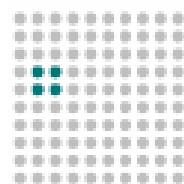


Progress in Quantum Computing in Condensed Matter Systems

Professor Robert Clark

**Director, Centre for Quantum Computer Technology
Australian Research Council Centre of Excellence**



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QUANTUM COMPUTER
TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

Mid-Level QC Roadmap: Status Metrics

QC Approach	1	1.1	2	2.1	2.2	2.3	3	3.1	3.2	3.3	3.4	3.5	3.6	4	4.1	4.2	4.3	4.4
NMR	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Trapped Ion	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Neutral Atom	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Cavity QED	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Optical	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Solid State:																		
Charged or exitonic qubits	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Spin qubits	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Superconducting	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
QC Approach	4	4.5	4.6	4.7	4.8	5	5.1	5.2	6	6.1	6.2	6.3	7	7.1	7.2	7.3	7.4	7.5
NMR	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Trapped Ion	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Neutral Atom	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Cavity QED	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Optical	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Solid State:																		
Charged or exitonic qubits	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Spin qubits	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲
Superconducting	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲	▲▲

Legend: ▲▲ = sufficient experimental demonstration

▲▲ = preliminary experimental demonstration, but further experimental work is required

▲▲ = no experimental demonstration and ▲▲ = a change in the development status between Versions 1.0 and 2.0

QC in Condensed Matter Systems: In the Beginning...

- **QC in Semiconductor QDs**

Gate-controlled, exchange- coupled electron spin qubits

D. Loss and D.P. Di Vincenzo
PRA 57, 120 (1998)

GaAs QDs

- **Impurity Spins**

B. E. Kane
Nature 393, 133 (1998)

Si: P

- **Optically-driven Spin-based Systems**

F. Rossi and P. Zoller (et al)
Cond-mat/0109337
L. Sham and D. G. Steel (et al)
PRL 89, 167402 (2002)

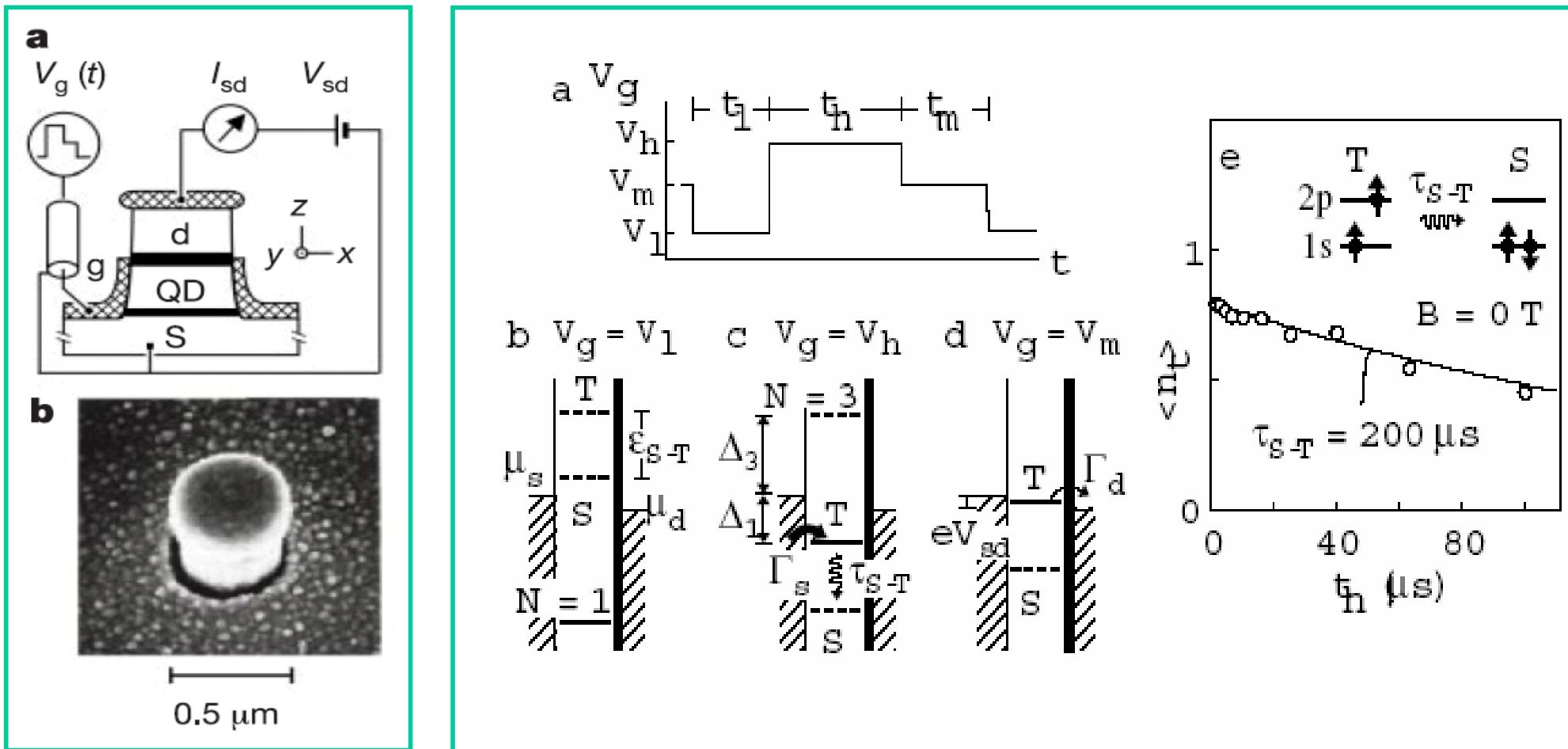
GaAs QDs

OUTLINE

GaAs	Si, SiGe	C	
Lateral QDs (Vertical) e-Spin	Atoms QDs e-Spin (n-spin) Charge	Atoms QDs e-Spin (n-spin)	
Electrical			
<ul style="list-style-type: none"> Single Shot Readout of Single Spin Coupled Spins Coherent Oscillations: Charge Qubit T_1 Measurements: Vertical QD Entanglement Experiment Electrons trapped by SAW 	<p>Delft</p> <p>Harvard</p> <p>NTT</p> <p>NTT</p> <p>Maryland</p> <p>Cambridge</p>	<p>Wisconsin, Pittsburgh</p> <p>CQCT Aust, UCLA, LPS, Ohio, Illinois, Utah, LBNL, LANL, Cornell</p> <p>Cambridge</p>	<p>Harvard</p> <p>Cambridge</p>
Optical	Optical	Optical	
<ul style="list-style-type: none"> Single QD: All Optical Quantum CROT Gate 	<ul style="list-style-type: none"> Si-SiGe QDs Si-Ge: P Na^+ in SiO_2 ^{29}Si nuclear spin in ^{28}Si $^{28}\text{Si:P}$ ESR ^{29}Si NMR 	<p>Many other advances in GaAs, Si, C - Eg. GaAs QDs: Basel, Berkeley, ETH, IBM, MIT, Munich, NRC Ottawa, Oregon, UCSB....</p>	

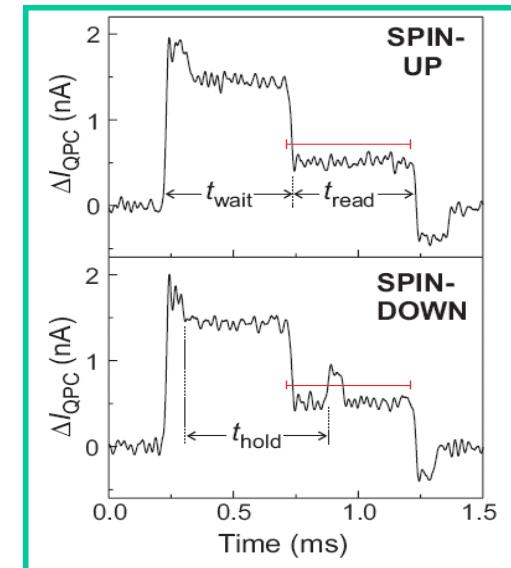
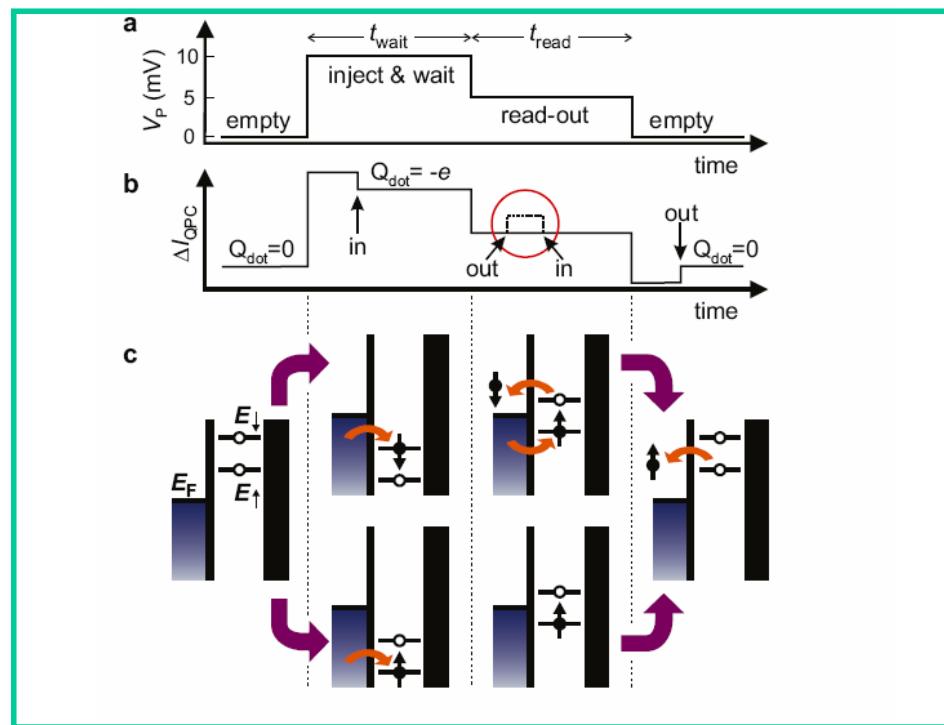
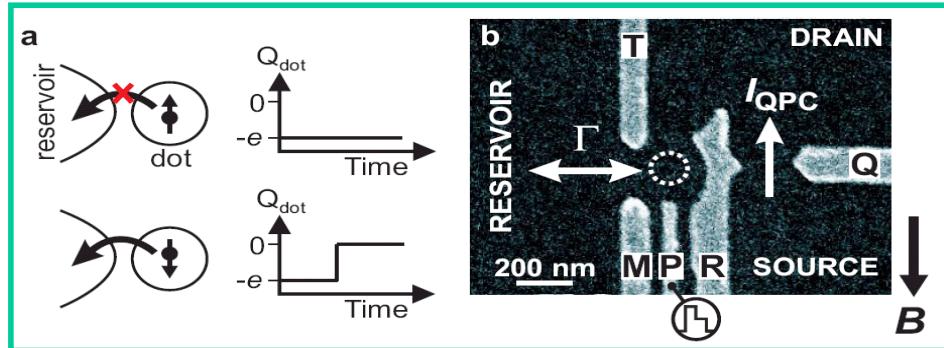
GaAs Vertical QDs: Spin, Electrical

Relaxation Measurements in Artificial H and He Atoms: $T_1 \sim 200 \mu\text{s}$



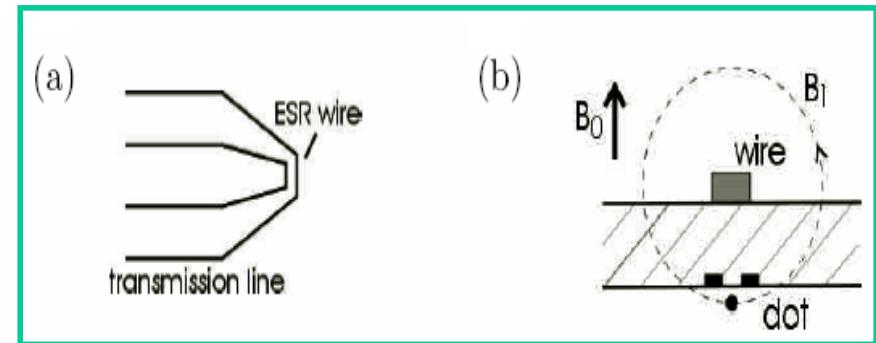
GaAs Lateral QDs: Spin, Electrical

Single Shot Readout of a Single Spin



J.M. Elzerman et al, Institute of Nanoscience, Delft – Submitted 2004

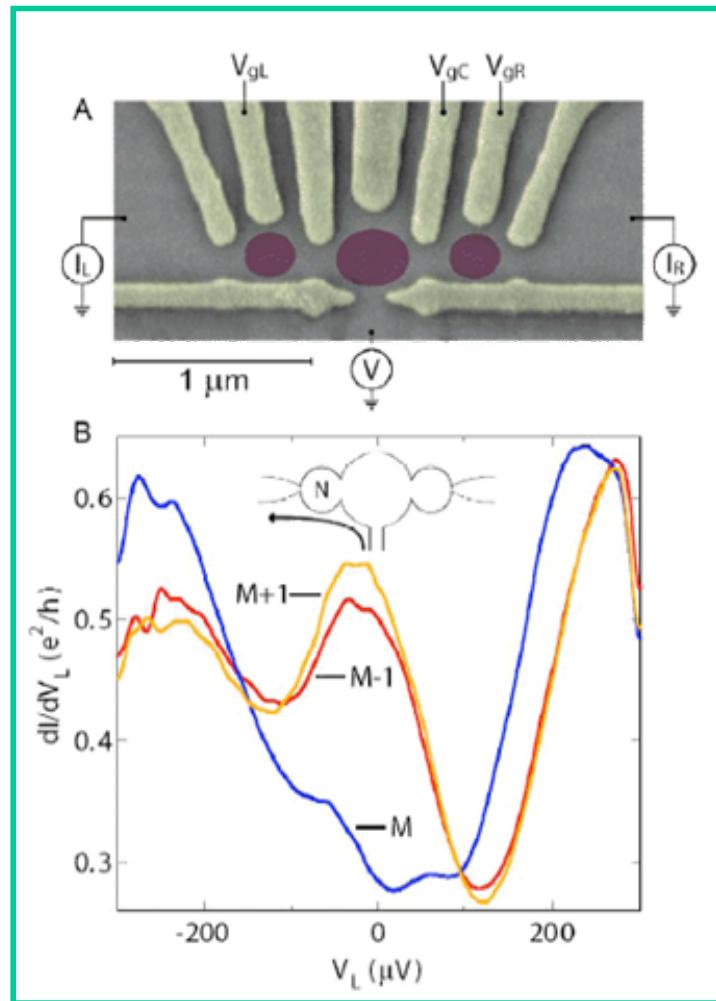
Spin manipulation



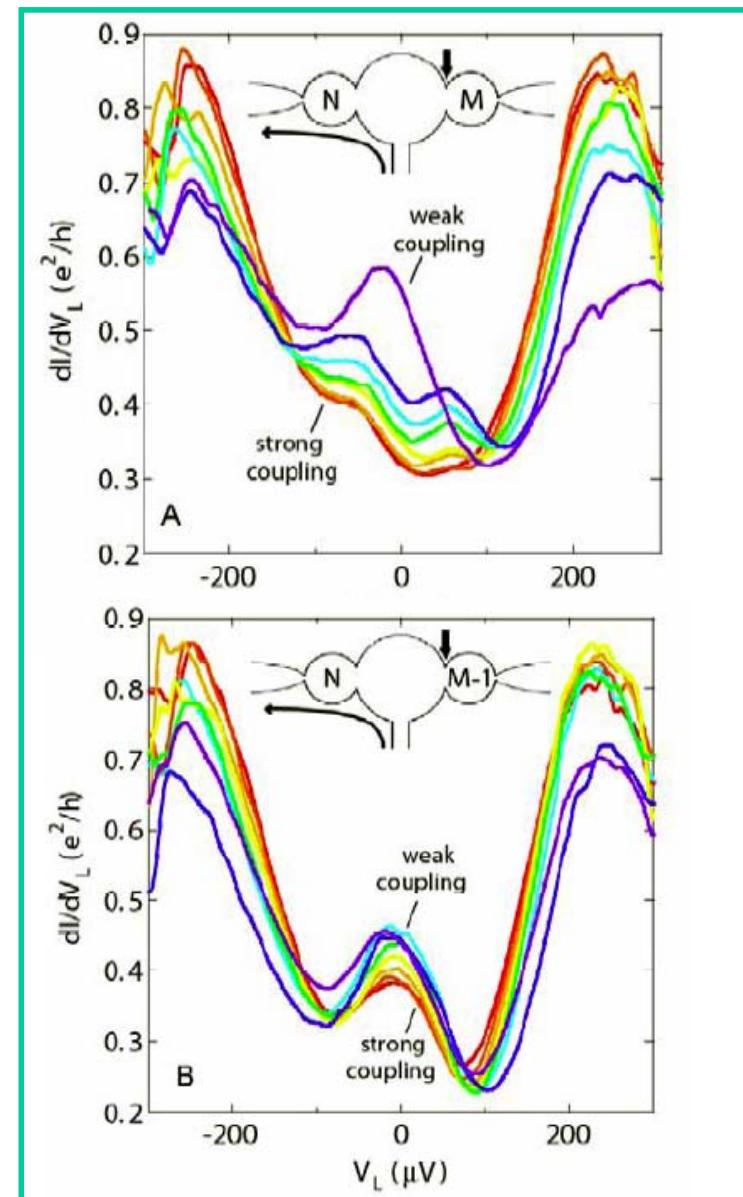
L. M. K. Vandersypen et al, Delft
quant-ph/0207059 (2002)

GaAs Lateral QDs: Spin, Electrical

Non-local Control of Coupled Spins

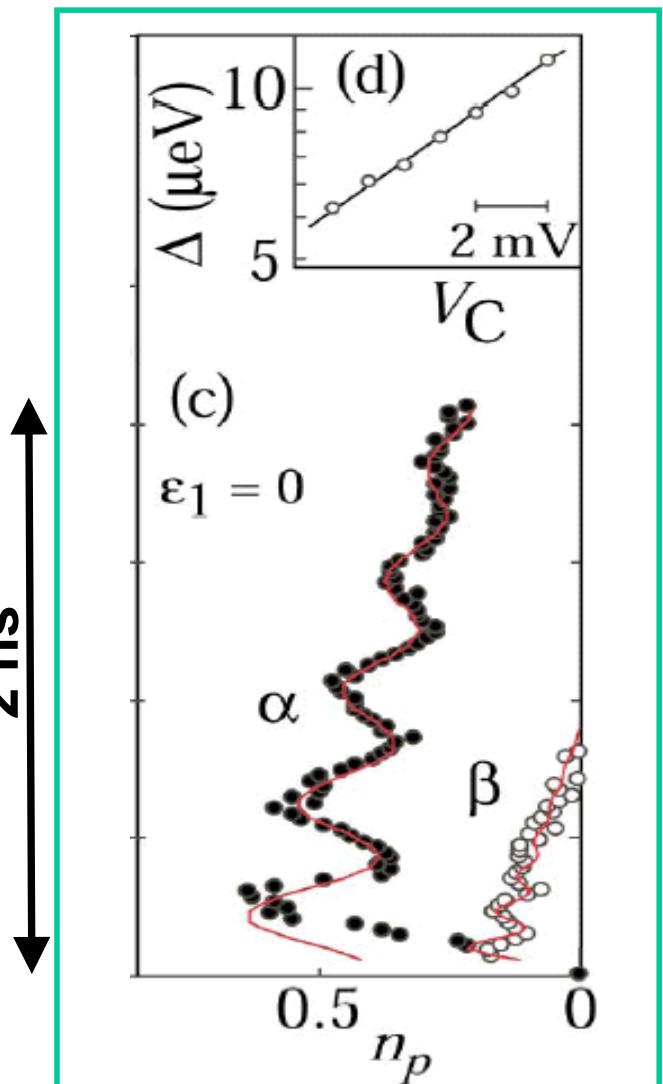
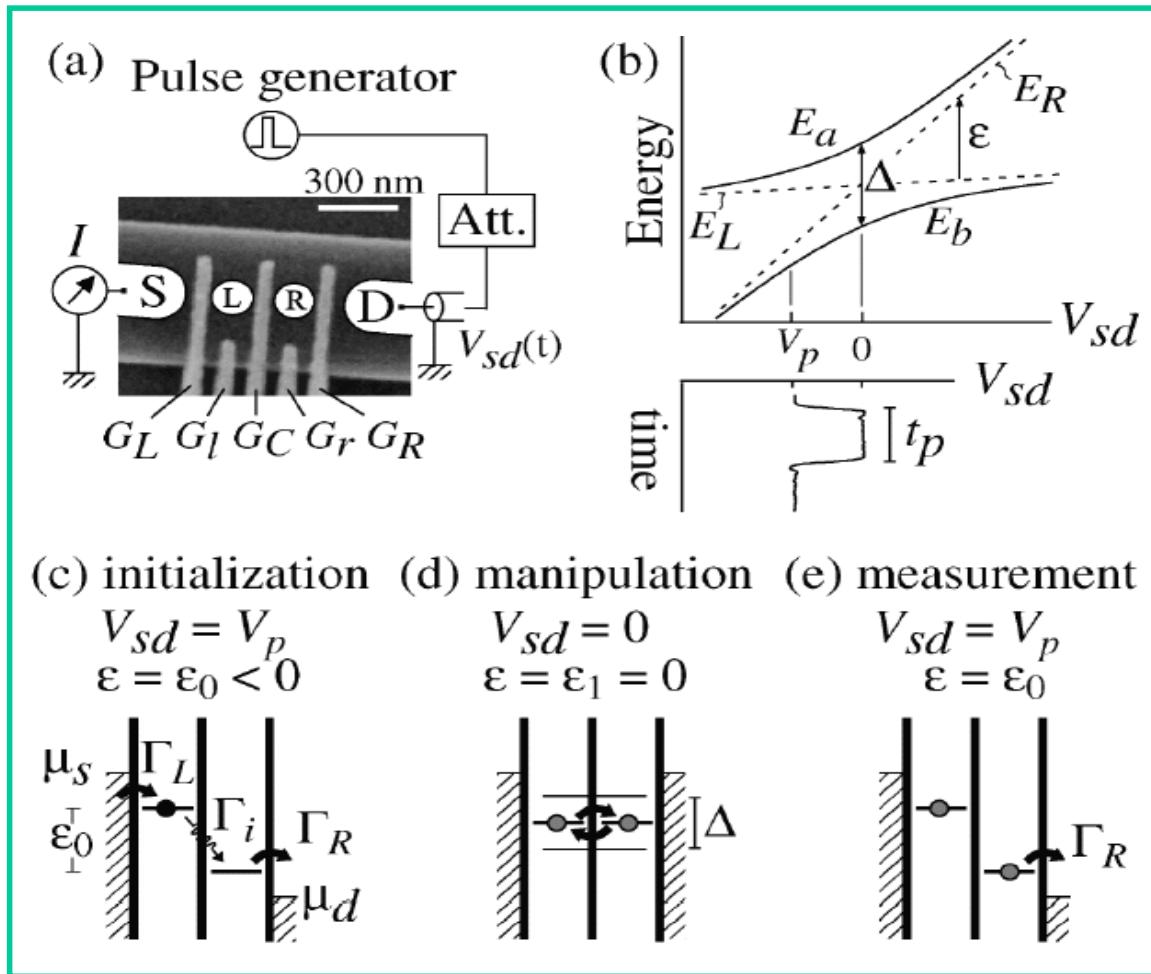


N. J. Craig et al, cond-mat/0404213 (2004)
Harvard, Santa Barbara



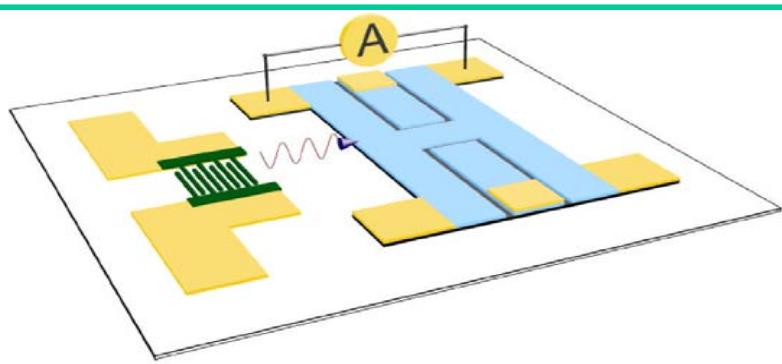
GaAs Lateral QDs: Charge, Electrical

Charge Qubit: Coherent Oscillations



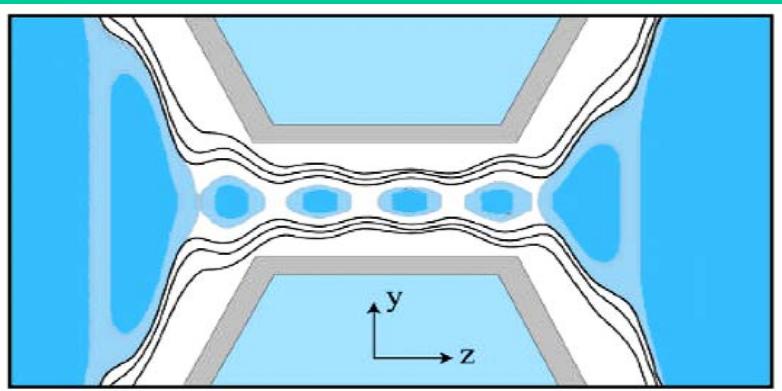
T. Hayashi et al, PRL 91, 226804 (2003) NTT

GaAs QD, QW: Spin, Electrical



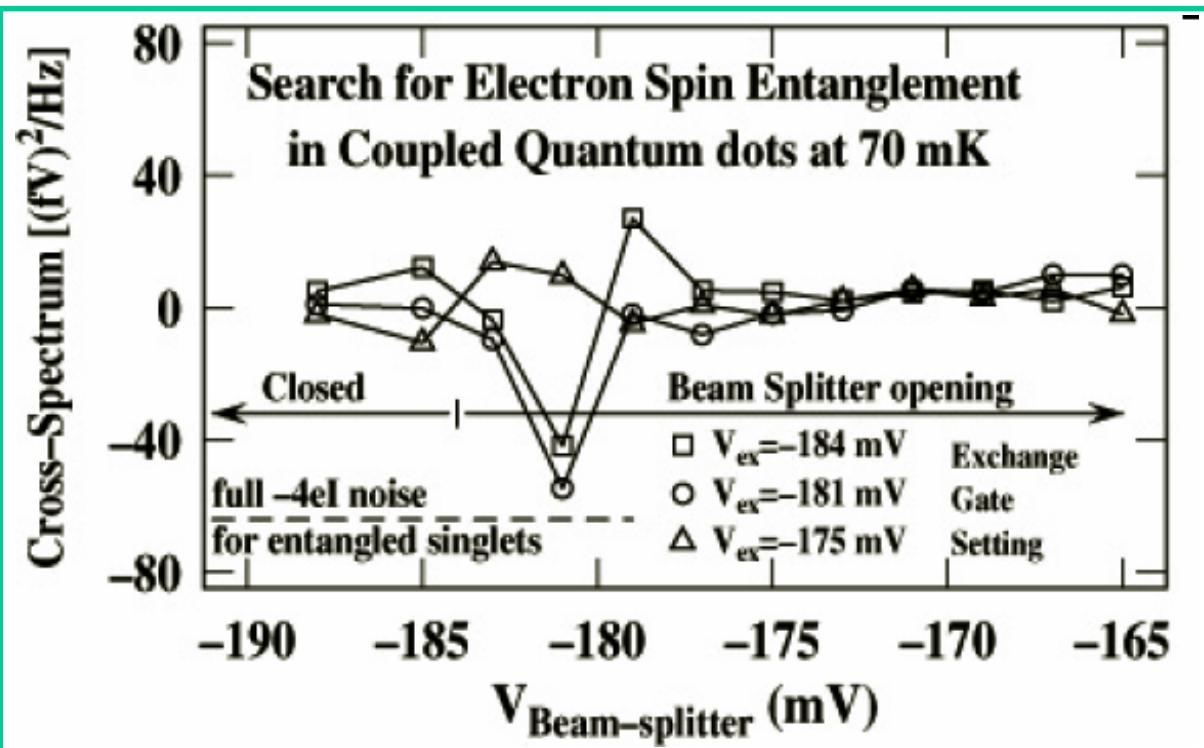
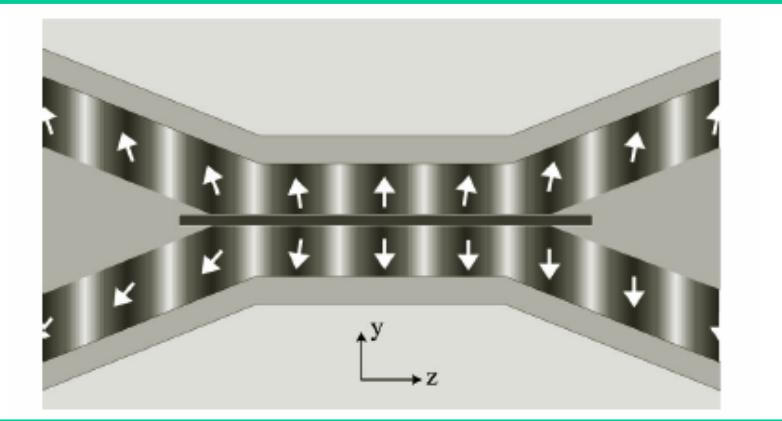
Electrons Trapped by SAW

C. H. W. Barnes et al, PRB 62, 8410 (2000) Cambridge

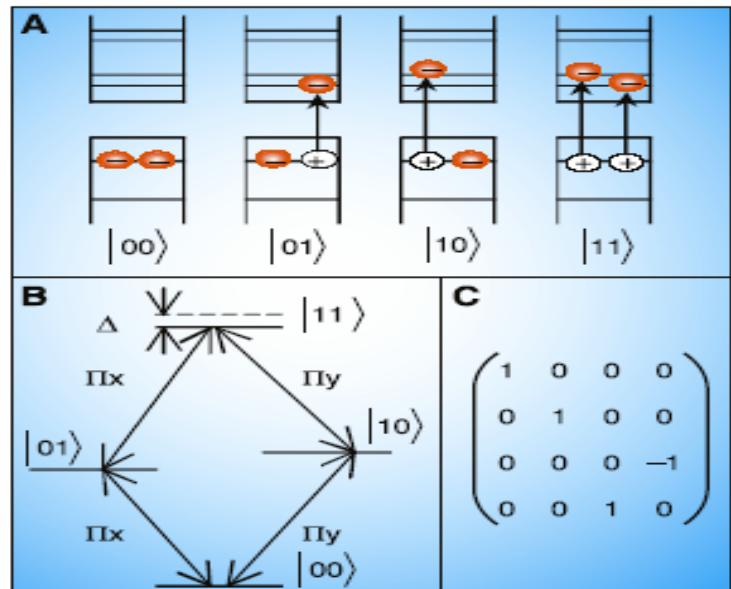


Coupled QD: Entanglement Measurement

R. A. Webb et al, Maryland

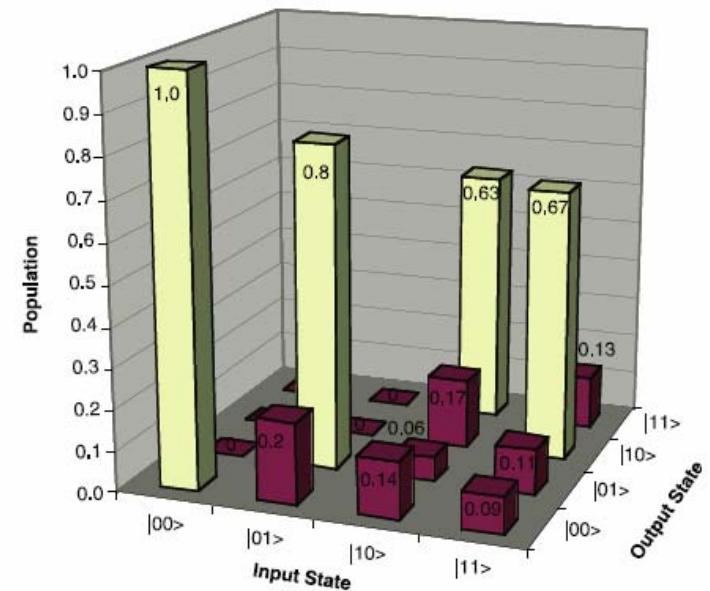
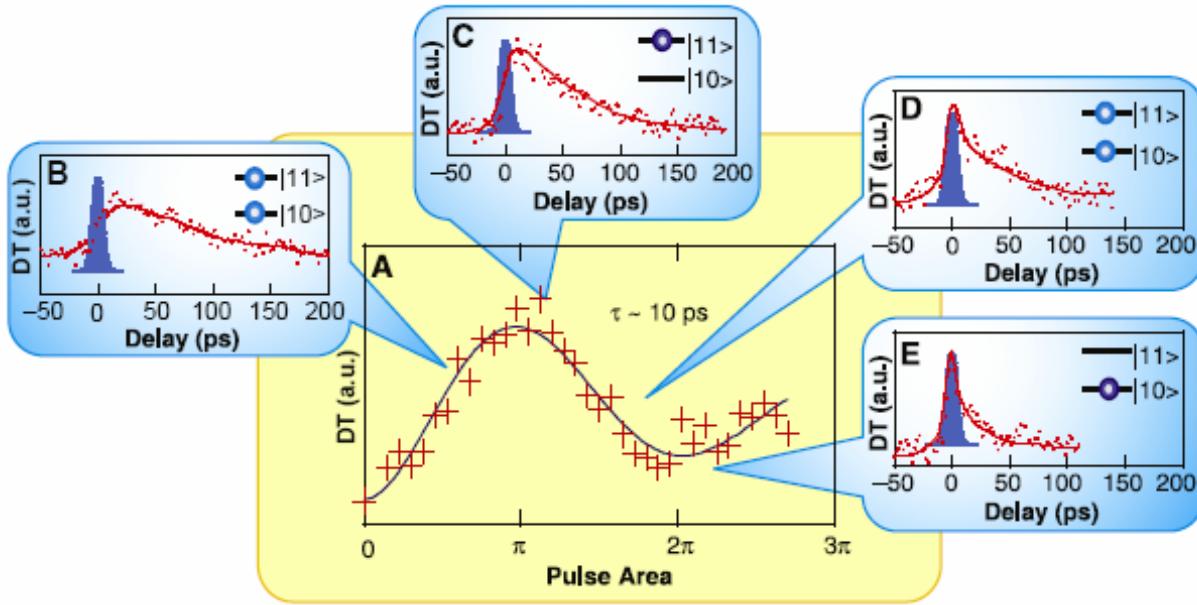
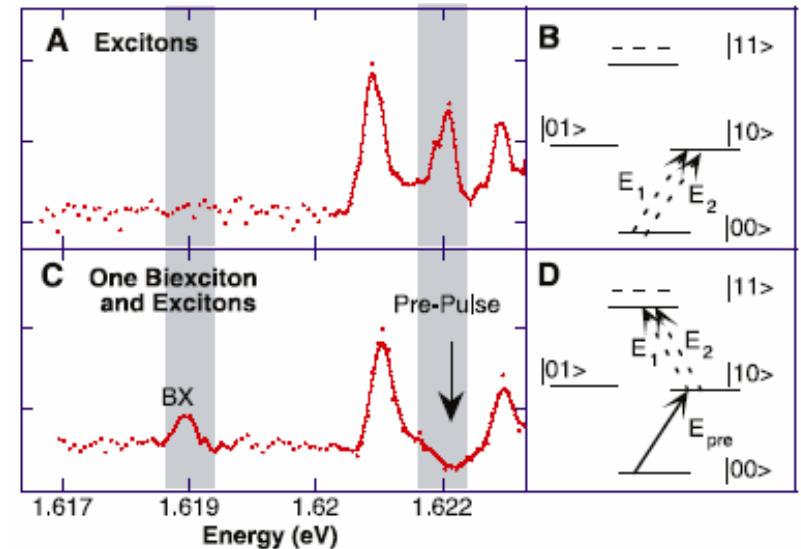


Biexciton in GaAs Single QD: All Optical Quantum CROT Gate



X. Li et al, Science
301, 809 (2003)

Michigan, NRL,
UC San Diego

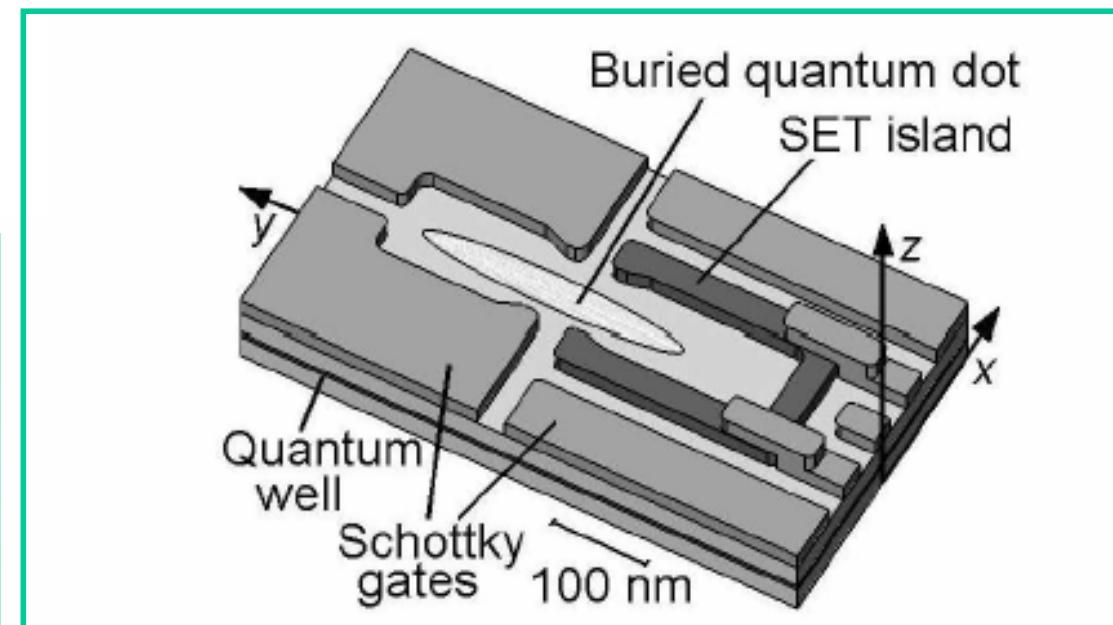
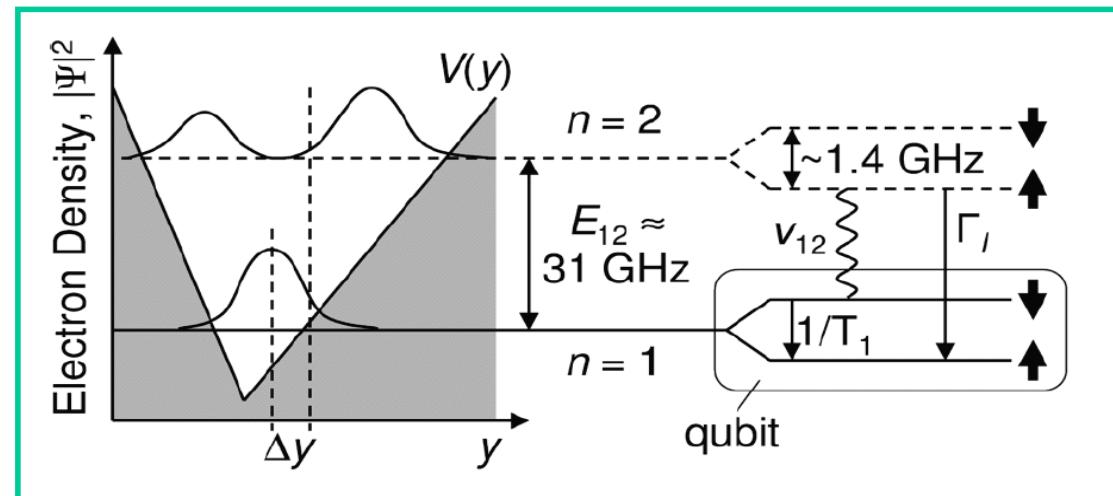
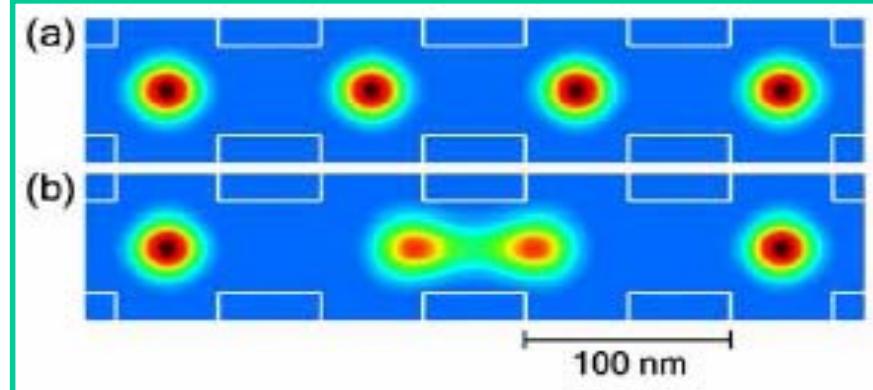
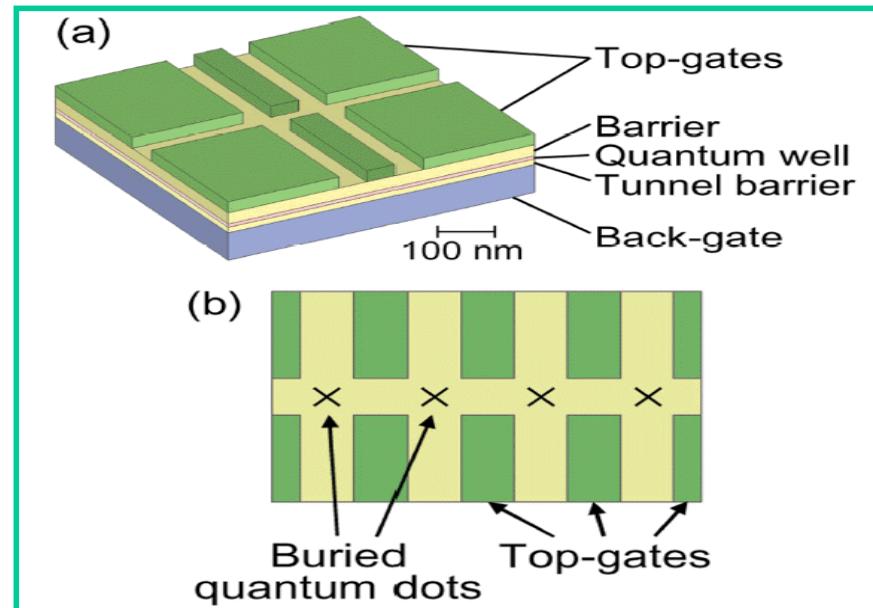


Si-SiGe Heterostructures

Si-SiGe QDs: Electron Spin Qubit

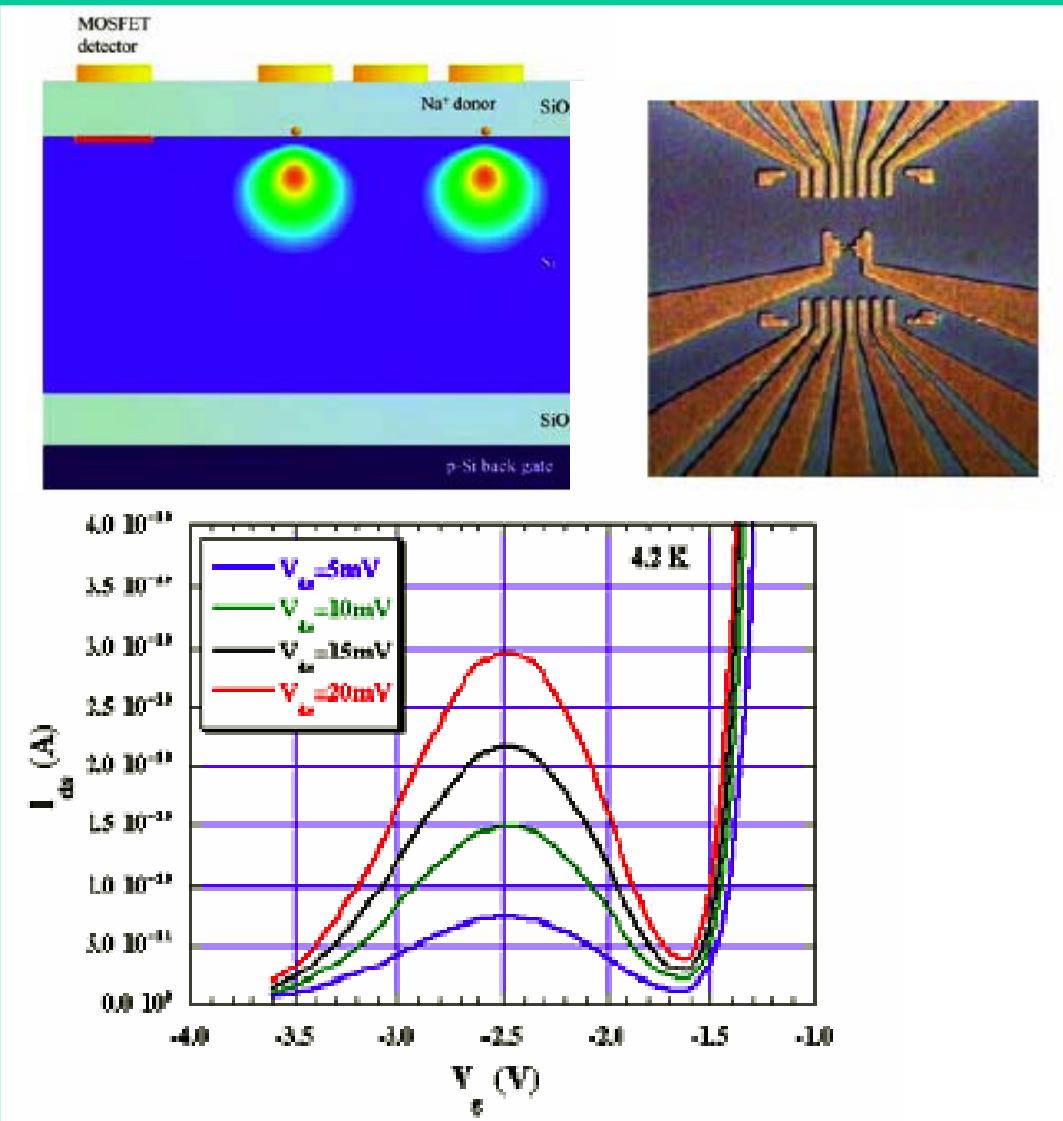
M. Friesen et al, PRB 67, 121301 (2003)

Wisconsin

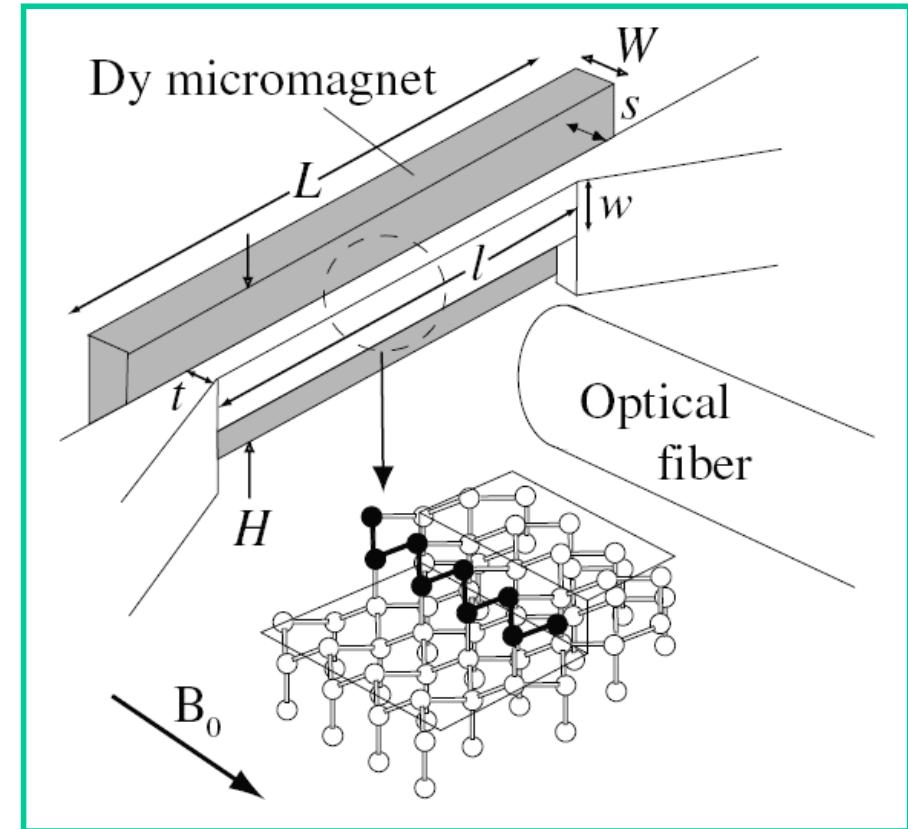


Silicon QC: Spin, Electrical & Optical

Na^+ in SiO_2 : Electron Spin Qubits in ^{28}Si



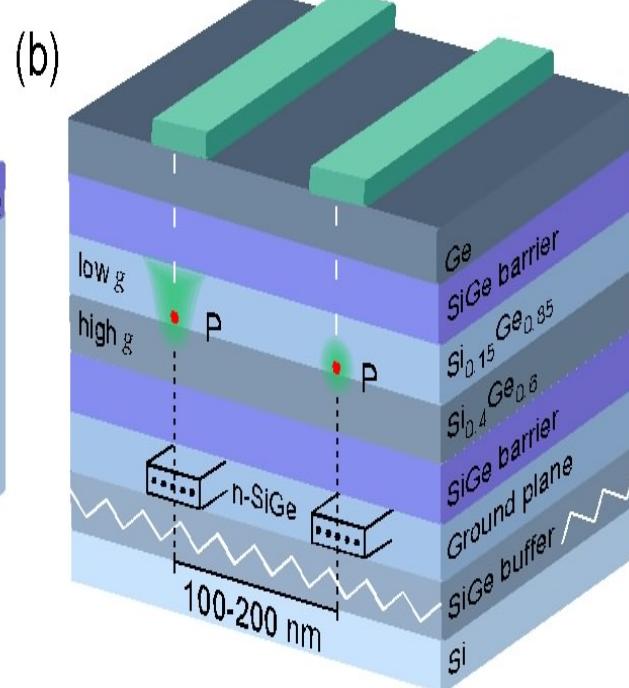
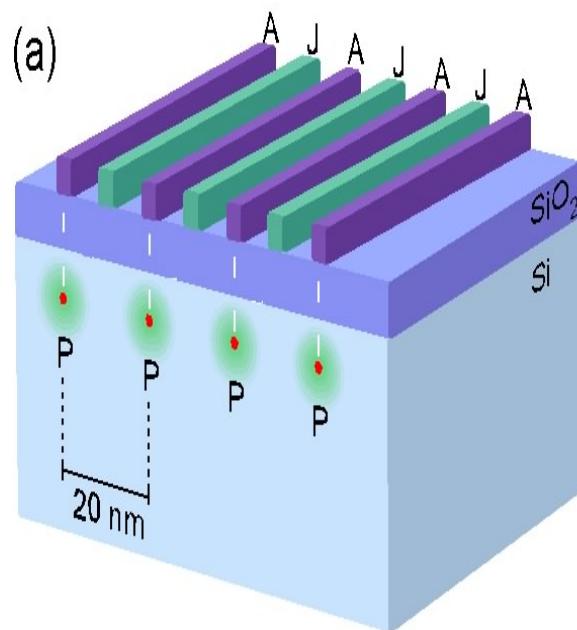
^{29}Si Nuclear Spin Qubits in ^{28}Si



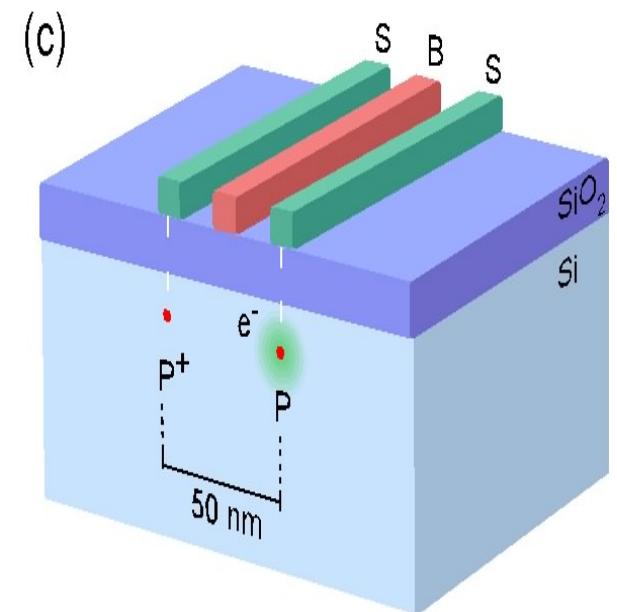
T. D. Ladd et al, PRL 89, 017901 (2002)
Stanford, Keio, JST

M. Pepper et al, Cambridge

Si (-Si-Ge): P QC Architectures: Spin & Charge Qubits



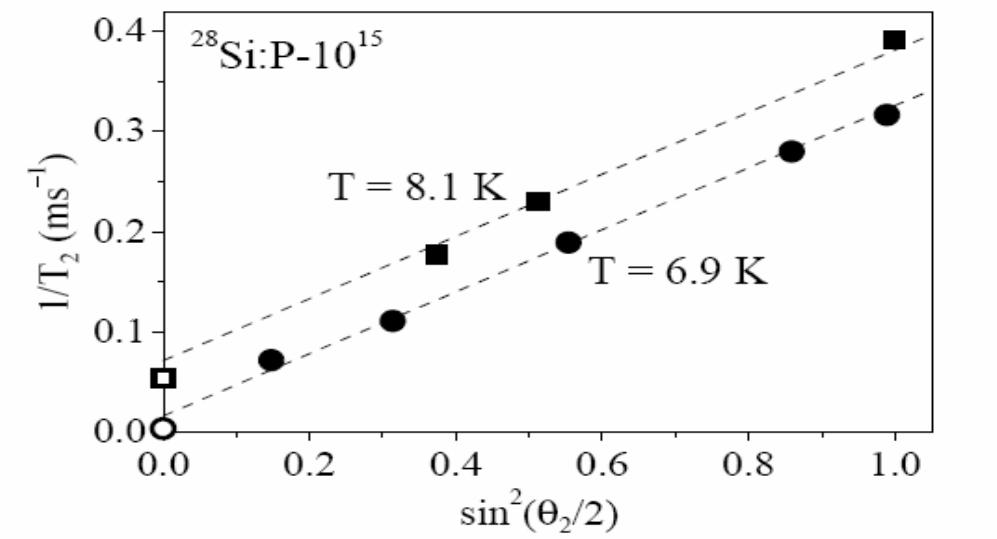
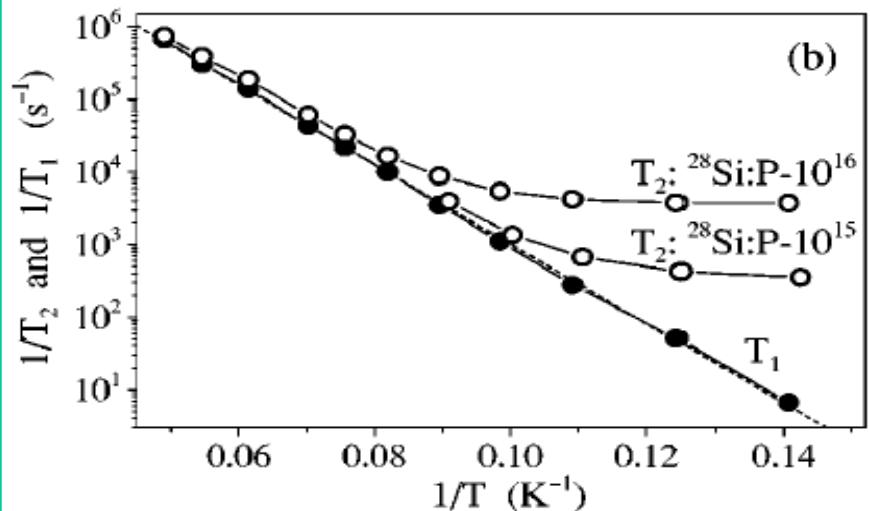
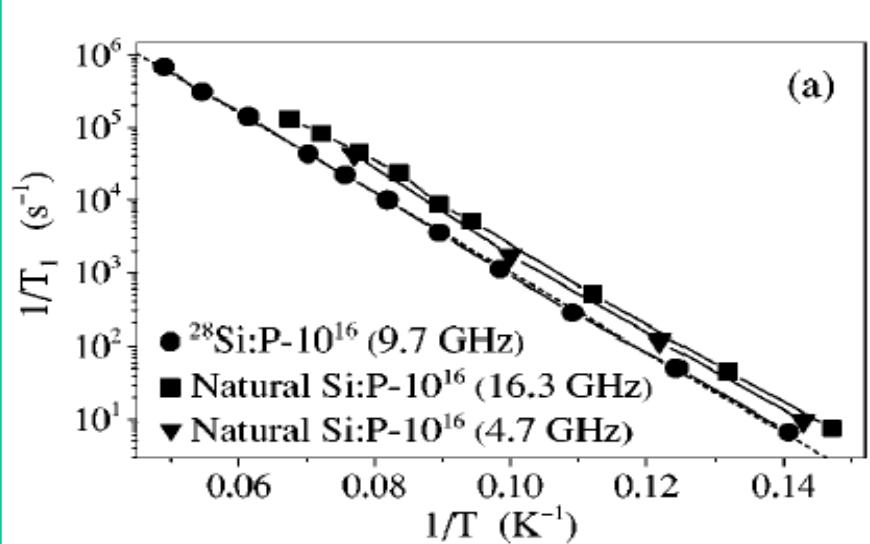
Spin



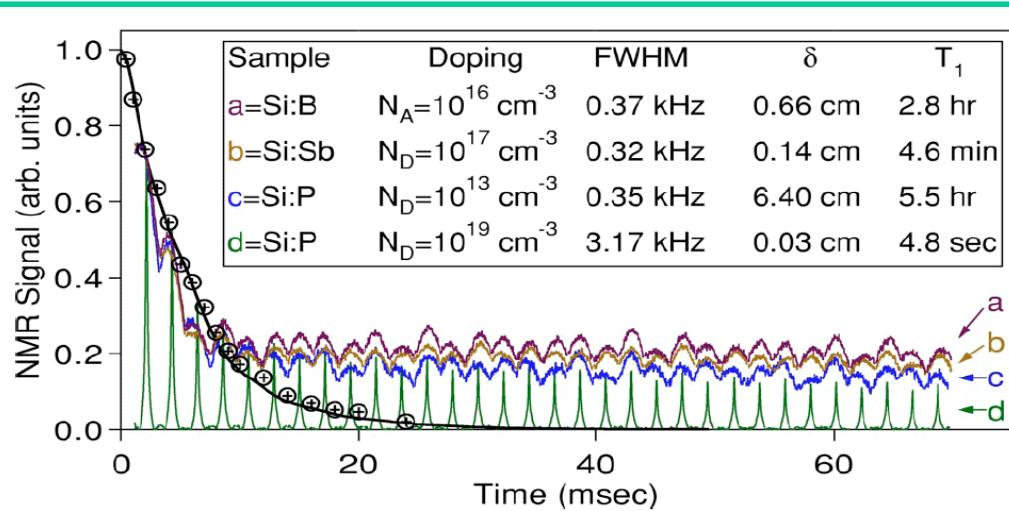
Charge

^{28}Si : P ESR, ^{29}Si NMR

^{28}Si : P ESR A.M. Tyryshkin et al, PRB 68
193207 (2003) Princeton



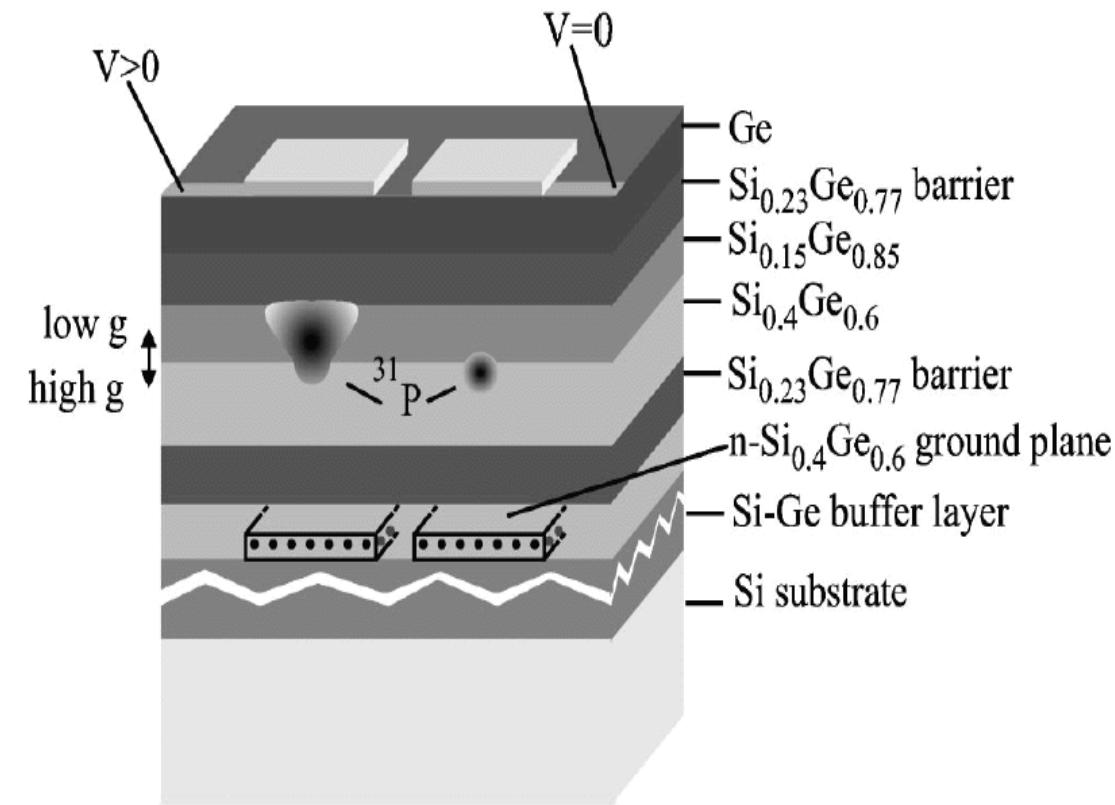
^{29}Si NMR A. E. Dementyev et al, PRB 68
153302 (2003) Yale



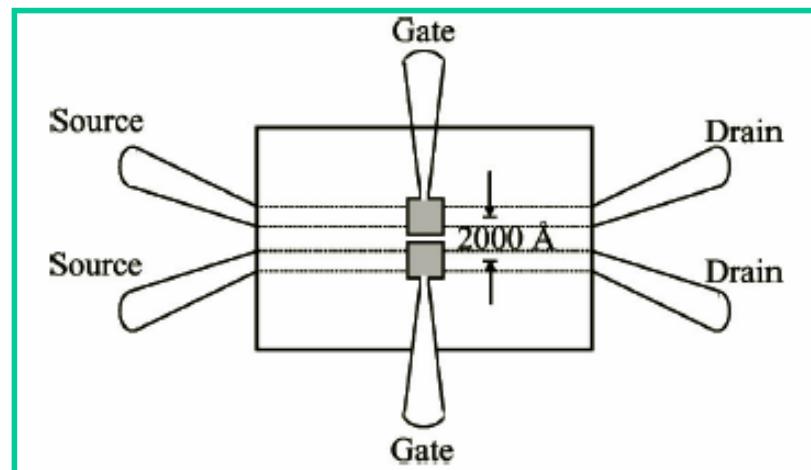
Si-SiGe Heterostructures

P-Atom Electron Spin Qubits G-Factor Engineering

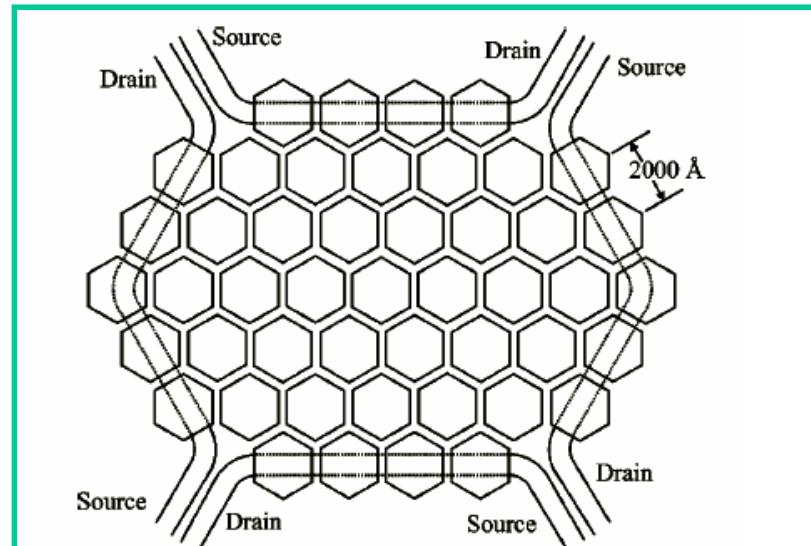
R. Vrijen et al, PRA 62 012306 (2000) UCLA, IBM



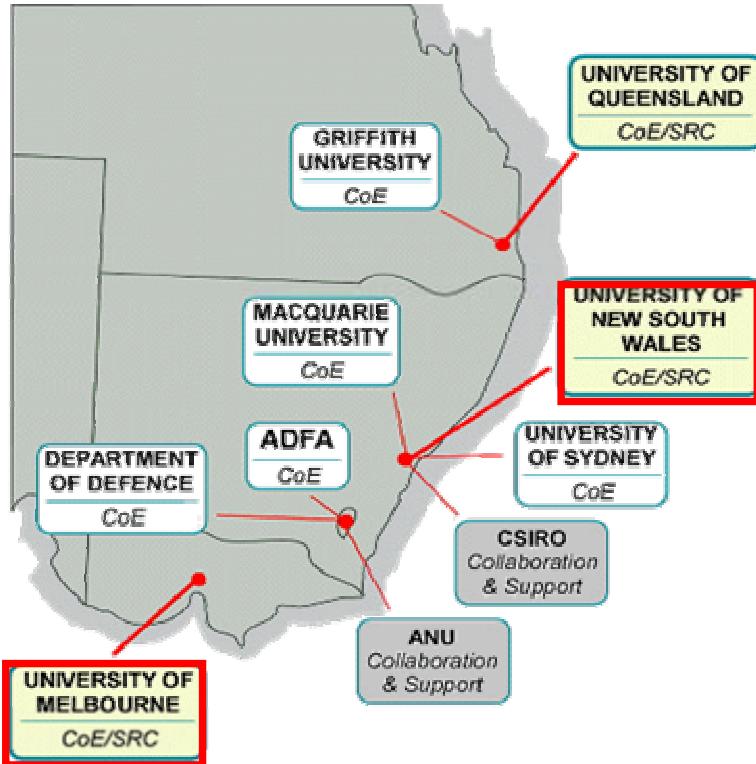
2-Qubit Test Structure



Large Qubit Array



The Centre for Quantum Computer Technology (CQCT)



Robert Clark, Director

Top-down fabrication

Andrew Dzurak, David Jamieson

**V. Chan, F.E. Stanley, M. Mitic, C. Yang,
C.I. Pakes, T. M. Buehler**

Quantum measurement

Alex Hamilton

**T. M. Buehler, D.J. Reilly, A. J. Ferguson,
R.P. Starrett**

Bottom-up STM/MBE fabrication

Michelle Simmons

**S.R. Schofield, N.J. Curson, L. Oberbeck,
F.J. Ruess, T. Hallam**

CQCT

More than 100 research staff & students

12 research programs (3 above)

6 Australian universities



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TECHNOLOGY**
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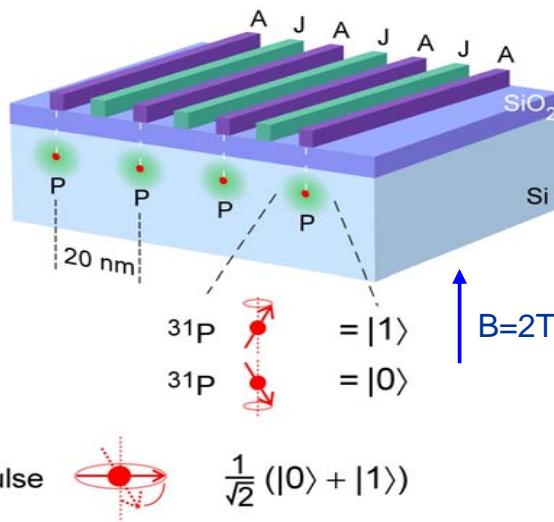
ARDA

Spin & Charge Buried Donor Si:P Qubits

Si:P Spin Qubit

One ^{31}P Atom

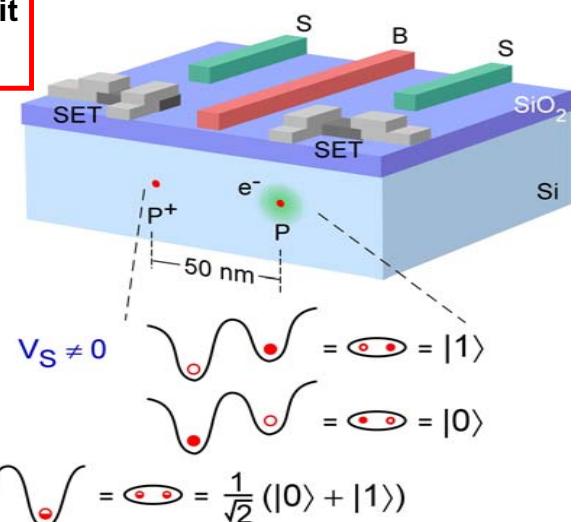
- n-spin: Kane, Nature (1998)
- e-spin: Vrijen et al, PRA (2000)
- n/e-spin: Skinner, Davenport & Kane, PRL (2003)
- Long Coherence Times in Si at 1K:
Nuclear – mins Electron – ms-s
- Scalable
- Industry Compatible



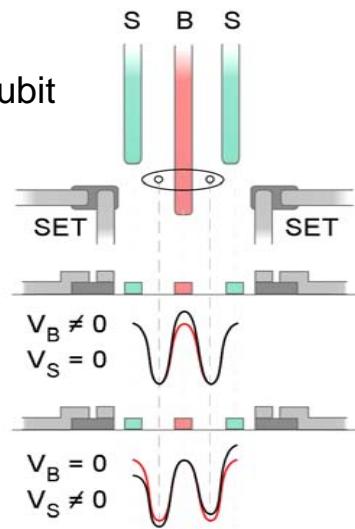
Si:P Charge Qubit

Two ^{31}P Atoms

- Hollenberg et al, cond-mat (2003)
- Fedichkin et al, Nanotech (2000)
- Ekert and Josza, Rev. Mod. Phys. (1996)

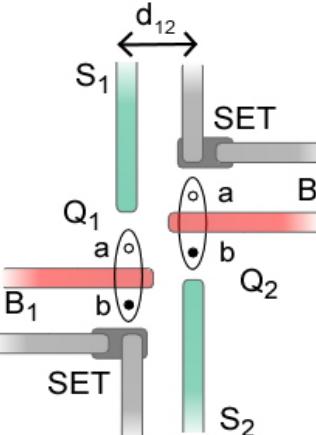


Charge Qubit

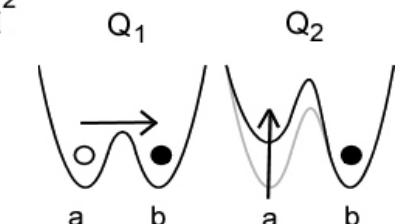


Barrier control

Symmetry control

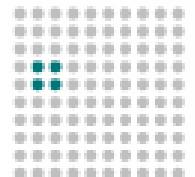


CPHASE



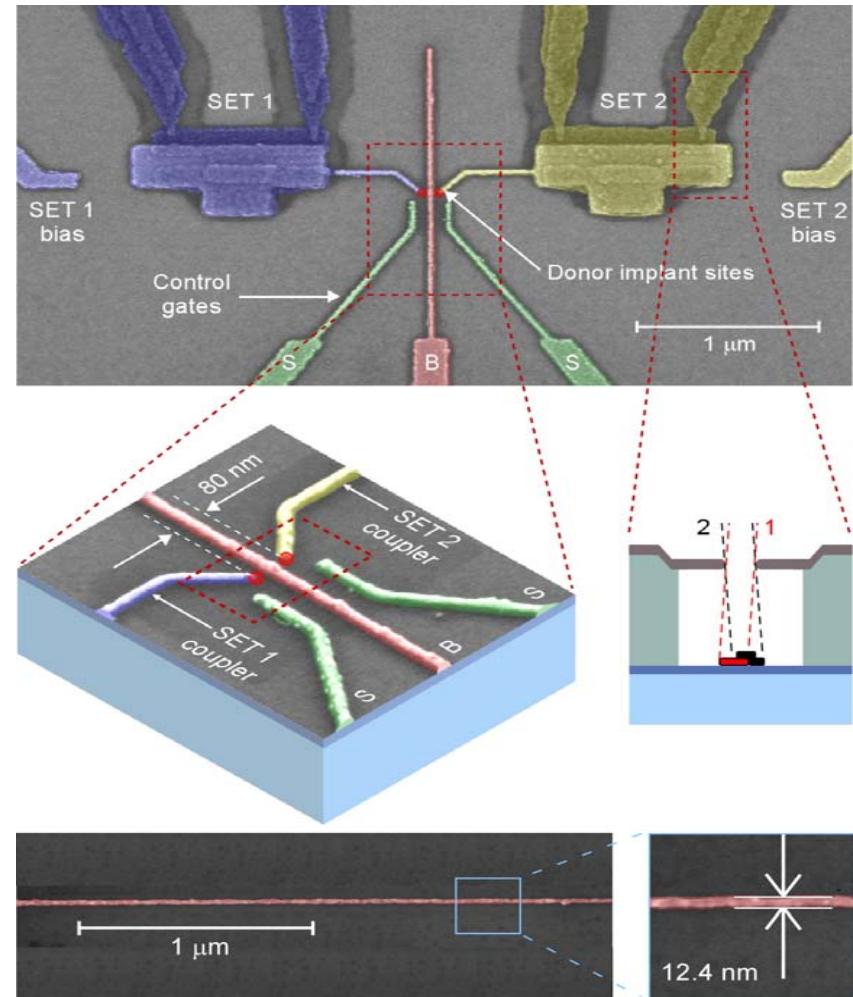
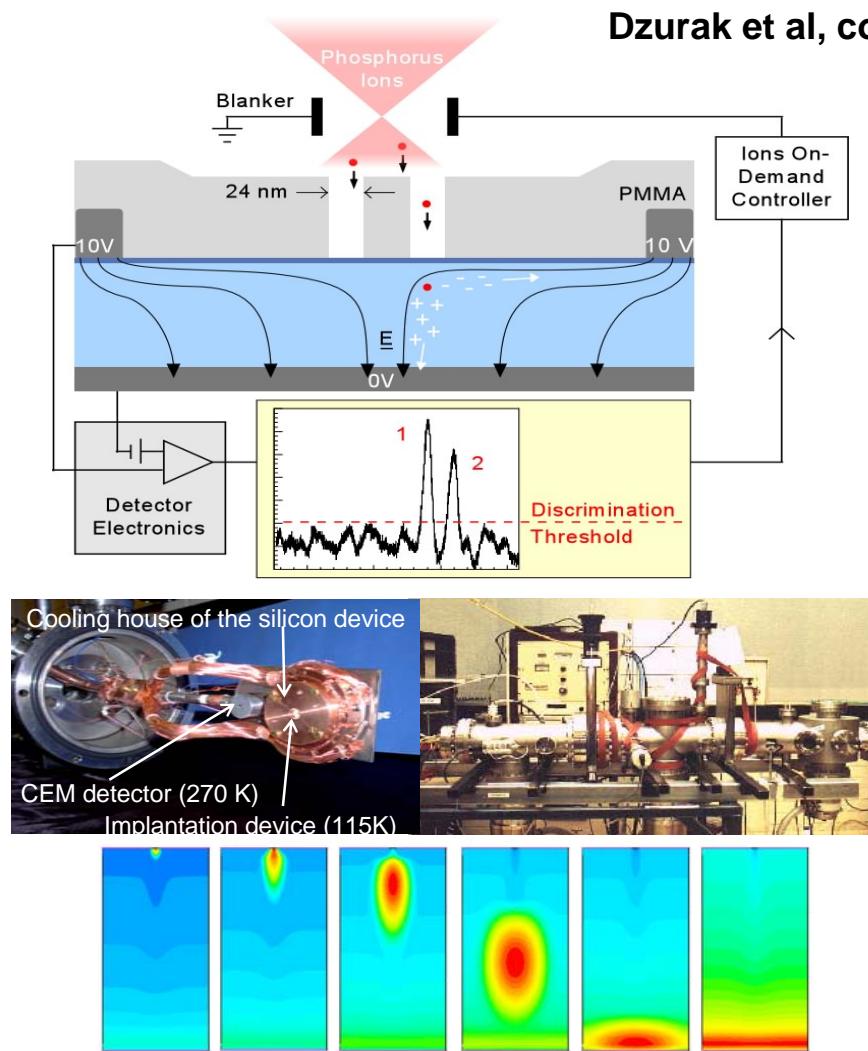
Top-down Fabrication

- Single-ion ^{31}P implantation, on-chip ion detection
- Fully assembled buried P atom devices



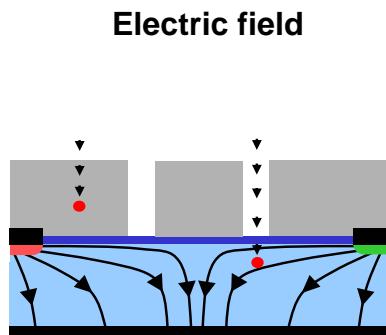
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Construction of Si:P Single Atom Qubits: Top-Down



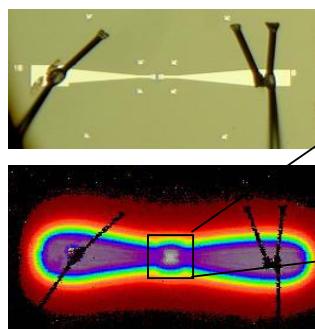
See also T. Schenkel et al, Journal of Applied Physics (2003)

Top-Down Construction: *Counted* Single P Ion Implants



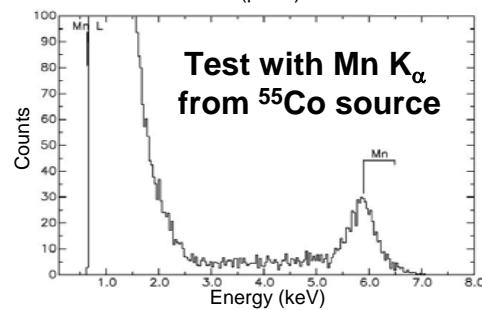
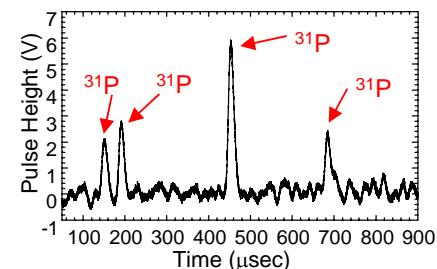
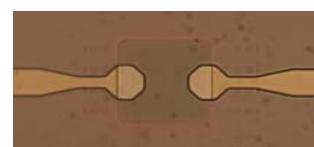
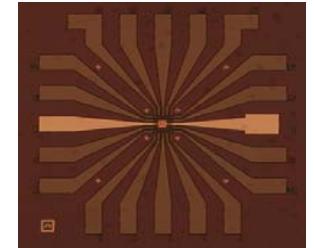
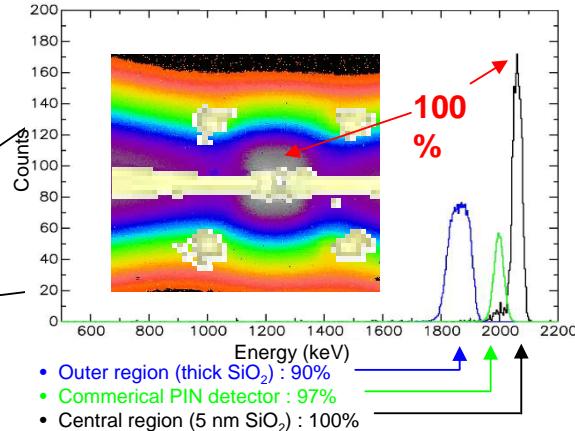
Vertical bias

Nuclear microprobe

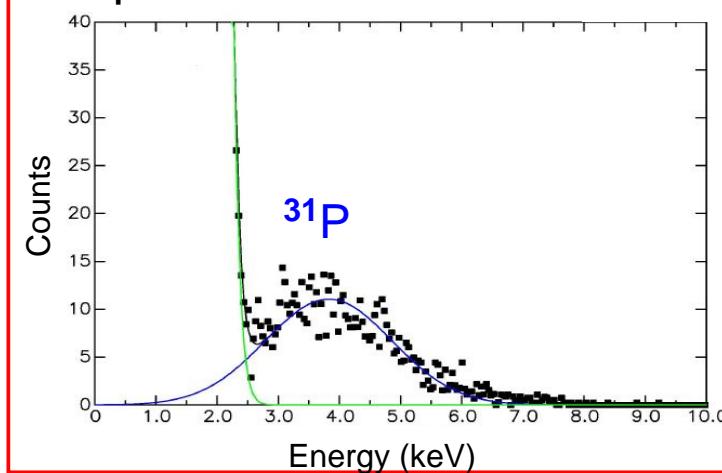


Measure CCE 2 MeV He

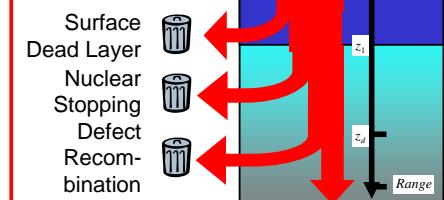
High efficiency and resolution



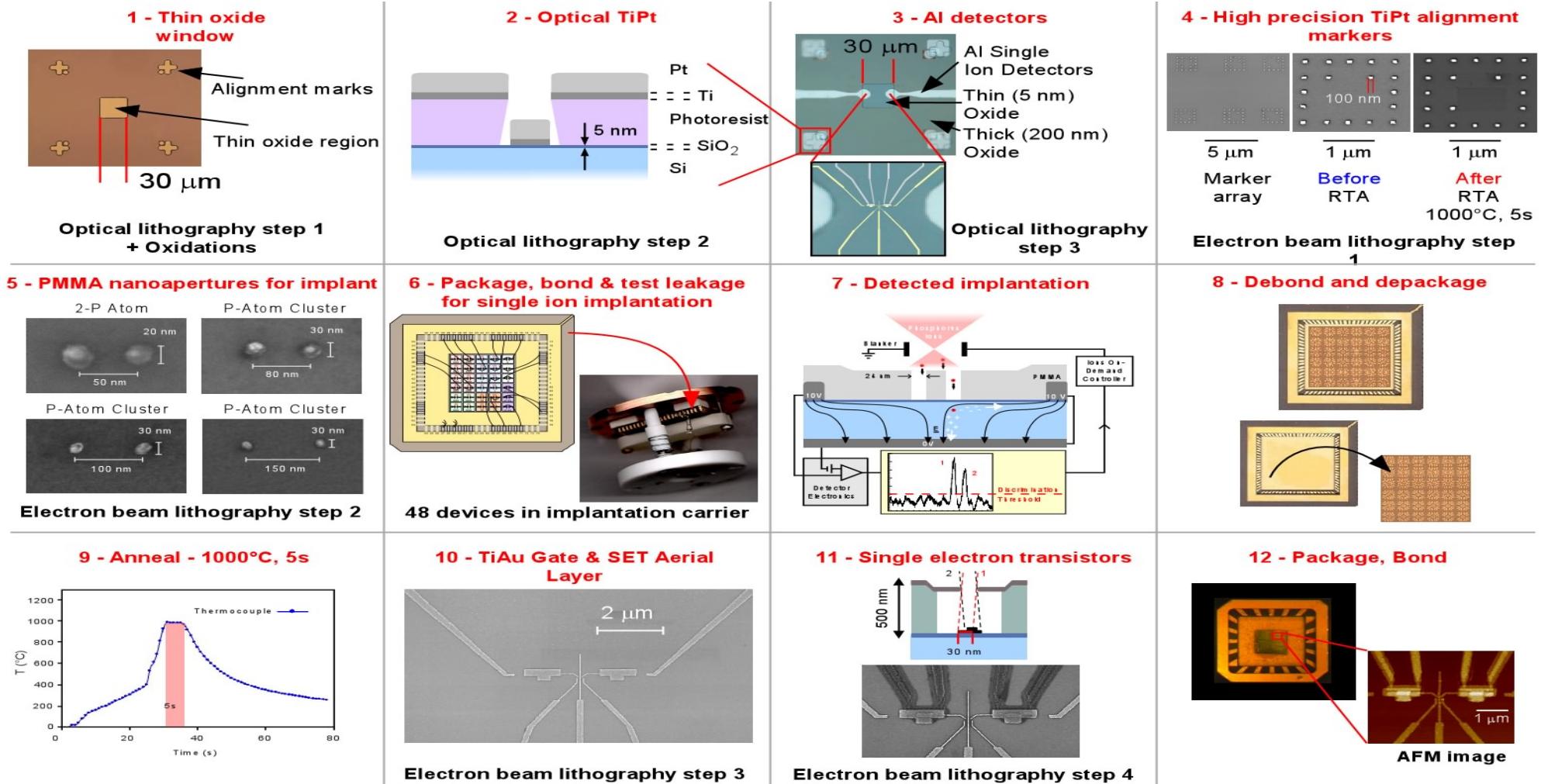
31P implants



Ionization energy

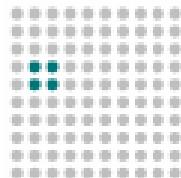


Top-Down Fabrication Process Flow



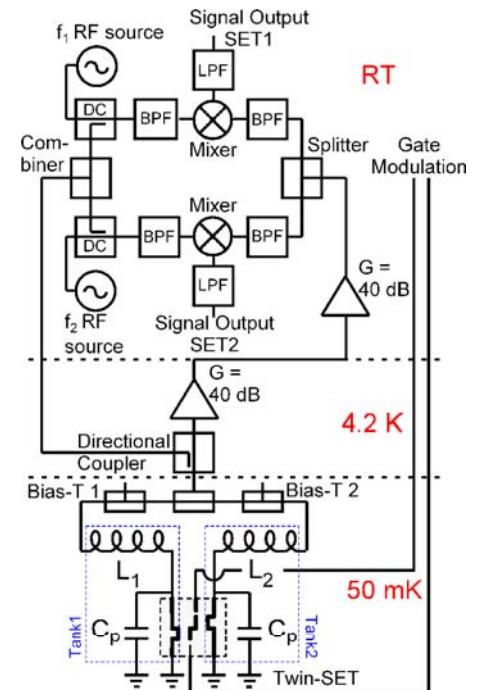
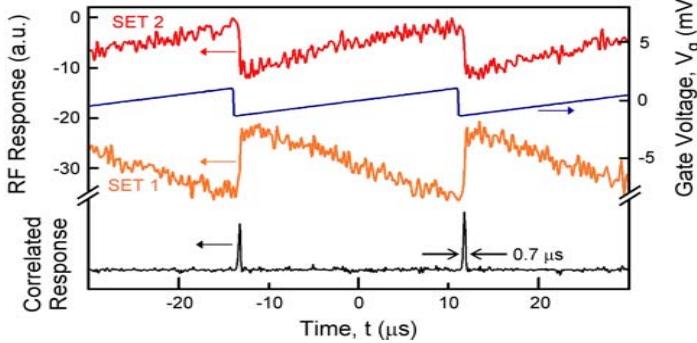
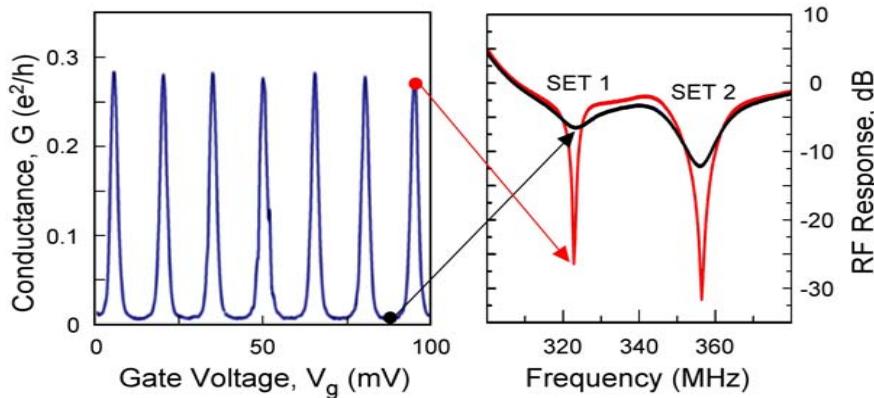
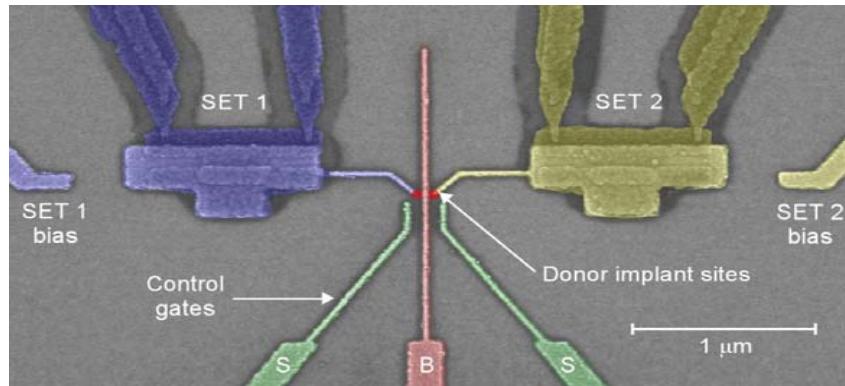
Quantum Measurement

- Twin rf-SETs for correlated single charge motion detection
- Periodic charge transfer between buried P atoms in Si



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Twin Radio-Frequency SETs for Fast Readout

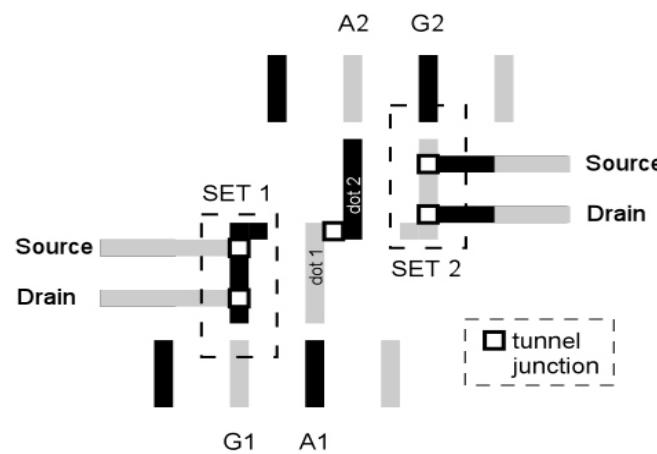
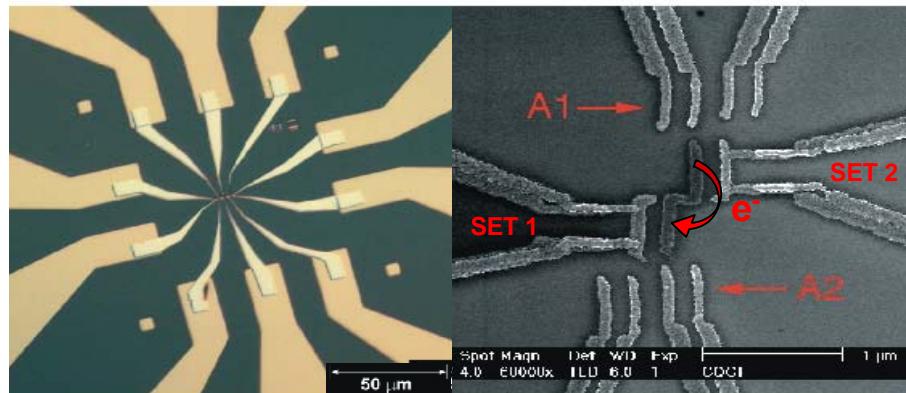


R.J. Schoelkopf et al, Science (1998)

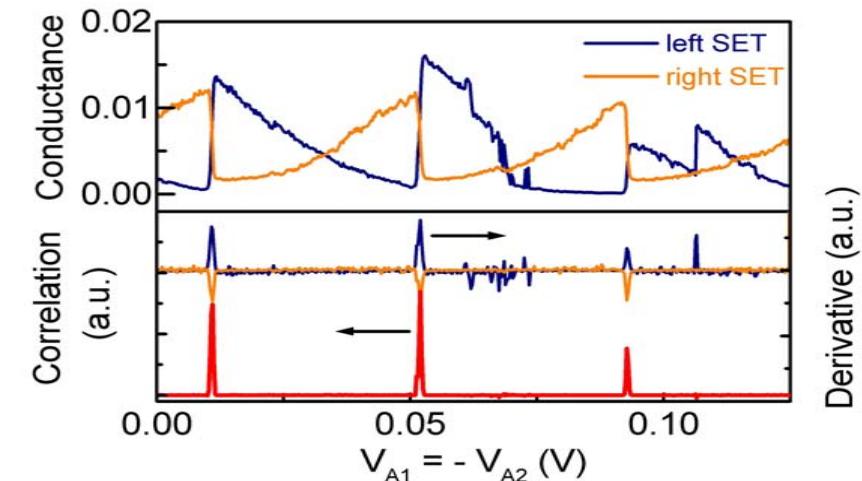
T. M. Buehler et al, cond-mat (2003)

Aluminium Double-Dot Simulation Device

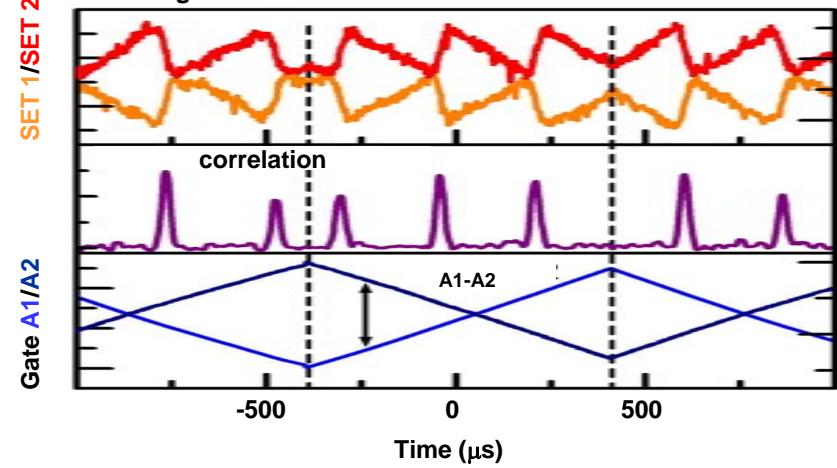
Double Quantum Dot (Metal Islands)



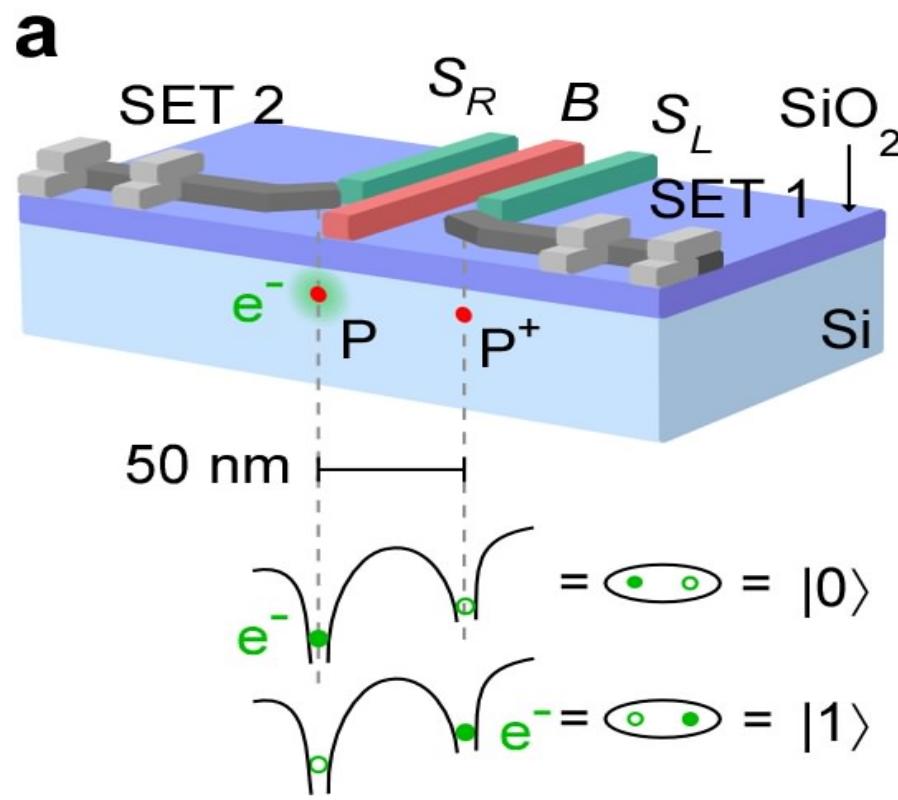
DC Measurement: Buehler et al, APL (2003)



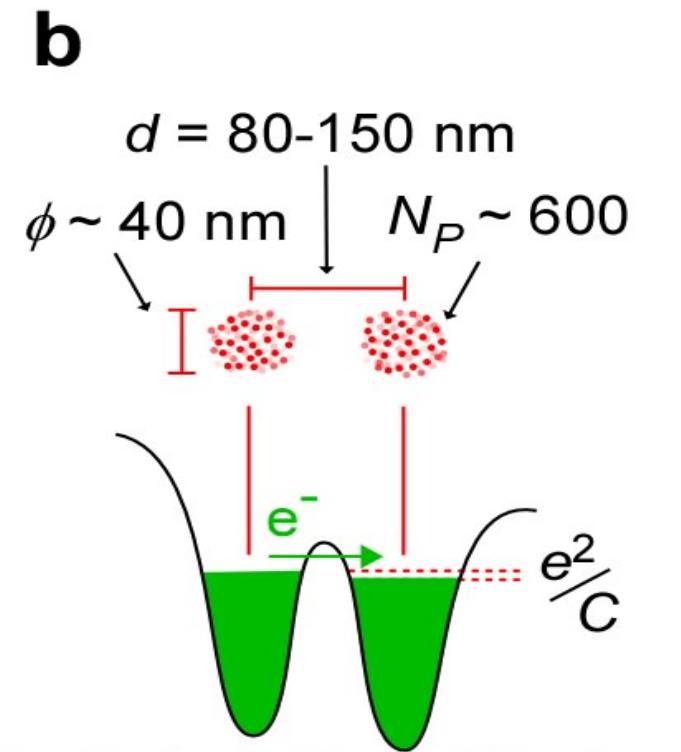
RF Measurement: Buehler et al, cond-mat (2003)
4 average



Buried Atom Si : P Devices



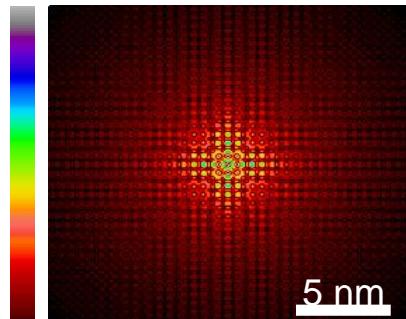
Two-P-Atom Charge Qubit



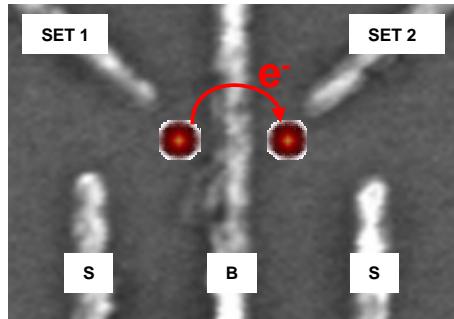
Buried P-Atom Cluster
Double Quantum Dot

Two P-Atom and P-Cluster Devices

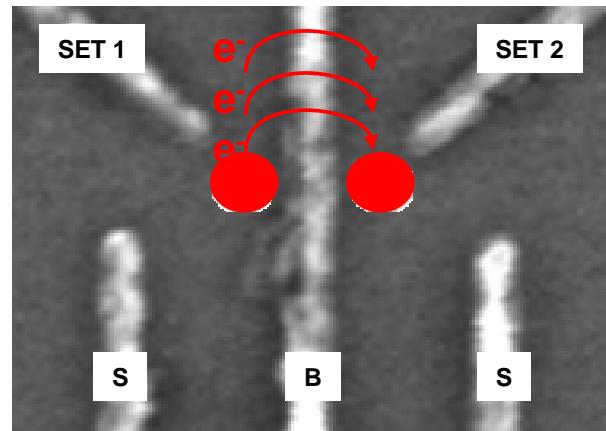
Wavefunction



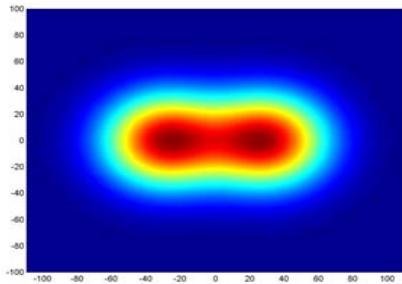
2-atom device



Cluster device

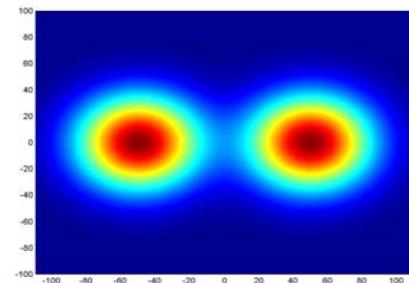


Electron density vs. spacing

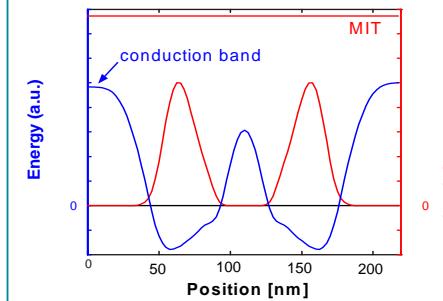


$d = 60 \text{ nm}$

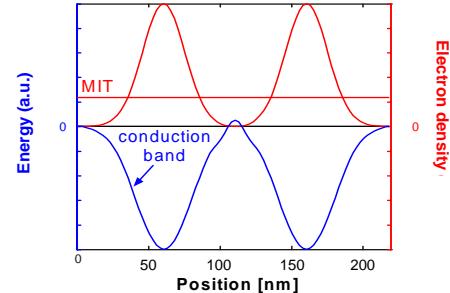
$d = 100 \text{ nm}$



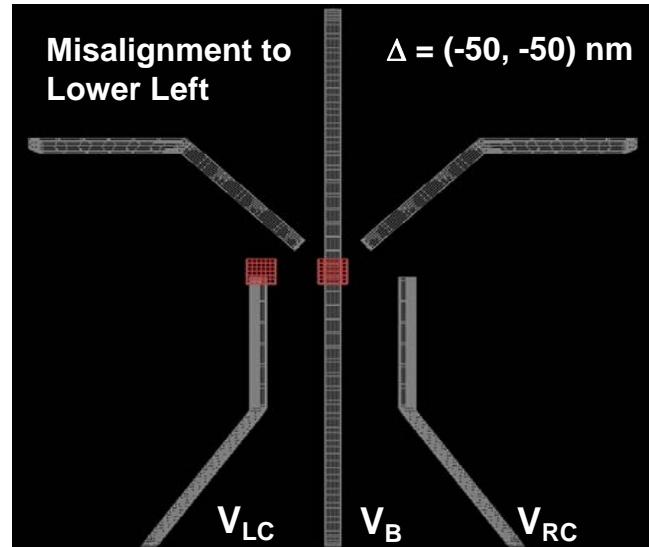
100 ions per cluster



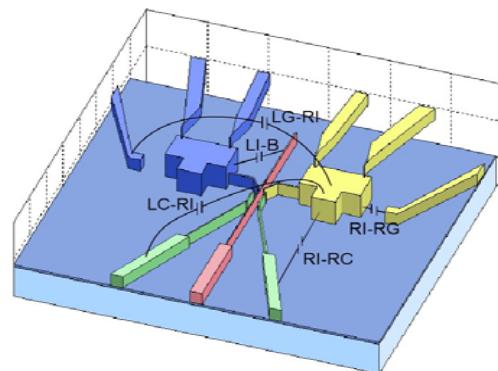
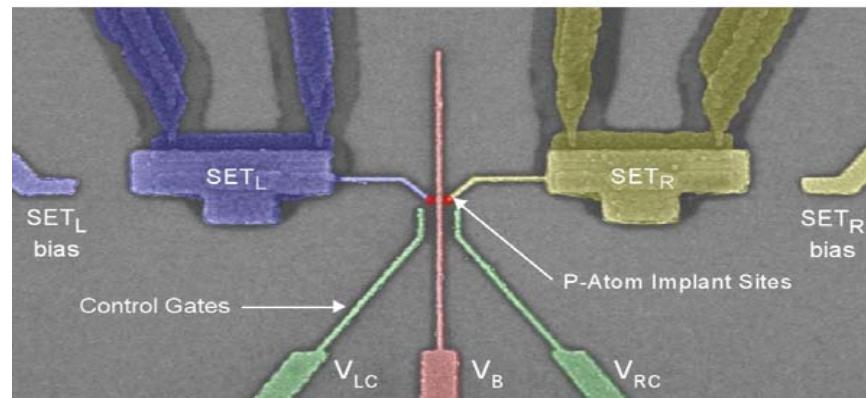
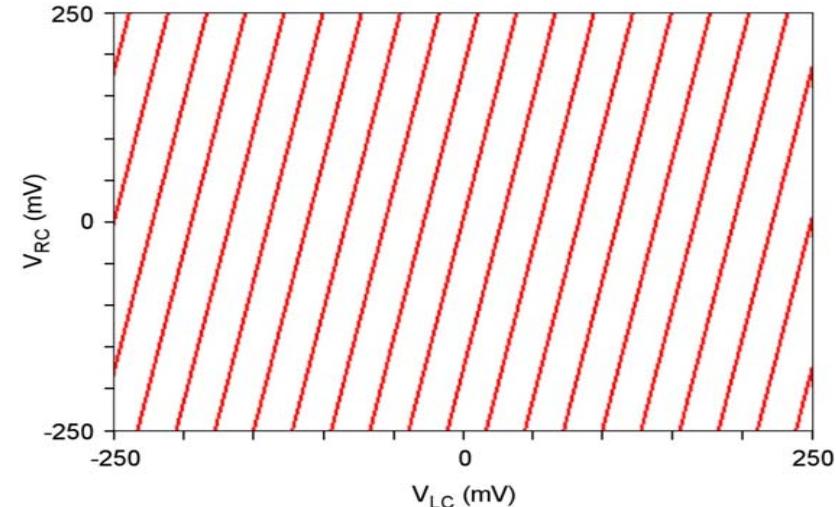
600 ions per cluster



Modelling Effect of Cluster Misalignment



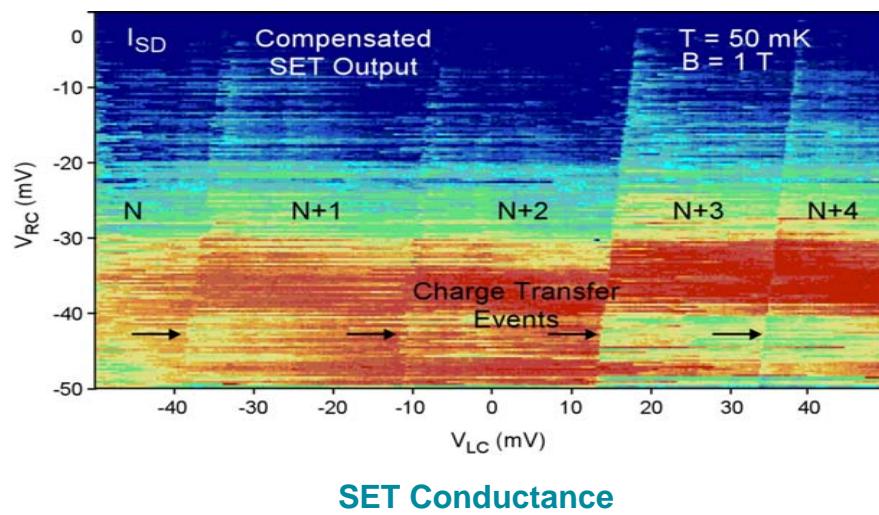
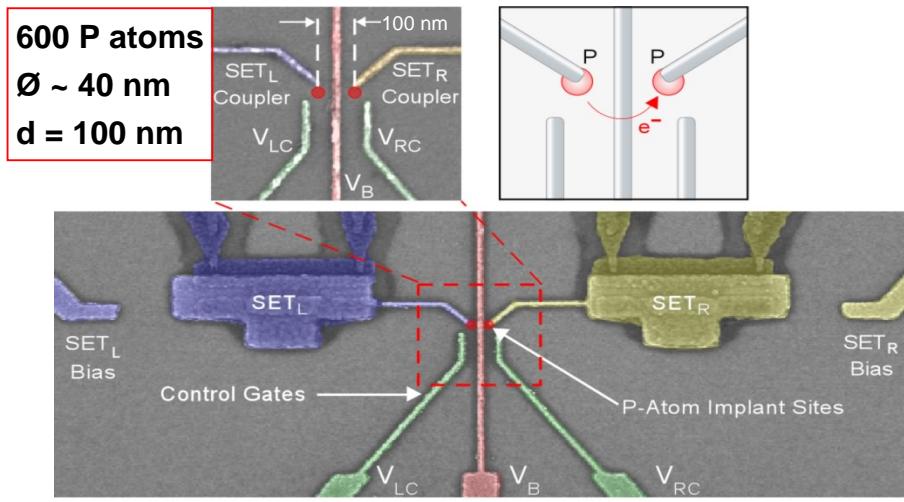
Transfer Events: Function of Left & Right Gate Voltages



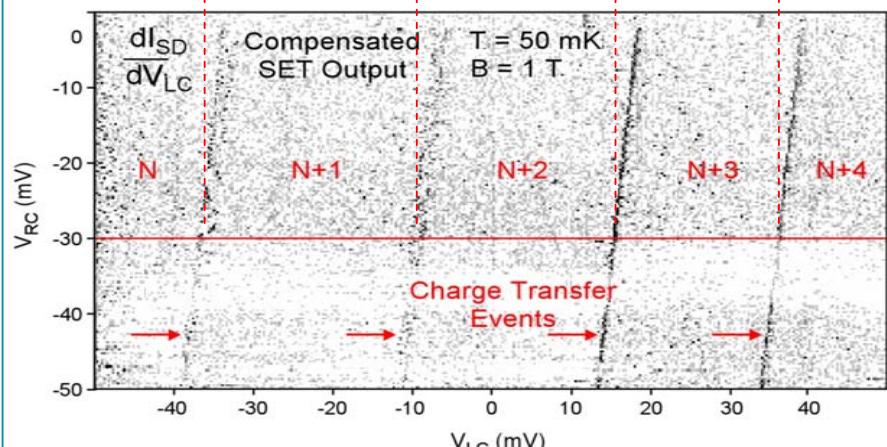
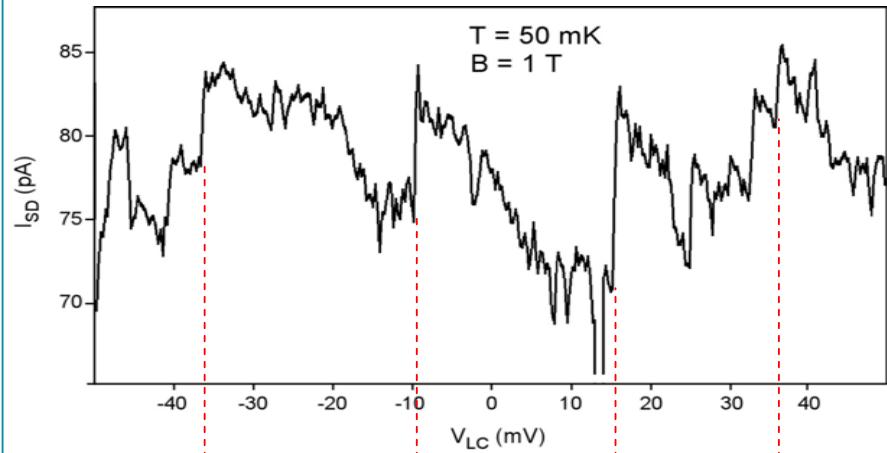
	Calc. (aF)	Meas. (aF)
LC-RI	10.3	13.1
LG-RI	3.65	6.30
RI-RG	23.4	25.6
RI-RC	24.3	22.7
LI-B	24.0	25.0

Fastcap Modelling

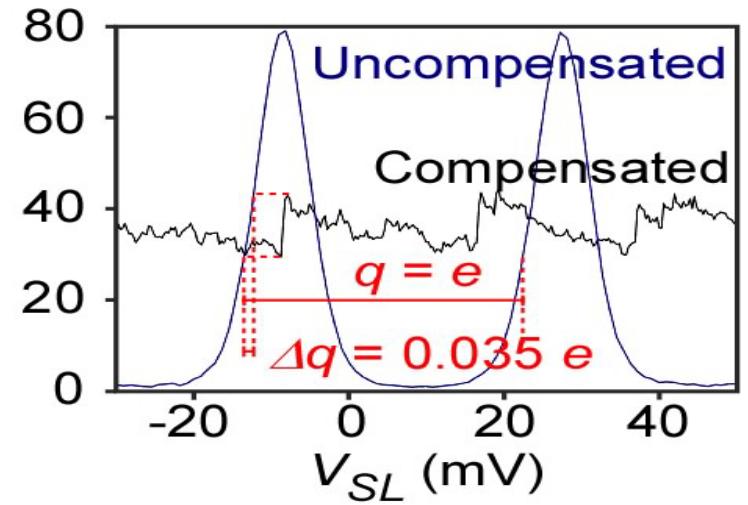
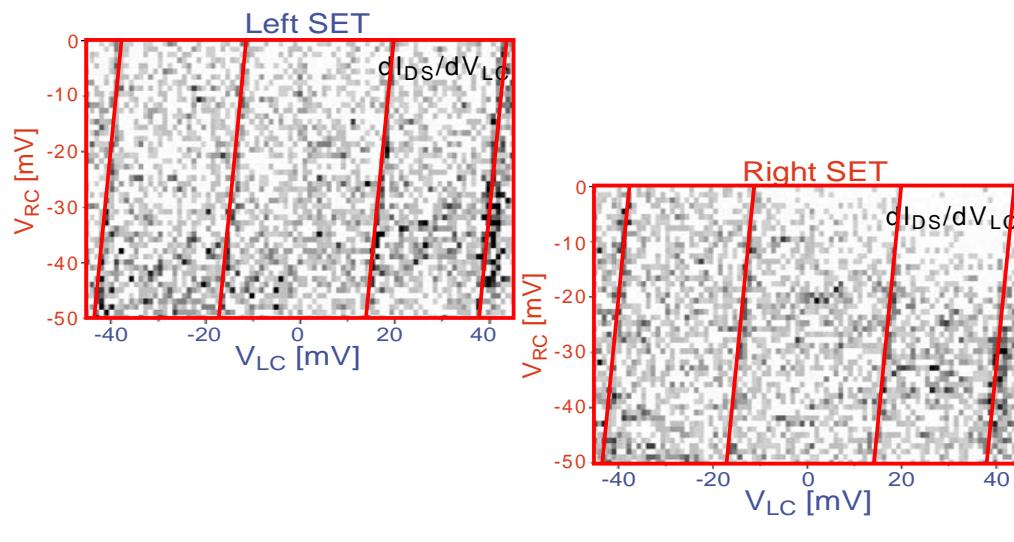
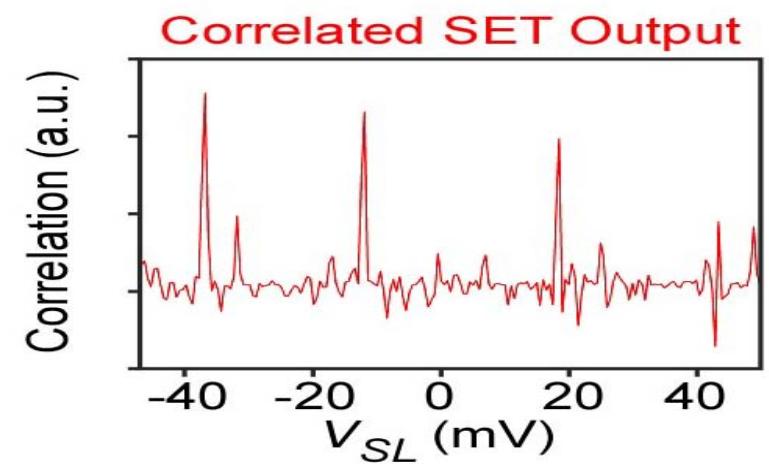
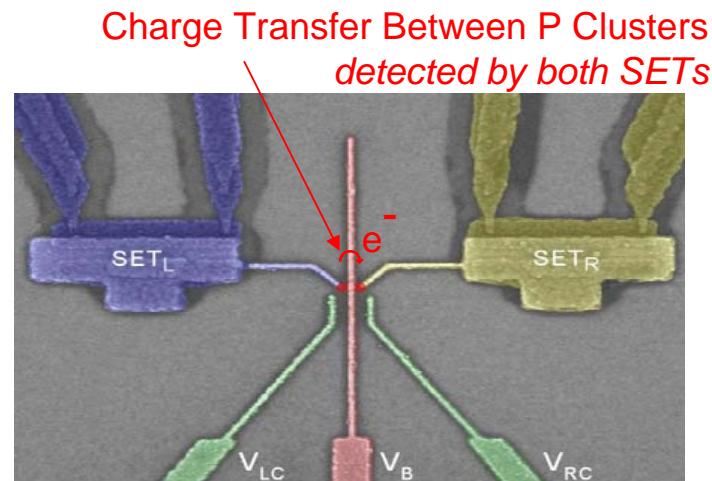
Si:P Clusters: Controlled Electron Transfer Observed



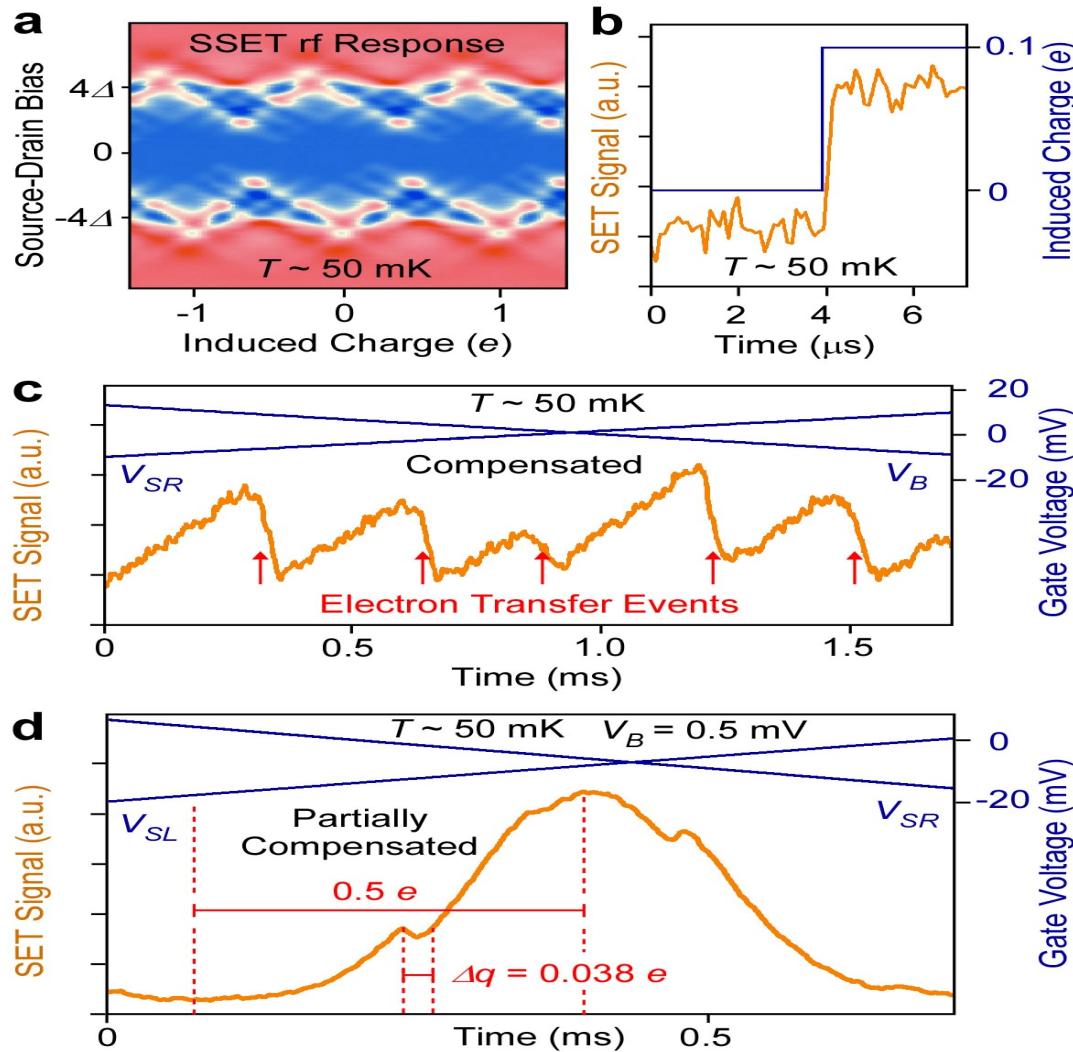
SET Source-Drain Current vs. Left Control Gate Voltage



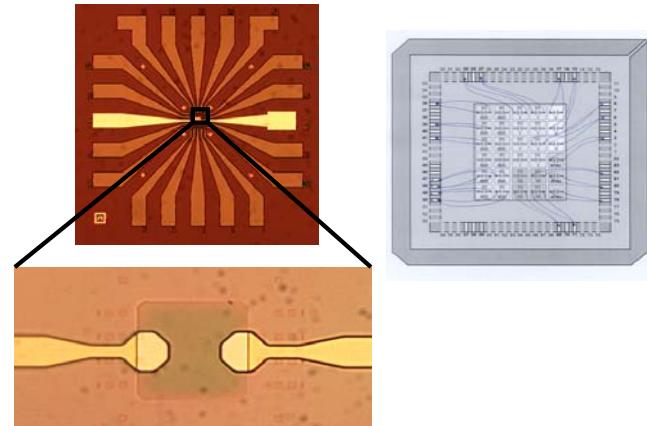
Correlated Detection of Single-Electron Transfer



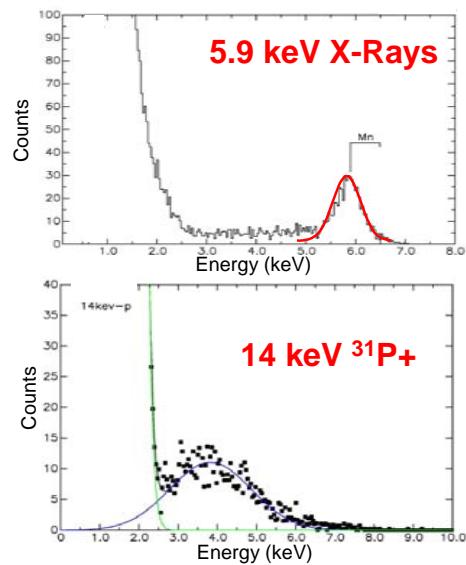
High Speed Detection of Single Electron Transfer



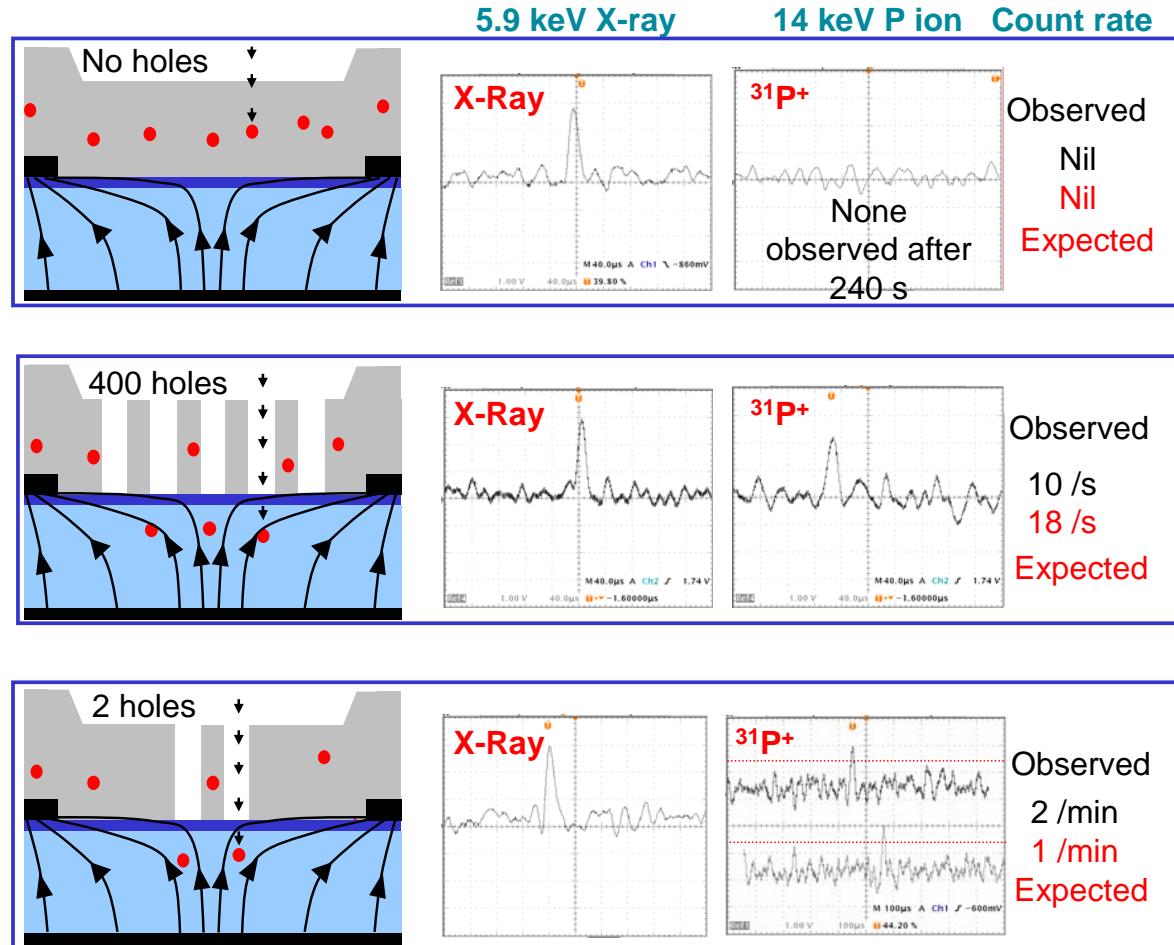
The Next Steps: 2-Atom P-P⁺ Devices



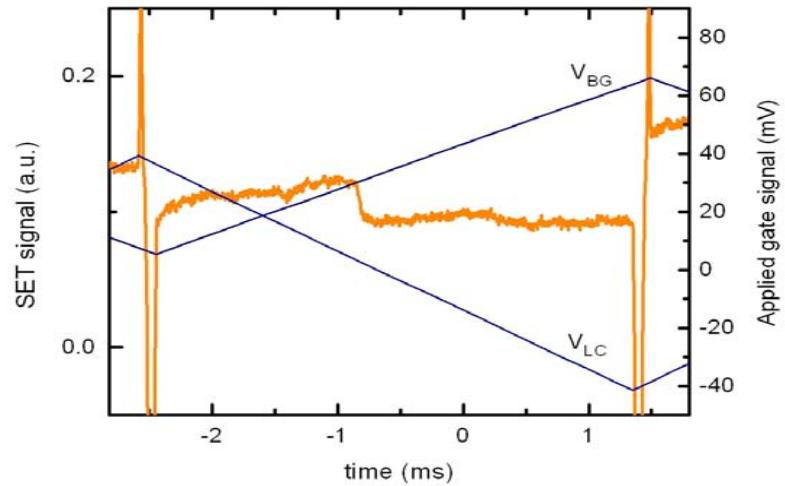
Pulse Height Spectra



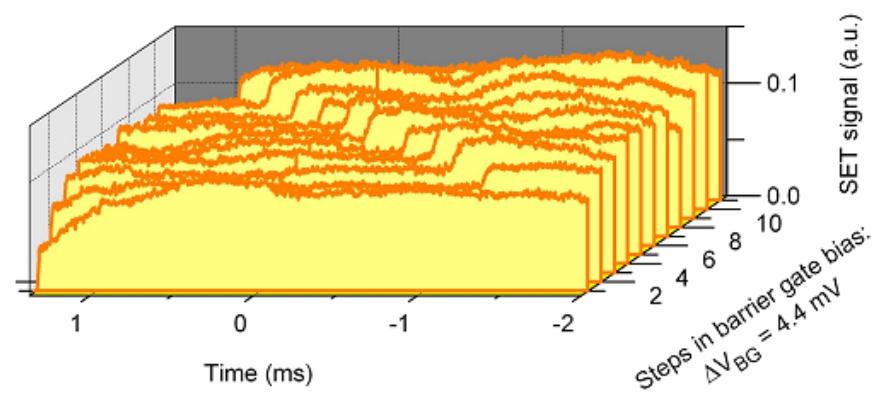
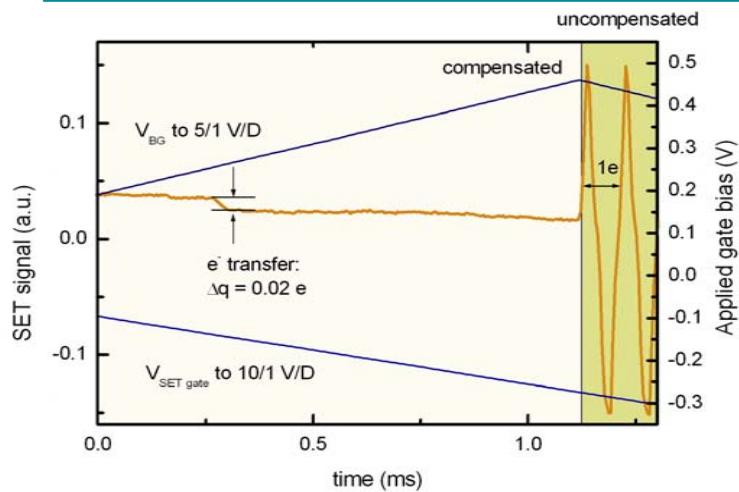
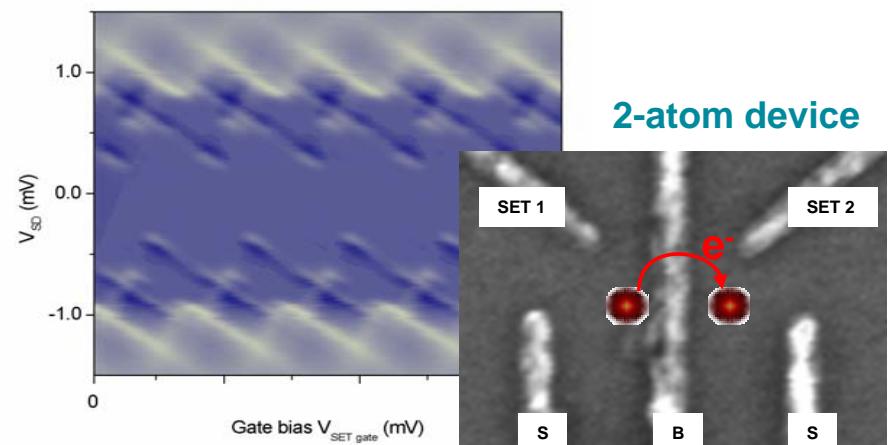
Single Ion Counting



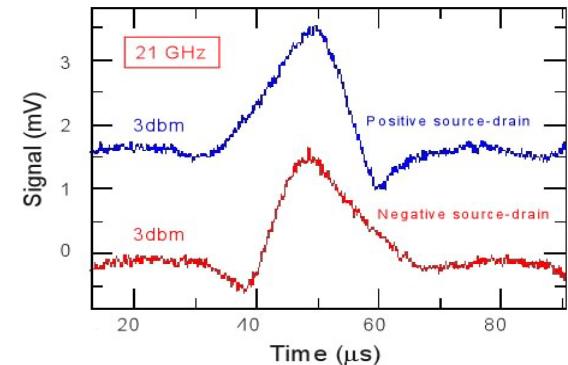
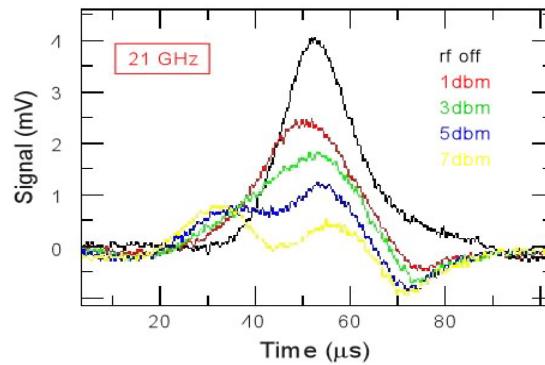
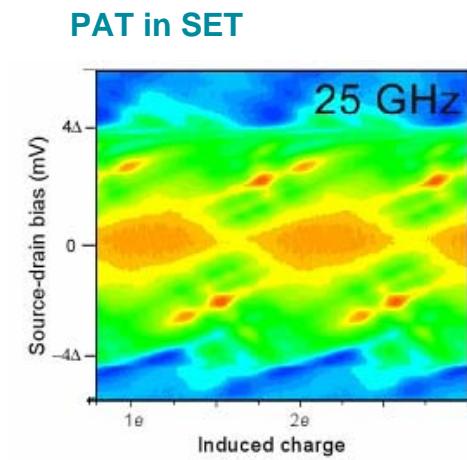
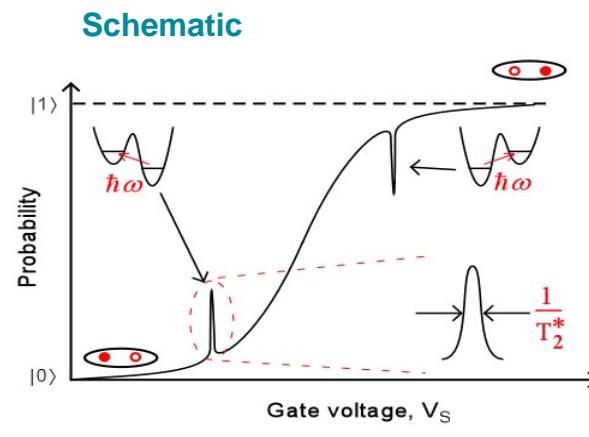
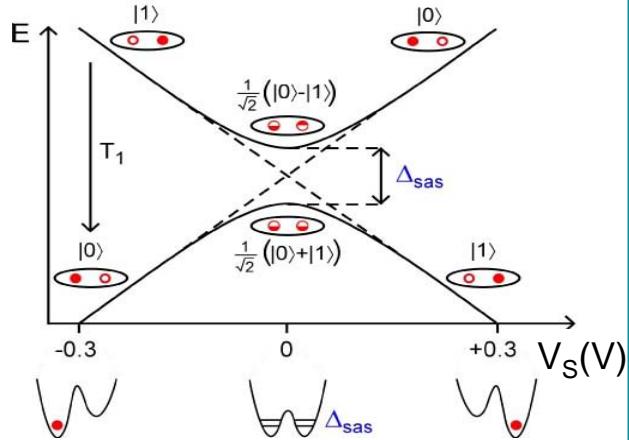
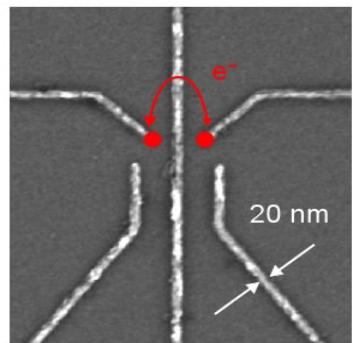
RF-SET Measurements of 2 Donor Device



SET Characterisation

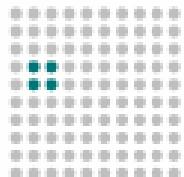


Future: Coherent Manipulation of Si:P Charge Qubits



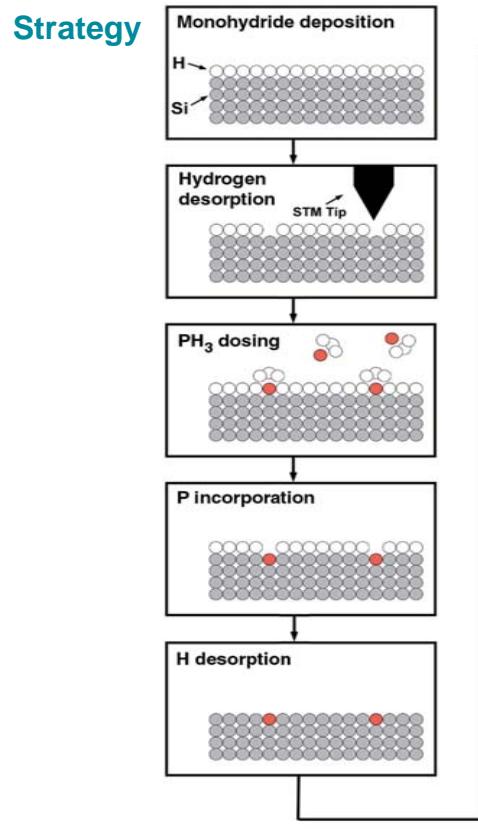
Bottom-up STM/MBE Fabrication

- Doping of Si with sub-nanometer precision
- Measurements of buried STM-defined Si:P devices

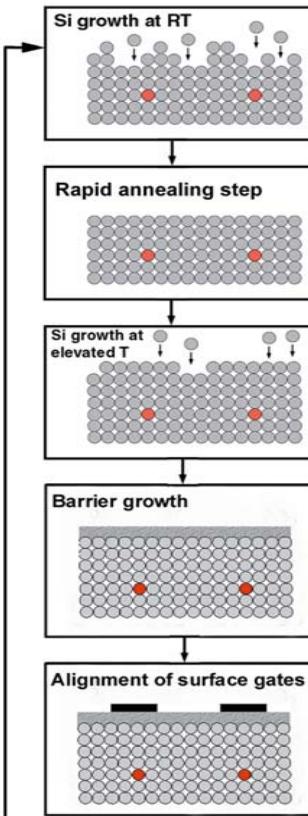
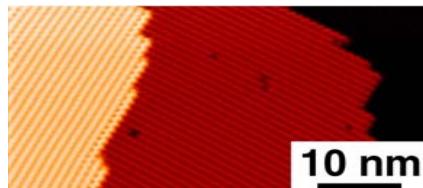


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Construction of Si:P Single Atom Qubits: Bottom-Up

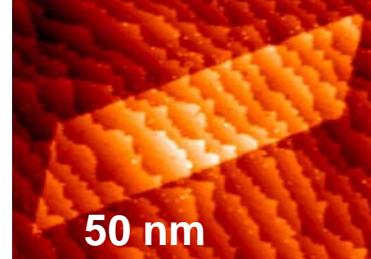


Si(001) 2×1



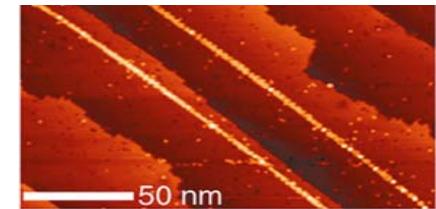
1. Controlled Si:H STM Lithography

Coarse



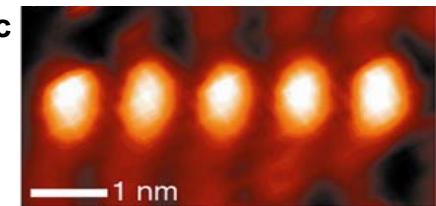
50 nm

Fine



50 nm

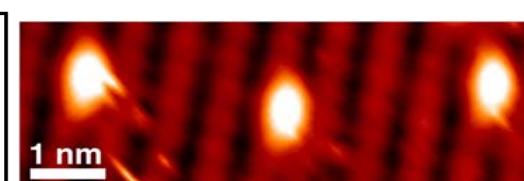
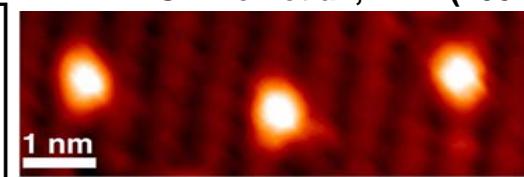
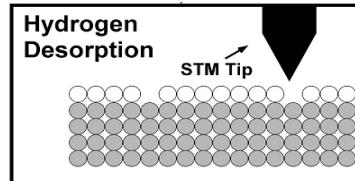
Atomic



1 nm

2. Controlled PH₃ Dosing

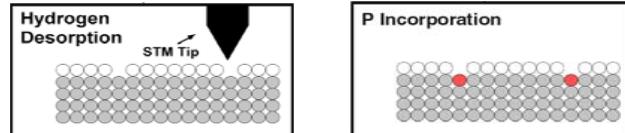
O'Brien et al., PRB (2001)



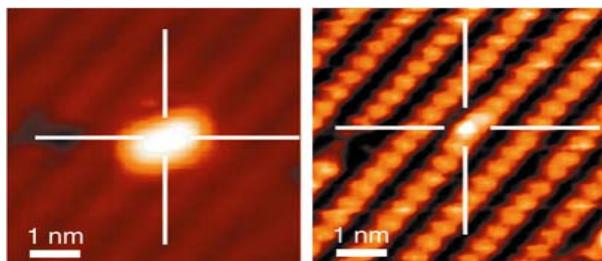
See also: J.R. Tucker and T-C. Shen, Solid State Electronics (1998)

Construction of Si:P Single Atom Qubits: Bottom-Up

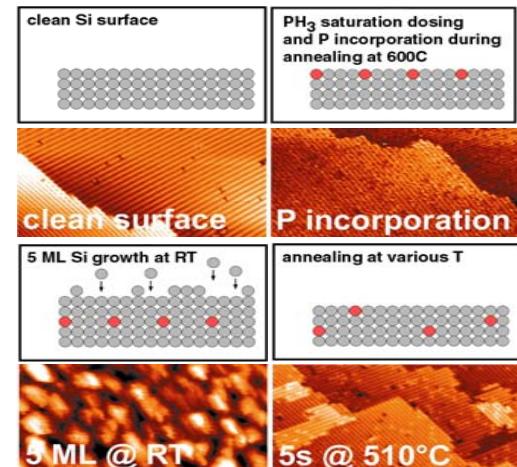
3. P Incorporation – Atomic Precision



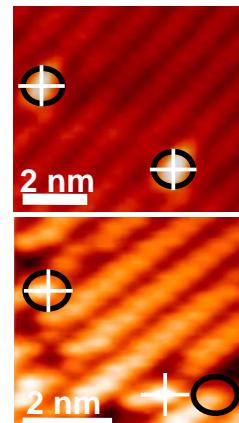
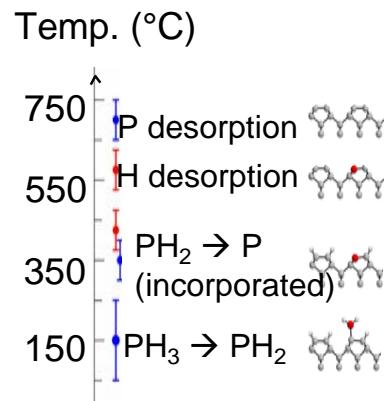
Schofield et al., PRL (2003)



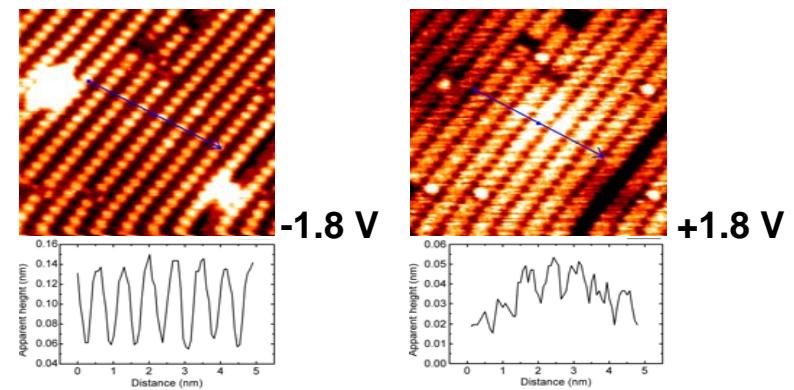
5. Si Growth at RT



4. H Desorption

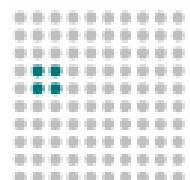


6. Optimising STM biasing conditions to image buried P dopant atoms



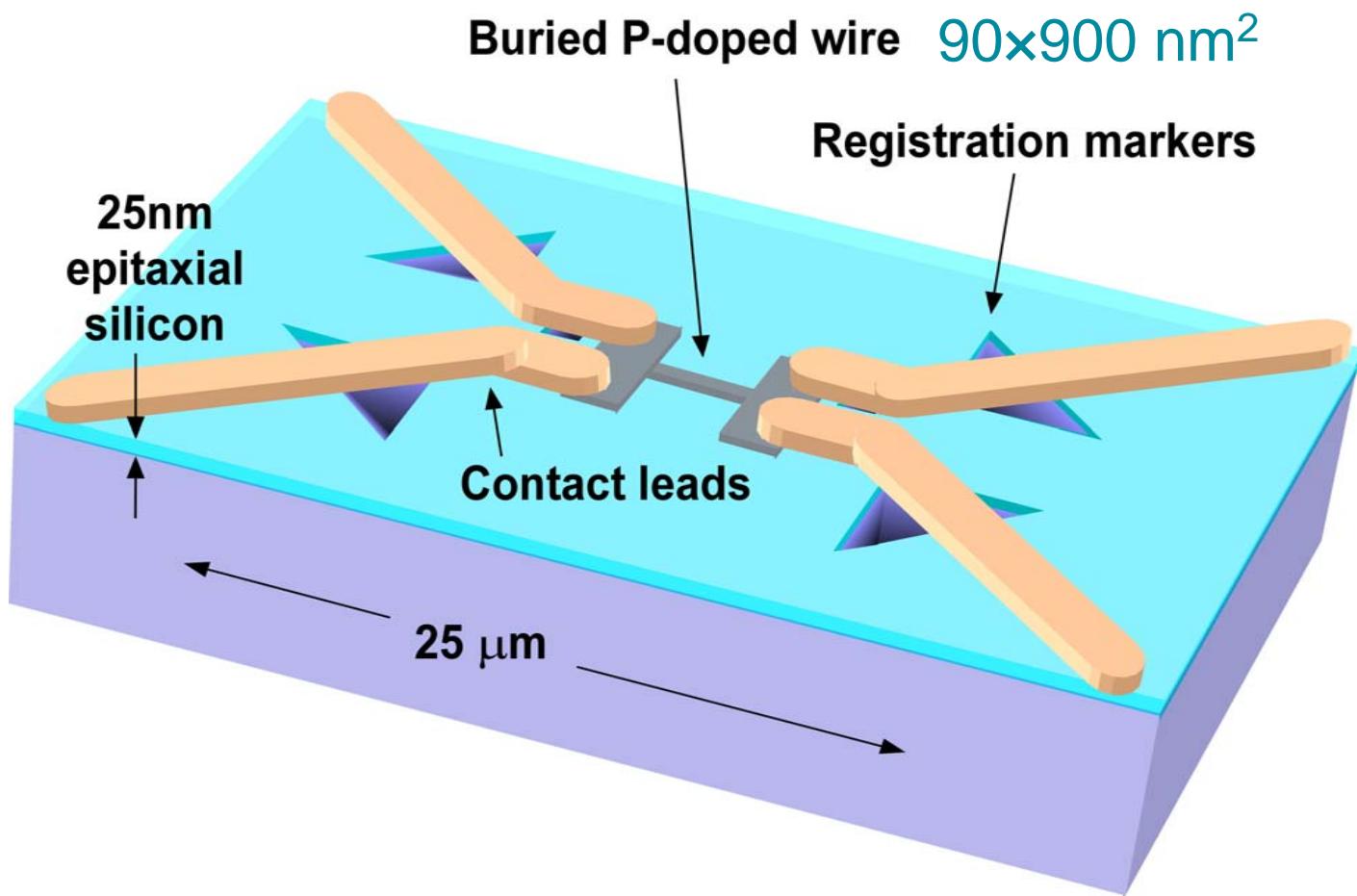
Buried Nanoscale Devices in Silicon

- Fundamental science
- Hybrid QC architectures

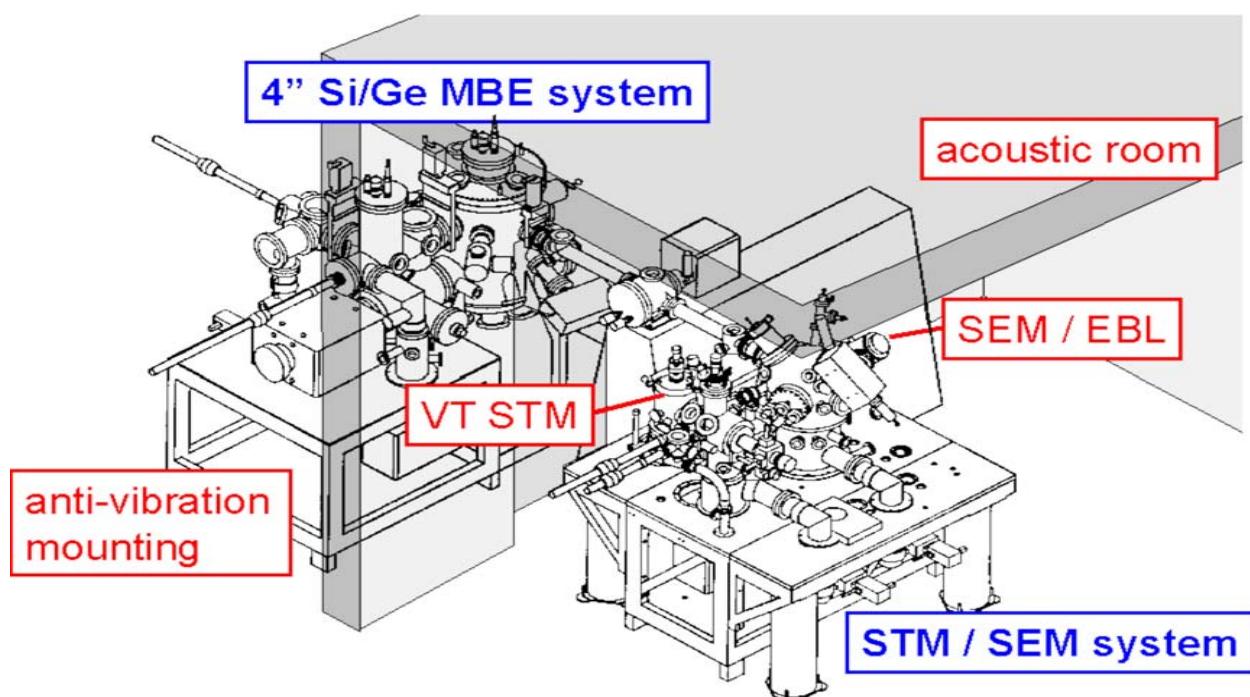


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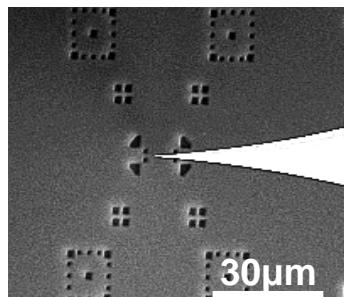
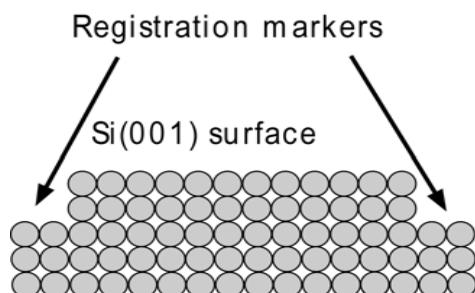
Device schematic



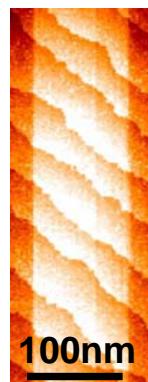
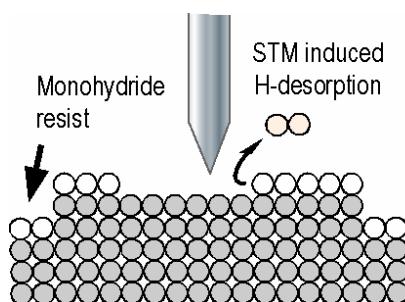
Custom-designed MBE - STM/SEM System



Fabrication scheme

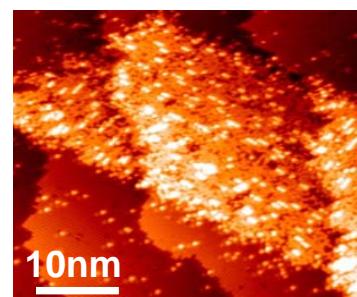
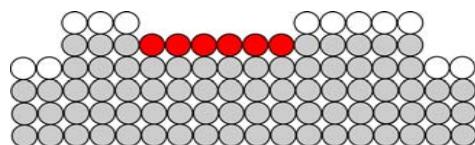


- Registration marker fabrication
- STM tip positioning using SEM



- STM-based desorption of hydrogen to pattern lithographic structures

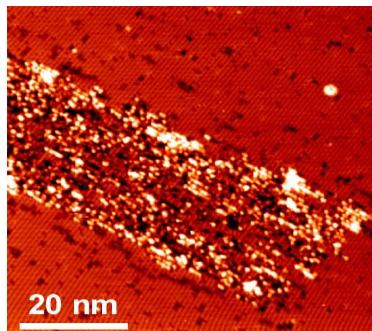
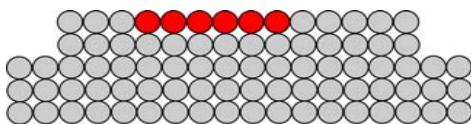
Rich literature: e.g.
J. R. Lyding et al., Appl. Phys. Lett. 64, 2010 (1994)
T-C Shen et al., Science 268, 1590 (1995)
B.S. Swartzentruber, JVST B 14, 1642 (1996)



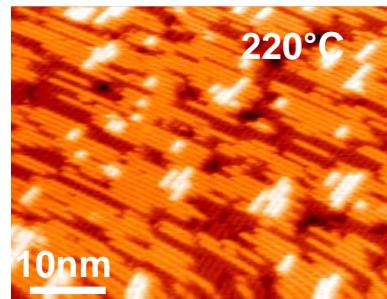
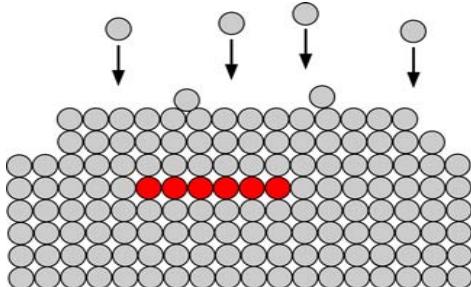
- Surface incorporation of P atoms from adsorbed PH₃ molecules while H-resist remains unchanged

S. R. Schofield et al.,
Phys. Rev. Lett. 91,
136104 (2003)

Fabrication scheme

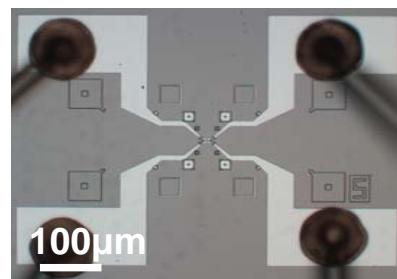
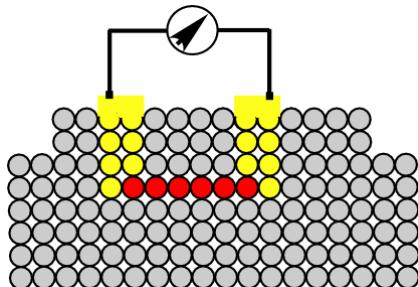


- Thermal hydrogen resist removal
- Dopant diffusion and defect generation minimised



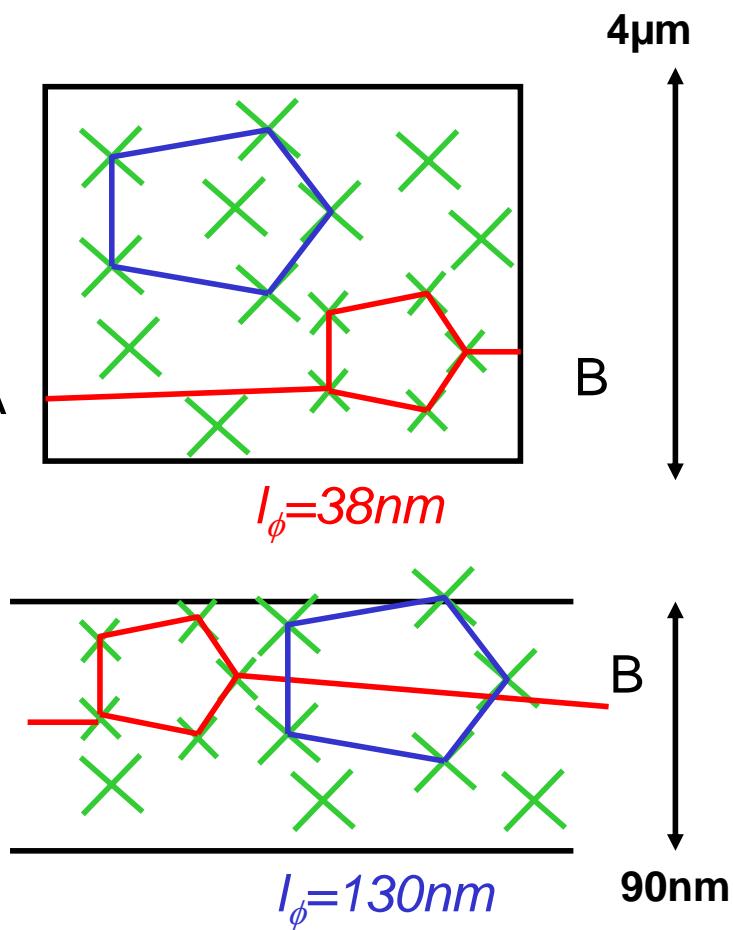
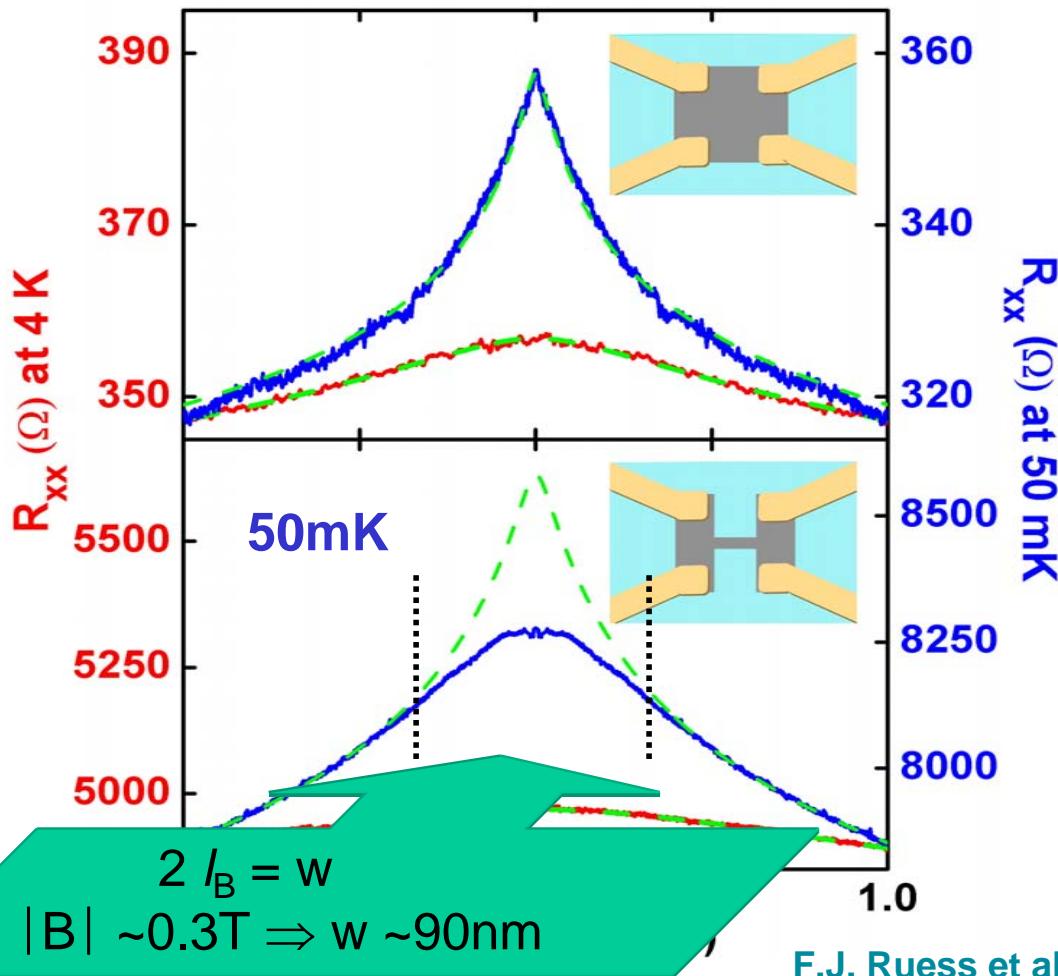
- Low temperature Si MBE growth
- Dopant diffusion and segregation minimised

T. -C. Shen et al., Appl. Phys. Lett. 80, 1580 (2002)
L. Oberbeck et al., Appl. Phys. Lett. 81, 3197 (2002)



- Surface Al contacts aligned to markers defined by optical lithography

Comparison: $4 \times 4 \mu\text{m}^2$ 2D patch and $90 \times 900 \text{ nm}^2$ wire

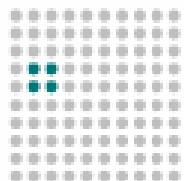


F.J. Ruess et al, submitted for publication (2004)

See also: J.R. Tucker and T-C. Shen, DARPA QUIST Workshop Proceedings (2003): STM-patterned Aharonov-Bohm Ring

Future Work

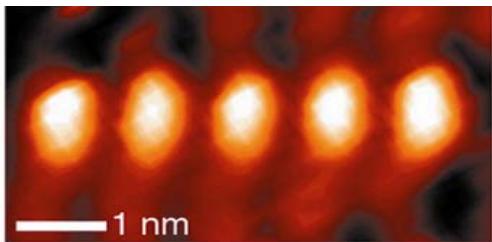
- Hybrid top-down/bottom up devices
- New single spin readout techniques



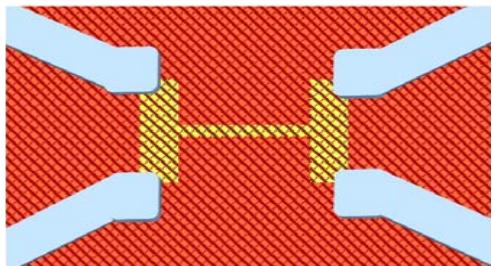
CENTRE FOR
QUANTUM COMPUTER
TECHNOLOGY
AUSTRALIAN RESEARCH COUNCIL CENTRE OF EXCELLENCE

Deep Buried Devices: Hybrid Bottom-Up / Top-Down

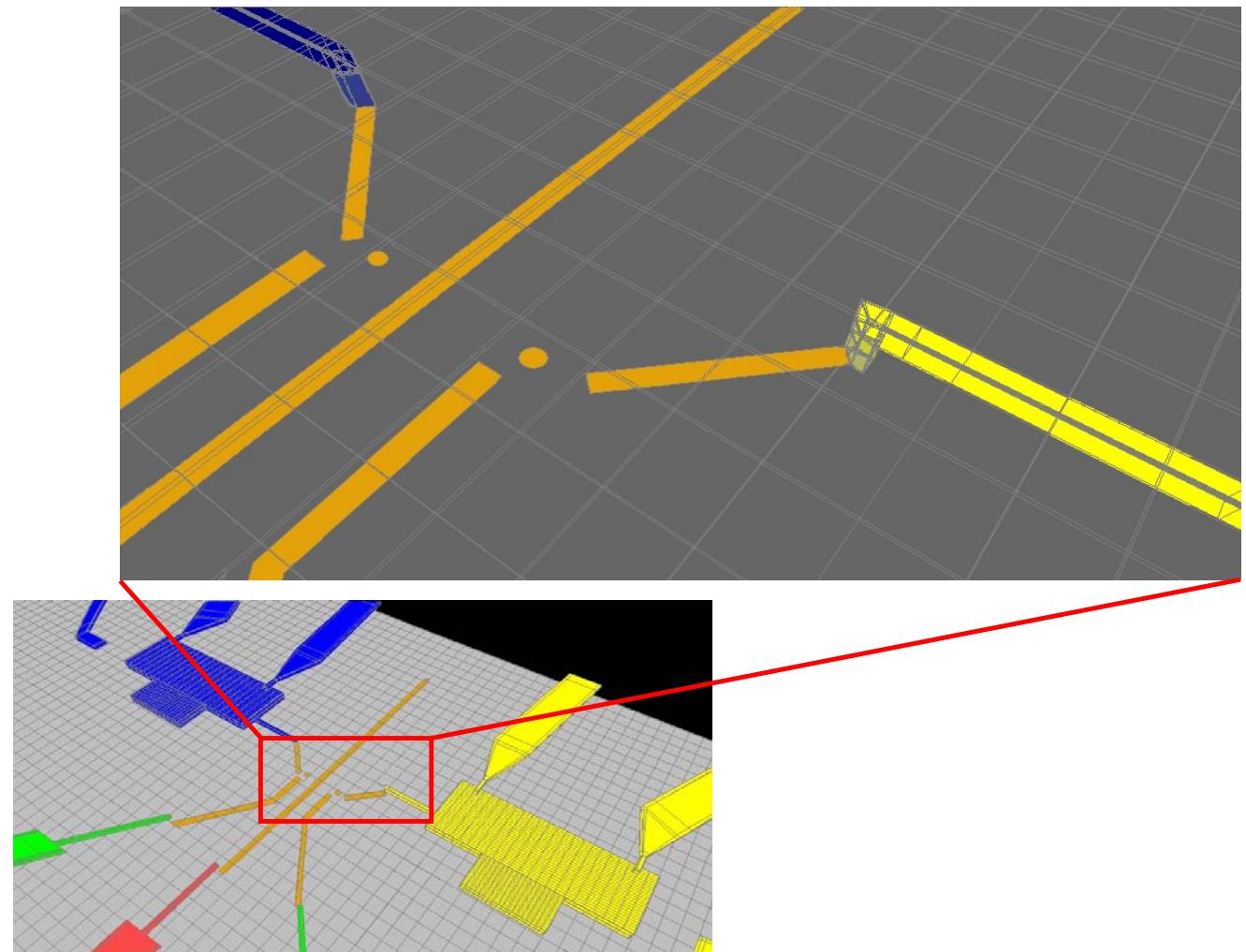
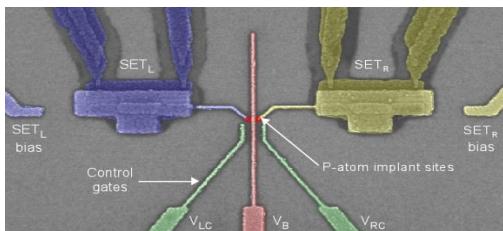
Single-atom lithography



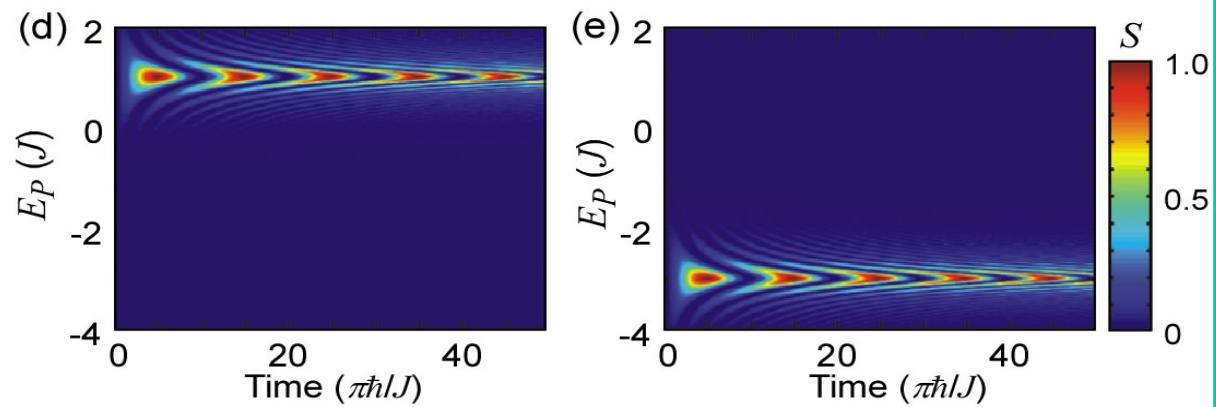
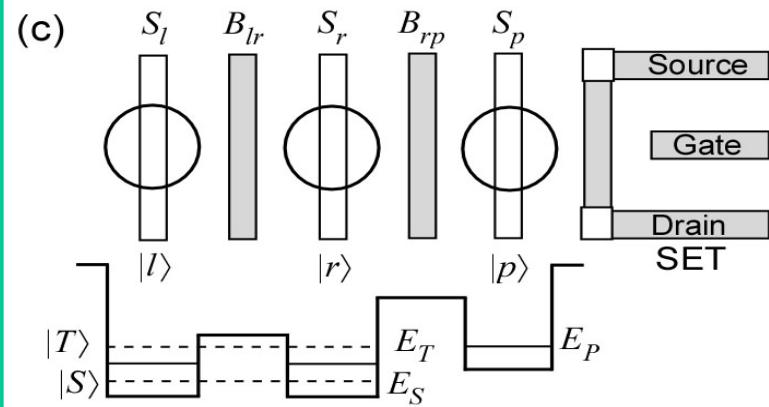
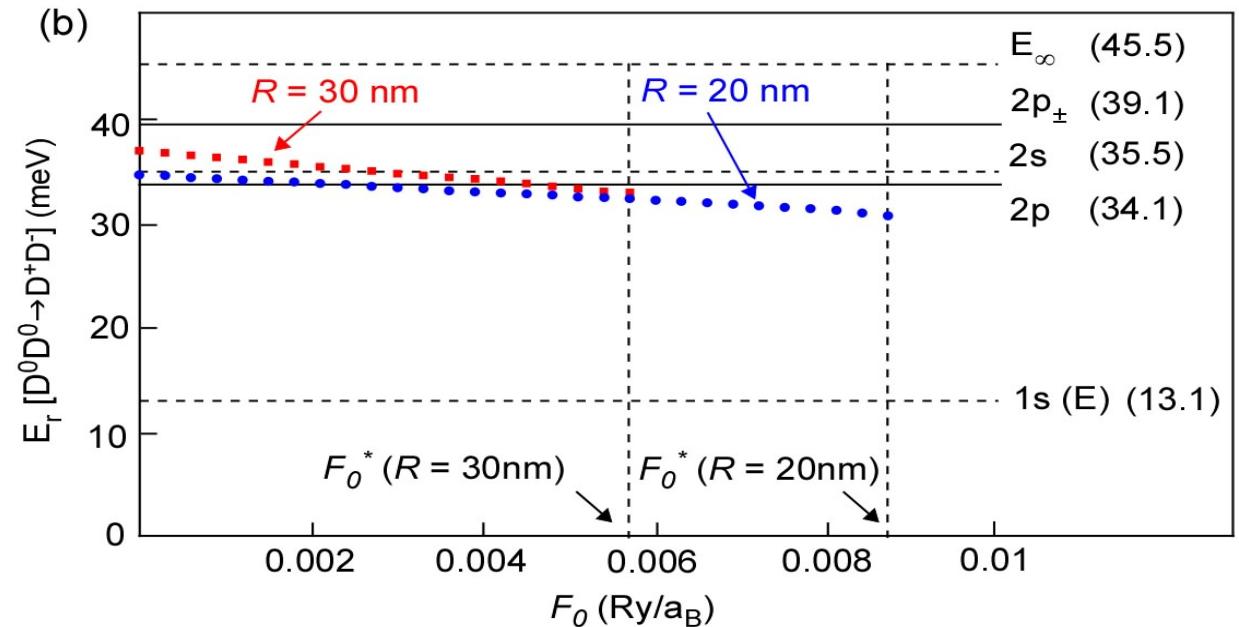
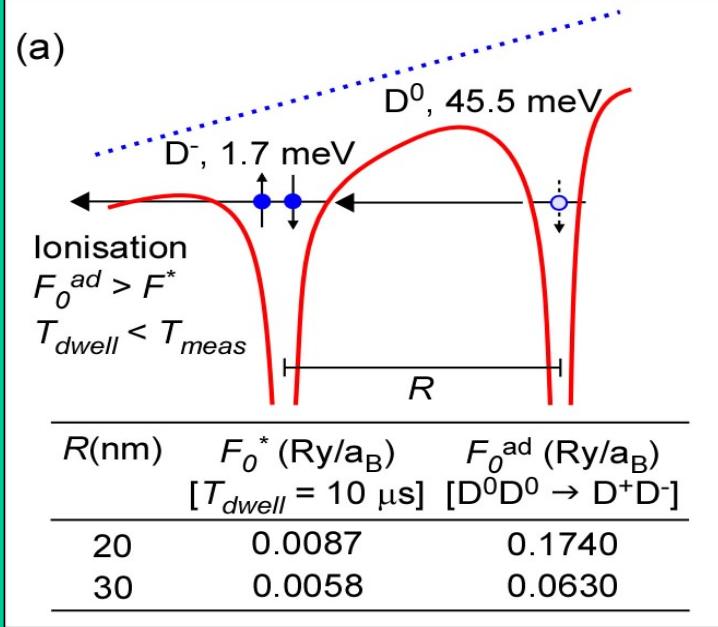
Atomic precision buried wires



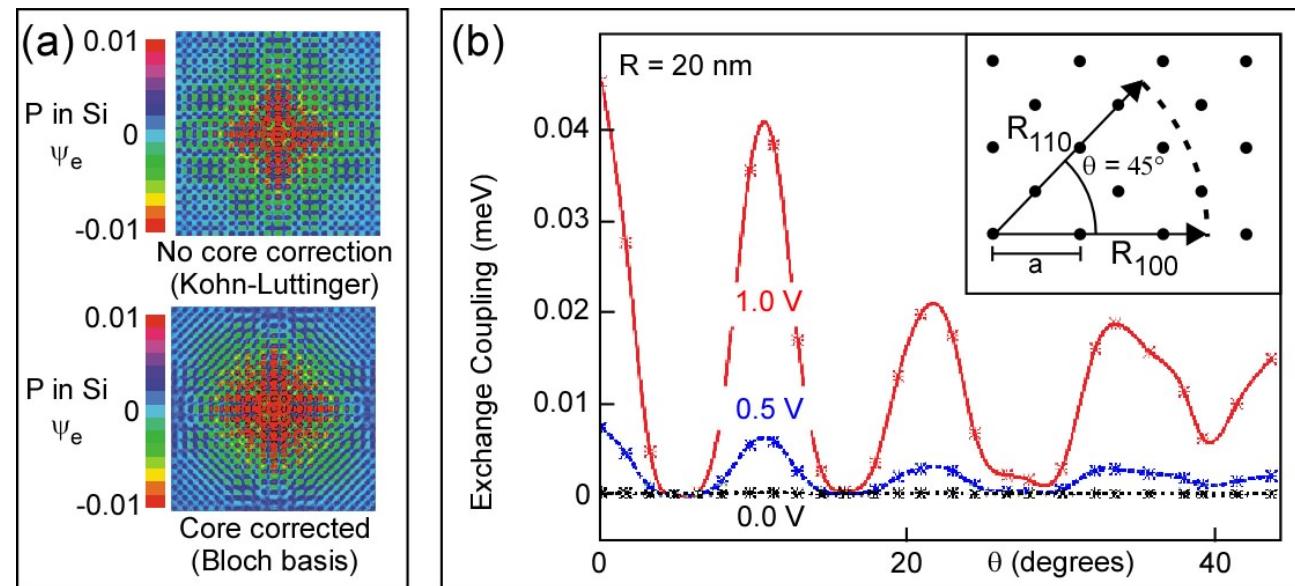
Top-down surface connections



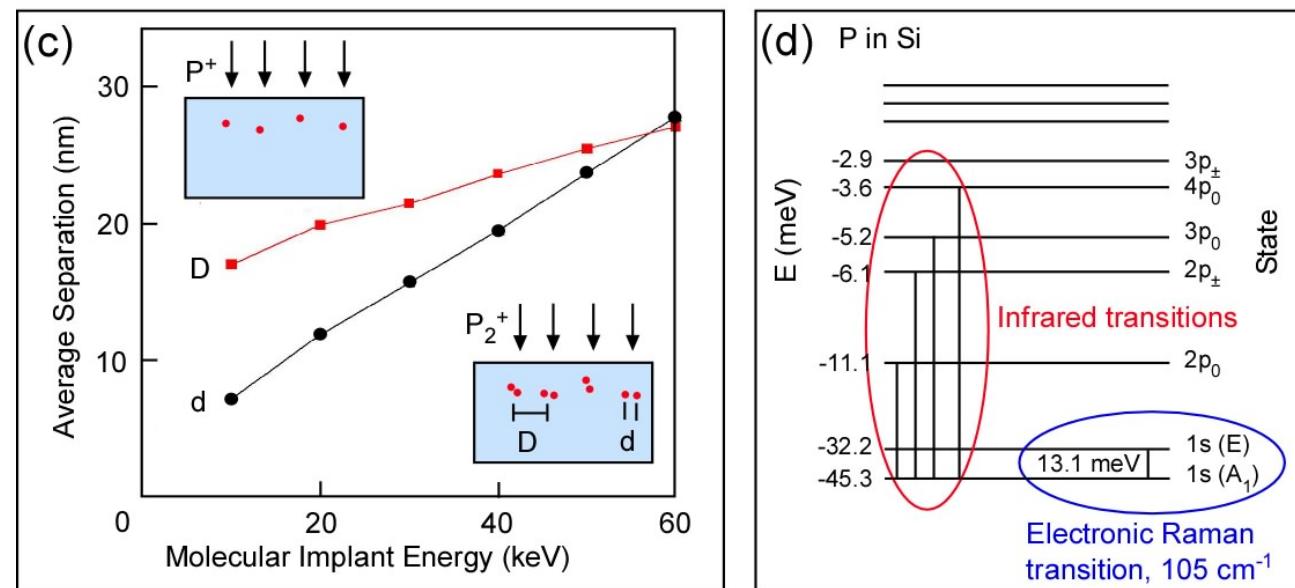
Single Spin Readout: Bias Spectroscopy & Charge Shelving



Exchange Coupling

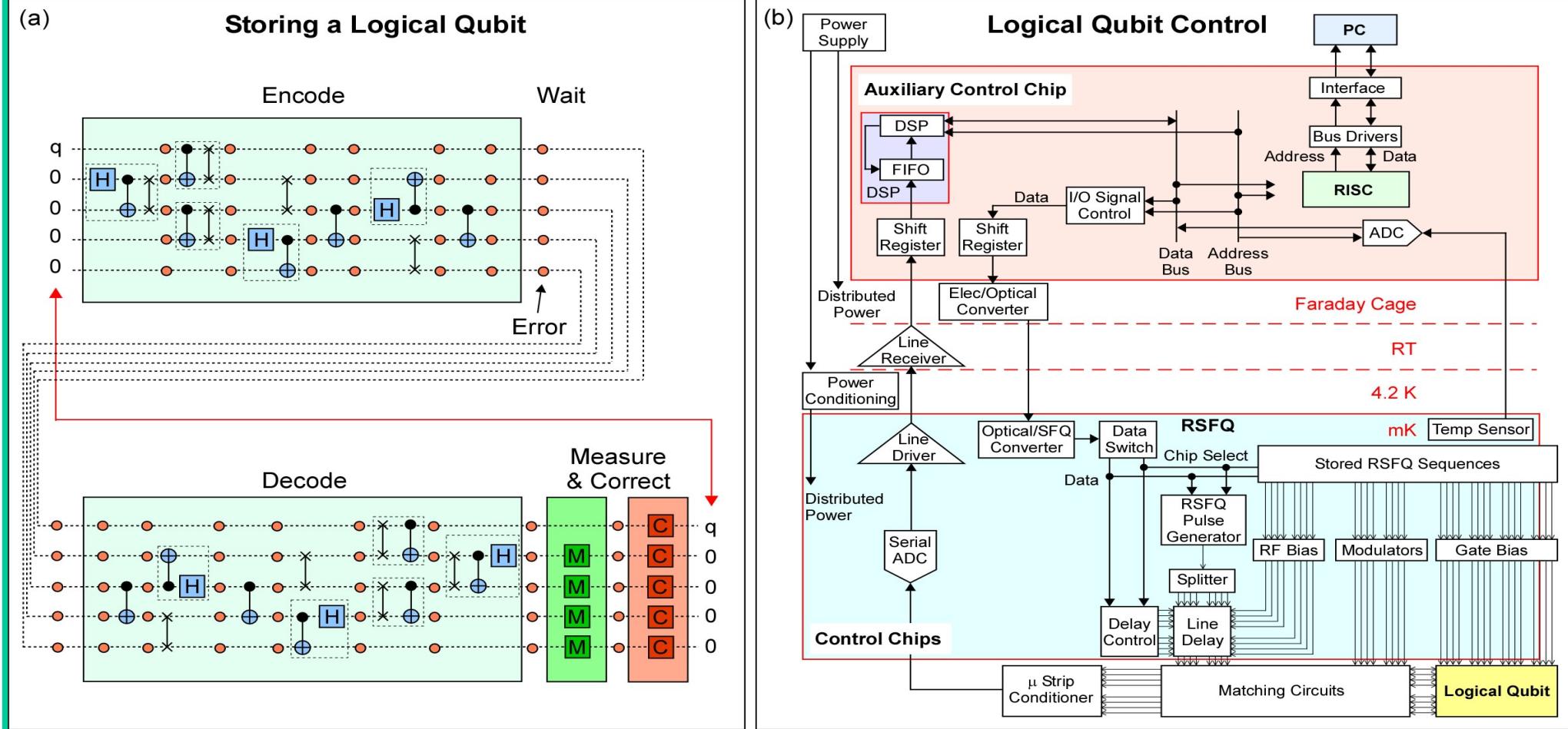


Theory

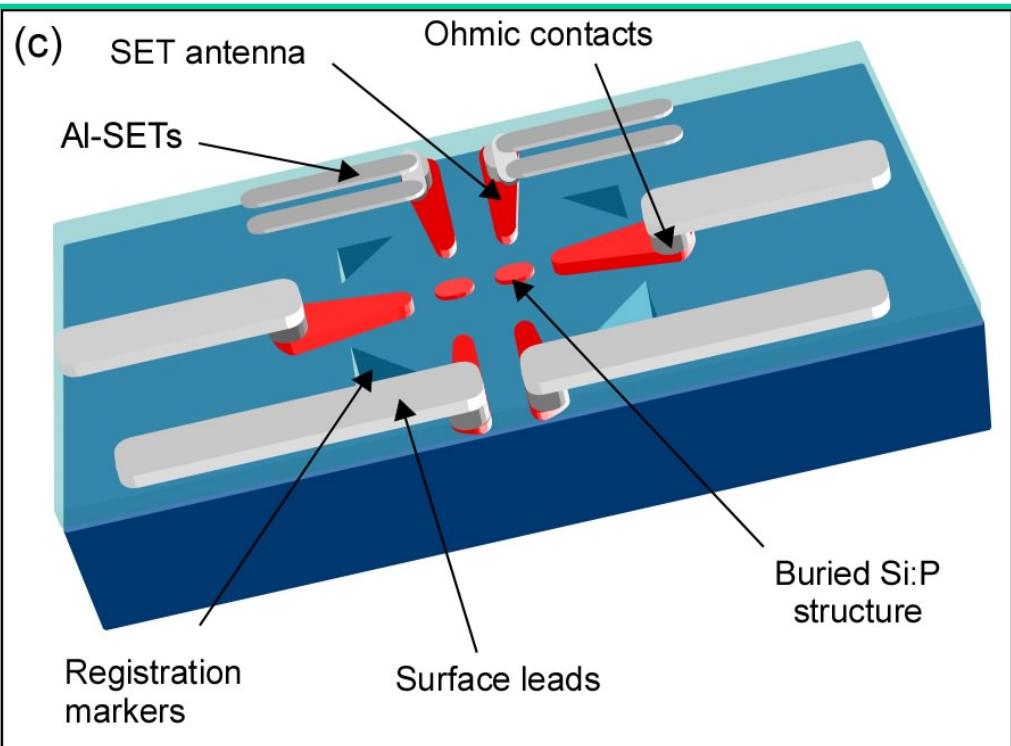
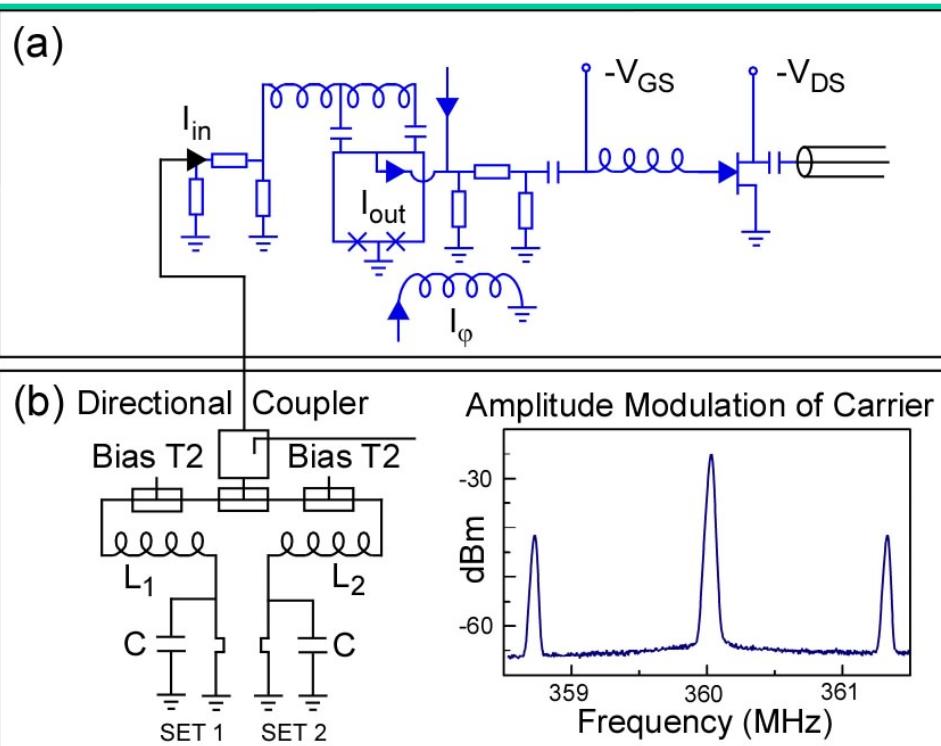


Raman
Experiment

Logical Qubits: Error Correction & Control Electronics

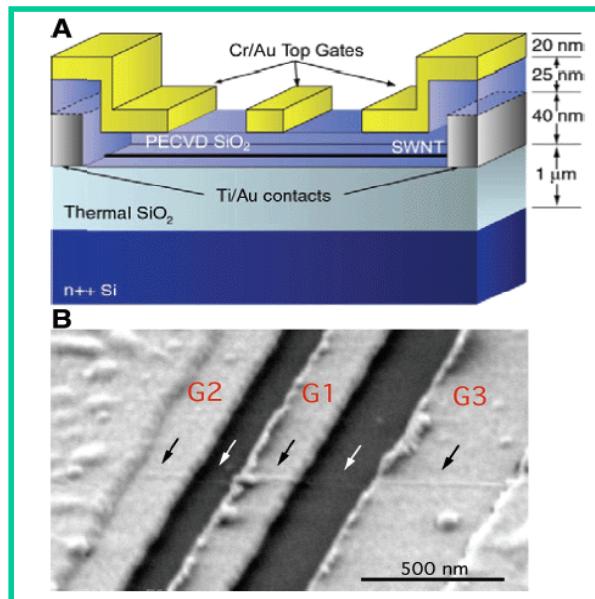


Future Advances: Readout Electronics & Hybrid Devices



Carbon-based Systems

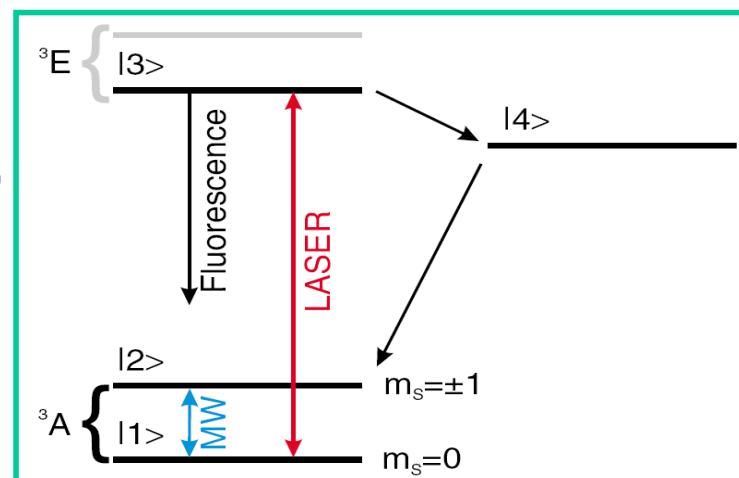
Nanotube: Double QD



N. Mason et al,
Science 303,
655 (2004)

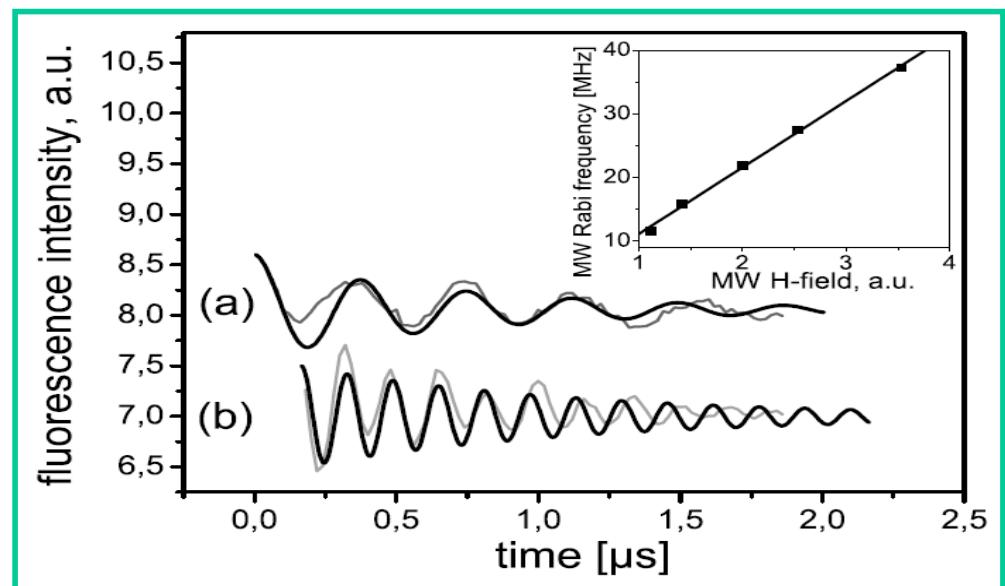
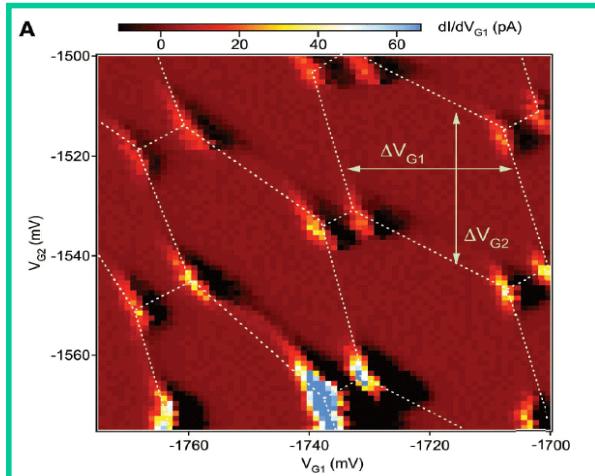
Harvard

Diamond: NV Centre



F. Jelezko et al,
PRL 92, 076401
(2004)

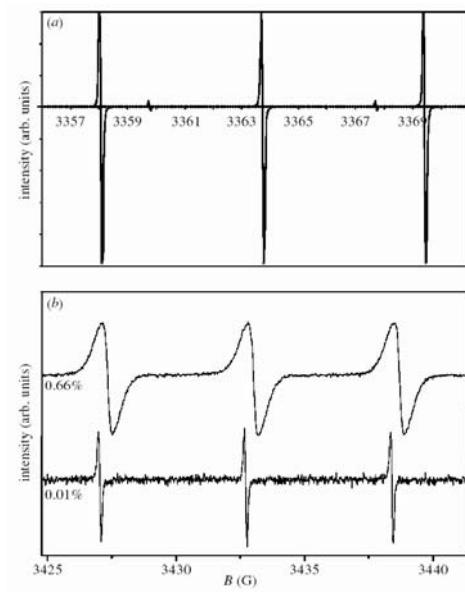
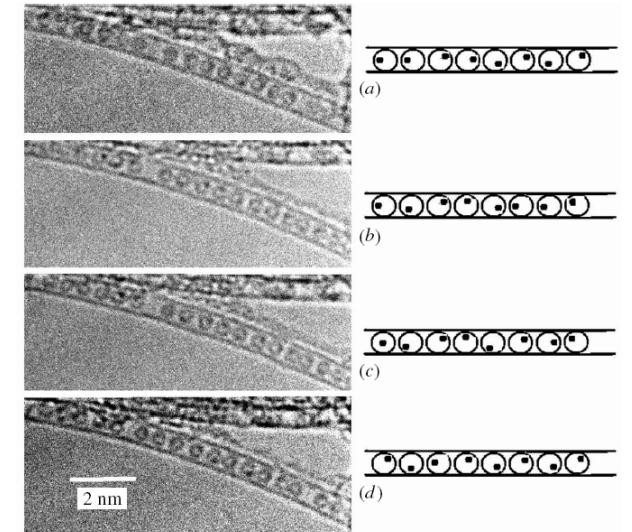
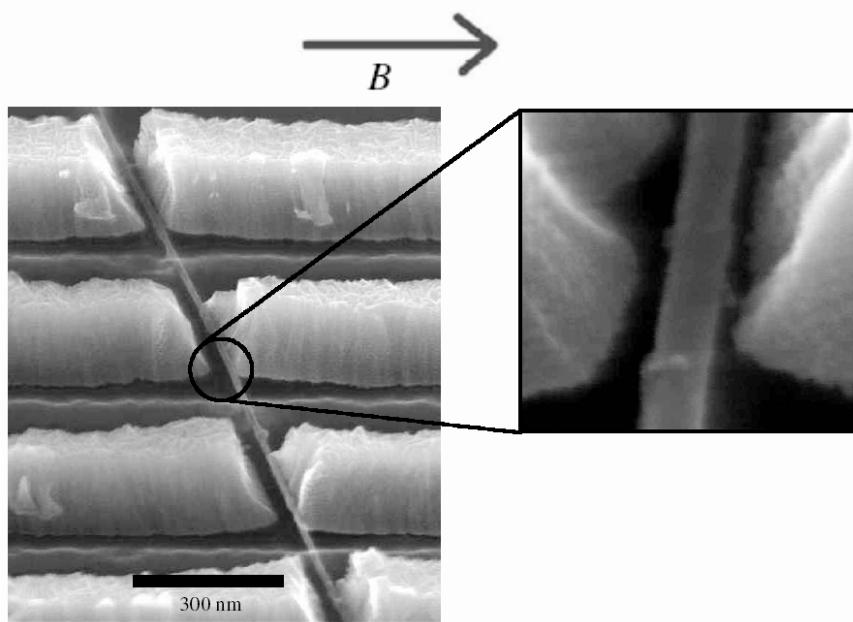
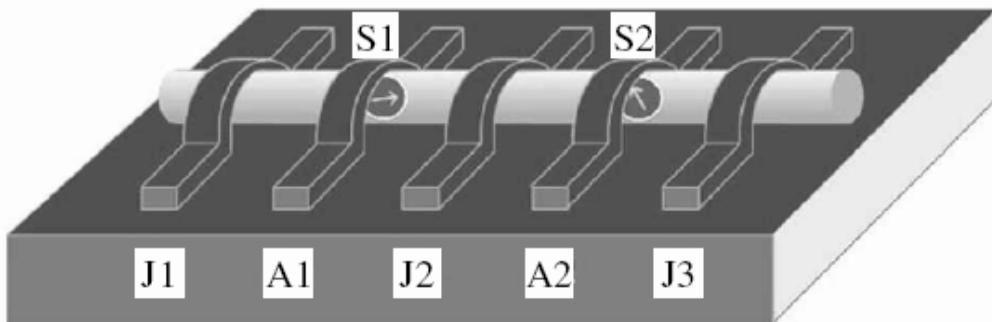
Stuttgart



C-based Systems

Electron Spin Qubits in C Nanotubes

A. Ardavan et al, Phil. Trans. R. Soc. Lond. A
361, 1473 (2003) Oxford



OUTLOOK

e-Spin

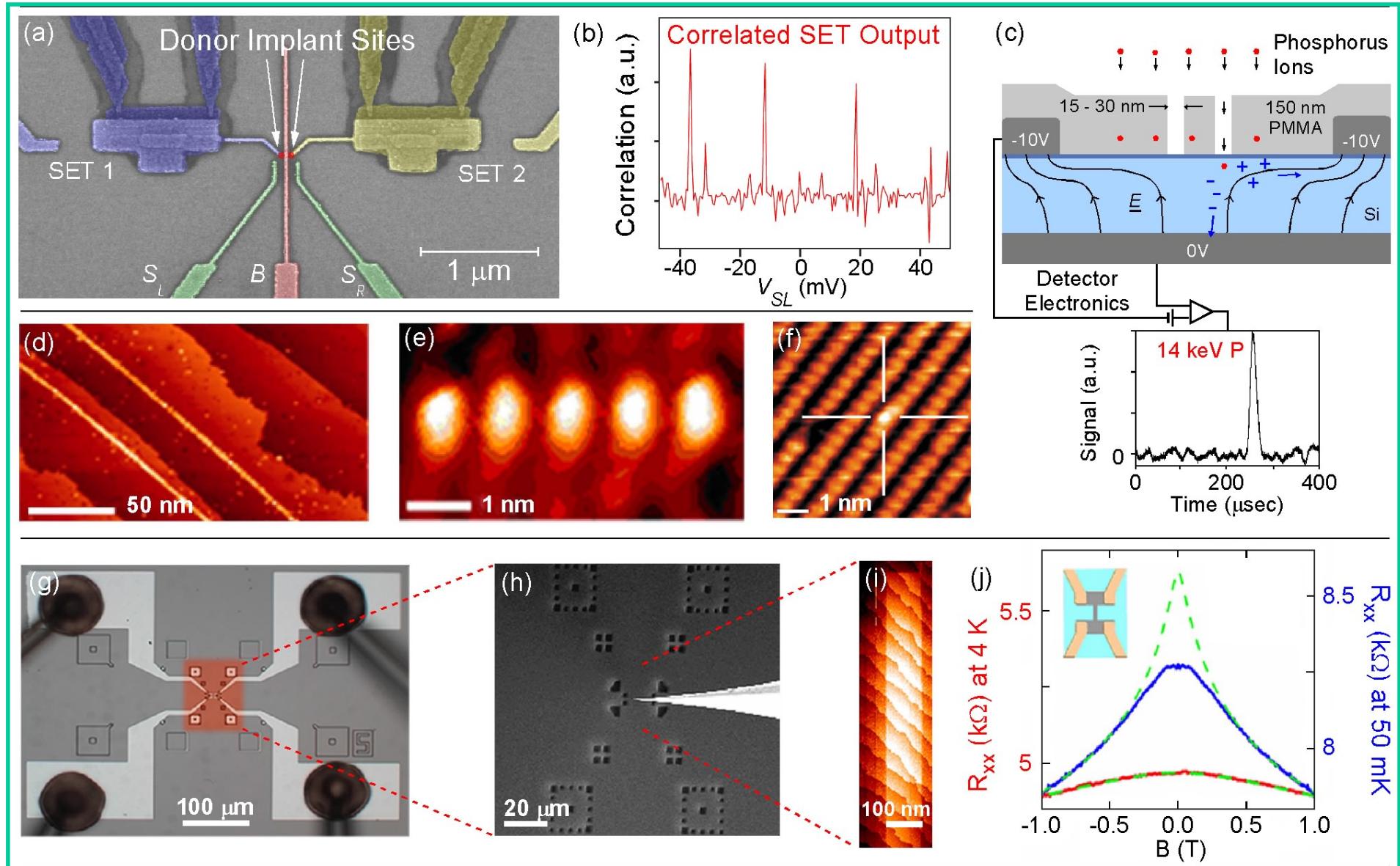
GaAs QDs		Si-SiGe		C-based Systems
Electrical/Optical		Electrical		Electrical/Optical
Electrical		Atoms	QDs	Nanotubes
Charge	Coherent Oscillations	Fabrication		Fabrication
Spin	Single Spin Readout Coupling Decoherence	Charge Readout Decoherence	Spin Decoherence (Ensemble)	NV Centre Single Spin Readout
Optical			Qubit Readout & Decoherence in QC Architecture	
Spin	All Optical Quantum CROT Gate		Coupling	Coupling
			Entanglement	Entanglement
	Scalable Spin-based Architectures			

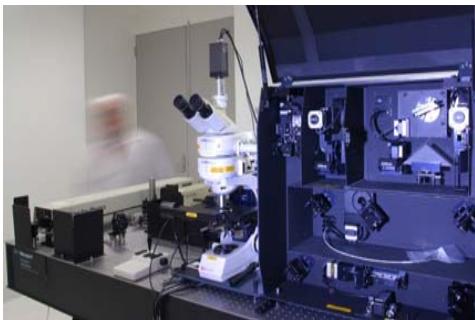
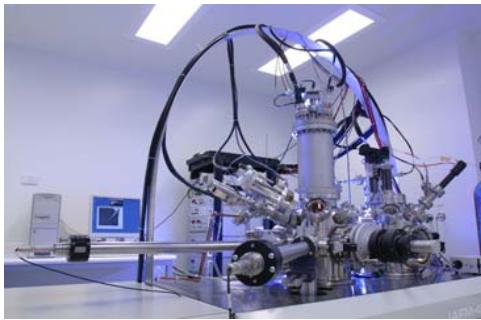
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graph TD
    subgraph GaAs [GaAs QDs]
        CO[Coherent Oscillations]
        SSR[Single Spin Readout  
Coupling  
Decoherence]
        AOG[All Optical Quantum CROT Gate]
        CO --> E[Entanglement]
        SSR --> E
        AOG --> SSA[Scalable Spin-based Architectures]
    end
    subgraph SiSiGe [Si-SiGe]
        FR[Fabrication]
        CR[Charge Readout  
Decoherence]
        SD[Spin Decoherence  
(Ensemble)]
        QR[Qubit Readout  
& Decoherence in QC Architecture]
        CR --> QR
    end
    subgraph Cbased [C-based Systems]
        NC[NV Centre]
        SSSR[Single Spin Readout]
        C[Coupling]
        E2[Entanglement]
    end

```

Si:P QC: Summary of Progress







Roadmap to Si:P Multi-Qubits



ARDA

