Quantum photonics and its applications

Assoc Prof Christophe Couteau
Laboratory « Light, nanomaterials & nanotechnologies »
CNRS-ERL 7004
University of Technology of Troyes

Location: city of Troyes

History...

& nanotechnology

Birth place of the Templar’s knights
University of Technology of Troyes

Location: city of Troyes

Province name: « Champagne »

History...

& nanotechnology

Birth place of the Templar’s knights
L2n laboratory at the UTT

L2n Created in 1994
Joint UTT-CNRS

1300 m² of office spaces

100 m² of lab spaces

1000 m² of lab spaces
(~ 700 m² of clean room)
L2n research signature

Observe  Study  Control

... light at the nanoscale

Numerical modeling & simulation  Instrumentation & fabrication  Material growth
Troyes: the stain-glass city = city of nano

1/3 of medieval stain-glass of France in Troyes

Metallic nanoparticles - plasmonics
1.2 ON THE QUANTUM MECHANICS OF COLLISIONS

[Preliminary communication]

Max Born

Through the investigation of collisions it is argued that quantum mechanics in the Schrödinger form allows one to describe not only stationary states but also quantum jumps.

\[ |\Psi(r, t)|^2 = \Psi^*(r, t)\Psi(r, t) \]

Nobel Prize in 1954

If one translates this result into terms of particles, only one interpretation is possible. \( \Phi_{n,m}(\alpha, \beta, \gamma) \) gives the probability* for the electron, arriving from the \( \alpha \)-direction, to be thrown out into the direction designated by the angles \( \alpha, \beta, \gamma \), with the phase change \( \delta \). Here its energy \( \tau \) has increased by one quantum \( h\nu_m \) at the

* Addition in proof: More careful consideration shows that the probability is proportional to the square of the quantity \( \Phi_{n,m} \).

\[ I(A) = P(A) \]
\[ I(A, B) = P(A \sqcup B) - [P(A) + P(B)] \]
\[ I(A, B, C) = P(A \sqcup B \sqcup C) - [P(A) + P(B) + P(C) + I(A, B) + I(A, C) + I(B, C)] \]

...
|1> General context for quantum technologies
    → why should we care?

|2> How is it so different?
    → what about the market?

|3> Quantum technologies and qubits: the photon

|4> The need for a quantum emitter
    → definition of a quantum emitter
    → radiating dipole
    → zoology of quantum emitters

|5> Particular case: the quantum dot
    → semiconductor quantum emitter
    → artificial atom

|6> Application: quantum cryptography
Why should we care?

Information technology and communication – ICT is everything !!!

ICT suffers from two limitations given by nature: ICT → Quantum Info Tech QIT?
1. Why should we care?

→ Limitation 1: end of Moore’s law

Observation: transistor # in integrated circuit (IC) X 2 every 2 years

Slow down

Gordon Moore (1929-): CEO & co-founder of Intel
| Why should we care? |

Size matters: 5 nm technology
TSMC: Taiwan Semiconductor Manufacturing Company

5 nm technology:
Gate oxide layer = Insulating layer

« Quantum tunneling » is the main issue!
Why should we care?

Limitation 2: some problems are « unsolvable »

Traveling salesman problem:
"Given a list of cities and the distances between each pair of cities, what is the shortest possible route that visits each city exactly once and returns to the origin city?"

NP-hard problem in combinatorial optimization
Why should we care?

→ Limitation 2: some problems are unsolvable

NP-hard = non-polynomial time to be solved

Halting problem

Would take the age of the Universe:

→ no computer now or ever...
How is it so different?

→ Uses the law of quantum physics/mechanics

- Quantum superposition

\[ |\Psi\rangle = \frac{|1\rangle + |2\rangle}{\sqrt{2}} \]

- Quantum entanglement

- Quantum parallelism: concrete example of factoring

Potential applications: AI, optimisation, computation, sensing, communications...

- No-cloning theorem

- Quantum teleportation
What about the market?

Quantum effort worldwide

Global effort 2020 $22b (estimate)

US National Quantum initiative $1.2b

European Quantum Flagship 1b € = $1.1b

India ₹73b = $11bn

Singapore $150m = $109m

China $16b

Russia R50b = $663m

Korea W44.5b = $37m

Japan ¥50b = ¥470m

Australia AU$130m = $94m

Germany 2.6b € = $3.1b

Netherlands 150m € = 1.77m

United Kingdom £1b = $1.3b

Quantum Canada CAS$1b = $766m

©2020 QuRECA Ltd – Confidential and Proprietary

12> What about the market?

THE EUROPEAN QUANTUM COMPUTING STARTUP LANDSCAPE

Start-ups only !!!

Hardware

Operating Systems

Computing

QQC  Alice/Bob  AQT  IQM

ORCA  IONICS  Universal  Quantum  eleQtron

Components & Materials

AegiQ  Qblox

Delft Circuits  Miraex  Qhuq

kiutra  Qnami

Software

Applications

Security & Encryption

QBaltic  QM  QUANTASTICA  RIVERLANE  ParityQC

Chemistry & Pharma

QUSIDE  PHEASCGRAFT  QuBalt

KRONUS  ArQit

Others

Quantum  Shield

KUANO  rahto

QuantumH  QQC  Ketita

QuantumReach  SigmaQuant

PharmaCela

CreativeQuantum

VeriCloud  AVANETIX  QuantFi

shyn  @alex_kiltz
What about the market?

Big ‘major’ companies

- Atos
- HP
- Mitsubishi
- Intel
- SK telecom
- Booz Allen Hamilton
- BT
- Nokia
- Airbus
- Fujitsu
- Google
- IBM
- Alibaba Group
- Raytheon
- Thales
- NEC
- kpn
- Microsoft
\[ |\psi\rangle = \alpha |0\rangle + \beta |1\rangle = \frac{\alpha}{\sqrt{|\alpha|^2 + |\beta|^2}} |0\rangle + \frac{\beta}{\sqrt{|\alpha|^2 + |\beta|^2}} |1\rangle \]

(normalised vector \( |\alpha|^2 + |\beta|^2 = 1 \))

\[ |\psi\rangle = \alpha |0\rangle + \beta |1\rangle \]

0 state \( \rightarrow |0\rangle \)
1 state \( \rightarrow |1\rangle \)

qubit is in the two states at the same time !!!

\[ |\psi\rangle = \alpha |0\rangle + \beta |1\rangle \]

\[ |...\rangle : \text{bracket notation} = <\text{bra}| - |\text{ket}\rangle \text{ notation} \rightarrow \text{Dirac notation} \]

\( \alpha, \beta \) are complex numbers
Different complex technologies

\[ |3\rangle \text{ Quantum technologies} \]

- 9 Superconducting qubits

Use of Photons & condensed matter

Trapped ions (ETH)

Impurities in Si
→ **Notion of spin: angular momentum**

\[ \vec{L} = \vec{r} \times \vec{p} = \vec{M} \propto \hbar \]

→ \( \vec{\mu} \) is the spin magnetic moment / ‘small’ magnet
spin is an angular momentum \( \propto \hbar \)

→ \( \hat{\mu}_z \) with 2 eigenvalues \( +\hbar/2 \) and \( -\hbar/2 \)

\[ \hat{S}_z = \begin{pmatrix} +\hbar/2 & 0 \\ 0 & -\hbar/2 \end{pmatrix} \Rightarrow \alpha|0\rangle + \beta|1\rangle \]

\( \vec{\mu} = \gamma \vec{S} = g \frac{q}{2m} \hat{S} \)
A quick reminder: polarisation

monochromatic plane wave (wavelength & frequency) \( \vec{E} = \vec{E}_0 \cos(\omega t - kx) \)

light is polarised according to the direction of the \( \vec{E} \) field
A quick reminder: polarisation

monochromatic plane wave (wavelength & frequency) \( \mathbf{E} = E_0 \cos(\omega t - kx) \)

light is polarised according to the direction of the \( \mathbf{E} \) field

**Linear polarisation along x and y:**
\[
\vec{E} = E_0 \cos(kz - \omega t) \hat{e}_x \\
\vec{E} = E_0 \cos(kz - \omega t) \hat{e}_y
\]

**Linear polarisation at +/- 45°:**
\[
\vec{E} = E_0 \cos(kz - \omega t) (\hat{e}_x + \hat{e}_y) \\
\vec{E} = E_0 \cos(kz - \omega t) (\hat{e}_x - \hat{e}_y)
\]

**Circular polarisation right or left-handed:**
\[
\vec{E} = E_0 \cos(kz - \omega t) \hat{e}_x + E_0 \cos \left( kz - \omega t + \frac{\pi}{2} \right) \hat{e}_y \\
\vec{E} = E_0 \cos(kz - \omega t) \hat{e}_x - E_0 \cos \left( kz - \omega t + \frac{\pi}{2} \right) \hat{e}_y
\]
A quick reminder: polarisation

**Linear polarisation along x and y:**
\[
\vec{E} = E_0 \cos(kz - \omega t)\hat{e}_x \\
\vec{E} = E_0 \cos(kz - \omega t)\hat{e}_y
\]

**Linear polarisation at +/- 45°:**
\[
\vec{E} = E_0 \cos(kz - \omega t)(\hat{e}_x + \hat{e}_y) \\
\vec{E} = E_0 \cos(kz - \omega t)(\hat{e}_x - \hat{e}_y)
\]

**Circular polarisation right or left-handed:**
\[
\vec{E} = E_0 \cos(kz - \omega t)\hat{e}_x + E_0 \cos \left( kz - \omega t + \frac{\pi}{2} \right)\hat{e}_y \\
\vec{E} = E_0 \cos(kz - \omega t)\hat{e}_x - E_0 \cos \left( kz - \omega t + \frac{\pi}{2} \right)\hat{e}_y
\]

Note: often we have \(|0\rangle = |V\rangle\) and \(|1\rangle = |H\rangle\)
for vertical & horizontal linear polarisation.
A quick reminder: what is a single photon?

Light is an electromagnetic wave. Also, particles = photons.

Polarisation beamsplitter

Half-wave plate $\lambda/2$

Quarter-wave plate $\lambda/4$

$|\text{V}>$, $|\text{H}>$, $|\text{+45}>$, $|\text{R}>$
Definition of a quantum emitter

→ two level system and single photons

Everything is quantum at its core

Sun, lamp, LED... not OK

A single emitter, not many

AND a two-level system is OK
Definition of a quantum emitter

→ Two level system and single photons

Laser → Poissonian distribution for the photons

Even very attenuated → Proba

\[ P_1 \] for 1 photon

\[ \frac{1}{2}P_1^2 \] for 2 photons

... 

Solution → Single dipole, a 2-level quantised system

isolated atom with an optical transition between 2 states

Takes time to reload
14> the need for a quantum emitter

Definition of a quantum emitter

→ Photon antibunching

Idea: « Split » the intensity in 2

Photon counting regime

Reflected and transmitted

but reflected OR transmitted

Construction of a temporal histogram function of $\tau$

Photon correlation function

$$g^{(2)}(\tau) = \frac{\langle I(t+\tau)I(t)\rangle}{\langle I(t) \rangle^2}$$

$$g^{(2)}(0)=0$$

Quantum optics
The need for a quantum emitter

Definition of a quantum emitter

→ Photon antibunching

* Poissonian Light, \( g^{(2)}(\tau) = 1 \)

\[ g^{(2)}(\tau) = \frac{\langle I(t+\tau)I(t) \rangle}{\langle I(t) \rangle^2} \]

\( R = 50\% \)
\( T = 50\% \)

* Bunched Light, \( g^{(2)}(\tau) > 1 \)

* Antibunched Light, \( g^{(2)}(\tau) < 1 \)

* Single Photons, \( g^{(2)}(\tau) < 1 \)

\( f = 80\text{MHz} \) → Photon Pistol

Photon Counting Regime

Continuous Excitation

\(|4\rangle\)
Radiating dipole

$\rightarrow$ Notion of dipole

$|4\rangle$ the need for a quantum emitter

Absorption in atoms

HOMO-LUMO in molecules

Displacement of charges and creation of a dipole $\vec{d}$

Semiconductors: band structures and excitons
$|4\rangle$ the need for a quantum emitter

**Radiating dipole**

→ Notion of dipole

\[ \vec{d} = q \cdot \vec{r} \]

Power/solid angle

\[ \frac{d \langle P \rangle}{d\Omega} = r^2 \hat{r} \cdot \langle S \rangle = \frac{ck^4p^2 \sin^2 \theta}{8\pi} = \frac{p^2\omega^4 \sin^2 \theta}{8\pi c^3} \]
Radiating dipole

\[ |4> \text{ the need for a quantum emitter} \]

**Radiating dipole**

→ Notion of dipole

Also used in antennas
Radiating dipole

→ Retarded potentials

Define $E$ and $B$ in terms of vector potentials $\mathbf{A}$ and electrical potential $V$:

\[
\mathbf{B} = \nabla \times \mathbf{A} \\
\mathbf{E} = -\nabla V - \frac{\partial \mathbf{A}}{\partial t}
\]

→ Maxwell’s equations with potentials

\[
\nabla^2 \mathbf{A} - \frac{1}{c^2} \frac{\partial^2 \mathbf{A}}{\partial t^2} = \frac{-j}{\varepsilon_0 c^2}
\]

\[
\mathbf{A}(M, t) = \frac{\mu_0}{4\pi r} \hat{z} \left(t - \frac{r}{c}\right)
\]

\[
V(r, \theta, t) = \frac{1}{4\pi \varepsilon_0} \frac{\cos \theta}{r^2} d \left(t - \frac{r}{c}\right) + \frac{1}{4\pi \varepsilon_0} \frac{\cos \theta}{rc} \dot{d} \left(t - \frac{r}{c}\right)
\]

\[
\mathbf{E}(r, t) \sim \frac{1}{4\pi \varepsilon_0 c^2} \frac{\sin \theta}{r} \dot{d} \left(t - \frac{r}{c}\right) \hat{e}_\theta
\]

\[
\mathbf{B}(r, t) \sim \frac{1}{4\pi \varepsilon_0} \frac{\sin \theta}{rc^3} \dot{d} \left(t - \frac{r}{c}\right) \hat{e}_\varphi
\]

Dipole along $z$

\[
\dot{d} = d_0 \cos \omega t \hat{e}_z
\]
14> the need for a quantum emitter

Radiating dipole

→ Poynting vector and radiating power

Poynting vector

\[ \mathbf{S} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B} \]

\[ \left\langle \mathbf{S}(r, t) \right\rangle = \frac{\omega^4 d_0^2}{32\pi^2 \varepsilon_0 c^3} \frac{\sin^2 \theta}{r^2} \mathbf{e}_r \]

\[ \Phi = \int \left\langle \mathbf{S}(r, t) \right\rangle \cdot d\mathbf{S} = \frac{\omega^4 d_0^2}{12\pi \varepsilon_0 c^3} \]
Radiating dipole

→ Poynting vector and radiating power

Experimental observations on semiconductor dipoles

PhD X. Brokmann
Radiating dipole

→ Poynting vector and radiating power

Radiating dipole

1. Nanocrystals
   - Nanocrystals deposited on the sample
   - PMMA (ε=50 nm)
   - Lamelle de verre (épaisse)

2. PDMS (ε~1 mm)
   - Lamelle de verre (épaisse)

PhD X. Brokmann
Zoology of quantum emitters

|4> the need for a quantum emitter

- Trapped atom
- Molecule
- Quantum dot
- Coloured center
- Nanocrystal
Zoology of quantum emitters

\( |4\rangle \) the need for a quantum emitter

- Different emitters: atoms
Zoology of quantum emitters

→ Different emitters: molecules

Single molecule observation

- Pentacene in p-terphenyl host matrix
- Low temperature 1.8 K
- Laser frequency modulation spectroscopy
- Electro-optical modulator for side-band excitation
14> the need for a quantum emitter

Zoology of quantum emitters

→ Different emitters: molecules

Small bandwidth

W. P. Ambrose, Nature 349, 225
Zoology of quantum emitters

Different emitters: molecules

All different:

Molecule spontaneously jumps in frequency space due to nearby host dynamics!

Optically induced spectral shifts!
Poisson kinetics observed.
4> the need for a quantum emitter

Zoology of quantum emitters

→ Different emitters: coloured centers (NV centers in diamond)

Zoology of quantum emitters

→ Different emitters: coloured centers (NV centers in diamond)

Doherty et al., Phys. Rep. 528, 1,
Zoology of quantum emitters

→ Different emitters: coloured centers (NV centers in diamond)

Splitting ground and excited states: $S=1$ and thus $m_s=±1$ or $m_s=0$

2 e- → spin-spin interaction with parallel spins $m_s=±1$ or antiparallel spins $m_s=0$

Note: There is also a hyperfine structure


Zoology of quantum emitters

⇒ Different emitters: coloured centers (NV centers in diamond)

Single photon emission

$g^{(2)}(\tau) = 1 - e^{-(r+\Gamma)\tau}$

$\frac{1}{\tau_{ns}}$


See demo for the correlation function

Used for quantum technologies
Zoology of quantum emitters

Different emitters: coloured centers

High band gap materials: SiC ($E_g = 3.23$ eV and $E_g = 5.47$ eV for diamond)

Castelletto et al., Nature Mat. 13, 151 (2014),
Zoology of quantum emitters

- Different emitters: coloured centers

High band gap materials: ZnO ($E_g = 3.37$ eV)

Wurtzite structure (hexagonal)

Morfa et al., Nanolett. 12, 949 (2012)
the need for a quantum emitter

Zoology of quantum emitters

Different emitters: defects in 2D materials

hBN
Hexagonal Boron Nitride

Trong Tran et al., Nature Nanotech. 11, 37 (2016),
Zoology of quantum emitters

- Different emitters: defects in 2D materials
- WSe$_2$ triangular flakes, atomically thin

He et al., Nature Nanotech. 10, 497 (2015), 14> the need for a quantum emitter
5> Particular case: quantum dot

Semiconductor quantum emitter

→ Spectroscopy of quantum emitters in semiconductors

Density of States
(how closely packed energy levels are)

Quantum confinement
Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors

Notion of hole and exciton

\[
\frac{1}{m_h^*} = \frac{1}{\hbar^2} \frac{\partial^2 \varepsilon_v}{\partial k^2}.
\]
Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors

Notion of hole and exciton

Exciton = Electron-hole pair
link by coulomb interaction

\[ E_x < E_G \]
Particular case: quantum dot

Laser Excitation

$E_g$

Conduction Band

Electron spin $\pm 1/2$

Hole spin $\pm 3/2$

Exciton in a quantum dot

Exciton: electron-hole pair

$|5\rangle$
Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors: nanocrystals

Louis Brus (Columbia University), discoverer of NCs

Quantum size effects in the redox potentials, resonance Raman spectra, and electronic spectra of CdS crystallites in aqueous solution

R. Rossetti, S. Nakahara, and L. E. Brus

Bell Laboratories, Murray Hill, New Jersey 07974
(Received 31 March 1983; accepted 5 May 1983)
Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors: nanocrystals

Fabrication of nanocrystals

- Chemical synthesis
- Nice collective properties but poor unity properties
- Unstable

TEM pictures
Semiconductor quantum emitters

\[ \Phi_1 (\text{green}) < \Phi_2 (\text{red}) \]
Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors nanocrystals

Accordability of nanocrystals: from a catalogue

### Core Shell TOPO EVIDOTS

<table>
<thead>
<tr>
<th>Color</th>
<th>Material System</th>
<th>Emission Peak</th>
<th>Typical FWHM [nm]</th>
<th>Suggested Excitation Wavelength [nm]</th>
<th>1st Exciton Peak</th>
<th>Crystal Diameter [nm-Nominal]*</th>
<th>Molar Extinction Coefficient** [10^5 cm^−1 M^−1]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Placid Blue</td>
<td>CdSe/ZnS</td>
<td>490 ± 10</td>
<td>&lt;40</td>
<td>&lt;400</td>
<td>~470</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Adirondack Green</td>
<td>CdSe/ZnS</td>
<td>520 ± 10</td>
<td>&lt;30</td>
<td>&lt;400</td>
<td>~505</td>
<td>2.4</td>
<td>1.3</td>
</tr>
<tr>
<td>Catskill Green</td>
<td>CdSe/ZnS</td>
<td>540 ± 10</td>
<td>&lt;30</td>
<td>&lt;400</td>
<td>~526</td>
<td>2.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Hops Yellow</td>
<td>CdSe/ZnS</td>
<td>560 ± 10</td>
<td>&lt;30</td>
<td>&lt;400</td>
<td>~555</td>
<td>3.2</td>
<td>2.0</td>
</tr>
<tr>
<td>Birch Yellow</td>
<td>CdSe/ZnS</td>
<td>580 ± 10</td>
<td>&lt;30</td>
<td>&lt;400</td>
<td>~566</td>
<td>3.5</td>
<td>2.4</td>
</tr>
<tr>
<td>Fort Orange</td>
<td>CdSe/ZnS</td>
<td>600 ± 10</td>
<td>&lt;30</td>
<td>&lt;400</td>
<td>~586</td>
<td>4.1</td>
<td>3.0</td>
</tr>
<tr>
<td>Maple-Red Orange</td>
<td>CdSe/ZnS</td>
<td>620 ± 10</td>
<td>&lt;30</td>
<td>&lt;400</td>
<td>~609</td>
<td>5.0</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>Deep Red EVIDOTS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>McIntosh Red</td>
<td>CdTe/CdS</td>
<td>620 ± 10</td>
<td>&lt;40</td>
<td>&lt;450</td>
<td>~605</td>
<td>4.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Cortland Red</td>
<td>CdTe/CdS</td>
<td>640 ± 10</td>
<td>&lt;35</td>
<td>&lt;450</td>
<td>~630</td>
<td>4.2</td>
<td>2.2</td>
</tr>
<tr>
<td>Rome Red</td>
<td>CdTe/CdS</td>
<td>660 ± 10</td>
<td>&lt;35</td>
<td>&lt;450</td>
<td>~650</td>
<td>4.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Empire Red</td>
<td>CdTe/CdS</td>
<td>680 ± 10</td>
<td>&lt;35</td>
<td>&lt;450</td>
<td>~680</td>
<td>5.2</td>
<td>3.3</td>
</tr>
</tbody>
</table>

* Estimates based upon Yu, Qu, Guo, Peng, February 20, 2003. ** Measured at first exciton peak
Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors nanocrystals

Quantised energies

with Born-Von Karman boundary conditions:

$$\psi(x + L_x, y, z) = \psi(x, y, z)$$

$$E_k = \frac{2\pi^2 \hbar^2}{mL^2} (n_x^2 + n_y^2 + n_z^2)$$

Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors nanocrystals

Auger effect
Quantum ‘boxes’: physical growth as opposed to chemical growth

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum dots

Growth by molecular beam epitaxy and characterization of InAs/GaAs strained-layer superlattices

L. Goldstein, F. Glas, J. Y. Marzin, M. N. Charasse, and G. Le Roux
Centre National d’Études des Télécommunications, 196 rue de Paris, 92220 France

FIG. 3. Photoluminescence at 77 K for (a) 2D and (b) 3D.
Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum dots

Quantum ‘boxes’ = quantum dots

10 K, 500 nm mesa

(also Pierre Petroff at U. Santa Barbara)
Particular case: quantum dot

Molecular Beam Epitaxy (MBE)

Growth of quantum dots

Stranski-Krastanov type of growth

Lattice parameter mismatch important between the 2 materials (CdTe/ZnTe : 7%)

Islands type Relaxation

Elastic Relaxation

1 CdTe ML

2 CdTe ML

ZnTe Barrier
Particular case: quantum dot

Semiconductor quantum emitters
→ Material consideration in semiconductors quantum dots

Bandgap engineering
Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum dots

Material effect...

Confinement effect...
Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum dots

Nanoscale islands

Quantum dots made of II-VI materials like CdTe/ZnTe or CdSe/ZnSe or III-V like InAs/GaAs

Nanometer scale

Quantum confinement effects

Dim: diameter 20 nm
  height 4 nm

TEM image from C. Bougerol
Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors

Selection of a single quantum dot
Inhomogeneous repartition of the relaxation

High density of QDs of $10^{10}$ cm$^{-2}$

Deposition of an Al mask of 100 nm thickness
Openings of $a=10 \mu m$ to $0.1 \mu m$

Spatial selection

→ for $a=0.2 \mu m$

$\approx 4$ excited QDs

Spectral selection

Size fluctuation of QDs

Unique spectrum for each QD
Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum dots

Quantum dots = artificial atoms

Main difference: no 2 identical quantum dots

as many ‘hydrogen atoms’ as there are quantum dots
|5> Particular case: quantum dot

CONDUCTION BAND

VALENCE BAND

Laser Excitation

$E_g$

Exciton: electron-hole pair

Electron spin $\pm 1/2$

Hole spin $\pm 3/2$

Exciton

|5>
5> Particular case: quantum dot

Biexciton: 2 electron-hole pair

Quantum cascade

$X_2$

$\lambda_{X_2}$

$X$

$\lambda_X$

Laser Excitation

$E_g$

CONDUCTION BAND

VALENCE BAND

Electron spin $\pm 1/2$

Hole spin $\pm 3/2$
Radiative transition of a 2-level atom \( \approx \)

Emission of single photons in a cascade

Spectral selection of the last exciton

\( \sum \) Particular case: quantum dot


Radiative transition of a 2-level atom
Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum dots

Fine spectroscopy
Particular case: quantum dot

Biexciton and exciton from a same dot

\[
\Delta_{x-x_2} = 5.3 \, \text{nm}
\]

\[
\text{InAs } \Delta = 1.5 \, \text{nm}
\]

Power dependence \((X/X_2)\)

Magnetic field dependence \((X/X^-)\)

Spectrum loaded from qd52_1.txt
|5> Particular case: quantum dot

禄 Perfect isotropic quantum dot:

Entangled state in polarisation:

禄 In reality, QDs are anisotropic:

No entanglement, only correlations

Fine spectroscopy splitting

\[
|\psi\rangle = \frac{1}{\sqrt{2}} \left( |\sigma^{+}\rangle_x |\sigma^{-}\rangle_{x_2} + |\sigma^{-}\rangle_x |\sigma^{+}\rangle_{x_2} \right)
\]

\[
\rho = \frac{1}{2} |H_x\rangle\langle H_{x_2}| + \frac{1}{2} |V_x\rangle\langle V_{x_2}|
\]
Particular case: quantum dot

III-V quantum dots:

Splitting $\delta_0 = 1$ to 100 $\mu$eV
$= 0.5$ to 40 GHz

Microwave region: 5 to 500 mm

Fine spectroscopy splitting
III-V quantum dots:

Shifting of the levels by magnetic field \( B \)

Zeeman effect shift: annihilation of the splitting

**Existent experiments: #1**
$\vert 5 \rangle$ Particular case: quantum dot

- **III-V quantum dots:**
  - Detuned lasers
  - AC Stark shift by virtual photons

Existing experiments: #2
Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum dots

Stark effect

Particular case: quantum dot

Semiconductor quantum emitters

→ Spectroscopy of quantum emitters in semiconductors quantum molecules

Quantum molecules

Coupled quantum dots or 'quantum molecules'

Quantum dot 1

Quantum dot 2

Interaction between excitons in each dots

New levels appear like for a molecule
Particular case: quantum dot

No correlations between the QDs laterally

Dipole-dipole coupling with observation of X5

checked by cross-correlations

Quantum molecules
Programme

1> General context for quantum technologies → why should we care?

2> How is it so different? → what about the market?

3> Quantum technologies and qubits: the photon

4> The need for a quantum emitter → definition of a quantum emitter → radiating dipole → zoology of quantum emitters

5> Particular case: the quantum dot → semiconductor quantum emitter → artificial atom

6> Application: quantum cryptography
A bit of history
- Notion of quantum bit
- Photons as qubits
- BB84 Protocol
- Entanglement with photons
- E91 Protocol
- What's next...
Cryptography:

Concept that makes sure information cannot be read by unauthorised people

Oldest known cryptographic system: scytale or Plutarque baton (400 before J. C.)

2 identical batons
1 ribbon with letters
A bit of history...

- Caesar's cipher
  - UTT= XWW
  - CHRISTOPHE=FKULVWRKH

- Le Grand Chiffre
  - Iron mask and Louis XIV (coding syllabes)

- Steganography

- Enigma
  - 2nd World War

Before

After
**Vernam cipher (one-time pad)**

- Only system proven secure (Vernam & Mauborgne)

**Key requirements:**
- Chosen at random
- Same length as message
- Used only once

**ALICE**

- XOR: OR exclusive Boole algebra
  - $0 + 0 = 0$
  - $1 + 0 = 1$
  - $1 + 1 = 0$
  - $0 + 1 = 1$

Message: 0 1 0 0 1 0 1 ...
Key: 1 1 0 1 0 0 1 ...

XOR: -------------------

Cryptogram: 1 0 0 1 1 0 0 ...

Cryptogram (public)

- Message: 0 1 0 0 1 0 1 ...
- Key: 1 1 0 1 0 0 1 ...
- XOR: -------------------

Cryptogram: 1 0 0 1 1 0 0 ...

Never random?
- Not easy
- Costly
RSA system (Rivest-Shamir-Adleman) used for e-commerce

Based on the principle that multiplying prime numbers is easy, but finding the prime numbers is difficult!

ALICE

Nowadays

BOB

p * q

p * q * m

m

p * q

p * q * m
More and more data transfer

A mad mathematician...

With a quantum computer: end of RSA

Mosca’s ‘threat’: store now, decrypt later...

Solution: quantum cryptography
**Notion of quantum bit**

- **Comparison: classical & quantum bit**

  Result: \( \Psi = 0 \) OR 1

- **Representation on the Bloch sphere**

  Result: \( |\Psi\rangle = \alpha |0\rangle + \beta |1\rangle \)
No-cloning theorem in Nature

Impossible to clone a quantum state

Dolly is OK but no-cloning machine


Notions of Electromagnetism

Photon = electromagnetic wave

Maxwell’s equations

\[ \nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \]
\[ \nabla \cdot \mathbf{B} = 0 \]
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]
\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \]

\[ \mathbf{E}, \mathbf{E} \cdot \mathbf{n}, \mathbf{B} = \frac{\mathbf{u} \wedge \mathbf{E}}{c} \]

\[ \Delta \mathbf{E} = \frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} \]

Wave propagation
Notions of Electromagnetism

Photon = electromagnetic wave

Maxwell's equations:
\[ \nabla \cdot \mathbf{B} = 0 \]
\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]
\[ \nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mathbf{E} \]

\[ \vec{E}, \vec{B}, \mathbf{J} \]
\[ \vec{B} = \frac{\vec{u} \wedge \mathbf{E}}{c} \]

\[ \Delta \mathbf{E} = \frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} \]

Wave propagation
The photon as a qubit

A quick reminder: polarisation

**Linear polarisation along x and y:**

\[
\vec{E} = E_0 \cos(kz - \omega t) \hat{e}_x \\
\vec{H} = E_0 \cos(kz - \omega t) \hat{e}_y
\]

**Linear polarisation at +- 45°:**

\[
\vec{E} = E_0 \cos(kz - \omega t) (\hat{e}_x + \hat{e}_y) \\
\vec{H} = E_0 \cos(kz - \omega t) (\hat{e}_x - \hat{e}_y)
\]

**Circular polarisation right or left-handed:**

\[
\vec{E} = E_0 \cos(kz - \omega t) \hat{e}_x + E_0 \cos \left( kz - \omega t + \frac{\pi}{2} \right) \hat{e}_y \\
\vec{H} = E_0 \cos(kz - \omega t) \hat{e}_x - E_0 \cos \left( kz - \omega t + \frac{\pi}{2} \right) \hat{e}_y
\]

\[|\psi\rangle = |0\rangle \text{ and } |1\rangle\]

\[|\psi\rangle = \frac{1}{\sqrt{2}} |0\rangle \pm \frac{1}{\sqrt{2}} |1\rangle\]

\[|\psi\rangle = \frac{1}{\sqrt{2}} |0\rangle \pm \frac{i}{\sqrt{2}} |1\rangle\]

Note: often we have $|0\rangle = |V\rangle$ and $|1\rangle = |H\rangle$

for vertical & horizontal linear polarisation
A quick reminder: what is a single photon?

- Light is an electromagnetic wave
- Also particles = photons

Half-wave plate $\lambda/2$

Quarter-wave plate $\lambda/4$

|V> $|V>$ $|V>$

$|+45>$

$|R>$

Polarisation beamsplitter

$|V>$

$|H>$

$|H>$

$|V>$
Bennett-Brassard quantum key distribution protocol (1984)

First experiment

EPR source

Einstein-Podolski-Rosen paradox (1935)

$\Psi = |\psi_1\rangle |\psi_2\rangle |\psi_3\rangle |\psi_4\rangle$

→ Notion of non-separable states

→ Global wave function

Polarisation photon entanglement

Type II non-linear crystal:

\[ |\psi^-(\mathcal{H}) \rangle = \frac{1}{\sqrt{2}} \left( |H\rangle_1 |V\rangle_2 - |V\rangle_1 |H\rangle_2 \right) \]

\[ \vec{k}_p = \vec{k}_1 + \vec{k}_2 \]

\[ E_p = E_1 + E_2 \]

Ekert91 protocol using photon entanglement
Quantum cryptography based on Bell’s theorem
Eve can be detected

As BB84, use of 2 different basis for Alice and Bob

Entanglement maintained in all basis!
Quantum key distribution

Entangled State

Receiving
- Basis
  - Measurement
  - Convert to bit: $\rightarrow = 0$, $\uparrow = 1$

Sifting
- Same basis?

Inversion
- Bob inverts his bits

Security
- Test for errors?

Final Key
- Kit bit generated

<table>
<thead>
<tr>
<th>Alice</th>
<th>Bob</th>
<th>Alice</th>
<th>Bob</th>
<th>Alice</th>
<th>Bob</th>
<th>Alice</th>
<th>Bob</th>
<th>Alice</th>
<th>Bob</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

- Yes
- No

Final Key:
- 1 0
- 0
Private amplification

1- Alice and Bob split their key up in half

2- They then XOR the two halves together

3- In order for Eve to have a bit in the final key, she must have known BOTH bits that were XOR’d together

001011101001011 \[\rightarrow\] XOR 0 0 1 0 1 1 1 1 10
1 0 0 1 0 1 1 1 1
1 0 1 1 1 0 0 1

Eve would have know both of these bits to know the final key bit
1- Alice encodes her information and sends it to Bob

2- Bob uses his copy of the secret key to decode the message and read what Alice sent

3- The encoding operation is the XOR gate from digital logic
Some records

Free Space Quantum Communication over 144 km

- Project QIPS from ESA, with MPQ+LMU, Bristol
- Source equipment in a container
- Receiving polarization analyzer and 4 Si APDs in the focus of OGS
- Two way tracking with green beacon lasers

Some recent experiments

- **100 km, Vienna**

- **107km (144 km), Los Alamos**

- **200 km, Tokyo**

- **250 km Genve**
Quantum Backbone

- Total Length 2000 km
- 2013.6-2016.12
- 32 trustable relay nodes
- 31 fiber links
- Metropolitan networks
  - Existing: Hefei, Jinan
  - New: Beijing, Shanghai
- Customer: China Industrial & Commercial Bank; Xinhua News Agency; CBRC
Shanghai control center of the Chinese quantum key distribution network and satellite
What about industry

Several start-up companies worldwide and big ones too

- IdQuantique (WCP, plug and play, CV system)
- MagiQ (WCP, plug and play)
- BBN (WCP+EPR, Network)
- Toshiba (Fastest gating, quantum dots)
- NTT (WCP, 200km with SSPD)
- Quintessencelabs (CV)
- HP-Labs Bristol (WCP, short range)
- QuTools (Components)
- Qinetiq (EPR, free Space)
- SmartQuantum (WCP, sideband modulation)
Conclusion