Donor impurities in silicon as a platform for few-body problems:
Donor excitation and donor-donor interactions

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Physics of isolated single donors

Experiments with large ensembles
A hydrogen-like atom in a silicon chip: The Group 5 impurity

P looks like Si with
- an extra +ve charge in the ion
- an extra electron orbiting

The electron-ion attraction is screened by $\varepsilon_r$

The mass is reduced by $m^*$
Scaling from hydrogen to donor

- **Binding energy:**
  \[ E_R = \frac{1}{2} \left( \frac{e^2}{4\pi\hbar} \right)^2 \frac{m_e}{\varepsilon^2} \]

- **Bohr radius**
  \[ a_B = \frac{4\pi\hbar^2}{e^2} \frac{\varepsilon}{m_e} \]

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At room temperature the valence electron is donated to conduction, but at low temperature it is bound to the ion, just like hydrogen. The Coulomb attraction is reduced by the dielectric constant, so the binding energy is very small, and the state radius is very large.
Rydberg spectrum of hydrogen

Hydrogen absorption spectrum seen superimposed on the emission from a very hot black body (a star)

\[ \frac{1}{\lambda} = \frac{1}{\lambda_0} \left[ \frac{1}{n^2} - \frac{1}{m^2} \right] \]

\( \lambda_0 = 91 \text{ nm} \)

Lyman series: 1s-2p, 1s-3p

Balmer series: 2s-3p, 3s-4p, 4s-5p, etc.
Rydberg spectrum of Si:P

Picus, Burstein and Henvis (1956)

First transmission spectrum of Si:P

\[ \frac{1}{\lambda} = \frac{1}{\lambda_0} \left[ \frac{1}{n^2} - \frac{1}{m^2} \right] \]

\[ \lambda_0 = 71 \mu m \]

\( \lambda \) is somewhat larger than \( \lambda_0 \), just because of quantum defect (ground state is deeper than expected)
Lyman series spectrum of $^{28}\text{Si:P}$


The cleanest solid material in the universe?
The THz Lyman lines are very sharp, so the lifetimes are very long.

INCOHERENT dynamics – orbitals are long lived.

**Si:P**

NQ Vinh *et al*, *PNAS* (2008)

Hubers *et al*, *PRB* (2013)

Stavrias *et al*, *PRB* (2017)

**Si:Bi**

Saeedi *et al*, *PRB* (2018)

NQ Vinh *et al*, *PRX* (2013)
The silicon environment is very clean, so the excitations are coherent.

Coherent dynamics – orbitals can be controlled coherently.


Litvinenko et al (2017)

Chick et al (2017)
Extreme diamagnetic response to magnetic fields


- The atomic unit of magnetic field

\[ B_a = \frac{\hbar}{(e a_B)^2} \]

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The donor THz dipole moments are very large

The absorption cross-sections of donors are very large (few nm$^2$ for silicon, many nm$^2$ for germanium)

- The atomic unit of electric field

$$F_a = E_H / \hbar \alpha_B$$

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<td>$F_a$</td>
<td>5.1 GVcm$^{-1}$</td>
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Scaling down to the single/few atom limit

Achievements and problems
Atomic Physics in the solid state – take advantage of microelectronics!

Donors have benefit over atoms in vacuum that they can be electrically read-out (with some violence) without the atom being kicked to kingdom come!

Electrical detection of donor Lyman lines through photoconductivity

[=Photo-thermal Ionization Spectroscopy (PTIS)]

We have detected as few as \(10^4\) donors …
Scaling down detection/readout to single atoms

Single-Shot Readout and Relaxation of Singlet and Triplet States in Exchange-Coupled 31P Electron Spins in Silicon
Andrew S. Dzurak, and Andrea Morello group UNSW
Single atom P positioning with H lithography in Si [collaborators at UCL]


Donors can be placed with (almost) atomic precision
Importance of Si:P QIP

Stoneham-Fisher-Greenland scheme: THz gated entanglement/ control/gating between qubits

Kane/Hollenberg scheme: THz induced spin-to-charge conversion between qubit and SET donors


Large scale silicon quantum computer architectures (I)

Some donor quantum computer architectures need very precise placement of atoms (few nm here)

Melbourne/U NSW (Simmons group) [C. D. Hill et al Science Advances 2015: 1, e1500707]
SIMPLE Single Ion Multispecies Positioning at Low Energy

Ion beam implantation – Surrey Ion Beam Centre, Ionoptika Ltd and Manchester

- SIMPLE is a high precision single ion implantation tool specifically targeted at supporting solid-state quantum technologies.
- The aim is for the tool to be a scalable and repeatable manufacturing method for arrays of qubits for quantum processors.
- This is a system developed around a liquid metal ion gun (LMIG) designed to produce sub 20nm spatial resolution, and fire with absolute certainty of the number of ions implanted.
- Species available for Implantation: Au, Ge, Bi. In future, available species: Se, Si, B, In
- The tool has measured beam spotsizes below 20nm – which along with implant straggle, determine the uncertainty of ion positioning.
- Ions can be implanted with energies ranging from 15-25keV.
How do we see what we have made?

Scanning probe microscopy

An AFM tip as a microwave antenna
Scanning Microwave microscopy (SMM)

An AFM tip as a near-field scatterer
Scattering-Scanning Near-field Optical Microscopy (s-SNOM)
SMM measurements of buried P resonators and ribbons/wires


After lithography and 15nm Si encapsulation. P triangle has incorporated phosphorus; H does not

Scale bar = 1.4μm

SMM is good for large conductors, but NOT single qubit level
Single InAs quantum dots have been observed with THz SNOM

The dipole moment of the s-p inter-sub-level transition in c.b. of a dot is about the same as for a donor.
Low temperature (10K) THz scanning SNOM Neaspec at Surrey

- 8 um QCL light source
- Base temperature 5.5K
- Best resolution so far 30nm (tip dependent)
- Interferometric detection (sample/tip is one arm of Michelson) gives amplitude and phase (related to real/imaginary parts)

Test with Si/SiO2 grid with dust speck

Note different contrast with topography/amplitude/phase indicates real SNOM effect
Outlook

- Silicon donors have interesting (extreme) properties (giant diamagnetism, giant non-linearities etc)
- Silicon donors are promising candidates for qubits
- Donors can be placed in designer clusters, so the interactions can be controlled
- Mid-IR to THz transitions control the orbital motion (and provide a means to control interactions between qubits)
- SNOM provides a way to characterize qubit sample structures
- The combination of THz pulses with SNOM might provide a way to address single qubits
- A route to designer few-body physics problems