Spectroscopy and capacitance measurements of tunneling resonances in an Sb-implanted point contact

Nathan Bishop,
Sandia National Laboratories

Funded by the Laboratory Directed Research and Development program.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND2010-5581C
Outline

- Our design and relation to previous work
- Silicon MOS quantum dots as sensitive charge sensors
- Donor transport device structure
- Comparison between experiment and capacitive model
- Future work – excited state spectroscopy and charge sensing
- Conclusion
Some previous work

Timed P-implant

Tan et al., Nano Lett. 2010

Morello et al., arxiv 2010

P-implant area

barrier/donor gate

V_{barrier}

Electron Layer

SiO_2

Al

Si

Source

SET island

Drain

Single electron

I_{SET}

Morello et al., arxiv 2010
Si MOS quantum dots as charge sensors

- Reverse normal usage: use a quantum dot to sense changes in a point contact.
- Can be used to sense the spin state of a donor embedded in the point contact.
Si MOS process flow

- Oxide growth
- Polysilicon deposition and patterning
- Ohmic contact implant and anneal
- Nitride and pre-metal dielectric dep.
- Silicide and metallization
- E-beam litho and polysilicon patterning
- More EBL and Sb implantation
- Strip metal and re-oxidize polysilicon
- Second dielectric (ALD $\text{Al}_2\text{O}_3$) dep.
- Final metallization
Control sample: Silicon implant

40 keV silicon implant
4 x 10^{11} cm^{-2} dose

Depletion gate voltage (V)
Control vs. implanted

Antimony allows high temperature post-implant processing.

100 keV antimony 4 x 10^{11} cm^{-2} dose

<table>
<thead>
<tr>
<th>Sample type</th>
<th>Q_{th} (q/cm^2)</th>
<th>D_{it} (q/cm^2/eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal process</td>
<td>+ 5 x 10^{10}</td>
<td>1 x 10^{10}</td>
</tr>
<tr>
<td>Silicon implant + RTA</td>
<td>+ 3 x 10^{11}</td>
<td>2 x 10^{11}</td>
</tr>
<tr>
<td>Silicon implant + reoxidation</td>
<td>± 1 x 10^{11}</td>
<td>1 x 10^{10}</td>
</tr>
</tbody>
</table>

\[ T \sim 250 \text{mK} \]
\[ V_{sd} = 0.5 \text{ mVrms} \]
Tunneling spectroscopy

Relevant features:
1. Aliasing – nearby charge environment
2. Excited states – structure of donors / dots
3. Slope of lines – capacitance

\begin{align*}
\text{Conductance} & (e^2 / h) \\
\text{Source drain bias (mV)} & \\
\text{Depletion gate bias (V)} & \\
\text{dI / dV (S)} & \\
\end{align*}

\begin{align*}
V_{sd} & = 50 \ \mu \text{Vrms} \\
\end{align*}
Capacitive model

Harold Stalford, Ralph Young
Triangulation of Resonances

**Graphical Representation**
- Experiment (A or B)
- Simulated dots (R = 12.5, 15, 18 nm)
- Simulated donors (depths = 5, 10, 20 nm)
- 2DEG Implant window
- Donor atom
- Only dots?
- Only donors?
- R = 12.5 nm
- R = 15 nm
- R = 28 nm
- 5 to 20 nm donor depth
- Top/CTotal
- 30 nm barrier
- 40 nm barrier
- 60 nm barrier
- H. Stalford

**Position and size determination**
1. Capacitance ratios are sensitive to small differences in geometry
2. Top gate, S/D and lateral gates cover all three spatial directions
   - Is resonance below the surface?
   - Still in progress
Spectroscopy: Sb in Si

Deeply buried donor

Donor near interface

Rajib Rahman

Energy

Position

oxide silicon

Energy

Position
Spectroscopy: excited states

$g\mu_B B$

$\frac{1}{2} g\mu_B B$
Conclusions

• Fabricated unique device which enables a wide variety of possible experiments.
• Identified tunneling resonances in implanted point contacts, which are rare in clean controls.
• Capacitive measurements locate the resonant states in the point contact, and are consistent with donors as the source.
• Charge sensing measurements ongoing.
Acknowledgements

Quantum Team:
Ed Bielejec
Malcolm Carroll
Kent Childs
Kevin Eng
Robert Grubbs
Paul Hines
Mike Lilly
Joel Means
Rick Muller
Eric Nordberg
Tammy Pluym
Rajib Rahman
Bev Silva
Harold Stalford
Jeff Stevens
Tom Tarman
Greg Ten Eyck

Quantum team cont’d:
Denise Tibbetts
Lisa Tracy
Joel Wendt
Wayne Witzel
Ralph Young

Australian collaborators:
Susan Angus
Andrew Dzurak
William Lee
Andrea Morello
Michelle Simmons
Dan Tomlinson
Extracting capacitance

Depletion gate bias (V)

Source drain bias (mV)

-0.30  -0.28  -0.26  -0.24  -0.22  -0.20

0  1  2  3  4  5

B peak slopes:
-0.281
0.417

A peak slopes:
-0.249
0.277

V_{sd}

S

D
Donor distribution

150 keV Sb implant
- SIMS, $^{121}\text{Sb}$
- SIMS, $^{123}\text{Sb}$
- SRIM, 150 keV

Sb concentration (cm$^{-3}$)

Depth (Å)

oxide

SIMS by Tony Ohlhausen, SNL
Ion implantation

- E-beam litho and polysilicon patterning
- More EBL and ion implantation
- Strip metal and re-oxidize polysilicon
- Second dielectric (ALD Al₂O₃) dep.
- Final metallization

Ion beam

25 nm SiNₓ
200 nm poly-Si
35 nm SiO²
250 nm SiO²

As n+ implant
p- Si substrate

Sb⁺

Back end
Lever arm analysis

\[ \frac{G}{G_{\text{MAX}}} = \frac{\Delta E}{4k_B T} \cosh^{-2}\left( \frac{\alpha (V - V_0)}{2k_B T_{\text{measured}}} \right) \]

\[ \alpha = \frac{eC_G}{C_\Sigma} \]

\[ \alpha = \frac{2k_B T_{\text{measured}}}{\delta V} \]

\( T_{MC} = 19 \text{ mK} \)
\( V_{SD} = 15 \mu \text{Vrms} \)

Kouwenhoven et al., Electron transport in quantum dots, NATO ASI 1997
Lever arm analysis

- A peak ($\alpha = 0.0167$)
- B peak ($\alpha = 0.0111$)

Perfect scaling

$V_{ds}$ limit = 0.174 K

Mixing chamber thermometer (K) vs. Measured temperature (K)
Poor scaling due to high $V_{ds}$

![Graph showing scaled temperature vs. mixing chamber thermometer temperature.]

- A peak ($\alpha = 0.165$)
- B peak ($\alpha = 0.135$)
- Perfect scaling
- $V_{sd}$ limit = 1.16K

Scaling factors are indicated with error bars on the graph.
Top gate lever arm

A slope:
\[ \frac{dV_{\text{Poly}}}{dV_{\text{TG}}} = -0.639 \]

B slope:
\[ \frac{dV_{\text{Poly}}}{dV_{\text{TG}}} = -0.625 \]
Top gate lever arm

A and B have nearly identical top gate lever arm. There is a disorder dot that does have a larger lever arm.
Ion implant damage

45 keV silicon implant, equivalent to 100 keV antimony implant
900 C furnace anneal, 24 minutes in O₂

Interface Trap Density vs. Trap Energy
Threshold difference

Implant damage increases interface trap density and fixed charge, but mostly repaired after high temperature processing.

CV measurements of Dit and Qf by Greg Ten Eyck