Semiconductor Quantum Dots as Entangled Light Sources
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Motivation: deterministic sources for entangled photons.

Semiconductor Quantum Dots: Sources for single and correlated photons on demand.


Polarization Tomography: Experimental determination of the two photon density matrix.

Entanglement by Spectral Filtering.

Why does it work in spite of spectral diffusion.

Entangled light source by addition of a temporal window.
ENTANGLEMENT

the intriguing non-classical correlations of quantum systems.

**Motivation**

- Entangled photons are particularly attractive due to their non-interacting nature, and the ease with which they can be manipulated.
- Teleportation, quantum computing, quantum communication require “Event ready” entangled photon pairs. Therefore, **deterministic** sources of entangled photons are needed.
Bright sources of Polarization entangled photons are available today by nonlinear optical effects.

Strain induced Self assembled Quantum Dots

This scanning tunneling microscope image shows quantum dots made of indium arsenide and gallium arsenide. They are the type researchers used to observe electrons trapped inside.

Source: University of Nottingham

3D confinement of charge carriers with discrete spectrum of (only) spin degenerate energy levels.

Perfect compatibility with modern microelectronics
Technion – Israel Institute of Technology, Physics Department and Solid State Institute

Single semiconductor quantum dot

Off resonance excitation

hν

P

S

P

S

emission due to radiative recombination


By Optical or Electronic Pulse Excitation – single photons \textit{on demand}
Entangled photon pairs from radiative cascades

Entangled two photon state:

\[ \alpha \left| \sigma^+_X \sigma^-_X \right> + \beta \left| \sigma^-_X \sigma^+_X \right> \]

Suggestion: Benson Yamamoto et al PRL 2000
The anisotropic e-h exchange interaction

The photons’ color indicate the decay path!

No entanglement!

Classical correlations only!

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Two photon pair polarization state and density matrix:

\[ \Psi = \alpha |H_{XX}H_X > |p_H > |G_H > + \beta |V_{XX}V_X > |p_V > |G_V > \]

\[
\begin{pmatrix}
|H| & |V| & |H| & |V| \\
|\alpha|^2 & 0 & 0 & \gamma \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
\gamma^* & 0 & 0 & |\beta|^2
\end{pmatrix}
\]

Quantum correlations - entanglement

Peres criterion for entanglement:


Maximal Bell inequality violation:


\[
Tr(B\rho) = 2\sqrt{1 + 4|\gamma|^2} > 2
\]
Schematics of the experimental setup
The experimental setup

Nika Akopian

Technion – Israel Institute of Technology, Physics Department and Solid State Institute
Schematic of the sample

InAs quantum dots

1.5 monolayers of InAs

GaAs substrate

11 pairs of AlAs/GaAs DBRs

GaAs Cavity

25.5 pairs of AlAs/GaAs DBRs

Integrated PL intensity (10^3 Counts/Sec)

Reflectivity

Energy (eV)

1.24 1.28 1.32 1.36
Selective wavelength imaging of MCQD sample

Low resolution (5μm step)

high resolution (0.5μm step)
Photoluminescence of single quantum dot

PL Energy (eV)

200K

PL Intensity (×10^2 cts/sec)
Polarization sensitive photoluminescence

\[ \Delta = 27 \mu eV \]

\[ 1.2762 \Delta 1.2764 \]

\[ 1.2803 \Delta 1.2805 \]

Spectral diffusion!!
Intensity Cross-Correlation Function:

Second order Intensity Correlation Function.

\[ g^{(2)}_{ij}(\tau) = \frac{\langle I_i(t)I_j(t+\tau) \rangle_t}{\langle I_i(t) \rangle_t \langle I_j(t) \rangle_t} \]

conditional probability of detecting photon from line j at time (t+\tau) after photon from line i had been detected at time (t)
Polarization Sensitive Intensity Cross-Correlation Measurements

Decay time of 0.8 nsec
$\Gamma = 1.6 \mu eV$

Number of coincidences from 2 distinct radiative cascades

$X^0 \leftrightarrow XX^0 \quad X^0 \rightarrow XX^0$

Number of correlated radiative cascades
The diagonal terms of the two photon polarization density matrix are given directly by the previous measurements:

\[ \rho_{HHHH} = \rho_{VVVV} = \frac{1}{2}; \quad \rho_{VHVH} = \rho_{HVHV} = 0 \]

Tomography is required for measuring the off-diagonal density matrix elements:

\[ \rho_{HVHV}; \rho_{VHVV}; \rho_{VHHV}; \rho_{VHHH}; \ldots \text{etc...} \]

Overall 16 different measurements in different bases are required:

\[ n_i - 16 \text{ various polarization dependent coincidence measurements} \]

\[ \rho = N \cdot \sum_{i=1}^{16} M_i n_i \]

\[ M_i 16 \text{ conversion matrices} \]

Polarization Tomography

Spectral window 200 μeV

\[
D = \sqrt{\frac{1}{2}} (H + V); \quad R = \sqrt{\frac{1}{2}} (H + iV); \quad L = \sqrt{\frac{1}{2}} (H - iV)
\]
Density matrix for \(XX \rightarrow X\) radiative cascade

Open monochromator Slits (200\(\mu\)eV)
Spectral Filtering - Elimination of the ‘which path’ Information.

Photons from both decay paths
Spectral filtering

\[ |A_H(\Delta, \Gamma)|^2 \quad |A_V(\Delta, \Gamma)|^2 \]

Total Number of radiative cascades:

\[
N = \int_{\text{spectral-window}} \left( |A_H|^2 + |A_V|^2 \right) d\varepsilon
\]

Relative number of cascades ‘common’ for both paths:

\[
r = \frac{1}{N} \int_{\text{spectral-window}} A_H^* A_V d\varepsilon
\]

\[ \Delta = 27 \mu\text{eV} \]

\[ \Gamma = 1.6 \mu\text{eV} \]
Density matrix – spectral window of 250 μeV (closed slits)

[Graph showing Re(ρ) and Im(ρ) for different polarization states]
Density matrix - spectral window of $25 \mu$eV
(closed slits)

\[ |\gamma'| = 0.18 \pm 0.05 \]

Peres criterion for entanglement is satisfied by more than 3 standard deviations of the experimental uncertainty

\[ 2\sqrt{1 + 4|\gamma'|^2} = 2.13 \pm 0.07 > 2 \]
Bell inequality violation
‘Which path’ information in the QD degrees of Freedom?

\[\Delta = 27 \mu eV\]
\[\Gamma = 1.6 \mu eV\]

\[r = |\gamma'|\]

within the experimental uncertainty

\[<G_H | G_V > \approx 1\]

No remnant ‘which path’ witness in the QD!!
Spectral Filtering in the presence of inhomogeneous broadening

Line of energy conservation
Spectral Filtering in the presence of inhomogeneous broadening

![Graph showing spectral filtering results](image-url)
no subtraction of events from distinct cascades!

1.5 ns temporal window

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<th>VV 1230 ±40</th>
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0.6 ns temporal window

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no subtraction of events from distinct cascades!
no subtraction of events from distinct cascades!

1.5 ns window

Largest negative eigenvalue of the partially transposed matrix: \[ \lambda_{\text{Peres}} = -0.03 \pm 0.06 \]

Suggestive but NOT entangled
QD Based Entangled Light Source – First Demonstration.

Largest negative eigenvalue of the partially transposed matrix: \( \lambda_{\text{Peres}} = -0.15 \pm 0.07 \)
Semiconductor quantum dots as entangled light sources

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Technion – Israel Institute of Technology, Physics Department and Solid State Institute
Technion’s Tradition: EPR & teleportation

Professors Nathan Rosen and Asher Peres

Technion – Israel Institute of Technology, Physics Department and Solid State Institute
Conclusions:


- The measured degree of entanglement \( \gamma \) equals the calculated relative number of radiative cascades ‘common’ to both decay paths \( r \). Therefore, there are no other witnesses to the ‘which’ decay path and deterministic entangled photon pair devices based on SCQD are possible.

- SCQD based quantum light source using spectral filtering and applying a temporal window.

Thanks for your attention!