Single photons from single quantum dots

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NCCR Quantum Photonics
Project 2A: Single-photon sources from self-organized quantum dots
1900: Photoelectric effect
1905: Einstein: *Light quanta*

Statistical properties of light (1955-...):

Hanbury Brown and Twiss experiment (1956)

$\langle I(t)I(t+\tau) \rangle$

classical

quantum

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How many particles?

Electronics:

# electrons to process one bit

1970: 10 μm gate, 10 V
⇒ 6x10^7 electrons/gate

2001: 65 nm gate, 1V
⇒ 2x10^4 electrons/gate

Photonics:

# photons to transmit one bit

1980: 45 Mbit/s, 1 mW
⇒ 10^8 photons/pulse

2001: 10 Gbit/s, 1 mW
⇒ 8x10^5 photons/pulse

⇒ Where is this all going?
The day after tomorrow...

Electronics:
Single-electron transistors

Photonics:
Single-photon emitters and detectors

A very-low-power source ???
What is a "single photon" ???

And what for ???

Courtesy CNR-IFN

Ford et al., 1993
"Quantum-secure" communication uses single photons:

- Two polarization coding sets:
  \[ \uparrow = 1 \]
  \[ \rightarrow = 0 \]
  \[ \swarrow = 1 \]
  \[ \searrow = 0 \]
- Alice chooses a polarization set randomly:
- Bob selects an analyzer set randomly:
- Only the bits where the same polarization sets were used are kept
Eavesdropping on single photons

To spy, Eve must intercept the photon and retransmit it:

A single photon cannot be split!

By monitoring the error rate Alice and Bob can check the channel security!
Quantum cryptography = Classical money?

- ≥ 2 start-ups
- Quantum cryptography systems being commercialized
- Practical systems much more complicated!
"Classical" light sources (e.g. a laser) are Poissonian:

\[ P(n) = \frac{n^n}{n!} e^{-\langle n \rangle} \]

\[ P(n) = \text{prob. of } n \text{ photons} \]
\[ \langle n \rangle = \text{average photon number} \]

\[ \sigma_n^2 = \langle n \rangle \]

Fluctuations are tied to the statistics

Let's attenuate a laser (=change \( \langle n \rangle \)):

\[ \langle n \rangle = 10^6 \]
\[ \sigma_n = 10^3 \]

Not a single-photon source!

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A true single photon source

Typical source used in quantum cryptography:
Attenuated laser, $<n> \approx 0.1$
$\Rightarrow P(1) = 9\%, P(2) = 0.45\%$

- Low bit rate
- Probability of two-photon pulses not negligible
$\Rightarrow$ Security not completely guaranteed

(Brassard et al., PRL 85, 1330 (2000))

For a true single-photon source we must trick Poisson:

Single quantum system:

Photon emission

"dead time"

(Because we are not changing the statistics...)

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The quest for single-\( \varphi \) sources

The simplest single-\( \varphi \) sources:

- Single atoms
- Single ions
- Single molecules
- ...

Wish list for single-\( \varphi \) sources:

- Compact
- Electrically pumped
- Room temperature
- Efficient

\( \Rightarrow \) A semiconductor LED!

(Diedrich and Walther, PRL 1987)
The challenge

Isolate a single quantum state in a semiconductor and pump it efficiently

Density of states in a semiconductor of volume $V$:

$$\rho(E) = \frac{V}{2\pi^2} \left(\frac{2m^*}{\hbar^2}\right)^{3/2} \sqrt{E - E_c}$$

In $\Delta E = 20$ meV ($\approx kT$): $\approx 2 \times 10^{17}$ states per cm$^3$ in CB

Need to isolate one state! $\Rightarrow V \approx (10 \, \text{nm})^3$

"Nano"semiconductors

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Semiconductor nanostructures

3D carrier confinement \(\Rightarrow\) Quantization of energy states

Bulk semiconductor:
- 

"Quantum Dot"
- 

\(\Rightarrow\) Quantum dots behave as "solid-state atoms"

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Nanostructure fabrication

■ "Straightforward" approach: Fabrication on the nanoscale
  - Need high-resolution lithography
  - Etching ⇒ Nonradiative defects

■ "Self-organized" methods: Making Nature work for us!
  - Strain-driven growth on planar substrates (*project 2A*)
  - Growth on patterned substrates (*project 2B*)
Self-organized growth

Epitaxial growth: Interplay of surface energy and strain

"Standard" (Frank-van der Merve) 2D epitaxial growth:

The epitaxial layers "wet" the surface $\Rightarrow$ 2D growth

Stranski-Krastanov 3D growth mode:

Strain too large $\Rightarrow$ island formation
Self-organized quantum dots

MBE growth of InAs on GaAs:

- Simple growth technique, no pre-growth patterning required
- High crystalline quality ⇒ High radiative efficiency at RT
- 1.3 μm operation possible
- Random nucleation sites ⇒ no control of island position
- Size dispersion ⇒ Emission energy dispersion

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The objectives

- Fabricate LEDs with single QDs
- Characterize single photon emission
- Application to quantum communication

This talk:

- Growth and characterization of QDs
- QD devices
- Towards a single QD LED
Quantum Dot optimization

Specifications:
- High radiative efficiency
- Wavelength $\approx 1300$ nm
- Low areal density ($\approx 10^9$ cm$^{-2}$)

Growth parameters:
- Temperature
- Growth rate
- Capping procedure

- $T \uparrow \Rightarrow$ diffusion $\uparrow \Rightarrow$ larger and fewer QDs
- $\text{In flow} \uparrow \Rightarrow$ more atoms on surface $\Rightarrow$ more QDs
**Growth optimization**

**Areal density:**

- 0.075 ML/s $\Rightarrow 1.9 \times 10^{10}$ cm$^{-2}$
- 0.037 ML/s $\Rightarrow 1.4 \times 10^{10}$ cm$^{-2}$
- 0.019 ML/s $\Rightarrow 6 \times 10^{9}$ cm$^{-2}$

**Emission wavelength:**

- PL peak (nm)
- FWHM

*Chen et al., JAP 91, 6710 (2002)*

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**Growth: Capping**

**GaAs capping** → **In segregation**

**InGaAs capping:**
- Suppression of In segregation
- Reduction of strain
- Bigger QDs

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Radiative properties of optimized QDs

Conclusions:
- High radiative efficiency ≈20% at RT
- Long carrier lifetime ≈ 1ns
- 1300 nm emission at RT
- Density ≈ 6x10^9 cm^2 ⇒ to be decreased

Markus et al., APL 80, 911 (2002)

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QDs in "standard" devices: LEDs

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QD lasers

Laser performance:
- $J_{th} < 100 \text{ A/cm}^2$
- $\eta_{ext} = 30-40\%$
- CW up to 80 C

2 mm, 3 QD layers, RT

3 QD layers, 18 µm stripe

Intensity (a.u.)

Power (mW)

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Simple approaches to single-QD devices

- Nanomesas for optical pumping:
  - 100 nm nanomesa by Ebeam lithography and reactive-ion etching

- Shadow-mask LED:
  - 300 nm opening in metal contact by Ebeam lithography and lift-off

It works! (Yuan at al., Science 2002)
But: Very low efficiency...

(Collaboration with CNR-IFN Rome)

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Towards single-QD LEDs

Macroscopic LED: (100x100 µm² = 10⁶ QDs)

Nano LED: (0.1x0.1 µm² = 1 QD)

Critical issues:

• High spatial resolution needed
• Alignment critical!
• Lateral carrier loss (current spreading, nonradiative recombination)
"Standard" LED structures:

Current density and efficiency do not scale with device size

⇒ Difficult to fabricate < 10 µm devices

Current spreading & NR recombination

- Large effective device area
- Decrease in efficiency
A new approach to nano-LEDs

- Epitaxial growth
- Optical lithography & etching
- Selective oxidation
- Metallization

- **Down to 100 nm current apertures** with simple optical lithography
- Can tailor both current and optical confinement
- Bandgap engineering to reduce current spreading

Fiore et al., to be published in APL
Good scaling of current-voltage and efficiency characteristics

⇒ Suppressed current spreading
⇒ Suppressed carrier diffusion in the QDs
⇒ Negligible nonradiative recombination
Conclusions & Perspectives

- Where we are:
  - QD growth optimized
  - Efficient QD devices
  - Technology for single-QD LEDs

- The future:
  - Even smaller: Getting the single-QD LED
  - Playing with single QDs and single photons…