Quantum Information Processing with Ferroelectrically Coupled Quantum Dots

Jeremy Levy
Department of Physics and Astronomy
University of Pittsburgh

Quantum Information: Entanglement, Decoherence and Chaos Program

Institute for Theoretical Physics
University of California at Santa Barbara

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Outline

• Requirements for Quantum Computation
• Proposed Approach
• Material Systems
• Future Experiments

• Universal quantum computation with spin-1/2 pairs
Quantum Information Processing with Ferroelectrically Coupled Quantum Dots

Center for Oxide-Semiconductor Materials for Quantum Computation (COSMQC)

- **Experimental**
  - Joachim Ahner, Seagate Research
  - David D. Awschalom, UC Santa Barbara
  - Bruce E. Kane, LPS, U. Maryland
  - Jeremy Levy, University of Pittsburgh
  - Rodney A. McKee, Oak Ridge National Laboratory
  - Darrell G. Schlom, Penn State University
  - John T. Yates, University of Pittsburgh

- **Theoretical**
  - Michael E. Flatté, University of Iowa
  - C. Stephen Hellberg, Naval Research Laboratory
  - Daniel Loss, University of Basel

- **Support**
  - Defense Advanced Research Projects Agency (DARPA)

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@pitt.edu

- **Levy Group**
  - **Postdoc**
    - Nitin G. Patil
  - **Graduate Student**
    - Henry Zhu
  - **Undergraduates**
    - Patrick Irvin
    - Sameer Khanna
Five Requirements for Quantum Computation

(D. P. Divincenzo, quant-ph/0002077)

- **Quantum Memory**
  - Quantum Coherence
- **Quantum Computer**
- **Quantum I/O**
  - Quantum Coherence
- **Quantum CPU**

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Five Requirements for Quantum Computation

R1. A scalable physical system with well-characterized qubits
R2. The ability to initialize the state of the qubits to a simple fiducial state, such as |000...0>
R3. Long relevant decoherence times, much longer than the gate operation time
R4. A “universal” set of quantum gates
R5. The ability to measure specific qubits

- Electron Spins in Ge/Si semiconductors
- Optical spin injection into Si using quasi-direct gap Ge quantum dots
- Long spin lifetimes in Si; very fast (2-qubit) gate operation times using ferroelectric gates
- One and two-qubit operations possible
- Single electron transistors (non-optical)
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COSMQC architecture

- Linear chain of electron spins
  » Localized near Ge/Si QDs
  » Coupled by FE nanowires
- CNOT is combination of
  » Exchange/swap operations $S_{i,i+1}$
  » Single qubit rotations $R$
- Long-range coupling
  » Using local swap operations
- Compatible with exchange-only approaches
  » DiVincenzo et al., Nature 408, 339 (2000).
  » Levy, quant-ph/0101057.

R1. Well characterized qubits

- Spins form natural qubits

Spintronics: $\Psi = \chi_s \cdot \psi(\vec{r})$
R1. Well characterized qubits

- Spins form natural qubits
- Groundbreaking experiments by Awschalom
  - ~100 ns electron spin lifetimes in GaAs at room temperature
    - J. M. Kikkawa, et al., Science 277, 1284 (1997)
  - Robustness against diffusion
    - I. Malajovich, et al., Phys. Rev. Lett. 84, 1015 (2000)
  - Transport across interfaces
    - J. M. Kikkawa and D. D. Awschalom, Nature 397, 139 (1999)
- Quantum dot proposals
  - D. Loss and D. P. DiVincenzo, Phys. Rev. A 57, 120 (1998)
  - R. Vrijen, E. Yablonovitch, K. Wang, et al., Phys. Rev. A 62, 1 (2000)
- Spins in Silicon Proposal
  - B. E. Kane, Nature 393, 133 (1998)

Ge/Si Quantum Dots

- Grow by self-assembly methods
  - Natural diameter too large ($d > 20$ nm)
- Direct/indirect crossover occurs near 10 nm
- Smaller QDs nucleate around impurities (C, Sb)
  - Diameters <10 nm
  - Strong photoluminescence observed
  - Possibility of “directed” self-assembly

Figure A-13. Comparison of PL spectra for SiGe quantum wells and C-induced Ge dots, showing the enhanced luminescence of the quantum dot nanostructures.
Directed Self-Assembly of Ge/Si Quantum Dots

Goal: produce controlled quantum dots with diameter < 10 nm

- UHV “nanoworkbench”
  
  *J. Ahner and J. T. Yates, Dept. of Chemistry, University of Pittsburgh*

- Four-tip STM, SEM, Auger analysis

- STM used for quantum dot formation, doping using “nano-MBE”

How to ferroelectrically couple quantum dots?
What is Ferroelectricity?

- Spontaneous reversible electric polarization below a critical temperature
- Ferroelectric is like a ferromagnet
  » Electric dipoles form domains that can be reoriented by electric fields
  » Domain walls can be atomically thin

Perovskite Structure (BaTiO$_3$)

$T > T_c$, Cubic

Dr. Jeremy Levy, University of Pittsburgh (ITP 10/11/01)
Perovskite Structure (BaTiO$_3$)
T<T$_c$, Tetragonal

Dr. Jeremy Levy, University of Pittsburgh (ITP 10/11/01)
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Ferroelectric Hysteresis

+ + + +

- - - -

P

E

P_s

P_r

E_c

- - - -

+ + + +

• Ferroelectric state is thermodynamically stable

Ferroelectric Memory CHiPs

I_A - I_B

(Pb,Zr)TiO_3/Pt/Si 10 µm

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Ferroelectric Field Effect

- Bound surface charges of ferroelectric attract/repel electrons in semiconductor
  - Interface states can screen ferroelectric charge
  - Interface quality is critical

Ferroelectric Nanostructuring of Semiconductors

- Near-perfect interface between ferroelectric (Ba,Sr)TiO₃ and semiconductor (Si,Ge)
  - Significant ferroelectric field effect
    - \( P_c \sim \pm 10^{14}/\text{cm}^2 \)
  - Nanoscale electronic structures can be created with scanning probe microscope

R. A. McKee, F. J. Walker, and M. F. Chisholm, Phys. Rev. Lett. 81, 3014 (1998).
Optical Rectification and Controlled Exchange

- Optical illumination reduces \( \text{magnitude} \) of ferroelectric polarization
- Tunneling barrier can be modulated optically
  - With ultrafast lasers 10,000 GHz rates achievable
  - Can be used to create a universal quantum gate

Magnitude of Nonlinear Polarization

\[
P_{\text{max}}^{(2)} = \left( 3.93 \times 10^{11} \text{e}^2/\text{cm}^2 \right) \left( \frac{I_{\text{avg}}}{10 \text{mW}} \right) \left( \frac{d}{\mu \text{m}} \right)^2 \times \left( \frac{76 \text{MHz}}{\Omega} \right) \left( \frac{r}{1.95 \times 10^{-11} \text{m/V}} \right) \left( \frac{\tau_{\text{opt}}}{100 \text{ fs}} \right) \left( \frac{n}{2.45} \right)^3
\]

- \( I_{\text{avg}} \) = average laser power
- \( r \) = electrooptic coefficient
- \( d \) = spot diameter
- \( \tau_{\text{opt}} \) = pulse width
- \( \Omega \) = repetition rate
- \( n \) = refractive index
Local Magnetic Fields

- Ferroelectric displacement currents give rise to transient inhomogeneous magnetic fields
  - Max strength ~ 40 gauss
  - Time dependence ~ $\delta'(t)$
  - Could exploit Berry’s phase to create single-qubit operations

$$B_{\text{max}} = \frac{\mu_0 R P_{\text{max}}^{(2)}}{\tau_{\text{opt}}} = \left(39.6 \text{ gauss}\right) \left(\frac{D}{1 \mu\text{m}}\right) \left(\frac{P_{\text{max}}^{(2)}}{6.29 \times 10^{-2} \mu\text{C/cm}^2}\right) \left(100 \text{ fs}\right)$$

Spin Sweeping

- Optical pulse sequence can “sweep” electrons along ferroelectric nanowire
- Useful for bringing electrons together for controlled exchange
- Similar to surface acoustic wave-driven transport
  - C. Rocke et al., PRL 78, 4099 (1997).
Optically Mediated Exchange Gate

- Controlled exchange produced by optical rectification
- Coupling is strong, fast
  
  » (Gate time ~ ps)
  » Important for battling decoherence

Heisenberg coupling via superexchange

(P. Recher, D. Loss and J. Levy, cond-mat/0009270)

- Use central quantum dot as “virtual chat room” for delocalized electrons
- Heisenberg coupling
  
  » Virtual tunneling onto small quantum dot
- Exchange constant:

\[ J = \frac{t_0^4}{\epsilon^3} \]

See also D. Loss and D. P. DiVincenzo, Phys. Rev. A 57, 120 (1998).
How to program the computer?

Spatiotemporal Control of Femtosecond Pulses

• Keith Nelson (MIT) has pioneered methods for shaping femtosecond optical pulses in both space and time.

R. M. Koehl, T. Hattori, and K. A. Nelson, Opt. Comm. 157, 57 (1998).

This method can be used to “program” the quantum information processor.
How to read out the result?

Detection/Readout Schemes

**Optical** (*e.g.* Faraday Rotation)

» Versatile, fast (>THz), low quantum efficiency (\(\eta<<1\))

\[ \theta_F \approx M_x \]

\[ \Delta t \]

\[ \text{Vary pump-probe delay} \]

\(-76\text{ MHz}\)

100 fs

\(T = 5\text{K-}300\text{K}\)

*e.g.*, J. M. Kikkawa and D. D. Awschalom, Nature **397**, 139 (1999).
Detection/Readout Schemes

Electronic
(e.g. single electron transistor)
- Fixed geometry
- Slower (~MHz)
- High quantum efficiency (η~1)

Experimental Approach

- Once structure is produced, need a way to
  - Write ferroelectric nanodomains
  - Optically excite electron spins
  - Use optical rectification to process quantum information
  - Optically detect final spin state
    - Faraday rotation
Variable-Temperature Apertureless Near-Field Microscope

- Atomic-scale optical probe
  - 4K-400K operation
  - ~30 Ångstrom spatial resolution
  - 100 fs time resolution
  - 8T axial / 2T transverse magnetic field
- Use to pattern ferroelectric, probe single quantum dots

Summary

- Experimental realization of a quantum information processor is challenging and exciting
- Ferroelectric/Semiconductor heterostructures may provide an architecture for electron spin-based quantum computation
- Many of the building blocks are already in place
Universal quantum computation with spin-1/2 pairs and Heisenberg exchange

• One application of a quantum computer: Simulation of quantum systems

• A quantum system can simulate its own behavior in real time using a single gate: \( U = \exp[-iHt] \)
  
  » A universal quantum computer must be capable of simulating any quantum system
  
  » Electron spin can be used to form a qubit
  
  » For universal quantum computation, two different physical interactions are required
    • single spin rotations (Zeeman magnetic)
    • spin-spin interaction (Heisenberg exchange)

Another approach: encoded qubits

• Qubit is formed from a 2-dimensional subspace of \( m \) physical two-level systems: cobits

\[ m = 3 \]
Decoherence-Free Subspaces

- Choice of qubit subspace is determined by symmetries of cobit Hamiltonian
- Example: three spins
  - DiVincenzo et al., Nature 408, 339 (2000).

- Heisenberg exchange interaction is universal
  - 3-4 cgate operations $\leftrightarrow$ single qubit operation
  - 19 cgate operations $\leftrightarrow$ cNOT operation

Why 3 spins? (Why not 2?)

- Not enough 1-qubit operations

\[
\begin{align*}
|0\rangle_Q & \leftrightarrow |01\rangle_C \\
|1\rangle_Q & \leftrightarrow |10\rangle_C
\end{align*}
\]

Heisenberg exchange interaction rotates qubit about $X$-axis:

\[
H_{ex} = J \left[ |0\rangle\langle 1|_Q + |1\rangle\langle 0|_Q \right] = J \Sigma_X
\]

Magnetic field does not couple to qubit
$\rightarrow Y$ or $Z$ rotations not possible
Solution: inequivalent magnetic environments

\[ g + \Delta g \]

\[ |0\rangle_Q \equiv |01\rangle_C \]
\[ |1\rangle_Q \equiv |10\rangle_C \]

\[ H_{ex} = J \left[ |0\rangle\langle 0|_Q + |1\rangle\langle 1|_Q \right] = J \Sigma_X \]

\[ H_{Zeeman} = \Delta g \mu_B \left[ |1\rangle\langle 1|_Q - |0\rangle\langle 0|_Q \right] = \Delta g \mu_B \Sigma_Z \]

Now all one-qubit operations are possible!

Qubit Resonance

- Cobit-qubit transformation transforms Heisenberg interaction into Zeeman interaction
  - Reminiscent of real-space renormalization group transformation
    - Introduces new couplings not previously present
  - Spin resonance techniques are mapped onto qubit resonance techniques

\[ \tau[U_z(\pi/2)] = \frac{35 \text{ ps}}{\Delta g} \left( \frac{\text{Tesla}}{H_{ext}} \right) \]

\[ \tau[U_x(\pi/2)] = 0.5 \text{ ps} \left( \frac{\text{meV}}{J} \right) \]

- Microwave magnetic fields are difficult to produce
  - Compared to \( B_x = 10 \) gauss, 4 orders of magnitude improvement!
Two-qubit gates

- One-to-one correspondence with Loss-DiVincenzo implementation for single-spin qubits*
  » No increase in number of gate operations
- Therefore...two-spin qubit+Heisenberg is Universal

*D. Loss and D. P. DiVincenzo, Phys. Rev. A 57, 120 (1998).

Scalability

- Easy to scale to higher spatial dimensions (in theory!)