SEMICONDUCTOR-BASED SOURCES OF QUANTUM LIGHT

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Example of application:

- Light as information carrier for short and long-distance communication: low attenuation in optical fibers, high speed and large bandwidth

- Light sources: Semiconductor laser diodes
Problem of classical communication: security (especially if/when quantum computers will become reality). Possible solution: data encryption via quantum keys

- Bits (qubits) of key encoded, e.g., in the polarization state of a photon
- Any attempt of Eve to measure the key will perturb the result (wavefunction collapse), which can be detected by Bob and Alice
- For long distance communication, photon losses become critical → Amplifiers (A) for classical channel. But qubits cannot be copied and amplified. Quantum repeaters (QR) needed, which - in turn - require indistinguishable photons and entanglement resources.

SATELLITE-BASED QUANTUM COMMUNICATION

Quantum key distribution (QKD) over 1200 km

Nature 549, 43 (2017)

Entanglement distribution over 1200 km
Science 356, 1140 (2017)
ENTANGLED PARTICLES

- Entangled state of two particles: state which cannot be factorized as a product of single-particle wavefunctions.

- Example of polarization-entangled two-photon state:

\[
|\psi\rangle = \frac{1}{\sqrt{2}} (|H\rangle_1 |H\rangle_2 + |V\rangle_1 |V\rangle_2) =
\]

\[
= \frac{1}{\sqrt{2}} (|D\rangle_1 |D\rangle_2 + |A\rangle_1 |A\rangle_2) =
\]

\[
= \frac{1}{\sqrt{2}} (|R\rangle_1 |L\rangle_2 + |L\rangle_1 |R\rangle_2)
\]

- Counterintuitive phenomenon, „Spooky action at a distance“ – Einstein

- Resource for quantum technologies (enables establishing correlations among remote quantum objects)

USE OF ENTANGLED PHOTON PAIRS FOR QKD – THE BB92 PROTOCOL


Need reliable and scalable sources of quantum light!
EPITAXIAL SEMICONDUCTOR QUANTUM DOTS

AFM of SK-InGaAs/GaAs QDs
scale 1400x700x12 nm³

TEM (HAADF)
20 nm

F. Ding et al. APL 90, 173104 (2007)

- 3D confinement → „artificial atom“
- Easy to integrate in optoelectronic devices
- Practical sources of quantum light „on demand“?

Dislocation-Free Stranski-Krastanow Growth of Ge on Si(100)

D. J. Eaglesham and M. Cerullo

AT&T Bell Laboratories, 600 Mountain Avenue, Murray Hill, New Jersey 07974
(Received 27 December 1989)

We show that the islands formed in Stranski-Krastanow (SK) growth of Ge on Si(100) are initially dislocation-free. Island formation in true SK growth should be driven by strain relaxation in large, dislocated islands. Coherent SK growth is explained in terms of elastic deformation around the islands, which partially accommodates mismatch. The limiting critical thickness, $h_c$, of coherent SK islands is shown to be higher than that for 2D growth. We demonstrate growth of dislocation-free Ge islands on Si to a thickness of $\approx 500\,\text{Å}$, 50× higher than $h_c$ for 2D Ge/Si epitaxy.

FIG. 1. Schematic diagram of the three possible growth modes: Frank-van der Merwe, Volmer-Weber, and Stranski-Krastanov. Where interface energy alone is sufficient to cause island formation, VW growth will occur; SK growth is uniquely confined to systems where the island strain energy is lowered by misfit dislocations underneath the islands.

FIG. 4. Plan-view and cross-section TEM images of large coherent SK islands close to their maximum size prior to dislocation introduction. (a) Bright-field image near the [202] Bragg position showing characteristic “bend-contour” contrast due to dome-shaped deformation of the substrate around the island. (b) (400) dark-field image; note strong strain contrast around island.
QDs as sources of single and polarization entangled photons: typically used levels

Biexciton XX – Exciton X cascade

Two decay paths possible
First left, then right polarized photon
\[ |\psi^{(1)}\rangle = |L\rangle_{XX} |R\rangle_X \]
viceversa
\[ |\psi^{(2)}\rangle = |R\rangle_{XX} |L\rangle_X \]

If paths are indistinguishable
\[ |\psi\rangle = \frac{1}{\sqrt{2}} \left( |R\rangle_{XX} |L\rangle_X + |L\rangle_{XX} |R\rangle_X \right) \]

Entangled state!

QDs as sources of polarization entangled photons

Biexciton (XX) radiative cascade

QDs could become "the perfect source of entangled photons"
Nature Photon. 8, 174 (2014), C.-Y. Lu and J.-W. Pan

Problem: fidelity to maximally entangled state still limited to ~0.8
A quantum relay with QD photons?


- Entanglement resource (ER): $XX \rightarrow X \rightarrow 0$ cascade in QD
- BSM (partial): two-photon Hong-Ou-Mandel (HOM) interference at a beam splitter

IDEAL PROPERTIES OF QD SOURCES

- **“Purity”**: not more than one photon (or photon pair) per excitation pulse
- **Short radiative decay times** to allow GHz operation
- **Entanglement**: generation of maximally entangled photon pairs
- **Brightness**: not (much) less than one photon (or photon pair) in desired optical mode per excitation pulse
- **Indistinguishability**: all photons emitted by the same source are identical to achieve perfect HOM interference (indispensable for photonic-based quantum computing and for long-distance quantum communication)
- **“Right” wavelength** depending on application
- **Scalability**: multiple sources emit mutually indistinguishable photons (requires ~Fourier-limited emission and matching of emission energies and decay times of relevant transitions)

PROBLEM: SPREAD IN QD EMISSION PROPERTIES

- QD potential varies from QD to QD

- FSS stemming from in-plane anisotropies hinders using most QDs as sources of entangled photon pairs

REASON – SPREAD IN STRUCTURAL PROPERTIES IN STRANSKI-KRASTANOW QDs

3D composition profiles of SiGe SK-dots obtained by AFM combined with selective etching.

Similar trends for InGaAs QDs

Horizontal slices spaced 3 nm in vertical direction

Local Ge fraction x

AFM Scale: 1670 x 2150 x 107 nm³

ALTERNATIVE MATERIAL SYSTEM:
GaAs QDs IN AlGaAs MATRIX

- Highly symmetric shape, limited intermixing with barrier, tunable size and wavelength, low density for single-QD devices

Y. Huo, A. Rastelli, O. G. Schmidt, APL 102, 152105 (2013)  
GaAs QDs in AlGaAs matrix by local droplet etching

Improved ensemble homogeneity and symmetry over InGaAs QDs

See also: Y. Huo, A. Rastelli, O. G. Schmidt, APL 102, 152105 (2013)
CREATION OF BIEXCITON IN GaAs QDs WITH TWO-PHOTON EXCITATION

- Deterministic preparation of XX state via resonant two-photon excitation (fidelity ~90%)

D. Huber et al., Nature Comm. 8 15506 (2017)
DECAY DYNAMICS UNDER TPE (EVIDENCE OF “WEAK CONFINEMENT”)

Lifetimes: ~125 ps (250 ps) for XX (X) $\rightarrow$ GHz operation possible
[For strong confinement, X lifetime > 480 ps $\rightarrow$ indication of weak confinement]


BACKGROUND-FREE SINGLE PHOTONS USING GaAs QDs EMBEDDED IN A PLANAR CAVITY

At least as good as real atoms!

For single trapped ions: $g^{(2)}(0) = (8.1 \pm 2.3) \cdot 10^{-5}$
Former record: $g(2)(0) = (3 \pm 1.5) \cdot 10^{-4}$

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ENERGY TUNABLE SOURCE OF ENTANGLED PHOTONS VIA POST-GROWTH STRAIN ENGINEERING

We need 1 “knob” to control $E^0_X$ and 2 for FSS (the two bright-exciton levels are coherently coupled) → 3 “tuning knobs”

■ Intuitive view:

■ 3 Knobs? In-plane stress components!

R. Trotta, J. Martín-Sánchez, I. Daruka, C. Ortix, A. Rastelli, PRL 114,150502 (2015) and refs
WAVELENGTH-TUNABLE SOURCE OF ENTANGLED PHOTONS

- Full control of in-plane stress tensor via three independent uniaxial stresses at 60°

\[
\begin{align*}
\sigma_{xx} &= \sigma_1 + \frac{1}{4}(\sigma_2 + \sigma_3) \\
\sigma_{yy} &= \frac{3}{4}(\sigma_2 + \sigma_3) \\
\sigma_{xy} &= \frac{\sqrt{3}}{4}(\sigma_2 - \sigma_3)
\end{align*}
\]

Entanglement fidelity preserved within tuning range


A. Rastelli, I. Daruka, R. Trotta, EP3077328B1
NEARLY MAXIMALLY ENTANGLED PHOTONS FROM GaAs QDS

GaAs QDs in cavity integrated on micromachined actuator for FSS tuning to 0

$$|\psi\rangle = \frac{1}{\sqrt{2}} (|R\rangle_{XX} |L\rangle_X + |L\rangle_{XX} |R\rangle_X)$$
NEARLY MAXIMALLY ENTANGLED PHOTONS FROM GaAs QDS

Reconstructed density matrix for 2 independent QDs with FSS<0.2 µeV (lifetime-limited homogeneous linewidth 2.3 µeV)

Fidelity to ψ up to 97.8(0.5)%

Highest reported so far for QD sources with no temporal nor spectral filtering. Reasons:

- Short X lifetime (250 ps)
- Full control of FSS
- Suppressed re-excitation
- Lower nuclear spin of Ga compared to In (?)

Residual imperfection attributed to exciton spin scattering

>99% fidelity achievable with moderate Purcell enhancement

QKD WITH ENTANGLED PHOTON PAIRS FROM A QD

Raw key rate = 646 bits/s
QBER = 2.6%

Error-corrected key rate = 415 bits/s
ENTANGLED PHOTON SOURCES: STATE-OF-THE-ART


*Y. Chen et al. Nature Communications 9, 2994 (2018)
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BOOSTING BRIGHTNESS AND RADIATIVE RATES THROUGH CIRCULAR BRAGG GRATINGS

Key features:
- Broadband enhancement of collection efficiency → tolerant to wavelength mismatch
- Broadband Purcell enhancement suitable for non-degenerate entangled-photons

Deterministic fabrication of device around preselected QD

- Membrane fabrication on back-reflector
- Precise location of QD position via PL imaging of QD emission + reflectivity of metal markers (~10 nm accuracy)
- E-beam + etching

**BOOSTING BRIGHTNESS AND RADIATIVE RATES THROUGH CIRCULAR BRAGG GRATINGS**

See also H. Wang, Phys. Rev. Lett. 11, 113602 (2019)

**Experimental performance:**

- Purcell enhancement: \(~4 \rightarrow X\) radiative rate >10 GHz
- Pair collection efficiency \(~0.65\)
- Entangled fidelity \(~0.88\) (limited by FSS)

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See also H. Wang, Phys. Rev. Lett. 11, 113602 (2019)
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PHOTON INDISTINGUISHABILITY OF GAAS QDS UNDER TPE

Hong-Ou-Mandel (HOM) type interference for consecutive photons (2 ns delay) emitted by the same QD

Visibility for different QDs under TPE: \(70 - 80\%\) with no filtering, Purcell enhancement, background subtraction

Limitations:
- Phonon interactions
- Time and energy correlations introduced by cascade

D. Huber et al, Nature Comm. 8, 15506 (2017)
See also M. Müller et al, Nature Photon 8, 224 (2014)
PHOTON INDISTINGUISHABILITY FOR GaAs QDsz UNDER STRICTLY RESONANT EXCITATION

- Resonant fluorescence (RF) obtained by suppressing laser stray light via crossed-polarization
- State of the art value in absence of Purcell enhancement and spectral filtering (for InGaAs dots see Y.M. He et al. Nat Nano 8, 213 (2013))

Data by J. Weber, S. Portalupi, P. Michler (Univ. Stuttgart)

M. Reindl et al., Phys. Rev. B 100 (15), 155420
See also: E. Schöll et al., Nano Lett. 19, 2404 (2019)
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- **Indistinguishability**: all photons emitted by the same source are identical to achieve perfect HOM interference (indispensable for photonic-based quantum computing and for long-distance quantum communication). Indistinguishability of photons from cascade to be improved.
- **“Right” wavelength** depending on application
- **Scalability**: multiple sources emit mutually indistinguishable photons

HOM INTERFERENCE BETWEEN PHOTONS FORM REMOTE GaAs QDS

Strain tuning to control relative energy

Visibility ~50% (with no spectral filtering and no Purcell effect)

FUTURE: CBR INTEGRATED ON MICROMACHINED ACTUATORS AS ROUTE TO SCALABLE ENTANGLEMENT SOURCES

- Actuator: Control of FSS and emission wavelength of remote sources
- QDs in weak confinement regime $\rightarrow$ Intrinsically high radiative rates
- CBR: Brightness + Purcell enhancement ($\rightarrow$ overcome charge-noise and dephasing and enable high HOM visibility for remote sources; boost rates to $>10$ GHz)
- Move to telecom wavelength (also to stay far from free surfaces)