Electrical Control of Single Spins in Semiconductor Quantum Dots

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Physics Department, Princeton University


Jason Petta, Princeton University
Quantum computing hardware

Trapped ion/atom QC

Superconducting QC

Spin based QC

Optical QC

NMR QC

Topological QC

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DiVincenzo Criteria

- Efficient initialization
- Readout
- Universal set of gates
- Long decoherence times ($T_1, T_2$)
- Scalable

Loss & DiVincenzo Proposal


- Prepare spin in ground state
- “Spin to charge conversion”
- ESR for single spin rotations
- Exchange interaction
- $T_1 \sim 1 \text{ second}, T_2 \sim 200 \mu s$
- Standard semiconductor fabrication

Jason Petta, Princeton University
Quantum condensed matter physics- The goals

1. Build quantum systems with experimentally tunable Hamiltonians

\[
H = \begin{pmatrix}
J(V_g) & \Delta B^Z_{\text{nuc}} \\
\Delta B^Z_{\text{nuc}} & 0
\end{pmatrix}
\]

2. Determine the limits of quantum coherence in the solid state

3. Extend coherence by tailoring the solid state environment (isotopic purification….)

4. Build artificial quantum materials

Atom

Molecule

Tri-atom

Ciorga et al. (2000)

Petta et al. (2005)

Gaudreau, Schroer (2007)

Spin chains & lattice

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Quantum condensed matter physics - The challenges

1. Quantum system must be isolated from the environment to preserve coherence
2. Hamiltonian must be experimentally tunable
3. Desire strong and controllable qubit coupling (not always compatible with 1.)
Lecture 1: Introduction to quantum dots

- Motivation for using spins in semiconductors
- Introduction to quantum dot physics
- Isolating and detecting single electrons
- Spin in quantum dots
- Spin-orbit and hyperfine interactions
- Measurements of the spin lifetime ($T_1$)

Jason Petta, Princeton University
Electron spin as a quantum bit

Single spin qubit

Qubit states:

$|0\rangle$ $|1\rangle$

$\hbar\omega$ $E_{\text{Zeeman}}$

Use electron spin resonance to drive coherent evolution

Loss and DiVincenzo
PRA 57, 120 (1998)

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Semiconductor technology: scaling and Moore’s law

First transistor 1947

410 Million Transistors (2009)

~$10^9$

Source: Intel

Jason Petta, Princeton University
Types of quantum dots

**Single molecules**

- Image of single molecules
- Groups: McEuen, Ralph

**Vertical semiconducting dots**

- Image of vertical semiconducting dots
- Groups: Kouwenhoven, Tarucha

**Metal nanoparticles**

- Image of metal nanoparticles
- Groups: Ralph, Petta

**Lateral semiconducting dots**

- Image of lateral semiconducting dots
- Groups: Marcus, Kouwenhoven, many others

Jason Petta, Princeton University
Quantum dots- “Artificial atoms”


Jason Petta, Princeton University
Quantum dots- “Artificial atoms”

3D confinement

Discrete spectrum

Molecular bonding

Quantum dots

V(x)

X

Cu nanoparticle Petta&Ralph (2002)

GaAs double dot Livermore (1996)

Jason Petta, Princeton University
Some differences between quantum dots and atoms

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Atoms</th>
<th>Quantum dots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>$d=1 \text{ Å}$</td>
<td>$d=1000 \text{ Å}$</td>
</tr>
<tr>
<td>Level spacing</td>
<td>$\delta \sim \text{eV}$</td>
<td>$\delta \sim 100's \text{ of } \mu\text{eV-}\text{meV}$</td>
</tr>
<tr>
<td># of nuclei</td>
<td>$N_{\text{nuc}}=1$</td>
<td>$N_{\text{nuc}}=10^5-10^6$</td>
</tr>
<tr>
<td>Spin-orbit</td>
<td>$\mathbf{L} \cdot \mathbf{S}$</td>
<td>Material dependent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Structure dependent</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anisotropic</td>
</tr>
</tbody>
</table>

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Lateral quantum dot fabrication

GaAs/AlGaAs heterostructure

Quantum point contact

Jason Petta, Princeton University
Evolution of quantum dot devices

**Many-electron quantum dots**

$N_e \sim 100$  
400 nm

Marcus group (1996)

**Few-electron quantum dots**

$N_e \sim 1$

Ciorga *et al.*, PRB 61, 16315 (2000)

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Coulomb blockade and charging

Charging energy $E_c = \frac{e^2}{2C}$

Kastner, RMP 64, 849 (1992)

Jason Petta, Princeton University
Non-interacting electrons-in-a-box model

Can resolve discrete states if $\delta E >> kT$

Petta and Ralph, PRL 87, 266801 (2001)

Jason Petta, Princeton University
Finite bias spectroscopy


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Trapping and detecting single electrons

**Transport measurements**

Ciorga et al., PRB 61, 16315 (2000)

**Charge detection**

Field et al., PRL 70, 1311 (1993)

Hanson et al., PRL 91, 196802 (2003)

Jason Petta, Princeton University
Spin: Zeeman splitting

Specific case: $\vec{B} = B\hat{z}$

$\delta E$

$eV$

$\delta \varepsilon_{\mu} = \frac{1}{2} g \mu_B B_Z^0$

BZ = 100 mT
$T_c \sim 80$ mK

Petta and Ralph, PRL 87, 266801 (2001)

Jason Petta, Princeton University
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Spin qubit initialization

Load spin-up electron

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Spin-to-charge conversion (Readout)

manipulate qubit

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![Diagram of DiVincenzo Criteria]

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Charge relaxation -vs- spin relaxation time ($T_1$)

Charge relaxation

\[ E_F \]
\[ \varepsilon_1 \]
\[ \varepsilon_0 \]

Requires: energy loss
phonon emission
\[ \Gamma_{\text{inel}}(\varepsilon_1-\varepsilon_0) \approx 100 \text{ MHz} \]

Spin relaxation

\[ E_F \]
\[ E \]

Requires: energy loss + spin flip
phonon emission + spin-orbit interactions
\[ \Gamma_{\text{SF}} \approx \text{kHz} \text{ (field dependent)} \]
phonon emission + hyperfine interactions
\[ \Gamma_{\text{SF}} \approx \text{kHz-MHz} \text{ (field dependent)} \]

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Spin-orbit interactions in quantum dots: \( H \propto \vec{L} \cdot \vec{S} \)

\[
H_{SO} \propto \left( \nabla V \times \vec{p} \right) \cdot \vec{\sigma}
\]

\( \vec{B}_E \) = effective B field

Structural inversion asymmetry (Rashba spin-orbit term)

\[
H_R = \alpha \left[ \sigma_x p_y - \sigma_y p_x \right]
\]

Bulk inversion asymmetry (Dresselhaus spin-orbit term)

\[
H_D = \beta \left[ -\sigma_x p_x + \sigma_y p_y \right]
\]

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Hyperfine interactions in quantum dots: $H \propto \vec{I} \cdot \vec{S}$

$$H = \hbar \gamma_e \vec{B}_{\text{Ext}} \cdot \vec{S} + \hbar \gamma_e \sum_{\beta,j} b_{\beta,j} \alpha_j \vec{S} \cdot \vec{I}_{\beta,j}$$

Zeeman Hyperfine

$$H = \hbar \gamma_e (\vec{B}_{\text{Ext}} + \vec{B}_{\text{Nuc}}) \cdot \vec{S}$$

Fully polarized nuclei, $B_{\text{Nuc}} = 5.3 \text{ T}$

Unpolarized nuclei, $B_{\text{Nuc}} \sim 2 \text{ mT}$

GaAs nuclear spins

$^{75}\text{As}$, $I=3/2$, 100%

$^{69}\text{Ga}$, $I=3/2$, 60%  $^{71}\text{Ga}$, $I=3/2$, 40%

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Single spin relaxation time measurements ($T_1$)


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Spin relaxation time measurements ($T_1$)

$T_1 \approx 0.5$ ms at 10 T


Optical measurements


$T_1 \propto B^{-5}$

spin-orbit limited at high field

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High field spin relaxation mechanism

\[ \Gamma = \frac{2\pi}{\hbar} \sum_{n,l} \left| \langle n' \uparrow \left| H_{e,ph} \right| n \downarrow \rangle \right|^2 D(E_Z) \]

phonon density of states \( \propto E_Z^2 \)

\[ \langle H_{SO} \rangle \propto E_Z \]

\[ H_{e,ph} = M_{\vec{q},j} e^{i\vec{q} \cdot \vec{r}} (b_{\vec{q},j}^\dagger + b_{-\vec{q},j}) \]

piezoelectric field scales as \( 1/\sqrt{q} \propto 1/\sqrt{E_Z} \)

electron-phonon coupling \( \propto E_Z \)

\[ \Gamma \propto \left( \frac{E_Z^3}{Z} \right)^2 E_Z^2 \propto E_Z^5 \]


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Energy dependence of the relaxation rate

\[ \frac{1}{T_1}(\text{ms}^{-1}) \]

\[ \Delta E_{s,t} \text{ (meV)} \]

\[ \lambda = \frac{hc_{ph}}{E_{ph}} \approx 16 \text{ nm} \]

\[ c_{ph} = 4000 \text{ m/s} \]

\[ E_{ph} \approx 1 \text{ meV} \]


Jason Petta, Princeton University
Electrical Control of Spin Relaxation in a Quantum Dot

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We demonstrate electrical control of the spin relaxation time $T_1$ between Zeeman-split spin states of a single electron in a lateral quantum dot. We find that relaxation is mediated by the spin-orbit interaction, and by manipulating the orbital states of the dot using gate voltages we vary the relaxation rate $W = T_1^{-1}$ by over an order of magnitude. The dependence of $W$ on orbital confinement agrees with theoretical predictions, and from these data we extract the spin-orbit length. We also measure the dependence of $W$ on the magnetic field and demonstrate that spin-orbit mediated coupling to phonons is the dominant relaxation mechanism down to 1 T, where $T_1$ exceeds 1 s.

![Graph showing the relationship between $W$ and $B$ for different $E_y$ values.](image)
Beyond single quantum dots…

Loss and DiVincenzo
PRA 57, 120 (1998)

Single spin rotations and spin-spin interactions, e.g. \(\sqrt{SWAP}\)
are sufficient for spin based quantum computation

→ Requires coupled quantum dots

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Single dots -vs- double dots

Require $E_Z \gg kT$
Freq. $= 4 \text{ GHz/Tesla}$

Interdot tunneling linewidth is independent of $kT$

Jason Petta, Princeton University