The Solid-State Quantum Network (SSQN)

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(theory)

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Imperial College

Würzburg
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(fabrication of pillars)

LPN (Paris)
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Olivier Krebs
Loïc Lanco
and co
(entangled photon sources)
Outline

- Motivation: What we are trying to achieve and why?
- Deliverables: What we have actually done
- Conclusions and Outlook

Diagram:
- "Traditional" entanglement swapping
- Solid-state (QD-cavity) implementation
- Alice
- Bob
- SPDC
- XX-X entangled pair source
- A1, A2, B1, B2
- S1, S2
The one dimensional atom

\[
\frac{1}{2} \hat{U} |L\rangle \hat{U} |L\rangle \left( |\uparrow\rangle + |\downarrow\rangle \right) \rightarrow \frac{1}{\sqrt{2}} \left( |L\rangle |L\rangle |\uparrow\rangle + |R\rangle |R\rangle |\downarrow\rangle \right).
\]
Realisation in pillar microcavities

- Based on the quantum dot spin-photon interface, Hu et al PRB83, 115303 (2011)
- Contains an electron spin as an intrinsic memory
- Micropillar increases the light-matter interaction strength and photon extraction efficiency.

\[ I(\omega) = |r(\omega)| e^{i\phi(\omega)} \]
Quantum Repeater

\[ |\psi^{ph}\rangle_1 = \alpha |R\rangle_1 + \beta |L\rangle_1 \]

\[ |\psi^{ph}\rangle_{23} = (|R\rangle_2 |L\rangle_3 + |L\rangle_2 |R\rangle_3)/\sqrt{2} \]

<table>
<thead>
<tr>
<th>Photons 1, 2</th>
<th>Spin</th>
<th>Photon 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(</td>
<td>H\rangle_1</td>
<td>H\rangle_2 \text{ or }</td>
</tr>
<tr>
<td>(</td>
<td>H\rangle_1</td>
<td>V\rangle_2 \text{ or }</td>
</tr>
<tr>
<td>(</td>
<td>H\rangle_1</td>
<td>H\rangle_2 \text{ or }</td>
</tr>
<tr>
<td>(</td>
<td>H\rangle_1</td>
<td>V\rangle_2 \text{ or }</td>
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Bringing it all together

- Develop high efficiency indistinguishable single photon sources and entangled pair photon sources.
- Theory from Imperial will aid this by developing protocols to allow development of error correction protocols to deal with photon loss.
- Challenge is in spin preparation and reduction of decoherence mechanisms.
Structure

• WP1: Fabrication and Sources (UWUERZ, LPN, BRIS, IMP)
• WP2: Spin-Photon Interface (BRIS, UWUERZ, LPN, IMP)
• WP3: Theory (IMP, BRIS)
• WP4: Integration (BRIS, UWUERZ, LPN, IMP)
‘Deliverables’

**D1.3 M6**: Charged QD- cavity device with high-Q (BRIS/UWUERZ)

**D1.4 M6**: Highly-polarization-degenerate high-Q pillars ($\Delta E < 2\mu$eV) (UWUERZ)

**D1.1 M12**: Violating Bell inequalities with ultrabright source of entangled pairs (LPN).

**D1.5 M18**: Spin-photon interface (charged QD strongly coupled to high extraction efficiency, polarization degenerate cavity) (BRIS/UWUERZ/LPN)

**D1.2 M24**: Entanglement purification of two entangled pairs from photonic molecule (?LPN/BRIS)

**D2.1 M12** Demonstrate $\pi/2$ phase shift dependent on spin state (BRIS)

**D2.2 M18** Demonstrate arbitrary spin initialisation (BRIS/LPN)

**D2.3 M24** Entangled photon-spin interface (BRIS/UWUERZ)

**D2.4 M30** Remote spin entanglement (BRIS).
D3.1 M8 Analysis of requirements of photon machine gun (IMP/all).
D3.2 M18 Analysis of multi-dimensional cluster state generation (IMP).
D3.5 M18 Protocols for entanglement purification via surface codes (IMP).
D3.7 M18 Error correcting schemes tailored for non-Markovian noise (IMP).
D3.4 M24 Analysis of fidelities of spin-photon interface repeaters (BRIS/IMP).
D3.3 M36 Schemes for distribution of entanglement via cluster states (IMP/BRIS).
D3.6 M36 Thresholds and overheads for error correction for loss and depolarizing noise using surface codes (IMP).
D4.1 M12 Report on design, feasibility studies and preparation of first integration experiments. (BRIS/LPN)
D4.2 M24 Report on demonstration of photon spin entanglement and relevance to networks (BRIS/LPN)
D4.3 M36 Report on demonstration of key concepts of quantum networks (All).
D4.4 M36 Report on continuous variable schemes for quantum networks (BRIS/IMP)

Potential request for no cost extension to March 31st 2014
Highly successful in publications:

• 16 published papers 3 PRL
• 25 invited conference presentations
• 20 student/postdoc conferences
• Workshop planned at end of SSQN
WP1  Fabrication and Sources
Würzburg
Cavity growth: Würzburg

delta Si-doped low density QDs in 25-15 Cavity

- Top DBR: 15 AlAs/GaAs MPs
- InAs QDs 10nm
- GaAs δ-Si doping
- Bottom DBR: 25 AlAs/GaAs MPs

SEM image of full structure

Reflection spectrum and PL of QDs

- C4020 reflectance @ RT
- C4020 PL @ 10K
Spectroscopic investigations

μPL investigations without top DBR:
*Low* QD-density (for single QD study)
*Narrow and bright QD lines*: reflects high QD quality despite delta doping

Cavity-QD-coupling:
Strong enhancement of QD signal on Resonance with cavity mode (Q~2000)
Würzburg/LPN: deterministic coupling

Establishing an in-situ lithography system:

Modification: We couple green (PL) and blue (litho) laser
Through the same fiber to avoid misalignment and preserve a good beam shape

Towards deterministic coupling

Power: 500 nW (blue laser)
1 sec. Exposure
Holes in optical resist

SEM image of pillar fabricated via in situ lithography

1µm sized hole in resist!

Polarization series on Cavity resonance (Q~ 30000): splitting < 15µeV!
Bristol: Deterministic charging studies

Results from planar sample, contacting pillar microcavity imminent
Indistinguishable photons from adiabatic micropillars

Lermer et al., PRL (2012)

Improved mode matching between localized cavity mode and evanescent DBR Bloch mode

Pronounced cQED effects can be expected
Setup

QD inside a l-He flow cryostat
QD is quasi resonantly pumped via
a Ti:Sa-Laser ($f_{\text{Rep}} = 82$ MHz)

Spectral filtering via a monochromator
QD emission is coupled into a polarisation maintaining fiber

Variable fiber coupled time delay
(500ps)
Allows for temporal and spatial overlap of the wave packets

Si-APDs for detection of the single photons ($\Delta t_{\text{Res}} = 400$ ps)
T1, T2 vs. Detuning

- T₁ was measured via timeresolving µPL
- Extracted Purcell-factor: \( F_P = (4.35 \pm 2.81) \)
- T₂-time was measured via a Michelson-Interferometer
- T₂ stays almost constant while T1 changes with the exciton-cavity-detuning
Two-photon-interference

- for $\Delta t \to \infty$, $g^{(2)}$ goes slightly above 0.5 due to a non vanishing $g^{(2)}_{HOM}$
- fitted lifetime $T_1$ matches the measured lifetime
- fitted coherence time $T_2$ is higher than the measured one due to spectral diffusion
- fitted visibility $\nu = (83 \pm 10)$ %
Data points were measured for a maximal temporal overlap.

Due to an increasing lifetime, $g^{(2)}_{\text{HOM}}$ increases also for higher detunings.
WP1 Sources (LPN)
Ultrabright source of indistinguishable photons

Gazzano et al.,
*Nature Communications, 4, 1425 (2013)*
**Contacted - pillar micro-cavity for electric control**

Novel cavity design for electrical control of the QD-pillar emission

Deterministic coupling of a single quantum dot to a connected pillar cavity
Electrically tunable bright single photon source

**Stark effect:**
red-shift up to 1.4 meV for negative applied electric field.


*Nature Communications* 5, 3240 (2014)
WP2: Spin-Photon Interface
LPN: Cavity enhanced monitoring of single quantum events

- Real time monitoring of single charge quantum jump
- μs time resolution

Christophe Arnold, Vivien Loo, Aristide Lemaître, Isabelle Sagnes, Olivier Krebs, Paul Voisin, Pascale Senellart, Loïc Lanco

Bristol: Resonant reflection characterisation
Saturation of QD absorption

Expected reflectivity with dot or resonance (based on experimentally obtained parameters):

Experimental data:

Intracavity photon number

<table>
<thead>
<tr>
<th>Incident Power (nW)</th>
<th>7.5</th>
<th>2.2</th>
<th>0.48</th>
<th>0.1</th>
<th>0.01</th>
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<tr>
<td>135</td>
<td>2.8</td>
<td>2.6</td>
<td>2.4</td>
<td>2.2</td>
<td>2.0</td>
</tr>
<tr>
<td>38</td>
<td>2.6</td>
<td>2.4</td>
<td>2.2</td>
<td>2.0</td>
<td>1.8</td>
</tr>
<tr>
<td>11.3</td>
<td>2.4</td>
<td>2.2</td>
<td>2.0</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>0.79</td>
<td>2.2</td>
<td>2.0</td>
<td>1.8</td>
<td>1.6</td>
<td>1.4</td>
</tr>
<tr>
<td>0.09</td>
<td>2.0</td>
<td>1.8</td>
<td>1.6</td>
<td>1.4</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Switching speed

\[ \kappa = 2.85 \, \mu \text{eV} \]
\[ \kappa_s = 20.5 \, \mu \text{eV} \]
\[ g = 13.4 \, \mu \text{eV} \]
\[ \gamma = 9.6 \, \mu \text{eV} \]

\[ n_c = 0.034 = \text{Critical photon number} \]

Satisfies strong coupling condition:
\[ g > (\kappa + \kappa_s + \gamma) / 4 \]
\[ 13.4 > 8.2 \]

Cavity lifetime = 30 ps
Ultrafast switching \( \sim 10 \, \text{GHz} \)
Switching energy

On resonance, equation simplifies to:

\[ r(\omega) = 1 - \frac{\kappa \frac{\gamma}{2}}{\frac{\gamma}{2} \left( \frac{\kappa}{2} + \frac{\kappa_s}{2} \right) + g^2 \frac{n_c}{\langle n \rangle + n_c}} \]

Nonlinear response of reflectivity to intracavity photon number.

Reflectivity drops to 50% of contrast at \(<n> = 0.13 = \text{number of intracavity photons required per cavity lifetime to control the switch.}\)

Equivalent to a switching energy = 0.03aJ
Resonant fluorescence characterisation
Removing surface charge and cleaning resonance fluorescence

Resonance Fluorescence Scan-C329713.1B

Energy (meV)

Normalized Counts/sec

Wavelength (nm)

No Ti:Sa
\[ \Delta E = 0 \, \text{meV} \text{ FWHM}=14.3 \, \text{meV} \]
\[ \Delta E = 5.3 \, \text{meV} \text{ FWHM}=6.0 \, \text{meV} \]
\[ \Delta E = 6.2 \, \text{meV} \text{ FWHM}=4.9 \, \text{meV} \]
\[ \Delta E = 8.8 \, \text{meV} \text{ FWHM}=3.5 \, \text{meV} \]
\[ \Delta E = 11.9 \, \text{meV} \text{ FWHM}=5.0 \, \text{meV} \]

Resonance Fluorescence Scan

Energy (meV)

Wavelength (nm)

no Ti:Sa
110 pW
170 pW
6 nW
50 nW
WP3 Theory
Bristol: Semi-analytical model fitting

\[ r(\omega) = 1 - \frac{\kappa [i(\omega_{QD} - \omega) + \frac{\gamma}{2}]}{[i(\omega_{QD} - \omega) + \frac{\gamma}{2}] [i(\omega_C - \omega) + \kappa_s + \frac{\kappa_s}{2}]} + g^2 \frac{n_c [\gamma^2 + 4(\omega_{QD} - \omega)^2]}{\langle n \rangle \gamma^2 + n_c [\gamma^2 + 4(\omega_{QD} - \omega)^2]} \]

- Equation represents reflectivity of photons with frequency \( \omega \) from the cavity, based on cavity and dot parameters (QD linewidth, cavity lifetime etc.)
- Assumes steady state solution. Photons modelled as average intensity of intracavity electric field.
- Master equation solutions support this model so far.
Phonon-enhanced coherent scattering from a driven semiconductor quantum dot


How do quantum dot - phonon interactions change emission?

At weak driving, very little:

- With phonons
- Without phonons

At larger driving strengths, quantum dot begins to thermalise with respect to the phonons - coherent scattering increases:

- Quantum dots have a regime of coherent scattering at large driving strengths
- This regime is not present in atoms, since it is caused by exciton-phonon coupling effects

Consider both the coherent and incoherent emission
Incoherent emission coherence is limited by spontaneous emission rate
Coherent emission:
- Is monochromatic
- Has laser-limited temporal correlations
- Displays anti-bunching
- Good for single photons

Coherent emission from an atom quickly drops to zero as the c.w. strength is increased
Effect of noise on entanglement generation


How does pure-dephasing noise affect entanglement generation?

Introduce three times during which both QDs undergo pure-dephasing and magnetic field rotations

$$\rho_i = e^{C_{t_3}} \left[ U_2 \left( e^{C_{t_2}} \left[ U_1 \left( e^{C_{t_1}} | \phi_{\text{tot}} \rangle \langle \phi_{\text{tot}} | \right) U_1^\dagger \right] \right) U_2^\dagger \right]$$

Liouvillian generates dissipative non-unitary dynamics:

$$\mathcal{L} \rho = -i \frac{1}{2} [\sigma_z^A + \sigma_z^B, \rho] + \sum_i \left( L_i \rho L_i^\dagger - \frac{1}{2} \{ L_i \rho, L_i \} \right)$$

$$L_1 = \sqrt{1/T_2} \sigma_z^A \quad L_2 = \sqrt{1/T_2} \sigma_z^B$$

Tomography of post-measurement state

Suppose the procedure is performed, and we're left with a QD-QD state with some entanglement, and we want to measure it

$$\rho_{AB} = \sum_{i,j} \alpha_{ij} \sigma_i \otimes \sigma_j$$

A second photon reveals information regarding the z-z correlation of the QD-QD state

$$\alpha = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0
\end{pmatrix}$$

Applying single-spin rotations about x or y before the second photon is injected reveals information about a different correlation

Remainder elements are found by allowing the photon to interact with only one QD

- Since z-z correlations are protected from pure-dephasing noise, time for second photon is unimportant
- Second measurement collapses QD-QD state into a protected subspace - more photons can be used
Loophole free Bell test and Device independent QKD

- Detection of an H or V photon heralds the storage of a qbit
- Coincident detection heralds storage of EPR pair spins
- Spin can be read out with weak coherent beams ~100% efficiency
- Limited by storage time = decoherence of stored qbit

WP4: Integration
LPN: Controlled NOT gate with a bright single photon source

Coupling into a monomode fiber ~90%

Ultrabright source of indistinguishable single photons

Preparation

Gate

Analysis

50/50 coupler

2.2 ns delay

H,V,D,A

C-NOT Gate

Spectro SPAD

Spectro SPAD

Correlations
Entangling two photons using a CNOT gate

Summary

SSQN is a European project focussed on replacing key components of a quantum communication network with loss-resistant solid-state ones:

- High efficiency QD-based triggered entangled pair sources (Y1)
- High efficiency indistinguishable photon sources (Y2)
- First integration of sources in linear CNOT gate (Y2)
- Strong coupling saturation/ single photon gates (Y1/Y2)
- Struggling to demonstrate spin-photon effects, but watch this space in (Y3).
- Theoretical understanding of decoherence and phonon effects (Y1/2).
- Loophole free Bell inequalities and device independent quantum key distribution.

Implementation would result in:

- Remove need for synchronised photon arrival and indistinguishability at the Bell-state anayser in the quantum repeater
- Intrinisic heralded quantum memory
- 1000km entanglement distances
Contributors

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• Imperial: D. McCutcheon, A. Nazir, T. Rudolph