Two-Qubit Gate of Combined Single-Spin Rotation and Interdot Spin Exchange in a Double Quantum Dot

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A crucial requirement for quantum-information processing is the realization of multiple-qubit quantum gates. Here, we demonstrate an electron spin-based all-electrical two-qubit gate consisting of single-spin rotations and interdot spin exchange in a double quantum dot. A partially entangled output state is obtained by the application of the two-qubit gate to an initial, uncorrelated state. We find that the degree of entanglement is controllable by the exchange operation time. The approach represents a key step towards the realization of universal multiple-qubit gates.
...follow-up from last week: (ok, no SOI this time)

- EDSR single spin manipulation
  + exchange interaction in double quantum dot

= two-Qubit gate

computational basis: single-electron qubits

\[ |\uparrow\rangle \uparrow\rangle, \ |\uparrow\rangle \downarrow\rangle, \ |\downarrow\rangle \uparrow\rangle, \text{ and } |\downarrow\rangle \downarrow\rangle \]
for standard double dot (S-T0 qubit):
- split-off triplets
- exchange J of S(1,1) and T0

leading parameter: detuning

here:
- T+,T- (single qubit) splitting >> B_N (B0=1T, 2T) --- PSB
- inhomogenous B_L, B_R:
different EDSR frequency --- single-spin manipulation
- double dot with QPC read-out
- slanted split micro-magnet (Co)
- in-plane field $B_0$

- EDSR excitation: Co-electrode

- detuning handle: left plunger (PL) compensated by complementary pulse on Co-electrode
- initialize in Pauli spin blockade (zero detuning)

- EDSR left spin rotation (large detuning)

- SWAP operation using exchange interaction (intermediate detuning)

- read-out (singlet return probability $P_s$)
- EDSR left spin rotation (large detuning)
- selective addressing left and right spin
- faster rotation on the left (higher field gradient along $z$)
- scaling with EDSR amplitude:

Rabi oscillation
- SWAP operation using exchange interaction (intermediate detuning)

- rotation in the 2-qubit basis \( | \uparrow \uparrow \rangle, | \downarrow \downarrow \rangle \)

  by exchange interaction \( J \)

  \[
  R_x(t) = e^{i \frac{\delta E z}{2 \hbar} t} \begin{pmatrix}
  e^{i \frac{\delta E z}{2 \hbar} \cos \Omega t - i \sin 2 \theta \sin \Omega t} & i e^{-i \frac{\delta E z}{2 \hbar} \cos 2 \theta \sin \Omega t} \\
  i e^{-i \frac{\delta E z}{2 \hbar} \cos 2 \theta \sin \Omega t} & e^{-i \frac{\delta E z}{2 \hbar} \cos \Omega t + i \sin 2 \theta \sin \Omega t}
  \end{pmatrix}
  \]

  Zeemann offset + nuc. field fluctuation

  \[
  \delta E_z = E_{zL} - E_{zR}
  \]
2-qubit operation

\[
T_{\pm}(1, 1) \xrightarrow{L(3\pi/2)} |\uparrow\rangle \pm |\downarrow\rangle \sqrt{2} \otimes |\uparrow\rangle \xrightarrow{J_0: \tau_{\text{ex}}} |\psi_1\rangle \xrightarrow{L(\pi/2)} |\psi_2\rangle,
\]

single spin rotations \(3/2\) and \(1/2\) to avoid T0 output component for both init-states

output: \[|\psi_2\rangle = \frac{1}{2}[T_{+}(1, 1) + T_{-}(1, 1) - \sqrt{2}iS(1, 1)]\]

charge detector gives: \[P_S = |\langle S|\psi_2\rangle|^2\]

- oscillation with exchange time
SWAP rate goes with coupling:

\[ t \approx \sqrt{\frac{1}{2}} J_0 \varepsilon \]
result

- experiment close to max. visibility
  ~ 24%

- but too low for testing
  *universal* quantum gate, EPR, Bell inequalities

- limited by dephasing by nuc. fluctuations

- SO negligible (they say):
  $f_{SO} < 25 \text{ MHz}$  \hspace{1cm} (40 MHz $< f_{\text{swap}}$ 80 MHz)

way out:
- larger stray field gradient
- MW gate closer to the dots