Building a quantum computer using quantum dots in silicon

Susan Coppersmith

University of Wisconsin-Madison
Department of Physics
UW-Madison Solid-State Quantum Computing Team

Pl: Mark Eriksson
Sam Neyens, Ryan Foote, Brandur Thorgrimsson, Trevor Knapp, Evan MacQuarrie, Nathan Holman, Joelle Baer, JP Dodson, Tom McJunkin, Don Savage, Max Lagally

SNC theory collaborators:
Mark Friesen
Yuan-Chi Yang, Joydip Ghosh, Ekmel Ercan, Adam Frees, Cameron King, John Gamble, Viktoriia Kornich, Robert Joynt

Sponsored in part by the Army Research Office, the Office of Naval Research, the Department of Energy, the National Science Foundation, and the United States Department of Defense.

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressly or implied, of the U.S. Government.
Overview of our approach: quantum dots in Si/SiGe heterostructures confined and controlled with voltages applied using top gates.

Voltages applied to top gates define electron potentials. Conductance through quantum point contact (QPC) depends on dot occupancies.

Why make qubits using silicon quantum dots?

Fabrication techniques similar to those used in (classical) electronics

→ Plausible path to large-scale scalability
→ Plausible path to integration with large-scale classical electronics

Overview of current status of silicon quantum dot qubits:

Single-qubit gates:
>99.9% fidelity gates demonstrated experimentally

Theory predicts even higher fidelities are possible by increasing driving strength

Two-qubit gates:
CNOT fidelity >90%; Bell state fidelities ~80%

There are strong indications that higher fidelities are achievable
Single-qubit gates in silicon quantum dots

Several groups have demonstrated single-qubit gate fidelities >99%
Yoneda et al. (Tarucha, RIKEN/Tokyo) have reported single-qubit gate fidelities >99.9%.

Single Clifford gate fidelity: 99.861±0.005%
Average single gate fidelity: 99.926±0.002%
Average fidelity from randomized benchmarking: 99.928%

Two-qubit gates in silicon quantum dots


A two-qubit gate: rotation rate of the second qubit depends on the state of the second qubit, and vice versa.

Yellow: Rotations of Qubit 2 when Qubit 1 is in state $|0\rangle$
Aqua: Rotations of Qubit 2 when Qubit 1 is in state $|1\rangle$

<table>
<thead>
<tr>
<th>state</th>
<th>fidelity</th>
<th>concurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Psi_+$</td>
<td>0.88$\pm$0.02</td>
<td>0.80$\pm$0.03</td>
</tr>
<tr>
<td>$\Psi_-$</td>
<td>0.88$\pm$0.02</td>
<td>0.82$\pm$0.03</td>
</tr>
<tr>
<td>$\Phi_+$</td>
<td>0.85$\pm$0.02</td>
<td>0.73$\pm$0.03</td>
</tr>
<tr>
<td>$\Phi_-$</td>
<td>0.89$\pm$0.02</td>
<td>0.79$\pm$0.03</td>
</tr>
</tbody>
</table>
Successful implementation of simple algorithms, but current two-qubit gate fidelities in Si are not yet good enough for scalable quantum computation. Dominant limitation is charge noise in the devices (but this is improving).
The field is progressing quickly, but the goal is challenging. Improving materials is crucial for making better silicon qubits.

Two examples:

- **Understanding the effects of defects in Si metal-oxide-semiconductor devices**
  - Impurities in the oxide can cause additional “impurity dots” that degrade performance
  - Problems can be mitigated both by improving materials and by changing gate designs.
  

- **Improving control of valley splitting in Si/SiGe heterostructures by modifying the materials stack**

Si/SiGe heterostructures versus Si MOS: Oxide defects versus control of valley physics

Which problem is easier to solve?

**Si-SiGe**
- Metal gates
- Oxide (a few nm)
- Silicon-germanium
- Silicon
- Electrons are close to defects in the oxide
- Valley splitting tends to be harder to control

**Si-MOS**
- Metal gates
- Oxide (a few nm)
- Silicon
- Valley splitting tends to be harder to control
Si MOS devices: Defects in oxide complicate behavior

A large fraction of Si MOS quantum dot devices unexpectedly fail to exhibit “spin blockade” (apparent violation of Pauli exclusion principle)

Natural explanation: defect induces impurity level with another electron.

Spin blockade in Si-MOS devices can be lifted via impurity-induced dots strongly coupled to lithographic dots

- **Impurity-induced dot requirements:**
  - Deep (1.0 meV) induced bound state level to avoid emptying during device tune up
  - Strong exchange coupling (>200 MHz) to nearby lithographic dot to allow random spin flips during singlet-triplet experiments

Volume of impurity locations leading to Pauli spin blockade (PSB) can be reduced by changing the device design so that screening of oxide layer is increased.

Overlapping gate devices allow for a large reduction in the volume of impurity locations that lead to an impurity-induced dot that lifts spin blockade.

SiGe heterostructure: need to improve control of the valley splitting of the electrons in the silicon quantum well.

Electron wavefunction perpendicular to quantum well oscillates with period $\sim 1$ nm.

The properties of the two valley states are very sensitive to disorder at the quantum well interface.

Need to control valley splitting — typically make it large enough so that valley states are well-separated from qubit subspace.
Valleys in Si

Si band structure

Constant energy surfaces above conduction band minimum (k-space)

Tensile strain in quantum well increases energy of 4 of the valleys, leaving two low-energy ±z valleys.
Splitting of $\pm z$ valleys is induced by jump in composition plus application of electric field

Increasing germanium concentration at interface increases the band offset between Si and SiGe, but tends to lower interface quality, which decreases valley splitting.
Heterostructure imperfections can suppress valley splitting significantly

- Valley splitting in a quantum well can be large (~1 meV or ~240 GHz)
- Requires ideal quantum well interface (uniform, infinitely sharp)
- In real samples, valley splitting is suppressed by non-uniformity
- Confinement improves valley splitting

Quantitative understanding of valley splitting requires a multiscale approach. (Valley splitting arises from atomic-scale physics, but want to use continuum equations to determine wavefunctions.)


But need to incorporate the effects of interface steps for the theory to be really useful for experiments.

Here, will discuss experimental measurements.
Strategy for improving control of valley splitting:

See if more complex materials stack for Si/SiGe heterostructures can make valley splitting larger and more controllable.

Motivation:
thoretical proposal by Zhang et al. (2013)

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Maximum VS (meV)</th>
<th>Optimum configuration of barrier</th>
</tr>
</thead>
<tbody>
<tr>
<td>%0 Ge</td>
<td>5.7 meV</td>
<td>Ge₄Si₄Ge₂Si₆Ge₄Si₄Ge₄Si₂…</td>
</tr>
<tr>
<td>%20 Ge</td>
<td>7.4 meV</td>
<td>Ge₄Si₄Ge₄Si₂Ge₄Si₆Ge₄Si₂…</td>
</tr>
<tr>
<td>%40 Ge</td>
<td>8.7 meV</td>
<td>Ge₄Si₂Ge₂Si₆Ge₄Si₄Ge₄Si₂…</td>
</tr>
</tbody>
</table>

The maximum VS and corresponding optimum configuration of ordered superlattice barrier identified by the inverse-band-structure search calculations (as shown in Fig. 2d-f). The Si well thickness is fixed to 40 MLs and the content of Ge in substrate ranges from 0 to 40%. The optimum configuration of barriers is given in the sequence of Si/Ge monolayers counted from the well boundary. Note the favorable Ge₄ starting sublayer in all cases.


Our work: One additional 0.5 nm layer of Ge near surface of quantum well
Three heterostructures were studied, one control and two with enhanced germanium at the quantum well interface.

Sample 1: 38 nm Si$_{0.71}$Ge$_{0.29}$
12.5 nm Si
~700 nm Si$_{0.71}$Ge$_{0.29}$

Sample 2: 38 nm Si$_{0.71}$Ge$_{0.29}$
~0.5 nm Ge
12.5 nm Si
~700 nm Si$_{0.71}$Ge$_{0.29}$

Sample 3: 38 nm Si$_{0.71}$Ge$_{0.29}$
~0.5 nm Ge
12.5 nm Si
~700 nm Si$_{0.71}$Ge$_{0.29}$

Adding the Ge monolayer increases band offset (which raises valley splitting), but it also can decrease disorder at the interface (which lowers valley splitting).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mobility (cm²V⁻¹s⁻¹) at carrier density n=4×10¹¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>control</td>
<td>100,000</td>
</tr>
<tr>
<td>“smooth” extra Ge</td>
<td>70,000</td>
</tr>
<tr>
<td>“abrupt” extra Ge</td>
<td>56,000</td>
</tr>
</tbody>
</table>

Heterostructures with extra Ge at interface have somewhat lower mobilities, indicating that the interfaces are somewhat more disordered.

So need to measure the valley splittings!
Temperature dependence of quantum Hall measurements are used to determine valley splittings as a function of carrier density, magnetic field.

Results of thermal activation measurements to determine valley splittings at two different filling factors and different densities

extra-Ge sample has enhanced valley splitting at this filling factor

Uncertainty of linear fits is smaller than marker size
Experimental and theoretical valley splitting work agrees that disorder from the substrate can dominate over interface composition.

For all samples:
\[ E_V \sim n^\alpha, \quad \alpha = 2.7 \pm 0.2 \]

Tight binding simulations give the same scaling for a narrow range of step densities, indicating samples are more alike than they are different.

Heterostructures were grown on different substrates to test the prediction that double-atom steps suppress valley splitting less than single-atom steps.

Three samples were grown by Don Savage on substrates with different miscuts, including:

- A 2° miscut along [010], producing single-atom steps
- A 4° miscut along [110], producing two-atom steps* (with same average step width)
- An on-axis sample (no miscut), as a control

Valley splitting was determined via thermal activation of Shubnikov-de-Haas minima in fields up to 8T.

Good mobilities were observed at $n = 4 \times 10^{11} \text{ cm}^{-2}$, for all samples, in the range 150,000-250,000 cm²/(V s).

$\nu = 3$ valley splitting at $n = 4 \times 10^{11} \text{ cm}^{-2}$

miscut angle [degrees]

Tom McJunkin
Developing new heterostructures to enhance valley splitting

Observation #1: disorder is difficult to change. Think about the structure.


Observation #2: growth constraints provide one sharp interface.

Proposed solution: grow a very narrow, thin barrier near the top of the quantum well.
Results of growth of mini-barrier

Ideal mini-barrier is narrow and sharp

D. Savage

TEM image
Tight-binding simulations of mini-barriers

Half-Gaussian barrier model:

Heterostructure, as grown

Wavefunction Prob.

Electron probability

Predicted valley splitting enhancement factor (this structure): 1.34

We can do even better:
- sharper barriers
- higher Ge content

Mark Friesen
Heterostructures grown with mini silicon layer above the quantum well to alter the overlap of the wave function into the SiGe barrier.

Dot and Hall bar fabrication is completed, valley splitting to be measured soon.
Summary of quantum Hall effect measurements of valley splittings:

“Abrupt” extra-Ge sample exhibits systematically larger valley splittings at filling factor $\nu=3$ than the control and “smooth” extra-Ge sample.

Measurements at $\nu=5$ do not exhibit enhanced valley splitting for samples with extra Ge at interface. (evidence that disorder and/or electron interactions could be playing an important role)

$\Rightarrow$ Need to conduct measurements in quantum dots
Summary

Silicon quantum dots are promising for quantum information processing.

Single-qubit gates with fidelities >99.9% have been demonstrated.

Two-qubit gates with fidelities >90% have been demonstrated.

Prospects for achieving higher fidelities and faster gate operations are good.

Improving materials is important to being able to scale up silicon quantum dot quantum computers.
UW-Madison Solid-State Quantum Computing Team

Pl: Mark Eriksson

Sam Neyens, Ryan Foote, Brandur Thorgrimsson, Trevor Knapp, Evan MacQuarrie, Nathan Holman, Joelle Baer, JP Dodson, Tom McJunkin, Don Savage, Max Lagally

SNC theory collaborators:
Mark Friesen
Yuan-Chi Yang, Joydip Ghosh, Ekmel Ercan, Adam Frees, Cameron King, John Gamble, Viktoriia Kornich, Robert Joynt

Sponsored in part by the Army Research Office, the Office of Naval Research, the Department of Energy, the National Science Foundation, and the United States Department of Defense.

The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the official policies, either expressly or implied, of the U.S. Government.
Thank you!

References


C. King, et al., arXiv:1807.11064