Toward Hole Spin Qubits in GeSi Nanowires

GeSi Nanowires - Introduction

- band structure engineering: hole gas
- strong spin-orbit interaction
  - natural strong lateral confinement
- long spin lifetimes
  - reduced contact hyperfine interaction
  - isotope purification

Fig.: TEM image of a GeSi Nanowire [2], scale bar: 5 nm

Fig.: Schematic and band structure of GeSi Nanowire [1]

Quantum Dot
Readout
Spin Lifetime
Spin-Orbit Interaction
$g^*$-factor
Quantum Dots in GeSi Nanowires

- gate defined quantum dots
- single hole regime desirable
- sequential dot filling observable
- highly tunable double quantum dots

Fig.: exemplary gate configuration [3]

Fig.: highly tunable double quantum dot [1]

Fig.: sequential dot filling [2]

Outline

Quantum Dot

Readout

Spin Lifetime

Spin-Orbit Interaction

$g^*$-factor
Charge Sensing and Spin Readout

- charge sensing: non-invasive read out
  - even in closed dot regime
- sensitive to interdot transitions
- spin readout with Pauli Spin Blockade

Fig.: comparison of transport and charge sensing measurement [1]

Fig.: double quantum dot with integrated charge sensor [1]

Outline

- Quantum Dot
- Readout
- Spin Lifetime
- Spin-Orbit Interaction
- $g^*$-factor
Spin Lifetime

- spin dephasing time\(^2\): \(T_2^* = 0.15 \mu s\)
- spin relaxation time\(^1\): \(T_1 = 0.6 \text{ ms}\)
- enhancement of spin lifetimes possible
  - isotope purification
  - orientation of fields

\[^1\] Hu et.al., Nat. Nanotechnology 7,47 (2012)
\[^2\] Higginbotham et.al., Nano Lett. 14, 3582 (2014)
\[^3\] Maier et.al., PRB 87, 161305(R) (2013)

Fig.: Relaxation rate \(T_1^{-1}\) depends strongly on the relative orientation of magnetic and electric field [3]

Fig.: coordinate system, adapted from [3]
Spin-Orbit Interaction - Theory

- Dresselhaus spin-orbit coupling is absent
- Luttinger-Kohn Hamiltonian: electronic structure of (bulk) valence bands
- Nanowire: radial confinement mixes heavy-hole and light-hole states\(^1\) -> new eigenstates \(|g_\pm\rangle, |e_\pm\rangle\)
- derive effective Luttinger-Kohn Hamiltonian
- it contains terms of form \(\langle e_\pm | H_{LK} | g_\mp \rangle\)
  - features spin-orbit interaction in valence band

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\(^1\) Csontos et.al., PRB 79, 155323 (2009)
\(^2\) Kloeffel et.al., PRB 84, 195314 (2011)
Spin-Orbit Interaction - Theory

- externally applied electric field $E_x$: dipolar coupling to the hole charge
- spin-orbit interaction in valence band: $E_x$ couples directly to hole spin: **direct Rashba spin-orbit effect**

**Fig.:** direct dipolar coupling of external electric field lifts degeneracy of valence band states. Note the resemblance to Rashba spin-orbit interaction [1]

Weak Antilocalization

- signature for spin-orbit interaction: weak antilocalization
- increased conductance at zero magnetic field
- decreases at high magnetic fields

Fig.: Weak antilocalization in transport through a GeSi nanowire [1]

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Strong Spin-Orbit Interaction

- Coulomb peak height fluctuates depending on the coupling between leads and ground-state wave function in the dot.
- Distribution statistic depends on spin-orbit coupling.
- Extracted spin-orbit length $l_{SO} \leq 20-25$ nm.

![Fig. 1: Peak height distributions at B=0 T indicate strong spin-orbit interaction [1], theory in [3].](image1)

![Fig. 2: Weak spin-orbit interaction in GaAs quantum dots [2].](image2)

\( g^* \)-factor

- measure for sensitivity to magnetic fields
- electric field tunes \( g^* \)-factor due to direct Rashba spin-orbit interaction\(^1\)
- allows fine tuning with an electric field

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**Fig.**: electric field dependent \( g^* \)-factor \(^1\)

**Fig.**: coordinate system used here \(^2\)

**Fig.**: \( g^* \)-factor dependence on magnetic field direction \(^2\)

\(^1\) Maier et.al., PRB 87, 161305(R) (2013)
\(^2\) Brauns et.al., PRB 93, 121408(R) (2016)
Summary

- GeSi nanowires as an outstanding platform
- Quantum dots are highly tunable and controllable
- Charge sensing
- Spin lifetimes
- Strong and tunable spin-orbit interaction
- Anisotropic and electric field tunable $g^*$-factor
Outlook

- exploit the direct Rashba spin-orbit interaction
- EDSR with spin-flip times of 100 ps
- address quantum gates individually
- all electrical control
- long range spin-spin interactions can be realized
  - floating gates
  - cavities

Fig.: Hole spin qubit interaction via cavity field [1]

- The End -

THANK YOU FOR YOUR ATTENTION