Optical control of the electron spins
Single Spin Optoelectronics

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Three key questions

1. Does an electron spin in a quantum dot qualify as a TLQS?
2. Can we make a team of the spins dance prettily?
3. Can one make money from it (by investing or taxing)?

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Optical control of electron spins in semiconductor nanodots

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Three Kinds of Semiconductor Quantum Dots

Self-assembled quantum dots (3-10 nm) 
\[ \Delta E \sim 100 \text{ meV} \]

InAs lattice mismatch

Interface fluctuation quantum dots (30x40x3 nm³) 
\[ \Delta E \sim 10 \text{ meV} \]

GaAs

GaAs

\[ \Delta E \sim 1 \text{ meV} \]

Gated quantum dots (100 nm)

Electrodes

AlGaAs

AlGaAs

Z

X

GaAs
Experimentalists’ view of Quantum Dots

Self-assembled quantum dot

Interface fluctuation quantum dot

Gated quantum dot


A. Zrenner, et al.

Theorists’ view of quantum dots

Square-well quantum dots

Lateral harmonic well quantum dots

Conduction band

States of interest

Electron

Empty

Occupied

Valence band

\[ E \]

\[ L_z \]

\[ Z \]
• Assumption: periodic lattice with no vibrations (low temperature).

• Consideration of e-e interaction, lattice symmetry and semiconductor band gap leads to the spectrum shown for an electron added to the ground state or removed from it.

• Without radiative interaction, the exciton is an exact excited state.

• Confinement of an electron in a quantum dot.

-Im G(k,E)

h e

continuum 0 E

Is an electron in a dot isolated?

N+1 electron problem

Kohn PR (1960)
Sham, PR (1966).
Sham and Rice, PR (1966).

Electron spectral density
Interaction of the dot spin with outside

• Preparation of initial state (initialization)
• Quantum operations by optical control
• Measurement of single spin state
• Decoherence and recovery - KITP Spintronics Program seminar 4/11/06
Optical transitions in a charged dot

Single particle levels

Multi-particle states

Spin State to Trion

Selection rules

Spin +3/2

Spin +1/2

Spin −1/2

Spin −3/2

Trion

Magnetic field along z

σ+

σ−
Trion states in a single dot

Ensemble Luminescence Spectra

Magnetic field along x

J.G. Tischler, D. Gammon and A.S. Bracker, NRL
Single Electron Spin Coherence

$\Gamma \quad \Gamma \quad \Gamma$

$\chi^-$

$\Gamma \quad \Gamma$

$\chi$

$\Gamma \quad \Gamma$

B = 1.1 T

4000psec

CNOS (a. u.)

Single Charged Exciton

Ensemble Charged Excitons

Single Neutral Exciton

LJ Sham 4/25/06
Where does the spin polarization come from?

Initially unpolarized system remains unpolarized.

\[ \hat{\rho}_T(t) = e^{-iH/t} \hat{\rho}_T e^{iH/t} = \hat{\rho}_T \]

One shot: 50% success rate, 10^3 cycles to improve to 0.999
Optical Decay of the Trion

\[ |t\rangle \]

\[ \gamma > 2\omega_B \]

\[ |+x\rangle \]

\[ |-x\rangle \]

Spontaneous emission creates spin coherence (SGC)


Rotation of single electron spin (single qubit gate)

Single particle levels

Multi-particle states

Spin State to Trion

Adiabatic NR Raman Spin-flip Process

Trion

Magnetic field along x

Theo est. op time $\sim < 10$ ps

Rotation about the optical (growth or z) axis

Initial spin state, \(|\psi\rangle = \alpha |+\rangle + \beta |-\rangle\)

- Pulse \(H\): \(\Omega \text{ sech}(\sigma t) e^{i\omega_0 t}\)
- Bandwidth
- Central frequency

Final state, \(|\psi\rangle = \alpha e^{-i\phi} |+\rangle + \beta |-\rangle\)

\(\Delta\) - detuning

\[
\tan \phi = \frac{2\sigma \Delta}{\Delta^2 - \sigma^2}
\]

Rosen & Zener, PR (1932)

Optical control of general spin rotation

2 pulses, input: amplitudes $\Omega_\uparrow(t)/\Omega_\downarrow(t) = \cot \beta$, relative phase $\alpha$, and detuning $\Delta$.

$\begin{align*}
\Omega_\uparrow &= \Xi \sin(2\phi) \cos \beta, \\
\Omega_\downarrow &= \Xi \sin(2\phi) \sin \beta, \\
\Delta &= 2\Xi \cos(2\phi).
\end{align*}$

$\Xi = \sqrt{\Omega_\uparrow^2 + \Omega_\downarrow^2 + \left(\frac{\Delta}{2}\right)^2}$.

Rotation axis polar angles $(2\beta, \alpha)$, angle =

$-2 \int dt \; \Xi(t) \sin^2 \phi(t)$

Conditions:
Zeeman $\gg$ pulse duration
Adiabatic, $|\dot{\phi}(t)| \ll 2\Xi(t)$

Optical decoherence 60 ps; spin decoherence longer than 10 ns.
Gaussian pulses of Rabi energy 1 meV, duration 8.74 ps, detuning 5 meV: the fidelity for a $\pi$ rotation is 0.991.
Imperfection of the selection rule

Heavy and light hole mixing, $J=3/2$, $m_J = \pm 3/2, \pm 1/2$

Hole state $|+3/2\rangle + \varepsilon |-1/2\rangle$

Spin $|-3/2\rangle - \varepsilon'|+1/2\rangle$

Trions

Optical axis is tilted away from the z axis - deterministic.
Spin state preparation by optical pumping

Multi-particle states

allowed $\Gamma > \gamma$ forbidden

A. Kastler (1952)

- Expt of SAQD InAs in GaAs
- Resonant laser excitation for a time ($\sim$300 ms) $>> 1/\gamma$ (1 µs) but less than $T_1$ due to tunneling
- Fidelity 0.998 at 3T (or spin $T \sim$20 mK for Zeeman$\sim$ 4K) - at op temp of 4K, B$\sim$62T, it would takes forever at rate $1/T_1$

Atatürü, Dreiser, Badolato, Högele, Karrai, Imamoğlu, Science Express, 4/6/06
Controlling spin interaction between two electrons in two quantum dots (ORKKY or Bloombergen-Roland)

Effective Heisenberg exchange between the electrons in two dots $J_{s_1 \cdot s_2}$

$J_1 s_1 \cdot s_c$

Continuum exciton

Continuum hole

Continuum electron

laser

photon

local spin

Single particle levels

Effective interaction between two electrons in separate dots under optical excitation (RPA)

\[ H = -2J(R)\sigma_1 \cdot \sigma_2. \]

\[ \Omega = \text{Rabi energy} \]
\[ \Lambda = \text{energy in dot} \]
\[ R = \text{interdot distance} \]
\[ \delta = \text{detuning} \]

\[ \kappa = \sqrt{\frac{\hbar^2}{2m\delta}} \]

Adiabaticity condition: pulse width in time \( \gg \frac{\Omega}{\delta^2} \)

2\( k_f R \) for above gap excitation
Effective exchange interaction vs dot separation $R$

Adiabatic limit

Host excitons in 2D

$\delta = \text{detuning}$

Excitons

Electron-hole pairs
Effective exchange interaction vs dot separation R

Additional exchange & correlation between local and itinerant spins

Electron-hole pairs

δ = detuning

2D Host

No kinetic exchange

Excitons

1D Host

Ramon, Lyanda-Geller, Reinecke, Sham, PRB 71, 121305R (2005)
Modified ORKKY for two spin qubits in two quantum dots

Exciton over 2 dots

Effective Heisenberg exchange between the electrons in two dots $J_{s_1 \cdot s_2}$

$J_{1s_1 \cdot s_c}$

Excited hole

Single particle levels

Laser

Local spin

Excited electron

Photon

A single photon wave packet of any shape may be produced by a suitable control of pulse shape of laser light.

Thus, a single photon source

Ultrasfast spin cooling using the waveguide as an entropy dump (qubit initialization)

Selection rules

\[
\begin{align*}
|T^+\rangle & \quad g_{cav} \quad |T^+\rangle & \quad |+,C\rangle \\
|T^-\rangle & \quad |T^-\rangle & \quad |-,C\rangle
\end{align*}
\]

\[
\begin{align*}
|X^-\rangle & \quad |X^-\rangle & \quad |+\rangle \\
|X^+\rangle & \quad |X^+\rangle & \quad |+\rangle
\end{align*}
\]

Yao, Liu and Sham, Phys. Rev. Lett. 95, 030504 (2005)
Solid State CQED for Spin State Measurement

Quantum Non-Demolition Measurement

The three steps may be recycled

Quantum Non-Demolition Measurement

What is not a QND:

- Measure $x$ of a free particle at time $t=0$
  - Uncertainty $\Delta x(0)$ leads to uncertainty $\Delta p(0) \sim h/\Delta x(0)$
- Then measure $x$ again at time $t$
  - $x = tp/m$
  - $\Delta x(t) \sim t \frac{h}{m\Delta x(0)}$ -- back-action noise

What is a QND:

- Measured observable $A$
  - $A(0)$ commutes with $A(t)$

Evidence for Strong Coupling CQED

Yoshie, Schere, Hendrickson, Khitrova, Gibbs, Ruppe, Ell, Shchekin, Deppe, Nature
Proposed applications

- Optical control for a quantum processor and a scalable system of SAQDs for QC
- Distributed quantum computation with a quantum network of nodes of QD and microcavity connected by wave guides
- Using QD as strong nonlinear elements to provide photon-photon interaction for devices
Spin coherence time ~ 10\(\mu\)s
Optical gate time ~ 10 ps

Energy Level Schematics for Optical Operations

- ORKKY
- Raman
- AC Stark
- Cooling

Architecture of a 7 bit QC

0.2 μm

Within each zipcode, each dot is addressed by its frequency

Resource estimate

TABLE I: Gates, pulses, and time-consumption required for factoring 15 with Shor’s quantum algorithm

<table>
<thead>
<tr>
<th></th>
<th># of one-bit gates(^a)</th>
<th># of swap gates</th>
<th># of phase gates</th>
<th># of pulses(^b)</th>
<th>time-consumption(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a=4</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>48</td>
<td>0.8 ns</td>
</tr>
<tr>
<td>a=13  (Toffoli gate)</td>
<td>19</td>
<td>8</td>
<td>15</td>
<td>159</td>
<td>1.2 ns</td>
</tr>
<tr>
<td>a=13  (S- Toffoli gate)</td>
<td>12</td>
<td>6</td>
<td>7</td>
<td>102</td>
<td>1.0 ns</td>
</tr>
</tbody>
</table>

\(^a\)All one-bit gates between two controlled gates are counted as one gate requiring 4 pulses which can be done within 10 ps

\(^b\)including 21 pulses for initialization

\(^c\)including the time for initialization, estimated as 100 ps per bit
### Distributed QIP or QC Hardware & Operations

<table>
<thead>
<tr>
<th>Qubits</th>
<th>Operations (clock speed 10 ps or 1 THz)</th>
<th>Write (initialization)</th>
<th>Readout</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Stationary: spins in semiconductor nanodots or excitons</td>
<td>- Optical control by lasers</td>
<td>- Optical pumping and decay</td>
<td>- Aims for one shot measurement</td>
</tr>
<tr>
<td>- Flying: photons (number states or polarization states) in fiber</td>
<td>- Photon-electron interaction in vacuum and in cavity</td>
<td>- Control of cavity electrodynamics</td>
<td>- Requires high efficiency single photon detector</td>
</tr>
</tbody>
</table>

Single Photon Source from semiconductors


LJ Sham 4/25/06
Quantum network with solid-state nodes

Full Raman Cycle

Initialize receiving node.

Map spin qubit to photon qubit by a full Raman Cycle at the sending node.

Photon qubit propagate in the quantum channel.

Map the photon qubit to the spin qubit at the receiving node by a full Raman Cycle.

Remote operations: swap & entanglement designed and simulated

Yao, Liu and Sham, Phys. Rev. Lett. 95, 030504 (2005)
A proposal for a solid-state phase gate for two-photon entanglement

Aim

• Strong interaction between flying qubits for a logic gate
• Mediation by semiconductors
  – photon polarization qubit and electron spin in quantum dot or exciton qubit
  – connection via cavity photon

Possible strengths

• Stable structures which are easy to integrate with electronics and photonics
• Strong nonlinearity from microcavity-quantum dot coupled system
  – Small cavity volume
  – Large transition dipole matrix element of quantum dot
• Qubit by polarization
  |X>, |Y>

• Cavity Modes

• Gate Transformation
  |XX> → e^{i\phi} |XX>
  |XY> → |XY>
  |YX> → |YX>
  |YY> → |YY>

• Linear reflection?
  Reduced by EIT which also yields laser cooling.

• Nonlinearity?
  Coupling to dot

Yao, Liu and Sham, PRL 92, 217402 (2004).
Summary

• An electron spin in a quantum dot is a sufficiently robust quantum system.

• Optical control shows significant experimental progress and provides potentially a broad range of operations with favorable clock speed and versatility for QIP and QC.

• Possibility of applications by a combination quantum optics and semiconductor nano-system is limited only by our imagination.