Exploration of quantum computer architectures with donor spin qubits in silicon

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The Quest for Quantum Computing

Classical information

Quantum Information

Classical (dissipative, Boolean logic)

Quantum (superposition of states, entanglement)

• Flavors of quantum computing approaches\(^1\)
  • Quantum circuit model
  • Measurement based quantum computing
  • Adiabatic quantum computing
  • Topological quantum computing
  • …

\(^1\)see e. g. “Quantum computers: Definition and implementations”, C. A. Perez-Delgado and P. Kok, Phys. Rev. A 83, 012303 (2011)
Criteria for physical implementation of a quantum computer (DiVincenzo)

1. Well defined extendible qubit array – stable memory
2. Initialization in the “000…” state
3. Long decoherence time (>10^4 operation time, to allow for error correction)
4. Universal set of gate operations (not, cnot)
5. Read-out: Single-quantum measurements (projective measurement)
6. Efficient quantum communication (form, transmit and convert “flying qubits”)

Nuclear and electron spins in silicon are promising qubit candidates

10 to 100 nm
Donor electron spin qubits in silicon

$^{31}\text{P}$ ("natural quantum dot")

Si: [Ne].3s$^2$.3p$^2$

P: [Ne].3s$^2$.3p$^3$

- 3p$^3$ binding energy: 45 meV
- 100% abundant isotope with I=1/2
- $^{28}\text{Si}$ matrix can be prepared with I=0
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   → Stark shift measurements (proto nuclear spin control gate)
   → electron-nuclear spin state transfer

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   → spin dependent transport in transistors

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   → electron shuttling
Exploration of spin qubits in donor – quantum dot devices

- Donor electron spins couple to donor nuclear spins for long term quantum memory
- Quantum logic on donor electrons coupled to quantum dot electrons and between adjacent quantum dots
- Quantum communication by coherent electron shuttling between quantum dots

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Single Ion Placement with Scanning Probe Alignment
- Non-destructive imaging and nm-apertures for nm-accuracy

A. Persaud, et al.,
Nano Letters 5, 1087 (2005)

Array of 90 nm dots in PMMA from ion implantation with scanning probe alignment

In situ scanning probe image of a FinFet
Motivation
• develop a non-contact scanning probe integrated with ion beams for high resolution imaging and alignment of single dopant ions to spin readout transistors
• develop a versatile ion source and beam line integrated with the scanning probe

Approach
• piezoresistive force readout and actuated cantilevers for non-contact imaging
• FIB processing for nano-apertures and imaging tips
• microwave driven permanent magnet ion source for donor ion beam formation

Microwave driven ion source (2.45 GHz)
co. Qing Ji
Setup for Ion Implantation with Scanning Probe Alignment

- camera and 5x5 cm range x-y stages for coarse alignment
- scan range of target piezo-stage is 30 x 30 µm
- Piezoresistive scanning force microscope technology in close collaboration with Prof. Ivo Rangelow, Tech. Univ. Ilmenau
Single Ion Detection in Readout Transistors through ion impact induced current changes

- single ion doping through detection of current transients from single ion impacts (dI~ few $10^{-4}$ dI/I, in 2x2 µm aFets)

A. Batra et al., Appl. Phys. Lett. 2007
Single ion implantation demonstrations in 100 nm scale devices

- **Xe$^{6+}$**
  - 48 KeV
  - 100 nm x 300 nm
  - Ion beam $1.3 \times 10^{-13}$ A/mm$^2$
  - $\Delta I/I = 10$ to 25%

- **Bi$^+$**
  - 10 keV
  - 80x4000 nm
  - Ion beam $1.3 \times 10^{-13}$ A/mm$^2$
  - $\Delta I/I \sim 5\%$
Depth profiles of ion implanted and annealed donors in silicon

- minimal straggling and diffusion for Bismuth

- P (blue, 58 keV, 4x10^{11} \text{ cm}^{-2}, 7 \text{ degree}, 920 \text{ C}, 10 \text{ s}) and As (top, red, 120 keV, 4x10^{11} \text{ cm}^{-2}, 7 \text{ degree}, 920 \text{ C}, 10 \text{ s}), Sb and Bi implanted into silicon. 121Sb: 60 keV, 2x10^{11} \text{ cm}^{-2}, 123Sb, 120 keV, 4x10 \text{ cm}^{-2} (850 \text{ C}, 10 \text{ s}) Bi: 120 keV, 1012 \text{ cm}^{-2} (with PAI: annealed at 600 \text{ C} for 4 \text{ min.}, without PAI, annealed at 650 \text{ C} for 9 \text{ min}).
1. Well defined extendible qubit array – stable memory

- qubit array formation by single ion implantation with scanning probe alignment
- non-destructive imaging with nm-accuracy
- C. D. Weis, et al., NIM B 267, 1222 (2009)
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The degenerate electron energy levels split in a magnetic field.

Free Electron

$\hat{H} = g_e \mu_B e B \cdot S$

Electron bound to $^{31}\text{P}$

$\hat{H} = g_e \mu_B e B \cdot S + A_{\text{hyperf}} S \cdot I - g_N \mu_B N B \cdot I$
Paramagnetic centers are identified via their microwave absorption spectrum.

<table>
<thead>
<tr>
<th>Species</th>
<th>$I$</th>
<th>$A$ (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{31}\text{P}$</td>
<td>$1/2$</td>
<td>117.53</td>
</tr>
<tr>
<td>$^{75}\text{As}$</td>
<td>$3/2$</td>
<td>198.35</td>
</tr>
<tr>
<td>$^{121}\text{Sb}$</td>
<td>$5/2$</td>
<td>186.802</td>
</tr>
<tr>
<td>$^{123}\text{Sb}$</td>
<td>$7/2$</td>
<td>101.518</td>
</tr>
<tr>
<td>$^{209}\text{Bi}$</td>
<td>$9/2$</td>
<td>1475.4</td>
</tr>
</tbody>
</table>
Electron spin coherence times are determined via pulsed ESR measurements.
Isolated Donor $T_2 \geq 10$ seconds in $^{28}\text{Si}$ at 2 K

- $T_1$: spin-lattice relaxation time
- $T_2$: spin-spin relaxation time (phase coherence)
- $2T_1 \geq T_2$

Bismuth is implanted into isotopically enriched silicon-28 for measurements of electron spin coherence.

28-Si (99.93%) epi layer (700nm)

natural Silicon

Secondary Ion Mass Spectroscopy

Implanted Bismuth

(Natural Si > 10 kΩcm for measurements of electrical activation)

Total fluence: $1.1 \times 10^{12}$ cm$^{-2}$

$E_{\text{kin}} = 40, 80, 120, 200$ and 360keV
Energy level splitting for bismuth in silicon.

\[ \hat{H} = g_e \mu_B e B \cdot S + A_{\text{hyp}} S \cdot I - g_N \mu_B N B \cdot I \]

\[ E_\pm = -\frac{A}{4} - g_N \mu_N B m \pm \left( I + \frac{1}{2} \right) \frac{A}{2} \sqrt{1 + \frac{2m}{I + \frac{1}{2}}} \alpha + \alpha^2 \]

\[ \alpha = \frac{g_e \mu_e B + g_N \mu_N B}{A(I + \frac{1}{2})} \]

\[ m = m_s + m_I \]

\[ ZFS = A(I + 1/2) \]

\[ ZFS_{\text{Bi}} = 63 \times ZFS_p \]
Cw-ESR measurements confirm electrically active Bismuth

Five stacked samples $\approx 1.5 \times 10^{12}$ Bi atoms
Criteria for physical implementation of a quantum computer

3. **Long decoherence time** (>10⁴ operation time, to allow for error correction)

![Graph showing relaxation times vs. temperature]

- Thermal activation and electron spin resonance measurements of implanted bismuth in isotopically enriched silicon-28
  - Coherence time much shorter than in idealized case due to higher donor concentration (9·10¹⁶ cm⁻³) near a noisy interface


- Idealized case of isolated donors (2·10¹² - 10¹⁴ cm⁻³)
Bismuth $T_{2e}$ times are comparable to other implanted donor species at similar dopant concentration per hyperfine line.

<table>
<thead>
<tr>
<th>Interface</th>
<th>Peak dopant depth (nm)</th>
<th>Apparent activation ratio</th>
<th>$T_1$ (ms) at 5.2 K</th>
<th>$T_2$ (ms) at 5.2 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>50</td>
<td>(3.4%)</td>
<td>15±2</td>
<td>0.3±0.03</td>
</tr>
<tr>
<td>H–Si</td>
<td>50</td>
<td>—</td>
<td>16±2</td>
<td>0.75±0.04</td>
</tr>
<tr>
<td>SiO₂</td>
<td>150</td>
<td>100%</td>
<td>16±1</td>
<td>1.5±0.1</td>
</tr>
<tr>
<td>H–Si</td>
<td>150</td>
<td>—</td>
<td>14±1</td>
<td>2.1±0.1</td>
</tr>
</tbody>
</table>

Implanted Bismuth: $T_{2e}=0.7\text{ms}$

- next: $T_{2e}$ at “clock transitions”, where $df/dB=0$, expected to be insensitive to surface magnetic noise
- preliminary results (Steve Lyon, Princeton): $T_{2e}$ at clock transition in these same Bismuth samples is over ten times longer than at standard electron spin transitions $\Rightarrow$ insensitivity to surface magnetic noise is very exciting for bismuth donor qubit integration near surfaces in devices! 

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Probing donor spins with Electrically-Detected Magnet Resonance (EDMR)

- Accumulation-mode Field Effect Transistors (aFETs)
  - Neutral donors in channel, gate-tunable conduction electron (2DEG) density (polarization)
  - Strength of EDMR (vs. tunneling): spectroscopic signature of donor species and optimization for scaling from large ensembles to single donor
  - Access to small spin numbers and probing of spin quality

\[ f = 9.6 \text{GHz} \]

- EDMR Intensity

\[ B_0 = 0 \quad B_0 \neq 0 \]

\[ R_{on-res.} \quad R_{off-res.} \]

\[ \Delta R \]

\[ m_s = \frac{1}{2} \]

\[ m_s = \frac{-1}{2} \]

\[ m_l = \frac{5}{2} \]

\[ m_l = \frac{3}{2} \]

\[ m_l = \frac{1}{2} \]

\[ m_l = -\frac{1}{2} \]

\[ m_l = -\frac{3}{2} \]

\[ m_l = -\frac{5}{2} \]

- x-band EDMR with \(^{121}\)Sb implanted aFets at 5 K

Readout of donor electron spins in silicon transistors

- Spin flips change transistor currents but not by much ($dI/I \sim 10^{-6}$ at x-band)

- Electrons in a two-dimensional electron gas (2DEG) and donor electrons are detected through measurements of current changes that are resonant with spin transitions

- Donors detected via polarization transfer:
  
  \[
  I \rho = f(p_c^2)
  \]

  - $p_c$ is the critical concentration of donors
  - $T_x^{-1}$ and $T_{1c}^{-1}$ are relaxation times

- Achieved sensitivity of a few thousand spins

- An alternative approach using spin dependent tunneling achieved single donor spin detection (Morello et al., Nature, ‘10)
Readout for single donor electron and nuclear spin by EDMR

- transfer quantum information from electron to nuclear spin\(^1\)
- measure nuclear spin population by detecting presence/absence of a spectral line
- need to measure within nuclear spin flip time
- repeat entire procedure → get values of \(\alpha\) and \(\beta\) for electron spin qubit with correct statistics

\[
|\Psi_e\rangle = \alpha |\uparrow\rangle_e + \beta |\downarrow\rangle_e
\]


Evidence for transport through single donor atoms (4.2K)

• several devices show strong resonance peaks after turn-on:

• Corner effects in FinFETs

\[ l_l = 76\text{nm}, \, w_l = 50\text{nm} \]
Readout – Find single donor transport resonances in FinFets and run ESR on these for single nuclear spin state detection (within $T_{1n}$).

Magneto transport, $l = 100$ nm, $w = 50$ nm triple gate FinFet. Bottom: (a) sub-threshold regime with isolated transport resonances. Some showing a strong magnetic field dependence, corresponding to the Zeeman shift of paramagnetic states, either donor or defect states (red line). (b) Same bias window at higher gate voltage. Coulomb oscillations of the multi-electron quantum dot do not exhibit strong magnetic field dependence at all. $T \sim 0.1$ K. Experiments at National High Magnetic Field Lab, Tallahassee.

But we did not succeed in detecting spin resonances on single dopant transport features.
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All-electrical nuclear spin polarization of donors

• “hot” 2DEG electrons from high source-drain bias fields, rapid exchange scattering leads to difference in spin and lattice (phonon) temperatures

• Nuclear polarization detected by EDMR

• 5K, 300GHz radiation and in-plane B-field (co. J. van Tol, NHMFL, Tallahassee)

\[ \tau_X \sim \frac{1}{B^2TA^2I} \]

- \( \tau_X \): electron-nuclear spin flip-flop rate scaling
  B: external magnetic field
  T: temperature
  A: hyperfine coupling strength
  I: nuclear spin

- \( P_n = \frac{(Y\uparrow n - Y\downarrow n)}{(Y\uparrow n + Y\downarrow n)} \) =66% for Phosphorus at 12 T (I=1/2, A=0.1 GHz)
  \( \rightarrow \) Expect for Bismuth at 0.3 T (I=9/2, A=1.5 GHz)
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   → coherent electron shuttling, ensemble tests in back gated 28-SOI devices (in progress, co. J. Morton)
Outlook – Exploration of quantum computer architectures with donor spin qubits in silicon

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