Fast spin information transfer between distant quantum dots using individual electrons

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Introduction

• Last FMM: spin – spin coupling in triple quantum dot
  • spins experience a superexchange interaction through empty middle dot
    - difficult to control many quantum dots
    - Limited to ~O(100nm)
  + high fidelity readout: ~96%
  
• Here transport of spins
  • use quantum dots to manipulate spins
  • surface acoustic waves (SAW) to move quantum dots
    - enabling (quantum) spintronic protocols
    + Conceptual simplicity → SAW can transport charge and spin
    + long range ~O(1um)
  - Relatively low fidelity: ~65%
Device

- \( n = 1.4 \times 10^{11} \text{ cm}^{-2} \)
- \( \mu = 1 \times 10^6 \text{ cm}^2/\text{Vs} \)
- 2DEG 90nm below surface
- \( T \sim 50 \text{ mK} \)
- Channel length \( \sim 4 \mu \text{m} \)

IDT: Interdigitated transducer

- 70x 250nm wide lines separated by 1\( \mu \text{m} \)
- Surface acoustic waves (SAW) via piezoelectric effect

\[ \text{\( \rightarrow \) Creates a moving potential modulation} \]
- \( f_{\text{GaAs}} = 2.6326 \text{ GHz}, v_{\text{SAW}} = 2.8 \text{km/s}, t_{\text{transfer}} \sim 1.4 \text{ns} \)
Stages of transfer process

- **R** reset
- **L**\(_{1,2}\): loading and preparing spins (for 1 or 2 electrons)
- **M**\(_{1,2}\): measurement of spins (for 1 or 2 electrons) → coupling to reservoirs needed
- **I**: Isolation
- **T**: transfer → suppression of coupling to reservoirs

1-10kHz

<<1kHz

Transfer of electrons

- SAW creates a moving QD across the channel

Burst times used for spin relaxation measurement

$N_{\alpha\beta\gamma\delta}$ Number of e in reception dot before ($\gamma$) and after ($\delta$) transfer

Number of e in source dot before ($\alpha$) and after ($\beta$) transfer

- $X \to$ output result disregarded
- Electrons propagate in different moving quantum dots
- Measured via charge sensing (isolated)
Normal SR measurement

SR mechanisms:
- Interaction with nuclear spins
- SOI mixes spin states via orbital states

1 electron dot

\[ g \mu_B B \]

2 electron dot

\[ |S(0,2)\rangle, |S(2,0)\rangle, |T_+\rangle, |T_-\rangle, |S(1,1)\rangle, |T_0\rangle \]

Energy levels:

\[ (0,2) \rightarrow (1,1) \rightarrow (2,0) \]

|T⟩ probability

\[ B_1 = 0 \text{ mT} \]

\[ B_1 = 100 \text{ mT} \]

no contrast

reduced contrast

hight contrast

Reception dot

\[ t_{\text{wait}} (\text{ms}) \]

Graphs showing different contrast levels and pulse effects on |T⟩ probability.
Local SR measurement in reception dot

- **Serves as calibration** – no spin transfer yet
- Better comparison to transfer measurement
- Difference to normal SRM: pulsing for 10us in $T'$
- Relatively low contrast (10% amplitude)
- Electron(s) in two weakly coupled QD during $T'$
  - Nuclear spins induce mixing between the two spin states

- $T_1(1e)=11.8\text{ms}; T_1(2e)=6.2\text{ms}$
Non-local spin transfer measurement

- Spins transferred from source to reception dot
- Load spins on $\mu$s time scale ($<<$relaxation time)
- Perform transfer protocol and measure spin relaxation at $M_{1,2}'$
  \( \rightarrow T_{1,\text{non-local}}(1e)=14.5\text{ms}; T_{1,\text{local}}(1e)=11.8\text{ms} \)
  \( \rightarrow T_{1,\text{non-local}}(2e)=7.7\text{ms}; T_{1,\text{local}}(2e)=6.2\text{ms} \)
- $\sim 30\%$ of spin polarization has been preserved during transfer
- 33000 single shot measurements for 1e
- 18000 for 2e
Spin transfer efficiency

- Compare local and non-local relaxation measurements
- Divide amplitudes: non-local/local = $c_i$
- $\varepsilon_i$, error probability to flip spin
- $c_i = 1 - 2\varepsilon_i$
- Fidelity $f = 1 - \varepsilon_i$
- Here:
  - 1 electron $\varepsilon_1 = 0.38 \pm 0.04 \rightarrow f = 62\%$
  - 2 electrons $\varepsilon_2 = 0.34 \pm 0.04 \rightarrow f = 65\%$

But:
Consider single spin flip processes during the transfer in the moving dots - $p$ probability to flip one spin:
$\varepsilon_2 = 2p(1-p) \rightarrow c_2 \sim 0.08 \ll$ observed
$\Rightarrow$ No spin flips during the transfer?!
Spin depolarization I

<table>
<thead>
<tr>
<th>L_1'</th>
<th>T_1' - 10μs</th>
<th>M_1'</th>
</tr>
</thead>
<tbody>
<tr>
<td>t_{wait}</td>
<td>t_{SAW}</td>
<td></td>
</tr>
</tbody>
</table>

1 electron dot system

- What causes the difference between local and non-local SRM?
  - SOI to small 1)
  - Spin flip during transfer would give a much smaller contrast
- Influence of SAW!
- 1 electron dot
  \[ \rightarrow \] many passages through anti-crossing 2) during SAW burst
  \[ \rightarrow \] mixing of spin states

Amplitude at 125ns ~6% but observed amplitude is only 3%

1) PRB 88,075301 (2013)
2) Anti-crossings due to: spin-orbit and hyperfine coupling
Spin depolarization II

2 electron dot system

- Determine precisely position of anti-crossing of S and T\textsubscript{+} state
- Load ground state
- Go to isolated position
- Apply 100ns pulse with different amplitudes
- Observe higher probability with increasing amplitude and closer to anti-crossing

\( \rightarrow \) SAW induces spin mixing

- Idea: go to a more isolated point and redo relaxation measurement!
Summary

• Local and non-local spin relaxation measurements

• ~30% of spin polarization is transferred over 4μm → classical fidelity of 65%
• Limited by mixing of spin states during SAW excitation
• But: reduction of visibility due to SAW is ~6% <3% as observed for 1e
  • Spin orbit interaction?

\[ \lambda_{SO} = \frac{\hbar^2}{2m|\alpha \pm \beta|} \theta \]

\[ \beta, \alpha_{GaAs} \sim 5\text{meVA} \rightarrow \theta \sim 2\pi \]

for 4μm