The Abdus Salam
International Centre
for Theoretical Physics
50th Anniversary 1964–2014

2572-13

Winter College on Optics: Fundamentals of Photonics - Theory, Devices and Applications

10 - 21 February 2014

Silicon Photonics

Lorenzo Pavesi
University of Trento
ITALY

Silicon Photonics

Lorenzo Pavesi

University of Trento

The University of Trento

About the University

- **middle-sized**, **comprehensive** University, located in the North-East of Italy
- **research oriented** and very active in enhancing **internationalization**
- structured in **10 Departments** and **3 Centres**
- Partner Node of **European Institute of Innovation** in ICT (EIT ICT Labs)
- involved in **20 Erasmus Mundus action 2 projects** (3 as coordinator)

National and International Rankings

The University of Trento (UNITN):

- confirms its position at the **top places** in national independent **CENSIS** Survey (**1st place for internationalization**)

- ranks **1st** in Italy among the middle-sized universities (**ANVUR - Quality of Research**)

- is the **1st** Italian university in the ranking **THE – TIMES Higher Education Rankings** 2013/2014, drawn up by Thomson Reuters for Times

- ranks among the best Italian universities in the world, according to the **QS World University Rankings** 2013/14

The University of Trento: a Few Data

People

573	Professors and Researchers
668	Technical and Administrative Staff
16.062	Total enrolled Students
1.686	Foreign enrolled students (EU/non EU) in 2012/13

and

Structures

10	Departments
3	Centres
61	Research Laboratories
2	Center of Excellence
1	Language Center
5	Main Libraries

UNITN Organization: 10 Departments

Department of Sociology and Social Research

Department of Physics

Department of Mathematics

Department of Economics and Management

Department of Information Engineering and Computer Science
(some courses in English at the undergraduate level)

Faculty of Law

Department of Humanities

Department of Civil, Environmental and Mechanical Engineering

Department of Industrial Engineering

Department of Psychology and Cognitive Science

Silicon Photonics

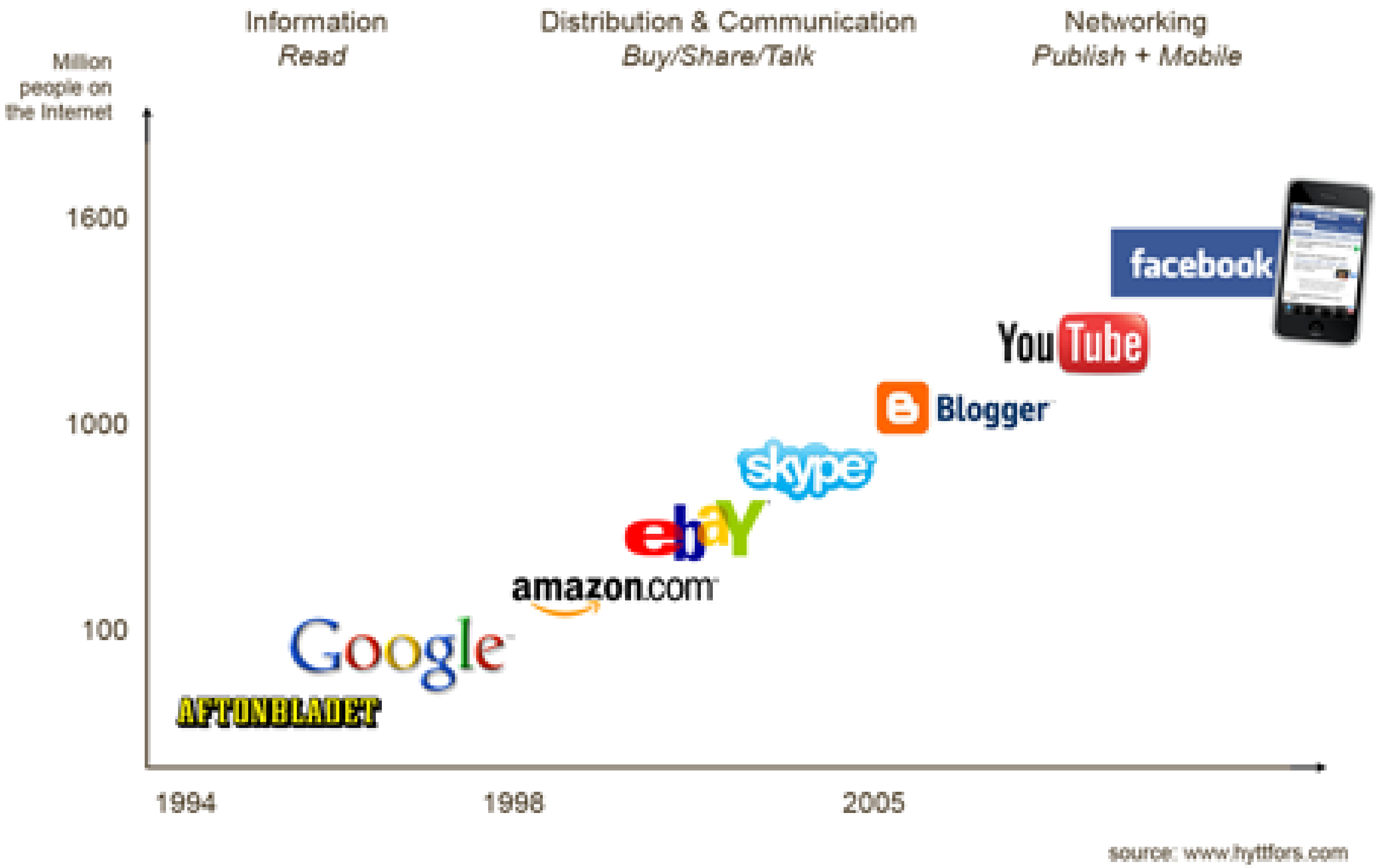
Lorenzo Pavesi

University of Trento

outline

- Silicon photonics
- The source problem
  - Back to basics
  - All silicon
  - Other approaches
- Conclusions

Evolution of Internet



source: www.hyttfors.com

What are the main problems associated to the internet growth?

Modern Data Center

- 100 MW power
- Million of servers
- Tens of thousands of fibers

From Donn Lee (Facebook)

Inside Facebook's green and clean arctic data centre

By Mark Gregory
BBC News, Lulea, Sweden

Checking in: If you are on Facebook anywhere in Europe today then that action probably went through the Lulea green data centre in Sweden

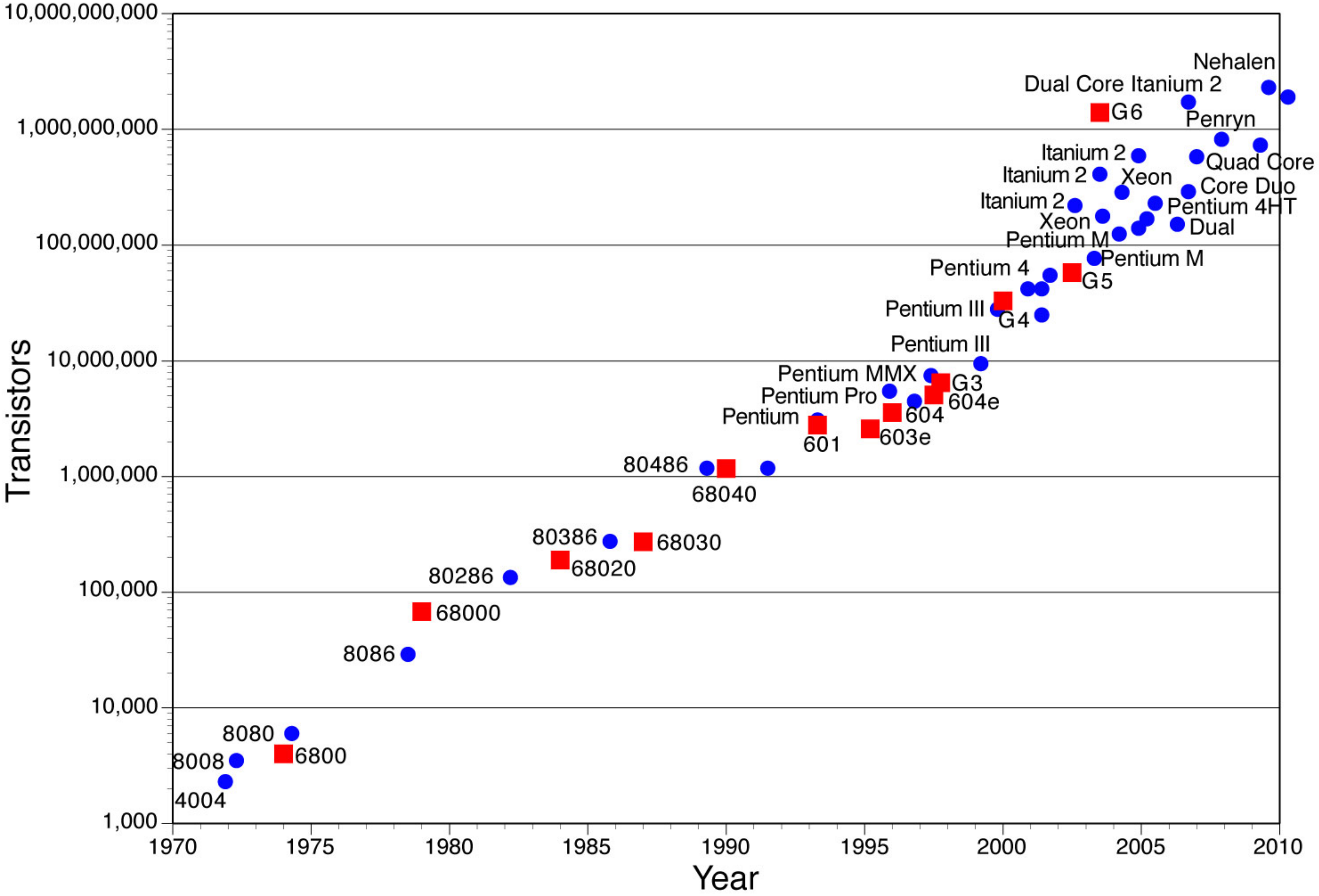
You've probably never thought about the electricity consumed by

The real truth of semiconductor industry

Smaller Cheaper Faster

by large scale integration

Moore’s law


Nehalen
Dual Core Itanium 2
G6
Penryn
Itanium 2
Itanium 2
Xeon
Quad Core
Core Duo
Itanium 2
Pentium 4HT
Xeon
Dual
Pentium M
Pentium M
Pentium 4
G5
Pentium III
G4
Pentium III
Pentium MMX
G3
Pentium Pro
604e
Pentium
604
601
603e
80486
68040
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68030
68020
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6800
4004
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1,000,000,000
100,000,000
10,000,000
1,000,000
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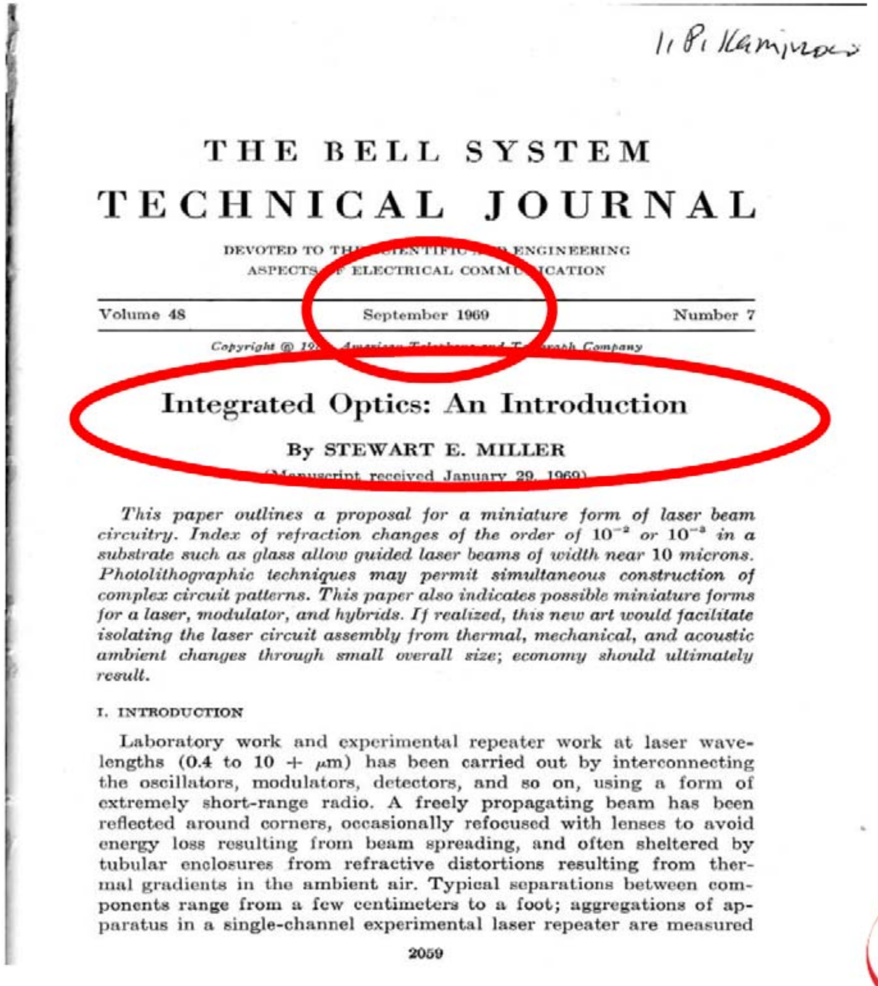
10,000
1,000
Transistors
1970
1975
1980
1985
1990
1995
2000
2005
2010
Year

Birth of the PIC Concept

"There is a conviction that the new miniaturized optical circuitry will prove useful… We must wait a while longer to find out how useful this new technology will become."



I. P. Kaminow

THE BELL SYSTEM
TECHNICAL JOURNAL

DEVOTED TO THE SCIENTIFIC AND ENGINEERING
ASPECTS OF ELECTRICAL COMMUNICATION

Volume 48	September 1969	Number 7

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Integrated Optics: An Introduction

By STEWART E. MILLER

(Manuscript received January 29, 1969)

This paper outlines a proposal for a miniature form of laser beam circuitry. Index of refraction changes of the order of 10^{-2} or 10^{-3} in a substrate such as glass allow guided laser beams of width near 10 microns. Photolithographic techniques may permit simultaneous construction of complex circuit patterns. This paper also indicates possible miniature forms for a laser, modulator, and hybrids. If realized, this new art would facilitate isolating the laser circuit assembly from thermal, mechanical, and acoustic ambient changes through small overall size; economy should ultimately result.

I. INTRODUCTION

Laboratory work and experimental repeater work at laser wavelengths (0.4 to 10 + μm) has been carried out by interconnecting the oscillators, modulators, detectors, and so on, using a form of extremely short-range radio. A freely propagating beam has been reflected around corners, occasionally refocused with lenses to avoid energy loss resulting from beam spreading, and often sheltered by tubular enclosures from refractive distortions resulting from thermal gradients in the ambient air. Typical separations between components range from a few centimeters to a foot; aggregations of apparatus in a single-channel experimental laser repeater are measured

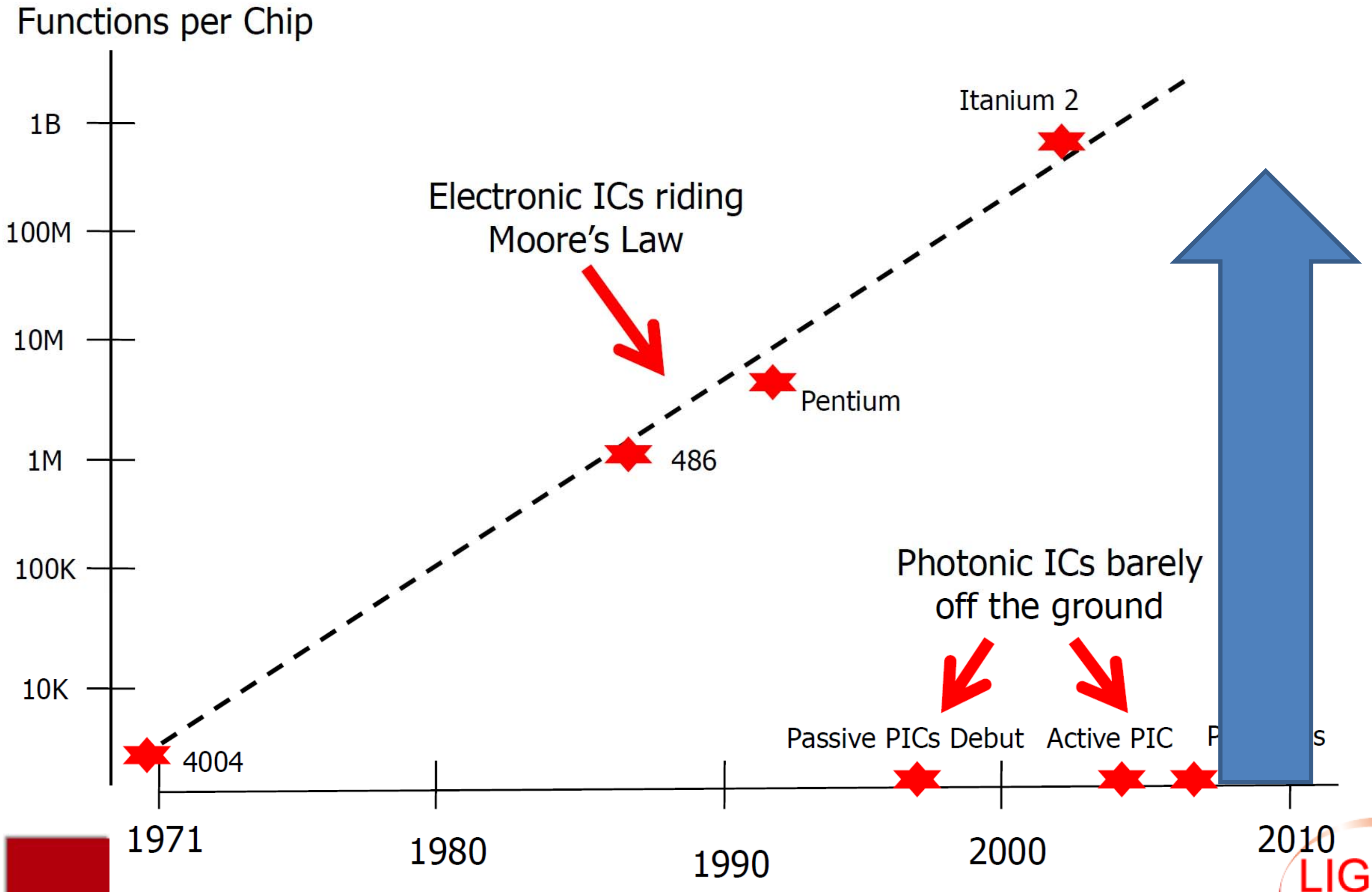
2059

HEAVY READING

LIGHT READING

29 January 1969

Comparing Technology Progress



Electronic ICs riding Moore's Law

Photonic ICs barely off the ground

Sources: Intel and Heavy Reading, 2008

HEAVY READING

LIGHT READING

Why?

Technology Comparison: Optics vs. ICs

Technologies	Semiconductor IC	Optical Components
Repeatable building block	Transistors	
Uniform material base	Silicon	
Dominant manufacturing process	CMOS	

Source: J. P. Morgan

No standardized technology for optical components manufacturing

Technology Comparison: Optics vs. ICs

Technologies	Semiconductor IC	Optical Components
Repeatable building block	Transistors	None (LD, PD, Mod, Filter, Isolator…)
Uniform material base	Silicon	None (InP, GaAs, Si…)
Dominant manufacturing process	CMOS	None (Hybrid, monolithic, active, passive…)

Source: J. P. Morgan

No standardized technology for optical components manufacturing

Complexity in today PIC

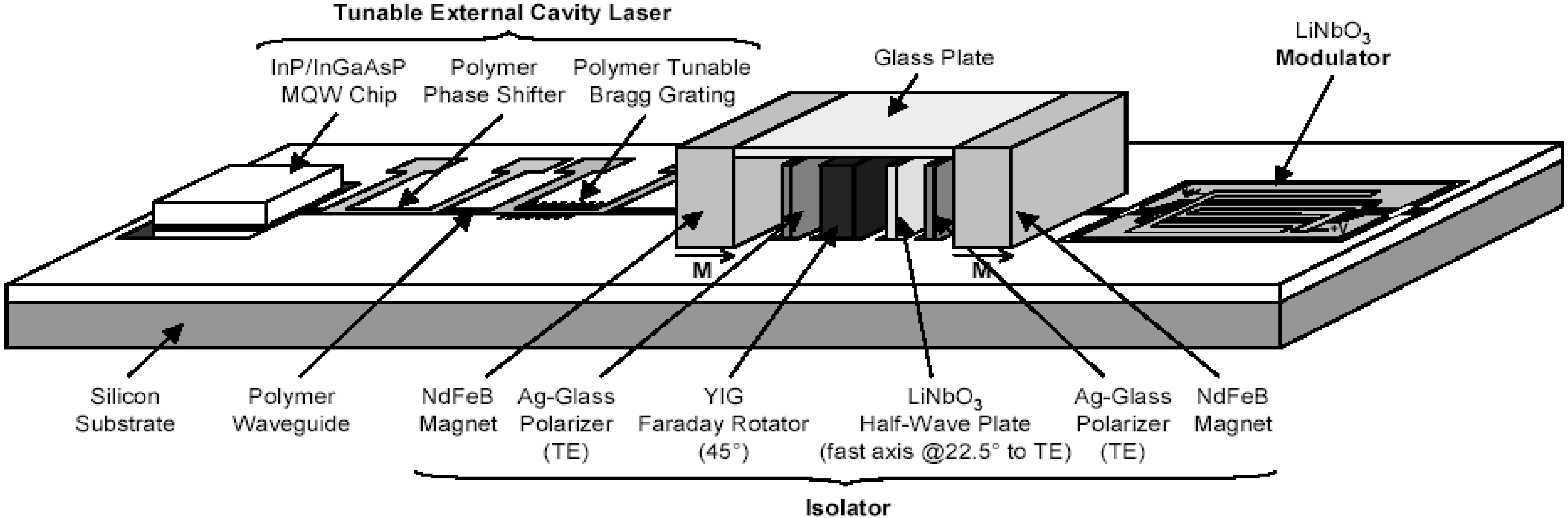


Figure 1. Tunable optical transmitter integrated in a polymer optical bench platform.

Technology Comparison: Optics vs. ICs vs. Silicon Photonics

Technologies	Optical Components	Semiconductor IC	Silicon Photonics
Repeatable building block	None (LD, PD, Mod, Filter, Isolator…)	Transistors	LD,PD, microrings, ….
Uniform material base	None (InP, GaAs, Si…)	Silicon	Silicon
Dominant manufacturing process	None (Hybrid, monolithic, active, passive…)	CMOS	CMOS

Source: J. P. Morgan

Silicon photonics is the standardization of photonics

Silicon photonics

Photonic devices produced within standard silicon factory and with standard silicon processing

Silicon pro’s and cons

Silicon pro’s and cons

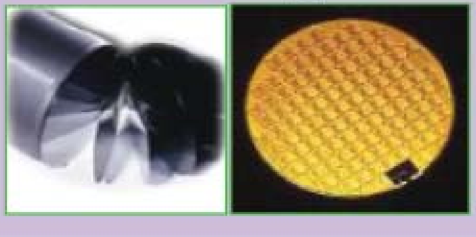
- **Transparent on 1.3-1.5 μm**
- CMOS compatibility
- Low cost
- High index contrast, small footprint

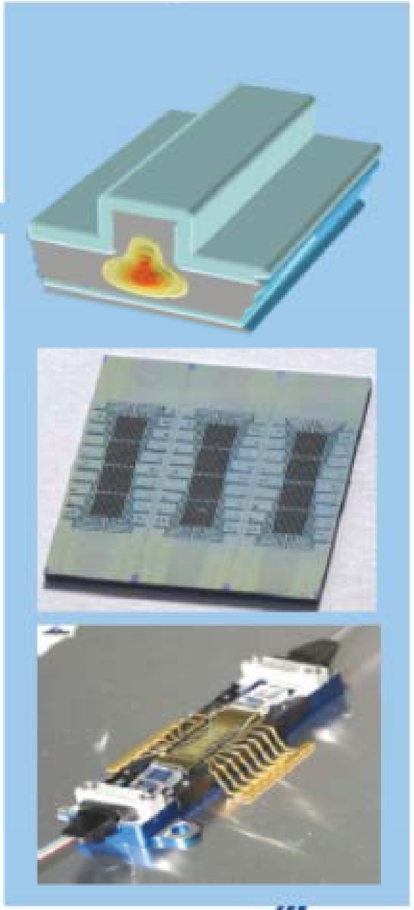
- No electro-optic effect
- No detection in 1.3-1.5 μm region
- High index contrast coupling
- Lacks efficient light emission

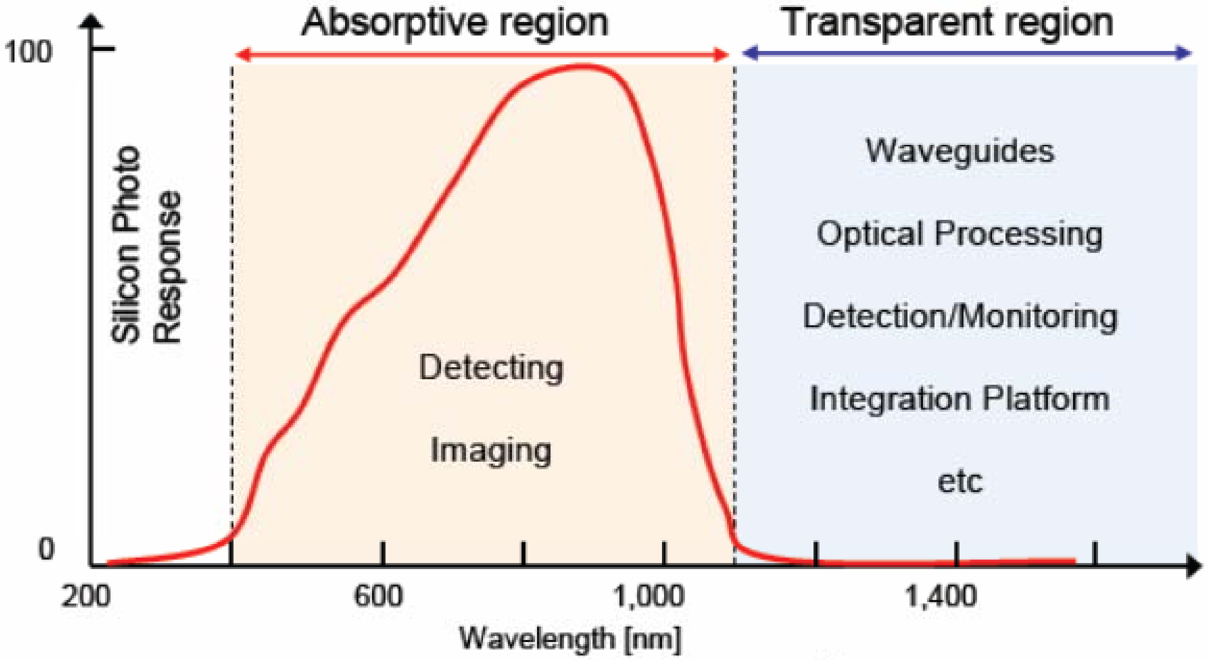
Silicon is Widely Utilized in Optics and Photonics

Conventional Play

Common Technology Platform

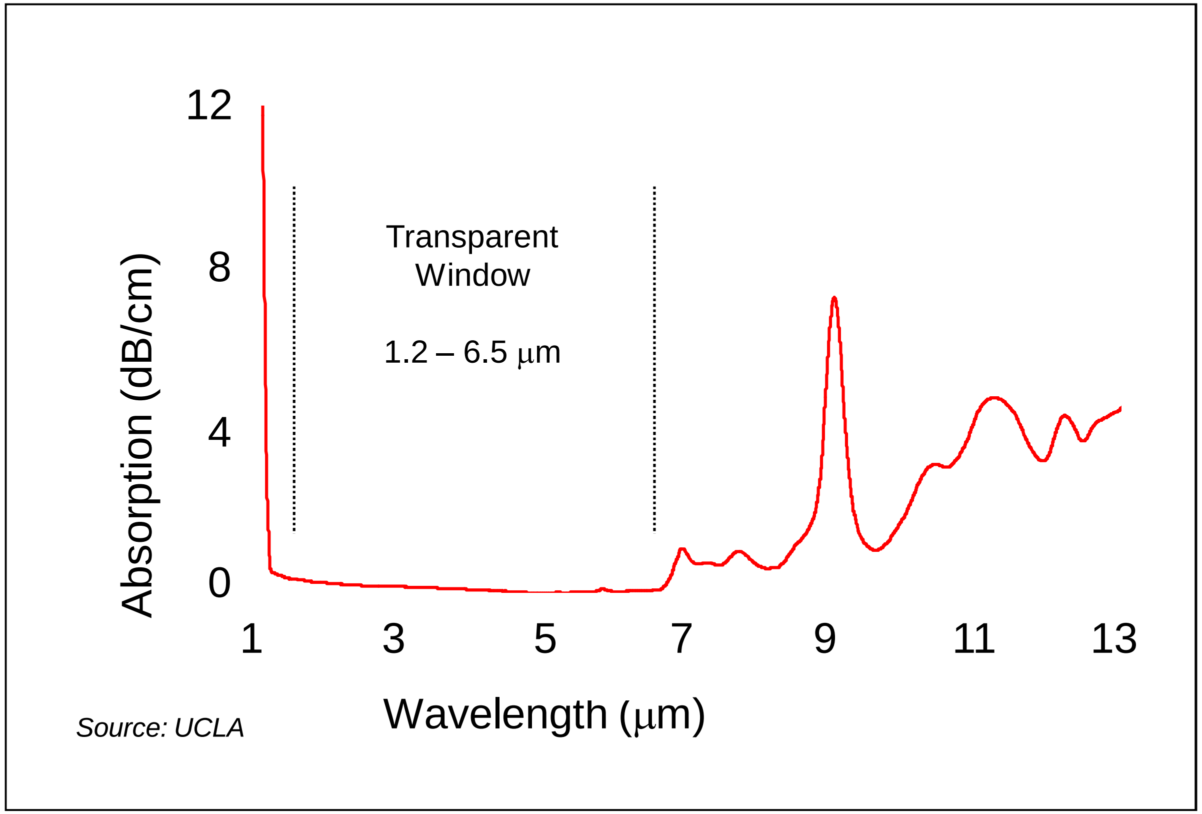






KOTURA

Silicon is an Excellent Optical Material



Source: UCLA

High refractive index difference with SiO_2

$n_{Si}=3.5$

$n_{SiO2}=1.45$

Silicon pro’s and cons

- Transparent on 1.3-1.5 μm
- **CMOS compatibility**
- Low cost
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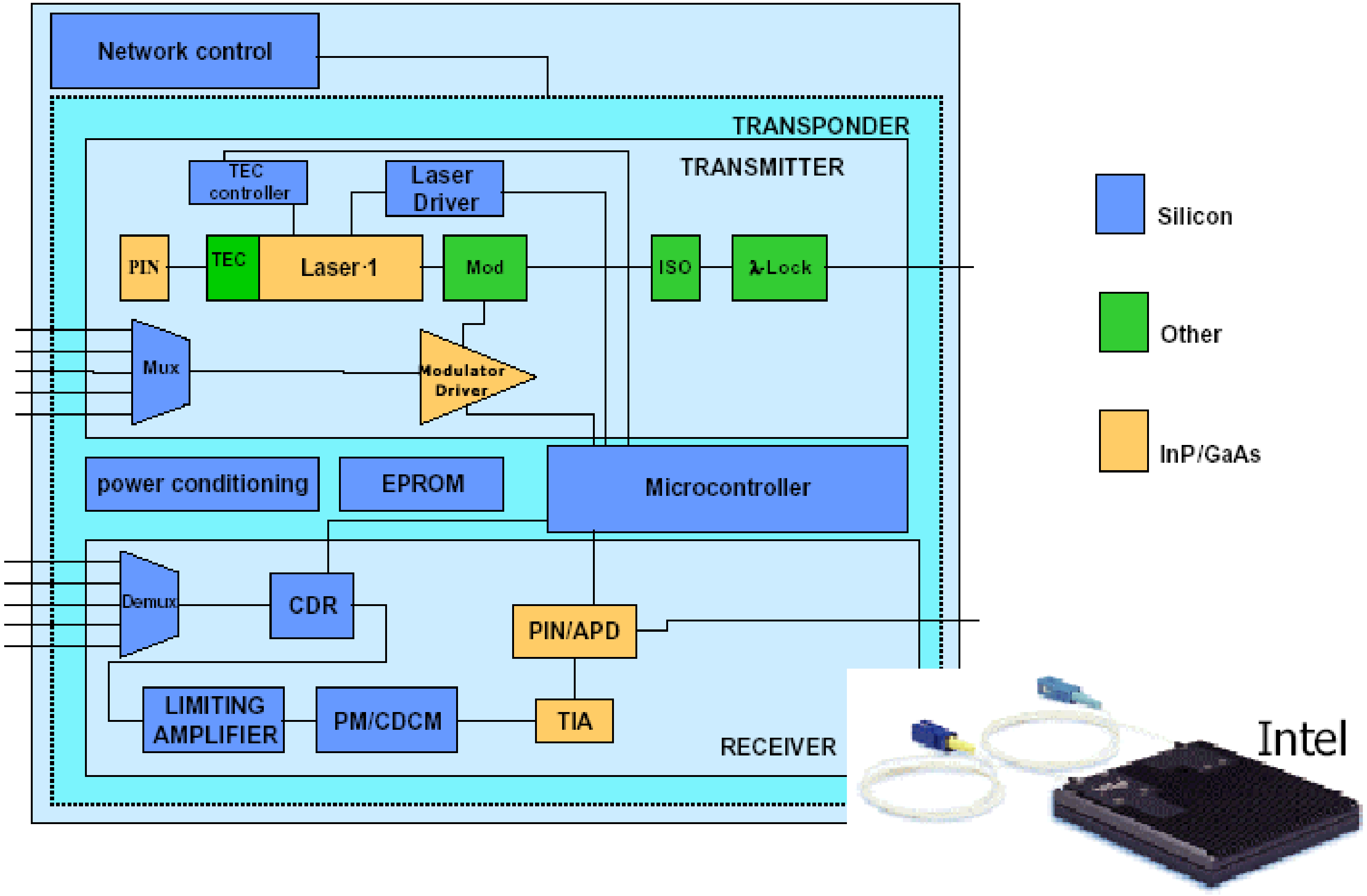
CMOS compatibility

Materials & Components in Transceiver

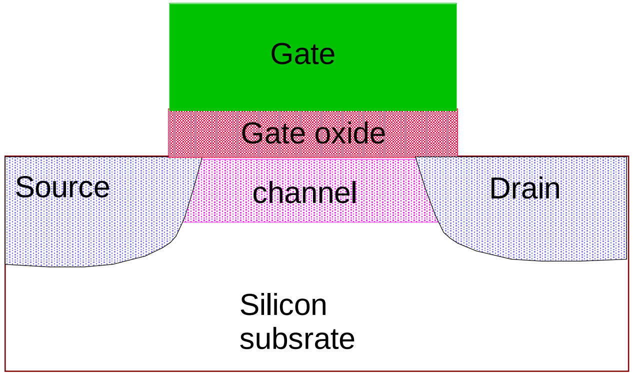


New Materials in Advanced CMOS

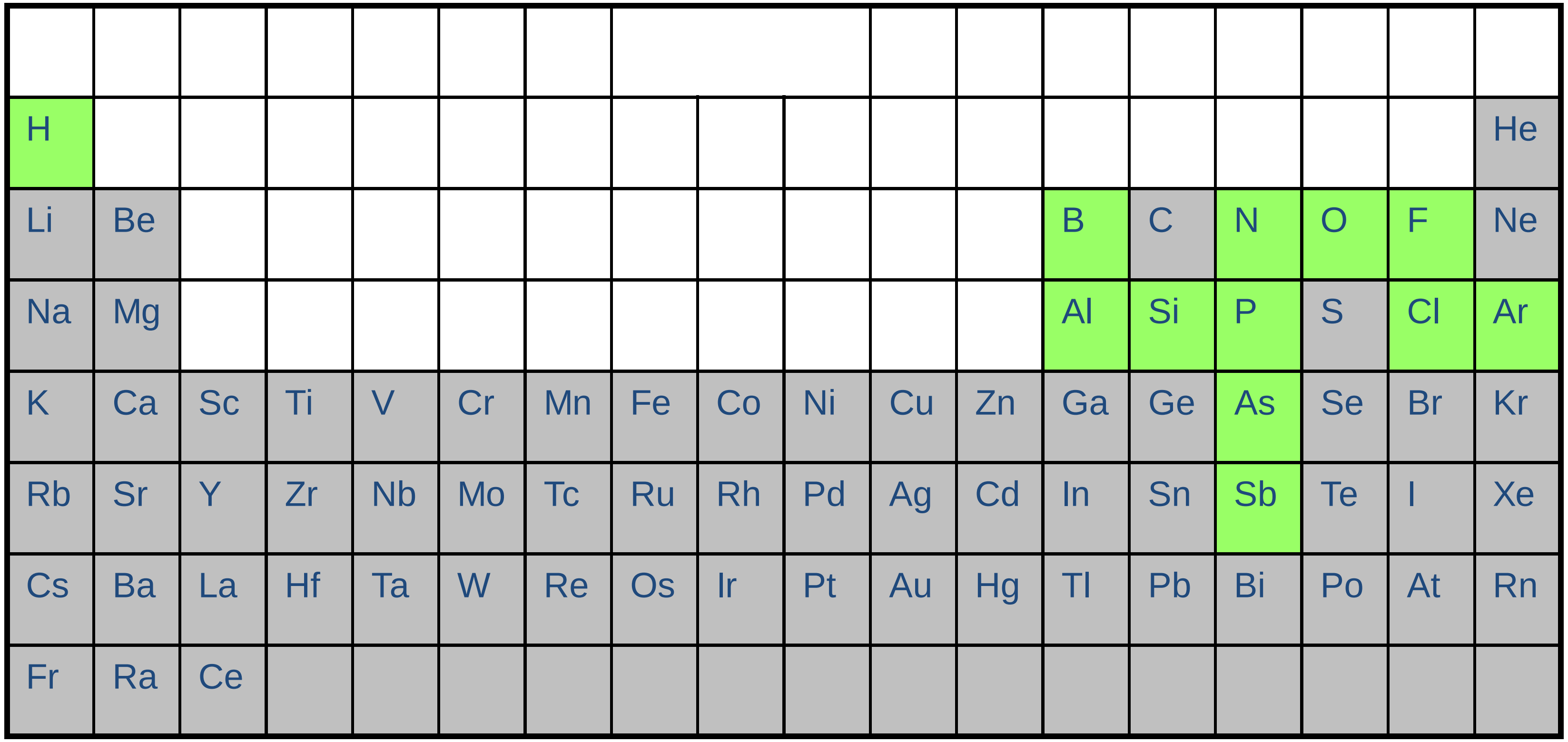
John Robertson

Contents

- High dielectric constant Gate Oxides
- Metal gates
- High mobility channels - Ge

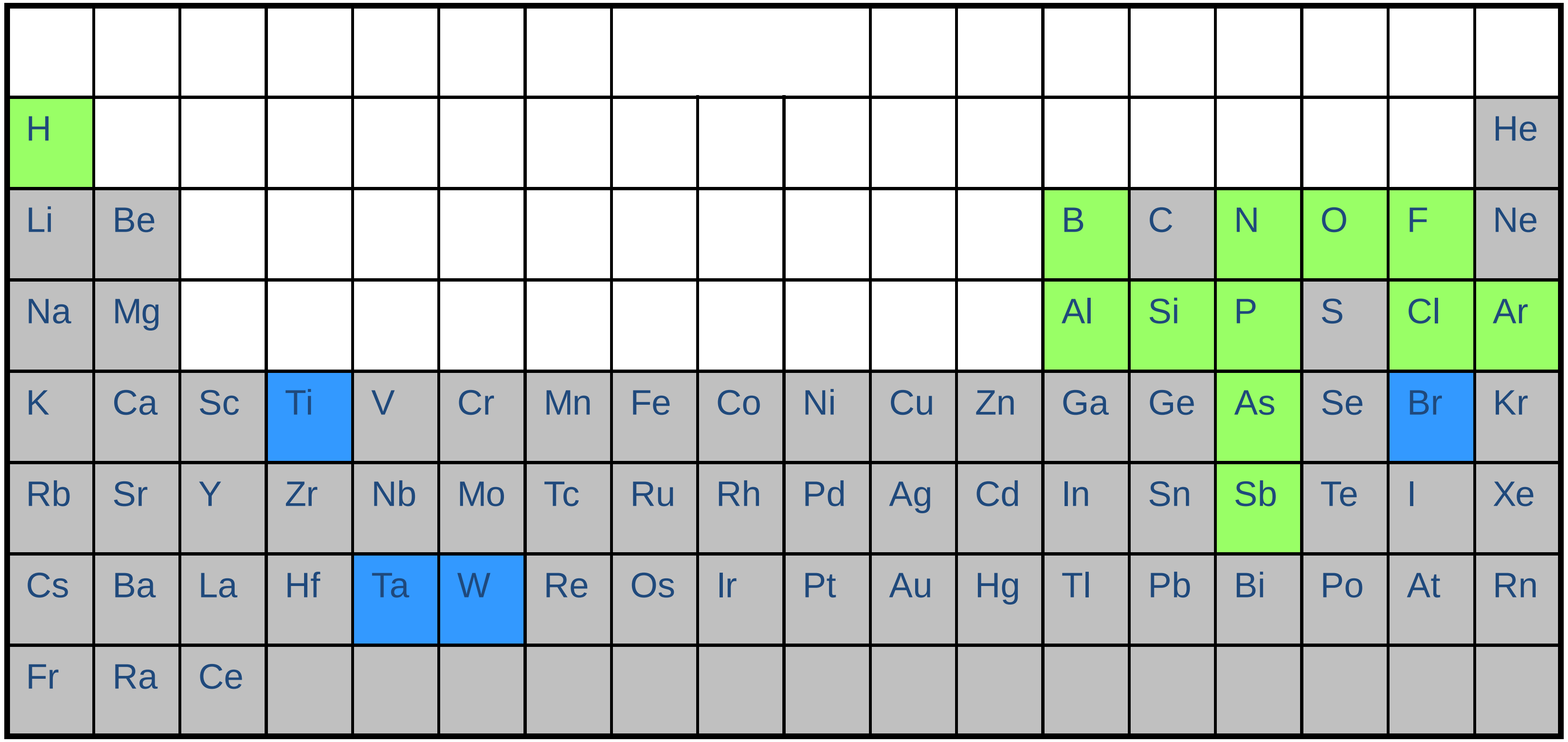


CMOS Periodic Table, 1970's



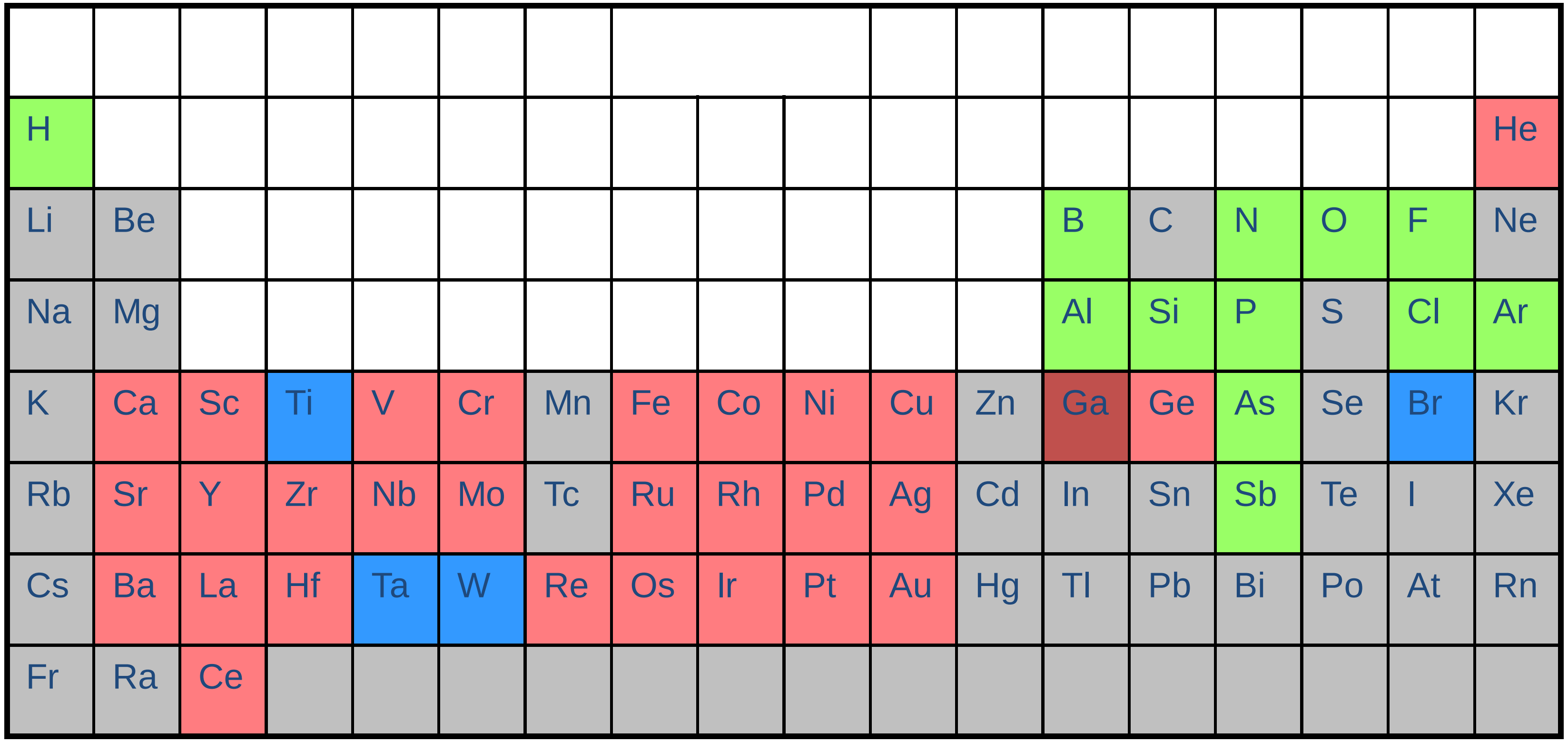
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ce															

CMOS Periodic Table, 1980's

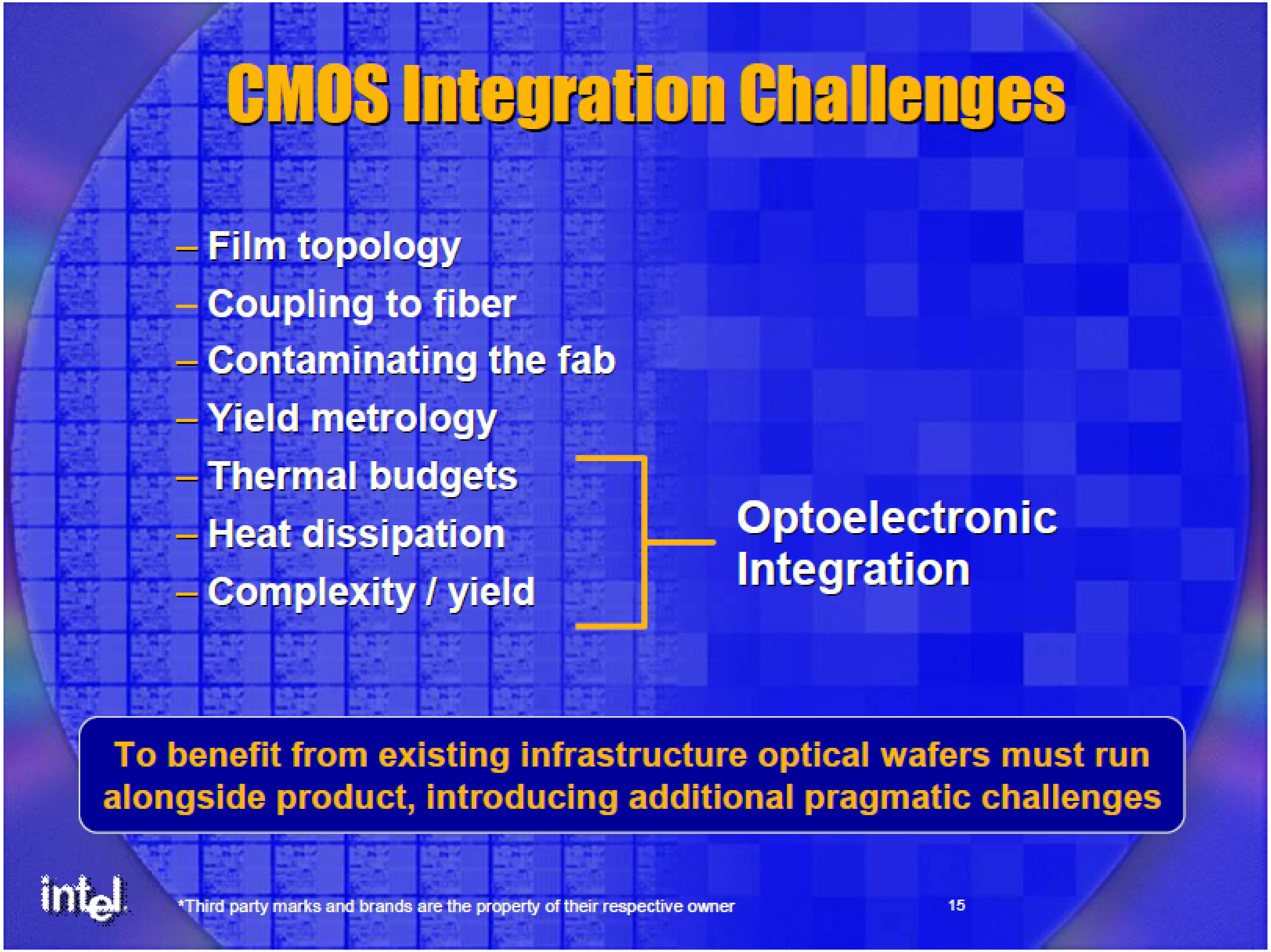


H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ce															

CMOS Periodic Table, 2000's



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ce															

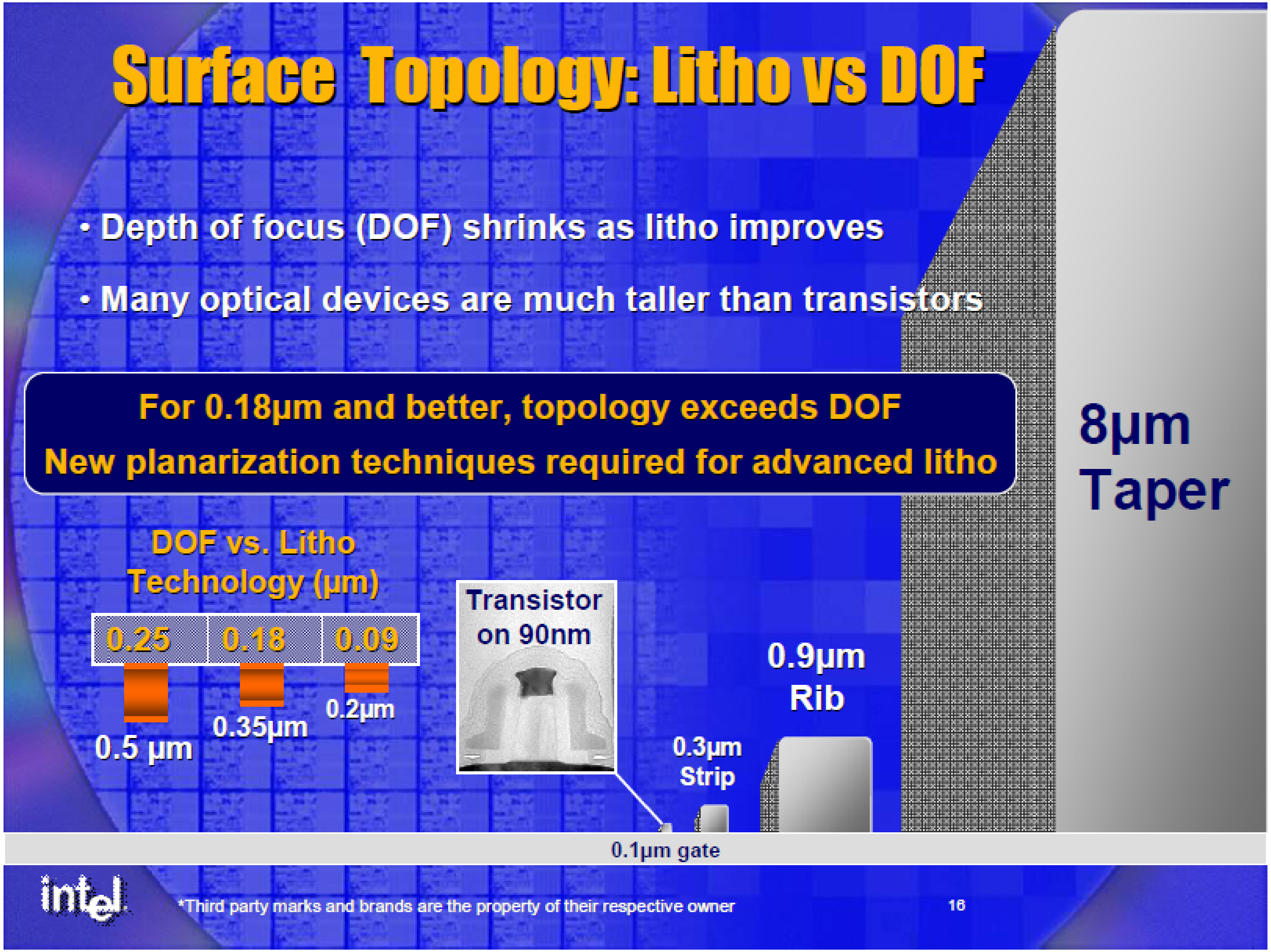


CMOS Integration Challenges

- Film topology
- Coupling to fiber
- Contaminating the fab
- Yield metrology
- Thermal budgets
- Heat dissipation
- Complexity / yield

Optoelectronic Integration

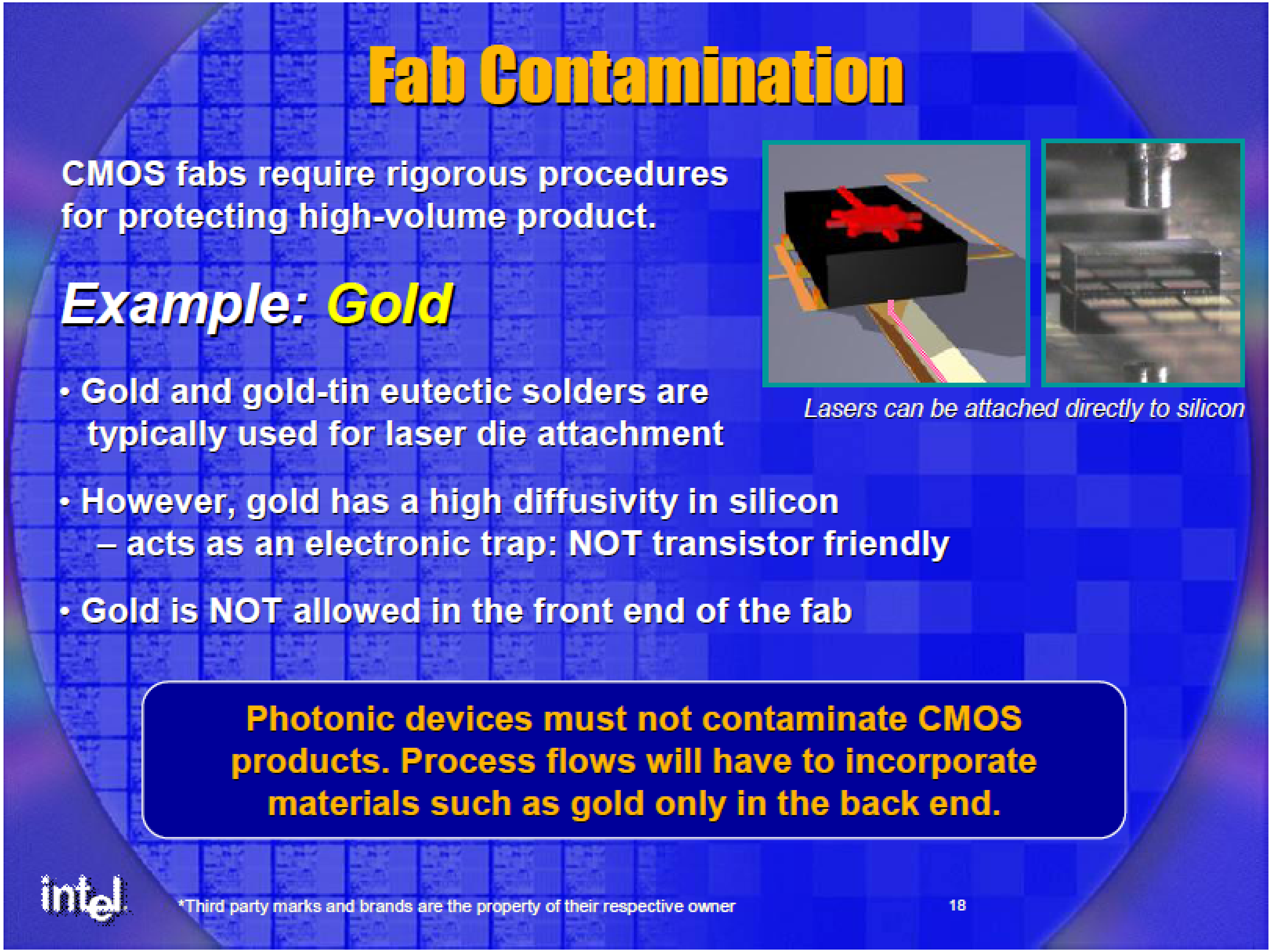
To benefit from existing infrastructure optical wafers must run alongside product, introducing additional pragmatic challenges



Surface Topology: Litho vs DOF

- Depth of focus (DOF) shrinks as litho improves
- Many optical devices are much taller than transistors

For 0.18µm and better, topology exceeds DOF
New planarization techniques required for advanced litho



Fab Contamination

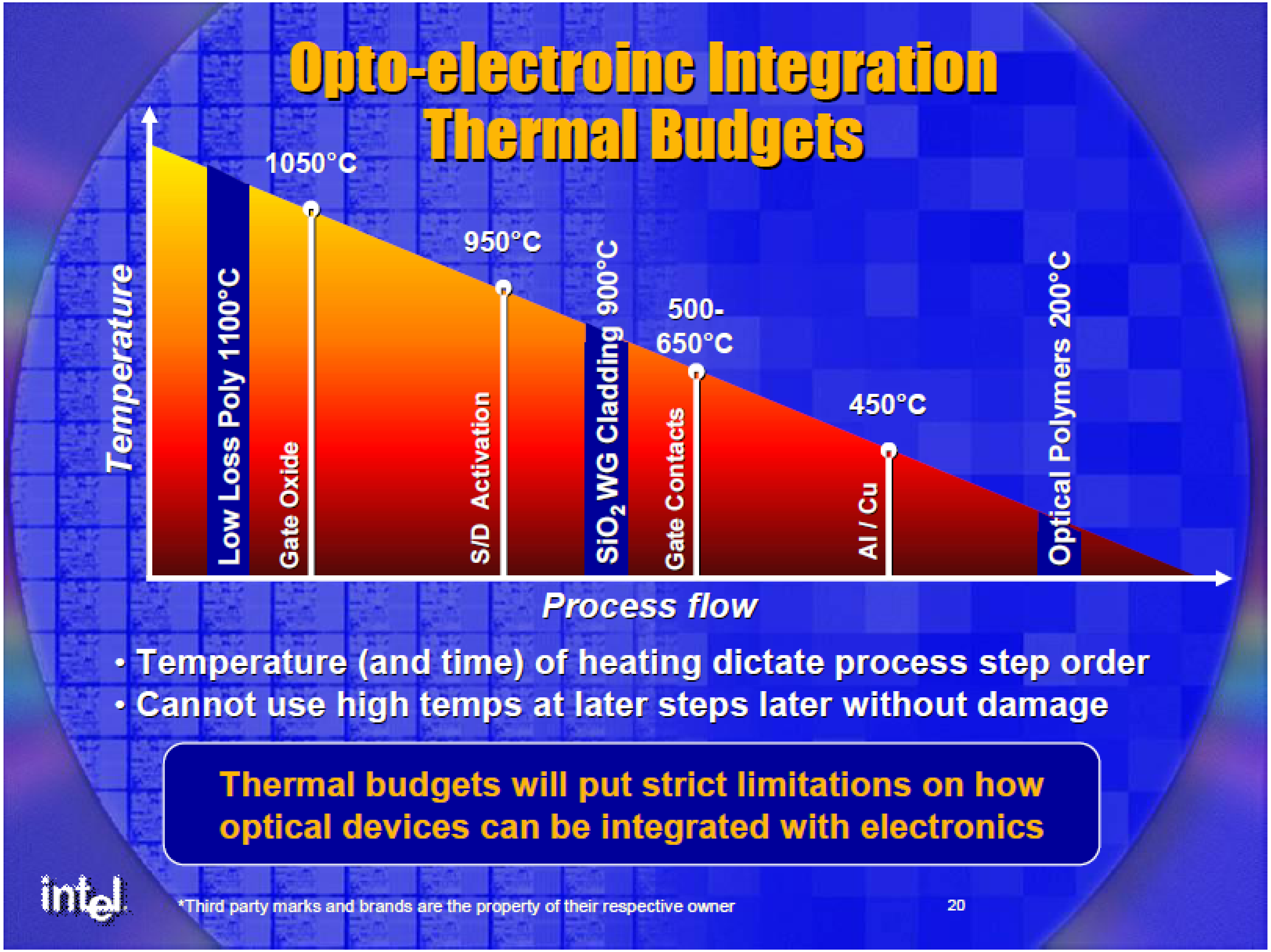
CMOS fabs require rigorous procedures for protecting high-volume product.

Example: Gold

- Gold and gold-tin eutectic solders are typically used for laser die attachment
- However, gold has a high diffusivity in silicon
  - acts as an electronic trap: NOT transistor friendly
- Gold is NOT allowed in the front end of the fab

Lasers can be attached directly to silicon

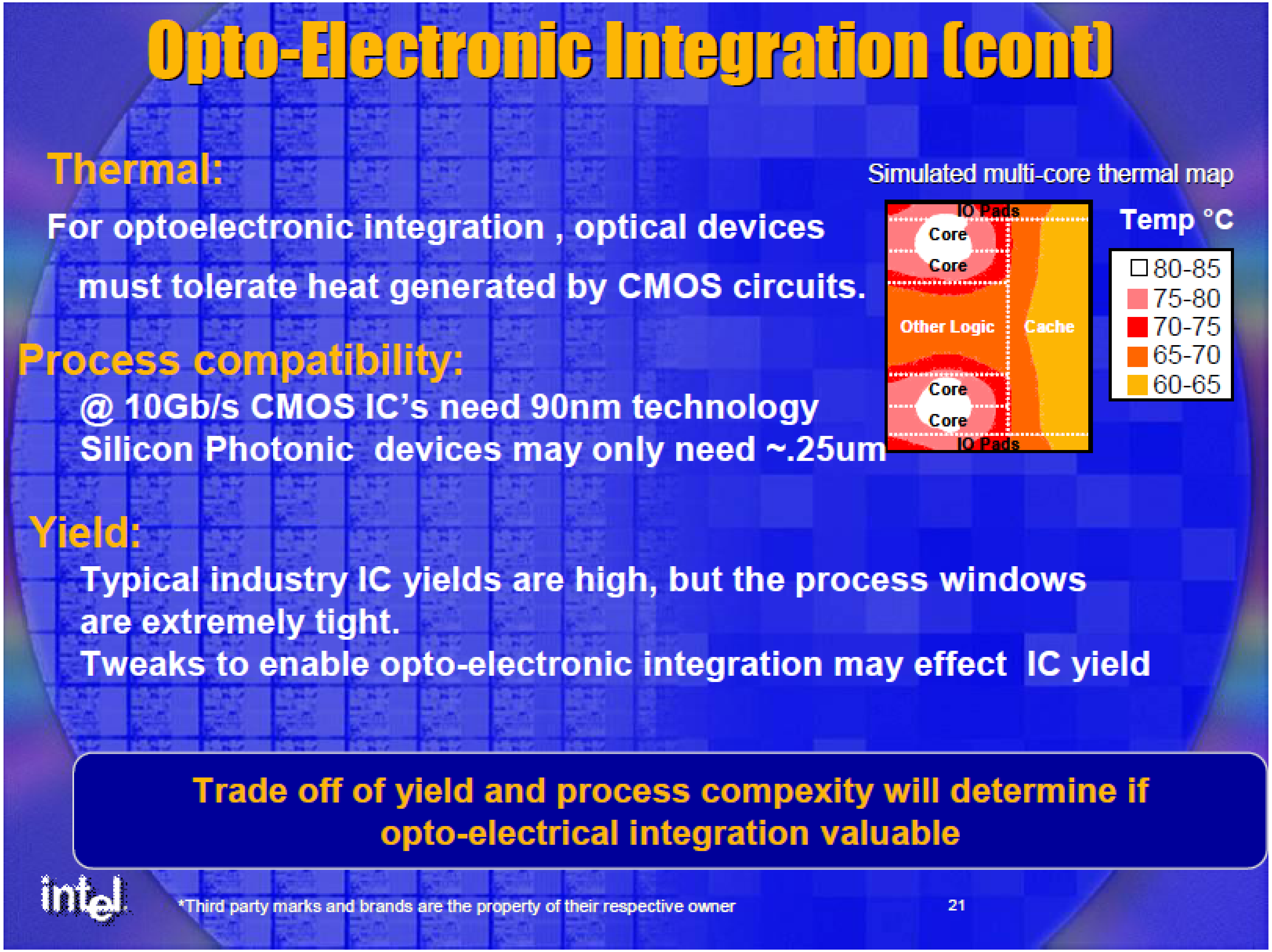
Photonic devices must not contaminate CMOS products. Process flows will have to incorporate materials such as gold only in the back end.



Opto-electroinc Integration Thermal Budgets

- Temperature (and time) of heating dictate process step order
- Cannot use high temps at later steps later without damage

Thermal budgets will put strict limitations on how optical devices can be integrated with electronics



Opto-Electronic Integration (cont)

Simulated multi-core thermal map

Thermal:

For optoelectronic integration , optical devices must tolerate heat generated by CMOS circuits.

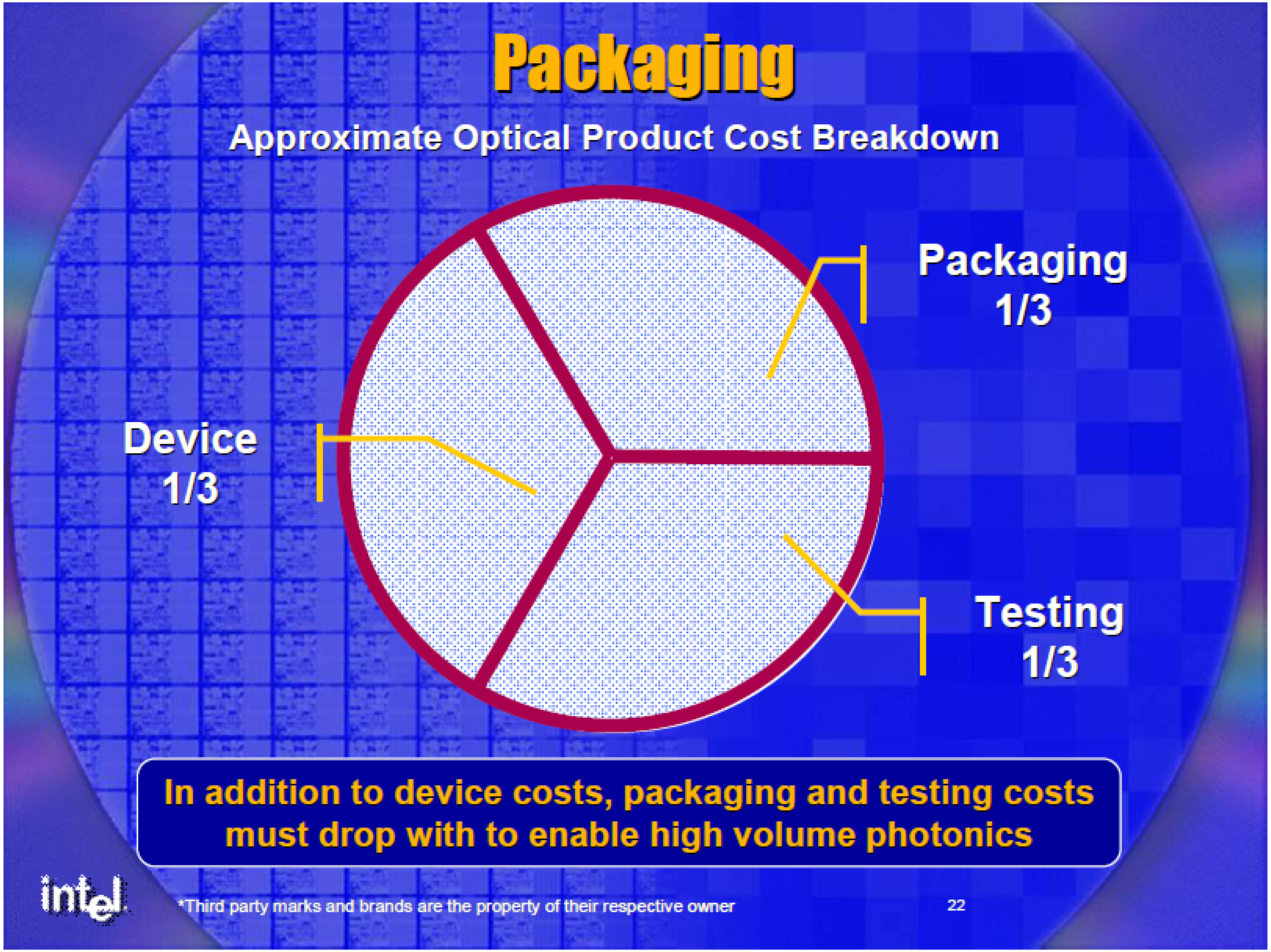
Process compatibility:

@ 10Gb/s CMOS IC's need 90nm technology
Silicon Photonic devices may only need ~.25um

Yield:

Typical industry IC yields are high, but the process windows are extremely tight.
Tweaks to enable opto-electronic integration may effect IC yield

Trade off of yield and process compexity will determine if opto-electrical integration valuable



Packaging

Approximate Optical Product Cost Breakdown

Packaging 1/3

Device 1/3

Testing 1/3

In addition to device costs, packaging and testing costs must drop with to enable high volume photonics

intel

*Third party marks and brands are the property of their respective owner

Silicon pro's and cons

- Transparent on 1.3-1.5 μm
- CMOS compatibility
- **Low cost**
- High index contrast, small footprint

- No electro-optic effect
- No detection in 1.3-1.5 μm region
- High index contrast coupling
- Lacks efficient light emission

Silicon is cheaper than other semiconductors (2009 data)

	Wafer size (research)	Wafer size (commercial)	Wafer cost (€)*	Die cost (€)**
Silicon	18”	12”	50	1
SOI		4”	400	28
InP	6”	3”	500	62
GaAs	8”	6”	500	11

P4 2.6GHz 200$

* Source waferworld.com

**Assumed equal processing cost (1000 €), die size 1 cm, yield =1

Cost = paradigm change

- 200 mm Si wafer 0.5 mm sized dies then 125,000 dies
- Cost processed CMOS wafers $2,000,000
- Cost per die: $16
- Laser size: 10x100 microns.
- Cost per laser: $ 0.064
- This is just like estimating the cost of transistors. They are free. Only the PIC cost matters.
- Emphasis is moved from components to the system

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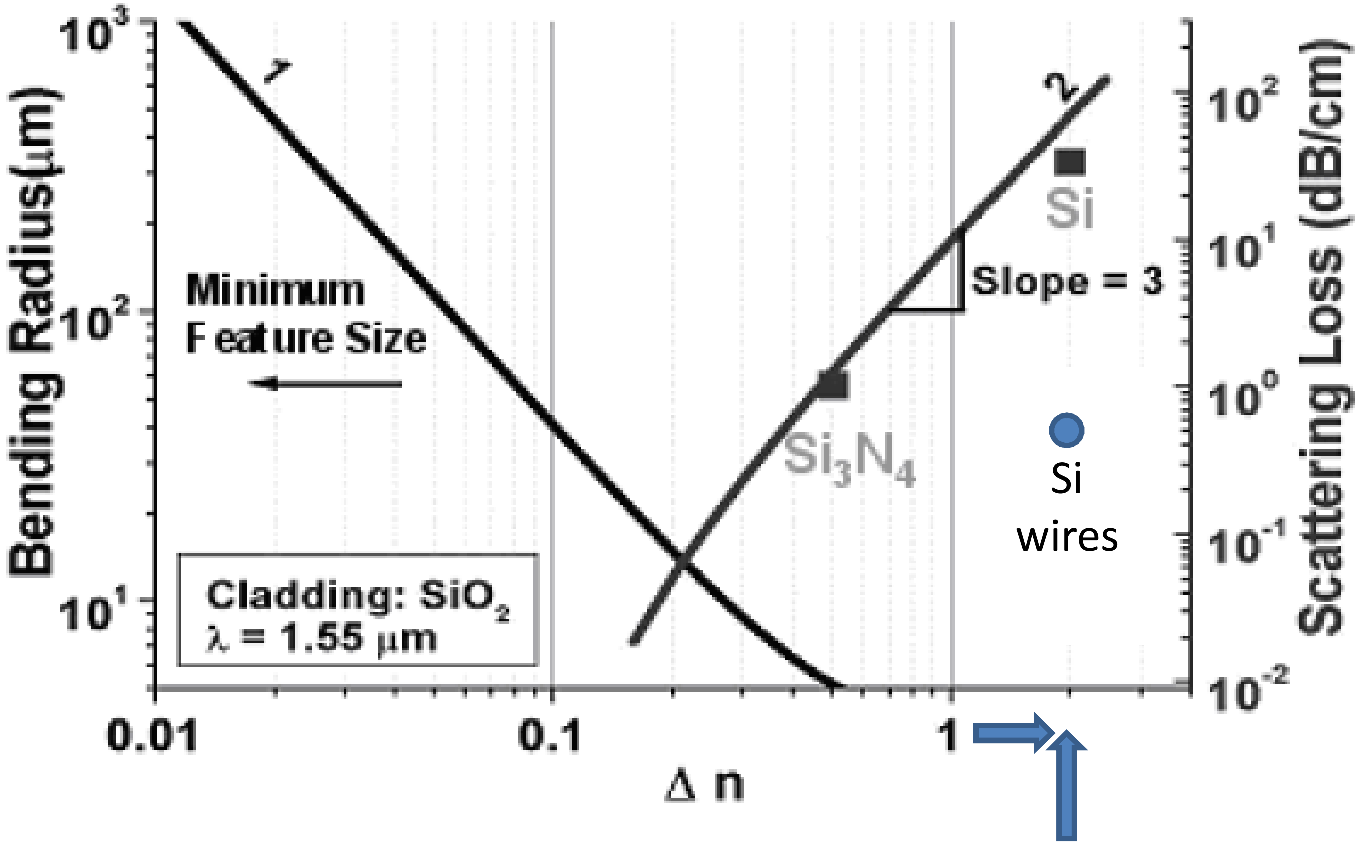
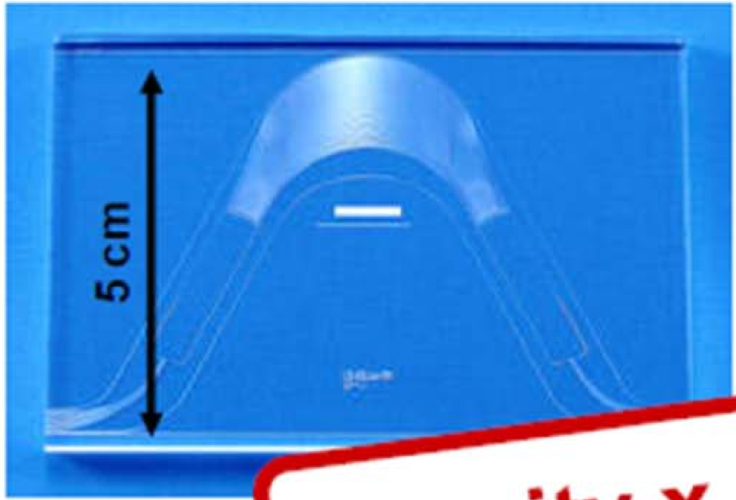


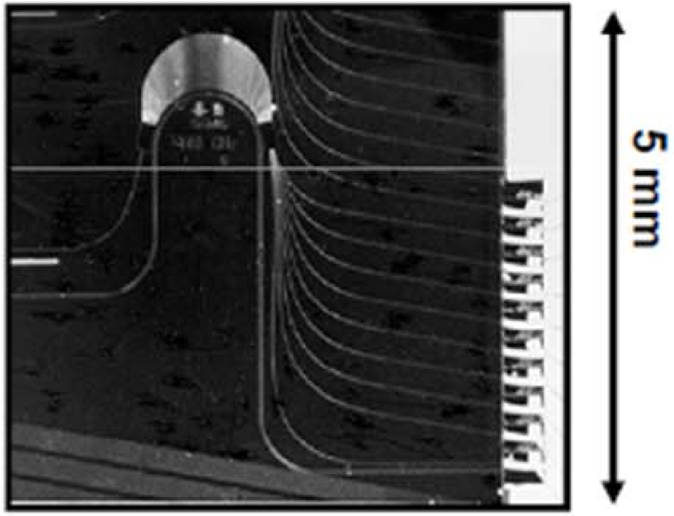
Fig. 3. Dimensional scaling for microphotonic component with index difference Δn and the consequent increase in scattering loss with with current pattern transfer technology [5].

Larger-scale integration

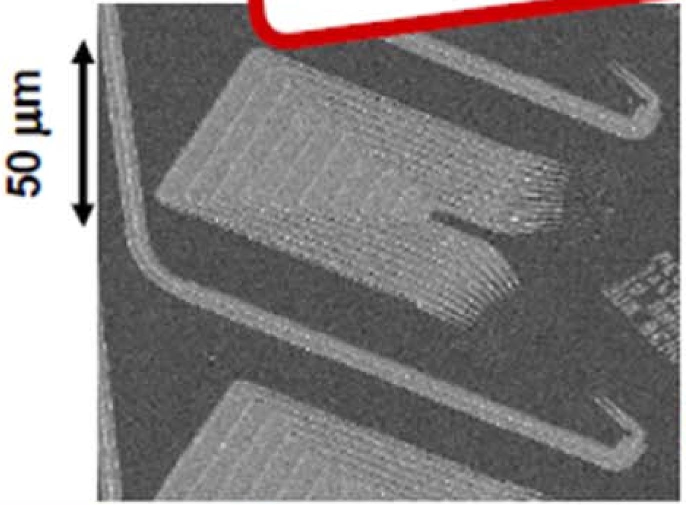


Low Contrast - Fiber Matched
(silica or polymer based)
Bend Radius ~ 5 mm
Size ~ several cm^2

Density x 10^6



Medium Contrast
(InP-InGaAsP)
Bend Radius ~ 500µm



Ultra-high Contrast
(Silicon on Insulator)
Bend Radius < 5µm

Silicon pro’s and cons

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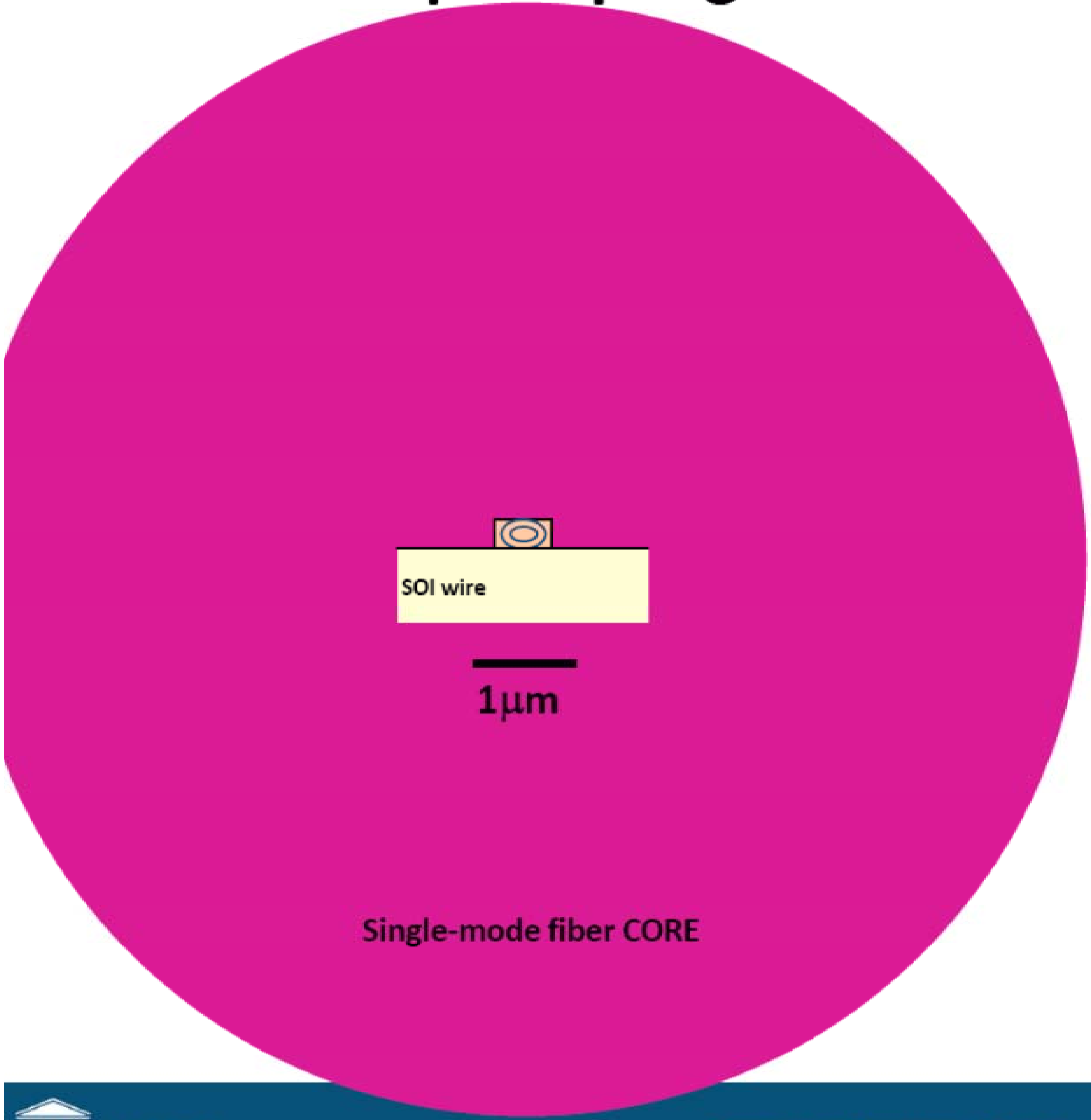
Fiber to chip coupling

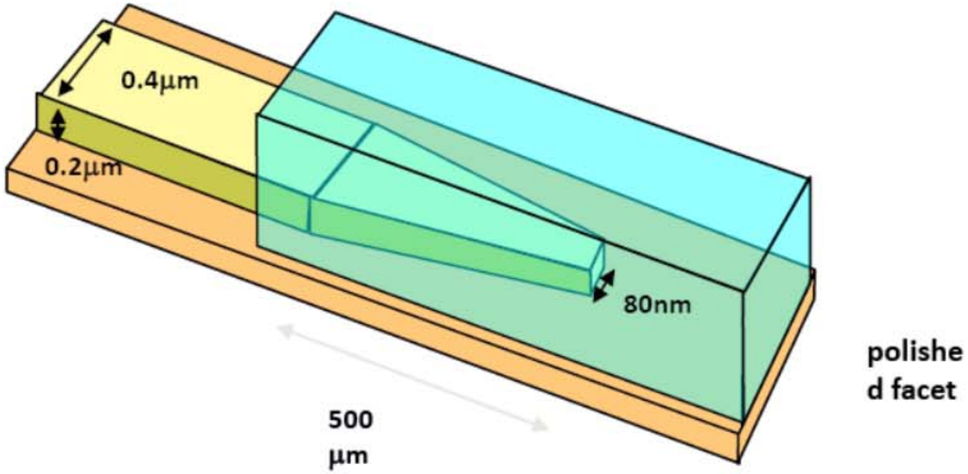


We would like

- Low loss
- Broadband
- High coupling tolerance
- No facet reflections
- Waferscale testability
- Easy to fabricate
- A solution for the polarization problem

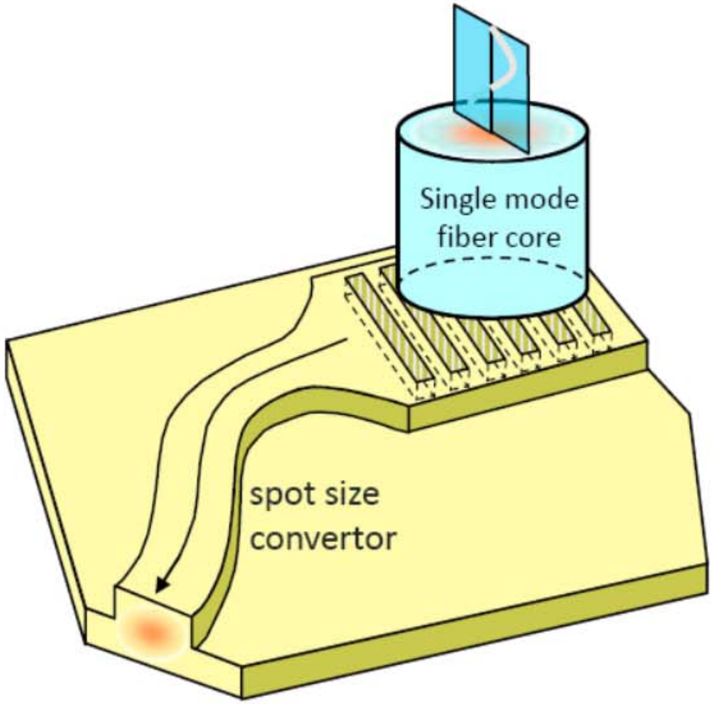
Two solutions

Two widely used solutions

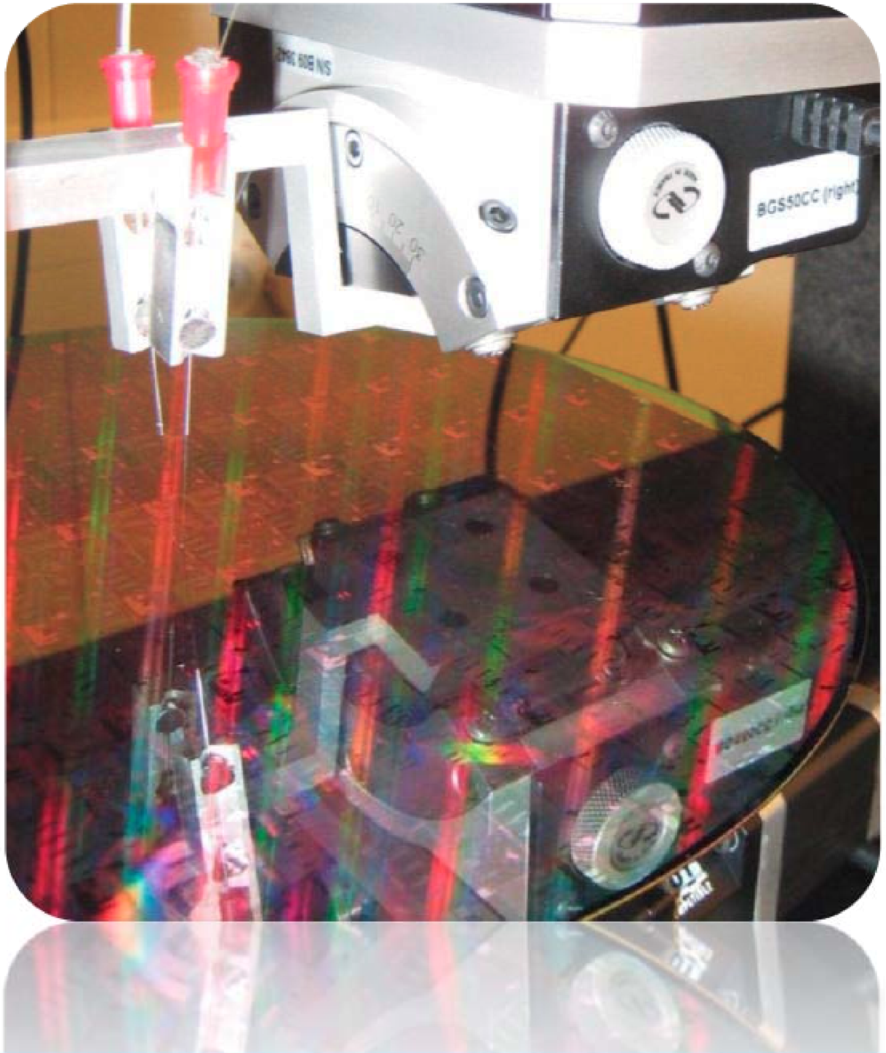


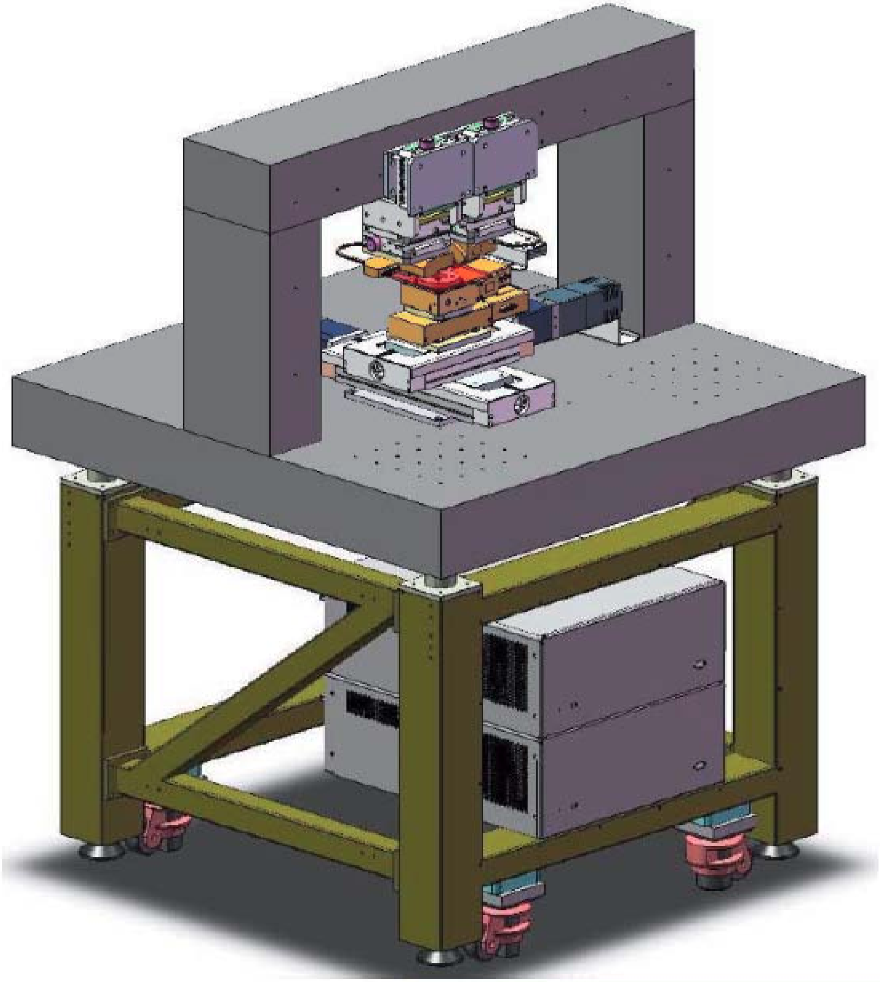
Inverted taper

Grating coupler



Automatic setup





Michael Vanslembroeck

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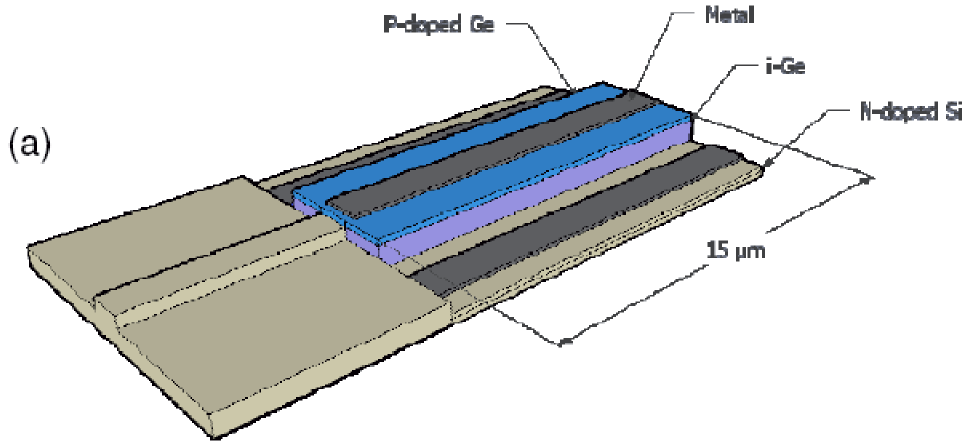
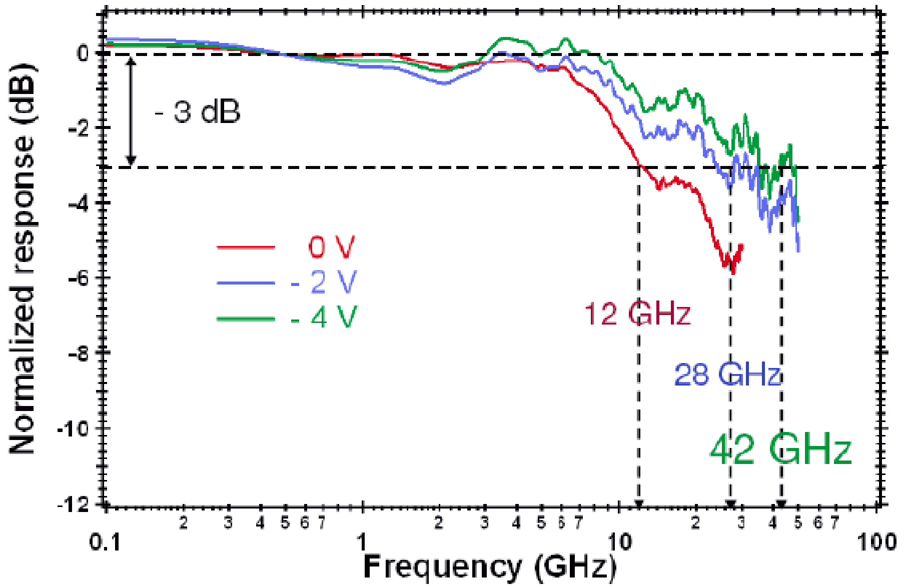
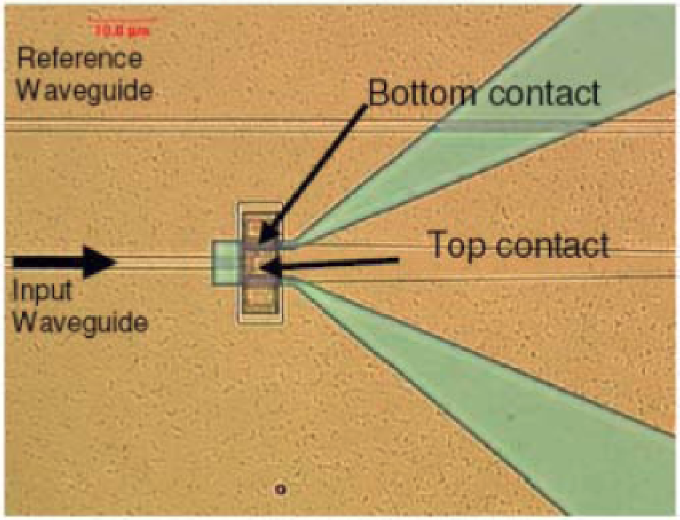
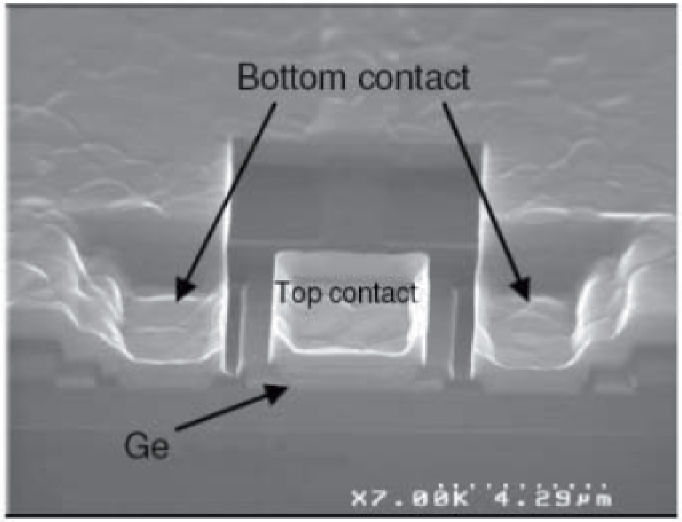
Ge-detector





Vivien e.a. , OE 17, pp. 6252 (2009)





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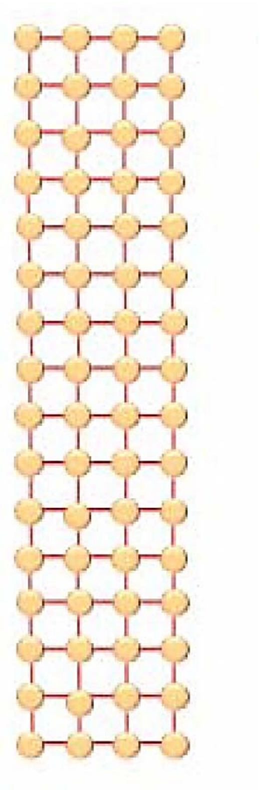
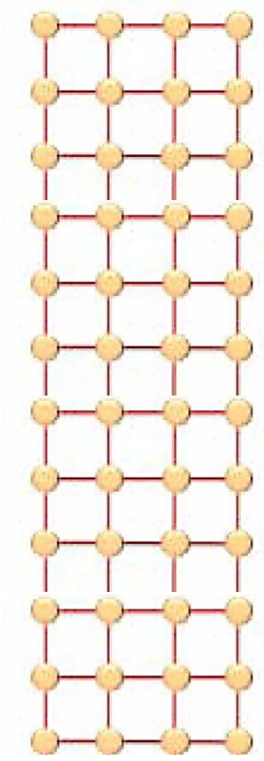
Strain-induced bulk $\chi^{(2)}$

Strain inhomogeinity



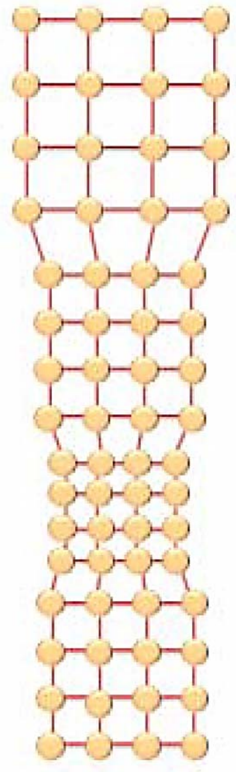
Unstrained silicon

$\chi^{(2)}_{bulk} = 0$



Uniformly strained silicon

$\chi^{(2)}_{bulk} = 0$



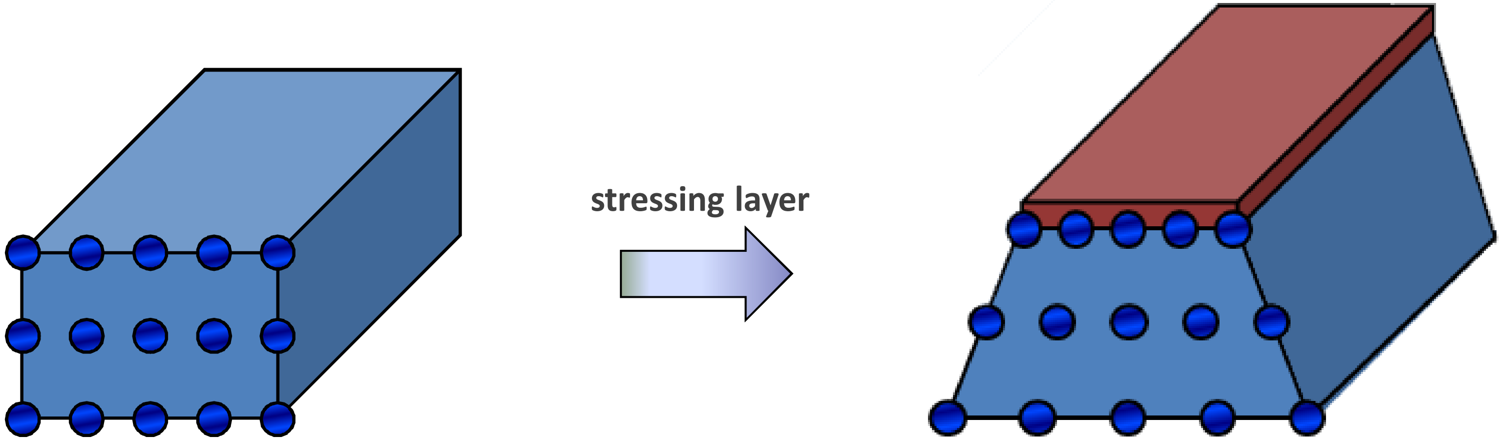
Non-uniformly strained silicon

$\chi^{(2)}_{bulk} \neq 0$

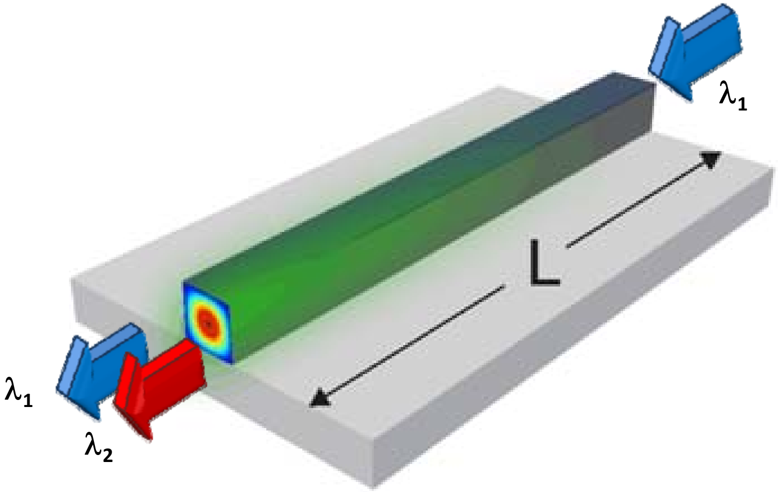
Strained silicon

Bulk symmetry breaking

Structural deformation



stressing layer



Optical modulators

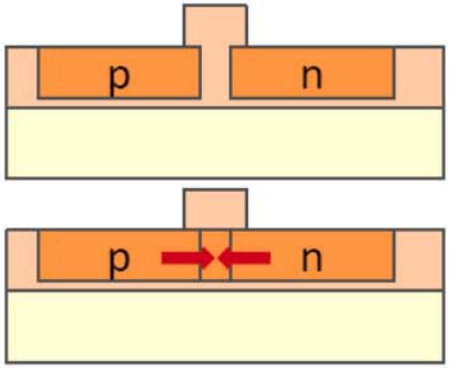
Drude effect Δn

Carrier injection

p-i-n diode in forward bias

Strong effect (many carriers)

Slow effect (~1GHz)

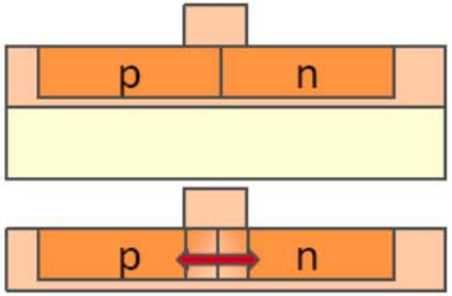


Carrier depletion

p-n diode in reverse bias

Weaker effect → hence device length large

Fast effect (>40GHz)

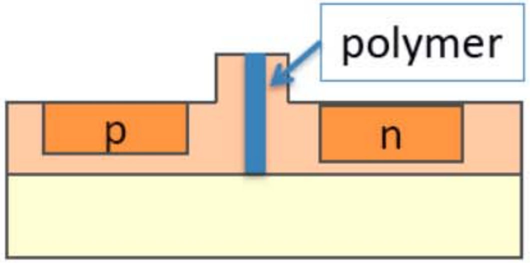


Slotted waveguide filled with electrooptic polymer

Polymer with strong electrooptic effect

Similar to capacitor

Very fast effect (>40 GHz)



Plasma dispersion modulators at imec

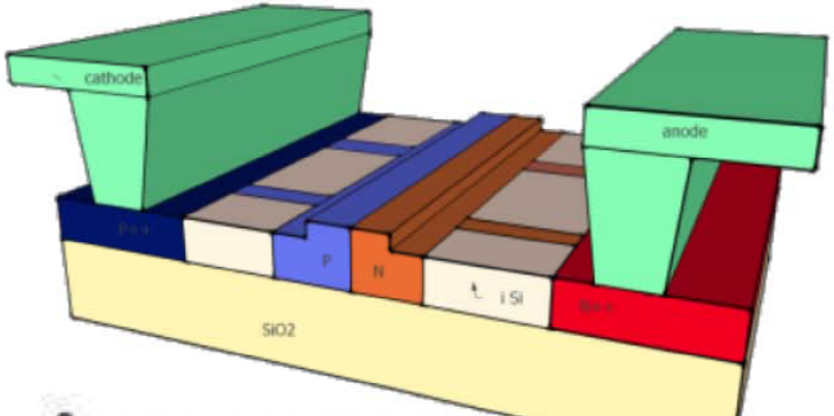
P-n junction in shallow waveguide

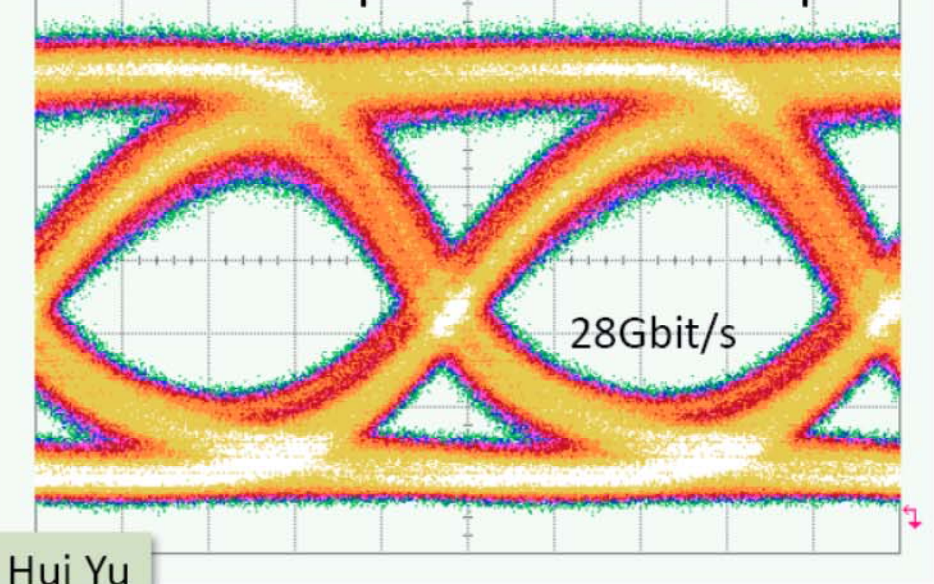
4 implantations

Travelling-wave electrodes

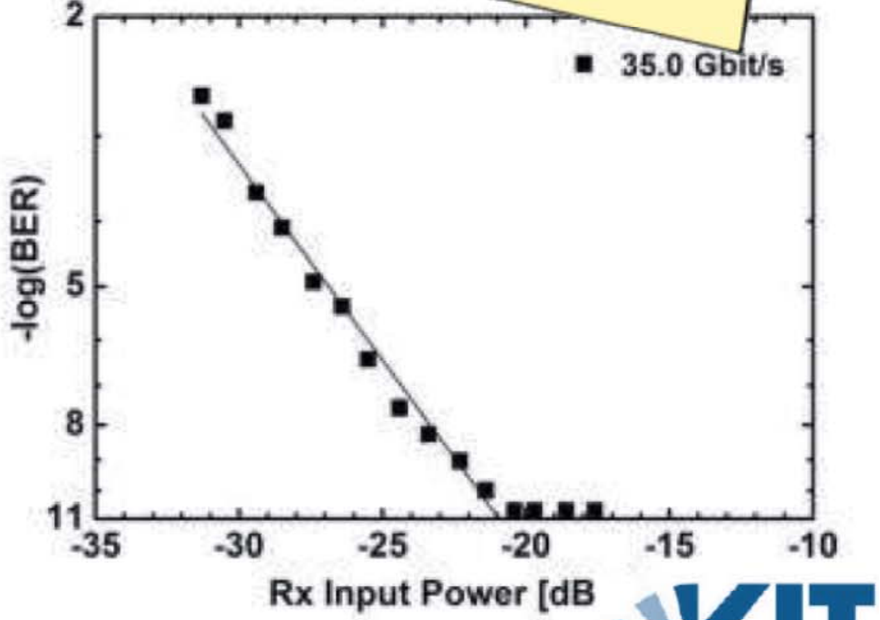
open eye at 40Gbps

error-free operation at 28Gbps





Hui Yu



measurements performed at KIT

Silicon pro’s and cons

- Transparent on 1.3-1.5 μm
- CMOS compatibility
- Low cost
- High index contrast, small footprint

- High index contrast coupling
- No detection in 1.3-1.5 μm region
- No electro-optic effect
- **Lacks efficient light emission**

The source problem

"If God wanted ordinary silicon to efficiently emit light, he would not have given us gallium arsenide,"

said Elias Towe of Carnegie Mellon University (Pittsburgh)

(quoted from *IEEE Spectrum* "Linking with Light," August 2002).

Back to basics

Luminescence

Electroluminescence

Lasing

Fermi’s golden rule

(spontaneous emission rate)

Selection rules due to the symmetry of energy bands

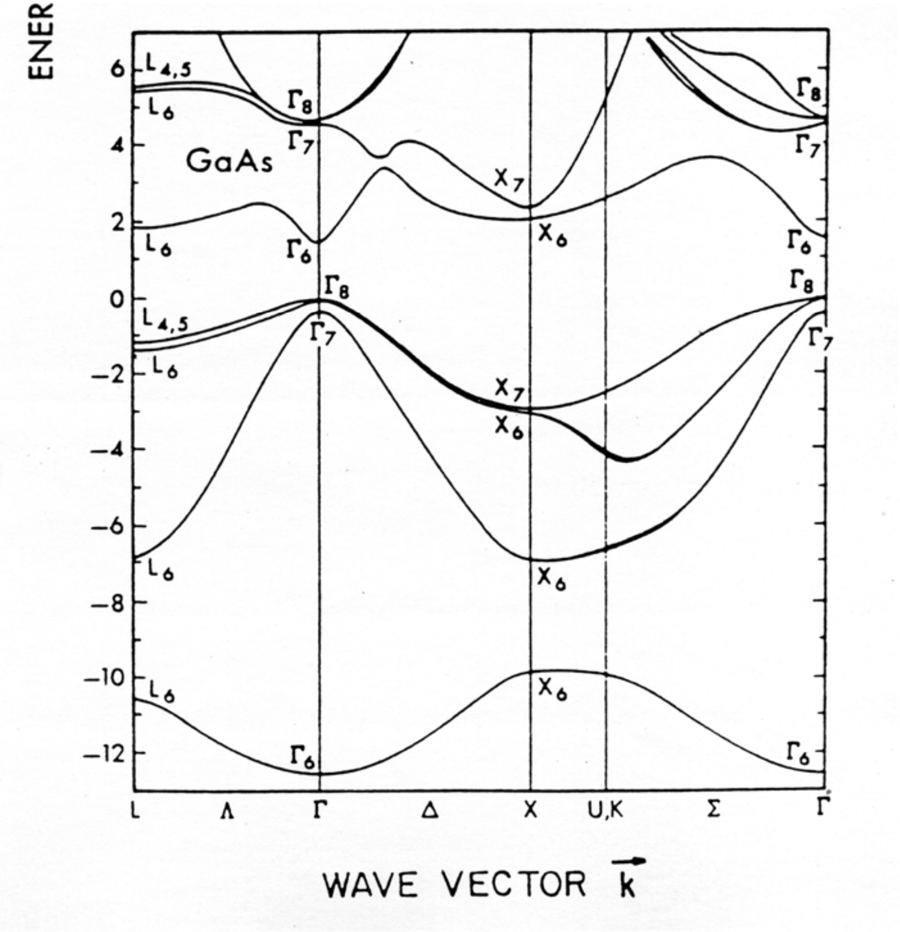
$$R_{sp}(\hbar\omega)\; d\hbar\omega \propto \sum_{k_e,k_h} \left|H(k_e,k_h)\right|^2 F(k_e)\left[1-F(k_h)\right]$$

$$\times\,\delta\left(E_c(k_e)-E_v(k_h)-\hbar\omega\right)\, d\hbar\omega$$

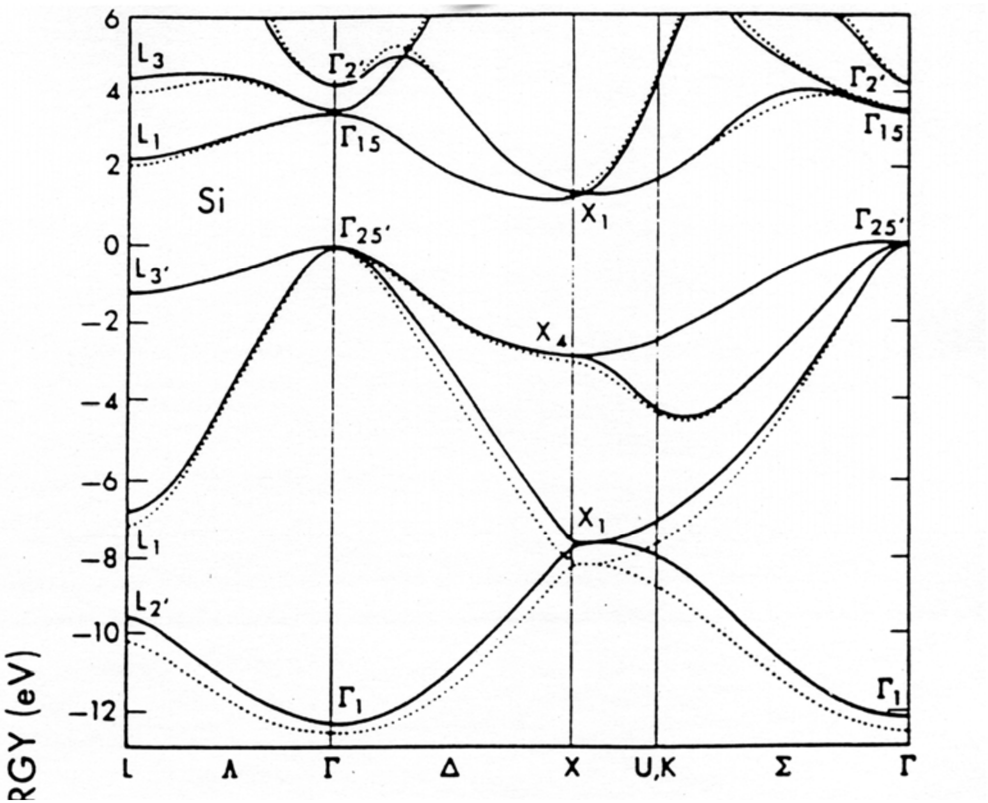
Energy and wavevector conservation

Band diagram

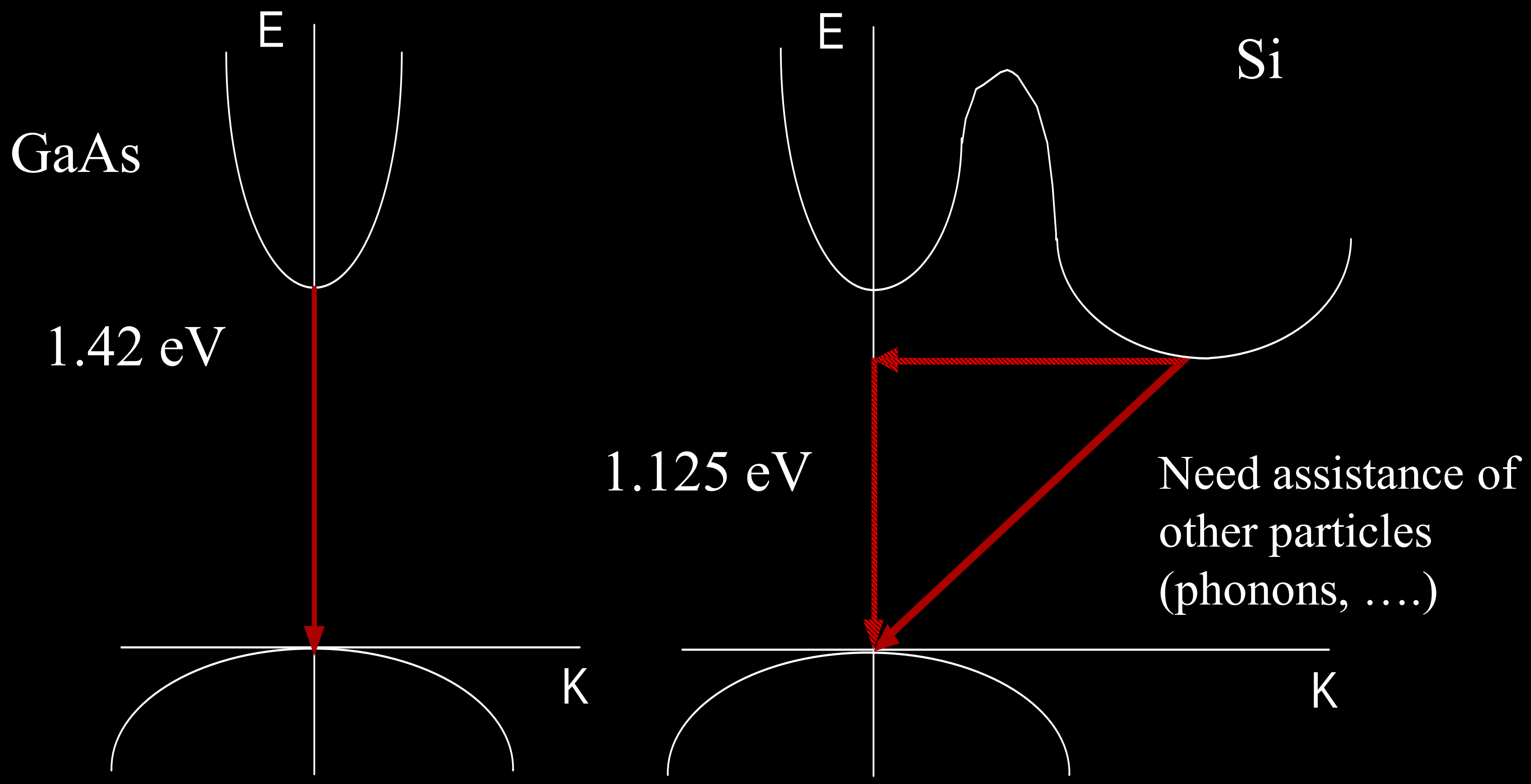
Gallium Arsenide



Silicon



Direct-indirect transitions



Need assistance of other particles (phonons, ….)

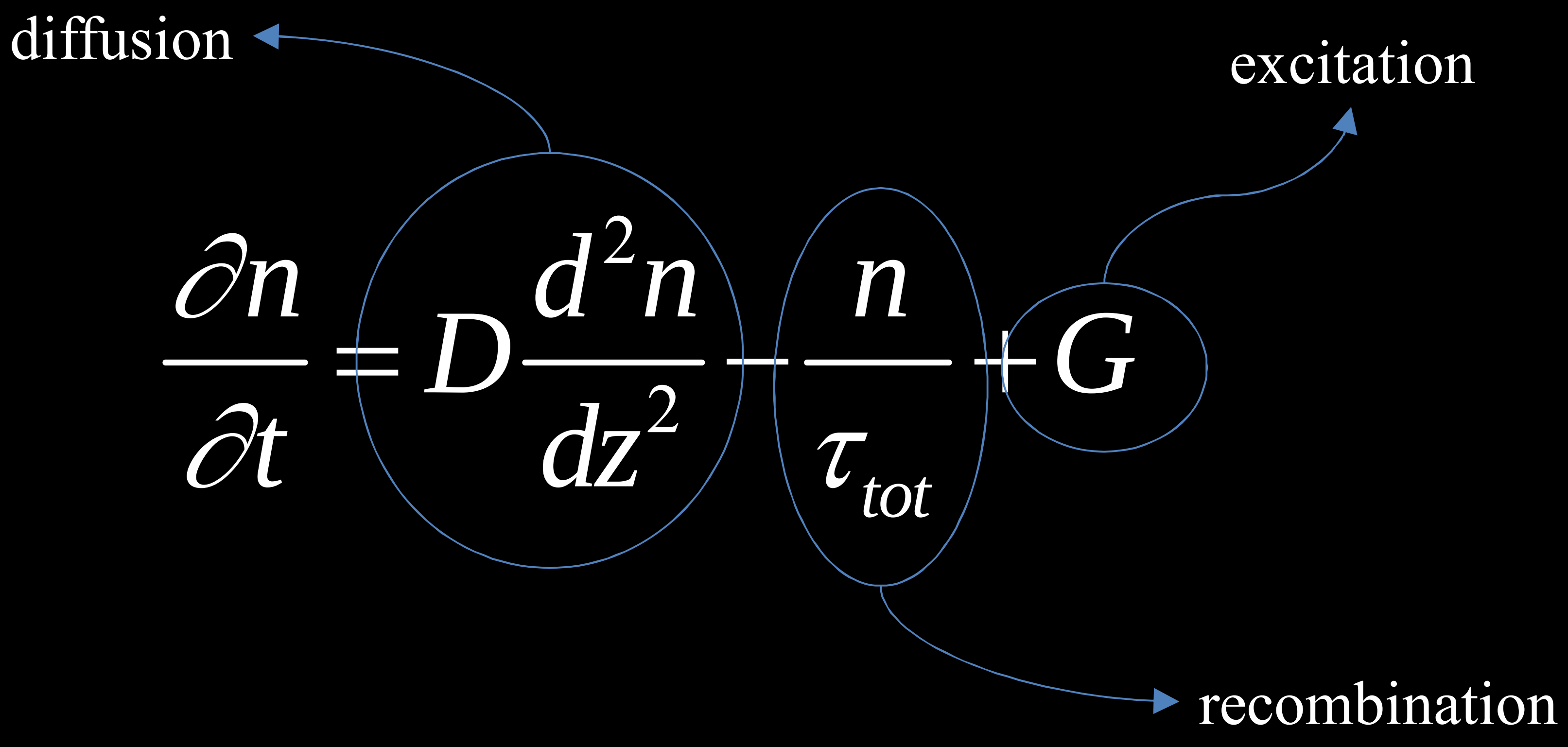
Fast (≈ns)
Efficient (≈10^{-1})

Slow (≈ms)
Inefficient (≈10^{-6})

Rate equation

$$D = \frac{\mu \; k_B T}{q}$$

$$G(z) = G(0) \; e^{-\alpha z}$$



$$\frac{\partial n}{\partial t} = D \frac{d^2 n}{dz^2} - \frac{n}{\tau_{tot}} + G$$

diffusion

excitation

recombination

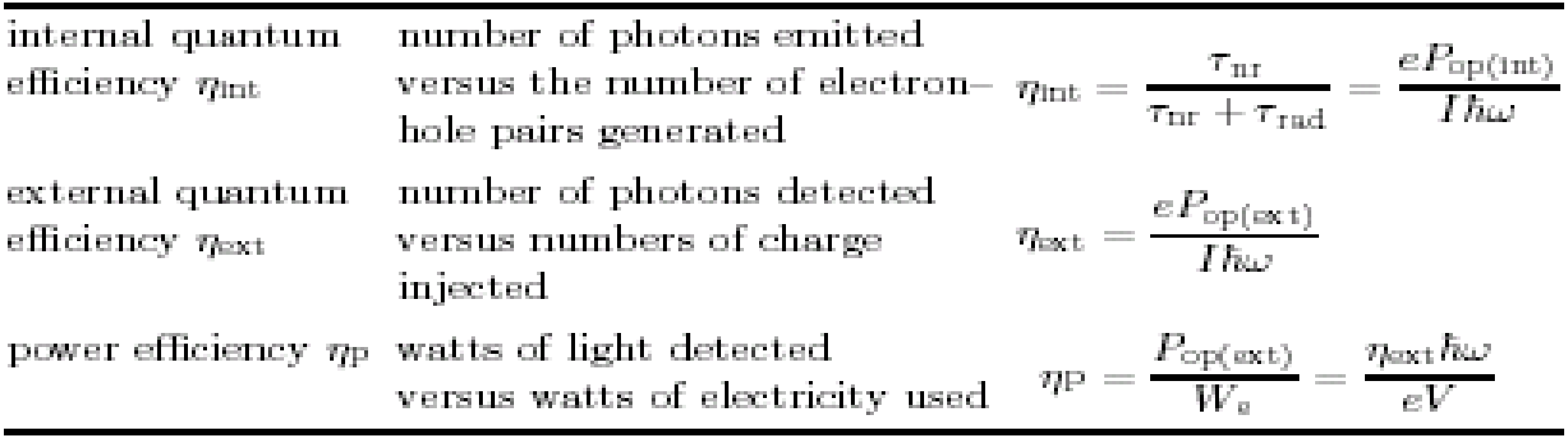
$$\frac{1}{\tau_{tot}} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{nr}}$$

Rate equation

$$\frac{\partial n}{\partial t} = D\frac{d^2 n}{dz^2} - \frac{n}{\tau_{tot}} + G$$

$$I_{PL} = \frac{n}{\tau_{rad}} \approx \alpha \frac{\tau_{tot}}{\tau_{rad}}$$

Basics on LED efficiency



internal quantum efficiency η_{int}	number of photons emitted versus the number of electron–hole pairs generated	$\eta_{\text{int}} = \dfrac{\tau_{\text{nr}}}{\tau_{\text{nr}} + \tau_{\text{rad}}} = \dfrac{eP_{\text{op(int)}}}{I\hbar\omega}$
external quantum efficiency η_{ext}	number of photons detected versus numbers of charge injected	$\eta_{\text{ext}} = \dfrac{eP_{\text{op(ext)}}}{I\hbar\omega}$
power efficiency η_{P}	watts of light detected versus watts of electricity used	$\eta_{\text{P}} = \dfrac{P_{\text{op(ext)}}}{W_e} = \dfrac{\eta_{\text{ext}}\hbar\omega}{eV}$

Internal quantum efficiency

$$\eta_{\text{int}} = \frac{W_R}{W_R + W_{NR}} = \frac{1/\tau_{rad}}{1/\tau_{rad} + 1/\tau_{nr}}$$

$$\eta_{\text{int}} = \left(1 + \frac{\tau_r}{\tau_{nr}}\right)^{-1}$$

τ_{nr} sensitive to sample purity and structure

- Auger 0.1μs (@10^{17} cm^{-3})
  0.5 ns (@ 10^{20} cm^{-3})
- Deep level

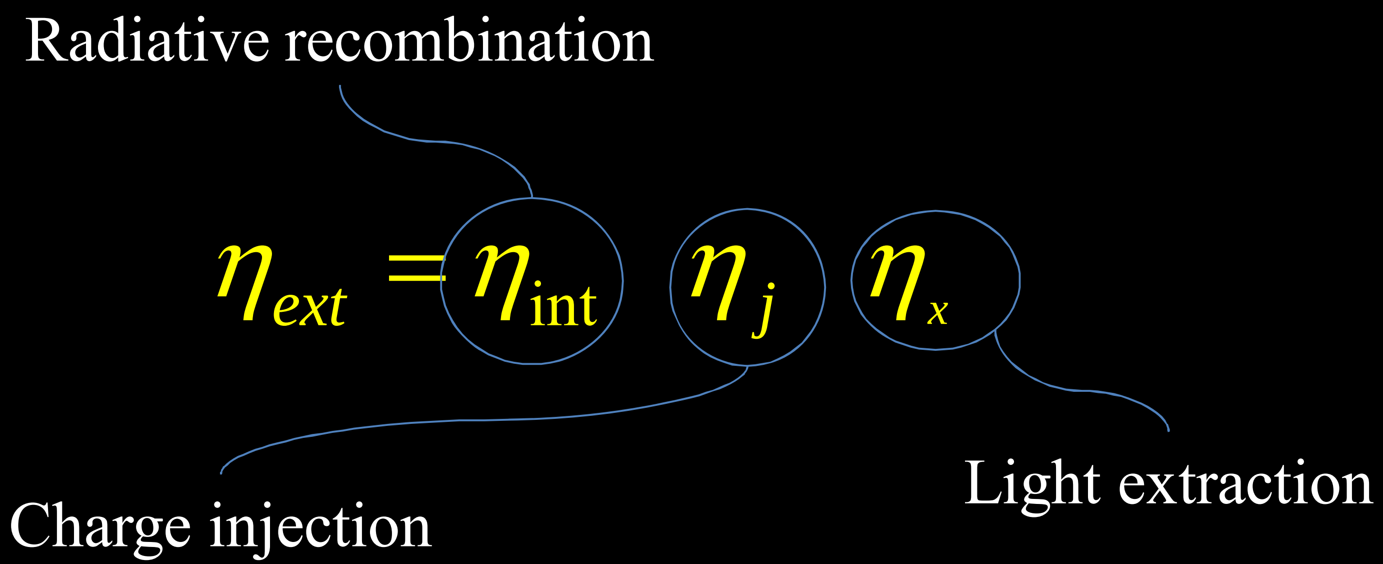
$$\tau_{nr} = \frac{1}{N_T v_{th} \sigma}$$

- Surface recombinations

Internal quantum efficiency

	Si	GaAs
τ_r	1 ms	100 ns
τ_{nr}	100 ns	100 ns
η_{int}	10^{-6}	0.5

External quantum efficiency of LED



Radiative recombination

$$\eta_{ext} = \eta_{\text{int}} \eta_j \eta_x$$

Charge injection

Light extraction

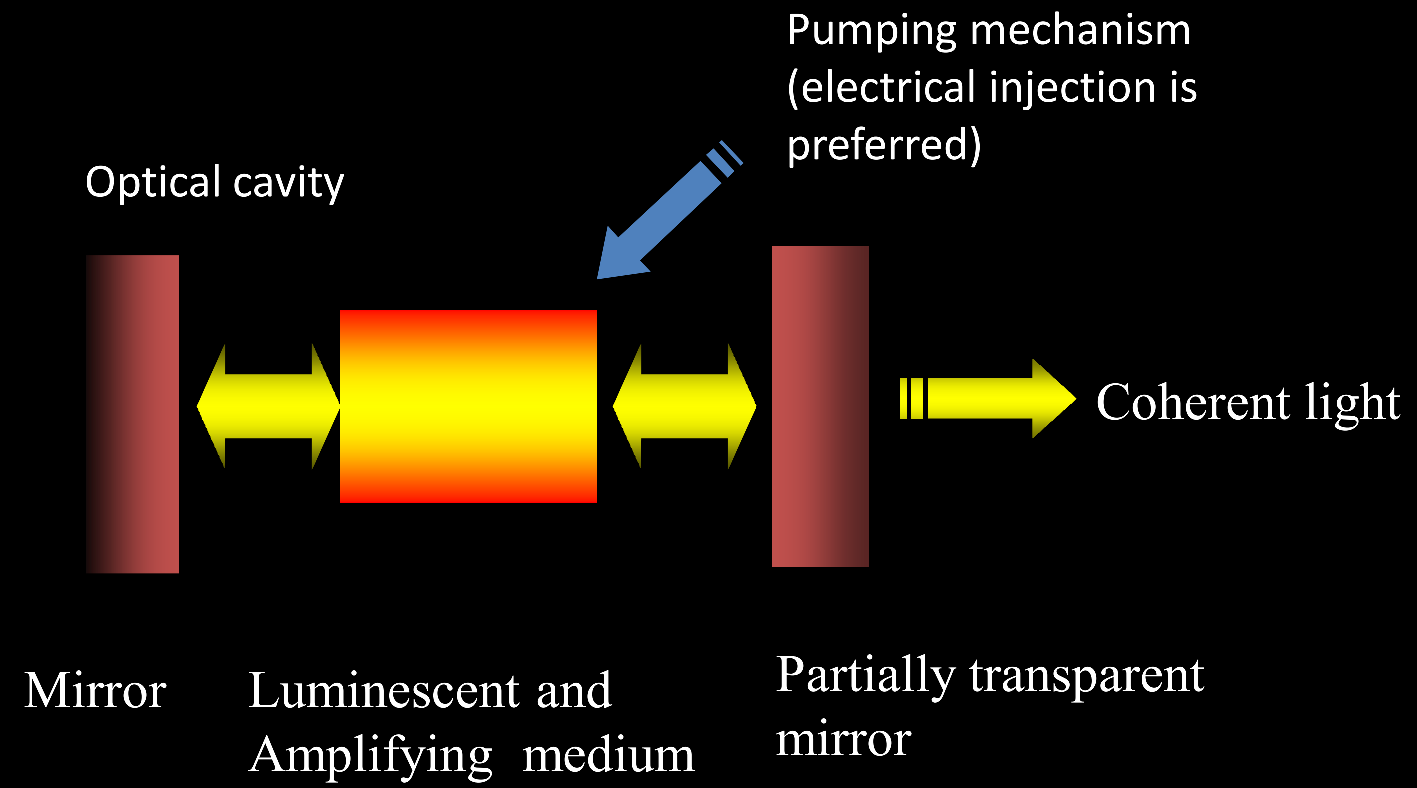
$$\eta_j = \left(1 + \frac{\mu_h N_A L_e}{\mu_e N_D L_h}\right)^{-1}$$

Injection efficiency for a flat pn junction

$$F_T = \frac{1}{4}\left(\frac{1}{n}\right)^2 \left[1 - \left(\frac{n-1}{n+1}\right)^2\right]$$

Transmission across a flat interface

What you need for a laser



Pumping mechanism (electrical injection is preferred)

Optical cavity

Coherent light

Mirror

Luminescent and Amplifying medium

Partially transparent mirror

Round trip gain $R^2G^2>1$

Basics on optical gain

Small signal gain is determined by population inversion (effective three level system)

$$G = \exp\left(\left(\Gamma g - \alpha\right) L\right)$$

$$= \exp\left[\left(\Gamma \sigma \left(N_2 - N_1\right) - \alpha\right) L\right]$$

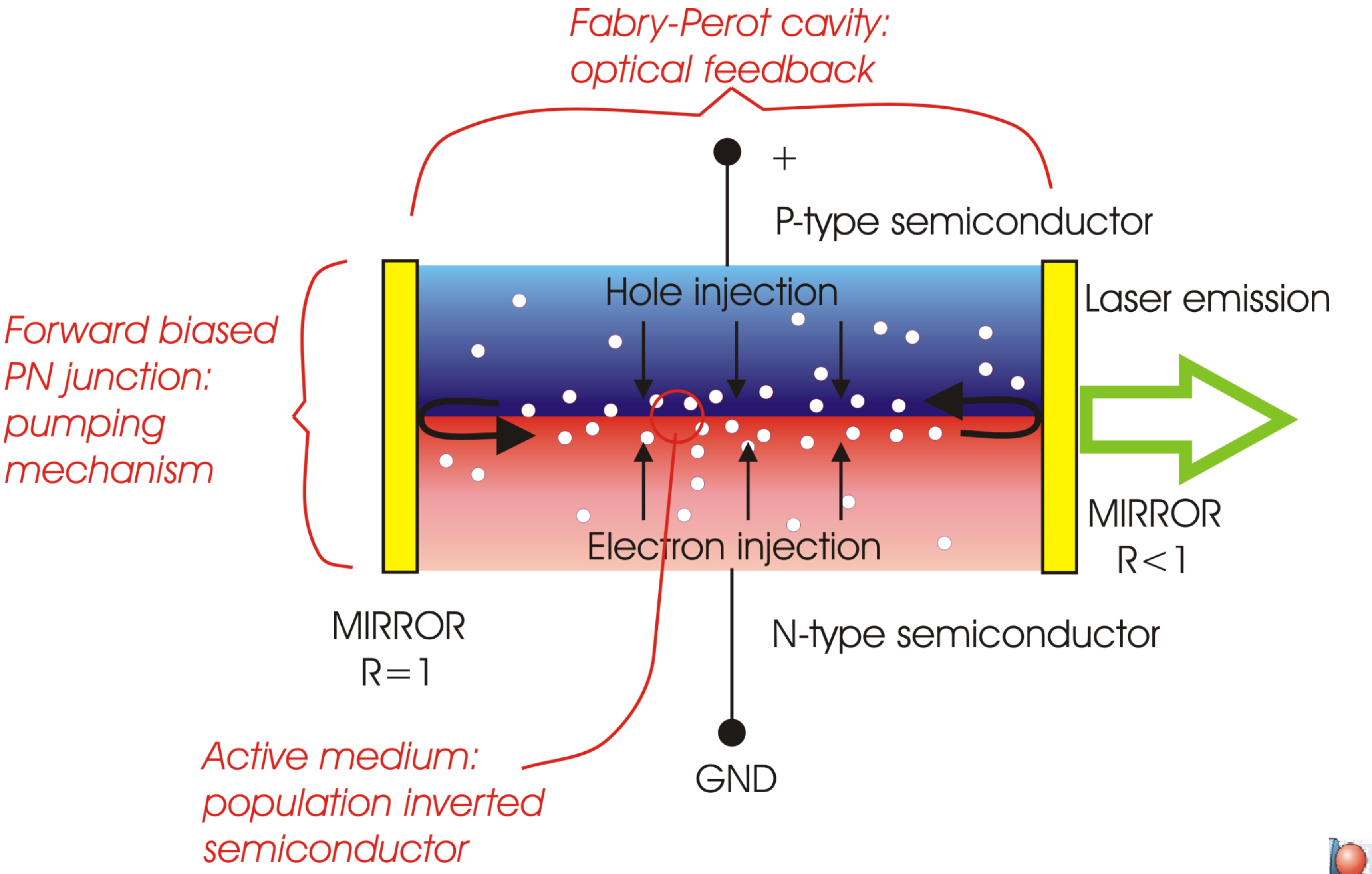
Emission/gain cross section

Optical/propagation losses

If $N_2 > N_1$ then $G > 1$

If $N_2 < N_1$ then $G < 1$ ← External pumping

Semiconductor injection laser



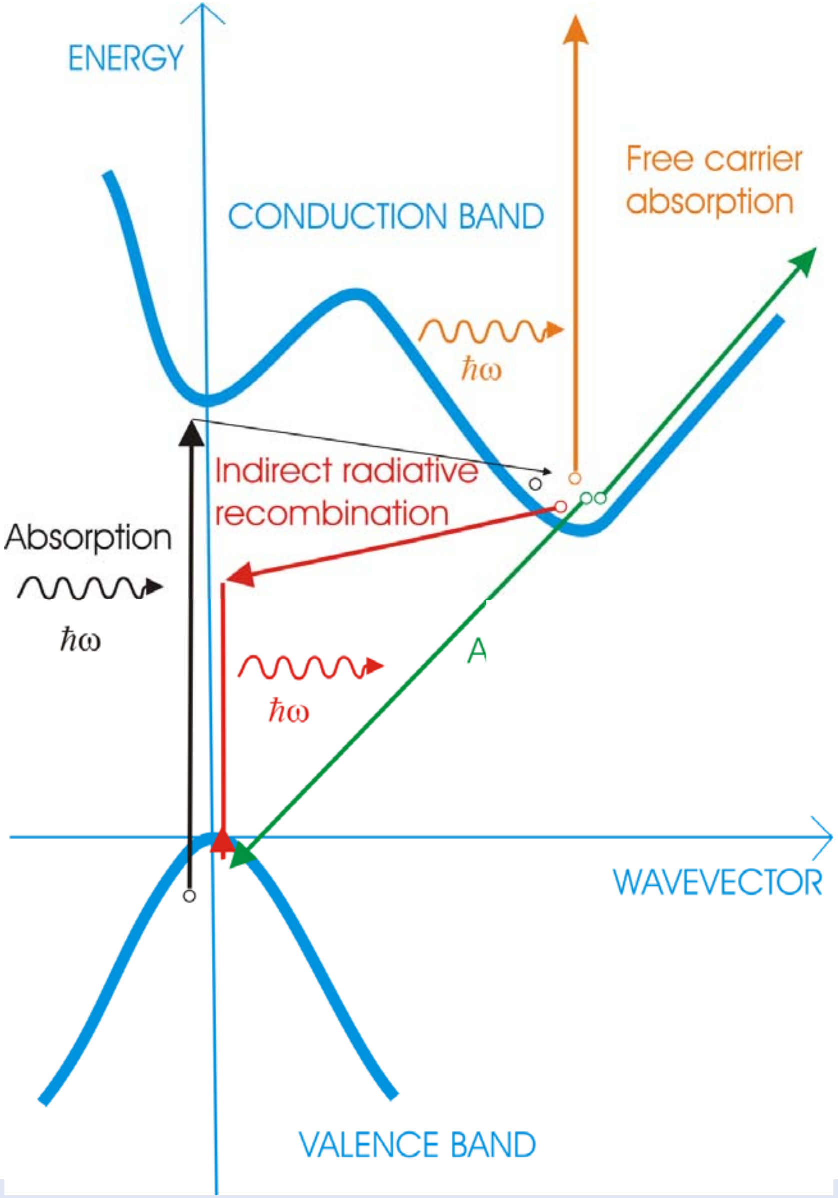
Bulk semiconductor

$$g\left(\hbar\omega\right)d\Phi\left(\hbar\omega\right)=dr_{stim}\left(\hbar\omega\right)-dr_{abs}\left(\hbar\omega\right)$$

$$=\frac{\lambda^2}{8\pi\tau_r}\rho\left(\hbar\omega\right)f_g\left(\hbar\omega\right)\Phi\left(\hbar\omega\right)dz$$

Silicon limits

What are the main problems with silicon?


ENERGY
CONDUCTION BAND
Free carrier absorption
ℏω
Indirect radiative recombination
Absorption
ℏω
ℏω
A
WAVEVECTOR
VALENCE BAND

Silicon luminescence

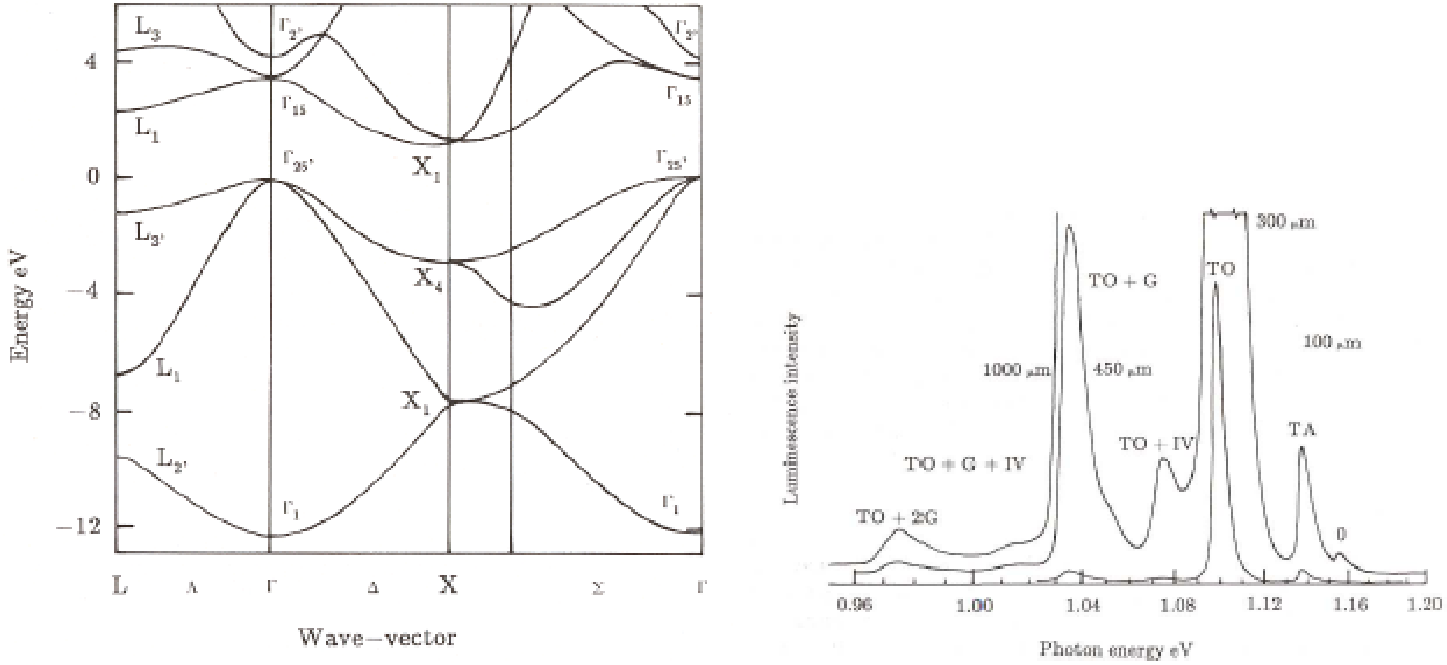


Fig. 1. Silicon band-structure and low-temperature photoluminescence spectrum. Radiative recombination without the participation of a phonon (peak labeled 0) is much weaker than radiative recombination involving at least one phonon. After Davies ([15])

Silicon limits: 1

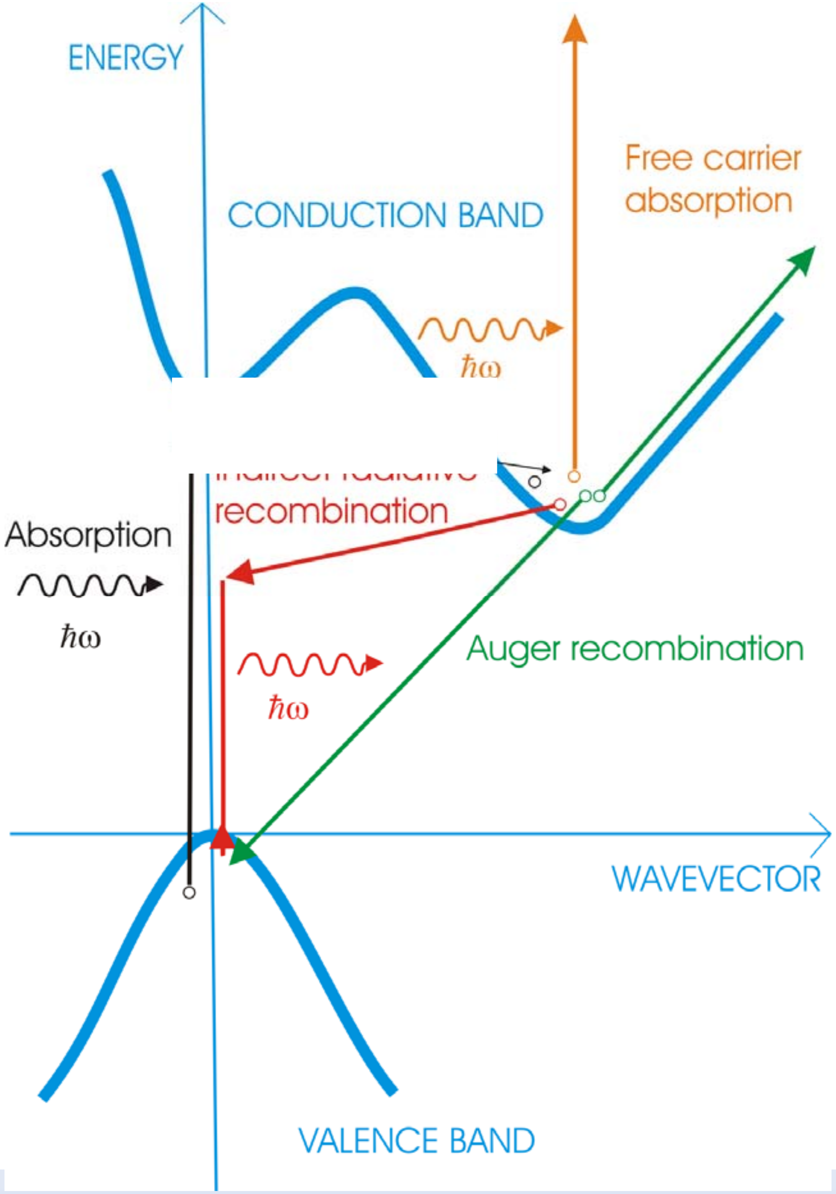
Indirect band gap =

low radiative recombination probability = long radiative lifetimes (ms)

- Free carriers move around =

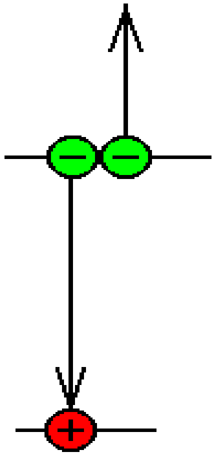
Non-radiative recombinations prevail

- Extremely low internal quantum efficiency in bulk silicon (10^{-6})


ENERGY
CONDUCTION BAND
Free carrier
absorption
ħω
recombination
Absorption
ħω
ħω
Auger recombination
WAVEVECTOR
VALENCE BAND

Silicon limits: 2

Efficient Auger recombinations prevent to reach population inversion



Silicon limits: 2

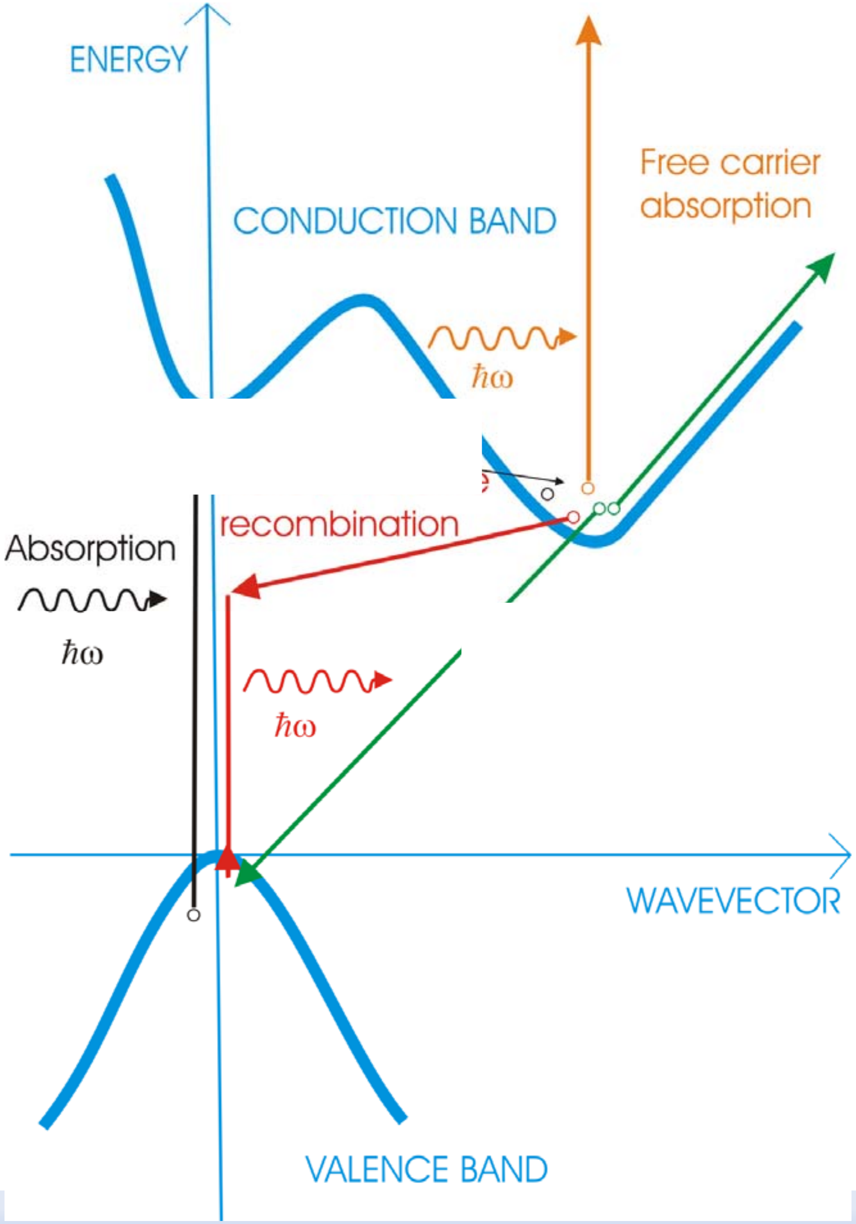
probability for an Auger recombination
since it is a three particle process

$$P_A \sim \Delta n^3$$

non-radiative recombination lifetime due to Auger

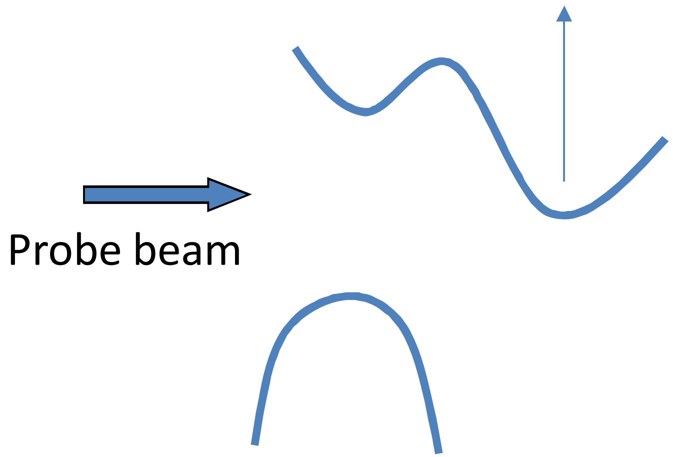
$$\tau_A = 1 / C \Delta n^2$$

For silicon C ~10^{-30} $cm^6 s^{-1}$
(i. e. τ_A= 10 ns for n=$10^{19} cm^{-3}$)


ENERGY
CONDUCTION BAND
Free carrier absorption
ħω
recombination
Absorption
ħω
ħω
WAVEVECTOR
VALENCE BAND

Silicon limits: 3

Free carrier absorption prevents to get stimulated emission



W.P.Dumke, Physical Review, 127 (1962) 1559

Silicon limits: 3

free carrier absorption coefficient at 300

$\alpha_n \sim 10^{-18}\, n_{fc} \cdot \lambda^2$

For $n_{fc}=10^{19}\text{cm}^{-3}$ and $\lambda=1.55\ \mu\text{m}$

$\alpha_n = 24\ \text{cm}^{-1}$

[Schroder, D. K., R. N. Thomos, and J. C. Swartz, *IEEE Trans. Electron. Dev.* **ED-25, 2**(1978) 254-261].

For heavily doped silicon this is the main limitations to lasing [dumke], while for intrinsic silicon this contribution can be exceedingly small.

Strategies to improve I_{PL}

Strategies to improve I_{PL}

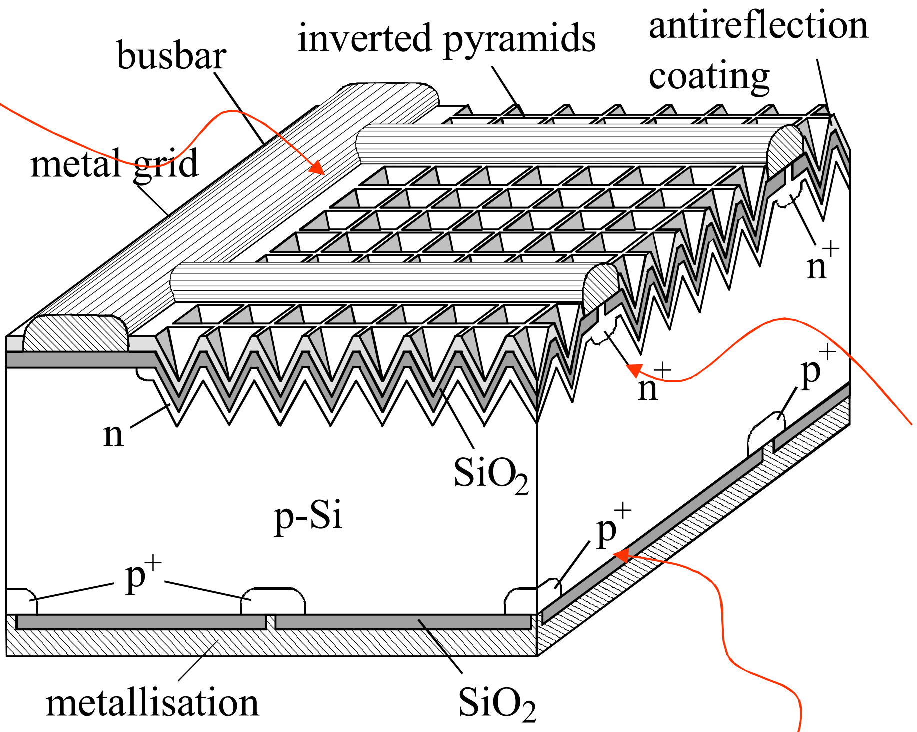
- Beat non-radiative recombinations
- Relax the k-selection rule
  - Impurity recombination
  - Amorphization
- Make the material direct
  - Alloy
  - Zone folding
  - strain
- Low dimensional silicon

Beat non radiative recombinations

Bulk Silicon

M. Green et al. NATURE 412 (2001) 805

Increased extraction efficiency



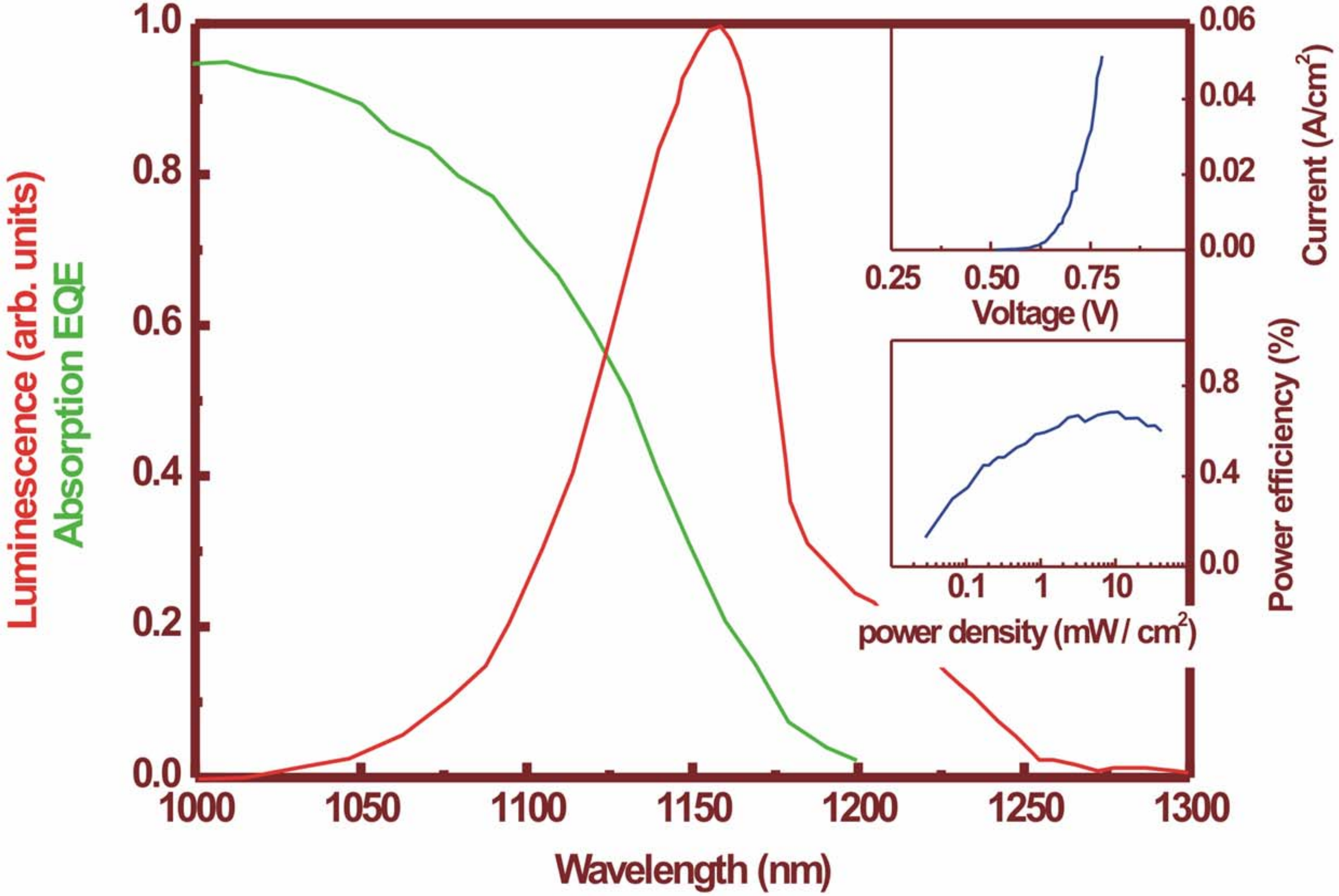
Low free carrier absorption

World record solar cells forward biased

Ultra-pure silicon with lifetime of 13 ms

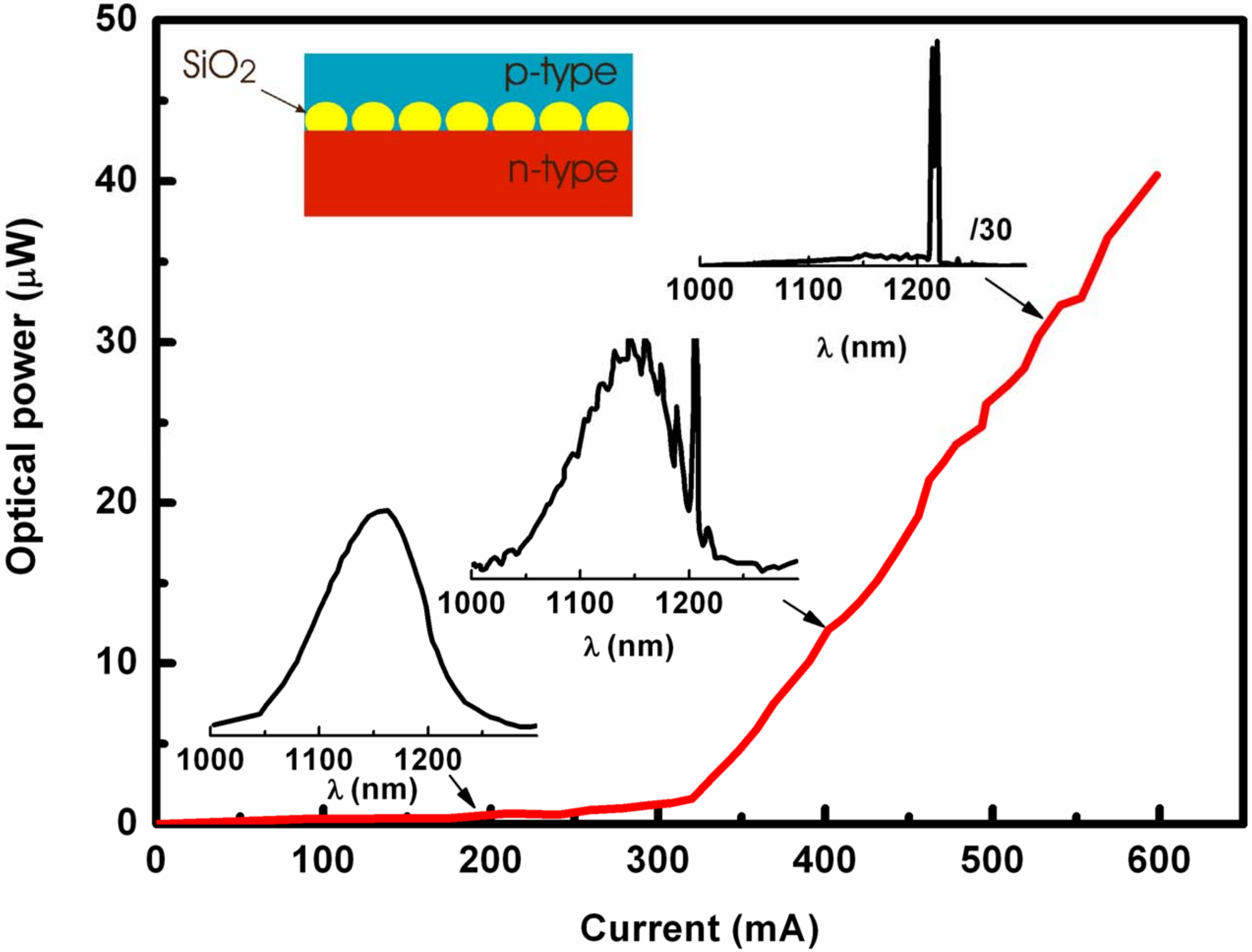
Bulk Silicon

M. Green et al. NATURE 412 (2001) 805



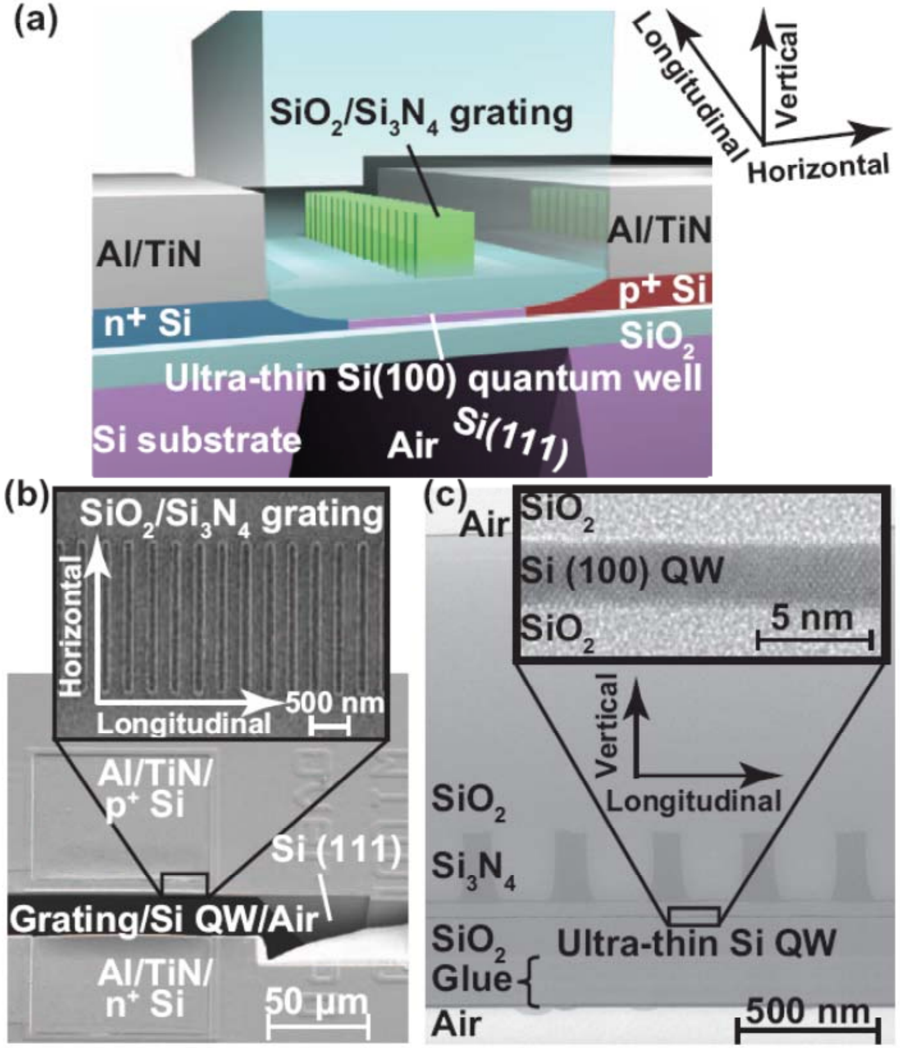
Bulk Silicon

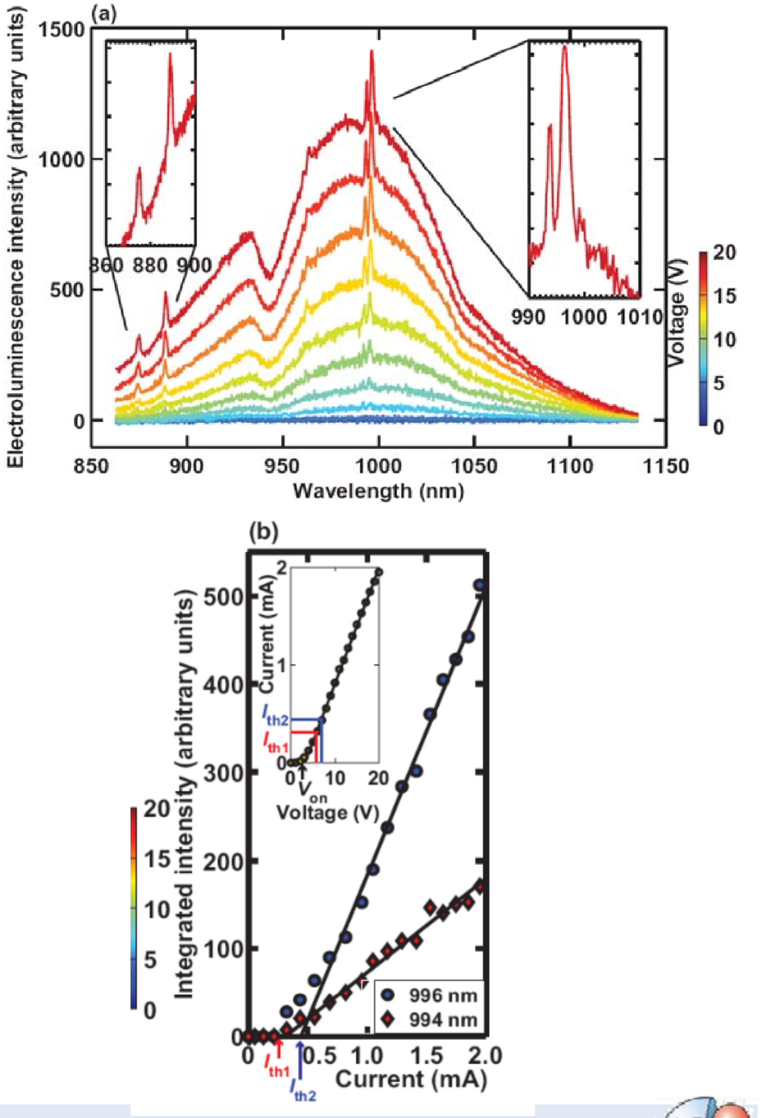
M. J. Chen, et al. APL 84 2004 2163



Bulk Silicon

S. Saito et al, APL 95, 241101 (2009)



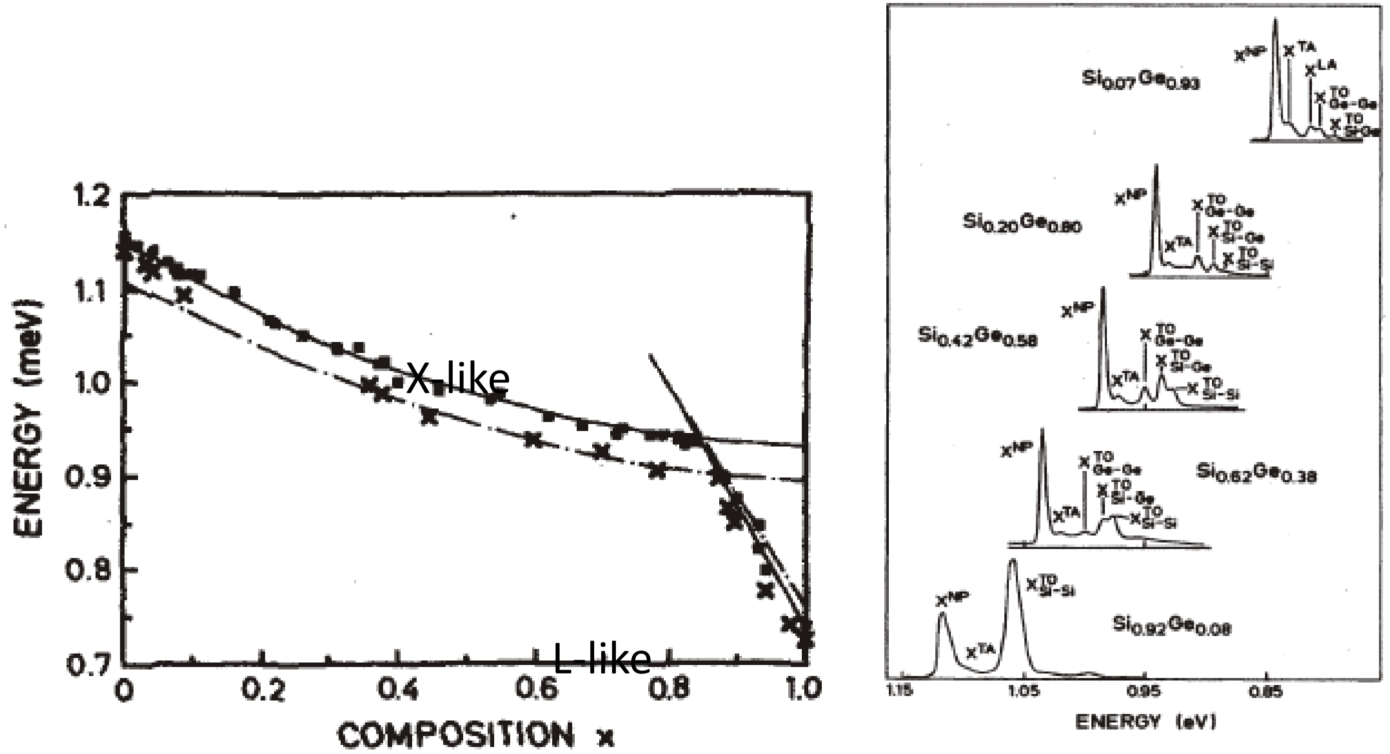


Band gap engineering

Beat the indirect band gap

Alloying

J. Weber Phys. Rev. B 40, 5683 (1989)

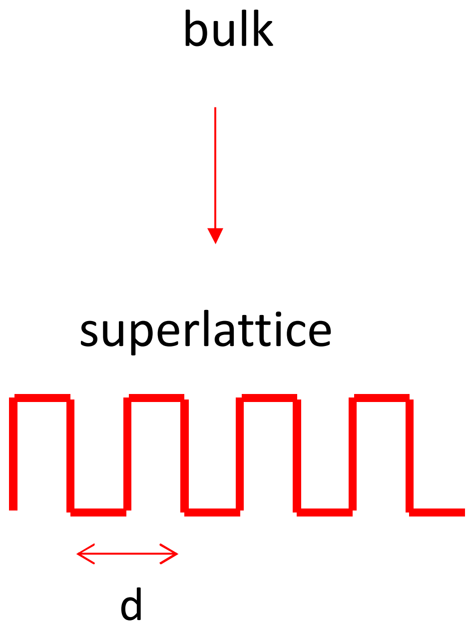


X-like

L-like

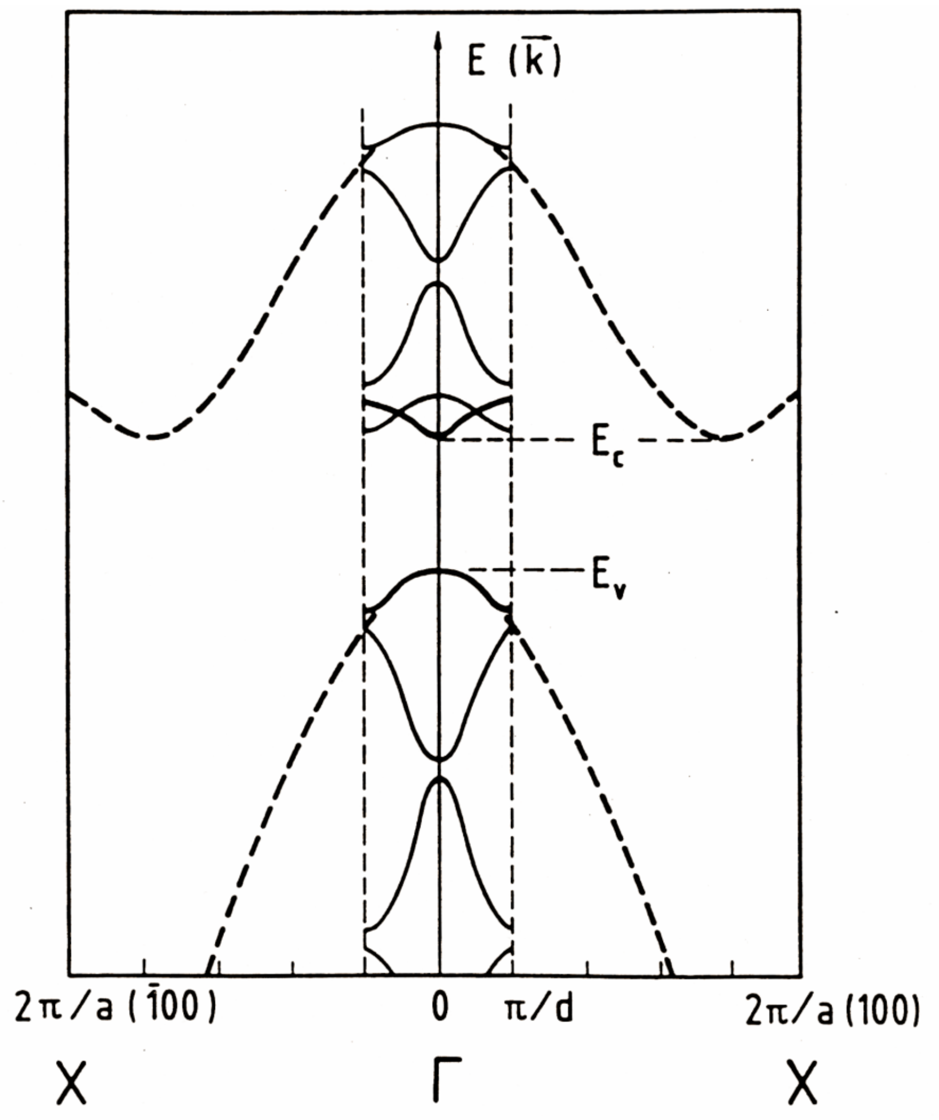
Fig. 1.11. *Left*: Excitonic band gap vs composition x for $Si_{1-x}Ge_x$ alloys. Square: [48]; cross: [49]. *Right*: Near band-gap luminescence spectra for several SiGe samples at 4.2 K. The optical transitions are named $X^j{}_i$ where j gives the type of transitions (no-phonon or phonon participation) and i specifies the nature of the phonon. After [48].

Zone folding concept


bulk

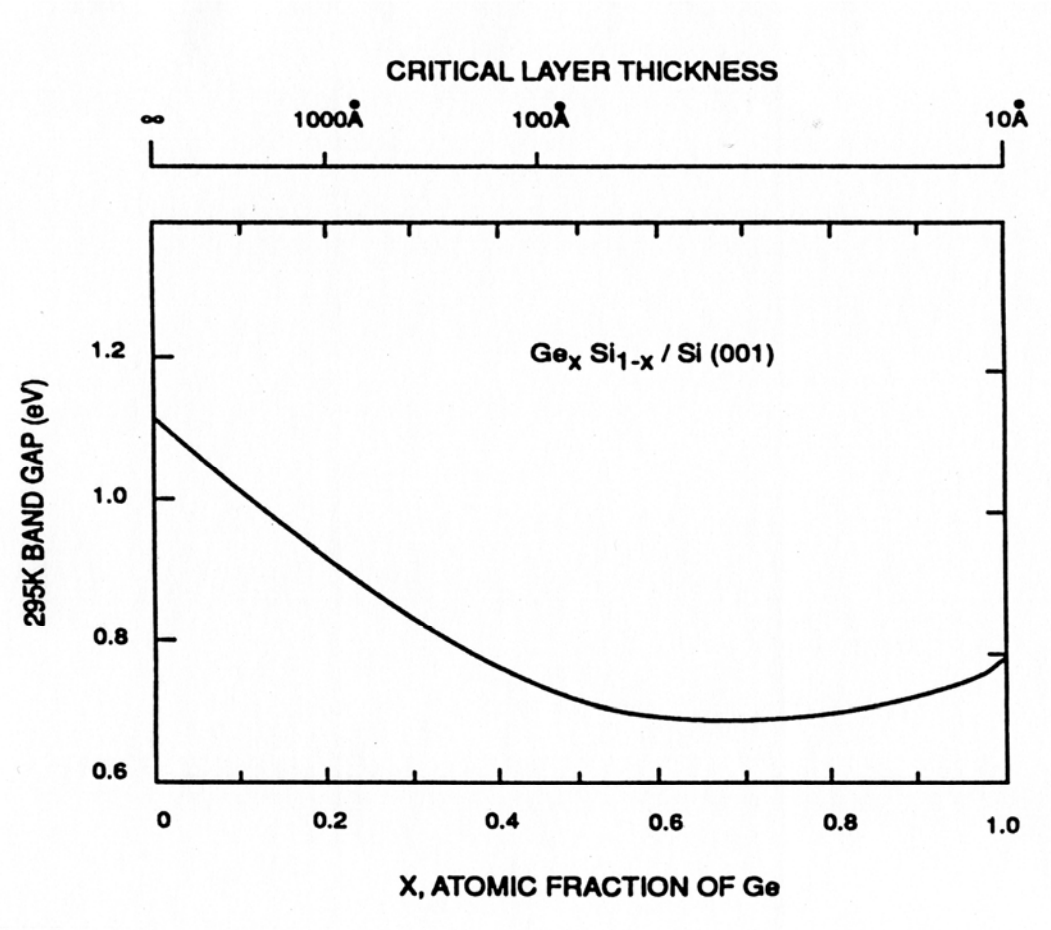
superlattice

d



Si-SiGe superlattice

Pearsall, Prog. Quantum Optics 18, 97 (1994)



Si-Ge mismatch of 4.2%

Strained Si-Ge superlattice

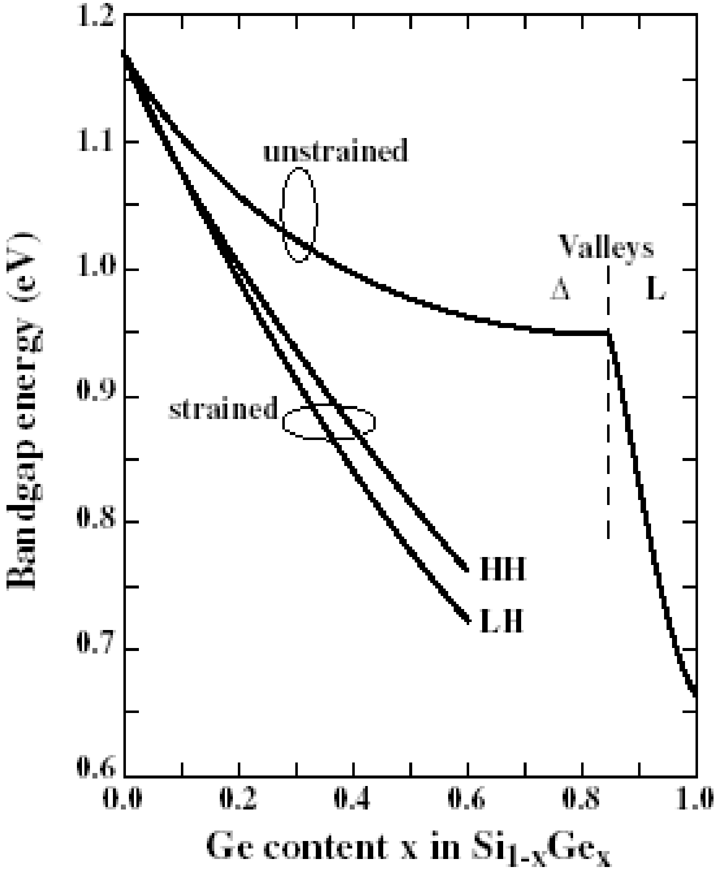


Figure 11. The bandgap in meV for strained $Si_{1-x}Ge_x$ grown on bulk-silicon substrates and for unstrained $Si_{1-x}Ge_x$ [56].

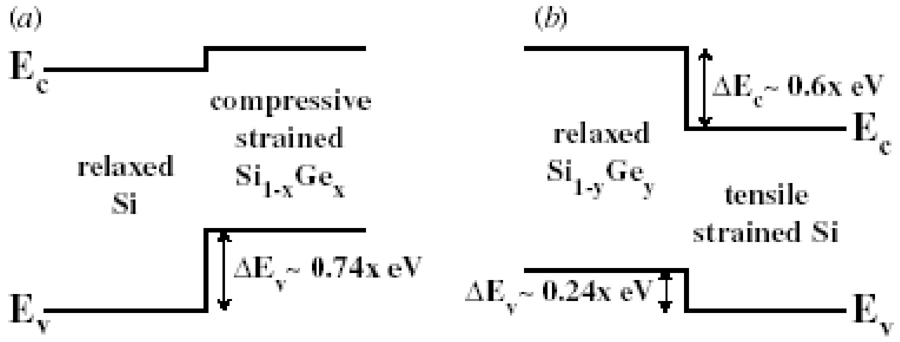


Figure 19. The band alignments and discontinuities for (*a*) a compressively strained-$Si_{1-x}Ge_x$ heterolayer grown on relaxed silicon and (*b*) a tensile strained-Si layer grown on relaxed $Si_{1-y}Ge_y$.

Ge dots in Silicon

K. Bruner, Rep. Prog. Phys. **65** (2002) 27–72

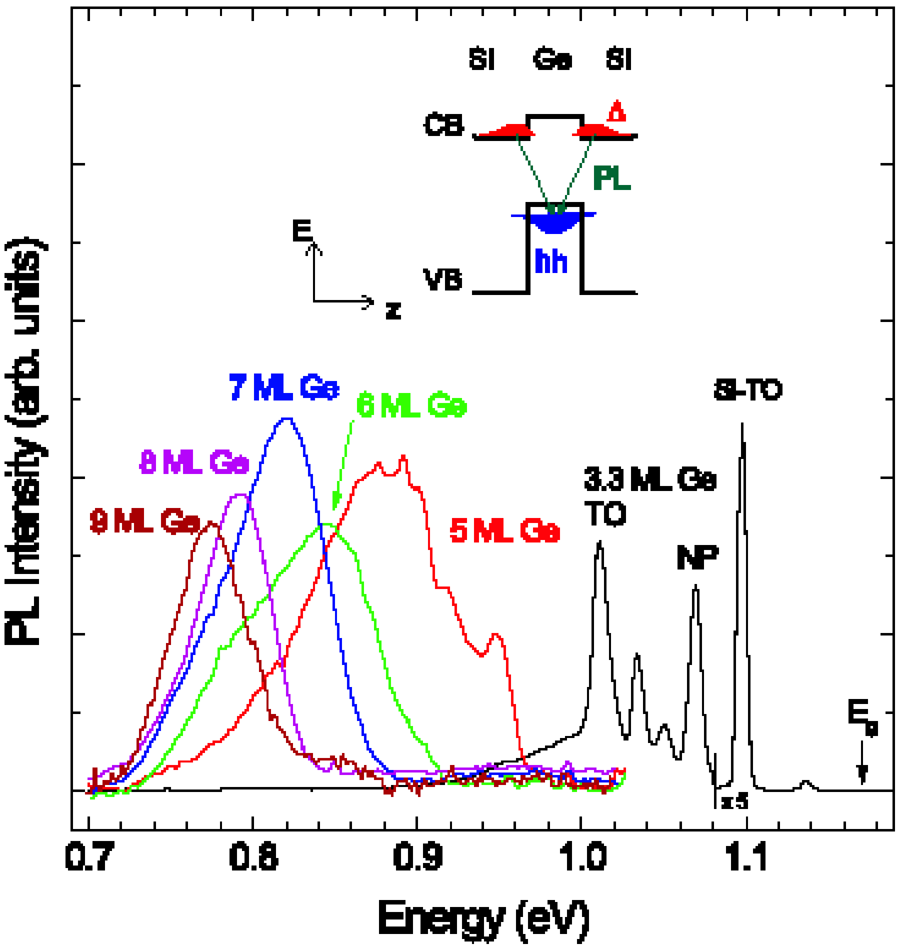
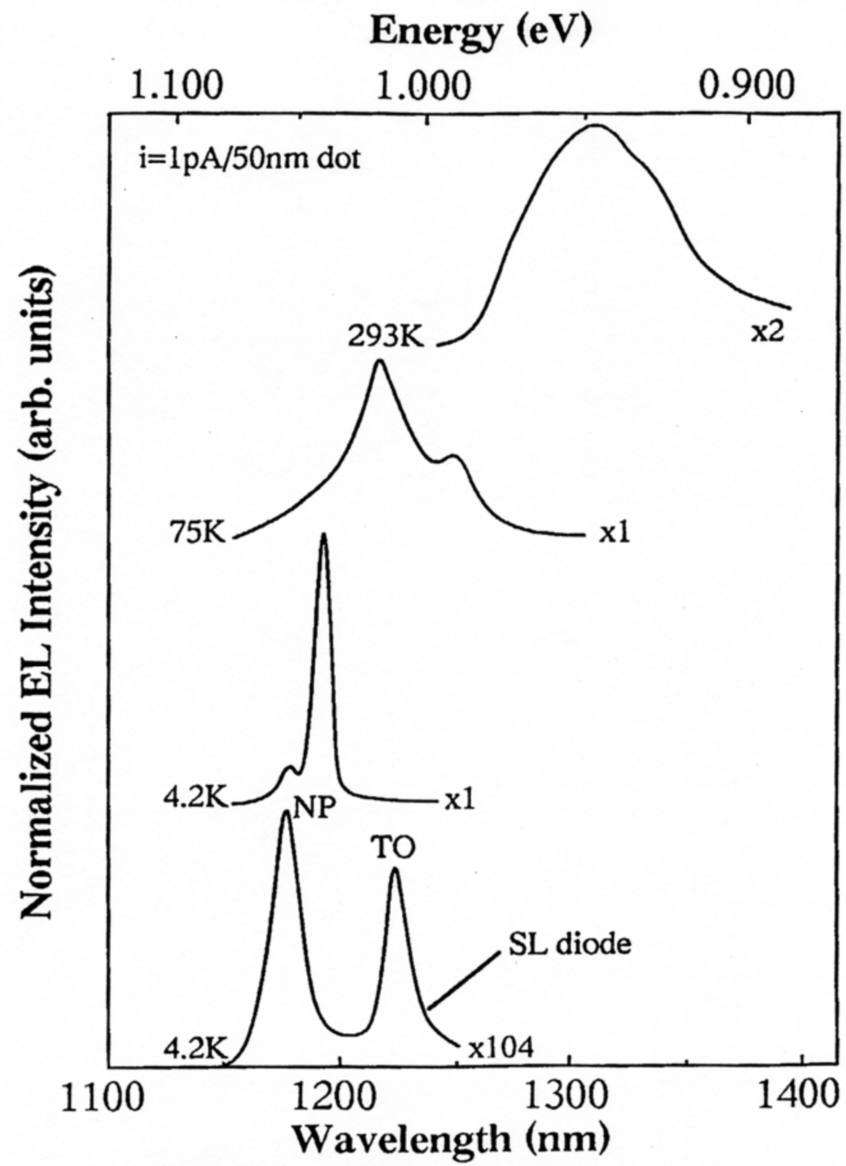


Figure 19. Low-temperature PL spectra from single Ge dot layers embedded in Si at $T_S = 510\,^{\circ}$C depending on Ge coverage. The inset sketches the band alignment and the indirect optical transition.

Electroluminescence from Ge dots

Y. S. Tang et al., Electron. Lett. 79, 1673 (2001)

Power efficiency 0.14%



Low dimensional Silicon

Beat the indirect band gap and avoid non radiative recombinations

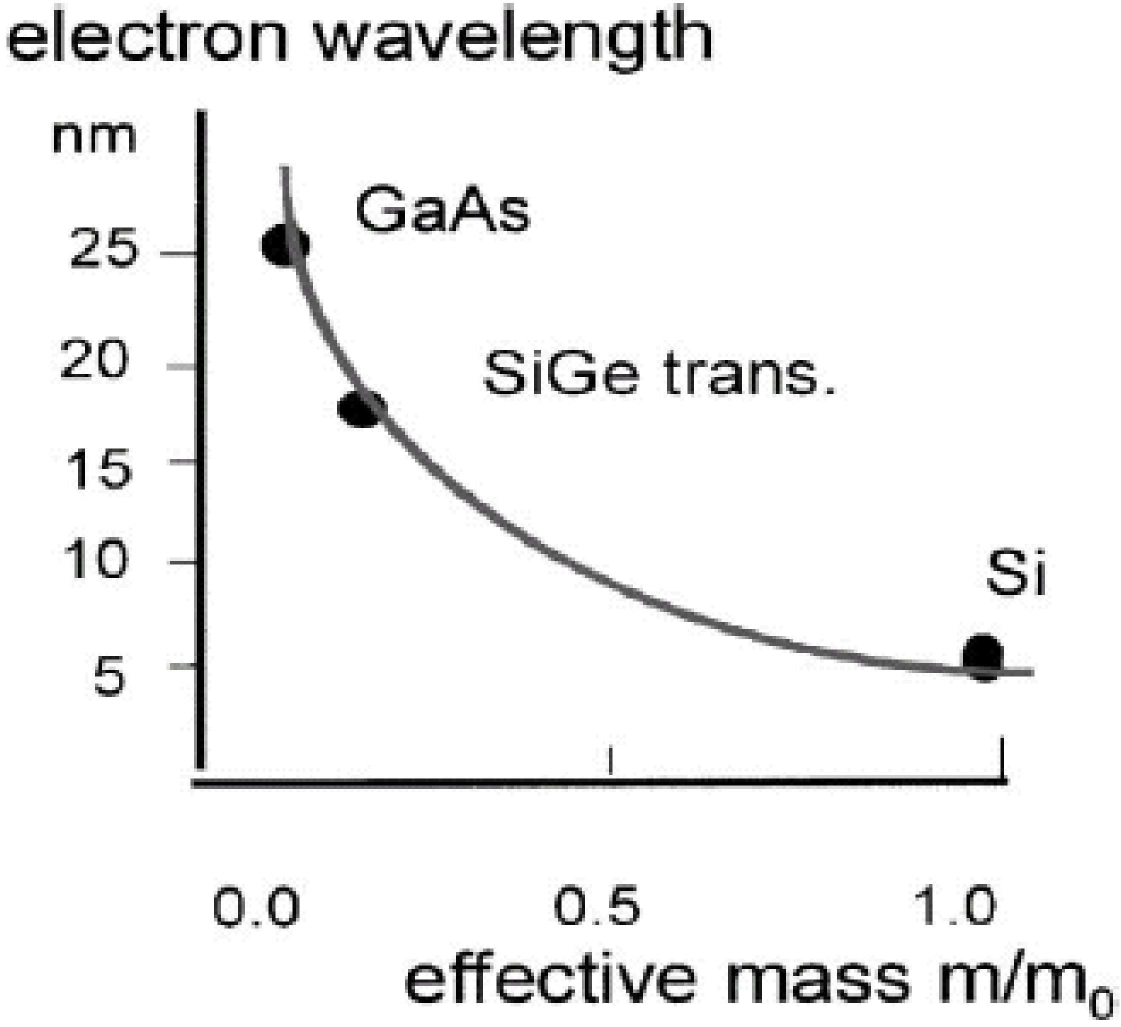
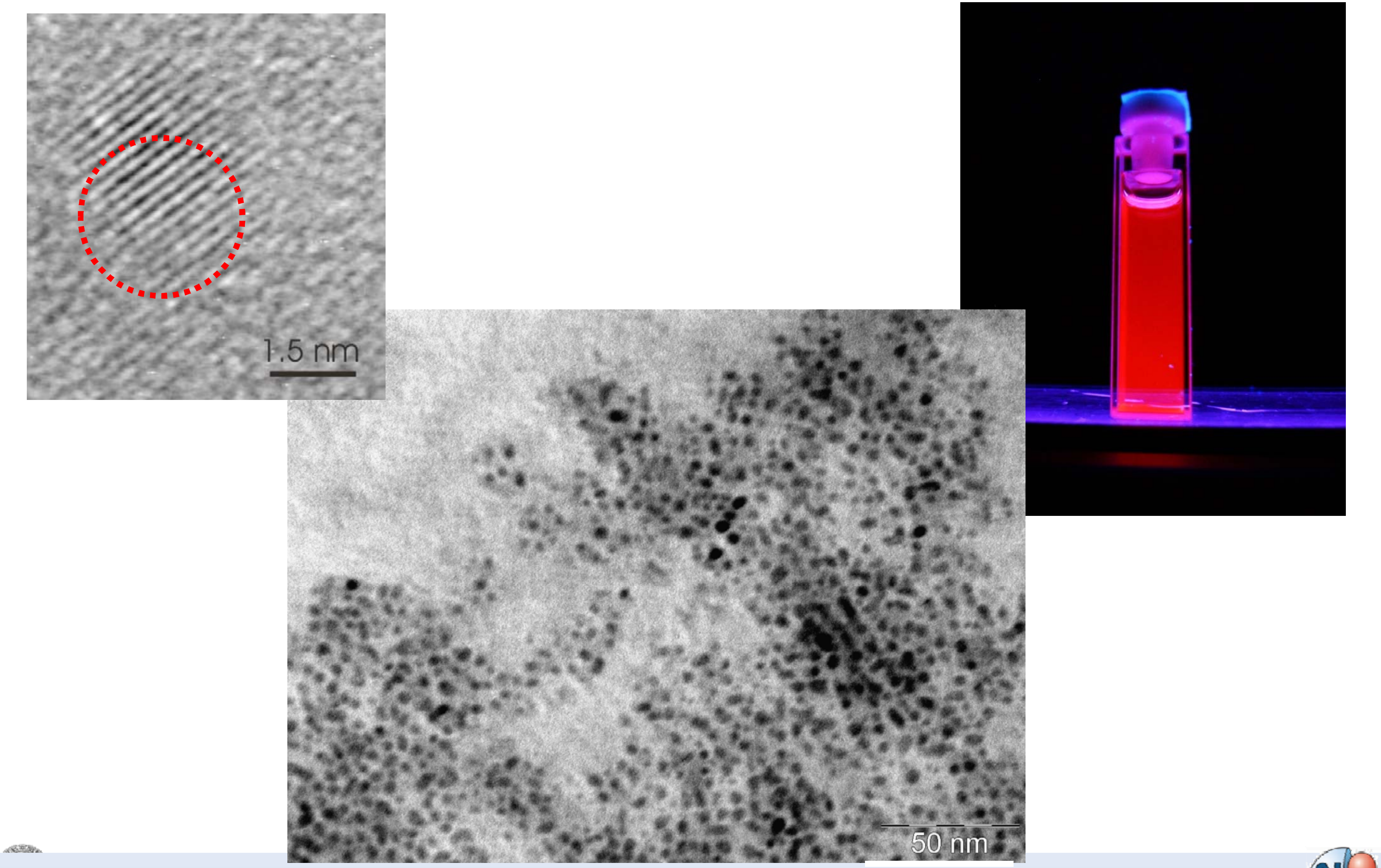


Fig. 3. De Broglie wavelength of an electron at 300 K.

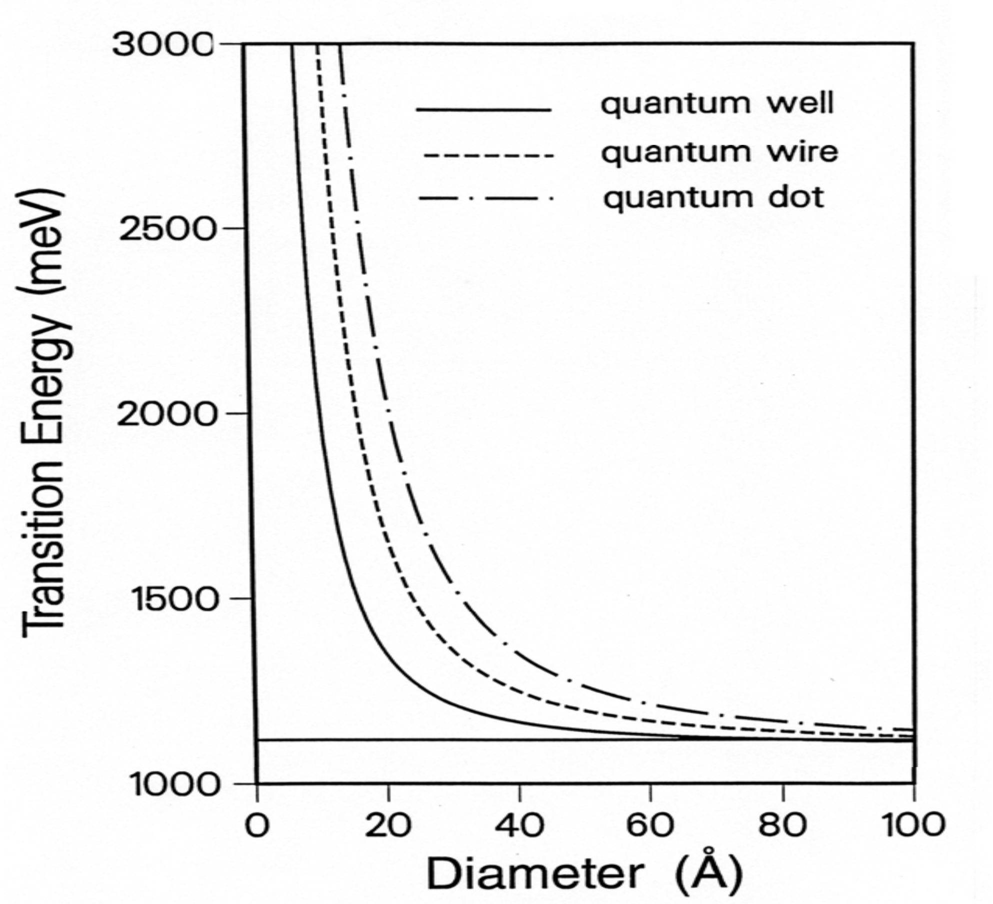
Low dimensional Silicon



Quantum = quantum size effects on the electronic properties of carriers in the silicon quantum dots

Quantum confinement: 1

$$E_{gap} = E_{gap}^{Si} + \frac{\hbar^2}{2m}\left(\frac{\pi}{L}\right)^2$$



Increase the emission energy

Quantum confinement: 2

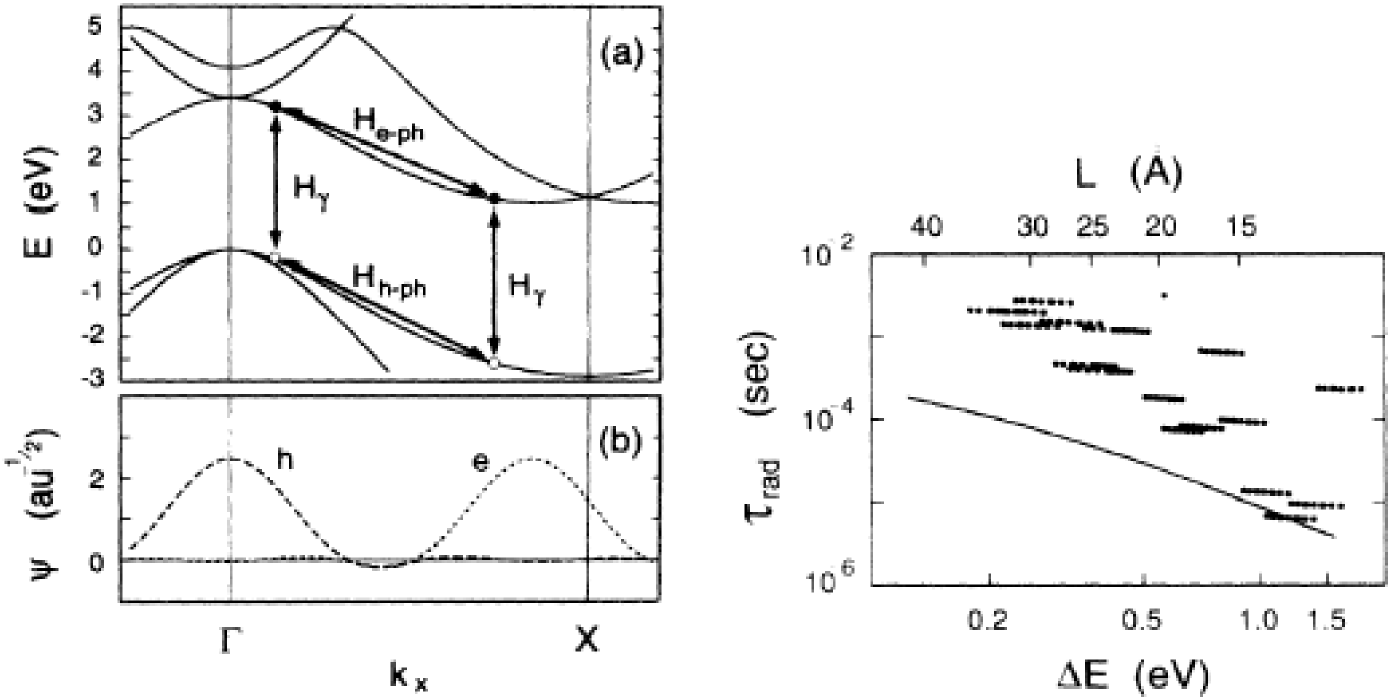
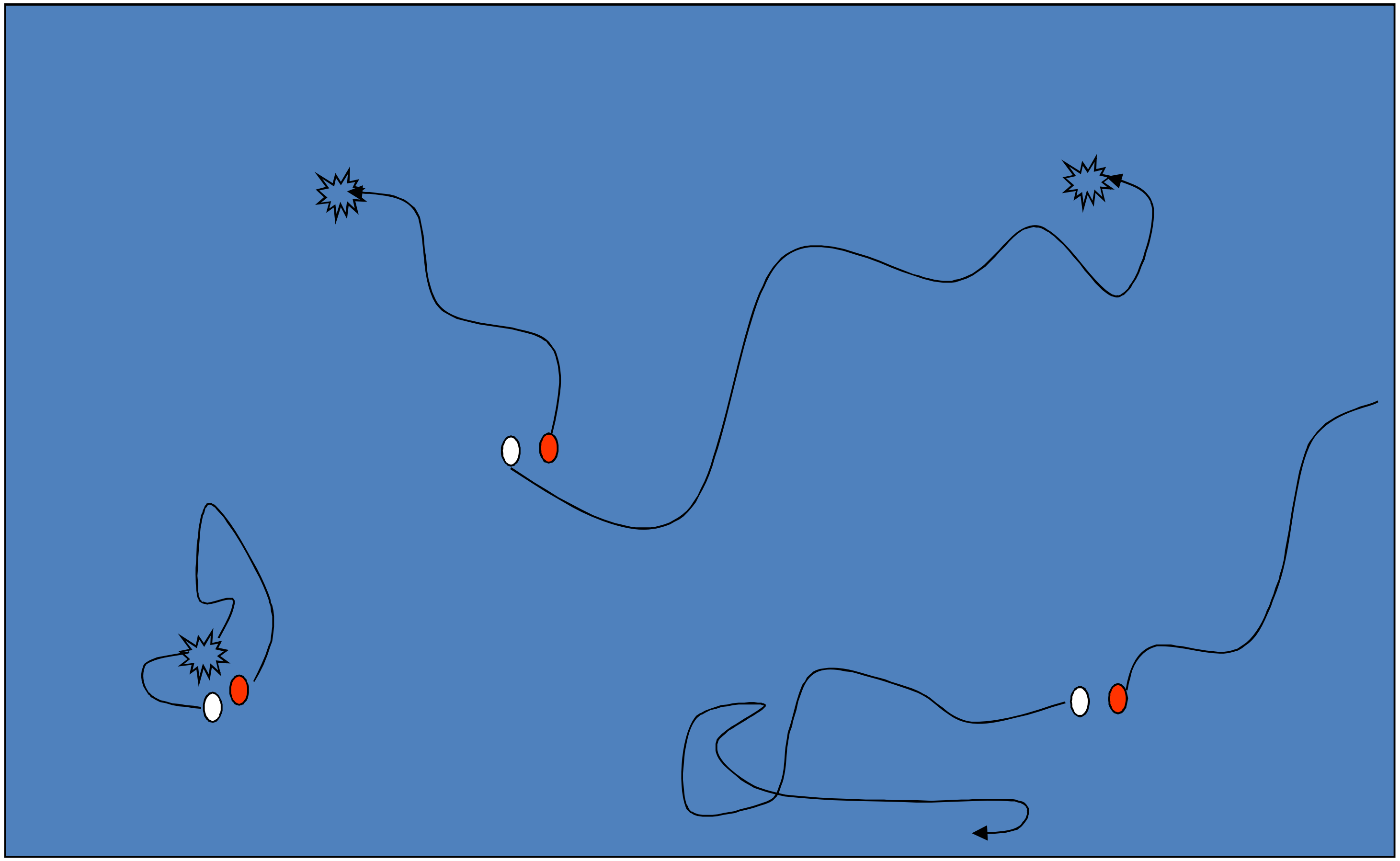


Fig. 3. Spread of the electron and hole wavefunction is a quantum dot and calculated radiative lifetime versus size for silicon quantum dots. The line corresponds to phonon-assisted recombination and the points to phonon-less recombination. After Hybertsen (Ref. [5])

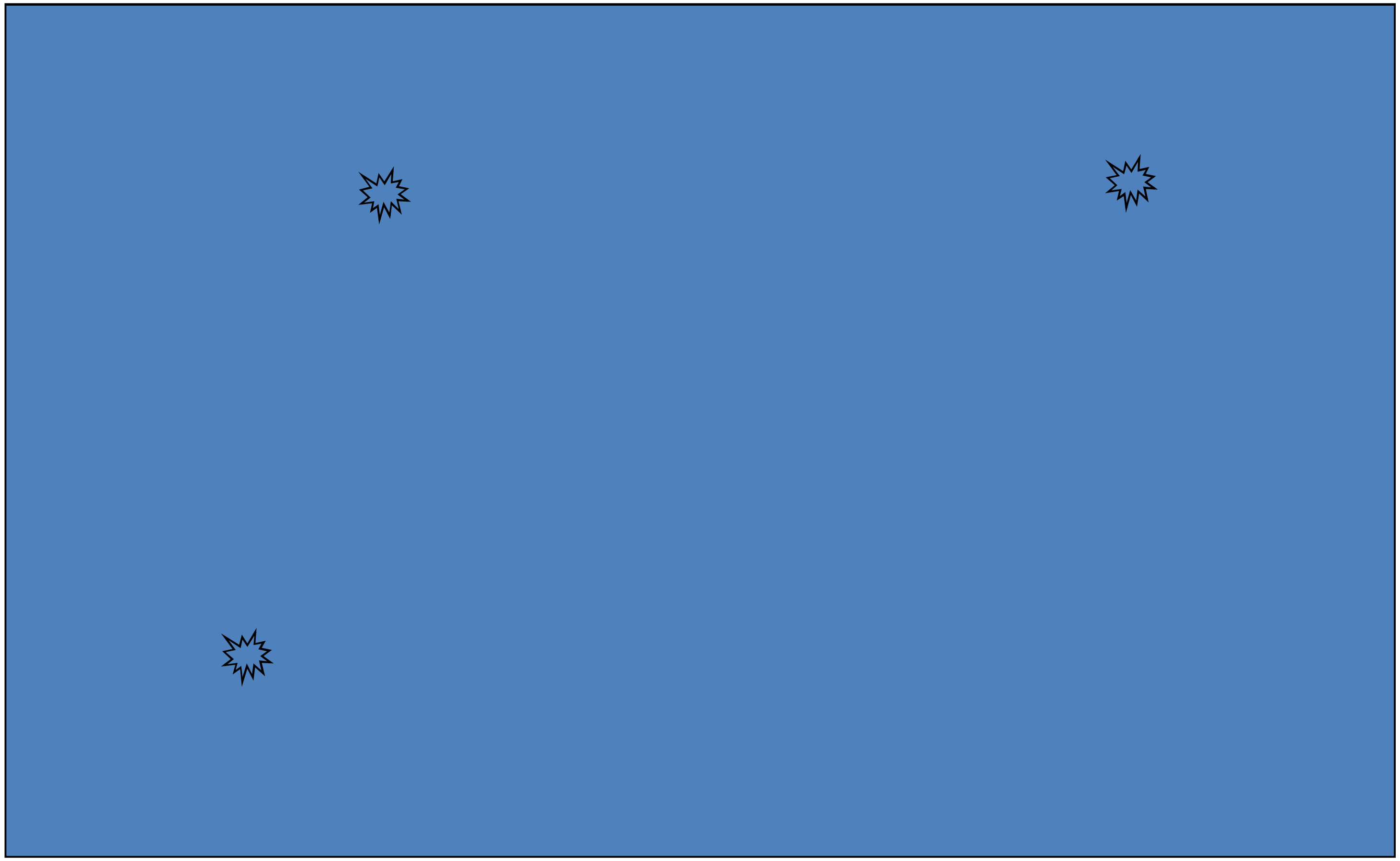
Increase the radiative recombination probability

Quantum confinement 3

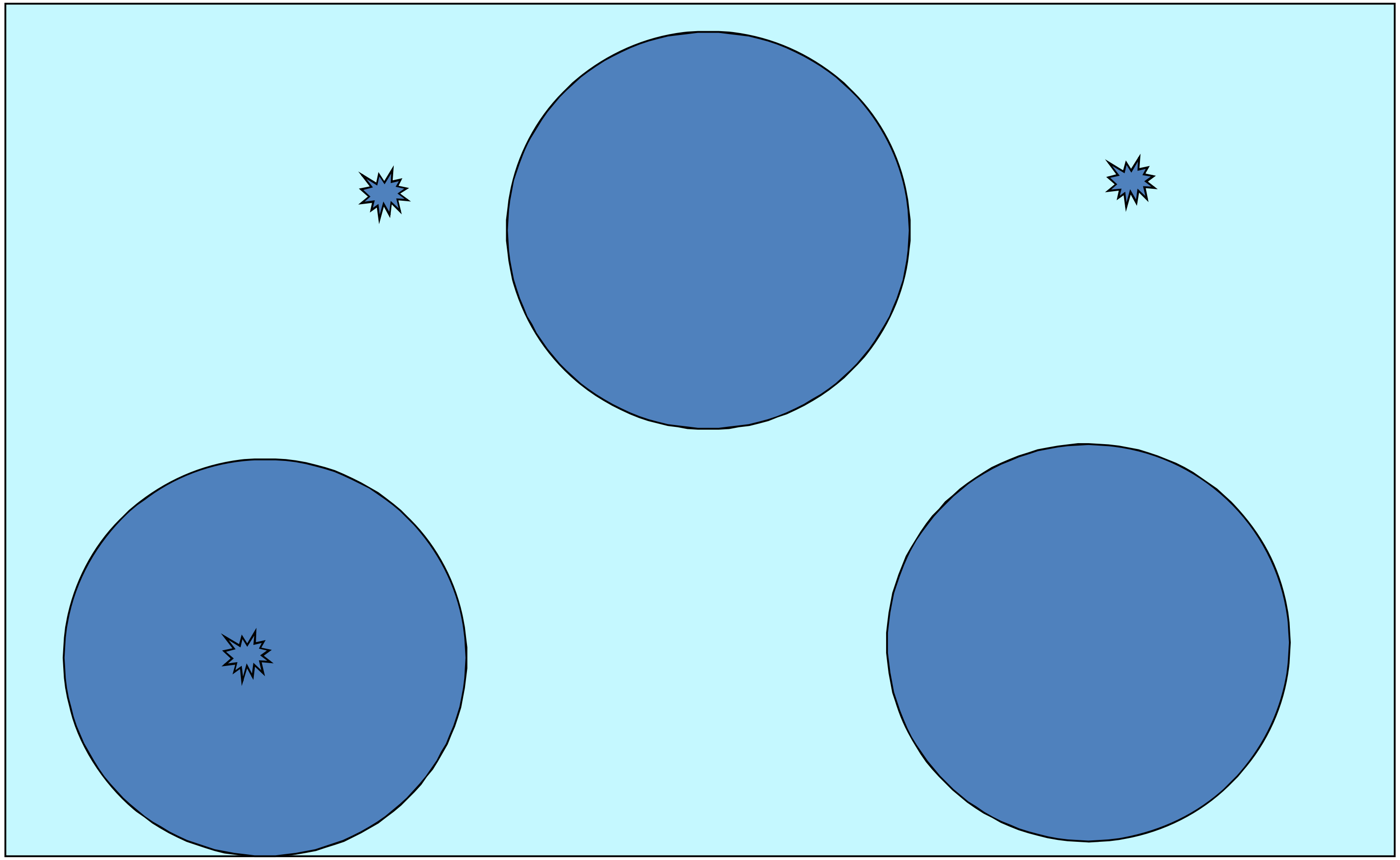
Quantum confinement 3



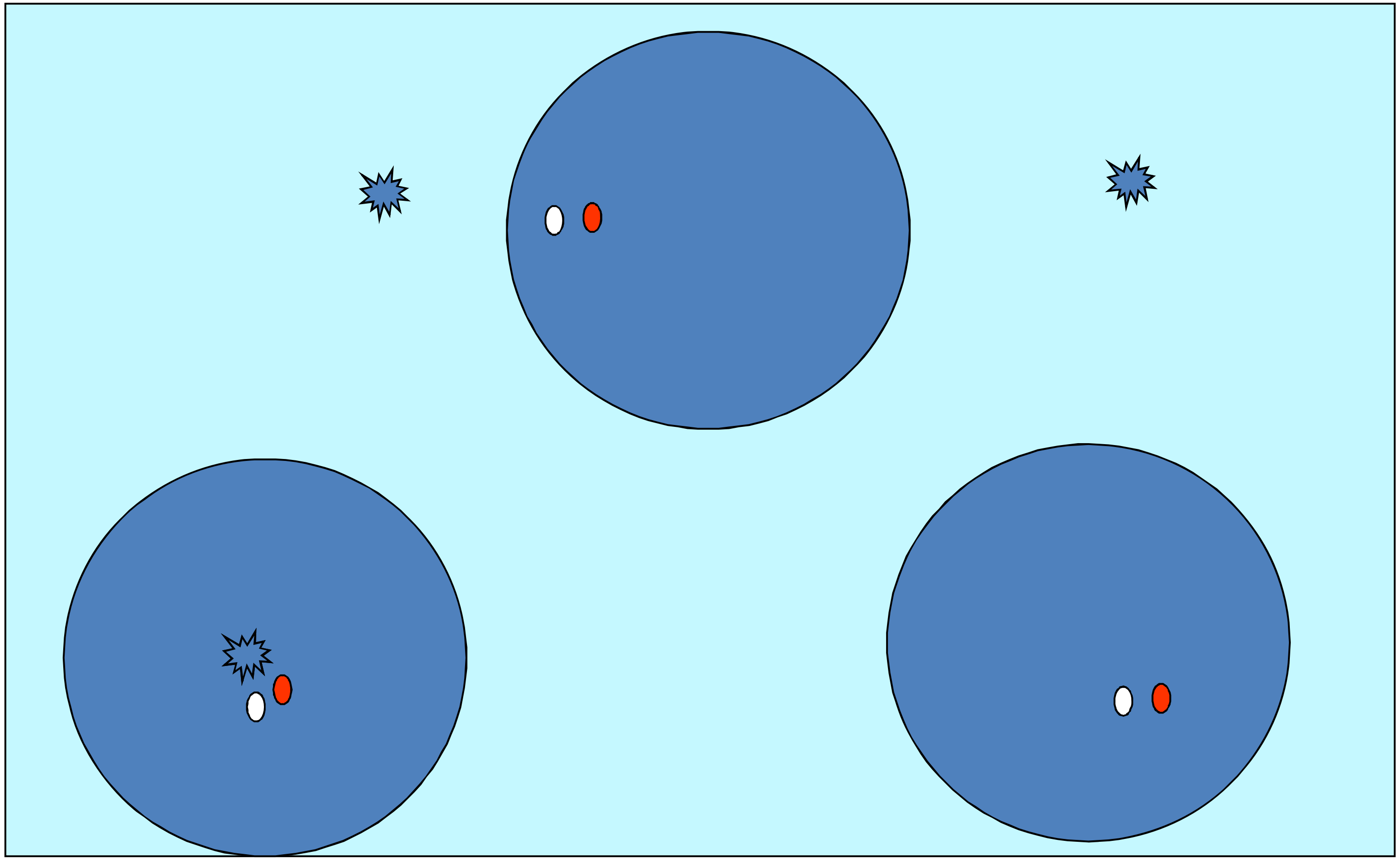
Quantum confinement 3



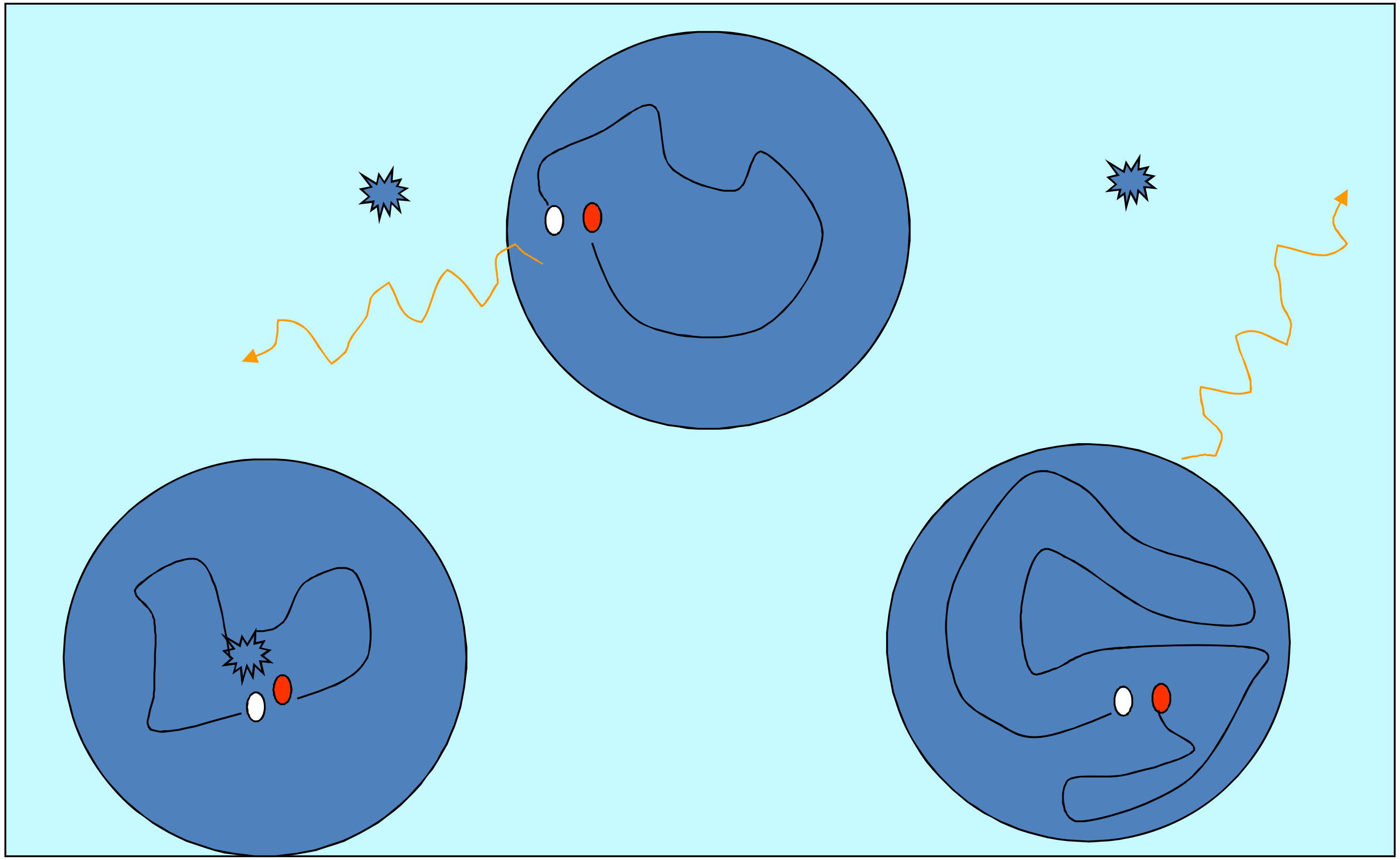
Quantum confinement 3



Quantum confinement 3

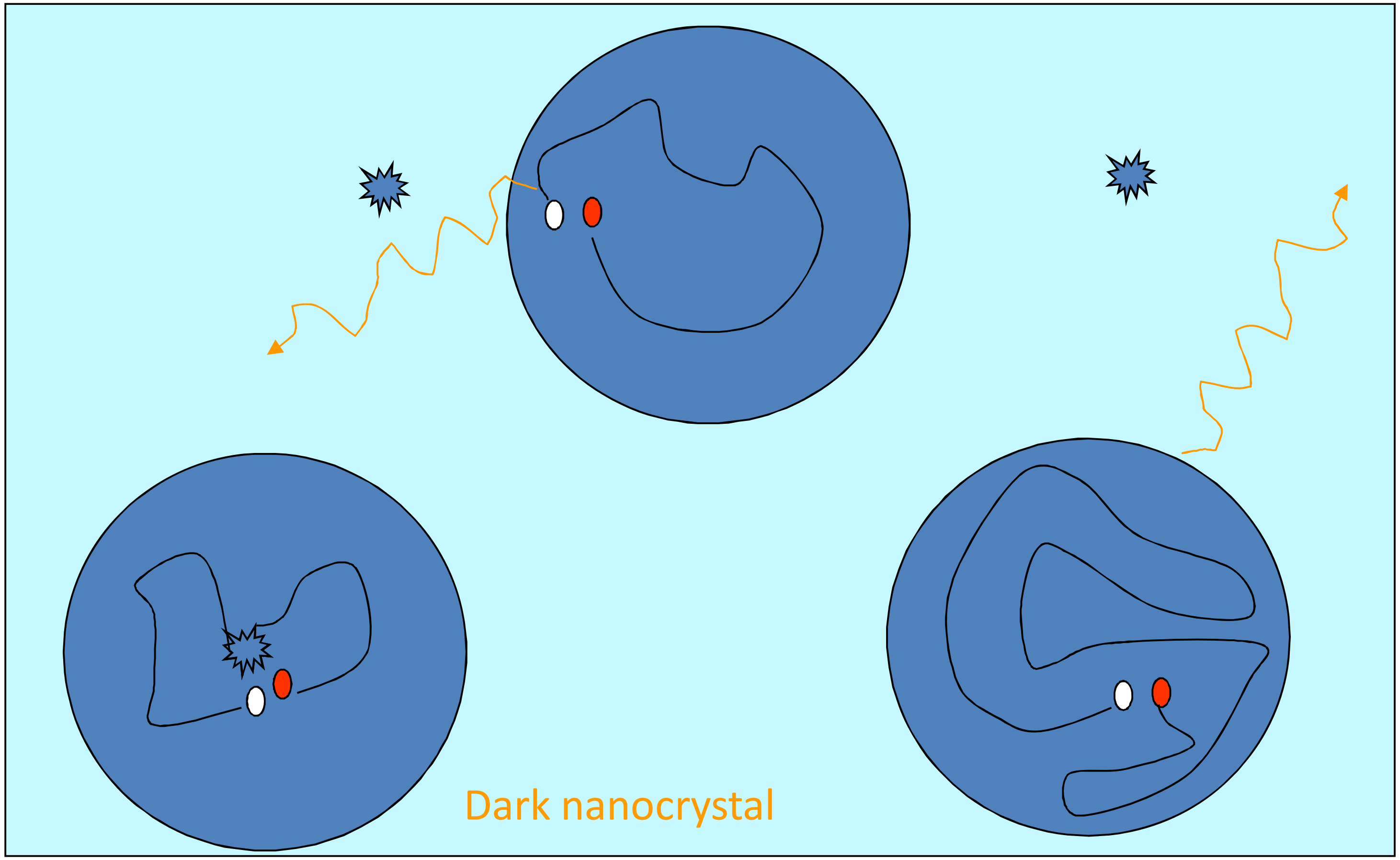


Quantum confinement 3



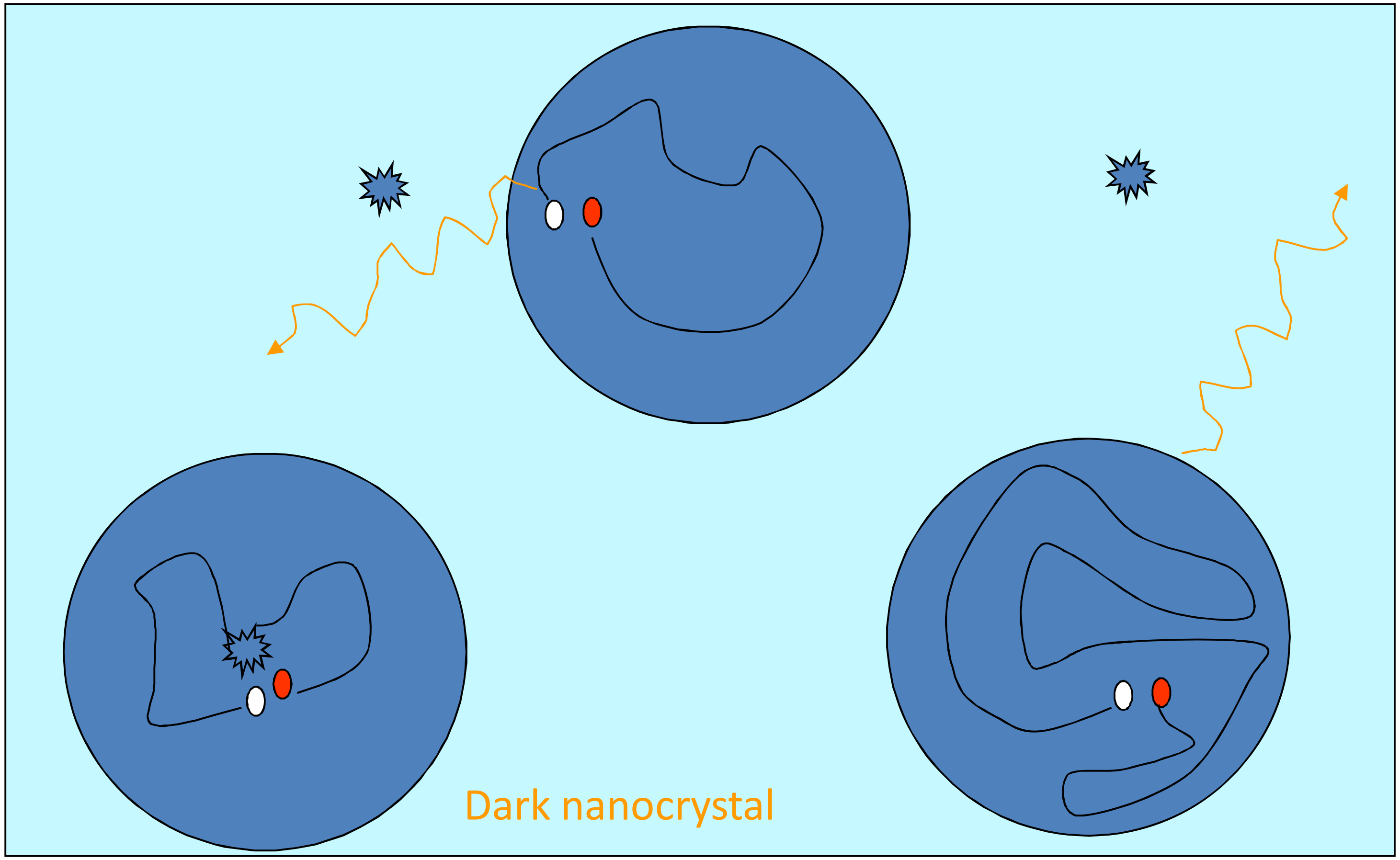
Quantum confinement 3

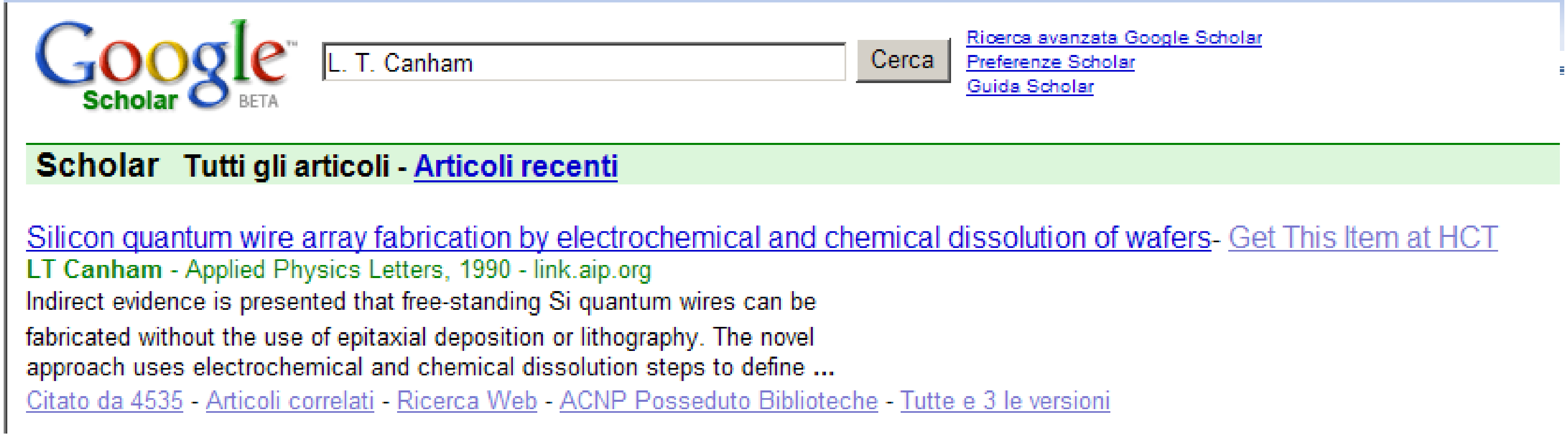
Reduce non radiative recombination by localization



Quantum confinement 3

Internal quantum efficiency = 0.66





Scholar **Tutti gli articoli** - **Articoli recenti**

Silicon quantum wire array fabrication by electrochemical and chemical dissolution of wafers- Get This Item at HCT

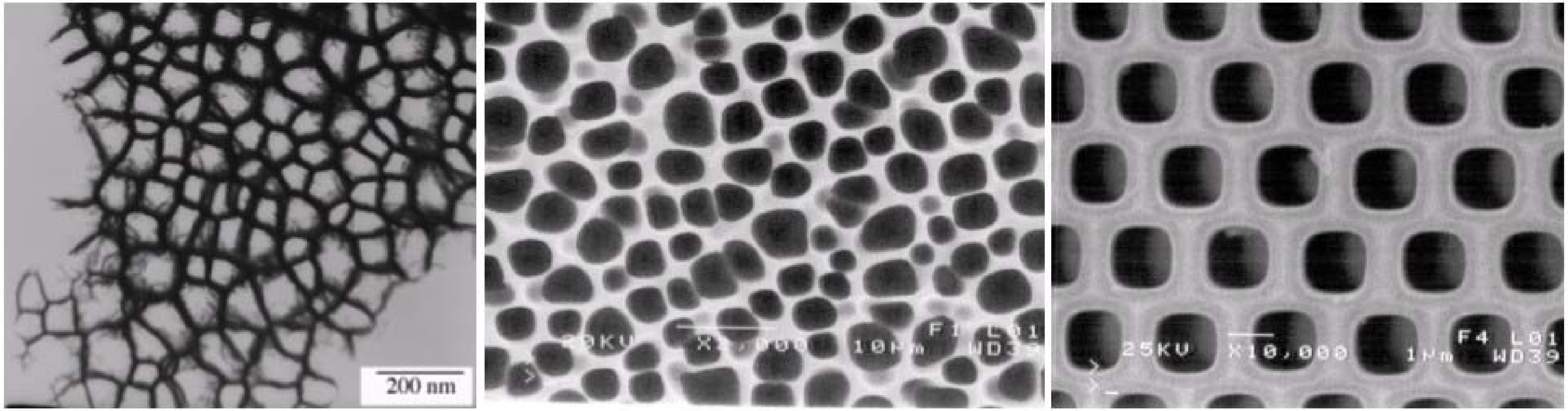
LT Canham - Applied Physics Letters, 1990 - link.aip.org

Indirect evidence is presented that free-standing Si quantum wires can be fabricated without the use of epitaxial deposition or lithography. The novel approach uses electrochemical and chemical dissolution steps to define ...

Citato da 4535 - Articoli correlati - Ricerca Web - ACNP Posseduto Biblioteche - Tutte e 3 le versioni

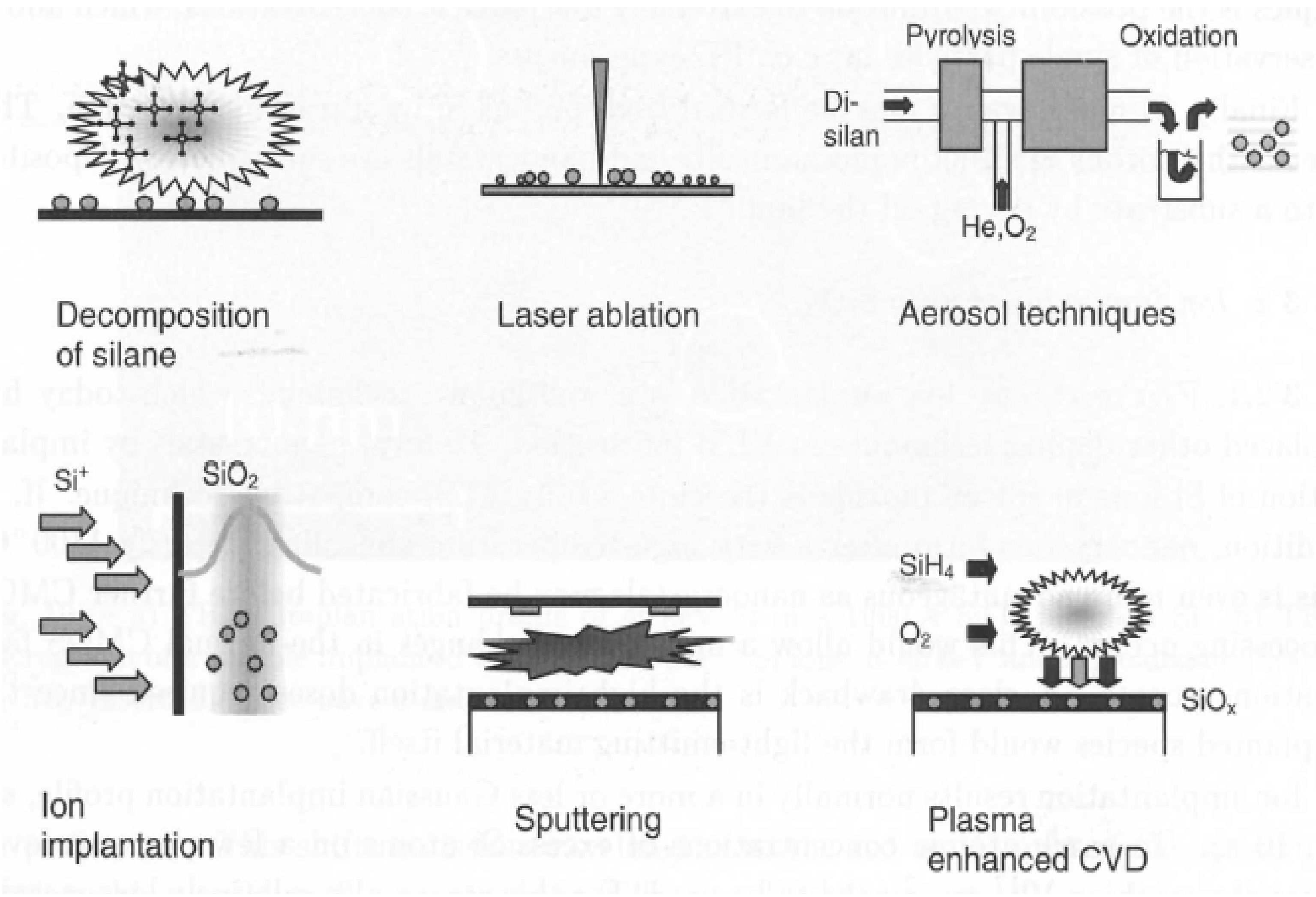
Strong light emission from silicon due to quantum confinement effects

To form silicon nanocrystals

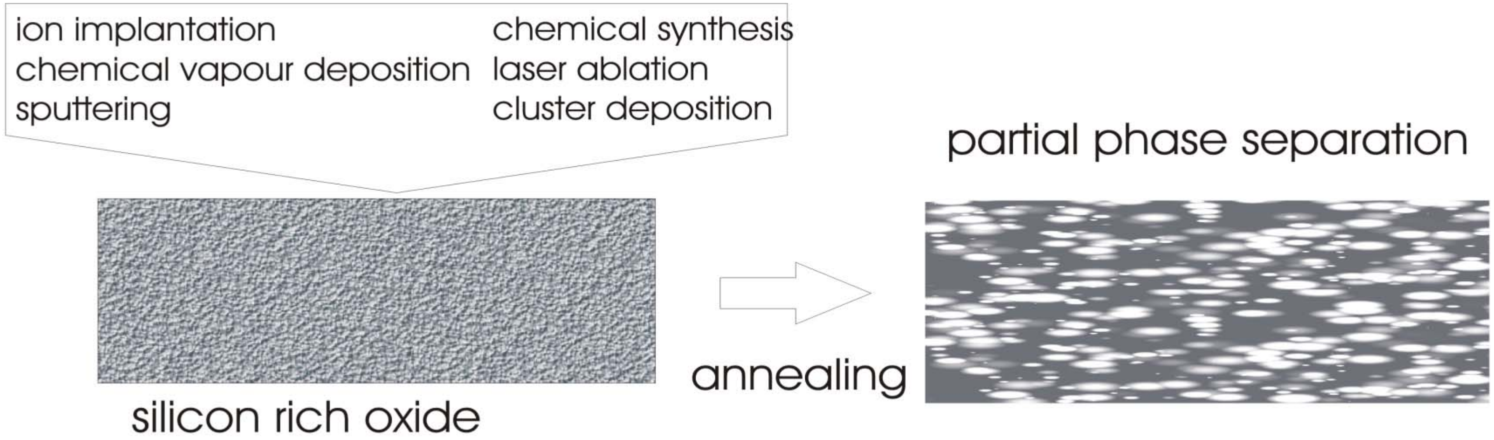


Porous silicon: partial electrochemical dissolution of silicon

To form silicon nanocrystals



Low dimensional Silicon

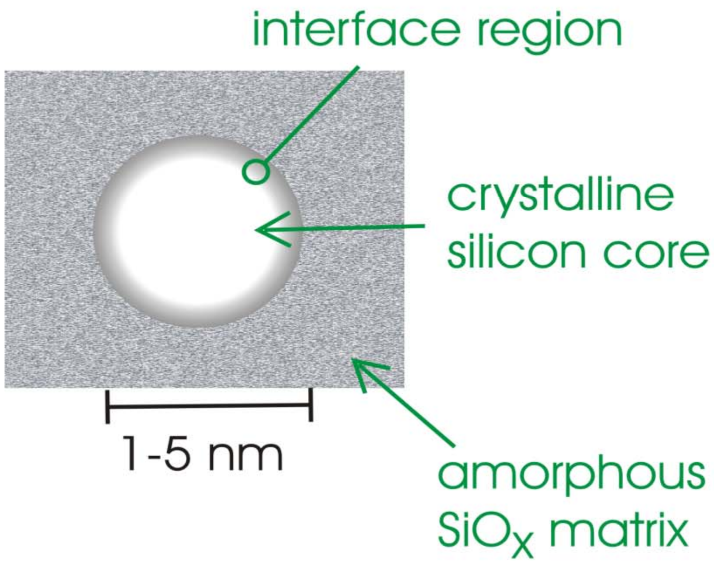


ion implantation
chemical vapour deposition
sputtering
chemical synthesis
laser ablation
cluster deposition

silicon rich oxide

annealing

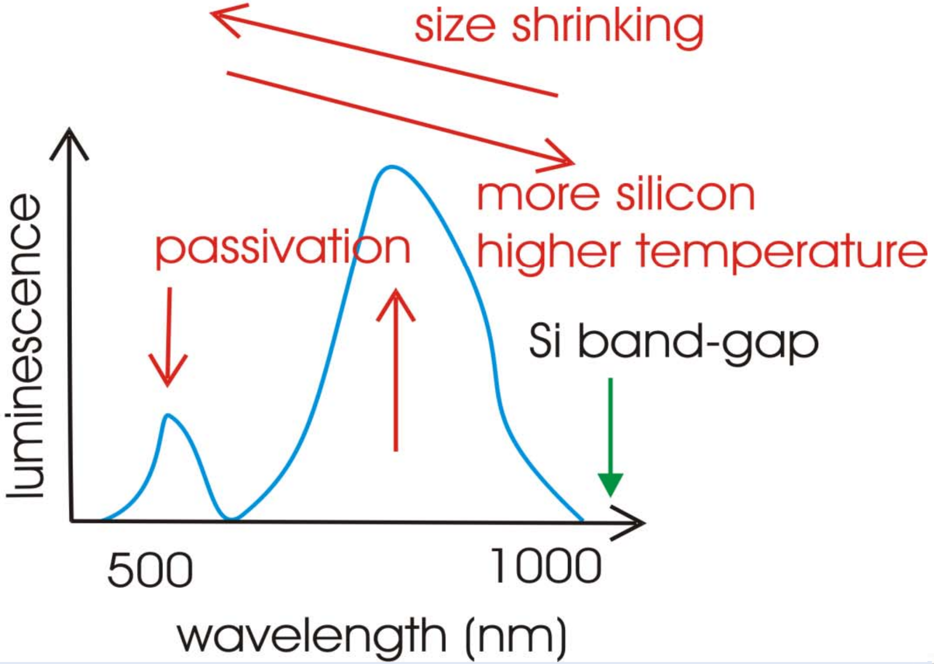
partial phase separation



interface region

crystalline silicon core

amorphous SiO_x matrix



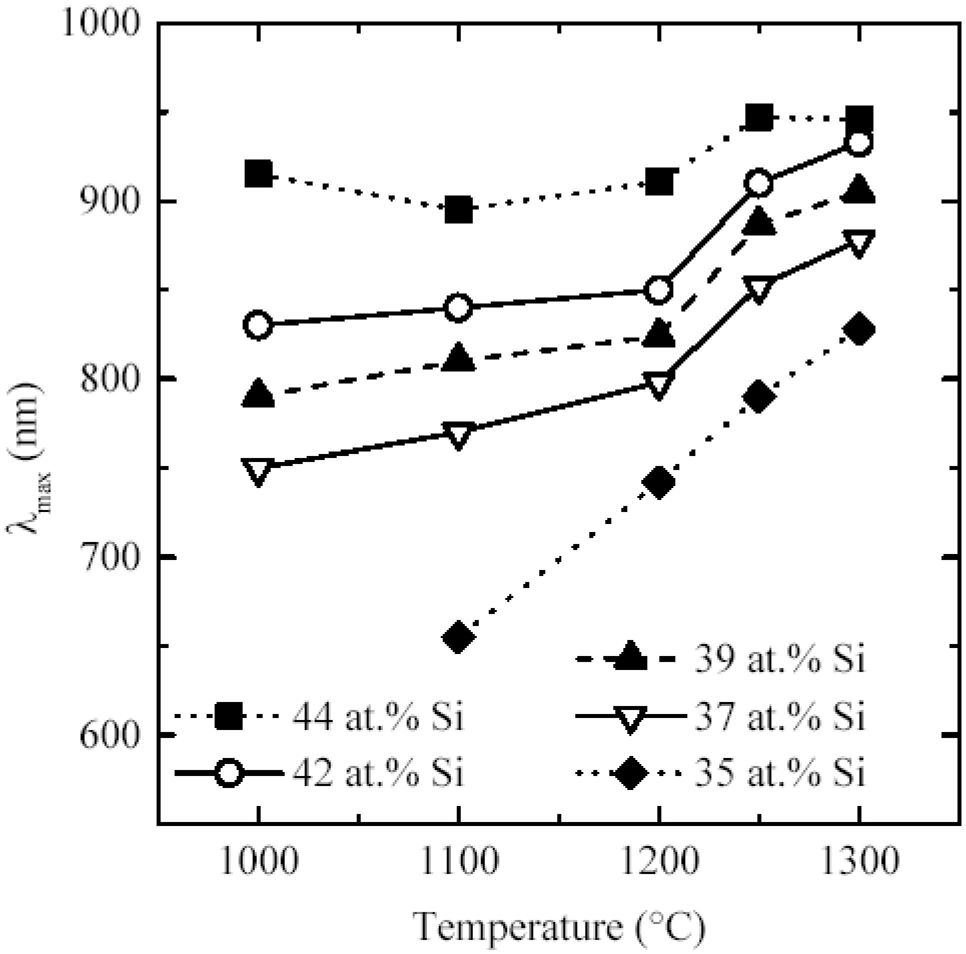
size shrinking

more silicon
higher temperature

passivation

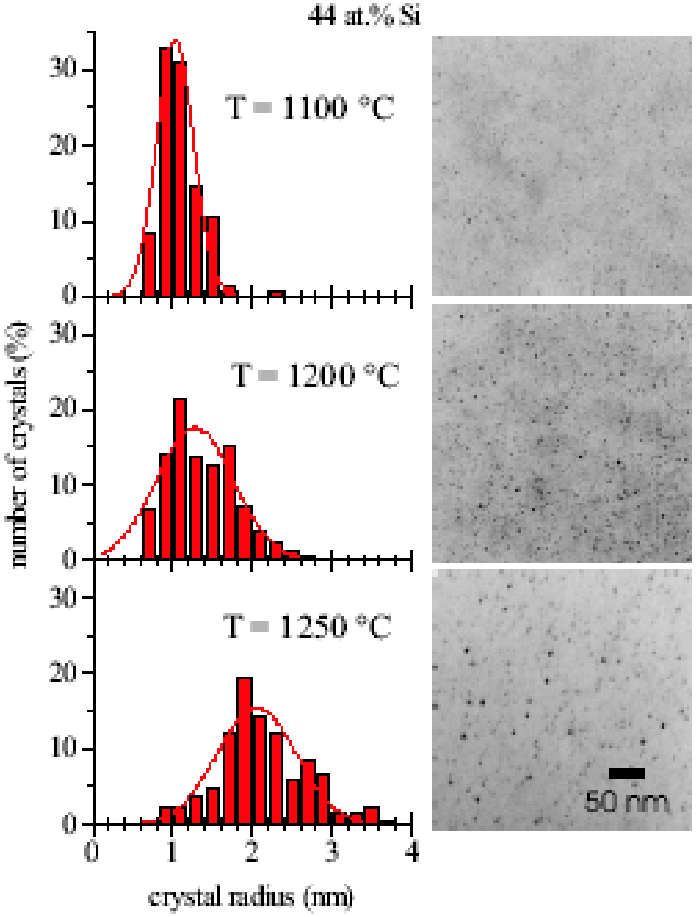
Si band-gap

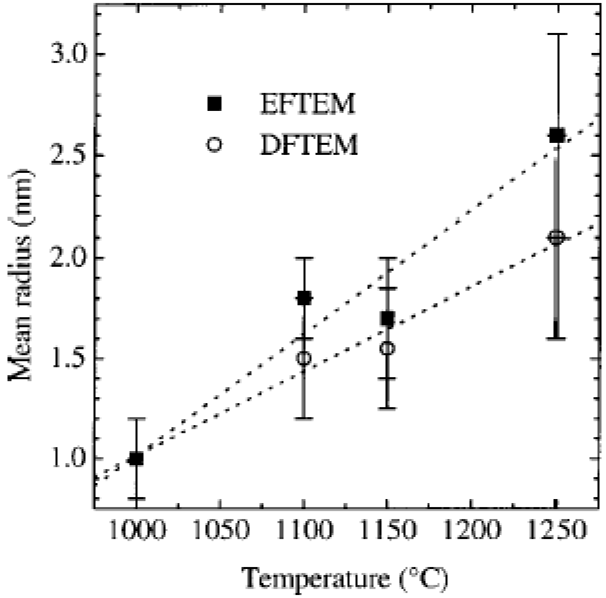
Tuning emission properties



F. Iacona et al. CNR Catania

Significant size dispersion





F. Iacona et al. CNR Catania

Reduce the size dispersion

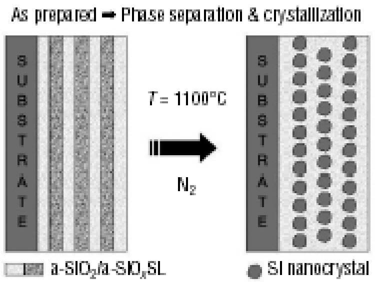


Figure 1. Fabrication of amorphous SiO/SiO₂ superlattice and thermally induced phase separation and crystallization.

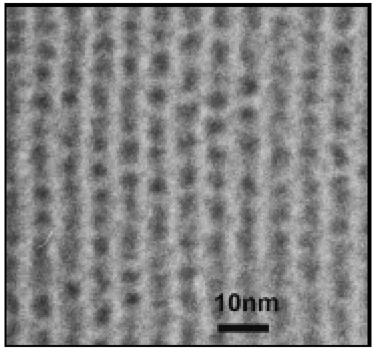


Figure 2. Cross-sectional transmission electron microscope image of layer-arranged Si crystals (~3 nm) closely separated by oxide.

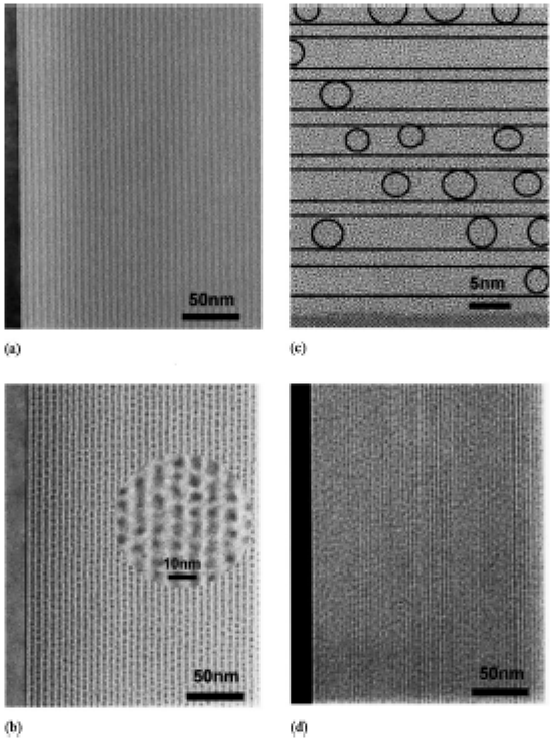
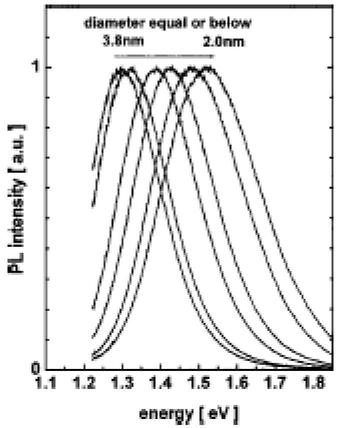
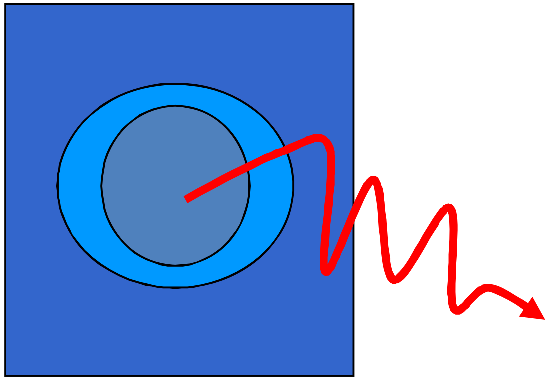


FIG. 1. Cross-sectional TEM images of SiO/SiO$_2$ superlattices: (a) As-prepared SiO/SiO$_2$ superlattice. The darker layers represent the SiO sublayers. (b) The same film after annealing. The separation of the nanocrystals by a thin oxide shell is clearly visible. (c) High resolution TEM image of the film. For clarity, the visible nanocrystals are highlighted by circles. The crystals are only found in the former SiO layers, which is emphasized by the lines in the image. (d) TEM image of a film with even thinner SiO layers ~2 nm after anneling.



M. Zacharias et al. MPI Halle

Where is the luminescence coming from?



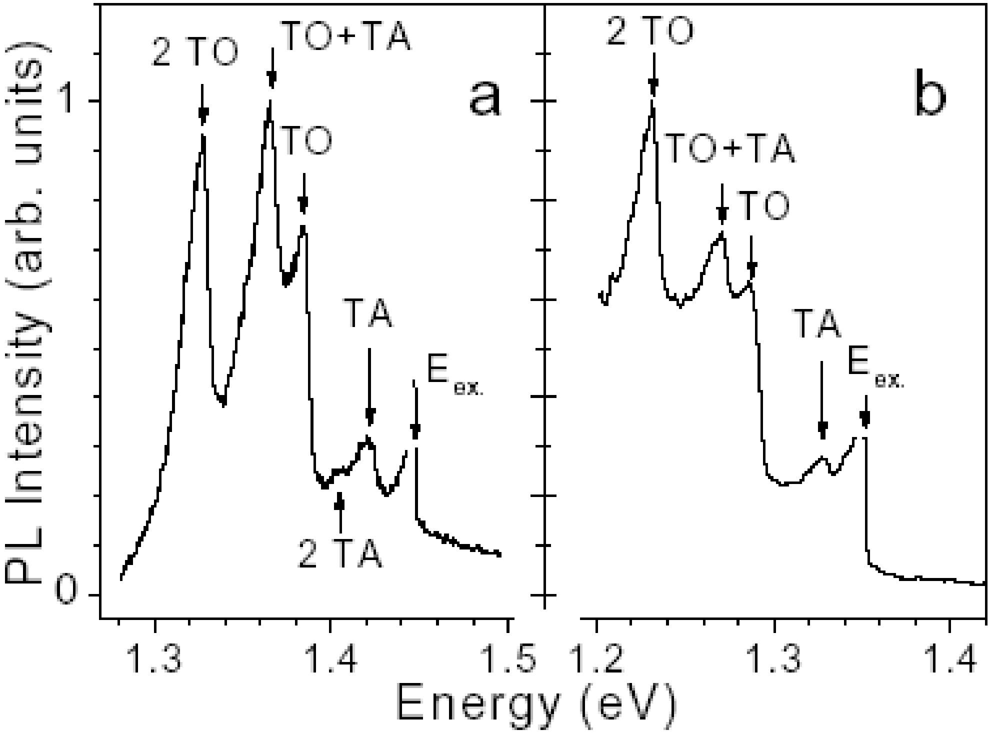
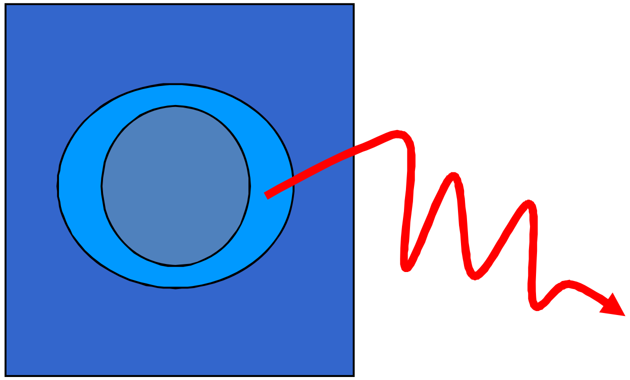
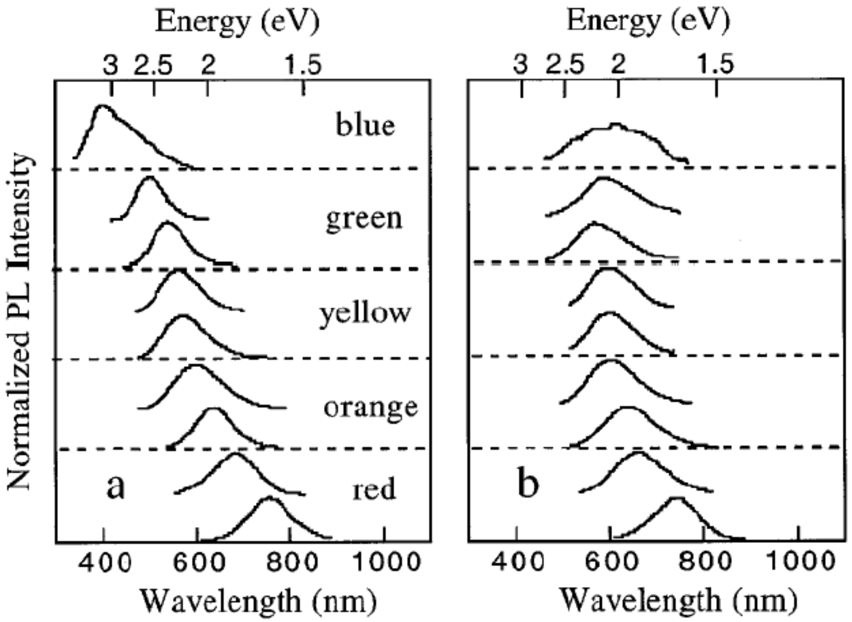


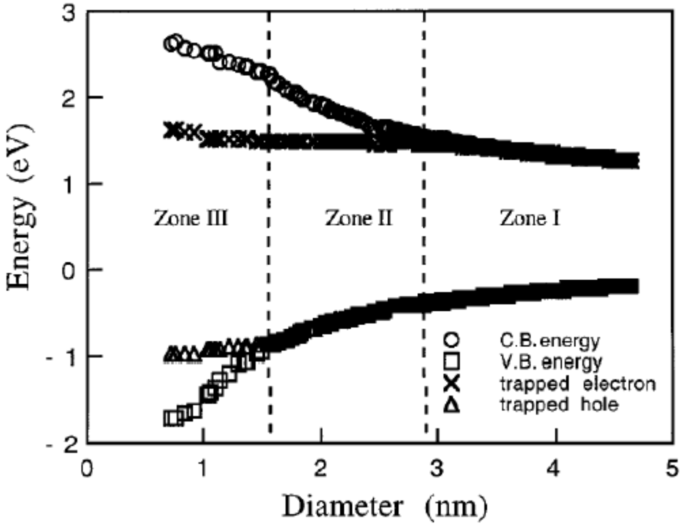
FIG. 1. The resonant PL spectra of naturally (a) and heavily oxidized (b) PSi. The arrows show the energy position of Si TA and TO momentum-conserving phonons with respect to the triplet exciton ground state.

D. Kovalev TUM Munich

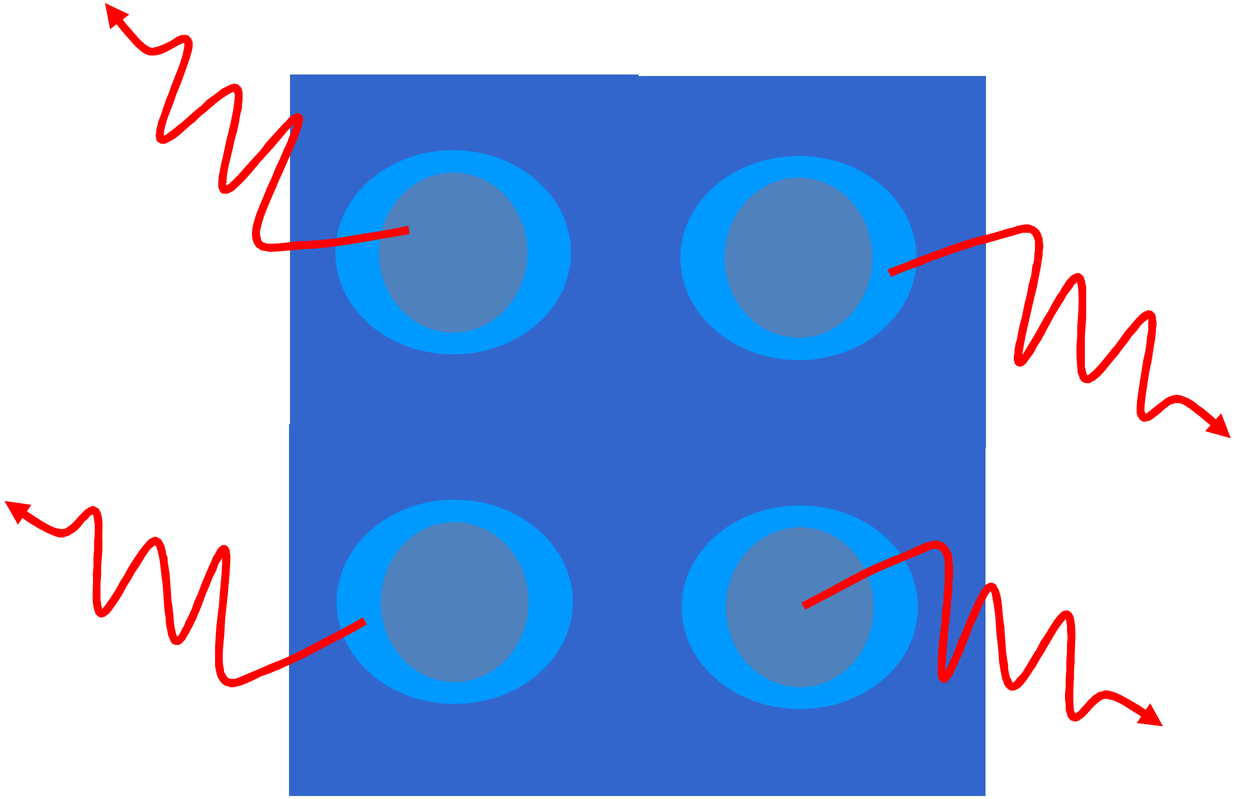
Where is the luminescence coming from?



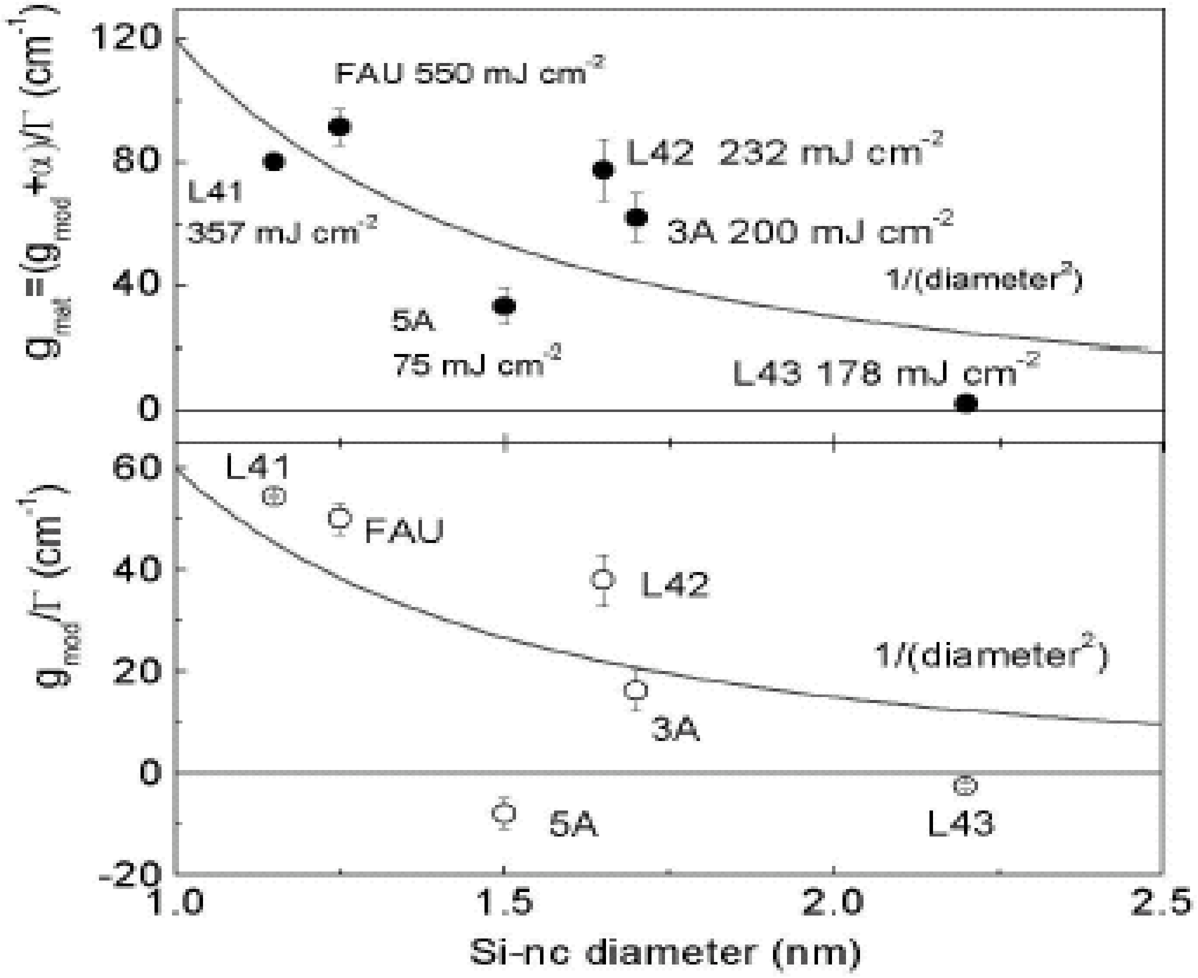




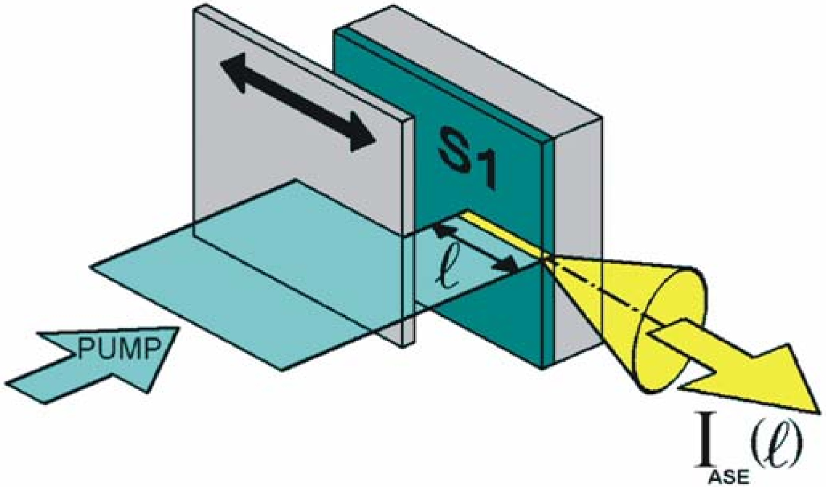
Where is the luminescence coming from?



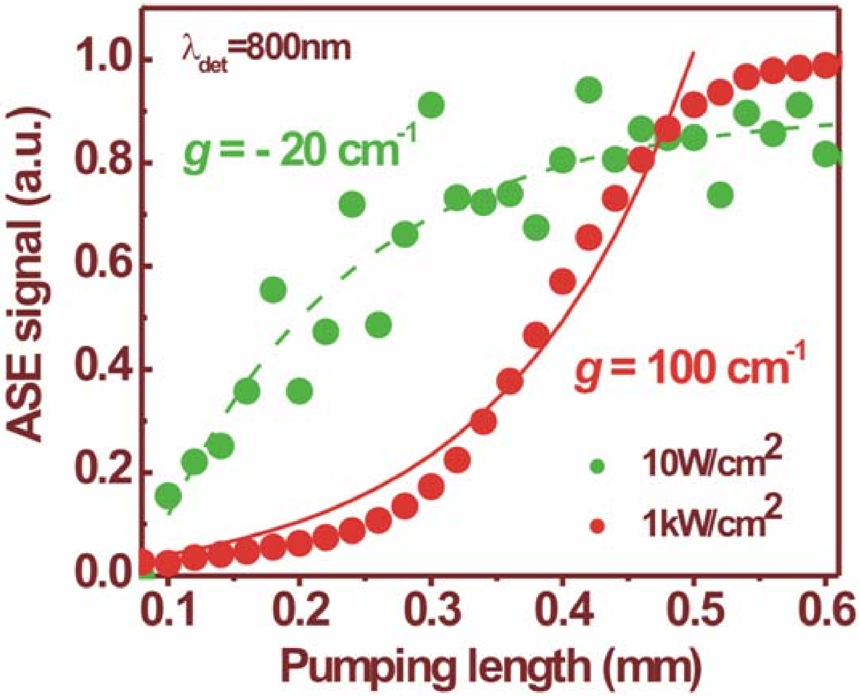
Optical gain in Si-nanocrystals



How we measured gain

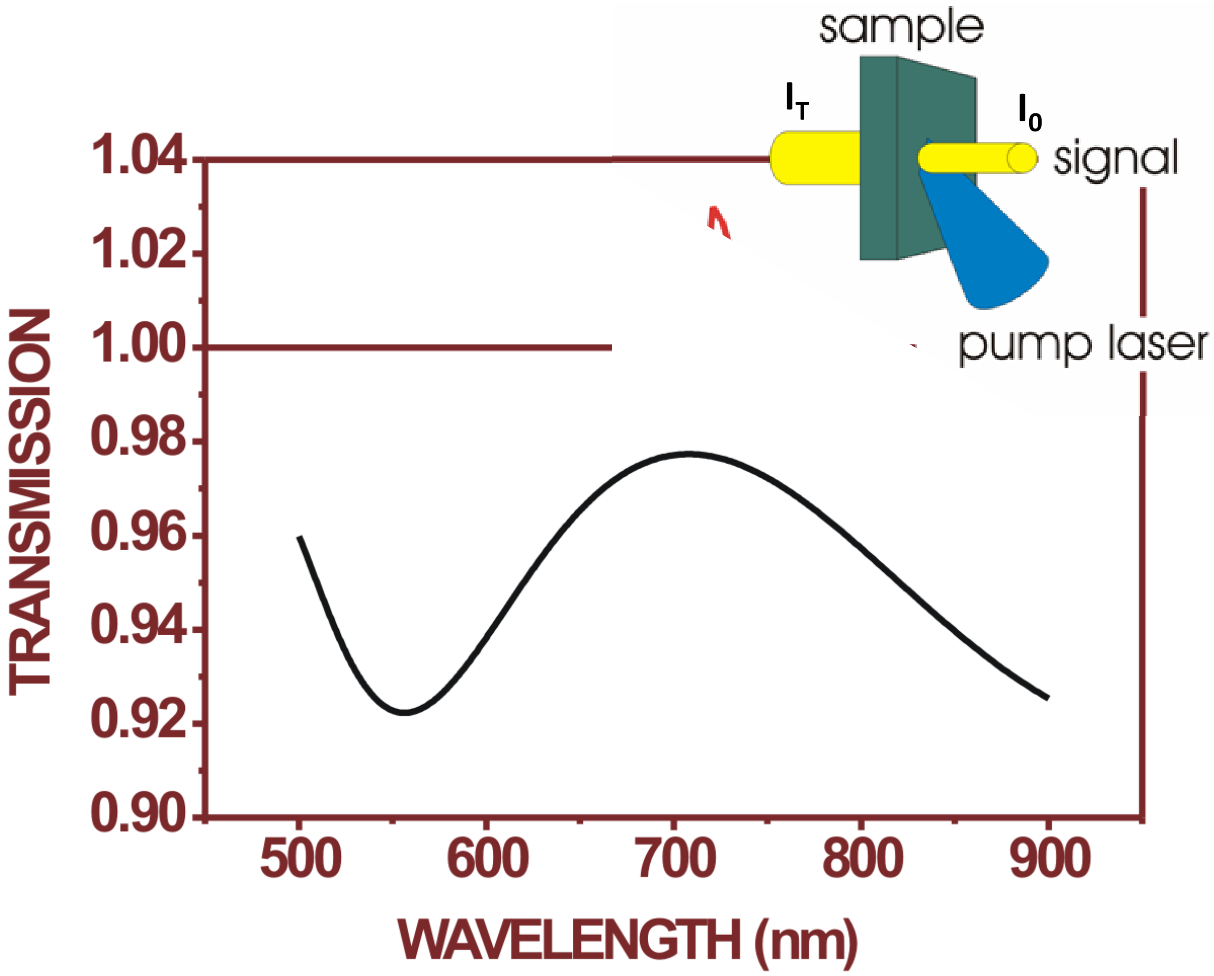


$$I_{ASE}(\ell) = \frac{J_{sp}(\Omega)}{g_{\mathrm{mod}}}\left(e^{(\Gamma g-\alpha)\ell}-1\right)$$



Nature **408** 440 (2000)

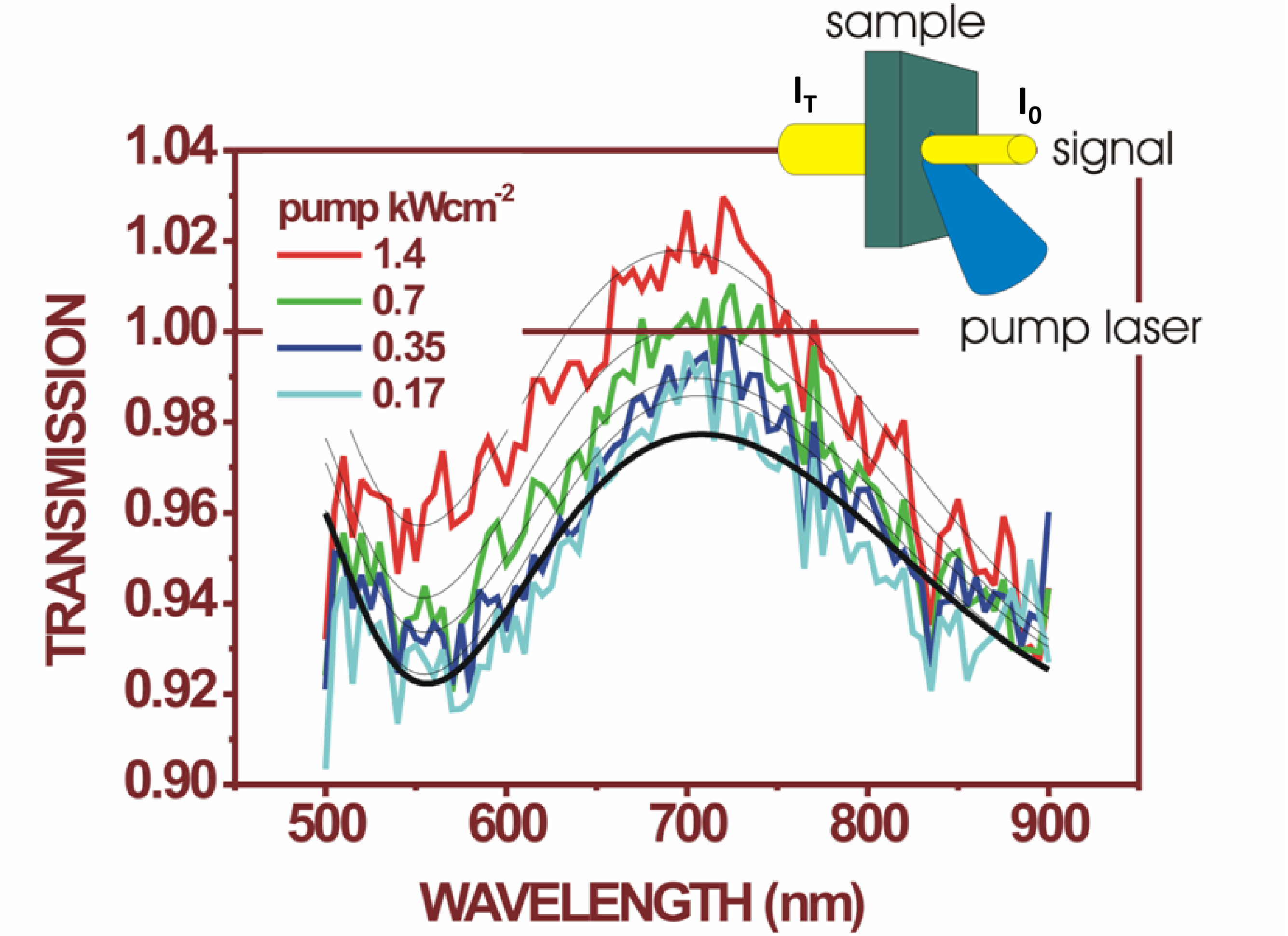
How we measured gain



JAP 96, 5747

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

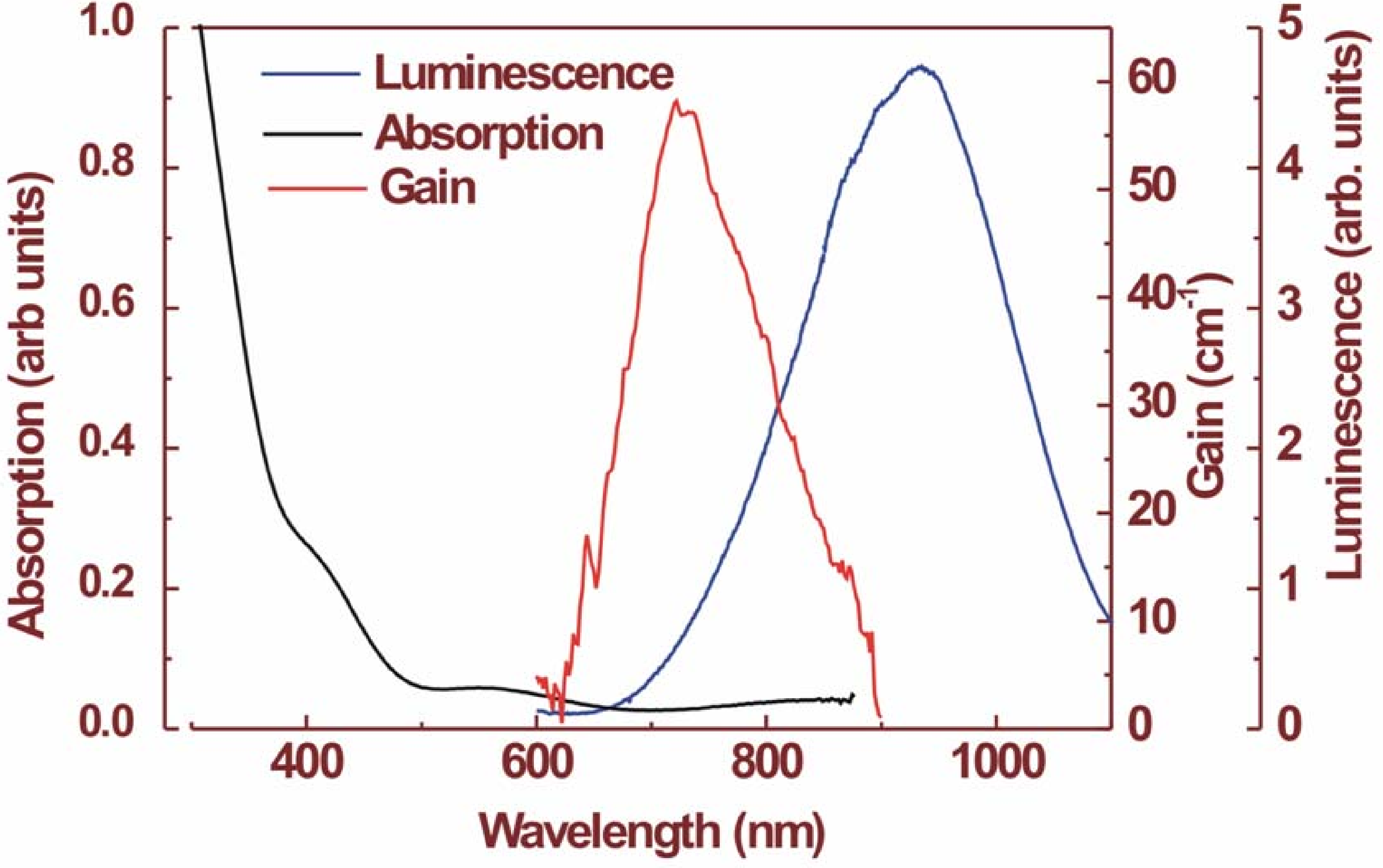
How we measured gain



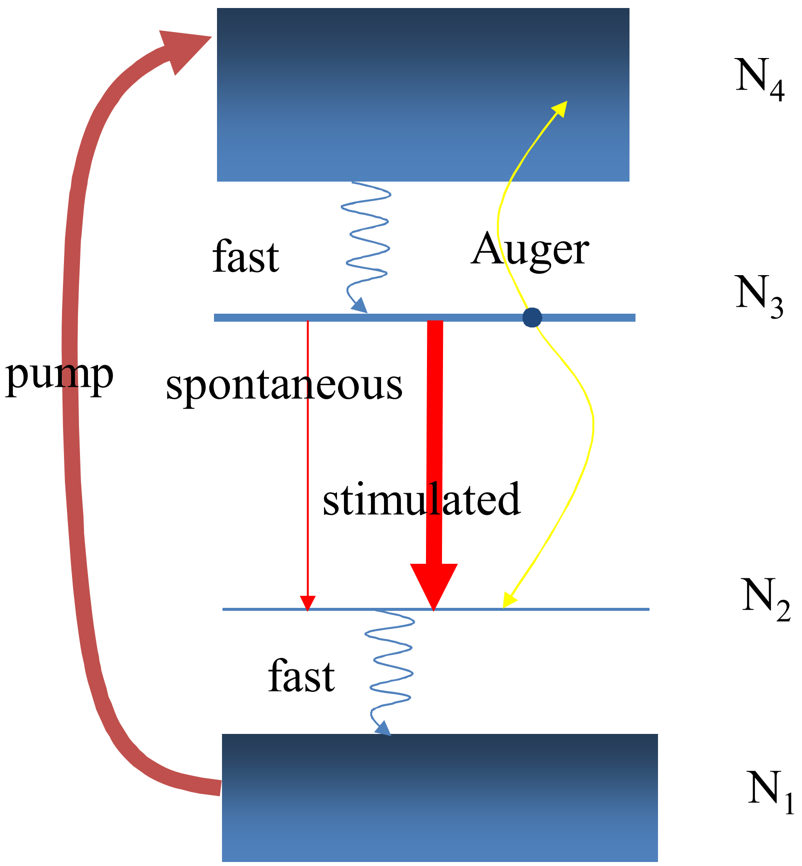
JAP 96, 5747

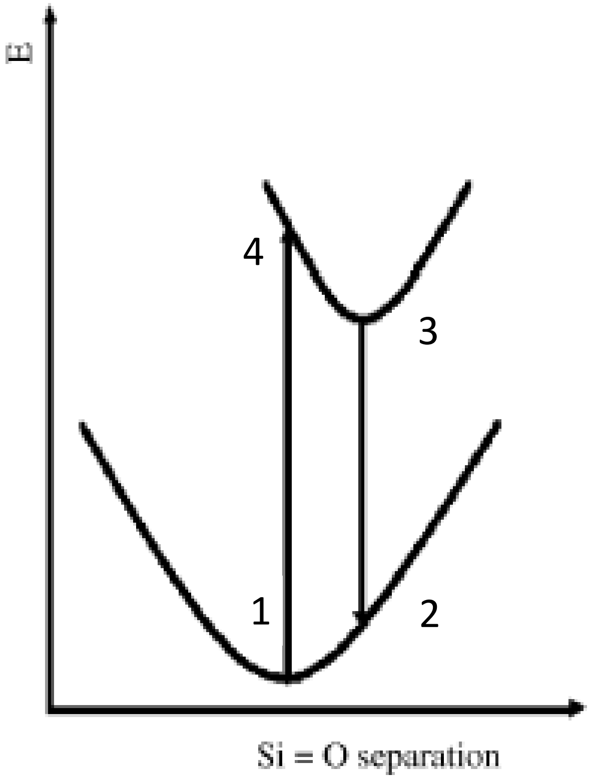
$$T = \frac{I_{ON} - I_{PL}}{I_O} = \exp\left[-\left(\alpha_{QZ} d_{QZ} - g_{Si-nc}\left(J_P\right) d_{Si-nc}\right)\right]$$

Summary on optical properties of Si-nc



4 levels system model

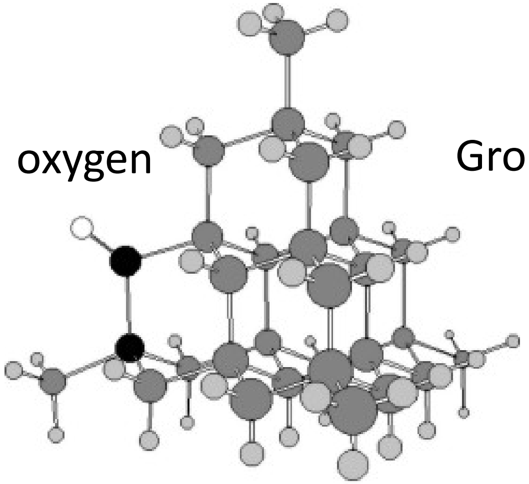




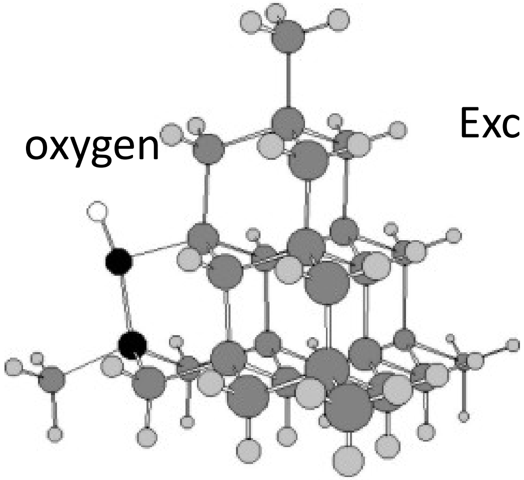
Model for the 4 levels

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

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



a)

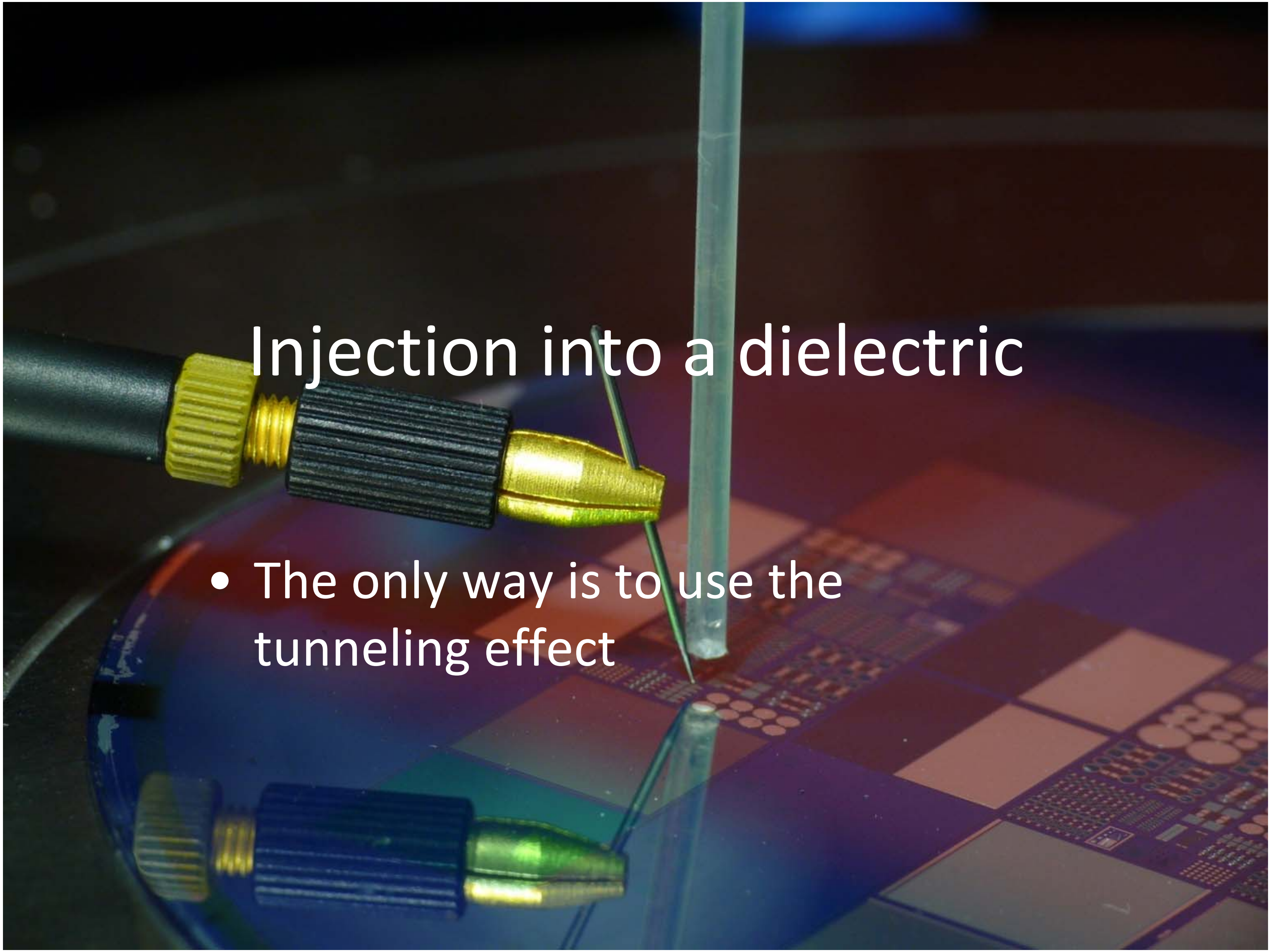


b)

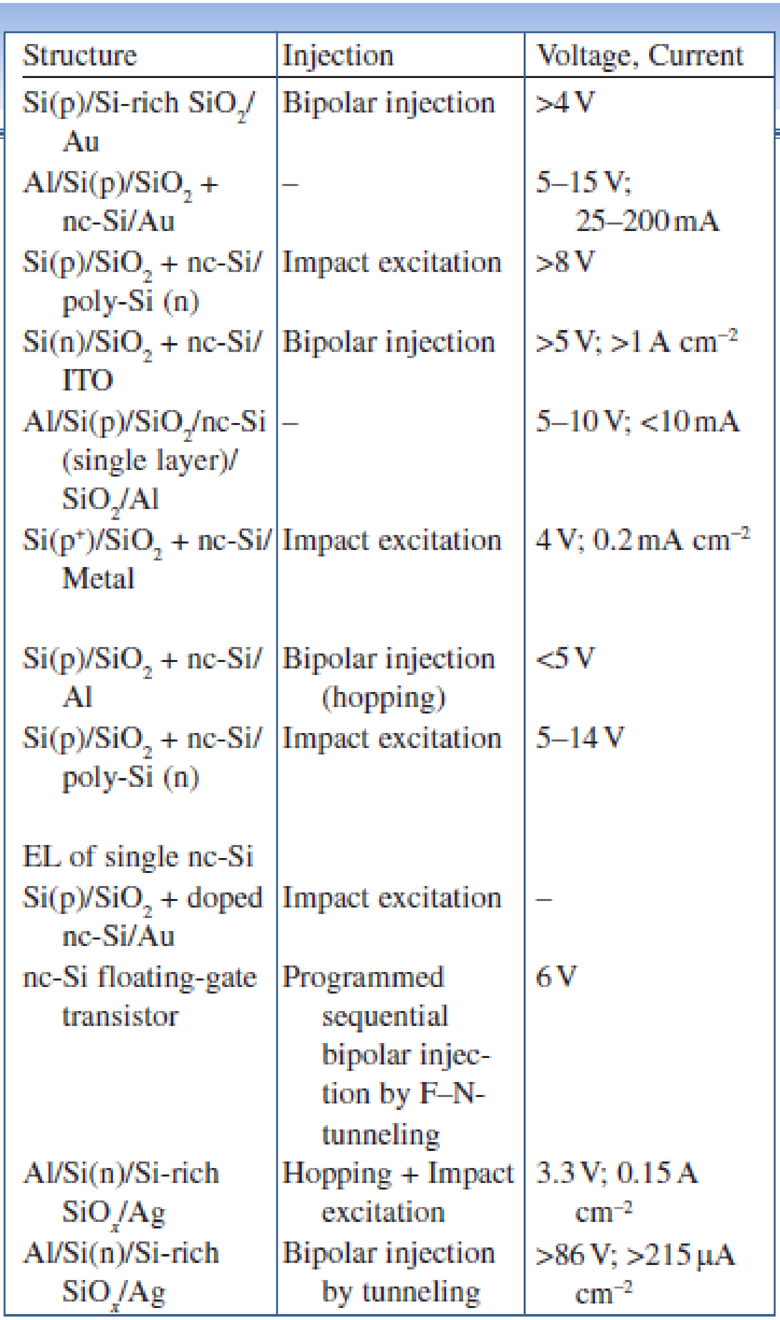
Is electrical injection possible?

The problem is related to the fact that the Si-nc are in an insulating matrix

Injection into a dielectric



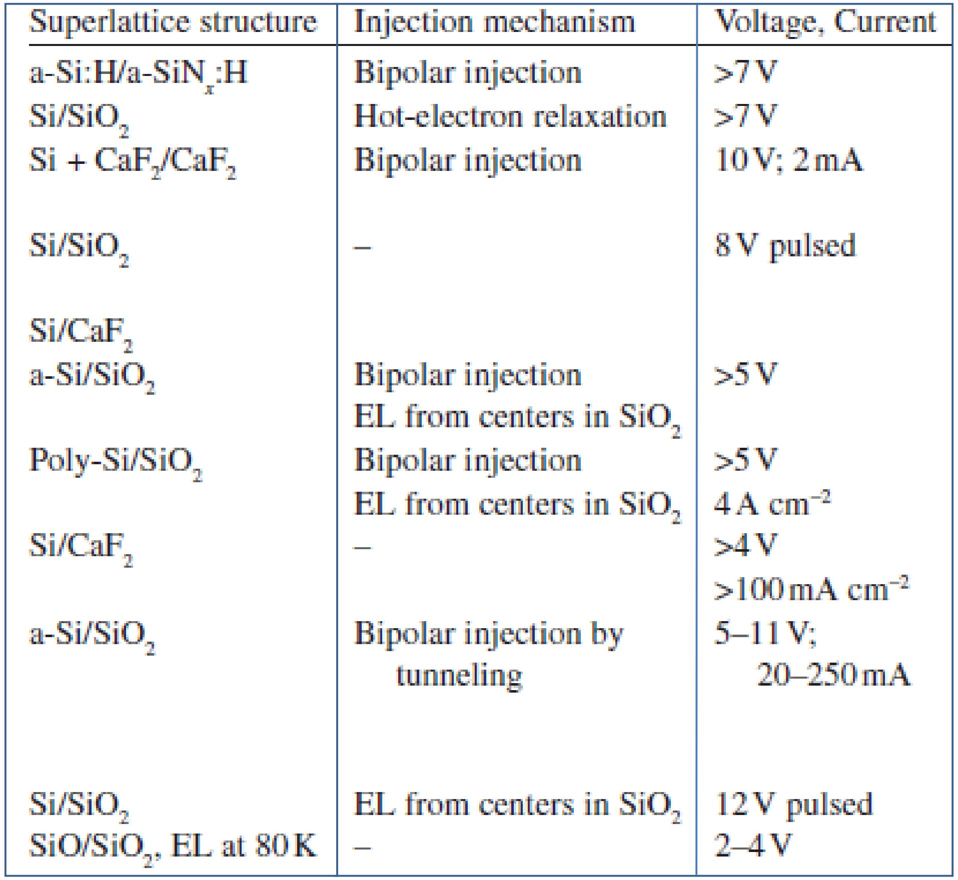
- The only way is to use the tunneling effect



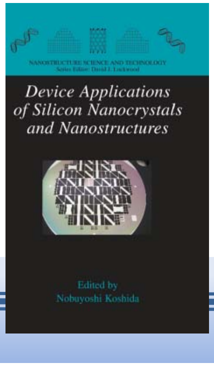
Structure	Injection	Voltage, Current
Si(p)/Si-rich SiO_2/Au	Bipolar injection	>4 V
Al/Si(p)/SiO_2 + nc-Si/Au	–	5–15 V; 25–200 mA
Si(p)/SiO_2 + nc-Si/poly-Si (n)	Impact excitation	>8 V
Si(n)/SiO_2 + nc-Si/ITO	Bipolar injection	>5 V; >1 A cm^{-2}
Al/Si(p)/SiO_2/nc-Si (single layer)/SiO_2/Al	–	5–10 V; <10 mA
Si(p^+)/SiO_2 + nc-Si/Metal	Impact excitation	4 V; 0.2 mA cm^{-2}
Si(p)/SiO_2 + nc-Si/Al	Bipolar injection (hopping)	<5 V
Si(p)/SiO_2 + nc-Si/poly-Si (n)	Impact excitation	5–14 V
EL of single nc-Si		
Si(p)/SiO_2 + doped nc-Si/Au	Impact excitation	–
nc-Si floating-gate transistor	Programmed sequential bipolar injection by F–N-tunneling	6 V
Al/Si(n)/Si-rich SiO_x/Ag	Hopping + Impact excitation	3.3 V; 0.15 A cm^{-2}
Al/Si(n)/Si-rich SiO_x/Ag	Bipolar injection by tunneling	>86 V; >215 μA cm^{-2}

← nc-Si/SiO_2 LEDs

Superlattice LEDs ↓



Superlattice structure	Injection mechanism	Voltage, Current
a-Si:H/a-SiN_x:H	Bipolar injection	>7 V
Si/SiO_2	Hot-electron relaxation	>7 V
Si + CaF_2/CaF_2	Bipolar injection	10 V; 2 mA
Si/SiO_2	–	8 V pulsed
Si/CaF_2		
a-Si/SiO_2	Bipolar injection	>5 V
	EL from centers in SiO_2	
Poly-Si/SiO_2	Bipolar injection	>5 V
	EL from centers in SiO_2	4 A cm^{-2}
Si/CaF_2	–	>4 V
		>100 mA cm^{-2}
a-Si/SiO_2	Bipolar injection by tunneling	5–11 V; 20–250 mA
Si/SiO_2	EL from centers in SiO_2	12 V pulsed
SiO/SiO_2, EL at 80 K	–	2–4 V

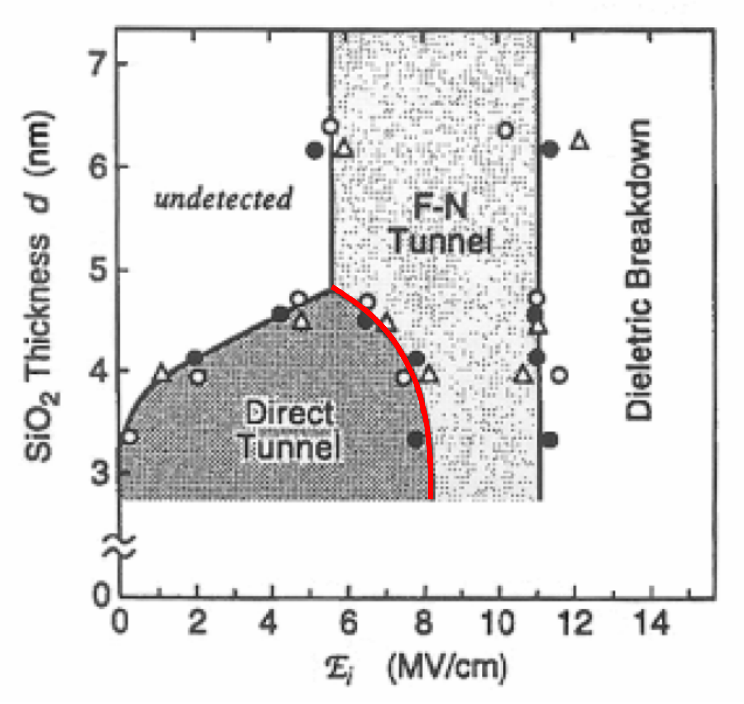


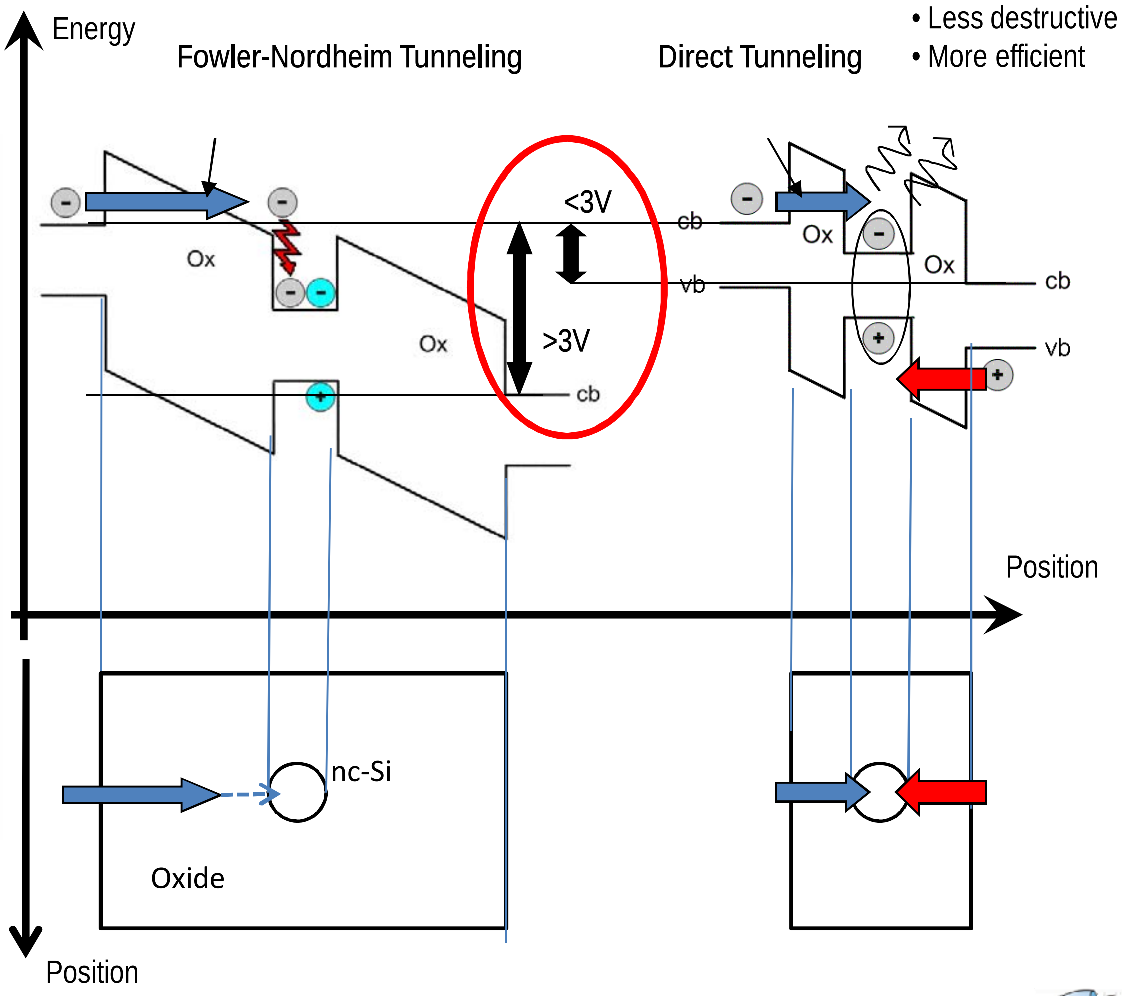
B. Gelloz and N. Koshida in *Device Applications of Silicon Nanocrystals and Nanostructures*, edited by N. Koshida (Springer, New York, 2009)

Tunneling injection

Onset voltages > 4.2 V (band offset for electrons)

Impact excitation is a dominant mechanism

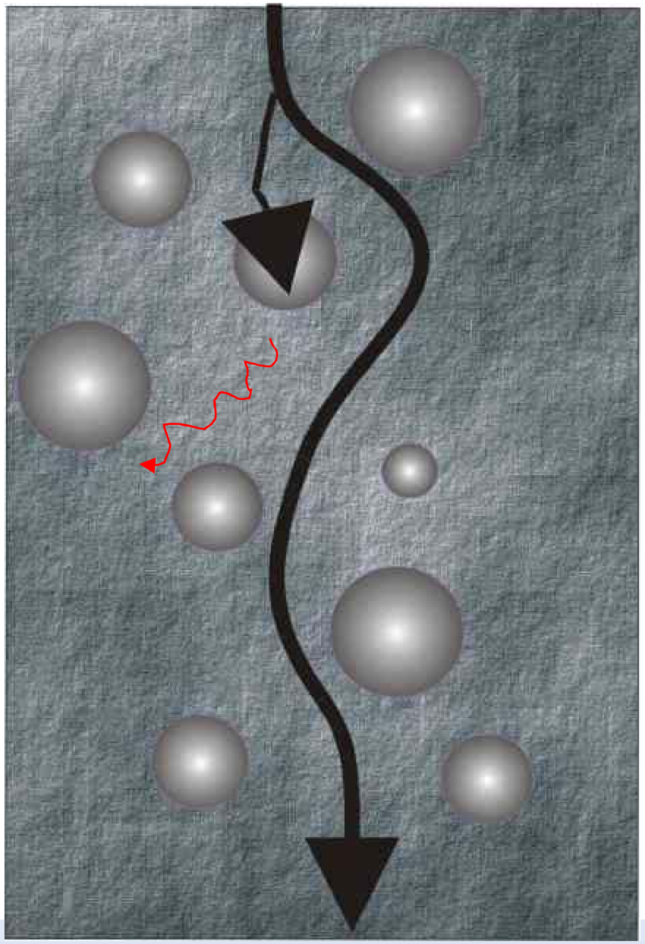




- Less destructive
- More efficient

Low electroluminescence efficiency

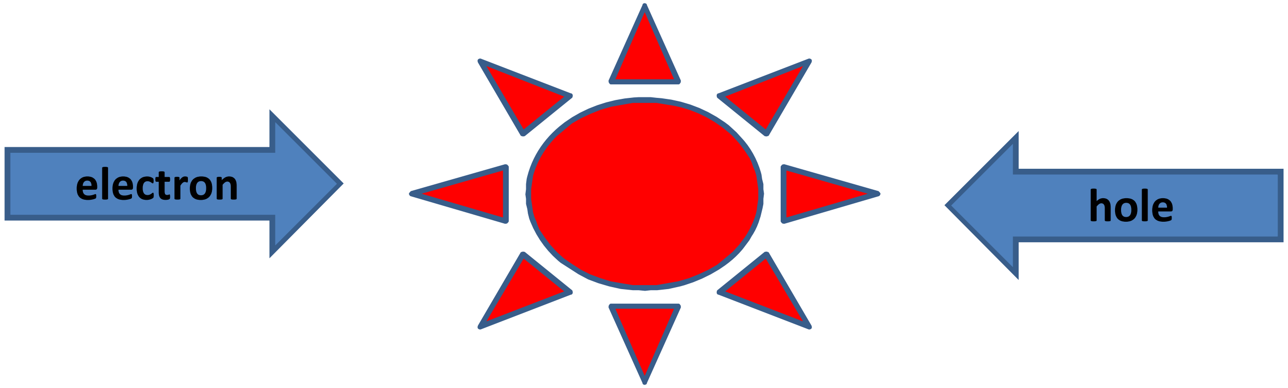
Unipolar injection



Impact excitation

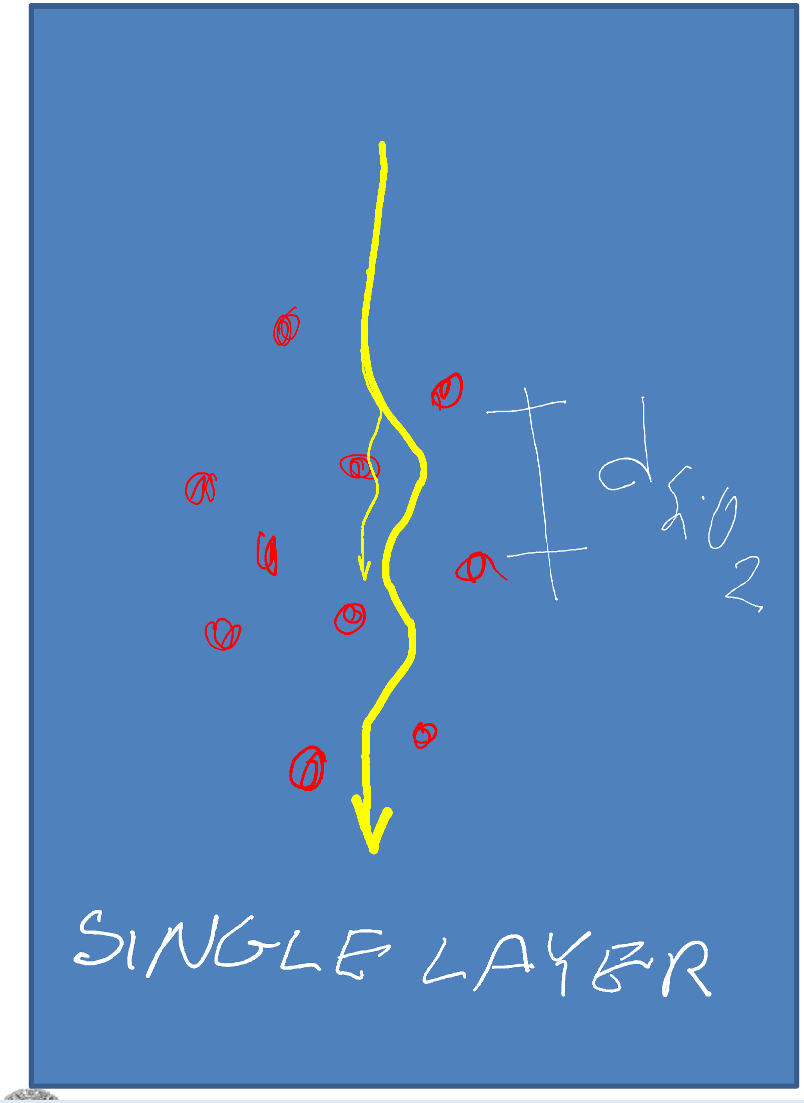
Shunt paths through the sub-stoichiometric oxide

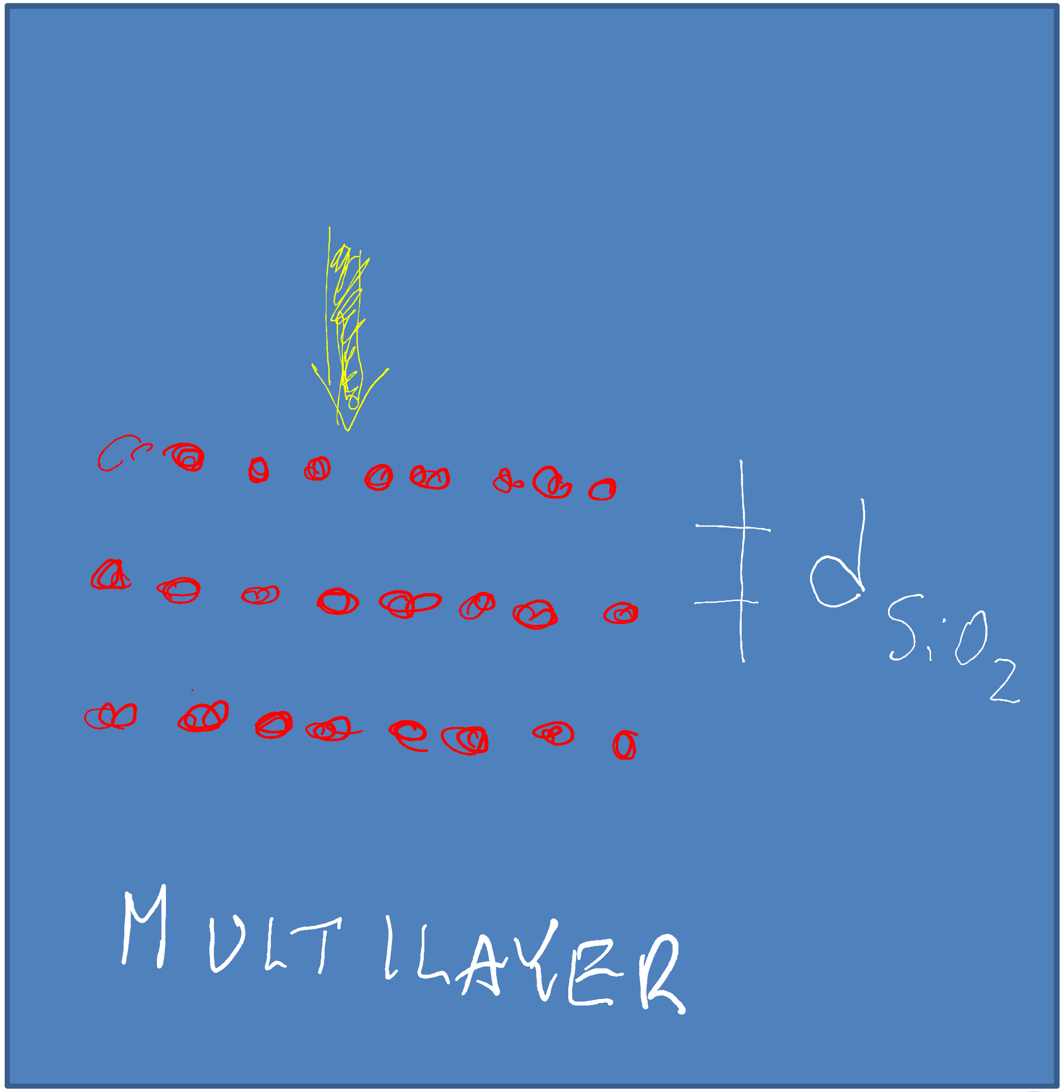
Bipolar injection



Appl. Phys. Lett. **94**, 221110 (2009)

Single vs multilayer



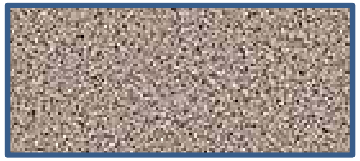


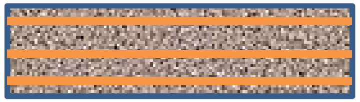
Single layer (run0) vs Multilayer LED (run3)

Two test MOS devices with the same overall silicon content but different structure:

Homogeneous layer   SiO2/Si-nc multilayer

50 nm



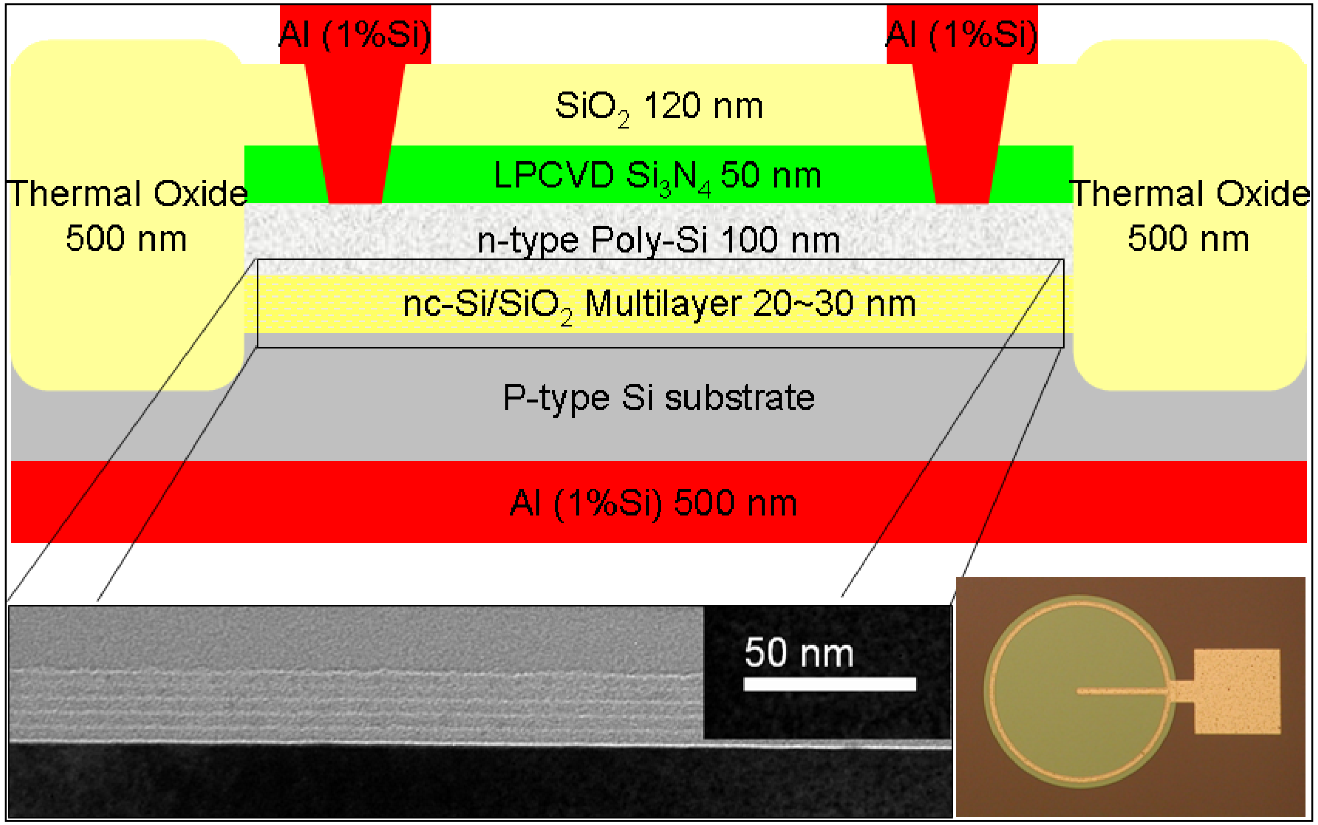


15 nm

Note different thicknesses, hence comparison with applied electric field and not voltage

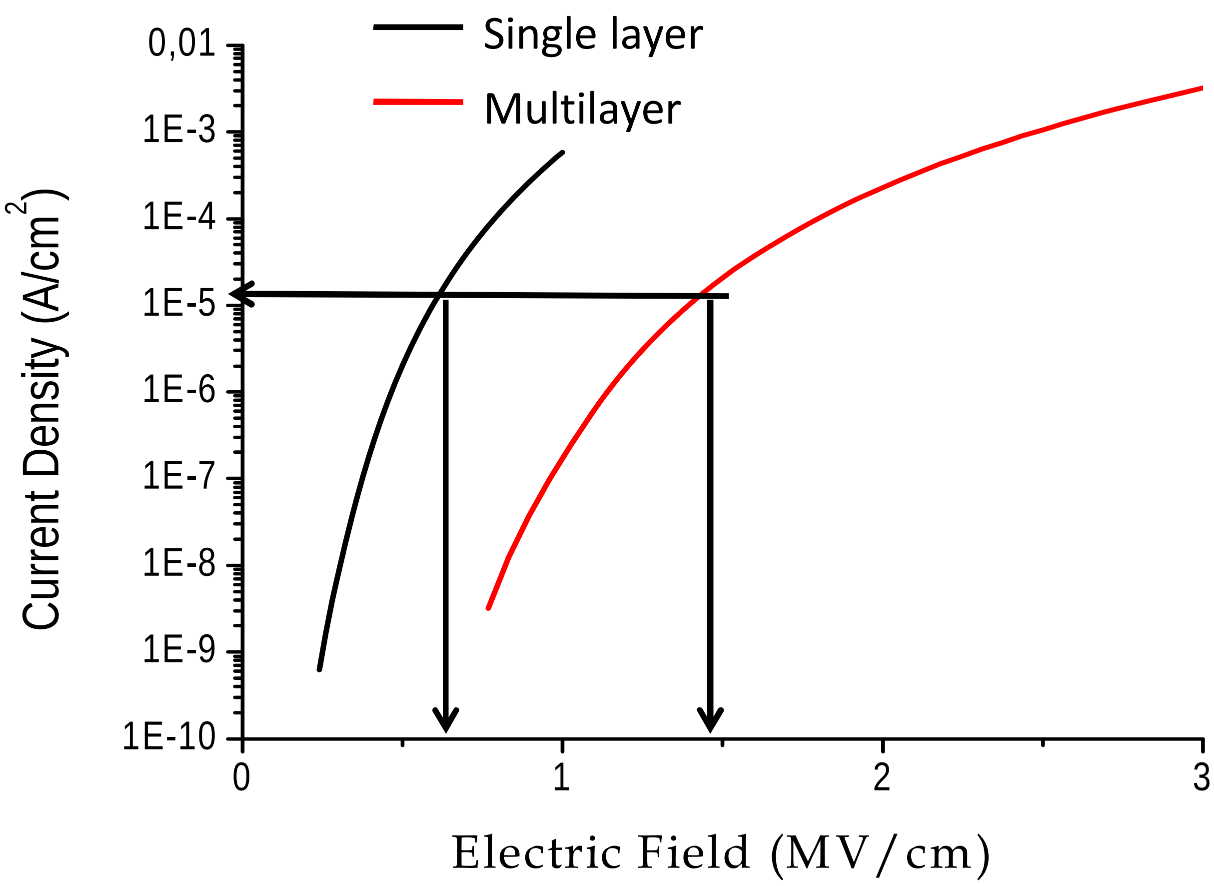
Device area $10^5\ \mu m^2$

nc-Si/SiO_2 Multilayer LED



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

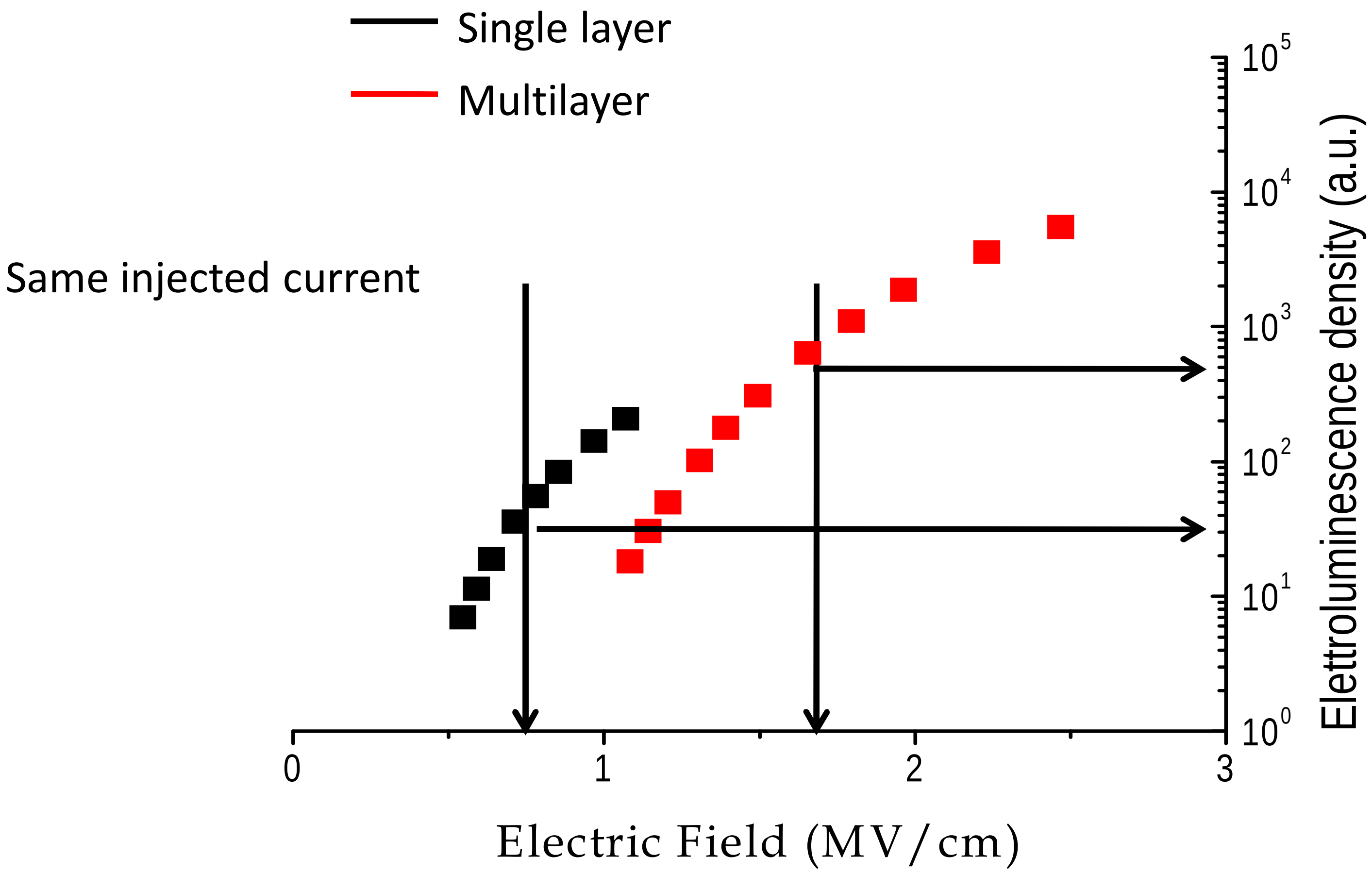
Single layer vs Multilayer LED



Single layer = large current Multilayer= large field

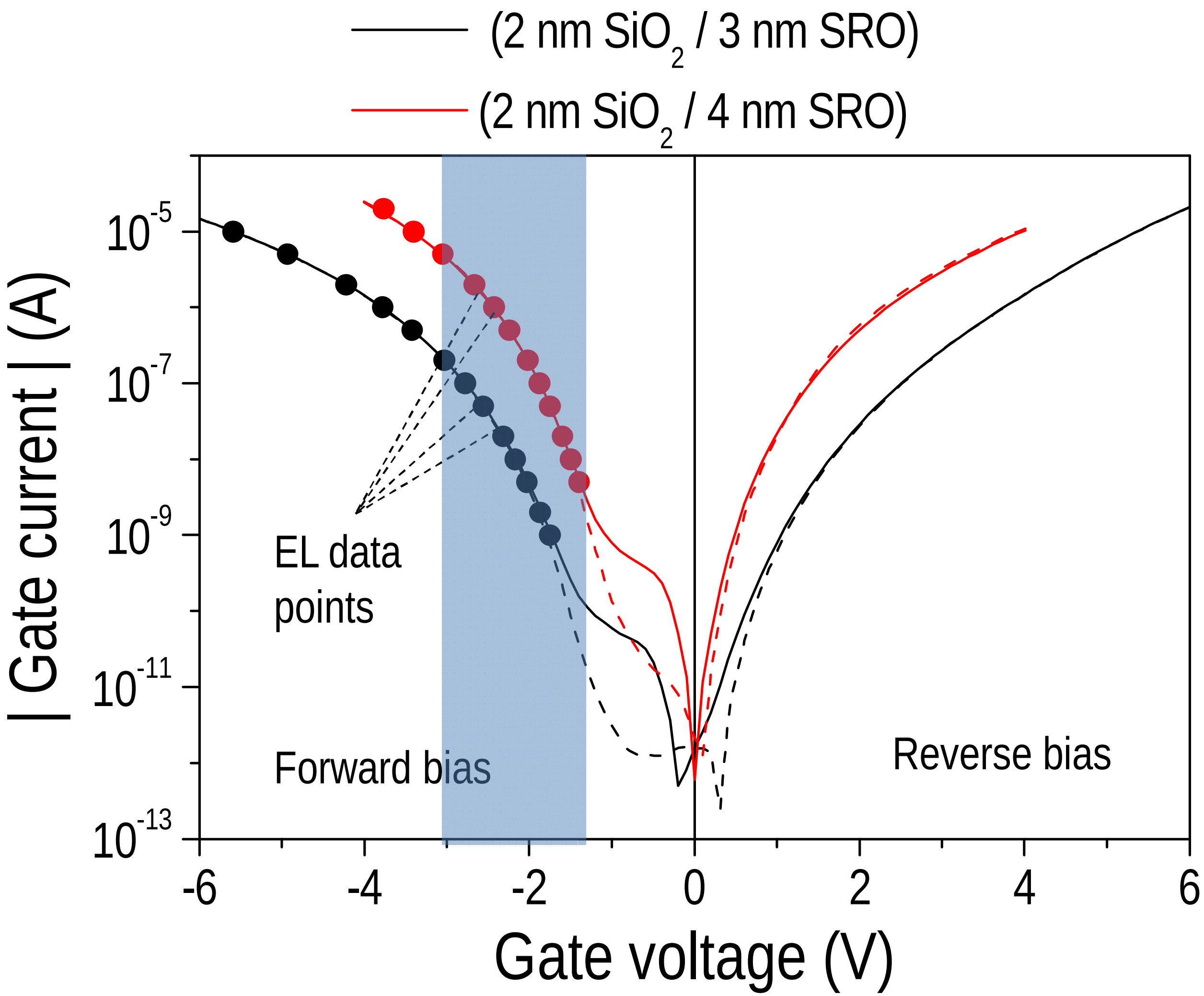
Larger Electric Field to achieve the same Current Density, i.e. reduced the leakage current

Single layer vs Multilayer LED

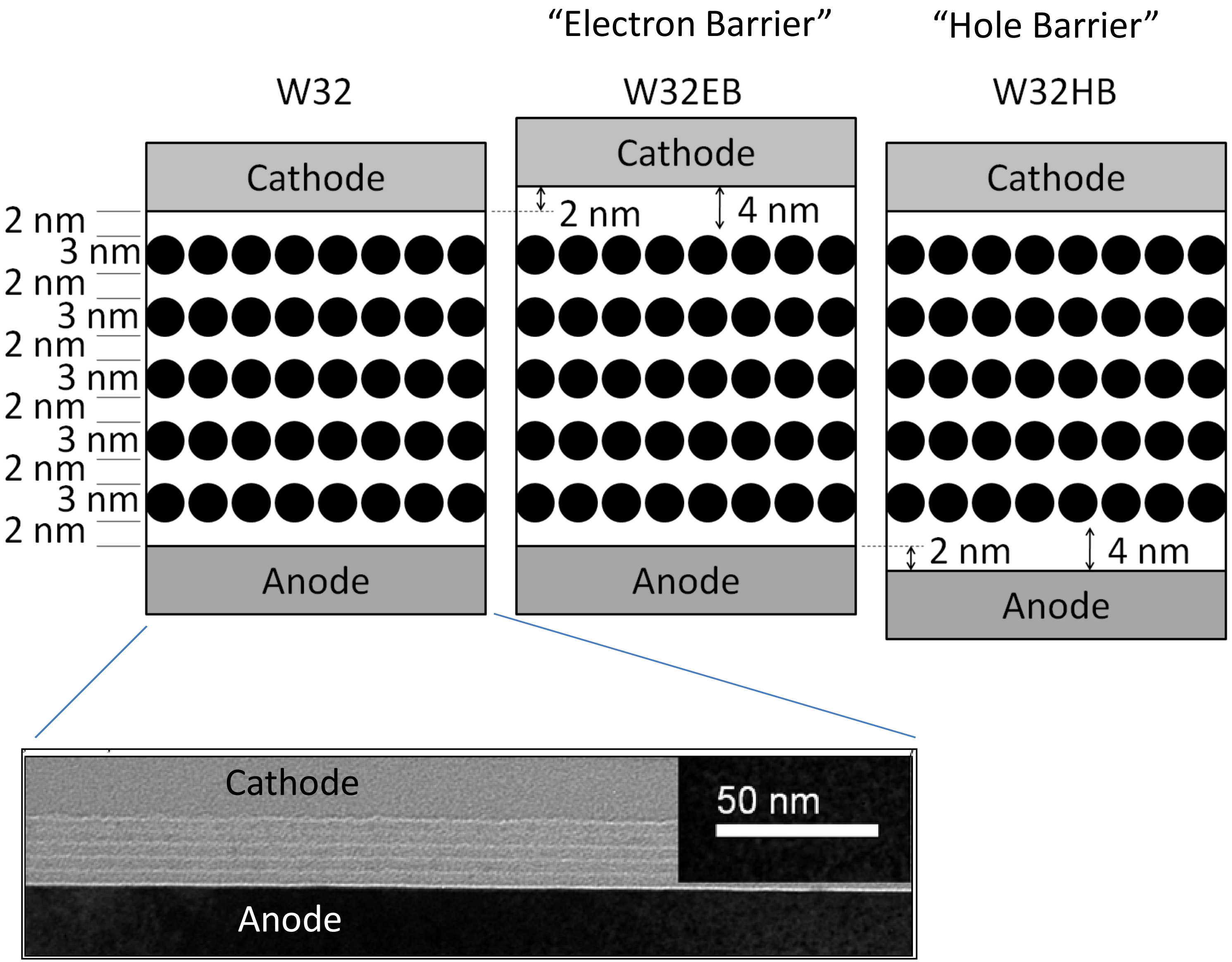


Increase of EL due to more effective injection into the Si-nc

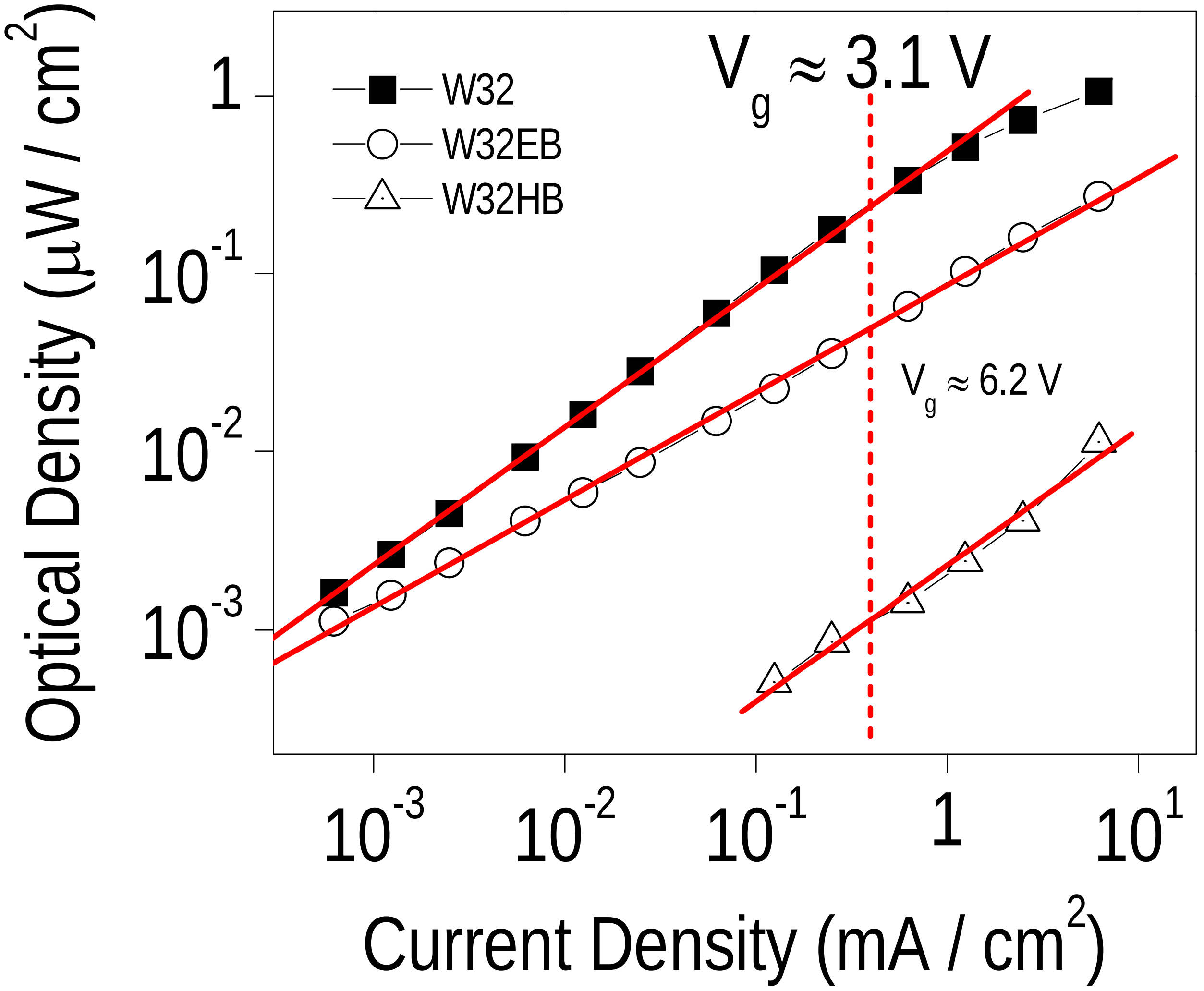
Low onset of EL voltages, < 3.2 V



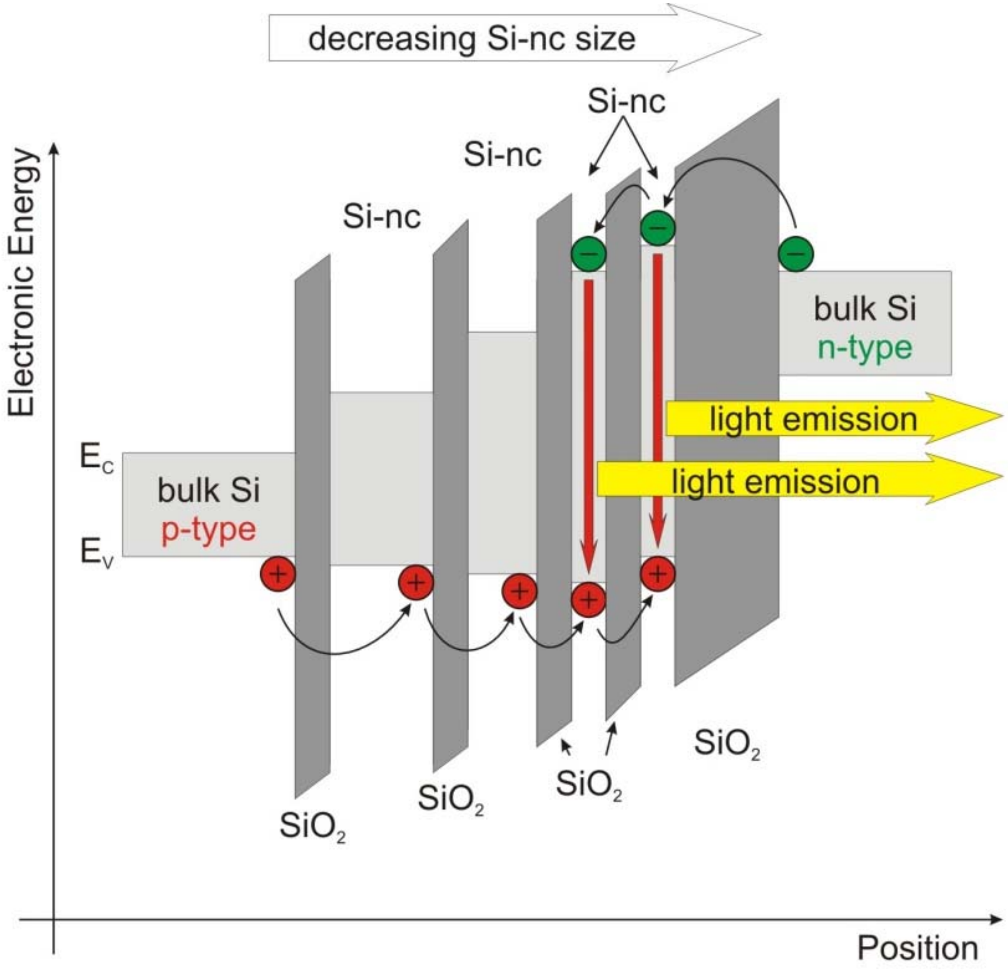
J. Appl. Phys. **106**, 033104 (2009)


“Electron Barrier”
“Hole Barrier”
W32
W32EB
W32HB
Cathode
Cathode
Cathode
2 nm
3 nm
2 nm
3 nm
2 nm
3 nm
2 nm
3 nm
2 nm
3 nm
2 nm
2 nm
4 nm
2 nm
4 nm
Anode
Anode
Anode
Cathode
50 nm
Anode

Light-current characteristics

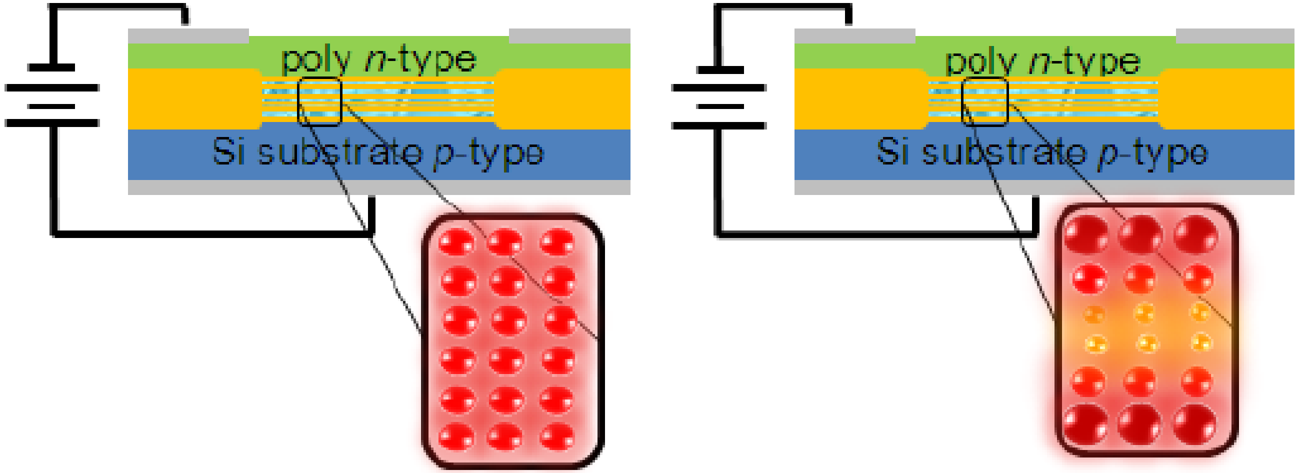


Injection rate engineering



Band gap engineering

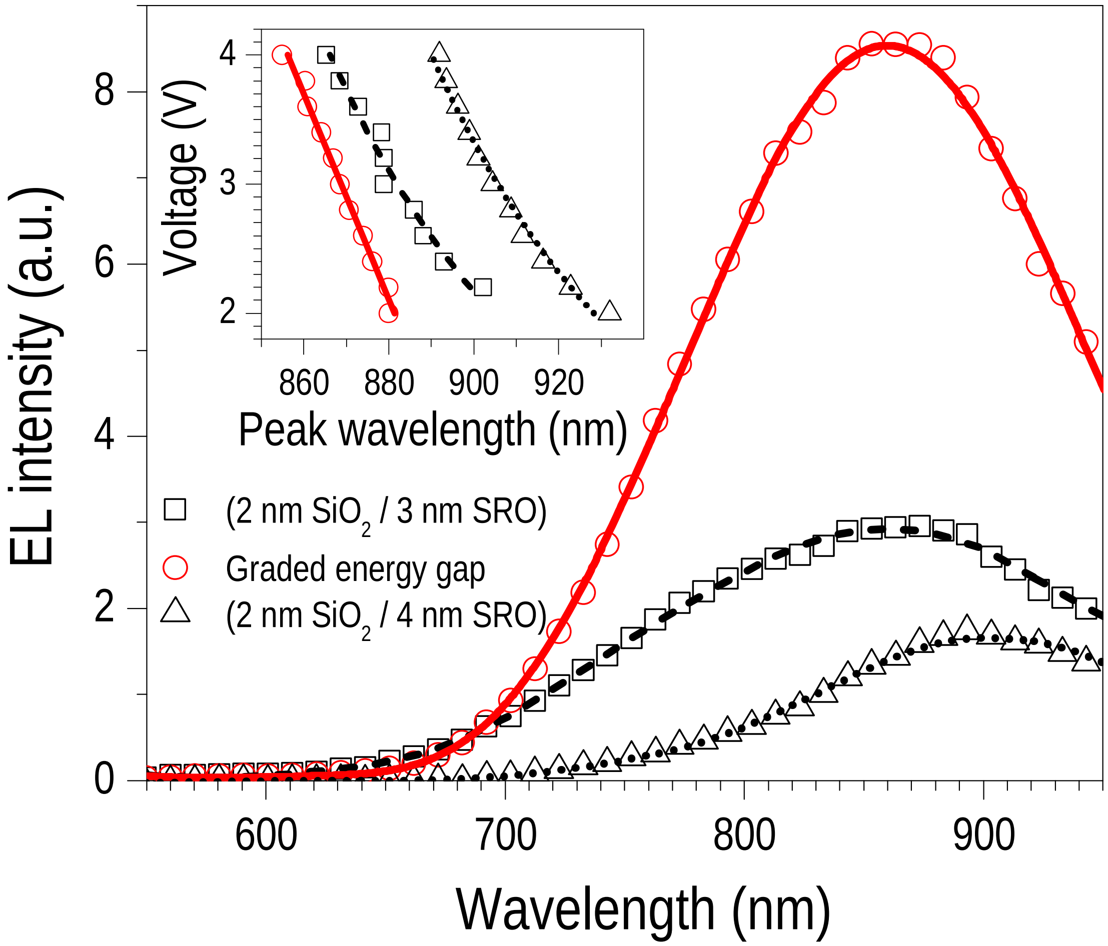
Optimized structures



Graded gap active layer

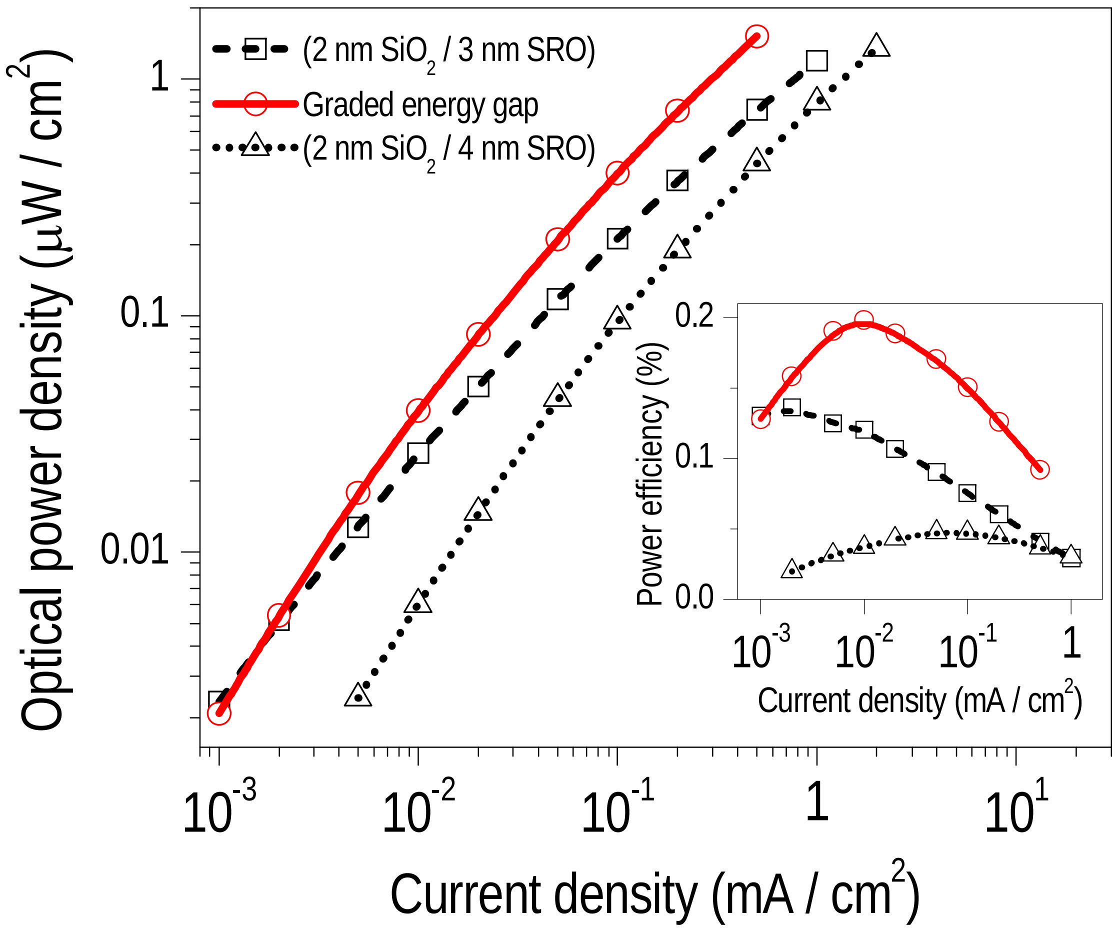
Large nanocrystals: Easy injection
Small nanocrystals: high emission

Optimized structures



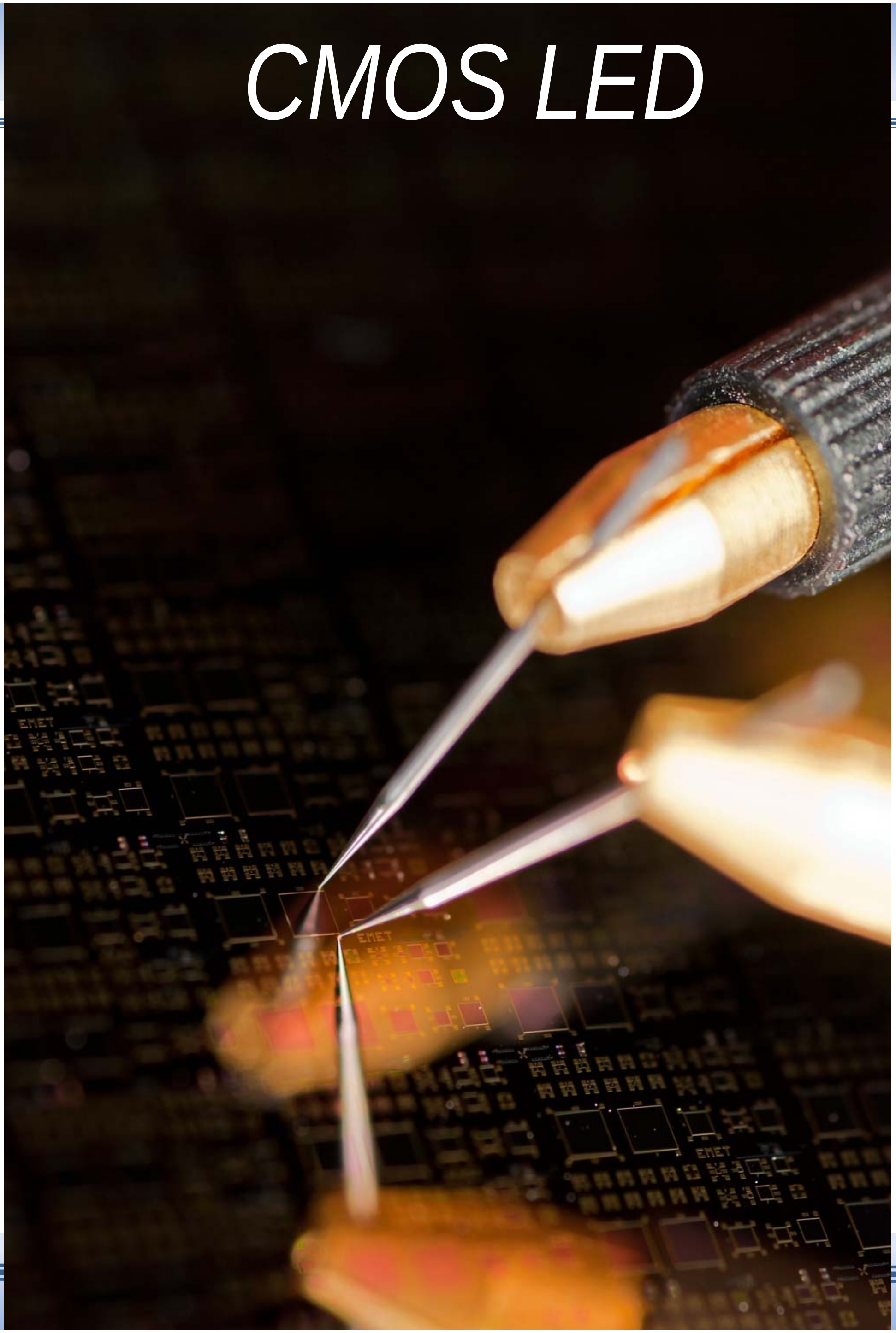
A Anopchenko, et al. Applied Physics Letters 99, 181108 (2011).

Optimized structures



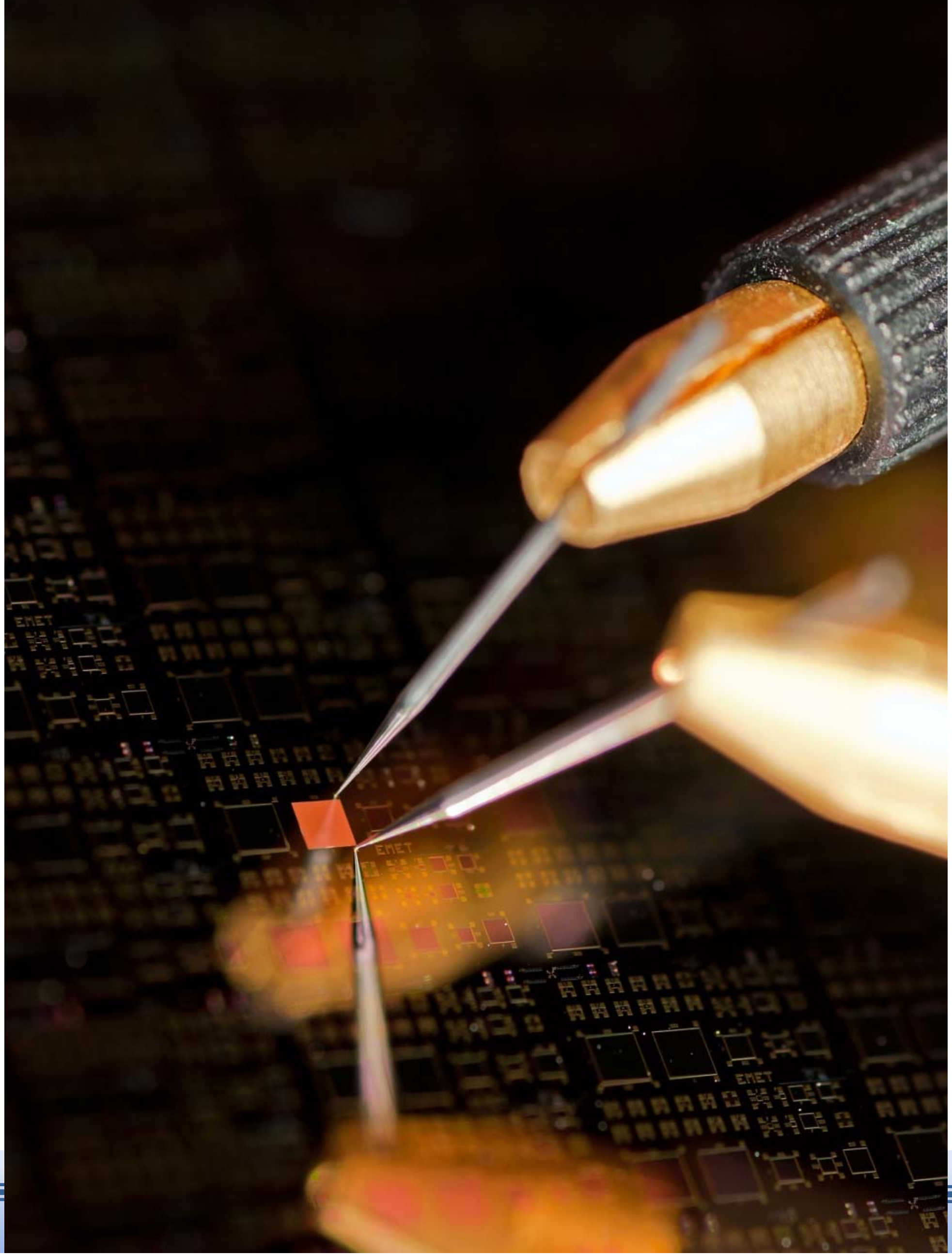
A Anopchenko, et al. Applied Physics Letters 99, 181108 (2011).

CMOS LED



Si-NC LED
on a CMOS wafer

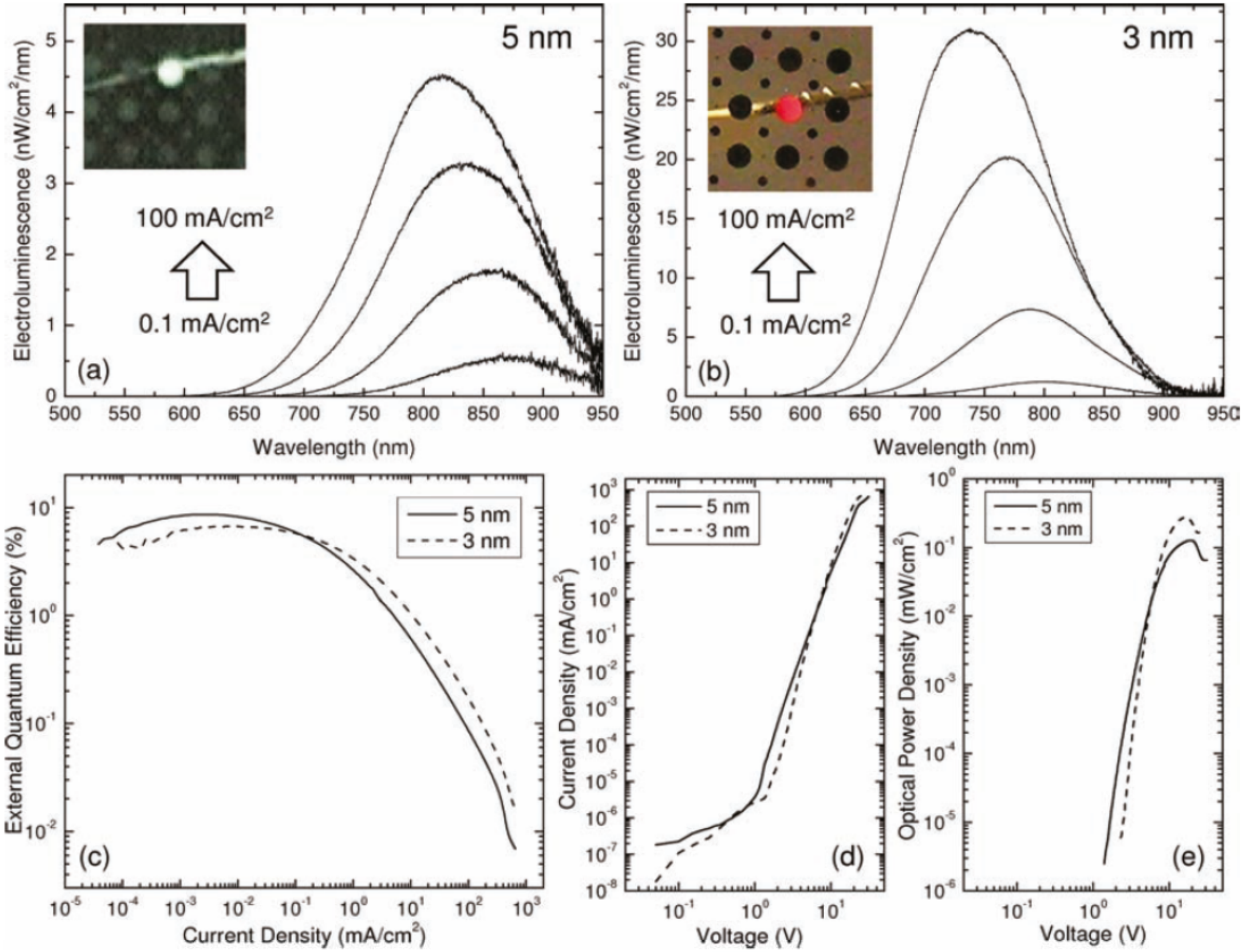
CMOS LED



Si-NC LED
on a CMOS wafer
0.2%

Colloidal Silicon nanocrystals

KY Cheng et al, Nanolett. 11 (2011) 1952



impurities

beat the indirect band gap with
relaxation of the k-conservation rule

The idea

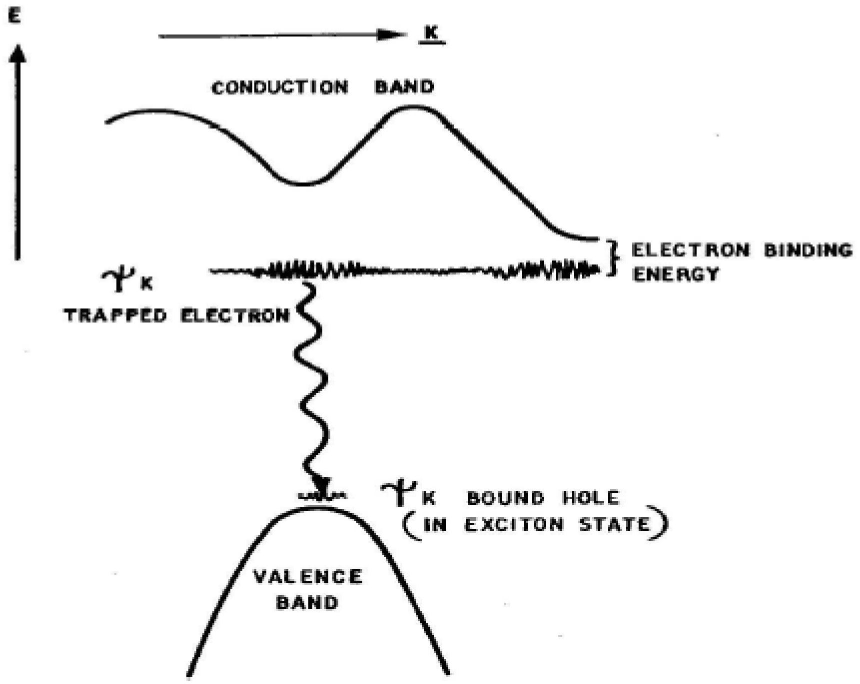
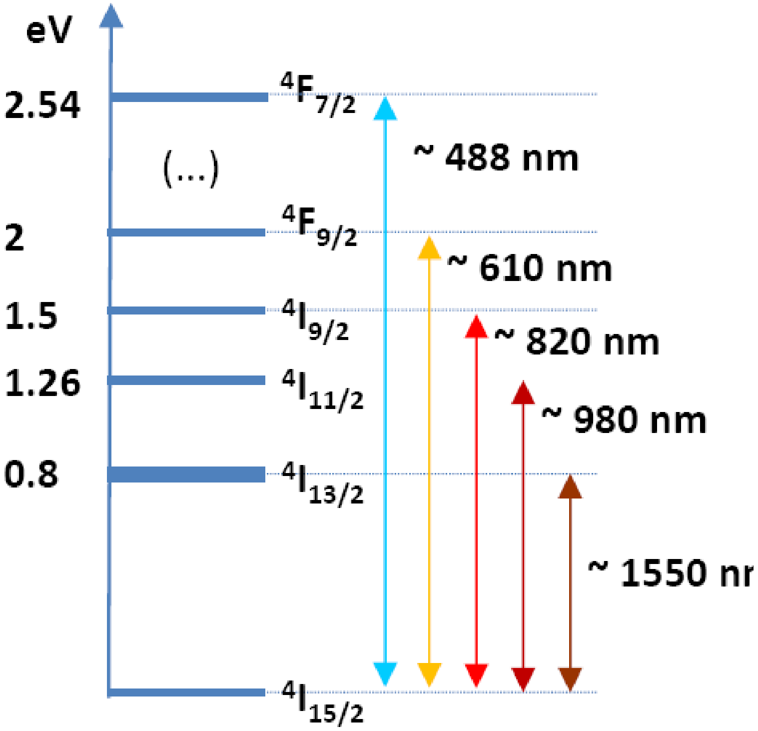


Fig. 1.9. The presence of an impurity leads to a spatial localization of an electron and to a delocalization of the wave function. After [7].

Er impurity

Rare-earth used to form EDFA

Internal transition at 1.535 μm



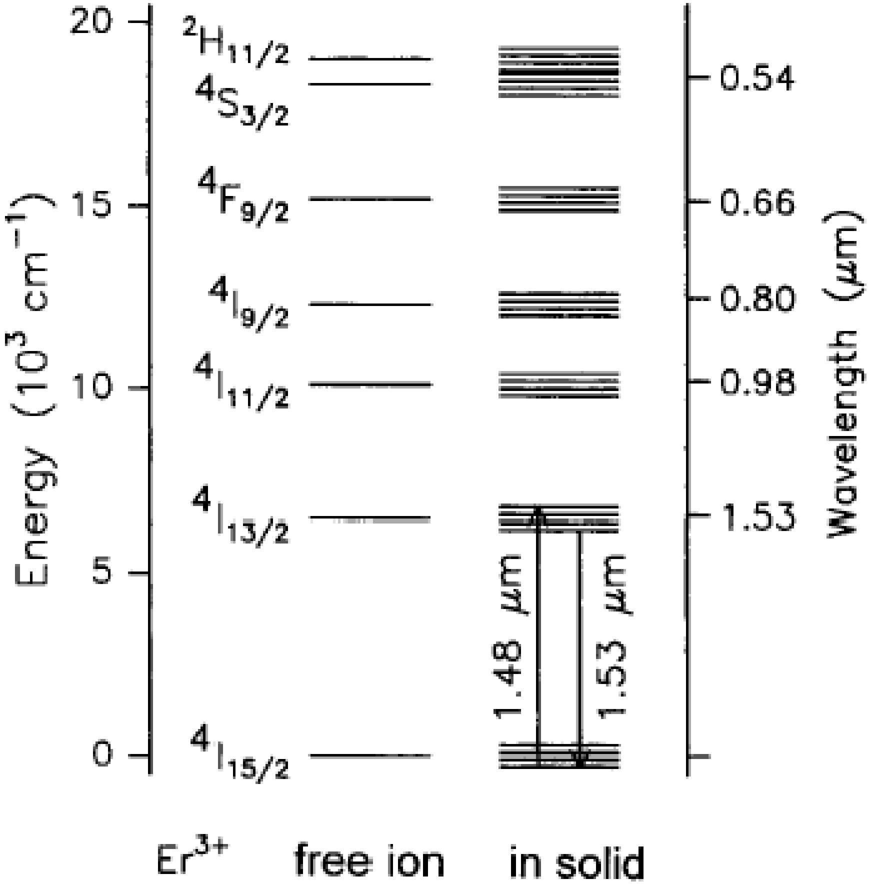
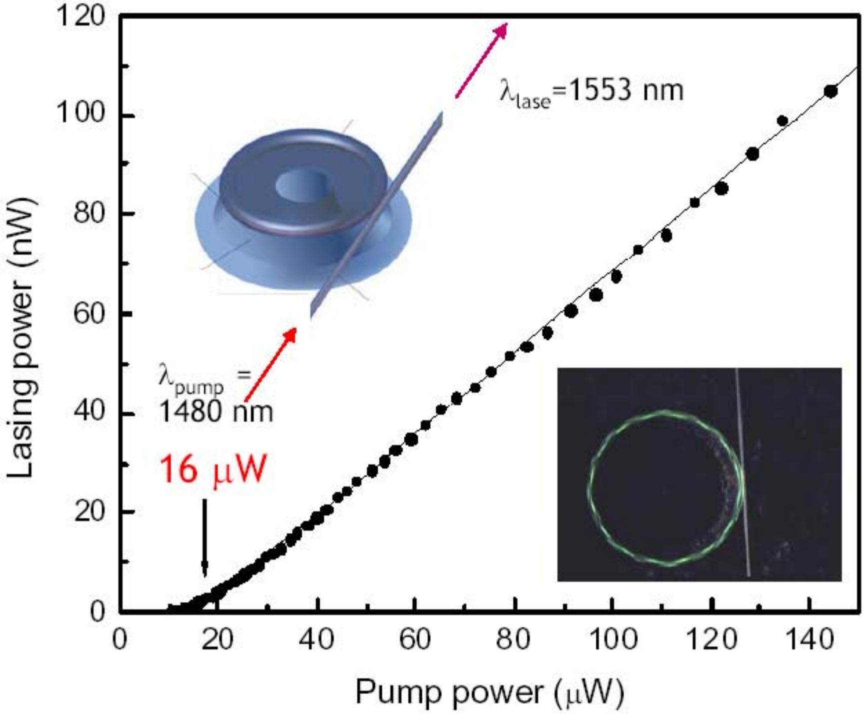


FIG. 1. Schematic energy level diagram of Er^{3+}. In the free ion the energy levels are sharp; in a solid the levels are split due to the Stark effect. Pump (1.48 μm) and signal (1.53 μm) wavelengths are indicated, together with the Russell–Saunders notation of the energy levels.

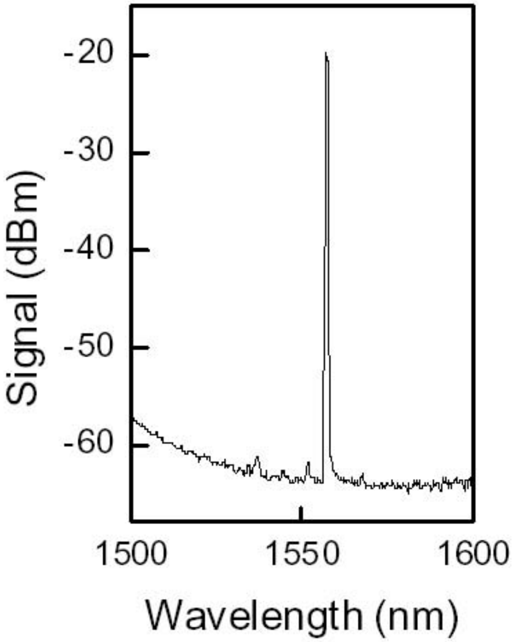
Er^{3+}: ….$4f^{11}$ $5s^2$ $5p^6$

Er laser

The first Er microlaser on Si fully made with CMOS technology



Single-mode lasing



Appl. Phys. Lett. **84**, 1037 (2004)

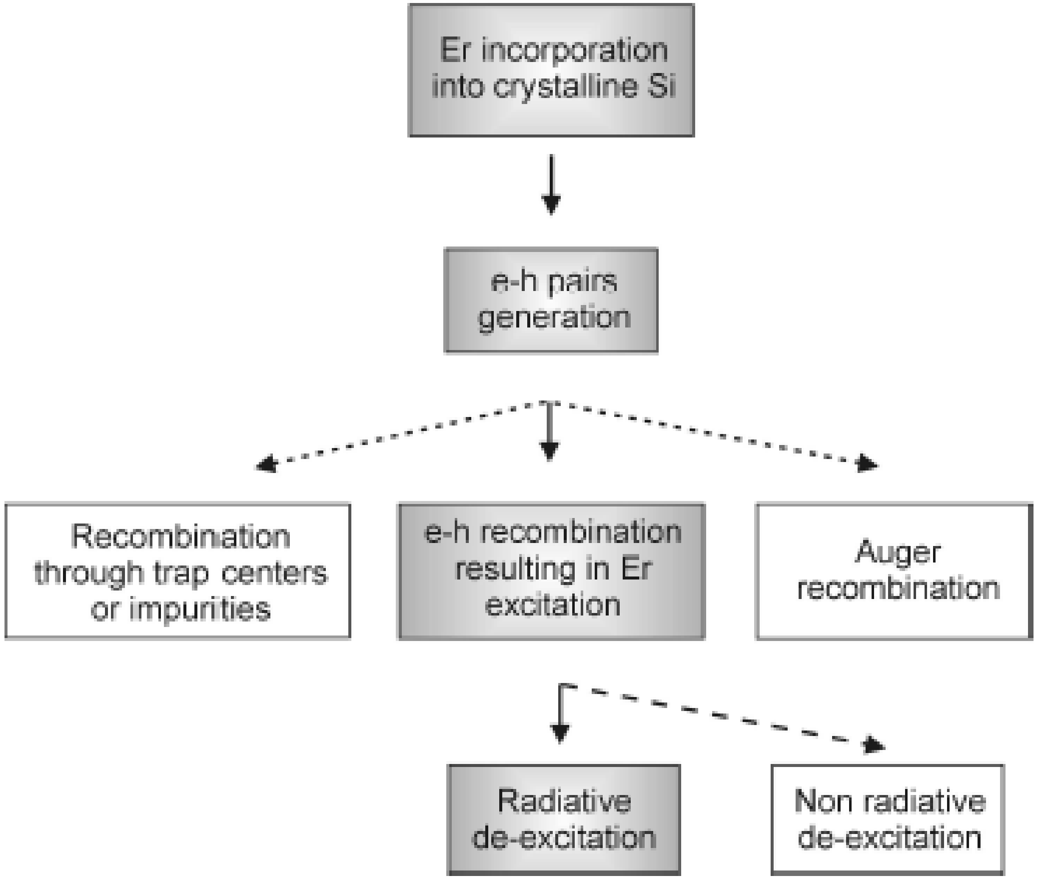
Phys. Rev. A **70**, 033803 (2004)

This was on silicon and not in silicon

Could we exploit the semiconducting properties of silicon to pump the system?

Rationale of Er in silicon

Processes towards Er luminescence in Si



Er incorporation into crystalline Si

e-h pairs generation

Recombination through trap centers or impurities

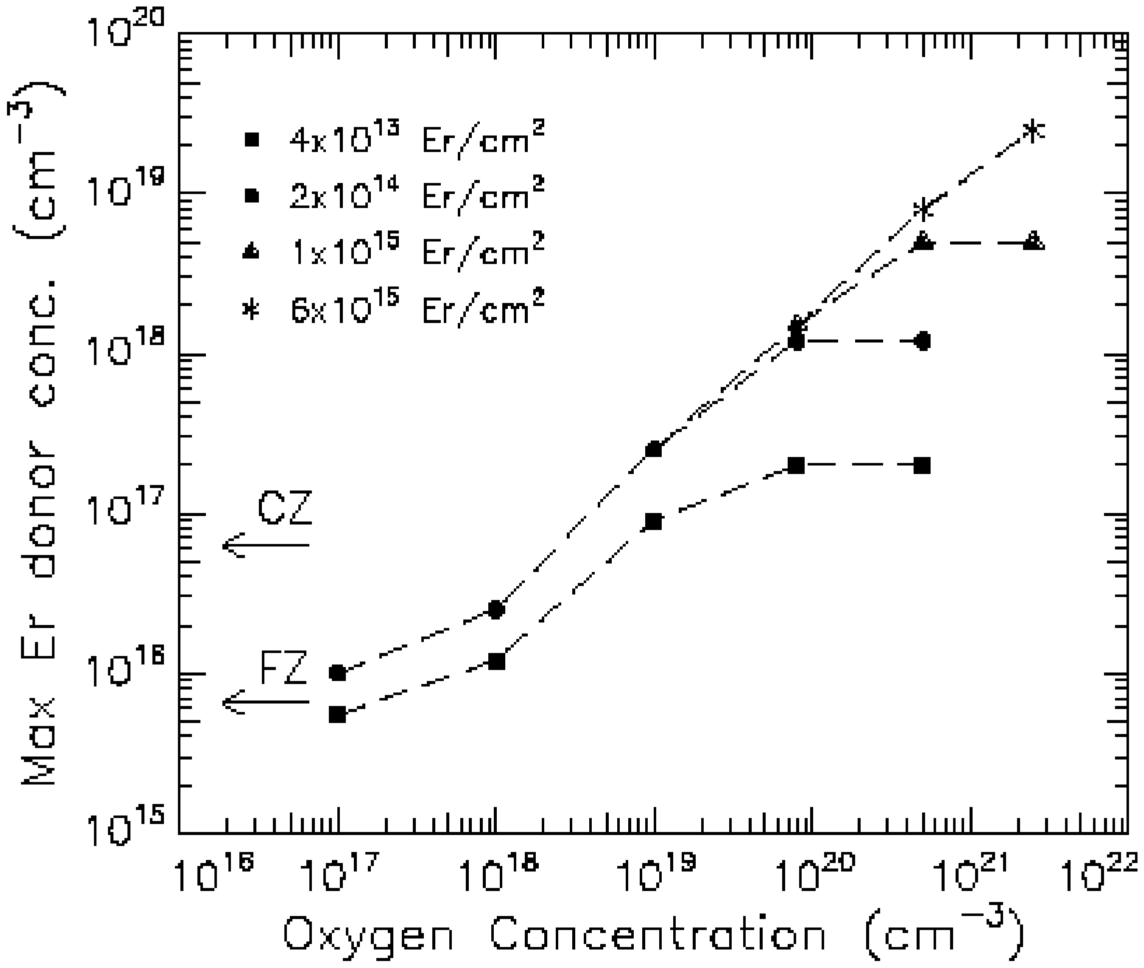
e-h recombination resulting in Er excitation

Auger recombination

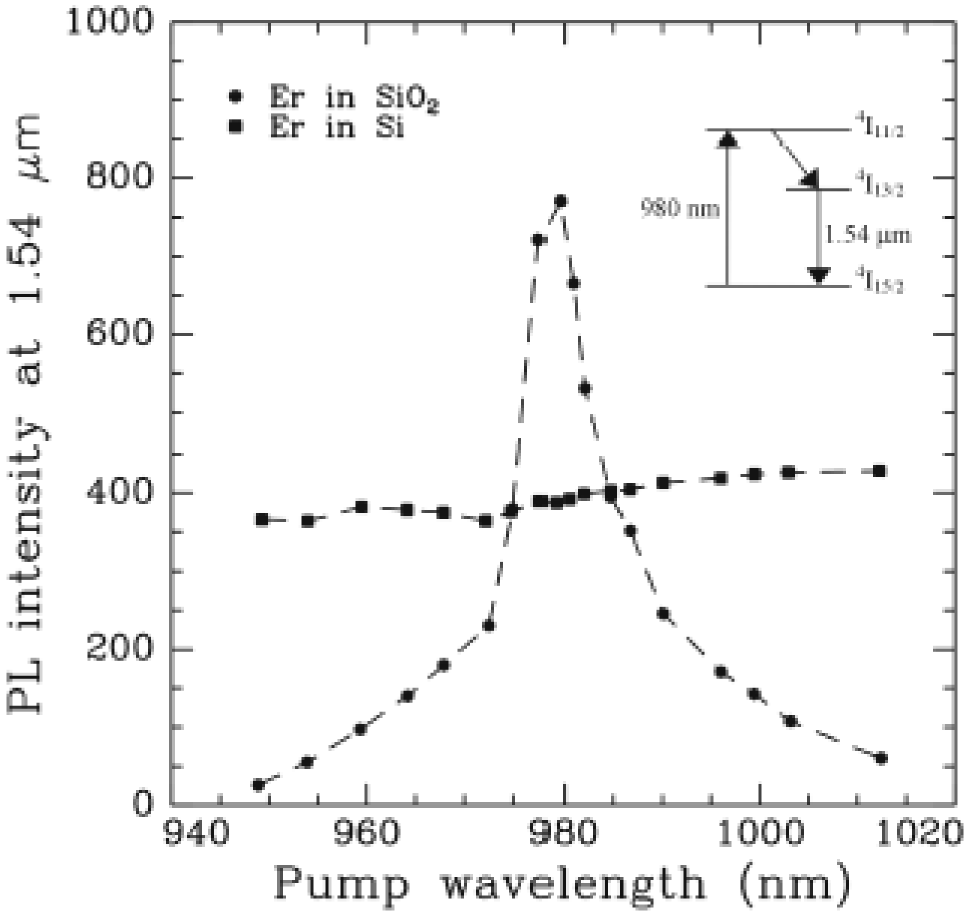
Radiative de-excitation

Non radiative de-excitation

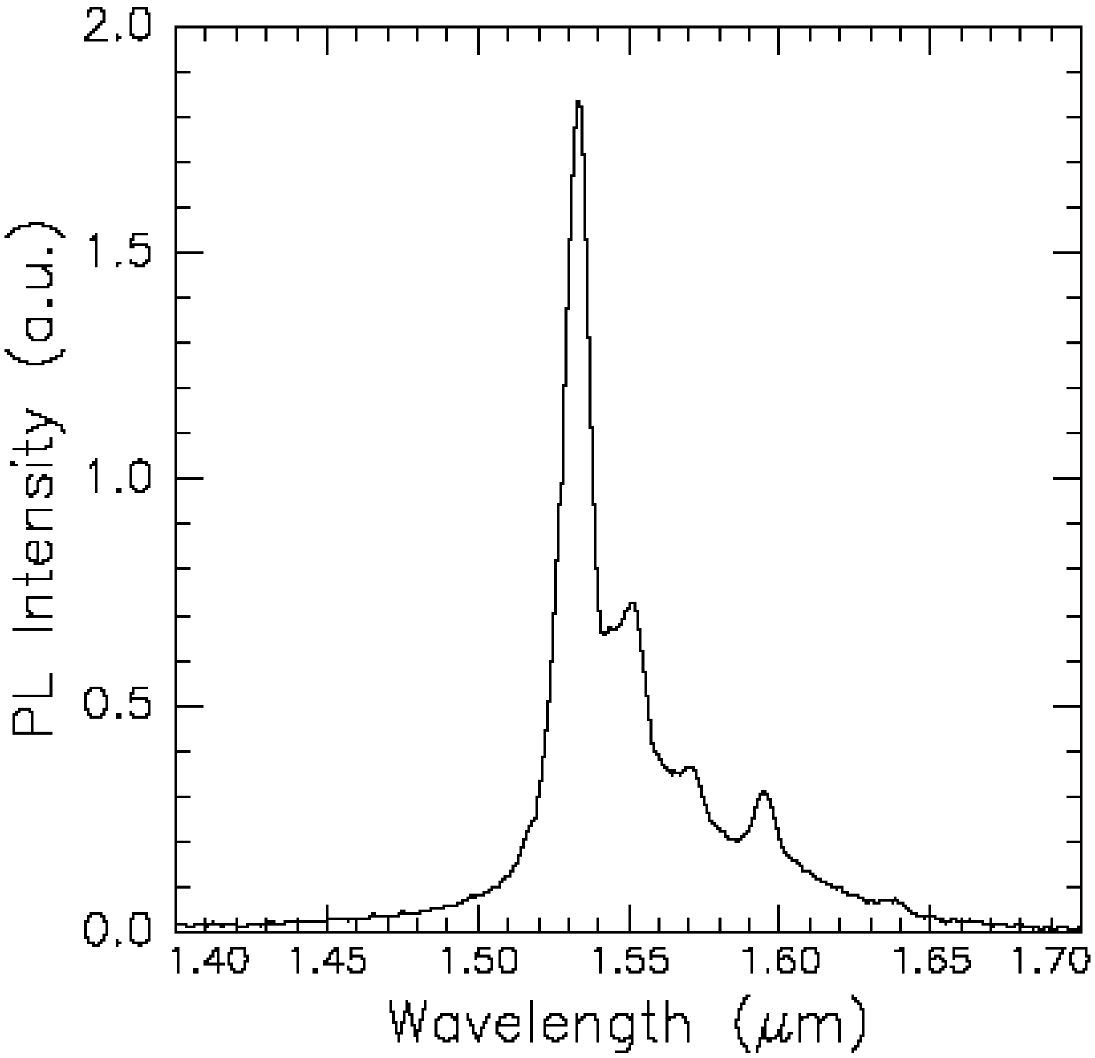
Reproduce an evironment similar to the one of Er in Silica



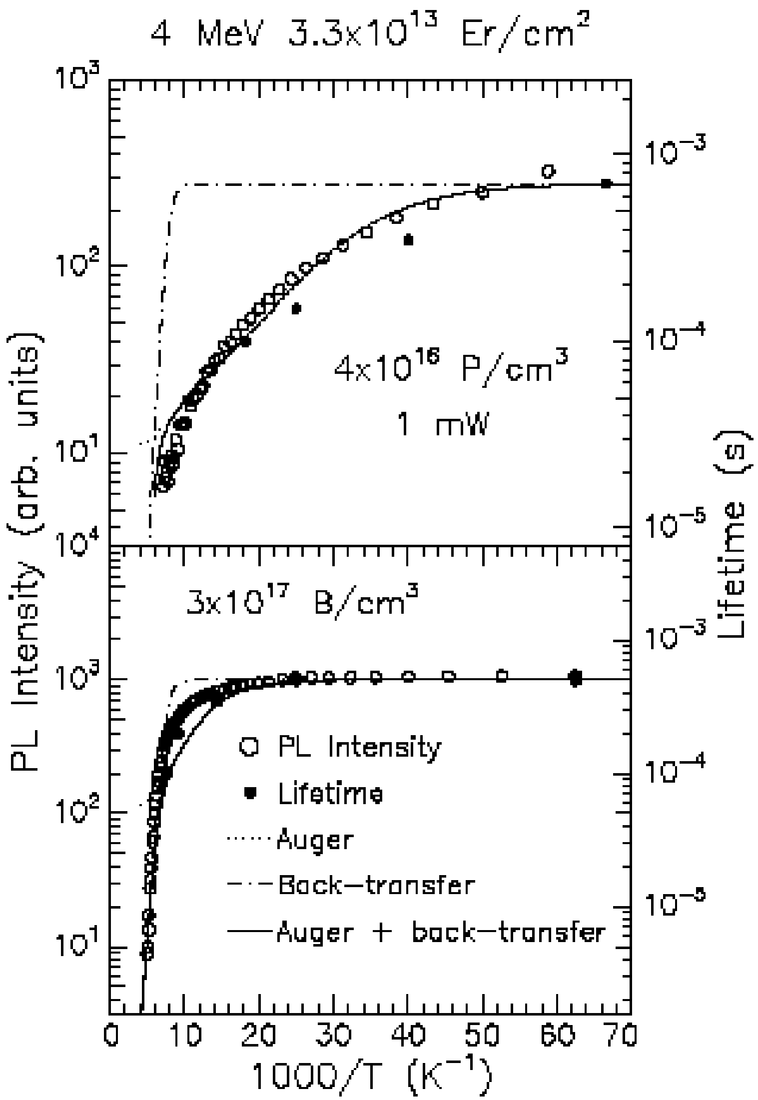
e-h pair assisted transfer to Er



Low T luminescence from Er



Temperature quenching of PL



Auger

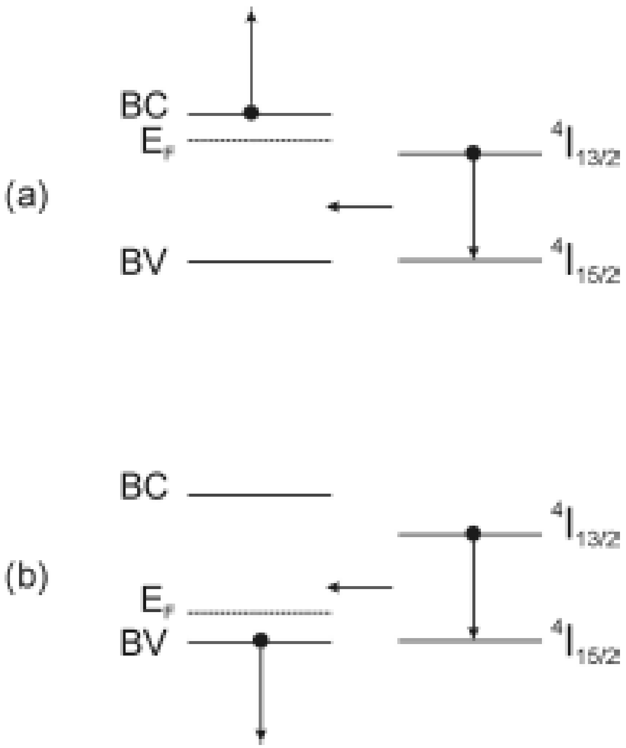
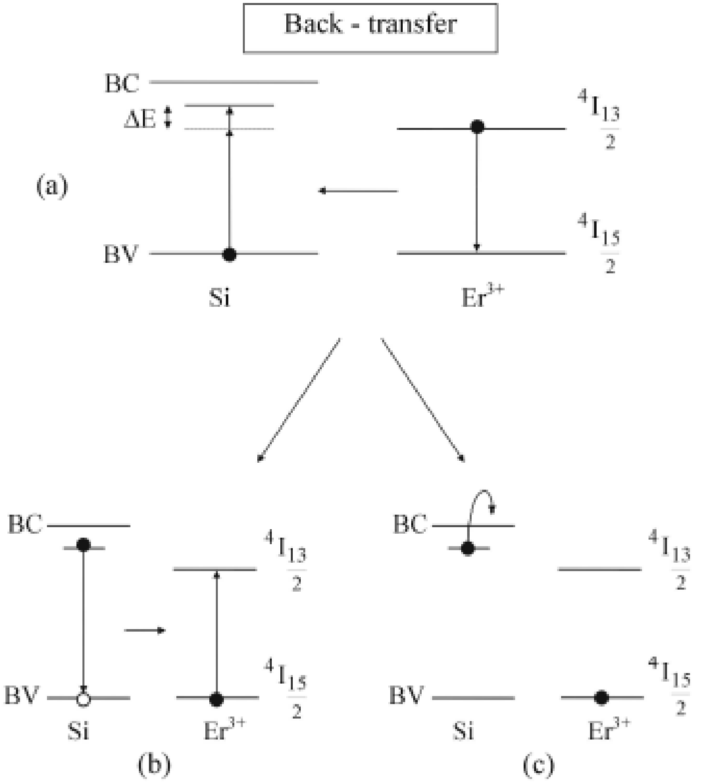


Fig. 5.16. Schematic representation of the Er Auger non-radiative de-excitation process with free electrons (a) or free holes (b).

Back transfer



re-excitation occurs restoring the initial situation

electron thermalization completes the back-transfer

Fig. 5.20. Schematic picture of the back-transfer process (a) and of the two possible processes that may occur after Er gives back the energy to the Si matrix: (b) the electron in the Er-related level recombines with a hole in the valence band causing the re-excitation of Er; (c) the electron in the Er-related level thermalizes in the conduction band and cannot excite Er.

…room temperature operation?

Enlarge the band-gap to avoid back-transfer

....silicon nanocrystals!

Large band-gap

No back-transfer

idea

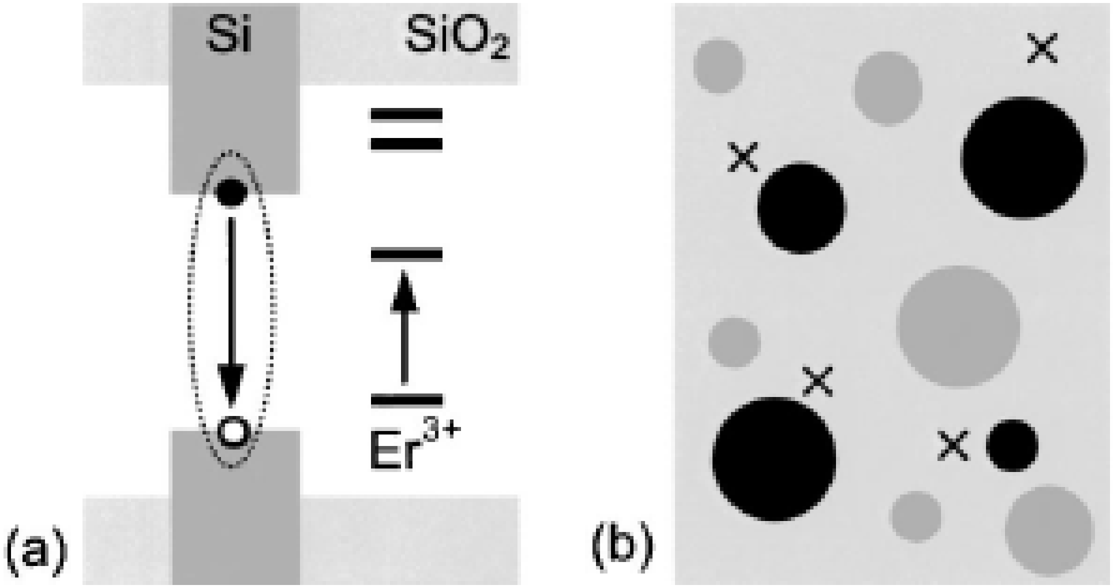


Fig. 9. (a) Schematic Er excitation model showing the electronic band structure of Si-nanocrystal-doped SiO_2 and the Er 4*f* energy levels. An optically generated exciton (dotted ellipse) confined in the nanocrystal can recombine and excite Er^{3+}. (b) Schematic representation of SiO_2 containing Er (crosses) and nanocrystals (circles). The nanocrystals that couple to Er (black circles) show no exciton luminescence. From Kik *et al.*, Ref. 37.

…questions?

- Does Si-nc activate the Er luminescence?
- Where is the Er?
- What are the limits?
- Is electroluminescence possible?
- Is gain possible?

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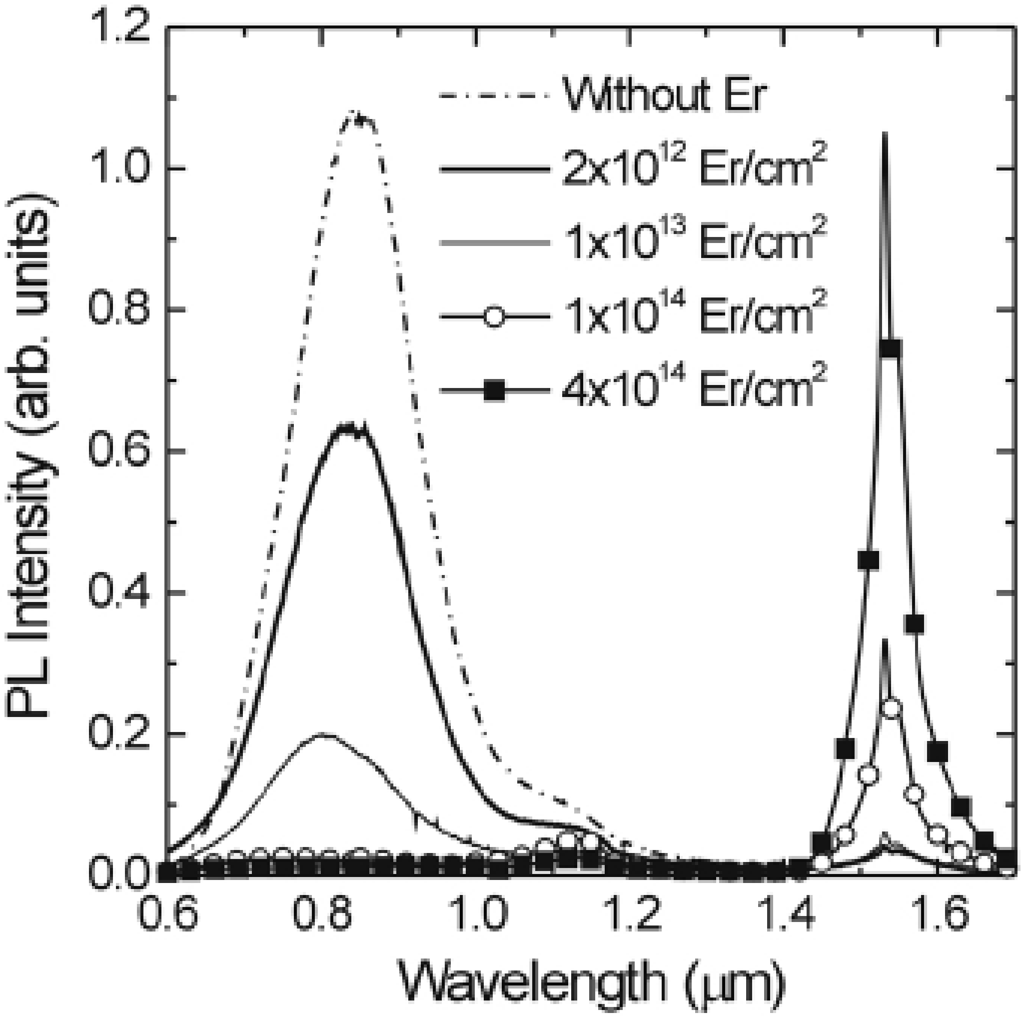
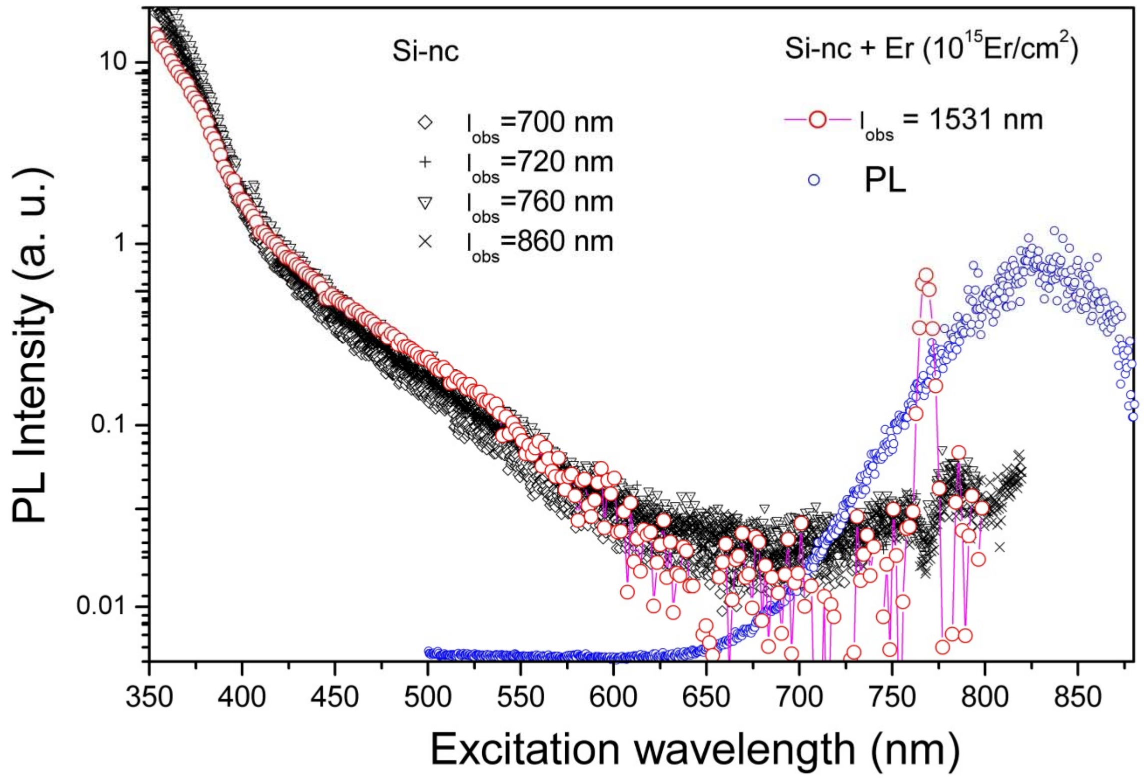
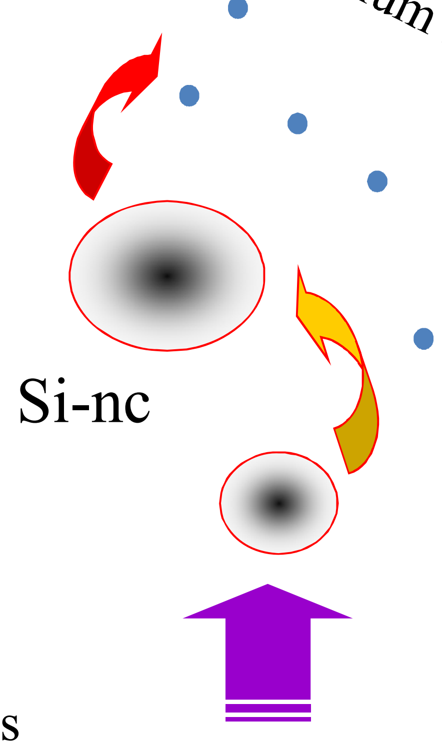
Er coupled Silicon nanocrystals



Er coupled Silicon nanocrystals




Si-nc absorbs energy and releases to Erbium ions

Si-nc

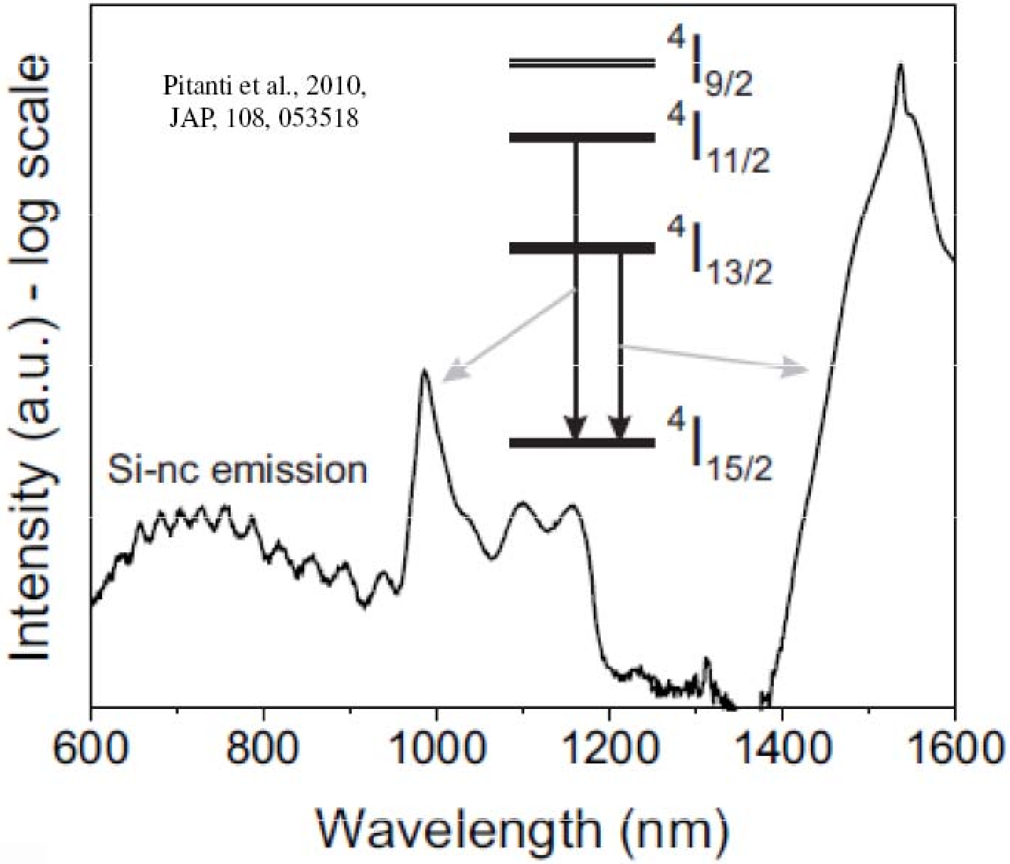
Si-nc acts as sensitizers for erbium ions

Si-nc as Er^{3+} sensitizers

Indirect excitation:

- 476 nm

Typical PL spectra
of Si-nc
co-doped with
erbium ions



High efficiency of pumping through Si-nc

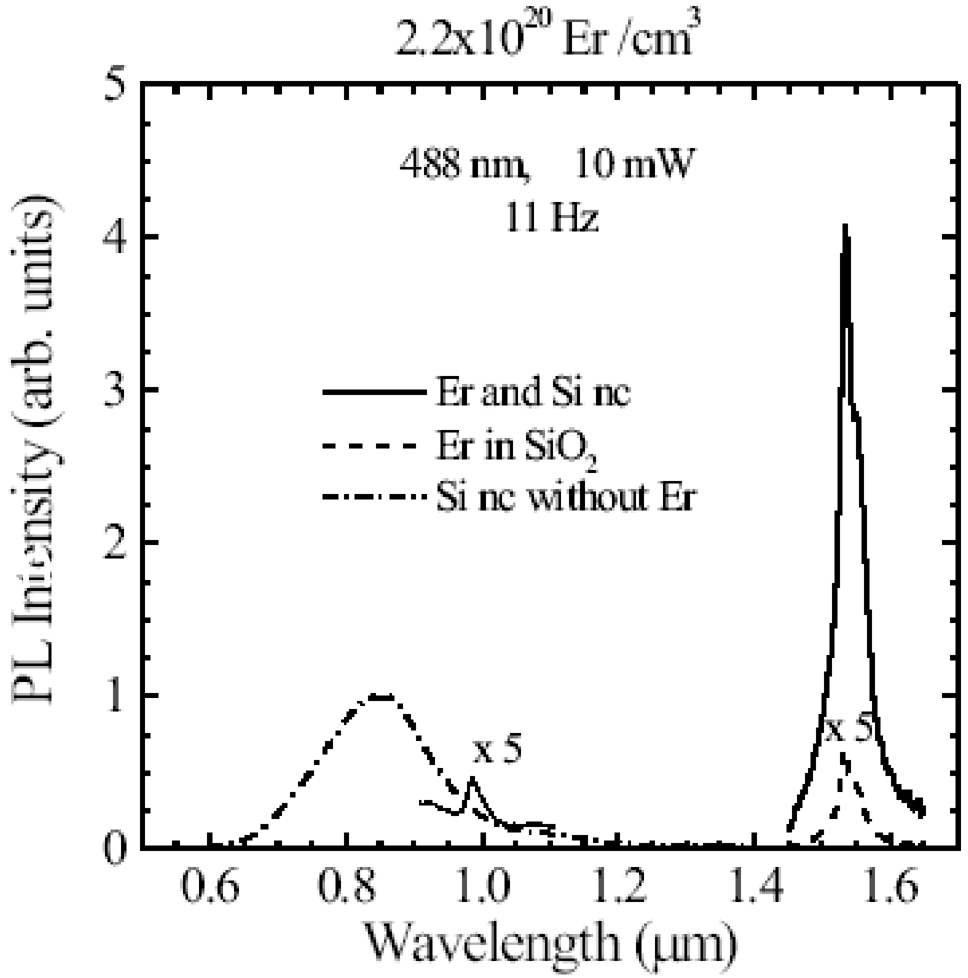


Figure 4.5. - Room temperature photoluminescence (PL) spectra for unimplanted Si nanocrystals (dash-dotted line), Er in SiO_2 (dashed line) and Er in presence of Si nanoclusters (continuous lines). The Er concentration in the two implanted samples is $2.2x10^{20}/cm^3$. All of the spectra have been normalized to the maximum PL intensity of Si nanocrystals.

No quenching of PL due to lack of back-transfer

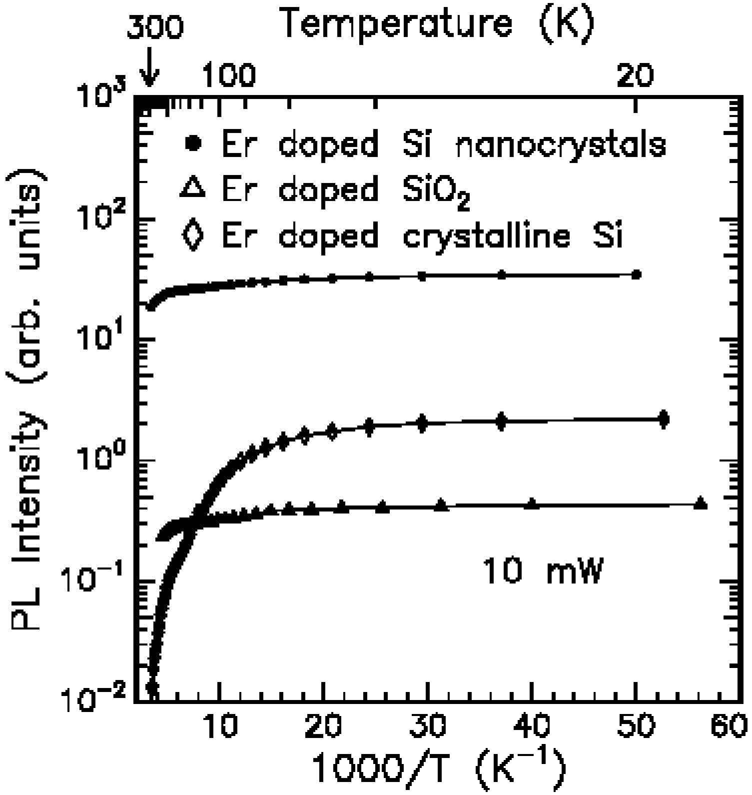


Figure 4.9. - Temperature behavior of the 1.54 μm luminescence intensity for Er in presence of Si nanoclusters, for Er in SiO_2 and for Er in crystalline silicon.

Long lifetime

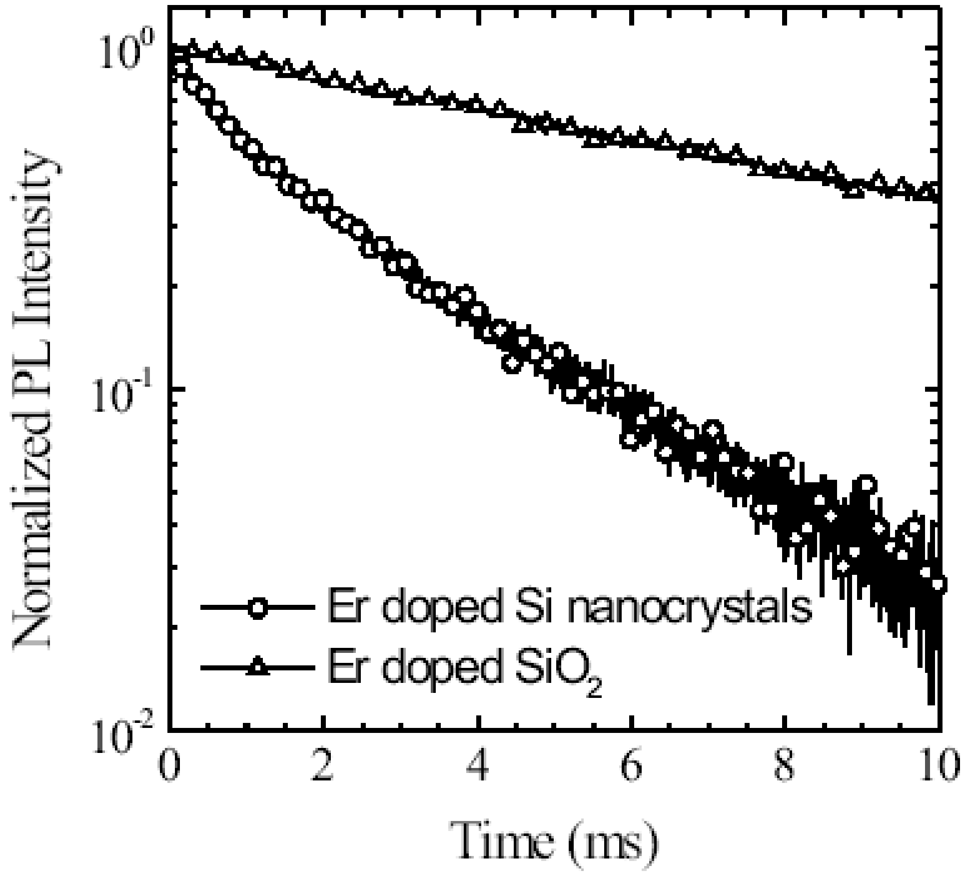


Figure 4.10. - Comparison between the decay-time curves of Er in presence of Si nanoclusters and in SiO_2, at room temperature.

Nanocrystals are not needed: better nanoclusters

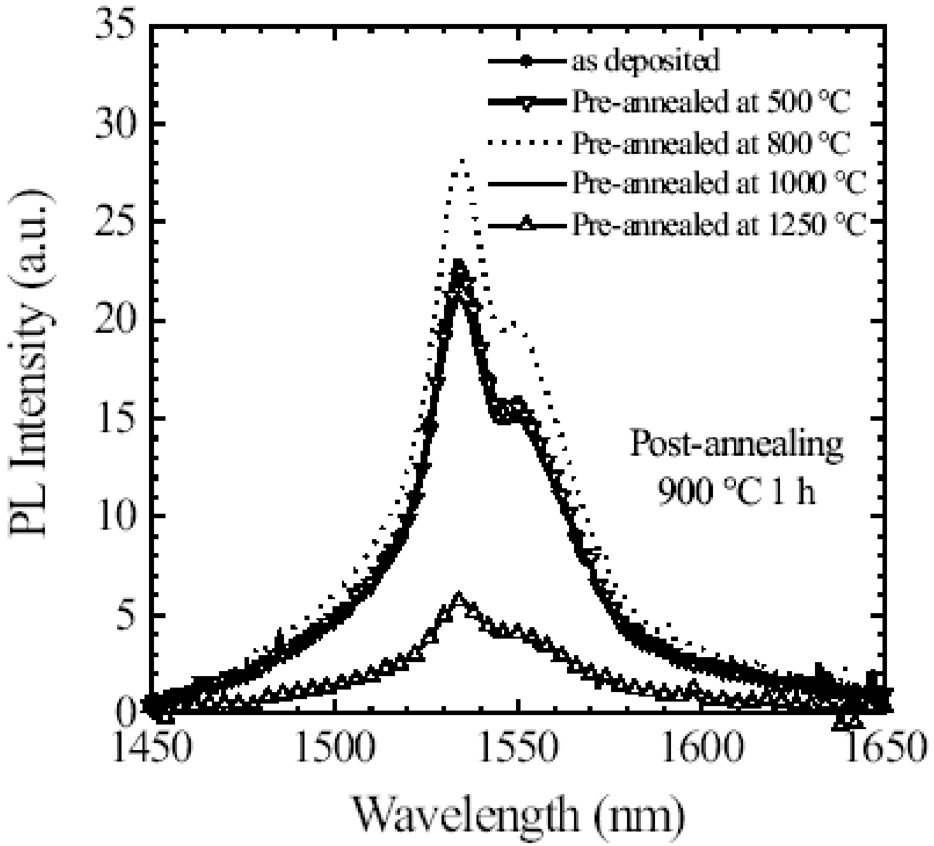


Figure 4.32. - Room temperature PL spectra taken by exciting with a 10 mW laser SiO_x samples pre-annealed at different temperatures and then implanted with 5×10^{14} Er/cm^2. The post-implantation thermal process was 900°C for 1 h for all of the samples.

...questions?

- Does Si-nc activate the Er luminescence?
- Where is the Er?

YES

- What are the limits?
- Is electroluminescence possible?
- Is gain possible?

...questions?

- Does Si-nc activate the Er luminescence?
- Where is the Er?
- What are the limits?
- Is electroluminescence possible?
- Is gain possible?

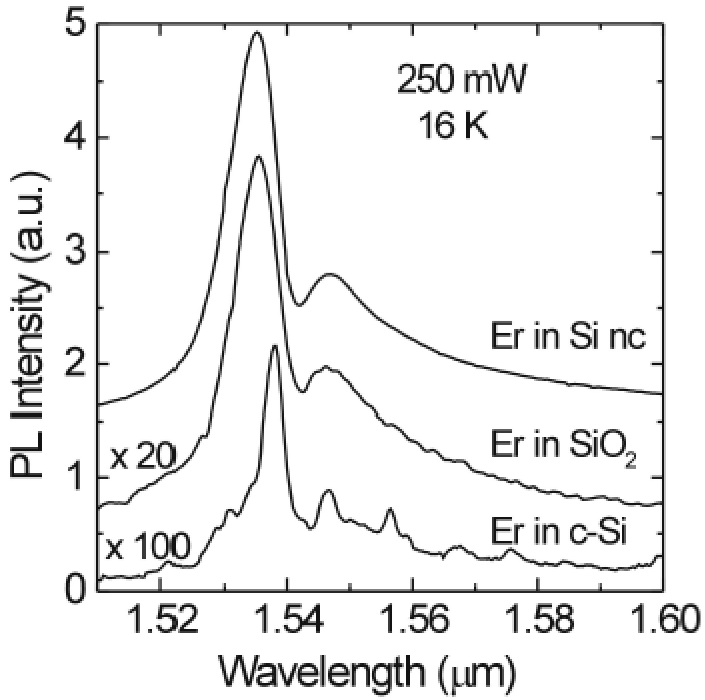


Fig. 5.34. High resolution (∼ 1 nm) photoluminescence spectra measured at 16 K by pumping with a laser pump power of 250 mW three different samples: Er+O implanted crystalline silicon; Er implanted SiO$_2$ and Er implanted Si nanocrystals. After [69].

...questions?

- Does Si-nc activate the Er luminescence? YES
- Where is the Er? In the oxide
- What are the limits?
- Is electroluminescence possible?
- Is gain possible?

...questions?

- Does Si-nc activate the Er luminescence?
- Where is the Er?
- What are the limits?
- Is electroluminescence possible?
- Is gain possible?

Concentration quenching

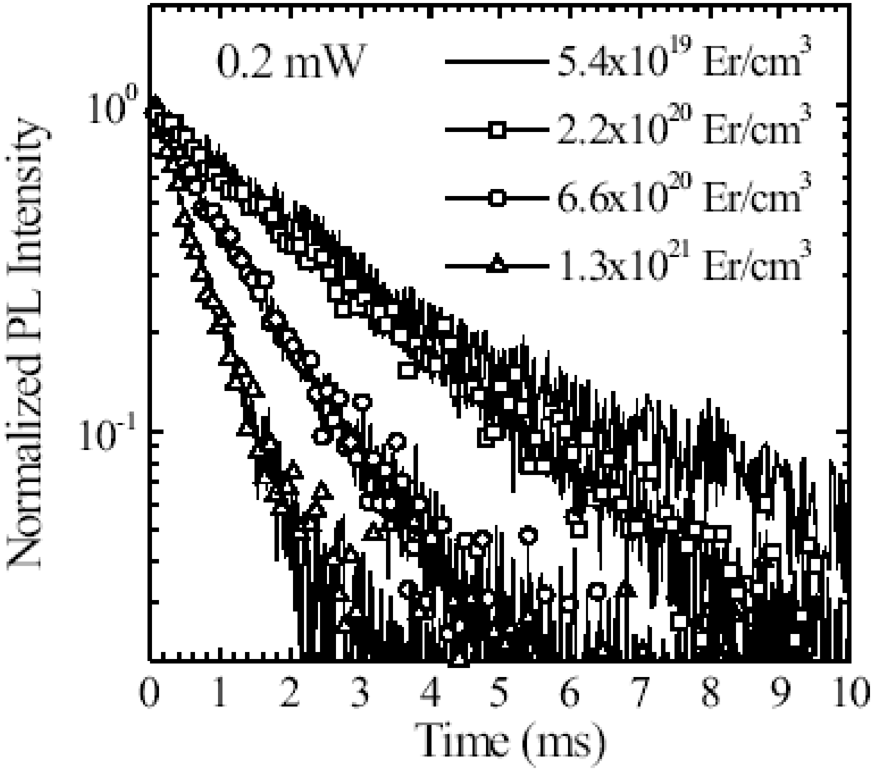


Figure 4.12. - Decay time measurements for the 1.54 μm Er luminescence for samples containing the very same Si nanoclusters and different Er concentrations. The pump power was 0.2 mW.

$$g = \sigma_{em} N_2 - \sigma_{abs} N_1$$

$$N_{tot} = N_1 + N_2$$

Up-conversion

$$g = \sigma_{em} N_2 - \sigma_{abs} N_1$$

$$N_{tot} = N_1 + N_2$$

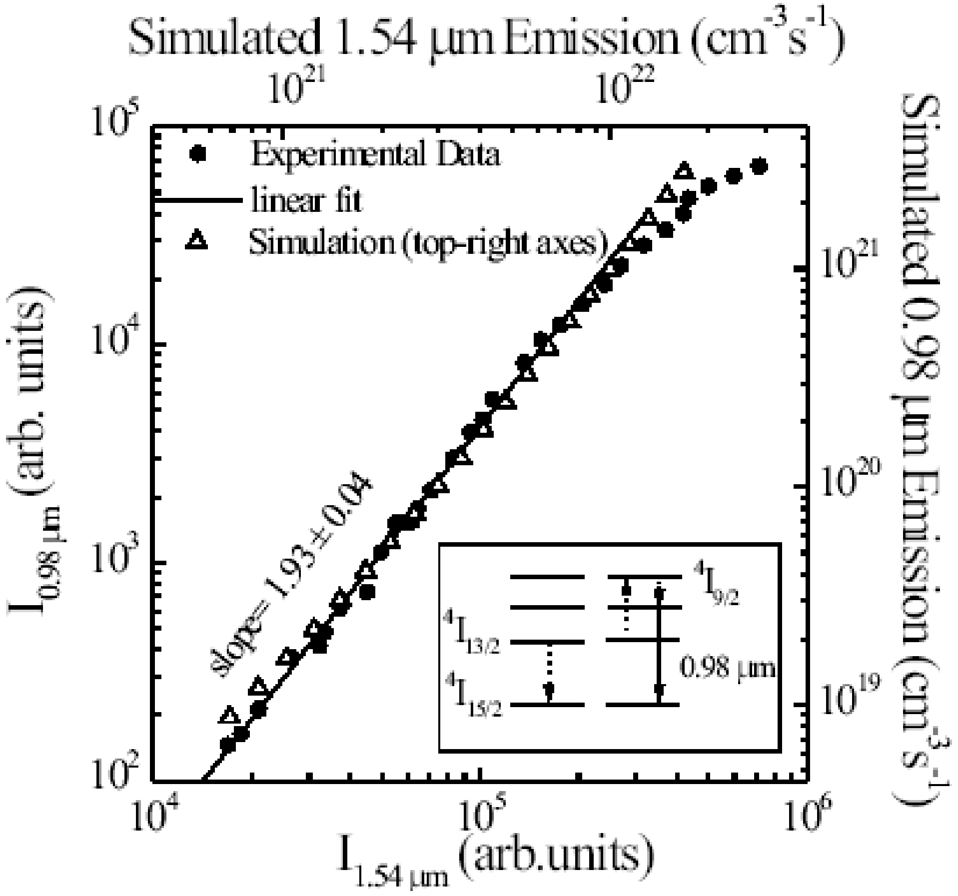


Figure 4.17. - Correlation graph reporting a quadratic dependence of the 0.98 μm intensity with respect to the 1.54 μm one for the sample containing 6.5x10^{20}Er/cm^3 in presence of Si nanoclusters. Solid circles represent experimental data as extracted from Fig. 4.16. Open triangles refer to simulated photon emission (top-right axes) as obtained by solving eq. (4.8). Inset: schematic diagram showing the cooperative up-conversion mechanism between two interacting Er ions, which determines the emission of a 0.98 μm photon at the expenses of two 1.54 μm photons.

...questions?

- Does Si-nc activate the Er luminescence? yes
- Where is the Er?   In the oxide
- What are the limits?
- Is electroluminescence possible?
- Is gain possible?

Upconversion and concentration quenching, may be other too...

...questions?

- Does Si-nc activate the Er luminescence?
- Where is the Er?
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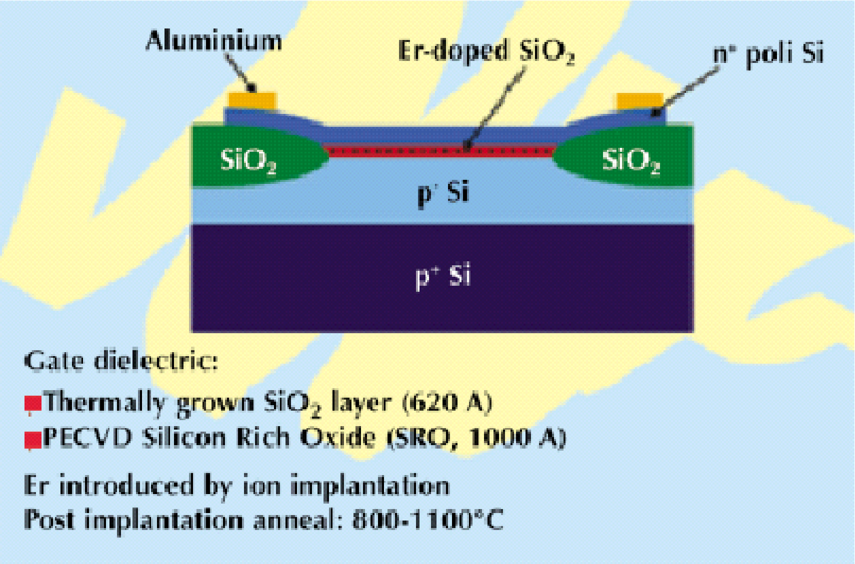
- Is gain possible?

Er coupled Silicon nanocrystals LED

Silicon Light-Emitting Diode



Gate dielectric:
- Thermally grown SiO_2 layer (620 A)
- PECVD Silicon Rich Oxide (SRO, 1000 A)

Er introduced by ion implantation
Post implantation anneal: 800-1100°C

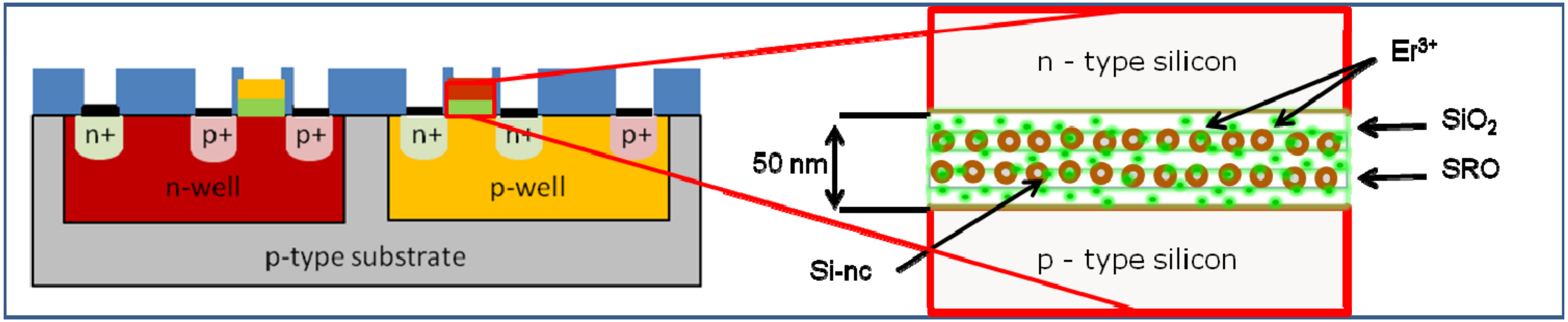
The quantum efficiencies achieved (around 20%) are about 100 times better than have previously been possible with silicon and are, for the first time, comparable to those obtained from GaAs and other compound semiconductors traditionally are used to make Light-Emitting Diodes. The frequency of the emitted light depends on the choice of rare-earth dopant.

Probably the best promise

for electrical injection efficiency

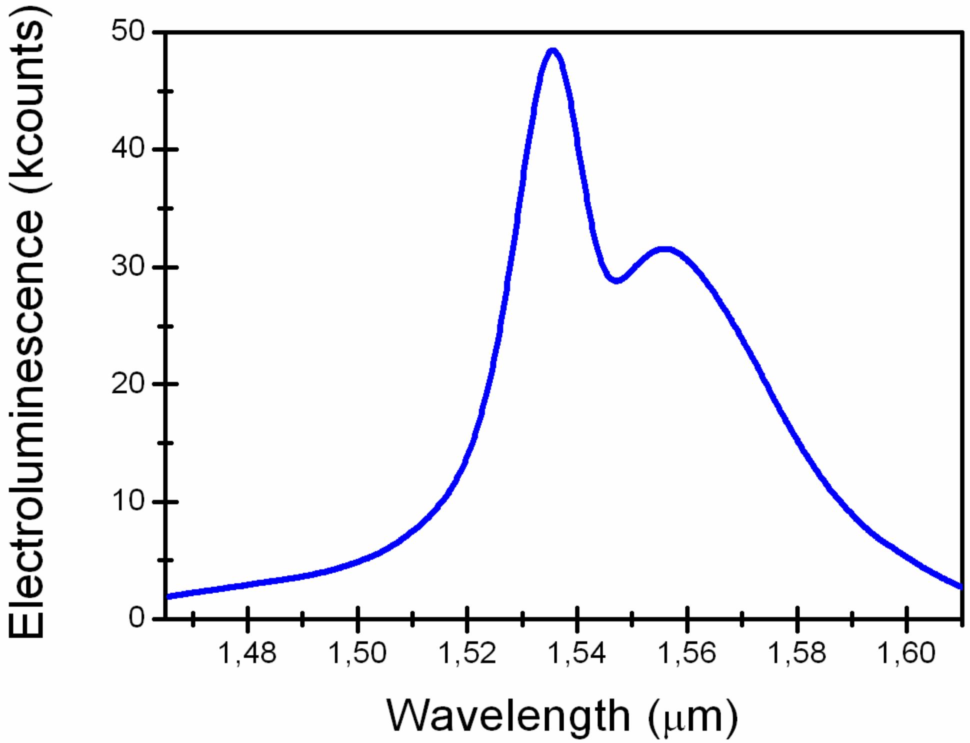
Si-NCs:Er LEDs

- 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

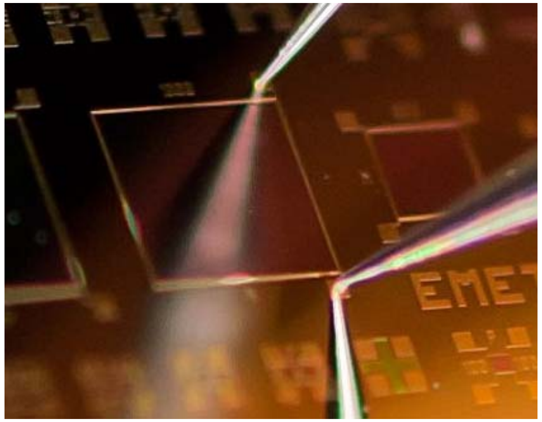


Si-NCs:Er LEDs - Results

External
Quantum
Efficiency
0.55 % in DC



Si-NCs:Er LEDs - Results



External
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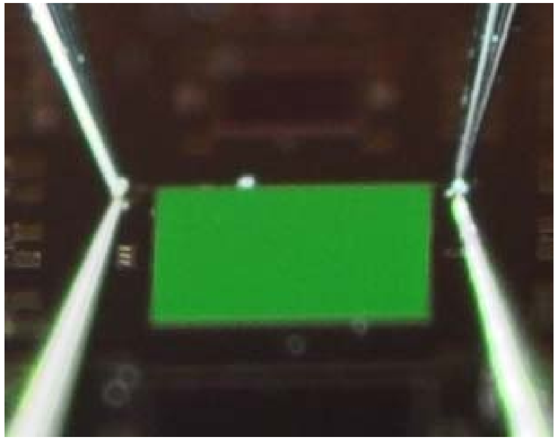
0.55 % in DC



As efficient as Si-nc LED injection

	Er in SiO_2 (cm^2)	Er in Si (cm^2)	Er in Si-nc (cm^2)
Effective excitation cross section of luminescence at a pumping energy of 488 nm	$1\text{-}8 \times 10^{-21}$	3×10^{-15}	$1.1\text{-}0.7 \times 10^{-16}$
Effective excitation cross section of electroluminescence		4×10^{-14}	1×10^{-14} by impact ionization
Emission cross section at 1.535 mm	6×10^{-21}	2×10^{-20}	
Absorption cross section at 1.535 mm	4×10^{-21}	2×10^{-20}	

Mostly data from F. Priolo's group

...questions?

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...questions?

- Does Si-nc activate the Er luminescence?
- Where is the Er?
- What are the limits?
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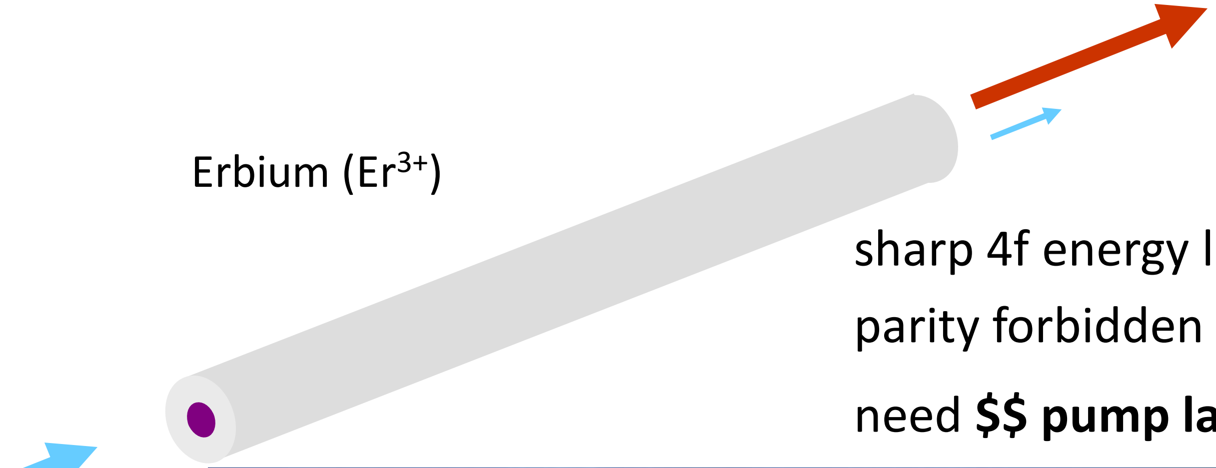
The vision……substitute this



Erbium (Er^{3+})

sharp 4f energy levels

parity forbidden $\Rightarrow \sigma_{abs} \approx \mathbf{10^{-21}\ cm^2}$

need **$$ pump laser**

EDFA