Quantum Dot Spin QuBits

Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots

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Quantum Devices for Information Technology
Outline

I. Double Quantum Dot

II. The Logical Qubit

III. Experiments
1. Reminder: Quantum Dot (QD)

AlGaAs/GaAs heterostructure $\rightarrow$ 2DEG at the interface.


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Electrically-defined island → top gates on a 2DEG
2 tunable parameters:
- source and drain bias
- plunger gate voltage

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Picture from:
2. Double Quantum Dot

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- source and drain bias
- plunger gate voltages


3. Two-electron regime

A Quantum Point Contact is used to determine the charge state in the dots.


I. Double Quantum Dot

3. Two-electron regime

A Quantum Point Contact is used to determine the charge state in the dots.

\[ S(1,1) = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}, \]
\[ T_+(1,1) = |\uparrow\uparrow\rangle, \]
\[ T_0(1,1) = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}, \]
\[ T_-(1,1) = |\downarrow\downarrow\rangle. \]

\[ S(0,2) = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}, \]
\[ T_+(0,2) = |\uparrow\uparrow\rangle, \]
\[ T_0(0,2) = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}, \]
\[ T_-(0,2) = |\downarrow\downarrow\rangle. \]
I. Double Quantum Dot

3. Two-electron regime

\[ \Delta V = \eta \Delta V \]


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3. Two-electron regime

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\[ \rightarrow (1,1) \text{ and } (0,2) \text{ hybridize.} \]
3. Two-electron regime

\[ \Delta V = \eta \Delta V \]

\[ \epsilon = \eta \Delta V \]

→ (1,1) and (0,2) hybridize.

→ Triplet states are split.

I. Double Quantum Dot

II. The Logical Qubit

III. Experiments
II. The Logical QuBit

1. Which System?

![Diagram showing energy levels and transitions labeled $(0,2)T_-, (0,2)T_0, (0,2)T_+$ and $(0,2)S$.]

II. The Logical QuBit

1. Which System?

![Graph showing energy levels and transitions labeled as $T_-$, $T_0$, $T_+$, and $(0,2)S$.]

II. The Logical QuBit

1. Which System?

II. The Logical QuBit

1. Which System?

- $\Delta B_z$ between the dots.
- $S$ and $T_0$ are mixed by hyperfine field.

Picture from:
II. The Logical QuBit

2. Singlet-Triplet QuBit

\[ H = \begin{pmatrix} J(\varepsilon) & \Delta B^Z_{\text{nuc}} \\ \Delta B^Z_{\text{nuc}} & 0 \end{pmatrix} \]

- \( J = \) exchange energy between singlet and triplet
  \( \rightarrow \) rotation around the z-axis.

- \( \Delta B^Z_{\text{nuc}} = \) difference in B-field seen by the two electrons
  \( \rightarrow \) rotation around x-axis

Picture from:
II. The Logical QuBit

3. Manipulation

1. Initialization

Source [6]
3. Manipulation

2. Spin separation
Fast sweep rate

Source [6]
II. The Logical QuBit

3. Manipulation

3. Adiabatic sweep
II. The Logical QuBit

3. Manipulation

4. Manipulation

Source [6]
II. The Logical QuBit

3. Manipulation

5. Read-out
Determination of the charge state via QPC
→ measurement of $P_s$
Outline

I. Double Quantum Dot

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1. Coherence

How long do two spatially separated electrons retain coherence?

→ Measurement of the dephasing time of S(1,1)

Determinant of the spin state using the calibrated QPC charge sensor

→ Estimation of $T_2^*$

~10ns
III. Experiments

2. Manipulation and SWAP

\[ \phi = \frac{J(\epsilon) \tau_E}{\hbar} \]

If \( \phi = \pi \): Swap!

Source [6]
III. Experiments

2. Manipulation and SWAP

If $\phi = J(\epsilon)\tau_E \Rightarrow \pi \Rightarrow 180\text{ps}$

$$\phi = \frac{J(\epsilon)\tau_E}{\hbar}$$

If $\phi = \pi$: Swap!
Conclusion

- Coherent control of a logical QuBit
- $T_2^*$ was measured
- Rabi Oscillations were observed
- $\sqrt{\text{SWAP}}$ operation-time $\sim 180\text{ps.}$
Demonstration of Entanglement of Electrostatically Coupled Singlet-Triplet Qubits

M. D. Shulman, O. E. Dial, S. P. Harvey, H. Bluhm, V. Umansky, A. Yacoby

3 weeks ago...
End of the presentation

Thank you for your attention!

And many thanks to Arkady.

Questions?


III. Experiments

3. Spin Echo

[Diagram showing experimental setup and data analysis]