Nanotecnologie: materiali e metodi di produzione

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***Web**: www.unipa.it/lamp/*

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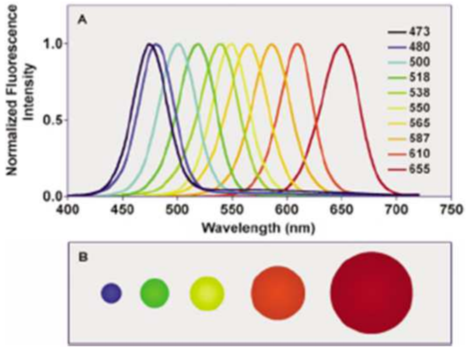
Sommario

Introduzione:

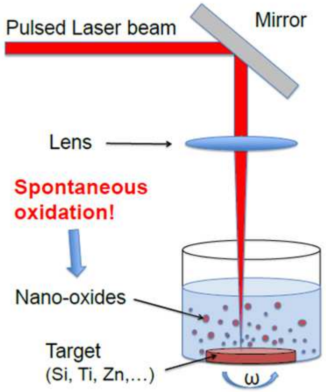
Proprietà peculiari dei materiali nanometrici

Alta superficie specifica --- Confinamento quantistico



Metodi di produzione

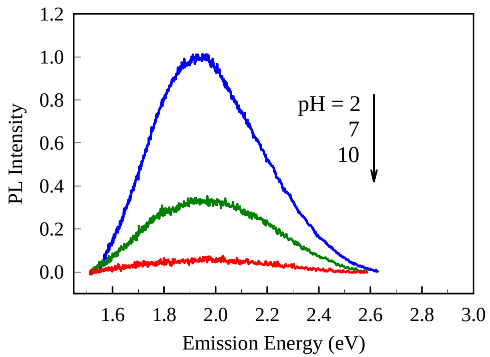
Pulsed Laser Ablation (PLA)



Applicazioni di PLA:

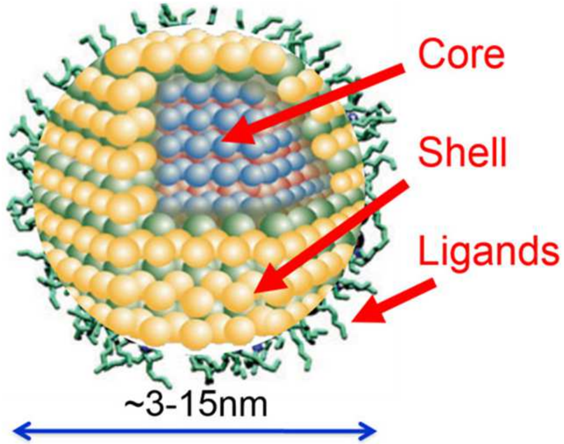
Nanocristalli di Silicio «ossidato»

Nanoparticelle di ZnO



troduzione

Il controllo delle proprietà ottiche/elettriche di un materiale è i principale **goal** delle moderne nanotecnologie

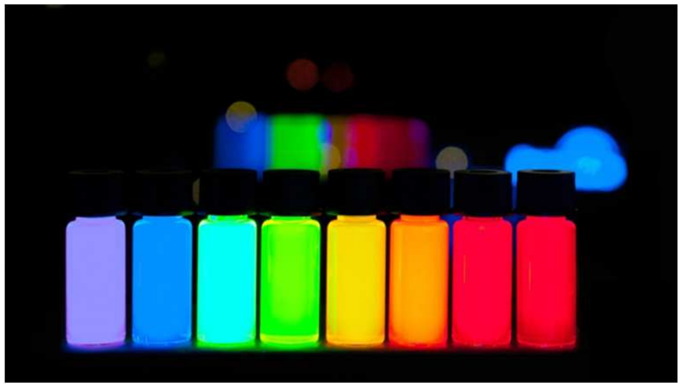


ntrollo della morfologia (dimensione, forma) e
a composizione chimica (volume, superficie)

raverso processi di sintesi

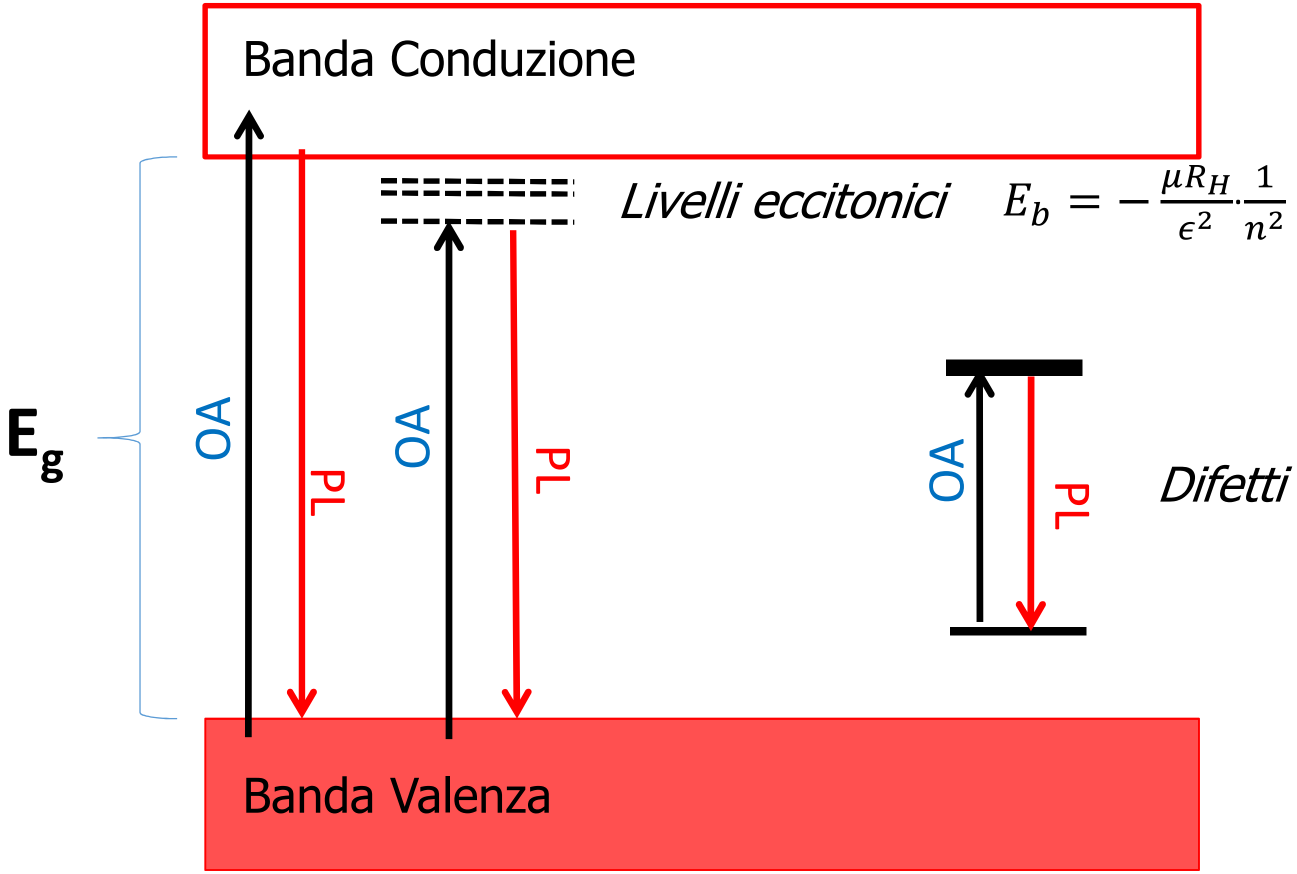
prietà peculiari dei materiali nanometrici
non dipendono esclusivamente dalla loro composizione

issione di luminescenza: tunabilità, stabilità, brillanza



minescenza

Proprietà ottica di Semiconduttori/Isolanti
Materiali con gap ottica E_g~1-10 eV

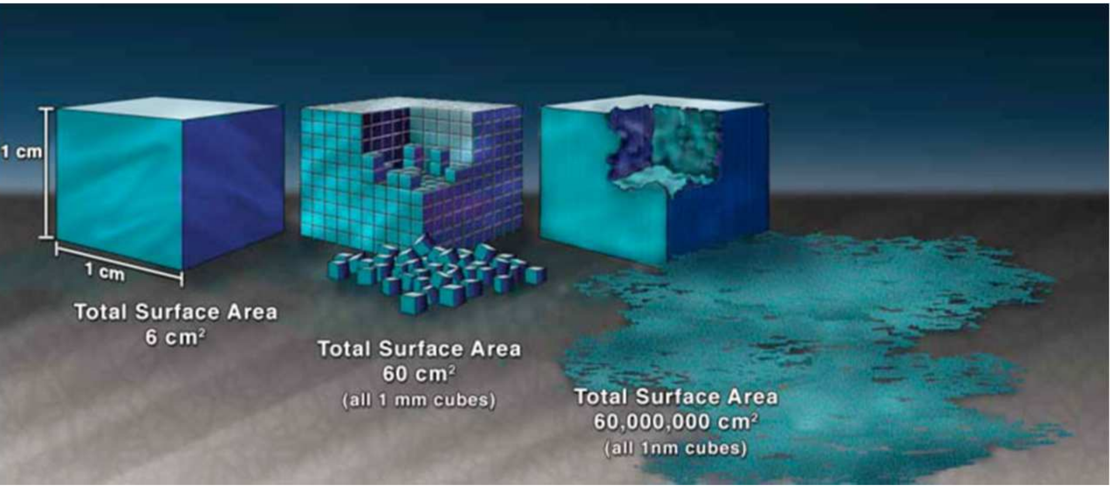


$$E_b = -\frac{\mu R_H}{\epsilon^2} \cdot \frac{1}{n^2}$$

- $\frac{1}{\mu} = \frac{1}{m_e^*} + \frac{1}{m_b^*}$ massa ridotta
- ϵ costante dielettrica dl mezzo
- R_H= 13.6 eV costante di Rydber

1/2 Proprietà peculiari dei materiali nanometrici (geometria)

macro → nano



Superficie specifica

$\sigma = sup_{tot}/massa\ [m^2/g]$

dimensioni delle particelle (r)

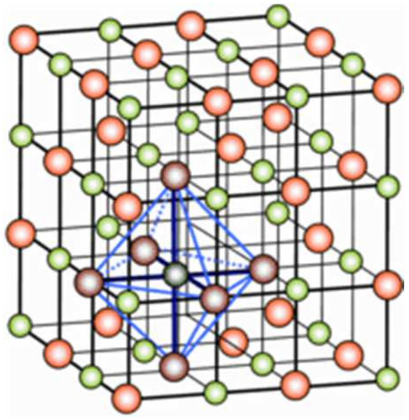
$\sigma \propto 1/r$

r ~ nm: nanoparticelle (NP) $\sigma \sim 100\ m^2/g$

~10 g di NP

2

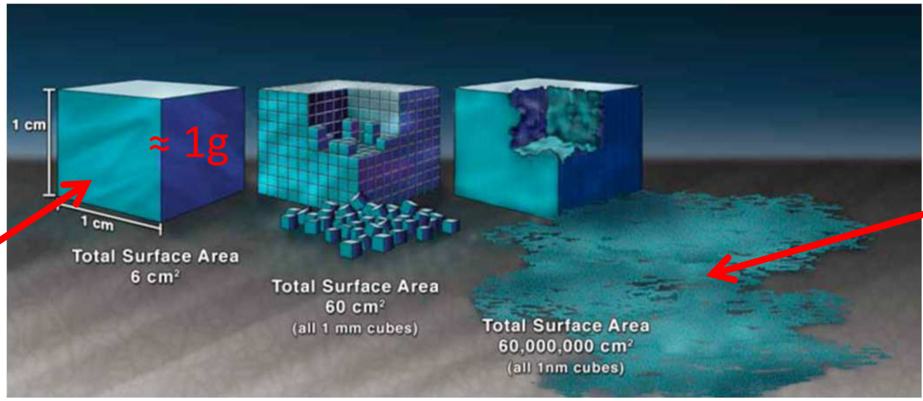
Superficie è *per definizione* un'interruzione del network cristallino



Propr. Elettr. (volume) ≠ Propr. Elettr. (superficie)
inv. traslazionale 3D

Superficie è:
1) Interfaccia fra il solido e l'ambiente esterno
2) Un «contenitore» di difetti (*dangling bonds*….);
densità superficiale $\phi \geq 10^{16}$ /m^2

difetti/massa = $\phi \cdot \sigma \propto 1/r$



$\geq 6 \cdot 10^{12}$ /g

$\geq 6 \cdot 10^{19}$ /g

I difetti di superficie dominano

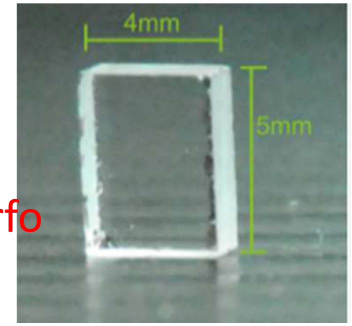
le proprietà ottiche dei sistemi nanon

Superficie poco estesa

Superficie molto estesa

macro (σ~10^{-4} m^2/g)

onio (grafite, diamante)



e - SiO_2 amorfo

nano (σ~10^{2} m^2/g)

Carbonio (nanoparticelle)

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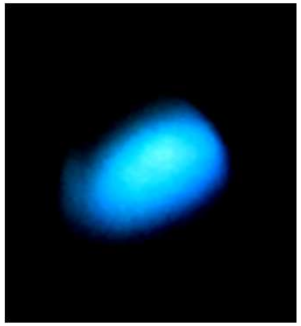
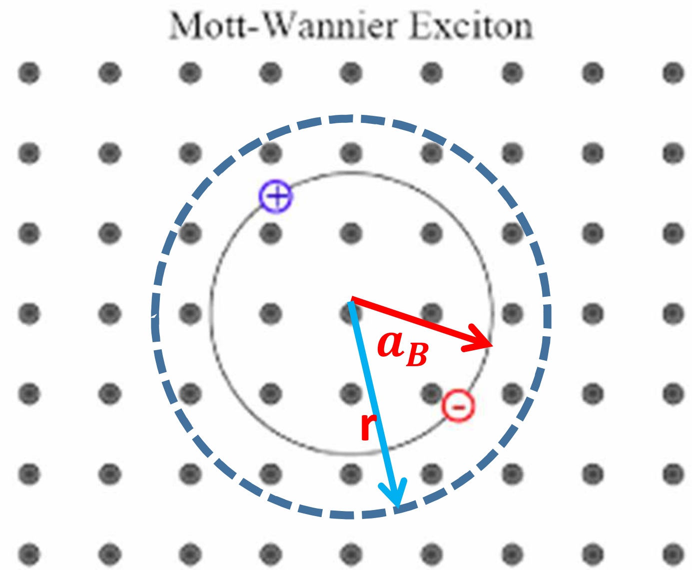


Silice (nanoparticelle)

2 Proprietà peculiari dei materiali nanometrici (confinamento quantisti

onfinamento Quantistico **(QC)** ⟺ Nanoparticelle: Quantum Dots **(QDs)**

nportanza della scala nanometrica si capisce attraverso il confronto con le
ensione dell'**eccitone** (coppia elettrone-buca)



$$a_B(n) = \frac{a_0\ \epsilon}{\mu/m_e} \cdot n^2; \qquad E_n = -\frac{\mu/m_e\, R_H}{\epsilon^2} \cdot \frac{1}{n^2}$$

a_0 ≈ 0.53 Å raggio di Bohr; $a_B(n=1)$ raggio _eccitone

$a_B(Ge) \approx 24.3\ nm; E$ ≈3 meV

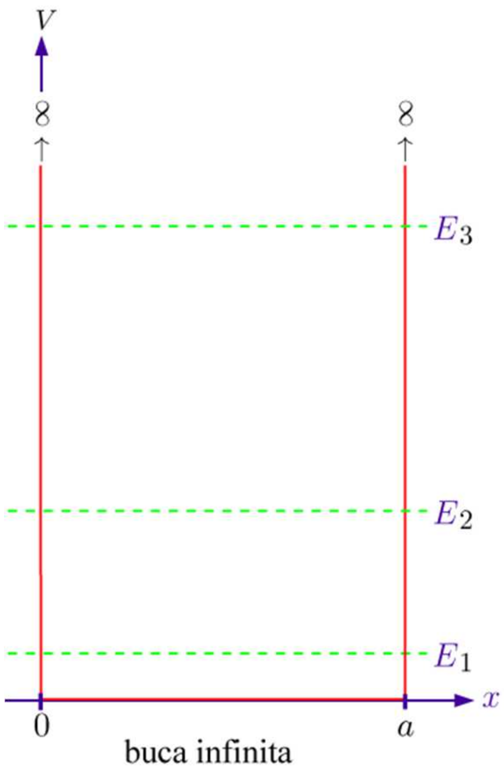
$a_B(Si) \approx 4.9\ nm; E$ ≈ 15 meV

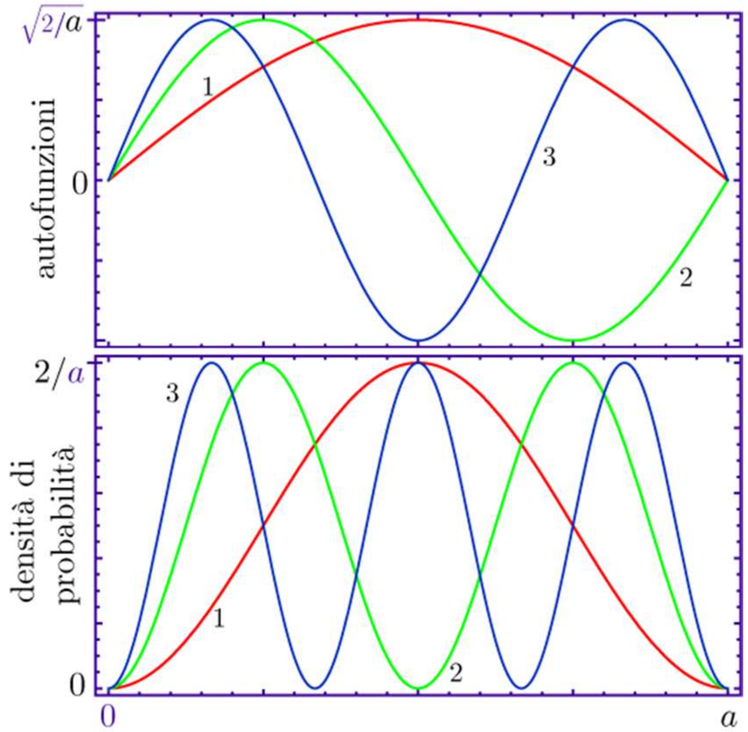
$a_B(ZnO) \approx 2.3\ nm; E$ ≈ 60 meV

QC si osserva se le dimensioni delle NPs e dell'eccitone sono confrontabili $(r | a_B)$

Confinamento Quantistico (QC)

r| a_B): il sistema può essere studiato qualitativamente utilizzando il modello di una
rticella (eccitone) all'interno di una **buca di potenziale a pareti infinite**





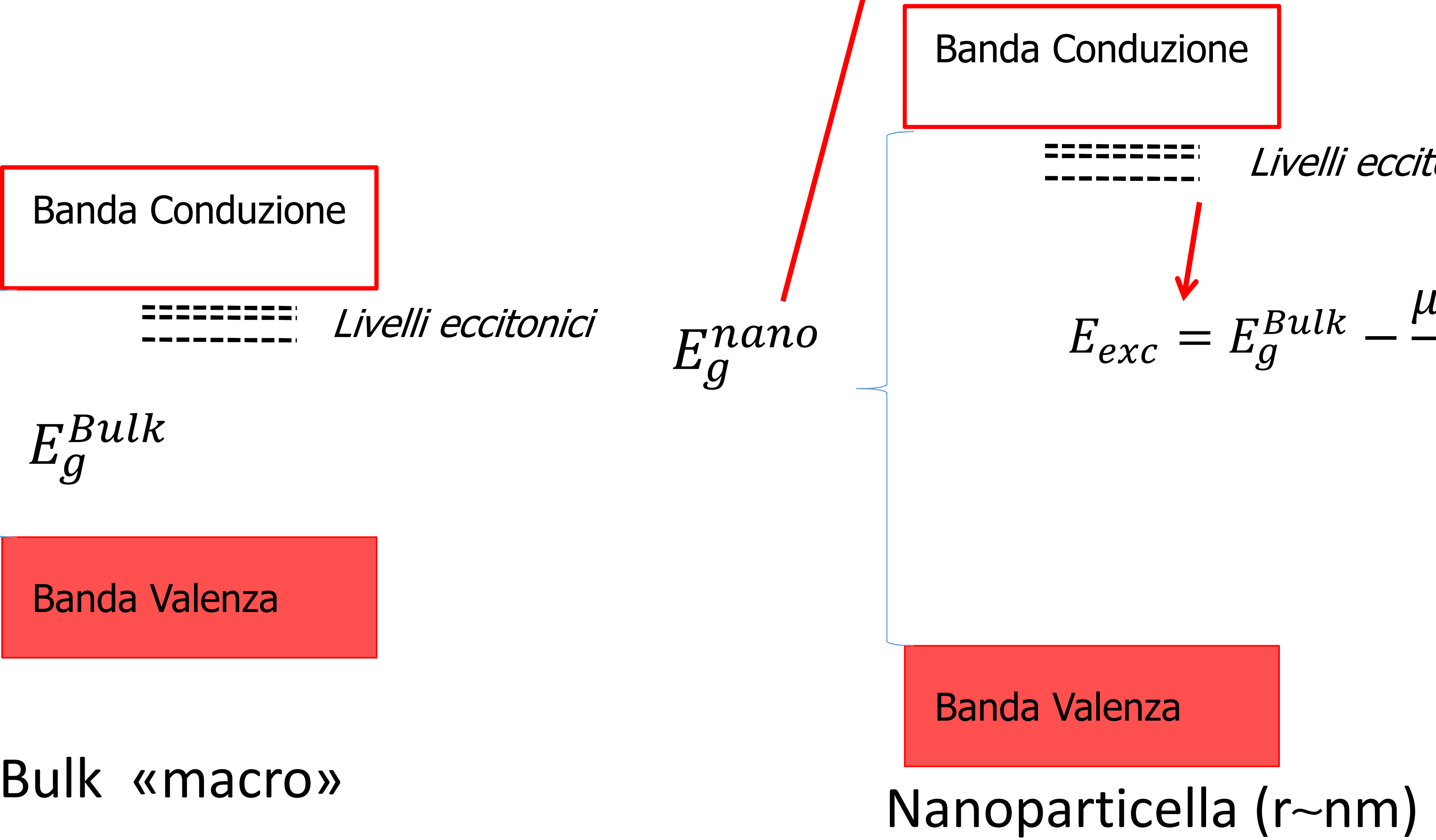
buca sferica (raggio r)

$$\textbf{QC:}\quad E_m = \frac{\hbar^2\pi^2 m^2}{2\mu r^2}$$

$$E_m = \frac{\hbar^2\pi^2 m^2}{2\mu a^2};\qquad \varphi(x) = \sqrt{\frac{2}{a}}\cdot\sin\left(\frac{m\pi x}{a}\right);\qquad m = 1, 2, 3, \ldots$$

QC: *il gap energetico aumenta*

$$E_g^{nano} = E_g^{Bulk} + \frac{\hbar^2\pi^2}{2\mu r^2}$$



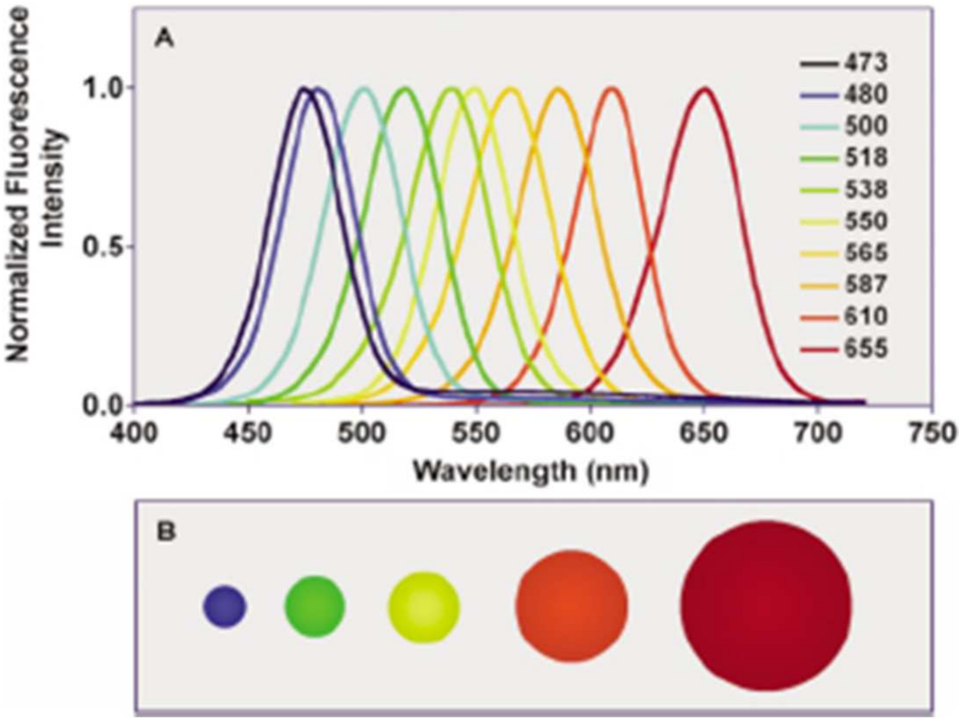
$$E_{exc} = E_g^{Bulk} - \frac{\mu/m_e\, R_H}{\epsilon^2}\cdot\frac{1}{n^2} + \frac{\hbar^2 \ldots}{2\mu \ldots}$$

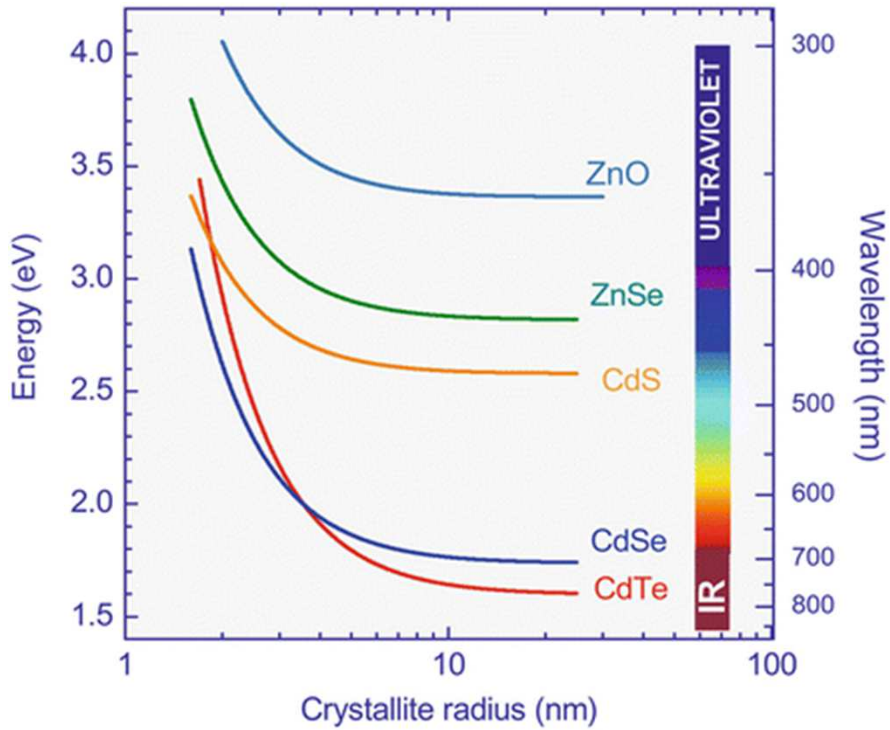
QC: *come si osserva?*

Spettro di emissione degli eccitoni

$$E_{exc} = E_g^{Bulk} - \frac{\mu/m_e\, R_H}{\epsilon^2} \cdot \frac{1}{n^2} + \frac{\hbar^2\pi^2}{2\mu r^2}$$

E_g vs. dimensioni - semicondutto

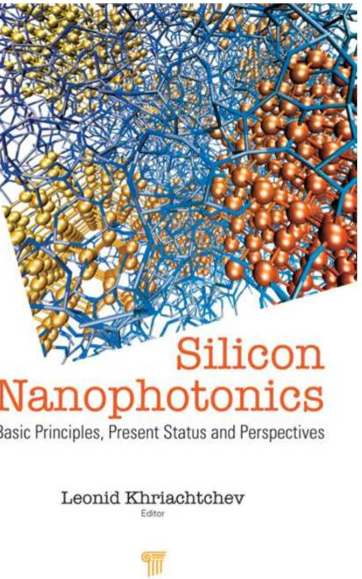


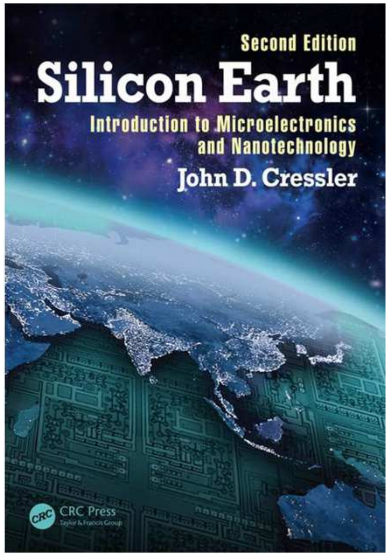


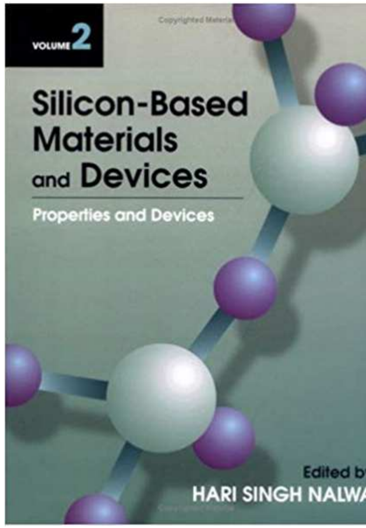
QC: esempio

Silicon nanocrystal Si-NC:

milestone in the development of nanotechnology

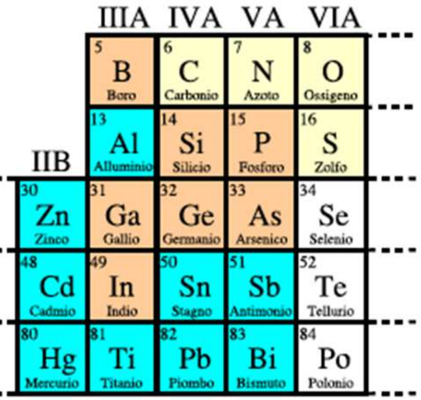






ilicio

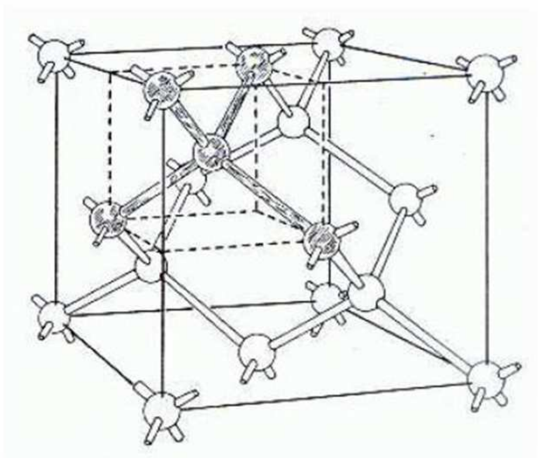
- V gruppo della tavola periodica
- truttura cristallina covalente cubica
  facce centrate
- Semiconduttore a gap indiretta

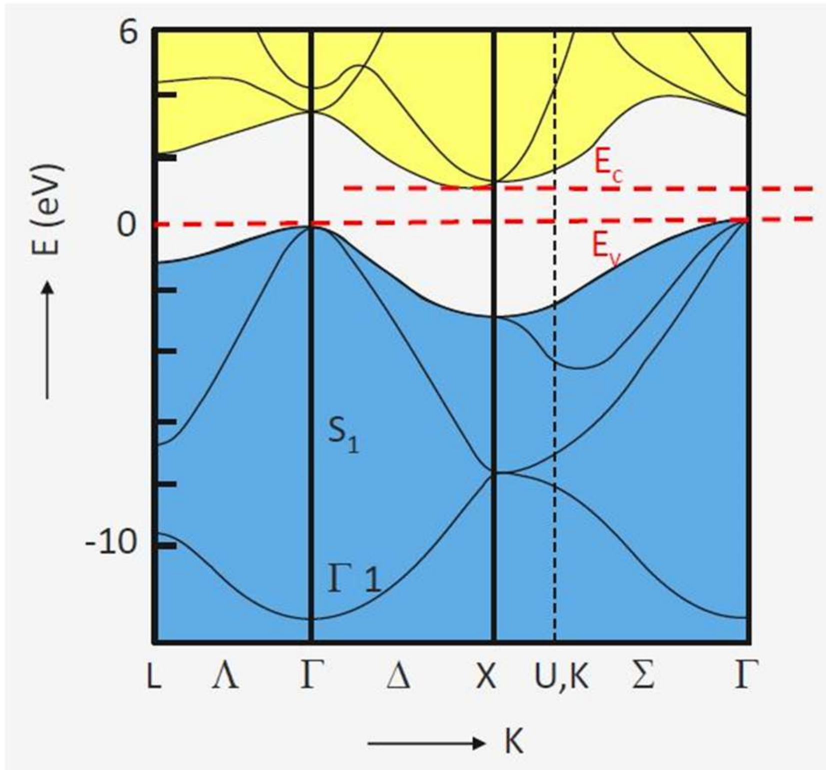


tori $\rho < 10^{-5}\,\Omega m$ $(rame: 3\cdot 10^{-8}\,\Omega m)$

nduttori $10^{-5} < \rho < 10^{3}\,\Omega m$ $(silicio: 2300\,\Omega m)$

$\rho > 10^{3}\,\Omega m$ $(diamante: 10^{14}\,\Omega m)$





$E_g \approx 1.1$

Γ (K={0,0,0}); X (K={1,0,0}2π/a); L({1/2,1/2,1/2}2π/a)

oprietà BULK E NANOCRISTALLI

SILICIO

BULK

LARGO IMPIEGO NELL'INDUSTRIA DEI SEMICONDUTTORI

(non tossico)

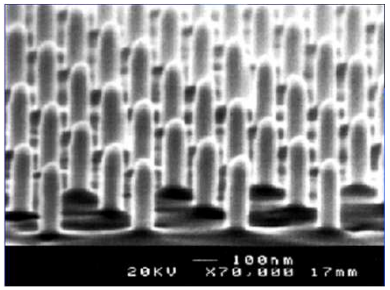
SECONDO ELEMENTO PIÙ ABBONDANTE NELLA CROSTA TERRESTRE

(ECONOMICO)

SCARSO EMETTITORE NEL VISIBILE

NANO-CRISTALLI

(NCs)



EMETTONO NEL VISIBILE

Interesse verso Si-NCs

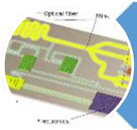
Si-NCs

Cristalli che hanno
le dimensioni dei
nanometri

nham (1990):
ma osservazione delle
oprietà di
oluminescenza nel range
visibile in silicio poroso.

Ha aperto la possibilità di
sviluppo di dispositivi
optoelettronici di Silicio!

A P P L I C A Z I O N I

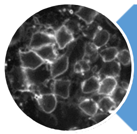


OPTOELETTRONICA
(laser, LED, OLED)

NANOELETTRONICA
(dispositivi di memoria)

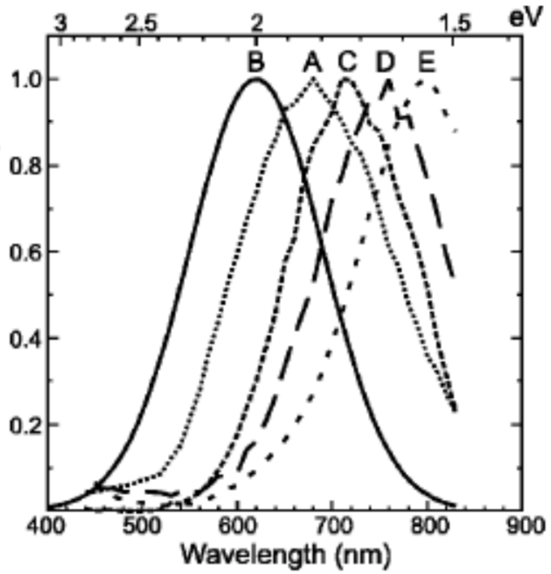
FOTOVOLTAICO

BATTERIE



APPLICAZIONI BIOLOGICHE

-NCs: prime evidenze sperimentali del **onfinamento Quantistico (QC)**



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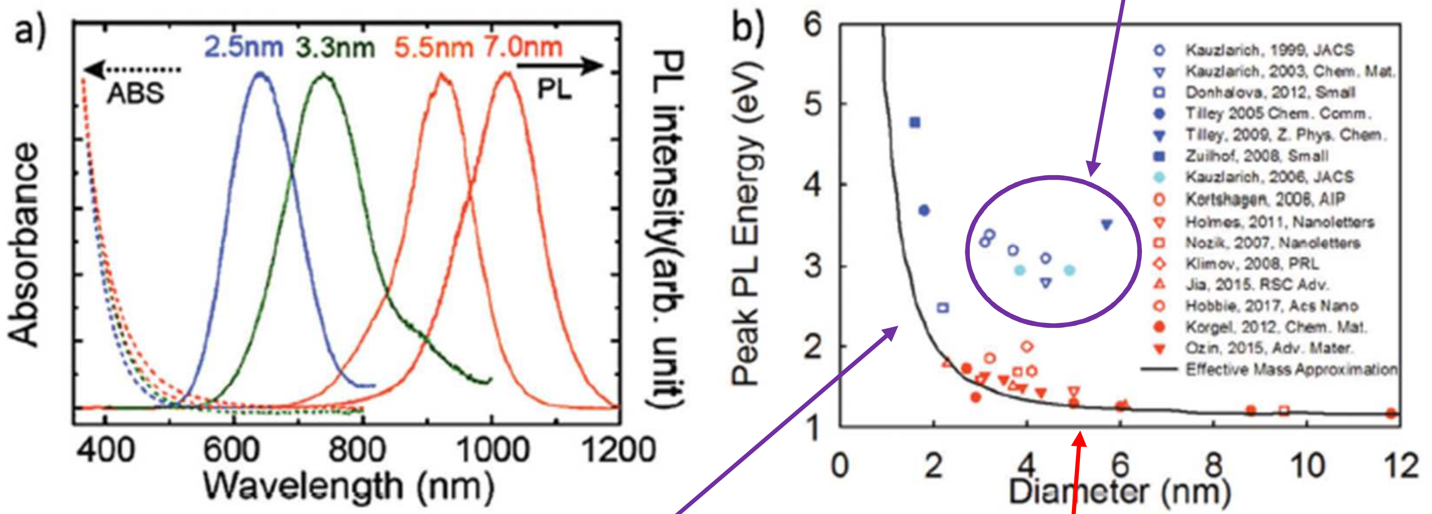
Difetti sulla superficie dei Si-N

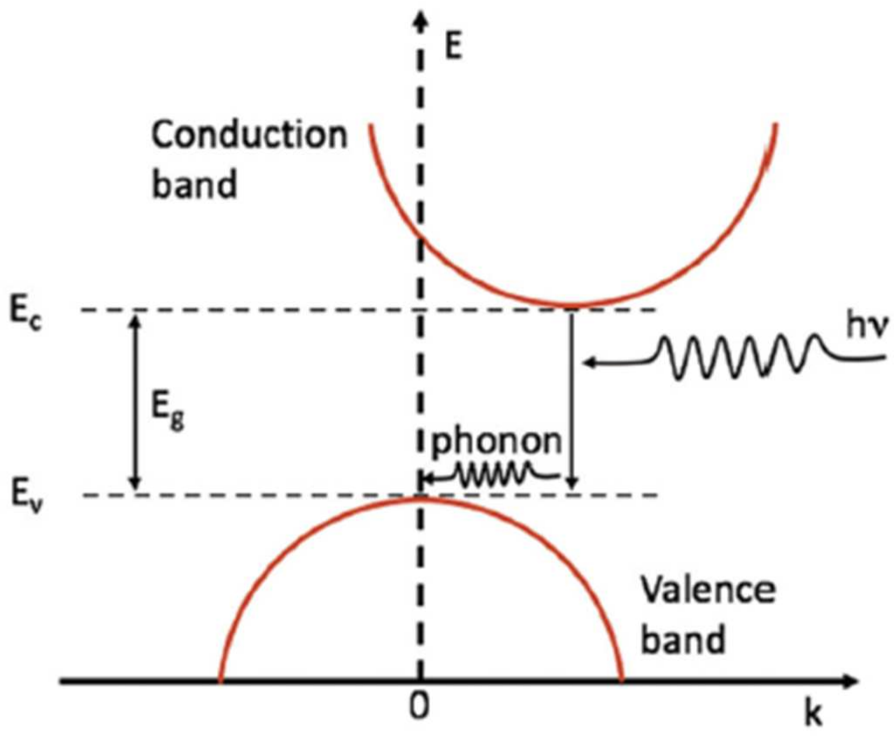


a_B

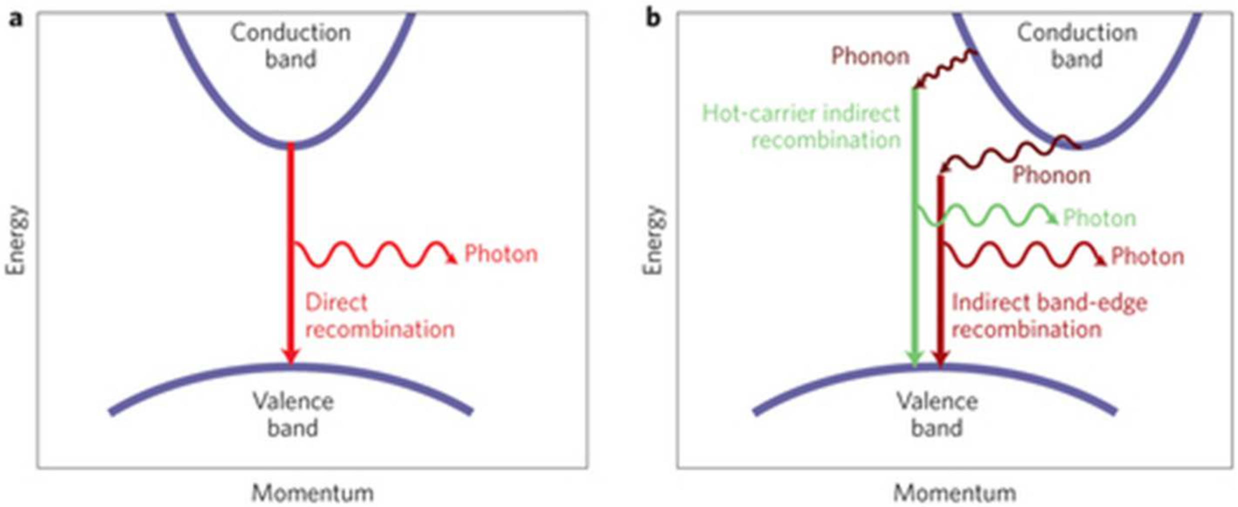
Se r<< a_B: forte confinamento limita l'emissione degli eccitoni

Proprietà sorprendenti rispetto al Si-Bulk

Il Silicio (Si) è un semiconduttore a gap indiretta.
A temperatura ambiente (T=300 K) l'energia-gap vale: $E_g \approx 1.1$ eV



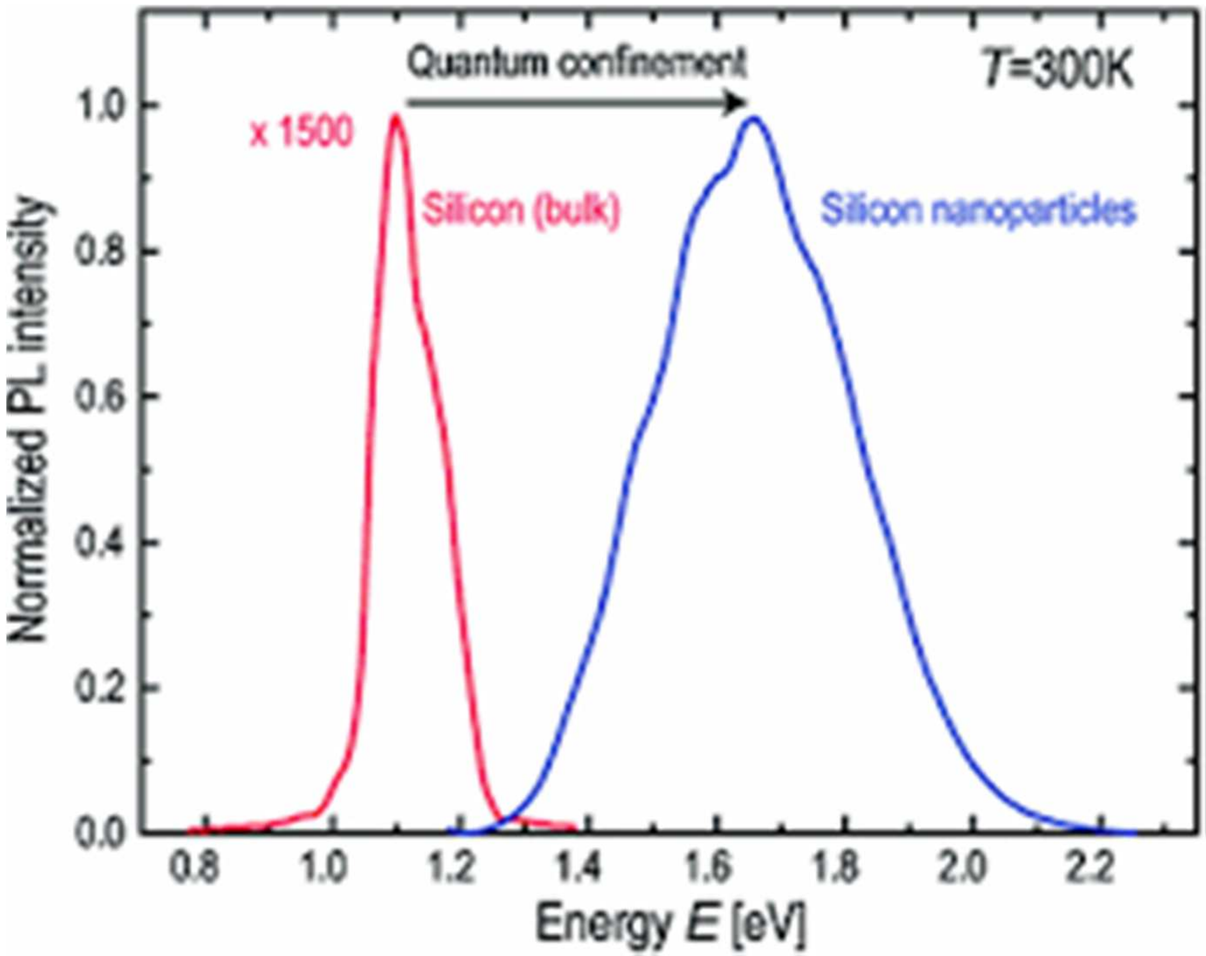
Nei semiconduttori a gap indiretta, il processo di fotoluminescenza avviene con probabilità minore (tempo di vita maggiore) rispetto ai semiconduttori a gap diretta.



Semiconduttori a gap diretta (ZnO; GaN..) : $\tau \sim 10^{-9} - 10^{-8}$ s
Semiconduttori a gap indiretta (Si; Ge..) : $\tau \sim 10^{-5} - 10^{-3}$ s

Le proprietà ottiche di un semiconduttore a gap diretta cambiano completamente se questo viene ridotto a dimensioni nanometriche.

Aumento del rate di emissione



Aumento del rate di emissione

$\Delta x \cdot \Delta p \sim \hbar$

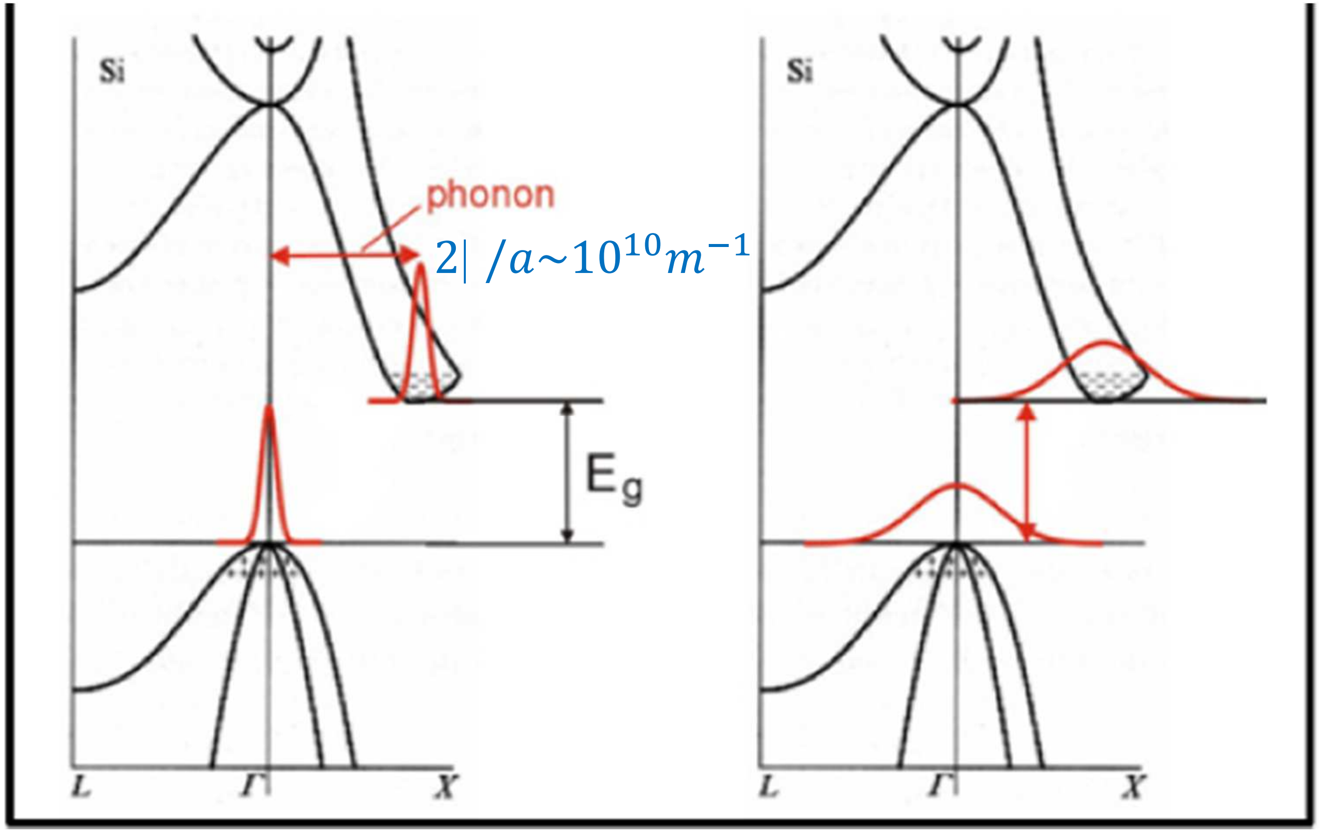
$\Delta x \cdot \Delta k \sim 1$ Principio d'indeterminazione

$\Delta x \rightarrow grande\ (\sim 10^{-2} m)\ \Rightarrow \Delta k \rightarrow piccolo\ (\sim 10^{2} m^{-1})$

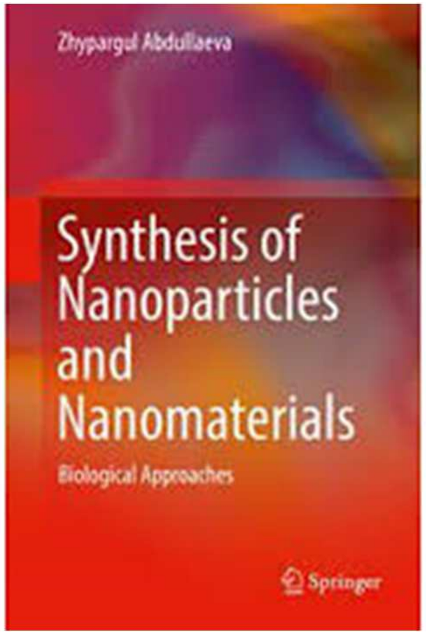
Fonone reticolare necessario alla ricombinazione

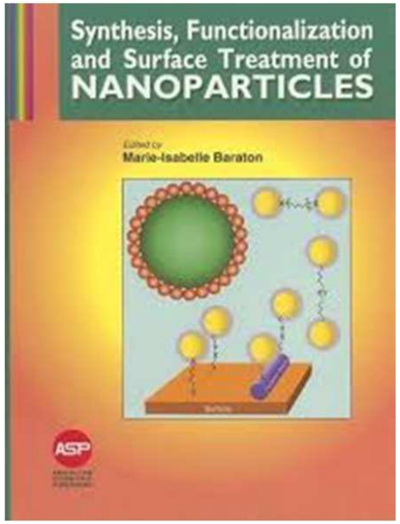
$\Delta x \rightarrow piccolo\ (\sim 10^{-9} m)\ \Rightarrow \Delta k \rightarrow grande\ (\sim 10^{9} m$

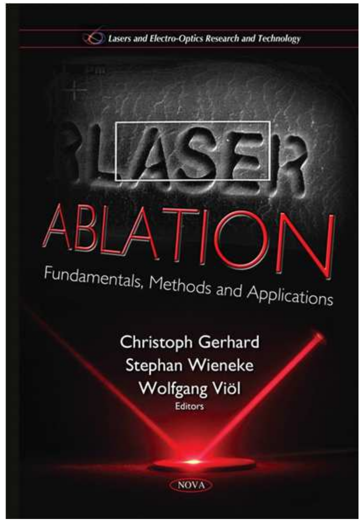
Funzioni d'onda di elettrone e buca si allargano.
Transizione *direct-like* favorisce la ricombinazione senza l'intervento del fonone



Metodi di produzione



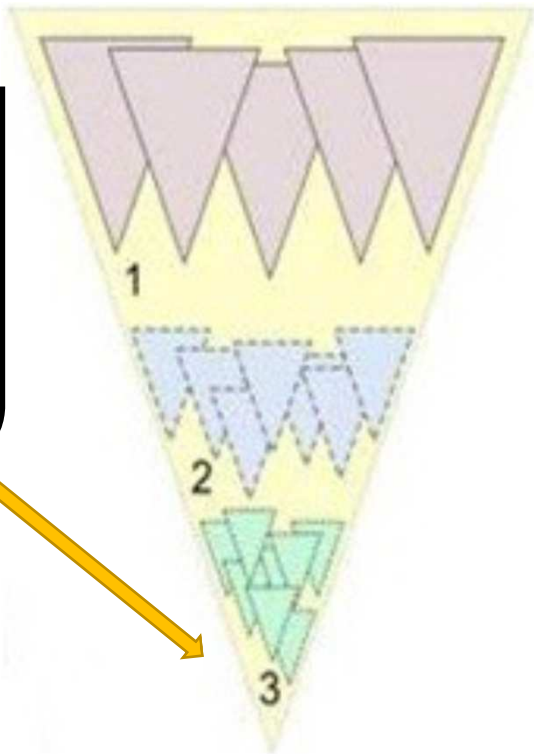




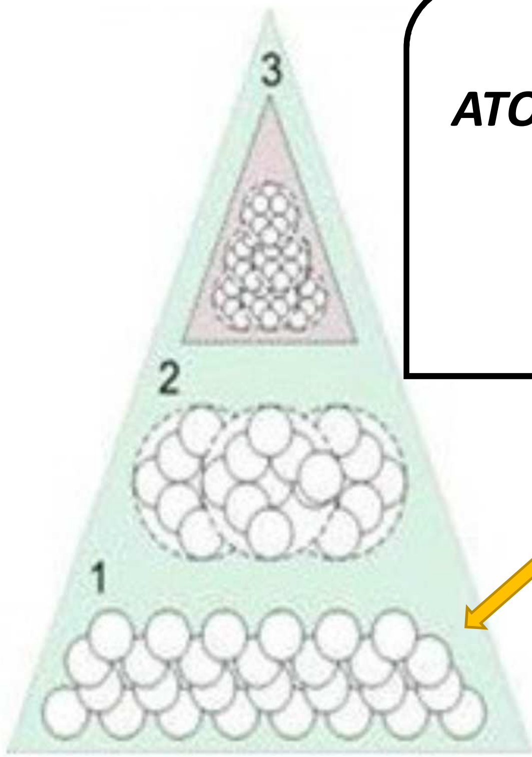
CNICHE DI PRODUZIONE

AL BULK VERSO I
NANOCRISTALLI

trazione di materiale)



Top-down



Bottom-up

DA
ATOMI / MOLECOLE VERSO I
NANOCRISTALLI

(aggregazione)

CNICHE DI PRODUZIONE

TOP-DOWN

ABLAZIONE LASER

IMPIANTAZIONE IONICA

ETCHING

POLVERIZZAZIONE CATODICA

BOTTOM UP

1. **DEPOSIZIONE CHIMICA DA VAPORE**
2. **OSSIDAZIONE / RIDUZIONE IN SOLUZIONE**
3. **EPITASSIA DA FASCI MOLECOLARI**

ECNICHE DI PRODUZIONE

TOP-DOWN

ABLAZIONE LASER

IMPIANTAZIONE IONICA

ETCHING

POLVERIZZAZIONE CATODICA

BOTTOM UP

1. **DEPOSIZIONE CHIMICA DA VAPORE**
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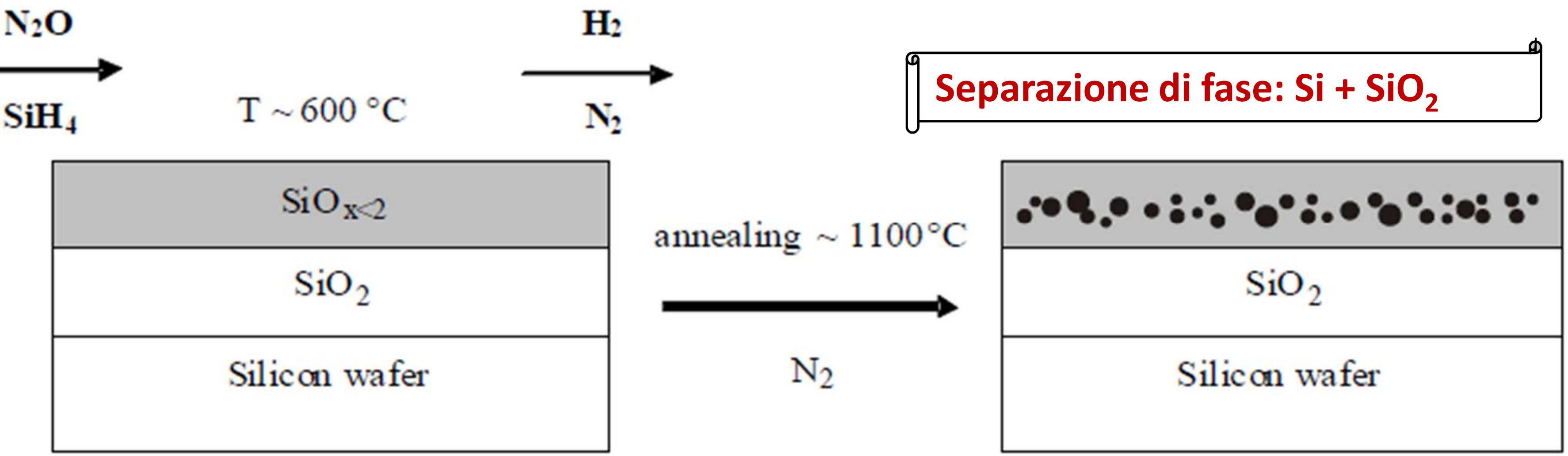
DEPOSIZIONE CHIMICA DA VAPORE (bottom-up)

PECVD (*Plasma-enhanced chemical vapor deposition*)



Separazione di fase: Si + SiO_2

EMBEDDED Si NCs

Le temperature di deposizione e annea influiscono sulla concentrazione e su dimensione dei NCs

$$SiH_4(g) + xN_2O(g) \rightarrow SiO_x(s) + 2H_2(g) + xN_2(g)$$

amples

O_x/SiO_2 multi-layers grown on a p-type crystalline Si substrate.

SiO_x produced by evaporation of SiO powder.

SiO_2 produced by electron beam evaporation of fused quartz

Sample	SiO_x/SiO_2 thickness (nm)	Ann. Temp (°C)	Layers number
1	2.2/2.8	---	64
2	2.2/2.8	1100	64
3	4.4/2.8	1100	32
4	8.4/2.8	1100	50

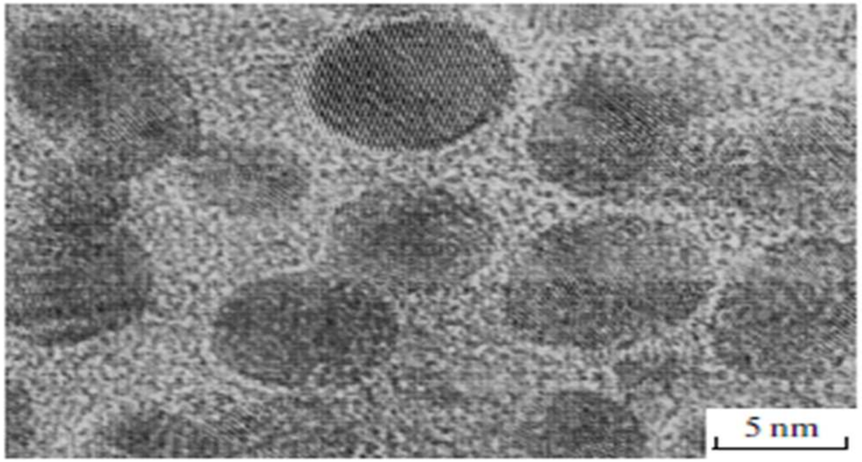
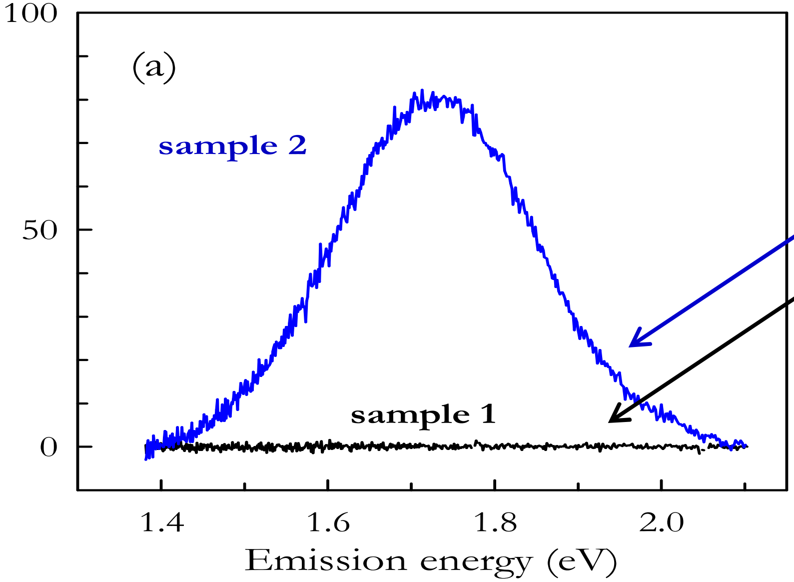


Fig. 2. HR TEM image of a cross section of the 4/3 nm MNS annealed at 1100°C.

2 hours annealing at 1100 °C induces the formation of Si-NCs

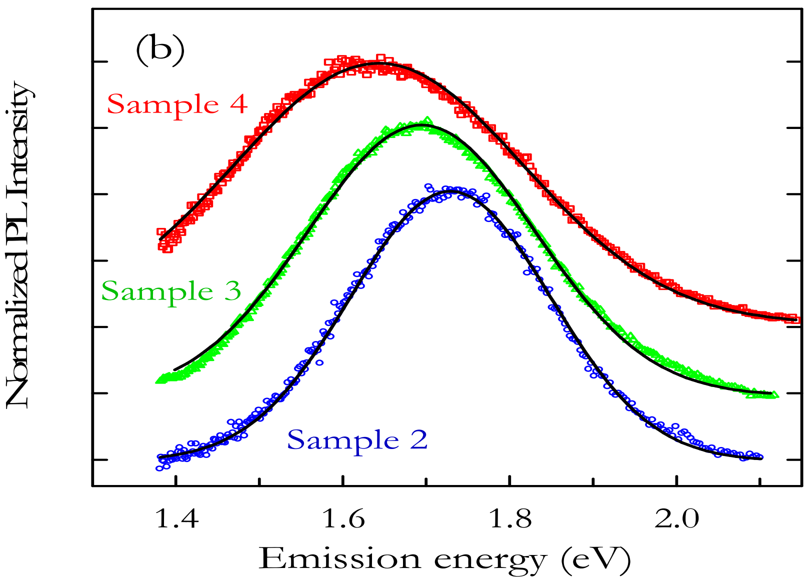
Luminescenza

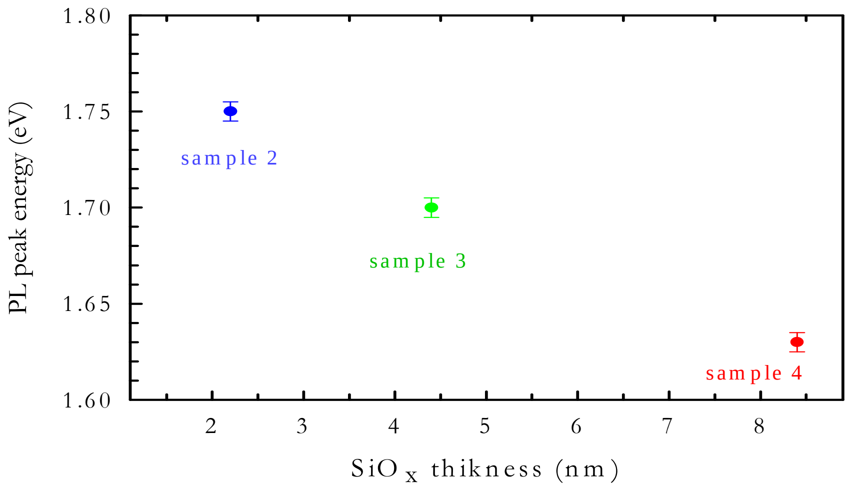
E_{exc} = 4.6 eV



After annealing

No annealing





QC effect

$$E_{PL}(d) = E_0 + \frac{3.73}{d^{1.39}}$$

Sample	E_{PL} (eV)	Si-NC size (nm)
2	≈1.73	d≈3.8
3	≈1.69	d≈4.1
4	≈1.63	d≈4.5

TECNICHE DI PRODUZIONE

TOP-DOWN

ABLAZIONE LASER

IMPIANTAZIONE IONICA

ETCHING

POLVERIZZAZIONE CATODICA

BOTTOM UP

1. **DEPOSIZIONE CHIMICA DA VAPORE**
2. **OSSIDAZIONE / RIDUZIONE IN SOLUZIONE**
3. **EPITASSIA DA FASCI MOLECOLARI**

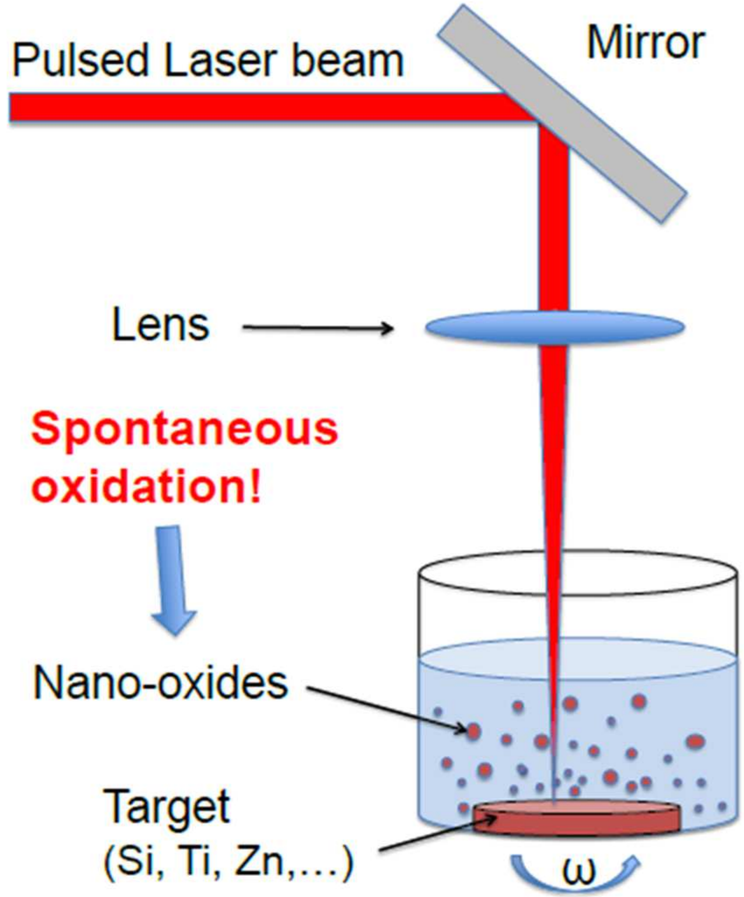
Pulsed laser ablation (PLA) in liquid

- Il fascio laser viene focalizzato sulla superficie del target.
- Il target viene ruotato o mosso per evitare che il laser colpisca sempre la stessa area.
- Fluenza (J/cm^2): densità di energia fornita.

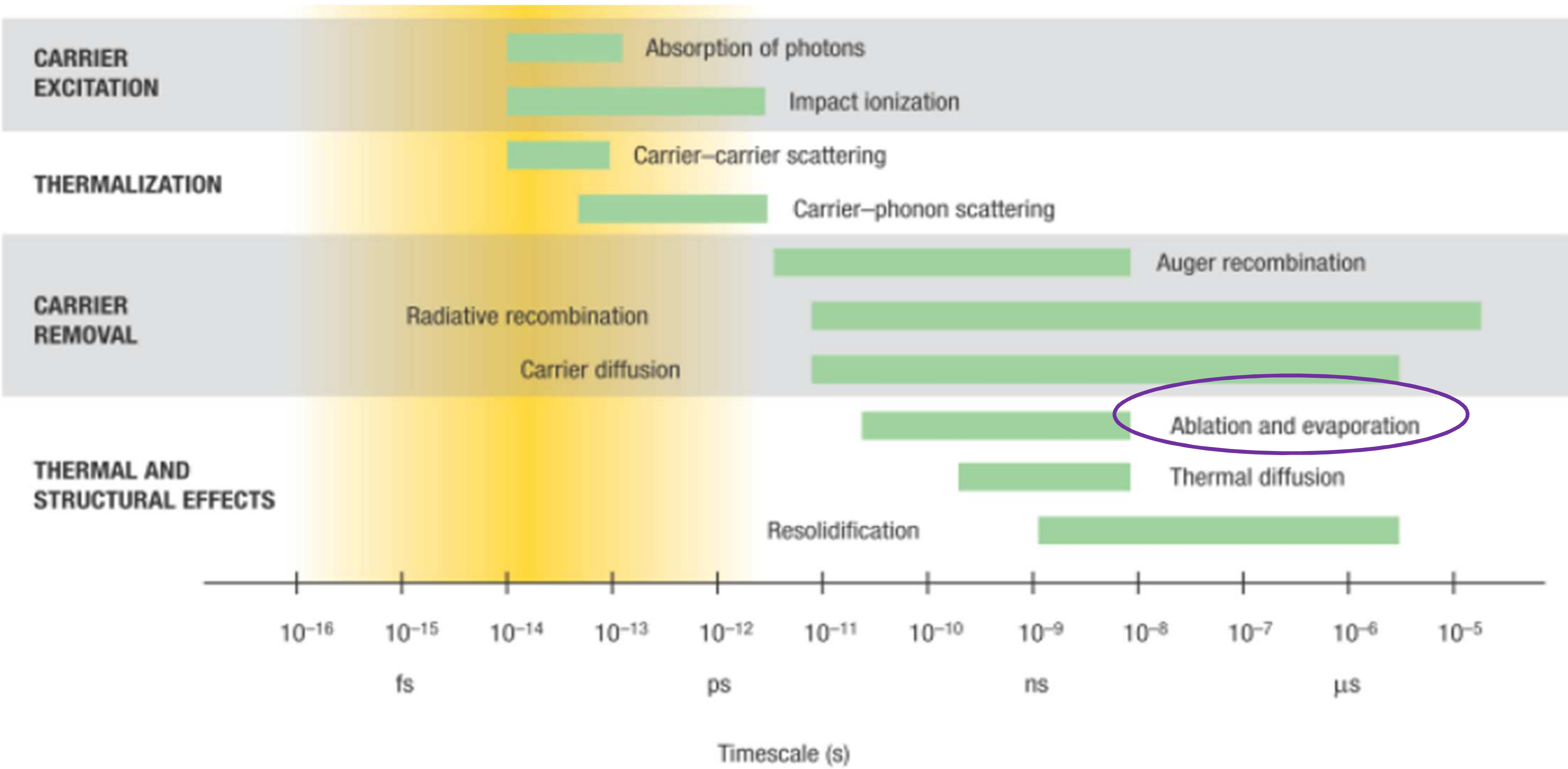
$$\Delta f = l\left(1 - \frac{f}{\sqrt{n^2 f^2 + (n^2 - 1)r^2}}\right)$$

$$r \ll f, \qquad \Delta f = l\left(1 - \frac{1}{n}\right)$$

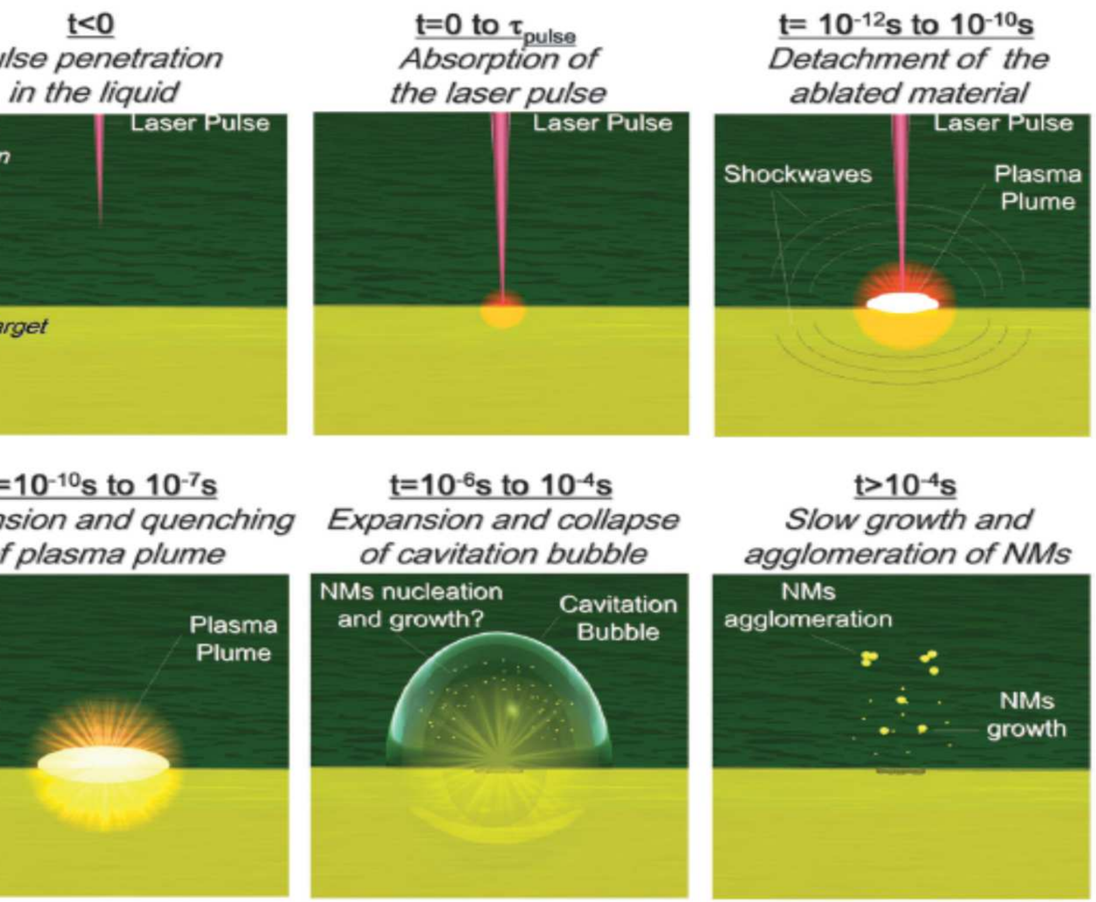
r : raggio del fascio laser
n : indice di rifrazione del solvente

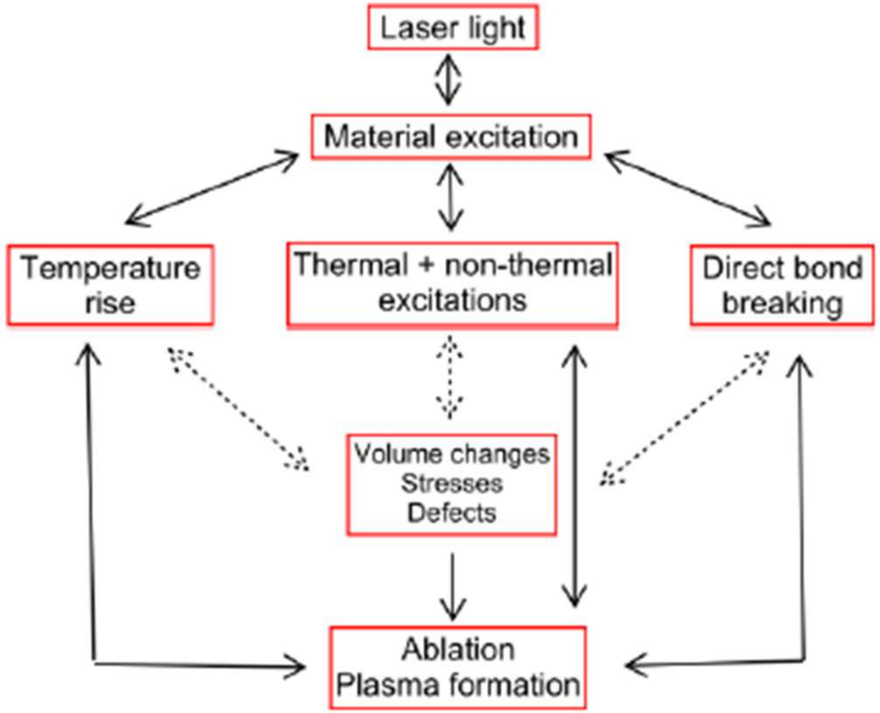


Interazione laser/materia



Principali step dell'ablazione





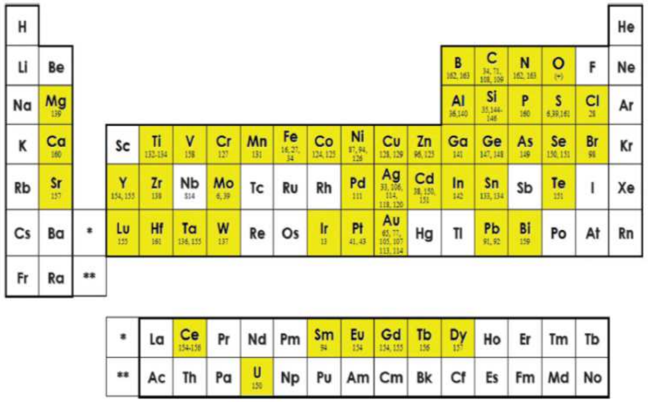
Parametri del plasma plume:

T ≈ 10^3 K
P ≈ 10^9-10^{10} Pa

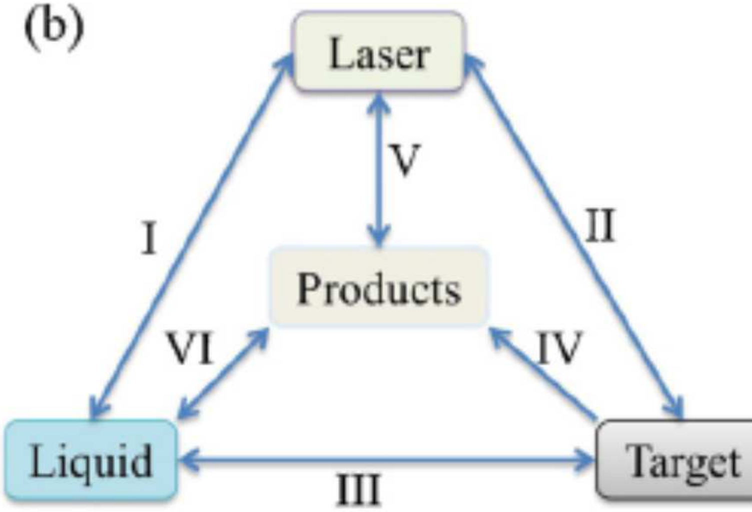
: l'ablazione in liquido si differenzia
l'ablazione in gas dopo 10^{-10} s

A

Vantaggi e svantaggi



- Semplicità e basso costo
- Metodo green
- Gran varietà di materiali ottenuti
- Controllo dei parametri di sintesi: laser, target, soluzione



- Non applicabile su larga scala (10 mg/ora)
- Scarso controllo della forma delle NP

Effetto dei parametri sperimentali

Parametri del laser

- Lunghezza d'onda
- Numero di impulsi
- Energia dell'impulso
- Durata dell'impulso
- Repetition rate

Parametri materiali

- Target bulk
- Solventi
- Soluti

ametri del laser: lunghezza d'onda (frequenza)

Condizioni da soddisfare:

La soluzione deve essere trasparente al fascio laser

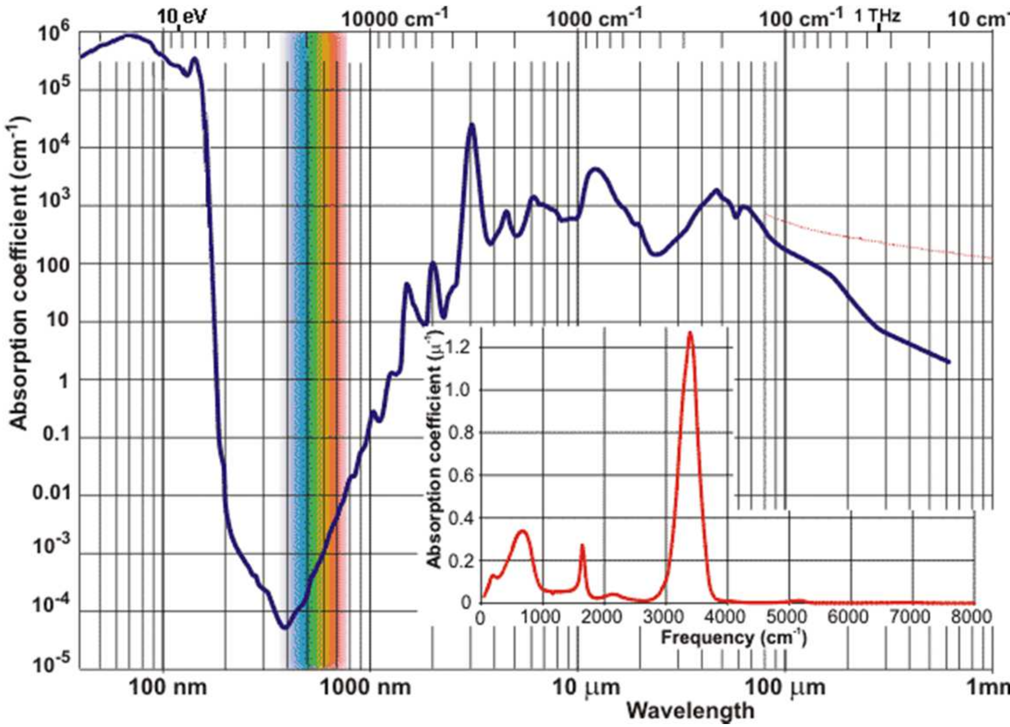
Il fascio laser deve essere assorbito dal target

«entro pochi nanometri»

$\alpha_{target}(\nu_{laser}) \geq 10^7 cm^{-1}$

Valida per i metalli in un ampio range spettrale

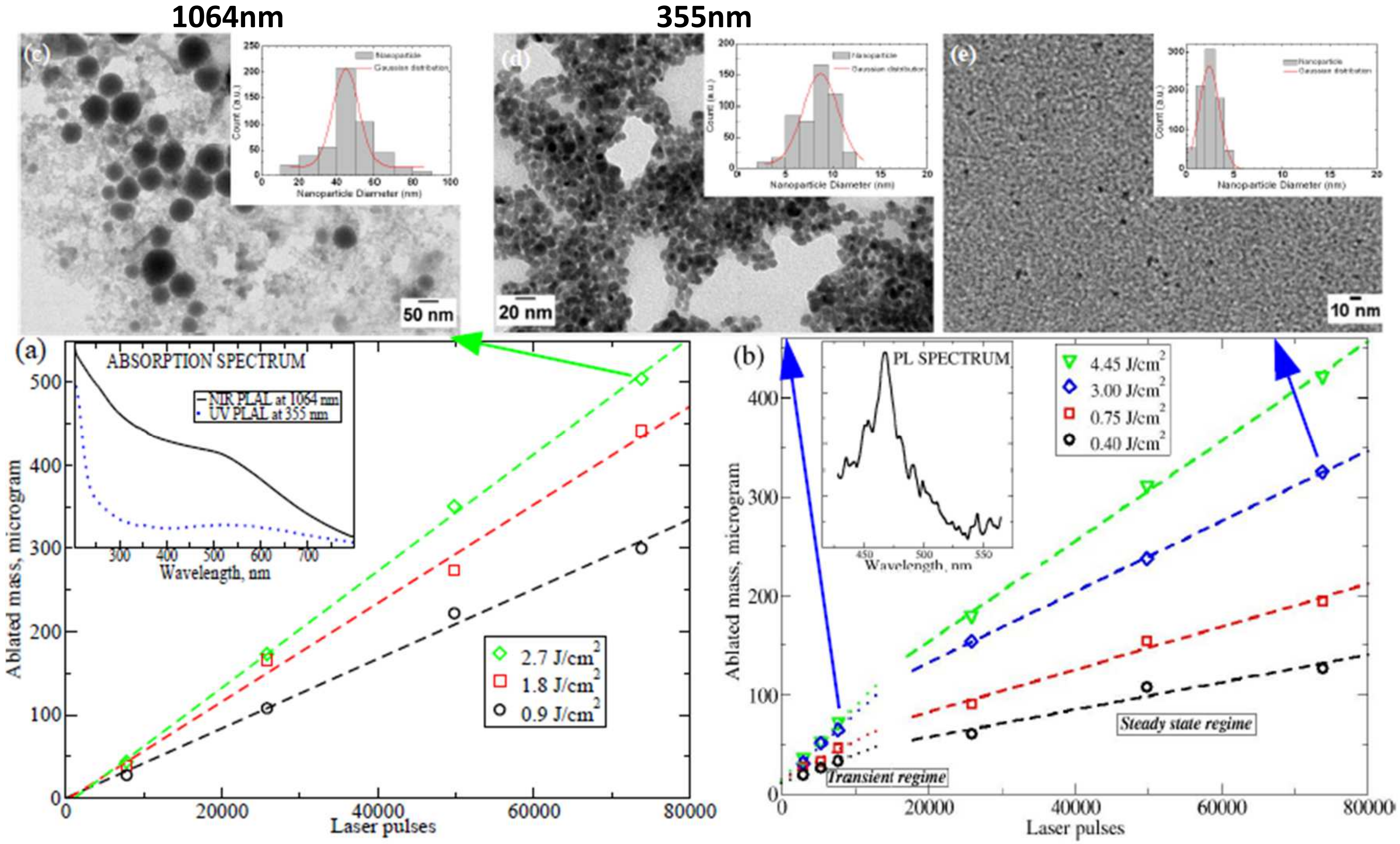
Valida per isolanti e semiconduttori se $h \cdot \nu_{laser} > E_g$



Esempio: Spettro assorbimento acqua distillat

Parametri del laser: numero impulsi

Laser: Nd-YAG 1064 nm, 355 nm 60 ps RR=20Hz d_{spot}=0.2mm
Target: Wafer di Silicio in 2 ml di acqua deionizzata (DIW)



Romuald.I. et al. DOI:10.1364/OE.22.003117(2014)

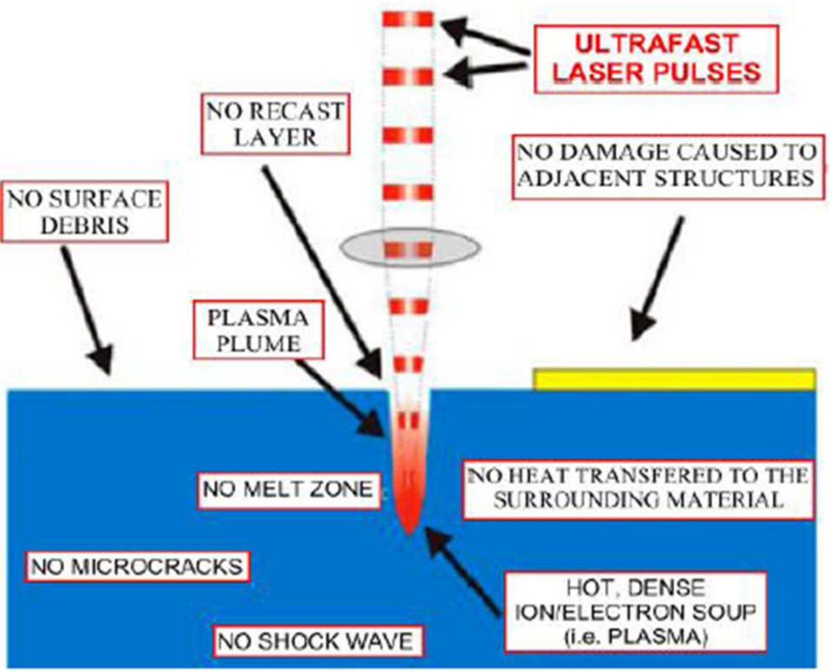
ametri del laser: durata dell'impulso (τ_{laser})

La criticità di questo parametro è legata al tempo di termalizzazione del target (τ_{therm}~ ps)

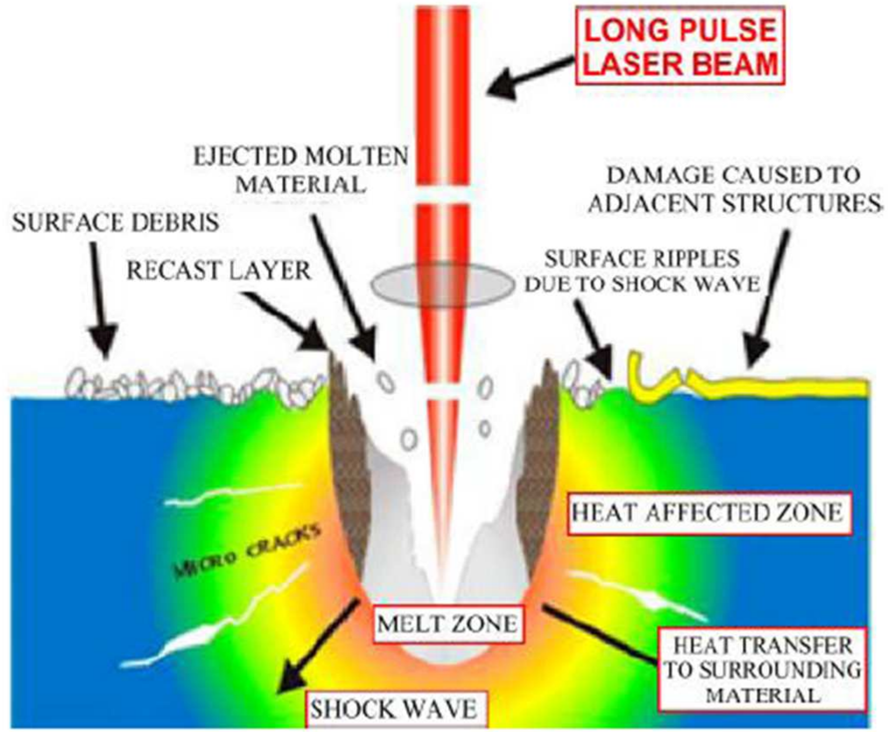
$_{ser}$~ ***fs* <<** τ_{therm} gli elettroni non hanno il tempo di termalizzare col reticolo

τ_{laser}~ ***ns* >>** τ_{therm} la termalizzazione coinvolge un area grande dello spot laser

Non-thermal ablation



thermal ablation



Parametri del laser: durata dell'impulso

thermal ablation

Non-thermal ablation

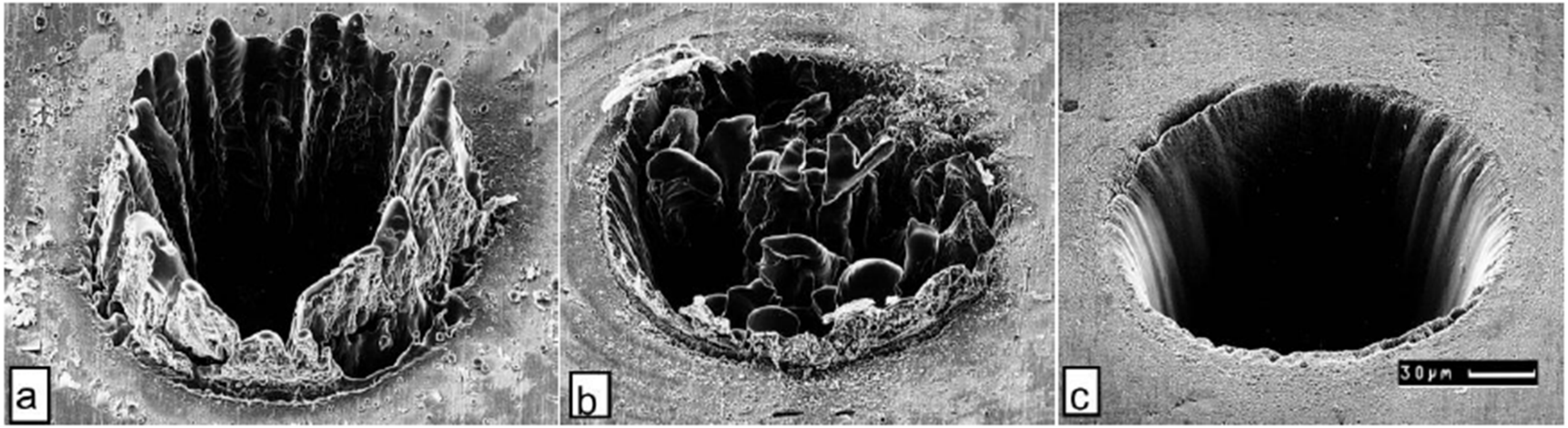
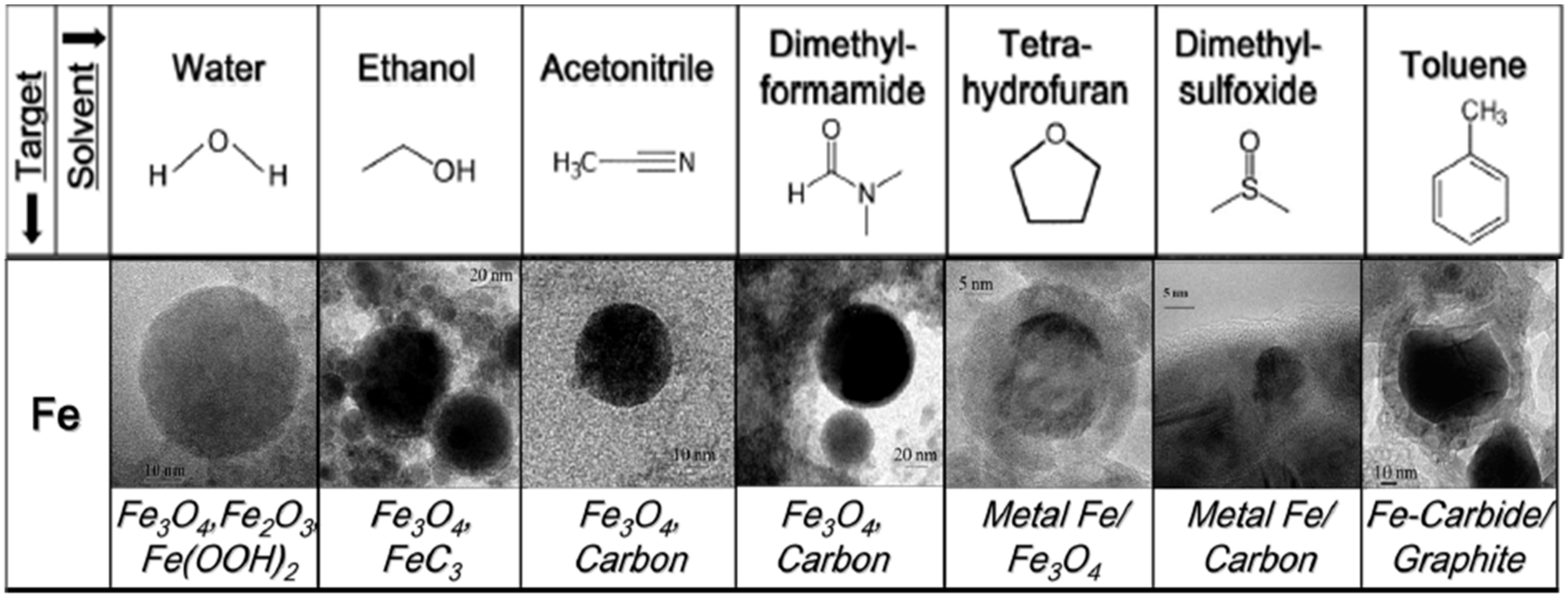


Figure 4: SEM photograph of a hole drilled in a steel foil with (a) 3.3 ns, 1mJ, $\phi = 4.2\,\mathrm{J}\ \mathrm{cm}^{1}$; (b) 80 ps, 900µJ, $\phi = 3.7\,\mathrm{J}\ \mathrm{cm}^{1}$; and (c) 200 fs, 120 µJ, $\phi = 0.5\,\mathrm{J}\ \mathrm{cm}^{1}$ laser pulses at 780 nm [12].

Effetto del solvente

- Viscosità, densità e tensione superficiale → Confinamento e dinamica del plume
- Interazione con le nanoparticelle → Capping e modifiche chimiche e strutturali

Esempio



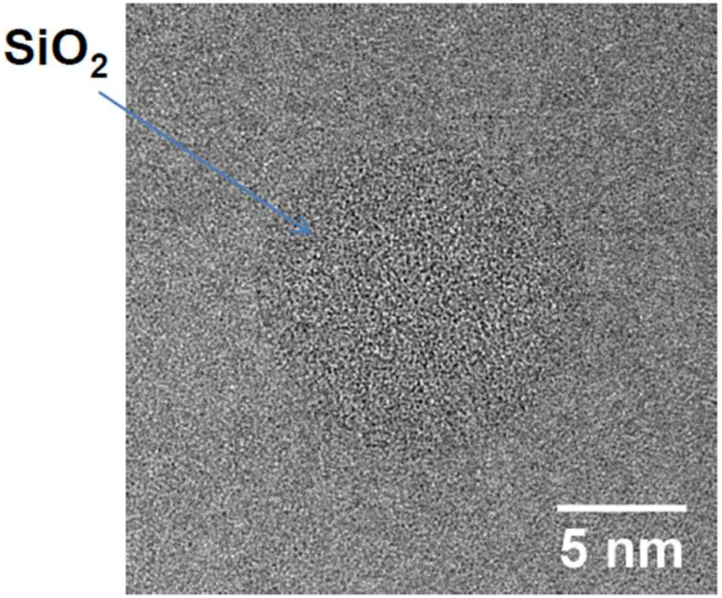
V. Amendola ,PCCP ,**15** (2013) 3009-3010

Effetto del solvente

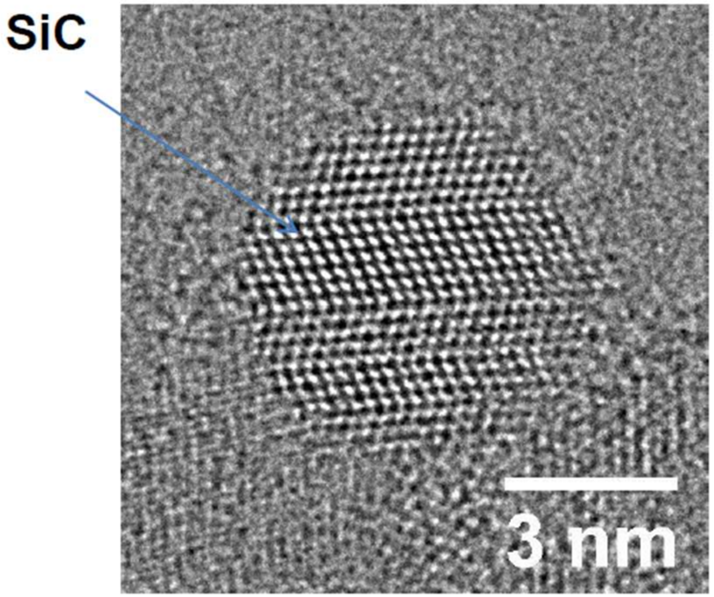
Esempio

Laboratory «Roberto Boscaino» of Advanced Materials

Ablazione di Silicio in acqua



Ablazione di Silicio in eptano C_7H_{16}



pplicazioni di PLA

Ossidi nano-strutturati sintetizzati con ablazione laser in liquido

1) Si/SiO_2

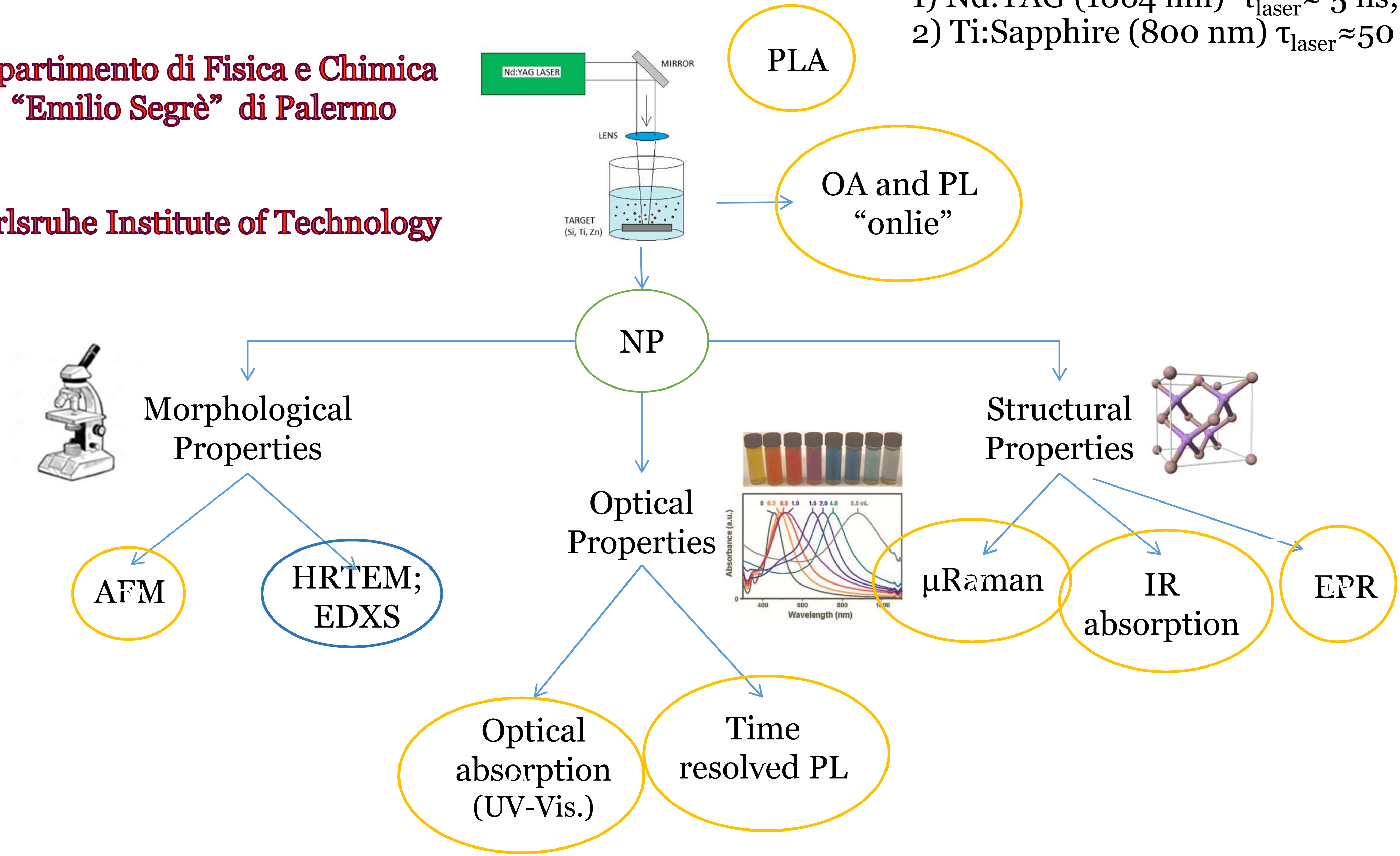
2) ZnO

...cniche sperimentali

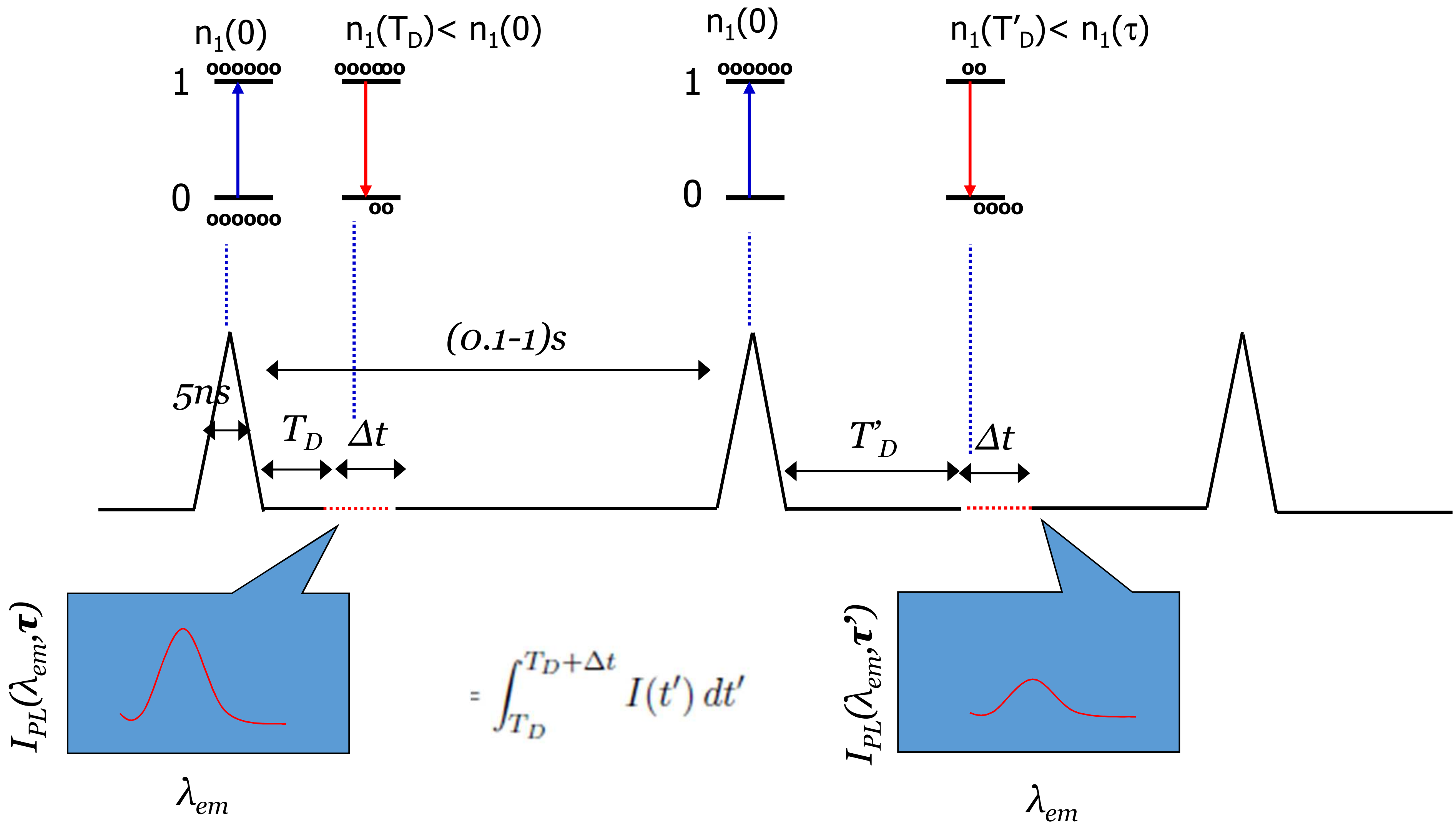
Dipartimento di Fisica e Chimica
"Emilio Segrè" di Palermo

Karlsruhe Institute of Technology

1) Nd:YAG (1064 nm) $\tau_{laser} \approx 5$ ns;
2) Ti:Sapphire (800 nm) $\tau_{laser} \approx 50$ fs



Time-resolved PL re-interpretata!!

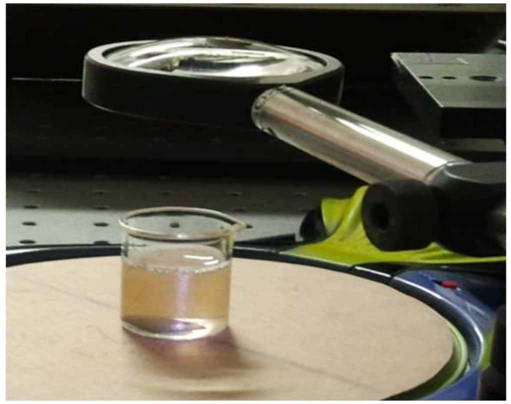


Gating:

ritardo τ, acquisizione Δt controllabili via computer (ns-ms)!!

possibilità di accumulare più spettri per ogni ritardo τ (sulla CCD e via software)

1) Production of Si-nc/SiO_2



Applied Surface Science 302 (2014) 62–65

Contents lists available at ScienceDirect

Applied Surface Science

journal homepage: www.elsevier.com/locate/apsusc

…minescent silicon nanocrystals produced by near-infrared …nosecond pulsed laser ablation in water

JOURNAL OF APPLIED PHYSICS 120, 024303 (2016)

Self-limiting and complete oxidation of silicon nanostructures produce… by laser ablation in water

…k for updates

Enhancing the luminescence efficiency of silicon-nanocrystals by interaction with H^+ ions†

…s. Chem. Chem. Phys.,

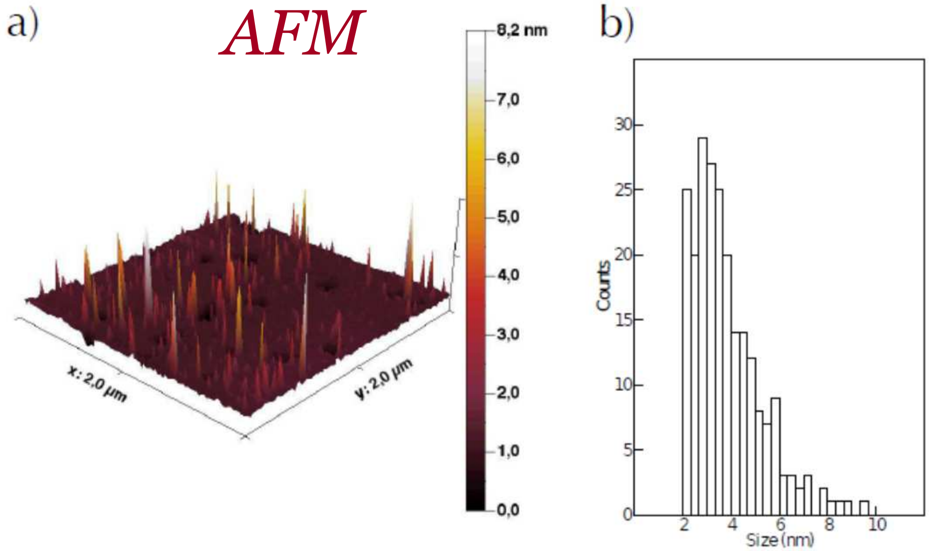
ORIGINAL PAPER

Si/SiO_2 Nanoparticles

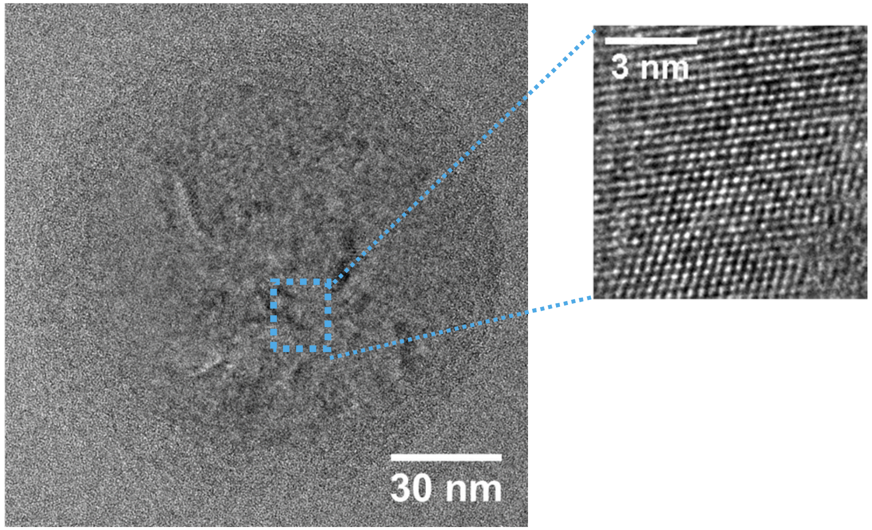
Luminescence Efficiency of Si/SiO_2 Nanoparticles Produced by Laser Ablation

Proprietà morfologiche/strutturali

AFM

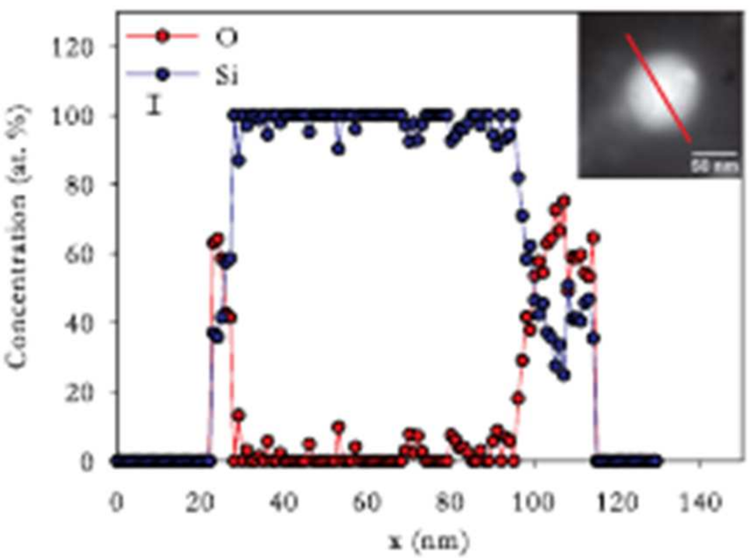


HRTEM



Si cubic structure:
lattice parameter a=5.4305 Å

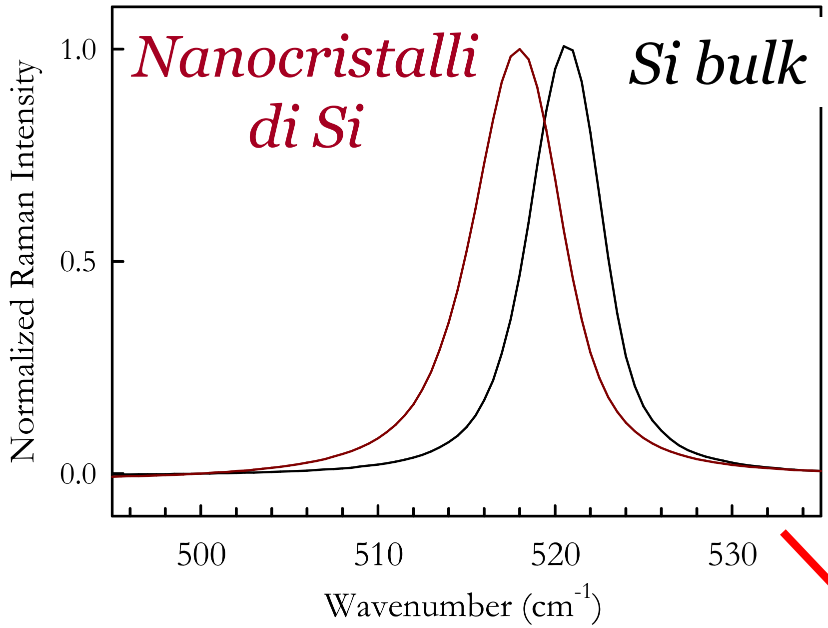
DXS



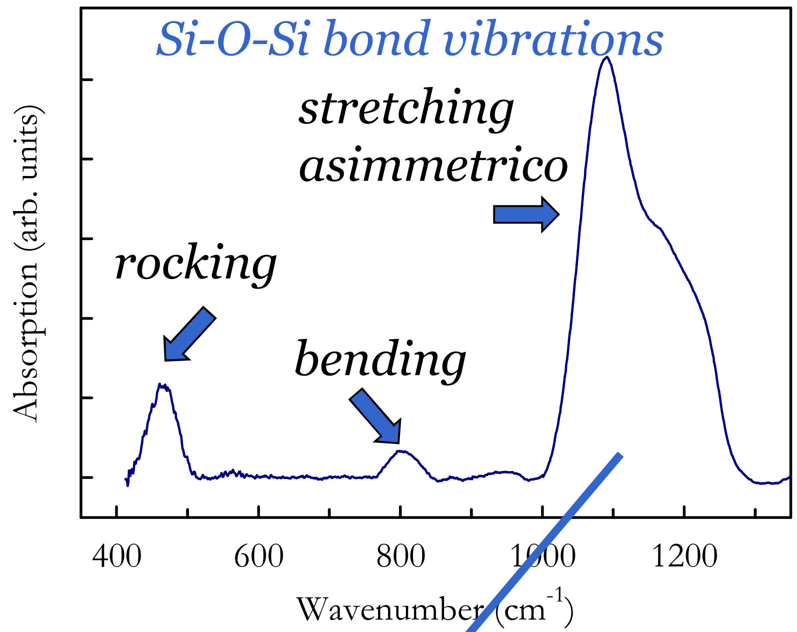
Si polycrystal surrounded by amorphous SiO_2 layer with an interface mainly composed by Si_3O

Proprietà vibrazionali IR

μ-Raman

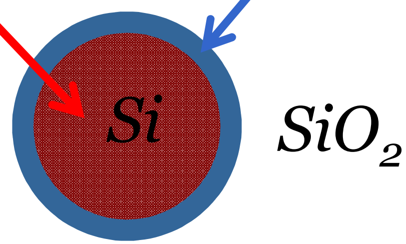


Assorbimento



Δν: quantum confinement (QC)

Size ~4 nm

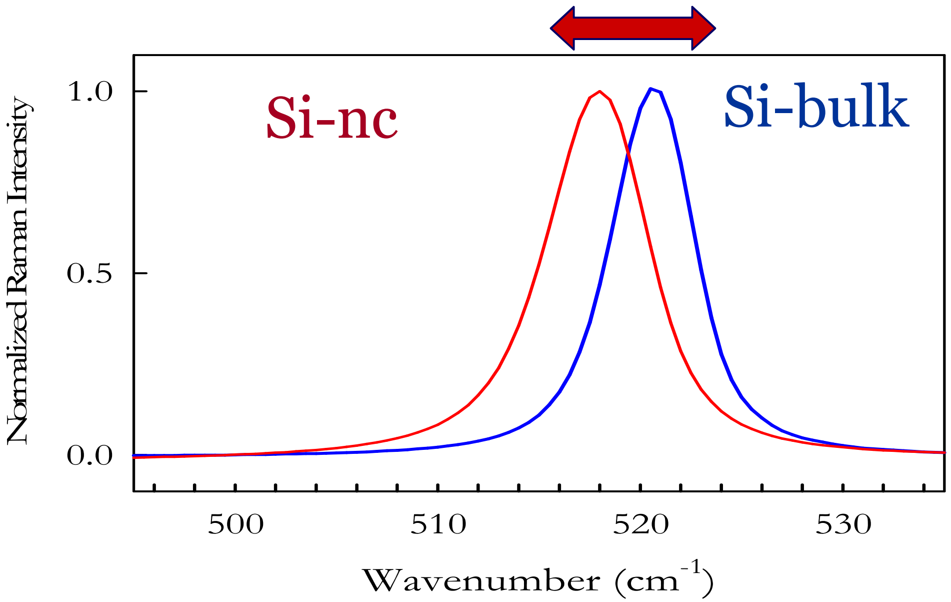


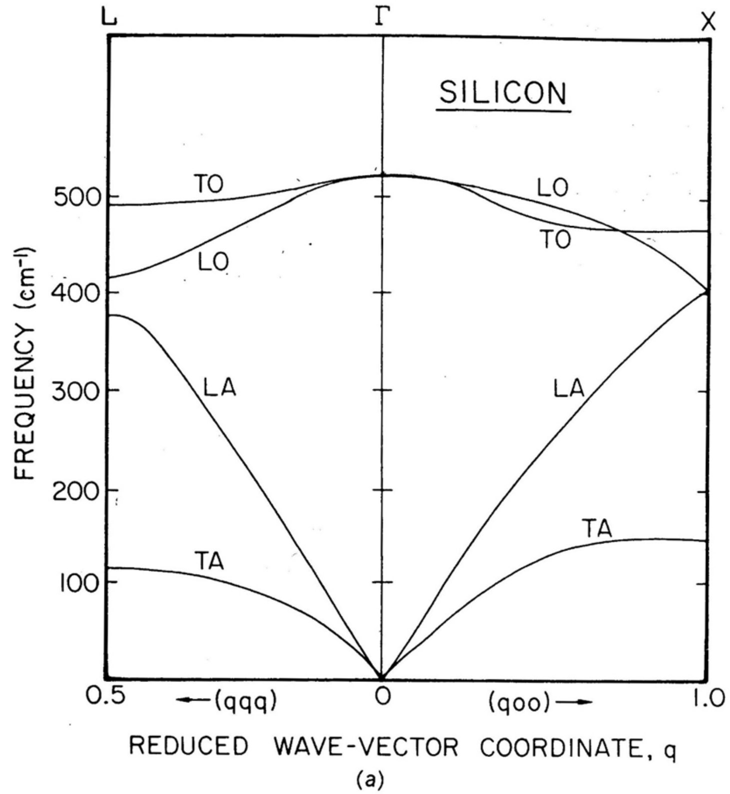
QC

$$\Delta x \cdot \Delta k \sim 1$$

Bulk: $\Delta x \rightarrow grande\ (\sim 10^{-2} m) \Rightarrow \Delta k \rightarrow piccolo\ (\sim 10^{2} m^{-1})$

NC: $\Delta x \rightarrow piccolo\ (\sim 10^{-9} m) \Rightarrow \Delta k \rightarrow grande\ (\sim 10^{9} m^{-1})$

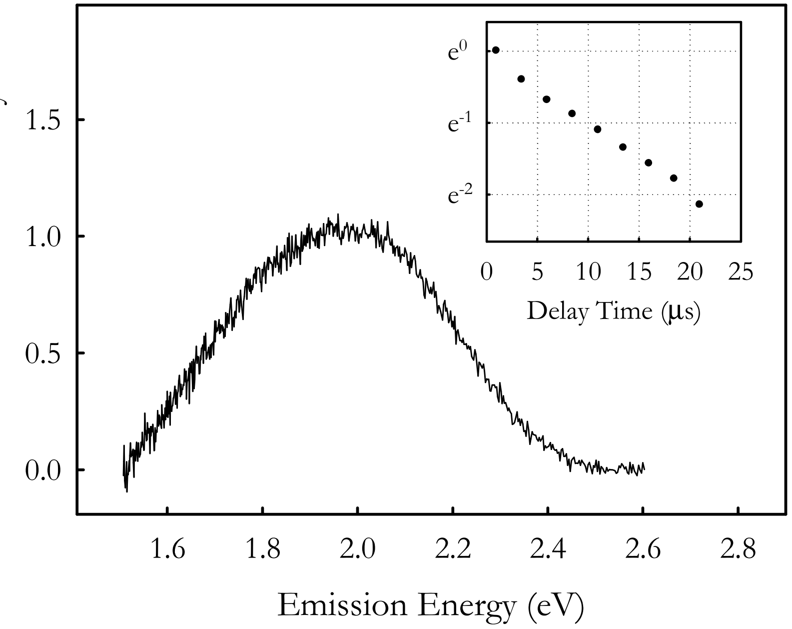


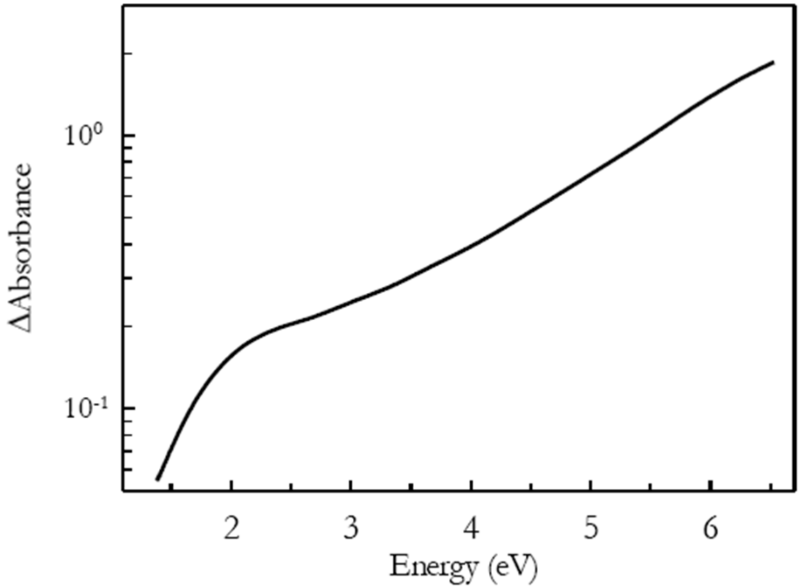


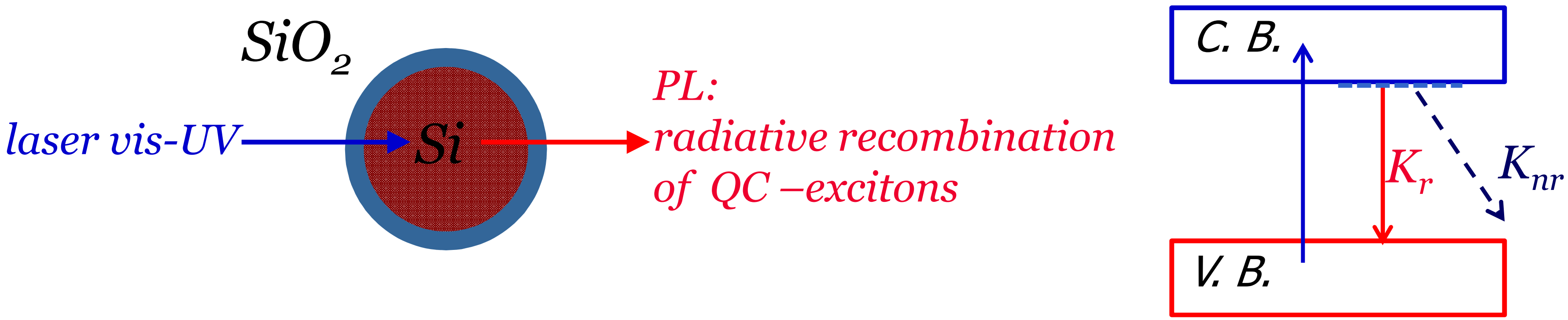
Proprietà ottiche PL/OA

PL a 1.9 eV

E_{exc}=4.13eV
t_D=1μs, Δ_T=10ms







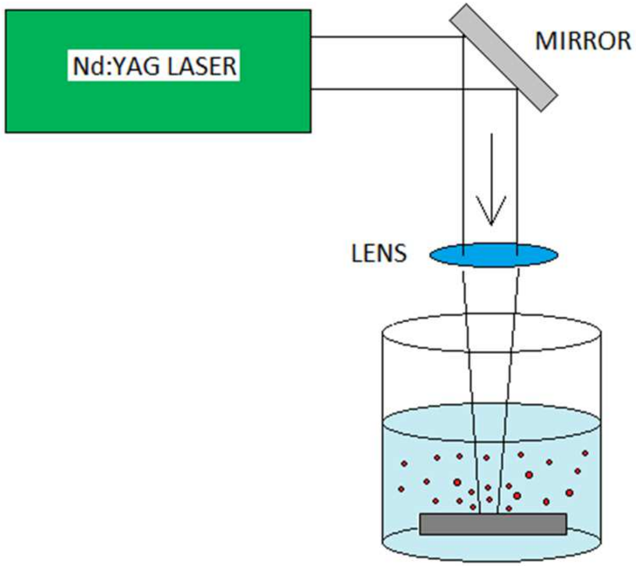
Goal!

Increase the brightness:

Enhancement of PL quantum efficiency

Experimental Methods

Laser Ablation



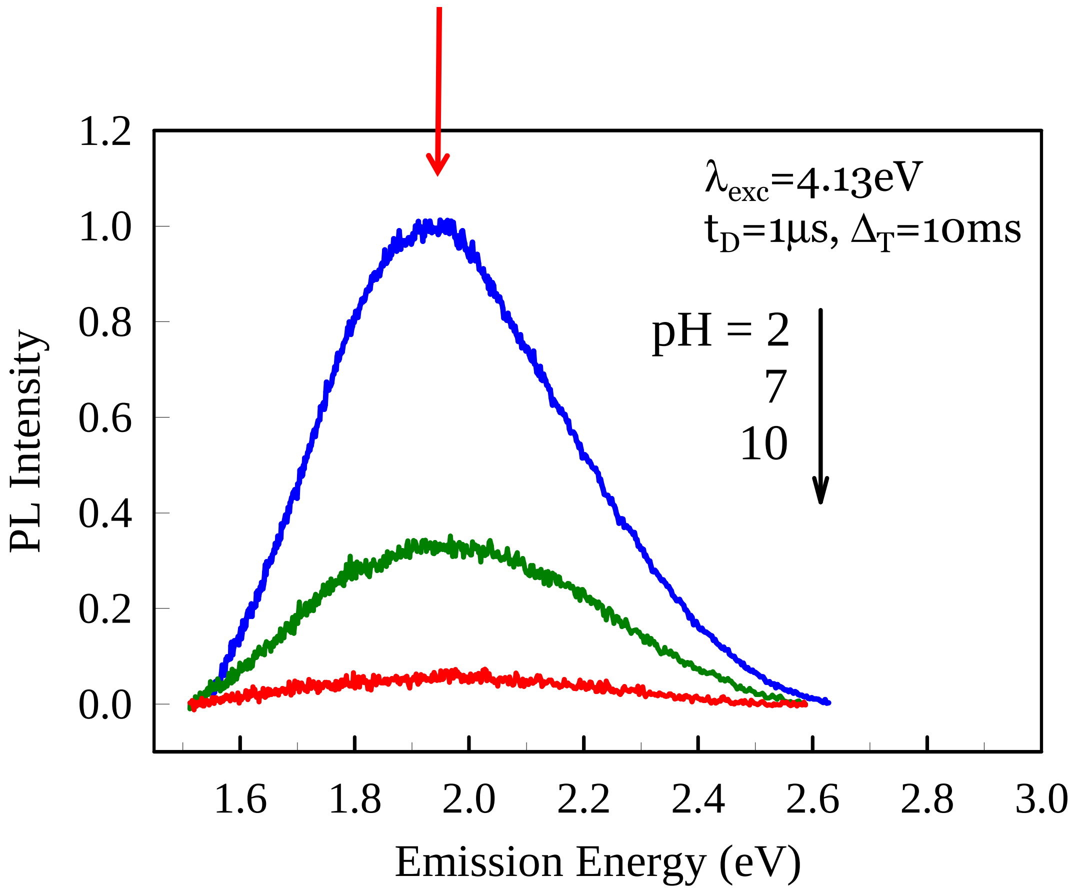
Si-Target
in deionized water

Soluzioni «acide» e «basiche»
Al variare del pH da 1 a 10

Time-resolved PL
IR absorption

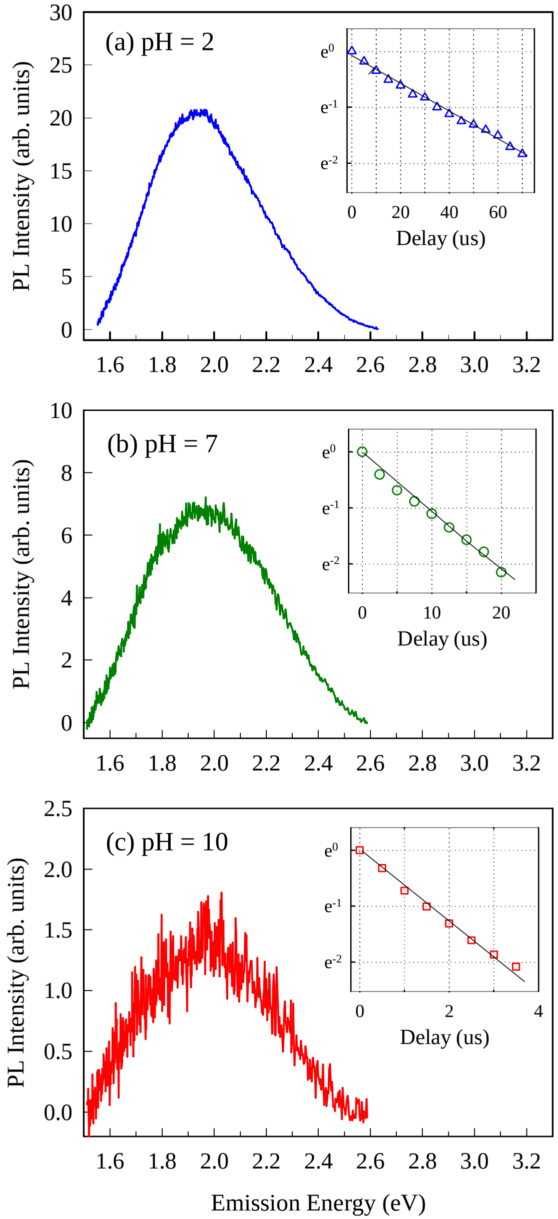
Results PL dependence on pH

PL peak at 1.95 eV



PL intensity increases by a factor of ~20 upon decreasing the pH from 10 to 2.

Results PL dependence on pH



Exponential decay: exp(-t/τ) $\tau=1_r/(k_r+k_{nr})$

τ≈35 µs

τ≈9.5 µs

τ≈1.8 µs

I_{PL} and τ are correlated

$I_{PL} \propto \eta = k_r/(k_r+k_{nr}) = k_r \times \tau$

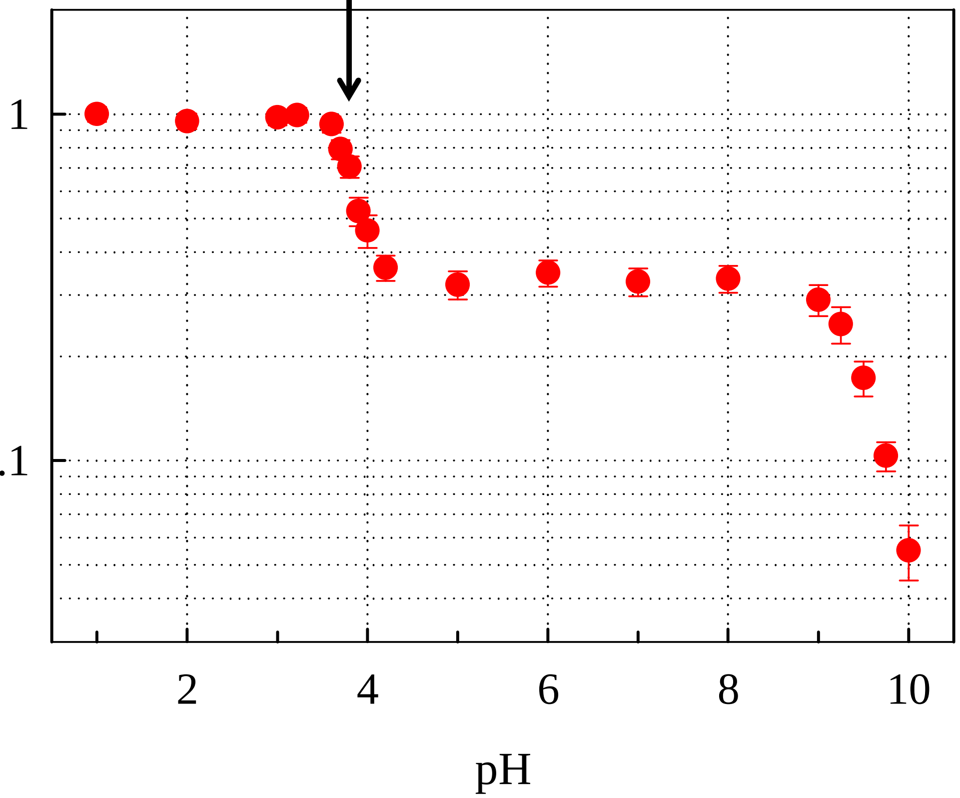
I_{PL} is related to the variation of η

Hypothesis:
η is limited by the existence of centers on which the excitons non-radiatively recombine (non-radiative defects)

Results

PL efficiency: dependence on pH

pH≈3.5; $[H^+]\approx 2\times10^{17}$ cm^{-3}



Maximum efficiency: $\eta_{max} = k_r \times \tau_{max}$

$k_r \leq 1/\tau_{max} \approx 3.6\times10^4$ s^{-1}

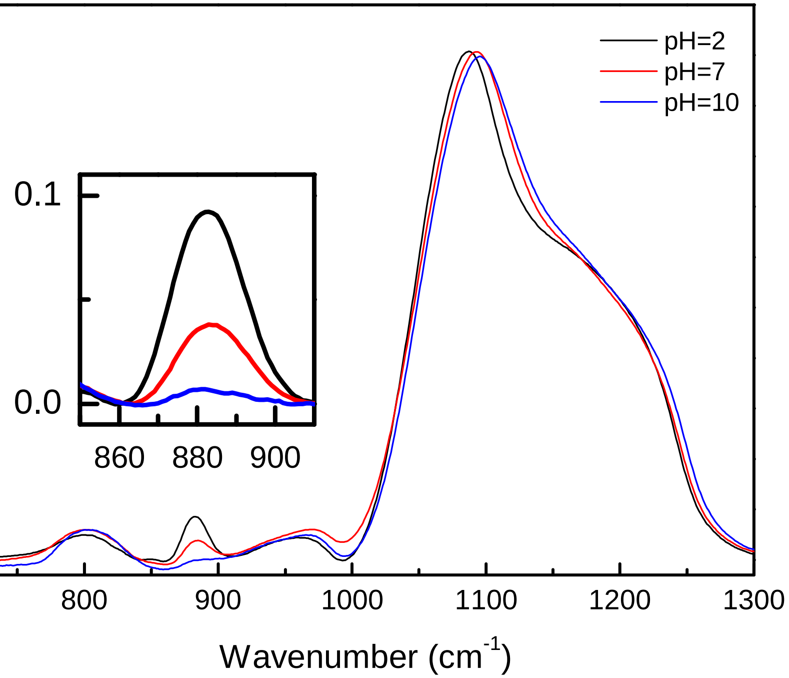
$\eta = k_r/(1/\tau) = k_r/(1/\tau_{max} + \Delta k_{nr})$

enhancement of η on increasing $[H^+]$,
consistently with the passivation non-radiative def

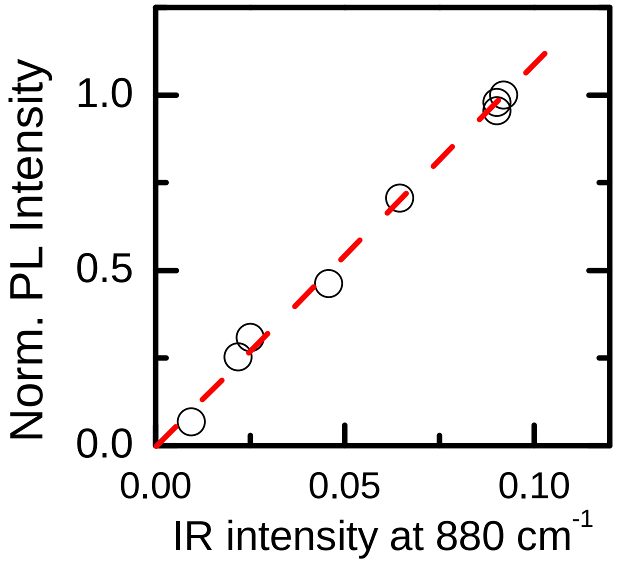
Results

IR absorption: dependence on pH

What about the origin of non-radiative defects?



Linear correlation between [SiH] and I_{PL}



When diluted in solution **$[SiH]_{max}$ ~ 10^{17} cm^{-3}**
in accordance with [H^+] that determines the saturation of η

0 cm^{-1} $\rightarrow$ SiH bending mode

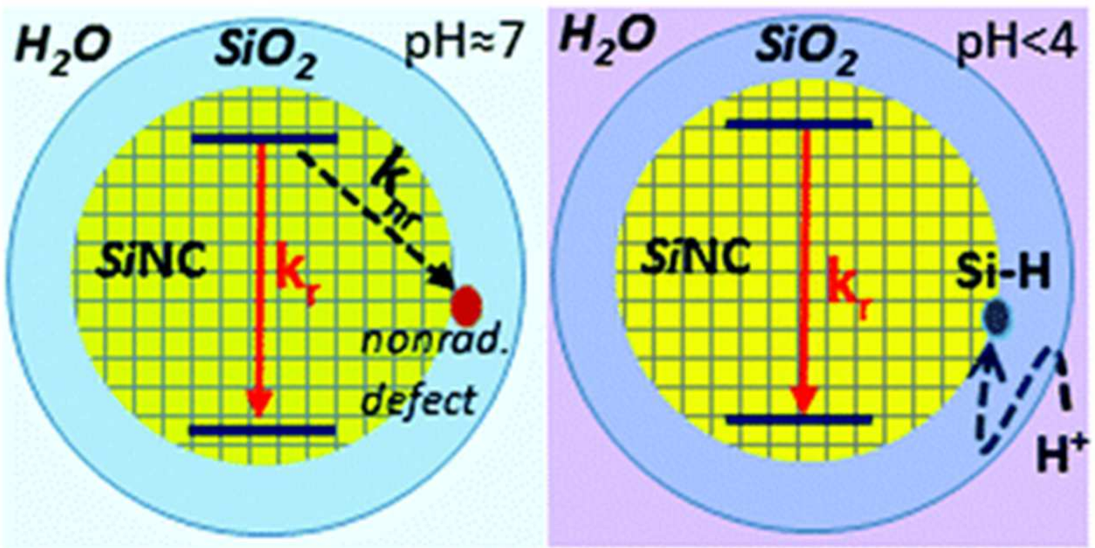
et al. J. Non-Cryst. Solids **185** (1995) 249

First proposal:
H^+ ions passivate the non radiative defects,
thus increasing [SiH]

The exact structure of non radiative centers remains open!!

Hypothesis!
Distorted Si—Si bonds and Si—O—Si bridging bonds at the Si/SiO_2 interface
[Lee et al. Adv. Funct. Mater, 22, 3233 (2012): pseudopotential simulations]

In our system:
The interface (~3 nm) is Si_3O …
Distorted Si—Si bonds and Si—O—Si bridging bonds could be present!



2) Production of ZnO-nc

AIP | Applied Physics Letters

ation of Zn nanoparticles probed by online optical spectroscopy during
osecond pulsed laser ablation of a Zn plate in H2O

PCCP

PAPER

CrossMark

Luminescence mechanisms of defective ZnO nanoparticles

Cite this: *Phys. Chem. Chem. Phys.*,

AIP | Journal of Applied Physics

ntrolling the oxidation processes of Zn nanoparticles produced by pulsed laser
lation in aqueous solution

Ossido di zinco (ZnO)

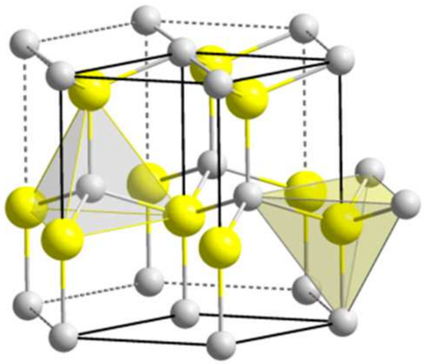
ZnO è un semiconduttore del II-VI gruppo

ZnO

Proprietà: Alta mobilità elettronica, ampio band gap, biocompatibilità, piezoelettricità e **intensa luminescenza a temperatura ambiente**

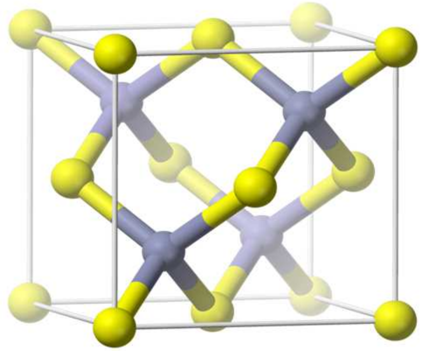
Strutture cristalline

Wurtzite



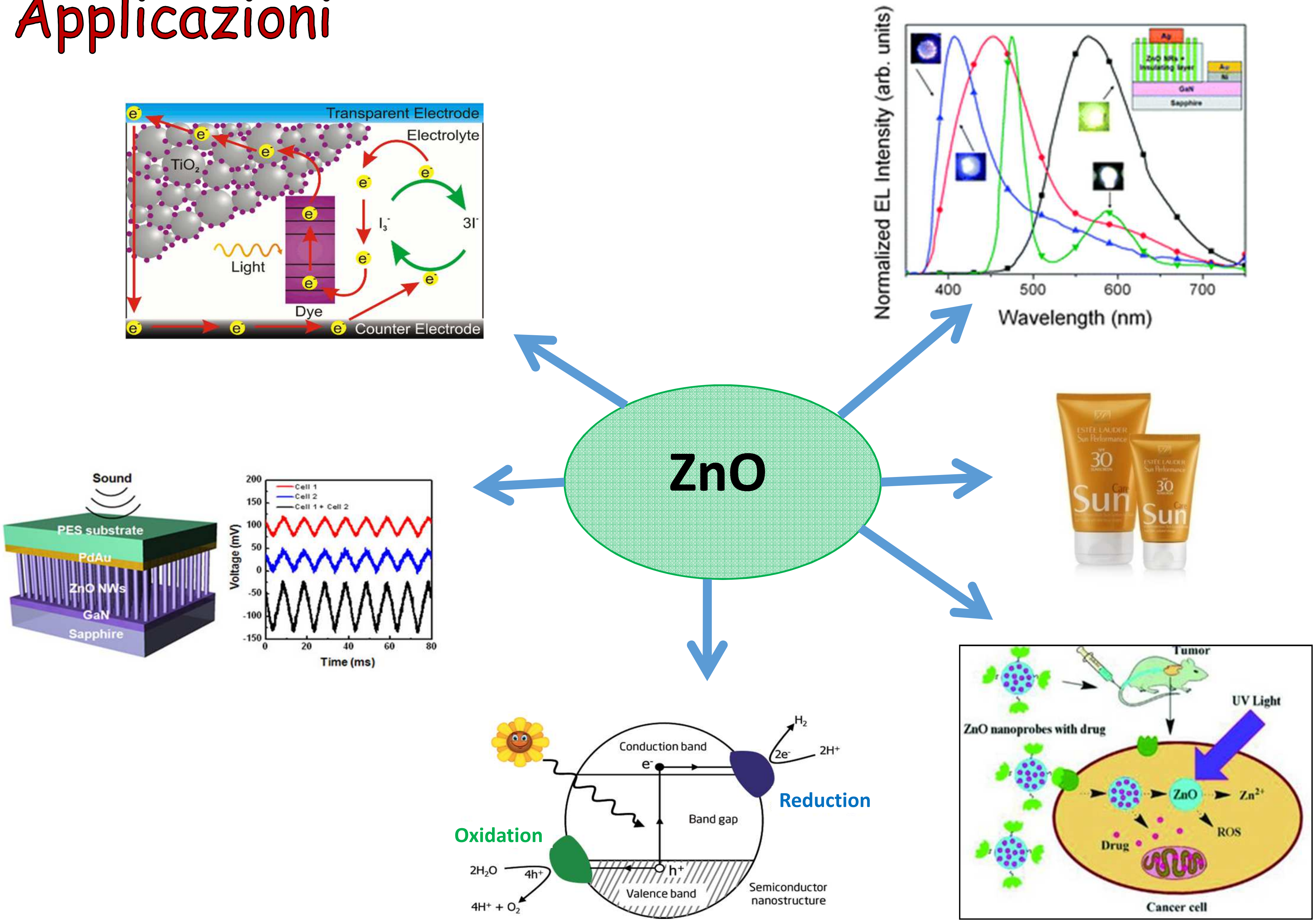
E_g = 3.37eV (direct-bandgap)

Zincoblenda



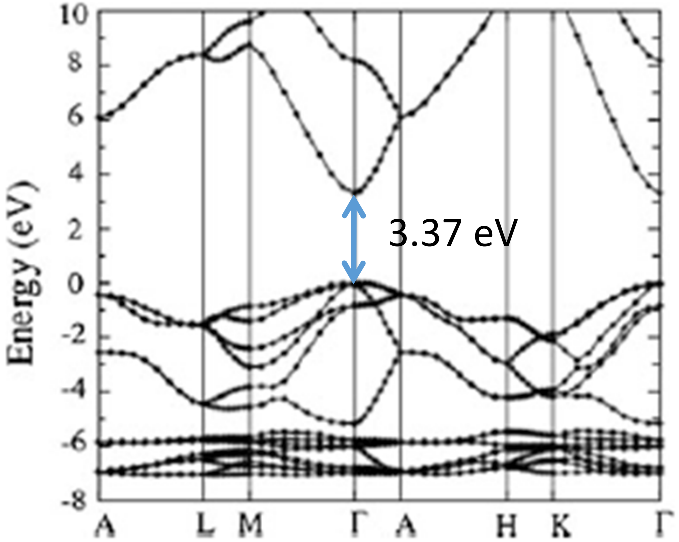
E_g = 3.27 eV (direct-bandgap)

O: Applicazioni



Proprietà elettroniche e ottiche

Struttura bande ZnO wurtzite



Rep. Prog.Phys 72, 126501 (2009)

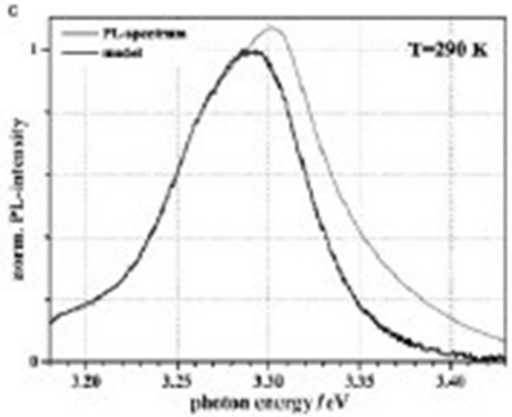
BV: livelli O-2p pieni

BC: livelli Zn-3s vuoti

Table 1.1 Comparison of physical properties of some key compound semiconductors

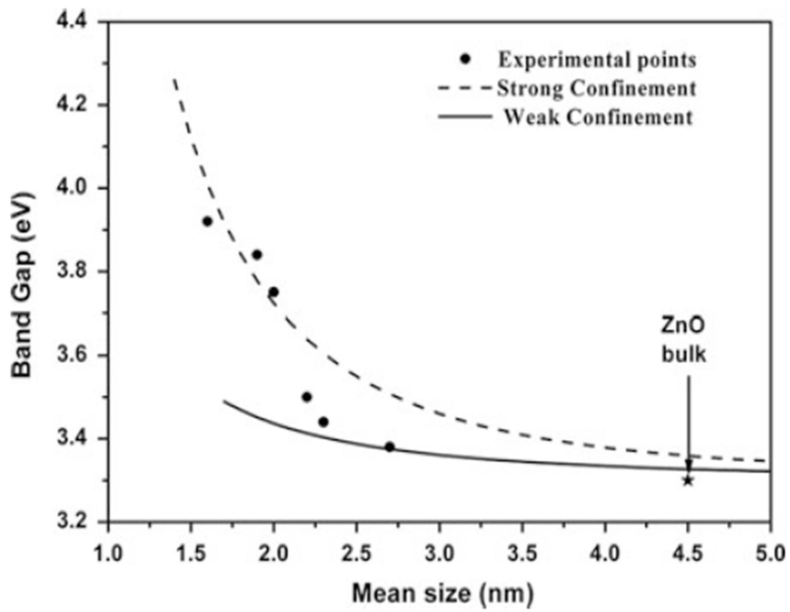
Material	Crystal structure	Lattice constants *a* and *c* (Å)	Band gap (eV)	Energy of fusion (K)	Exc. binding energy (meV)	Dielectric constant ε (0) and ε (∞)
ZnO	Wurtzite	3.25 5.21	3.37	2,248	60	8.75 3.75
ZnS	Wurtzite	3.82 6.26	3.8	2,103	30	9.6 5.7
ZnSe	Zinc blende	5.66	2.7	1,793	20	9.1 6.3
GaAs	Zinc blende	5.65	1.43		4.2	12.9 10.9
GaN	Wurtzite	3.19 5.19	3.39	1,973	21	8.9 5.35
SiC	Wurtzite	3.18 15.12	2.86	>2,100	–	9.66 6.52

Luminescenza eccitonica

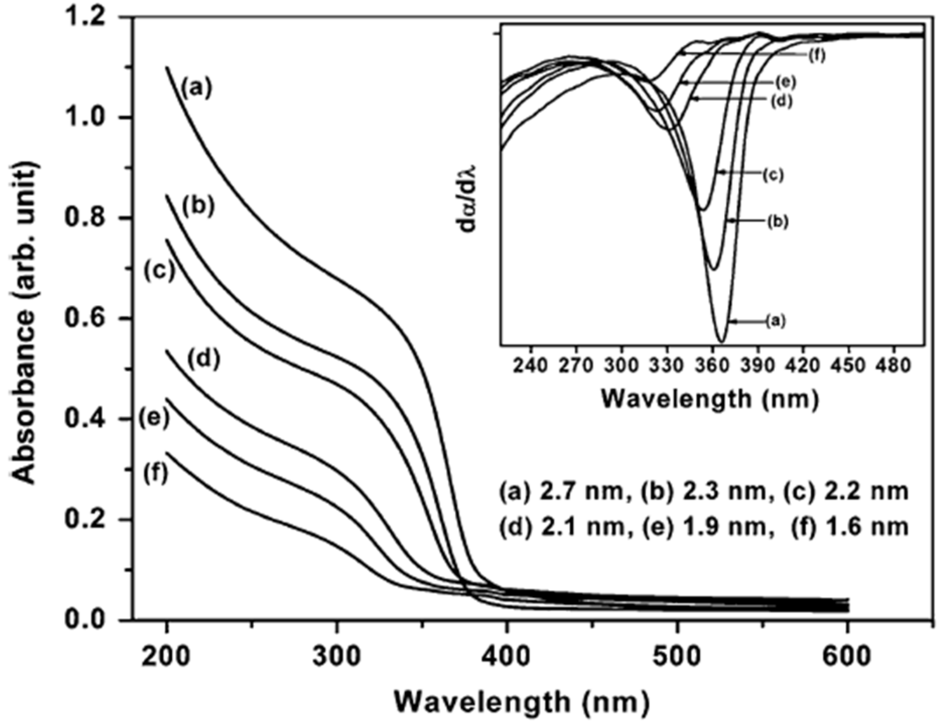


ZnO NPs: effetti QC

$R_B \; ZnO = 2.23 \, nm$



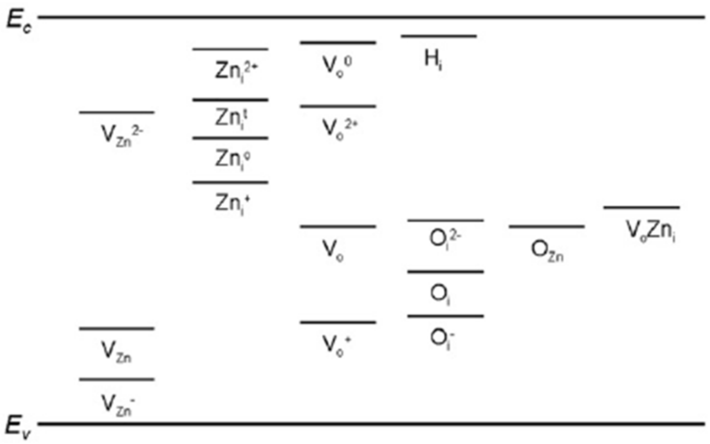
Assorbimento UV-Vis



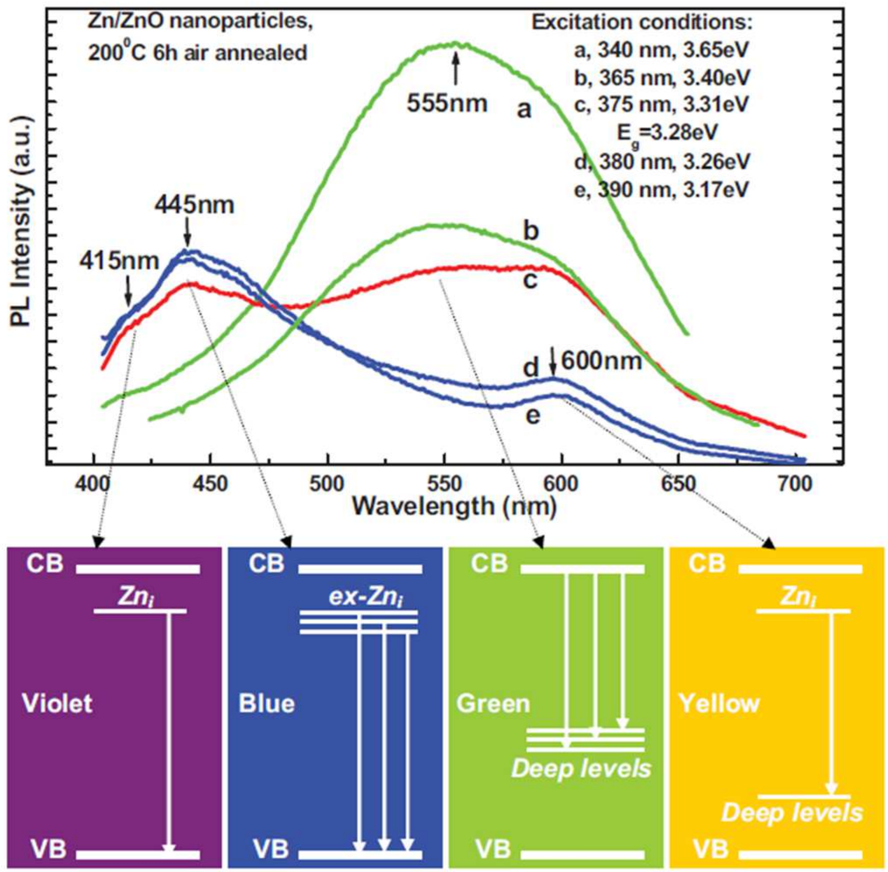
Difetti ZnO nano-strutturato

Difetti intrinseci

Livelli energetici calcolati tramite DFT



- O_i : banda gialla (2 eV)
- Zn_i: banda blu (2.8 eV)
- V_O: banda verde (2.3 eV)
- V_{Zn}: banda verde (2.5 eV)



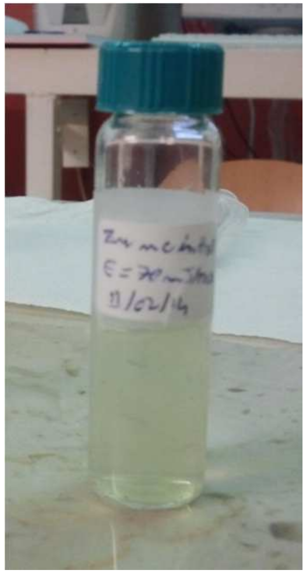
Adv. Funct. Mater. **2010**, 20, 561–572

Ablazione di zinco in acqua

Setup sperimentale:
Foil di Zn in 10mL di acqua deionizzata (becker 100mL)
Laser Nd-Yag (1064 nm), ≈ 5 ns;
Laser Ti:Sapphire (800 nm), ≈50 fs

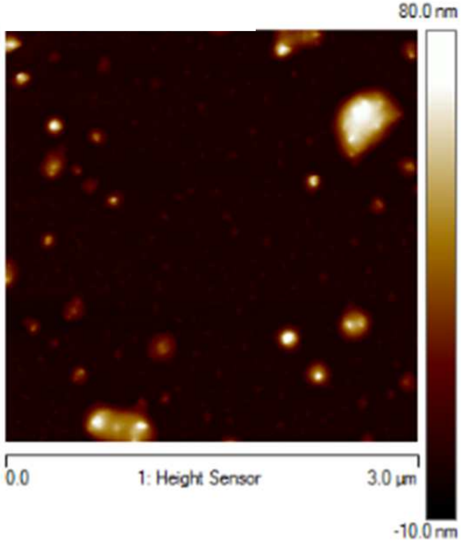
Subito dopo l’ablazione

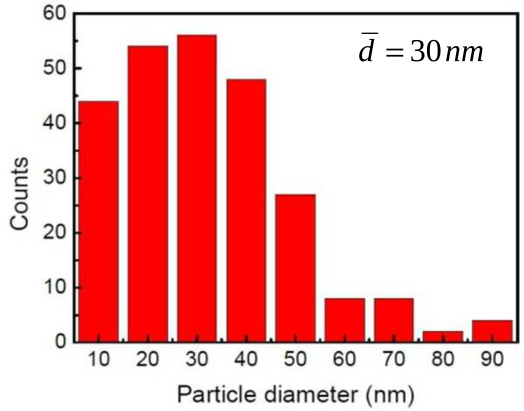
dopo un ora



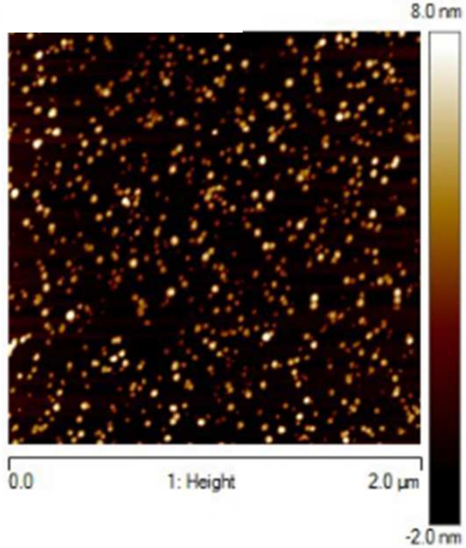
ratterizzazione microscopica:
fetto della durata dell'impulso

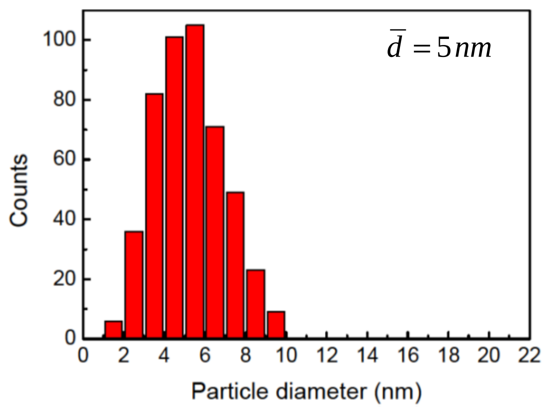
$E_p = 90\, mJ, 5\, ns$





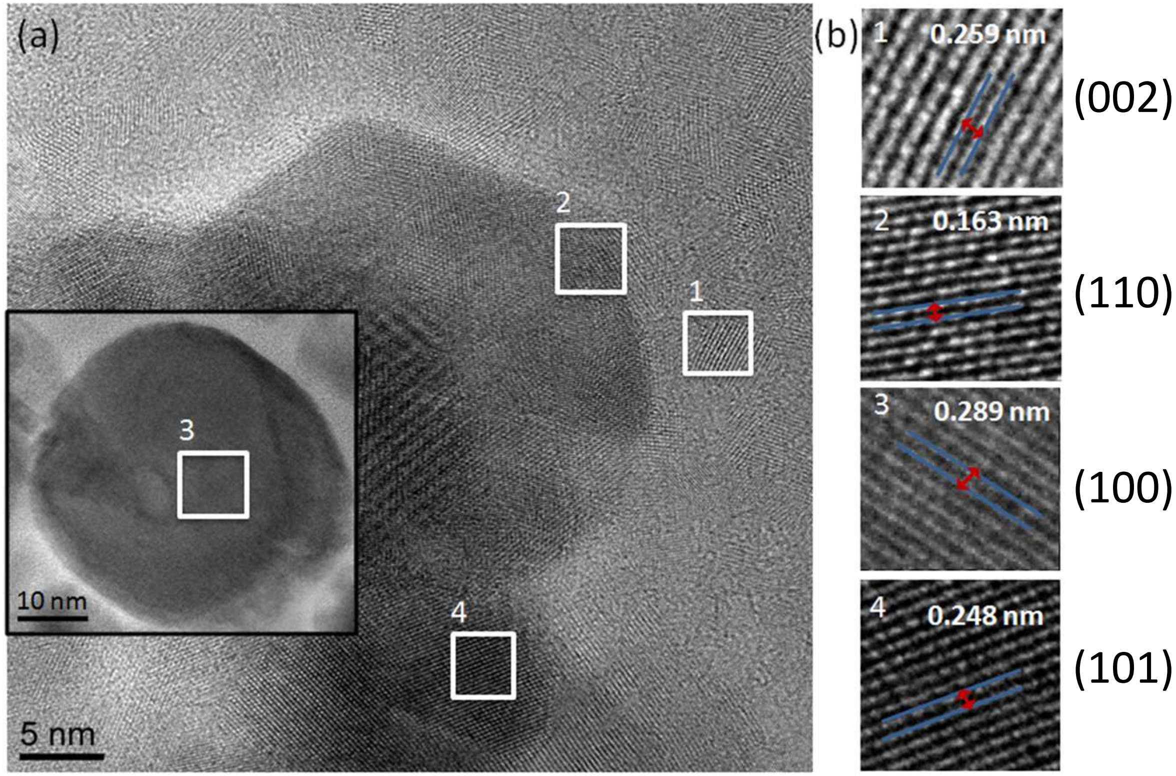
$E_p = 150\, \mu J, 60\ fs$



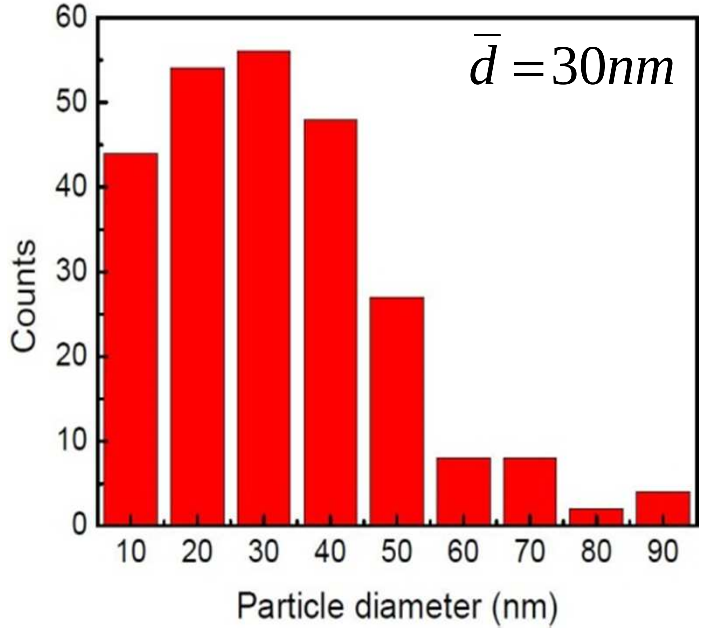


Morphology and structure

HRTEM



AFM size distribution



Wurtzite ZnO
a= 0.325 nm, c= 0.521 nm

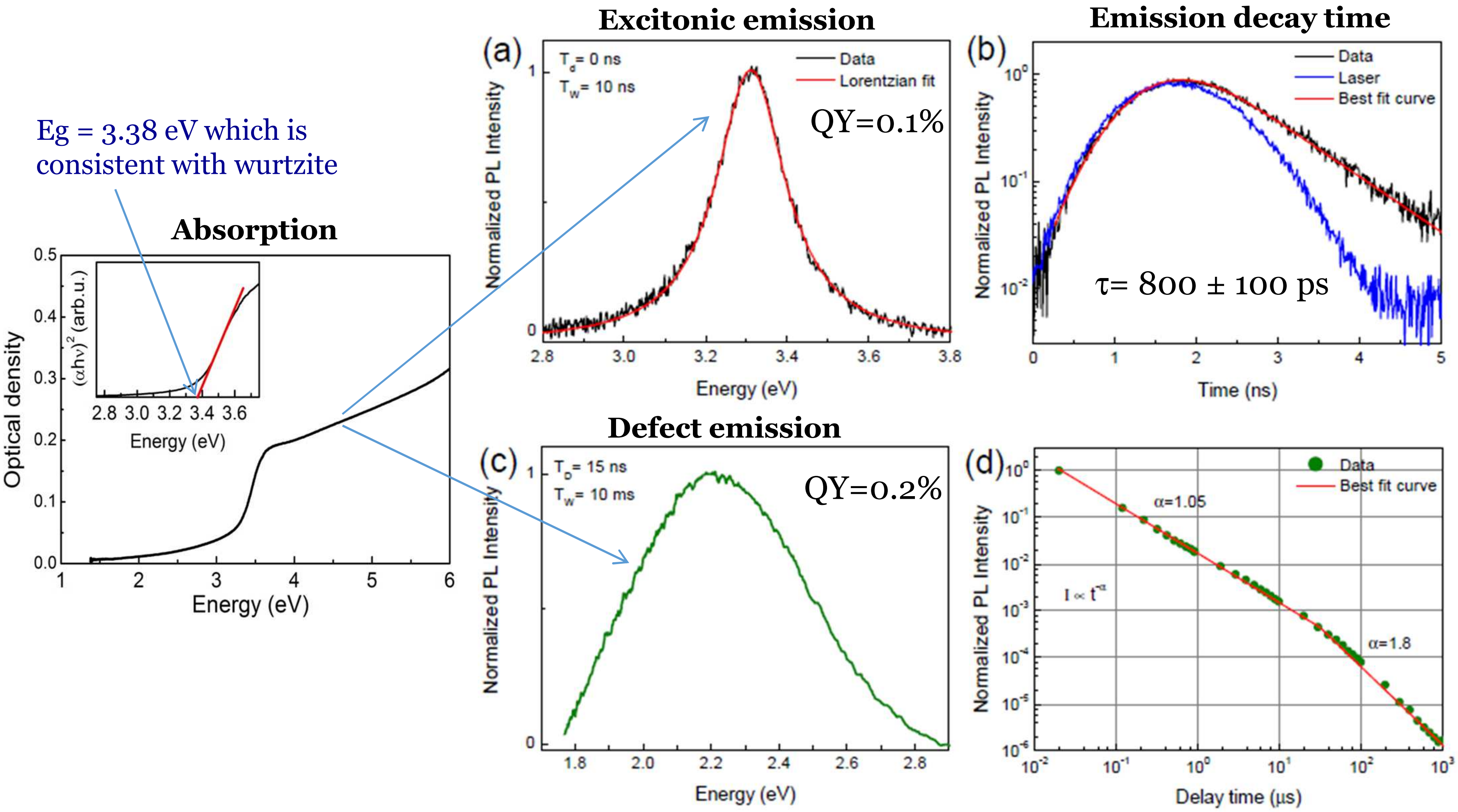
(h k l)	(0 0 2)	(1 1 0)	(1 0 0)	(1 0 1)
Measured d(nm)	0.259±0.001	0.1630±0.0006	0.289±0.001	0.248±0.002
Reported d(nm)	0.2602	0.1625	0.2814	0.2476

$$\frac{1}{d^2} = \frac{4}{3}\left(\frac{h^2 + hk + k^2}{a^2}\right) + \frac{l^2}{c^2}$$

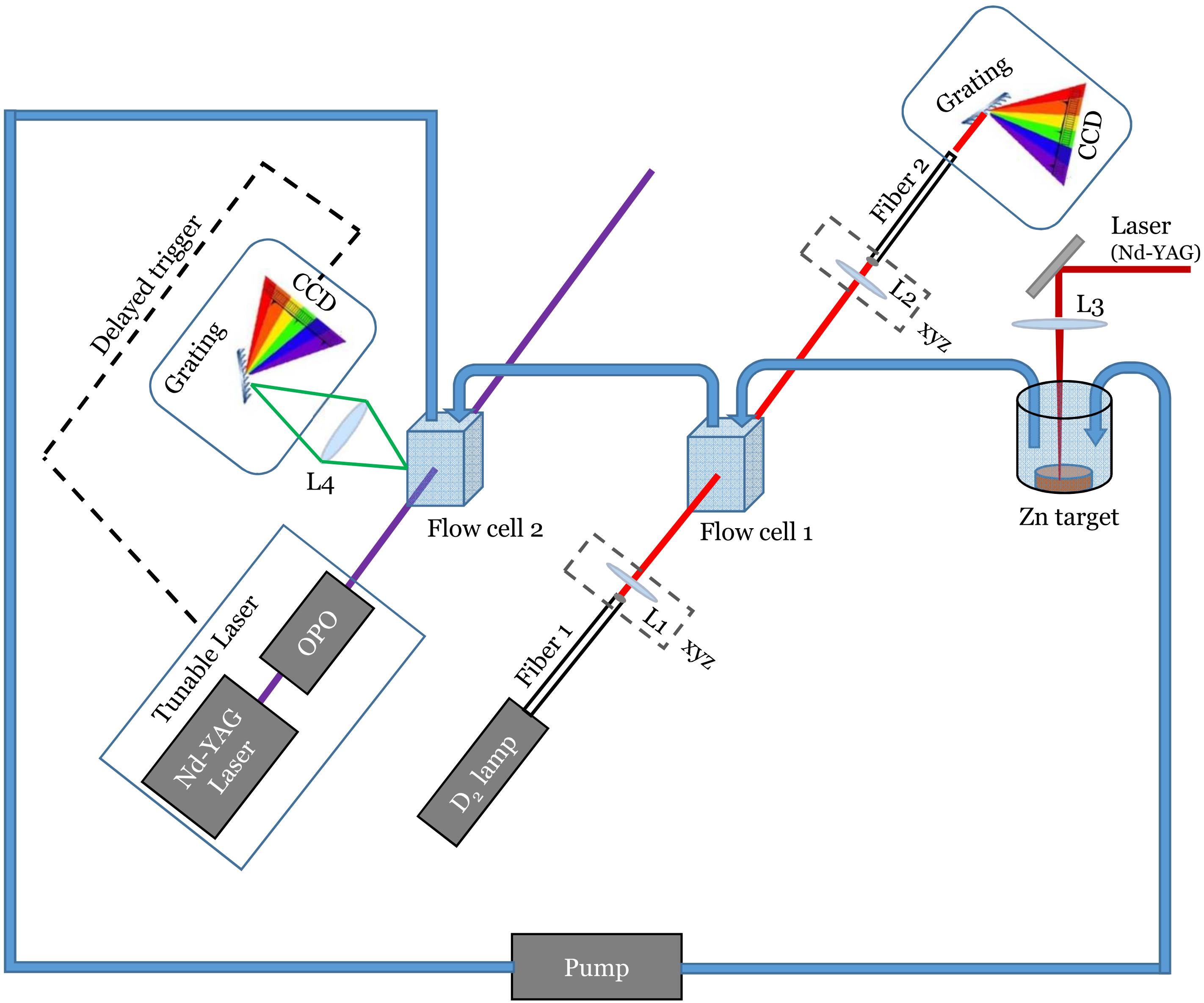
a_{exp}= 0.334 ± 0.001 nm

P. Camarda, Phys. Chem. Chem. Phys., vol. 18, pp. 16237, 2016.

Optical properties

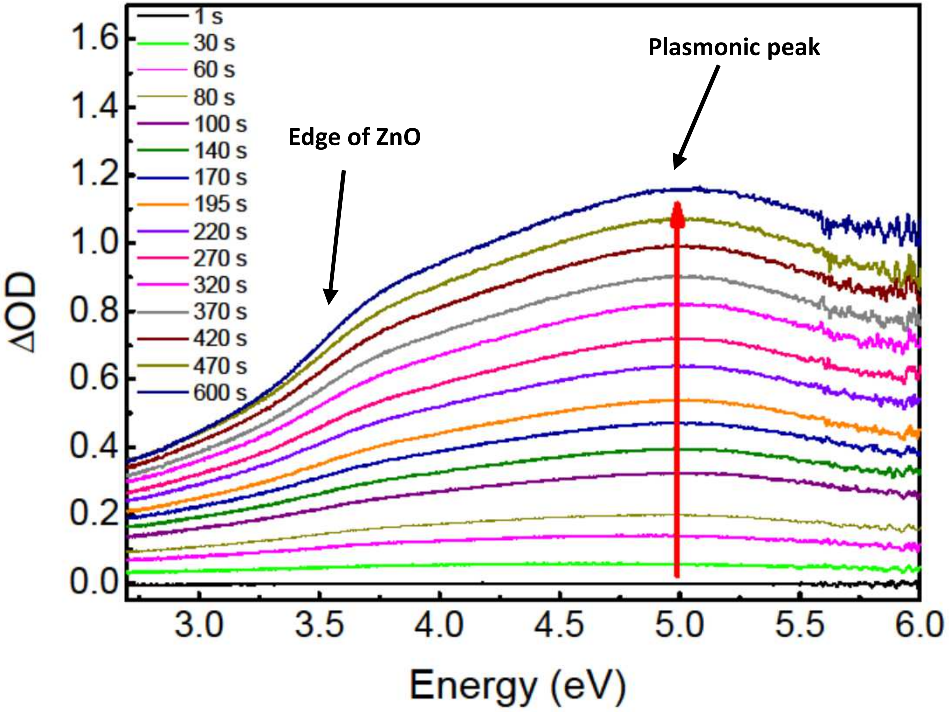


Misure ottiche in situ

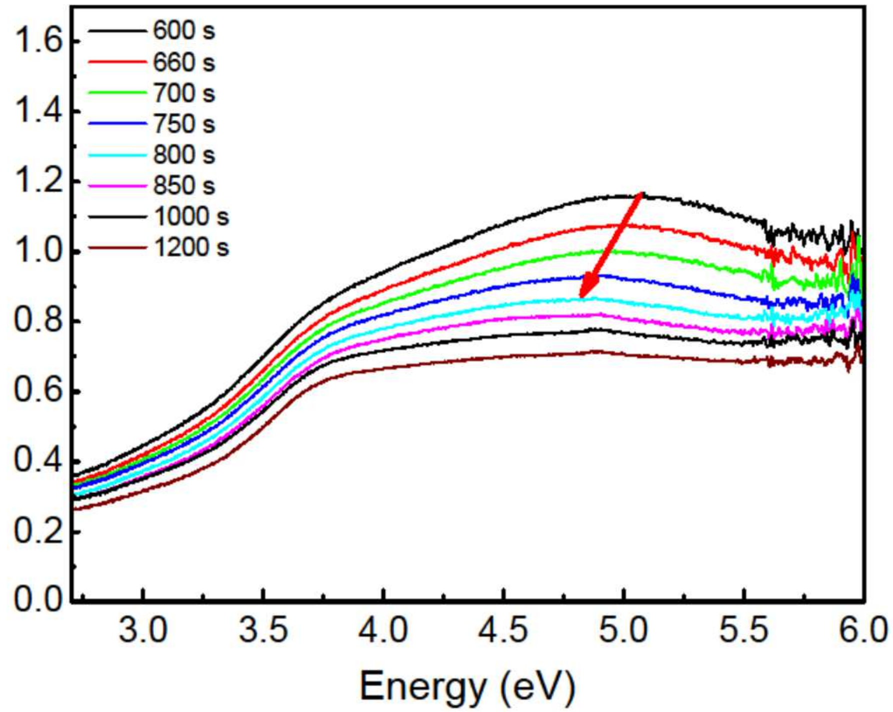


Misure OA online

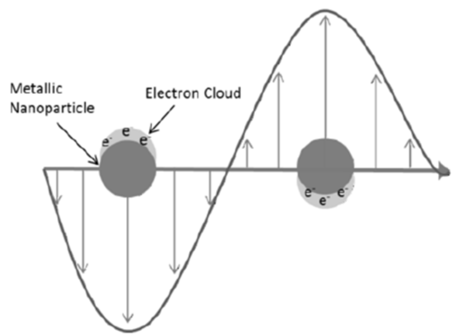
Durante l'ablazione



Dopo l'ablazione

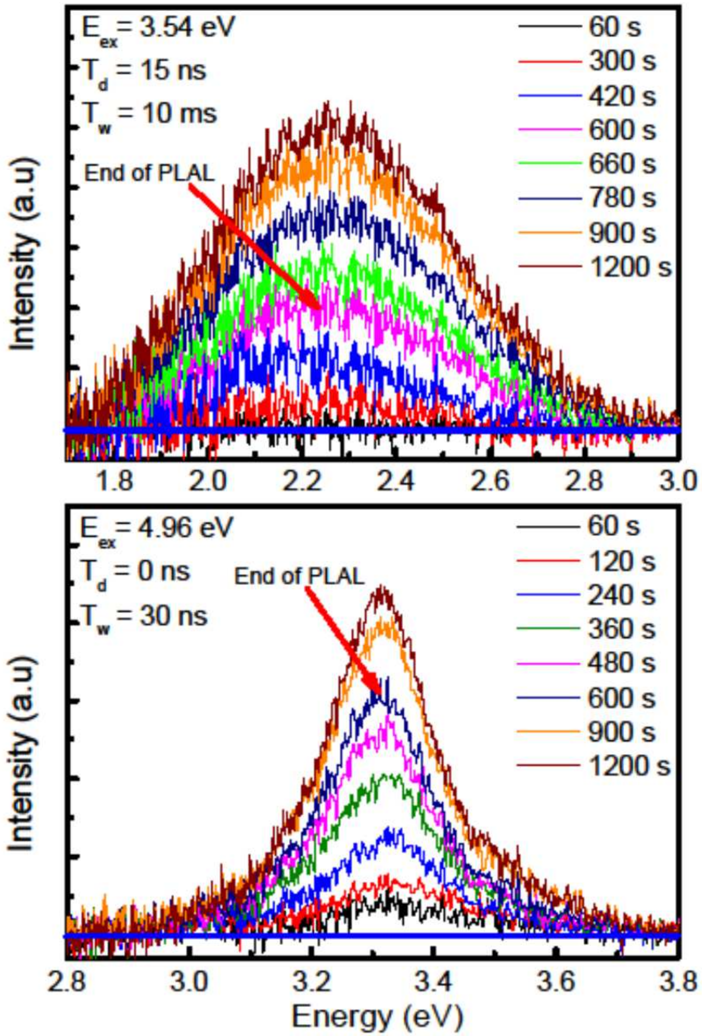


Edge ZnO :
Formazione di ZnO.

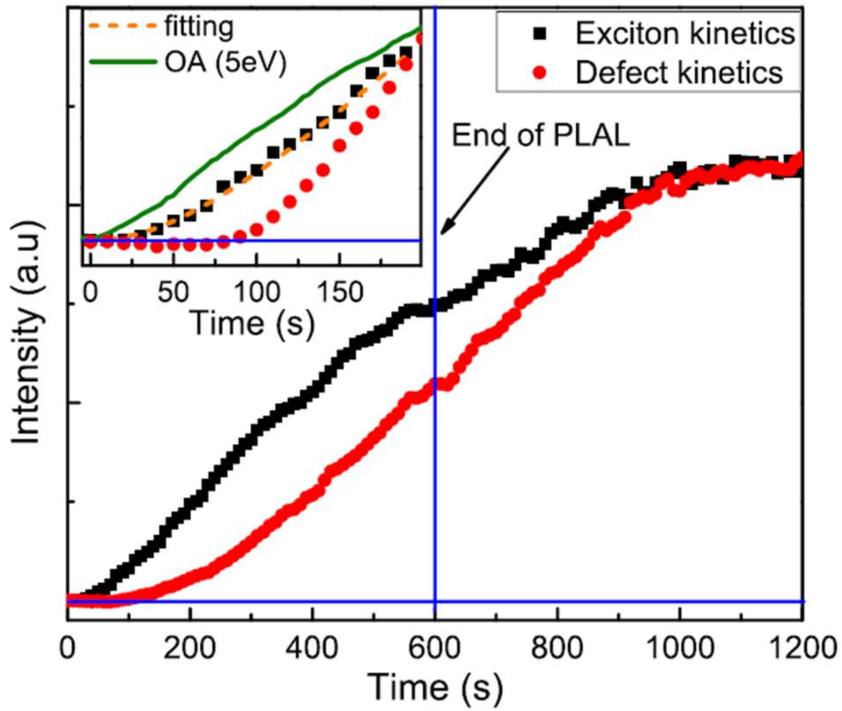


Plasmonic peak:
oscillazione degli elettroni del meta
Indotta dalla radiazione e.m.

Misure PL online

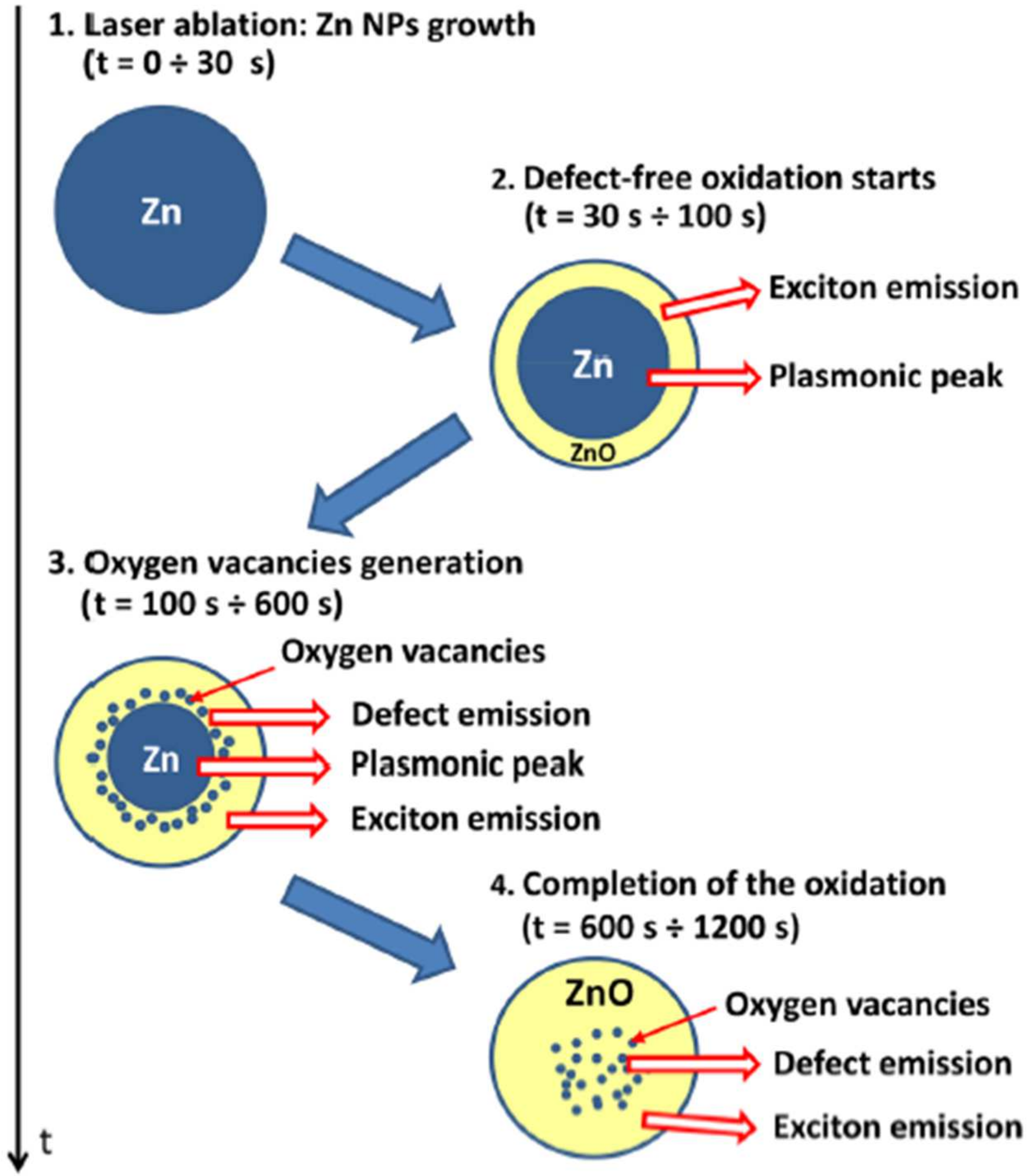


Defect PL
Formazione di ZnO con difetti



Exciton peak
Formazione di ZnO.

ocesso multi-steps
l'ossidazione di Zn-NPs
rante l'ablazione in acqua



per la vostra attenzione!!!