Fast Charge– and Spin–State Readout in a Double Quantum Dot Using Adjacent Sensing Quantum dot

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Experimental evidence produced in Marcus Lab at Harvard University

Using a quantum dot for charge– and spin–readout in 2DEG heterostructures yield greater sensitivity and lower signal–to–noise than traditional quantum point contact sensors.

... this is cool because:

a) Allows for more sensitive (∼ 20 times more sensitive) readout of charge–states on double quantum dots → more precise measurements of charge–states

b) Allows for faster (∼ 200ns) single–shot readout of the singlet–triplet qubit in double quantum dots → better weapon against relaxation and decoherence of qubits
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How and why of charge sensing in 2DEG

- Charge-sensing is a technique for determining the number of electrons on quantum dots – useful for e.g. few-electron physics, qubits etc.
- Measure conductance through proximal electron conduction path, whose electrostatic, and hence conductance, characteristics are sensitive to changes on the (double) dot configuration

*modified from J.R. Petta et al., Science, 2005*

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- This work uses a proximal sensor quantum dot (SQD)
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The Business of Charge Sensing
Experimental Evidence
Theory & Simulation

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Device Properties: 2DEG Heterostructure
- Ti/Au gates on GaAs/Al\textsubscript{0.3}Ga\textsubscript{0.7}As,
- 2DEG: $\rho = 2 \cdot 10^{15}$ m\textsuperscript{-2}, 100nm below surface

Measurement
- $B = 100mT$ along DD-line
- $T \lesssim 150$ mK (electrons, from CP)
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⇒ **SQD** and **QPC1** most sensitive to changes $\delta g$ at $\Delta V_g = 60\text{mV}$, the *operating point*.

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(a,c): **SQD**, (b,d): **QPC1**, where $\Delta g = g_{(1,1)} - g_{(0,2)}$ and $\bar{g} = (g_{(1,1)} + g_{(0,2)})/2$
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⇒ SQD and QPC1 most sensitive to changes $\delta g$ at $\Delta V_g = 60 \text{mV}$, the operating point.

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Data 2: Single–shot spin–state readout
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- Readout scheme: Prepare in (0,2), drive into (1,1) for \((1, 1)T_0 \leftrightarrow (0, 2)S\) mixing, wait for time \(t_s = 1 - 200\,\text{ns}\), drive back into (0, 2): Only \((0, 2)S\) can return, \((1, 1)T_0\) trapped for relaxation time.

Measure reflectometry (rf)-amplitude, \(v_{rf}\), integrate over time \(\tau_M\) for one singleshot measurement (one dot on figures) [C. Barthel, PRL, 2009]. Use that \(V_{rf} \propto g\) to map charge-state [D.J Reilly, APL, 2007]

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We define *conductivity sensitivity* of a QPC/SQD (arising from gate or charge–rearrangement) as:

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    s_{\text{QPC}} &= \frac{\partial g}{\partial V_{\text{QPC}}^{\text{eff}}} = \frac{\partial g}{\partial \phi_{\text{SP}}} \frac{\partial \phi_{\text{SP}}}{\partial V_{\text{QPC}}^{\text{eff}}} = \alpha_{\text{QPC}} \frac{\partial \phi_{\text{SP}}}{\partial V_{\text{QPC}}^{\text{eff}}} \\
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- Can find *effective lever-arms*, \( \alpha^{\text{eff}} \), by self–consistent DFT modelling of real device geometry and parameters using SETE–code (on next slide).
- From numerics: \( \frac{\alpha_{\text{SQD}}}{\alpha_{\text{QPC}}} \approx 20 \)
- Difference attributed to
  1. *screening*: \( \Delta V_{\text{QPC}} \) is screened by charges in 2DEG, \( \Delta V_{\text{SQD}} \) only screened by other gates (dot is isolated by tunnel barriers).
  2. Width of levels of a QPC and an QD – but sensitivity is more than just \( \frac{dg}{dV} \), due to different capacitative coupling
General theory of QPC and SQD performance

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SETE: Self-Consistent DFT to Poisson Eq. [M. Stopa, PRB, 1996]

**Incorporates**
- Wafer profile, growth-direction
- Geometry of gates
- Full control of gatevoltages
- Temperature and magnetic field

**Calculates**
- Electrostatic potential, $\phi(x,y)$
- Charge density, $\rho(x,y)$
- Total free energy, $\mathcal{F}(N, V_g, T, B)$
- $\epsilon_n(x,y), \xi_n(x,y), \Gamma$ (regions)

**Sample density (in (1,1)–state):**

**Input:** 10 $V_g$'s, $T$, 2DEG properties, donor concentration, (0,2) or (1,1) (optional)

**Output:** $\phi(x,y), \rho(x,y), \phi$'s at saddlepoints, $\epsilon_n(x,y)$ in regions, charge in regions

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Fast Charge– and Spin–State Readout in a DQD Using a Quantum dot
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### Diagram:

- 500nm
- \( n \left( 10^{10} \text{cm}^{-2} \right) \)

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10/12  Fast Charge– and Spin–State Readout in a DQD Using a Quantum dot
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\phi(x, y) &= \rho(x, y) \\
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\(\text{500nm} \)

\(n (10^{10} \text{cm}^{-2})\)

\(\text{g} (\text{e}^2/\hbar)\)

\(\Delta g (\text{e}^2/\hbar)\)

\(\Delta V_{Q1} (\text{mV})\)

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Method
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- \(-\nabla^2 \phi = (4\pi \epsilon / \kappa) \rho\)
- WKB to \( T \)
- \( k_B T \ll \Delta E \)

\[ \Delta g / \bar{g} \]
- Exp.: 0.9
- Theory: 1.4

SQD: \( \hbar \Gamma \ll k_B T \) not valid, assumed in calculation
Take–home message

Taking advantage of the increased sensitivity of a proximal sensor quantum dot (SQD) (instead of a proximal quantum point contact (QPC)), an order of magnitude faster readout of the singlet–triplet qubit and a factor of $\sim 30$ increase in sensitivity was measured.

The difference can be attributed to difference in screening from 2DEG in the SQD and in the QPC. This claim was supported by self–consistent numeric calculations in agreement with experiment.
Acknowledgements

- Experimental work and useful discussions
  Christian Barthel (co–author)
  Jim Medford (co–author)
  Ferdinand Kuemmeth
  Edward Laird

- Principal advisors
  Dr. Mike Stopa (co–author)
  Prof. Charlie Marcus (principal investigator, co–author)

- Others
  Karsten Flensberg
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  Højgaard Foundation
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Reference

Fast sensing of double-dot charge arrangement and spin state with an rf sensor quantum dot
C. Barthel, M. Kjaergaard, J. Medford, M. Stopa, C. M. Marcus, M. P. Hanson, A. C. Gossard
arXiv/cond-mat/1001.3585