Implementing gates in quantum dot spin qubits

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Source:


David P. DiVincenzo Double Quantum Dot as a Quantum Bit. Science 309, 2173 (2005);
Outline

- Two electron spin qubit
- Device
- Energy levels
- Manipulation of states
  - Dephasing
  - Rabi oscillations
  - Spin echo technique
motivation

Semiconductor quantum dots:

- Engineered artificial atoms
- Long lifetime of the quantum states ($T_1$) compared to pulse frequency
- Short coherence lifetime $T_2$
  -> spin echo
Two electron spin qubit

- Double-well potential = $\text{H}_2$ molecule
- ground state = Singlet
  excited state = Triplet
- Difference: Spin coupled to $10^6$ spins of host crystal nuclei
Bloch sphere representation

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

\( |T\rangle \rightarrow |S\rangle \) exchange interaction

\( |T\rangle \rightarrow |S\rangle \) hyperfine interactions
Device

- Quantum Dots (QDs) confined in 2DEG (GaAs/AlGaAs interface) with split gate technique
- The voltage $V_L, V_R$ controls charge in QDs
- $V_T$ tunes interdot tunneling
- Single electrons can be detected by measuring the conductance $g_s$ over the quantum point contact (QPC)
Charge state dependent QPC conductance

- \((m,n) = \) electrons in (left, right) dot
- Additional electrons reduce the conductance \textit{discretely}
- QPC is more sensitive to the right dot
  - \(\rightarrow\) difference between (0,2) and (1,1)
- \(V_L\) also affects right dot
  - \(\rightarrow\) honeycomb shape
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Energy depending on detuning

- The triplet states \((m = -1, 0, +1)\) are split off by a 100mT external magnetic field.
- Detuning parameter \(\varepsilon \sim (V_R - V_L)\).
- Only states with similar energies can mix (consider \(S=T_0, S=T_+\)).
General method for propagation and readout

- Initialize in \((0,2)S\)
- Pulse transfers \((0,2)S\) into the spatially separated \((1,1)S\) state
- \((1,1)S\) and \((1,1)T\) form a two level system
- The \((1,1)S\) state is manipulated
- The state is projected back onto \((0,2)S\) if the final state was \((1,1)S\) and measured with the QPC. Triplet state is blocked
Manipulation of states, dephasing

- Short voltage pulse to large detuning suppresses exchange interaction of separated spins
- Due to different hyperfine interactions caused by the GaAs nuclei in the QDs, different rotations occur
- -> dephasing
Limits of the coherence

- Weak interaction with $\sim 10^6$ other GaAs atoms
- Fluctuations of the magnetic field of 1-5mT, changing at around $10\mu$s
Experimental results of dephasing

- Correlation of the states decays gaussian
- With B-field of 100mT, S state can only mix with the $T_0$ state and thus S has a higher probability than with B=0mT
The four states can be mapped on the Bloch sphere.

At an energy of slightly below $\varepsilon$ the state rotates between the states $|l\rangle >$ and $|l\rangle >$.

After a time $\tau_E$ the state changes from $|l\rangle >$ to $|l\rangle >$ or vice versa, this is called $\sqrt{\text{SWAP}}$. 
Rabi oscillations

- By a slow decrease of $\varepsilon$ the state gets initialized in the $|\uparrow \downarrow>$ state
- Small detuning leads to a rotation around the z-axis due to large exchange interaction
- Depending on $\tau$ the state is in a superposition of $|\uparrow \downarrow>$, $|\downarrow \uparrow>$
- The slow increase of $\varepsilon$ leads either to (1,1)S or (1,1)T state
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Experimental results of Rabi oscillations

- Rotations about the $x$-axis leads to oscillations on the singlet probability
- The decay time is proportional to the frequency
- Small detuning leads to higher exchange and therefore to faster rotations
Spin echos

- **Idea:** reduce the dephasing by using rabi oscillations
- rotation by \((2n+1)=\pi\) about z-axis
- Let system evolve for the same time \(\tau_S = \tau_{S'}\)
- dephasing is interfering destructively
Conclusion

- Coherent control of a logical qubit based on two-electron spin states
- Electrostatic gate control only
- Rabi oscillations and SWAP operation were demonstrated
- Spin echo technique reduces the decoherence caused by B-field fluctuations
  -> enhanced coherent spin-lifetime of 1μs