec{R}^\alpha \right)^2 \]

\[ \omega_e = \frac{2\pi N}{T_R} = g_e \mu_B (B + B_N) / \hbar \]

\~ 100,000 nuclei per QD
Do the long-living nuclear spins show up in the FR studies?

Optically induced relaxation

FR decay only for system under illumination!

FR amplitude constant over an hour time scale, when system is held in darkness!

Nuclear spin relaxation times

Nuclei relaxation time (s)

electron precession frequency $\omega_e$ (GHz)

Spin precession density

background of unlocked dots is removed!

broad spin precession distribution is transferred to comb-like distribution!

focussing drastically enhances density at the positions of mode-locked frequencies

important: change of precession frequency comparable to mode locking spacing

Current work

- Optical spin rotation
- Ensemble single mode spin precession
  - ~million inhomogeneous electrons focussed on single precession mode
- Application to EIT, slow light?
Conclusions

Quantum effects will play a key role in the next generation of information technologies!

**EXCITONS**
- coherence time: ~ns
- manipulation time: ~ps
- sufficient for quantum communication!

**ELECTRON SPINS**
- coherence time: ~µs
  (manipulation time: ~ps)
- sufficient for simple processors!
Publications

- Further submitted papers