

# 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**

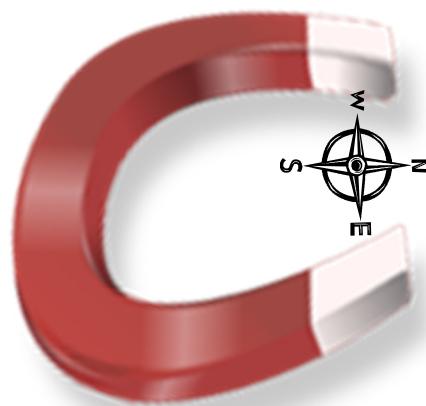


# Experiments with spin qubits in silicon and diamond: overview

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



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



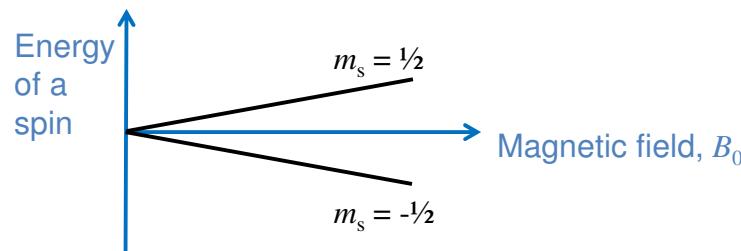
Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

## Magnetic resonance: prepare

- put a spin  $\frac{1}{2}$  into a magnetic field

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

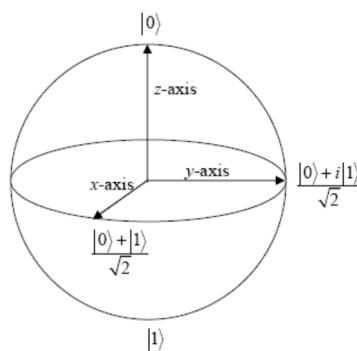
with energy,  $\hbar \omega_S = g \mu_B B_0$   
 for  $g$ -factor,  $g \sim 2$ ,  
 Bohr magneton  $\mu_B = e \hbar / 2m_e$ ,  
 electron spin  $S = \frac{1}{2}$



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## Magnetic resonance: prepare

- put a spin  $\frac{1}{2}$  into a magnetic field

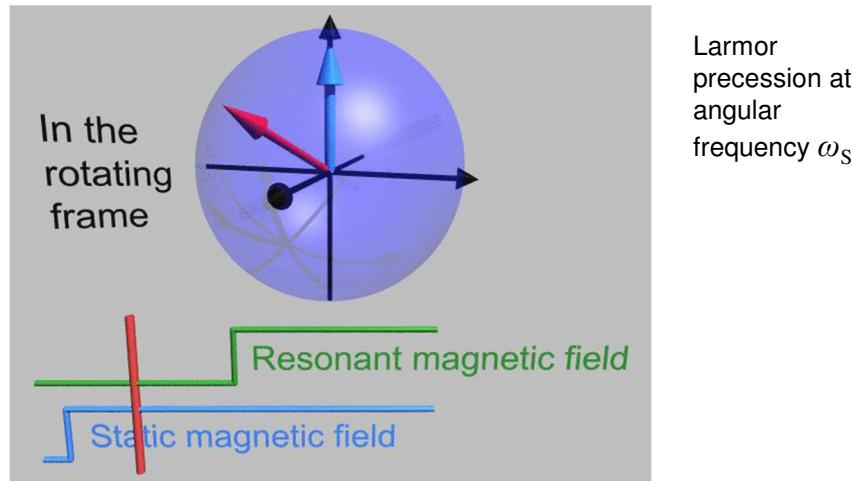


Larmor  
precession at  
angular  
frequency  $\omega_S$

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## Magnetic resonance: prepare

- put a spin  $\frac{1}{2}$  into a magnetic field



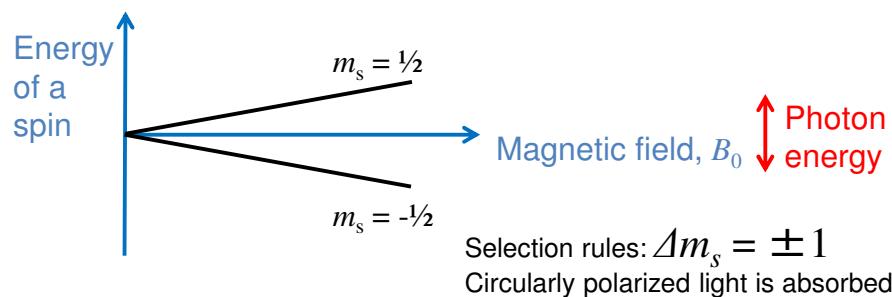
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## Magnetic resonance: control

- send in electromagnetic radiation

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

$$\hbar \omega_s = \Delta E$$



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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)

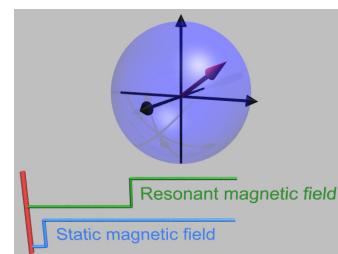
Footnote: the terms electron spin resonance (ESR) and electron paramagnetic resonance (EPR) are used interchangeably

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# 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)

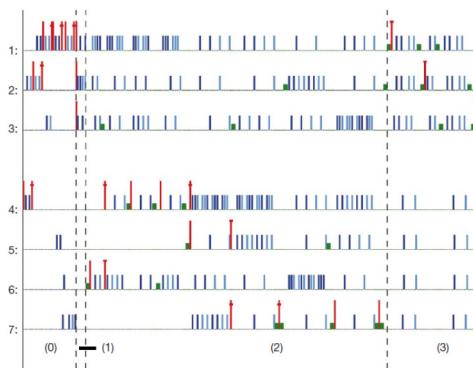
ESR: A Schweiger & G Jeschke, *Principles of Pulse Electron Paramagnetic Resonance* (Oxford University Press, Oxford, 2001)

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

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# 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).

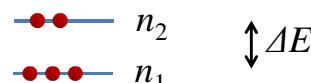
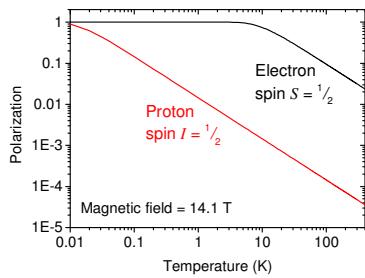
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# Magnetic resonance for QIP

## 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:  
 $P = (n_1 - n_2) / (n_1 + n_2)$

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# Magnetic resonance for QIP

Pioneering work: liquid-state NMR QIP

...pseudo-pure states

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

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

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

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

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# Magnetic resonance for QIP

Pioneering work: liquid-state NMR QIP

...pseudo-pure states

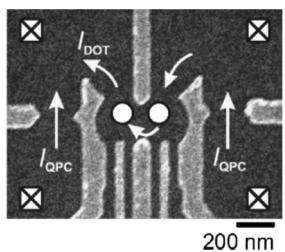
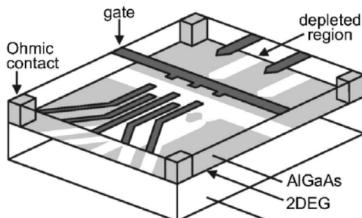
$$N(p_1 - \bar{p}) \approx \frac{-\frac{NE_1}{k_B T}}{2^q - 1}$$

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

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# Magnetic resonance for QIP

## Pioneering work: GaAs quantum dots



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

200  $\mu$ s spin coherence time:  
H Bluhm *et al*, Nature Physics  
7, 109 (2011)

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

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# Magnetic resonance for QIP

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

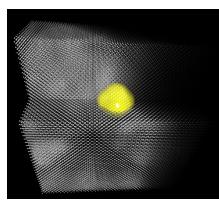
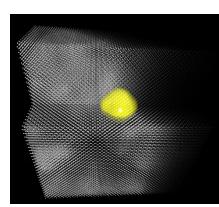


Image by Manuel Vögeli



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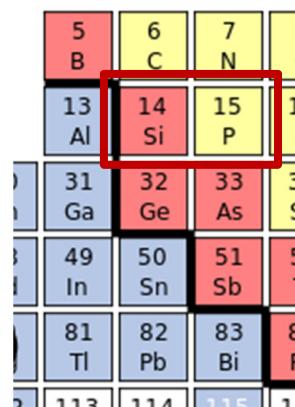
# Donors in silicon



Group Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	H																He	
2	Li		Be														Na	
3	Mg																Al	
4	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Zn	Ru	Ge	Se	S	Br	Ar	
5	Rb	Sr	Y	Zr	Ta	W	Ta	Os	Ir	Pt	Sn	Re	Te	Te	Te	Te	Xe	
6	Cs	Ba	La	Hf	Ta	W	Ta	Os	Ir	Pt	Sn	Re	Te	Te	Te	Te	Xe	
7	Fr	Ra		Rf	Ts	Os	Th	Hs	Mt	Ds	Uut	Uub	Fl	Uup	Uus	Uuo	Uuu	
Metals																		
Lanthanides																		
	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71			
	La	Ce	Pr	Dy	Pm	Sm	Gd	Tb	Er	Ho	Er	Tm	Lu					
	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103			

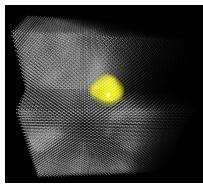
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## Donors in silicon



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## 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,  $\epsilon_r$   
Effective mass,  $m^*$

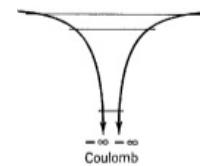
W Kohn, Shallow Impurity States in Silicon and Germanium, Solid State Physics 5, 257 (Academic, New York 1957)

Coulomb potential:  $V = \frac{e^2}{4\pi\epsilon_0 r}$

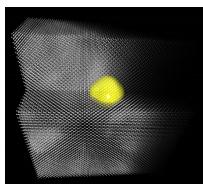
${}^1\text{H}$  energy levels:  $E = -\frac{13.6 \text{ eV}}{n^2}$

Donor energy levels:

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

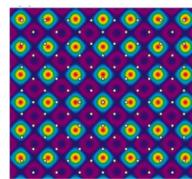


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## Donors in silicon

- Hydrogenic model



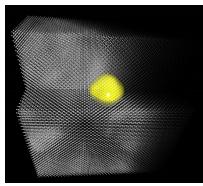
B Koiller, RB Capaz, X Hu and S Das Sarma, PRB 70, 115207 (2004)

	Relative permittivity, $\epsilon_r$	$m^*/m_e$	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:

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

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## Donors in silicon

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

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)

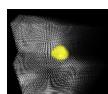


**Bell Laboratories**

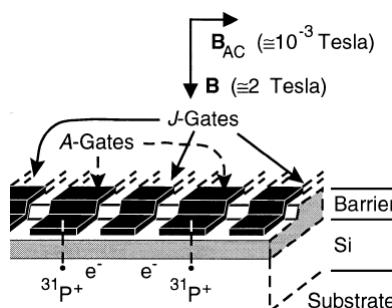
Pioneering early work:

- 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)

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## Donor qubits in silicon

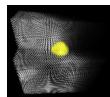


Kane proposal:  
BE Kane, *A silicon-based nuclear spin quantum computer*, Nature **393**, 133 (1998)

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)

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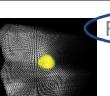


## Donor qubits in silicon

### Mini-overview

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

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Fabrication   Initialisation   Readout   Control   Coherence

## Atomically-precise fabrication

Using scanning tunnelling  
microscopy (STM)

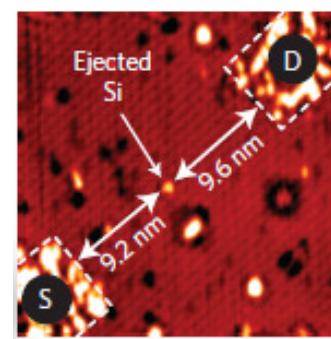


JL O'Brien *et al.*, PRB **64**, 161401 (2001)

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)



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Fabrication Initialisation Readout Control Coherence

**Scanning tunnelling microscopy (STM)**

The diagram illustrates the principle of STM. A grey 'sample' plate with red horizontal lines is shown with a 'tip' at the top. A circular inset shows a cross-section of the tip above a layer of atoms (represented by blue and red spheres). Red arrows labeled 'tunneling electrons' indicate the flow between the tip and the sample. A small image of a yellow dot on a grid pattern is shown in the top left corner.

[www.nobelprize.org/educational/physics/microscopes/scanning](http://www.nobelprize.org/educational/physics/microscopes/scanning)

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**Atomically-precise fabrication**

**Using STM and hydrogen lithography**

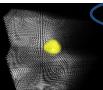
The diagram shows a four-step process:

- Mono-hydride Deposition:** An STM tip is positioned above a silicon (Si) surface. Hydrogen (H) atoms are shown above the surface, with arrows indicating their movement onto the Si atoms.
- Hydrogen Desorption:** The STM tip is moved closer to the surface, causing the hydrogen atoms to desorb from the silicon surface.
- PH<sub>3</sub> Dosing:** Phosphine (PH<sub>3</sub>) molecules are shown above the surface, with arrows indicating their movement onto the desorbed silicon atoms.
- Silicon Overgrowth:** The final state shows a layer of silicon atoms overgrown with smaller grey circles, representing phosphorus atoms.

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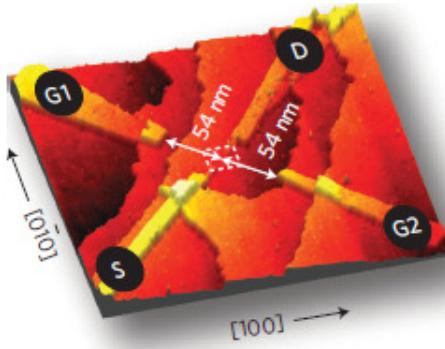
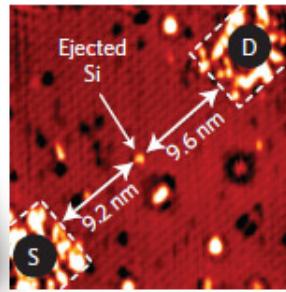


## Atomically-precise fabrication

Using STM and hydrogen lithography

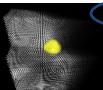
A Single Atom Transistor  
M Ruechle et al., Nat Nano 7, 242 (2012)

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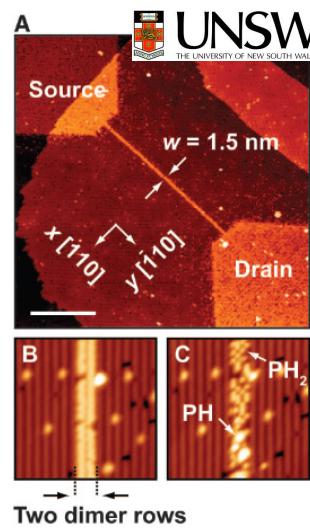


## Atomically-precise fabrication

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

Using STM and hydrogen lithography

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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

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Fabrication Initialisation Readout Control Coherence

## Initialisation by spin polarization

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

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

$\text{Polarization}$

$\text{Electrons}$

$\text{Protons}$

Magnetic field = 10 T

Temperature (K)

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:  $P_{\text{measured}} = 68\%$

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## 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  $^{28}\text{Si}$  "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

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

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

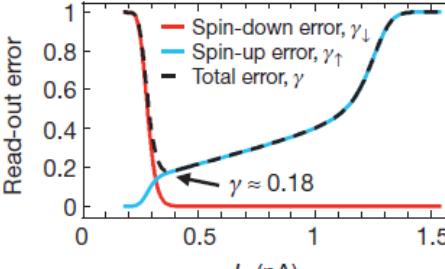
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Fabrication Initialisation **Readout** Control Coherence

## Initialisation using a readout

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Read-out error

Spin-down error,  $\gamma_{\downarrow}$

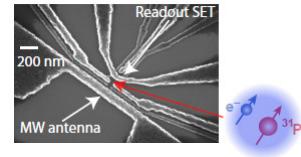
Spin-up error,  $\gamma_{\uparrow}$

Total error,  $\gamma$

$I_T$  (nA)

$\gamma \approx 0.18$

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%



Readout SET

200 nm

MW antenna

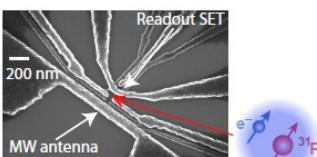
$e^-$   $^{31}P$

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Fabrication Initialisation **Readout** Control Coherence

## Single-shot single-spin SET readout

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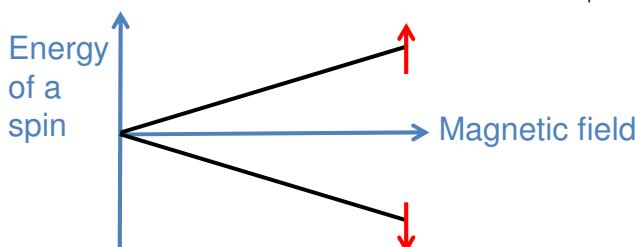
Readout SET

200 nm

MW antenna

$e^-$   $^{31}P$

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)



Energy of a spin

Magnetic field

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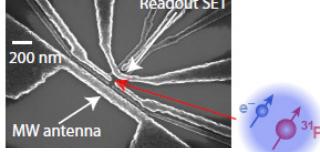
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## Single-shot single-spin SET readout

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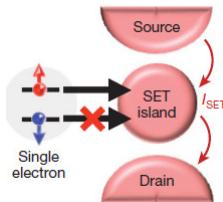
A Morello et al., *Single-shot readout of an electron spin in silicon*, Nature **467**, 687 (2010)

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



Energy

donor metal island



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

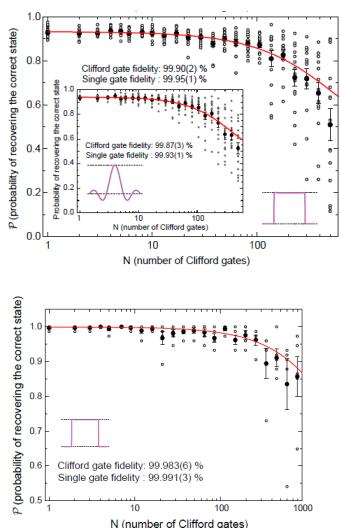
Fabrication Initialisation Readout Control Coherence

## 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  $^{28}\text{Si}$ :  
99.95% for electron  
99.99% for nucleus



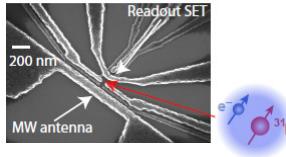
$P$  (probability of recovering the correct state)

$N$  (number of Clifford gates)

Clifford gate fidelity: 99.87(0) %  
Single gate fidelity: 99.95(2) %

Clifford gate fidelity: 99.87(0) %  
Single gate fidelity: 99.93(1) %

Clifford gate fidelity: 99.983(6) %  
Single gate fidelity: 99.991(3) %



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Fabrication Initialisation Readout Control **Coherence**

## Measuring coherence

spin  
echo  
decay

In rotating frame

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Fabrication Initialisation Readout Control **Coherence**

## Coherence: donor qubit ensembles

**Silicon:**

- Low impurity density
- Low density of nuclear spins
- Can use enriched  $^{28}\text{Si}$
- Low spin orbit coupling

Normalized Signal (log scale)

Total delay (min)

Cryogenic XY-16

1.2K  
1.9K  
4.2K

$T_2 = 180\text{ min}$

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

$T_1$  and  $T_2$  (s)

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

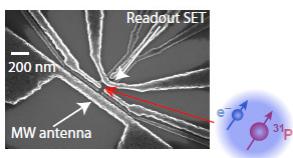
Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

Fabrication Initialisation Readout Control **Coherence**

## Coherence of a single electron spin

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



Normalized echo signal vs Total precession time (ms) for electron spin coherence.

Plot 1:  $T_{2e}^H = 0.95 \text{ ms}$ ,  $n = 3.5$ . Sequence:  $\pi/2 - \pi - \pi/2$ .

Plot 2:  $T_{2e}^H = 559 \text{ ms}$ ,  $n = 3.1$ . Sequence:  $\pi/2 - \pi - X - Y - Y - X - \pi/2$  (scaled by 8,192).

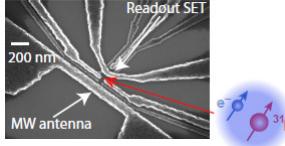
Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

Fabrication Initialisation Readout Control **Coherence**

## Coherence of a single nuclear spin

 **UNSW**  
THE UNIVERSITY OF NEW SOUTH WALES

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



Normalized echo signal vs Total precession time (ms) for nuclear spin coherence.

Plot b:  $T_{2n}^H = 20.4 \text{ ms}$ ,  $n = 1.4$ . Sequence:  $\pi/2 - \pi - \pi/2$ .

Plot c:  $T_{2n}^H = 1.75 \text{ s}$ ,  $n = 2.0$ . Sequence:  $\pi/2 - \pi - \pi/2$ .

Plot c:  $T_{2n}^{CPMG} = 19.6 \text{ ms}$ ,  $n = 1.4$ . Sequence:  $\pi/2 - \pi - X - Y - Y - X - \pi/2$  (scaled by 32).

Plot c:  $T_{2n}^{CPMG} = 35.6 \text{ s}$ ,  $n = 2.2$ . Sequence:  $\pi/2 - \pi - X - Y - Y - X - \pi/2$  (scaled by 1024).

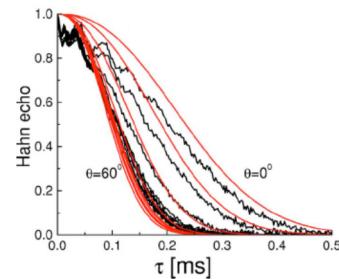
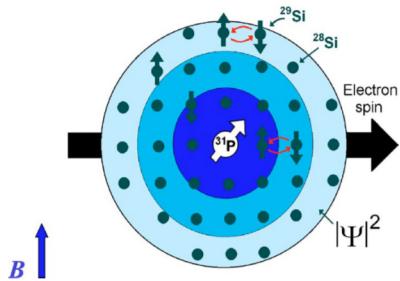
Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

Fabrication Initialisation Readout Control **Coherence**

## Simulating coherence

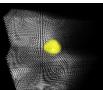
Central spin problem: one electron spin in a bath of >1000 nuclear spins.  
Intractable to do a full quantum simulation with a classical computer.

### 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)

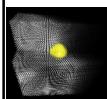
Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015

 Fabrication Initialisation Readout Control Coherence

## Conclusions and perspective

Need to couple up two donors

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## Bismuth donors in silicon

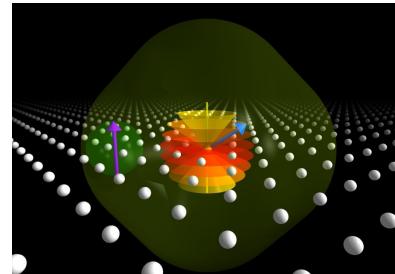
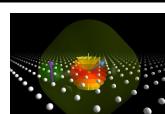


Image by Manuel Vögeli

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)

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

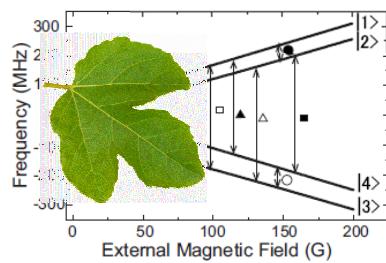


## Phosphorus qubits in silicon

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

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

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



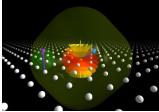
$$|1\rangle = |\uparrow\uparrow\rangle,$$

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

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

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

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

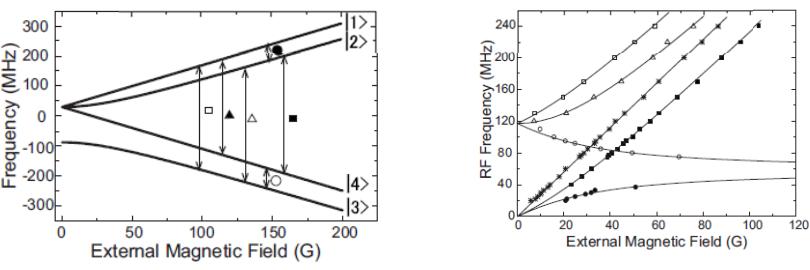


## Phosphorus qubits in silicon

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

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

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

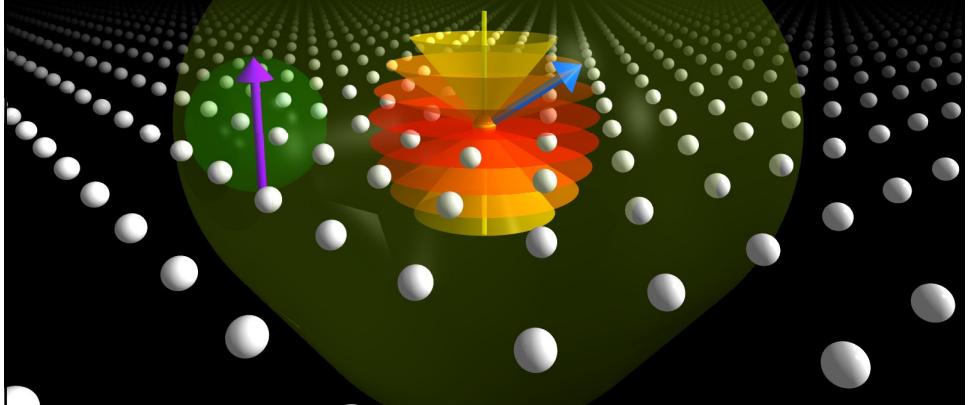


The left plot shows Energy (MHz) on the y-axis (ranging from -300 to 300) versus External Magnetic Field (G) on the x-axis (ranging from 0 to 200). It displays four energy levels: |1> (top), |2>, |3>, and |4> (bottom). Arrows indicate transitions between levels. The right plot shows RF Frequency (MHz) on the y-axis (ranging from 0 to 240) versus External Magnetic Field (G) on the x-axis (ranging from 0 to 120). It shows multiple sets of curves for different transitions, with data points represented by various symbols (squares, triangles, circles) and solid lines connecting them.

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

## Bismuth qubits in silicon

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

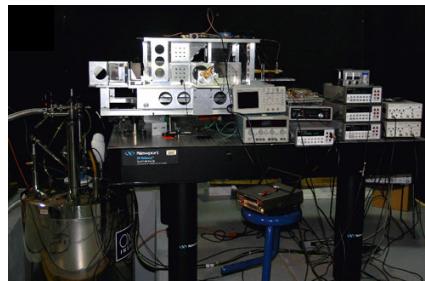
$$S = 1/2, I = 9/2 \text{ and } A/2\pi = 1475 \text{ MHz}$$


A 3D visualization of a silicon lattice (represented by white spheres) containing a bismuth atom (represented by a central yellow/orange cluster with three blue arrows indicating spin). The background is dark green.

# 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)



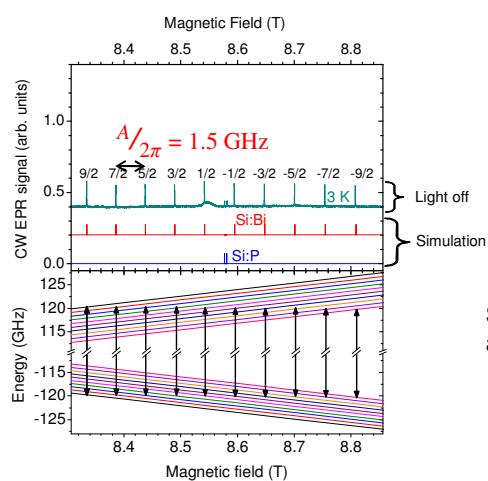
99.9% electron spin polarization



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

Bismuth donors in silicon

## ESR of Si:Bi at 240 GHz

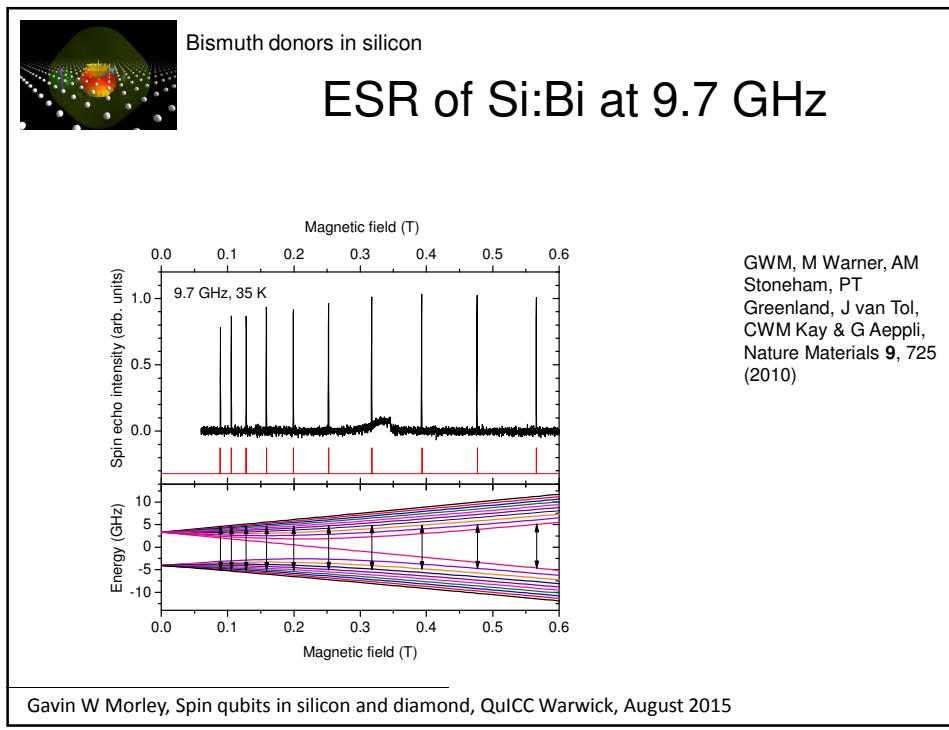
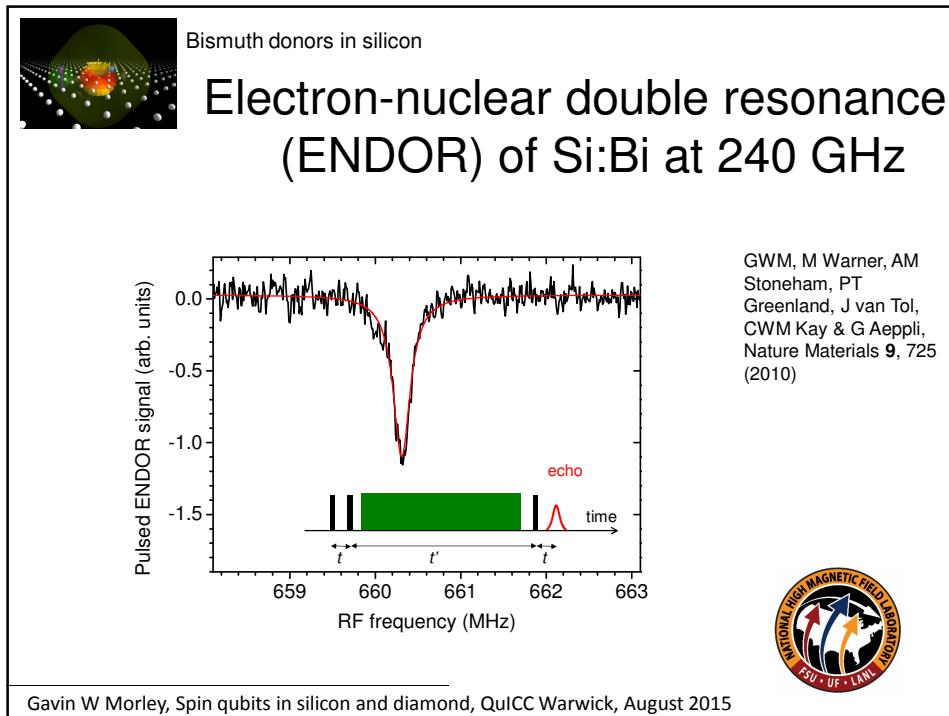


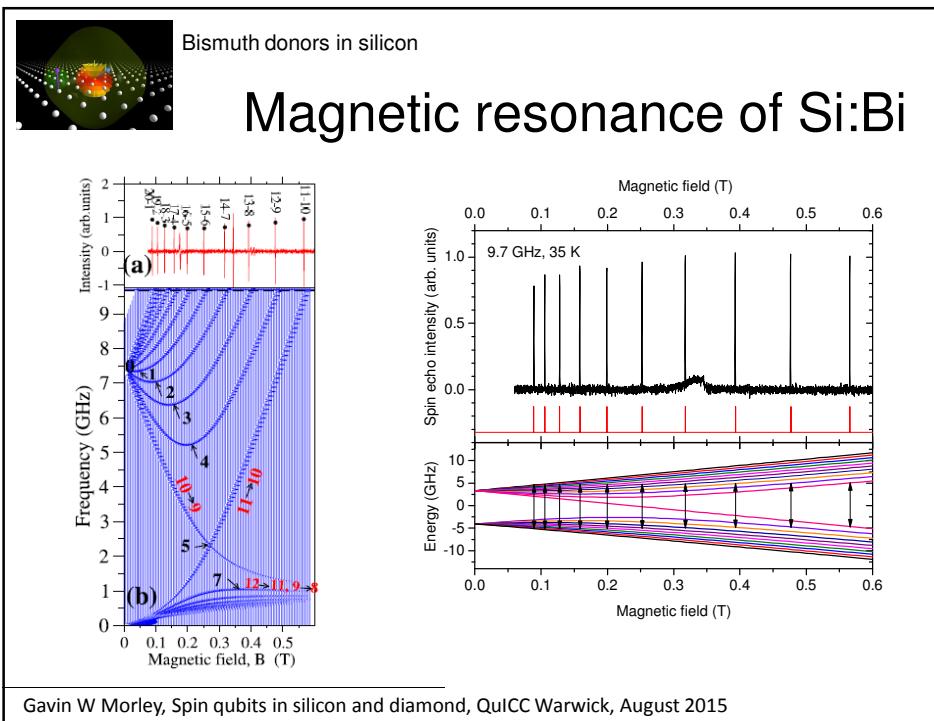
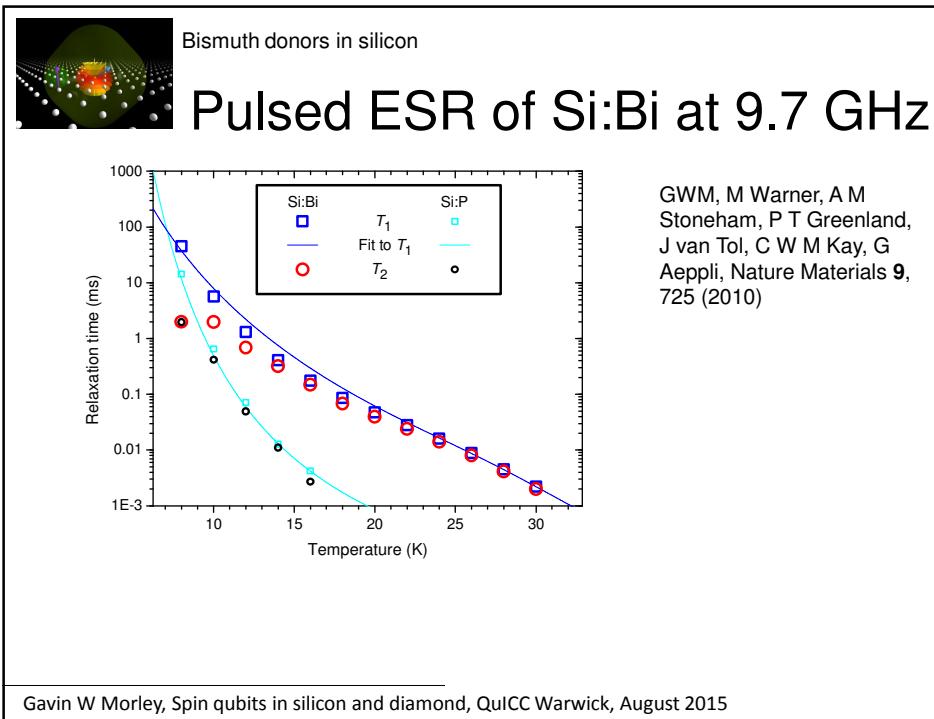
GWM, M Warner, AM Stoneham, PT Greenland, J van Tol, CWM Kay & G Aepli, Nature Materials **9**, 725 (2010)

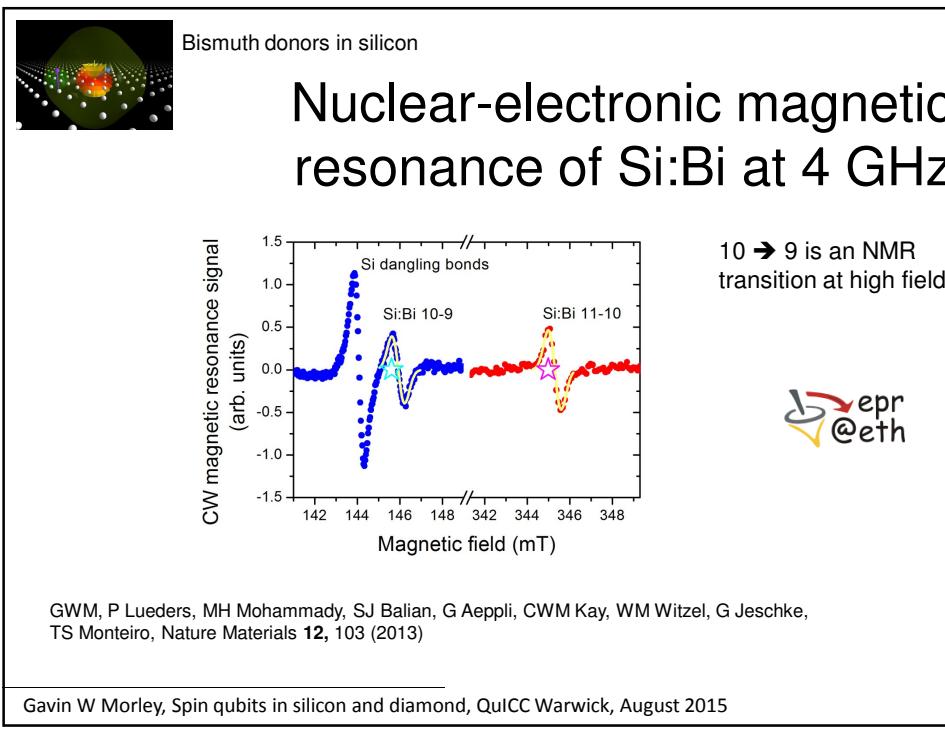
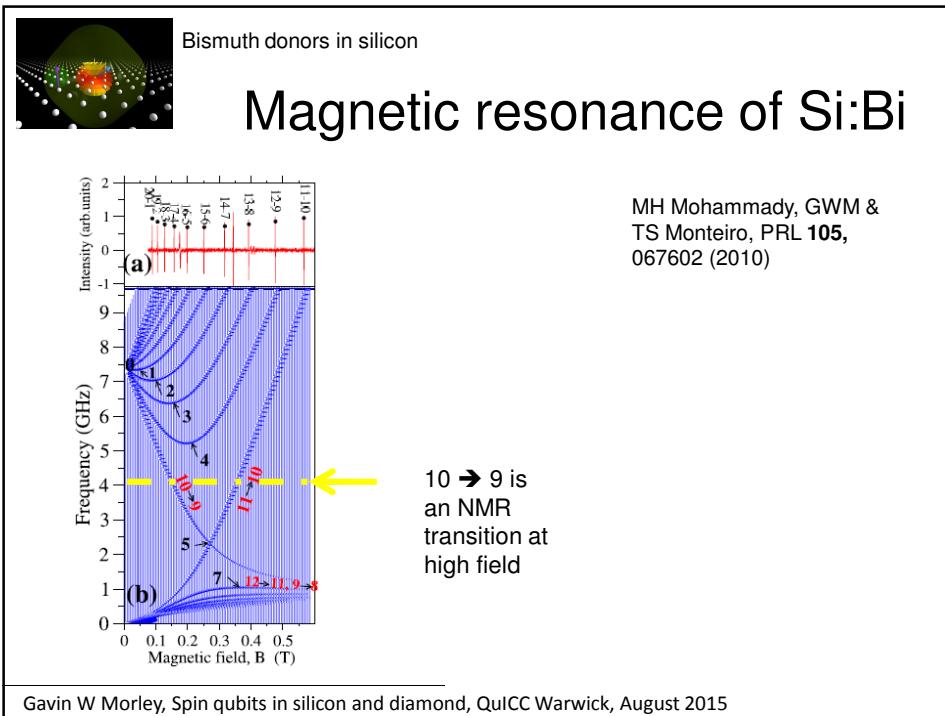
Si:P and Si:Bi resonances are resolved



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







Bismuth donors in silicon

## Quantum control of a hybrid nuclear-electronic spin system

Integrated echo intensity (arb. units) vs Time,  $\tau$  (ns). The plot shows two curves: 11-10 (High field) in red and 10-9 (Low field) in blue. An inset shows the pulse sequence:  $\pi/2$ ,  $\tau$ ,  $\pi/2$ ,  $\pi$ , echo, time.

Fourier Magnitude (arb. units) vs Frequency ( $\text{ns}^{-1}$ ). The plot shows two peaks: 11-10 (High field) at approximately 0.015  $\text{ns}^{-1}$  and 10-9 (Low field) at approximately 0.018  $\text{ns}^{-1}$ .

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

epr @eth

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

Integrated echo intensity (arb. units) vs Time,  $t$  (ms). The plot shows two curves: 11-10 (High field) in red and 10-9 (Low field) in blue. An inset shows the pulse sequence:  $\pi/2$ ,  $\tau$ ,  $\pi/2$ ,  $\pi/2$ ,  $\pi/2$ , echo, time.

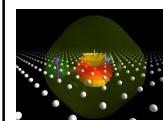
Relaxation time (ms) vs Temperature (K). The plot shows data for 10-9 (low field) and 11-10 (high field) transitions at 10 GHz. The relaxation times  $T_1$ ,  $T_2$ , and  $T_s$  are plotted against temperature. A fit curve is shown for  $T_1$ .

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

epr @eth

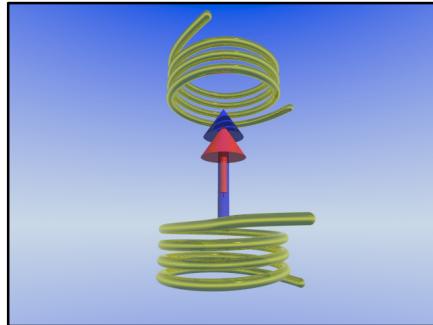
Sandia National Laboratories

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



Bismuth donors in silicon

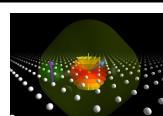
# Hybrid MR of Si:Bi at 4 GHz



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

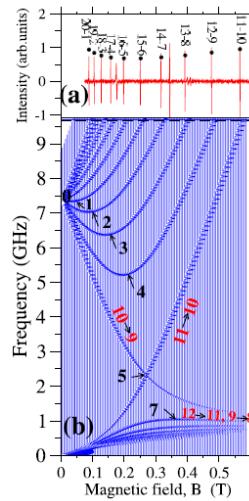
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Gavin W Morley, Spin qubits in silicon and diamond, QuICC Warwick, August 2015



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)
  - S J Balian *et al.*, PRB **89**, 045403 (2014)

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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**

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