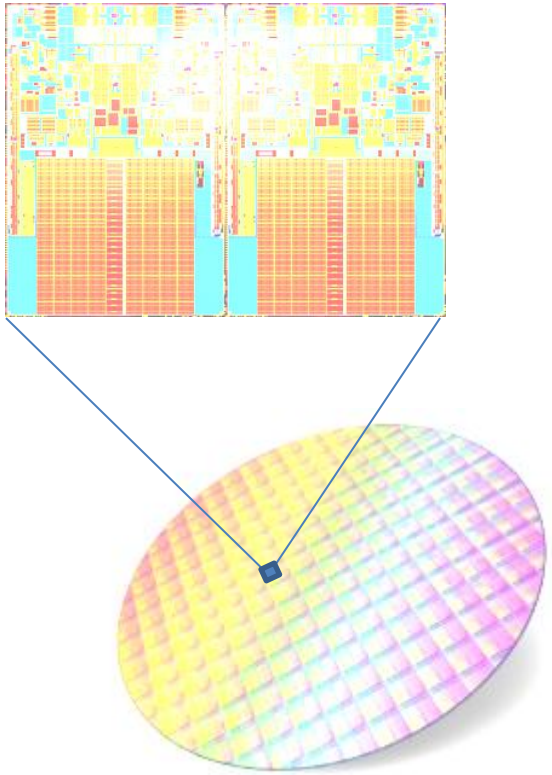
Nanophotonics with silicon nanocrystals

Lorenzo Pavesi

Introduction – Silicon photonics

Material of choice for microelectronics:

- **Advanced fabrication capabilities**
- **Mass production**
- **Cheap**



Courtesy of Intel.

Solarpowerninja.com

http://www.galleries.com/Rock_crystal

- Semiconductor
- Band-gap: 1.12 eV
- Refractive index: 3.4
- Transparent in IR

- Insulator
- Band-gap: 8.9 eV
- Refractive index: 1.46
- Transparent in visible and IR

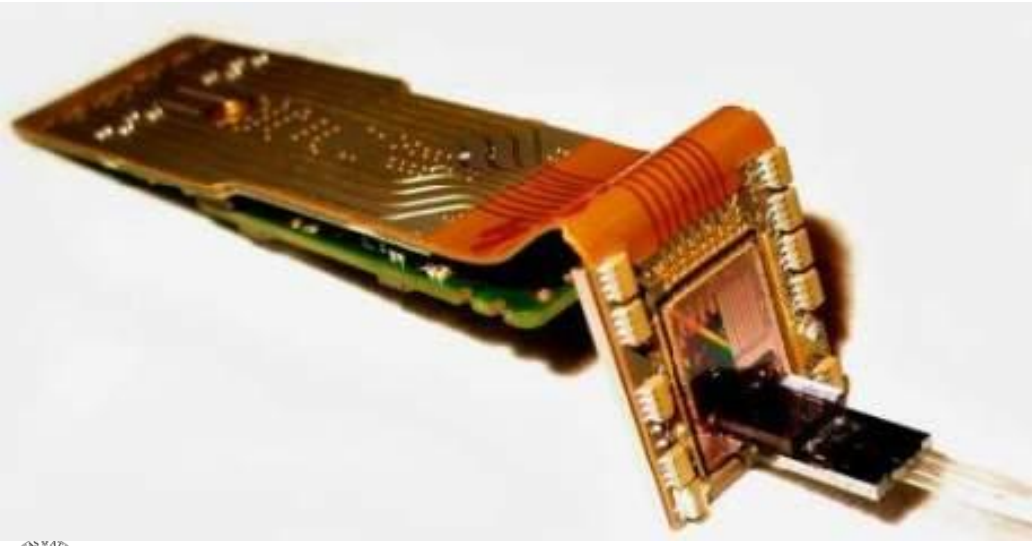
Silicon photonics

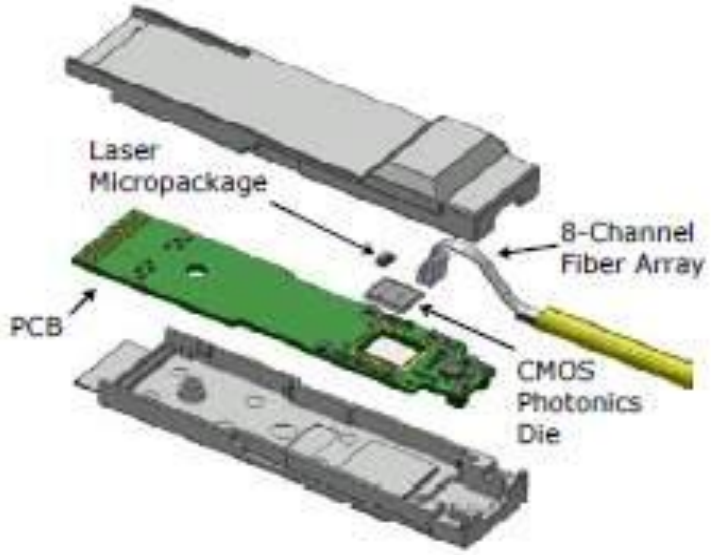
Integrated "On-chip" optical elements

CMOS compatibility

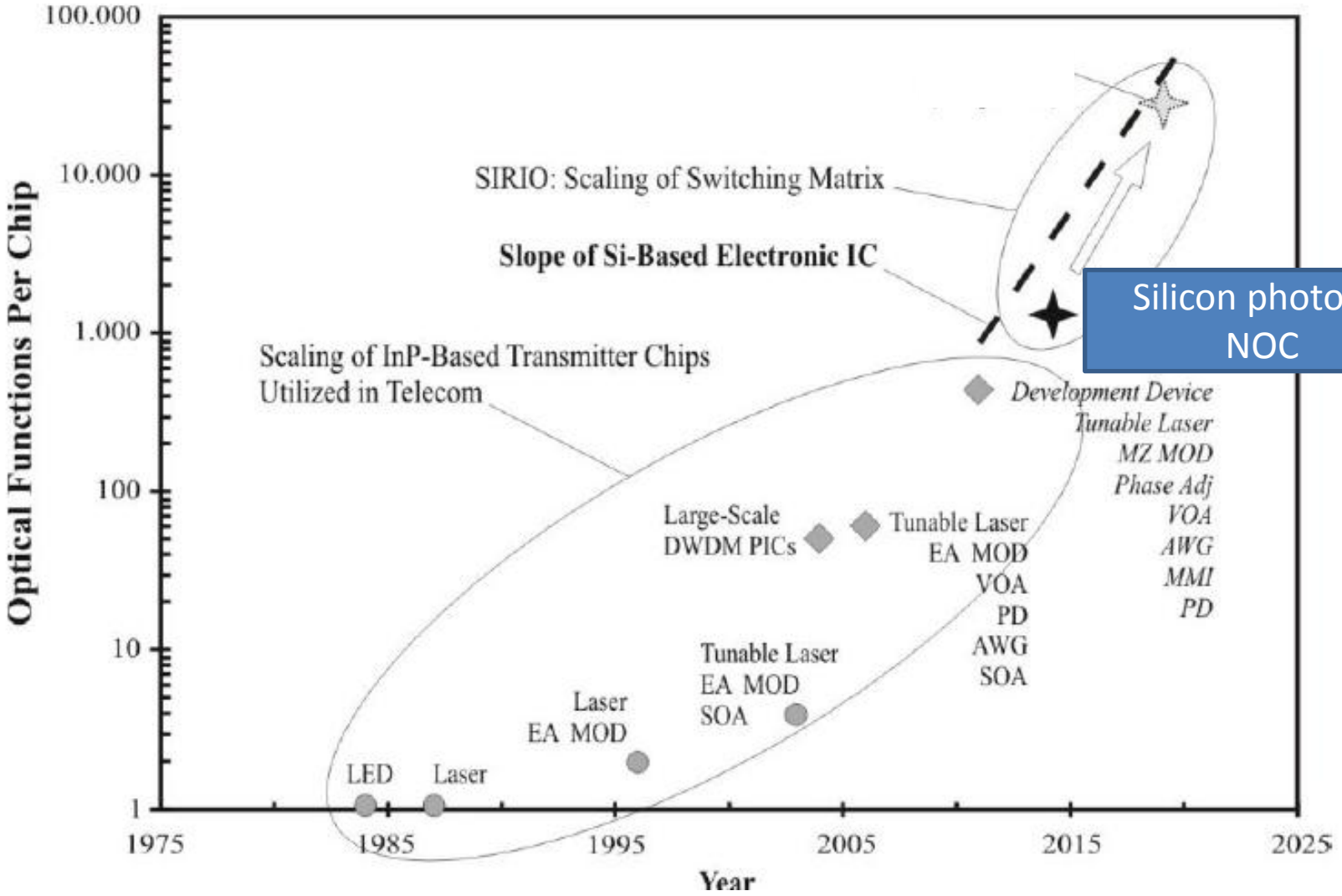
Luxtera single-chip 100-Gbps transceiver targets multiple applications

- The new transceiver chip, which measures 5x6 mm, offers 4x28-Gbps transmission over single mode fiber.
- The device features waveguide, waveguide structures, modulators, couplers, and photodetectors integrated at the wafer level. The photodetectors are germanium, but applied to the wafer using the same CMOS processes as the other devices. A single CW laser powers all four channels; it attaches to the CMOS wafer via a hybrid integration process.





Projected integration density



Silicon photonic NOC

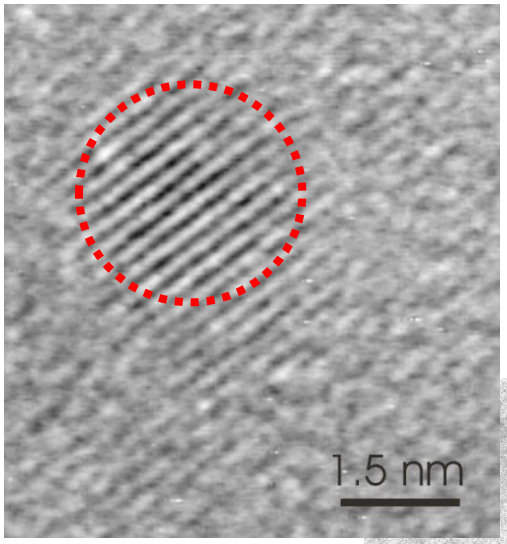
Silicon Nanocrystals

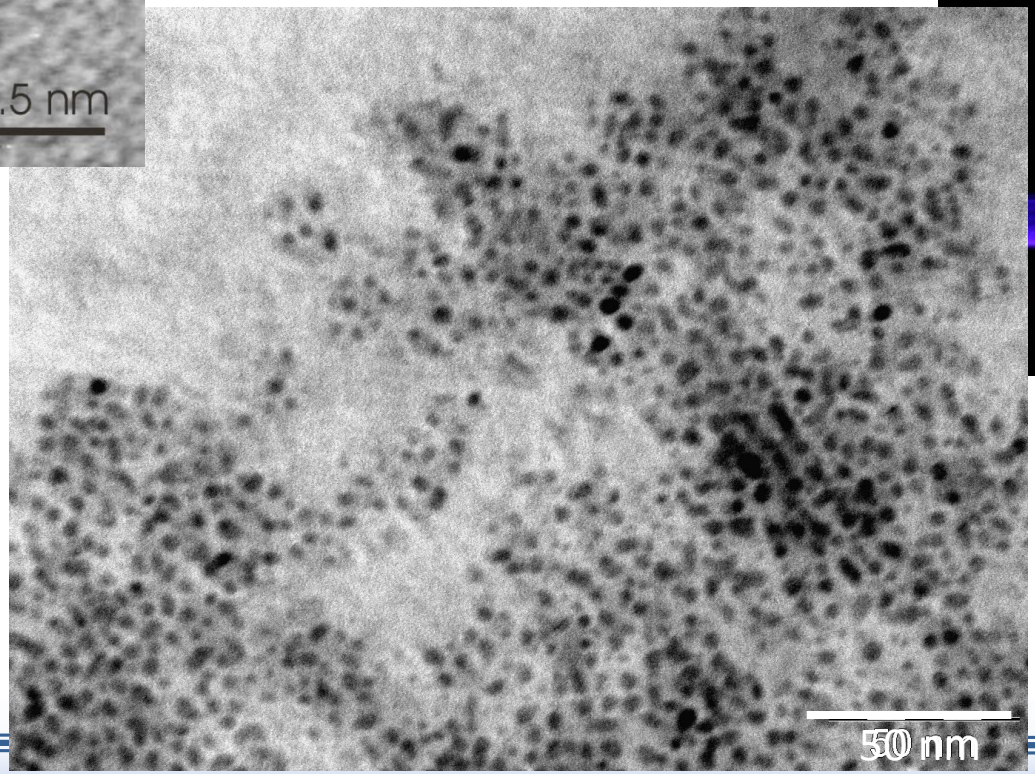
a material to widen the scope of silicon photonics

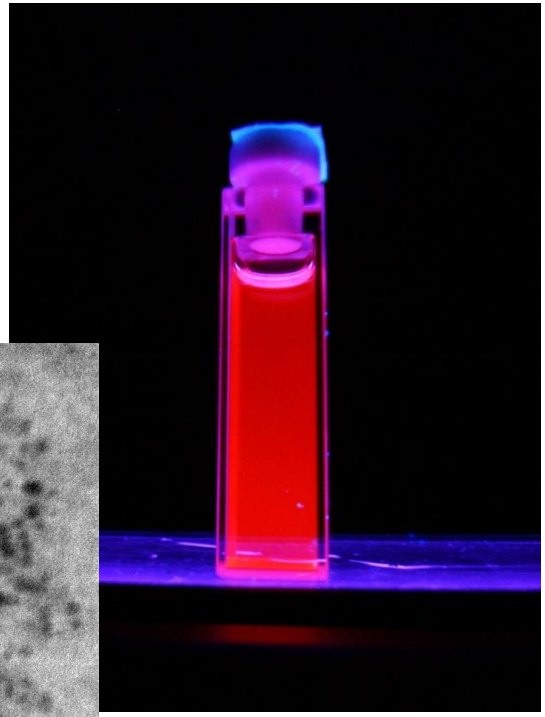
Silicon quantum dots

- Light emission
- Optical gain
- Nonlinear optical effects
- Photoresponse
- Biocompatibility
- Interface properties
- Sensitization action
- …

Silicon quantum dots







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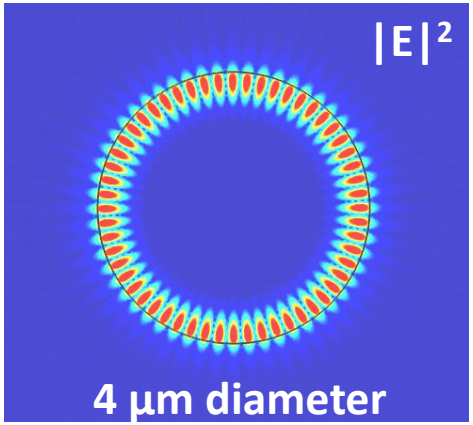
Micro-disk resonators

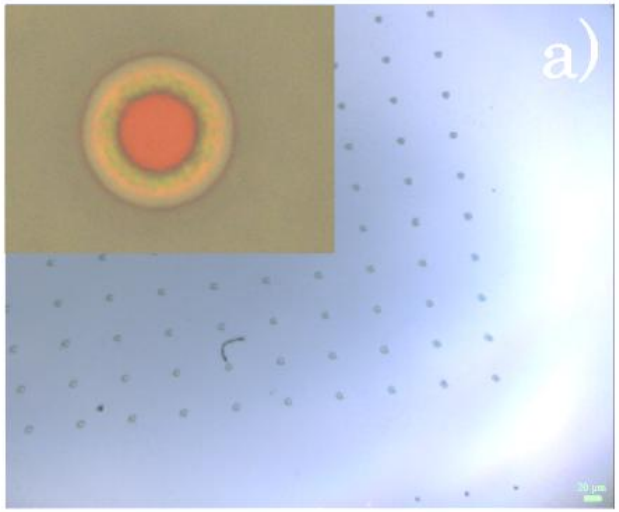
Whispering-gallery mode (WGM) resonators:

Light recirculation by total internal reflection.

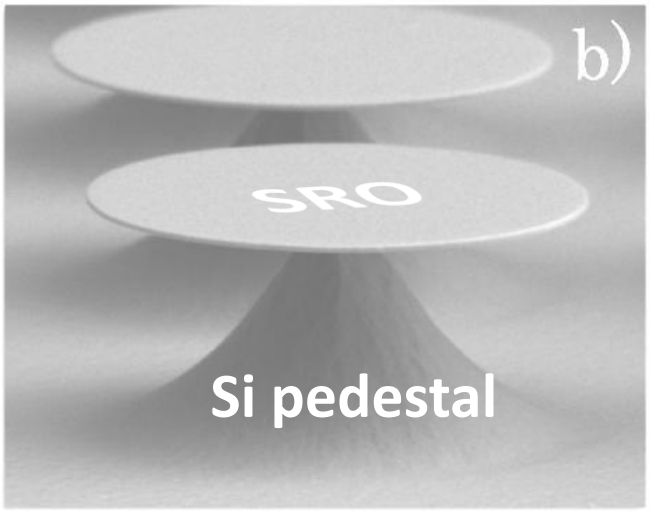
- **Free-standing geometry**
  (Silicon-rich oxide film [SRO] on silicon pedestal)

- **Far field detection based on radiative loss of optical resonator**





Microscope image



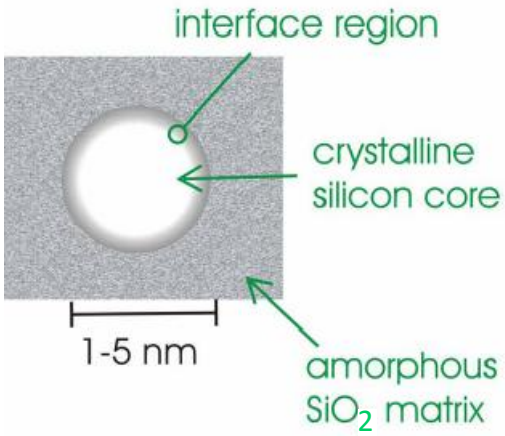
SEM image

SRO film thickness:
200 nm

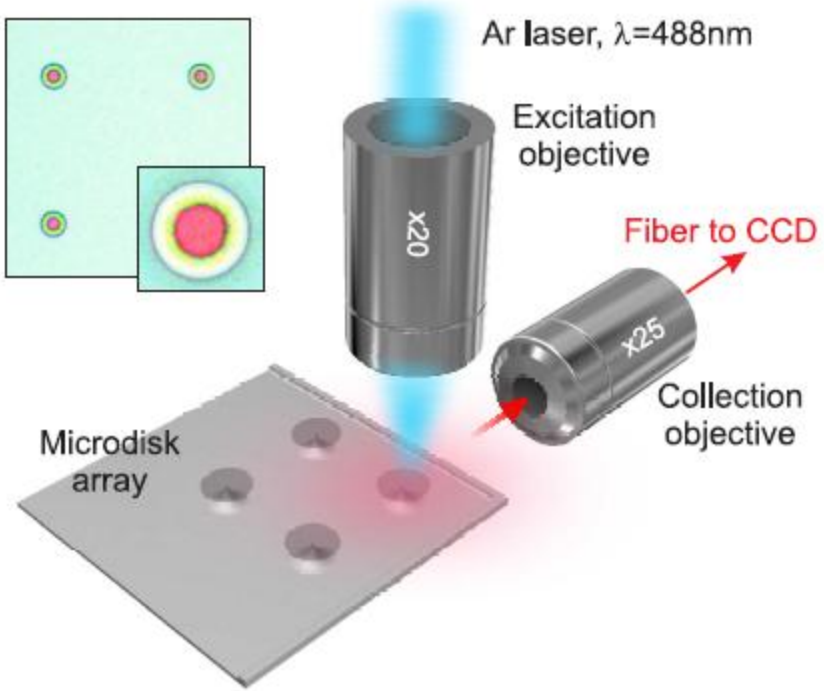
µ-disk diameter:
7 µm

Active microdisks

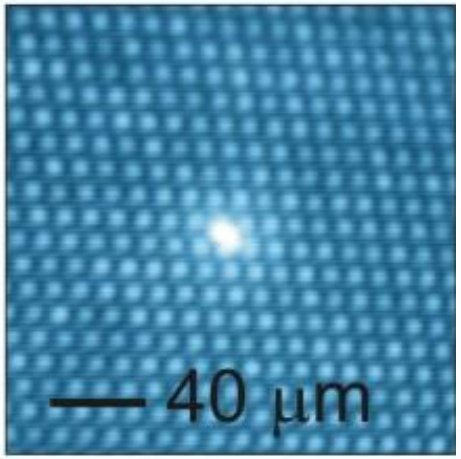
Low dimensional Si (Si nanoclusters)

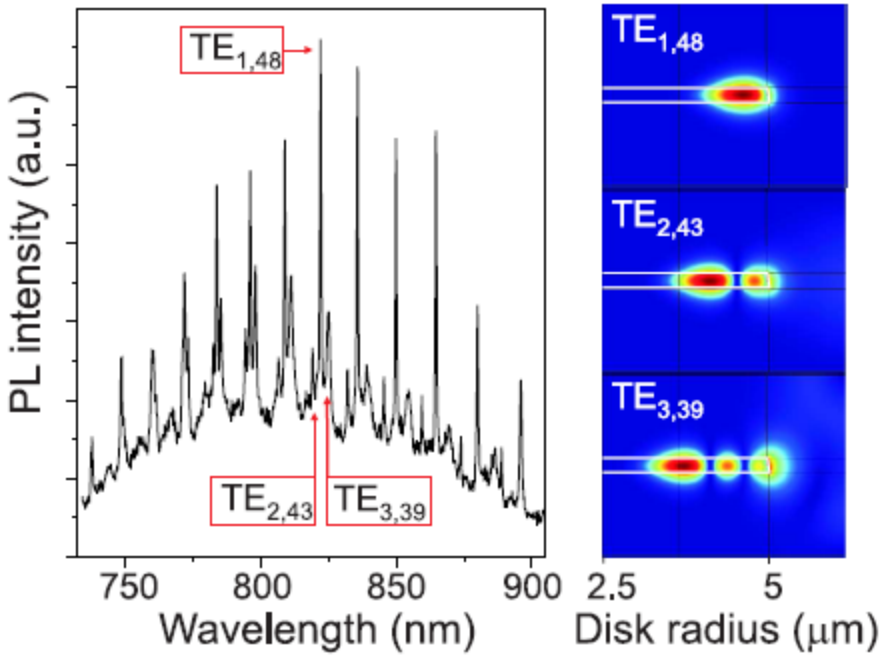


Whispering gallery mode microdisk-cavity:


Ar laser, λ=488nm
Excitation objective
x20
Fiber to CCD
x25
Collection objective
Microdisk array

(b)


40 μm


TE1,48
TE2,43
TE3,39
PL intensity (a.u.)
750
800
850
900
Wavelength (nm)
2.5
5
Disk radius (μm)

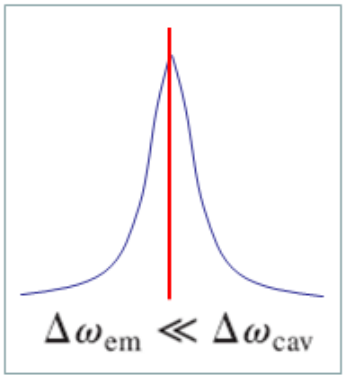
The radiative rate of a two-level system $|i\rangle$, $|f\rangle$

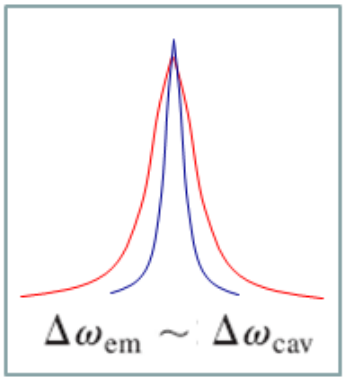
Fermi's golden rule $$\Gamma_{f\to i} = \frac{2\pi}{\hbar}|\langle i|H'|\rangle f|^2 \rho(\omega)$$

emiitter's nature

photonic density of states

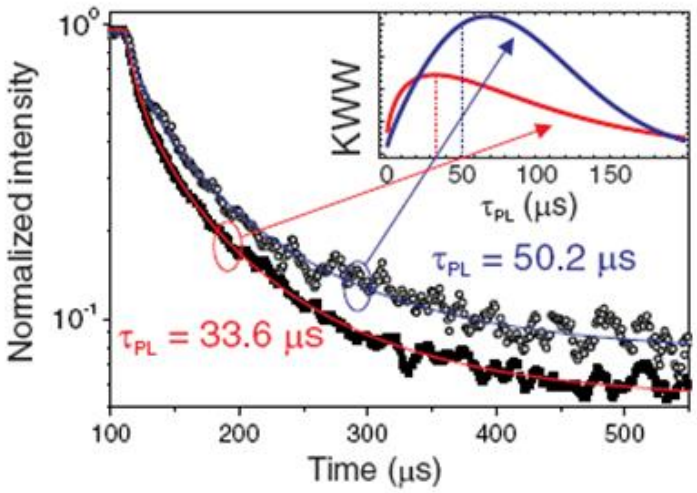
expected enahncement $$F_P = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V}$$

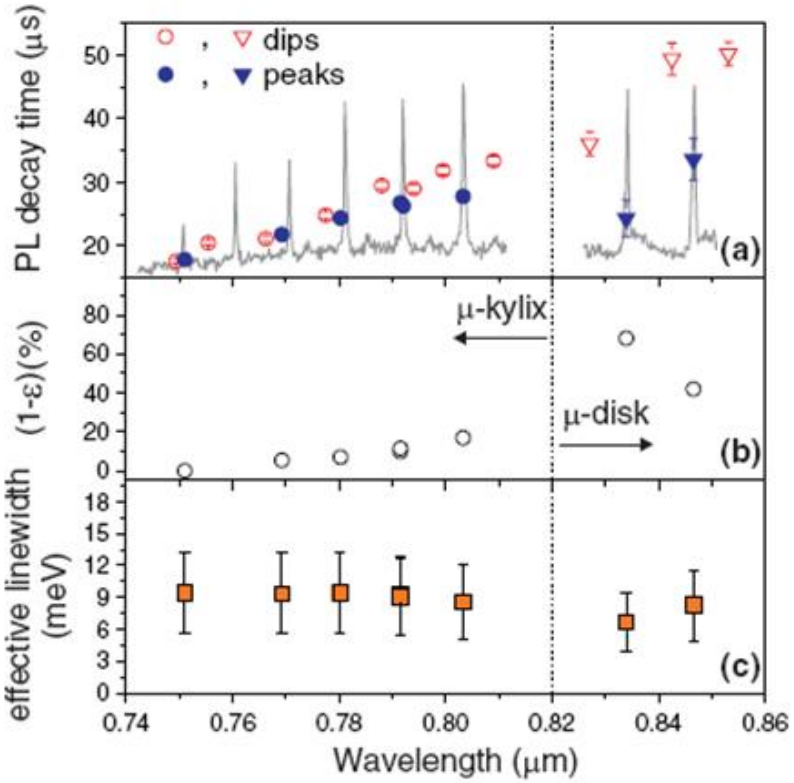




bad emitter regime $$\tilde{F}_P = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q_{eff}}{V}\frac{\Delta\omega_c^2}{\Delta\omega_c^2 + 4(\omega-\omega_c)^2}\frac{|\vec{E}(\vec{r})|^2}{|\vec{E}|^2_{max}}\eta^2$$

Purcell enhancement of radiation rate in Si-nc





Measured $\epsilon = 1 + \frac{\tau_{dip}}{\tau_r}(\tilde{F}_P - 1)$

ϵ represents the lower limit of $\tilde{F}_P$ when non-radiative recombination rates are non-negligible

$$Q_{eff} = \left(\frac{1}{Q_{cav}} + \frac{\Delta\omega_{em}}{\omega_{em}}\right)^{-1}$$

~200 - upper limit on cavity Q

A. Pitanti, M. Ghulinyan, G. Pucker, and L. Pavesi, PHYS. REV. LETT. **104**, 103901 (2010)

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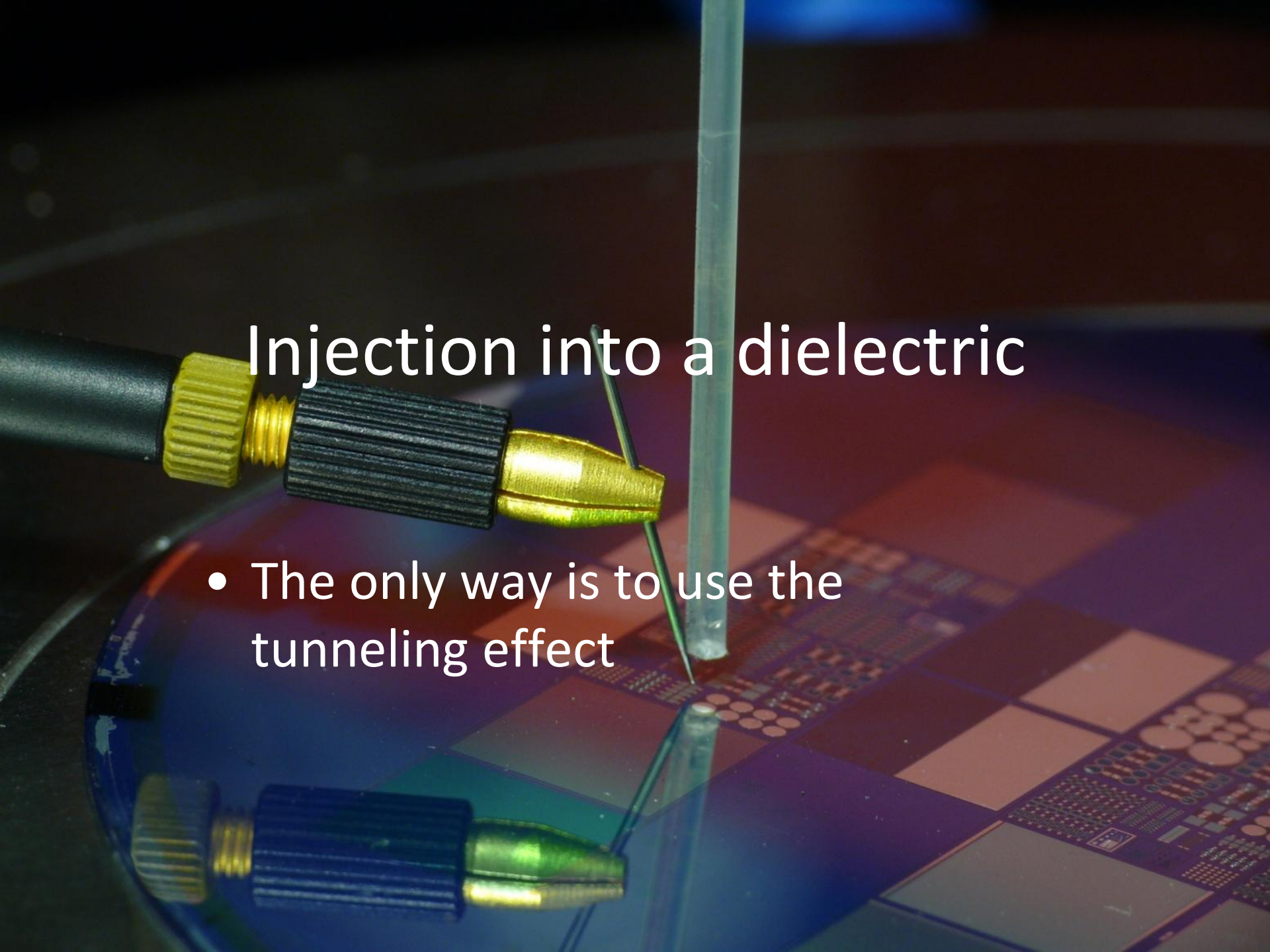
Photoluminescence: excitation by optical pumping

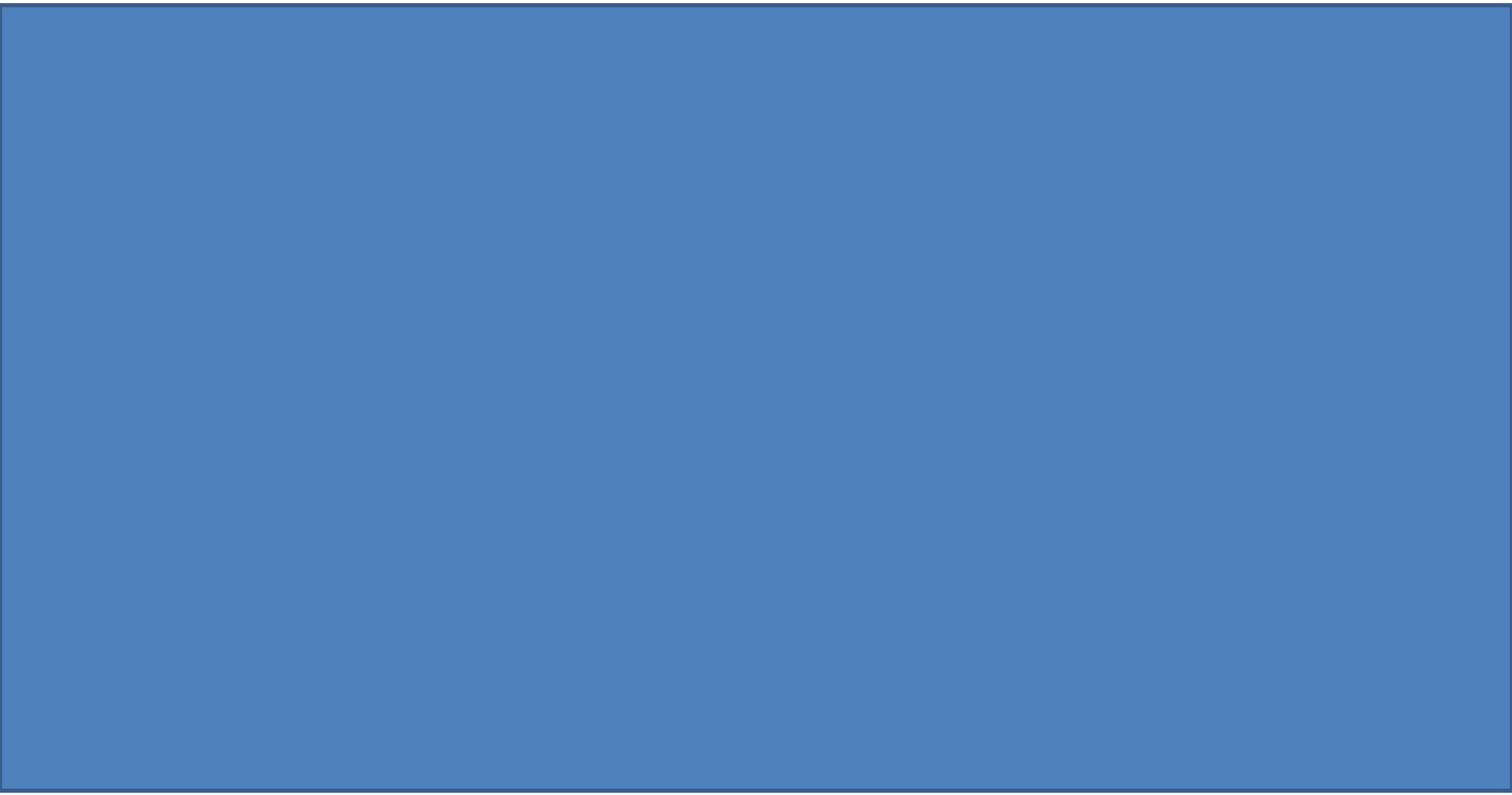
Electroluminescence: excitation by electrical injection



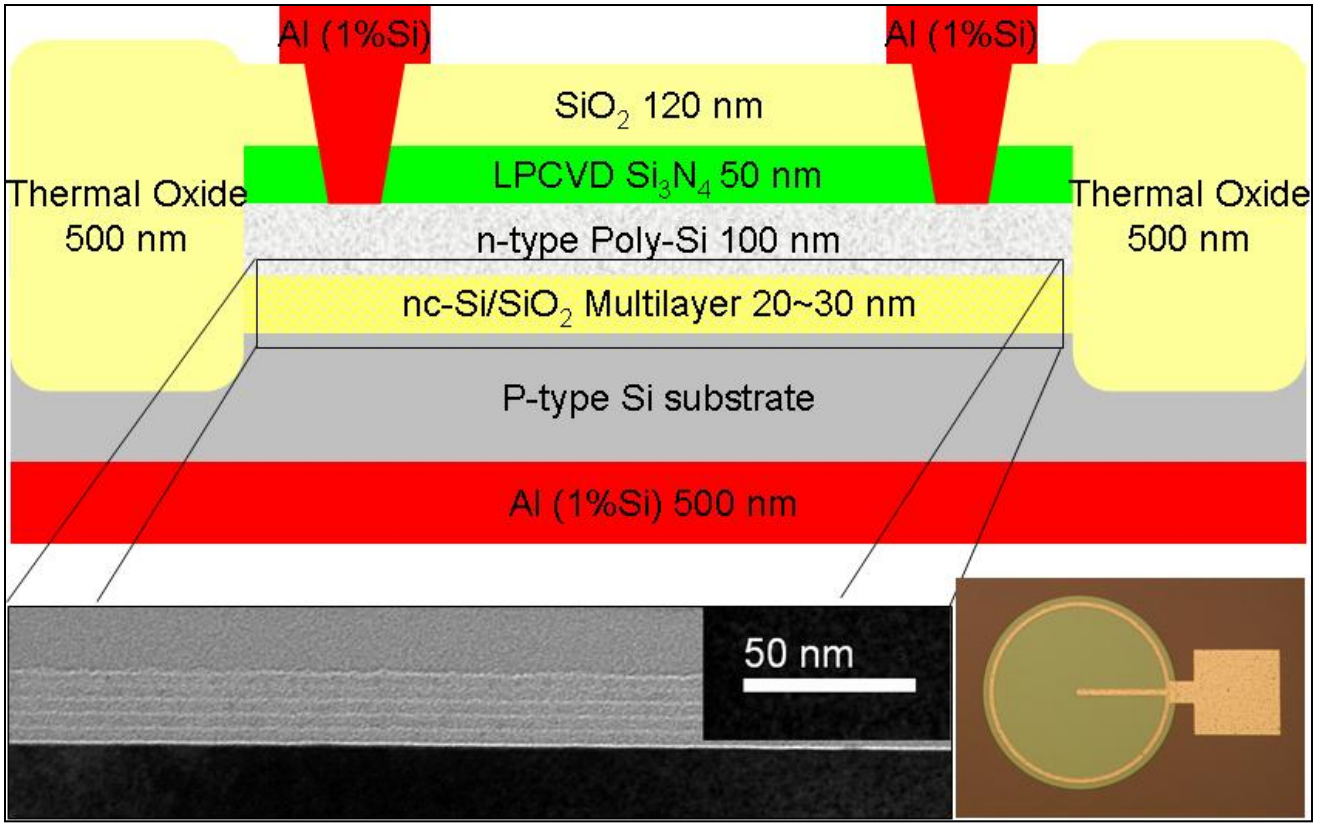
Injection into a dielectric

- The only way is to use the tunneling effect

Injection rate engineering

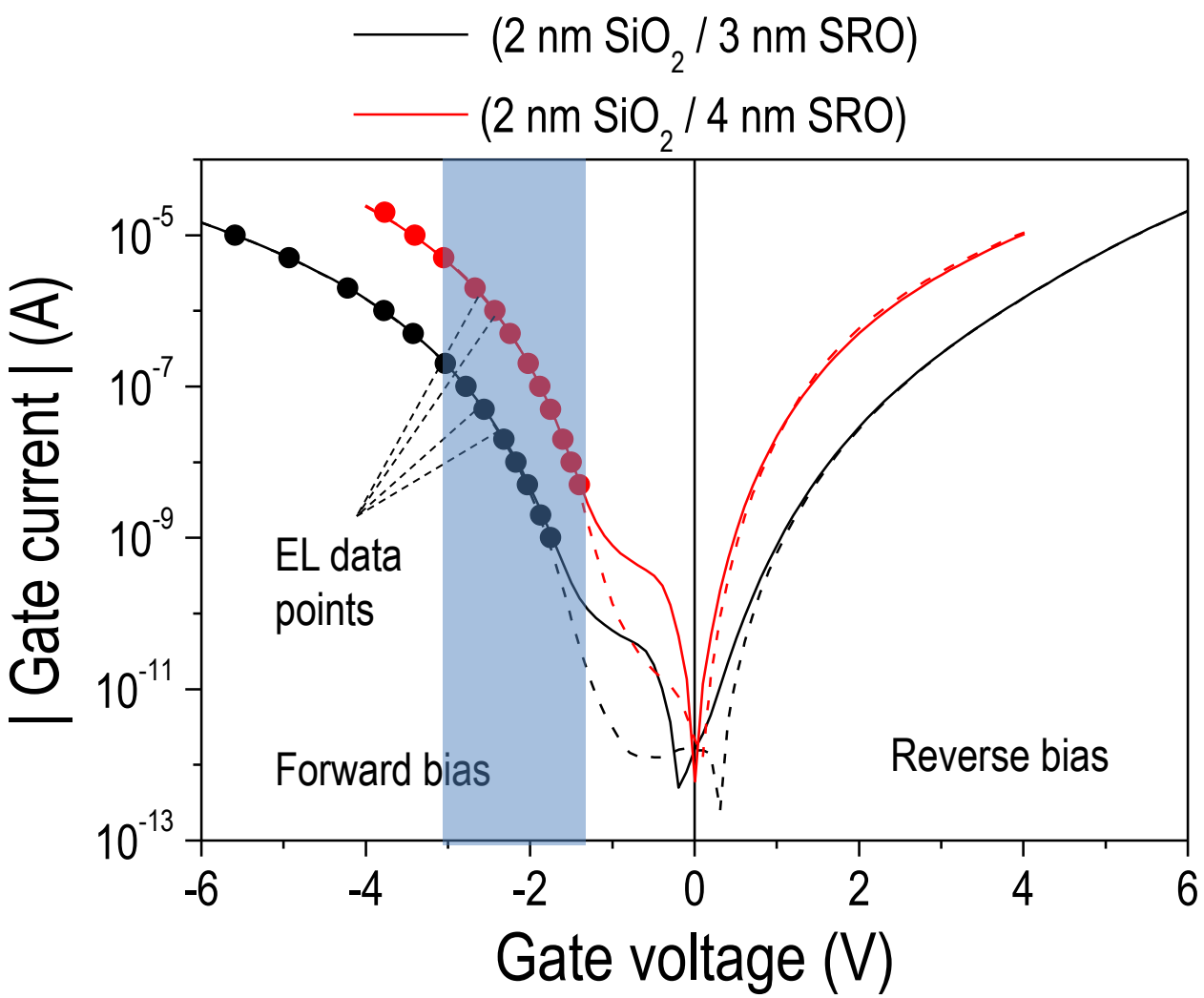


nc-Si/SiO_2 Multilayer LED

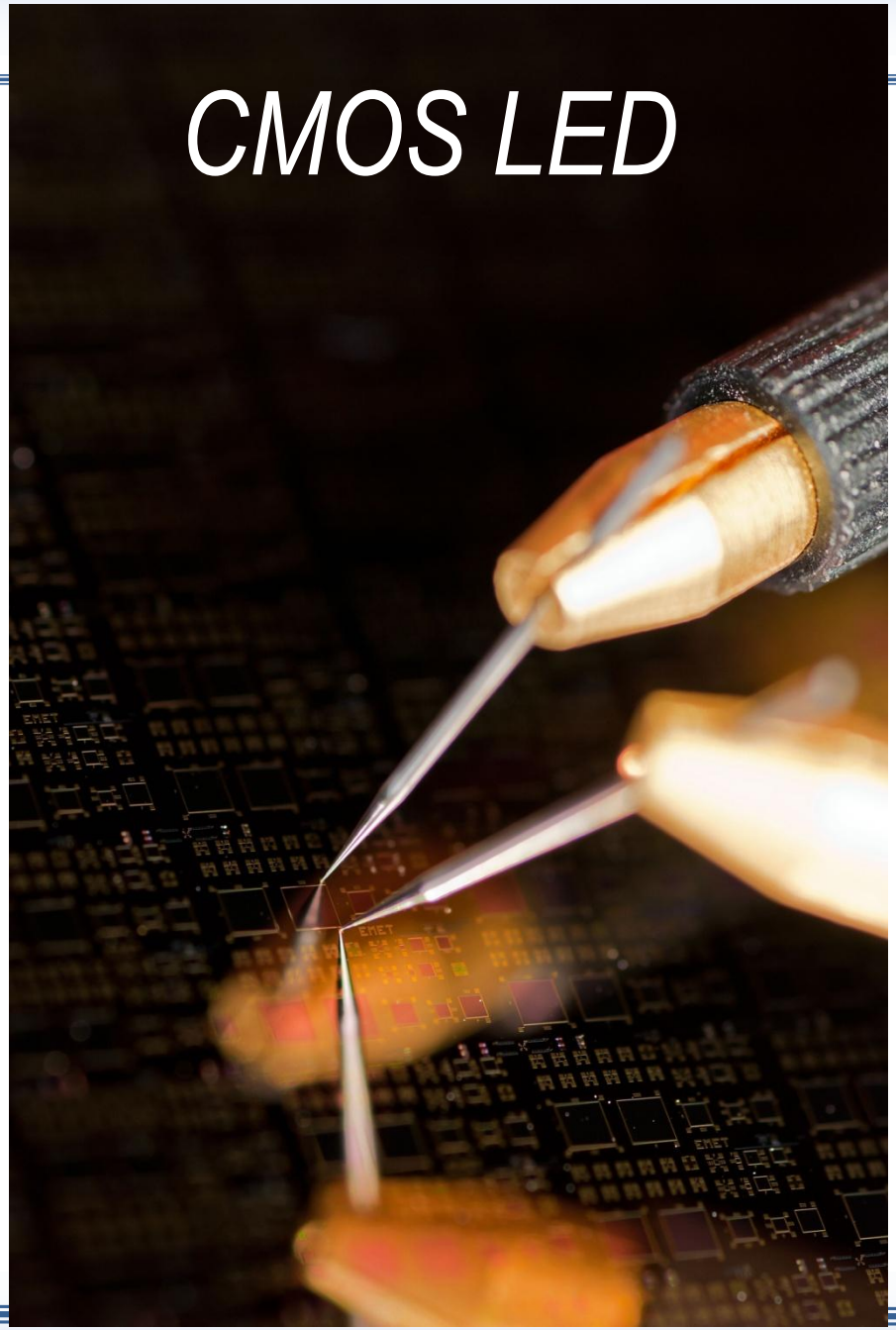


- Confined growth of nanocrystals
- Better oxide quality
- Control over the oxide thickness

Low onset of EL voltages, < 3.2 V

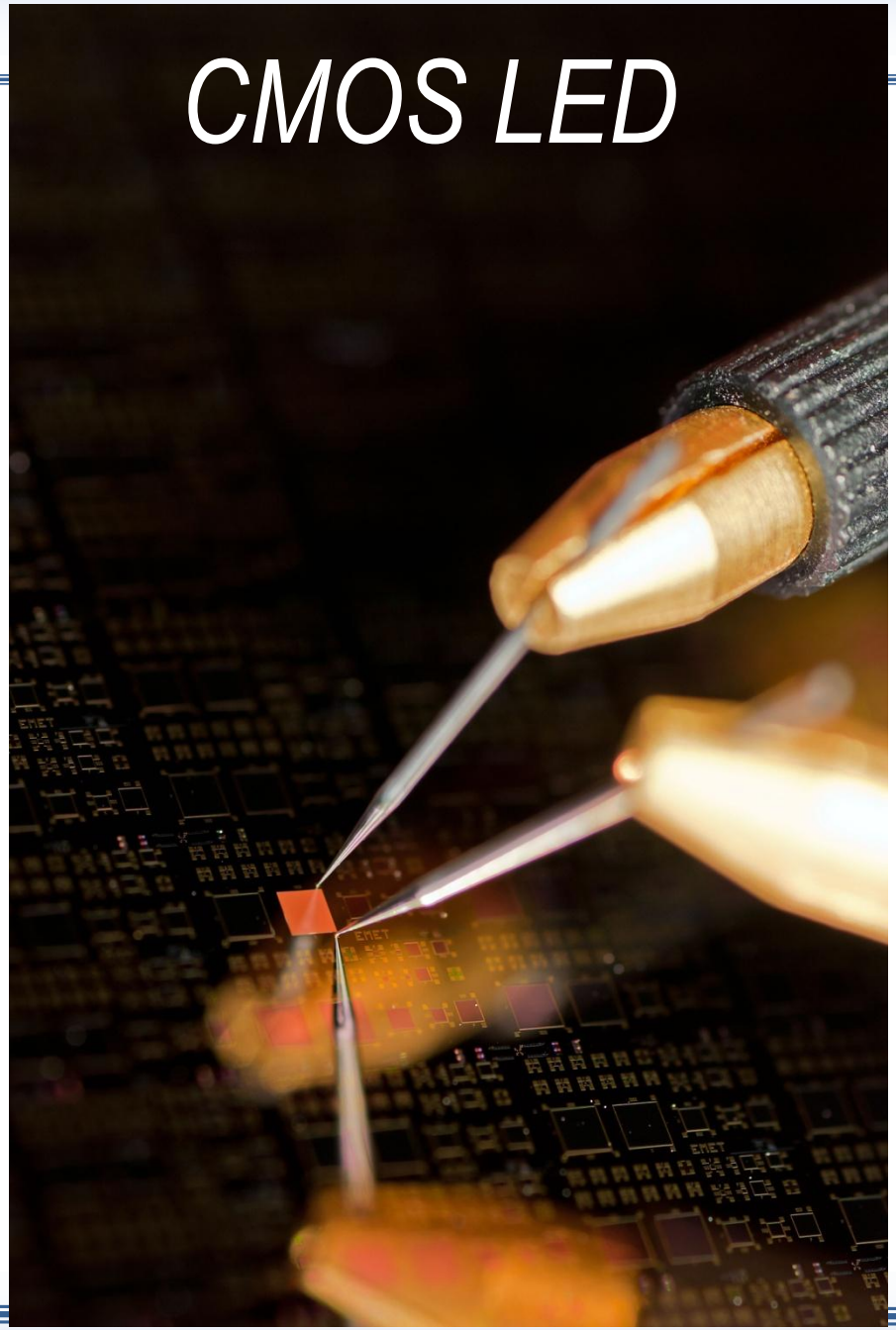


J. Appl. Phys. **106**, 033104 (2009)



Si-NC LED
on a CMOS wafer

CMOS LED



Si-NC LED
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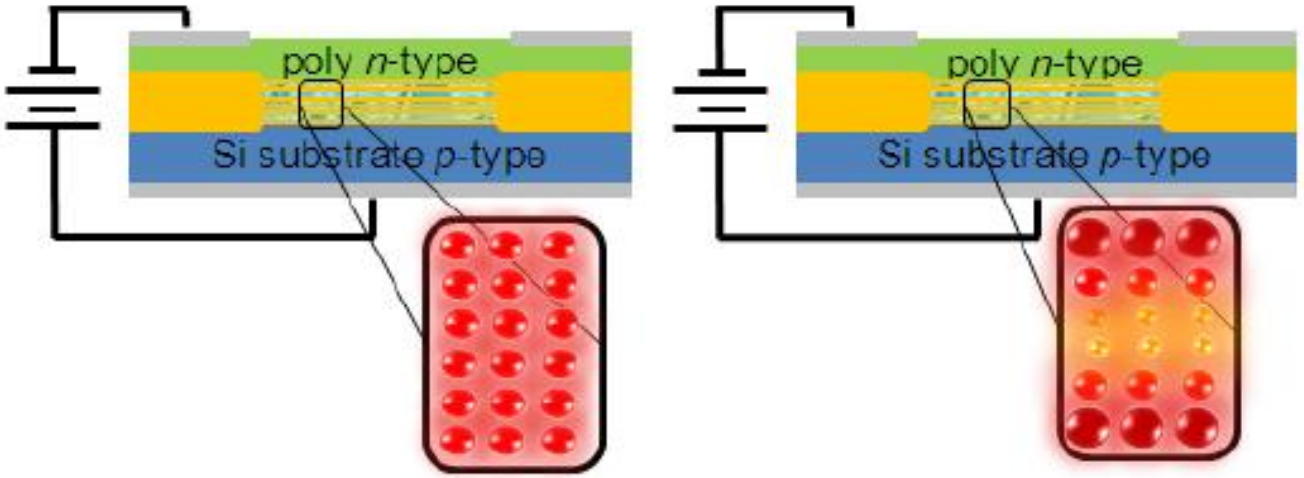
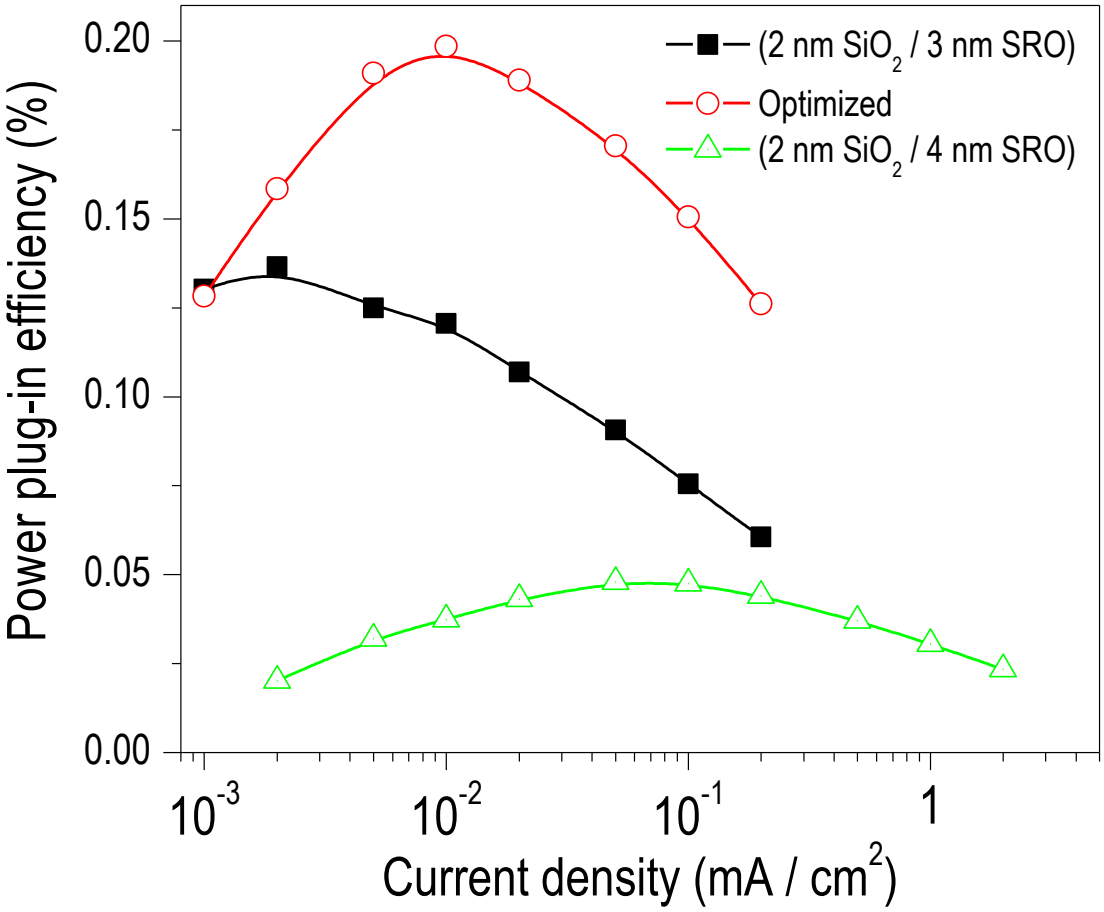
Injection rate engineering



Graded gap active layer

Large nanocrystals: Easy injection
Small nanocrystals: high emission


Power plug-in efficiency (%)
0.20
0.15
0.10
0.05
0.00
10^-3
10^-2
10^-1
1
Current density (mA / cm^2)
(2 nm SiO2 / 3 nm SRO)
Optimized
(2 nm SiO2 / 4 nm SRO)

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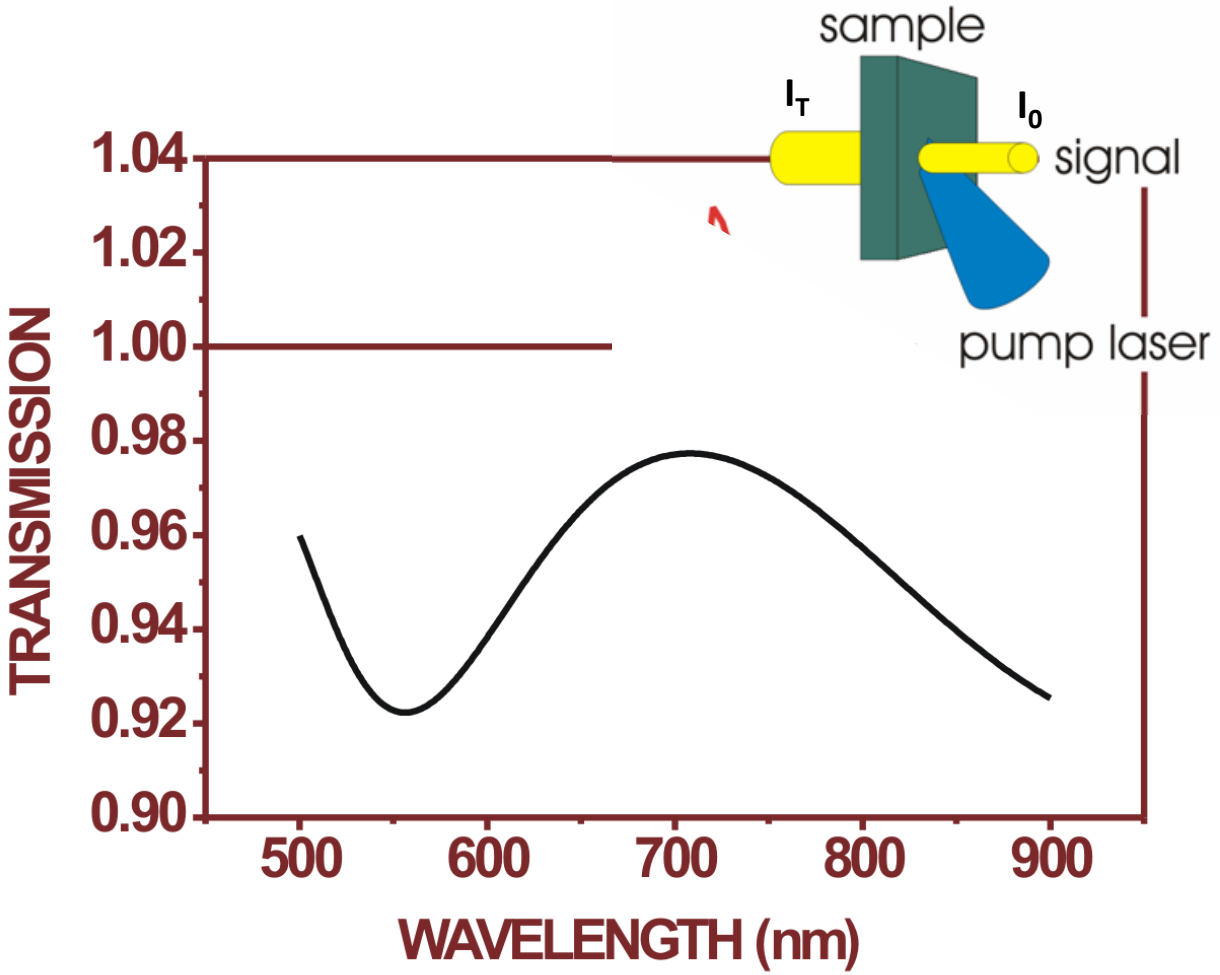
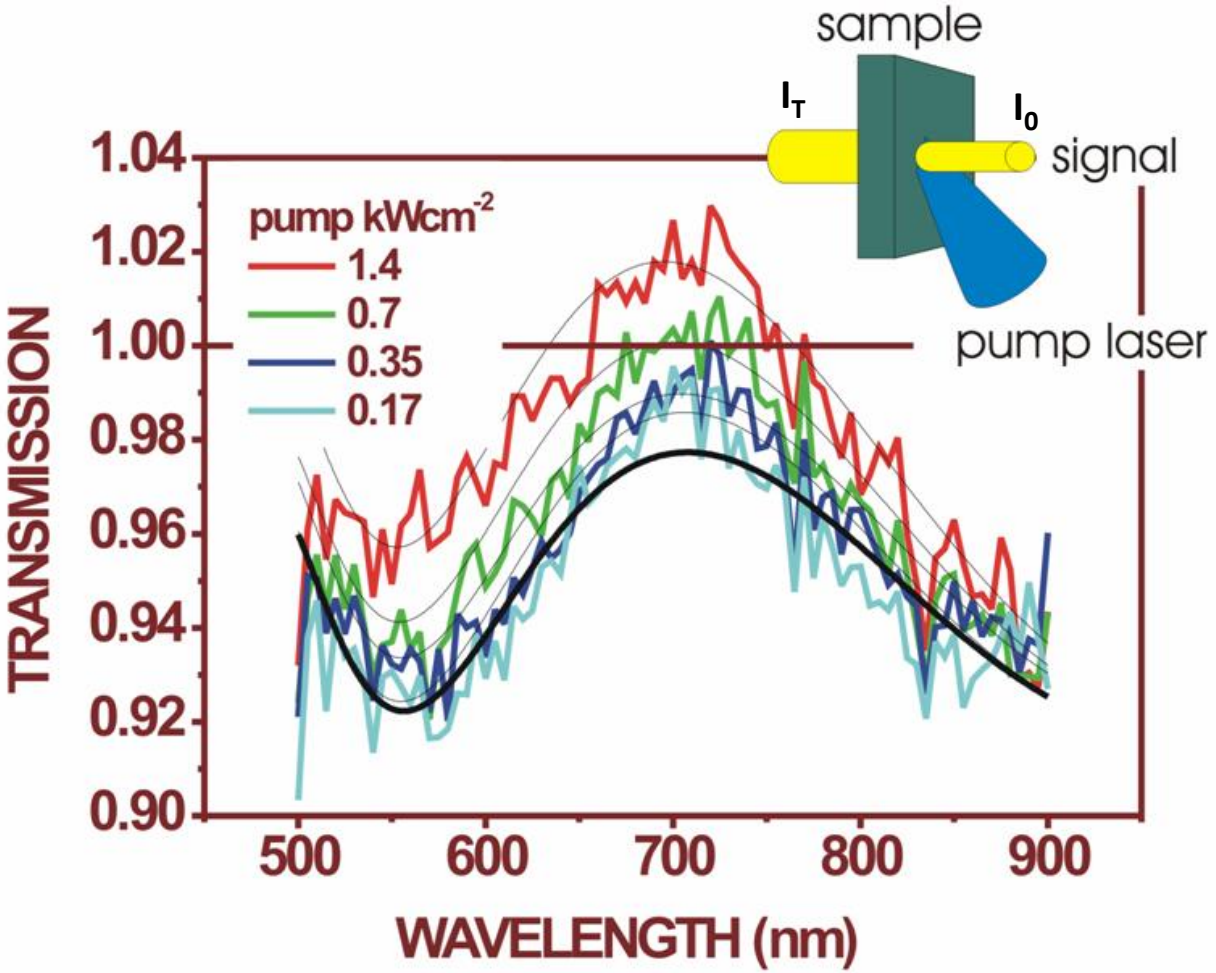
Optical gain



JAP 96, 5747

$$T = \frac{I_{ON} - I_{PL}}{I_O} = \exp\left[-\left(\alpha_{QZ} d_{QZ} - g_{Si-nc}\left(J_P\right) d_{Si-nc}\right)\right]$$

How we measured gain



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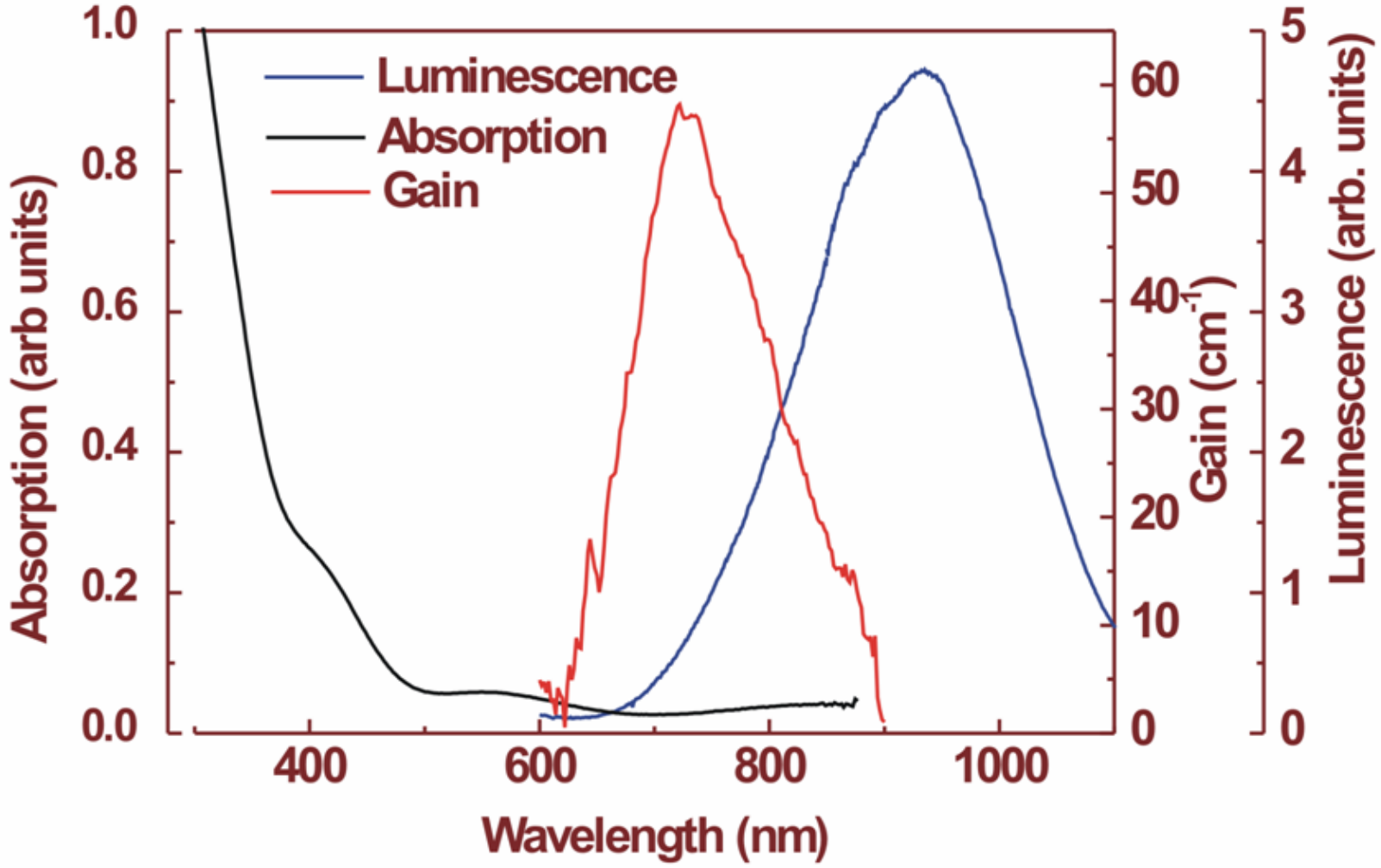
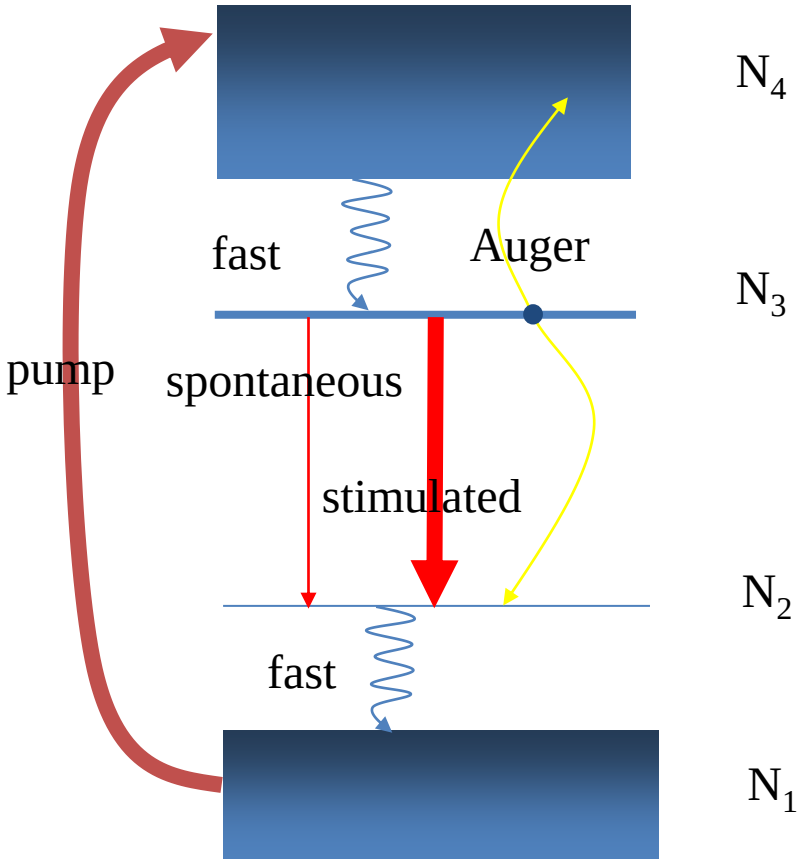
Summary on optical properties of Si-nc



4 levels system model

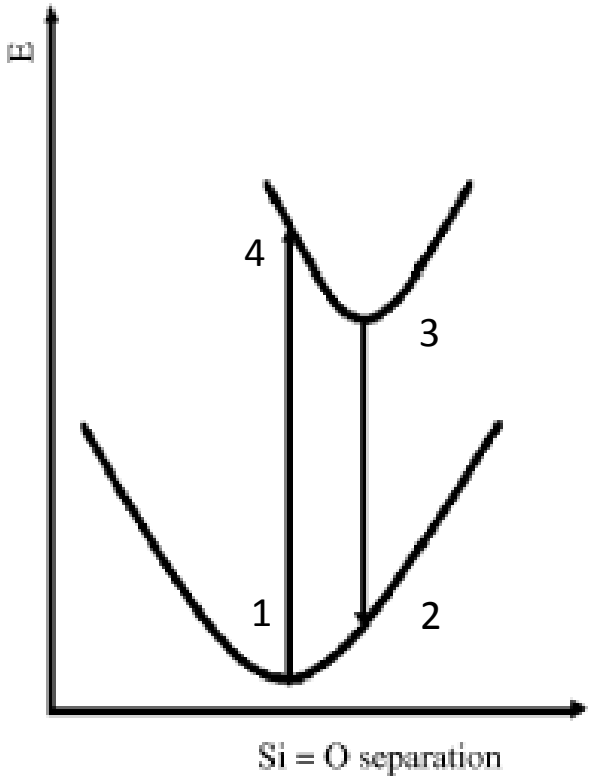


N_4

N_3

N_2

N_1

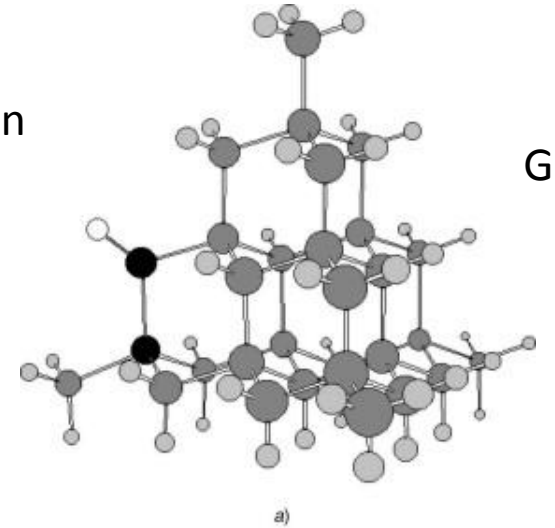


Model for the 4 levels

Si=O bond formed at the interface of the Si-nc with the matrix

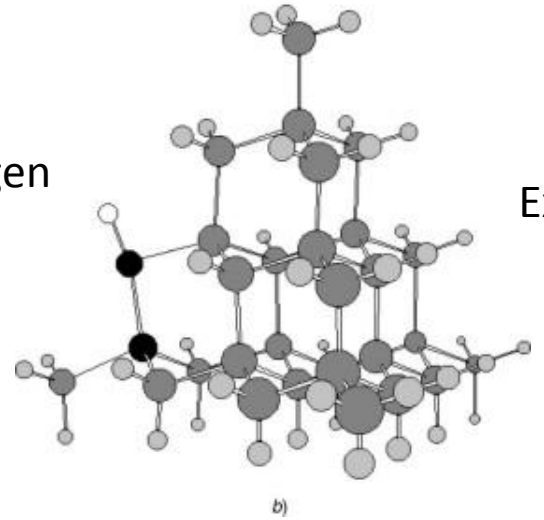
A. Filonov, S. Ossicini, PRB **65** 195317 (2002)

oxygen



Ground state

oxygen



Excited state

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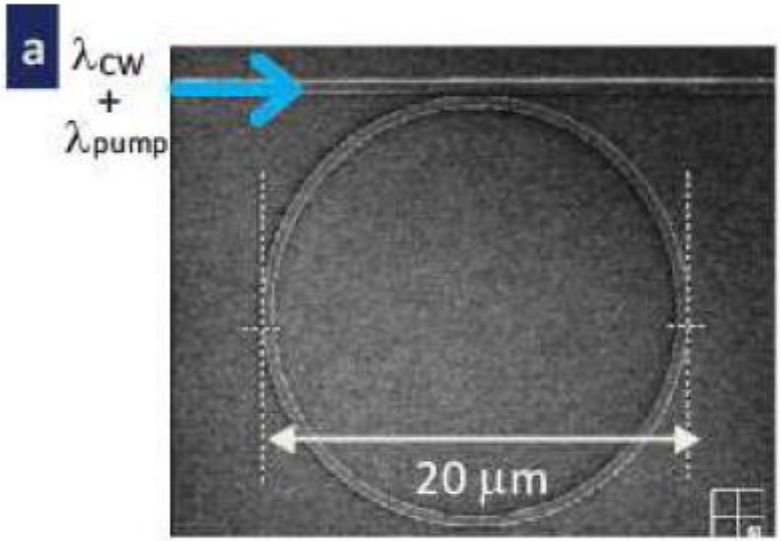
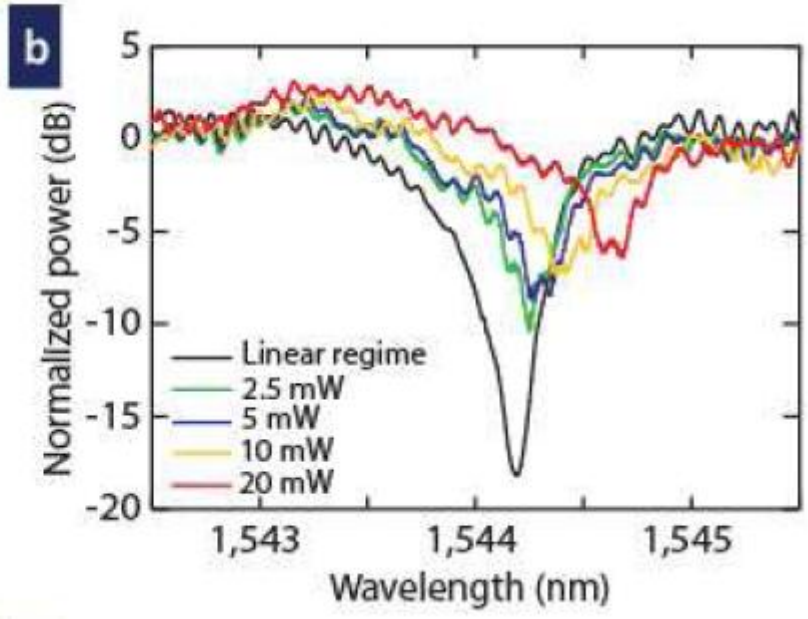
Silicon nanocrystal nonlinearity

$$n = n_0 + n_2 I$$

Silica	→	$n_2 = (1.54 \times 10^{-16})$ cm^2/W
Bulk Silicon	→	$n_2 = (4.5 \times 10^{-14})$ cm^2/W
GaAs	→	$n_2 = (1.59 \times 10^{-13})$ cm^2/W
Si-ncs	→	$n_2 = (2 \div 8 \times 10^{-13})$ cm^2/W

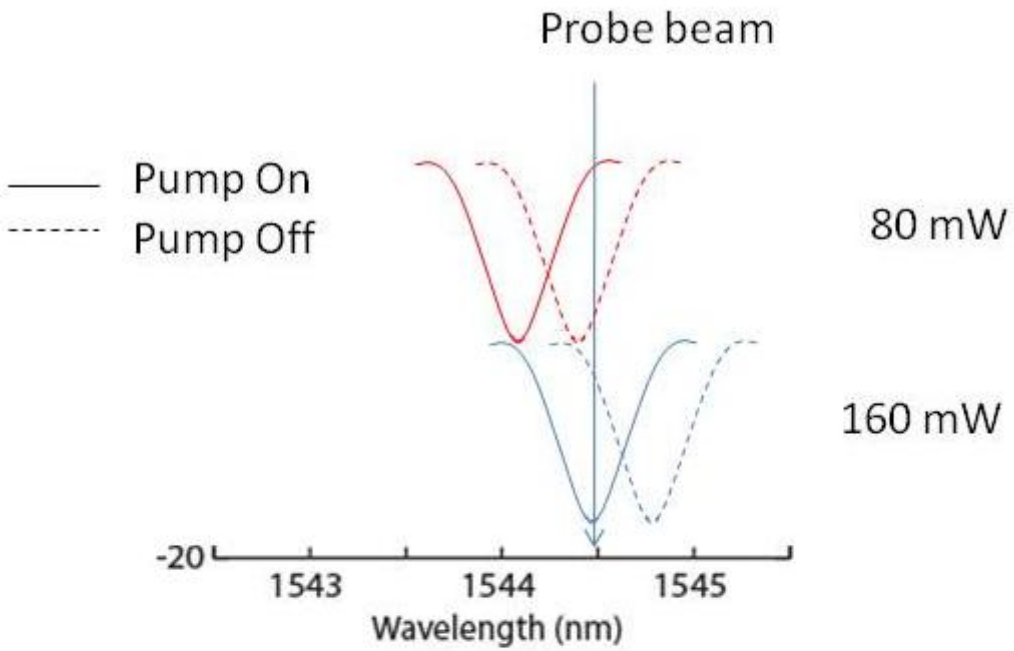
All optical switching

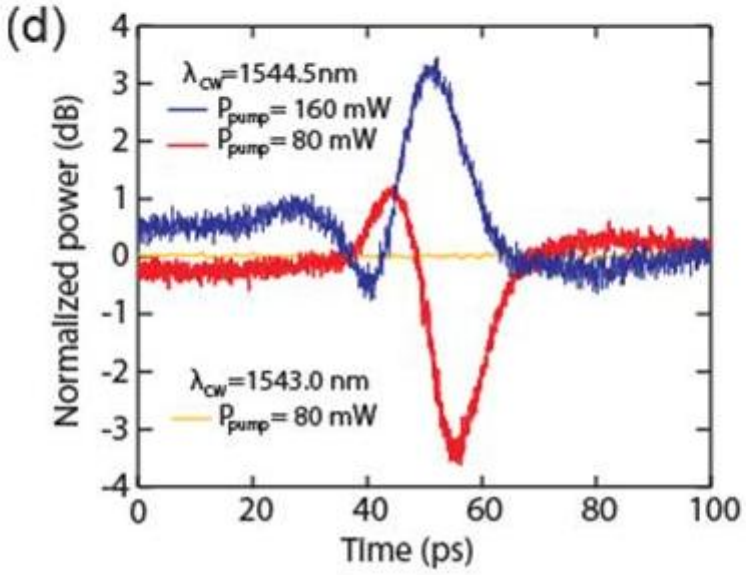




$\lambda = n\, d$

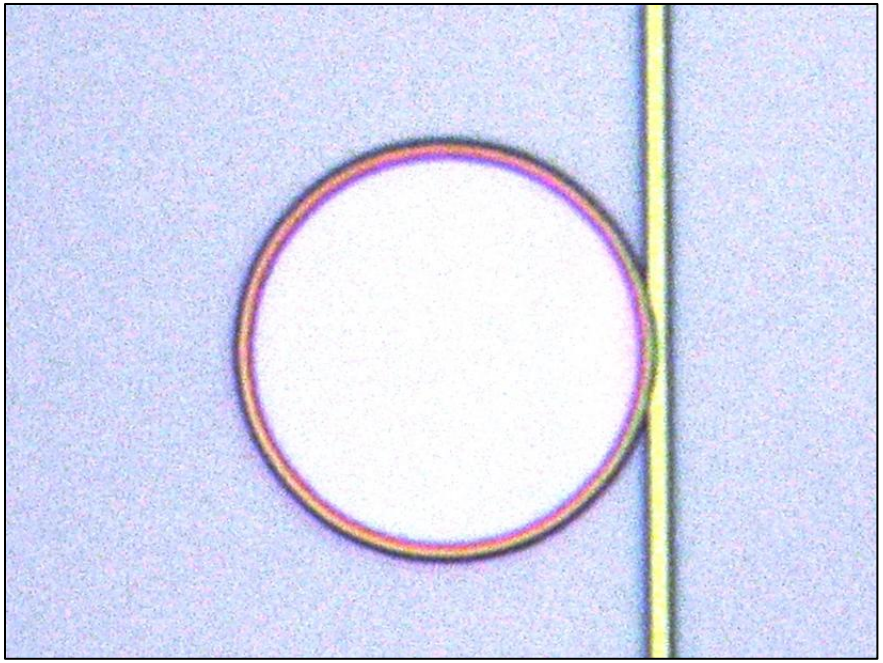
A. Martinez et al. Nanoletters (2010)

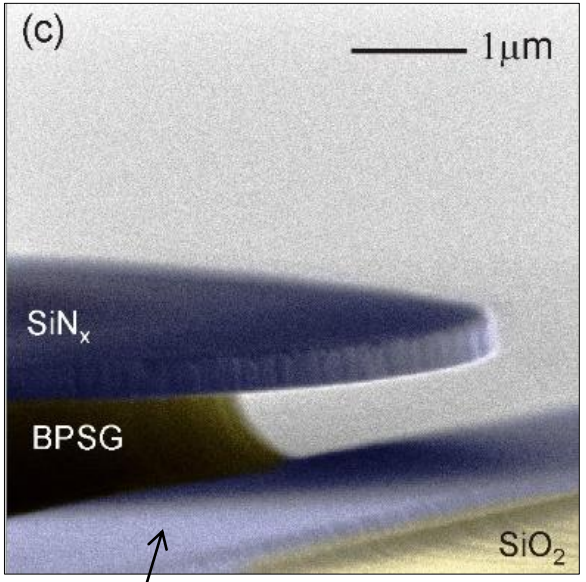




A. Martinez et al. Nanoletters (2010)

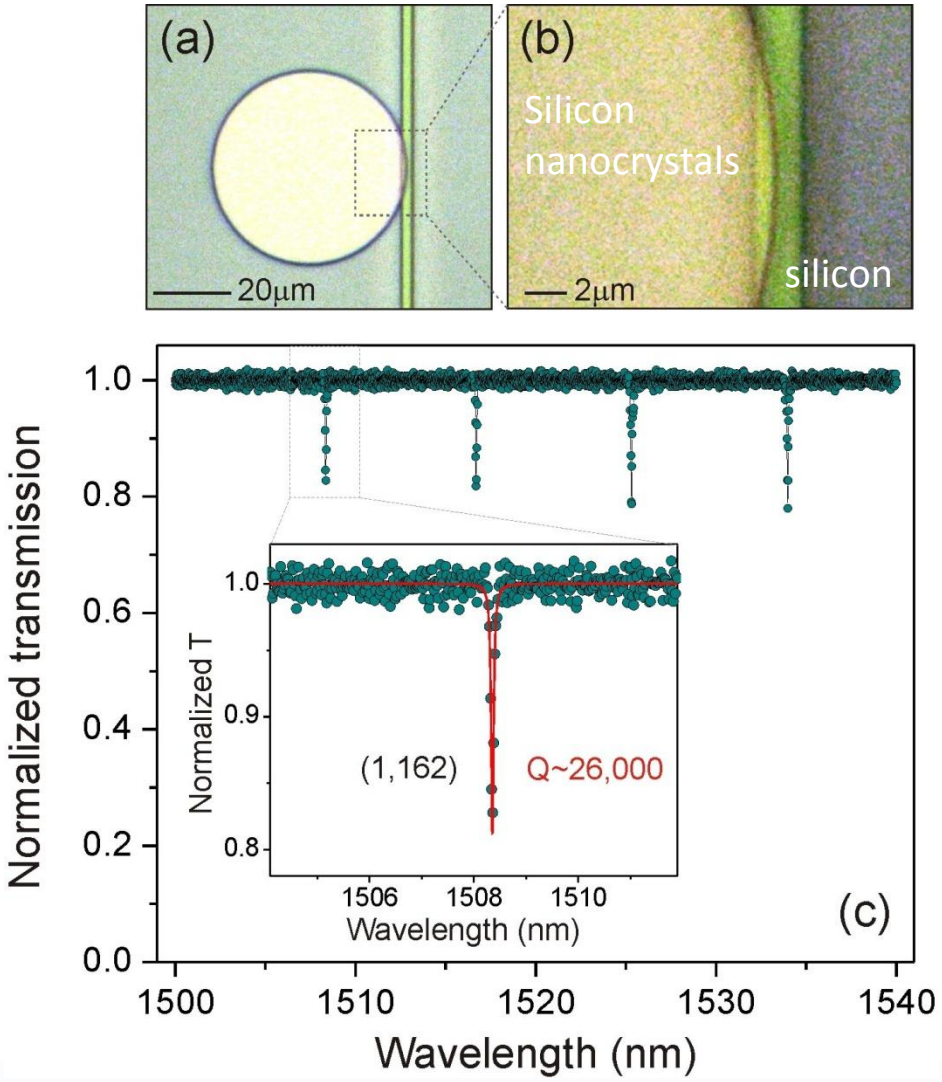
Active microdisk for optical switching



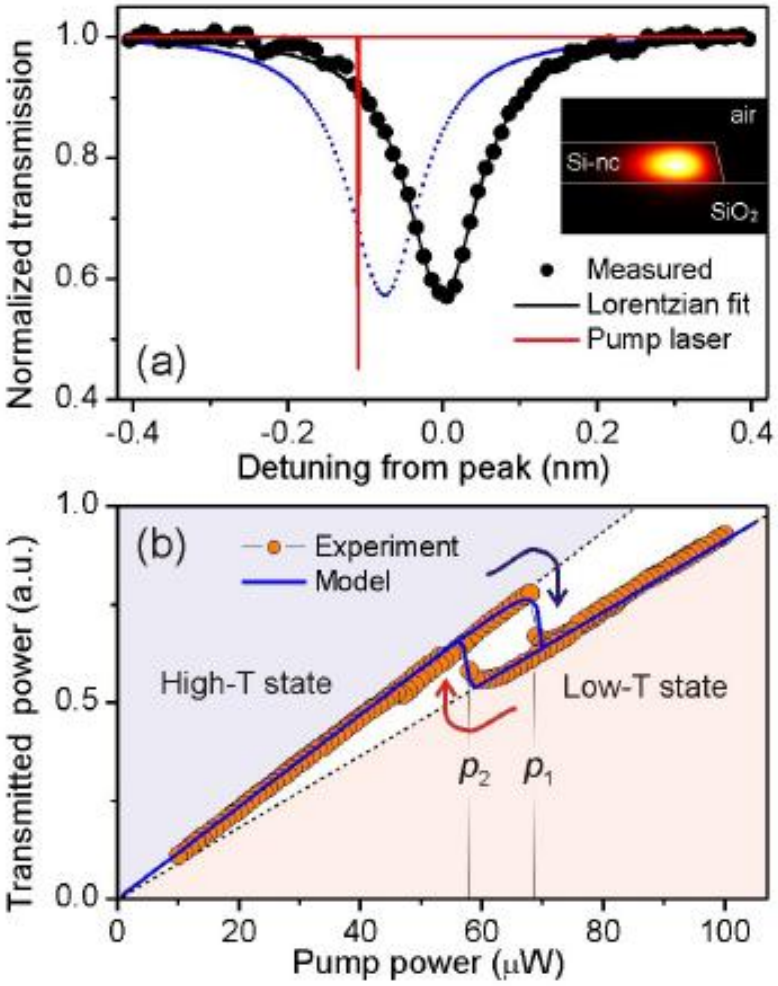


The top of the waveguide is free

Active microdisk for optical switching



Optical bistability



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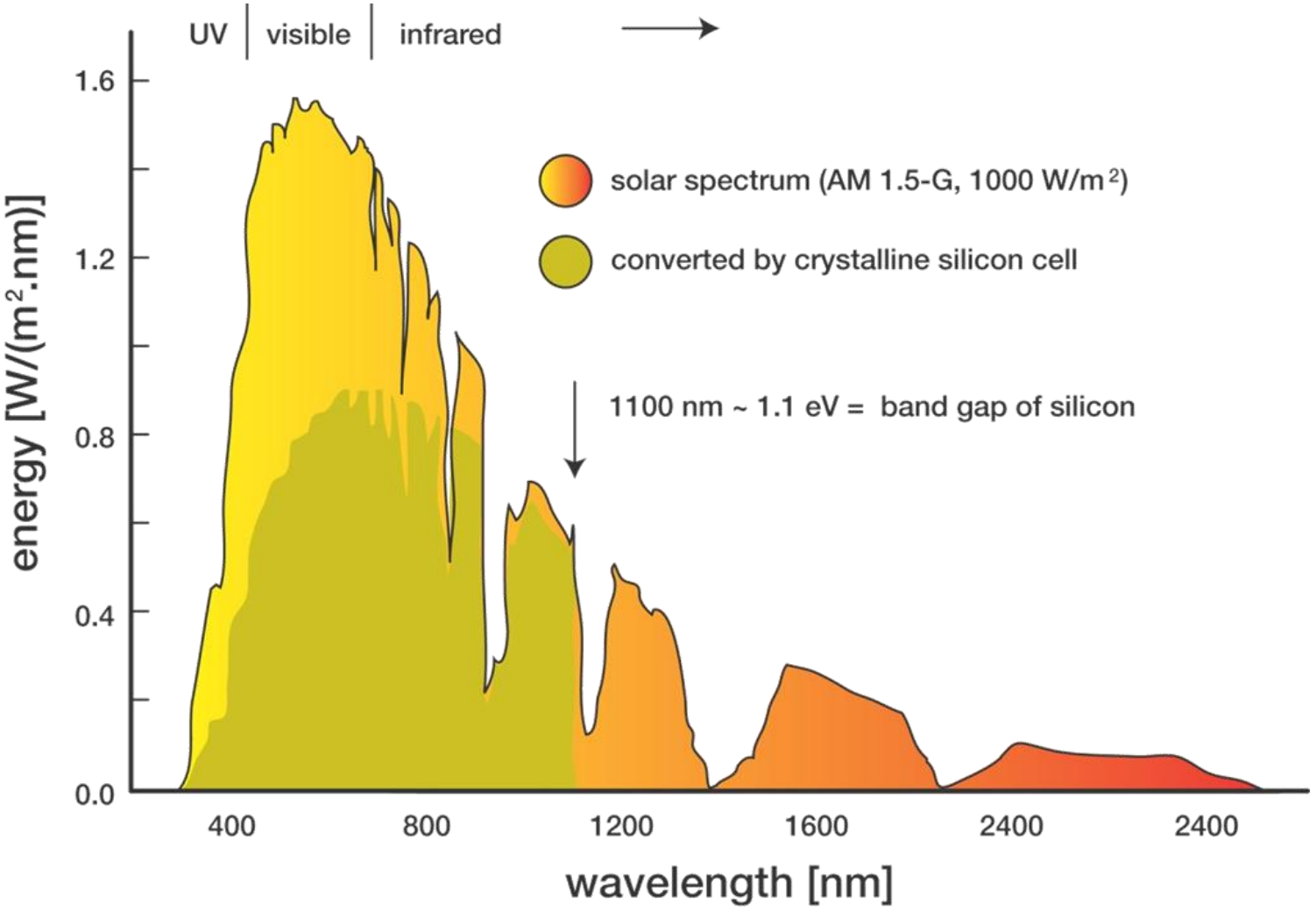
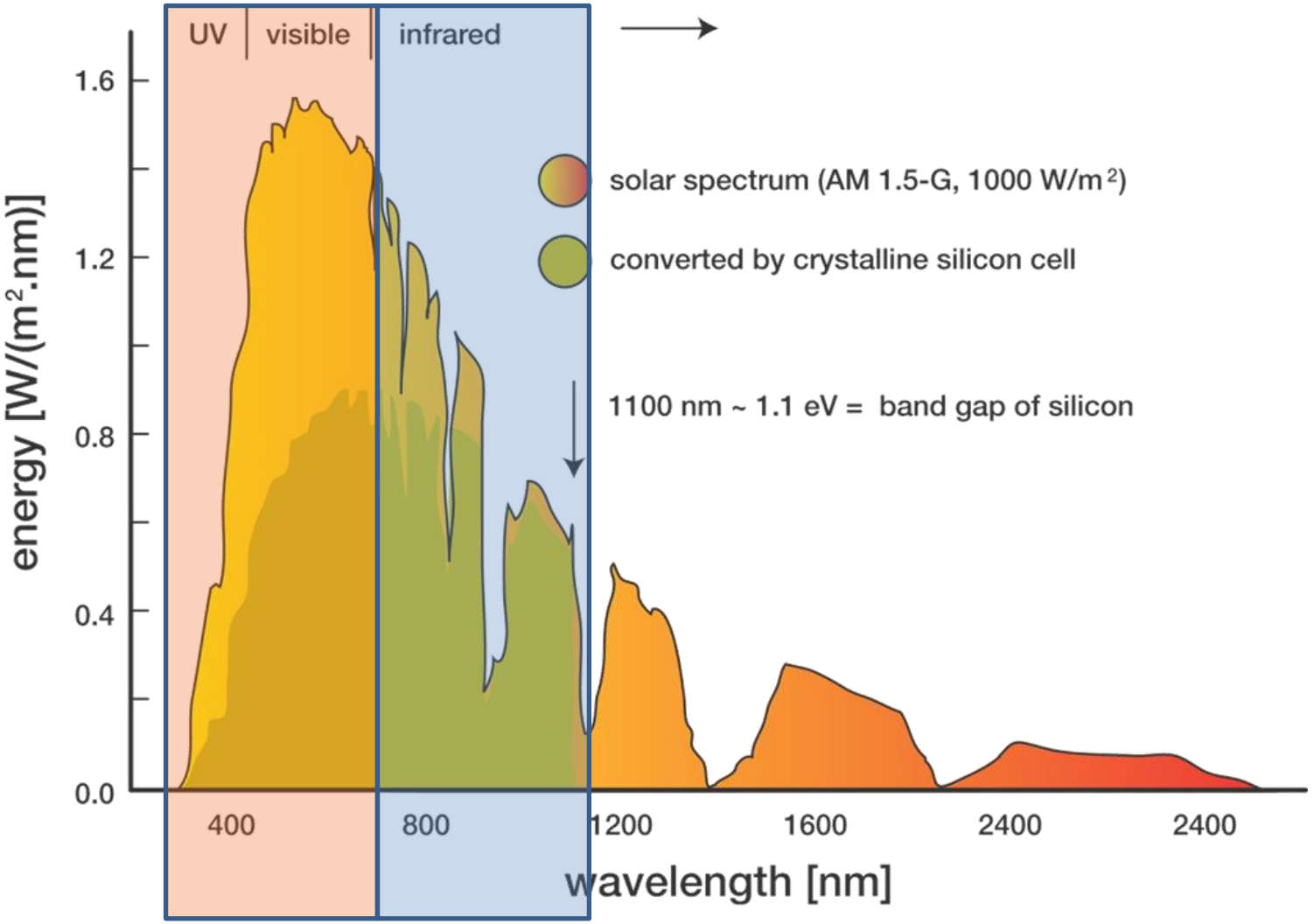
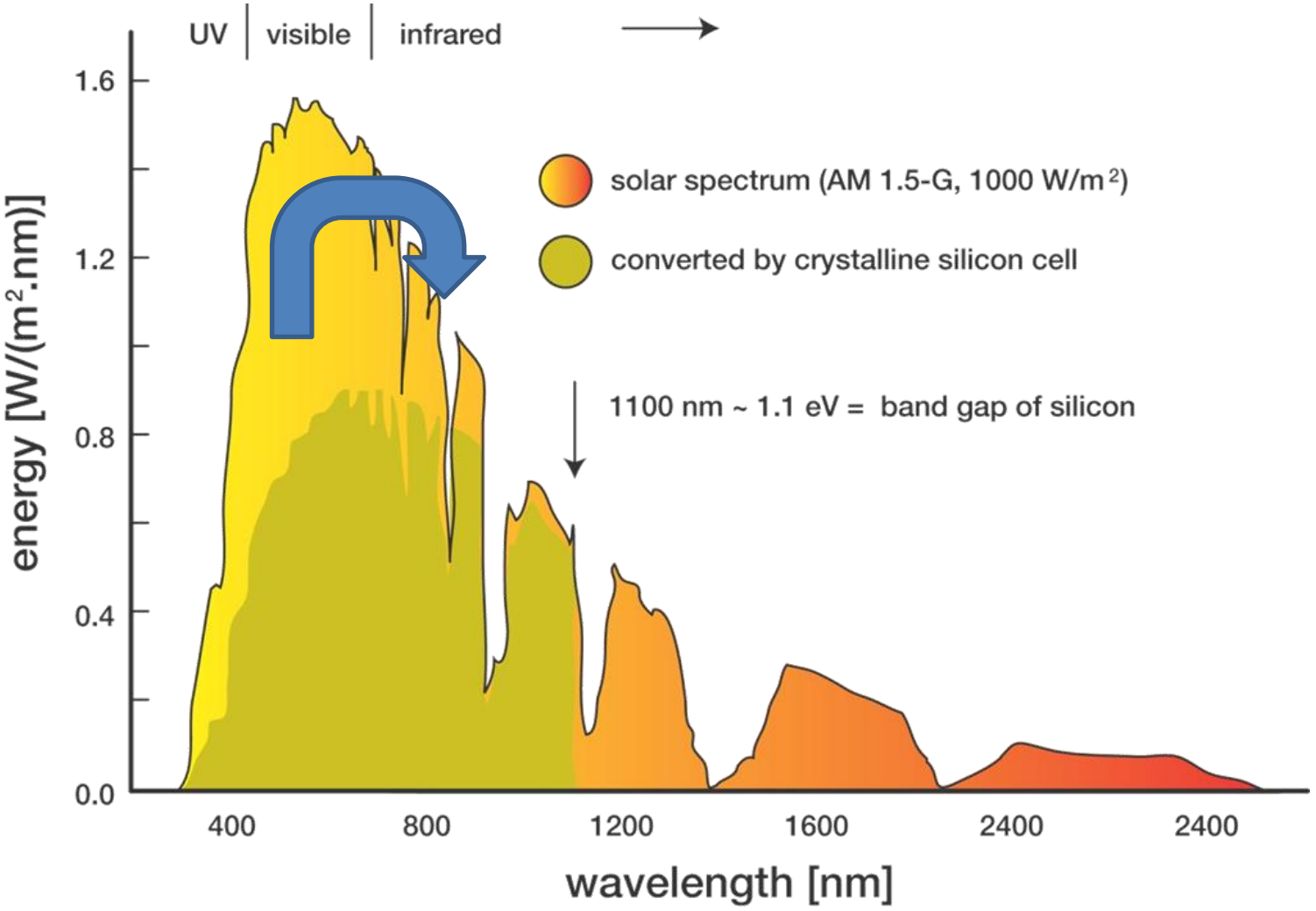
Use of solar spectrum in crystalline silicon cells



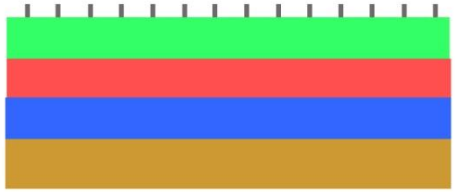
Use of nanocrystals: tandem cells



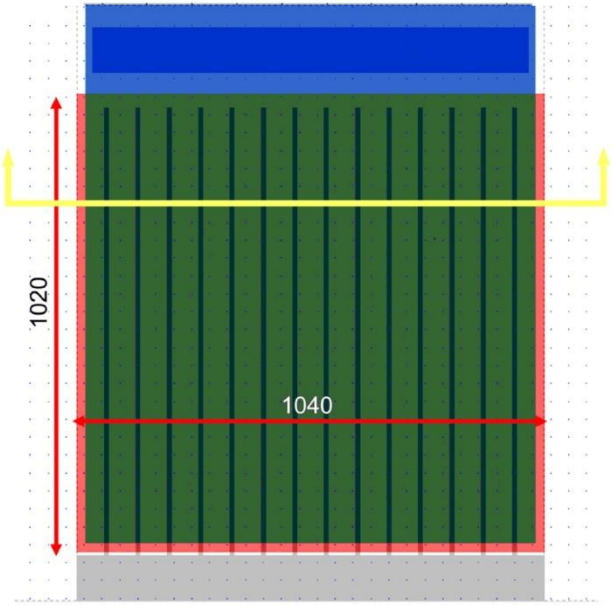
Use of nanocrystals: downshifter layer



The structure of the device



Cross-section



Top-view

Unit in μm

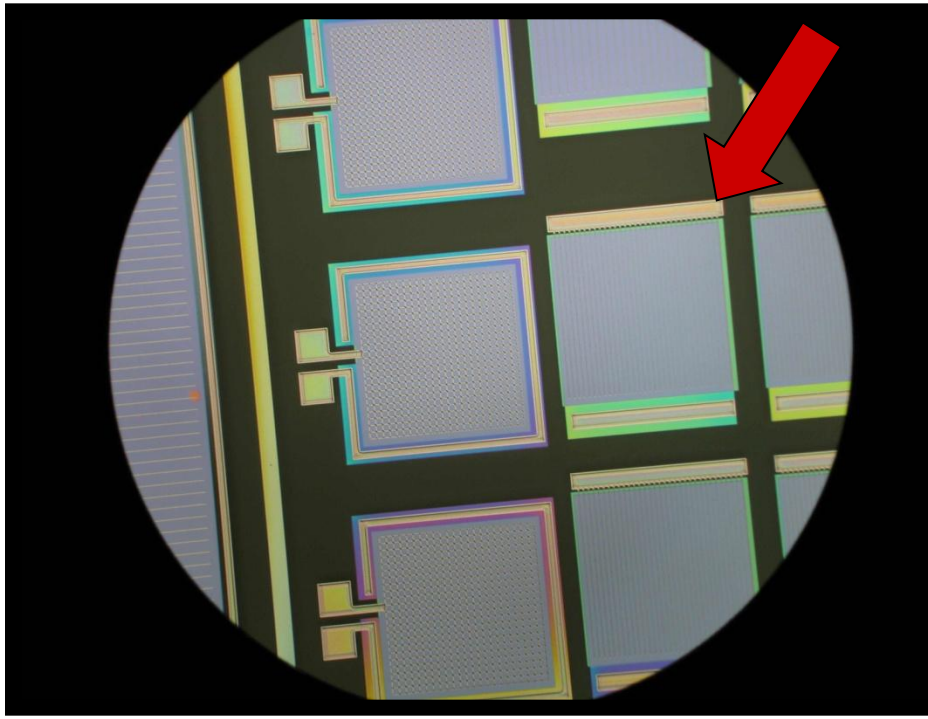
metal

n^+-poly Si

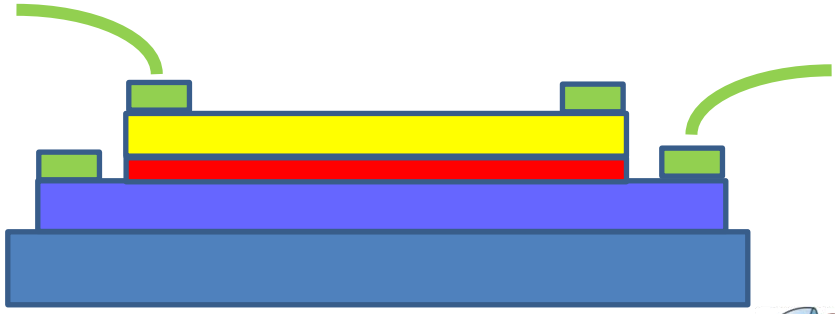
Active layer

p^+-poly Si

quartz



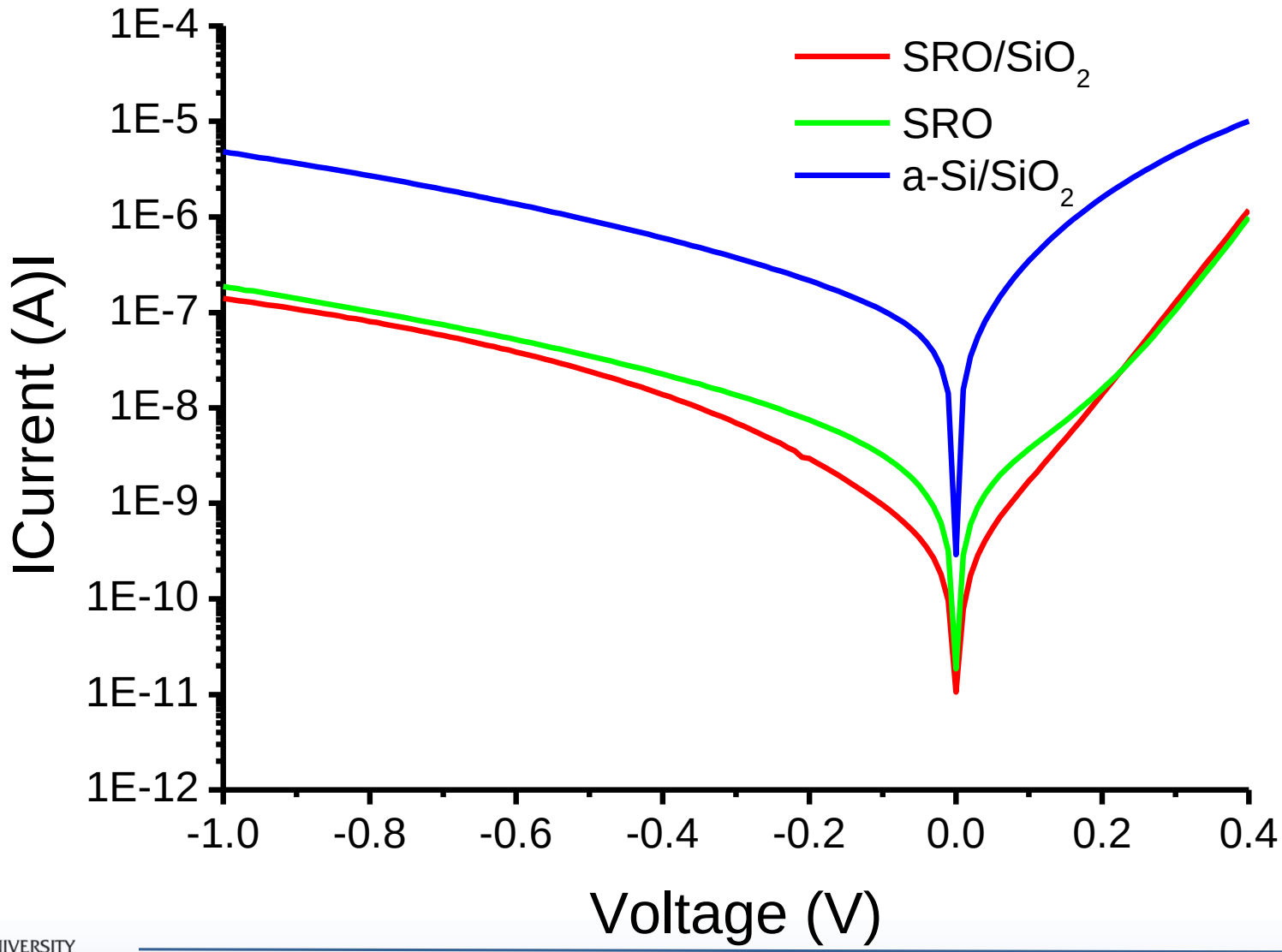
Red arrows indicate the active area



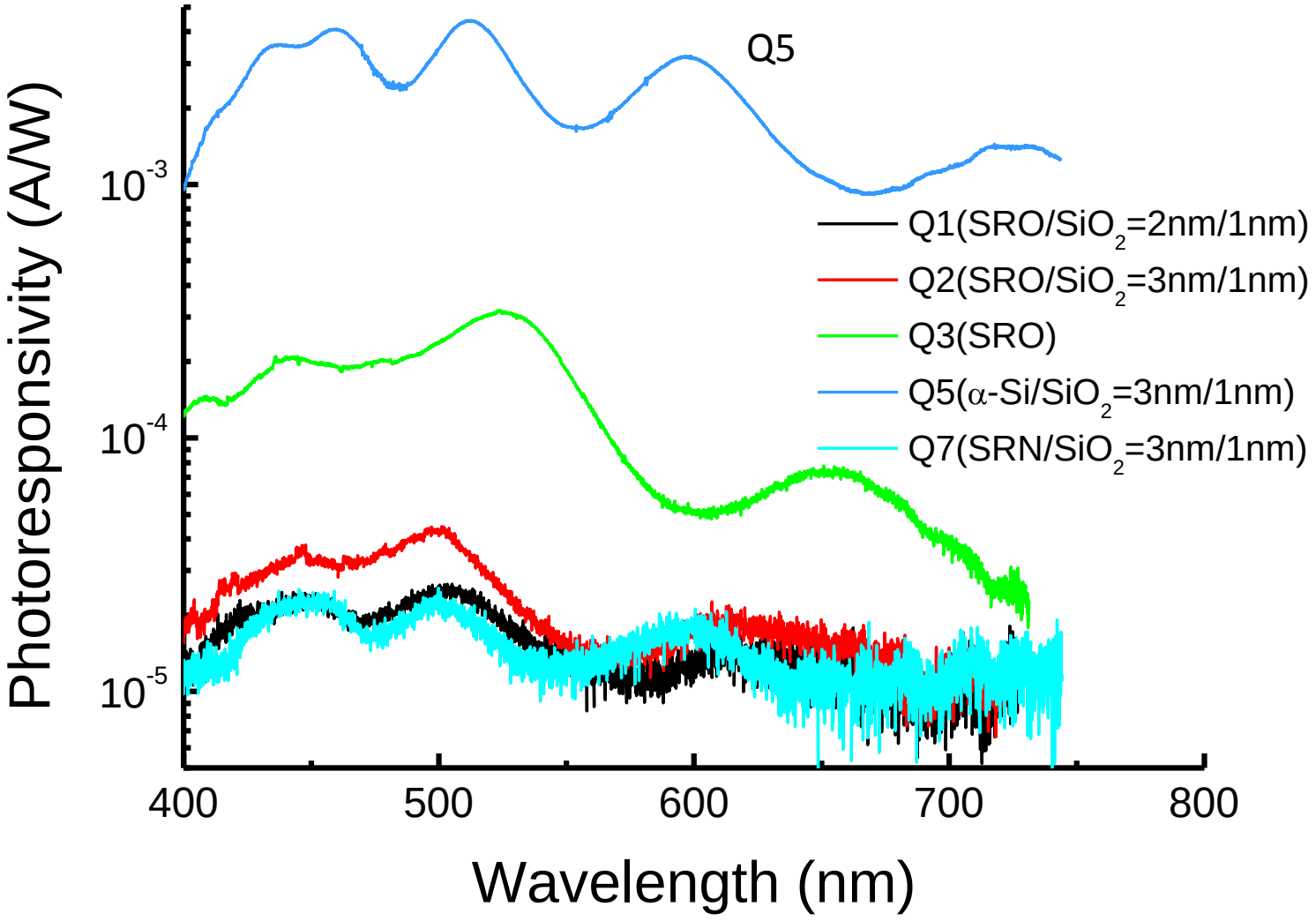
The structure of the device

No.	Active layer	Period of multi-layer	Layer thickness
Q1	SRO/SiO_2	5	2 nm +1 nm
Q2	SRO/SiO_2	5	3 nm + 1 nm
Q3	SRO		20 nm
Q5	α-Si/SiO_2	5	3 nm + 1 nm
Q7	SRN/SiO_2	5	3 nm + 1 nm
Q8	SRO/Si_3N_4	5	3 nm + 1 nm
Q9	SRN/Si_3N_4	5	3 nm + 1 nm

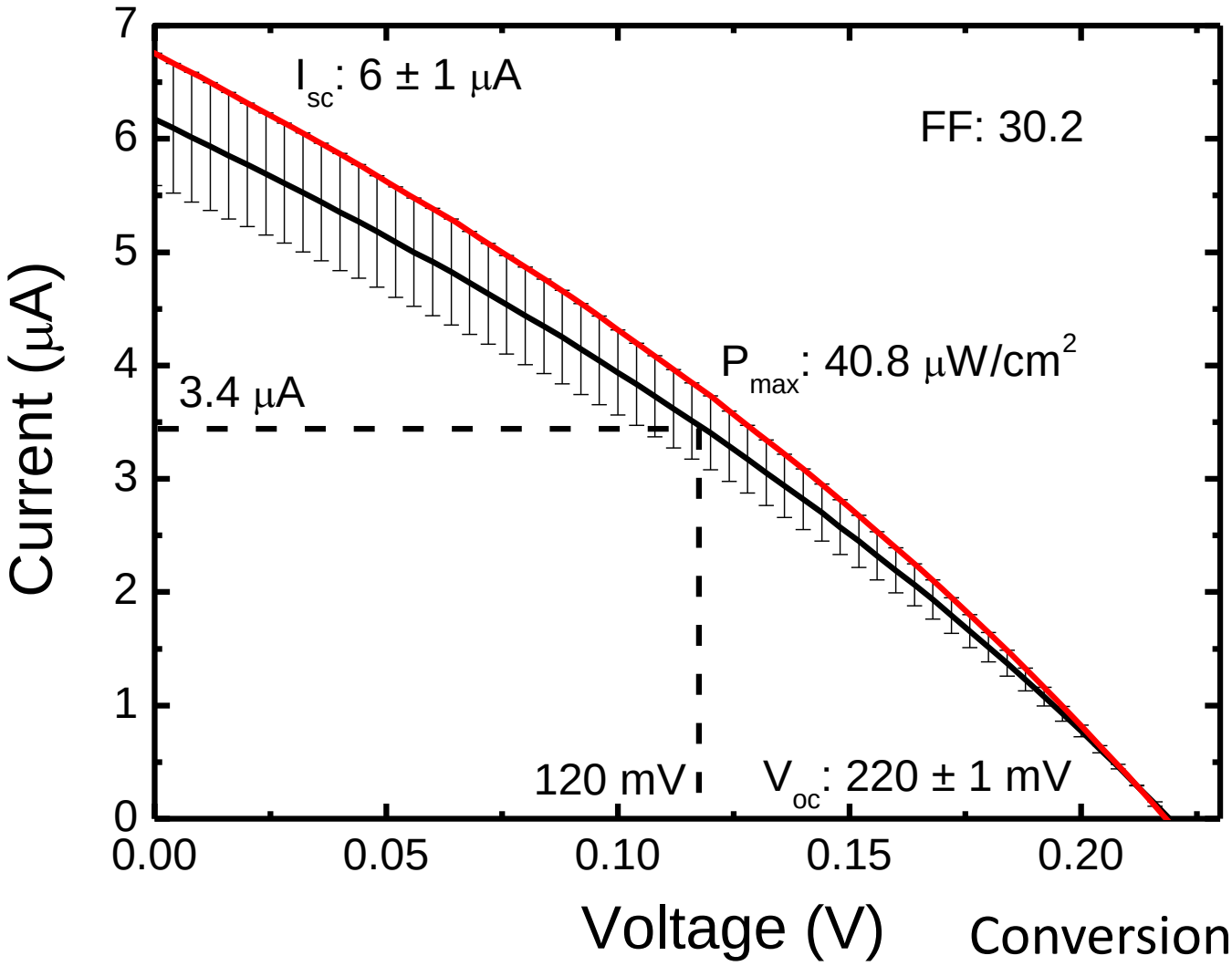
I-V curves measured in dark



Photoresponsivity



a-Si/SiO_2 shows the best PV effect



R_{serial} = 23.6 kΩ

R_{shunt} = 51.2 kΩ

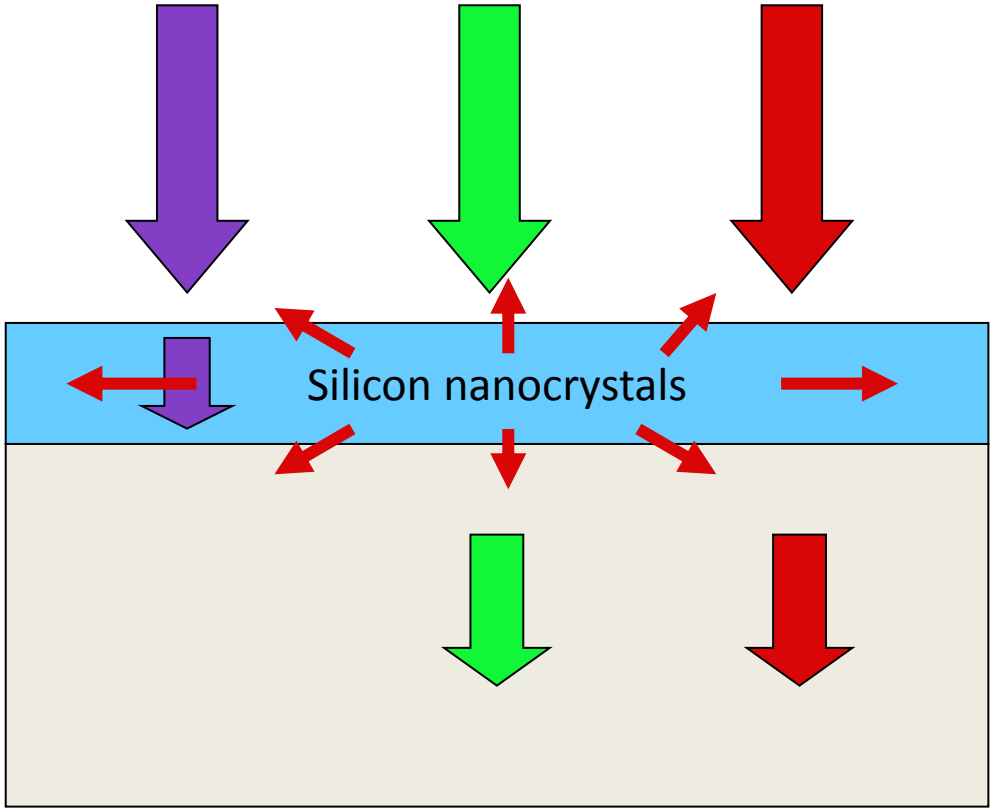
Lambert W function

R_{serial} = 6.41 kΩ

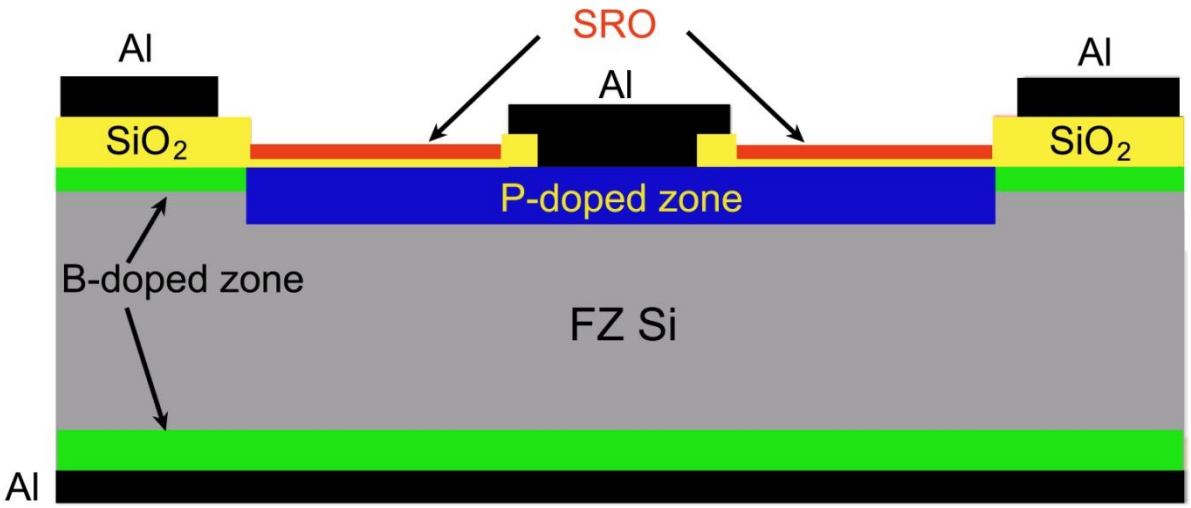
R_{shunt} = 54.1 kΩ

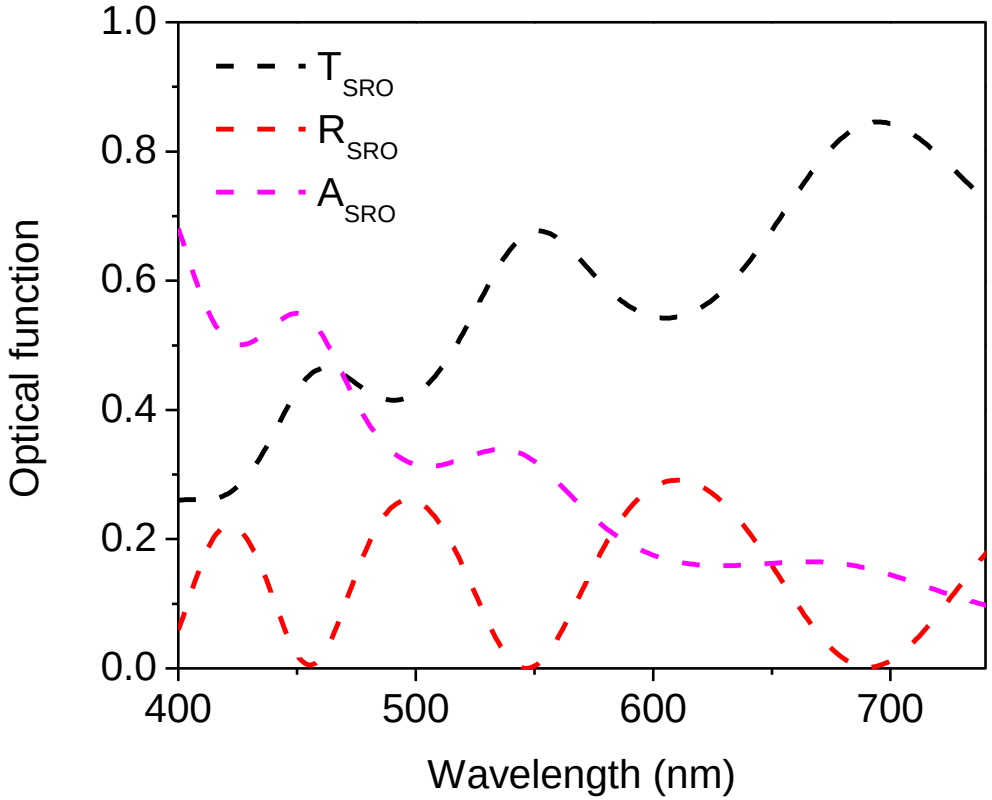
Conversion efficiency 0.41 %

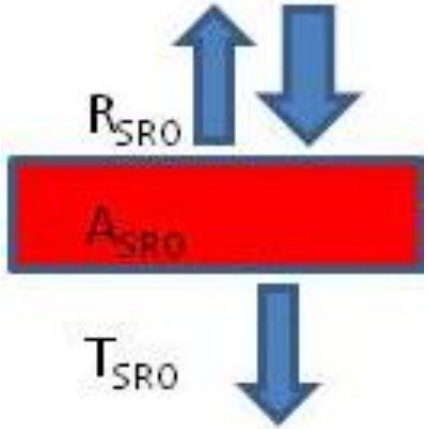
Si-nc as down-shifter layer

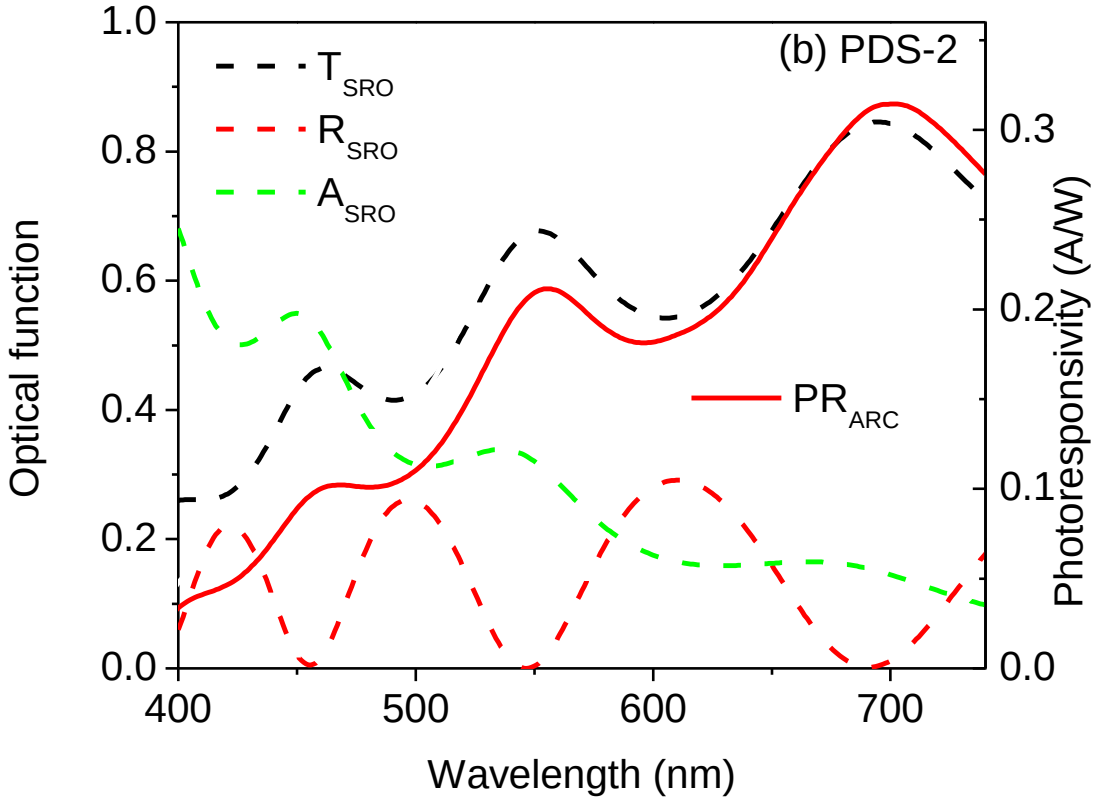


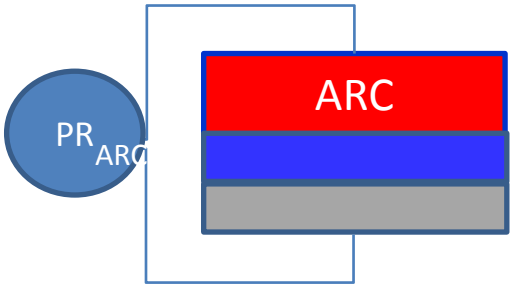
Si-nc as down-shifter layer



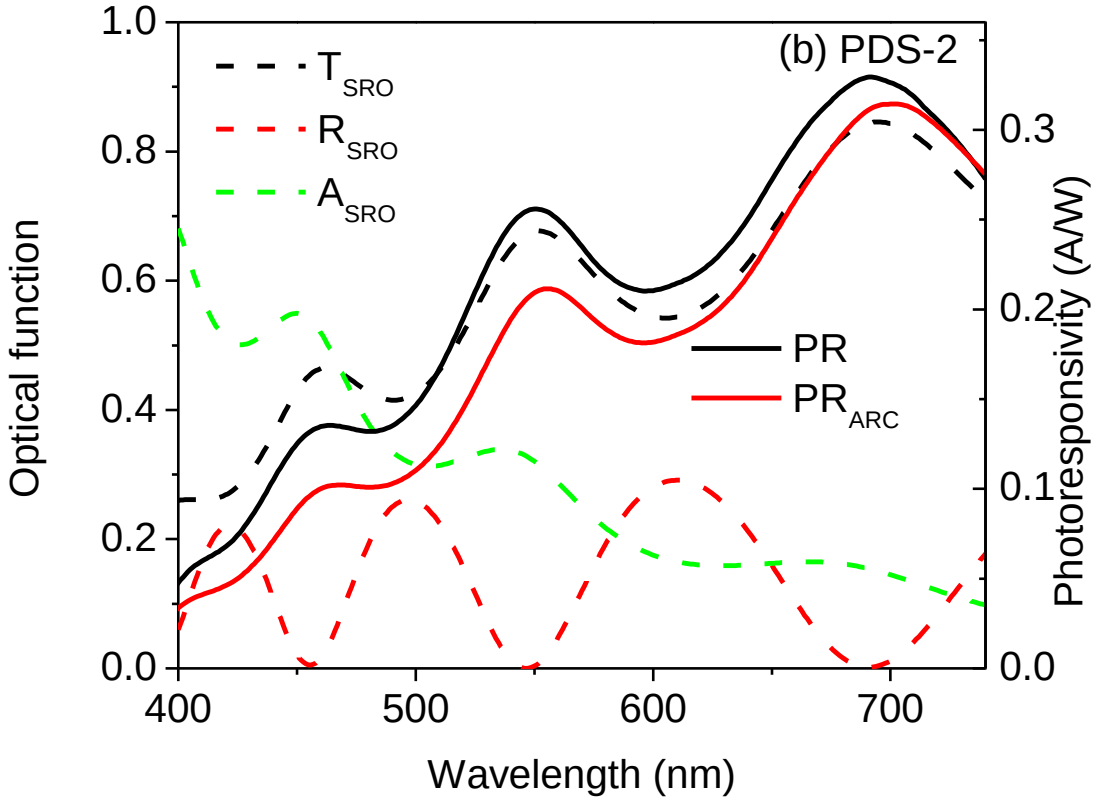

1.0
0.8
0.6
0.4
0.2
0.0
400
500
600
700
Optical function
Wavelength (nm)
T SRO
R SRO
A SRO

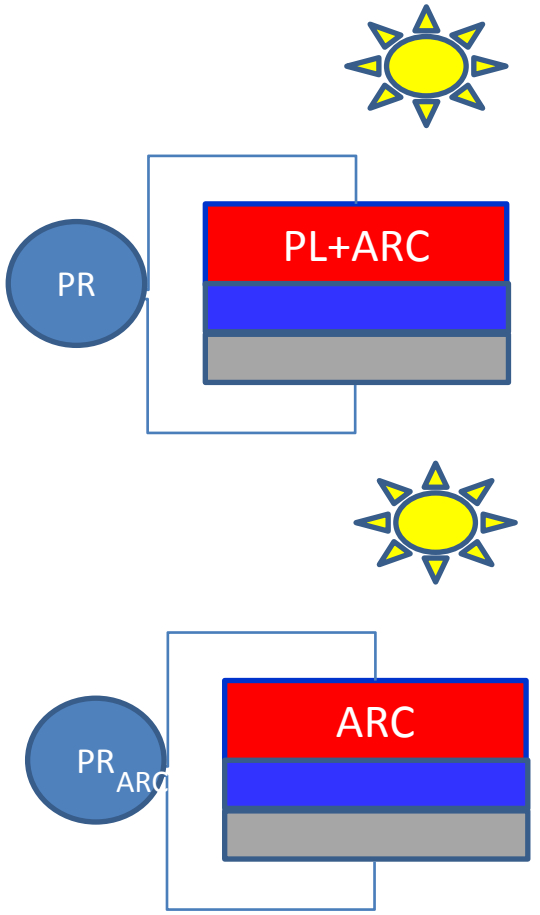

R SRO
A SRO
T SRO





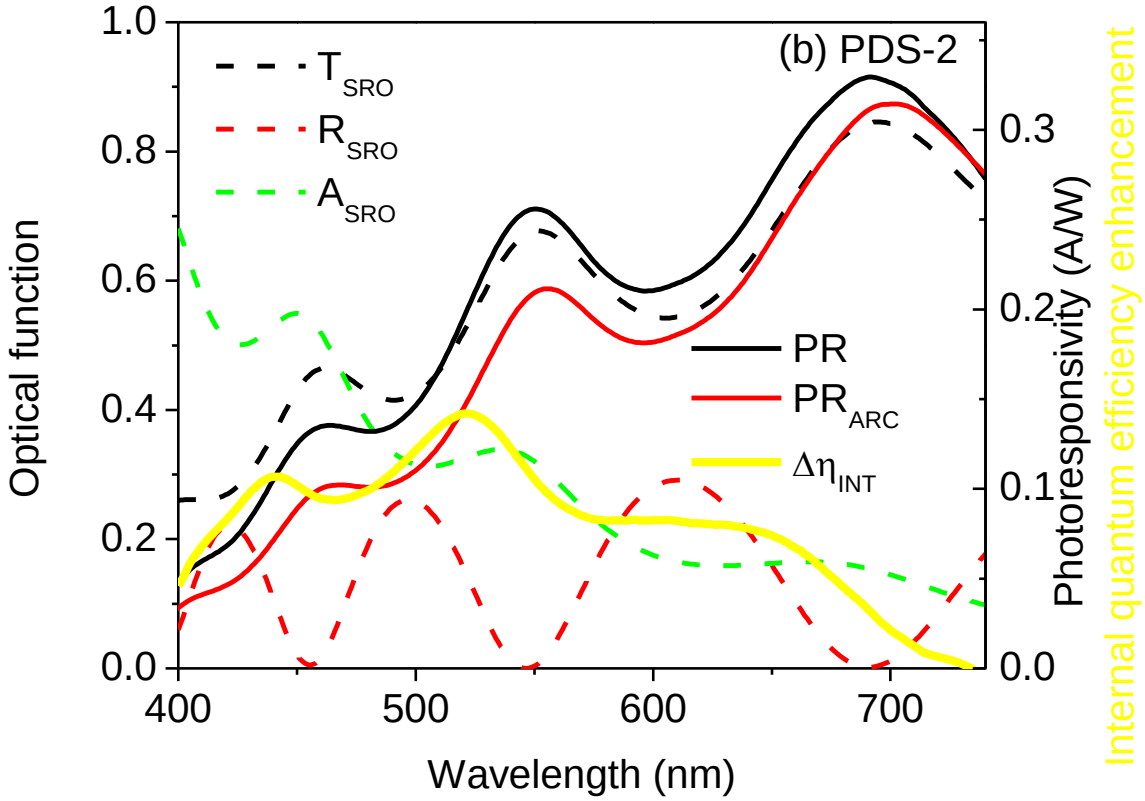
PR_{ARC} calculated photoresponsivity with a passive layer





PR measured photoresponsivity

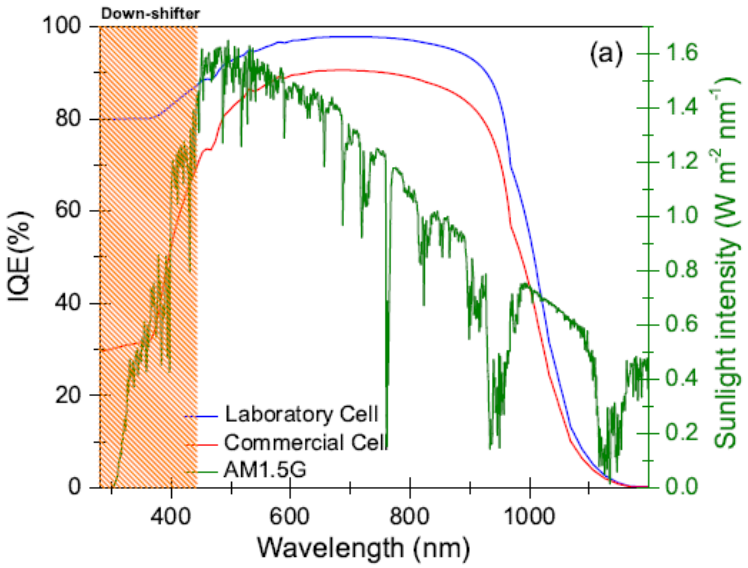
PR_{ARC} calculated photoresponsivity with a passive layer

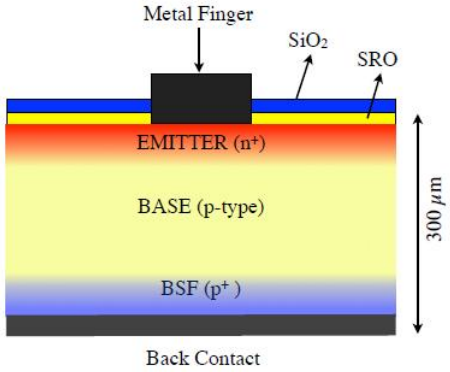


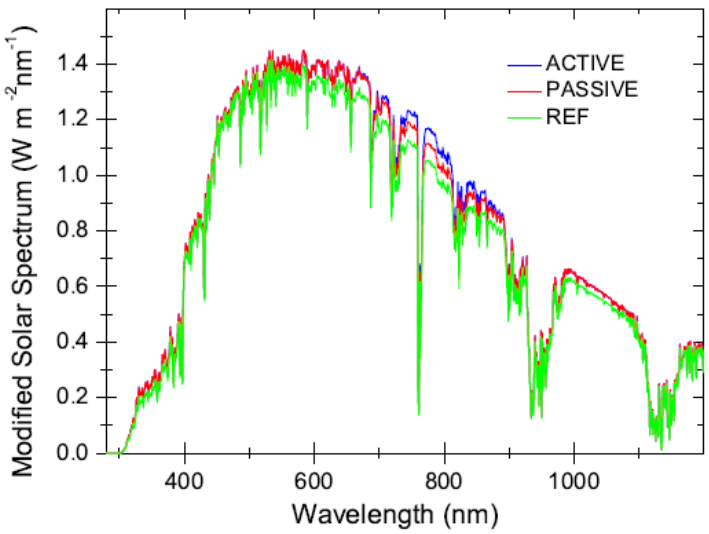
$$\Delta\eta_{INT}(\lambda) = \left(PR(\lambda) - PR_{ARC}(\lambda)\right)\frac{1.24}{\lambda}\frac{1}{\left(1-R_{SRO}\right)}, \text{ when } \lambda \text{ is in } \mu m$$

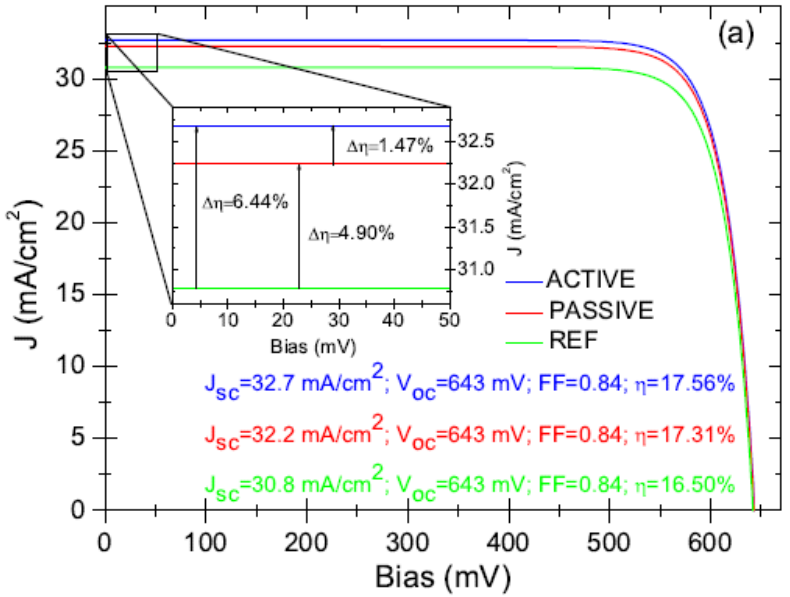
A maximum enhancement of the internal quantum efficiency of 14%

Modeling of Si-QD solar cells









Laboratory reference	Laboratory DS layer	Commercial Reference	Commercial DS layer
16.50 %	17.56 %	14.20 %	15.11 %

Silicon quantum dots

- Light emission
- Optical gain
- Nonlinear optical effects
- Photoresponse
- Biocompatibility
- Interface properties
- Sensitization action
- …

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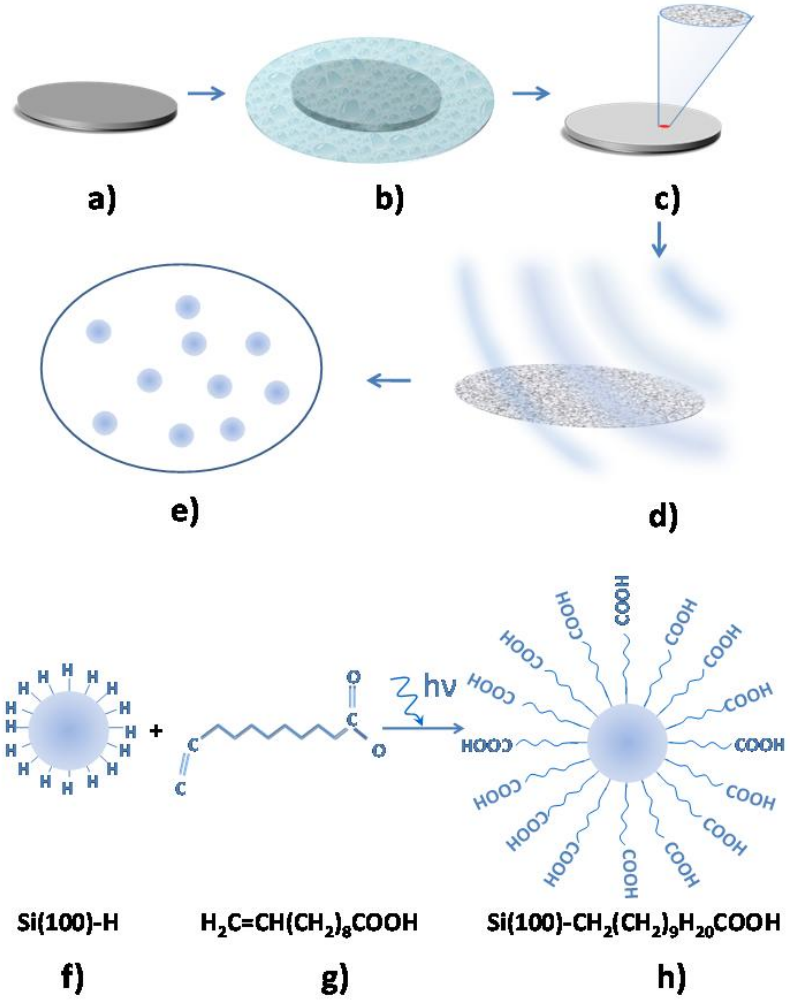
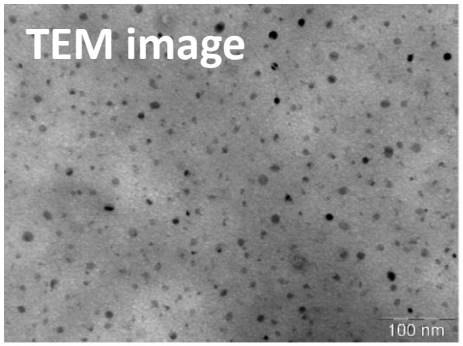
Si-nc as imaging agents

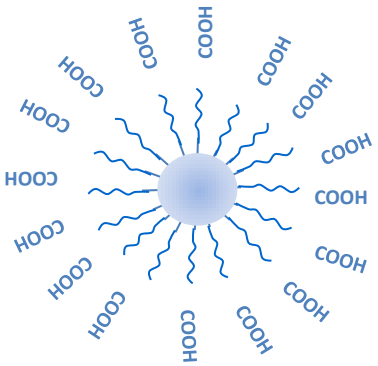


Preparation:

1. Sonication of porous silicon
2. Photoinduced hydrosilylation reaction between undecylenic acid and hydrogen passivated Si-nc surface

Si-nc as bioimaging agent



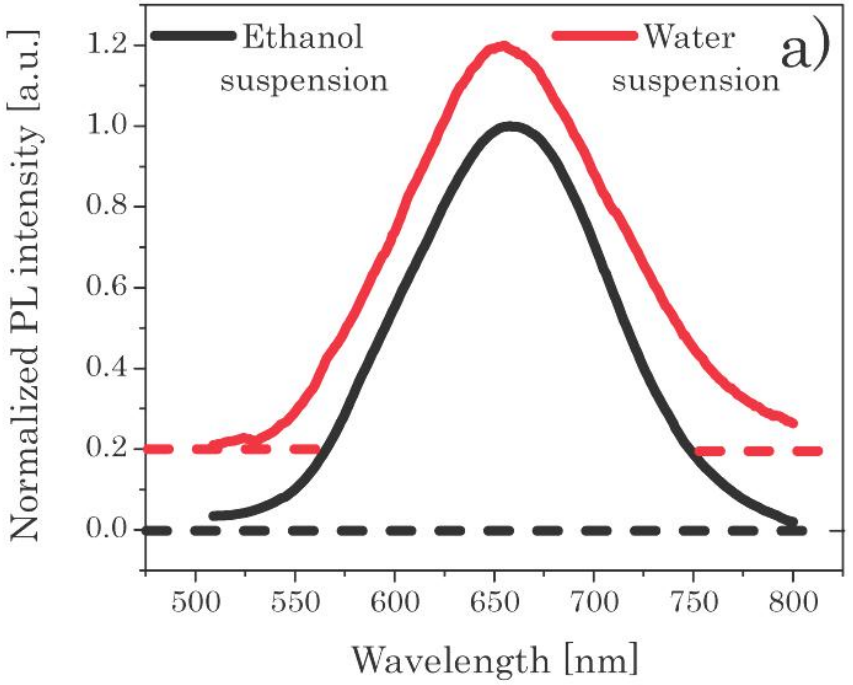


Hydrophilic alkyl-capped Si-nc

Luminescent clear suspension in different solvents (water, ethanol).

No change in PL lineshape in different solvents.

High quantum yield
QY ~ 30 %



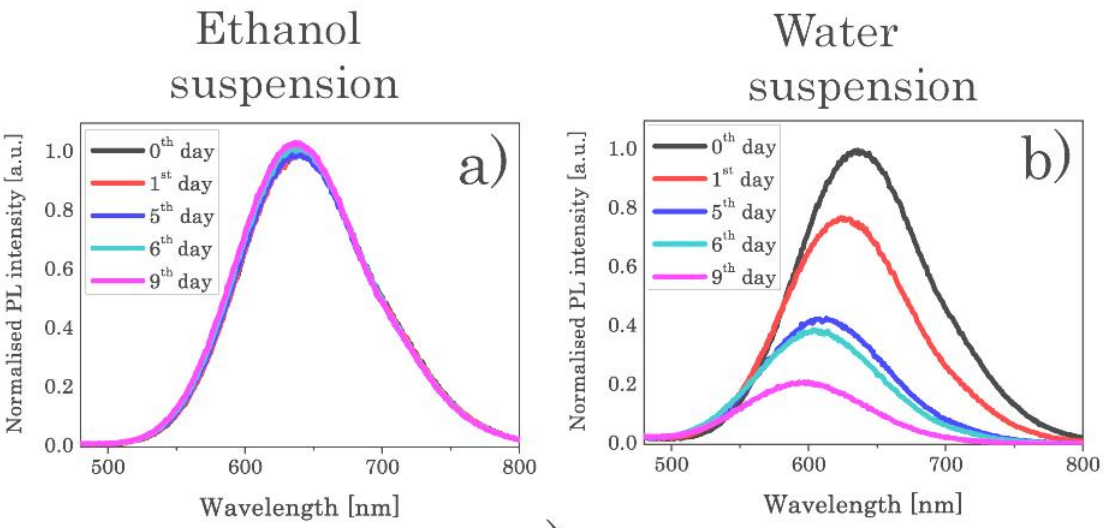
Si-nc as bioimaging agent

Si-nc-COOH without physical coating:

1. **Si-nc-COOH can be stored in ethanol for long periods of time.**

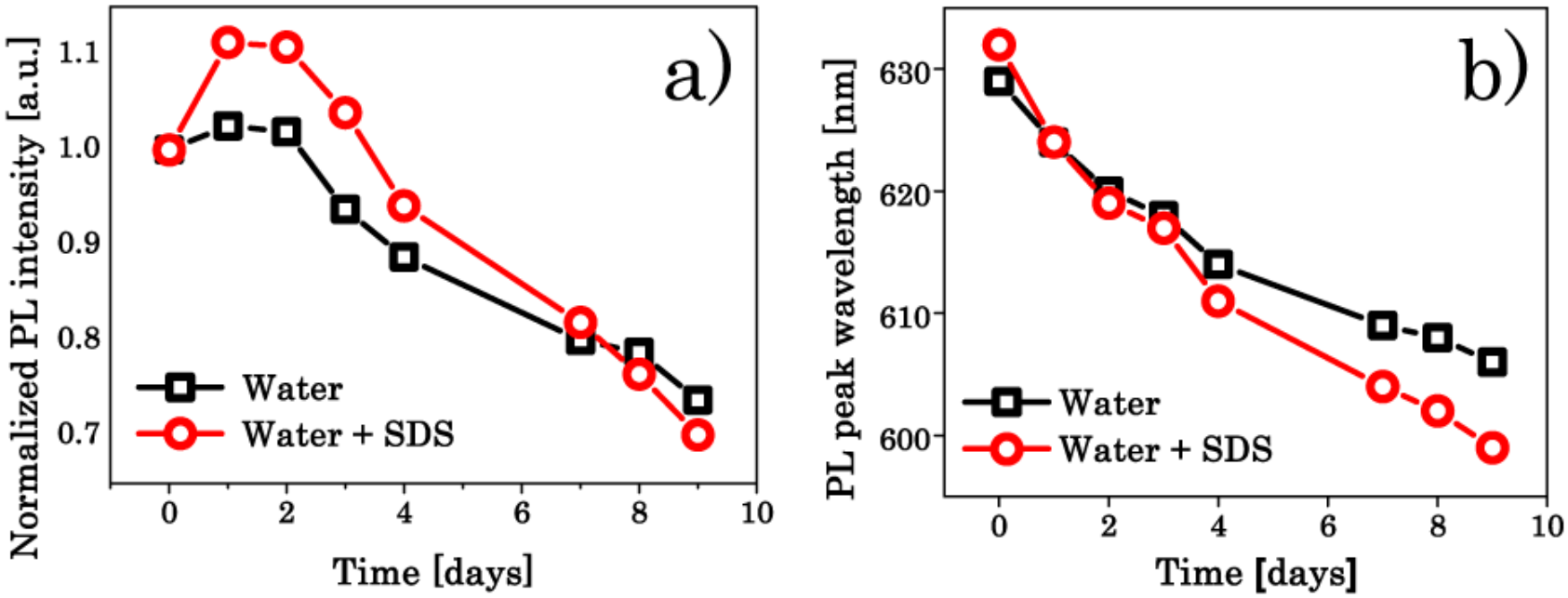
2. **In water Si-nc-COOH slowly oxidized and dissolve.**

Biodegradability is achieved.



Si-nc as bioimaging agent

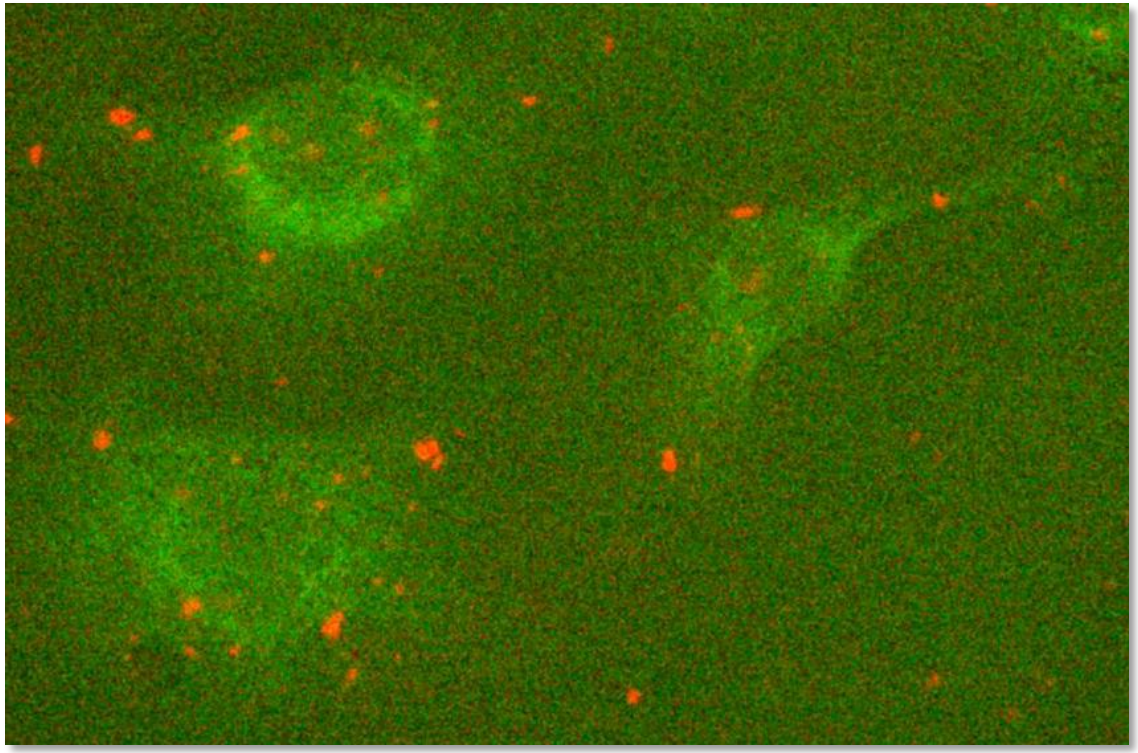
Si-nc-COOH with physical coating:



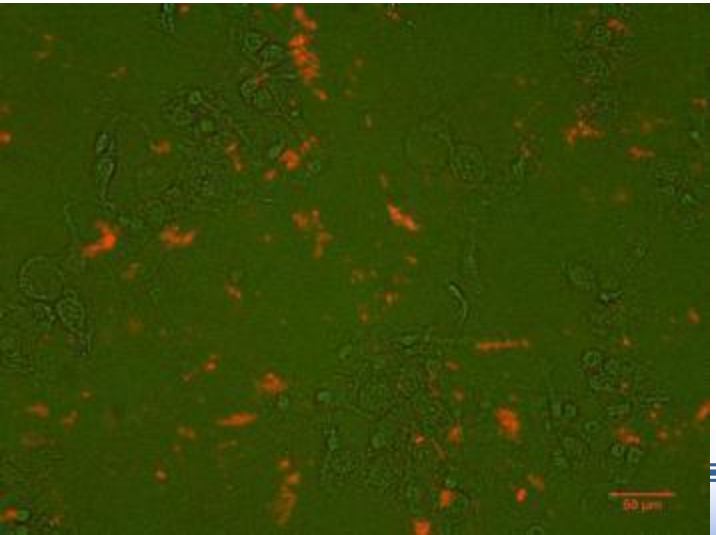
Biodegradability is mantained.

Bio imaging

- **DCA** (sodium deoxycholate monohydrate) shows similiar behaviour as **SDS**
- **DCA** less toxic than **SDS**



Fluorescence images of SKOV-3 cells incubated with Si-nc-COOH+DCA for 30 min.



DCA was not added

Silicon quantum dots

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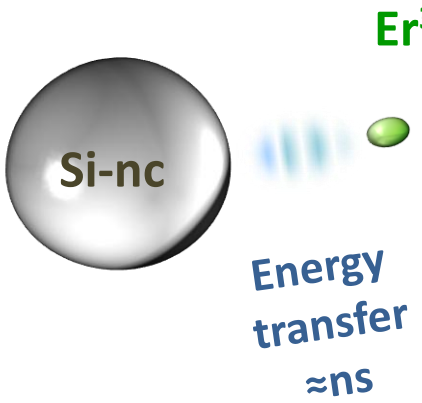
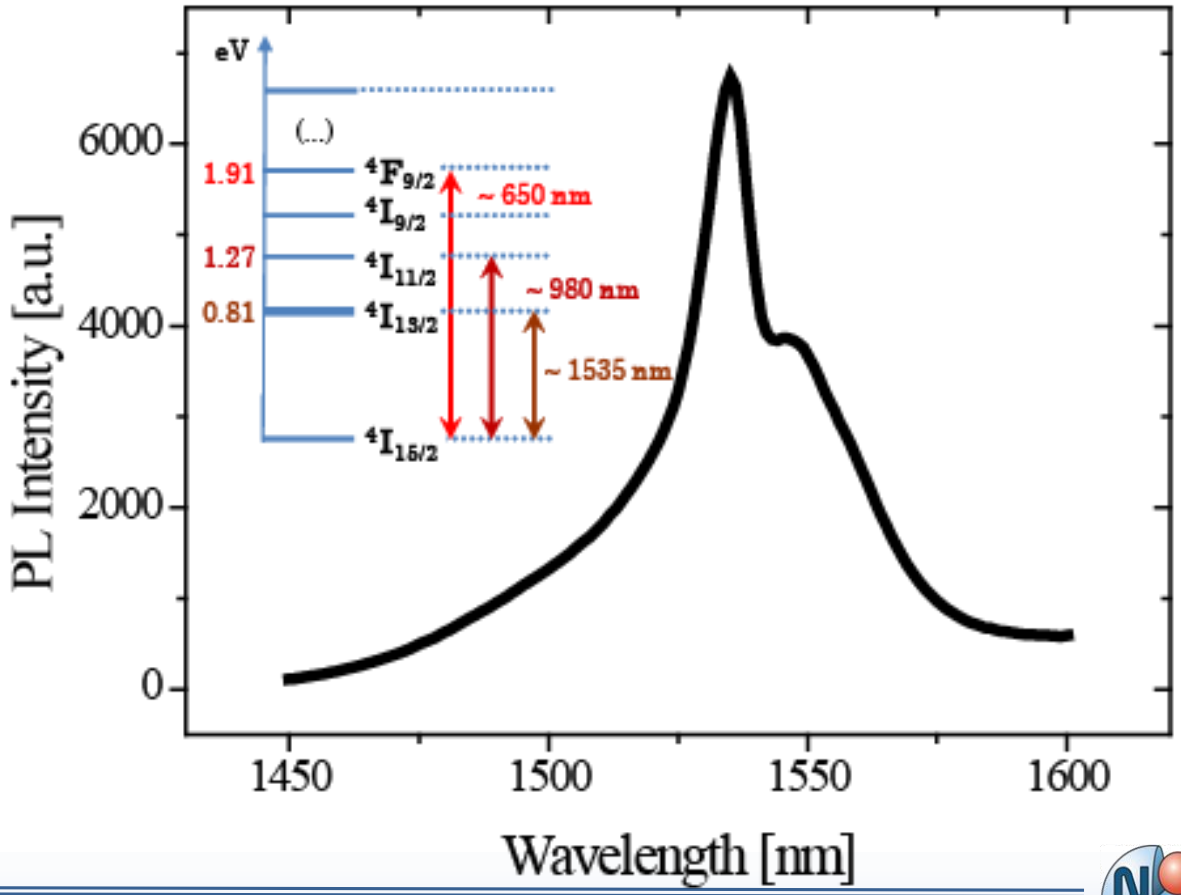
Si-nc as Er^{3+} sensitizer

Sensitization:

Si-nc upon excitation (optical or electrical) transfers its energy to nearby Er^{3+} ions.

$^4I_{13/2}$ - $^4I_{15/2}$ Er^{3+} radiative transitions falls in the third telecom window (maximum transparency of silica fibers).

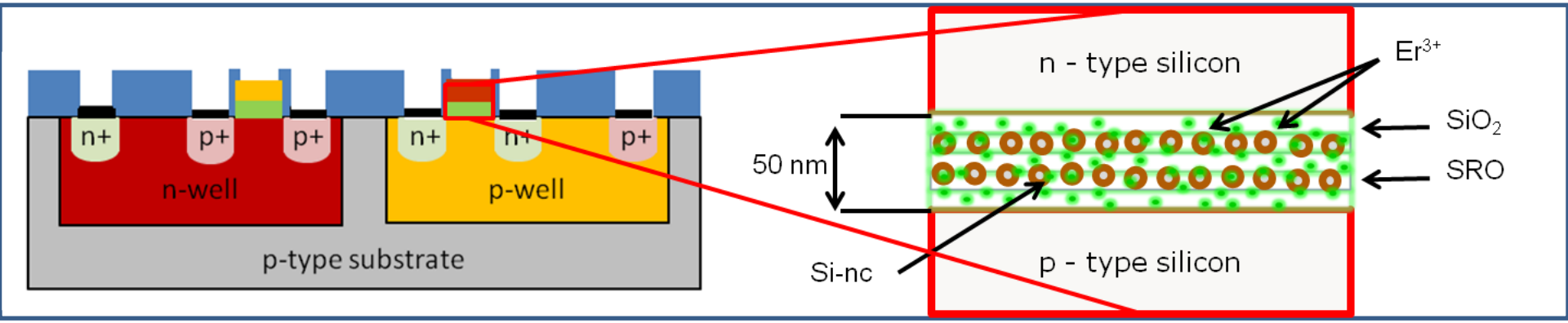




- **Increase in effective excitation cross-section for up to 5 orders of magnitudes ($\approx 10^{-21} \rightarrow \approx 10^{-16}$ cm^2)**
- **Broadband excitation**

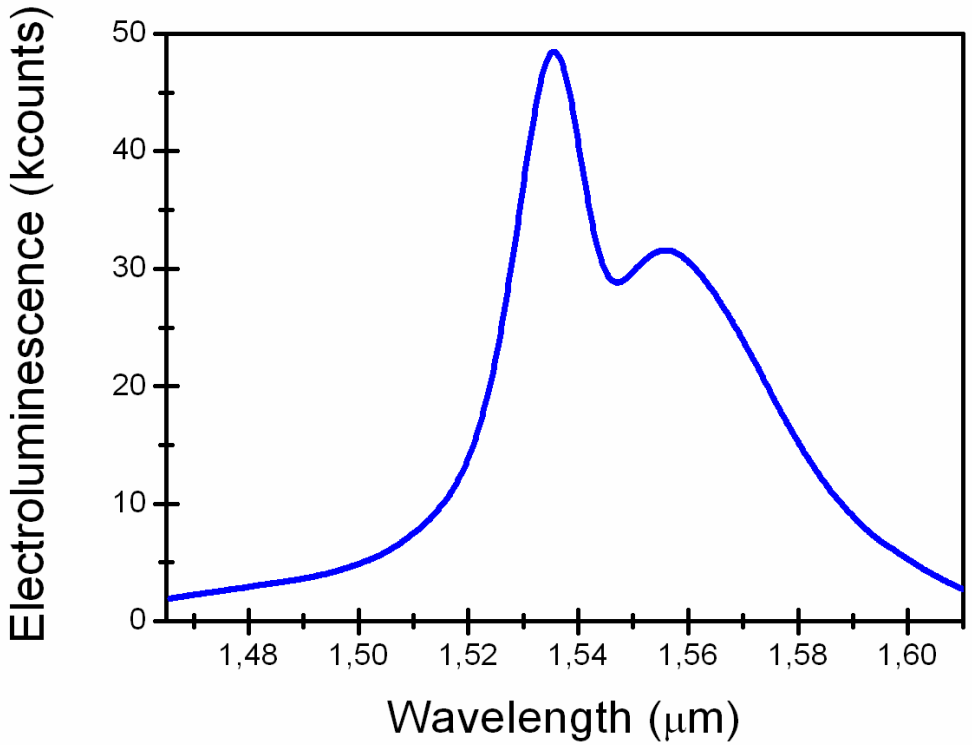
Si-NCs:Er LEDs

- SiO_x: LPCVD ~ 50 nm, Si excess: 9-16 at. %;
- SiO_x anneal: 900°C, 1 h;
- Er implantation: 20 keV, $1x10^{15}/cm^2$;
- Er post-implantation anneal: 800°C, 6 h



Si-NCs:Er LEDs - Results

External Quantum Efficiency 0.55 % in DC



Si-NCs:Er LEDs - Results

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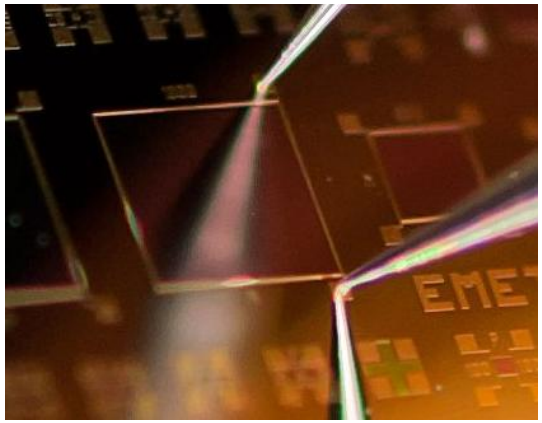

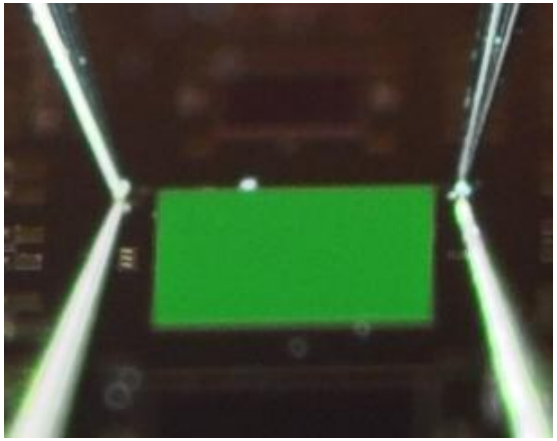

Conclusions

- Silicon nanocrystals are a viable platform to improve-enable-widen the scope of silicon photonics

- A lot of new physics can be found in an already mature research field such as Silicon Photonics

Bulk silicon crystals constitute the main material of today's microelectronic, photovoltaic and MEMS technologies. The reduction of size and dimensionality towards silicon nanocrystals unveils completely new physical and chemical properties that lead to exciting new applications as the already realized nanocrystal-based transistor or non-volatile memory devices. While being an innovative approach, the silicon nanocrystal technology can be integrated seamlessly in existing ones. The book introduces the reader to the unique optical, electrical and thermal properties of silicon nanocrystals that arise from their greatly reduced dimensions. It covers their synthesis and characterization from both chemical and physical viewpoints, including ion implantation, colloidal synthesis and vapor deposition methods. Another major part is devoted to applications in microelectronics as well as photonics and nanobiotechnology. This book is an invaluable addition to the bookshelves of Materials Scientists, Chemists, Physicists, Solid State Chemists, Semiconductor Physicists, Libraries, Institutions, and Institutes.

Lorenzo Pavesi is Professor of Experimental Physics and Head of the Nanoscience Laboratory at the University of Trento, Italy. He received his Ph.D. in physics in 1990 from the Ecole Polytechnique Federale de Lausanne, Switzerland. In Trento he founded the research activity in semiconductor optoelectronics and established fabrication for photonics growth and advanced treatment of materials. Lorenzo Pavesi concentrates his research activity on silicon-based photonics, aiming at the integration of photonics and electronics by using silicon nanostructures. He holds six patents, is author or co-author of more than 150 papers, several reviews and two books as well as editor of more than ten books.

Rasit Turan is Professor in the Department of Physics of the Middle East Technical University (METU) in Ankara, Turkey, where he heads the Semiconductor Materials and Devices group. He obtained his Ph.D. in 1990 from the University of Oslo, Norway, and worked as post-doc and visiting scientist at Linköping University, Sweden, and Toronto University, Canada. His work on fabrication, characterization and applications of nanostructured semiconductors, in particular Si nanocrystals, in addition to his research, Rasit Turan serves as the coordinator of the nanotechnology and nanobiotechnology initiatives at METU.

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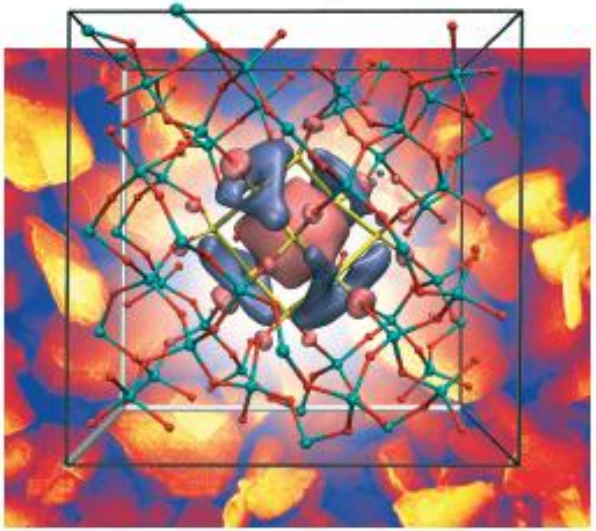
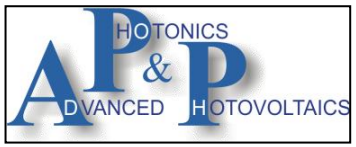
Silicon Nanocrystals

Fundamentals, Synthesis and Applications



Acknowledgments



Acknowledgments