Oxide-Semiconductor Materials for Quantum Computation

Jeremy Levy

North American Molecular Beam Epitaxy Conference (NA-MBE)

Keystone, CO

2 October 2003

Outline

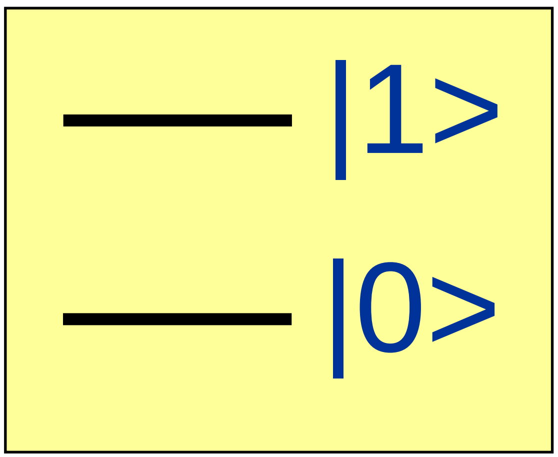
- Introduction to quantum computation
- COSMQC architecture
- Selected results
- Future directions

What is a Quantum Computer?

- A quantum computer processes quantum information

What is quantum information?

- Quantum information is stored in quantum bits (qubits)



Qubit can be in a quantum superposition of |0> and |1>

What can quantum computers do?

- Quantum computers can factor numbers exponentially faster than classical computers (Shor, 1994)

Difficulty of factoring numbers is foundation of public key encryption

1143816257578888676692357799761466120102182967212423625625618429357069352457338978305971235639587050589890751475992900268795435 41

=

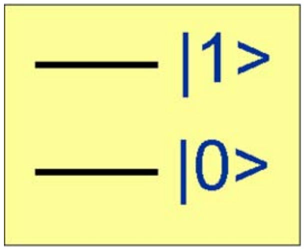
34905295108476509491478496199038981334177646384933878439908205 77

X

3276913299326670954996198819083446141317764296799294253979828853 3

Why are quantum computers so much faster?

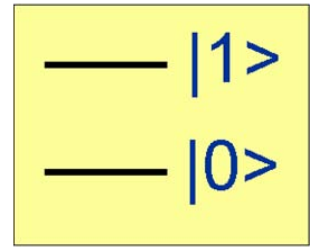
Qubit Phase Space



- A single qubit exists in a 2-dimensional space

$$|\psi\rangle = a_0|0\rangle + a_1|1\rangle, \qquad |a_0|^2 + |a_1|^2 = 1$$

Qubit Phase Space



- A single qubit exists in a 2-dimensional space

$$|\psi\rangle = a_0|0\rangle + a_1|1\rangle, \qquad |a_0|^2 + |a_1|^2 = 1$$

- For *n*-qubit system, 2^n complex numbers required

$$|\Psi\rangle = a_0|\underbrace{000\cdots000}_{n}\rangle + a_1|000\cdots001\rangle + a_2|000\cdots010\rangle + \cdots + a_{2^n-1}|111\cdots111\rangle$$

A state with n=100 qubits is specified by $2^{100} \cong 10^{30}$ coefficients !

A quantum program is specified by $(2^{100})^2 \cong 10^{60}$ coefficients !!

(Final answer is a string of *n* classical bits)

Quantum Information Science and Technology Roadmap

December 1, 2002
Version 1.0

SOLID STATE QUANTUM COMPUTING

Quantum dot and spin based

TIME LINES.

ARDA

This document is available electronically at: http://qist.lanl.gov

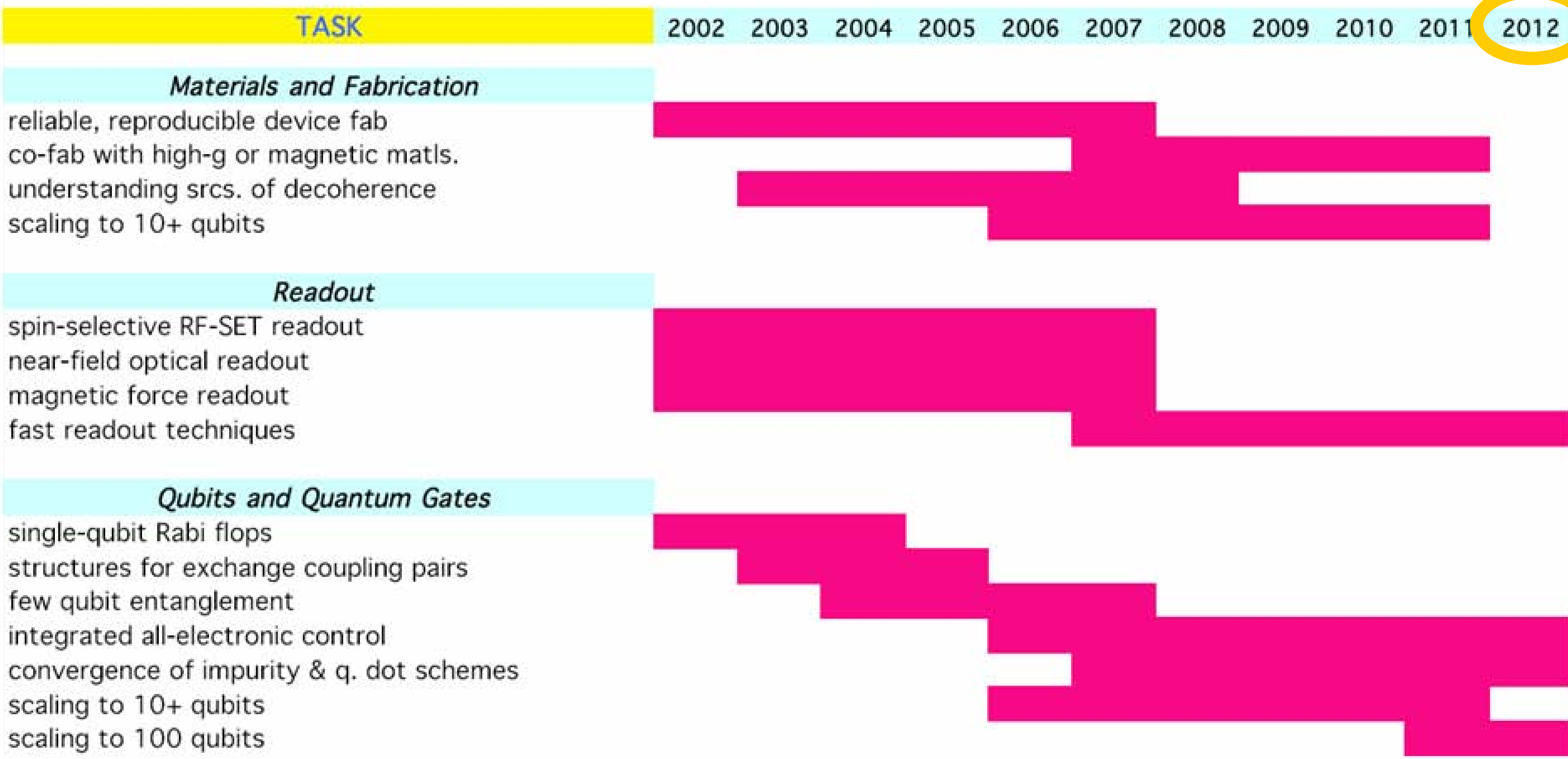
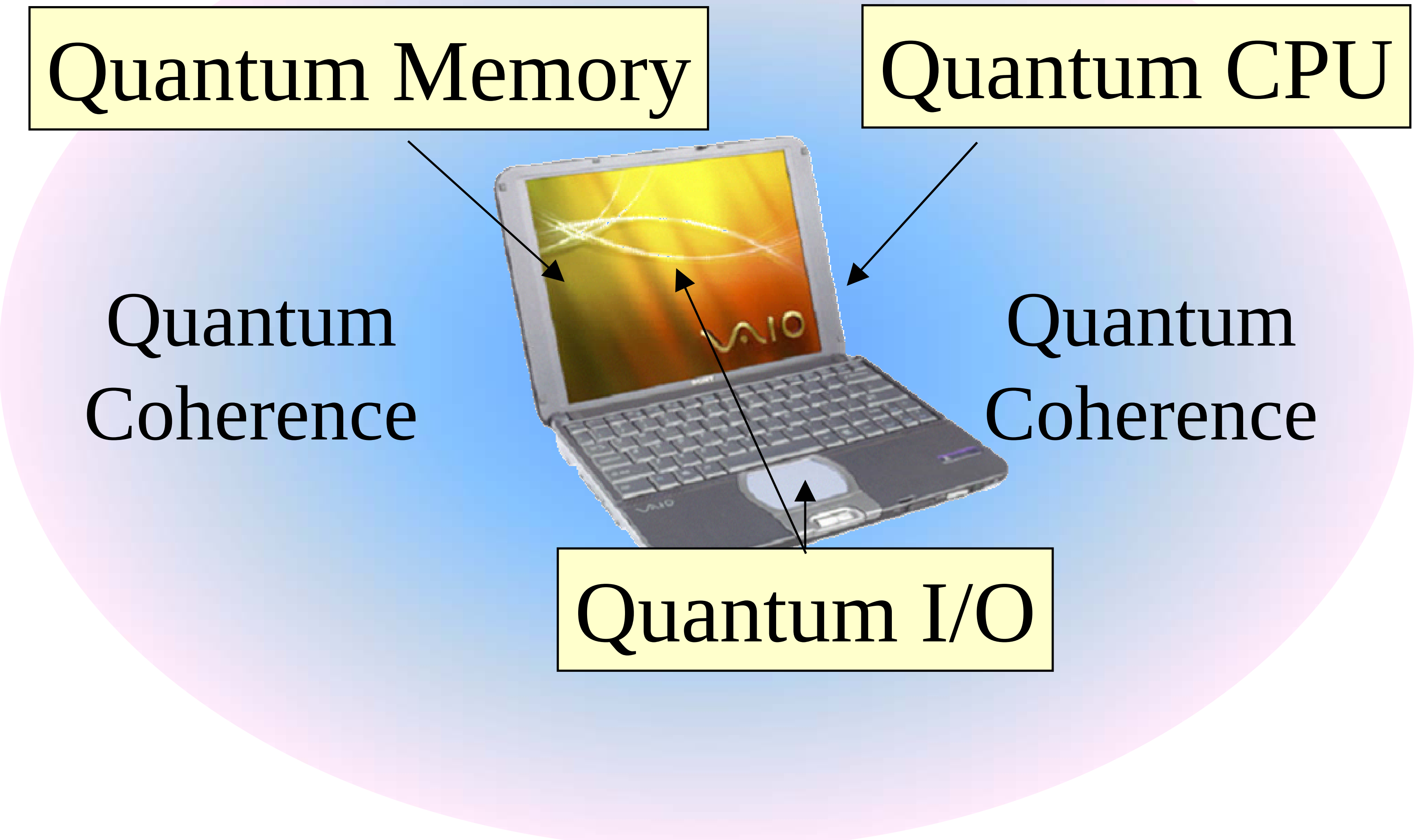
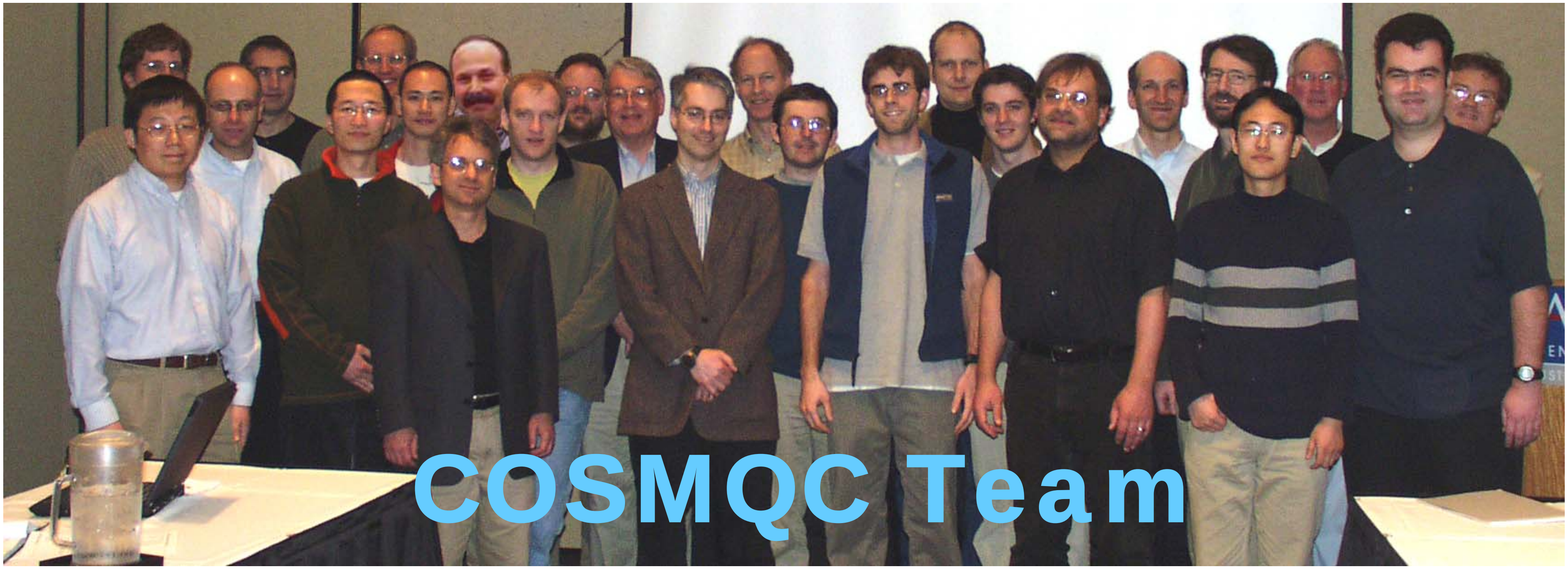


Figure 6-1. Solid state QC developmental timeline

Five Requirements for Quantum Computation

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





Materials

- Darrell G. Schlom (Penn State U.)
  - » Venugopalan Vaithyanathan
  - » Lisa Edge
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- John T. Yates, Jr. (U. Pittsburgh)
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  - » Sergey Mezhenny
  - » Hubertus Marbach
- Joachim Ahner (Seagate)
- Rodney A. McKee (ORNL)

Experiments

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  - » Petru Fodor
  - » Patrick Irvin
  - » Amlan Basak
  - » Ajay Kochhar
  - » Scott Rothenberger
- Keith Nelson (MIT)
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  - » Wayne Lau
  - » Zhi Gang Yu
  - » Ionel Tifrea
  - » Michael Leuenberger
  - » Ben Moehlmann
- Daniel Loss (U. Basel)
  - » Florian Meier
- C. Stephen Hellberg (NRL)
  - » Larry L. Boyer

COSMQC architecture

J. Levy, Phys. Rev. A **64**, 052306 (2001).

(R1) Qubit

» Electron spin(s) localized near Ge QDs

(R2) Initialization

» Optical orientation in Ge quantum dots

(R3) Long Coherence Times

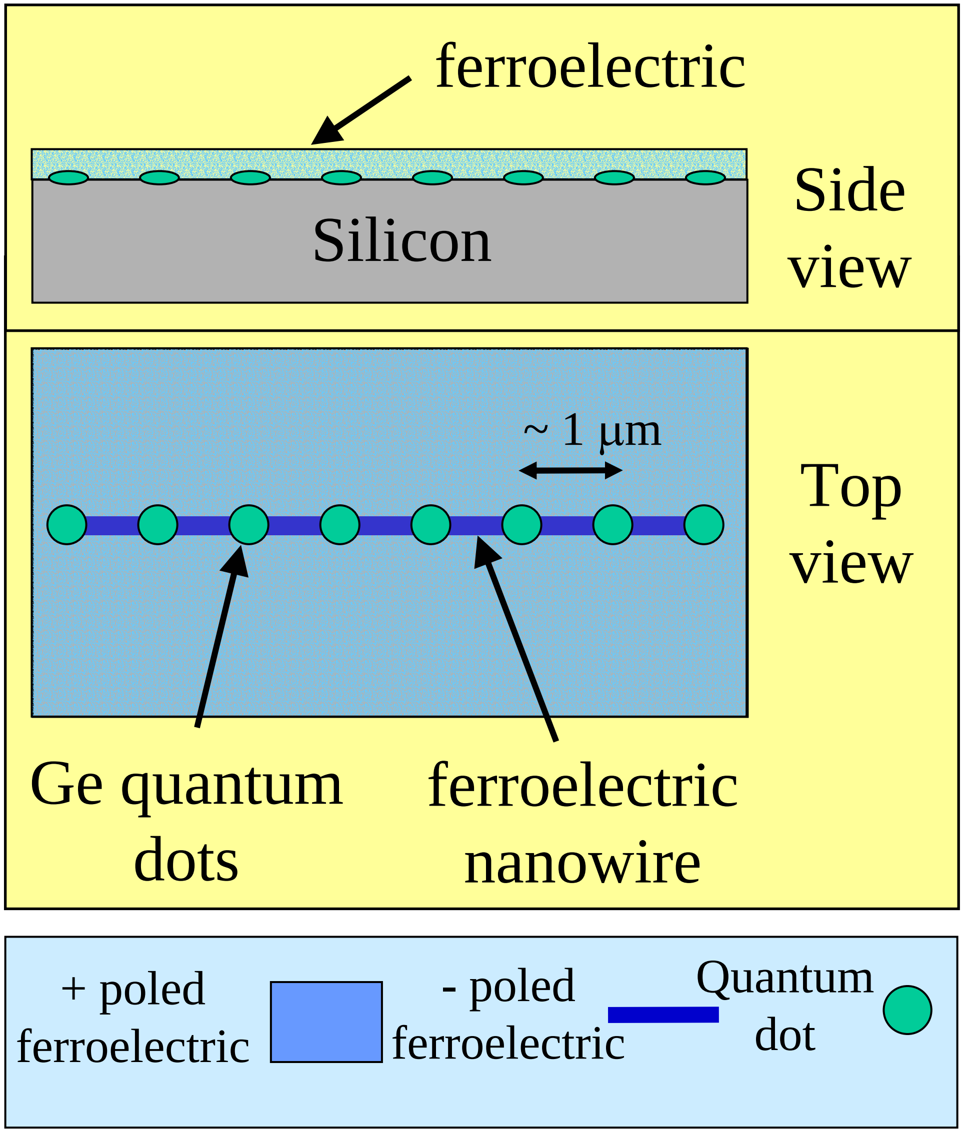
» T_2 ~ ms for Si ; T_{gate} ~ps

(R4) Gating

» Ferroelectric coupling / optical rectification

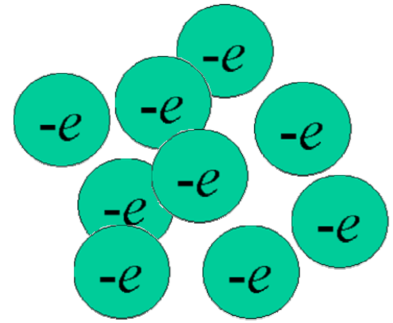
(R5) Readout

» Optical (weak); SET (strong)



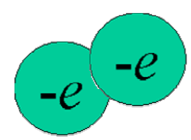
Charge bits *vs*. spin qubits

Electron charge bits



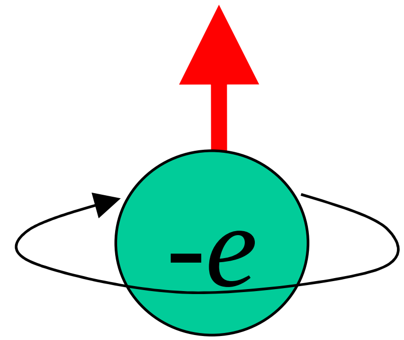
$= 1$

Electronics: $\Psi = \psi(\vec{r}) \cdot \chi_s$



$= 0$

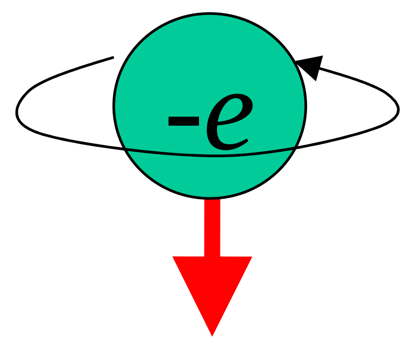
Electron spin qubits



$$= \left|1\right\rangle$$

Spintronics: $\Psi = \chi_s \cdot \psi(\vec{r})$

- Use ferroelectric to mediate spin interactions in semiconductors



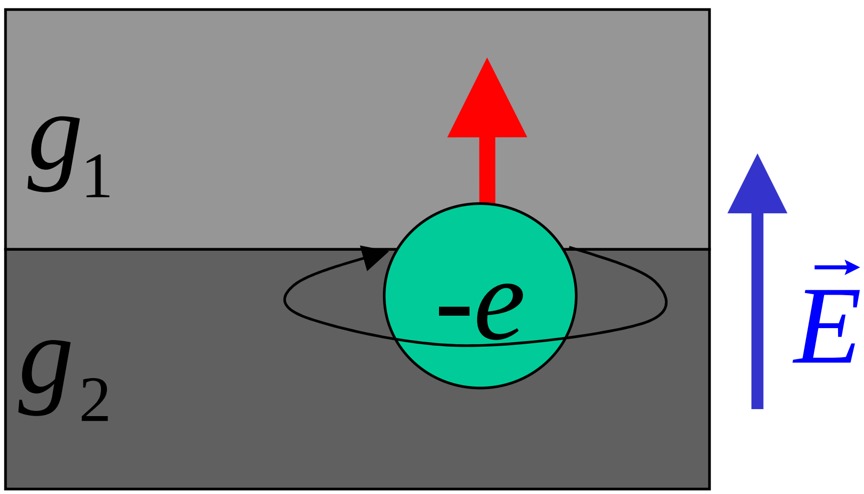
$$= \left|0\right\rangle$$

Ferroelectric Gating of Electron Spin

Ferroelectric enables fast, local optical control of electric fields

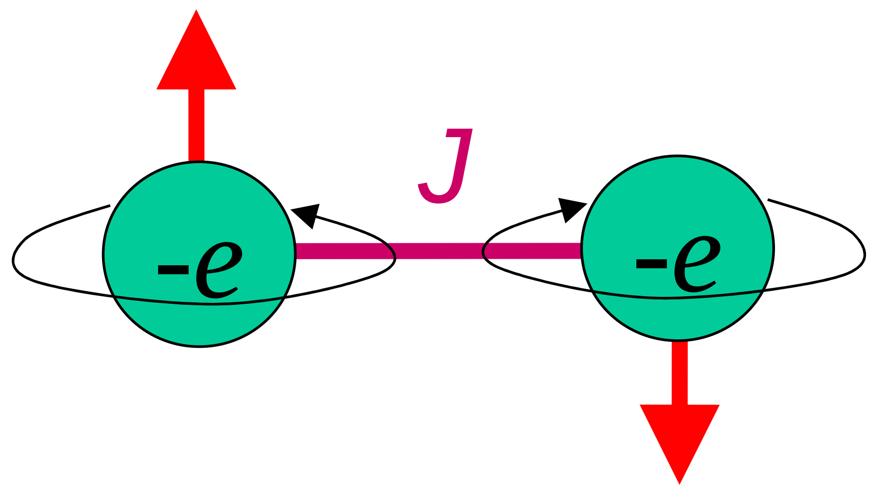
Zeeman one-qubit

$$H_Z = \mu_B \vec{s} \cdot \overleftrightarrow{\mathbf{g}}(\vec{E}) \cdot \vec{B}$$



Heisenberg two-qubit

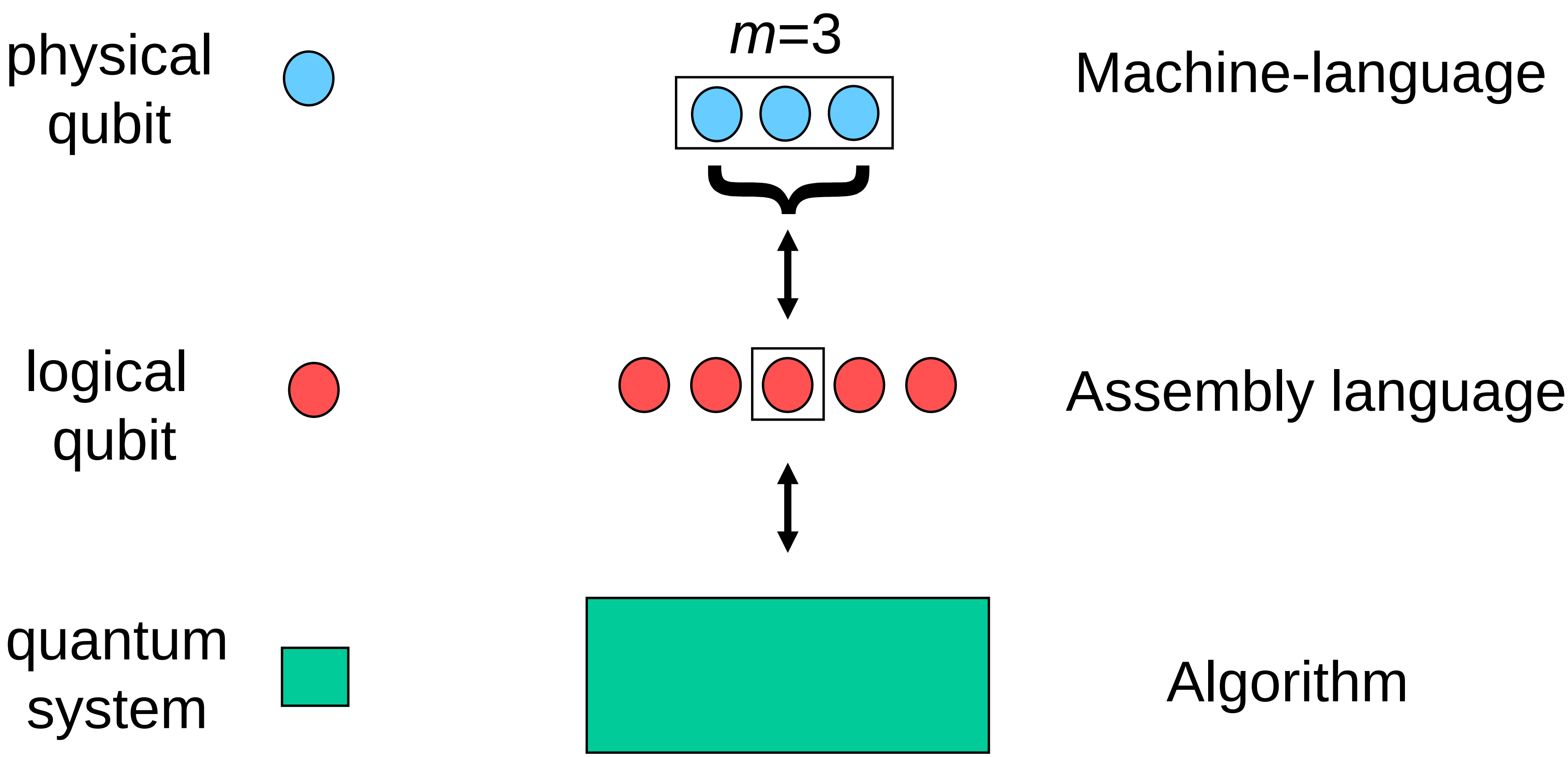
$$H_{ex} = J(\vec{E})\, \vec{s}_1 \cdot \vec{s}_2$$



One-qubit and two-qubit gates sufficient for universal quantum computation

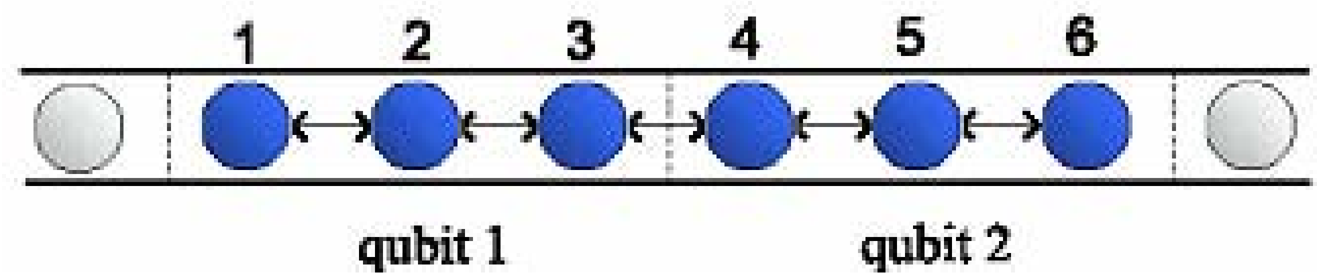
Designer qubits

"Logical" qubit is formed from a 2-dimensional subspace of *m* "physical" qubits



Designer qubits

- Example: *m*=3
  - DiVincenzo *et al.*, Nature **408**, 339 (2000).



- Heisenberg exchange interaction is *universal*
  - » 3-4 Heisenberg operations ↔ single qubit operation
  - » 19 Heisenberg operations ↔ cNOT operation

1<<2!

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

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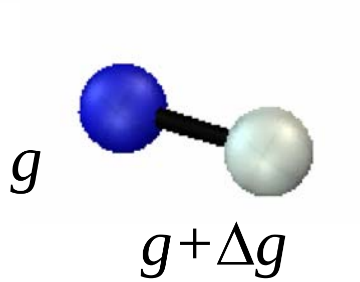
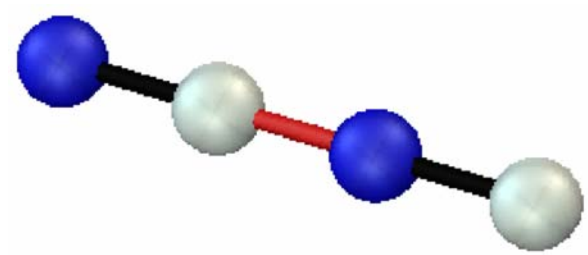
(Received 23 January 2001; published 17 September 2002)

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.



$$|0\rangle_Q \leftrightarrow |01\rangle_C$$
$$|1\rangle_Q \leftrightarrow |10\rangle_C$$



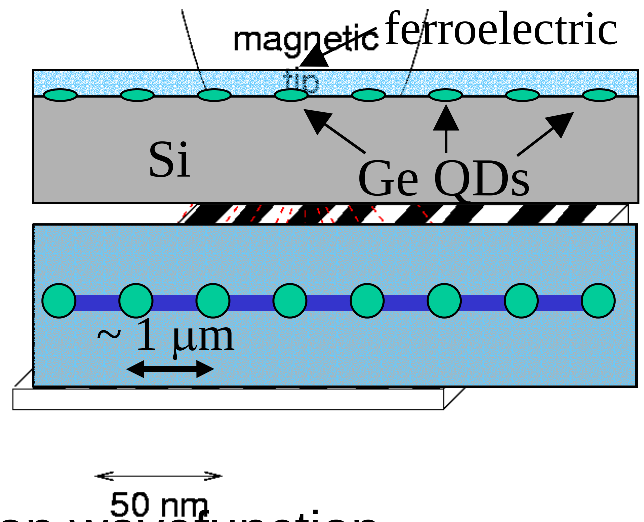
One logical qubit **represented by** **Two physical qubits**

Heisenberg, Zeeman qugates **implemented by** **Heisenberg only**

Quantum computing with spin cluster qubits

Florian Meier, Jeremy Levy, and Daniel Loss, PRL <u>90</u>, 047901 (2003)

- Design of spin-based qubits and qugates challenging
  - » Control over electron exchange, magnetic interactions
  - » Encoded qubits eliminate Zeeman, but still sensitive to internal structure



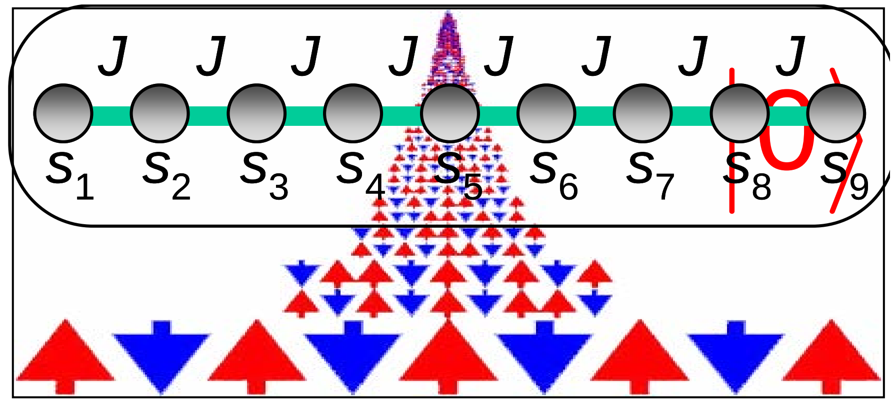
Loss and DiVincenzo, Phys. Rev. A 57, 120 (1998).
J. Levy, Phys. Rev. A 64, 52306 (2001).

- Ideal "designer" qubit:
  - large compared compared to electron wavefunction
  - » insensitive to variations smaller than <u>qubit</u>

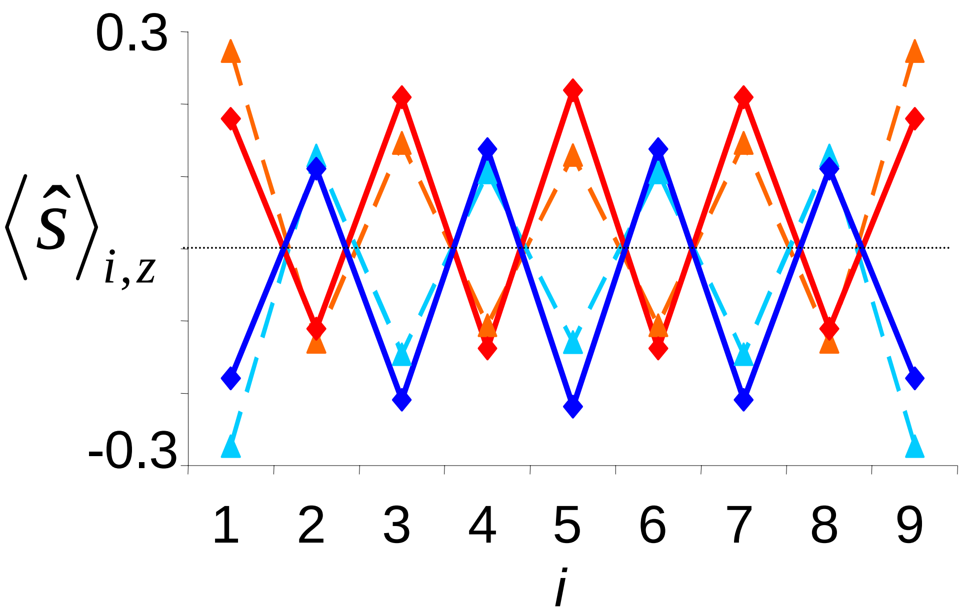
Spin chains as qubits

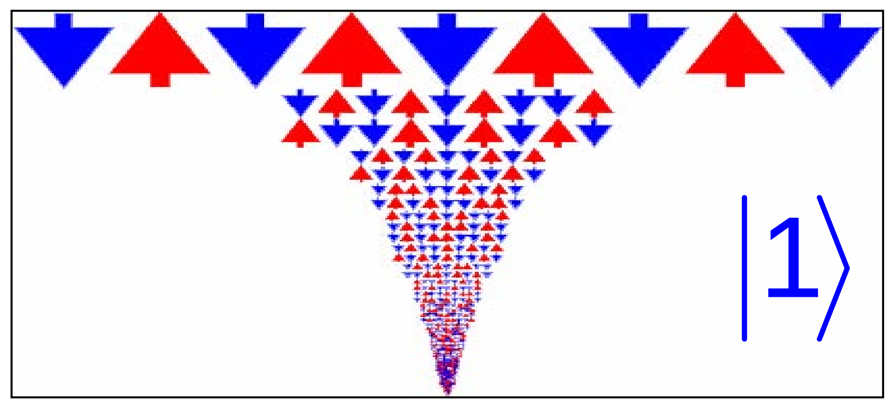
$$\hat{H} = J \sum_{i=1}^{n_C - 1} \hat{s}_i \cdot \hat{s}_{i+1}$$

Open spin chain with n_c sites:
(*e.g.*, neighboring QDs)



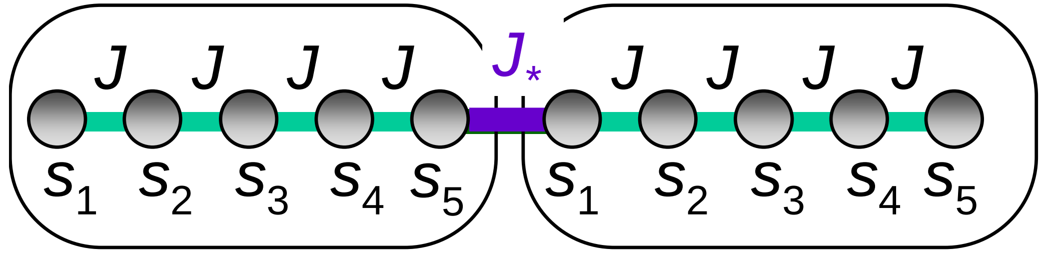
For n_c odd, ground state is doubly degenerate, with S_{tot}=1/2





Coupling Cluster Qubits

$$\hat{H}_* = J_*(t)\,\hat{s}^{I}_{n_c}\cdot\hat{s}^{II}_{1}$$

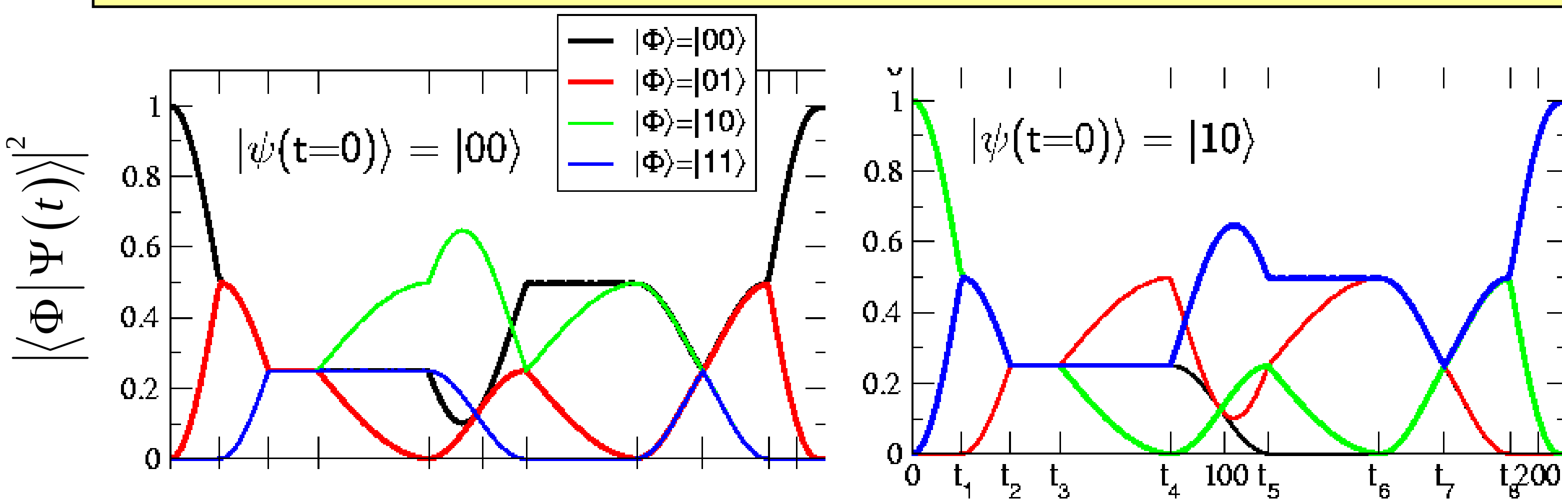


Effective Hamiltonian in basis {|00⟩, |01⟩, |10⟩, |11⟩}:

$$\hat{H}_* = \frac{J_*}{4}\left|\langle 0|\hat{s}_{1,z}|0\rangle\right|^2 \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 2 & 0 \\ 0 & 2 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

CNOT:

$$U_{CNOT} = e^{-i\pi S^{II}_y/2} e^{i2\pi \mathbf{n}_1\cdot\mathbf{S}^I/3} e^{i2\pi \mathbf{n}_2\cdot\mathbf{S}^{II}/3} U_*(\pi/2) e^{i\pi S^{II}_y} U_*(\pi/2)\; e^{-i\pi S^{I}_x/2} e^{-i\pi S^{II}_x/2} e^{i\pi S^{II}_y/2}$$



Scaling of Decoherence

- Fluctuating fields and nuclear spins contribute to spin decoherence in semiconductors
  - » Magnetic moment of spin cluster qubit same as for single spin
- For spatially uniform (random) magnetic fields

$$\hat{H}_{\phi}^{B} = b(t)\sum_{i=1}^{n_c}\hat{S}_{i,z} \qquad \langle b(t)b(0)\rangle = 2\pi\gamma^{B}\delta(t)$$

decoherence independent of n_c

- For independent fluctuating fields

$$\hat{H}_{\phi}^{B} = \sum_{i=1}^{n_c} b_i(t)\hat{S}_{i,z} \qquad \langle b_i(t)b_j(0)\rangle = 2\pi\gamma^{B}\delta(t)\delta_{ij}$$

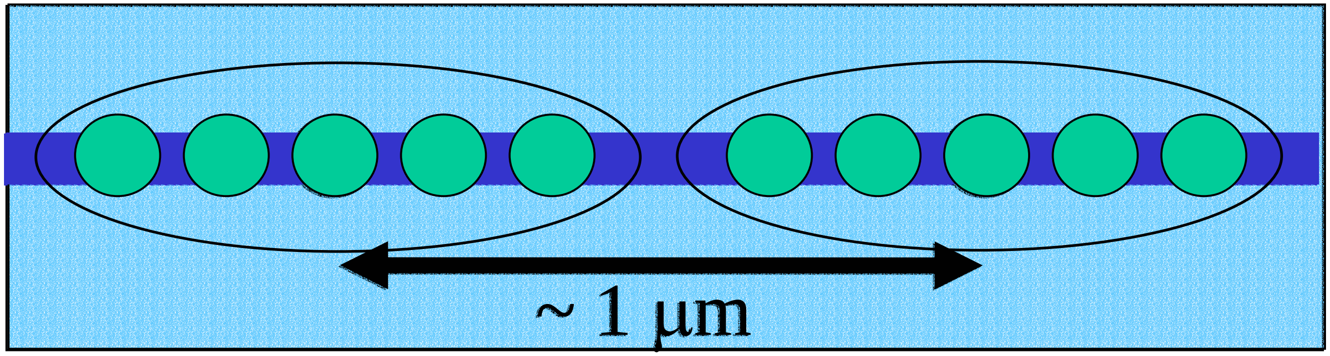
decoherence proportional to n_c

Additional properties of spin cluster qubits

- Spin cluster qubit is robust against
  - » disorder
  - » topology of intra-cluster exchange
  - »symmetry of exchange (*e.g.,* Heisenberg, XY)
- •Significant advantage
  - »quantum computing possible without local control over spin interactions

Applications to ferroelectrically coupled quantum dots

Original proposal[1] with spin cluster qubit



Improvement: electrons are localized

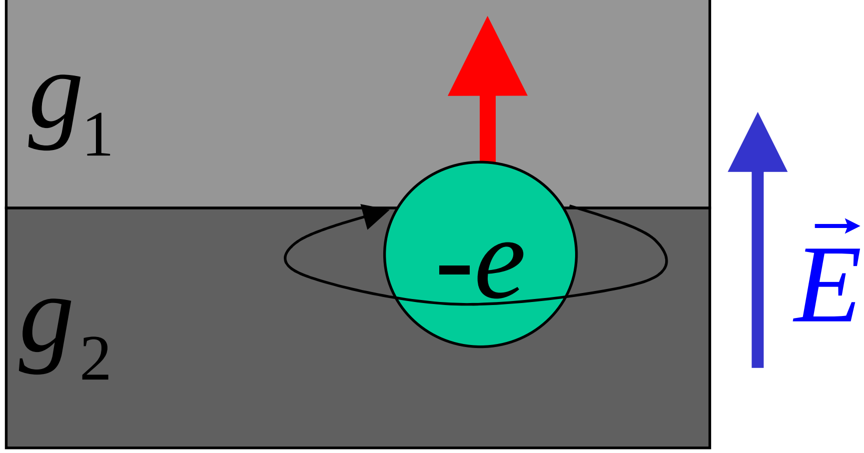
[1]J. Levy, Phys. Rev. A **64**, 52306 (2001).

Physical Qugates

One-qubit gates

(voltage-controlled electron spin resonance)

$$H_Z = \mu_B \vec{s} \cdot \overleftrightarrow{\mathbf{g}}(\vec{E}) \cdot \vec{B}$$



Sciencexpress Report

Gigahertz Electron Spin Manipulation Using Voltage-Controlled g-Tensor Modulation

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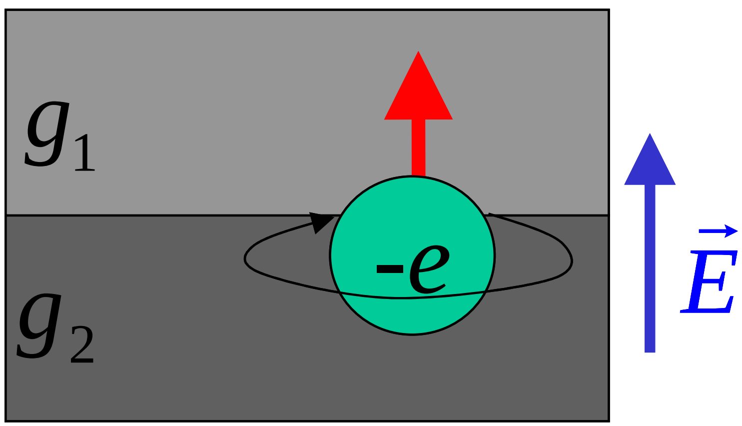
We present a scheme that enables gigahertz-bandwidth three-dimensional control of electron spins in a semiconductor heterostructure using a single voltage signal. Microwave modulation of the Landé g-tensor produces frequency-modulated electron spin precession. Driving at the Larmor frequency results in g-tensor modulation resonance, functionally equivalent to electron spin resonance but without the use of time-dependent magnetic fields. These results provide proof of concept that quantum spin information can be locally manipulated using high-speed electrical circuits.

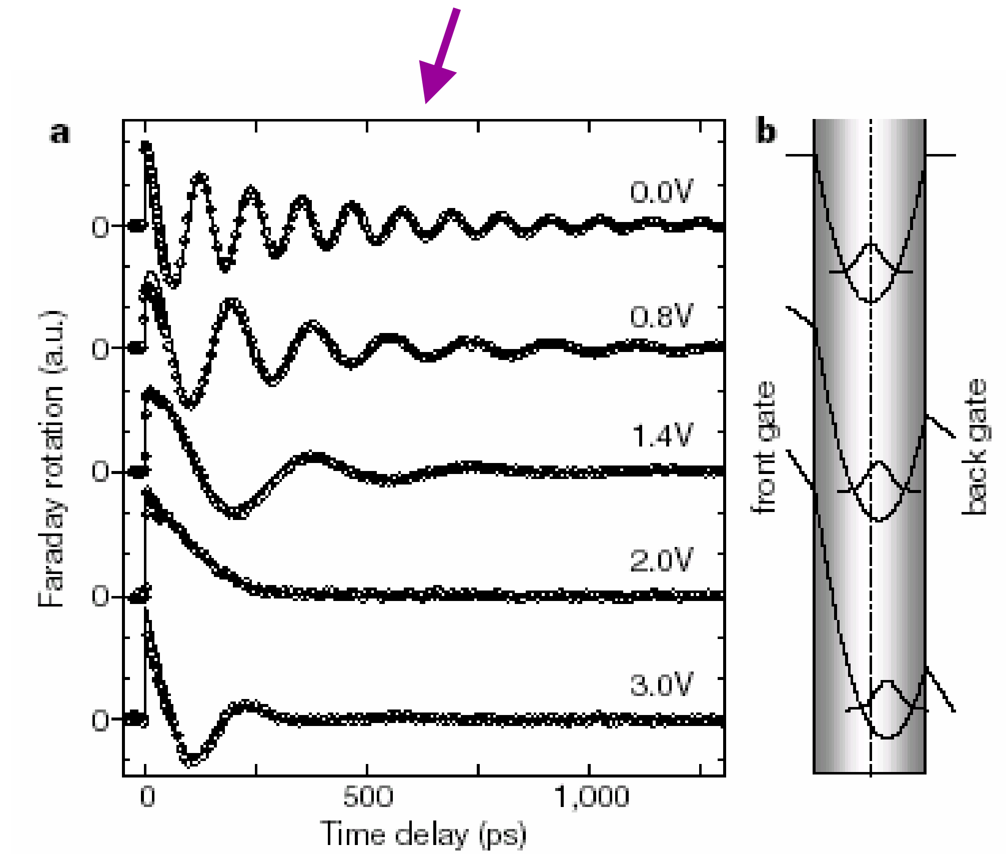
Electron spin dynamics can be described by an effective Hamiltonian $H(t) = (\mu_B/\hbar)\mathbf{S}\cdot\overleftrightarrow{\mathbf{g}}\cdot\mathbf{B} \equiv \mathbf{S}\cdot\Omega(t)$, where μ_B is the Bohr magneton, $\hbar$ is the Planck's constant, $\mathbf{S}$ is the spin angular momentum operator, $\overleftrightarrow{\mathbf{g}}$ is the Landé g-tensor, and $\mathbf{B}$ is the magnetic field. The Hamiltonian is conventionally separated into two terms $H(t) = H_0 + H_1(t)$, where $H_0 = (\mu_B/\hbar)\mathbf{S}\cdot\overleftrightarrow{\mathbf{g}}\cdot\mathbf{B}_0 \equiv \mathbf{S}\cdot\Omega_0$ is time-independent and $H_1(t) = \mathbf{S}\cdot\Omega_1(t)$ governs spin dynamics in the rotating frame. The effect of $\Omega_1(t)$ can be seen by resolving it into

Background: g-factor engineering

- g-factor tuning in a parabolic quantum well
  - » Electric field shifts electron into region of GaAs/AlGaAs with varying g-factor



Optical detection of spin precession



G. Salis, Y. Kato, K. Ensslin, D. C. Driscoll, A. C. Gossard, and D. D. Awschalom, Nature **414**, 619 (2001).

Exploiting g-Tensor Anisotropy

$$H(t) = (\mu_B / \hbar)\mathbf{S} \cdot \overleftrightarrow{\mathbf{g}} \cdot \mathbf{B} \equiv \mathbf{S} \cdot \Omega(t)$$

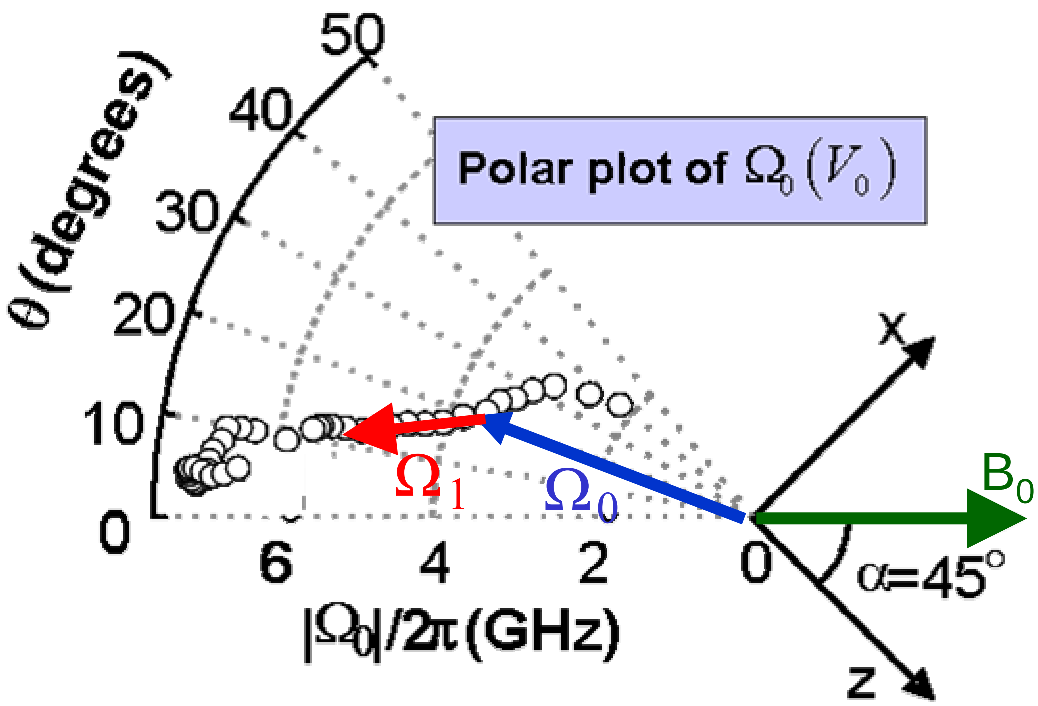
where $\overleftrightarrow{\mathbf{g}} = \overleftrightarrow{\mathbf{g}}(V(t))$ and $\mathbf{B}$ is static

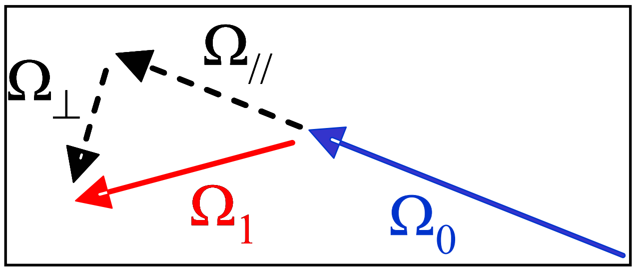
- **Precession vector Ω is not always parallel to B**
  - » **Changes in <u>magnitude</u> of Ω produce frequency-modulated spin precession**
  - » **Changes in <u>direction</u> of Ω produce effective ESR**

g-Tensor Modulation

$$\Omega_0(V_0) = \begin{pmatrix} \Omega_{0x} \\ \Omega_{0z} \end{pmatrix} = \frac{\mu_B}{\hbar} \begin{pmatrix} g_{90}(V_0) & 0 \\ 0 & g_0(V_0) \end{pmatrix} \cdot \begin{pmatrix} B_0 \sin\alpha \\ B_0 \cos\alpha \end{pmatrix} = \frac{\mu_B}{\hbar} B_0 \begin{pmatrix} g_{90}(V_0)\sin\alpha \\ g_0(V_0)\cos\alpha \end{pmatrix}$$

$$V(t) = V_0 + V_1(t) \longrightarrow \mathbf{\Omega}(t) = \mathbf{\Omega}_0 + \mathbf{\Omega}_1(t)$$



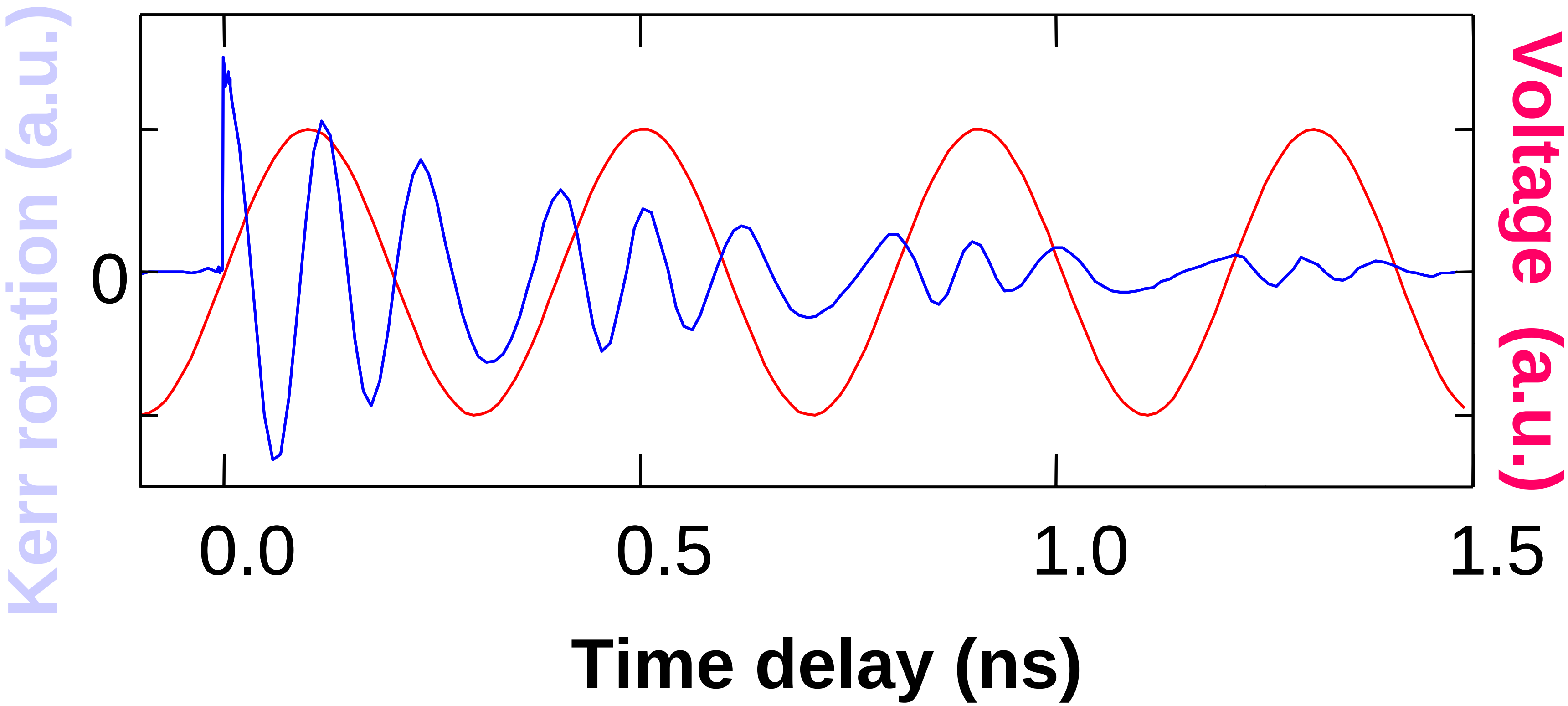


$$\mathbf{\Omega}_1(t) = \mathbf{\Omega}_{\parallel}(t) + \mathbf{\Omega}_{\perp}(t)$$

Frequency-Modulated Spin Precession

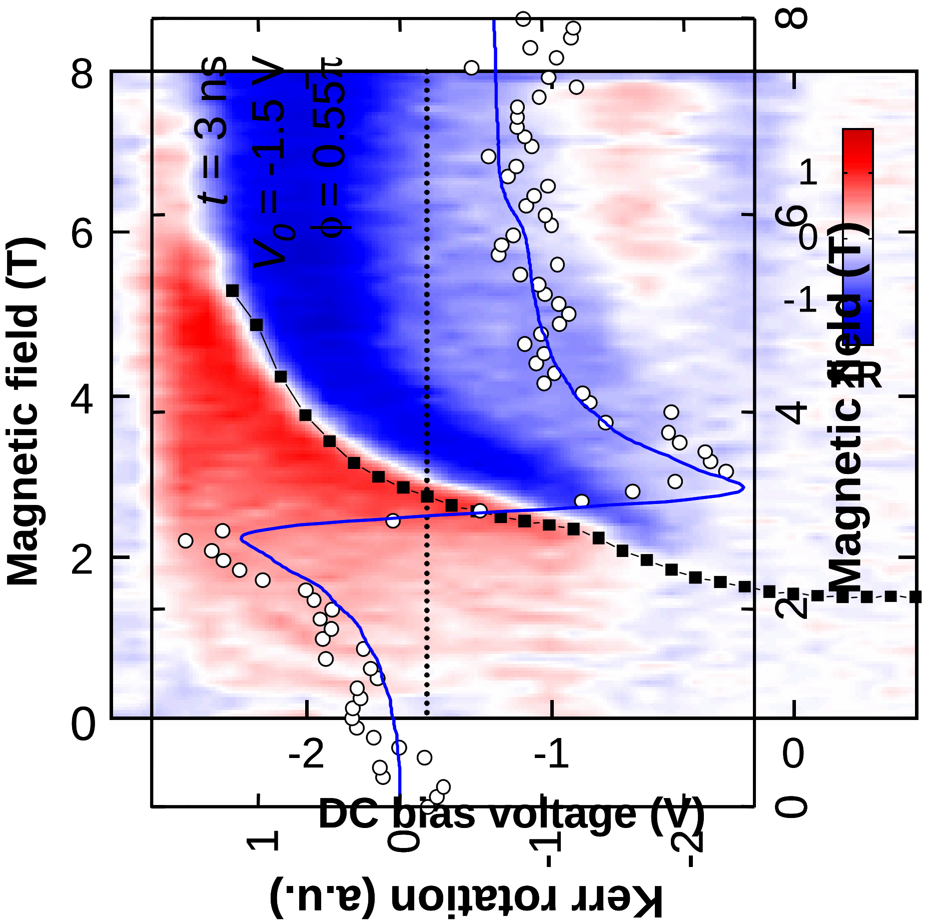
$$\mathbf{\Omega}_1(t) = \boxed{\mathbf{\Omega}_{\parallel}(t)} + \mathbf{\Omega}_{\perp}(t)$$

- Electrical “pump” (red) modulates electron spin precession (blue) at GHz frequencies



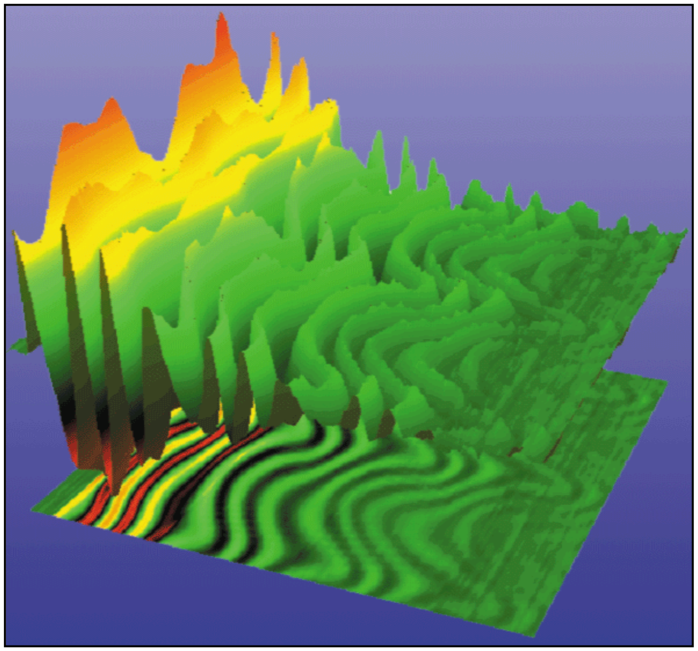
g-Tensor Modulation Resonance

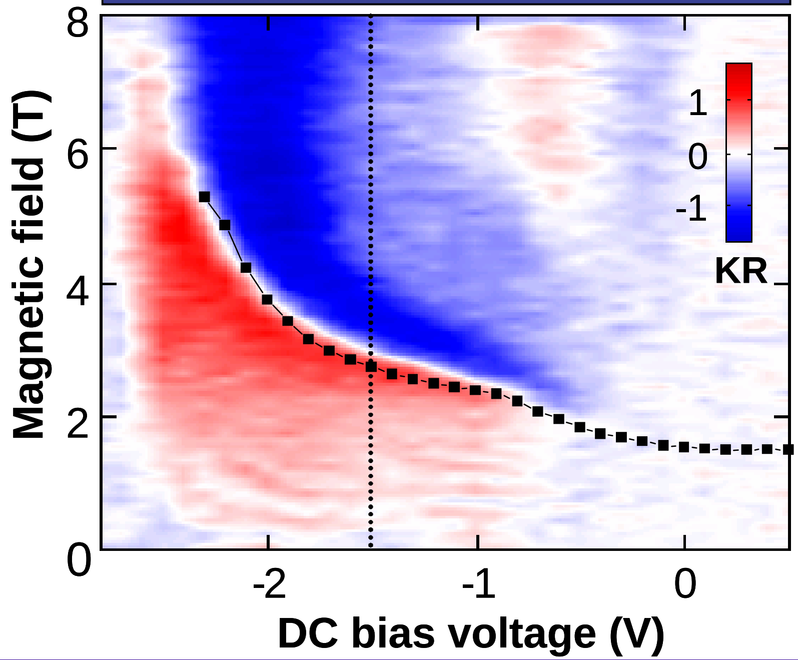
$$\mathbf{\Omega}_1(t) = \mathbf{\Omega}_{\parallel}(t) + \mathbf{\Omega}_{\perp}(t)$$



Discussion

- Full 3D electrical control of spin coherence demonstrated
  - » voltage gating compatible with existing Si technology
- Universal gating possible
  - » with Heisenberg exchange "backbone"
- Future directions
  - » Ferroelectric control of ESR
  - » scaling down to single spin

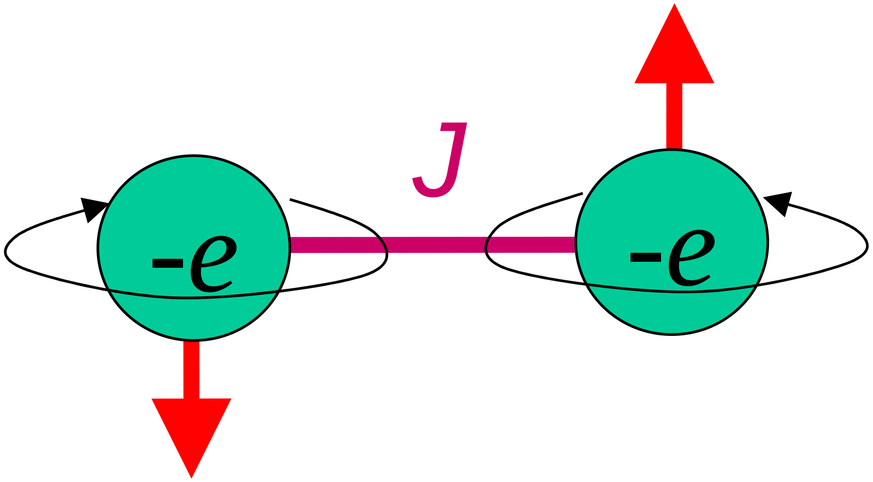




Two-qubit gates

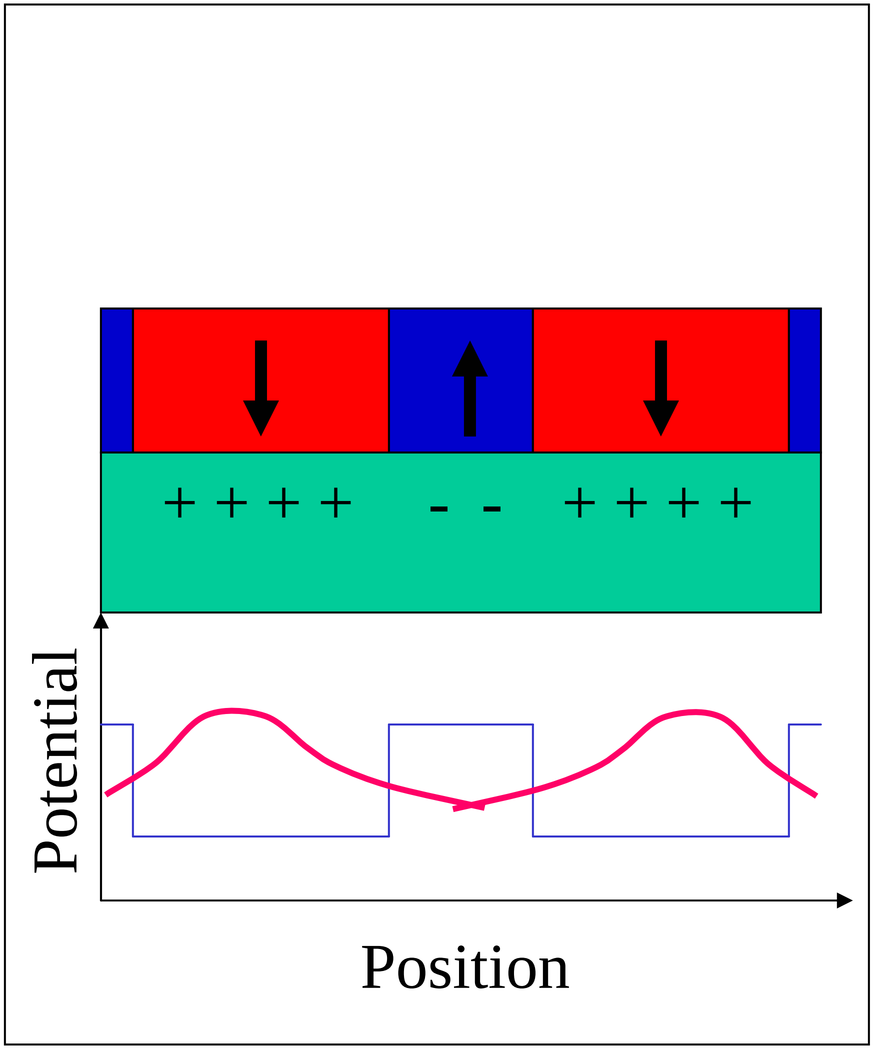
(ferroelectrically controlled spin exchange)

$$H_{ex} = J(\vec{E})\,\vec{s}_1 \cdot \vec{s}_2$$



Optical Rectification and Controlled Exchange

- Optical illumination reduces *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



Optical Rectification and Controlled Exchange

- Optical illumination reduces *magnitude* of ferroelectric polarization
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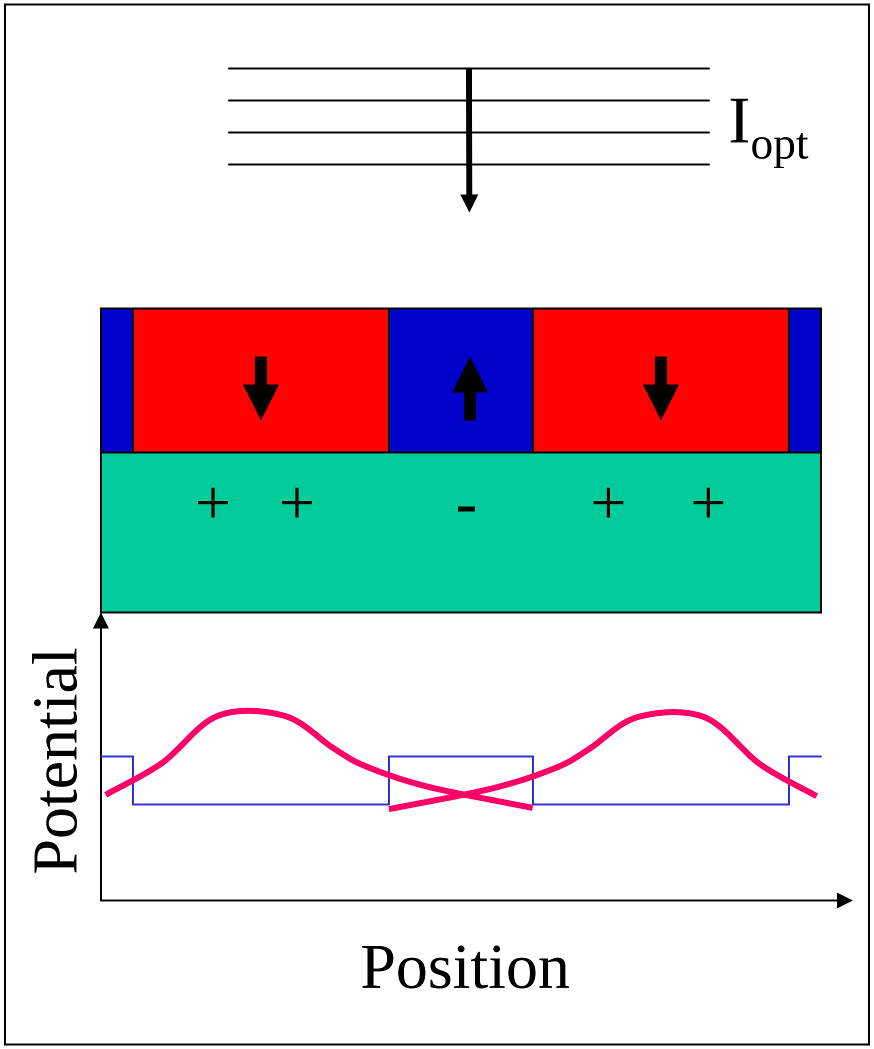


Magnitude of Nonlinear Polarization

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

I_{avg}= average laser power

r = electrooptic coefficient

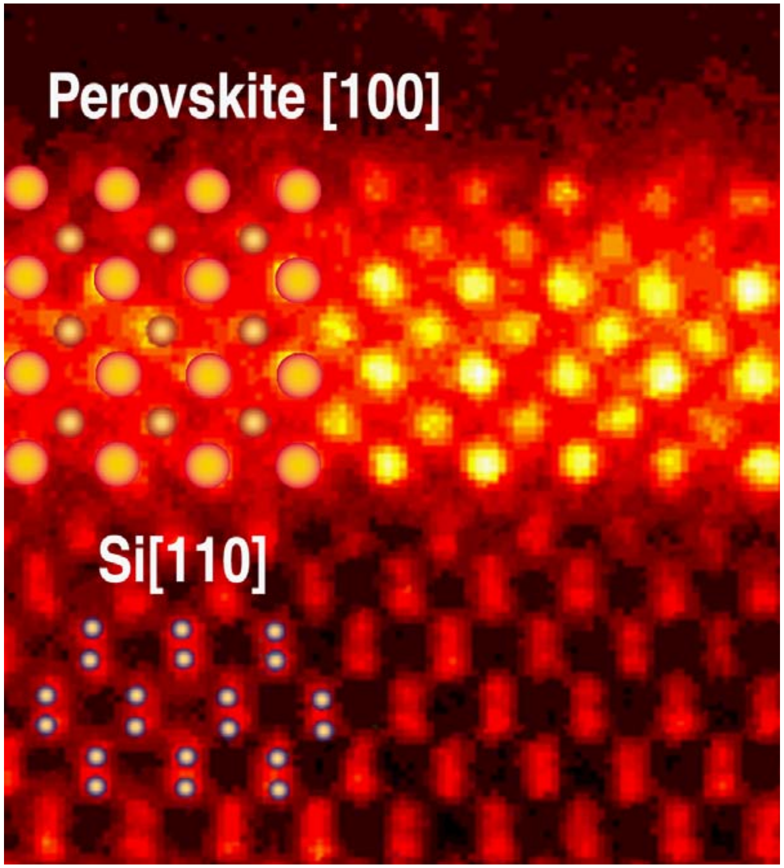
d = spot diameter

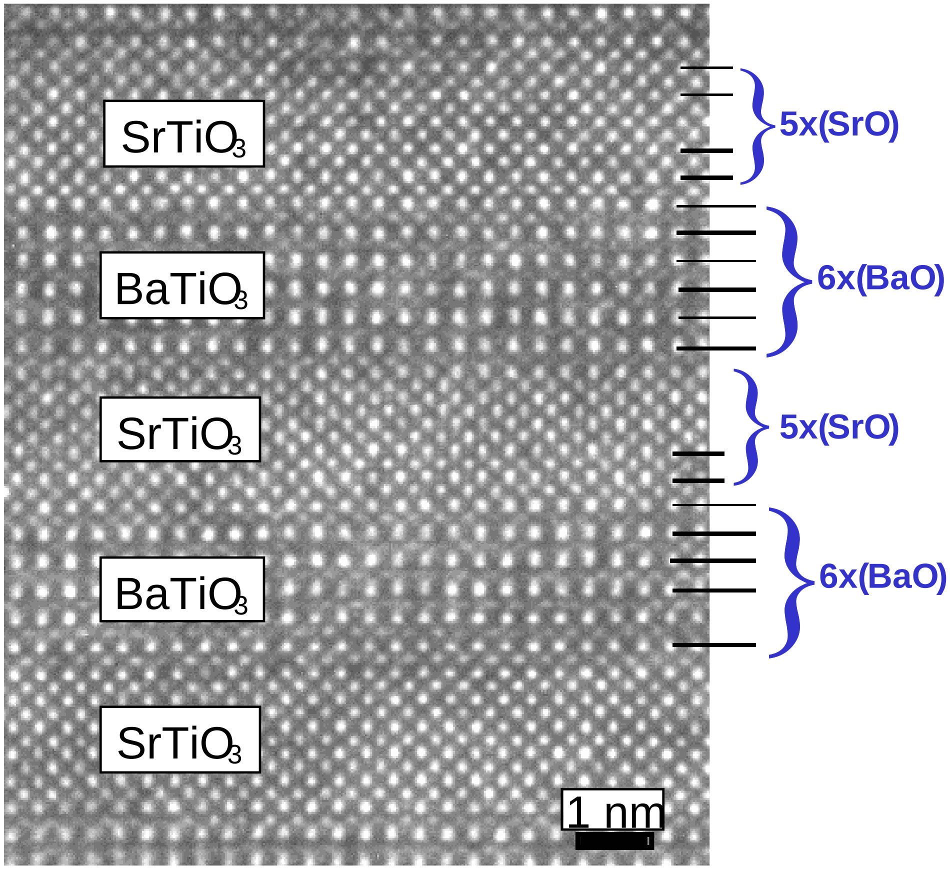
τ_{opt}= pulse width

W= repetition rate

n = refractive index

COSMQC Materials
Ferroelectric Oxides on Silicon





Rodney McKee, ORNL

Darrell Schlom, Penn State U.

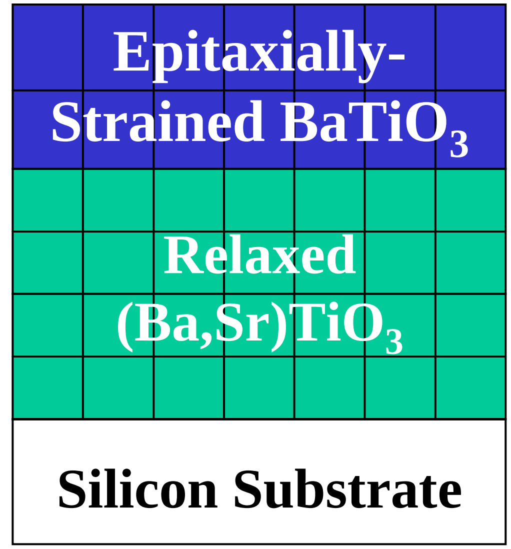
COSMQC oxides on silicon

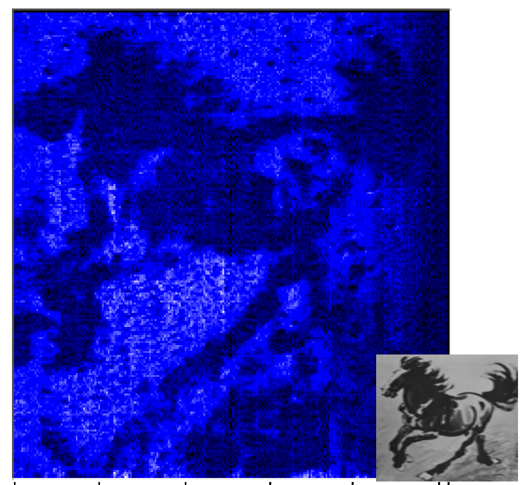
- Requirements for quantum computing architecture
  - » strong ferroelectric field effect for qubit gating
  - » uniform, uniaxial out-of-plane polarization
  - » large electrooptic response for optical rectification
- Two approaches taken so far by Schlom group
  - » commensurate $SrTiO_3$/Si
  - » commensurate $BaTiO_3$/Relaxed $(Ba,Sr)TiO_3$/Si

$BaTiO_3$ with Out-of-Plane Polarization on Si to Control Spin Interactions

Darrell G. Schlom, Penn State University

- Prior $BaTiO_3$ / Si Films have all had *In-Plane* Polarization because
  - Large lattice mismatch (3.8%)
  - Large thermal expansion mismatch
- To Achieved Out-of-Plane Polarization in $BaTiO_3$ / $(Ba,Sr)TiO_3$ / Si
  - Use epitaxial strain to counteract thermal expansion strain
  - Rocking curve <0.5° for $BaTiO_3$
- To Improve Control of Spin Interactions want Thinner $(Ba,Sr)TiO_3$ Buffer Layer
  - 100 Å works
  - 40 Å does not work so far, but optimizing



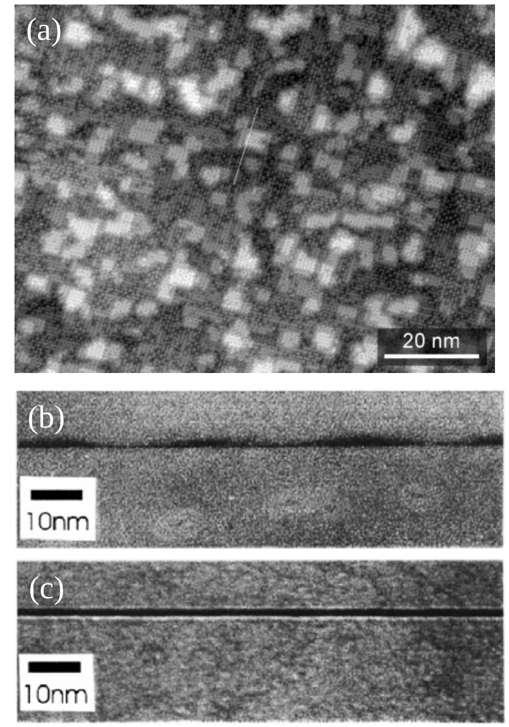


Ge/Si Quantum Dots

- Grow by self-assembly methods
  - » Natural diameter too large (d>20 nm)
- Direct/indirect crossover occurs near 10 nm
- Smaller QDs nucleate around carbon
  - » Diameters <10 nm
  - » Strong photoluminescence observed
  - » "directed" self-assembly

QDs with C →

No C, no QDs →

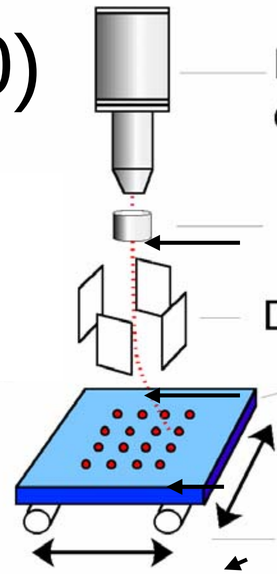


(a) D. Gruetzmacher, www1.psi.ch/ www_lmn_hn/shine/sigec.htm

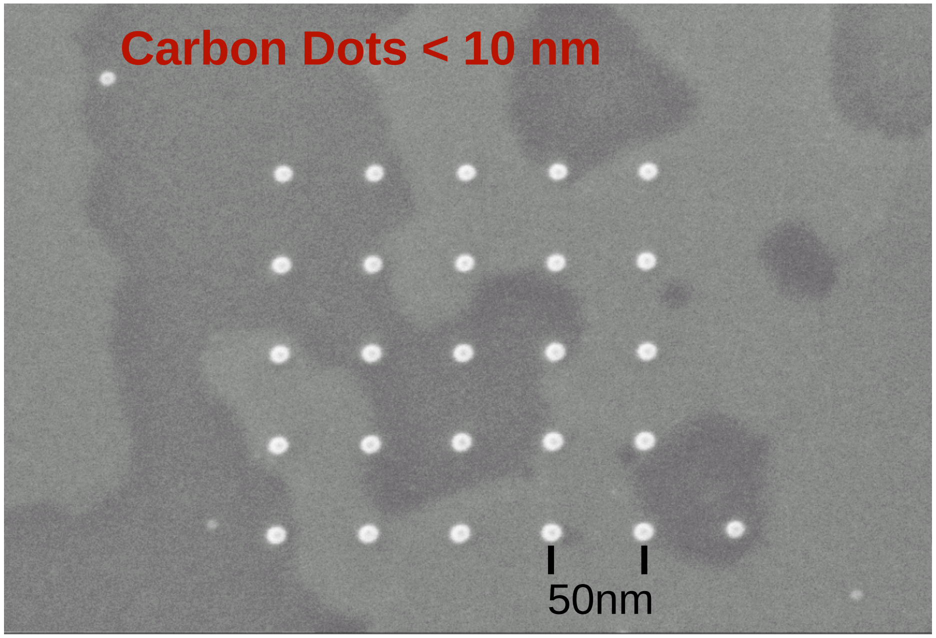
(b) (b) X-TEM image of Si-C-Ge quantum dots with 4 ML Ge.

(c) (c) Same as (b), but without Carbon present, showing absence of QDs. [O. G. Schmidt *et al.*, Appl. Phys. Lett. **71**, 2340-2 (1997)].

Patterning Carbon Dots / Si(100)



Goal – To deposit carbon as a template for Ge Quantum Dot Growth



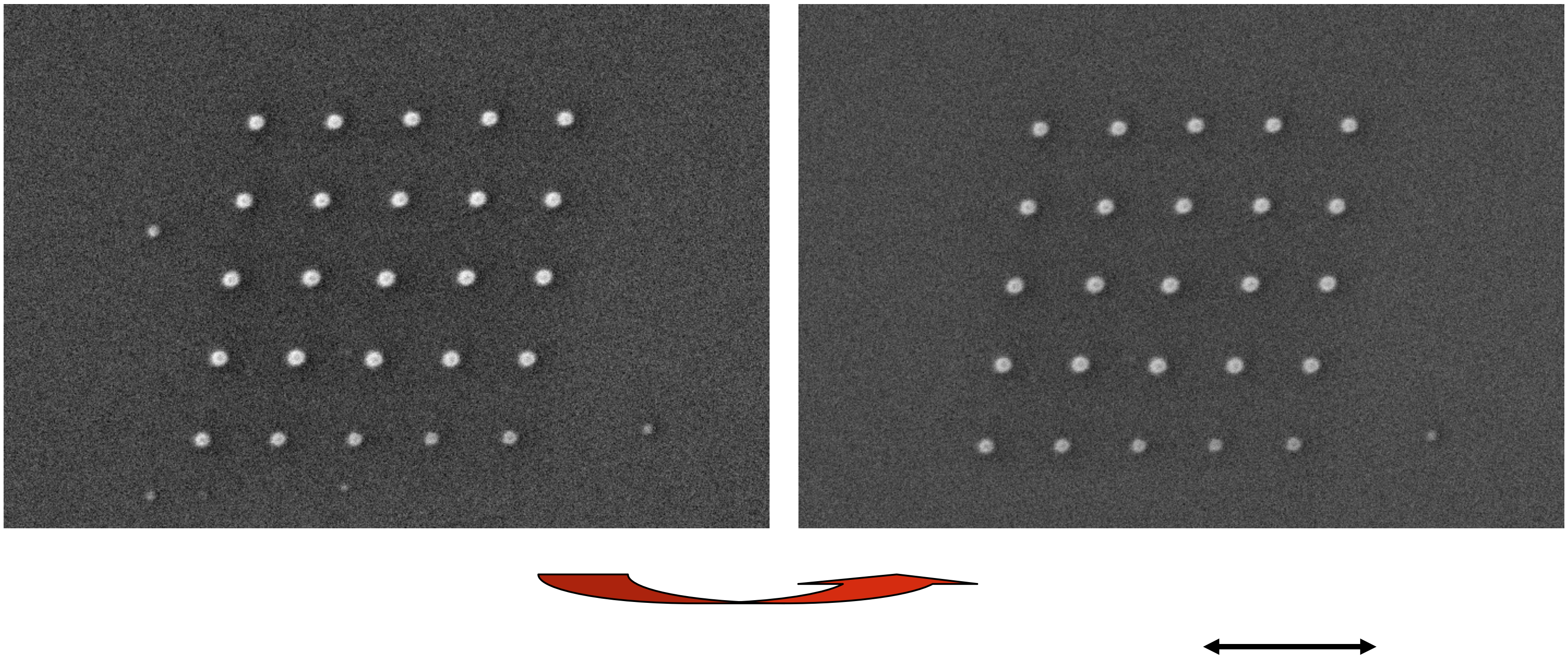
V_e = 20 KeV

Beam Diameter < 1nm

Primary beam current ~ 340pA

	Now	Soon
Field of play:	50µm x 50 µm	2mm x 2mm
Max. # dots:	~ 10^5	~ 10^8
Time:	~10^5 seconds	~ 10^3 seconds
	i.e. ~27h	i.e. < 20min.

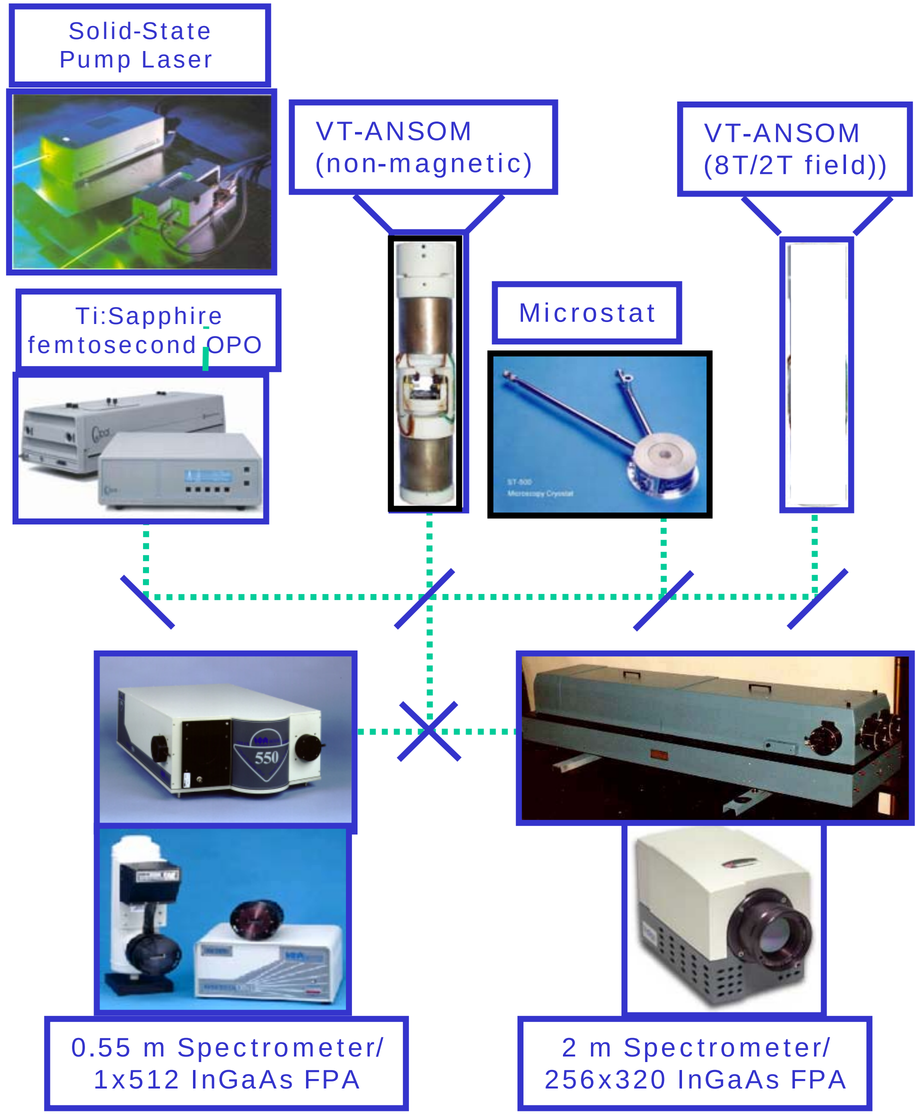
Thermal Properties of Patterned C-Dots



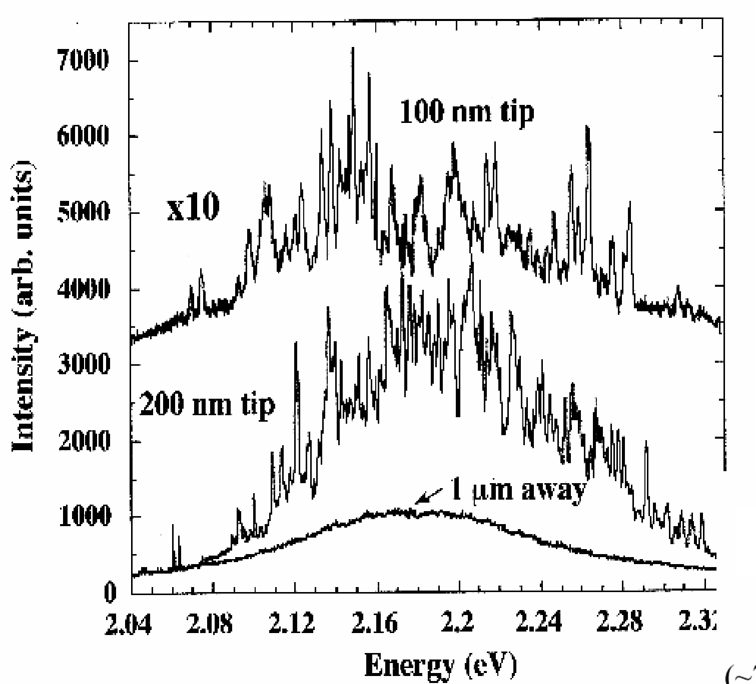
Annealing at 1300K (30”) – no change   300nm

Optical and Scanning Probes of Ferroelectric/Semiconductor Heterostructures

- Apertureless NSOM (ANSOM)
- Ti:Sapphire→OPO (1μm-2μm)
- Three cryostats
  - » Microcryostat for photoluminescence (PL), Kerr microscopy
  - » Non-magnetic for ANSOM
  - » Vector field (8T/2T) for ANSOM, transport
- Two spectrometers
  - » 0.55meter spectrometer with cooled InGaAs array for PL
  - » 2.0 meter spectrometer with 2D focal plane array for spectrally resolved Kerr rotation



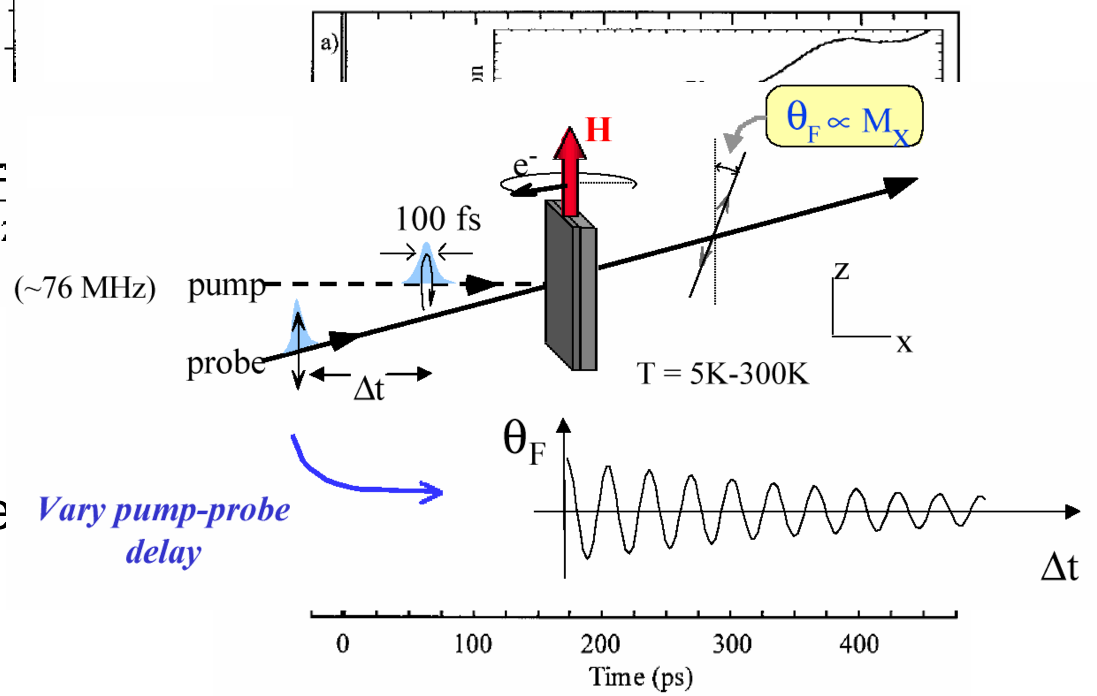
Coherent Spin Dynamics of a Single Quantum Dot: Background



Flack *et al.*, PRB **54**, R17312-15 (1996).

Photoluminescence spectroscopy combines spatial and spectral resolution, but does not probe spin coherence

Time-resolved Faraday Rotation



Gupta *et al*, PRB **59**, R10421 (1999).

Previous investigations of quantum dot spin coherence probed large numbers of quantum dots…

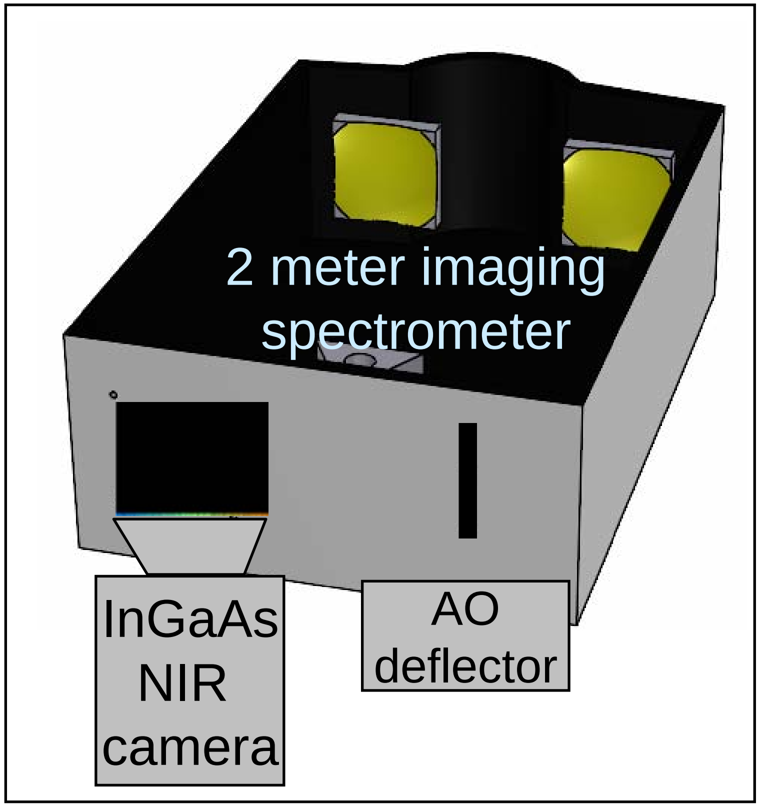
Our Approach

Combine high spatial and spectral resolution to measure coherent spin dynamics in single quantum dots

Spatial Resolution

Variable-temperature Apertureless NSOM

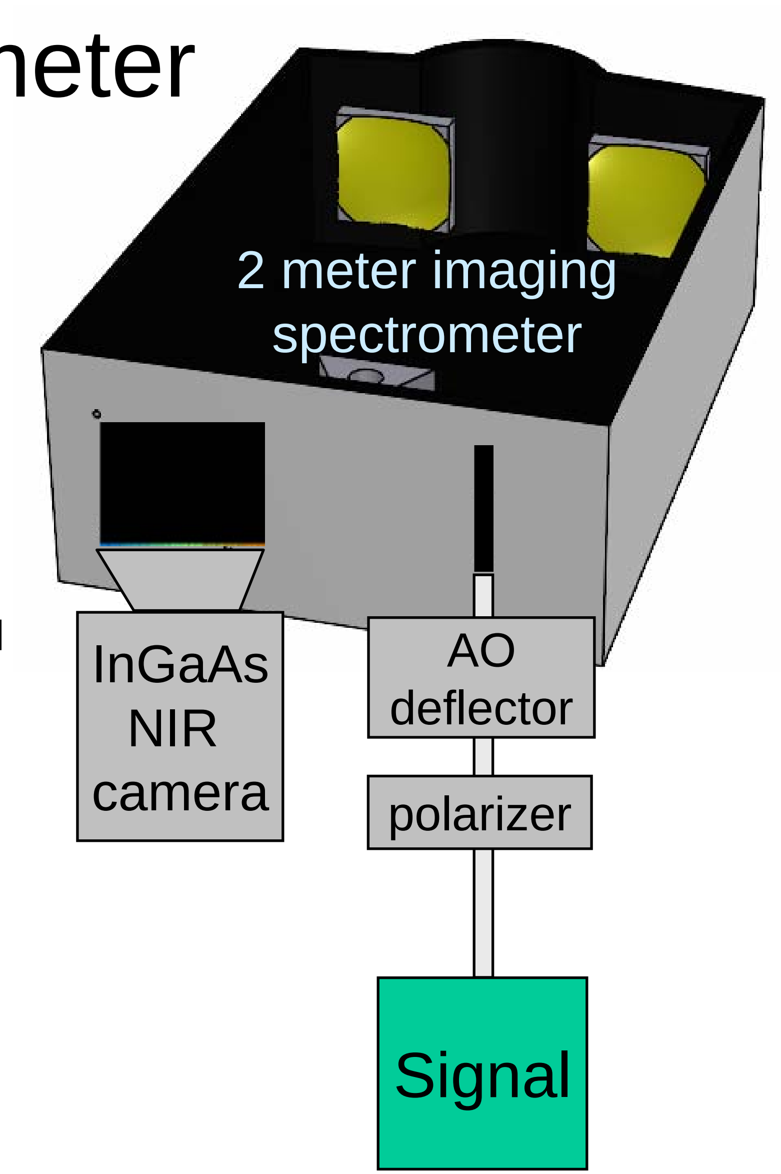
Spectral Resolution

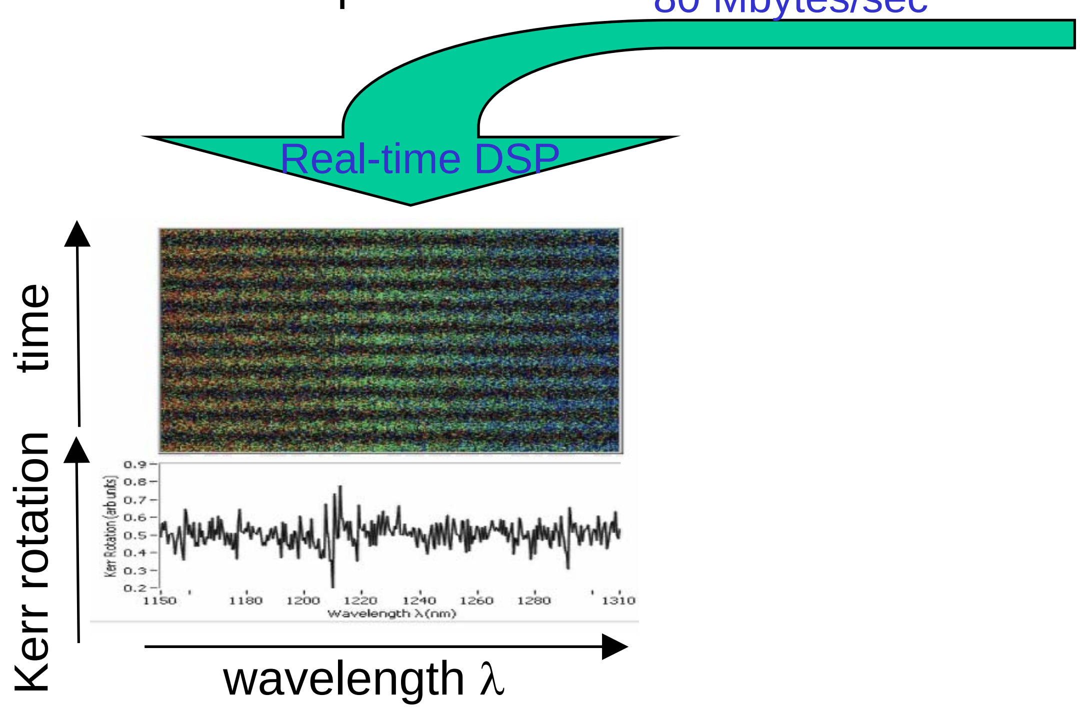


Lock-in Optical Spectrometer

Lock-in Spectrometer

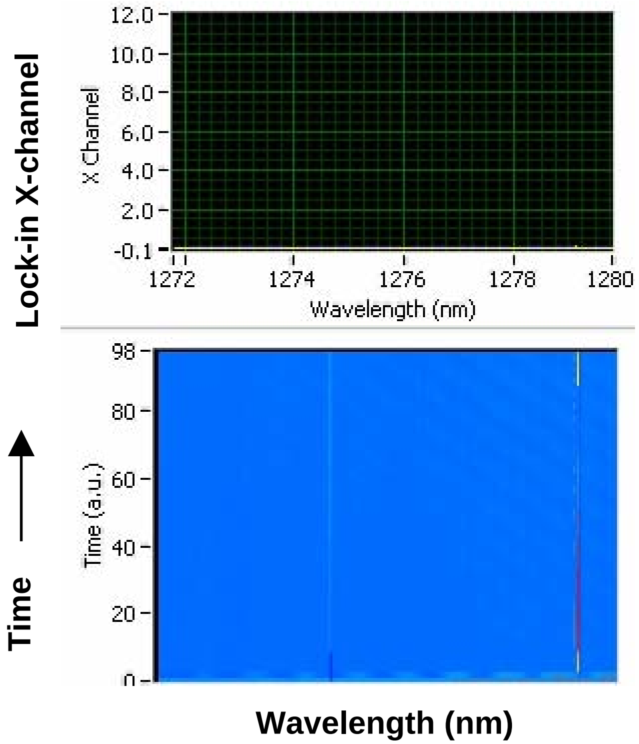
- Goal: spectroscopy of single quantum dots
  - » time-resolved absorption
  - » time-resolved Kerr rotation of single spins
- Challenge: achieving necessary SNR
  - » Photon number fluctuations dominant source of noise
  - » Need an array of large-area detectors with lock-in amplifiers!

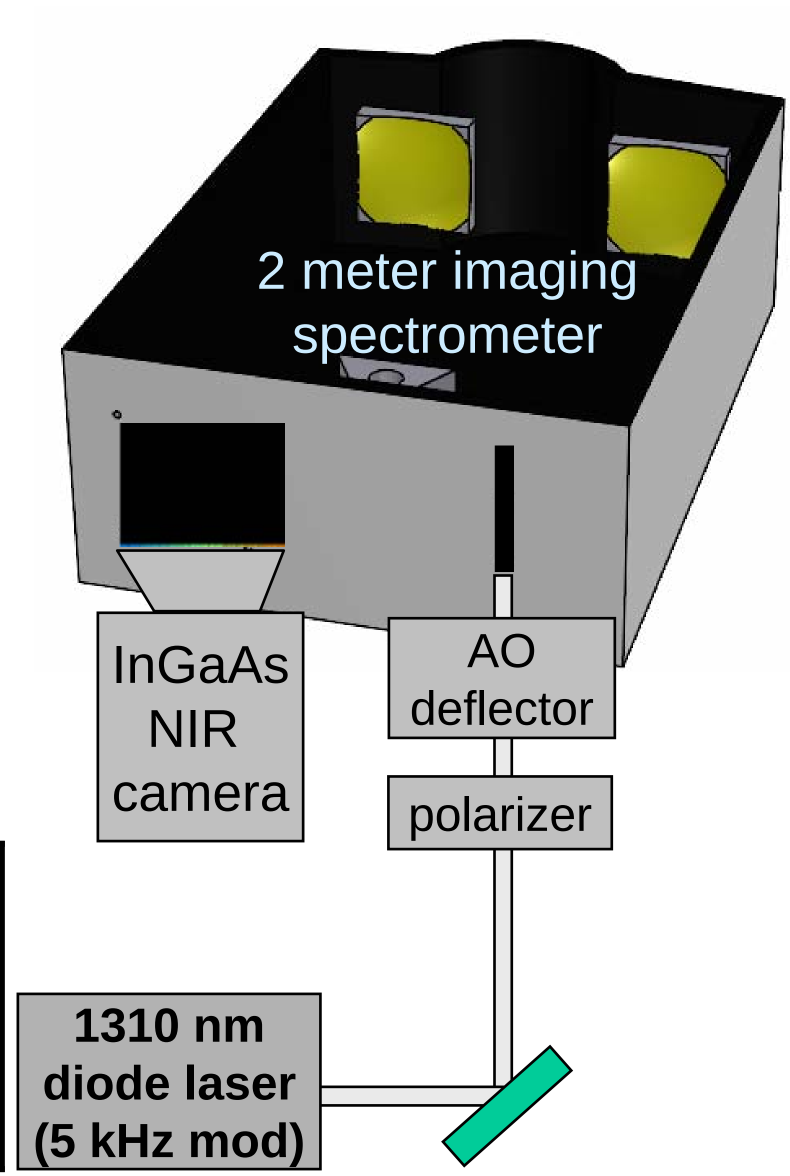




Lock-in Optical Spectrometer: First Test

“Sample”: 1310 nm diode laser



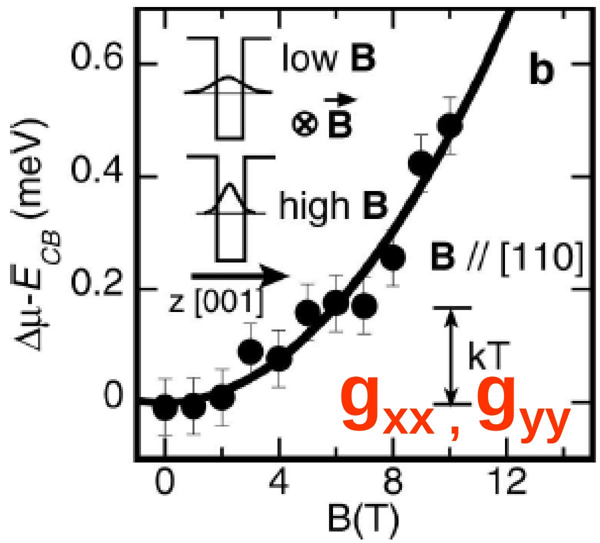


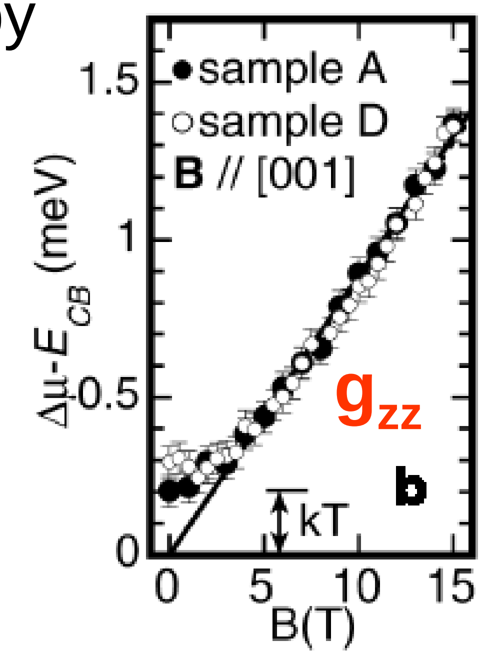
Number of channels	320x2=640
Spectral bandwidth @1300nm	5 meV
Spectral resolution	<50 μeV
Noise-equivalent power	<$5x10^{-12}$ W/cm^2

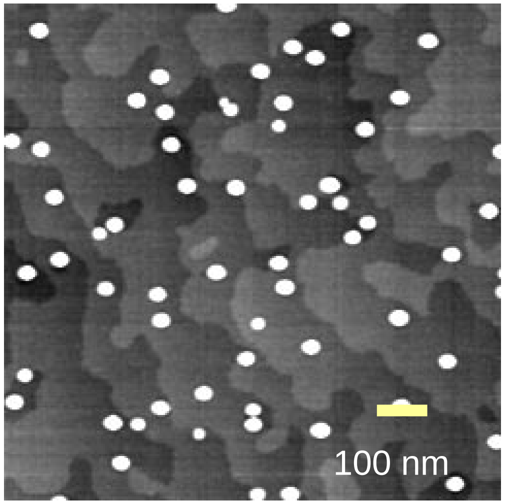
InAs:GaAs Quantum Dots

G. Medeiros-Ribeiro
Laboratório Nacional de Luz Síncrotron, Campinas, Brazil

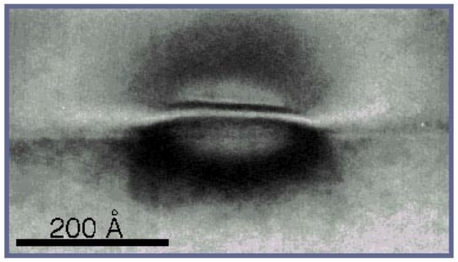
- Interband absorption energies comparable to Ge quantum dots
  - » 950 meV-1 eV, λ=1.25-1.3μm
  - » Density 10^8 cm^{-2} → ~100 dots/μm^2
- Large g-tensor anisotropy



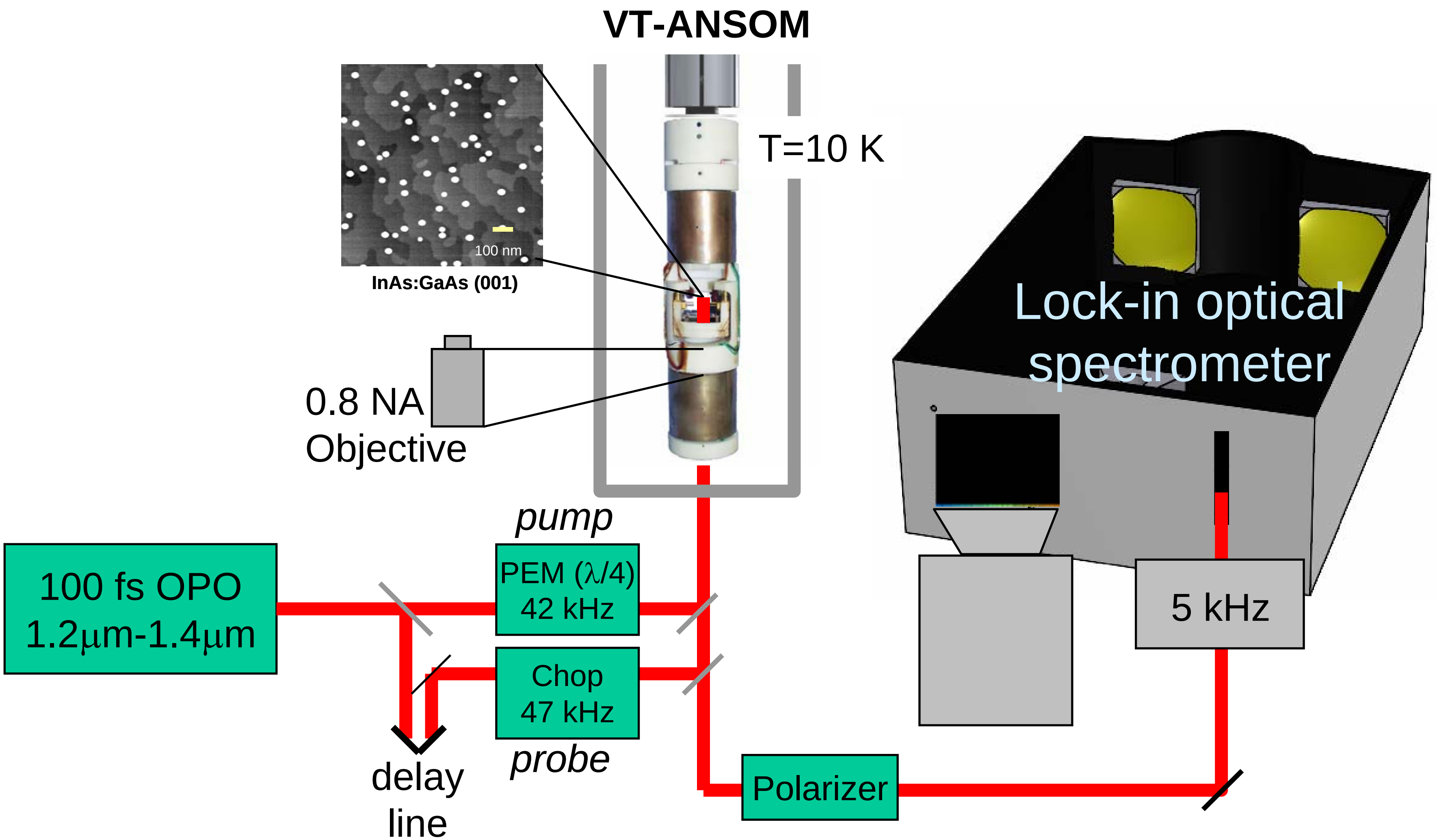




InAs:GaAs (001)



Experiment in Progress…



Summary

- Quantum computation presents many materials, experimental and theoretical challenges
- New device applications for ferroelectric/ semiconductor heterostructures