Deterministic Coherent Writing and Control of the Dark Exciton Spin using Short Single Optical Pulses

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Overview

• Three main experimental results:
  1. Deterministic, all-optical excitation of a quantum-dot confined dark exciton (DE)
  2. Coherent “writing” of its spin state using single polarized picosecond pulse.
  3. Coherent control of the DE spin state using a picosecond optical pulse

• This talk:
  – Qubits in quantum dots
  – Deterministic DE generation and spin writing
  – DE life and coherence times
  – Coherent control of the DE spin state

Semiconductor Quantum Dots

Cross-sectional TEM of an uncapped QD

self assembled dots
Advantages of Quantum Dots

• Live forever
• Easily incorporated into microcavities and devices
• Easily accessed optically and electronically
• Level separation compatible with fast optics (picoseconds)
• Can be easily charged and discharged

• Disadvantages:
  – Every dot is different (size, structure, location)
  – Coupled to their solid state environment (phonons)
Conduction band
Empty of electrons

Valence band
Full of electrons

Orbital angular momentum \( \pm 1 \)
and spin \( \pm \frac{1}{2} \)
aligned: \( \pm \frac{3}{2} \)

Discrete set of energy levels

Photon emission
Due to recombination of e-h pair

Randomized carrier spin

Dark Exciton \( | \pm 2 \rangle \)

Photon does not alter electron spin.

From Spin to Polarization

Orbital angular momentum (0)
and spin (1/2)

Orbital angular momentum (±1)
and spin (±1/2)
aligned: ±3/2

Photon Polarization ↔ Exciton Spin State

Discrete set of energy levels

Conduction band
Empty of electrons

Valence band
Full of electrons
(no holes)

Resonant Excitation

Non-Resonant Excitation

Photon Polarization

Photon does not alter electron spin.

Resonant Excitation

Dark Exciton \( | \pm 2 \rangle \)

Randomized carrier spin

Benny et al., PRL (2011).

Photon Polarization

Exciton Spin State

Non-Resonant Excitation

Dark Exciton \( | \pm 2 \rangle \)

Randomized carrier spin

Benny et al., PRL (2011).
Dark Excitons in Quantum Dots

A long-lived two-level system. A qubit?

DiVincenzo criteria for QIP:

Fortschr. Phys. 48 77 (2000)

– We need to find some quantum property of a **scalable** physical system in which to encode our bit of information (**qubit**). It should live long enough to enable performing computation.

– **Initial state preparation.** Setting the state of the qubits to zero before each new computation.

– **Isolation** from the environment to maintain the quantum nature of the qubit - reducing the effects of decoherence.

– **Gate implementation.** Manipulation of the states of individual qubits with reasonable precision, and inducing interactions between them in a controlled way. The gate operation time must be much shorter than the decoherence time (allow error corrections)

– **Readout.** It must be possible to measure the final state of our qubits once the computation is finished, to obtain the output of the computation.
# Other Quantum Dot Qubits

<table>
<thead>
<tr>
<th>System</th>
<th>Lifetime</th>
<th>Coherence Time</th>
<th>Initialization</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No Field</td>
<td>B Field</td>
<td>No Field</td>
</tr>
<tr>
<td>Electron Spin</td>
<td>&lt;1µs$^1$</td>
<td>10s of ms$^1$</td>
<td>1-10 ns$^1$</td>
</tr>
<tr>
<td>Hole Spin</td>
<td>1 µs$^2$</td>
<td>Few ms$^2$</td>
<td>1-20 ns$^2$</td>
</tr>
<tr>
<td>Bright Exciton</td>
<td>1 ns$^3$</td>
<td>Same</td>
<td>&gt;10 ns$^3$</td>
</tr>
<tr>
<td>Dark Exciton</td>
<td>&gt;1µs$^4$</td>
<td>&gt;100 ns$^4$</td>
<td></td>
</tr>
</tbody>
</table>

Optically active: Short lifetime, electrostatic fluctuations.

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$^3$See Benny et al. *PRL* (2011) and others.

The Dark Exciton Bloch Sphere

\[ |s\rangle = (\uparrow\uparrow + \downarrow\downarrow) / \sqrt{2} \]

\[ |a\rangle = (\uparrow\uparrow - \downarrow\downarrow) / \sqrt{2} \]

\[ \psi = A|s\rangle + B|a\rangle \]

\[ \psi(t) = |s\rangle + e^{i\omega t}|a\rangle \]

\[ \Delta_2 \approx 1.3 \mu eV \]

\[ T = 2\pi / \omega = h / \Delta_2 \approx 3.1 ns \]
Heralding and Probing the DE Spin State

\[ |S\rangle = \left( \uparrow\uparrow + \downarrow\downarrow \right) / \sqrt{2} \]

\[ |A\rangle = \left( \uparrow\uparrow - \downarrow\downarrow \right) / \sqrt{2} \]

Spectroscopy of the DE

Rabi Oscillations and Spin Rotation

Rabi oscillations:
\[ |g\rangle = \text{empty dot} \]
\[ |e\rangle = \text{DE} \]
Change pulse area by varying laser intensity
Rabi Oscillations

\[ \delta = \omega - \omega_0 \neq 0 \]

Pulse Area \( A = 2\pi \)

\[ |s\rangle = |2\rangle + |-2\rangle \]

Spin rotation:
Direction determined by polarization
Angle determined by detuning

Y. Kodriano et al. PRB 85, 241304(R) (2012).
DE Rabi Oscillations

Pulse width 50ns
Rep rate 1 MHz

Deterministic writing of the DE!
Direct Measurement of the DE Lifetime

\[ \tau_{DE} \approx 1.1 \, \mu s \]
Life and Coherence Time of the Dark Exciton

Autocorrelation of the biexciton emission line under D-polarized CW resonant excitation

Coincidences

\[ P = \frac{1 + \cos(\omega t)}{2} - \frac{1 - \cos(\omega t)}{2} = \cos(\omega t) \]

Polarization Degree

\[ P = \frac{I_{\sigma^+\sigma^+} - I_{\sigma^+\sigma^-}}{I_{\sigma^+\sigma^+} + I_{\sigma^+\sigma^-}} \]
Coherence of the Dark Exciton

$T_2^* \approx 100\text{nsec}$

Rep rate 76MHz
Controlling the DE Spin State

Bloch Sphere

\[ \frac{\left( \uparrow \uparrow + \downarrow \downarrow \right)}{\sqrt{2}} \]

\[ \frac{\left( \uparrow \uparrow - \downarrow \downarrow \right)}{\sqrt{2}} \]

Pulse Sequence

\[ \left| \uparrow \downarrow (\uparrow \uparrow) \right> \]

\[ \left| \uparrow \uparrow - \downarrow \downarrow \right> \]

\[ \left| 0 \right> \]

Pump

Control (ps)

Probe

\[ I(t) \]

\[ t \]
Controlling the Dark Exciton Spin

\[
\frac{(\uparrow\uparrow + \downarrow\downarrow)}{\sqrt{2}}
\]

\[
\frac{(\uparrow\uparrow - \downarrow\downarrow)}{\sqrt{2}}
\]

Pump (H)  Control (ps, R)  Probe (R)

Time from Control Pulse (nsec)
Writing the spin of the bright exciton by one short optical pulse

\[ H \equiv \frac{1}{\sqrt{2}} (R + L) \]

\[ \left| V \right> = i \left( \downarrow \uparrow - \uparrow \downarrow \right) \]
\[ \left| H \right> = \frac{1}{\sqrt{2}} (\downarrow \uparrow + \uparrow \downarrow) \]
\[ \Delta = 34 \mu \text{eV} \]
\[ |V> \]
\[ |H> \]

\[ \left| L \right> \]
\[ \left| R \right> \]

\[ \frac{1}{\sqrt{2}} \left| R + L \right> \]
\[ \frac{1}{\sqrt{2}} \left| R + iL \right> \]
\[ \frac{1}{\sqrt{2}} \left| R - iL \right> \]
\[ \frac{1}{\sqrt{2}} \left| R - L \right> \]

Poincare sphere

\[ \frac{1}{\sqrt{2}} \left| \uparrow \right> \]
\[ \frac{1}{\sqrt{2}} \left| \downarrow \right> \]

Bloch sphere

\[ T = \frac{\hbar}{\Delta} = 122 \text{ps} \]
‘Writing’ the spin of the bright exciton with one optical pulse

\[ \alpha \cdot R + \beta \cdot L \]

\[ \begin{aligned} |L\rangle & \rightarrow \frac{1}{\sqrt{2}} |R + L\rangle \\ \frac{1}{\sqrt{2}} |R - L\rangle \\ \frac{1}{\sqrt{2}} |R + iL\rangle \\ \frac{1}{\sqrt{2}} |R - iL\rangle \end{aligned} \]

\[ \begin{aligned} |H\rangle & \rightarrow \frac{1}{\sqrt{2}} |\uparrow \uparrow\rangle \\ \frac{1}{\sqrt{2}} |\uparrow \downarrow\rangle \\ \frac{1}{\sqrt{2}} |\downarrow \downarrow\rangle \\ \frac{1}{\sqrt{2}} |\downarrow \uparrow\rangle \end{aligned} \]

\[ X^0 \]

\[ \begin{aligned} |V\rangle & \rightarrow \frac{i}{\sqrt{2}} (\downarrow \uparrow - \uparrow \downarrow) \\ \Delta = 34 \mu\text{eV} \\ \frac{1}{\sqrt{2}} (\downarrow \uparrow + \uparrow \downarrow) \end{aligned} \]

Poincare sphere

Writing the spin of the dark exciton by one ps optical pulse

BE-DE mixing induced by the QD asymmetry

\[
\begin{align*}
\begin{array}{c}
\uparrow \\
\downarrow
\end{array} & \begin{array}{c}
\uparrow \\
\downarrow
\end{array} = \alpha \begin{array}{c}
\uparrow \\
\downarrow
\end{array} + \beta \begin{array}{c}
\downarrow \\
\uparrow
\end{array}
\end{align*}
\]

Unpolarized DE quasi resonance

Coherent Writing the Dark Exciton spin State by a Single Picosecond-long Optical Pulse
**Summary**

The dark exciton is a neutral, long-lived, physical two-level system:

- Lifetime: longer than 1 µs
- Coherence time ($T_2^*$): longer than 100 ns
- *No magnetic field, without spin echo!*

We demonstrate:

- **Deterministic photogeneration** of the DE.
- **Control** of the DE state by a picosecond pulse - 6 and 5 orders of magnitude faster than its lifetime and coherence time, respectively.
- **Coherent writing** by a single polarized picosecond pulse

Consequently, the dark exciton is an excellent solid state spin qubit.
Thank you for your attention!