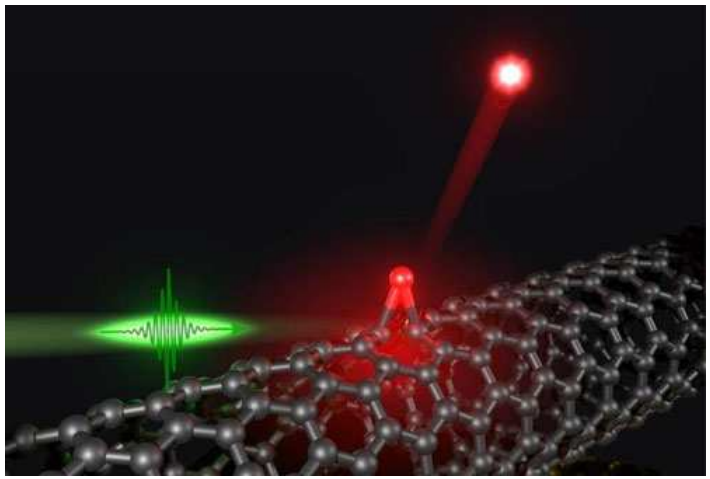
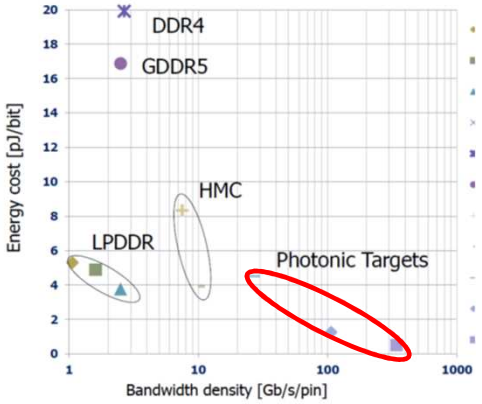
Non-Classical Photon Sources for Integrated Quantum Photonic Circuits

Xuedan Ma
Center for Nanoscale Materials
Argonne National Laboratory



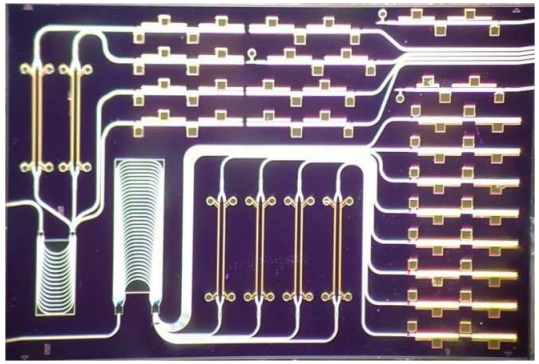
December 13, 2017

CMOS Photonic Integration: Computing beyond Moore's Law



Intel Developer Forum 2011

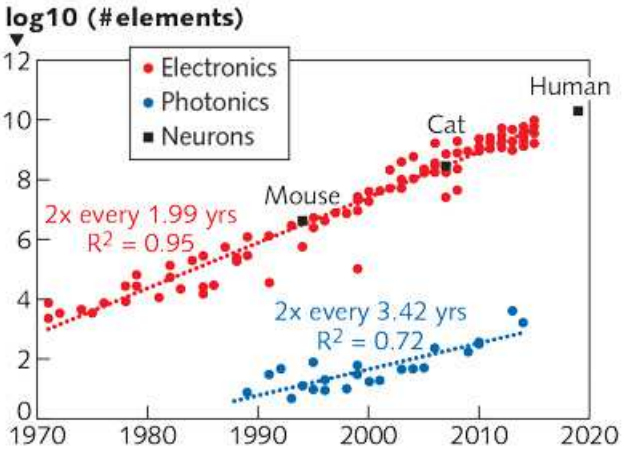
- Electrical interfaces cannot simultaneously improve the energy-efficiency and bandwidth-density.



JePPIX

Photonic integrated circuit:

- **Energy-efficiency**: distance-independent energy cost, low-loss optical components.
- **Bandwidth density**: massively parallel dense wavelengths in a single logical channel.



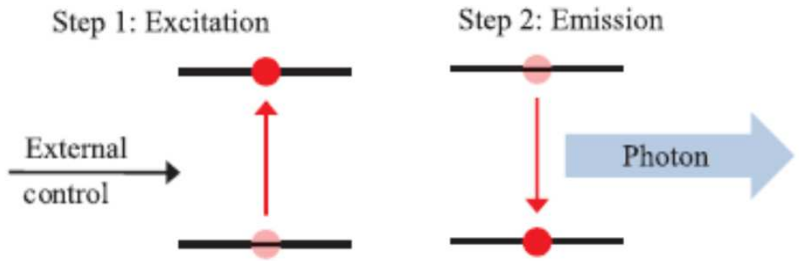
- Moore's Law representation of the electronic and photonics number of elements vs. year.
- Development ecosystems of photonic integrated circuit still faces challenges.

Laser Photon. Rev., 6, 1-13 (2012)

Argonne NATIONAL LABORATORY

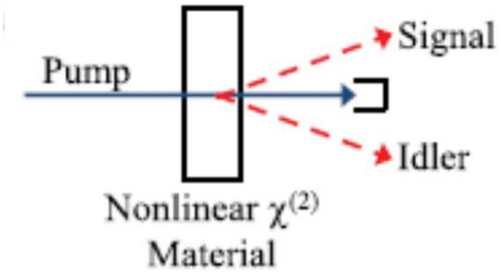
Two Types of Single Photon Sources

deterministic sources



- Excited by some means then emits a single photon.
- Emission stability and single photon purity are usually the limiting factors.

probabilistic sources

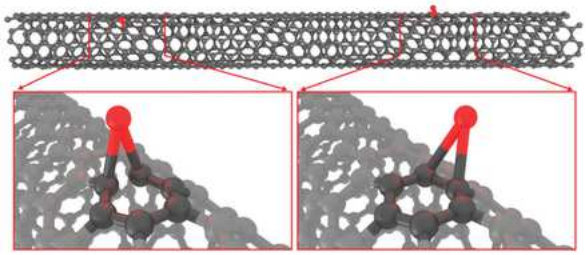


- Parametric downconversion of one input photon to two output photons.
- The creation of photons is probabilistic rather than deterministic.
- There is a nonzero probability of generating more than one pairs of photons.

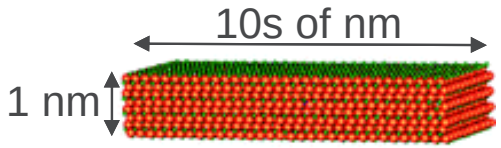
Rev. Sci. Instrum. 82, 071101 (2011)

Argonne NATIONAL LABORATORY

Non-Classical Photon Source Platforms

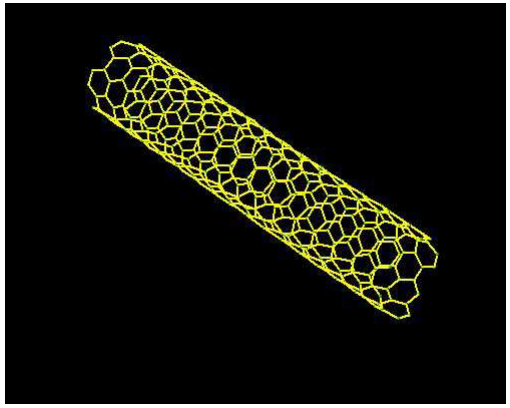


Carbon Nanotube



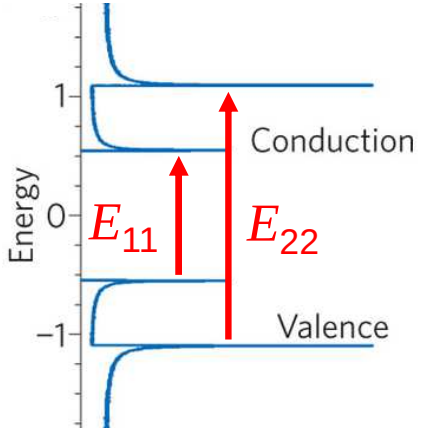
Semiconductor nanoplatelets

Semiconducting SWCNTs



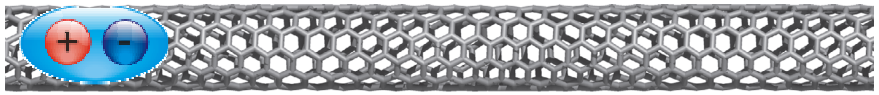
- a stripe of a graphene sheet rolled into a tube

Density of States

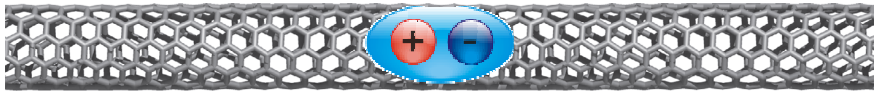


- Transition happens between Van Hove singularities.

room temperature



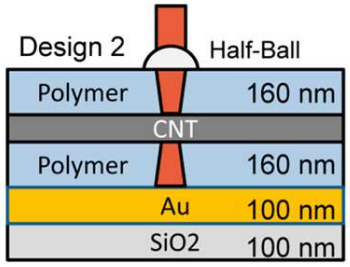
cryogenic temperature

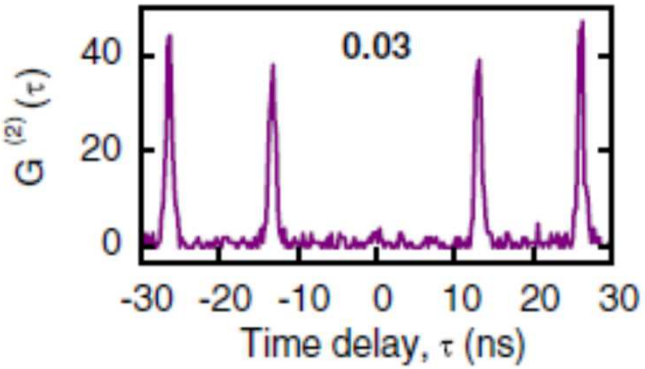


- room temperature: 1D, diffusive along tube axis.
- low temperature: 0D, localized at local potential traps.

Photon Emission Statistics of SWCNTs

T < 9 K



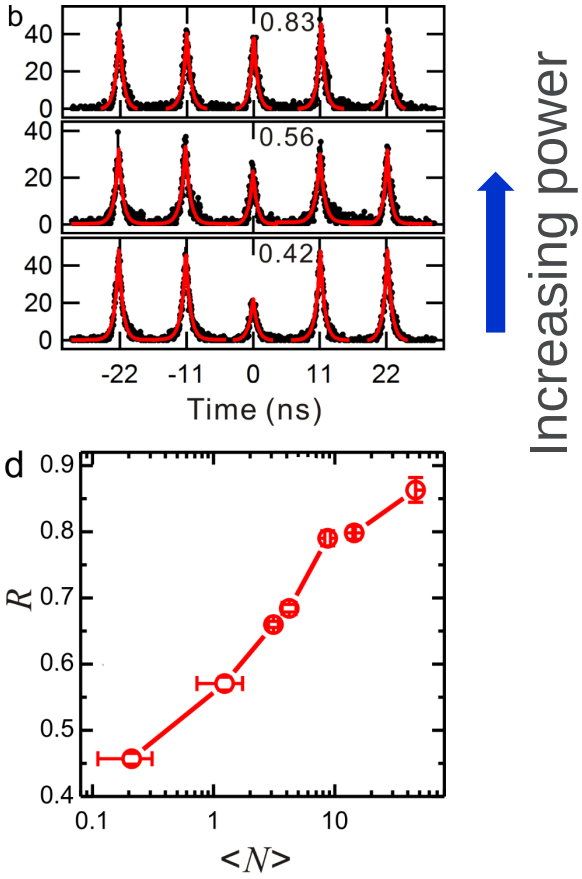


$R < 0.5$

- Photon antibunching has been observed at low temperatures.

Stefan et al. Nano Lett. 2012, 12, 1934
Hoegele et al. Phys. Rev. Lett. 2008, 100, 217401

room temperature

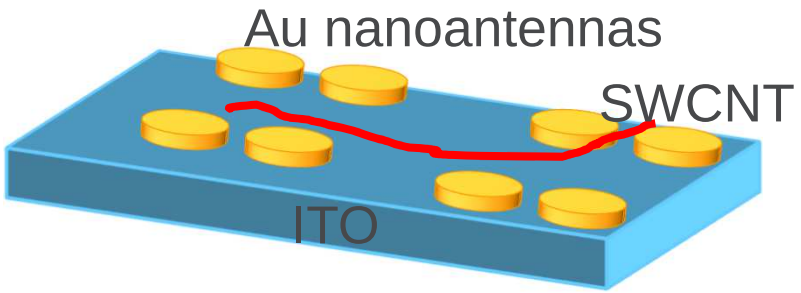


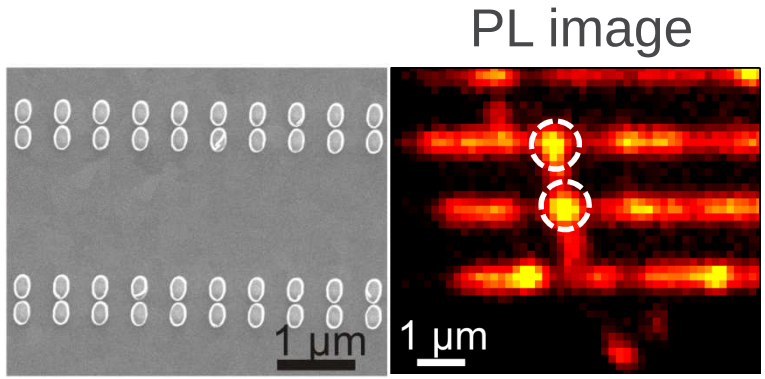
- Room temperature single photon generation has been found to be impossible in undoped tubes.

Ma et al. Phys. Rev. Lett. 2015, 115, 017401
Endo et al. Appl. Phys. Lett. 2015, 106, 113106

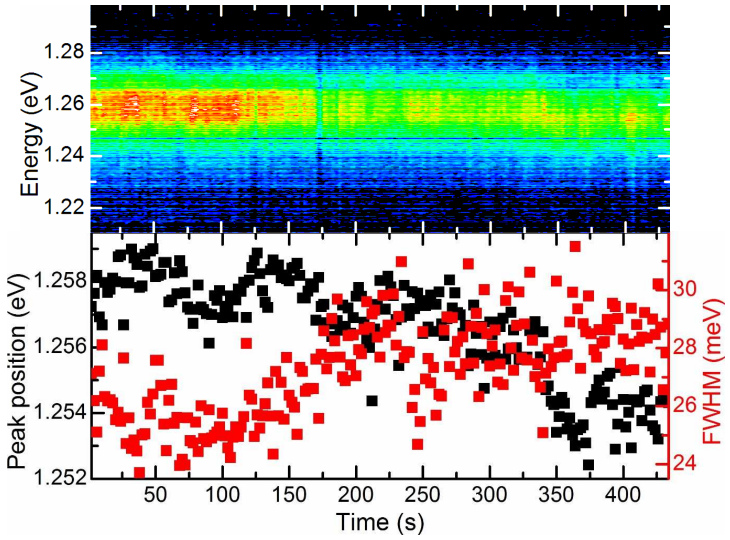
Argonne NATIONAL LABORATORY

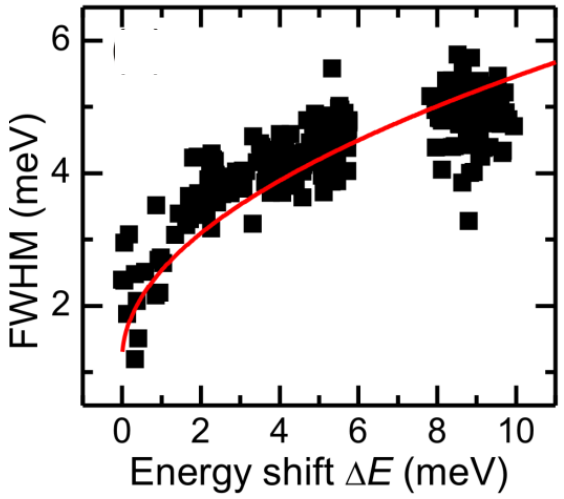
Surface Plasmon Localized Excitons





localized bright spot



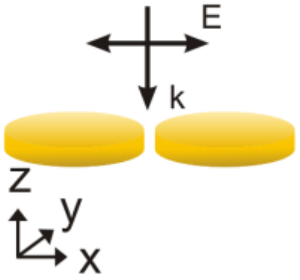


$\sigma \propto \sqrt{\Delta E}$

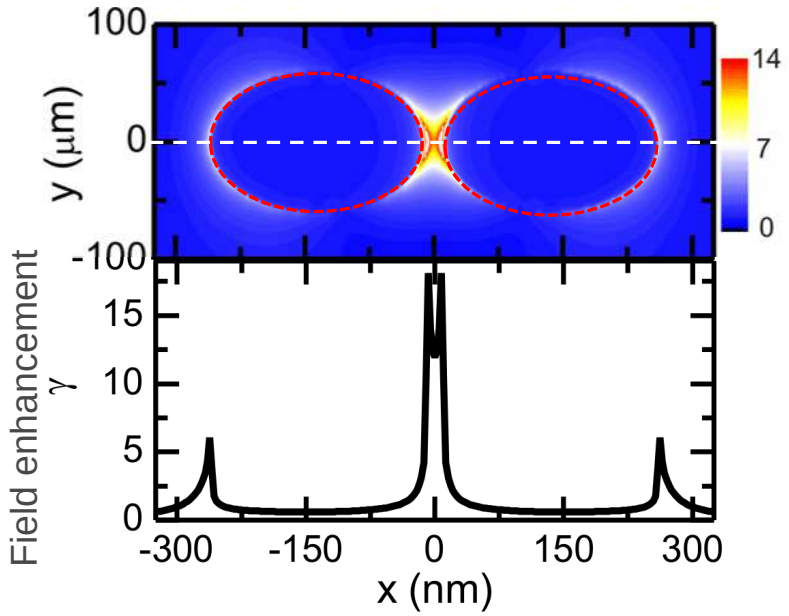
exciton “localization” at room temperature

Argonne NATIONAL LABORATORY

Localized Excitation



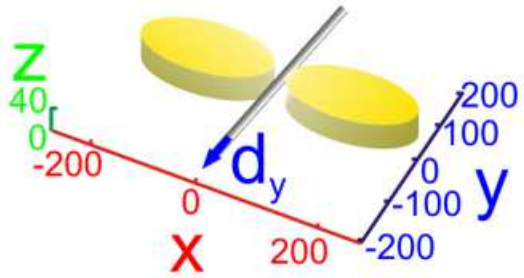
local electric field enhancement factor distribution

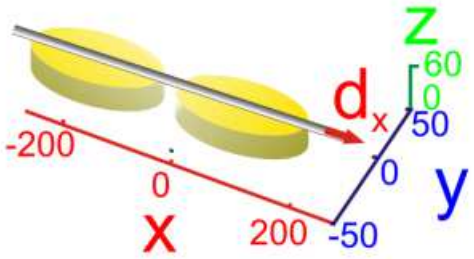


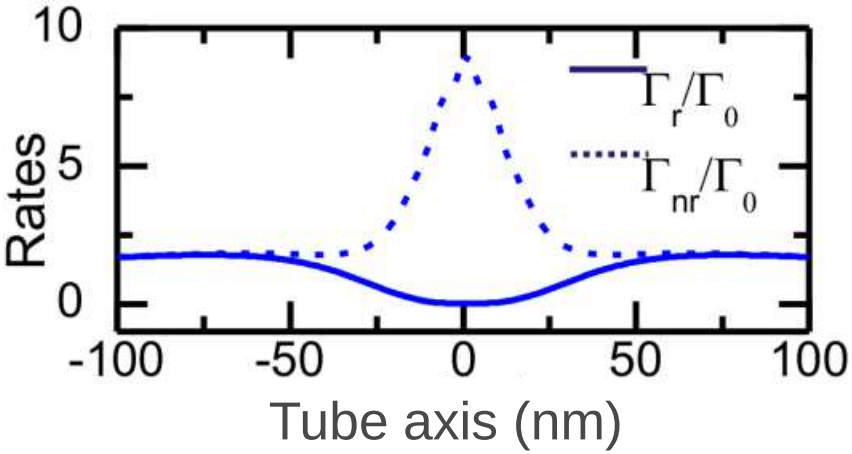
- highly confined excitation regime (<30nm)

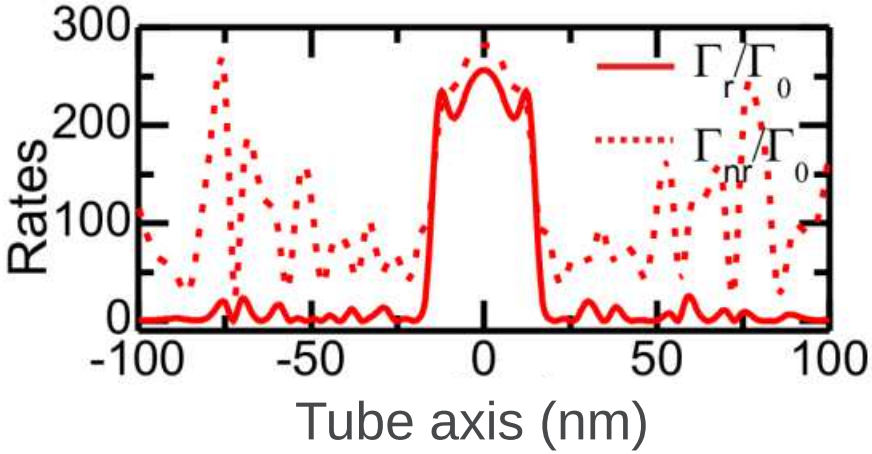
Argonne NATIONAL LABORATORY

Localized Emission









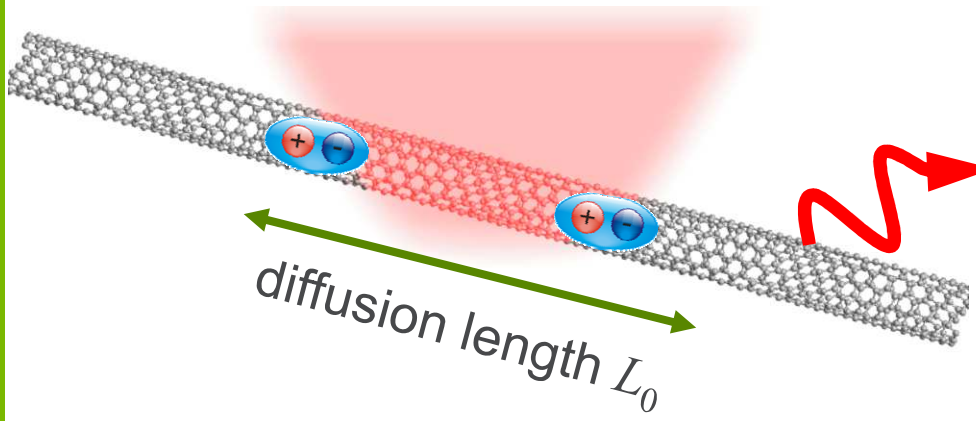
Γ_0: decay rate without Au

- Decay rates in the gap regime are strongly enhanced.

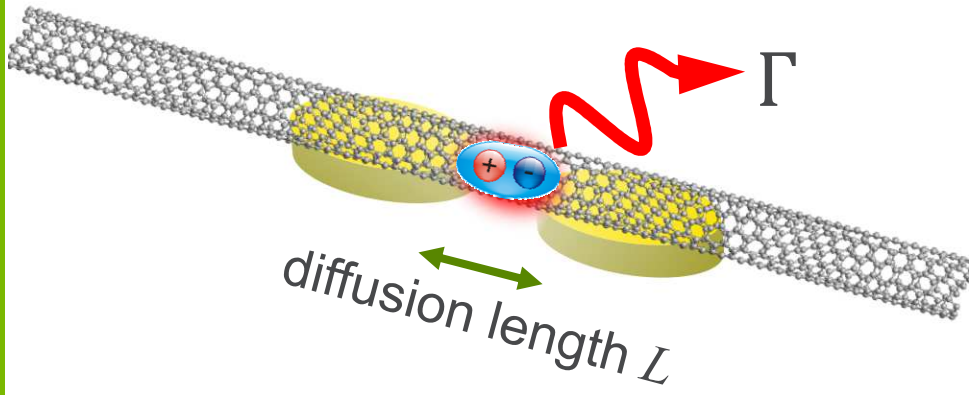
Roslyak et al. J. Phys. Chem. B 2014, 118, 8070

Argonne NATIONAL LABORATORY

Exciton Localization Mechanism



- decay rate Γ_0 ≤ diffusion rate
- L_0 ~ 200 nm.



- Excitation mainly happens in the gap.
- decay rate Γ >> diffusion rate

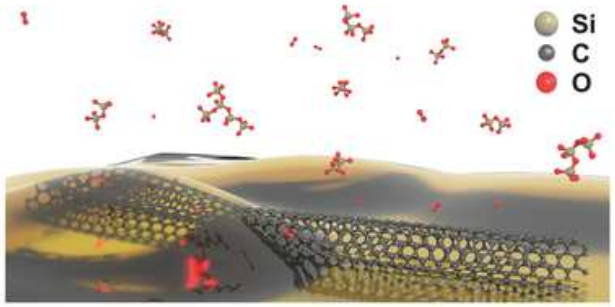
- highly confined excitation regime (<30nm)
- strongly enhanced decay rates in the gap
- Surface plasmons can manipulate photon position.

Ma et al. ACS Nano 2014, 8, 10613

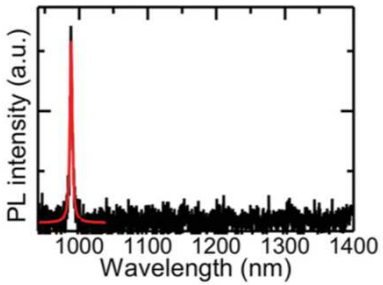
Argonne NATIONAL LABORATORY

Single Photon Sources from Doped Carbon Nanotubes

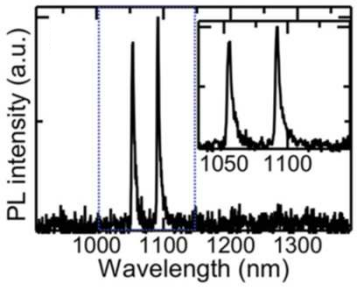
A solid-state doping approach



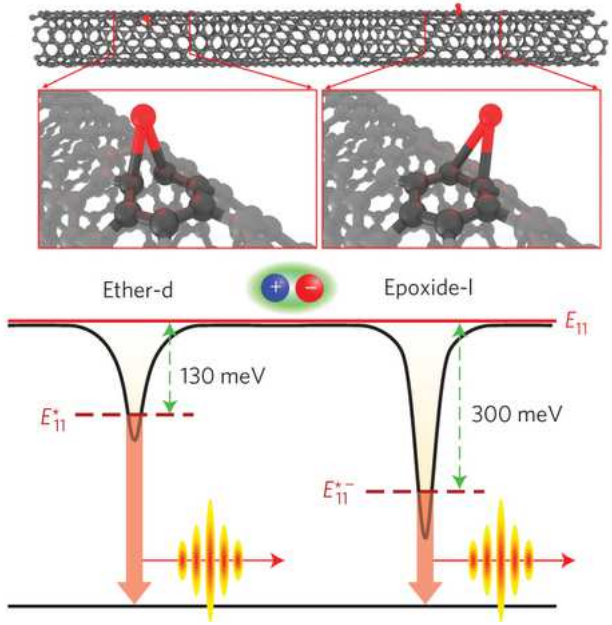
before

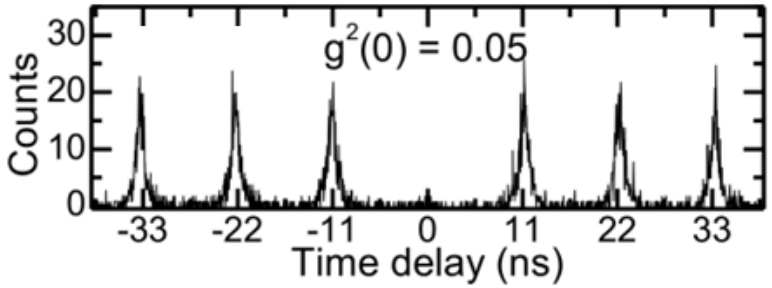


after



Room temperature single photon emission

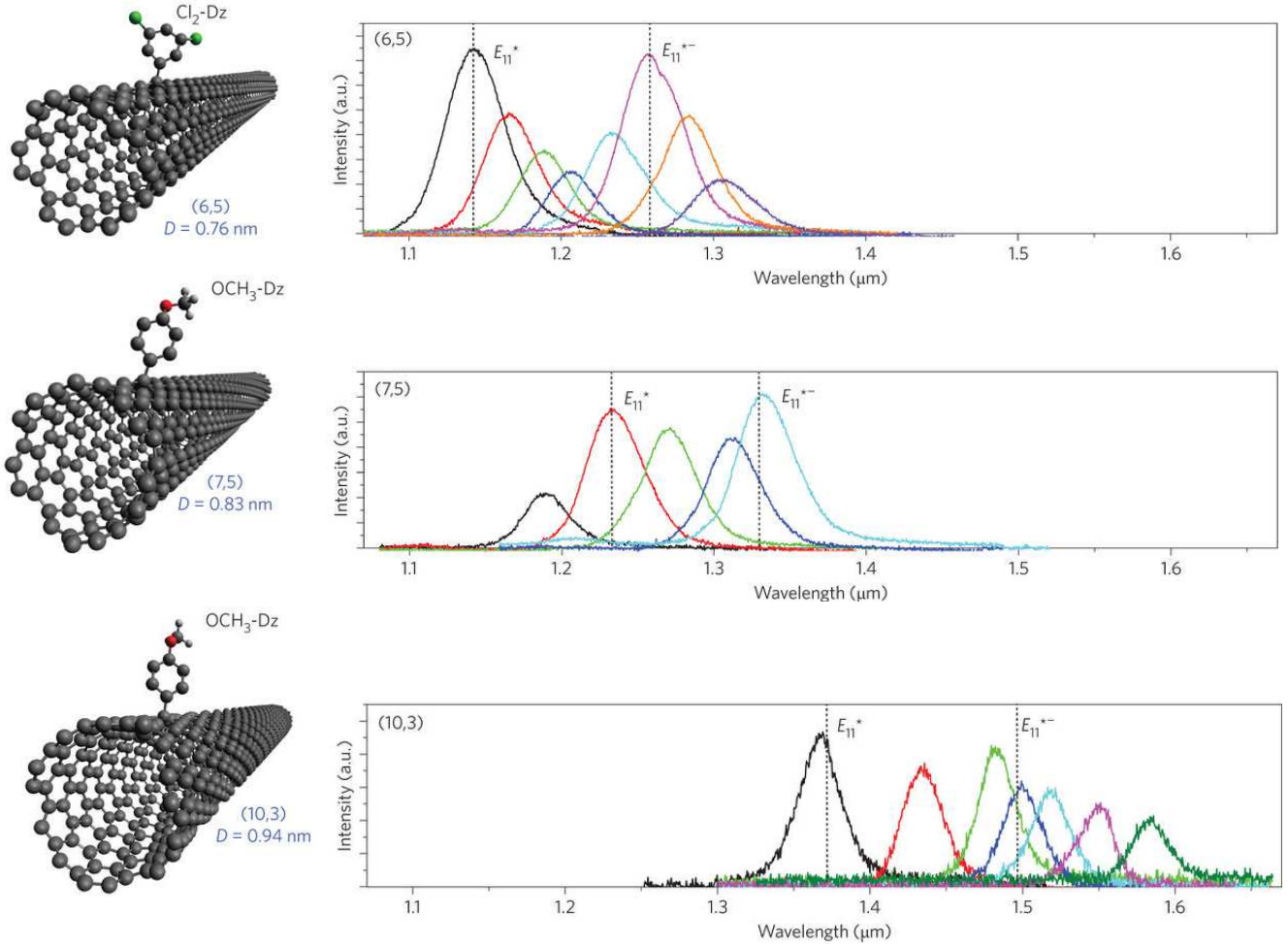




Ma et al. ACS Nano 2014, 8, 10782
Ma et al. Adv. Funct. Mater. 2015, 25, 6149
Ma et al. Nat. Nanotechnol. 2015, 10, 671

Argonne NATIONAL LABORATORY

Tunable Single Photon Emission at Telecom Range



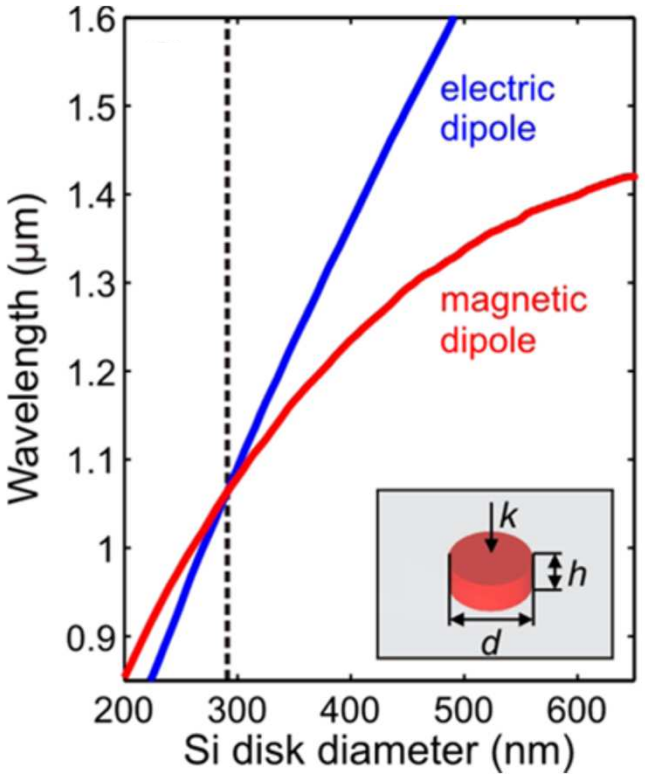
- Diameter-dependent emission wavelength tunable to the telecom wavelength range.

Ma et al. Phys. Rev. Lett. 2015, 115, 017401
Ma et al. Nanoscale, 2017, 9, 16143
He et al. Nat. Photon. 2017, 11, 577

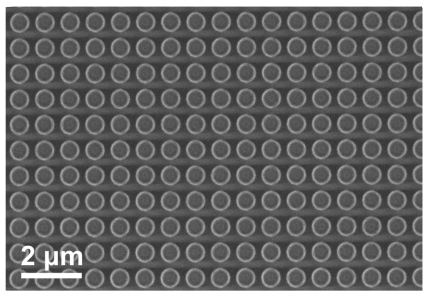
Argonne NATIONAL LABORATORY

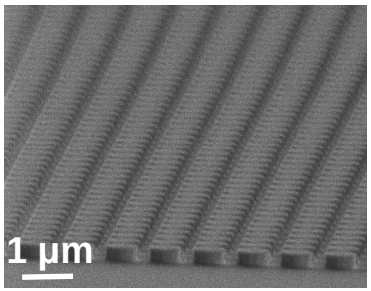
Dielectric Metasurface Modified Emission Polarization

- Low intrinsic losses at optical frequencies.
- Support both electric and magnetic modes.

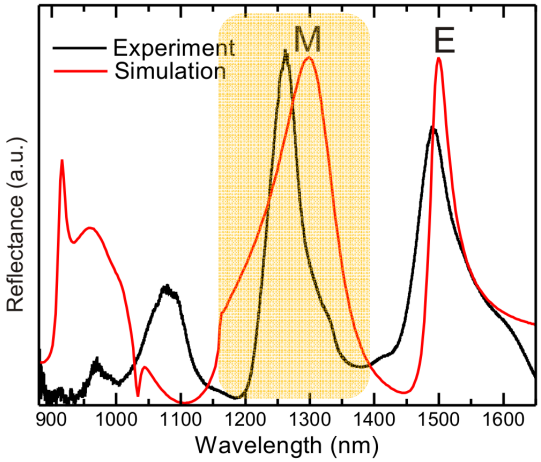


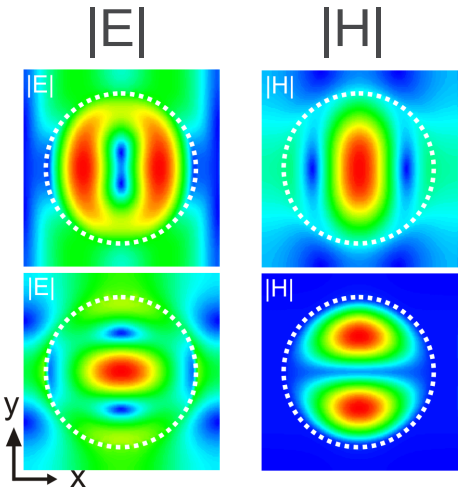
Staude et al. ACS Nano. 2013, *7, 7824*





D = 640 nm

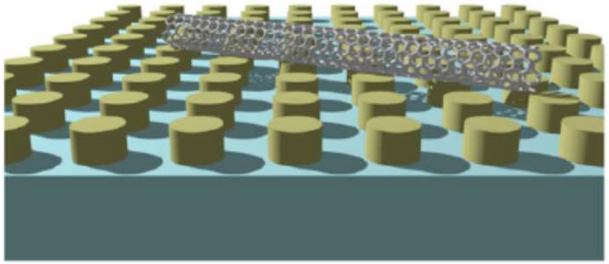


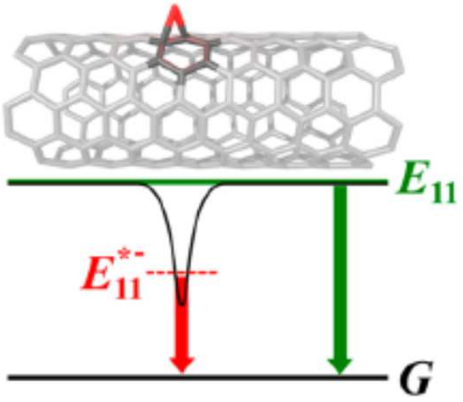


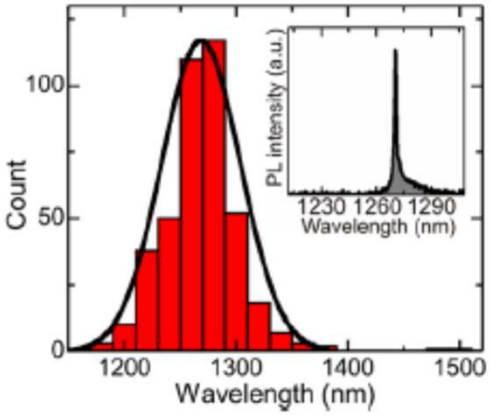
Ma et al. ACS Nano. 2017, *11, 6431*

Argonne NATIONAL LABORATORY

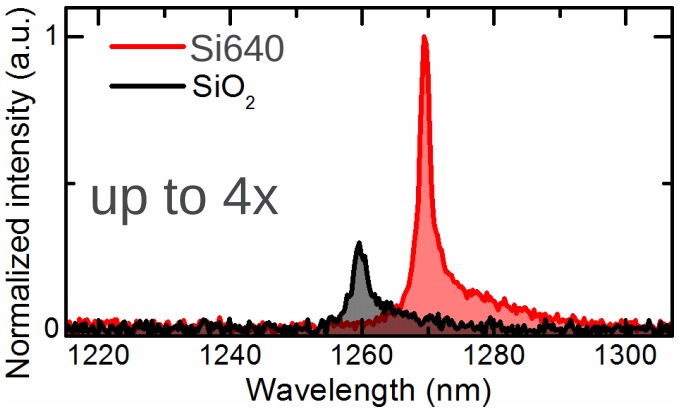
Single Photon Manipulation by Dielectric Metasurfaces



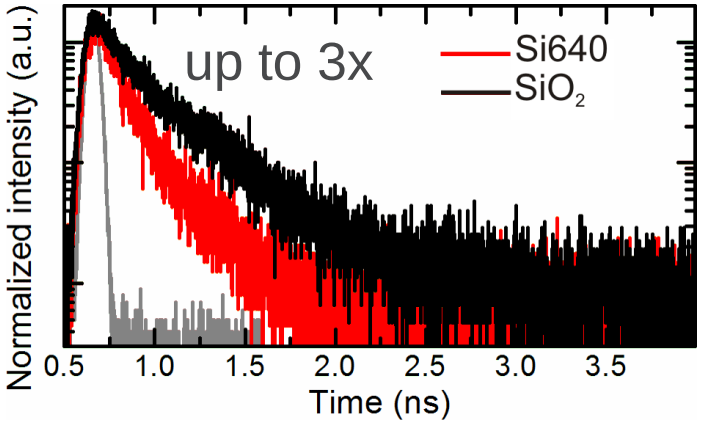




- In resonance with the magnetic mode of Si nanodisks.



- PL enhancement

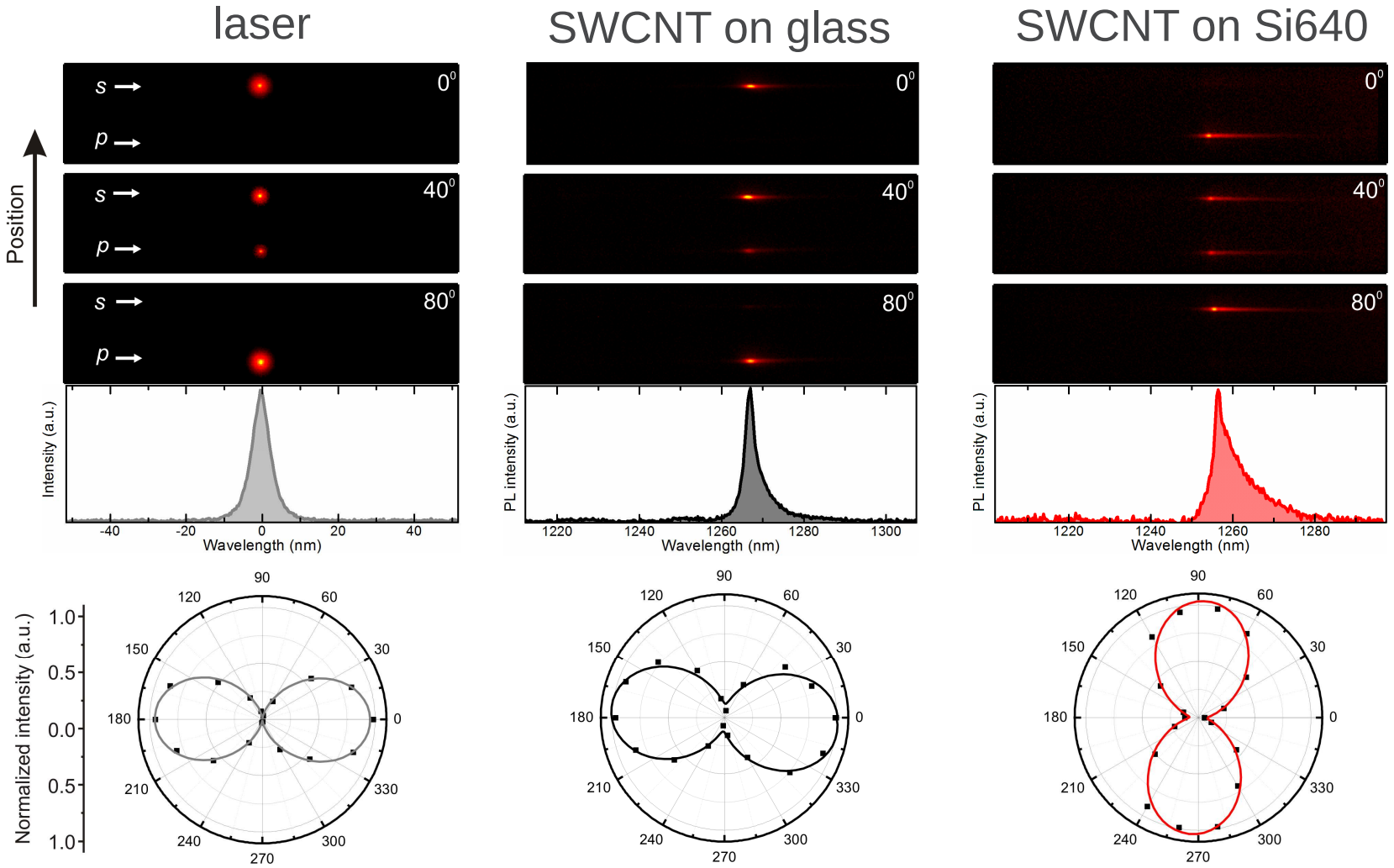


- decay rate enhancement

➡ Purcell effect

Argonne NATIONAL LABORATORY

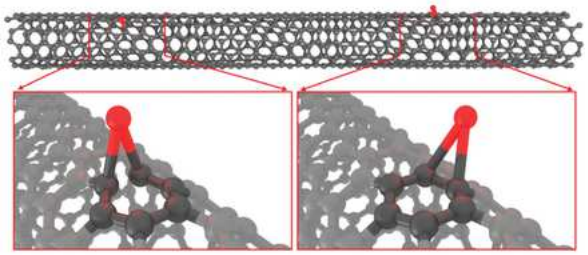
Single Photon Polarization Modulation



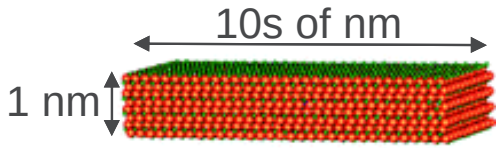
- linearly polarized emission
- polarization rotation

Argonne NATIONAL LABORATORY

Non-Classical Photon Source Platforms

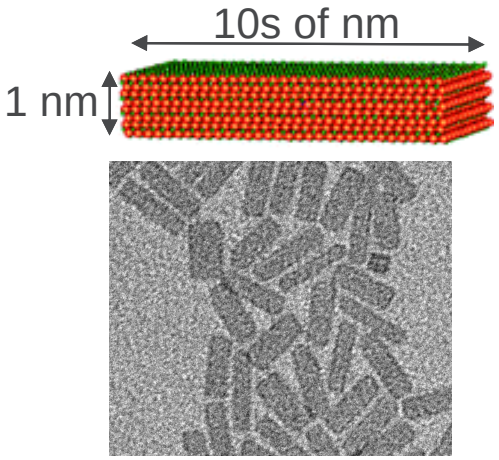


Doped Carbon Nanotube



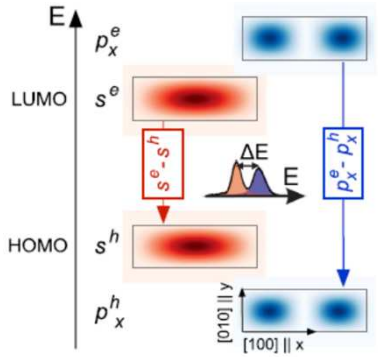
Semiconductor nanoplatelets

Semiconductor Nanoplatelets



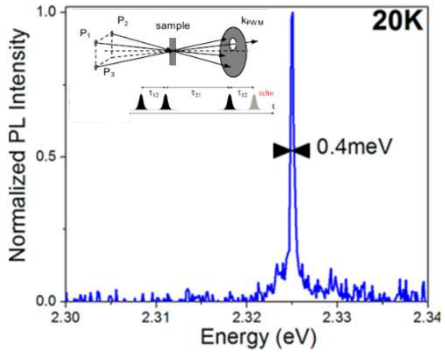
CdSe nanoplatelets (NPLs)

- Excitons are strongly confined in the vertical direction.
- An ideal system for studying transitions from 0D to 2D quantum confinement.



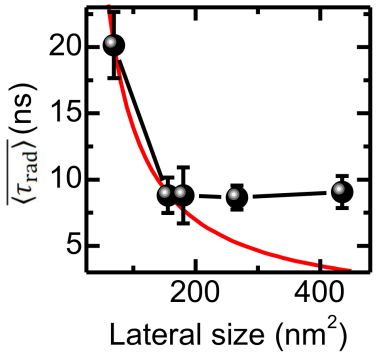
- Weak exciton-phonon interaction due to size tunable LP phonon bottleneck.

Achtstein *et al. Phys. Rev. Lett.* 2016, 116, 116802



- Intrinsic lifetime-limited spectral linewidth.

Naeem et al. Phys. Rev. B 2015, 91, 121302
Tessier et al. Nano Lett. 2012, 6, 6751



- Giant oscillator strength.

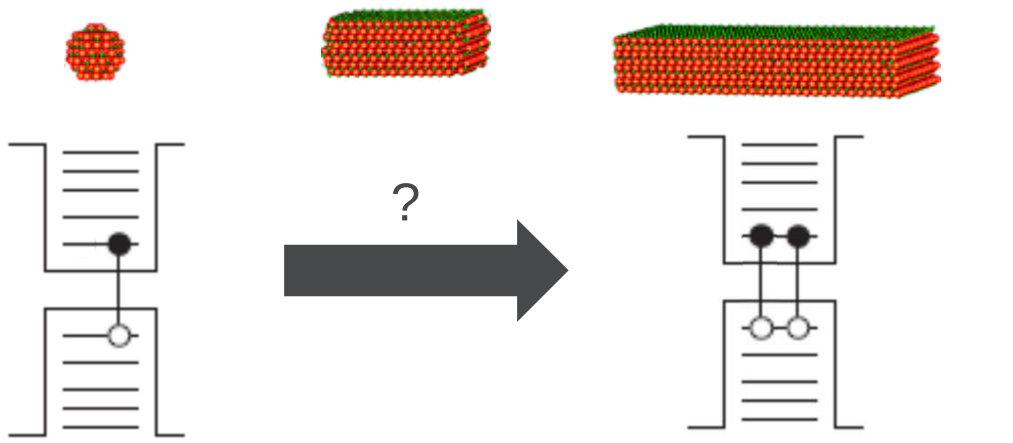
Ma et al. ACS Nano 2017, 11, 7119
Ithurria et al. Nat. Mater. 2011, 10, 936

Argonne NATIONAL LABORATORY

Excitons in Semiconductor Nanoplatelets

Fundamental questions:

- How does the exciton population evolve with the increase of lateral size from 0D to 2D?



large Auger effect
→single exciton

small Auger effect
→biexciton

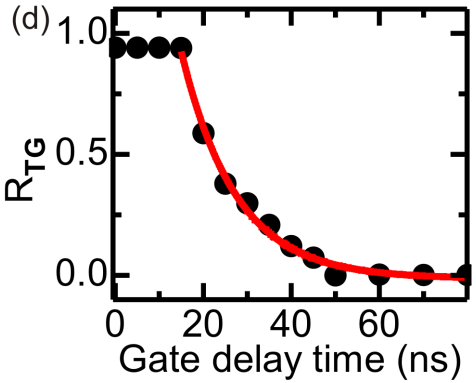
Lateral Size-Dependent Emission Statistics

- In the low excitation limit:

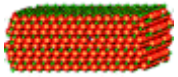
$$R = \frac{< n_{NC}(n_{NC} - 1) >}{< n_{NC} > 2} \approx \frac{\eta_{BX}}{\eta_X}$$

η_{BX}: biexciton quantum yield
η_X: exciton quantum yield

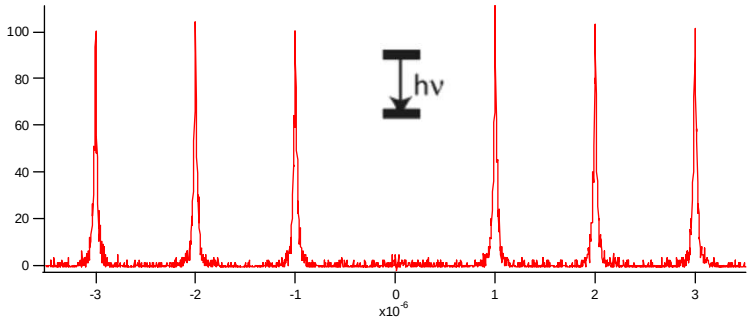
- Application of a time gating technique to verify that the studied emitter is a single NPL.



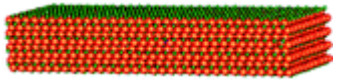
small NPL



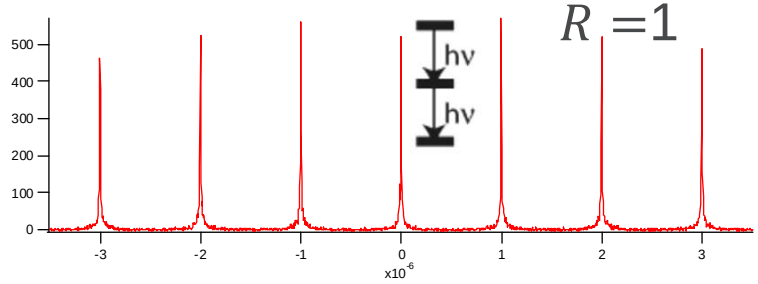
$R = 0$



large NPL



$R = 1$

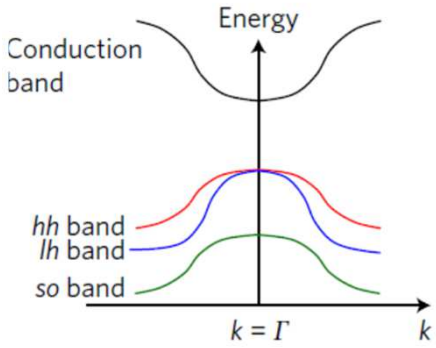


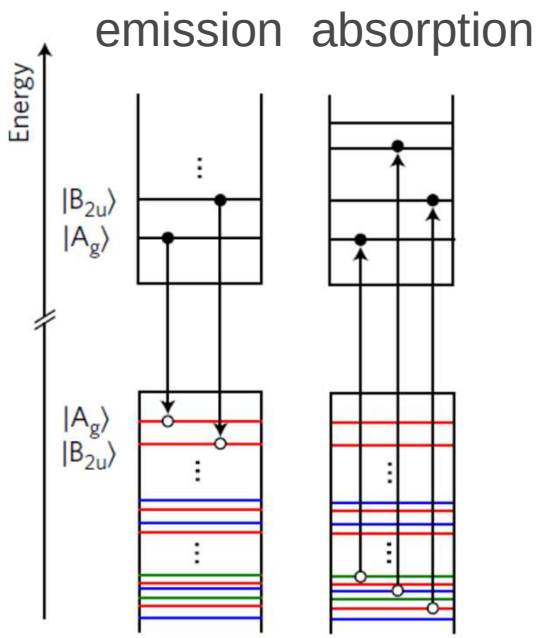
- Larger NPLs can have unity biexciton quanum yields → promising for entangled photon pair generation.

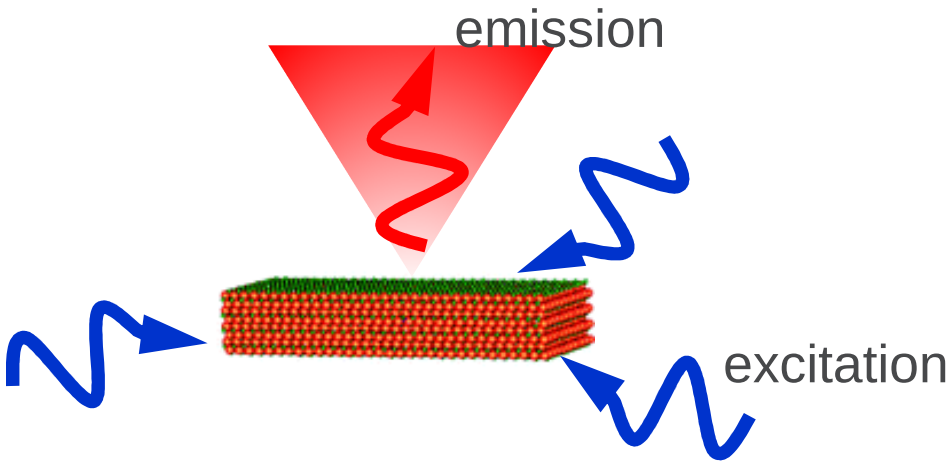
Ma et al. *ACS Nano*, 2017, 11, 9119

Argonne NATIONAL LABORATORY

Independent Absorption and Emission Processes







isotropic absorption

⇕

out-of-plane emission

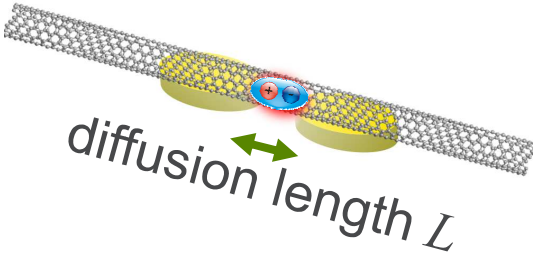
Scott et al. Nat. Nanotechnol. 2017, 12, 1155-1160

Argonne NATIONAL LABORATORY

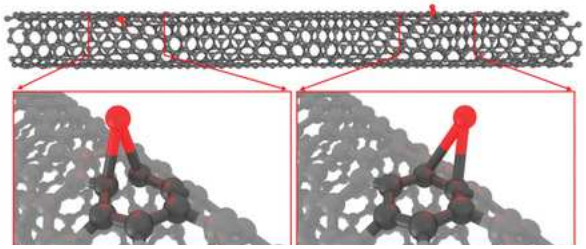
Summary

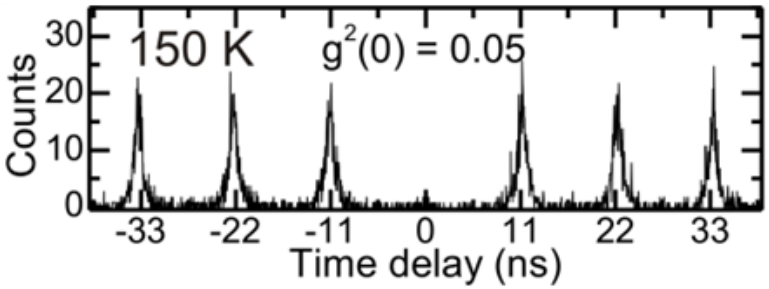
Single-walled carbon nanotubes

surface-plasmon localized excitons



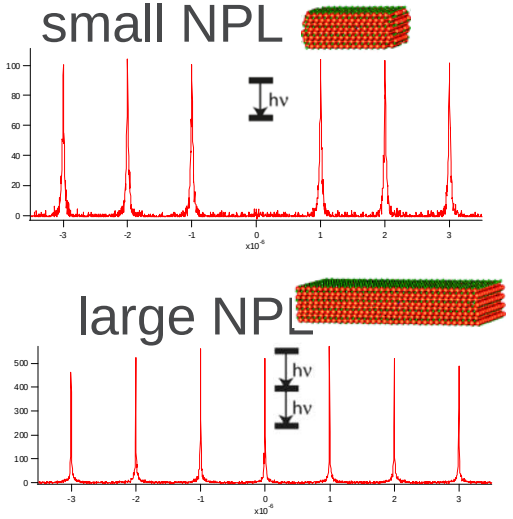
doped SWCNT as single photon sources



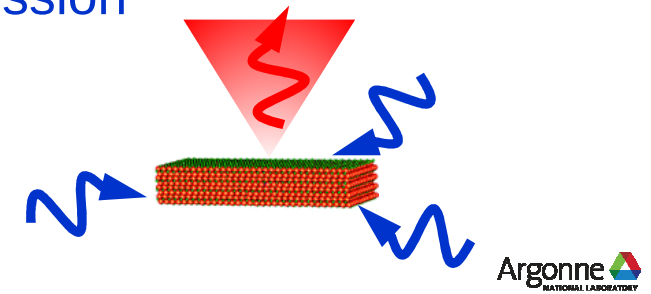


Semiconductor Nanoplatelets

size-controlled emission statistics



excitation-independent directional emission



Acknowledgements

ANL/UChicago
- Richard Schaller (ANL)
- Ben Diroll (ANL)
- Dmitri Talapin (UChicago)
- Igor Fedin (UChicago)
- Wooje Cho (UChicago)
- Stephen Gray (ANL)
- Gary Wiederrecht (ANL)
- David Gosztola (ANL)
- Ralu Divan (ANL)

LANL/SNL
- Stephen K. Doorn (LANL)
- Han Htoon (LANL)
- Nicolai F. Hartmann (LANL)
- Igal Brener (SNL)
- Michael Sinclair (SNL)
- Jon Baldwin (LANL)
- Ting S. Luk (SNL)
- Hou-Tong Chen (LANL)

Use of the Center for Nanoscale Materials, an Office of Science user facility, was supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

This work since 4/4/2016 was performed at the Center for Nanoscale Materials, a U.S. Department of Energy Office of Science User Facility under Contract No. DE-AC02-06CH11357.

U.S. DEPARTMENT OF ENERGY | Office of Science

Argonne NATIONAL LABORATORY