Free Spin Quantum Computer

Wei-Min Zhang

Department of Physics
Center for Quantum Information Science

Talk at NTHU

Nov. 23, 2005

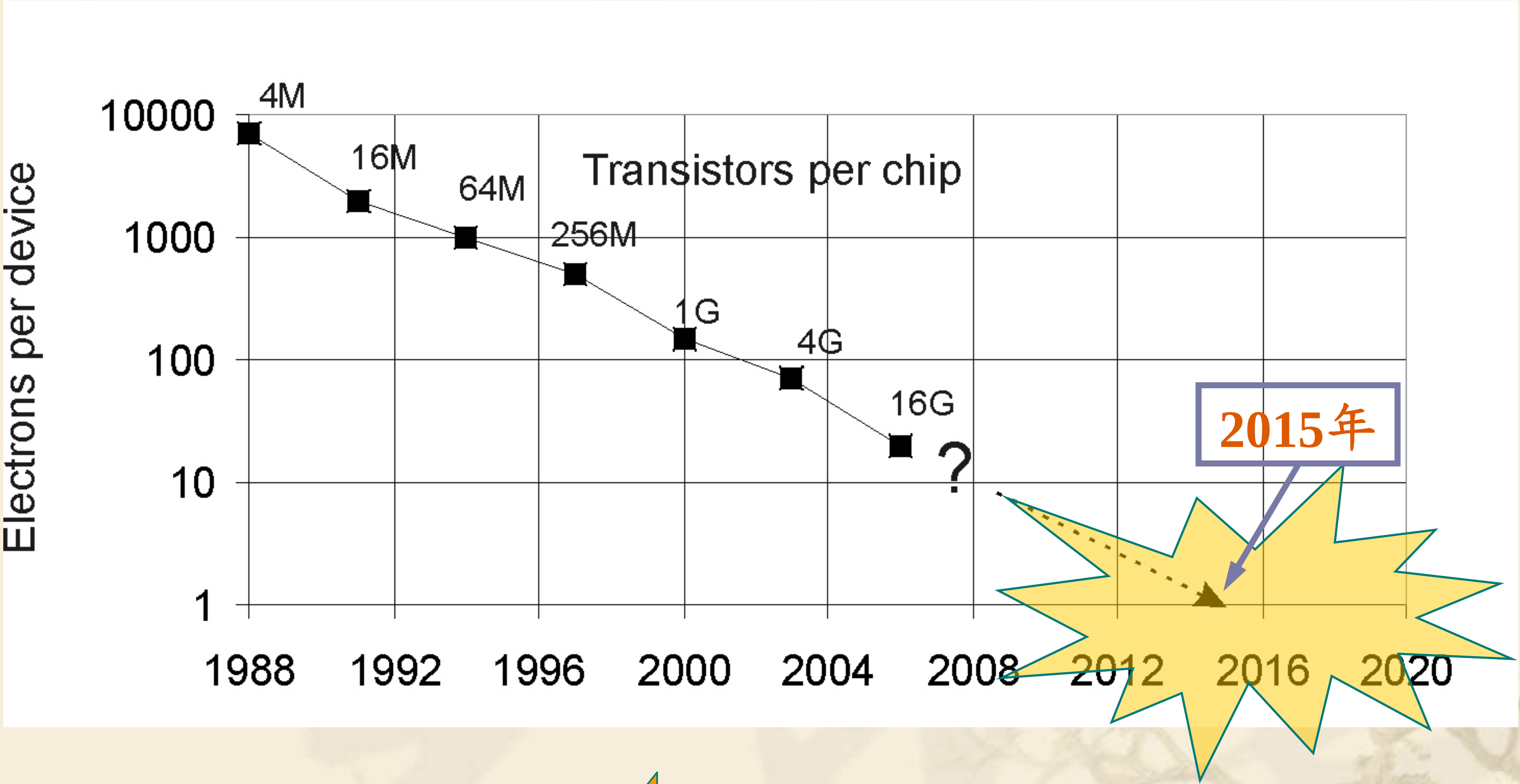
- 二十一世紀工業發展的核心:

  QUANTUM TECHNOLOGY

- QUANTUM TECHNOLOGY 核心:

  QUANTUM INFORMATION SCIENCE (QIS)

Towards the quantum limit



Quantum technology ← **Limits or Opportunities?**

QUANTUM TECHNOLOGY

- Semiconductors' ultimate limit:
  - Single electron
- Optics and fiber's ultimate limit:
  - Single photon
- Nano-materials' ultimate limit:
  - Single Atom

Manipulation of Single Electron, photon and atom ➲ building blocks of quantum information

QIS DEVELOPMENT IN TAIWAN

- 2002, NSC 提議規劃末來幾年物理的重點發展方向
  - 汪治平：建議 Photon entanglement and ultrafast optical controls
  - 張慶瑞：建議 Spintronics ……
  - 諸德三：建議 Cavity QED……
  - ……………
  - 張為民：All the above suggested topics are the subject of the new emerged field, called “Quantum Information Science (QIS)”

→ 由我負責綜覽 **QIS** 近年來的研究及發展

- 2003, NSC 征求奈米國家型學術卓越計畫
  - 要求以國際上還沒提出過的或還沒實現的 new ideas 為其研究目的

- WE PROPOSED A NANO-PROJECT:

  量子資訊科學： 利用半導體元件-量子點-實現量子資訊之光電操控

  FUNDING FOR 3 YEARS

Now, Taiwan has a QIS community

- **NCKU:** QIS center
- **NTHU:** Po-Chung Chen……
- **NTU:** Hsi-Sheng Goan
- **NTCU:** Der-San Chuu's group
- **AS:** Chi-Yee Cheung, Chii-Dong Chen
- **CYCU**: Li-Yi Hsu & Chih Long Chou
- **NCCU:** Waston Kuo
- **CCU:** Dian Jiun Han
- ....

- 為達到國科會奈米國家型學術計畫的基本要求，即：

在國際上還沒提出過的或還沒實現的
new ideas

我們構想：

Free Spin
Quantum Computer

NO-GO THEOREM:

The exponential speedup of quantum over classical algorithms cannot be reached with single electron Hamiltonians assisted by single-spin measurements

L. Valiant, Proc. ACM STOC (2001)
Knill, quant-ph/0108033
Terhal and DiVicenzo, PRA65 (2002)

OUR NEW IDEA:

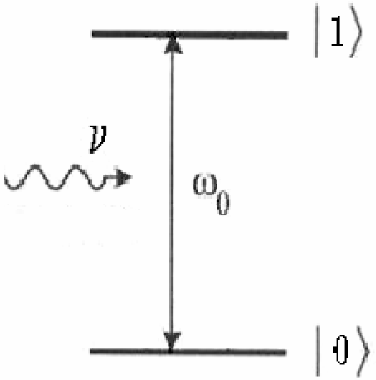
Taking the excess conduction electron spin in a unit cell of multiple semiconductor quantum-dot structure as the qubit, we can propose an implementation of a scalable quantum computer without resorting to spin-spin couplings, and also without assisted by single-spin measurements.

Zhang, Wu and Soo
quant-ph/0502002

ELEMENTARY UNIT OF QIP: QUANTUM BIT (QUBIT)

- qubit: Any two-level physical system,

$$|\phi\rangle=\alpha|0\rangle+\beta|1\rangle, \quad |\alpha|^2+|\beta|^2=1$$



Information processing
with electrons and photons

e.g. 電子自旋(Spin of Electron) : $\{ |\uparrow\rangle , |\downarrow\rangle \}$

原子的基態與激發態: $\{ |g\rangle , |e\rangle \}$

光子的極化態(Polarization of Photon): $\{ |+\rangle , |-\rangle \}$

UNIVERSAL QUANTUM COMPUTATION:

- Quantum gates:

  unitary evolutions of the designed Hamiltonians acting on qubits.

- Universal quantum computing:

  all unitary evolutions can be approximated by a set of logic gates up to a global phase.

- Logic gates:

  unitary evolutions acting on one or two qubits.

RELIABLE PHYSICAL SYSTEMS FOR QIP:

- OPTICAL SYSTEMS

  One photon and two photon devices (linear and nonlinear quantum optics)

- SOLID-STATE SYSTEMS (QUANTUM DOTS, SILICON-BASED NUCLEAR SPINS, SC…)

  Tunable spin-spin interactions, effective local magnetic fields (Heisenberg-type spin systems in condensed matter physics),…

- ATOMIC SYSTEMS (CAVITY QED, TRAPPED IONS, OPTICAL LATTICE, …)

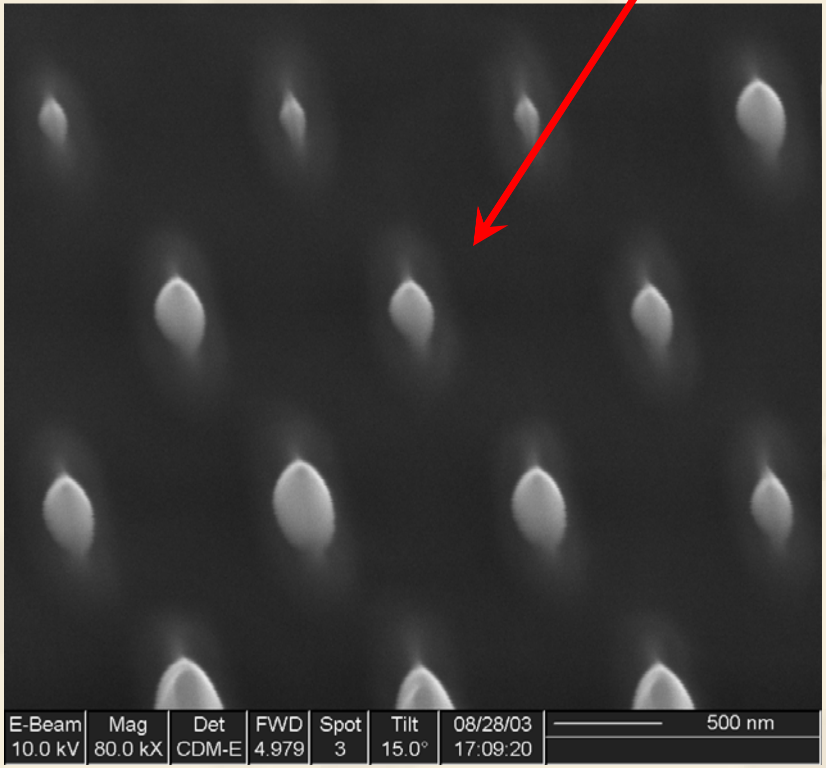
  Electromagnetic fields, laser beams and atoms (electron-photon coupling in atomic physics),…

WHY SEMICONDUCTOR QUANTUM DOTS:

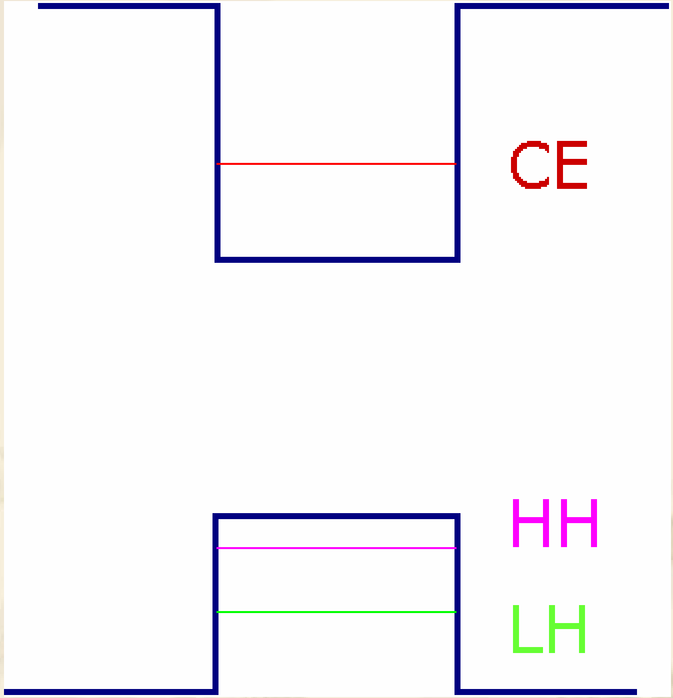
- Experiments have been made for QIP in systems of trapped ions, cavity-atom, and nuclear magnetic resonance (NMR) on small-scale QIP.
- Current techniques to a large-scale, e.g. hundreds to thousands of qubits, quantum computer architecture should be based on solid-state hardware exploiting present nanotechnology.
- Nanotechnology opens technological possibilities to fabricate mesoscopic devices. Semiconductor nanostructure, especially quantum dots (QDs) structures are very promising for the realization of quantum computation and quantum information processing.

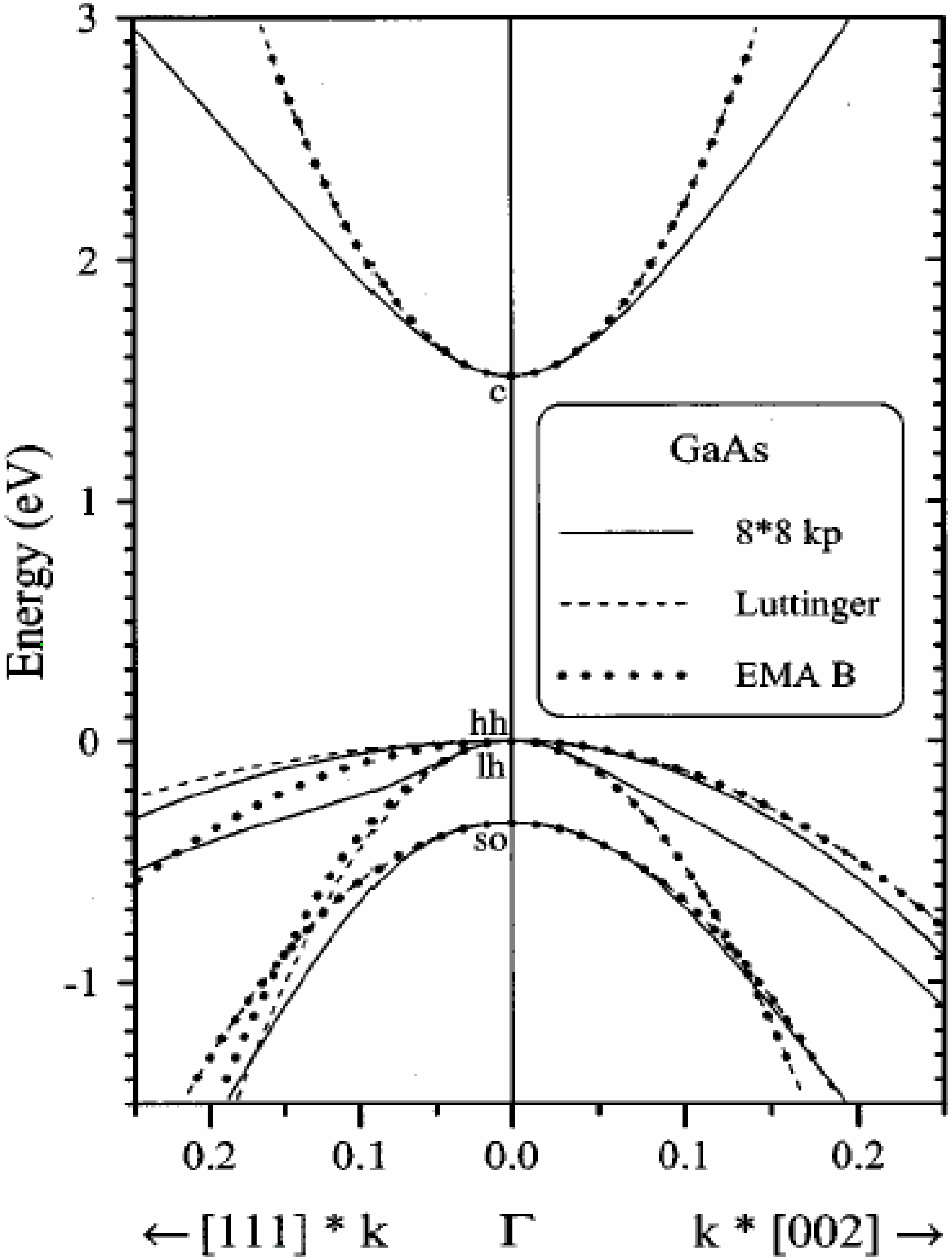
QUANTUM DOTS ARRAY:

Artificial atoms



Using Focused Ion Beam (FIB) on Si





Conduction band

$$\left|\frac{1}{2},\pm\frac{1}{2}\right\rangle$$

Valence band

$$\left|1,m\right\rangle\oplus\left|s,\pm1/2\right\rangle$$

$$\left|\frac{3}{2},\pm\frac{3}{2}\right\rangle \quad \left|\frac{3}{2},\pm\frac{1}{2}\right\rangle$$

$$\left|\frac{1}{2},\pm\frac{1}{2}\right\rangle$$

QDs AS BUILDING BLOCKS FOR QIP:

Quantum Dots (QDs) offer all possible ways for QIP Implementations, because:

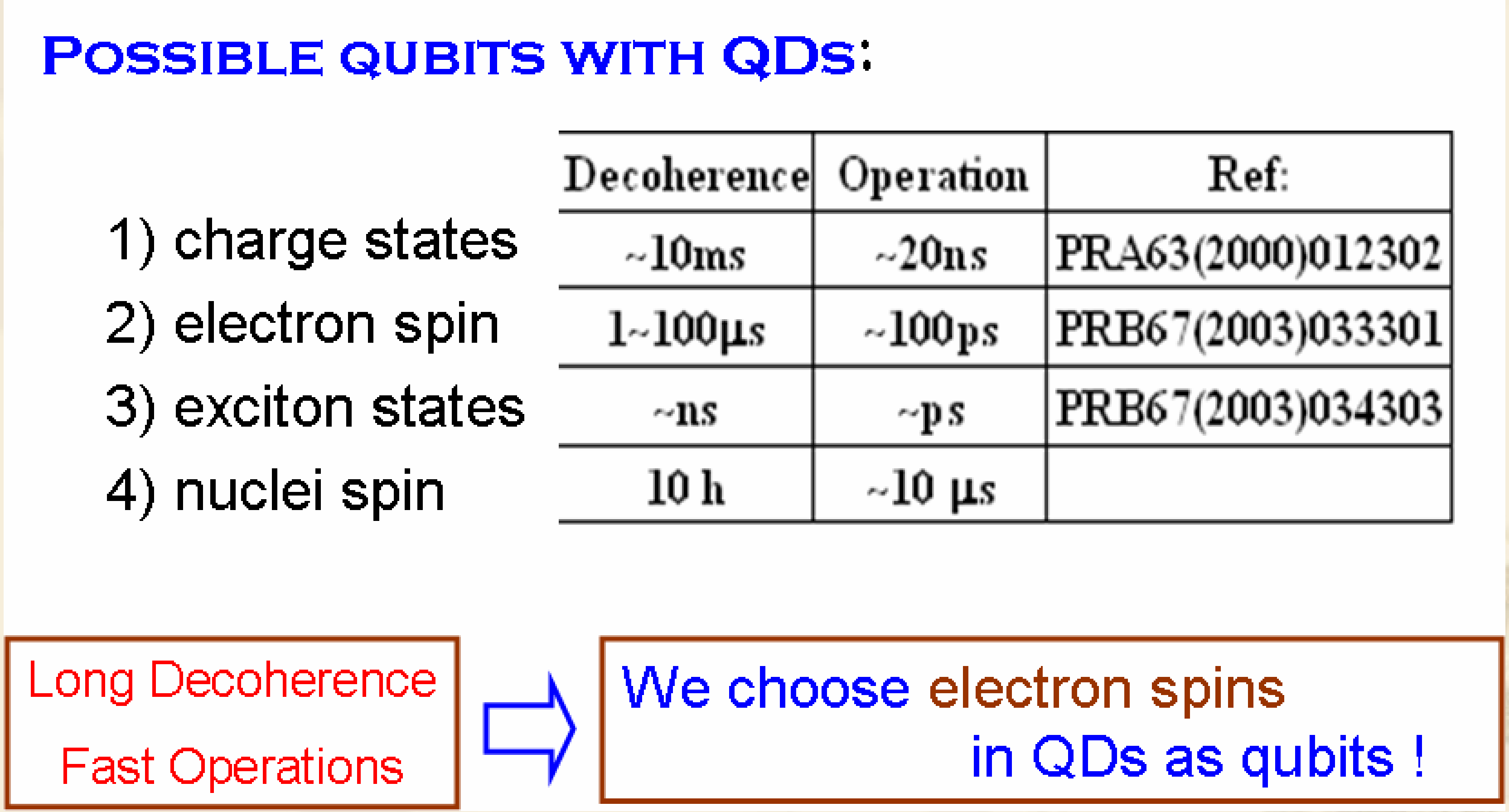
Qubits with QDs:

- Charge state of QDs
- Electron Spin States in QDs
- Exciton States in QDs

Quantum Logical Gates with QDs:

- Electromagnetic controls on QDs
- Optical controls on QDs
- Optical-electric controls on QDs

CHOICES OF QUBITS WITH QDs:



POSSIBLE QUBITS WITH QDs:

	Decoherence	Operation	Ref:
1) charge states	~10ms	~20ns	PRA63(2000)012302
2) electron spin	1~100μs	~100ps	PRB67(2003)033301
3) exciton states	~ns	~ps	PRB67(2003)034303
4) nuclei spin	10 h	~10 μs	

Long Decoherence

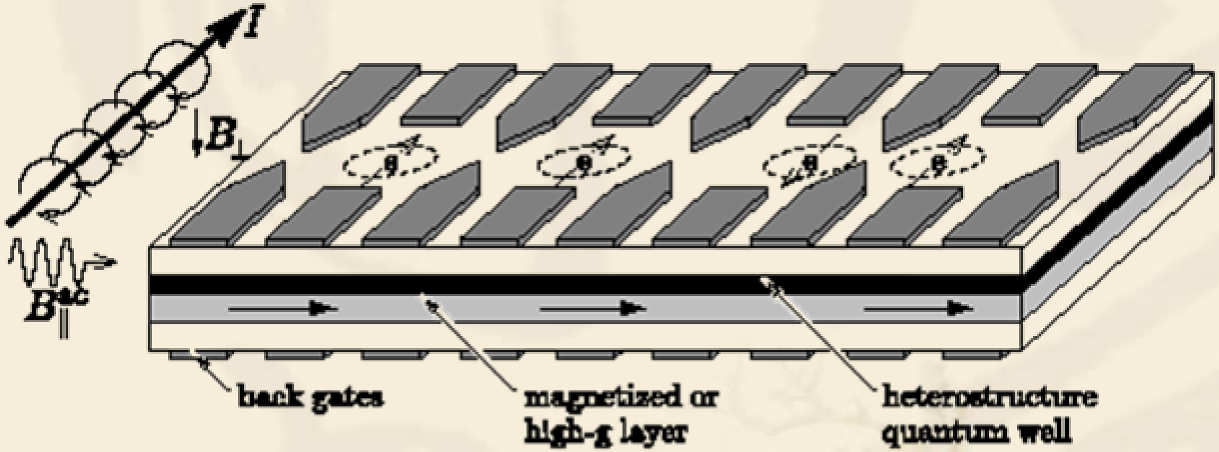
Fast Operations

⇨

We choose electron spins in QDs as qubits !

Previous proposed implementations:

1. Electric and magnetic field controls of spin qubits:



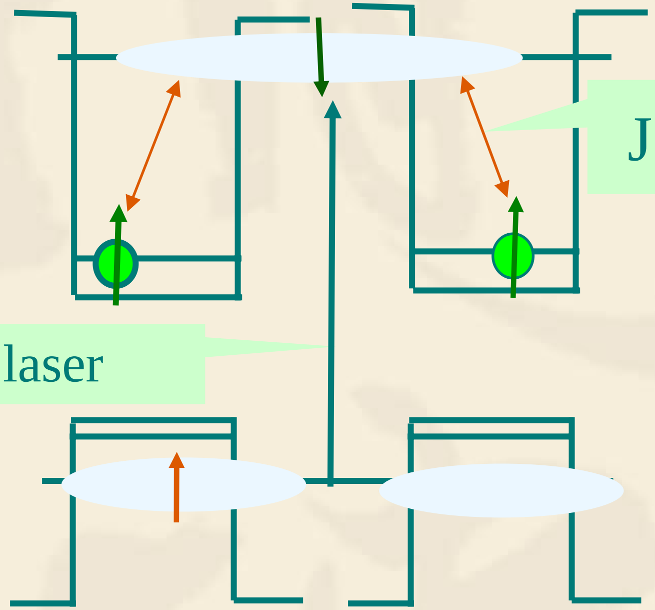
$$H(t) = \sum_{i<j} J_{ij}(t) S_i \cdot S_j + \sum_i \mu_B g(t) B_i(t) \cdot S_i$$

By D. Loss and D.P. DiVincenzo, PRA57, 120 (1998)
G. Burkard, H.A. Engel, and D. Loss, FPPP, **48**, 965-986(2000)

2. OPTICAL CONTROLLING SPIN INTERACTION BETWEEN TWO ELECTRONS IN TWO QUANTUM DOTS (ORKKY):

Exciton over 2 dots

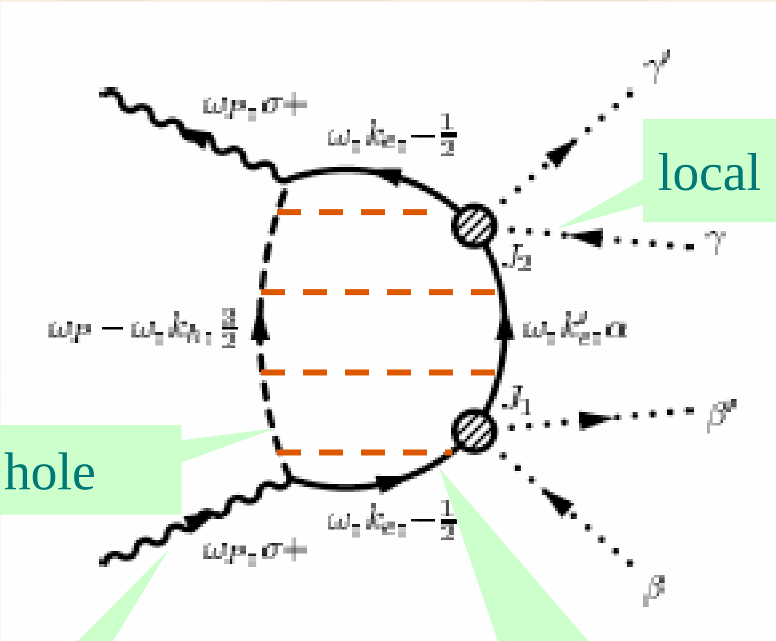
Effective Heisenberg exchange between the electrons in two dots $Js_1.s_2$



$Js_1.s_2$

laser

Single particle levels



local spin

excited hole

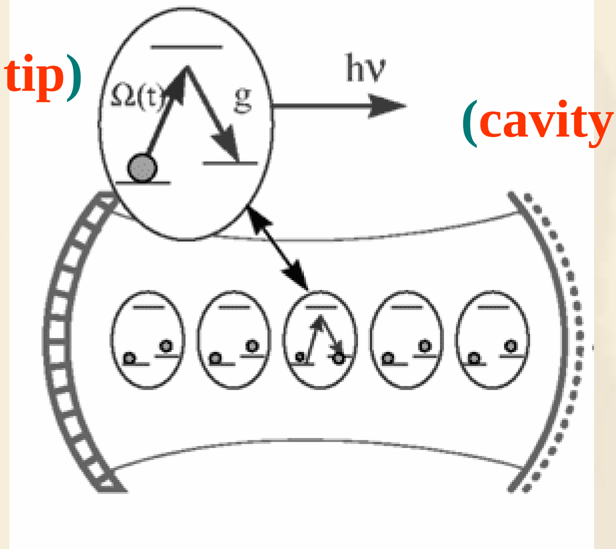
photon

excited electron

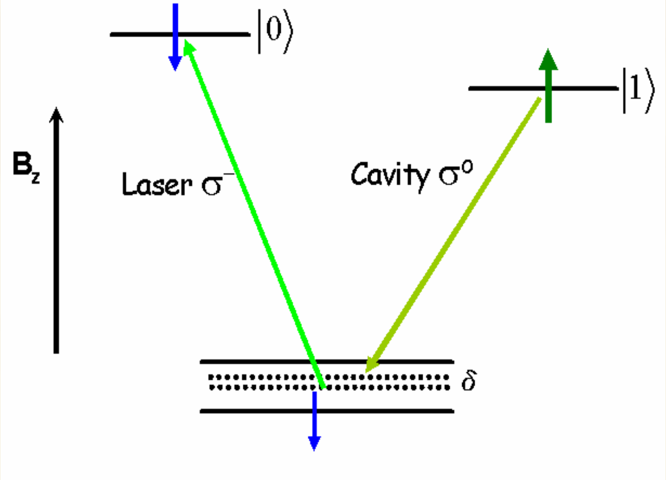
C. Piermarocchi, P. Chen, L.J. Sham, and D.G. Steel, Phys. Rev. Lett. **89** (2002).

3. CAVITY-DOT FOR SOLID-STATE CQED:

(fiber tip)



(cavity)



$$H = \hbar\omega_C a^+ a + \varepsilon^0 |0\rangle\langle 0| + \varepsilon^1 |1\rangle\langle 1| + \varepsilon^X |X\rangle\langle X| + \frac{g}{2}|X\rangle\langle 0| a + \frac{\Omega(t)}{2} e^{-i\omega_L t} |X\rangle\langle 1| + h.c.$$

Cavity

Laser

$$H_{eff} = \sum_{k=1,2} (\varepsilon_k^0 |0\rangle_k \langle 0| + \varepsilon_k^1 |1\rangle_k \langle 1|) + \frac{\overline{\Omega}(t)}{2} \left(|1\rangle_1 \langle 0||0\rangle_2 \langle 1| + |1\rangle_2 \langle 0||0\rangle_1 \langle 1| \right)$$

XY Model

Imamoglu et al. PRL83 (1999) ; Feng et al. PRA67 (2003); Yao, Liu and Sham, arXiv, q-ph/0408148)

A little progress has been made experimentally on spin quantum computation with quantum dots

WHY SOLID-STATE QUANTUM COMPUTATION IS DIFFICULT TO BE IMPLEMENTED?

- Operation time ~ interaction coupling constant → we need a strong spin-spin coupling.
- Spin exchange couplings are weak comparing to the Coulomb interaction (by the order of 10^{-3})
- Optically generating a tunable spin-spin interaction in nano-structures in sufficient strength is technically very difficult.

FREE INTERACTION QUANTUM COMPUTATION :

- IMPLEMENTING QIP WITH FREE QUBITS
  - Simplify the manipulations of physical devices
  - Reduce the effects of decoherences
- SCHEMES ON FIQC:
  - Linear optics [beam splitters, phase shifters with single-photon detectors with feedback, Knill, Laflamme & Milburn, *Nature*, 409 (2001) 46]
  - Flying fermion qubits [beam splitters, single spin rotations with charge detectors, Beenakker et. al, *PRL* 93 (2004) 020501]

NO-GO THEOREM FOR FREE-FERMION QUANTUM COMPUTATION

Knill, quant-ph/0108033
Terhal and DiVicenzo, PRA65 (2002)

IS FREE INTERACTION QUANTUM COMPUTATION POSSIBLE?

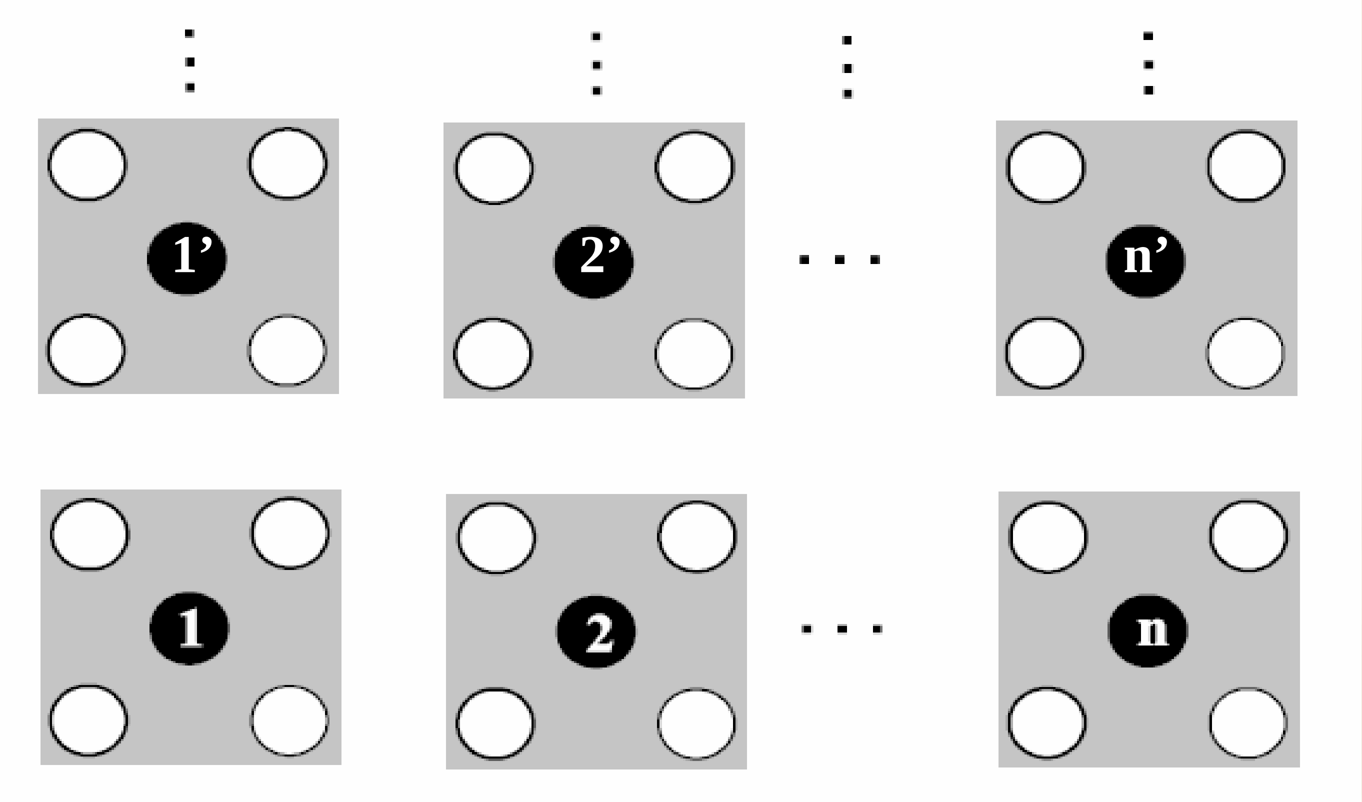
- Universal logical gate contains a two-qubit controlled operation, which requires in principle a qubit-qubit coupling to carry out such a two-qubit controlled gate.

PHYSICALLY, IT IS A BIG CHALLENGE:

- For photons, they do not directly interact each other
  ➔ free photon quantum computer. [*Nature*, 409 (2001) 46]

- For fermions (spins), it is not easy to generate and control a strong enough spin-spin coupling in nano-structures
  ➔ free spin quantum computer. ?????

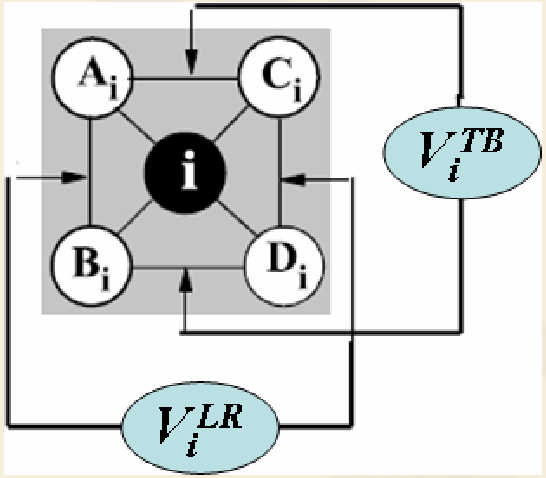
OUR ARCHITECTURE FOR A FREE SPIN QC:

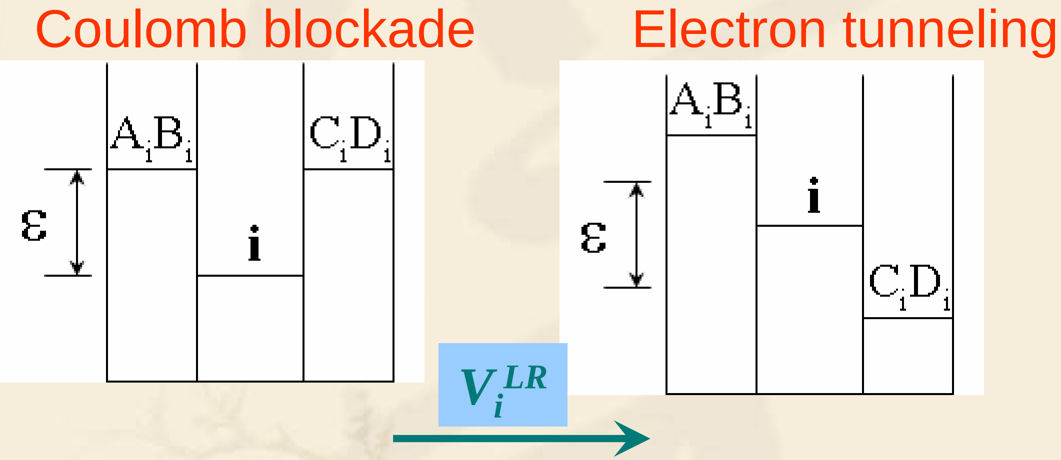


1. **The shading box (contains five dots) is a basic device (a unit cell)**
2. **Each cell contains only one excess conductor electron**
3. **The excess electron spin states are selected as the qubit states.**

Basic device for free spin QC:

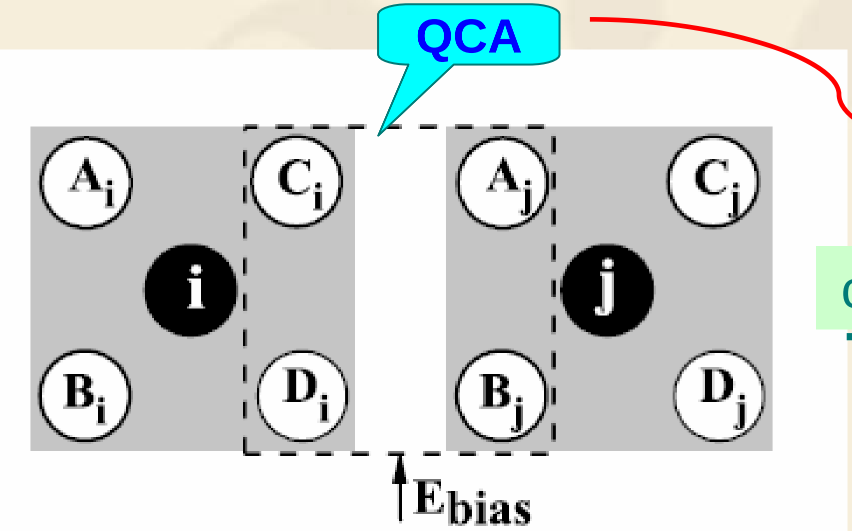
A. Structure of unit cell (1 qubit dot surrounded by 4 ancilla dots)

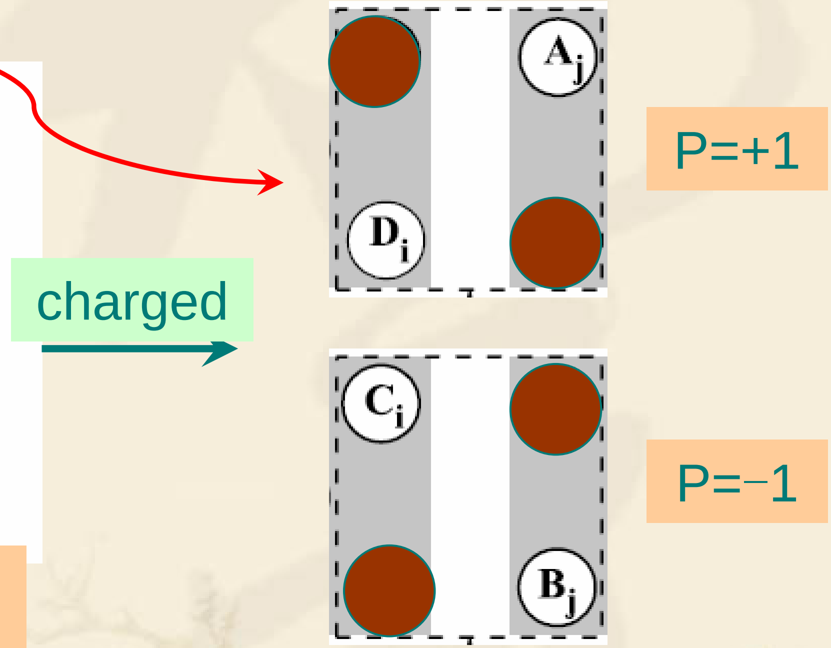




1. **Central (black) dot is called as a qubit dot, surrounding four (empty) dots are called as ancilla dots.**
2. **Lines between dots indicate the possibility of interdot tunnelings**
3. **Bias electrode pulses V_i^{LR} and V_i^{TB} control the electron tunneling among dots in the cell**

TWO QUBIT DOTS MEDIATED WITH A QCA:





Charge Bias Polarization:

$$H = E_{bias}\boldsymbol{P}$$

1. **Tunneling of electron between different unit cell is forbidden.**
2. **The neighboring four ancilla dots form a Coherent Quantum-dot Cellular Automata (QCA).**
3. **When a QCA is charged with two electrons, the electrons will occupy coherently two diagonal sites (two charge polarizations) as a result of coulomb repulsion**

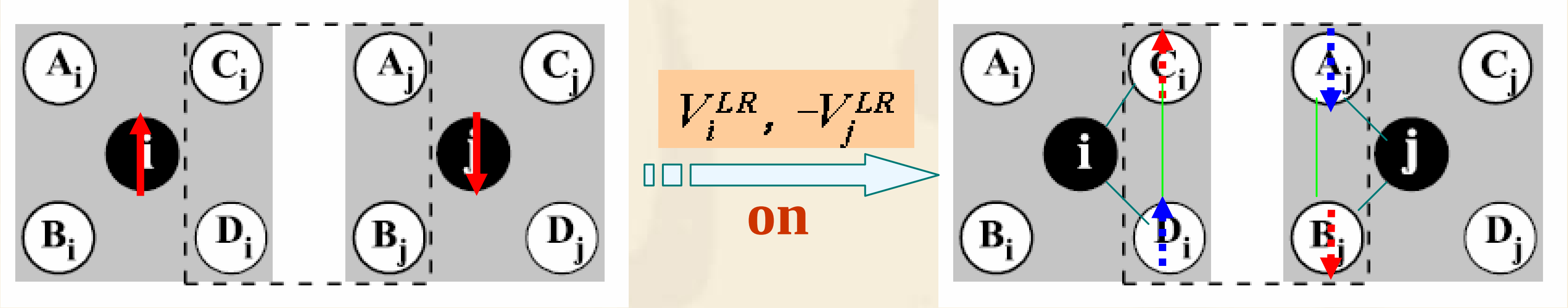
G. Toth and C.S. Lent, PRA63 (2001)

BASIC IDEA FOR IMPLEMENTATION:

- We use external bias electrodes to control single electron tunnelings that creates naturally an electron charge entangled state with the help of quantum-dot cellular automata (QCA).
- The electronic charge entangled state is then converted into an electronic spin entangled state using only single spin rotations.
- Spin-spin interactions are not required in this implementation and deterministic two-qubit controlled gates can be easily implemented.
- Single-shot read-put of spin states can also be realized through spin-to-charge conversion with help of quantum point contact (QPC)
- As a result, a free spin scalable quantum computation is feasible in semiconductor nanostructures.

CHARGE ENTANGLEMENT STATE VIA QCA:

- **Initial state:** $|\Psi_0\rangle = |\overset{0}{S_i}\overset{1}{S_j}\rangle|e_ie_j\rangle$, **All ancilla dots are identical,**



- **After tuning on the pulses** $V_i^{LR}, -V_j^{LR}$ **, it becomes:**

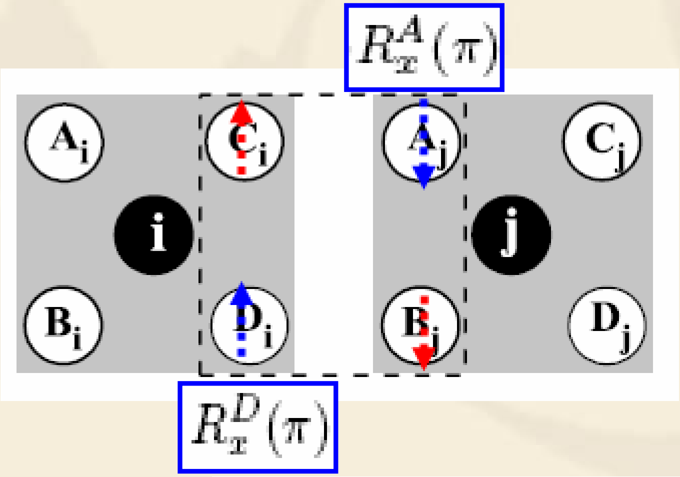
$$|\Psi_0\rangle \xrightarrow{(V_i^{LR},-V_j^{LR})_{on}} |\Psi_1\rangle = |01\rangle\boxed{\frac{1}{\sqrt{2}}\left(|e_i^C e_j^B\rangle + |e_i^D e_j^A\rangle\right)}$$

QCA

Maximum charge entangled state

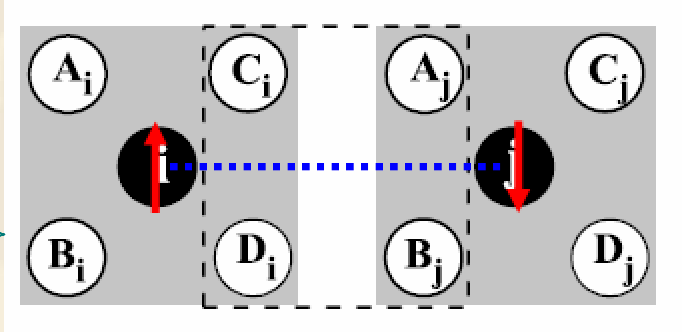
Due to coherent charge polarization

SWAPING CHARGE ENTANGLED STATE INTO SPIN ENTANGLED STATE:



$V_i^{LR}, -V_j^{LR}$

off



$$\begin{matrix} |e_i^C e_j^B\rangle \\ |e_i^D e_j^A\rangle \end{matrix} \longrightarrow |e_i e_j\rangle$$

Then: $|01\rangle \boxed{\frac{1}{\sqrt{2}}\left(|e_i^C e_j^B\rangle + |e_i^D e_j^A\rangle\right)}$

$$\xrightarrow{R_x^D(\pi) R_x^A(\pi)} \frac{1}{\sqrt{2}}\left(|01\rangle|e_i^C e_j^B\rangle - |10\rangle|e_i^D e_j^A\rangle\right)$$

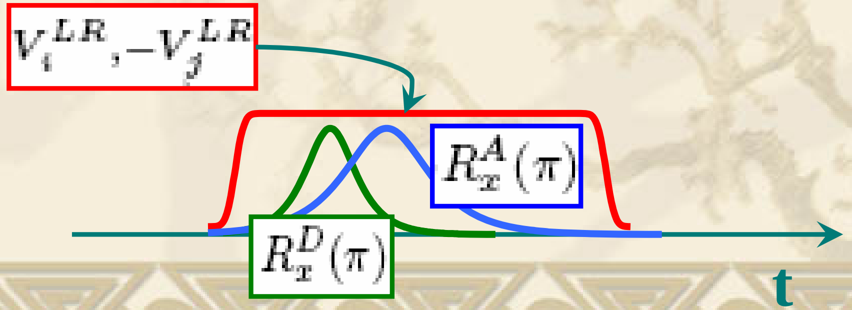
$$\xrightarrow{(V_i^{LR}, -V_j^{LR})_{\text{off}}} \boxed{\frac{1}{\sqrt{2}}\left(|01\rangle - |10\rangle\right)}|e_i e_j\rangle.$$

GENERATING FOUR SPIN BELL STATES:

$$
\begin{aligned}
|01\rangle|e_ie_j\rangle &\xrightarrow{R_x^D(\pi)R_x^A(\pi)} \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)|e_ie_j\rangle,\\
|01\rangle|e_ie_j\rangle &\xrightarrow{R_x^D(\pi)R_x^A(3\pi)} \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)|e_ie_j\rangle,\\
|00\rangle|e_ie_j\rangle &\xrightarrow{R_x^D(\pi)R_x^A(\pi)} \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)|e_ie_j\rangle,\\
|00\rangle|e_ie_j\rangle &\underbrace{\xrightarrow{R_x^D(\pi)R_x^A(3\pi)}}_{V_i^{LR},-V_j^{LR}} \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)|e_ie_j\rangle.
\end{aligned}
\quad \rightarrow \quad
\begin{aligned}
&|\psi^-\rangle\\
&|\psi^+\rangle\\
&|\varphi^-\rangle\\
&|\varphi^+\rangle
\end{aligned}
$$

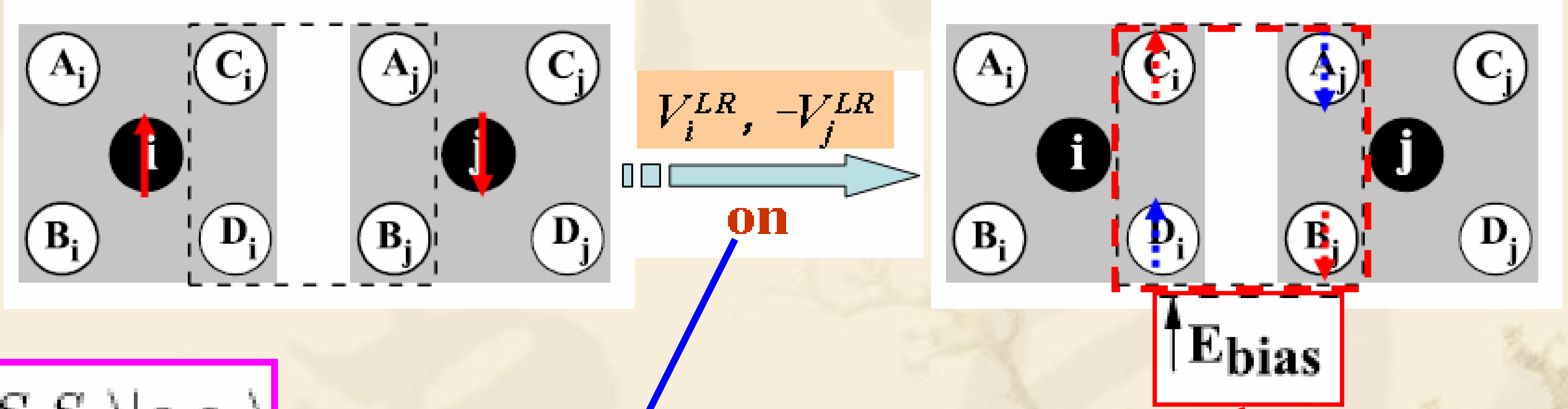
Without using spin-spin couplings

Pulses sequence:



IMPLEMENTING A CNOT GATE:

- To implement a spin CNOT gate via QCA, we need to modify the charge entangled state with the help of a π/2 pulse of the charge bias polarization:

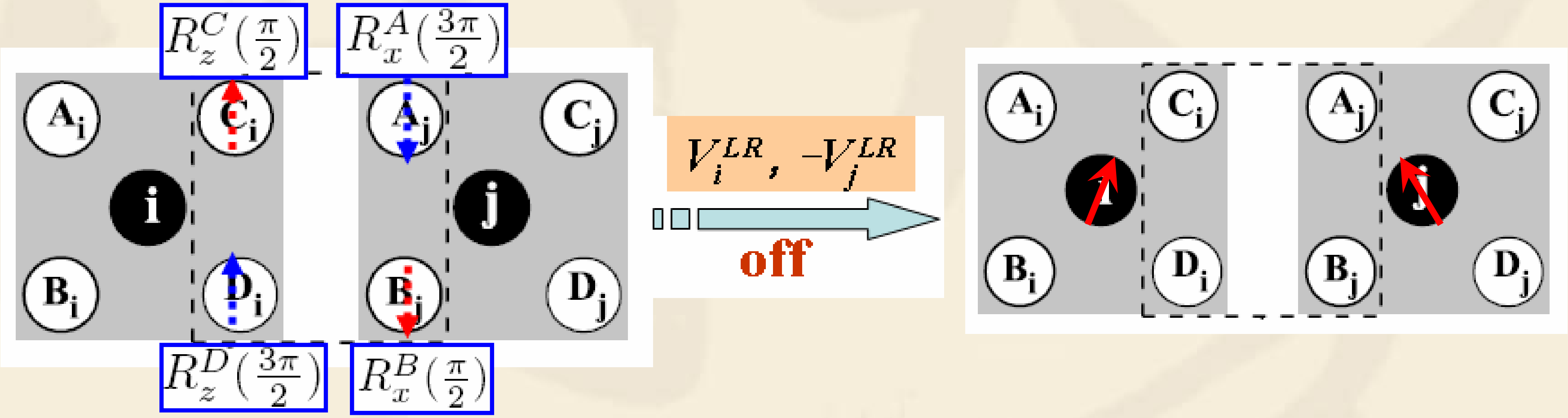


$$|S_iS_j\rangle|e_ie_j\rangle$$

$$|S_iS_j\rangle\frac{1}{\sqrt{2}}\left(|e_i^C e_j^B\rangle+|e_i^D e_j^A\rangle\right)$$

$$\xrightarrow{R_P(\frac{\pi}{2})} e^{i\pi/4}|S_iS_j\rangle\frac{1}{\sqrt{2}}\left(|e_i^C e_j^B\rangle-i|e_i^D e_j^A\rangle\right)$$

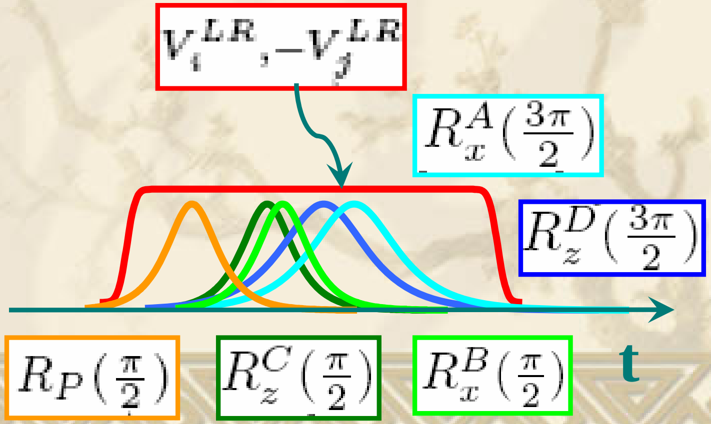
- After the $\pi/2$ charge polarization pulse, applying a single spin rotation on each dot C_i, D_i, A_j, B_j in the QCA as shown, then tuning off the bias voltage pulses $V_i^{LR}, -V_j^{LR}$:



Result:

$$\begin{array}{lcl} |00\rangle|e_ie_j\rangle & & |00\rangle|e_ie_j\rangle \\ |01\rangle|e_ie_j\rangle & & |01\rangle|e_ie_j\rangle \\ & \underbrace{\xrightarrow{U(P)U(ABCD)}}_{V_i^{LR},-V_j^{LR}} & \\ |10\rangle|e_ie_j\rangle & & |11\rangle|e_ie_j\rangle \\ |11\rangle|e_ie_j\rangle & & |10\rangle|e_ie_j\rangle \end{array}$$

Pulses sequences:



MANIPULATION OF A FREE SPIN QC:

The free spin QC proposed in this work is based on how to manipulate single electrons with following operations via QCA:

- Bias electrodes for controlling single electron tunnelings (techniques developed for single electron transistors, etc.)
- Bias polarization for controlling charge polarization (the same technology of using the bias electrodes)
- Single spin rotations (extensively investigated in the last few years in nano-technology) based on
  - Local magnetic fields
  - Local effective g-factor
  - Ultrafast optical controls of single spin coherence

Manipulating single electron spin:

$$\boxed{(g\mu_B \mathbf{S}\cdot\mathbf{B})(t)}$$

- Local magnetic fields can be generating by
  - Magnetic tip of a scanning force microscope
  - Electron-spin-resonance (ESR) techniques ……

~ ns time scale

- Local effective g-factor can be generating with
  - Using external bias voltage
  - Magnetic impurities……

~ ns time scale

- Using exchange coupling to FM dots…
  - This is not our choice for a free spin QC

ULTRAFAST OPTICAL CONTROLS OF SINGLE SPIN COHERENCE:

Techniques have been developed for coherent all-optical control over electron spins in semiconductors on femtosecond time scale

- **Optical tipping pulses can enact single spin rotations through the optical Stark effect (**Gupta, Knobel, Samarth and Awschalom, ***Science*** 292 (2001) 2458**)**

  ~ 200 fs (time scale)

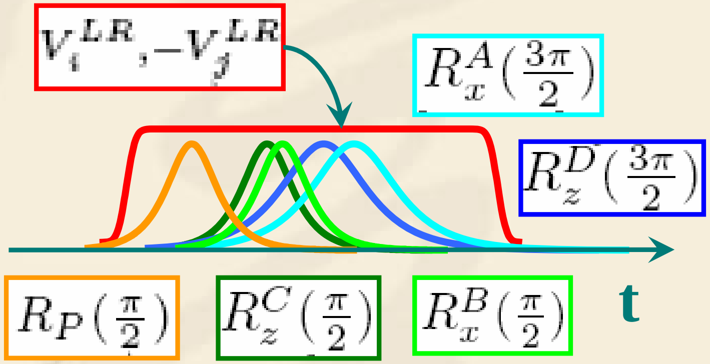
- **Spin-flip Raman transitions using the adabatic process of two ultrafast laser pulses can fully control single spin rotations in a semiconductor quantum dot. [**Vitanov et al., ***Annu. Rev. Phys. Chem*** (2001); Imamoglu et al. ***PRL*** (1999); Pazy et al., ***Europhys. Lett***. (2003); Chen et al., ***PRB*** (2004)]

  ~ 20 ps (time scale)

DECONHERENCE PROBLEM:

- Decoherence time of electron spin in semiconductor → ~ 50 μs
- Bias voltage pulses → ~ 200 ps
- Optical control of single spin rotations → 20 ps ~ 100 fs

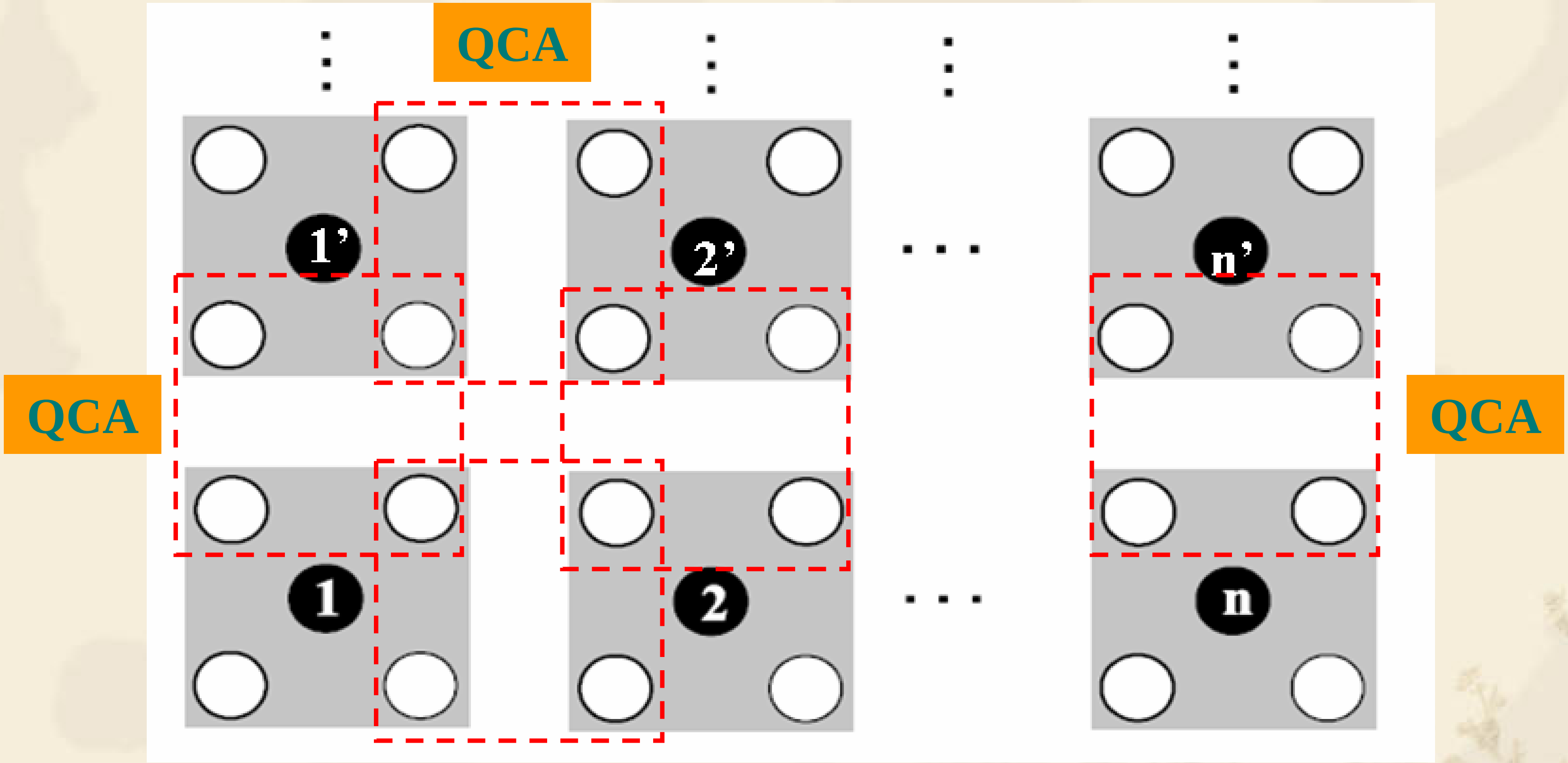
Decoherence should not be a real trouble here:



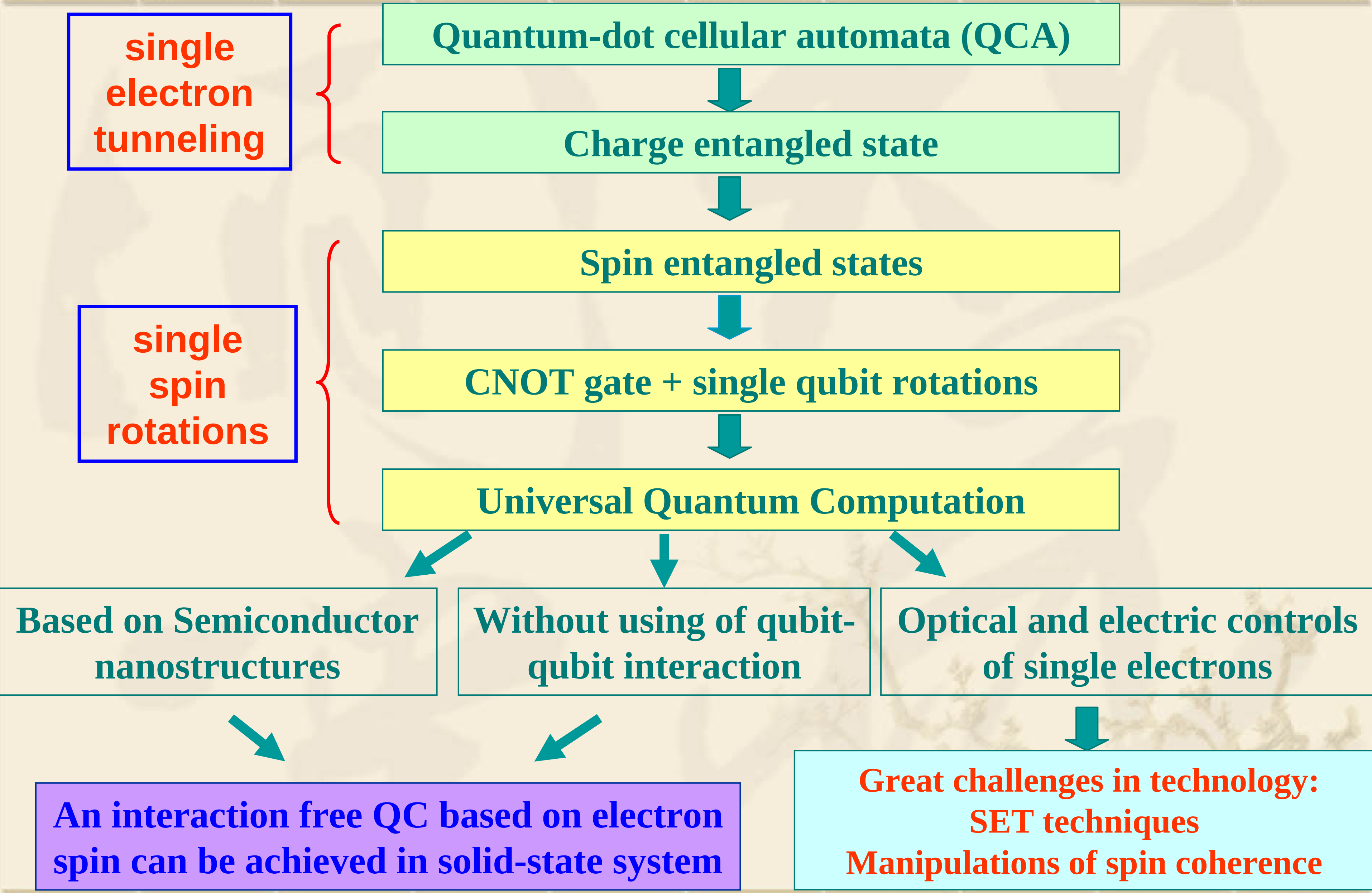
FULLY DETERMINISTIC:

- Previous proposed free interaction QC in which single particle detectors must be used → one can obtain non-deterministic or near-deterministic free interaction QC
- In our implementation, with help of QCA, no particle detectors are required → **our free spin QC is fully deterministic**!

EFFICIENCY OF FREE SPIN QC:



Integrating qubit dots by mediating with QCA in a two-dim architecture, we achieve FSQC with very low linear resources.



single electron tunneling

Quantum-dot cellular automata (QCA)

Charge entangled state

single spin rotations

Spin entangled states

CNOT gate + single qubit rotations

Universal Quantum Computation

Based on Semiconductor nanostructures

Without using of qubit-qubit interaction

Optical and electric controls of single electrons

An interaction free QC based on electron spin can be achieved in solid-state system

Great challenges in technology:
SET techniques
Manipulations of spin coherence

WHY NO LIMIT FROM NO-GO THEOREM:

- Implementing free fermion quantum computation is a very challenge subject in principle due to the no-go theorem.
- We are able to achieve such an implementation because of using two degrees of freedom for electron, spin and charge, and also due to the help of the QCA structure.
- QCA offers an intrinsic charge interaction to bring the electrons a fixed coupling that plays an alternatively indirect implementation for qubit-qubit couplings (instead of using single particle detectors and beam splitters).
- Since spin exchange couplings are much weaker than electron Coulomb interaction (by the order of 10^{-3}). A spin quantum computation with the above indirect realization of qubit-qubit coupling has the advantage of being robust against the technical difficulties of generating strong spin-spin interactions.