Conditional operation of a spin qubit

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We report coherent operation of a singlet-triplet qubit controlled by the arrangement of two electrons in an adjacent double quantum dot. The system we investigate consists of two pairs of capacitively coupled double quantum dots fabricated by electrostatic gates on the surface of a GaAs heterostructure. We extract the strength of the capacitive coupling between qubit and double quantum dot and show that the present geometry allows fast conditional gate operation, opening pathways to multi-qubit control and implementation of quantum algorithms with spin qubits.
Overview

• Five (plus two) requirements for QC

• Device and motivation

• Energy diagram / electrostatic coupling

• Measurement scheme

• Coherent control / conditional operation

• Conclusions
Five (plus two) requirements for QC

• A scalable physical system with well characterized qubits:
  • 2-level syst, well known phys. parameters (internal Hamiltonian, coupling to higher states / other qubits / ext. fields)

• The ability to initialize the state of the qubit to a simple fiducial state, such as $|000...>$
  • quantum error correction requires low entropy initialized states (reinitializing)

• Long relevant coherence times, much longer than the gate operation time

• A “universal” set of quantum gates
  • Quantum Algorithm : set of unit. transf. U1,U2,U3,U4,... acting on little qubits
  • ideally: indentify Hamiltonians $U1=\text{e}^{iH_1t/h}$, $U2=\text{e}^{iH_2t/h}$, ...
    t0-t1: switch $U1$, t1-t2: switch $U2$, ...
  • realistically: one-two qubit interaction, cNOT gate

cNOT gate

- cNOT: Controlled NOT gate
- XOR gate: classical analogue of cNOT
  - 2 qubit operation:
    - flips target qubit iff control qubit is 1
- Simulation of any quantum circuit to arbitrary precision possible using combination of cNOT operations and single qubit rotations.

http://www.wikipedia.org
Five (plus two) requirements for QC

• A qubit specific measurement capability
  • readout of single qubit (with 100% Q-efficiency) without disturbing other qubits
  • much less is needed for quantum computation (question of efficiency)

• Example: single bit output (decision problem), 90% fidelity
  Want to achieve 97% fidelity => measure with 3 qubits

  Yes: 0.9^3 + 3*0.1*0.9^2 = 0.972
  No:  0.1^3 + 3*0.9*0.1^2 = 0.028

• Even quantum efficiency <<1% can be used successfully for QC:
  Bulk model of NMR
  macroscopic # QC (different types of molecules in solution)

+2: requirements for communication

• The ability to interconvert stationary and flying qubits

• The ability faithfully to transmit flying qubits between specified locations

• Quantum cryptography only requires 2. statement

• Communication using QM states can reduce required amount of communication data

Device and motivation

- Possible formulation of qubit: Use DQD, \(|S>, |T_0>\)
  (not as sensitive to environmental charge fluctuations as single electron spin as qubit)

- Most requirements for QC satisfied: all electrical full single qubit control

- Scalability, coupling of qubits?
  Electrostatic interaction btw. DQD ==> sufficient interaction for universal QC

- GaAs/AlGaAs, 2DEG at 110nm, Ti/Au gates
- Mobility $2 \times 10^{15} \text{cm}^2/\text{Vs}$
- $T_e = 150 \text{mK}$
- $B_{\text{ext}} = 0.1 \text{T}$ inplane (split of triplet states)

- Adjacent DQD with QPs for charge sensing

Electrostatic coupling strength

• Larger energy needed to put electrons close together
  => int.strength, $E_{\text{cpl}}^0 = E[(0,2)_C,(2,0)_T] - E[(1,1)_C,(1,1)_T]$

• Determine detuning axis: scan plunger gates of indiv. DQD vs each other

• How to find exchange energy
  \text{do2d}(``\varepsilon_\text{C}'',-7.5,7.5,50,0.1,``\varepsilon_\text{T}'',-2,2,1000,0.01)
E-diagram at the $(1,1)_T-(2,0)_T$ transition

- What happens at the $(1,1)_T-(2,0)_T$ charge transition?
  - There are two available singlet states (in one dot, or separated).
  - Tuning $\epsilon$, makes either the one or the other more favorable.
  - Transfer btw. states possible => avoided x-ing $|S^*|=\cos(\theta) |S>+\sin(\theta) |S(2,0)>$
What happens at the \((1,1)_T-(2,0)_T\) charge transition?

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Transfer btw. states possible \(\Rightarrow\) avoided x-ing

- Energy difference at large pos. detuning \(\Rightarrow\) max. coupl. energy \(E_{\text{cpl}}\)

- Exchange energy (btw. singlet and triplet) of target depends strongly (around zero detuning) on the charge state of control
Measurement scheme

• Measurement: load $S(2,0)_T$, adiabatic transfer to $S(1,1)$ and interaction with $|T_0>$, adiabatically back to measurement point ($|S>$ or $|T_0>$ => charge sensing)
• Plot singlet prob. as a function of delay time => coherent oscillations

1ns pulse rise time: much faster than Overhauser precession time (avoid S-T+ mixing) but much slower than charge tunneling time (ensure cross over from $S(2,0)$ to $S(1,1)$, rather than staying in $S(2,0)$)

• Repeat the measurement for “control” in the other charge state (change of exchange energy => different phase accumulates btw $|S>$ or $|T_0>$ during interaction period
Coherent control over target

• Coherent oscillations of singlet population as a function of interaction time

• Oscillations present for both charge states of control QD with different frequency

• 2D plots with frequency jump at $S(0,2)_C$, $S(1,1)_C$ charge transition
Conditional operation

• cNOT: target qubit if control qubit is in state 1

• Optimize settings st. after short time a phase difference of $\pi$ accumulates (btw state evolution with control QD in $S(0,2)$ or $S(1,1)$)

• achieved conditional operation times of 30ns
  - control QD in $S(1,1)$ 4$\pi$ oscillation
  - control QD in $S(0,2)$ 3$\pi$ oscillation
Conclusions

• Conditional operation in electrostatically coupled singlet – triplet qubits (realized through adjacent DQDs) with operation time of 30ns

• Extracted (maximum) electrostatic coupling of 23μeV

• Calculated/Estimated coupling for 30ns cond.operation time yields 0.01*23μeV
  this sets a limit of 3μs on two qubit gate (spin state of control influences the one of target)
  working close to zero detuning reduces this number to 0.4ns

• Device geometries with stronger electrostatic coupling btw. the DQDs are under study