# Coherence in semiconductor nanostructures
# Part I: Generalities

Jacek Kasprzak

UNIWERSYTET WARSZAWSKI | ZIP ZINTEGROWANY PROGRAM ROZWOJU

Equipe mixte CEA-CNRS "Nanophysique et semicondcuteurs"
Institut Néel - CNRS
Grenoble France

Warsaw University, October-December 2020

# Plan of the Lectures, 30 hours

1. Semiconductors, nanostructures & excitons
2. Enhancing light-matter interaction with photonic devices
3. Spontaneous coherence in ensembles of excitons and polaritons
4. Notions of nonlinear spectroscopy
5. Retrieving single exciton coherence: experimental challenges
6. Single exciton coherence exploited with four-wave mixing
7. Exciton-cavity system in the quantum strong coupling regime
8. Coherent coupling in small ensembles of excitons
9. Coherent spectroscopy of excitons in TMDs and their heterostrucutres

# Plan of the Lectures, 30 hours

1. Semiconductors, nanostructures & excitons
2. Enhancing light-matter interaction with photonic devices
3. Spontaneous coherence in ensembles of excitons and polaritons
4. Notions of nonlinear spectroscopy
5. Retrieving single exciton coherence: experimental challenges
6. Single exciton coherence exploited with four-wave mixing
7. Exciton-cavity system in the quantum strong coupling regime
8. Coherent coupling in small ensembles of excitons
9. Coherent spectroscopy of excitons in TMDs and their heterostrucutres

# Plan of the Lectures, 30 hours

1. Semiconductors, nanostructures & excitons
2. Enhancing light-matter interaction with photonic devices
3. Spontaneous coherence in ensembles of excitons and polaritons
4. Notions of nonlinear spectroscopy
5. Retrieving single exciton coherence: experimental challenges
6. Single exciton coherence exploited with four-wave mixing
7. Exciton-cavity system in the quantum strong coupling regime
8. Coherent coupling in small ensembles of excitons
9. Coherent spectroscopy of excitons in TMDs and their heterostrucutres

# Plan of the Lectures, 30 hours

1. Semiconductors, nanostructures & excitons
2. Enhancing light-matter interaction with photonic devices
3. Spontaneous coherence in ensembles of excitons and polaritons
4. Notions of nonlinear spectroscopy
5. Retrieving single exciton coherence: experimental challenges
6. Single exciton coherence exploited with four-wave mixing
7. Exciton-cavity system in the quantum strong coupling regime
8. Coherent coupling in small ensembles of excitons
9. Coherent spectroscopy of excitons in TMDs and their heterostrucutres

# Plan of the Lectures, 30 hours

1. Semiconductors, nanostructures & excitons
2. Enhancing light-matter interaction with photonic devices
3. Spontaneous coherence in ensembles of excitons and polaritons
4. Notions of nonlinear spectroscopy
5. Retrieving single exciton coherence: experimental challenges
6. Single exciton coherence exploited with four-wave mixing
7. Exciton-cavity system in the quantum strong coupling regime
8. Coherent coupling in small ensembles of excitons
9. Coherent spectroscopy of excitons in TMDs and their heterostrucutres

# Plan of the Lectures, 30 hours

1. Semiconductors, nanostructures & excitons
2. Enhancing light-matter interaction with photonic devices
3. Spontaneous coherence in ensembles of excitons and polaritons
4. Notions of nonlinear spectroscopy
5. Retrieving single exciton coherence: experimental challenges
6. Single exciton coherence exploited with four-wave mixing
7. Exciton-cavity system in the quantum strong coupling regime
8. Coherent coupling in small ensembles of excitons
9. Coherent spectroscopy of excitons in TMDs and their heterostrucutres

# Plan of the Lectures, 30 hours

1. Semiconductors, nanostructures & excitons
2. Enhancing light-matter interaction with photonic devices
3. Spontaneous coherence in ensembles of excitons and polaritons
4. Notions of nonlinear spectroscopy
5. Retrieving single exciton coherence: experimental challenges
6. Single exciton coherence exploited with four-wave mixing
7. Exciton-cavity system in the quantum strong coupling regime
8. Coherent coupling in small ensembles of excitons
9. Coherent spectroscopy of excitons in TMDs and their heterostrucutres

# Plan of the Lectures, 30 hours

1. Semiconductors, nanostructures & excitons
2. Enhancing light-matter interaction with photonic devices
3. Spontaneous coherence in ensembles of excitons and polaritons
4. Notions of nonlinear spectroscopy
5. Retrieving single exciton coherence: experimental challenges
6. Single exciton coherence exploited with four-wave mixing
7. Exciton-cavity system in the quantum strong coupling regime
8. Coherent coupling in small ensembles of excitons
9. Coherent spectroscopy of excitons in TMDs and their heterostrucutres

# Plan of the Lectures, 30 hours

1. Semiconductors, nanostructures & excitons
2. Enhancing light-matter interaction with photonic devices
3. Spontaneous coherence in ensembles of excitons and polaritons
4. Notions of nonlinear spectroscopy
5. Retrieving single exciton coherence: experimental challenges
6. Single exciton coherence exploited with four-wave mixing
7. Exciton-cavity system in the quantum strong coupling regime
8. Coherent coupling in small ensembles of excitons
9. Coherent spectroscopy of excitons in TMDs and their heterostrucutres

# Outline

1. Semiconductors
2. Nano-scale
3. Exciton Generalities
4. Nano-Structures

# What is a semiconductor ?

A solid in which opto-electronic properties
can be tuned via size, composition & controlled doping

- Electronic transport

- Absorption and emission of light

Photo-Voltaics

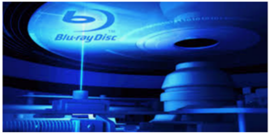
Light Emitting Diodes

# What is a semiconductor ?

A solid in which opto-electronic properties
can be tuned via size, composition & controlled doping

Tunable Laser diodes

Avalanche Photo Diodes





From UV and blue to Mid-Infra Red and THz range

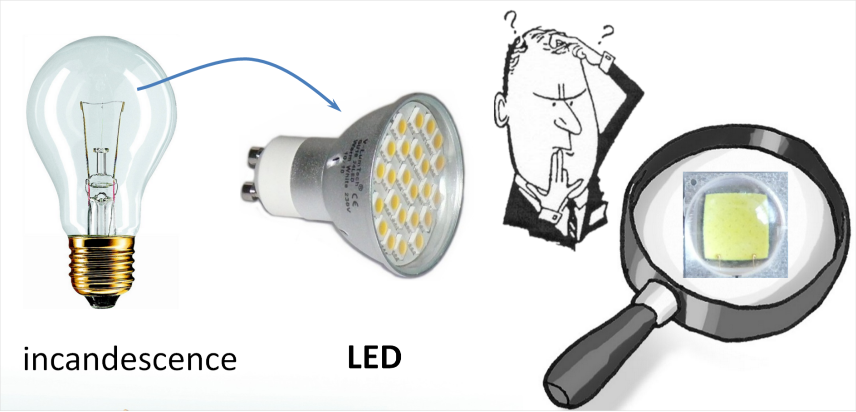
# What is a semiconductor ?

A solid in which opto-electronic properties
can be tuned via size, composition & controlled doping

incandescence LED

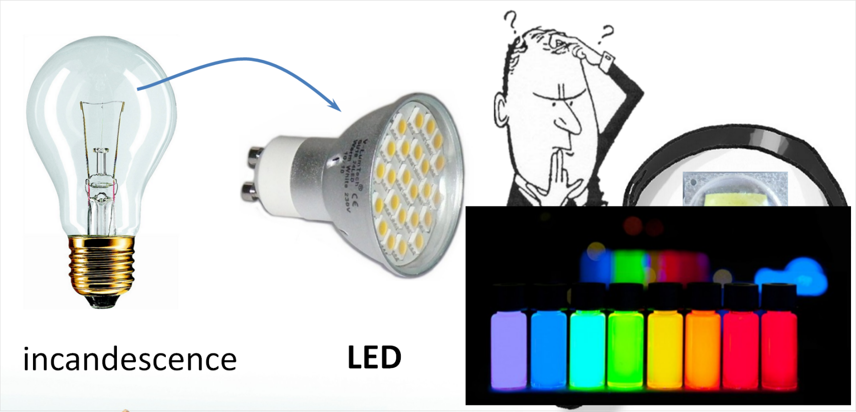
# What is a semiconductor ?

A solid in which opto-electronic properties
can be tuned via size, composition & controlled doping



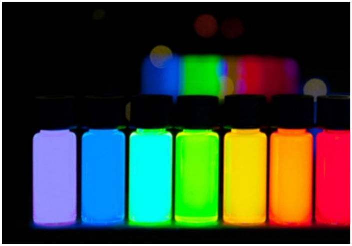
# What is a semiconductor ?

A solid in which opto-electronic properties
can be tuned via size, composition & controlled doping



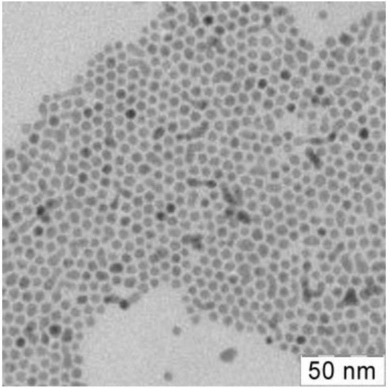
# Towards the nanophysics

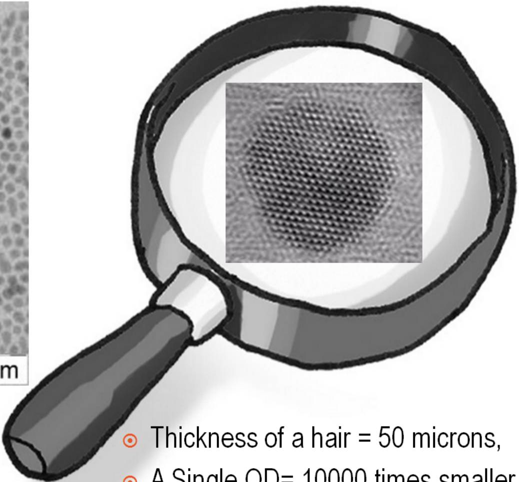
NanoMeter=0.000000001 Meter



# Towards the nanophysics

NanoMeter=0.000000001 Meter

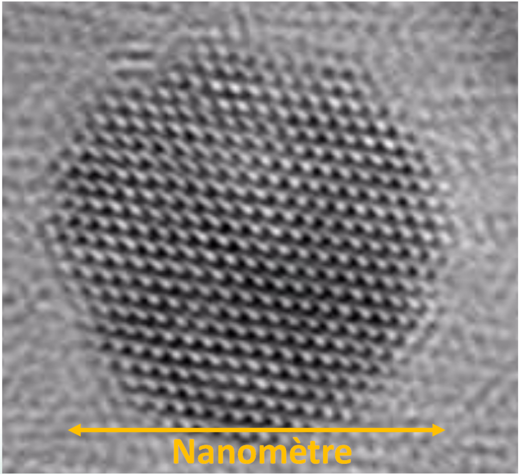


- Thickness of a hair = 50 microns,
- A Single QD= 10000 times smaller

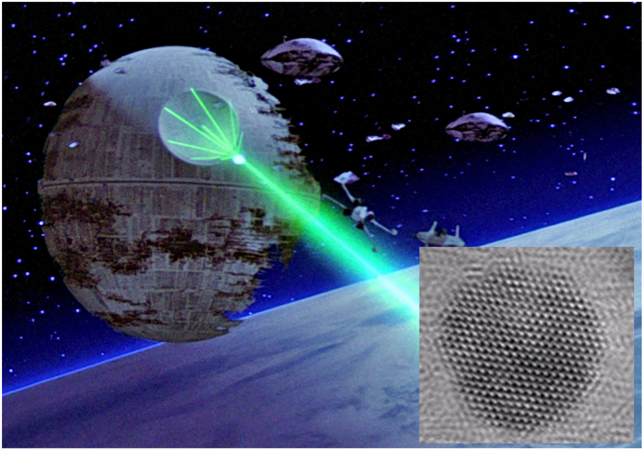
# Nano-emitter ⇒ A single semiconductor Quantum Dot

nanometric trap for charge carriers, **1** photon out each nano-second



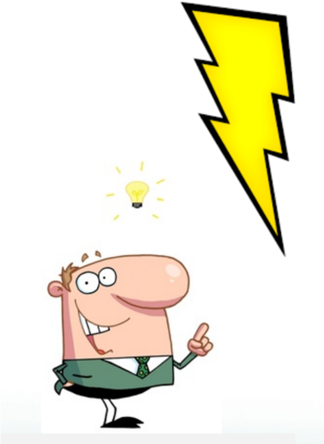
# Nano-emitter ⇒ A single semiconductor Quantum Dot

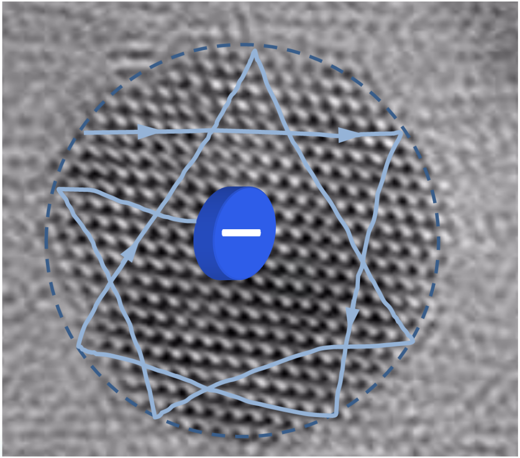
nanometric trap for charge carriers, **1** photon out each nano-second



# Nano-emitter $\Rightarrow$ A single semiconductor Quantum Dot

nanometric trap for charge carriers, **1** photon out each nano-second



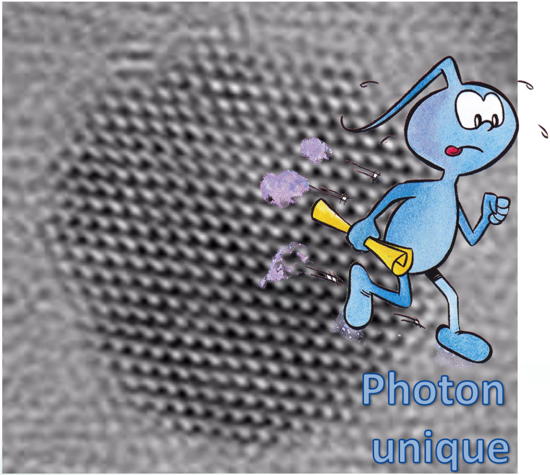


# Nano-emitter ⇒ A single semiconductor Quantum Dot

nanometric trap for charge carriers, **1** photon out each nano-second

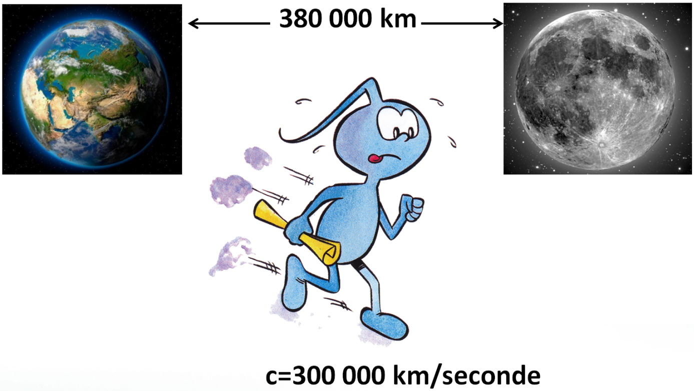
# Nano-emitter ⇒ A single semiconductor Quantum Dot

nanometric trap for charge carriers, **1** photon out each nano-second



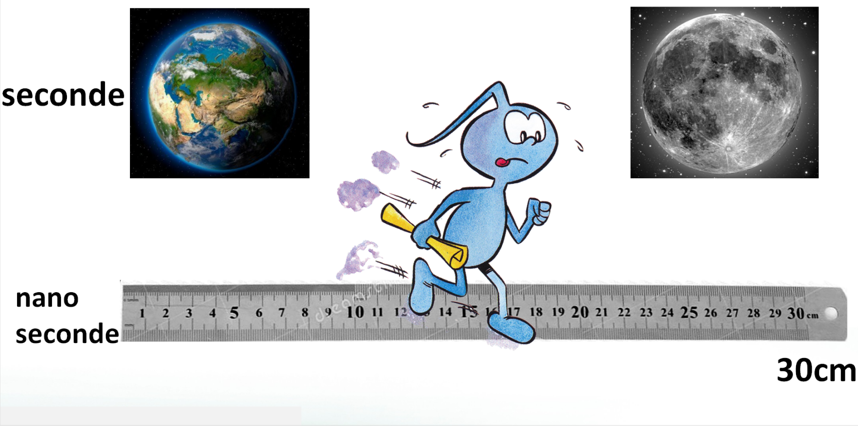
# Nano-emitter ⇒ A single semiconductor Quantum Dot

nanometric trap for charge carriers, **1** photon out each nano-second



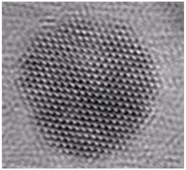
# Nano-emitter ⇒ A single semiconductor Quantum Dot

nanometric trap for charge carriers, **1** photon out each nano-second

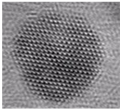


# Optical spectroscopy

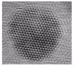
color = size + composition (alloys)




red




green

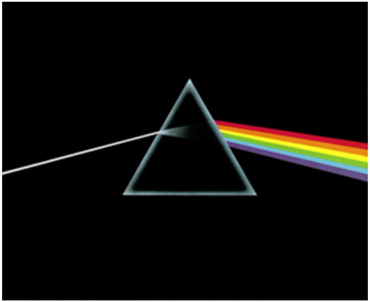


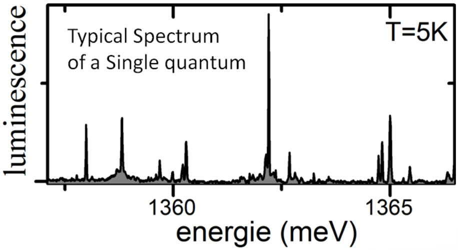

blue

# Optical spectroscopy

color = size + composition (alloys)

- Intensiy vs. Color (Energy, wavelength, frequancy)

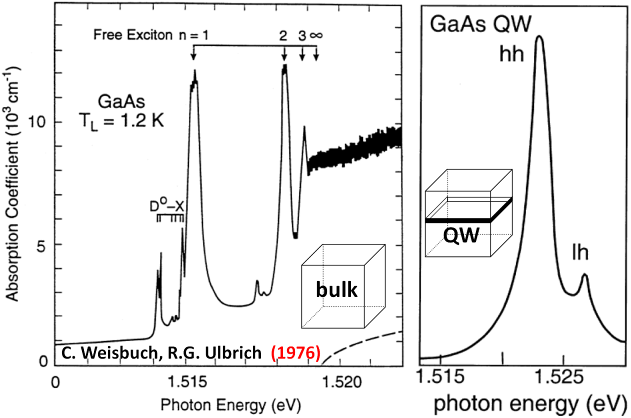




# Semiconductor Optics ⇒ Excitons

Ryd∼0.01 eV, 1000 times weaker than in atoms

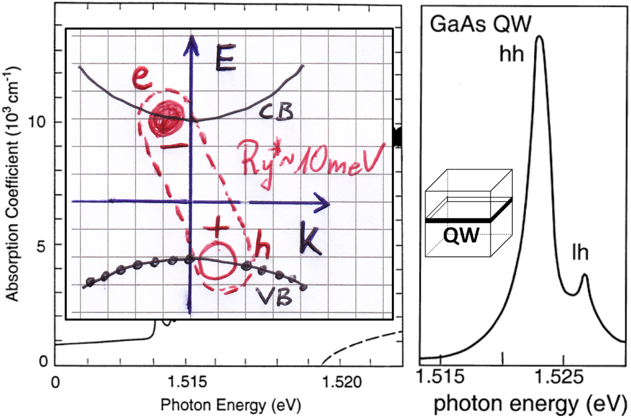
**G. H. Wannier Phys. Rev. 52, 191 (1937): "the electron cannot escape its hole completely"**



# Semiconductor Optics ⇒ Excitons

Ryd∼0.01 eV, 1000 times weaker than in atoms

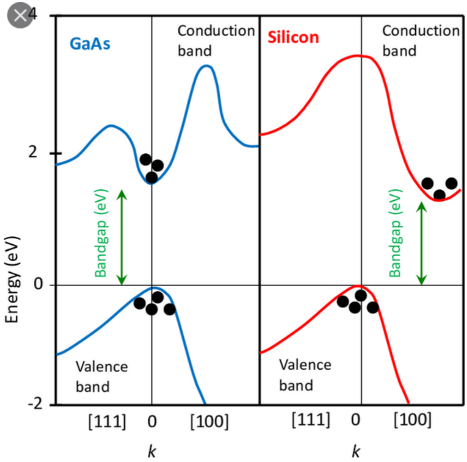
G. H. Wannier Phys. Rev. 52, 191 (1937): "the electron cannot escape its hole completely"



# Optical Activity ⇒ Bandgap: Direct vs. Indirect

Direct: GaAs, InAs, CdTe, TMD monolayers, $Cu_2O$

Indirect: Si, Ge, TMDs bulk and multilayers



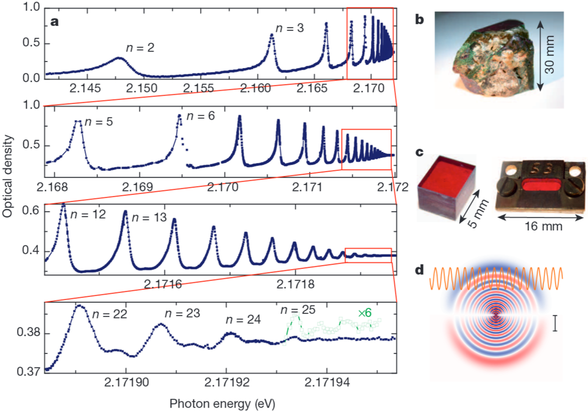
# How to enhance the light-matter interaction ?

Increase exciton oscillator strength, most prominent example is $\mathbf{Cu_2O}$

**Gross (1952),...,Kazimierczuk et al., Nature 514, 343 (2014)**

Exciton extension up to 2 $\mu$m for high Rydberg states

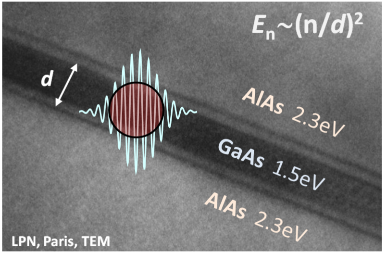
## Giant Rydberg excitons in the copper oxide $Cu_2O$

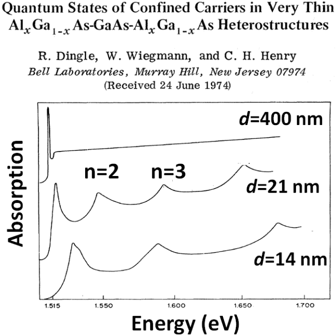


# Quantum confinement in nanostructures

## Material growth with atomic precision ⇒ wavefunction engineering

**Quantum Wells: $d \sim \lambda_{dB} \sim (mT)^{-1/2}$**

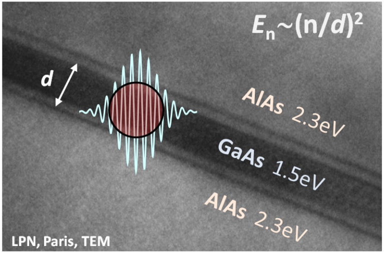


# Quantum confinement in nanostructures

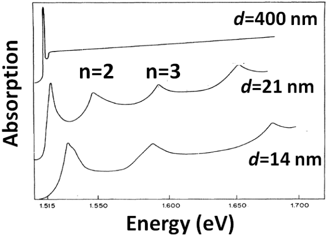
Material growth with atomic precision $\Rightarrow$ wavefunction engineering

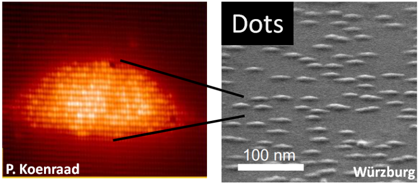
**Quantum Wells: $d \sim \lambda_{dB} \sim (mT)^{-1/2}$**

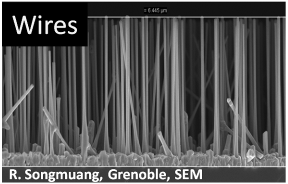



Quantum States of Confined Carriers in Very Thin $Al_xGa_{1-x}As$-GaAs-$Al_xGa_{1-x}As$ Heterostructures

R. Dingle, W. Wiegmann, and C. H. Henry
*Bell Laboratories, Murray Hill, New Jersey 07974*
(Received 24 June 1974)



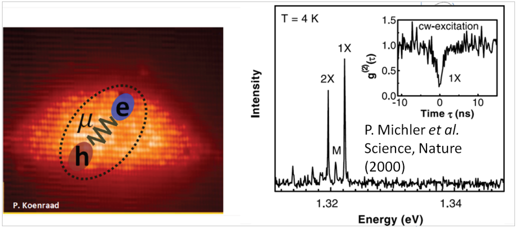



# A quantum dot exciton

Bright, nano-scopic source of quantum light from the solid

Optically driven, fast qubit ?




two-level system

embedded in the crystal → phonons

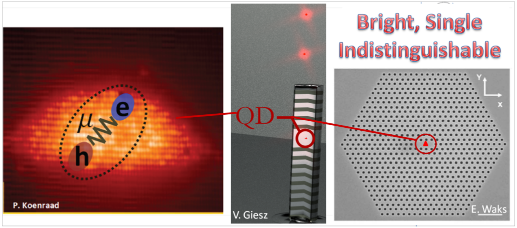
robust coupling with UV-VIS-NIR light → coherent control

price to pay: short lifetime, ns

# A quantum dot exciton

Bright, nano-scopic source of quantum light from the solid

Optically driven, fast qubit ?




two-level system

embedded in the crystal → phonons

robust coupling with UV-VIS-NIR light → coherent control

price to pay: short lifetime, ns

# A quantum dot exciton

Bright, nano-scopic source of quantum light from the solid

Optically driven, fast qubit ?

PRL **116,** 020401 (2016) PHYSICAL REVIEW LETTERS

**On-Demand Single Photons with High Extraction Efficiency and Near-Unity Indistinguishability from a Resonantly Driven Quantum Dot in a Micropillar**

Xing Ding,[1,2,3] Yu He,[1,2,3] ... Sven Höfling,[1,5,6] Chao-Yang Lu,[1,2,3,*] and Jian-Wei Pan

**Near-optimal single-photon sources in the solid state** N. Somaschi[1†], V. Giesz[1†], L. De Santis[1,2†], ...L. Lanco[1,6] and P. Senellart[1,7*] nature photonics (2016)

**Two-photon interference from a bright single-photon source at telecom wavelengths** (2016) optica

Je-Hyung Kim,[1] Tao Cai,[1] Christopher J. K. Richardson,[2] Richard P. Leavitt,[2] and Edo Waks[1,3,*]

two-level system

embedded in the crystal → phonons

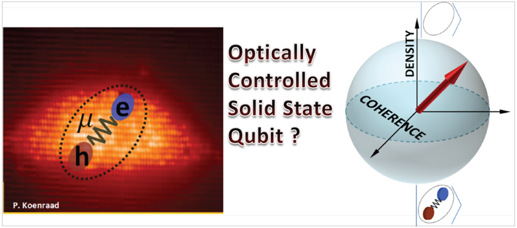
robust coupling with UV-VIS-NIR light → coherent control

price to pay: short lifetime, ns

# A quantum dot exciton

Bright, nano-scopic source of quantum light from the solid

Optically driven, fast qubit ?




two-level system

embedded in the crystal → phonons

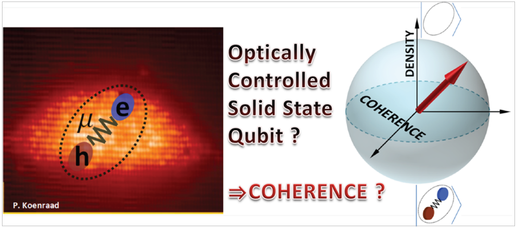
robust coupling with UV-VIS-NIR light → coherent control

price to pay: short lifetime, ns

# A quantum dot exciton

Bright, nano-scopic source of quantum light from the solid

Optically driven, fast qubit ?



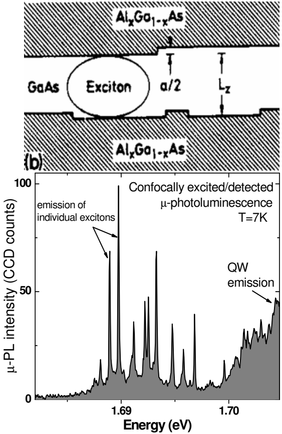

two-level system

embedded in the crystal → phonons

robust coupling with UV-VIS-NIR light → coherent control

price to pay: short lifetime, ns

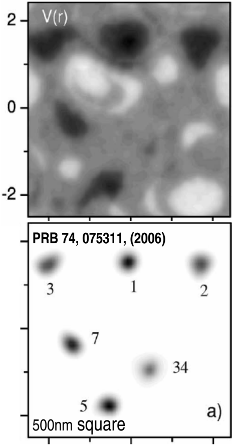
# Single excitons localized on interface fluctuations of a Quantum Well



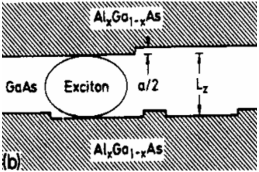

## AlAs/GaAs/AlAs
## 5 nm single QW

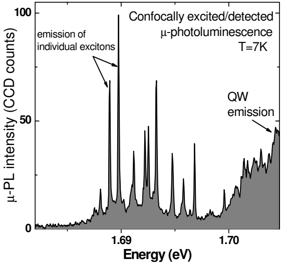
- Growth Interruption ⇒ Formation of Monolayer Islands
- Wedge ⇒ Variation of Average Thickness
- Disorder Potential ⇒ $|\Psi|^2$ of localized X
- Large Extension ⇒ Large Osc. Str. ⇒

Suitable for Non-Linear Spectroscopy



# Single excitons localized on interface fluctuations of a Quantum Well

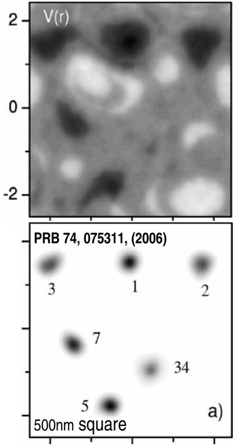



## AlAs/GaAs/AlAs 5 nm single QW

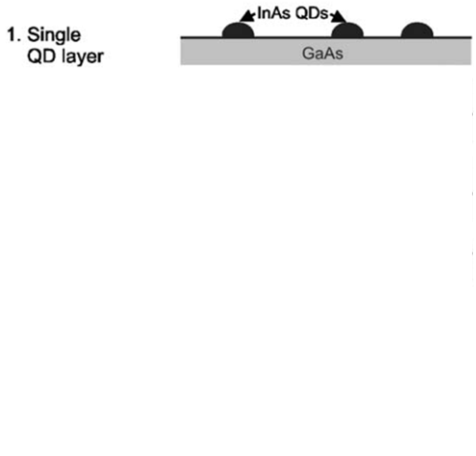
- Growth Interruption ⇒ Formation of Monolayer Islands
- Wedge ⇒ Variation of Average Thickness
- Disorder Potential ⇒ $|\Psi|^2$ of localized X
- Large Extension ⇒ Large Osc. Str. ⇒

  Suitable for Non-Linear Spectroscopy



# Multi-step self-assembly of Quantum Dots

Phys. Rev. Lett. 92, 166104, (2004)

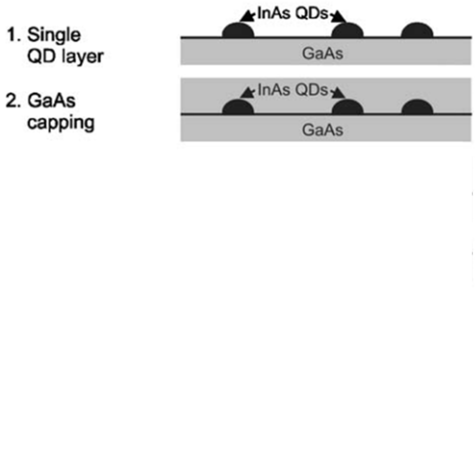



**Characteristics**

- emission $\sim$ 750 nm
- strong-confinement: 200 meV
- ultra-low density
- strain-free
- controlled geometry

# Multi-step self-assembly of Quantum Dots

Phys. Rev. Lett. 92, 166104, (2004)

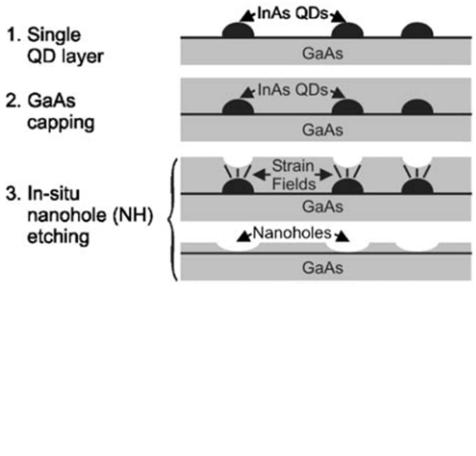



## Characteristics

- emission $\sim$ 750 nm
- strong-confinement: 200 meV
- ultra-low density
- strain-free
- controlled geometry

# Multi-step self-assembly of Quantum Dots

Phys. Rev. Lett. 92, 166104, (2004)

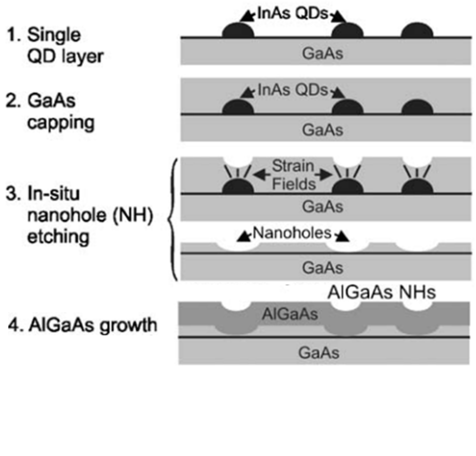



## Characteristics

- emission $\sim$ 750 nm
- strong-confinement: 200 meV
- ultra-low density
- strain-free
- controlled geometry

# Multi-step self-assembly of Quantum Dots

Phys. Rev. Lett. 92, 166104, (2004)

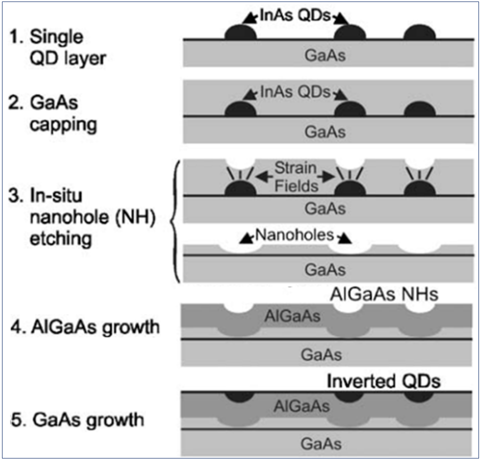



## Characteristics

- emission $\sim 750$ nm
- strong-confinement: 200 meV
- ultra-low density
- strain-free
- controlled geometry

# Multi-step self-assembly of Quantum Dots

**Phys. Rev. Lett. 92, 166104, (2004)**

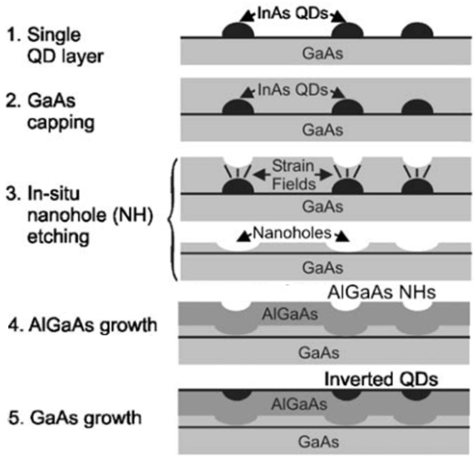



## Characteristics

- emission $\sim 750$ nm
- strong-confinement: 200 meV
- ultra-low density
- strain-free
- controlled geometry

# Multi-step self-assembly of Quantum Dots

**Phys. Rev. Lett. 92, 166104, (2004)**



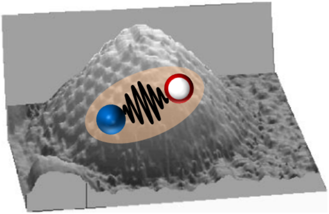

## Characteristics

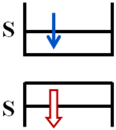
- emission $\sim 750\,\mathrm{nm}$
- strong-confinement: 200 meV
- ultra-low density
- strain-free
- controlled geometry

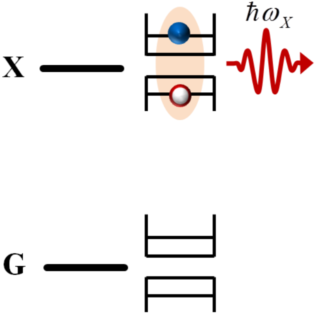
# Typical exciton complexes in a semiconductor QD

Neutral excitons, biexcitons, trions, radiative cascades

**Y. Benny et al.Phys. Rev. B 86, 085306 (2012), PhD de Santis**



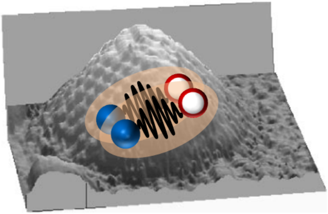


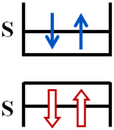



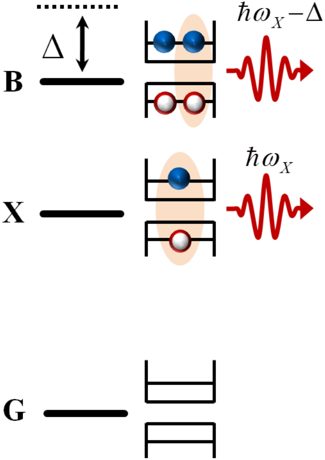
# Typical exciton complexes in a semiconductor QD

Neutral excitons, biexcitons, trions, radiative cascades

Y. Benny et al.Phys. Rev. B 86, 085306 (2012), PhD de Santis



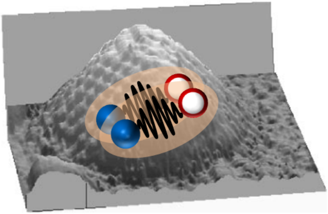


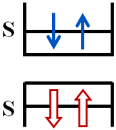



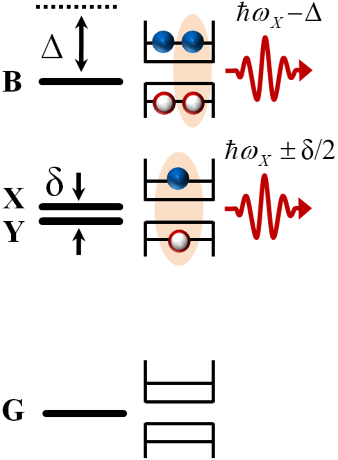
# Typical exciton complexes in a semiconductor QD

## Neutral excitons, biexcitons, trions, radiative cascades

**Y. Benny et al.Phys. Rev. B 86, 085306 (2012), PhD de Santis**



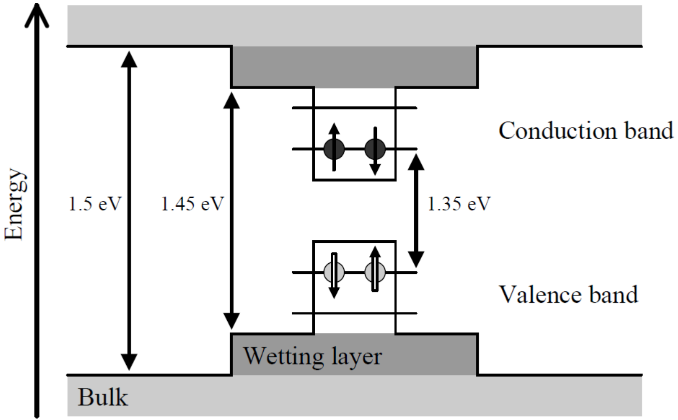




# Typical exciton complexes in a semiconductor QD

Neutral excitons, biexcitons, trions, radiative cascades

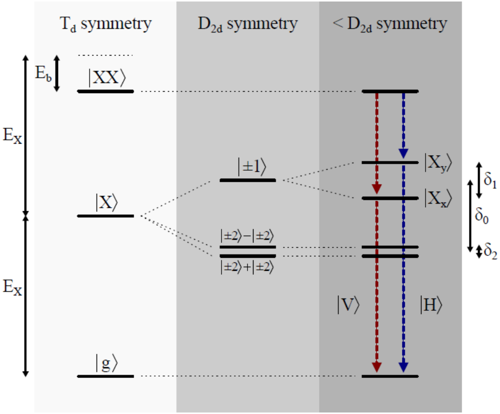
**Y. Benny et al.Phys. Rev. B 86, 085306 (2012), PhD de Santis**



# Typical exciton complexes in a semiconductor QD

Neutral excitons, biexcitons, trions, radiative cascades

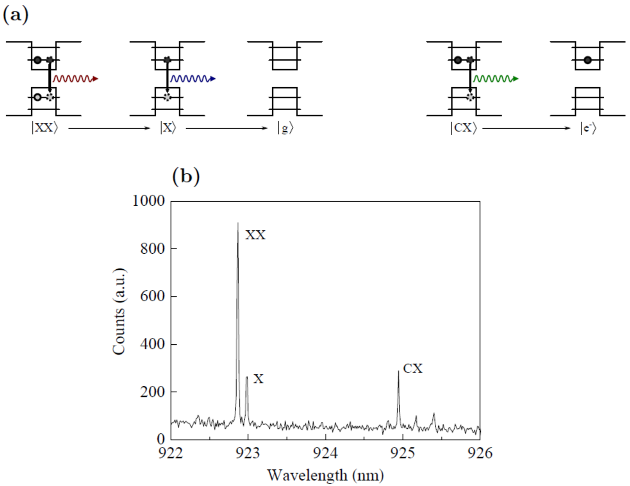
**Y. Benny et al.Phys. Rev. B 86, 085306 (2012), PhD de Santis**



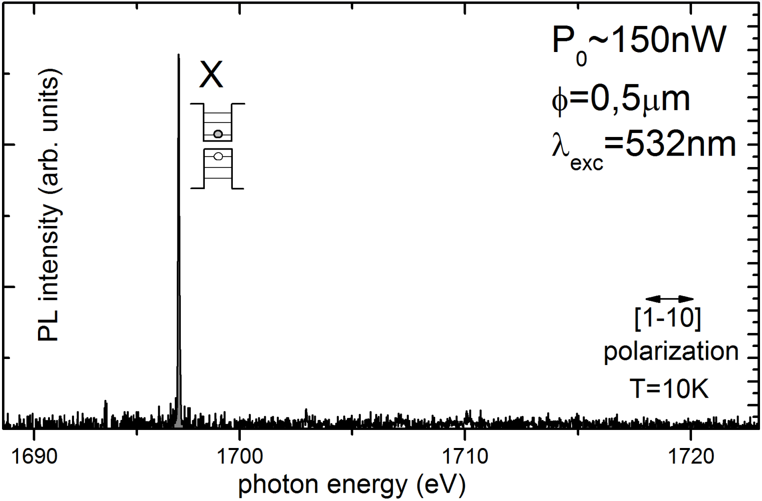
# Typical exciton complexes in a semiconductor QD

Neutral excitons, biexcitons, trions, radiative cascades

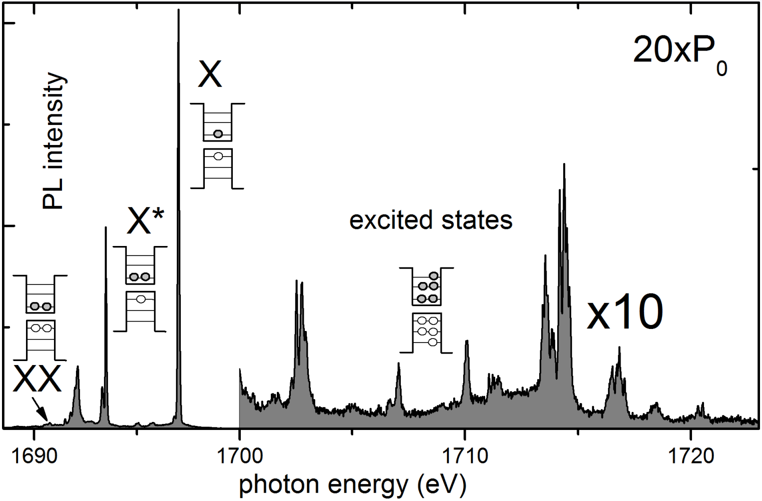
**Y. Benny et al.Phys. Rev. B 86, 085306 (2012), PhD de Santis**



# Typical photoluminescence

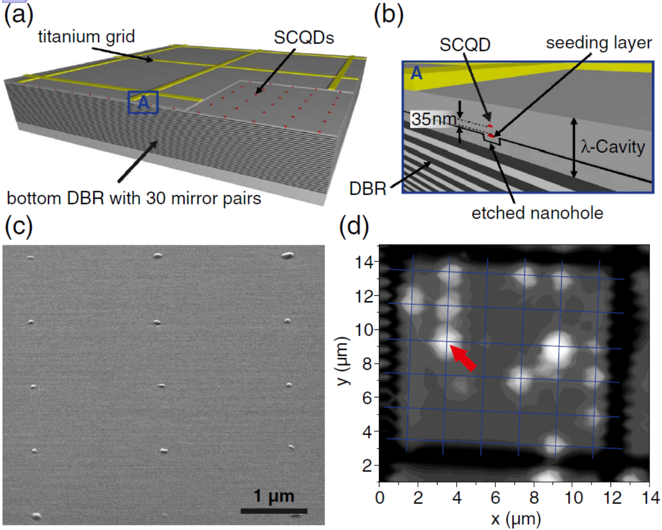


# Typical photoluminescence



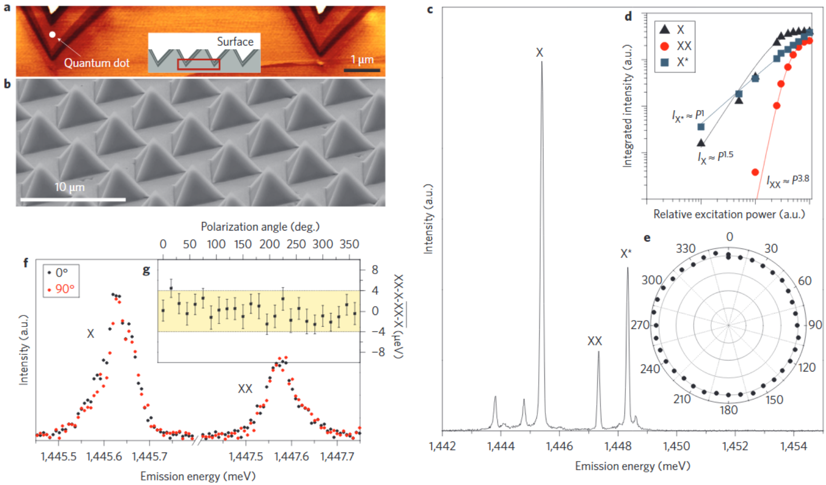
# Site-controlled fabrication of Quantum Dots

Optica 15, 2334, (2015)



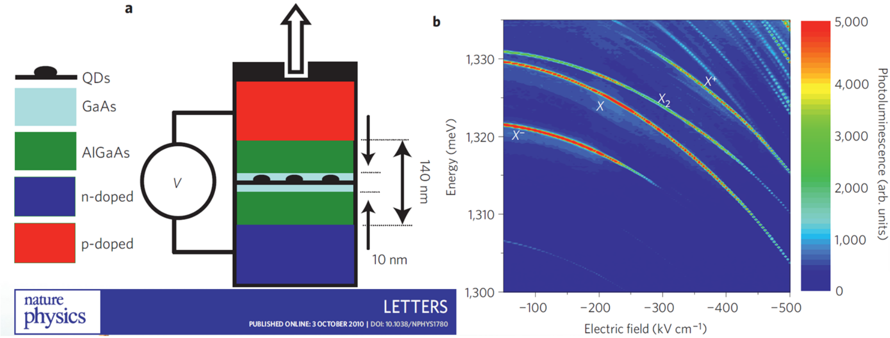
# Highly uniform deterministic arrays of pyramidal QDs

LETTERS NATURE PHOTONICS DOI: 10.1038/NPHOTON.2013.128



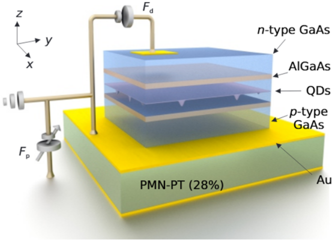
# Tuning of exciton transitions in Nanostructures

Temperature, strain, magnetic field, electric field via Stark effect

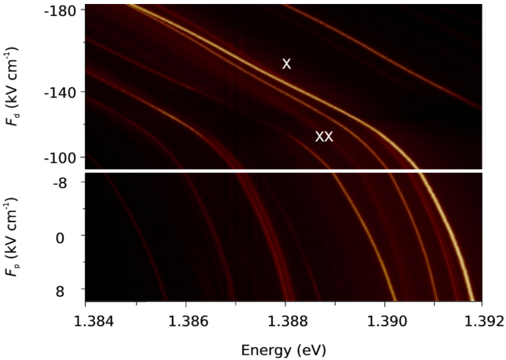


# Tuning of exciton transitions in Nanostructures

Temperature, strain, magnetic field, electric field via Stark effect

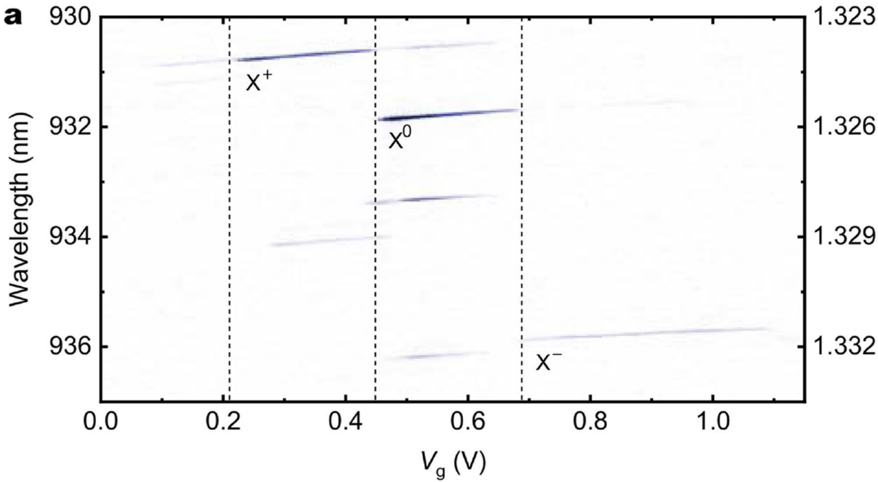



*Nano Lett.* 2017, **17**, 501–507



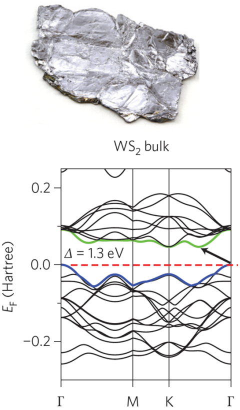
# Tuning of exciton transitions in Nanostructures

Temperature, strain, magnetic field, electric field via Stark effect



# Excitons in Semiconducting TMDs

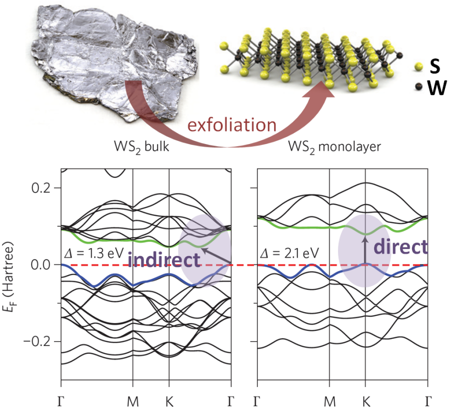
K. F. Mak Phys. Rev. Lett. 105, 136805 (2010): "a crossover to a direct-gap material in the limit of the single monolayer (...) increase in luminescence by $10^4$ compared with the bulk"




Nat. Nanotechnol. **7**, 699

# Excitons in Semiconducting TMDs

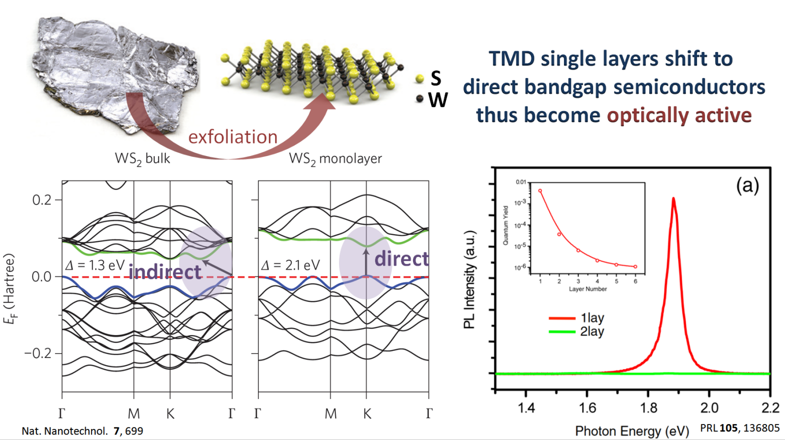
K. F. Mak Phys. Rev. Lett. 105, 136805 (2010): "a crossover to a direct-gap material in the limit of the single monolayer (...) increase in luminescence by $10^4$ compared with the bulk"




Nat. Nanotechnol. **7**, 699

# Excitons in Semiconducting TMDs

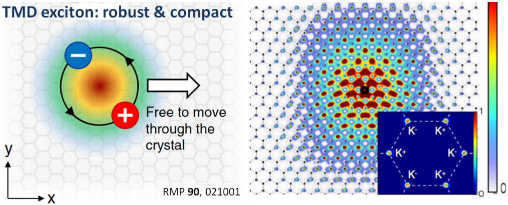
**K. F. Mak Phys. Rev. Lett. 105, 136805 (2010): "a crossover to a direct-gap material in the limit of the single monolayer (...) increase in luminescence by $10^4$ compared with the bulk"**



# Basic characteristics of free 2D excitons

L. C. Andreani, lectures

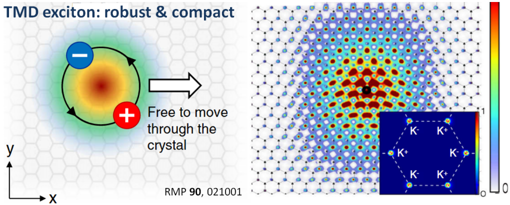
- Wannier picture applicable to large extent
- Energy: $E_n(K_{||}) = E_g + E_e + E_h + \frac{\hbar^2 K_{||}^2}{2M} - \frac{R^*}{(n-1/2)^2}$, $R^* = \frac{\mu^* e^4}{(2\epsilon^2 \hbar^2)}$ >100 meV
- Bohr radius: $a_{2D} = \frac{\epsilon \hbar^2}{(\mu^* e^2)} \simeq$ 1 nm (Compact!)
- 10% (Strong!) Linear absorption $\propto$ oscillator strength $\propto 1/a_{2D}^2$
- Chiral selection rules $\sigma^{\pm} \leftrightarrows K^{\pm}$



# Basic characteristics of free 2D excitons

L. C. Andreani, lectures

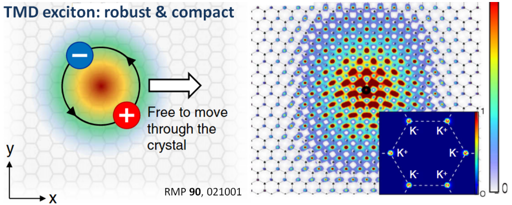
- Wannier picture applicable to large extent
- Energy: $E_n(K_{||}) = E_g + E_e + E_h + \frac{\hbar^2 K_{||}^2}{2M} - \frac{R^*}{(n-1/2)^2}$,
  $R^* = \frac{\mu^* e^4}{(2\epsilon^2 \hbar^2)} > 100\,\text{meV}$
- Bohr radius: $a_{2D} = \frac{\epsilon \hbar^2}{(\mu^* e^2)} \simeq 1\,\text{nm}$ (Compact!)
- 10% (Strong!) Linear absorption $\propto$ oscillator strength $\propto 1/a_{2D}^2$
- Chiral selection rules $\sigma^\pm \leftrightarrows K^\pm$



# Basic characteristics of free 2D excitons

L. C. Andreani, lectures

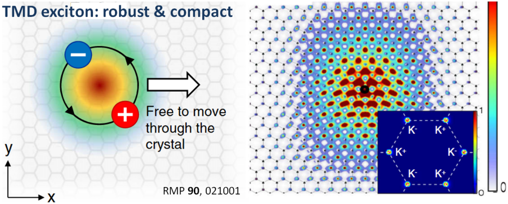
- Wannier picture applicable to large extent
- Energy: $E_n(K_{||}) = E_g + E_e + E_h + \frac{\hbar^2 K_{||}^2}{2M} - \frac{R^*}{(n-1/2)^2}$,
  $R^* = \frac{\mu^* e^4}{(2\epsilon^2 \hbar^2)} > 100\,\text{meV}$
- Bohr radius: $a_{2D} = \frac{\epsilon \hbar^2}{(\mu^* e^2)} \simeq 1\,\text{nm}$ (Compact!)
- 10% (Strong!) Linear absorption $\propto$ oscillator strength $\propto 1/a_{2D}^2$
- Chiral selection rules $\sigma^\pm \leftrightarrows K^\pm$



# Basic characteristics of free 2D excitons

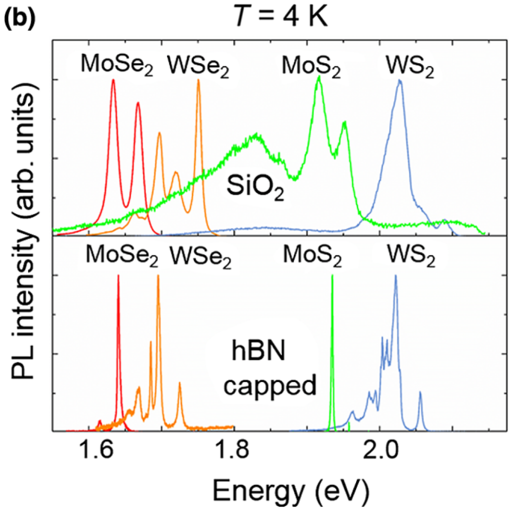
**L. C. Andreani, lectures**

- Wannier picture applicable to large extent
- Energy: $E_n(K_{||}) = E_g + E_e + E_h + \frac{\hbar^2 K_{||}^2}{2M} - \frac{R^*}{(n-1/2)^2}$,
  $R^* = \frac{\mu^* e^4}{(2\epsilon^2 \hbar^2)} > 100\,\text{meV}$
- Bohr radius: $a_{2D} = \frac{\epsilon \hbar^2}{(\mu^* e^2)} \simeq 1\,\text{nm}$ (Compact!)
- 10% (Strong!) Linear absorption $\propto$ oscillator strength $\propto 1/a_{2D}^2$
- Chiral selection rules $\sigma^\pm \leftrightarrows K^\pm$



# Improving optical quality with heterostructures

Flattening, Shielding & Isolating from excess charges $\Rightarrow$ suppressing $\sigma$



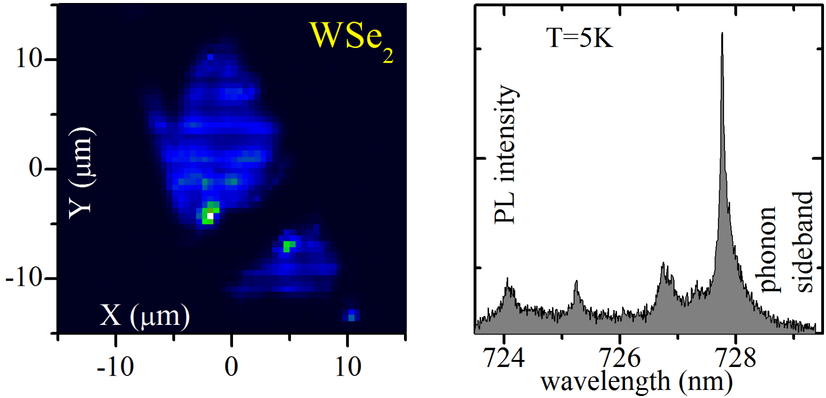
# Improving optical quality with heterostructures

Flattening, Shielding & Isolating from excess charges $\Rightarrow$ suppressing $\sigma$

# Localized quantum emitters in monolayers

Driven by local strain/disorder, ...but on-demand arrays now at hand

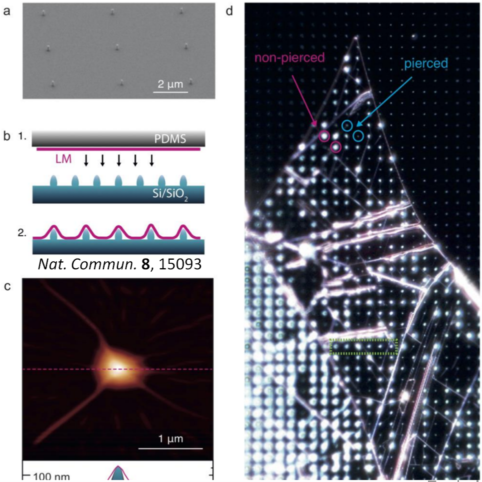
Koperski et al., Nature Nanotech. 10, 503 (2015), arXiv:1609.04244 (!)



# Localized quantum emitters in monolayers

Driven by local strain/disorder, ...but on-demand arrays now at hand

Koperski et al., Nature Nanotech. 10, 503 (2015), arXiv:1609.04244 (!)




*Nat. Commun.* **8**, 15093

# Excitons in Perovskites

## Basic Physical Properties Structure

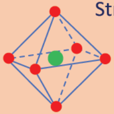
### Halide perovskites $ABX_3$

- A = [Organic/inorganic]$^+$ cation: *$CH_3NH_3$, Cs, Rb, ...*
- B = [Metal]$^{++}$ cation: *Pb, Sn, Ge, ...*
- X = [Halide]$^-$ anion: *I, Br, Cl, F*

➤ Hybrid (organic-inorganic) perovkites
*$CH_3NH_3$ $BX_3$*

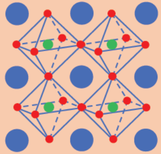
➤ All-inorganic perovskites
*Cs $BX_3$*

Inorganic **$BX_6$** octahedron
Strong B-$X_6$ **ionic bonding**



**Perovskite electronic properties**
*Bandgap, optical, transport properties, ...*

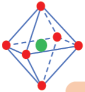
**3D** *Corner-sharing $BX_6$ network*
*Weak A-$BX_6$ bonding*




Active **"core" $BX_6$** - **"shell" A**

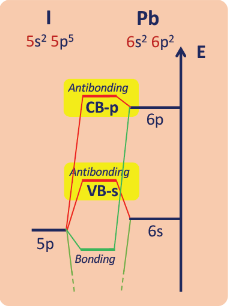
# Excitons in Perovskites

## Basic Physical Properties Structure



**$BX_6$**

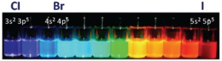
B = Pb, X = I




| s-p dipolar interband | VB | CB |
|---|---|---|
| Perovskites | s | p |
| CdTe, GaAs, GaN, ... | p | s |

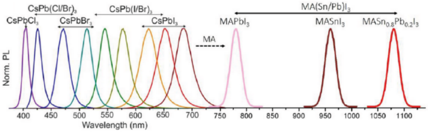
**Band gap tunability 400 – 1100 nm**

Saliba et al., Angew. Chem. Int. Ed. (2017)



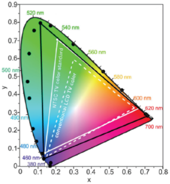

**$CsPbX_3$ nanocrystals**

Protesescu et al., Nano Lett. (2015)




**Broad color gamut**

$CsPbX_3$ NCs = black dots

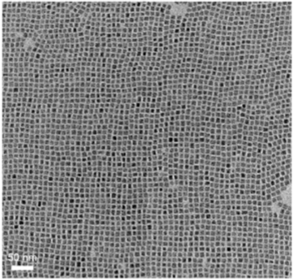


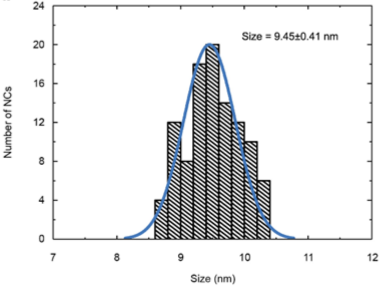
# Excitons in Perovskites

## Basic Physical Properties Structure

# Superfluorescence from lead halide perovskite quantum dot superlattices

Gabriele Rainò[1,2,3,5]*, Michael A. Becker[3,4,5], Maryna I. Bodnarchuk[2], Rainer F. Mahrt[3], Maksym V. Kovalenko[1,2]* & Thilo Stöferle[3]*




**Extended Data Fig. 1 | Quantitative analysis of $CsPbBr_3$ NC size distribution. a,** Low-resolution TEM image of the NC material used to prepare the superlattices. **b,** Histogram of NC sizes (of >100 NCs) as obtained from TEM image analysis. The solid line is a fit with a normal distribution, and the given mean size (9.45 nm) and standard deviation (0.41 nm) are obtained from this fit.

# Perovskites: "miracle" materials for photovoltaics ?

**Perovskites**

✓

| Solar cell desirable features | Benefits |
|---|---|
| Broad bandgap tunability 400 – 1100 nm | Solar radiation, multi-junction |
| Direct band gap + absorption ≥ $10^4$ $cm^{-1}$ | Thin film technology |
| High photo-generation of free carriers | High Power Conversion Efficiency ($J_{SC}$ , $V_{OC}$) |
| Low radiative recombination losses | |
| Carrier diffusion length > absorption depth | |
| High carrier collection | |
| Cost-effective growth | Consumer market |
| Scalability, environmental impact, toxicity | |
| Lifespan ≥ 25 years | |