Experiments with spin qubits in silicon and diamond

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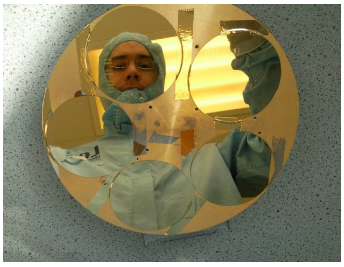
Experiments with spin qubits in silicon and diamond: overview

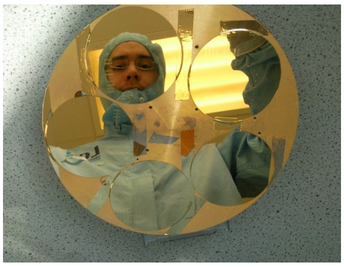
- Lecture 1
  - Magnetic resonance
  - Silicon
- Lecture 2
  - Silicon (cont.)
- Lecture 3
  - Diamond

← Lab tours Friday morning



Experiments with spin qubits in silicon and diamond: overview

- Lecture 1
  - Magnetic resonance
    1. Prepare (spin Hamiltonian)
    2. Control (electromagnetic pulses)
    3. Measure (spin state readout)
  - Silicon



- Magnetic resonance
  1. Prepare (spin Hamiltonian)
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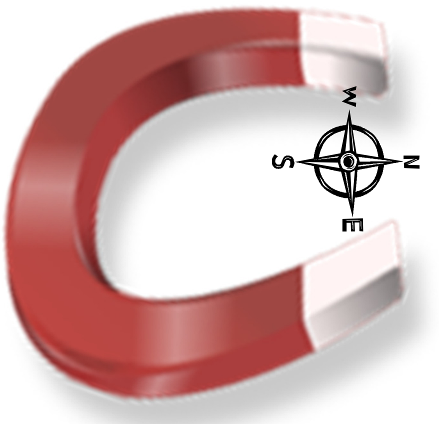
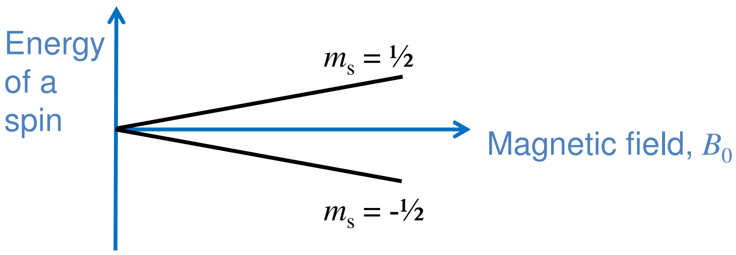


Magnetic resonance: prepare

- put a spin ½ into a magnetic field

Hamiltonian $\mathcal{H} = \omega_S \hat{S}_z$

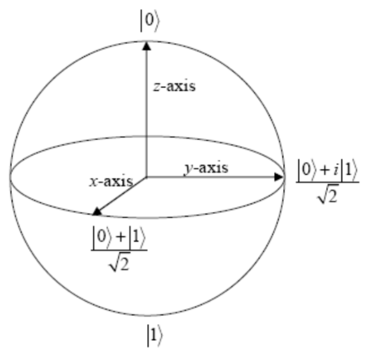
with energy, $\hbar\,\omega_S = g\,\mu_B\,B_0$
for *g*-factor, $g \sim 2$,
Bohr magneton $\mu_B = e\,\hbar/2m_e$,
electron spin $S = ½$



Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

Magnetic resonance: prepare

- put a spin ½ into a magnetic field

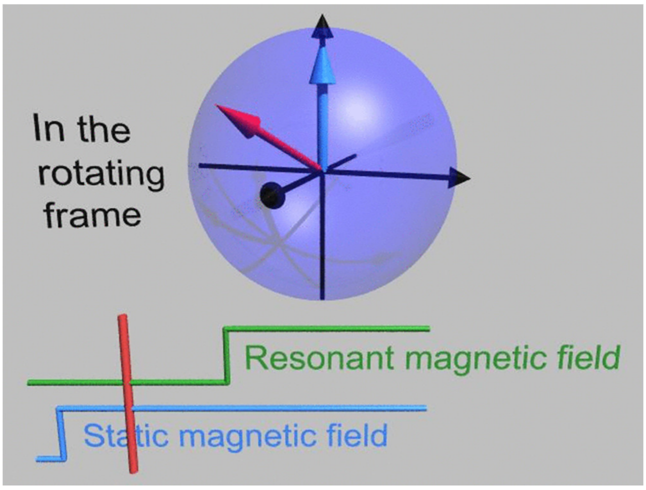


Larmor precession at angular frequency ω_S

Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

Magnetic resonance: prepare

- put a spin ½ into a magnetic field



Larmor precession at angular frequency ω_S

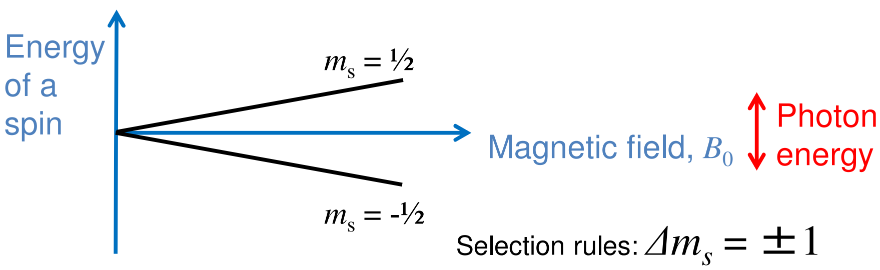
Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

Magnetic resonance: control

- send in electromagnetic radiation

Energy gap is $\Delta E = g\, \mu_B\, B_0$,
magnetic resonance occurs when photon energy

$$\hbar\, \omega_S = \Delta E$$



Selection rules: $\Delta m_s = \pm 1$
Circularly polarized light is absorbed

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Magnetic resonance: measure
- spin readout

- Large ensembles
  - Precessing magnetic moments induce current in a coil (standard for NMR of $>10^{15}$ nuclei)
  - Detect microwave power absorbed or emitted (standard for ESR of $>10^9$ electron spins)

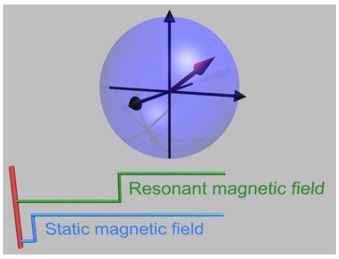
- Single spins
  - Electrically (eg in silicon)
  - Optically (eg in diamond)

Footnote: the terms electron spin resonance (ESR) and electron paramagnetic resonance (EPR) are used interchangeably

Magnetic resonance

Mini-summary:

1. Prepare (spin Hamiltonian)
2. Control (electromagnetic pulses)
3. Measure (spin state readout)



References:

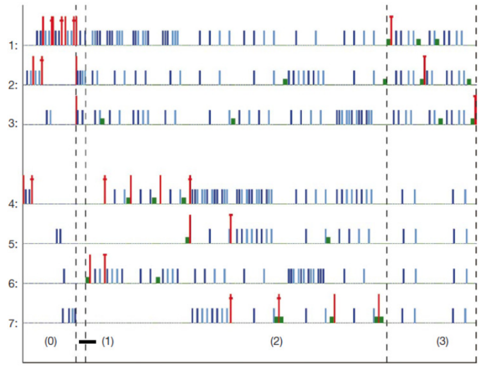
MR for QIP theorists: MH Mohammady, PhD thesis, Chapter 3, UCL (2012)

ESR: A Schweiger & G Jeschke, *Principles of Pulse Electron Paramagnetic Resonance* (Oxford University Press, Oxford, 2001)

NMR: MH Levitt, *Spin Dynamics* (Wiley, 2001)

Magnetic resonance for QIP

Pioneering work: liquid-state NMR QIP



LMK Vandersypen *et al*, *Experimental realization of Shor's quantum factoring algorithm using nuclear magnetic resonance*, Nature **414**, 883 (2001)

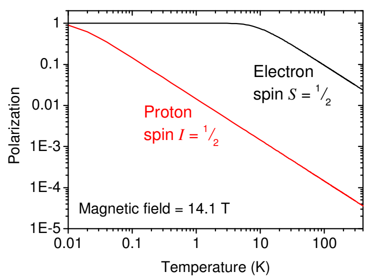
WS Warren, *The usefulness of NMR quantum computing*, Science **277**, 1688 (1997).

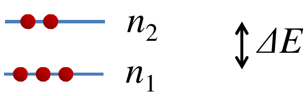
Magnetic resonance for QIP

Pioneering work: liquid-state NMR QIP

Mini-summary:

1. Prepare (pseudo-pure state)
2. Control (NMR pulses)
3. Measure (spin state of large ensemble)





At thermal equilibrium:
$n_2/n_1 = \exp(-\Delta E / k_B T)$

Define polarization as:
$P = (n_1 - n_2) / (n_1 + n_2)$

Magnetic resonance for QIP

Pioneering work: liquid-state NMR QIP

…pseudo-pure states

$$\rho_{\text{thermalized}} = N \begin{pmatrix} p_1 & 0 & 0 & \cdots & 0 \\ 0 & p_2 & 0 & \cdots & 0 \\ 0 & 0 & p_3 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 0 & p_m \end{pmatrix}$$

$$p_i = \frac{e^{\frac{-E_i}{k_B T}}}{\sum_{j=1}^{m} e^{\frac{-E_j}{k_B T}}}$$

$$p_1 = \frac{e^{\frac{-E_1}{k_B T}}}{\sum_{j=1}^{m} e^{\frac{-E_j}{k_B T}}} \approx \frac{1 - \frac{E_1}{k_B T}}{m}$$

$$\rho_{\text{pseudo}} = N \begin{pmatrix} p_1 & 0 & 0 & \cdots & 0 \\ 0 & \bar{p} & 0 & \cdots & 0 \\ 0 & 0 & \bar{p} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 0 & \bar{p} \end{pmatrix} = N\bar{p} \begin{pmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} + N(p_1 - \bar{p}) \begin{pmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Magnetic resonance for QIP

Pioneering work: liquid-state NMR QIP

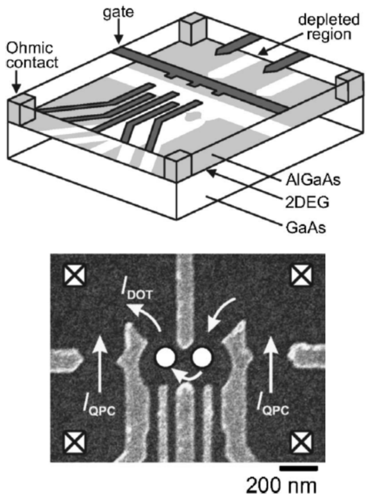
…pseudo-pure states

$$N(p_1 - \bar{p}) \approx \frac{-\frac{NE_1}{k_B T}}{2^q - 1}$$

$$\rho_{\text{pseudo}} = N \begin{pmatrix} p_1 & 0 & 0 & \cdots & 0 \\ 0 & \bar{p} & 0 & \cdots & 0 \\ 0 & 0 & \bar{p} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 0 & \bar{p} \end{pmatrix} = N\bar{p} \begin{pmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 1 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} + N(p_1 - \bar{p}) \begin{pmatrix} 1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

Magnetic resonance for QIP

Pioneering work: GaAs quantum dots



GaAs is a semiconductor ie ”a place where electrons can be individuals”

200 μs spin coherence time: H Bluhm *et al*, Nature Physics **7**, 109 (2011)

R Hanson *et al*, Reviews of Modern Physics **79**, 1217 (2007)

Magnetic resonance for QIP

Use electron spins in semiconductors which have a low background of nuclear spins:
Silicon and Diamond

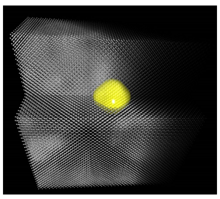
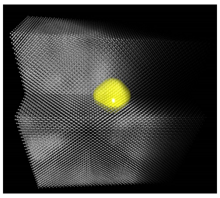
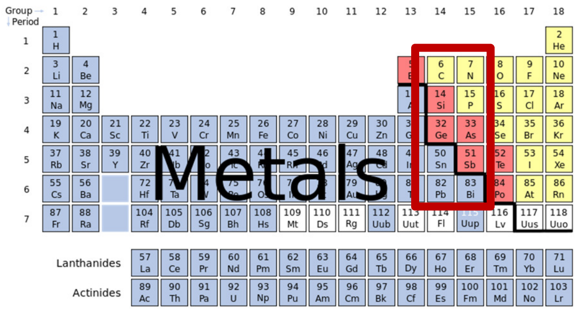


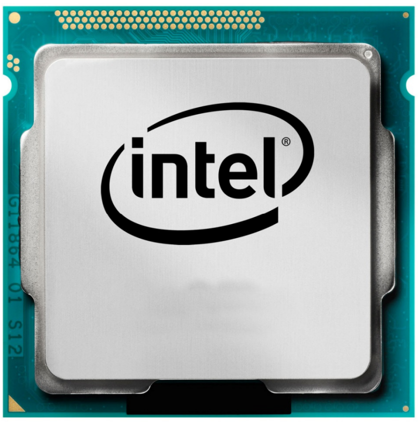
Image by Manuel Vögtli

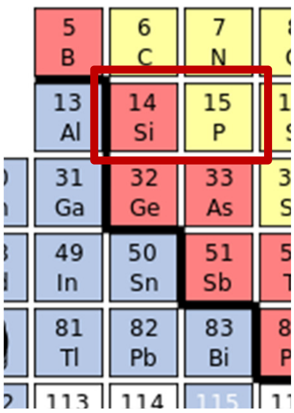
Donors in silicon

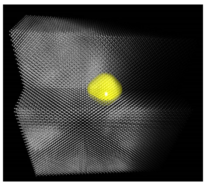




Donors in silicon







Donors in silicon

- Hydrogenic model

Solve Schrödinger's equation for an electron in a box:

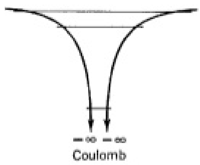
$$-\frac{\hbar^2}{2m_e}\left(\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}\right)\Psi + V\Psi = E\Psi$$

Relative permittivity, ε_r
Effective mass, m^*

W Kohn, Shallow Impurity States in Silicon and Germanium, Solid State Physics 5, 257 (Academic, New York 1957)

Coulomb potential: $V = \frac{-Ze}{4\pi\varepsilon_0 r}$

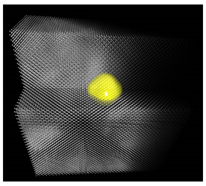
[1]H energy levels: $E = -\frac{13.6\ \text{eV}}{n^2}$



Donor energy levels:

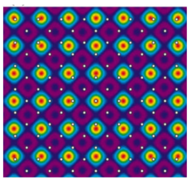
$$E = \frac{-m^*}{m_e}\frac{1}{\varepsilon_r^2}\frac{13.6\ \text{eV}}{n^2}$$

Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015



Donors in silicon

- Hydrogenic model



B Koiller, RB Capaz, X Hu and S Das Sarma, PRB **70**, 115207 (2004)

	Relative permittivity, ε_r	m^*/m_e	**Binding energy for phosphorous dopant (meV)**
Silicon	11.7	0.98 (long.) 0.19 (trans.)	46
Diamond	5.5 - 10	1.4 (long.) 0.36 (trans.)	500

Donor energy levels:

$$E = \frac{-m^*}{m_e}\frac{1}{\varepsilon_r^2}\frac{13.6\ \text{eV}}{n^2}$$

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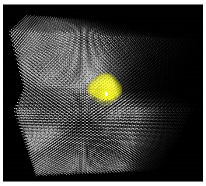


Donors in silicon

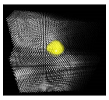
$$\mathcal{H} = \omega_S \hat{S}_z - \omega_I \hat{I}_z + A\, \hat{\mathbf{S}} \bullet \hat{\mathbf{I}}$$

with electron spin S = 1/2 and nuclear spin:
I = 1/2 for phosphorous (Si:P)
I = 3/2 for arsenic (Si:As)
I = 5/2 or 7/2 for antimony (Si:Sb)
I = 9/2 for bismuth (Si:Bi)

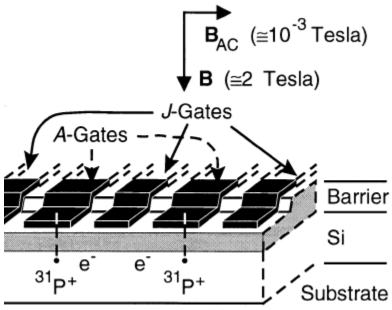
Bell Laboratories

Pioneering early work:

- G Feher and EA Gere, Physical Review **114**, 1245 (1959)
- G Feher, Physical Review **114**, 1219 (1959)
- JP Gordon and KD Bowers, Physical Review Letters **1**, 368 (1958)



Donor qubits in silicon



Kane proposal:
BE Kane, *A silicon-based nuclear spin quantum computer*, Nature **393**, 133 (1998)

Recent silicon QIP reviews:

- DD Awschalom *et al*, *Quantum Spintronics: Engineering and Manipulating Atom-Like Spins in Semiconductors*, Science **339**, 1174 (2013)
- FA Zwanenburg *et al*, *Silicon quantum electronics*, Rev Mod Phys **85**, 961 (2013)
- GW Morley, *Towards Spintronic Quantum Technologies with Dopants in Silicon*, book chapter in SPR Electron Paramagnetic Resonance Volume 24, arXiv1407.6250 (2014)

Donor qubits in silicon

Mini-overview

- Atomically-precise device fabrication
- Qubit initialisation
- Readout
- Control
- Coherence times

Atomically-precise fabrication

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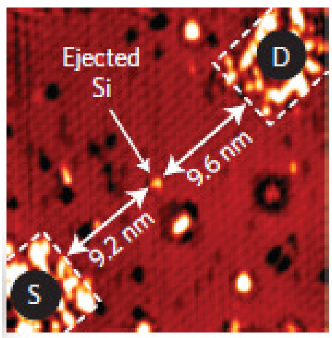
Using scanning tunnelling microscopy (STM)

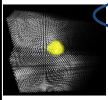
JL O'Brien *et al.*, PRB **64**, 161401 (2001)

SR Schofield *et al.*, PRL **91**, 136104 (2003)

M Fuechsle *et al.*, Nat Nano **7**, 242 (2012)

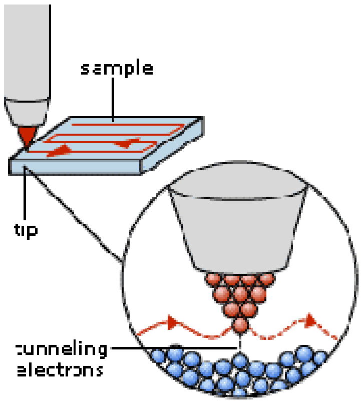
B Weber *et al.*, Science **335**, 64 (2012)





Fabrication Initialisation Readout Control Coherence

Scanning tunnelling microscopy (STM)



www.nobelprize.org/educational/physics/microscopes/scanning

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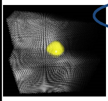
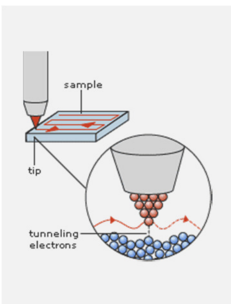
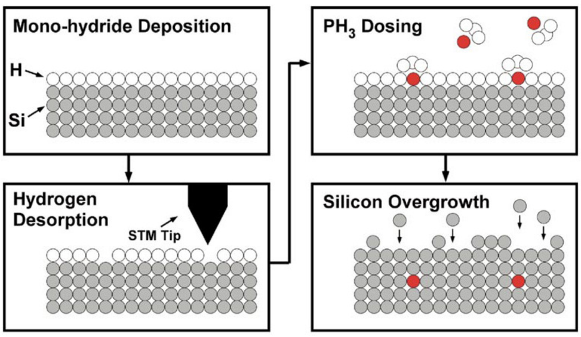


Fabrication Initialisation Readout Control Coherence

Atomically-precise fabrication

Using STM and hydrogen lithography





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Fabrication Initialisation Readout Control Coherence

Atomically-precise fabrication

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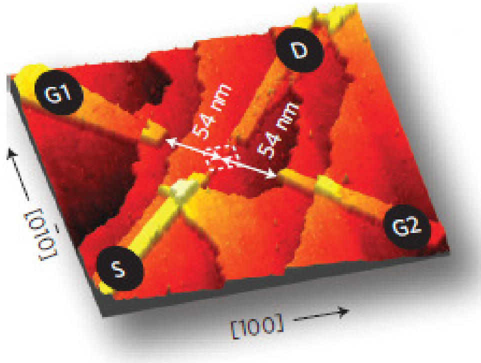
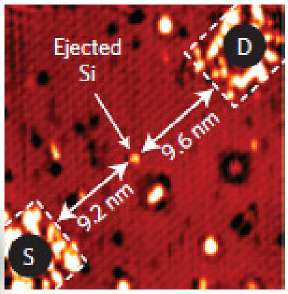
Using STM and hydrogen lithography

A Single Atom Transistor
M Fuechsle *et al.*, Nat Nano **7**, 242 (2012)





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Fabrication Initialisation Readout Control Coherence

Atomically-precise fabrication

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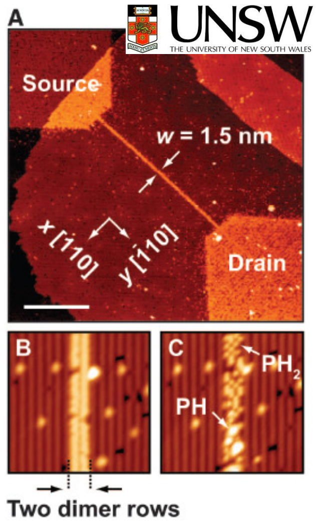
Using STM and hydrogen lithography

Ohm's law Survives to the Atomic Scale
B Weber *et al.*, Science **335**, 64 (2012)



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Atomically-precise fabrication

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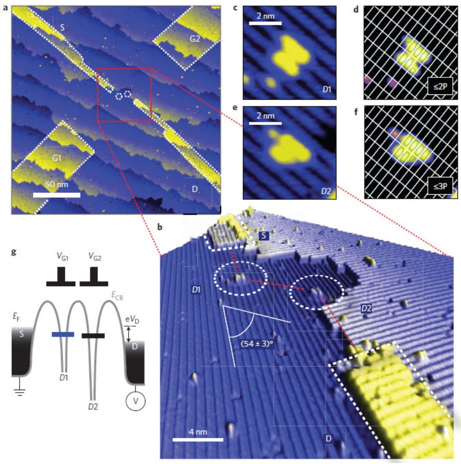
Using STM and hydrogen lithography



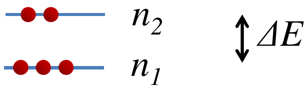
Spin blockade and exchange in Coulomb-confined silicon double quantum dots
B Weber *et al.*, Nature Nano **9**, 430 (2014)

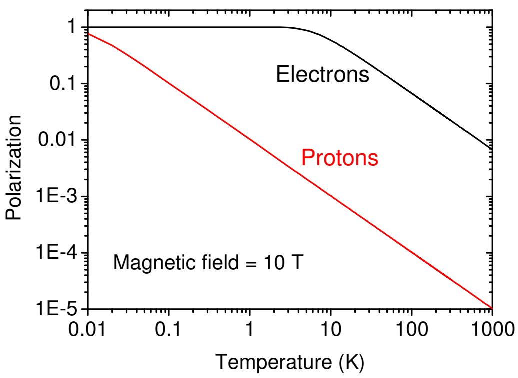
Remaining slides do not use STM or hydrogen lithography

Initialisation by spin polarization

Thermal (Boltzmann) equilibrium:
$n_2 / n_1 = \exp(-\Delta E / k_B T)$

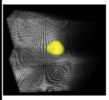
Define polarization as:
$P = (n_1 - n_2) / (n_1 + n_2)$





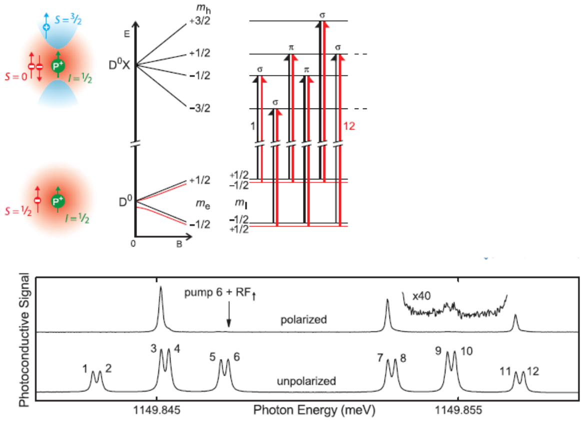
DR McCamey, J van Tol, GW Morley and C Boehme, *Fast Nuclear Hyperpolarization of Phosphorus in Silicon,* Physical Review Letters, **102**, 027601 (2009)

Electron spin: $P_{\text{Boltzmann}}$ = 99.9%, Nuclear spin: P_{measured} = 68%



Fabrication Initialisation Readout Control Coherence

Qubit initialisation with lasers



A Yang *et al.*, *Simultaneous subsecond Hyperpolarization of the Nuclear and Electron Spins of Phosphorus in Silicon by Optical Pumping of Exciton Transitions*, Physical Review Letters **102**, 257401 (2009)

M Steger *et al.*, *Quantum Information Storage for over 180s Using Donor Spins in a ^{28}Si "Semiconductor Vacuum"*, Science **336**, 1280 (2012)

Electron spin: $P_{\text{bound exciton}}$ = 97%
Nuclear spin: $P_{\text{bound exciton}}$ = 90%

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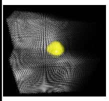

Fabrication Initialisation Readout Control Coherence

Initialisation by spin polarization

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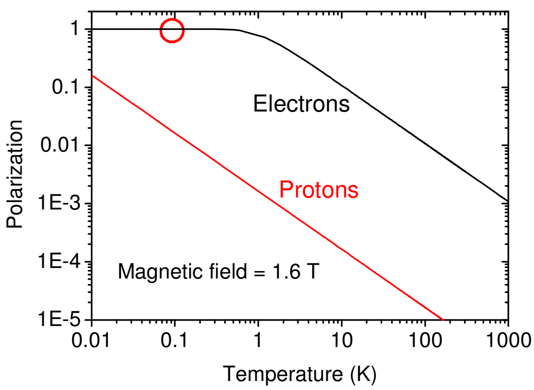
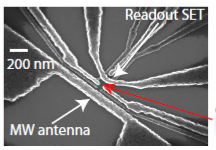
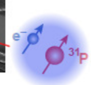


JT Muhonen *et al.*, *Storing quantum information for 30 seconds in a nanoelectronic device*, Nature Nanotechnology, 9, 986 (2014)

Electron spin: $P_{\text{Boltzmann}}$ = 99.9999999%





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Initialisation using a readout

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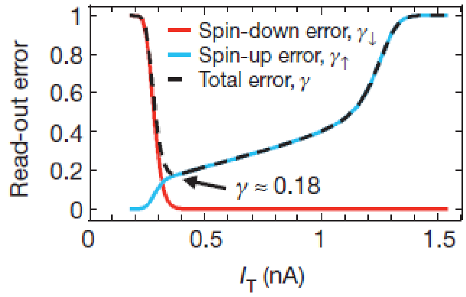
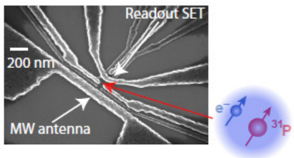


JJ Pla *et al.*, *A single-atom electron spin qubit in silicon*, Nature **489**, 541 (2012)

Electron spin readout error ~18%
Fast initialisation (spin-down) error ~1%



Fabrication Initialisation Readout Control Coherence

Single-shot single-spin SET readout

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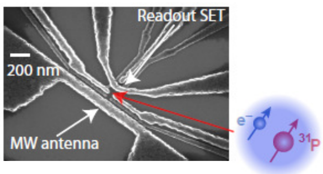
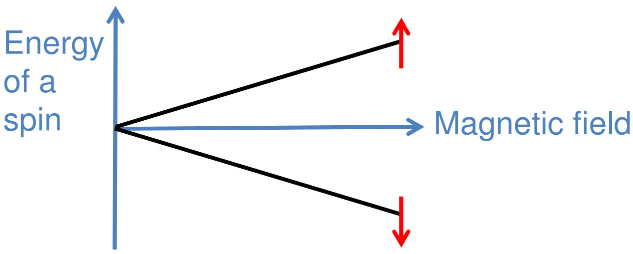
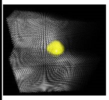


A Morello *et al.*, *Single-shot readout of an electron spin in silicon*, Nature **467**, 687 (2010)

JJ Pla *et al.*, *A single-atom electron spin qubit in silicon*, Nature **489**, 541 (2012)





Single-shot single-spin SET readout

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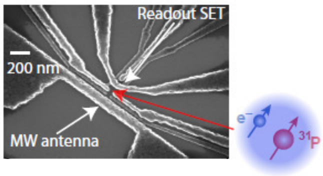

A Morello *et al.*, *Single-shot readout of an electron spin in silicon*, Nature **467**, 687 (2010)

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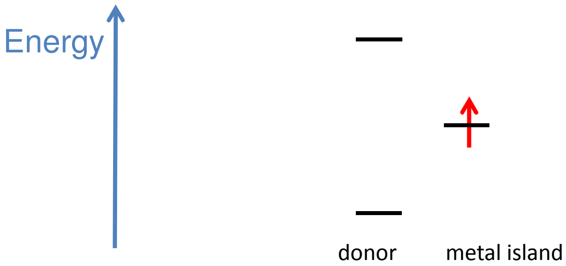

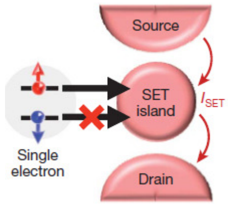

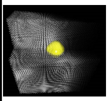

Qubit control

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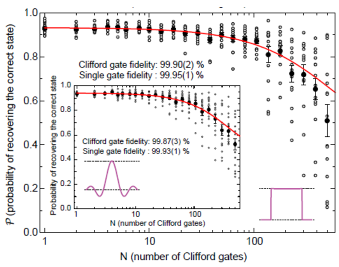
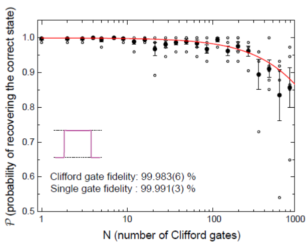
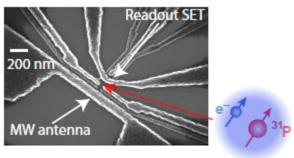


JT Muhonen *et al.*, *Quantifying the quantum gate fidelity of single-atom spin qubits in silicon by randomized benchmarking*, arXiv:1410:2338

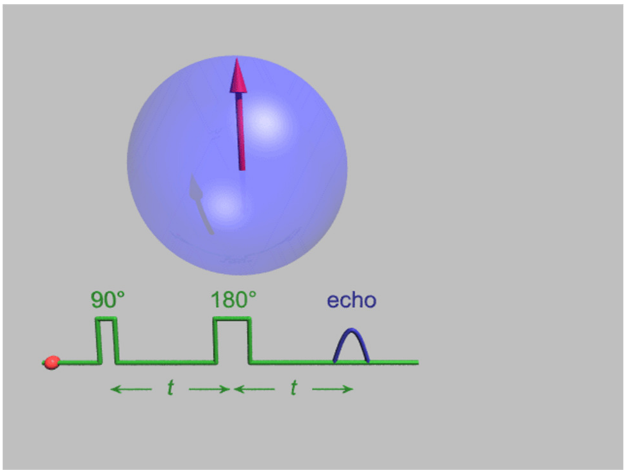
Average gate fidelities with ^{28}Si:
99.95% for electron
99.99% for nucleus





Fabrication Initialisation Readout Control Coherence

Measuring coherence



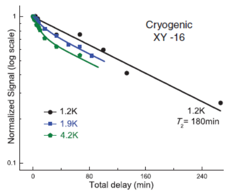
spin
echo
decay

In rotating frame

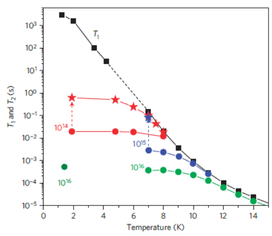
Fabrication Initialisation Readout Control Coherence

Coherence: donor qubit ensembles

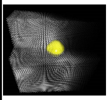
Silicon:
- **Low impurity density**
- **Low density of nuclear spins**
- **Can use enriched ^{28}Si**
- **Low spin orbit coupling**



Nuclear T_2 = 3 hours
K Saeedi *et al.*, Science **342**, 830 (2013)



Electron T_2 > 1 second
AM Tyryshkin *et al.*, *Electron spin coherence exceeding seconds in high-purity silicon*, Nature Materials **11**, 143 (2012)



Fabrication Initialisation Readout Control Coherence

Coherence of a single electron spin

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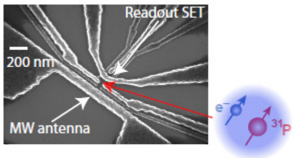
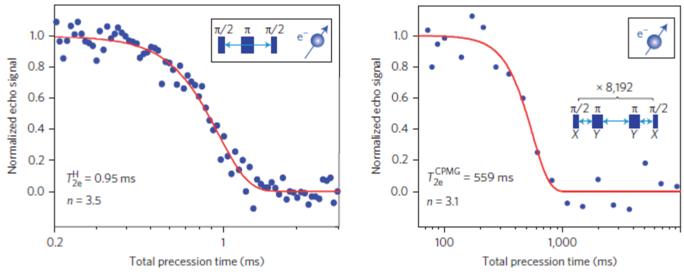
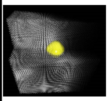


Use ^{28}Si:
JT Muhonen *et al.*, *Storing quantum information for 30 seconds in a nanoelectronic device*, Nature Nano **9**, 986 (2014)



Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015



Fabrication Initialisation Readout Control Coherence

Coherence of a single nuclear spin

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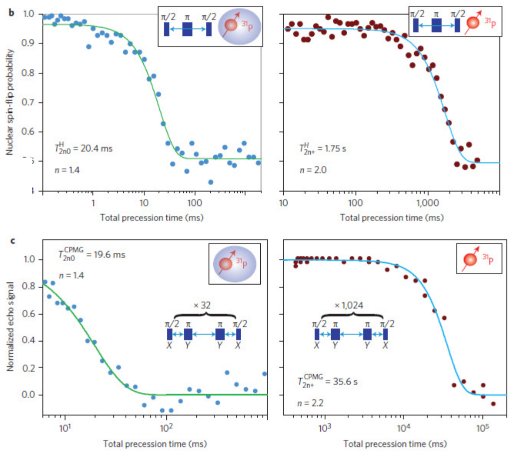
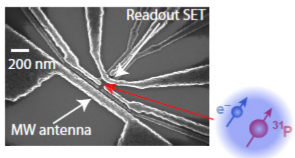


Use ^{28}Si:
JT Muhonen *et al.*, *Storing quantum information for 30 seconds in a nanoelectronic device*, Nature Nano **9**, 986 (2014)

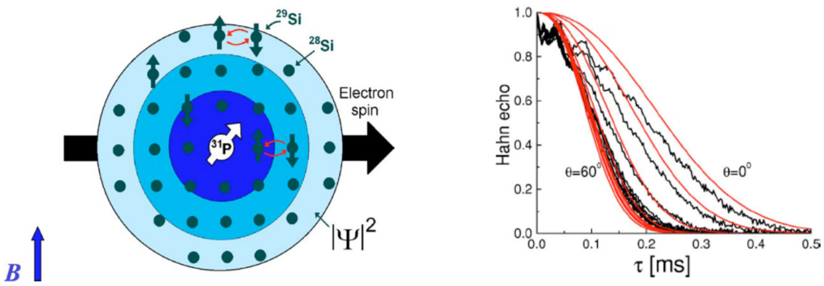


Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

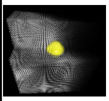
Simulating coherence

Central spin problem: one electron spin in a bath of >1000 nuclear spins.
Intractable to do a full quantum simulation with a classical computer.

Spectral diffusion of a Si:P spin

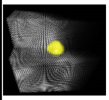


- WM Witzel & S Das Sarma, PRB **74**, 035322 (2006)
- W Yang & R-B Liu, PRB **78**, 085315 (2008)



Conclusions and perspective

Need to couple up two donors



Bismuth donors in silicon

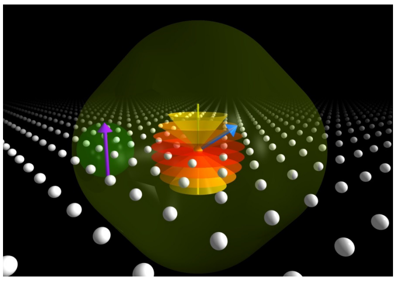
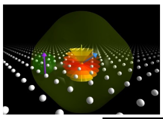


Image by Manuel Vögtli

T Sekiguchi *et al.*, PRL **104**, 137402 (2010)
GW Morley *et al.*, Nature Materials **9**, 725 (2010)
MH Mohammady, GW Morley & TS Monteiro, PRL **105**, 067602 (2010)
RE George *et al.*, PRL **105,** 067601 (2010)
GW Morley *et al.*, Nature Materials **12**, 103 (2013)
G Wolfowicz *et al.,* Nature Nano **8**, 561 (2013)

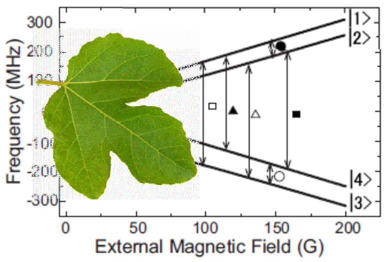


Phosphorus qubits in silicon

$$\mathcal{H} = \omega_S \hat{S}_z - \omega_I \hat{I}_z + A\hat{S}\hat{I}$$

$$S = I = 1/2\,, \ A/2\pi = 118 \text{ MHz}$$

$$\beta = \sin \frac{\arctan\left(\frac{\hbar\, A/B}{g_e\mu_e - g_n\mu_n}\right)}{2}$$

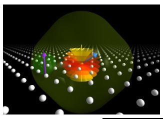


$|1\rangle = |\uparrow\uparrow\rangle,$

$|2\rangle = \alpha|\uparrow\downarrow\rangle + \beta|\downarrow\uparrow\rangle,$

$|3\rangle = -\beta|\uparrow\downarrow\rangle + \alpha|\downarrow\uparrow\rangle,$

$|4\rangle = |\downarrow\downarrow\rangle$

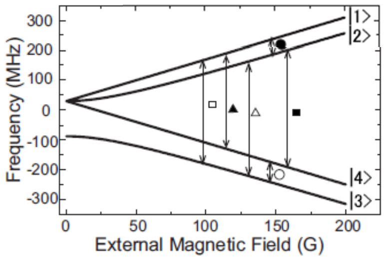


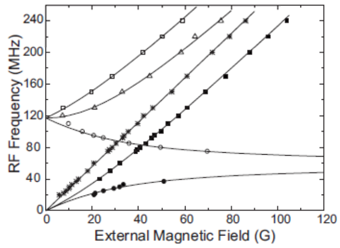
Phosphorus qubits in silicon

$$\mathcal{H} = \omega_S \hat{S}_z - \omega_I \hat{I}_z + A\hat{S}\hat{I}$$

$$S = I = 1/2\,,\ \ A/2\pi = 118\ \text{MHz}$$

H. Morishita, L. S. Vlasenko, H. Tanaka, K. Semba, K. Sawano, Y. Shiraki, M. Eto & K. M. Itoh, Physical Review B **80**, 205206 (2009).



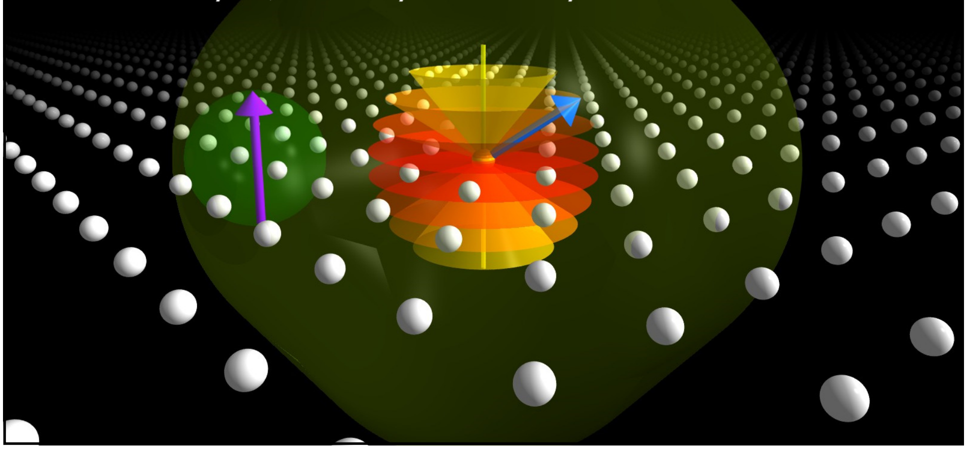


Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

Bismuth qubits in silicon

$$\mathcal{H} = \omega_S \hat{S}_z - \omega_I \hat{I}_z + A\hat{S}\hat{I}$$

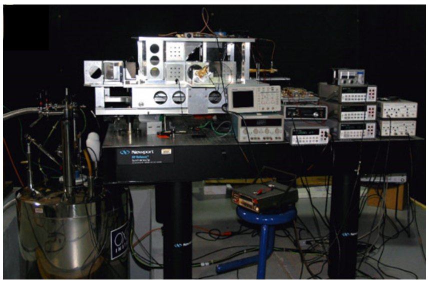
$$S = 1/2\,,\ \ I = 9/2\ \text{and}\ A/2\pi = 1475\ \text{MHz}$$



Pulsed electron spin resonance (ESR) at 110 – 336 GHz, 12.5 T

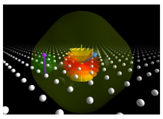
GWM, L-C Brunel & J van Tol, Rev Sci Instrum **79,** 064703 (2008)

CW & transient EPR: J van Tol, L-C Brunel & R J Wylde, Rev Sci Instrum **76,** 074101 (2005)



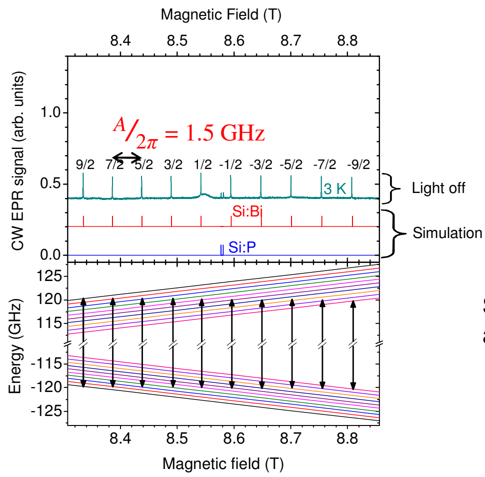
99.9% electron spin polarization

Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015



Bismuth donors in silicon

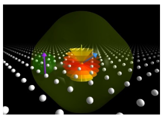
ESR of Si:Bi at 240 GHz



GWM, M Warner, AM Stoneham, PT Greenland, J van Tol, CWM Kay & G Aeppli, Nature Materials **9**, 725 (2010)

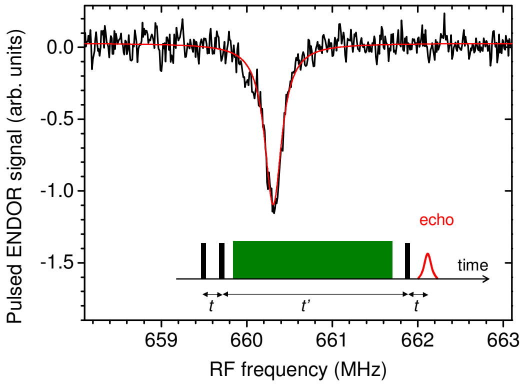
Si:P and Si:Bi resonances are resolved

Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015



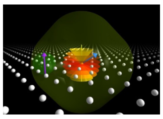
Bismuth donors in silicon

Electron-nuclear double resonance (ENDOR) of Si:Bi at 240 GHz



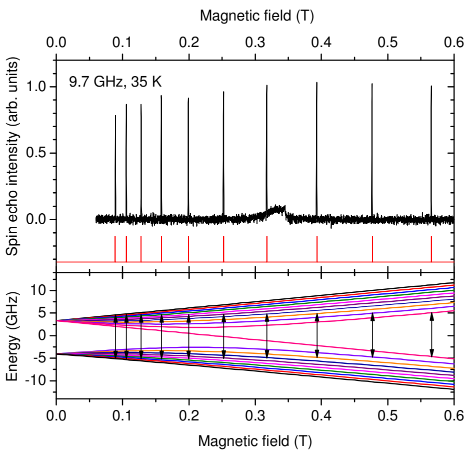
GWM, M Warner, AM Stoneham, PT Greenland, J van Tol, CWM Kay & G Aeppli, Nature Materials **9**, 725 (2010)

Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015



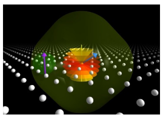
Bismuth donors in silicon

ESR of Si:Bi at 9.7 GHz



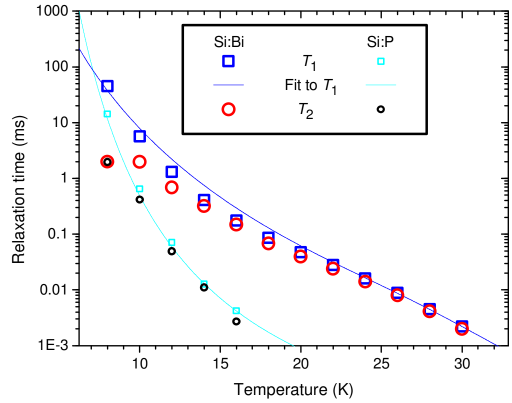
GWM, M Warner, AM Stoneham, PT Greenland, J van Tol, CWM Kay & G Aeppli, Nature Materials **9**, 725 (2010)

Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

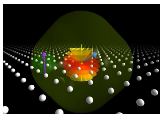


Bismuth donors in silicon

Pulsed ESR of Si:Bi at 9.7 GHz

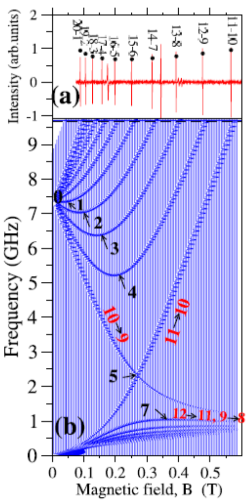


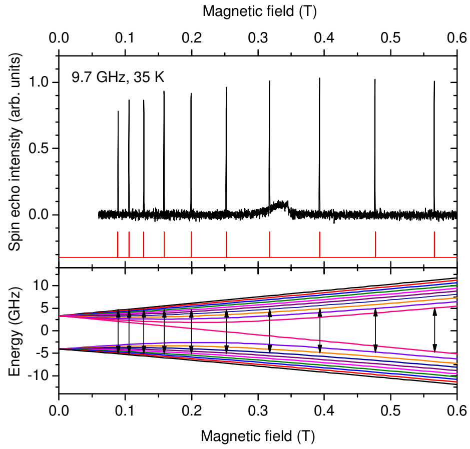
GWM, M Warner, A M Stoneham, P T Greenland, J van Tol, C W M Kay, G Aeppli, Nature Materials **9**, 725 (2010)

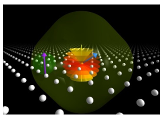


Bismuth donors in silicon

Magnetic resonance of Si:Bi

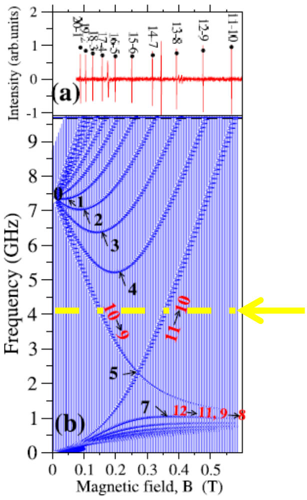






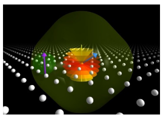
Bismuth donors in silicon

Magnetic resonance of Si:Bi



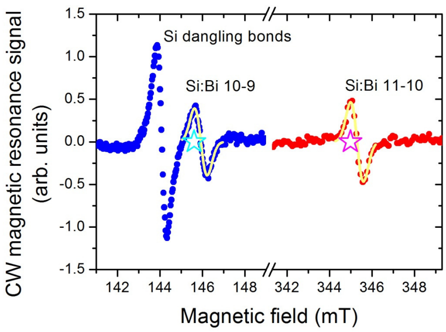
MH Mohammady, GWM & TS Monteiro, PRL **105,** 067602 (2010)

10 ➔ 9 is an NMR transition at high field



Bismuth donors in silicon

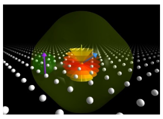
Nuclear-electronic magnetic resonance of Si:Bi at 4 GHz



10 ➔ 9 is an NMR transition at high field

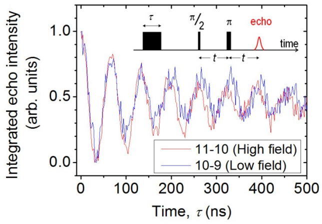
epr @eth

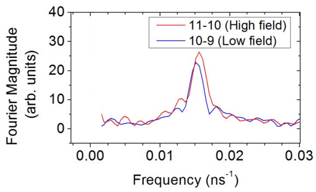
GWM, P Lueders, MH Mohammady, SJ Balian, G Aeppli, CWM Kay, WM Witzel, G Jeschke, TS Monteiro, Nature Materials **12,** 103 (2013)



Bismuth donors in silicon

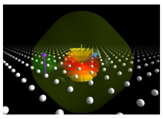
Quantum control of a hybrid nuclear-electronic spin system





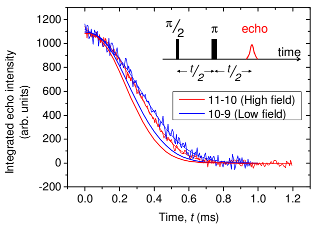
GWM, P Lueders, MH Mohammady, SJ Balian, G Aeppli, CWM Kay, WM Witzel, G Jeschke, TS Monteiro, Nature Materials **12,** 103 (2013)

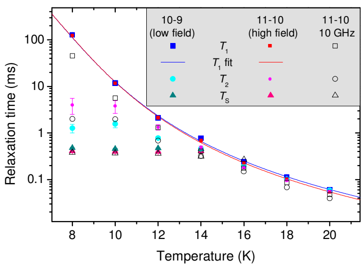
Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015



Bismuth donors in silicon

Hybrid MR of Si:Bi at 4 GHz



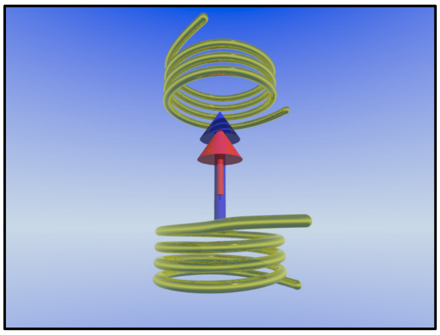


GWM, P Lueders, MH Mohammady, SJ Balian, G Aeppli, CWM Kay, WM Witzel, G Jeschke, TS Monteiro, Nature Materials **12,** 103 (2013)

Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

Bismuth donors in silicon

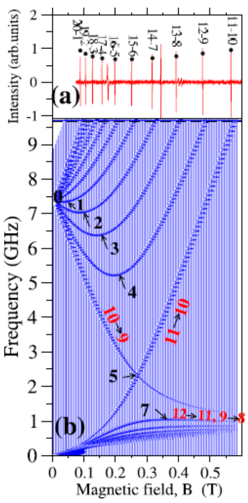
Hybrid MR of Si:Bi at 4 GHz



GWM, P Lueders, MH Mohammady, SJ Balian, G Aeppli, CWM Kay, WM Witzel, G Jeschke, TS Monteiro, Nature Materials **12,** 103 (2013)

Bismuth donors in silicon

Si:Bi magnetic resonance



- T Sekiguchi et al., PRL 104, 137402 (2010)
- M Belli *et al.*, PRB **83,** 235204 (2011)
- S J Balian *et al.*, PRB 86, 104428 (2012)
- M H Mohammady *et al.*, PRB 85, 094404 (2012)
- C D Weis *et al.*, APL **100,** 172104 (2012)
- G Wolfowicz *et al.*, PRB **86,** 245301 (2012)
- P Studer *et al.*, ACS Nano **6,** 10456 (2012)
- P A Mortemousque *et al.*, APL **101**, 082409 (2012)
- G Wolfowicz *et al.*, Nature Nano **8**, 561 (2013)
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Donor qubits in silicon: conclusions

- Atomically-precise device fabrication
- Qubit initialisation
- Readout
- Control
- Coherence times
- Using Si:Bi offers extra benefits
- **Need to couple up two donors**