Quantum computation with spin qubits

Xin (Sunny) Wang

Department of Physics,
City University of Hong Kong

Department of Physics
物 | 理 | 學 | 系

香港城市大學
City University of Hong Kong
專業 創新 胸懷全球
Professional · Creative
For The World

Outline

- **Background**
- **Charge qubit**
- **Spin qubit**
  - Loss-DiVincenzo qubit
  - Singlet-triplet qubit
  - Exchange-only qubit
  - Resonant-exchange qubit
  - Hybrid qubit
- **Summary**

Why quantum computing?

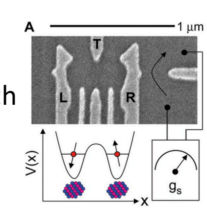
- *Quantum computer:* a device which computes according to the laws of quantum mechanics (unitary evolution, entanglement, coherent superposition, …)

- Applications:
  - Integer factorization → cryptography
  - Quantum search algorithm
  - Simulation of quantum mechanical system
  - Secure Communication … and more

Nielsen and Chuang, *Quantum Computation and Quantum Information* (Cambridge, 2000)

Realizing quantum computation in physical systems

- Candidates:
  photons, trapped ions, superconducting qubits, spin qubits, nitrogen-vacancy center in diamonds, etc.
- *This talk:* **spin qubits** in semiconductor quantum dots
  - (+) Reasonably long coherence time
  - (+) Prospects for scalability (semiconductor industry)
  - (-) Decoherence from interacting with the environment
  - (-) Difficulty in manipulating coupled qubits

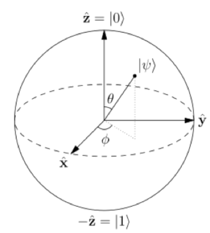


Petta *et al.*, *Science* **309**, 2180 (2005)

Ladd et al., Nature **464**, 45 (2010)

Essential ingredients for computation

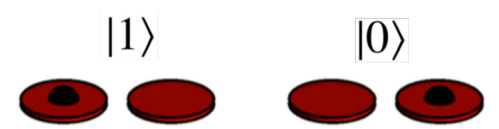
- Classical computation:
  - Bits: **0** and **1**
  - Gates: *NOT*: **0** $\Longleftrightarrow$ **1**
    AND & *OR*
    } Universal computation
- Quantum computation:
  - **Qu**bits: $|0\rangle$ and $|1\rangle$
    $|\psi\rangle = \cos\left(\frac{\theta}{2}\right)|0\rangle + e^{i\phi}\sin\left(\frac{\theta}{2}\right)|1\rangle$
  - Quantum gates:
    Arbitrary single-qubit rotation, and one "entangling" two-qubit gate
    $\longrightarrow$ Universal quantum computation



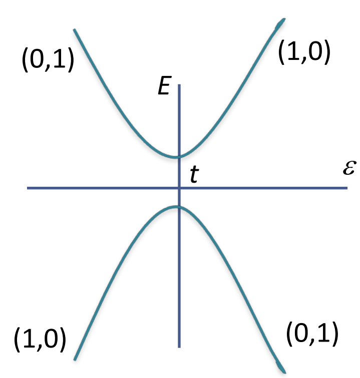
Courtesy of Wikipedia

Bloch, Phys. Rev. **70**, 460 (1946)
Nielsen and Chuang, *Quantum Computation and Quantum Information* (Cambridge, 2000)

Charge qubit



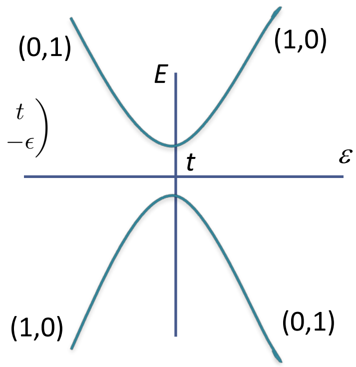
- V_L & V_R applied to each dot
  $\varepsilon=(eV_L-eV_R)/2$
  $\varepsilon<0$: favors (1,0)
  $\varepsilon>0$: favors (0,1)
- Tunneling between the two dots: t



Charge qubit

$|1\rangle$ $|0\rangle$

$$H = \begin{pmatrix} eV_L & t \\ t & eV_R \end{pmatrix} = e\frac{V_L + V_R}{2} + \begin{pmatrix} \epsilon & t \\ t & -\epsilon \end{pmatrix}$$

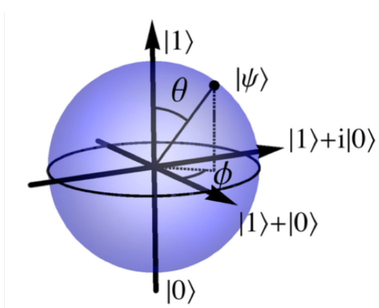


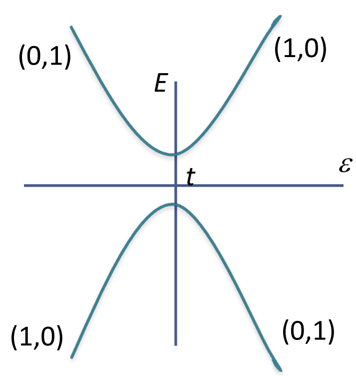
$$\boxed{\mathcal{H} = \epsilon\sigma_z + t\sigma_x}$$

Charge qubit

$|1\rangle$ $|0\rangle$

$$\boxed{\mathcal{H} = \epsilon\sigma_z + t\sigma_x}$$





Charge qubit

$|1\rangle$ $|0\rangle$

$$\mathcal{H} = \epsilon\sigma_z + t\sigma_x$$

charge qubit

+ qubit definition, manipulation, initialization, readout

– sensitivity to electric field fluctuations

Loss-DiVincenzo qubit

- Simplest proposal for a spin qubit: a single electron spin (S=1/2) serves as a qubit (Loss-DiVincenzo qubit)

$|0\rangle = |\uparrow\rangle$
$|1\rangle = |\downarrow\rangle$

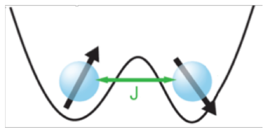
PHYSICAL REVIEW A VOLUME 57, NUMBER 1 JANUARY 1998

Quantum computation with quantum dots

Daniel Loss[1,2,*] and David P. DiVincenzo[1,3,†]
[1]*Institute for Theoretical Physics, University of California, Santa Barbara, Santa Barbara, California 93106-4030*
[2]*Department of Physics and Astronomy, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*
[3]*IBM Research Division, T.J. Watson Research Center, P.O. Box 218, Yorktown Heights, New York 10598*
(Received 9 January 1997; revised manuscript received 22 July 1997)

We propose an implementation of a universal set of one- and two-quantum-bit gates for quantum computation using the spin states of coupled single-electron quantum dots. Desired operations are effected by the gating of the tunneling barrier between neighboring dots. Several measures of the gate quality are computed within a recently derived spin master equation incorporating decoherence caused by a prototypical magnetic environment. Dot-array experiments that would provide an initial demonstration of the desired nonequilibrium spin dynamics are proposed. [S1050-2947(98)04501-6]

2-qubit gate of an LD qubit



Heisenberg exchange interaction

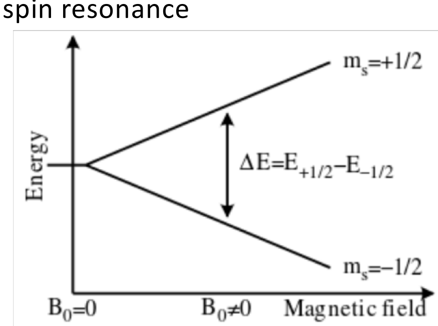
$$H_s(t) = J(t)\vec{S}_1 \cdot \vec{S}_2$$

$$U_{XOR} = e^{i(\pi/2)S_1^z} e^{-i(\pi/2)S_2^z} U_{sw}^{1/2} e^{i\pi S_1^z} U_{sw}^{1/2}$$

U_{sw}: the "SWAP" gate

1-qubit gate of an LD qubit

Electron spin resonance



(-): hard to localize; heating up the sample

Recent realization of the LD qubit

Launcht *et al.* Sci. Adv. 2015;1:e1500022 10 April 2015

CONDENSED MATTER PHYSICS

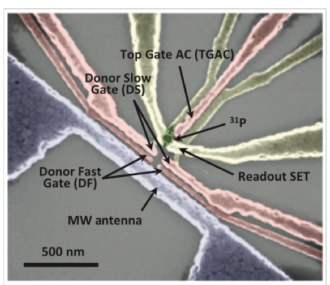
Electrically controlling single-spin qubits in a continuous microwave field

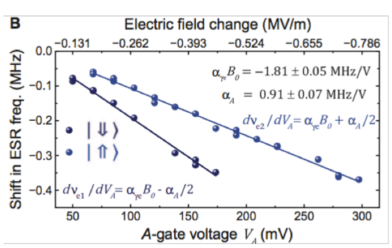
10.1126/sciadv.1500022

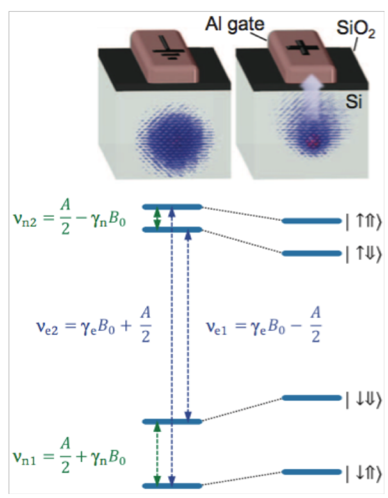
Arne Laucht,[1]* Juha T. Muhonen,[1] Fahd A. Mohiyaddin,[1] Rachpon Kalra,[1] Juan P. Dehollain,[1] Solomon Freer,[1] Fay E. Hudson,[1] Menno Veldhorst,[1] Rajib Rahman,[2] Gerhard Klimeck,[2] Kohei M. Itoh,[3] David N. Jamieson,[4] Jeffrey C. McCallum,[4] Andrew S. Dzurak,[1] Andrea Morello[1]*

Large-scale quantum computers must be built upon quantum bits that are both highly coherent and locally controllable. We demonstrate the quantum control of the electron and the nuclear spin of a single ^{31}P atom in silicon, using a continuous microwave magnetic field together with nanoscale electrostatic gates. The qubits are tuned into resonance with the microwave field by a local change in electric field, which induces a Stark shift of the qubit energies. This method, known as *A*-gate control, preserves the excellent coherence times and gate fidelities of isolated spins, and can be extended to arbitrarily many qubits without requiring multiple microwave sources.

Recent realization of the LD qubit







Summary of the LD qubit

Loss-DiVincenzo qubit / single-spin qubit

+ qubit definition, noise properties, two-qubit gates

− single-qubit gates

Qubit with more than one spin

Universal Quantum Computation with Spin-1/2 Pairs and Heisenberg Exchange

Jeremy Levy

Center for Oxide-Semiconductor Materials for Quantum Computation, and Department of Physics and Astronomy, University of Pittsburgh, 3941 O'Hara Street, Pittsburgh, Pennsylvania 15260

(Received 23 January 2001; published 17 September 2002)

An efficient and intuitive framework for universal quantum computation is presented that uses pairs of spin-1/2 particles to form logical qubits and a single physical interaction, Heisenberg exchange, to produce all gate operations. Only two Heisenberg gate operations are required to produce a controlled π-phase shift, compared to nineteen for exchange-only proposals employing three spins. Evolved from well-studied decoherence-free subspaces, this architecture inherits immunity from collective decoherence mechanisms. The simplicity and adaptability of this approach should make it attractive for spin-based quantum computing architectures.

DOI: 10.1103/PhysRevLett.89.147902

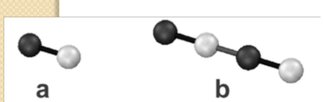


FIG. 1. (a) Logical qubit Q formed from the $S_z = 0$ subspace of two spin-1/2 physical qubits with different Landé g factors g_1 (gray) and g_2 (white). Heisenberg coupling within the logical qubit is represented by a solid black line. (b) Two logical qubits coupled via Heisenberg exchange, represented by a solid gray line.

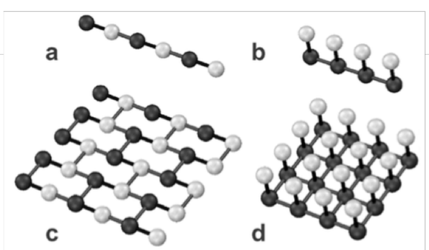
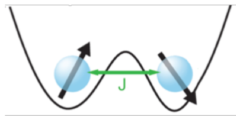


FIG. 2. Scalable qubit geometries in $d = 1, 2$ dimensions. (a) Longitudinal $d = 1$ layout. (b) Vertical $d = 1$ layout. (c) Horizontal $d = 2$ layout. (d) Vertical $d = 2$ layout.

Singlet-triplet (ST) qubit

- A qubit can alternatively be encoded in the $S_z = 0$ singlet and triplet states of two electrons:



$$|0\rangle = |T_0\rangle = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$$
$$|1\rangle = |S\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$$

- $|\uparrow\uparrow\rangle$ and $|\downarrow\downarrow\rangle$ are split away by a homogeneous magnetic field (B-field).
  (minimizing leakage; robust against homogenous fluctuations in the B-field; all-electrical control)

Petta *et al.*, *Science* **309**, 2180 (2005)

Realization of the ST qubit

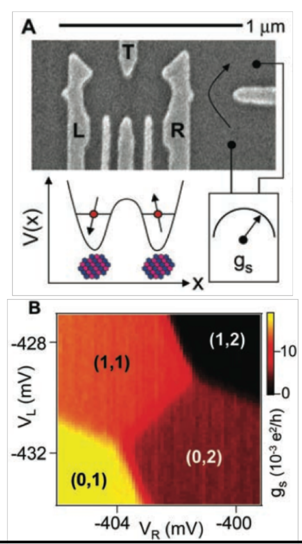
30 SEPTEMBER 2005 VOL 309 SCIENCE www.sciencemag.org

RESEARCH ARTICLES

Coherent Manipulation of Coupled Electron Spins in Semiconductor Quantum Dots

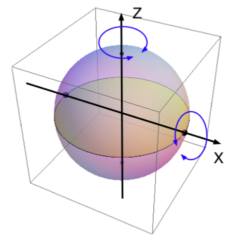
J. R. Petta,[1] A. C. Johnson,[1] J. M. Taylor,[1] E. A. Laird,[1] A. Yacoby,[2] M. D. Lukin,[1] C. M. Marcus,[1] M. P. Hanson,[3] A. C. Gossard[3]

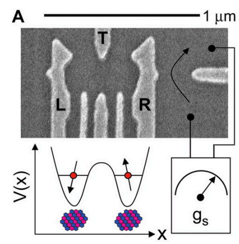
We demonstrated coherent control of a quantum two-level system based on two-electron spin states in a double quantum dot, allowing state preparation, coherent manipulation, and projective readout. These techniques are based on rapid electrical control of the exchange interaction. Separating and later recombining a singlet spin state provided a measurement of the spin dephasing time, T_2^*, of ~10 nanoseconds, limited by hyperfine interactions with the gallium arsenide host nuclei. Rabi oscillations of two-electron spin states were demonstrated, and spin-echo pulse sequences were used to suppress hyperfine-induced dephasing. Using these quantum control techniques, a coherence time for two-electron spin states exceeding 1 microsecond was observed.



Controlling the ST qubit

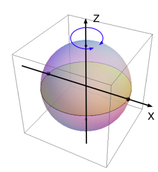
- Full single-qubit control: requires ability to rotate around two independent axes of the Bloch sphere (e.g. x and z axes)
- In the gate-defined quantum dot system, the control is achieved by applying "gate voltages".





Petta *et al.*, *Science* **309**, 2180 (2005)

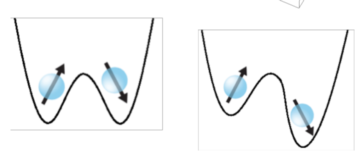
Z-rotation



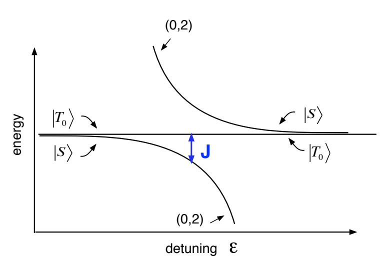
- Gate voltages
  → detuning
  → exchange interaction J
- Control over J suffices for Z-rotation.
- J is constrained:

$$0 \le J \le J_{\max}$$

  - One may only rotate along one direction.
  - One cannot do "delta" pulse.

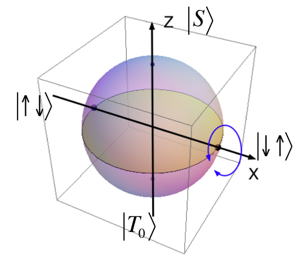


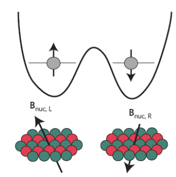
Detuning ε small   ε large



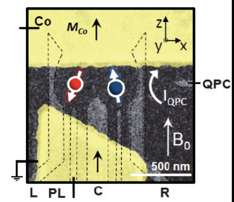
X-rotation

- X-rotation is achieved by an **in**homogeneous Zeeman field $h = g\mu_B \Delta B$ where ΔB is the magnetic field gradient.
- h is generated either by Overhauser nuclear field or a micromagnet.
- h cannot be directly controlled.





Foletti et al, Nat. Phys. 2009



Brunner et al, PRL 2011

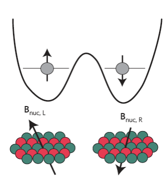
Control Hamiltonian

$$H = \frac{J(t)}{2}\sigma_z + \frac{h}{2}\sigma_x$$

$$0 \le J \le J_{\max}$$

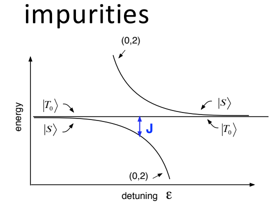
Noises

- **Nuclear (Overhauser) noise**: Fluctuations in the nuclear magnetic field surrounding the quantum dots



$$h \to h + \delta h$$

- **Charge noise**: Shift of energy levels induced by charged impurities



$$J(t) \to J(t) + g(J)\delta\varepsilon$$

- **It is one of the central tasks of the physics of quantum computation to fight against noises**.

Two qubit gate

CNOT gate: an "entangling" two-qubit gate

$$\begin{array}{c|c} & \begin{array}{cccc} |00\rangle & |01\rangle & |10\rangle & |11\rangle \end{array} \\ \begin{array}{c} \langle 00| \\ \langle 01| \\ \langle 10| \\ \langle 11| \end{array} & \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix} \end{array}$$

It is sufficient to generate a "locally equivalent" gate to CNOT, i.e. a gate which differ from CNOT by single-qubit rotations

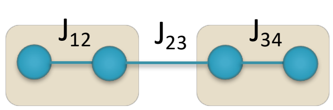
$$CNOT = e^{i\pi/4} e^{i\sigma_y \otimes I\pi/4} \boxed{e^{i\sigma_x \otimes \sigma_x \pi/4}} e^{-i(\sigma_x \otimes I + I \otimes \sigma_x)\pi/4} e^{-i\sigma_y \otimes I\pi/4}$$

"Ising gate"

Klinovaja *et al.*, *PRB* **86**, 084523 (2012)
Li *et al.*, *PRB* **86**, 205306 (2012)

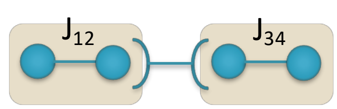
2-qubit gates of ST qubits

"Exchange-coupled"



- Theoretically elegant (and simpler) but experimentally less feasible
  - Breaking down the Hilbert space into 2*2 subspaces (treating two spins each time)
  - Analytical results available
  - "Gate cross-talk"

"Capacitively coupled"



- Experimentally demonstrated but theoretically difficult
  - Full 4*4 Hilbert space
  - Analytical results unavailable/very complicated

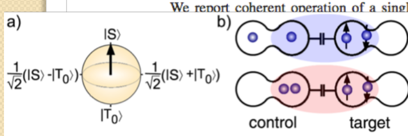
Experimental Realization of 2-qubit gates

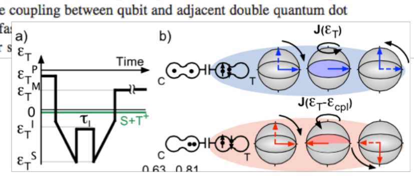
PRL 107, 030506 (2011) PHYSICAL REVIEW LETTERS week ending 15 JULY 2011

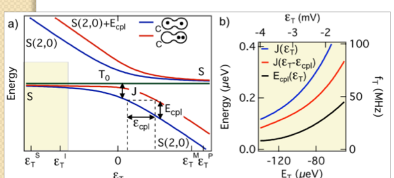
Charge-State Conditional Operation of a Spin Qubit

I. van Weperen,[1,2] B. D. Armstrong,[1] E. A. Laird,[1,*] J. Medford,[1] C. M. Marcus,[1] M. P. Hanson,[3] and A. C. Gossard[3]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, The Netherlands*
[3]*Materials Department, University of California, Santa Barbara, California 93106, USA*
(Received 9 February 2011; published 15 July 2011)

We report coherent operation of a singlet-triplet qubit controlled by the spatial arrangement of two
uantum dot that is electrostatically coupled to the qubit. This
netry needed for two-qubit operations of a two-electron spin
ive coupling between qubit and adjacent double quantum dot
s fa
for s







Experimental Realization of 2-qubit gates

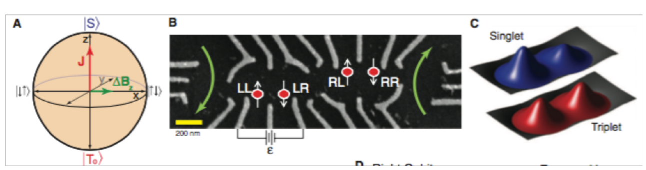
13 APRIL 2012 VOL 336 SCIENCE www.sciencemag.org
REPORTS

Demonstration of Entanglement of Electrostatically Coupled Singlet-Triplet Qubits

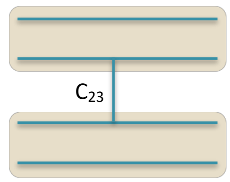
M. D. Shulman,[1*] O. E. Dial,[1*] S. P. Harvey,[1] H. Bluhm,[1†] V. Umansky,[2] A. Yacoby[1‡]

fidelity ~ 0.72

Quantum computers have the potential to solve certain problems faster than classical computers. To exploit their power, it is necessary to perform interqubit operations and generate entangled states. Spin qubits are a promising candidate for implementing a quantum processor because of their potential for scalability and miniaturization. However, their weak interactions with the environment, which lead to their long coherence times, make interqubit operations challenging. We performed a controlled two-qubit operation between singlet-triplet qubits using a dynamically decoupled sequence that maintains the two-qubit coupling while decoupling each qubit from its fluctuating environment. Using state tomography, we measured the full density matrix of the system and determined the concurrence and the fidelity of the generated state, providing proof of entanglement.



Exchange-coupled 2-qubit gate (theoretical proposal)

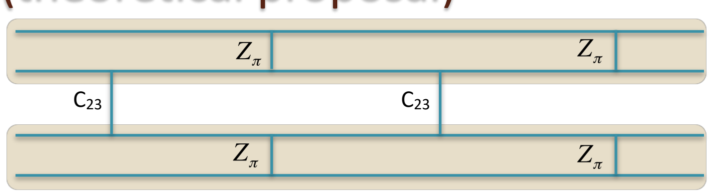


- To achieve any entangling two qubit gate, one must invoke the inter-qubit rotation, C_{23}.
- However, (1) a naïve implementation of C_{23} possibly causes leakage:

$$|\uparrow\downarrow\uparrow\downarrow\rangle \rightarrow |\uparrow\uparrow\downarrow\downarrow\rangle$$

(2) Other issues: C_{23} assigns undesired phases dependent on the local B-field

Exchange-coupled 2-qubit gate (theoretical proposal)



Klinovaja et al., Phys. Rev. B 86, 085423 (2012)

C_{23} needs to be a $2N\pi$ rotation (around whatever axis) in the subspace of the 2^{nd} and 3^{rd} spins to eliminate leakage, i.e.

$$|\uparrow_2\downarrow_3\rangle \rightarrow e^{i\phi}|\uparrow_2\downarrow_3\rangle$$

It also acquires a phase proportional to $J_{23}T/2$ (what we want)

The above sequence also ensures that other unnecessary phases (dependent on local B-field) are cancelled.

Summary of the ST qubit

ST_0 qubit / two-electron double-dot qubit

+ noise properties, single-qubit gates, initialization, readout

− two-qubit gates

- Simplest spin qubit proposal which can be manipulated all-electrically
- Still needs a magnetic field gradient to achieve the x-rotation.

Qubits based solely on the exchange interaction?

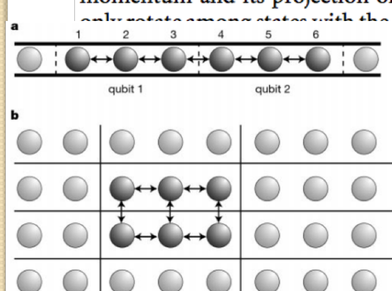
NATURE | VOL 408 | 16 NOVEMBER 2000 | www.nature.com

Universal quantum computation with the exchange interaction

D. P. DiVincenzo*, D. Bacon†‡, J. Kempe†§‖, G. Burkard¶ & K. B. Whaley†

* IBM Research Division, T. J. Watson Research Center, Yorktown Heights, New York 10598, USA
† Department of Chemistry, ‡ Department of Physics, § Department of
ia 94720, USA
rue Barrault,
sel,

The reason that the Heisenberg interaction alone does not give a universal quantum gate is that it has too much symmetry: it commutes with the operators $\hat{S}^2$ and $\hat{S}_z$ (for the total spin angular momentum and its projection on the z axis), and therefore it can same S, S_z quantum numbers. But ones for which the spin quantum me—the Heisenberg interaction e-spin operations with all their led.



m computers are that must be met at present involve Recent solid-state tom nuclear spins[3] e basic two-qubit hange interaction reas the one-qubit gates require control over a local magnetic field. Compared to the Heisenberg operation, the one-qubit operations are significantly slower, requiring substantially greater materials and device complexity—potentially contributing to a detrimental increase in the decoherence rate. Here we introduced an explicit scheme in which the Heisenberg interaction alone suffices to implement exactly any quantum computer circuit. This capability comes at a price of a factor of three in additional qubits, and about a factor of ten in additional two-qubit operations. Even at this cost, the ability to eliminate the complexity of one-qubit operations should accelerate progress towards solid-state implementations of quantum computation[1].

Eigenstates of a three-spin model

$$H = J_{12}\left(\mathbf{S}_1 \cdot \mathbf{S}_2 - \frac{1}{4}\right) + J_{23}\left(\mathbf{S}_2 \cdot \mathbf{S}_3 - \frac{1}{4}\right) - E_Z(S_1^z + S_2^z + S_3^z)$$

	1	2	3	4	5	6	7	8
S	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{3}{2}$	$\frac{3}{2}$
$S_{1,2}$	0	0	1	1	1	1	1	1
S_z	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$\frac{3}{2}$	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{3}{2}$

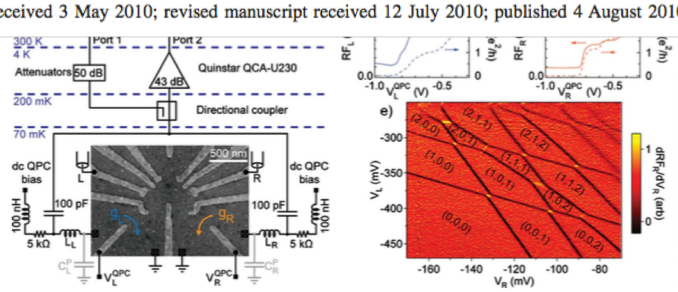
$$\begin{aligned}
|1\rangle &= \tfrac{1}{\sqrt{2}}(|010\rangle - |100\rangle) &&= |S_0\rangle\,|0\rangle \\
|2\rangle &= \tfrac{1}{\sqrt{2}}(|011\rangle - |101\rangle) &&= |S_0\rangle\,|1\rangle \\
|3\rangle &= \sqrt{\tfrac{2}{3}}\,|001\rangle - \tfrac{1}{\sqrt{6}}\,|010\rangle - \tfrac{1}{\sqrt{6}}\,|100\rangle &&= \frac{1}{\sqrt{3}}(\sqrt{2}\,|T_+\rangle\,|1\rangle - |T_0\rangle\,|0\rangle) \\
|4\rangle &= \tfrac{1}{\sqrt{6}}\,|011\rangle + \tfrac{1}{\sqrt{6}}\,|101\rangle - \sqrt{\tfrac{2}{3}}\,|110\rangle &&= \frac{1}{\sqrt{3}}(|T_0\rangle\,|1\rangle - \sqrt{2}\,|T_-\rangle\,|0\rangle) \\
|5\rangle &= |000\rangle &&= |T_+\rangle\,|0\rangle \\
|6\rangle &= \tfrac{1}{\sqrt{3}}(|001\rangle + |010\rangle + |100\rangle) &&= \frac{1}{\sqrt{3}}(|T_+\rangle\,|1\rangle + \sqrt{2}\,|T_0\rangle\,|0\rangle) \\
|7\rangle &= \tfrac{1}{\sqrt{3}}(|011\rangle + |101\rangle + |110\rangle) &&= \frac{1}{\sqrt{3}}(\sqrt{2}\,|T_0\rangle\,|1\rangle + |T_-\rangle\,|0\rangle) \\
|8\rangle &= |111\rangle &&= |T_-\rangle\,|1\rangle
\end{aligned}$$

Realization of the exchange-only (EO) qubit

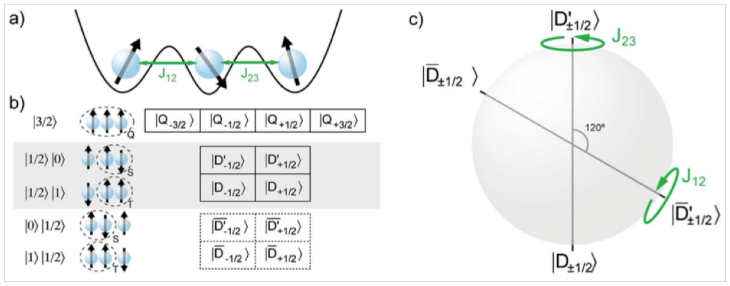
PHYSICAL REVIEW B **82**, 075403 (2010)

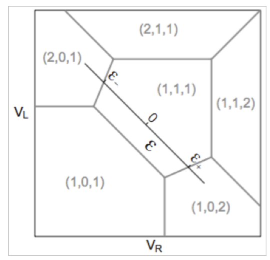
Coherent spin manipulation in an exchange-only qubit

E. A. Laird,[1,*] J. M. Taylor,[2] D. P. DiVincenzo,[3] C. M. Marcus,[1] M. P. Hanson,[4] and A. C. Gossard[4]
[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA*
[3]*IBM T. J. Watson Research Center, Yorktown Heights, New York 10598, USA*
[4]*Materials Department, University of California, Santa Barbara, California 93106, USA*
(Received 3 May 2010; revised manuscript received 12 July 2010; published 4 August 2010)



Realization of the exchange-only (EO) qubit



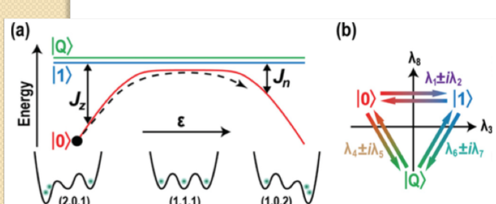


Leakage error

PHYSICAL REVIEW B **86**, 125408 (2012)

Hyperfine-induced decay in triple quantum dots

Thaddeus D. Ladd
HRL Laboratories, LLC, 3011 Malibu Canyon Road, Malibu, California 90265, USA
(Received 8 May 2012; published 6 September 2012)



$$|0\Uparrow\rangle = |\bar{D}'_{+1/2}\rangle = \frac{|\uparrow\downarrow\uparrow\rangle - |\downarrow\uparrow\uparrow\rangle}{\sqrt{2}},$$

$$|1\Uparrow\rangle = |\bar{D}_{+1/2}\rangle = \frac{|\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\uparrow\rangle}{\sqrt{6}} - \sqrt{\frac{2}{3}}\,|\uparrow\uparrow\downarrow\rangle,$$

$$|Q\Uparrow\rangle = \frac{|\uparrow\downarrow\uparrow\rangle + |\downarrow\uparrow\uparrow\rangle + |\uparrow\uparrow\downarrow\rangle}{\sqrt{3}}.$$

Hamiltonian of an EO qubit in computational bases

$$H = H_c + H_{hf}$$

$$H_c = J_{12}(t)E_{12} + J_{23}(t)E_{23}$$

$$H_{hf} = \left(\frac{\lambda_1}{2\sqrt{3}} + \frac{\lambda_4}{\sqrt{6}}\right)\Delta_{12} + \left(\frac{\lambda_3}{3} + \frac{\sqrt{2}}{3}\lambda_6\right)\Delta_{\overline{12}},$$

$$E_{12} = -\frac{\lambda_3}{2} - \frac{\lambda_8}{2\sqrt{3}}, \quad E_{23} = -\frac{\sqrt{3}}{4}\lambda_1 + \frac{\lambda_3}{4} - \frac{\lambda_8}{2\sqrt{3}}$$

$$\Delta_{12} = B_1 - B_2 \qquad \Delta_{\overline{12}} = B_3 - (B_1 + B_2)/2$$

Gell-Mann Matrices

$$\lambda_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \lambda_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix},$$

$$\lambda_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \lambda_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \lambda_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \lambda_8 = \frac{1}{\sqrt{3}}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$

Summary of EO qubit

exchange-only qubit / three-electron triple-dot qubit

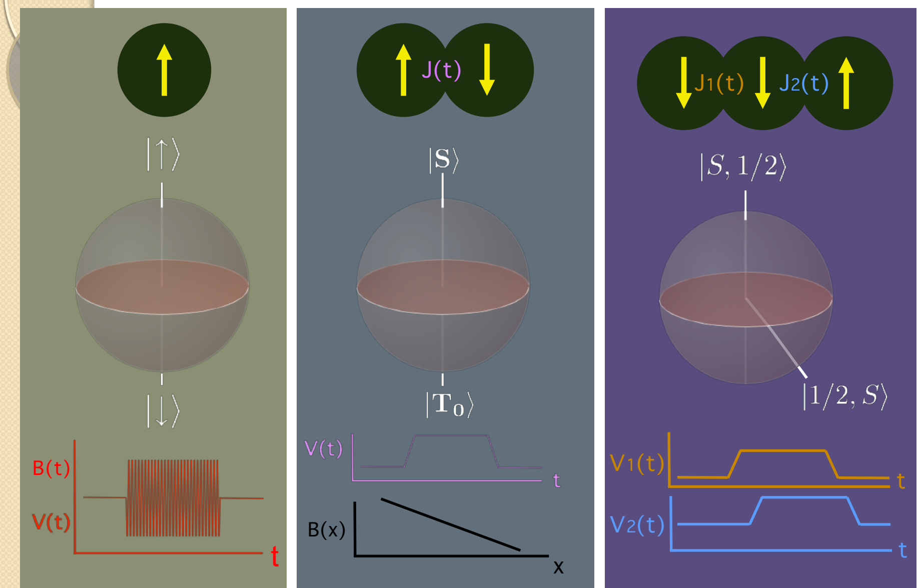
+ noise properties, single-qubit gates

− complexity of qubit encoding, fairly large number of QDs

- No need of a B-field gradient; the exchange interaction alone suffices for universal computation
- All-electrical two-axis control

Spin qubits so far

LD Qubit | ST Qubit | EO Qubit



Loss DiVincenzo, PRA 1998 | Levy, PRL 2002 | DiVincenzo, et al, 2000

Resonant-exchange (RX) qubit

- Same as the EO qubit, but now rotate the entire reference frame by $\pi/3$

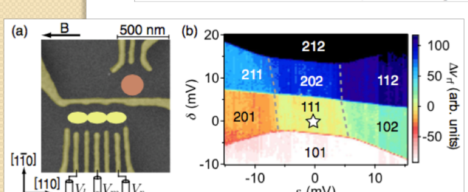
PRL **111,** 050501 (2013) PHYSICAL REVIEW LETTERS week ending 2 AUGUST 2013

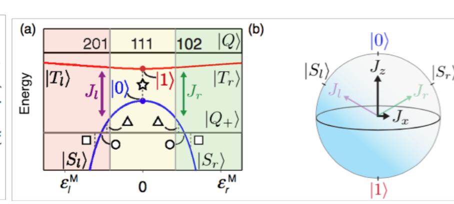
Quantum-Dot-Based Resonant Exchange Qubit

J. Medford,[1] J. Beil,[2] J. M. Taylor,[3] E. I. Rashba,[1] H. Lu,[4] A. C. Gossard,[4] and C. M. Marcus[2]

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, Universitetsparken 5, 2100 Copenhagen, Denmark*
[3]*Joint Quantum Institute/NIST, College Park, Maryland 20742, USA*
[4]*Materials Department, University of California, Santa Barbara, California 93106, USA*

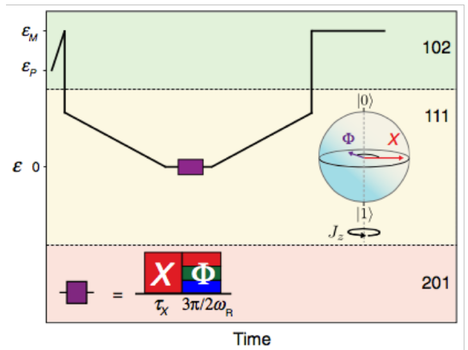
(Received 11 April 2013; published 31 July 2013)





Resonant-exchange (RX) qubit

- Charge noise greatly suppressed (J insensitive to $\delta\varepsilon$)
- Full single-qubit control achieved using the phase differences of the microwave pulses



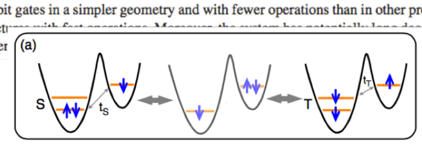
Hybrid qubit (Madison qubit)

PRL **108,** 140503 (2012) PHYSICAL REVIEW LETTERS week ending 6 APRIL 2012

Fast Hybrid Silicon Double-Quantum-Dot Qubit

Zhan Shi,[1] C. B. Simmons,[1] J. R. Prance,[1] John King Gamble,[1] Teck Seng Koh,[1] Yun-Pil Shim,[1] Xuedong Hu,[2] D. E. Savage,[1] M. G. Lagally,[1] M. A. Eriksson,[1] Mark Friesen,[1] and S. N. Coppersmith[1]
[1]*Department of Physics, University of Wisconsin-Madison, Madison, Wisconsin 53706, USA*
[2]*Department of Physics, University at Buffalo, SUNY, Buffalo, New York 14260, USA*
(Received 3 November 2011; revised manuscript received 23 December 2011; published 4 April 2012)

We propose a quantum dot qubit architecture that has an attractive combination of speed and fabrication simplicity. It consists of a double quantum dot with one electron in one dot and two electrons in the other. The qubit itself is a set of two states with total spin quantum numbers $S^2 = 3/4$ ($S = 1/2$) and $S_z = -1/2$, with the two different states being singlet and triplet in the doubly occupied dot. Gate operations can be implemented electrically and the qubit is highly tunable, enabling fast implementation of one- and two-qubit gates in a simpler geometry and with fewer operations than in other proposed quantum dot qubit architect... herence times. These are all extrer... evices.



Hybrid qubit (Madison qubit)

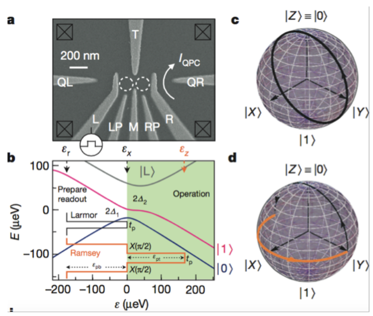
LETTER

70 | NATURE | VOL 511 | 3 JULY 2014

doi:10.1038/nature13407

Quantum control and process tomography of a semiconductor quantum dot hybrid qubit

Dohun Kim[1], Zhan Shi[1], C. B. Simmons[1], D. R. Ward[1], J. R. Prance[1], Teck Seng Koh[1], John King Gamble[2], D. E. Savage[3], M. G. Lagally[3], Mark Friesen[1], S. N. Coppersmith[1] & Mark A. Eriksson[1]



Resonant driving of the hybrid qubit

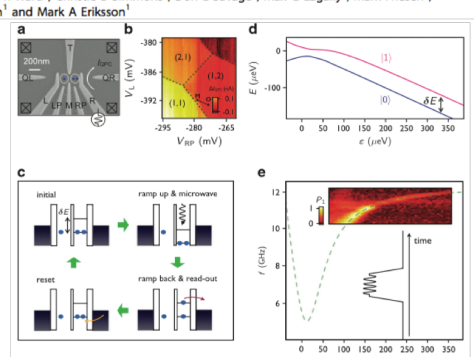
npj | Quantum Information

www.nature.com/npjqi

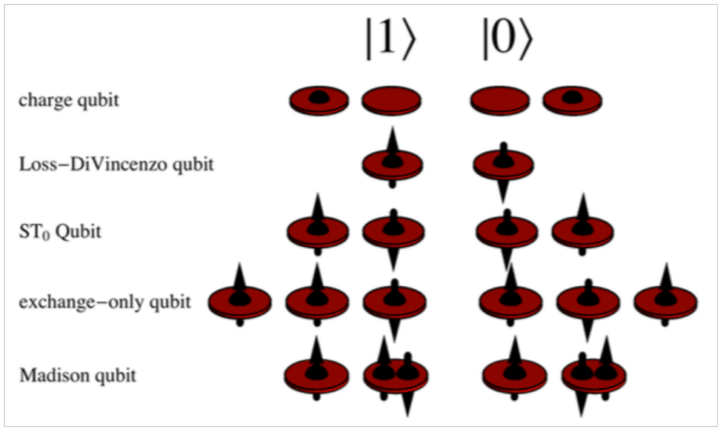
ARTICLE OPEN

High-fidelity resonant gating of a silicon-based quantum dot hybrid qubit

Dohun Kim[1,2], Daniel R Ward[1], Christie B Simmons[1], Don E Savage[3], Max G Lagally[3], Mark Friesen[1], Susan N Coppersmith[1] and Mark A Eriksson[1]



Summary



|1⟩
|0⟩
charge qubit
Loss–DiVincenzo qubit
ST0 Qubit
exchange–only qubit
Madison qubit