

Photoluminescence and electroluminescence properties of undoped and Er-doped Si nanocrystals

Fabio Iacona



CNR-IMM, Catania (Italy)

Giorgia Franzò, Alessia Irrera,
Domenico Pacifici, Maria Miritello, and Francesco Priolo



INFM and



Dipartimento di Fisica dell'Università di Catania (Italy)

Luca Dal Negro and Lorenzo Pavesi



INFM and



Dipartimento di Fisica dell'Università di Trento (Italy)

OUTLINE

- Preparation of Si nc embedded in SiO_2
- Structural and optical properties of Si nc
- Si nc in an optical microcavity
- Electroluminescent devices based on Si nc
- Preparation of Er-doped Si nc
- Optical properties of Er-doped Si nc
- Er ions and Si nc in an optical microcavity
- Electroluminescent devices based on Er-doped Si nc
- Conclusions

Aim:

development of efficient Si-based light sources
operating in the visible or in the infrared region

Our proposal:

Si nanocrystals prepared by PECVD

Advantages of PECVD-prepared Si nanocrystals:

- fully compatible with VLSI technology
- good efficiency
- high stability
- tunability

Si nanocrystals



visible or near-IR
(650 - 950 nm)

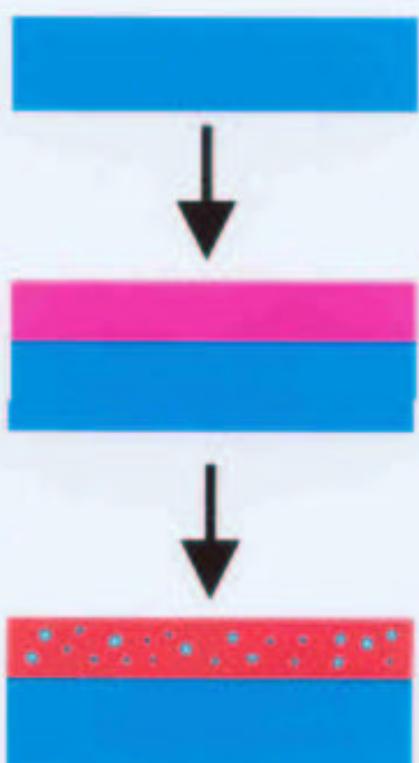
Er-doped
Si nanocrystals



IR
(1.54 μm)

Si nc embedded in SiO₂ from SiO_x films

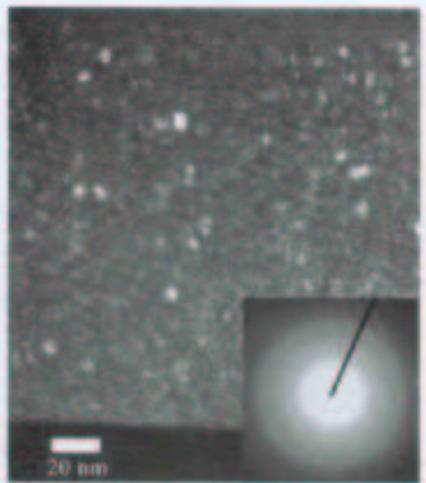
a) SiO_x film
deposition
(200 nm thick)



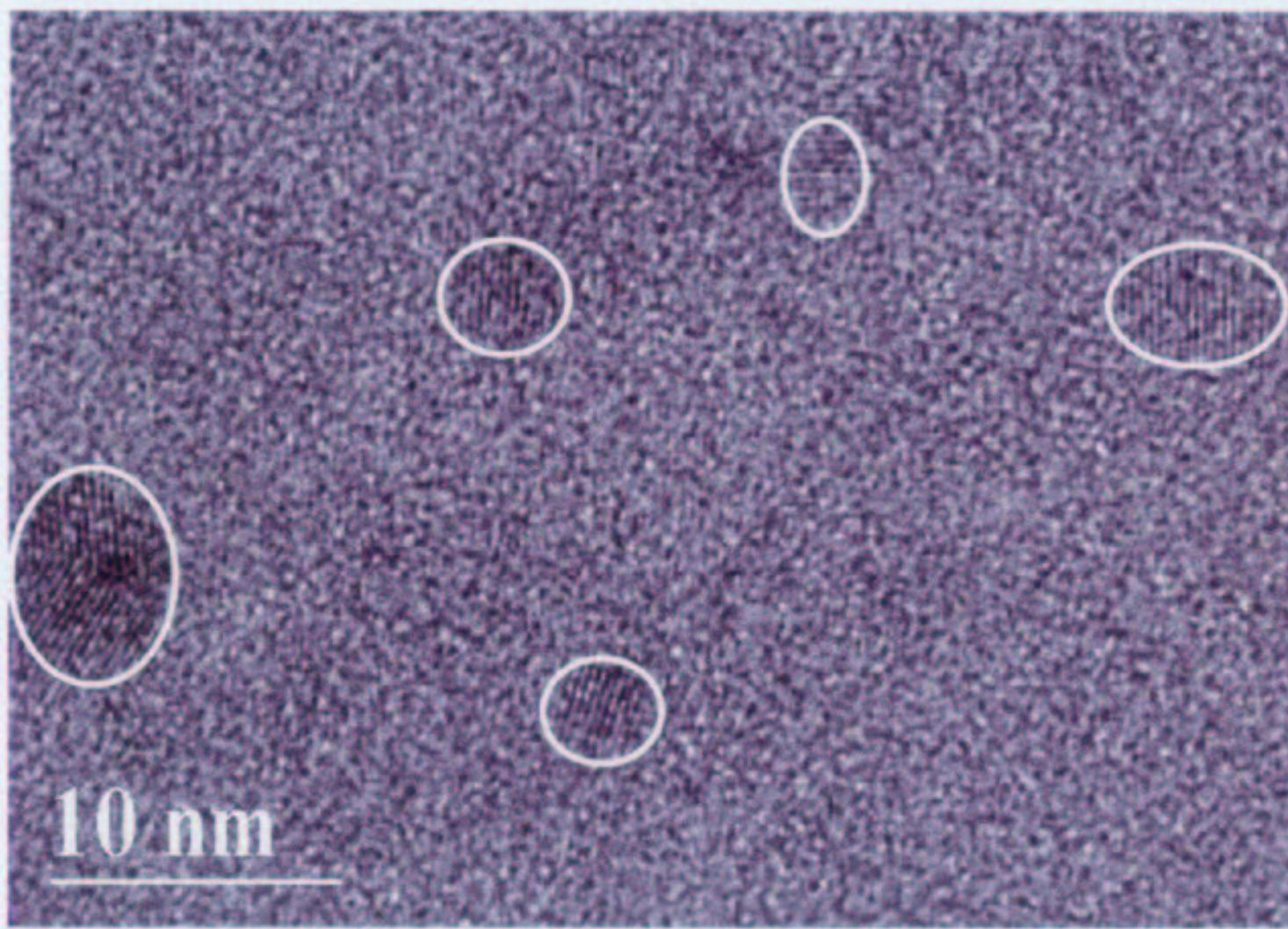
PECVD
 $\text{SiH}_4 + \text{N}_2\text{O}$
 $T = 300^\circ\text{C}$

b) Si nc
formation

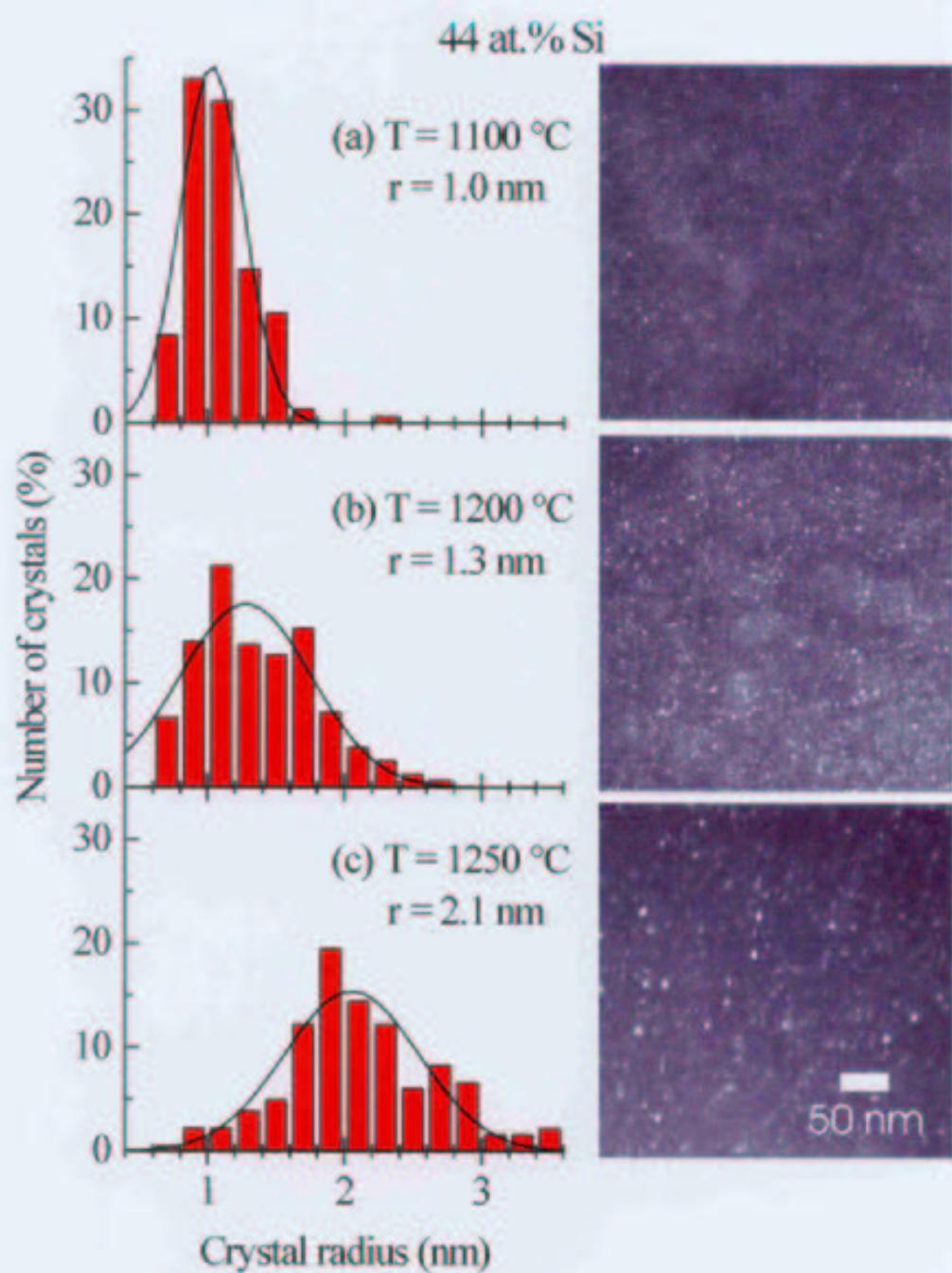
thermal annealing
 N_2 ambient
 $T = 1000 - 1250^\circ\text{C}$



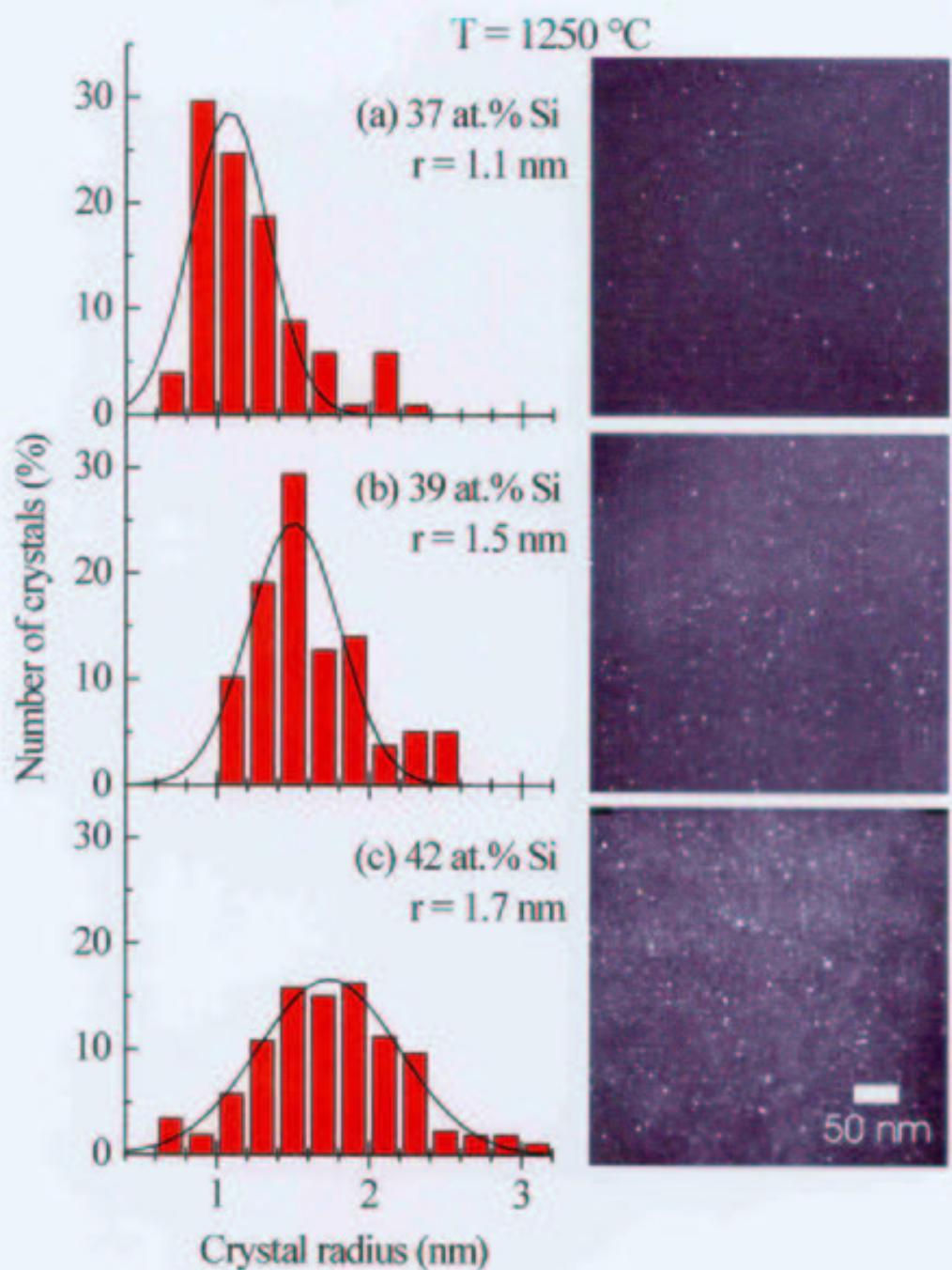
High resolution TEM



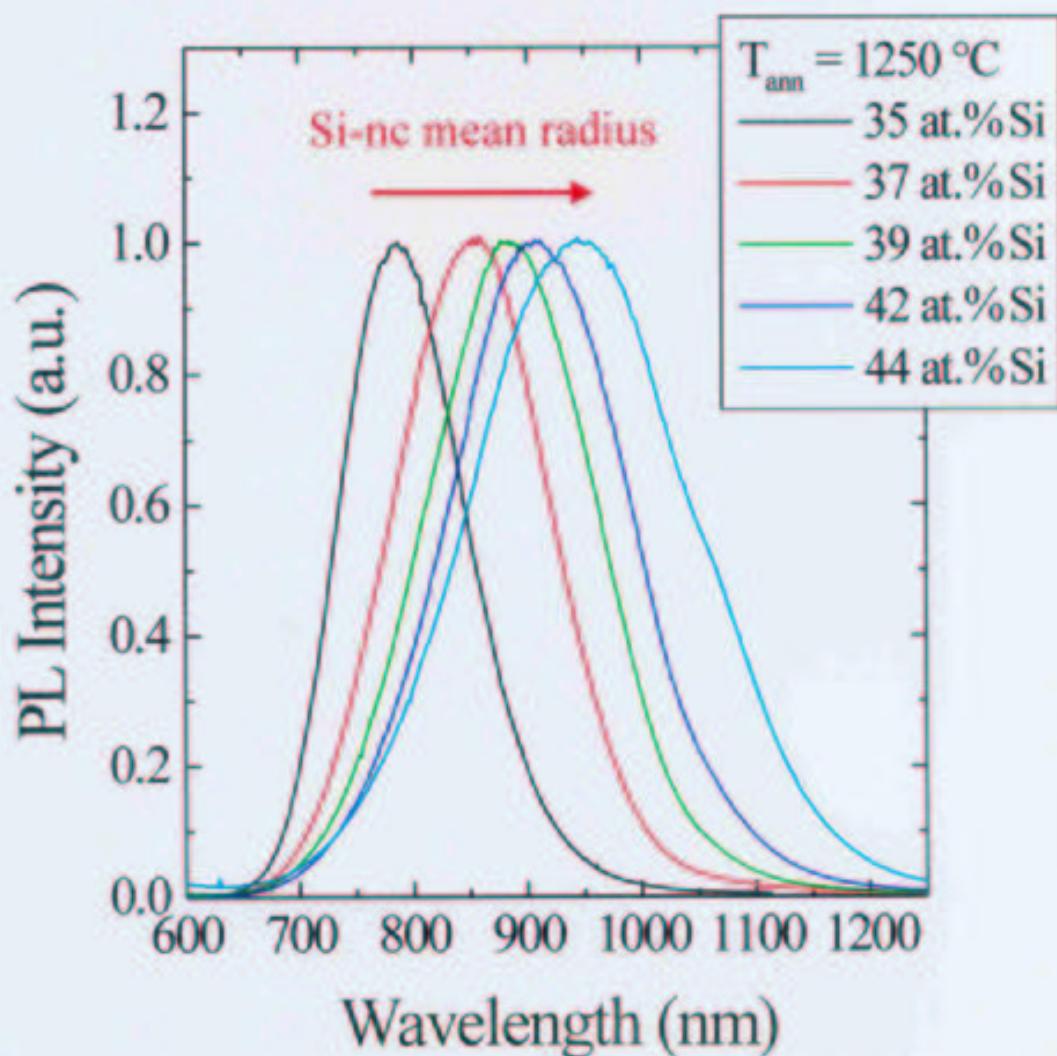
Si nc from SiO_x films: effect of the annealing temperature



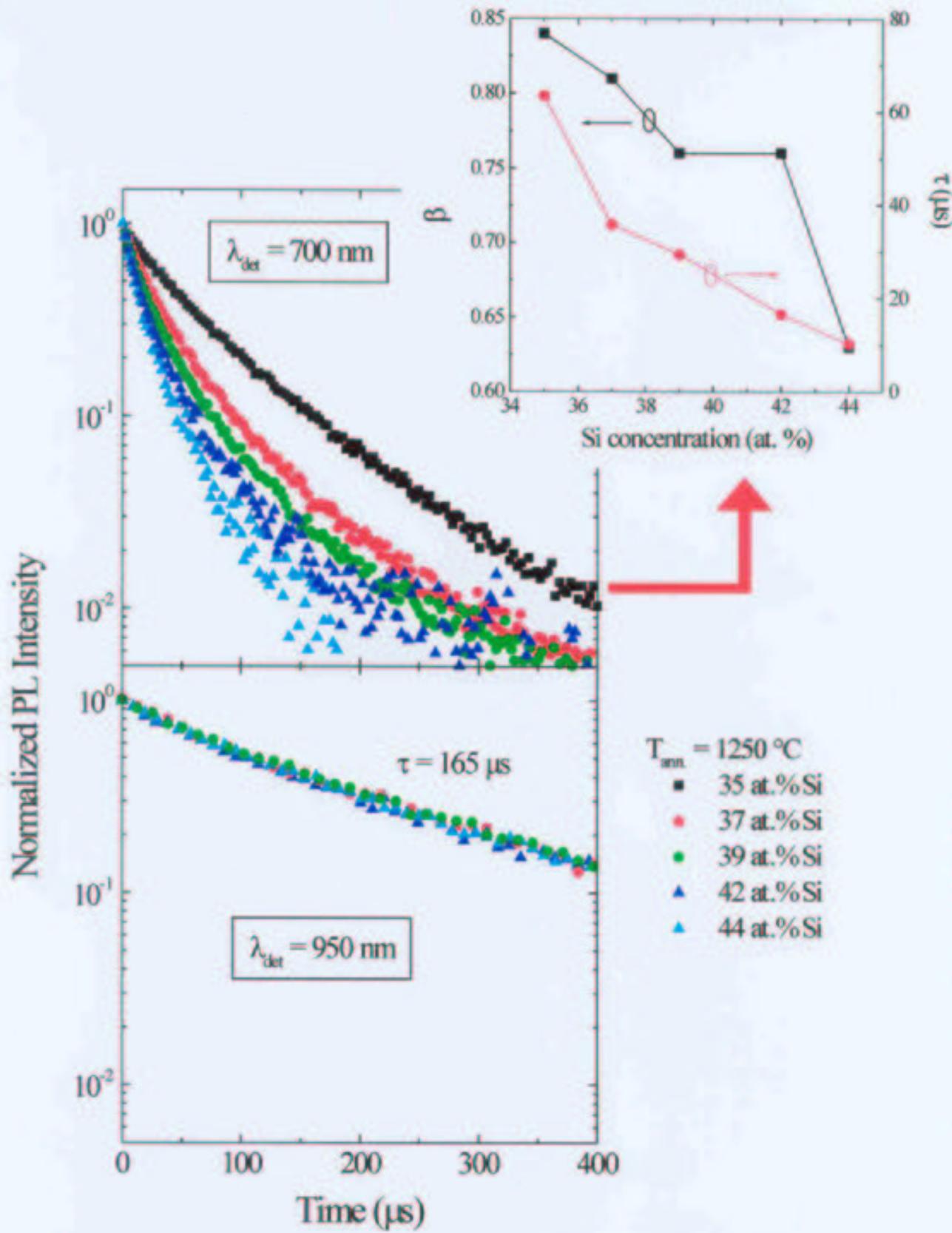
Si nc from SiO_x films: effect of the Si concentration



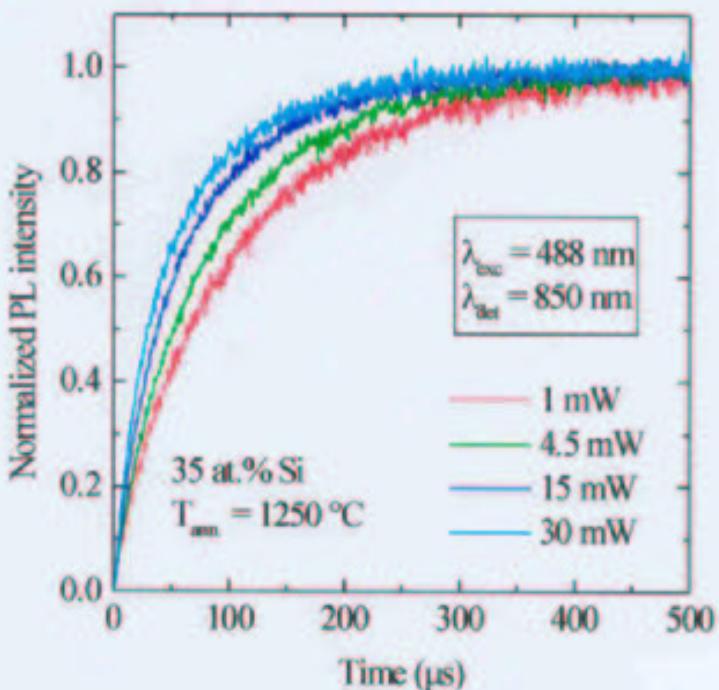
Room temperature PL from Si nc embedded in SiO₂



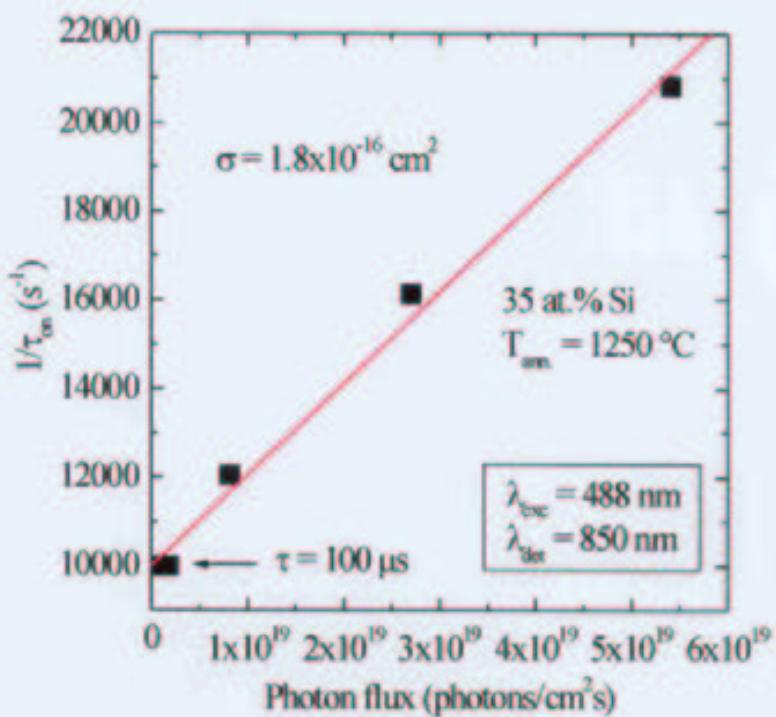
Analysis of the PL decay time

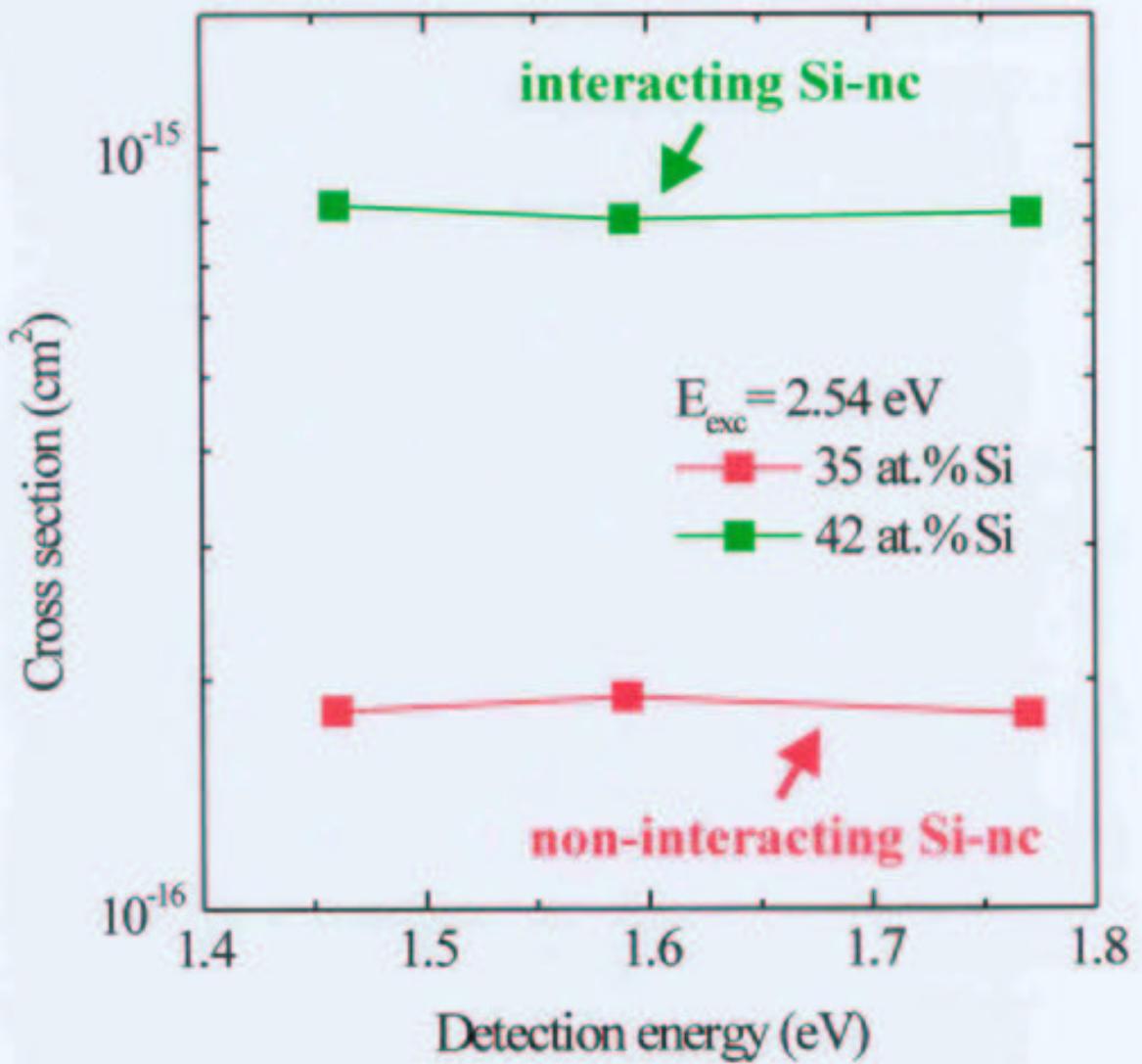


CROSS SECTION FOR Si nc EXCITATION



$$I(t) = I_0 \left\{ 1 - \exp \left[- \left(\sigma \varphi + \frac{1}{\tau} \right) t \right] \right\} \quad \frac{1}{\tau_{\text{on}}} = \sigma \varphi + \frac{1}{\tau}$$

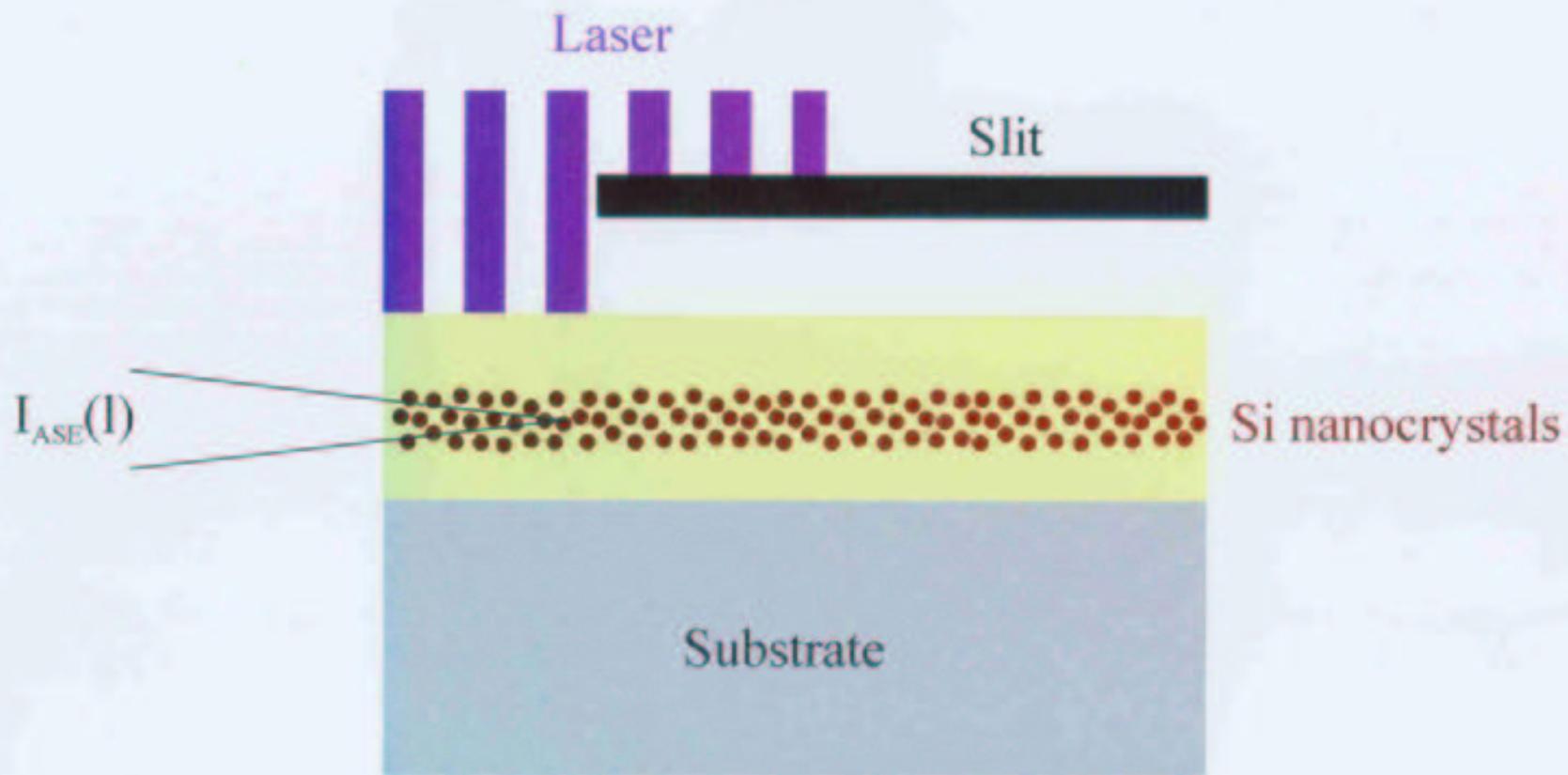




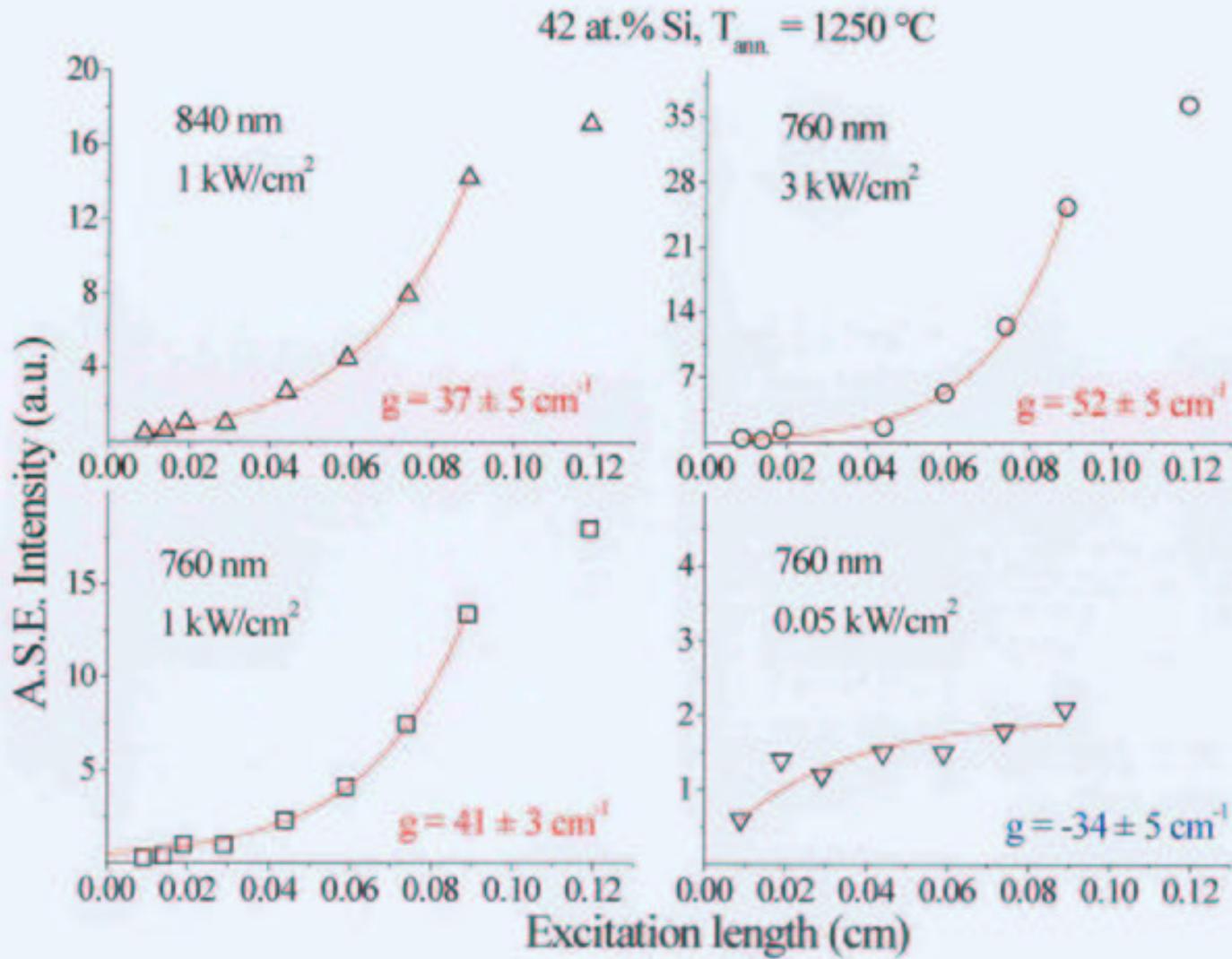
σ depends on the interaction
among nanocrystals

Variable Stripe Length Method

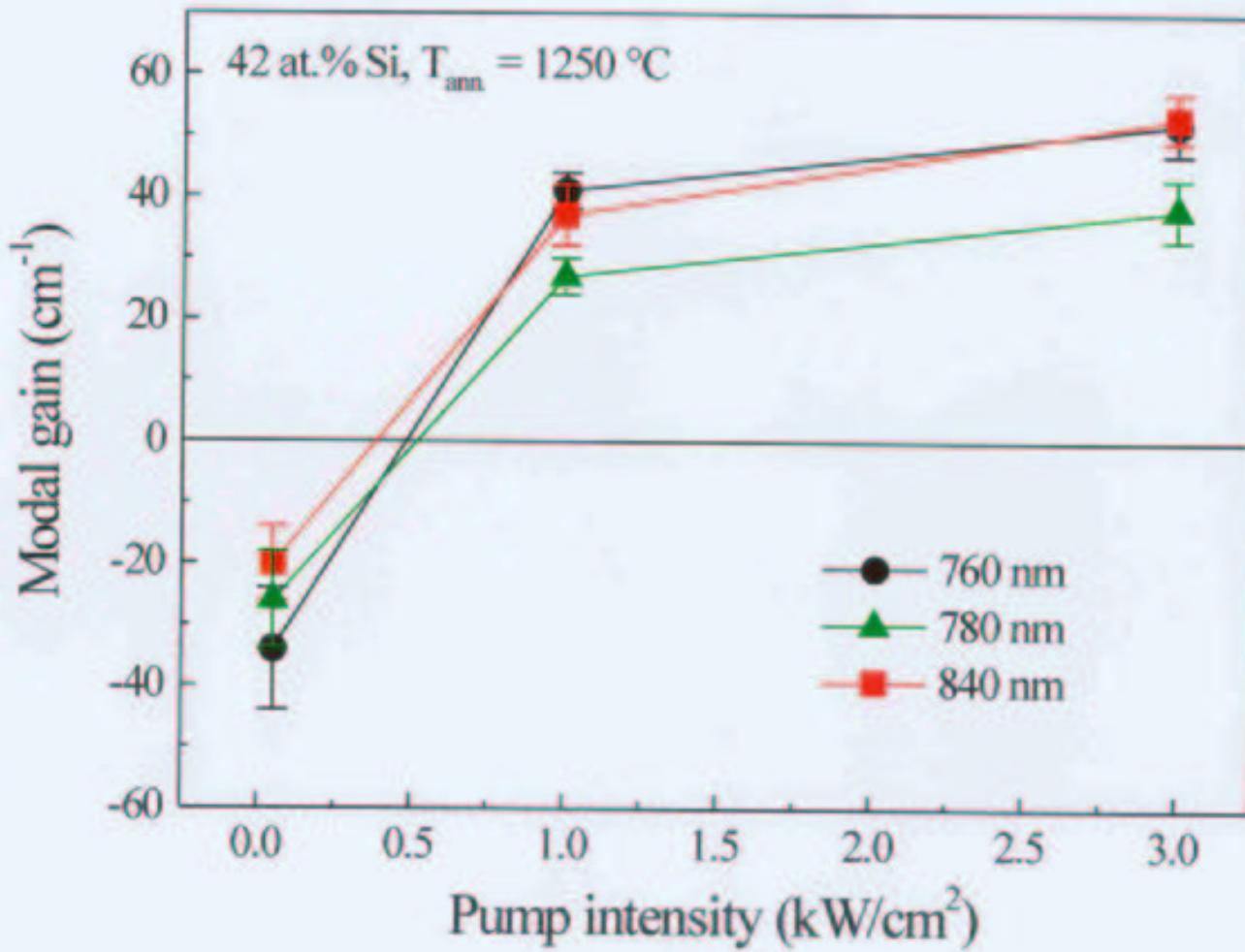
$$I_{ASE}(l) \propto \frac{I_{SPONT} \times \Omega}{g - \alpha} (e^{(g - \alpha)l} - 1)$$



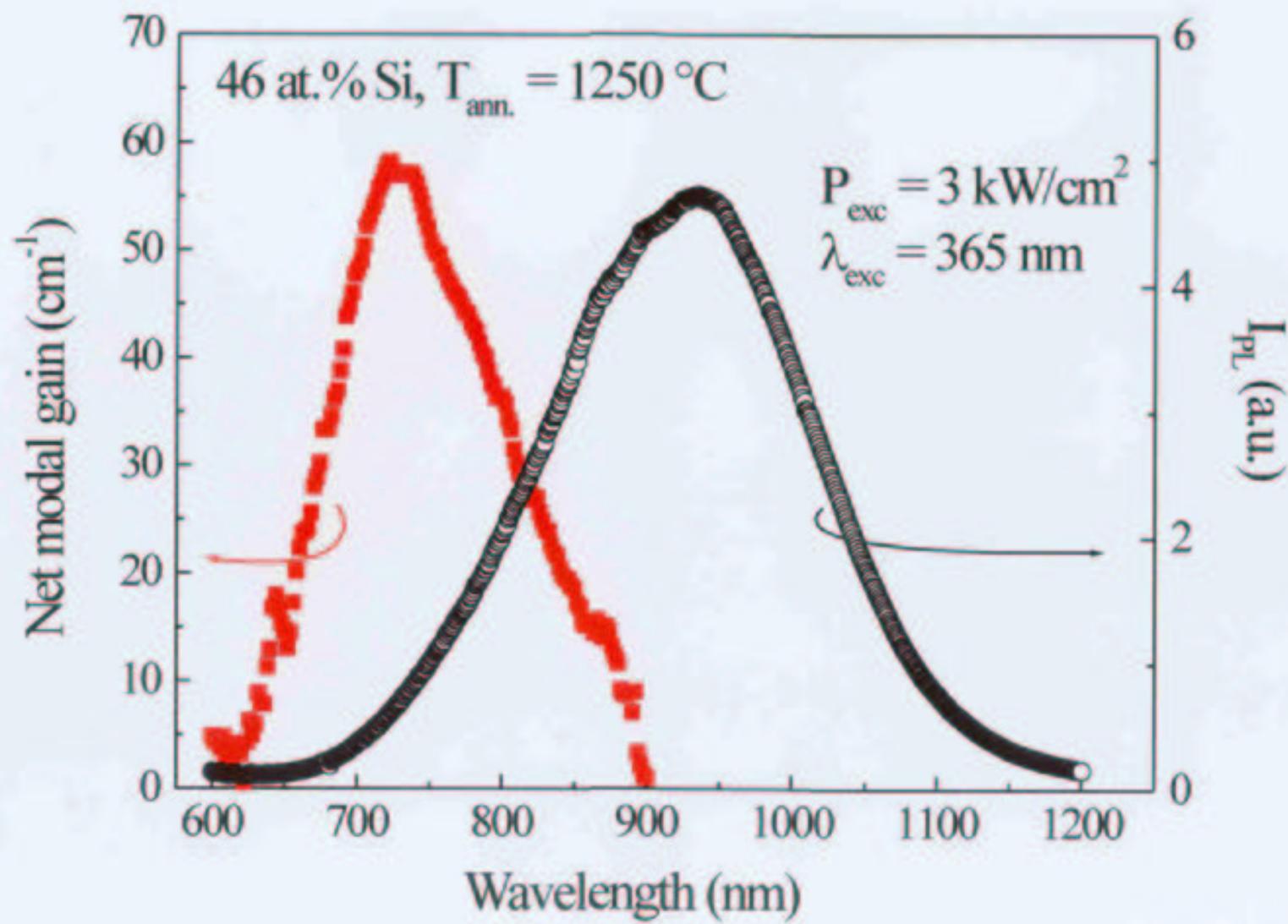
VSL measurements on Si nc

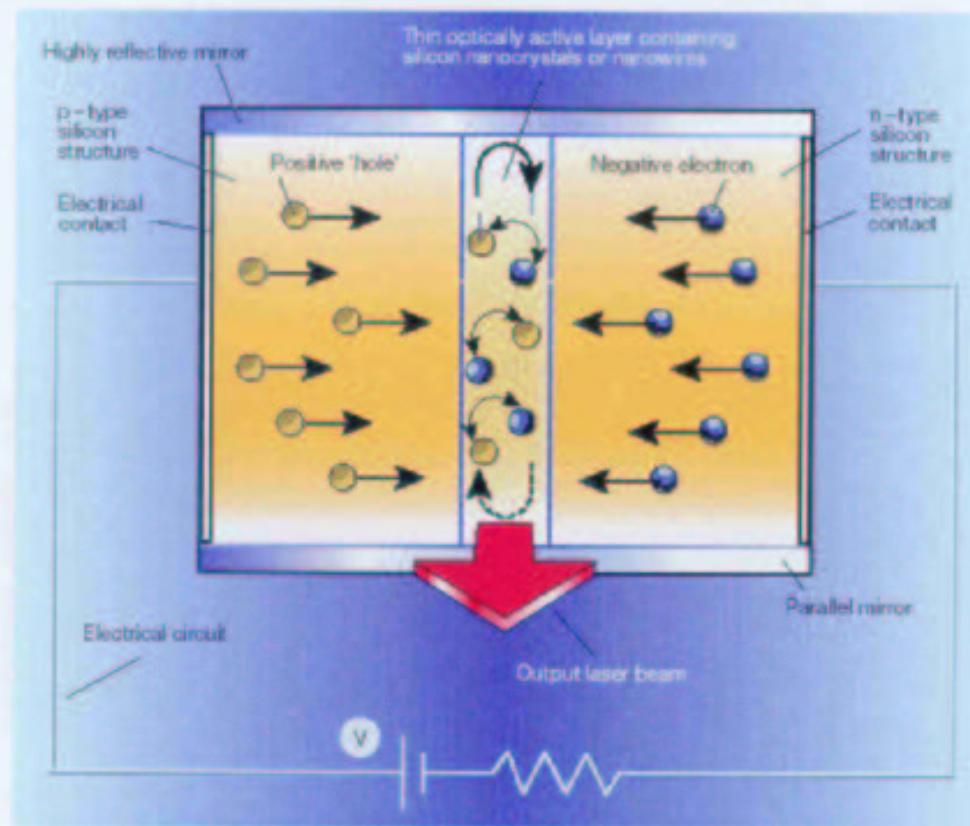


VSL measurements on Si nc

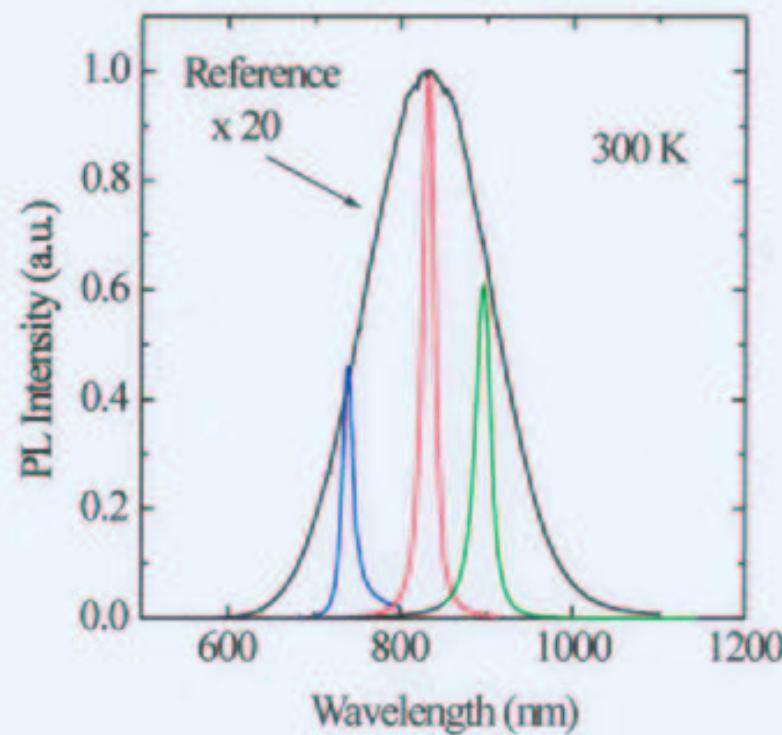
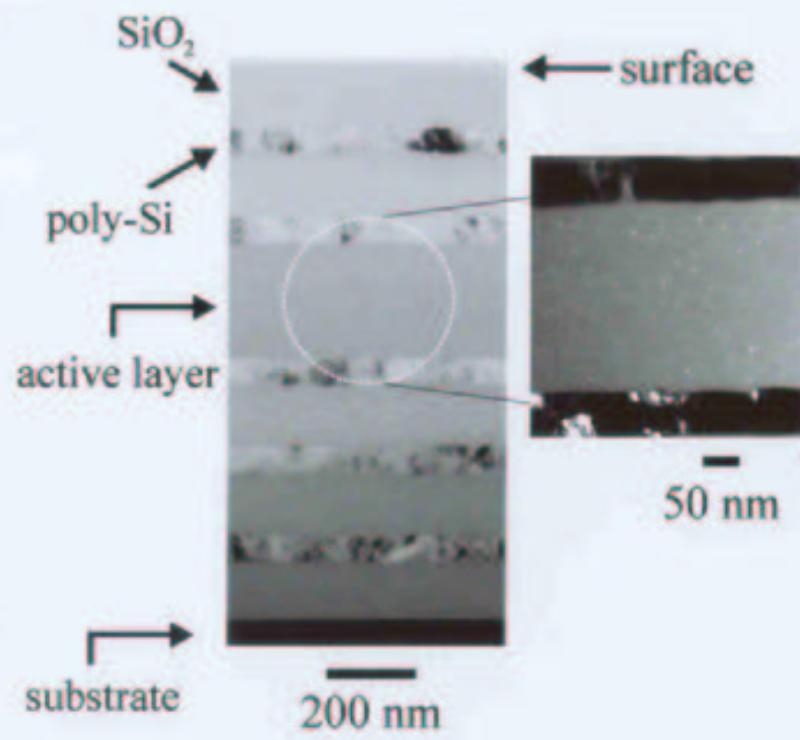


Modal gain spectrum vs. PL spectrum





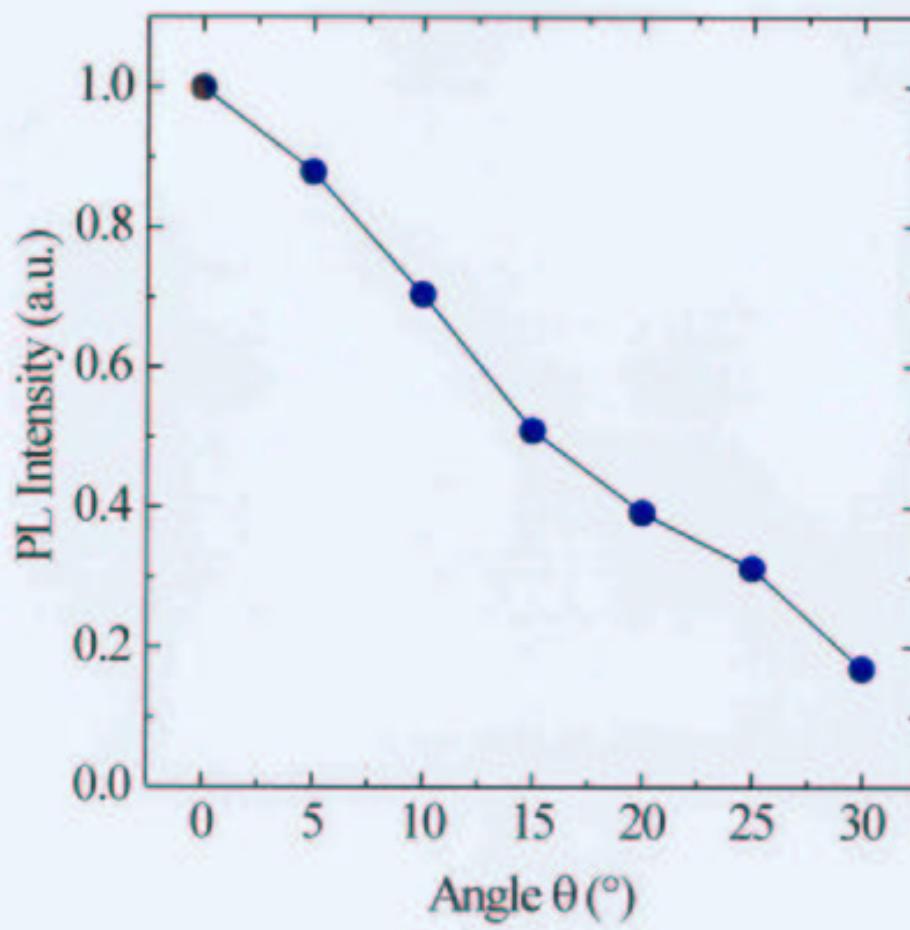
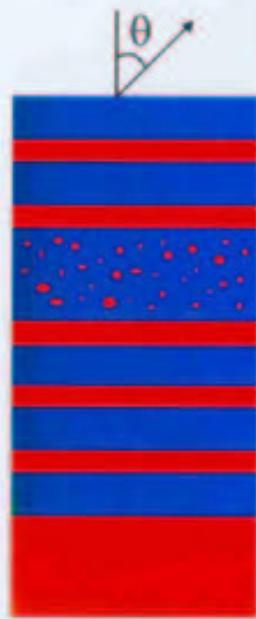
OPTICAL MICROCAVITIES BASED ON Si NANOCRYSTALS



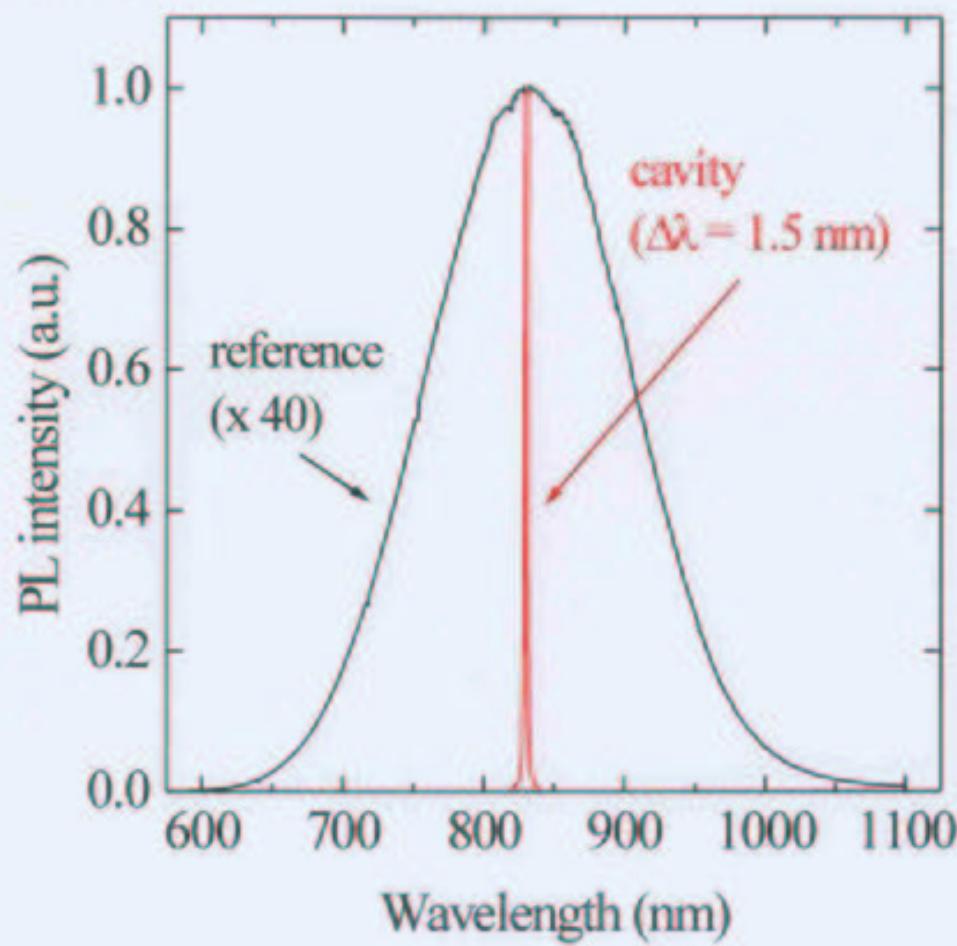
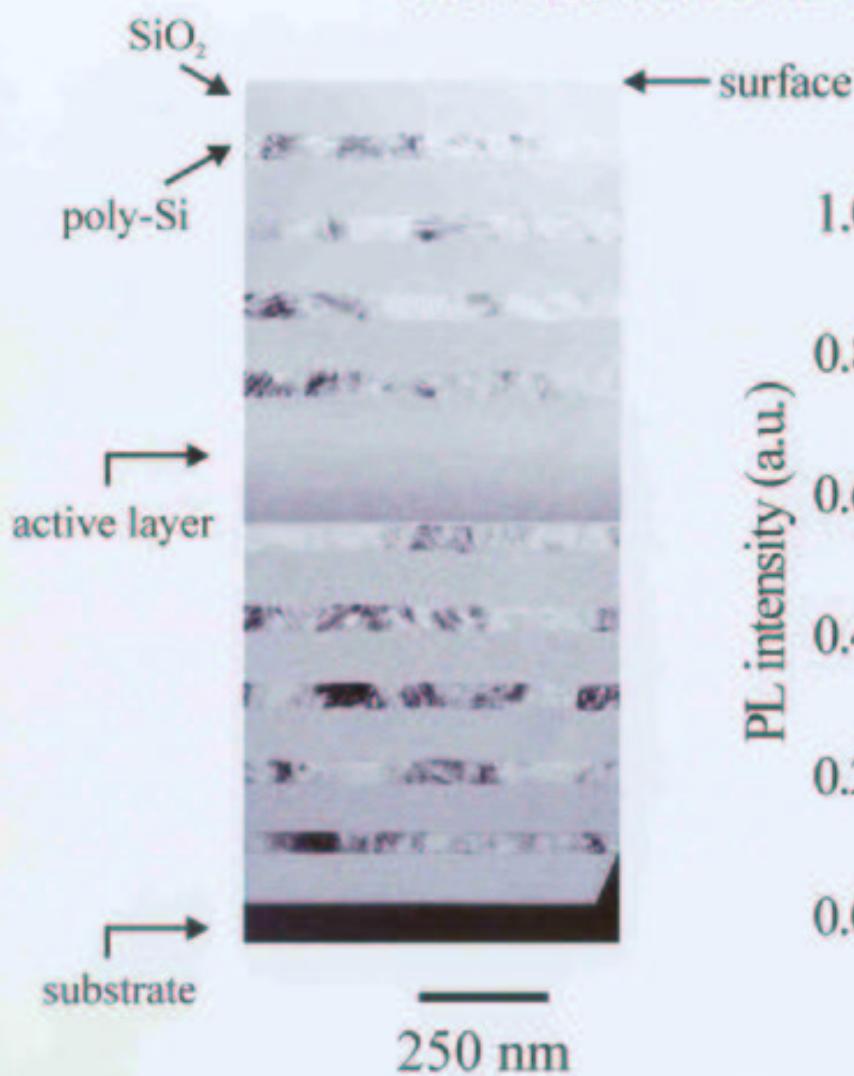
$$\Delta\lambda \sim 14 \text{ nm}$$

$$Q = \lambda / \Delta\lambda \sim 80$$

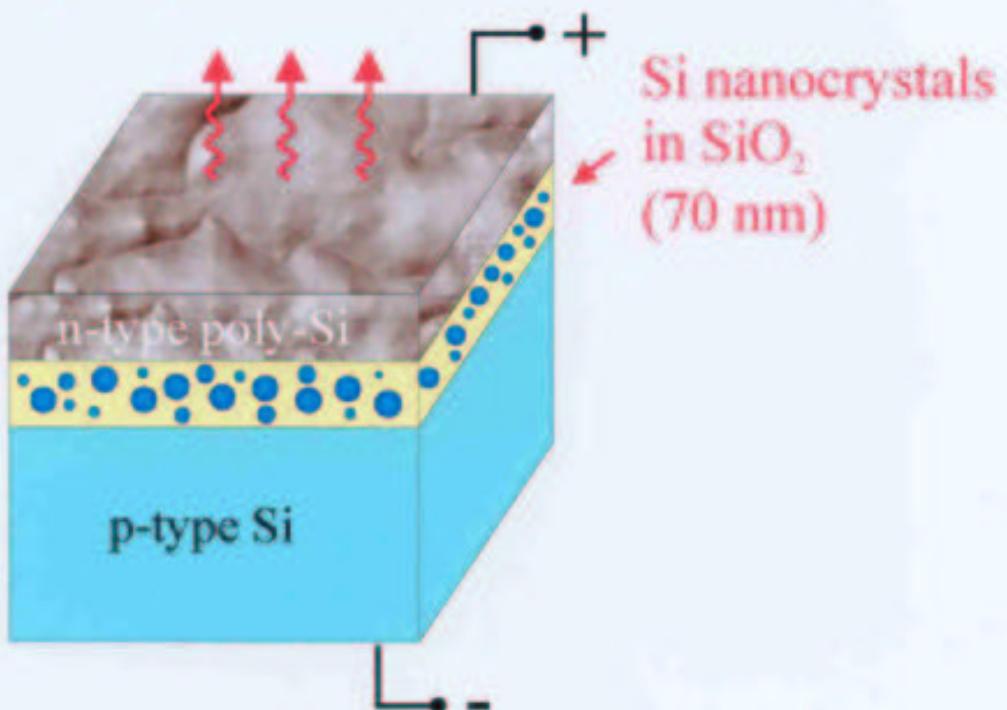
DIRECTIONALITY PROPERTIES OF Si nc-BASED MICROCAVITIES



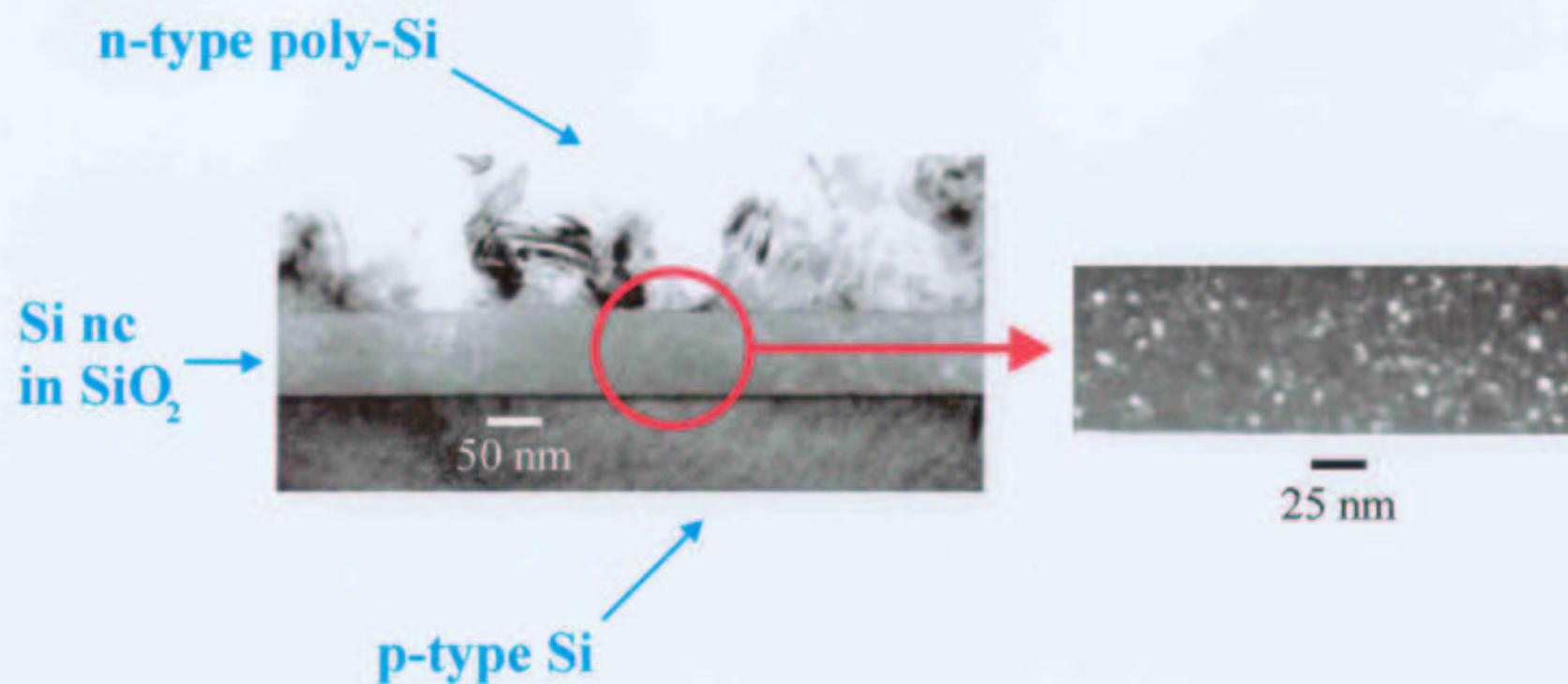
Optical microcavities based on Si nc: the effect of the reflectivity of the mirrors



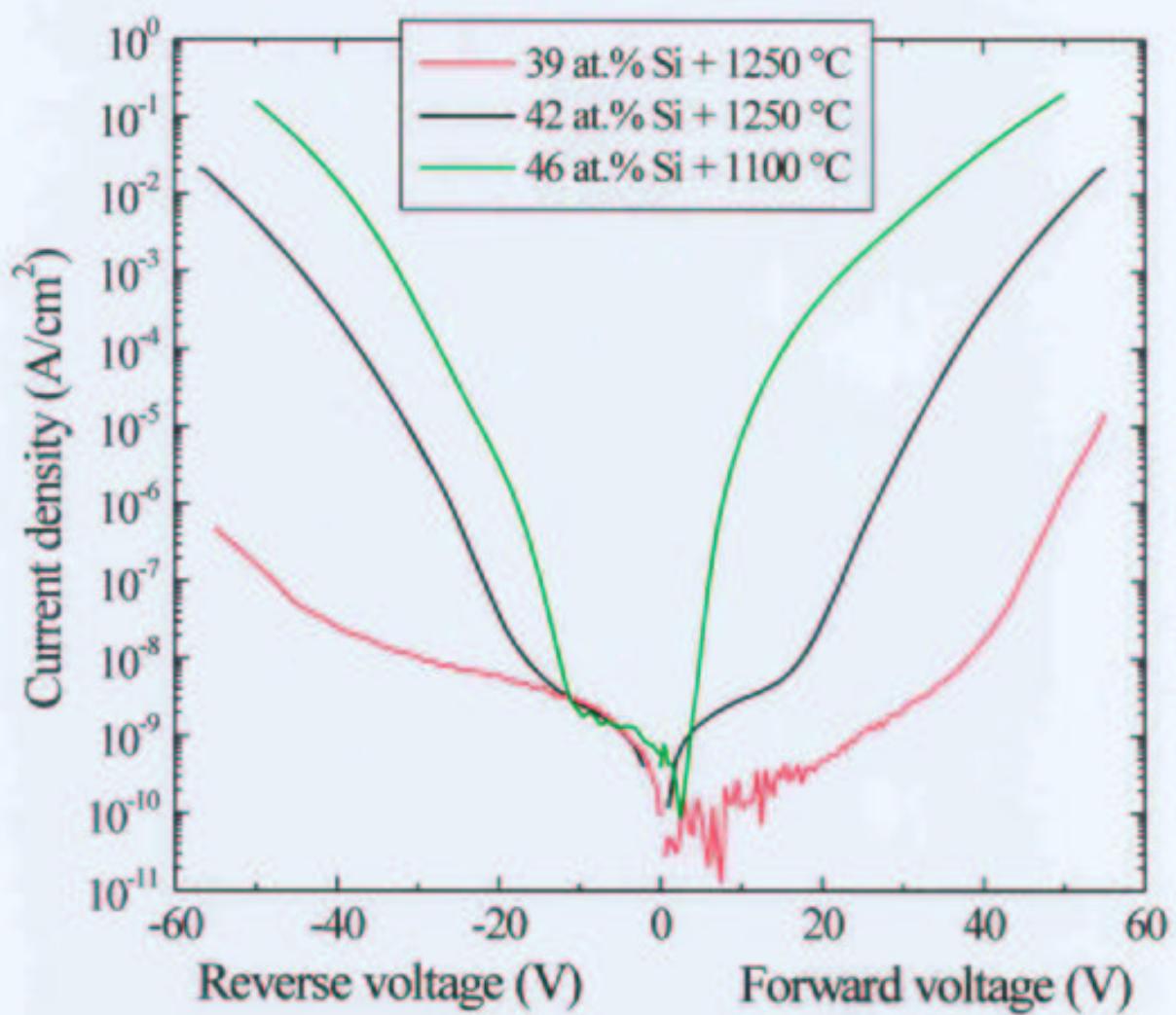
Electroluminescent MOS



Electroluminescent MOS



I-V characteristics of Si nc devices

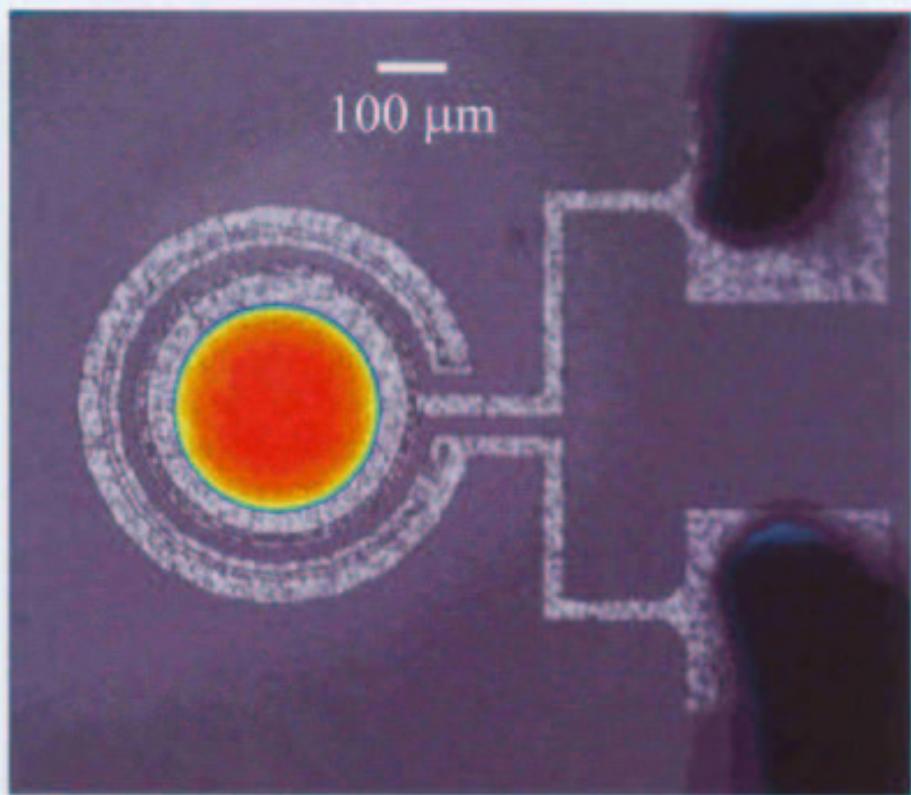


*

Electroluminescent MOS based on Si nc

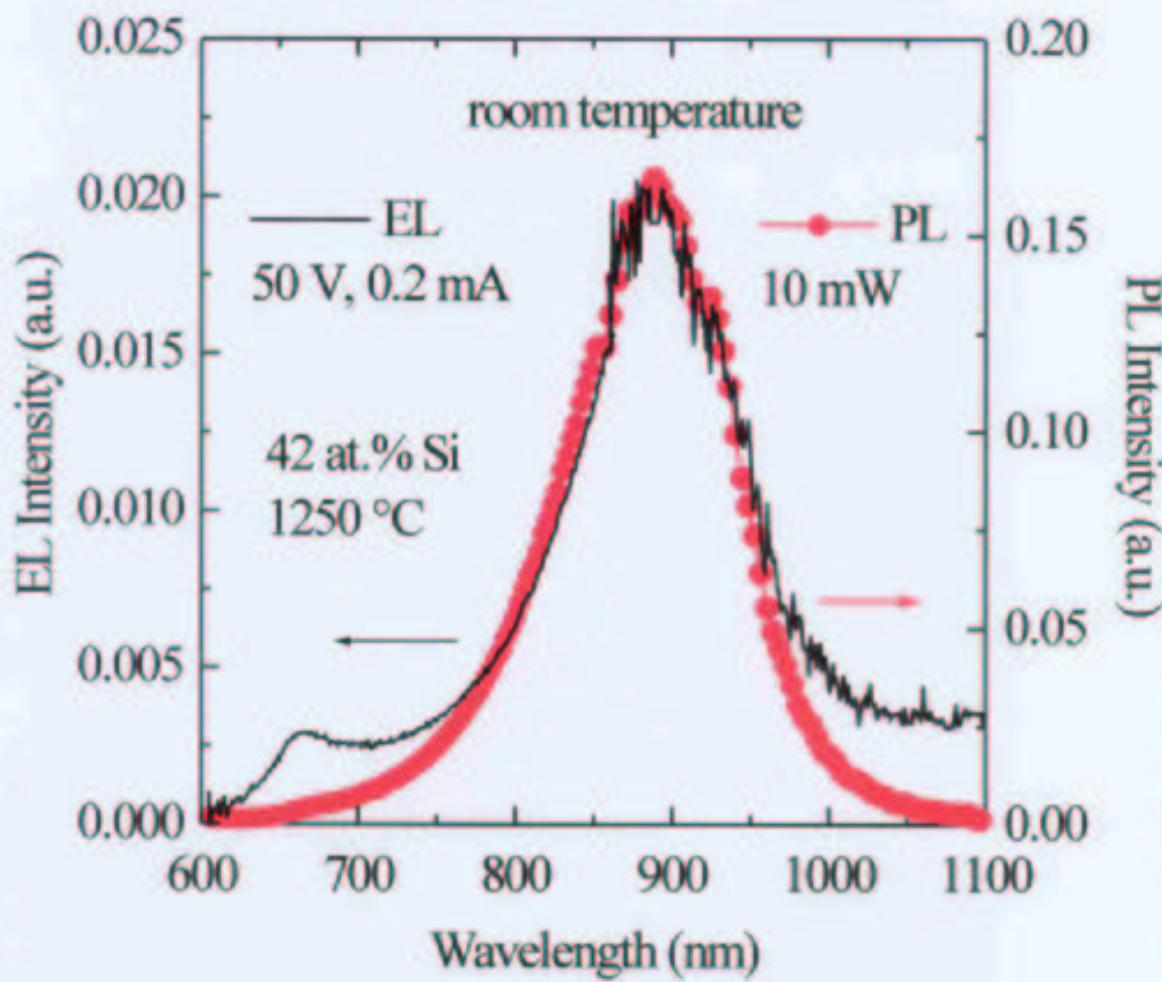
Emission
Microscopy

46 at.% Si
1100 °C

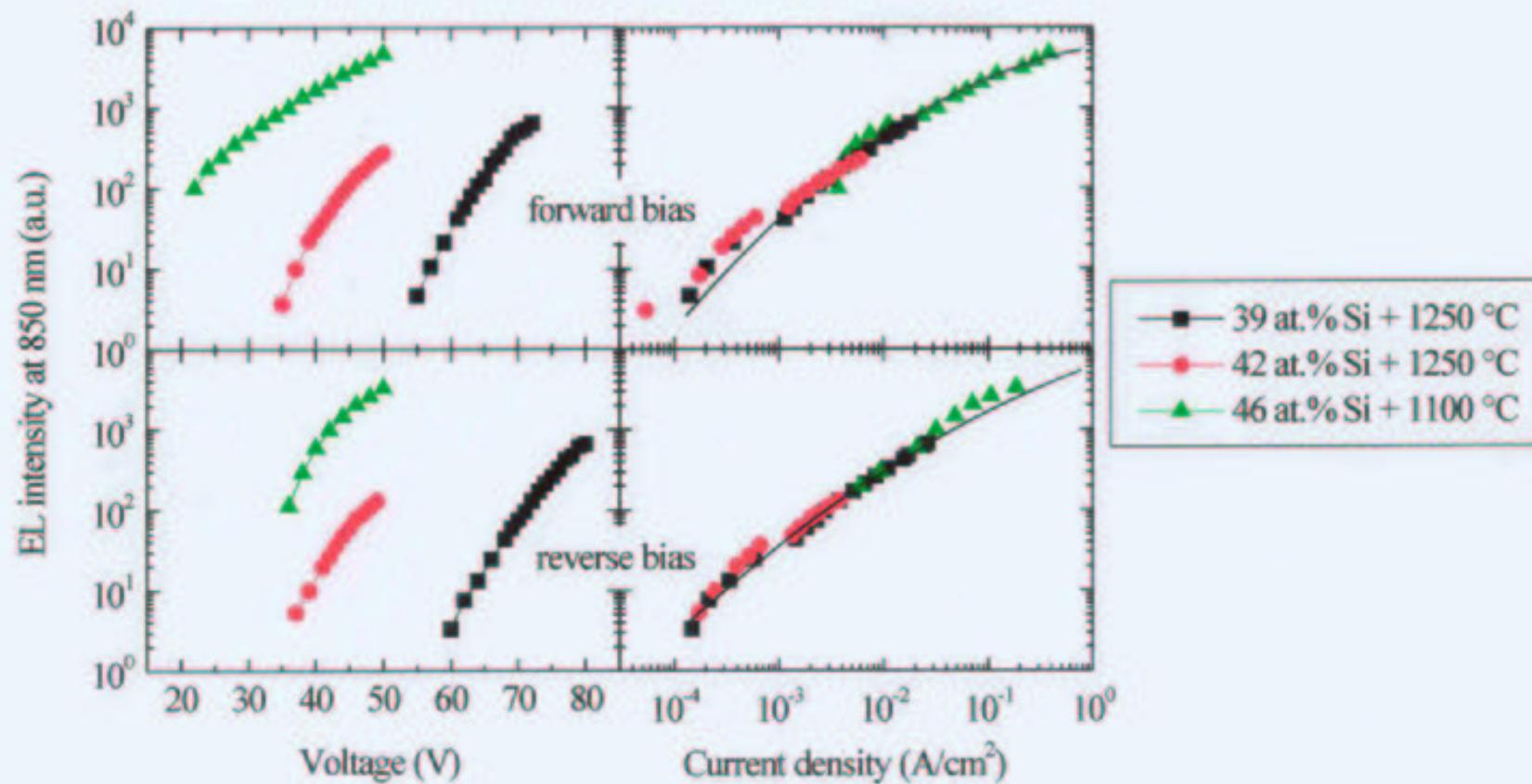


25 V
1 mA/cm²

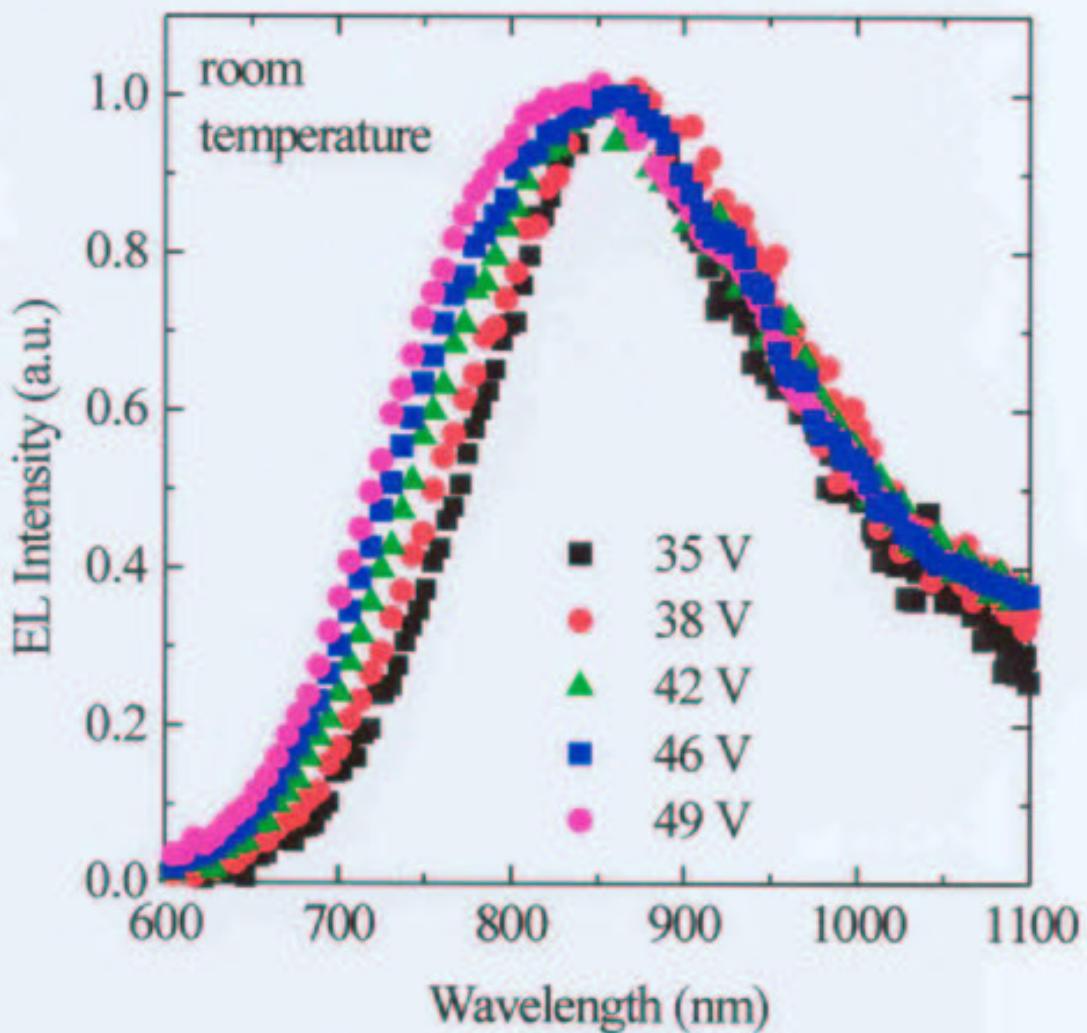
Comparison between EL and PL of Si nc



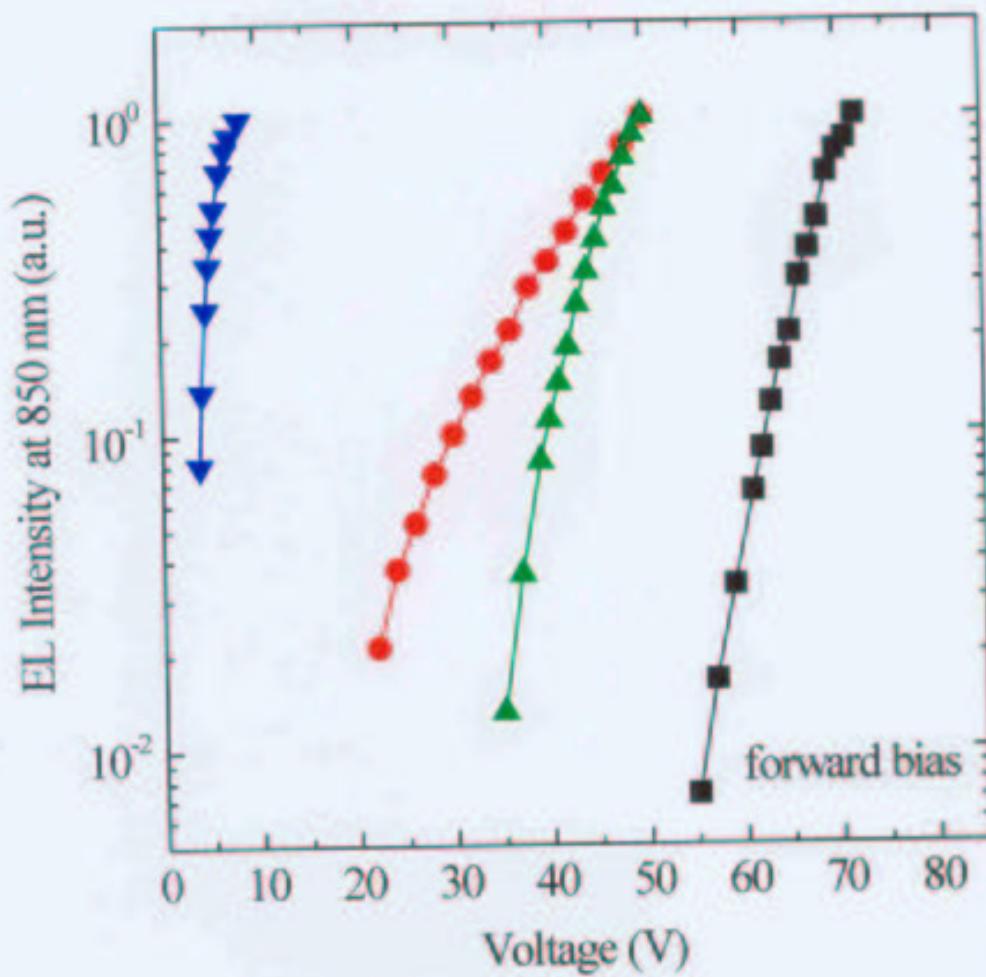
EL intensity vs. voltage and current density for Si nc devices



Influence of the applied voltage on the EL peak shape of Si nc

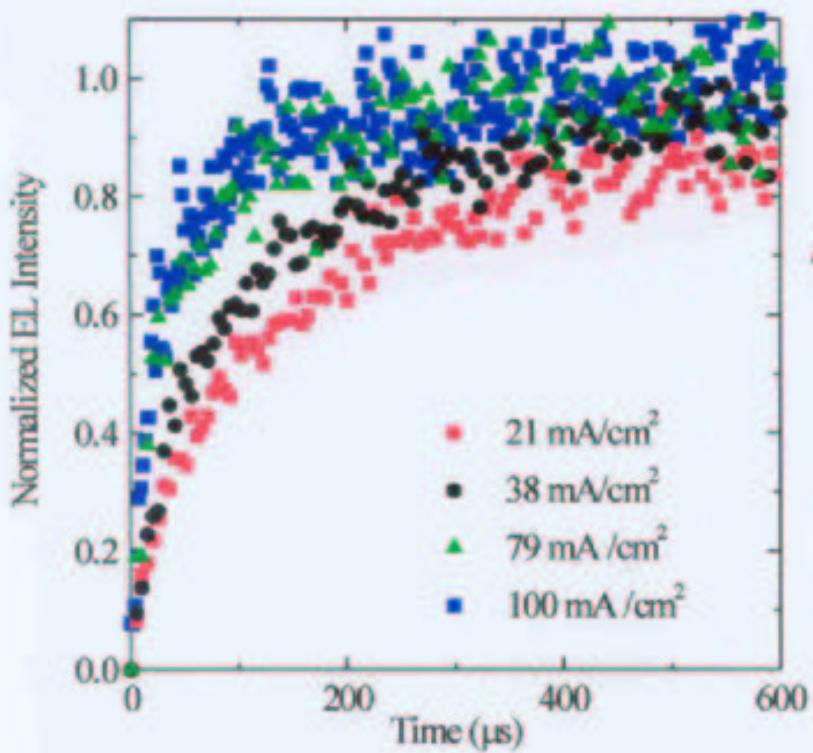


Si nc-based devices: optimization of the active layer



- 39 at.% Si, $T_{\text{ann}} = 1250 \text{ }^\circ\text{C}$, 75 nm
- ▲ 42 at.% Si, $T_{\text{ann}} = 1250 \text{ }^\circ\text{C}$, 75 nm
- 46 at.% Si, $T_{\text{ann}} = 1100 \text{ }^\circ\text{C}$, 75 nm
- ▼ 46 at.% Si, $T_{\text{ann}} = 1100 \text{ }^\circ\text{C}$, 25 nm

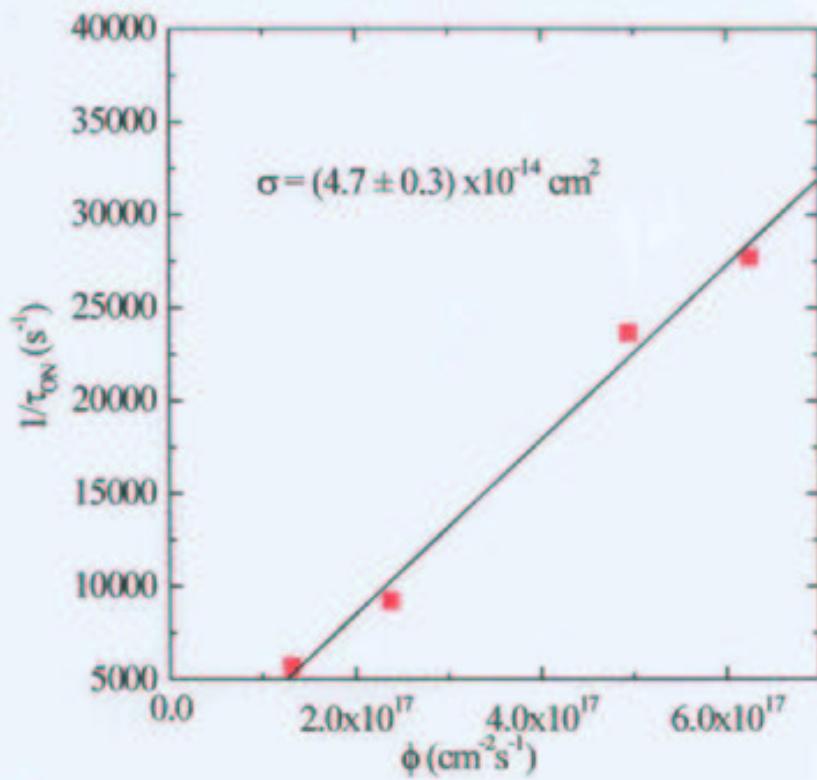
Cross section for Si nc excitation in Si nc based devices



$$I(t) = I_0 \left\{ 1 - \exp \left[- \left(\sigma \varphi + \frac{1}{\tau} \right) t \right] \right\}$$

$$\frac{1}{\tau_{on}} = \sigma \varphi + \frac{1}{\tau}$$

46 at.% Si
1100°C
25 nm



Er-doped Si nc from SiO_x films

a) SiO_x film deposition



PECVD
 $\text{SiH}_4 + \text{N}_2\text{O}$
 $T = 300^\circ\text{C}$

b) Si nc formation



thermal annealing
 N_2 ambient
 $T = 1250^\circ\text{C}$

c) Er ion implantation



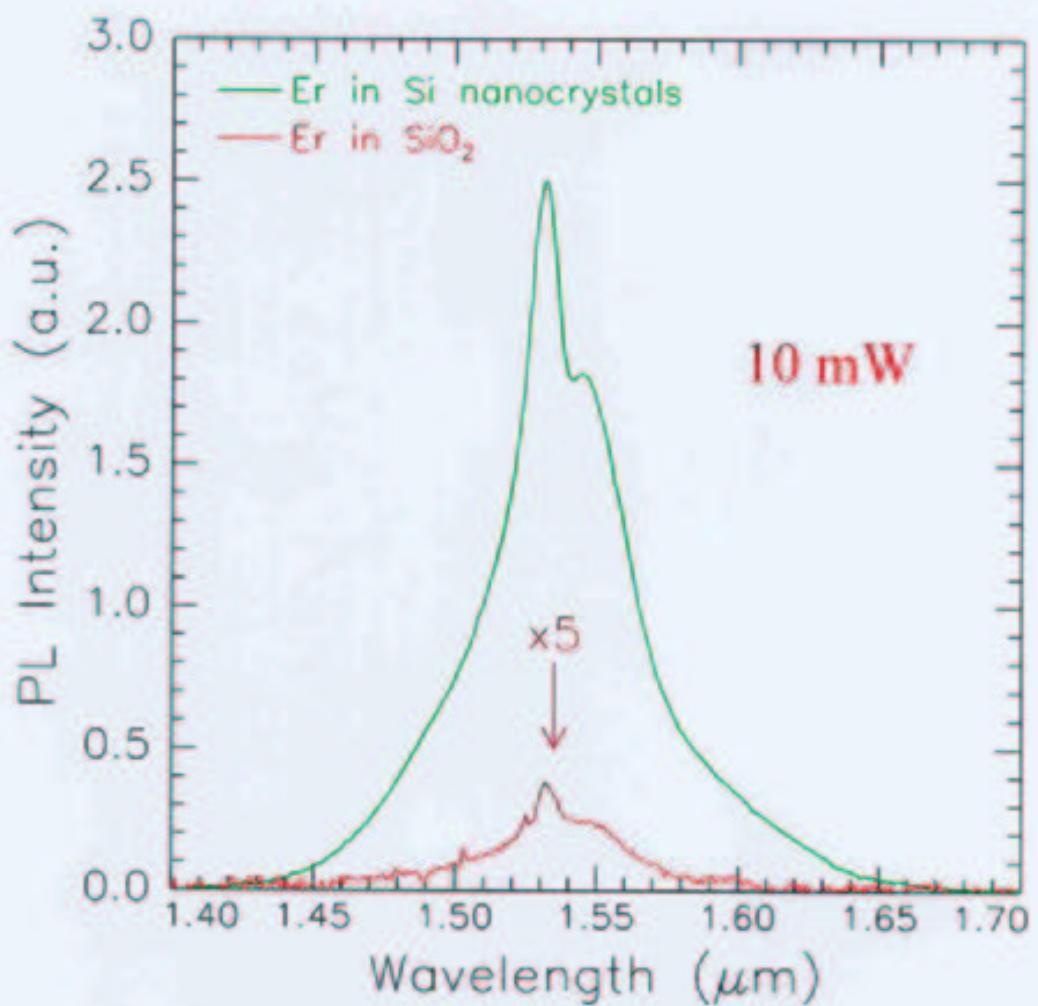
Er^+ multiple or single implants
($10^{19} - 10^{21} / \text{cm}^3$)

d) Er-doped Si nc formation

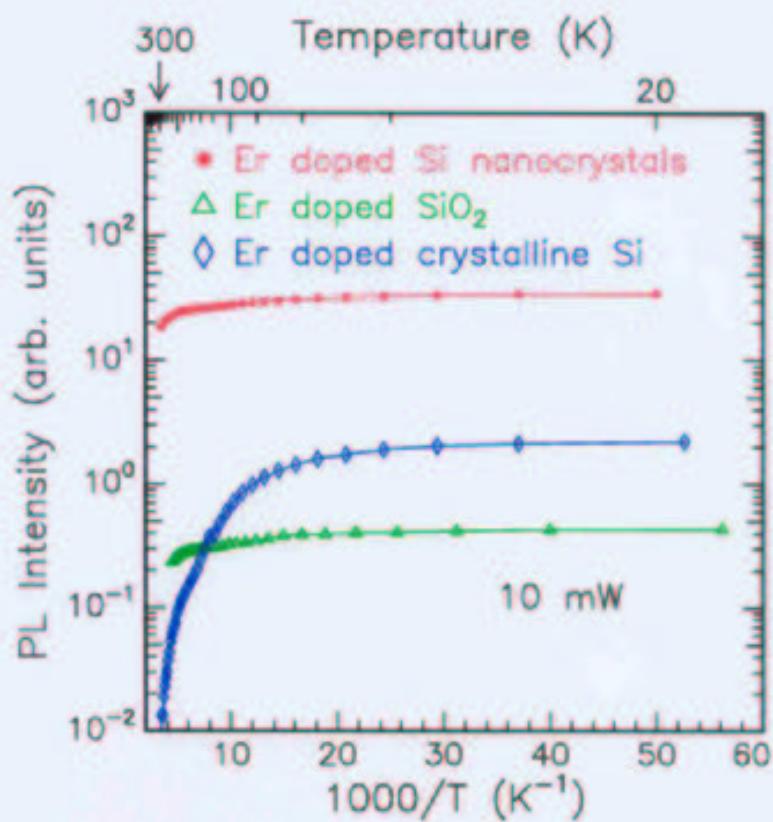
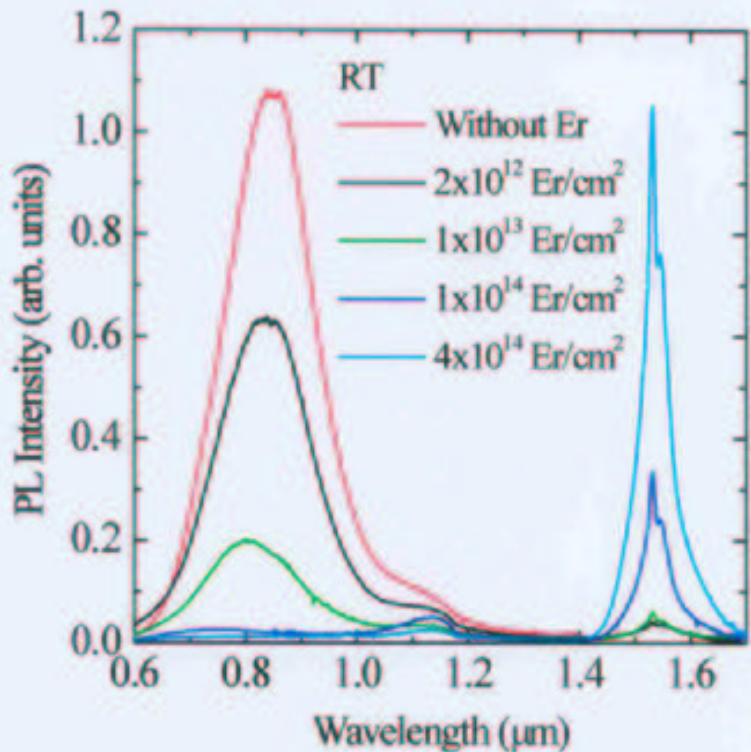


thermal annealing
 N_2 ambient
 $T = 900^\circ\text{C}$

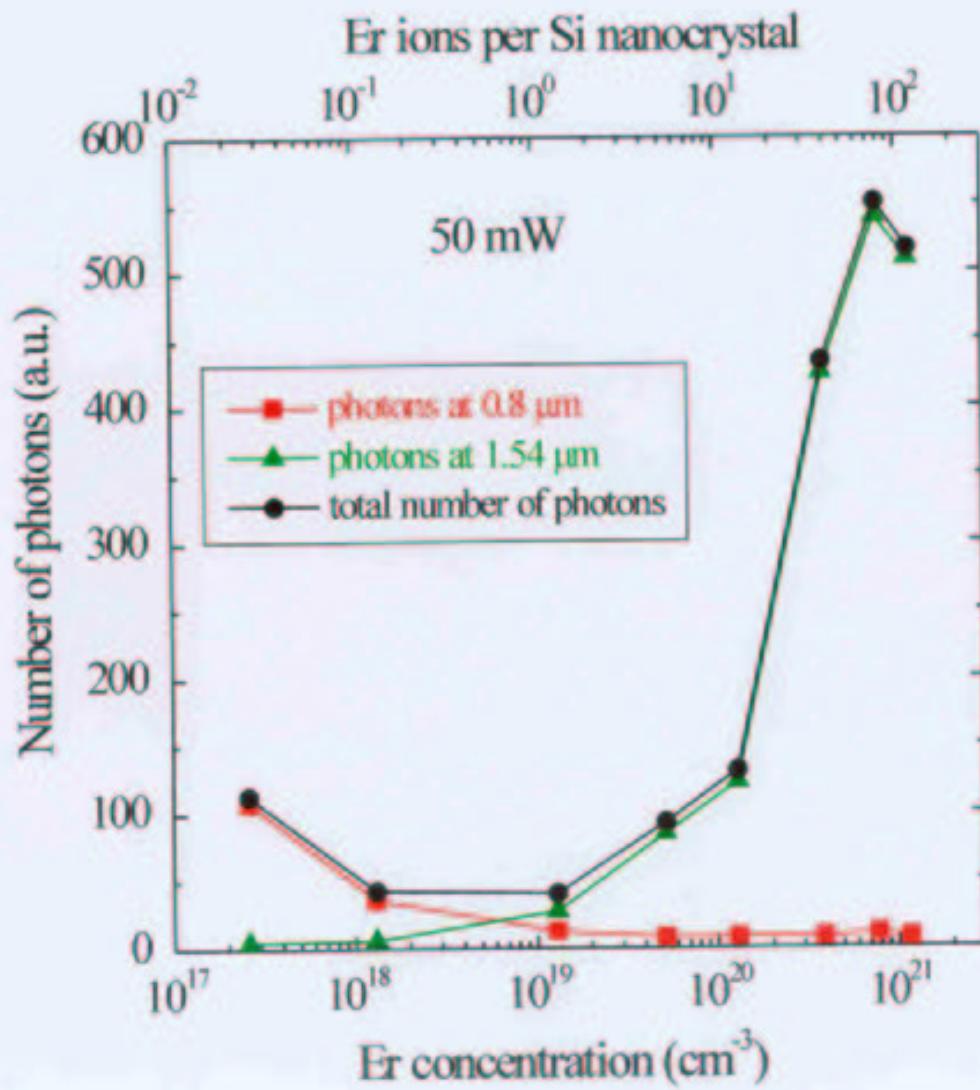
Er-doped Si nc: room temperature luminescence



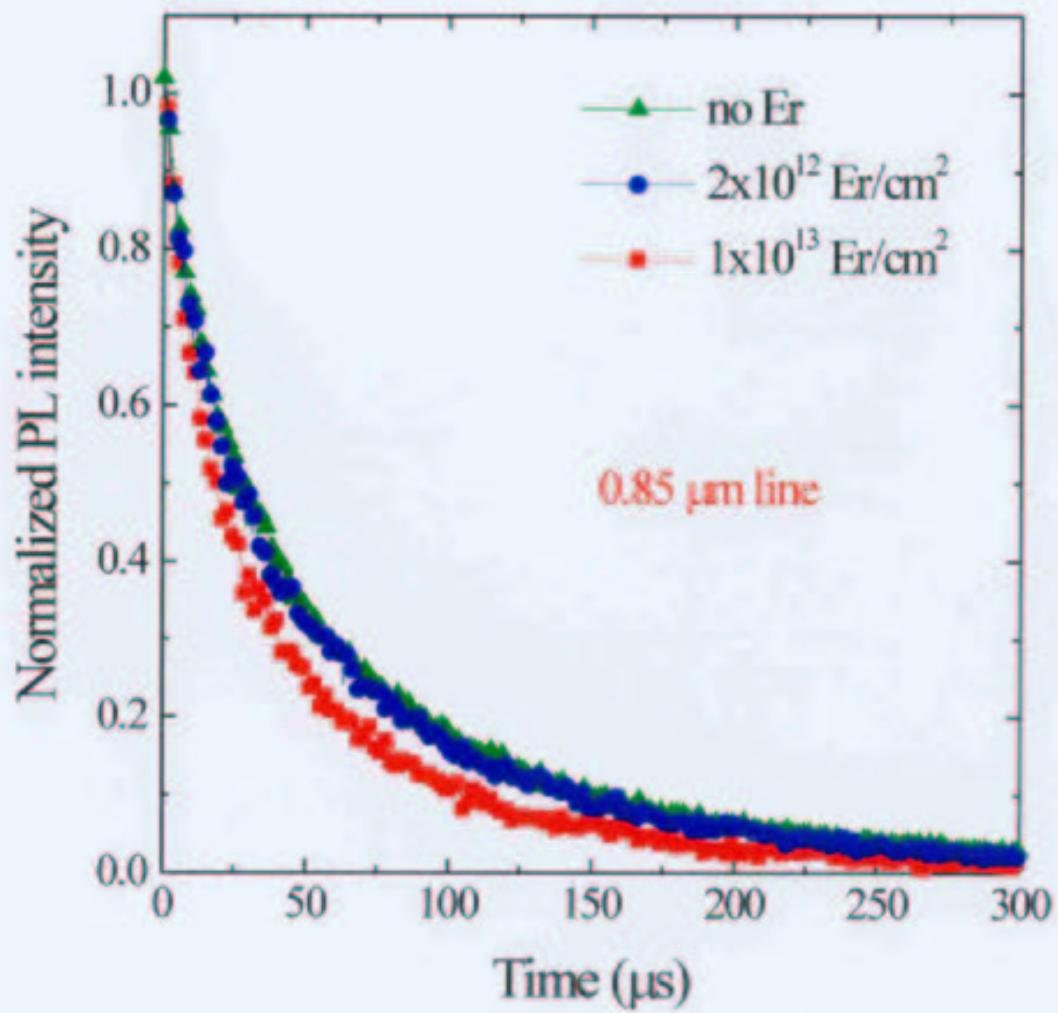
Luminescence from Er-doped Si-nc



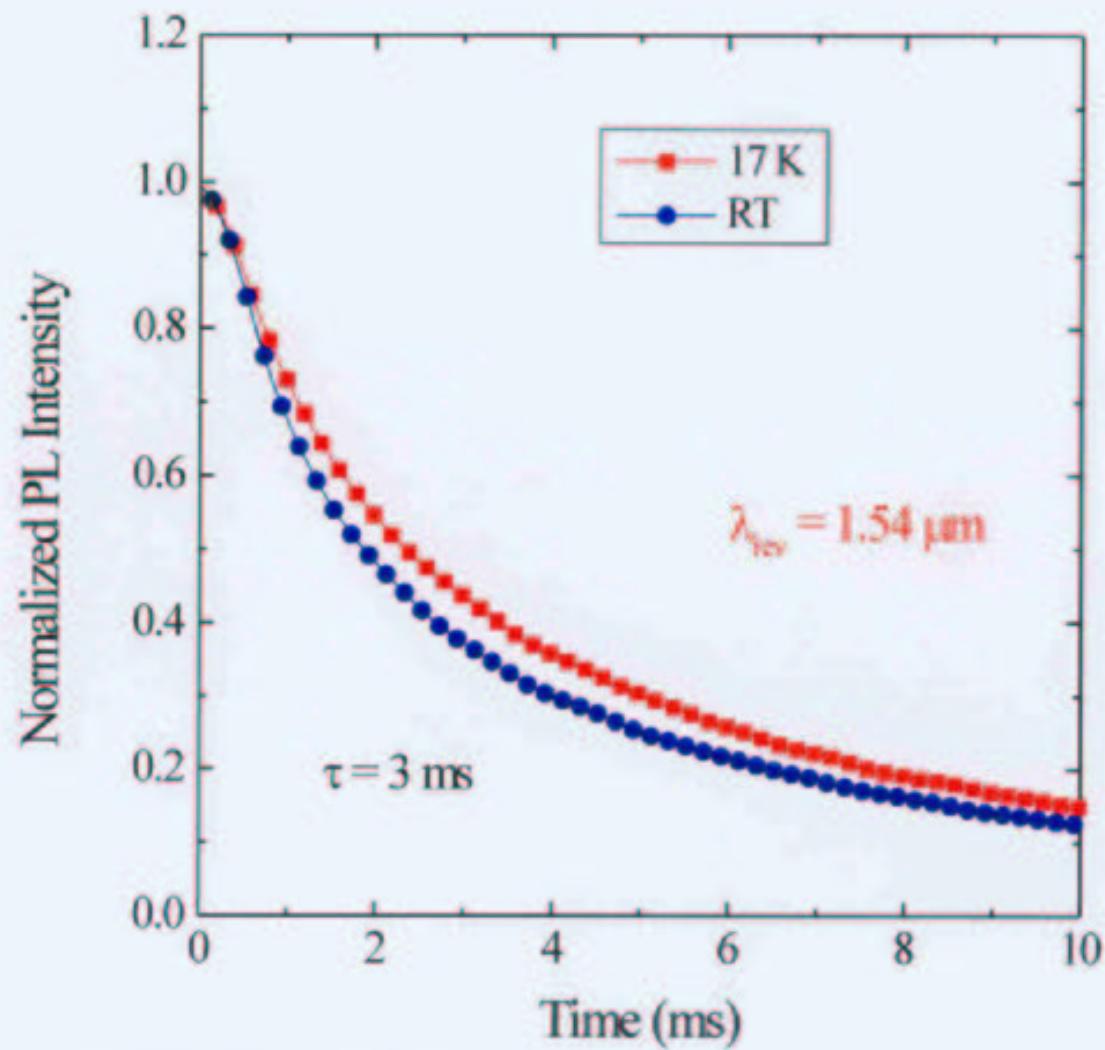
Energy transfer in Er-doped Si nc



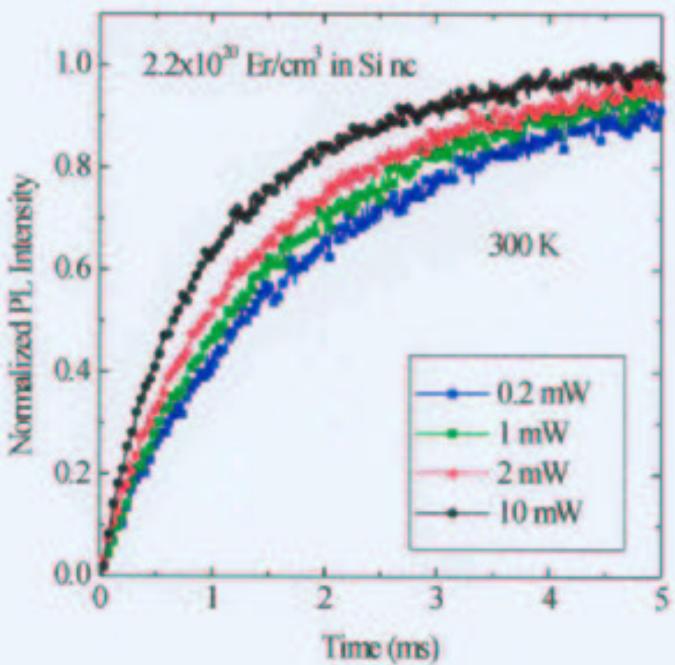
Er influence on the lifetime of Si nc



Effect of the temperature on the lifetime of Er-doped Si nc

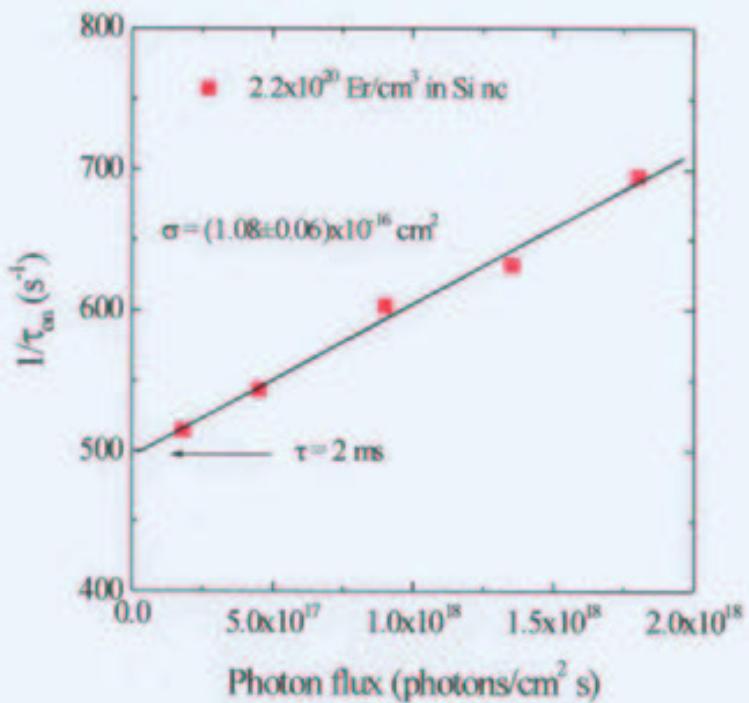


Cross section for Er excitation in Er doped Si nc

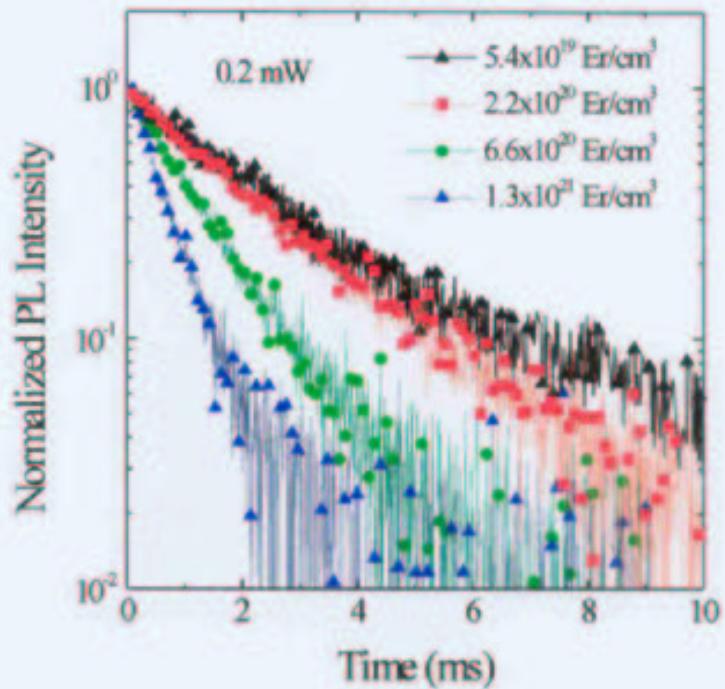
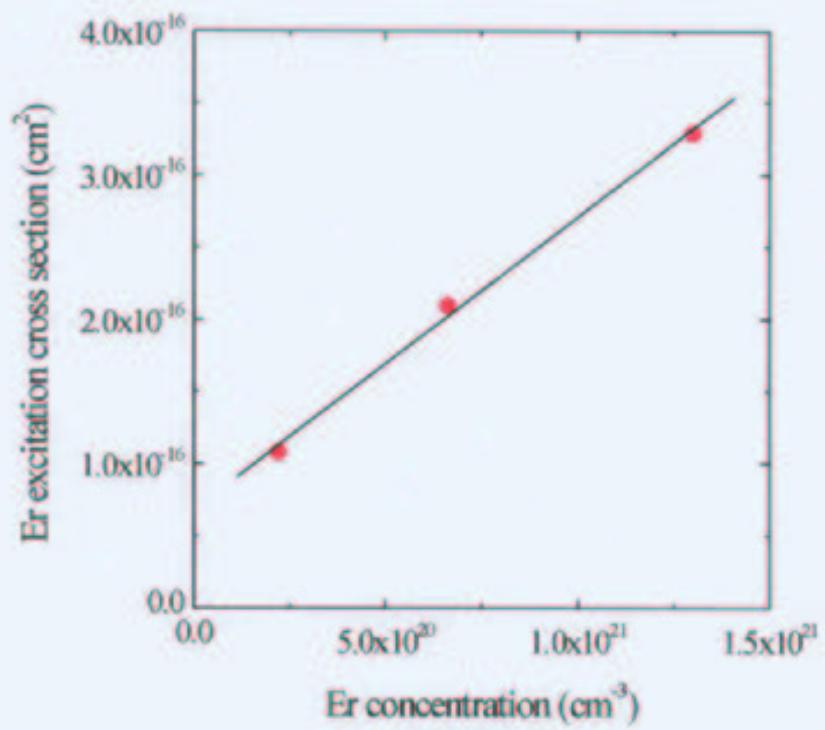


$$I(t) = I_0 \left\{ 1 - \exp \left[- \left(\sigma \varphi + \frac{1}{\tau} \right) t \right] \right\}$$

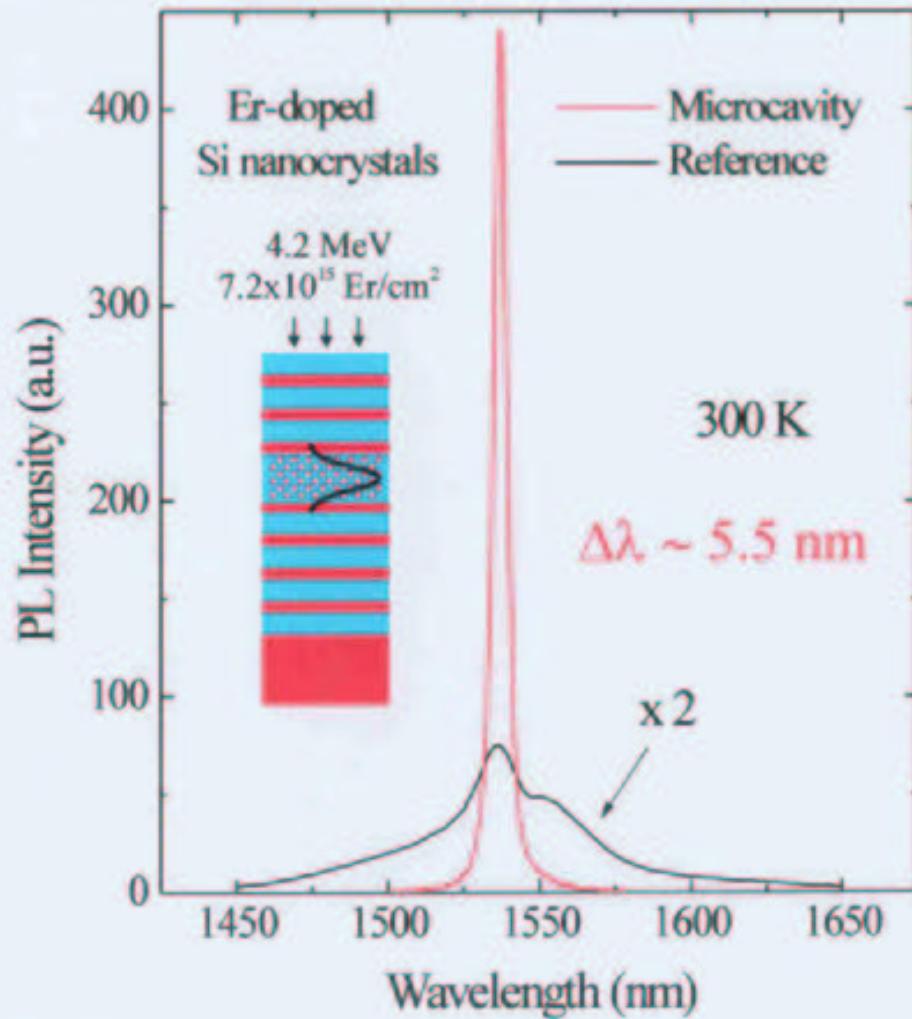
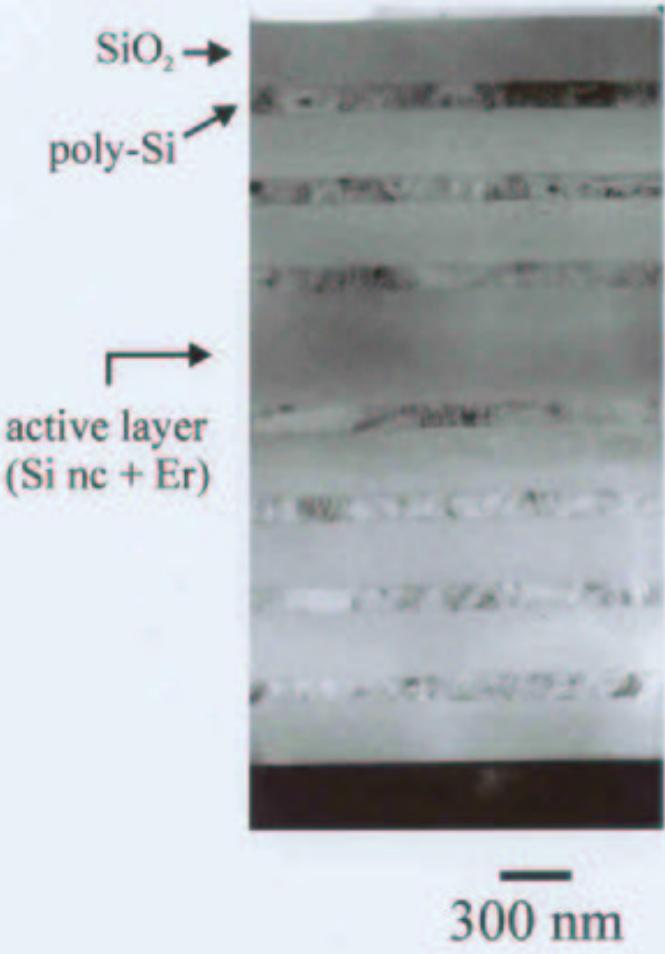
$$\frac{1}{\tau_{on}} = \sigma \varphi + \frac{1}{\tau}$$



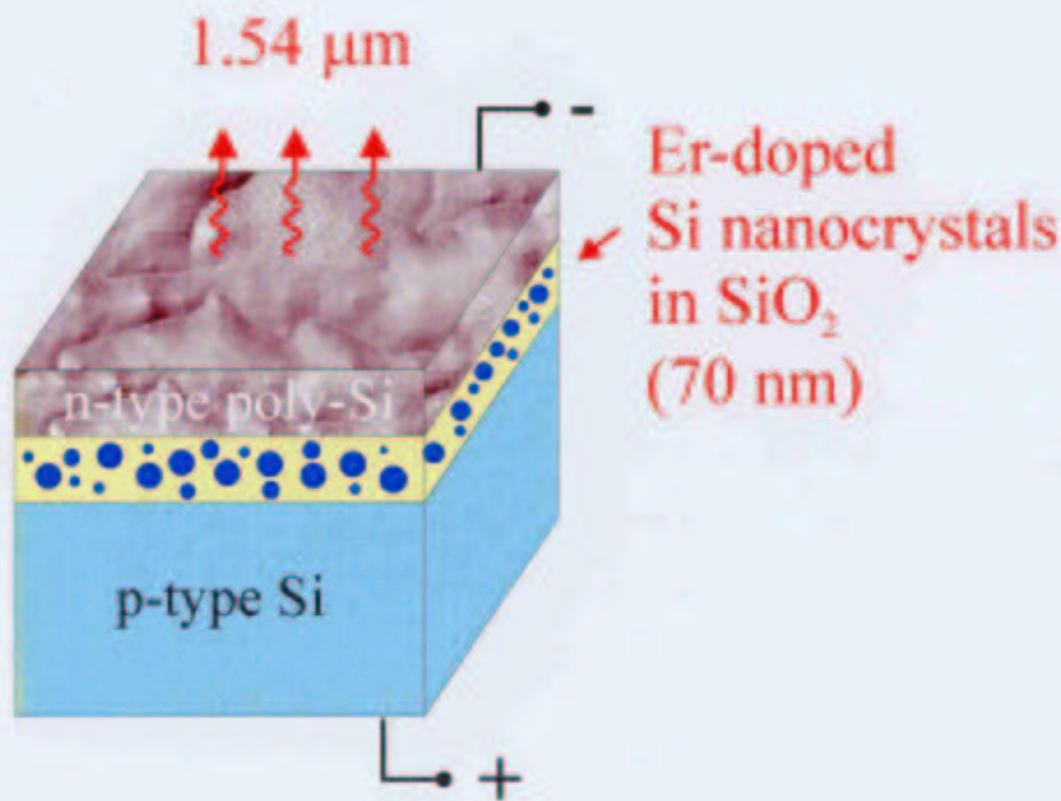
Effect of the Er concentration on σ and τ in Er doped Si nc



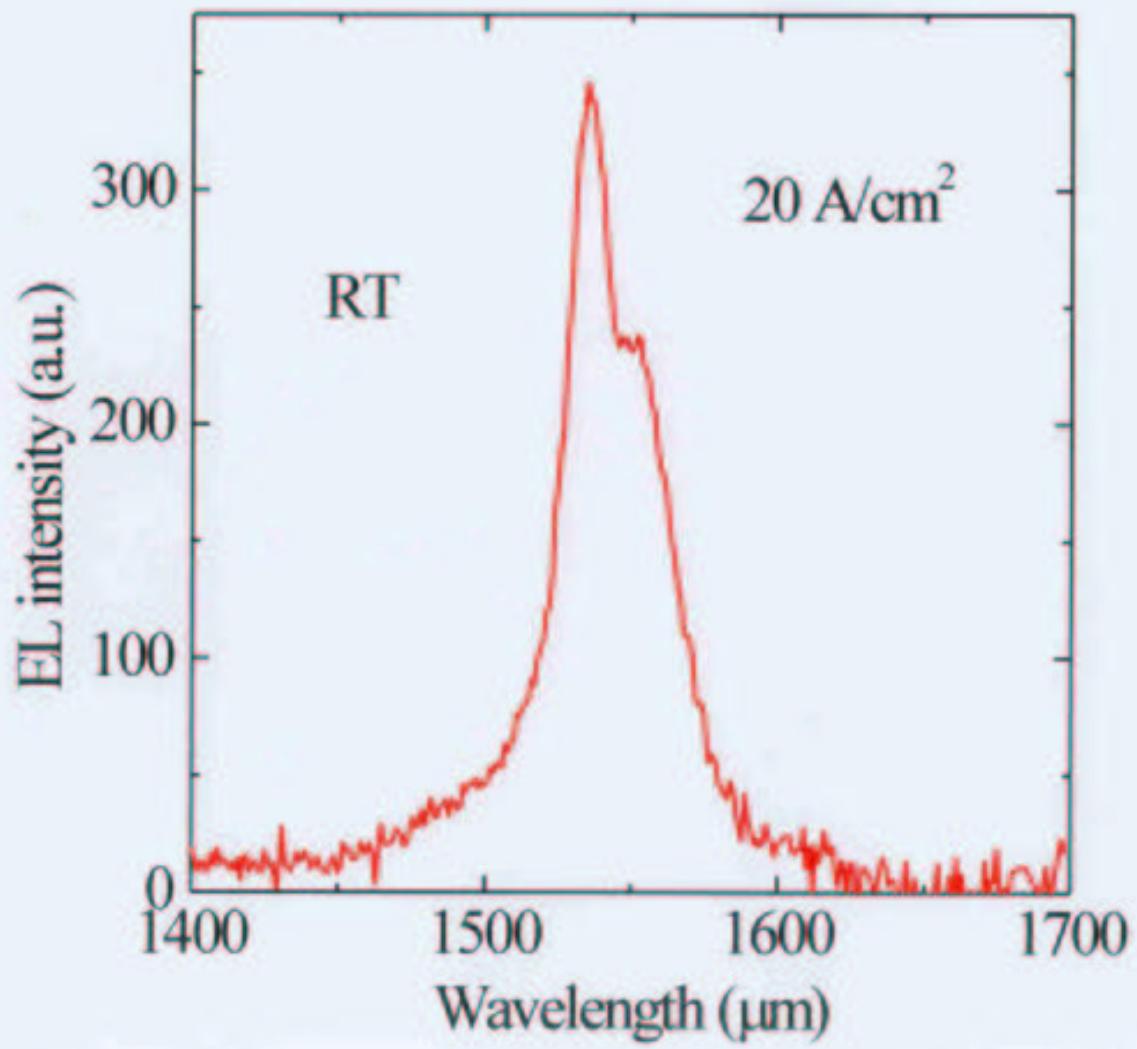
OPTICAL MICROCAVITIES BASED ON Er-DOPED Si-nc



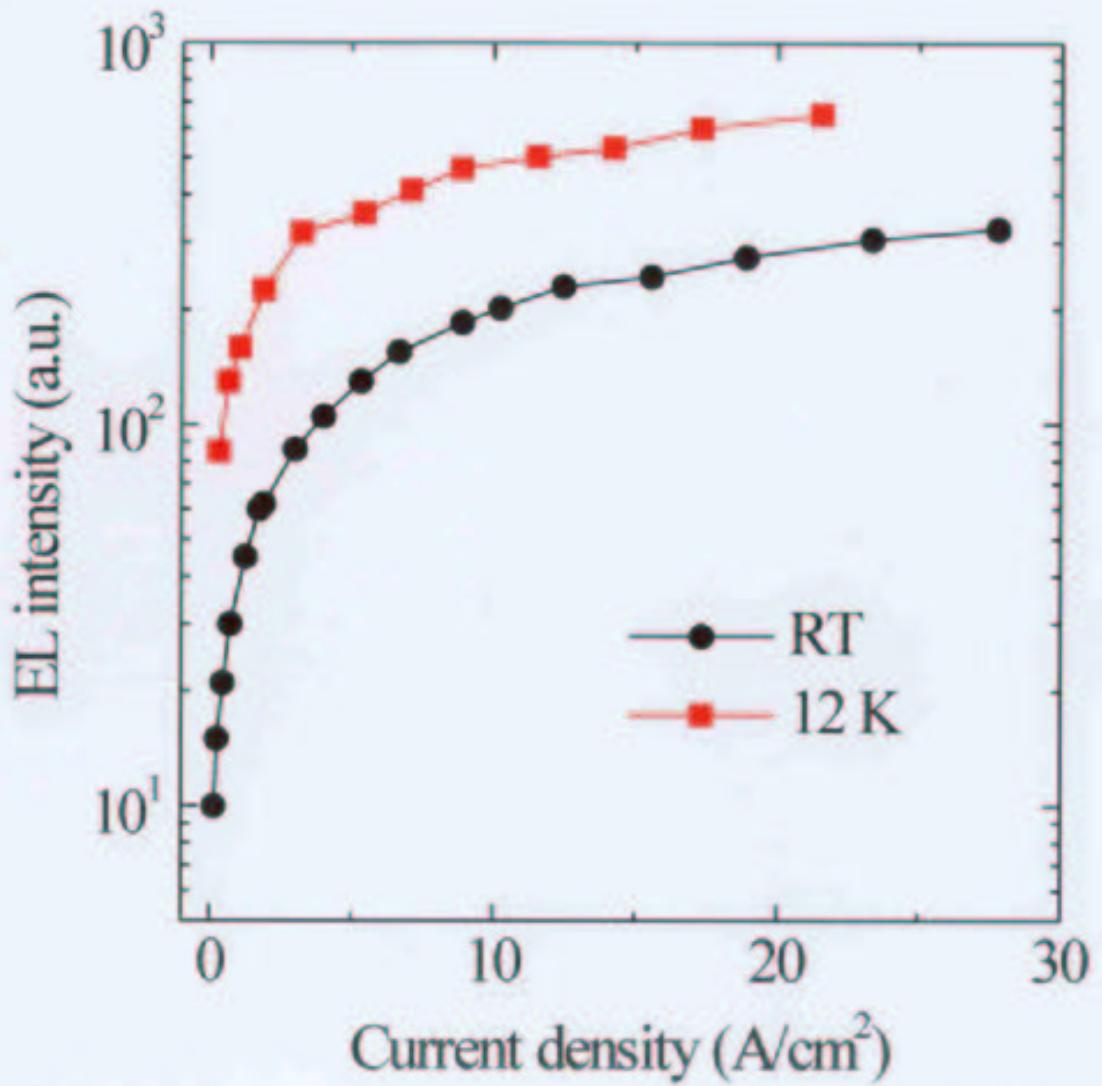
Electroluminescent MOS based on Er-doped Si nc



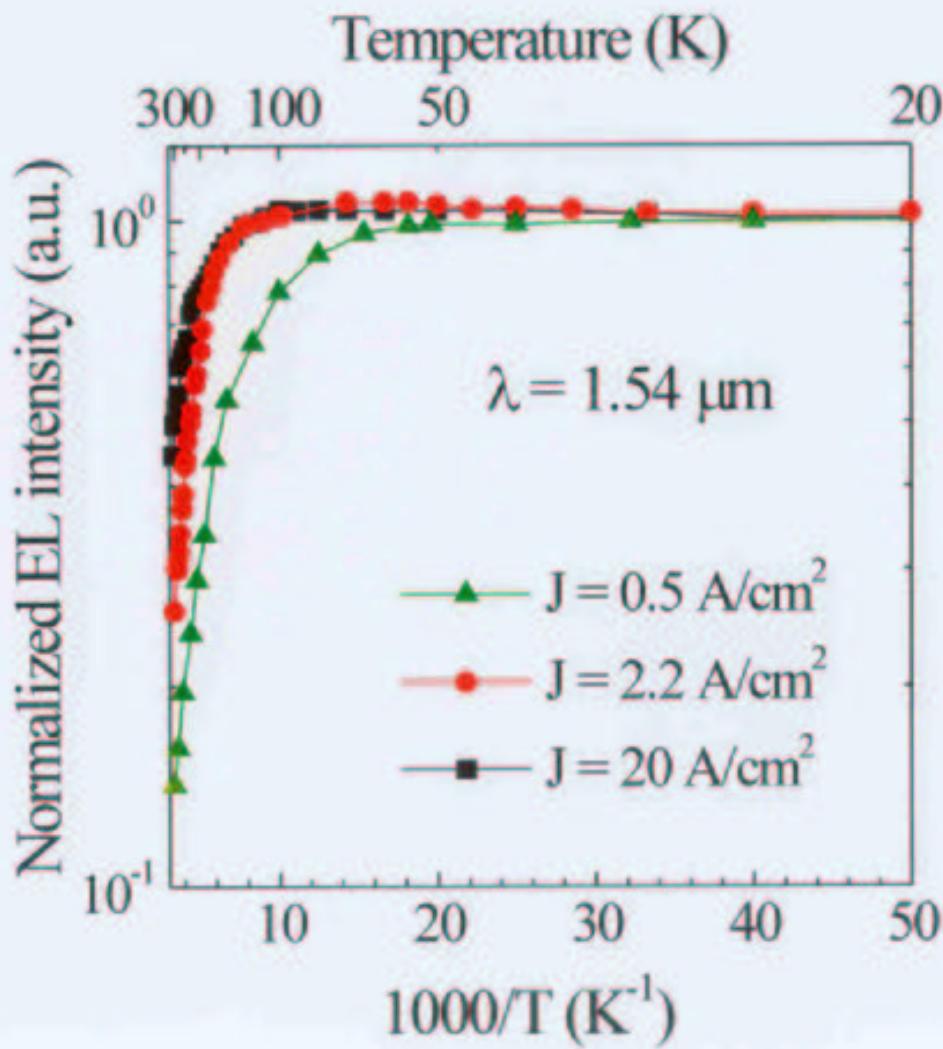
Room temperature electroluminescence from Er-doped Si nc based devices



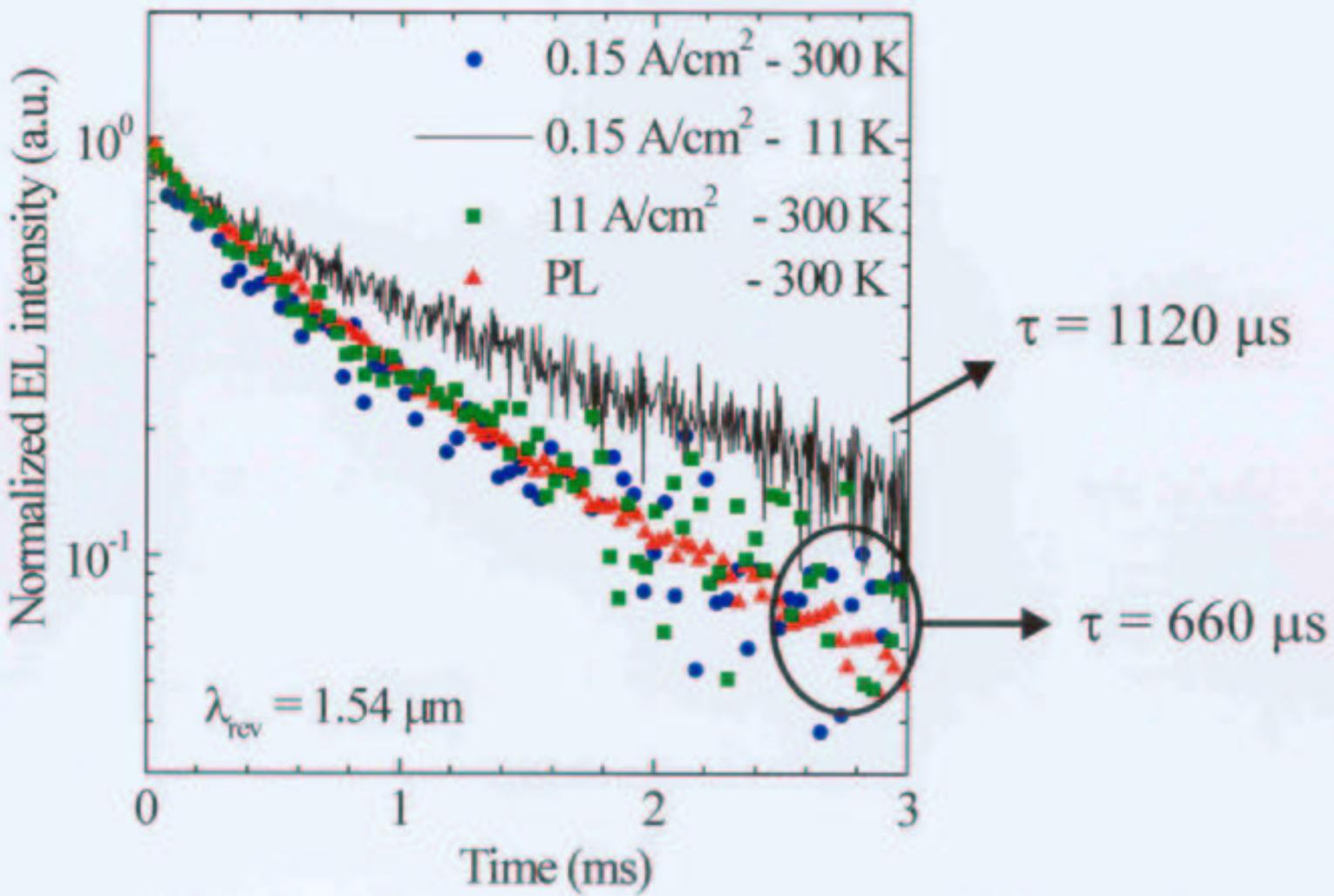
EL from Er-doped Si nc based devices: the effect of the current density



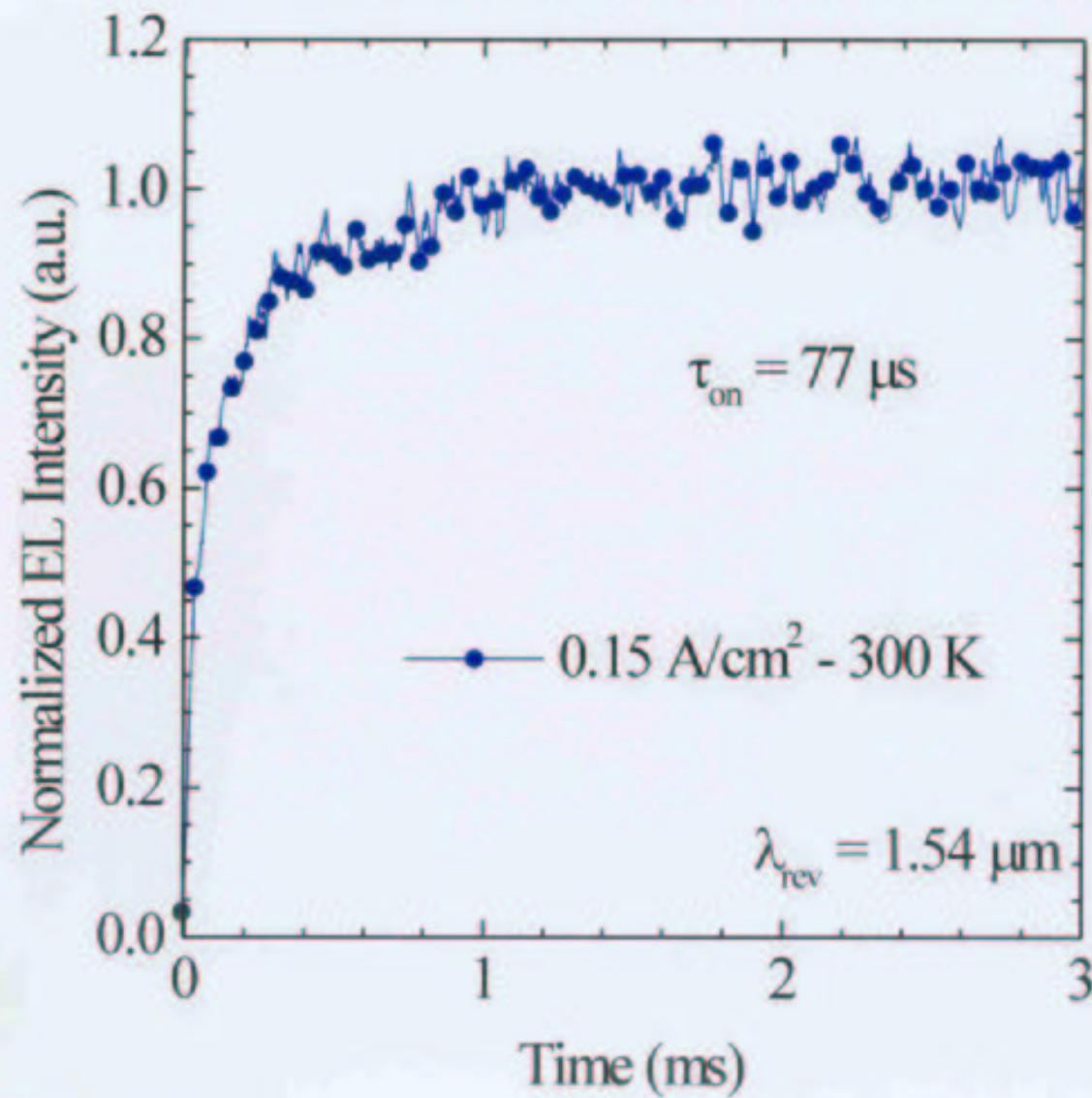
EL from Er-doped Si nc based devices: the effect of the temperature



Time-resolved EL measurements in Er-doped Si nc based devices



Time-resolved EL measurements in Er-doped Si nc based devices



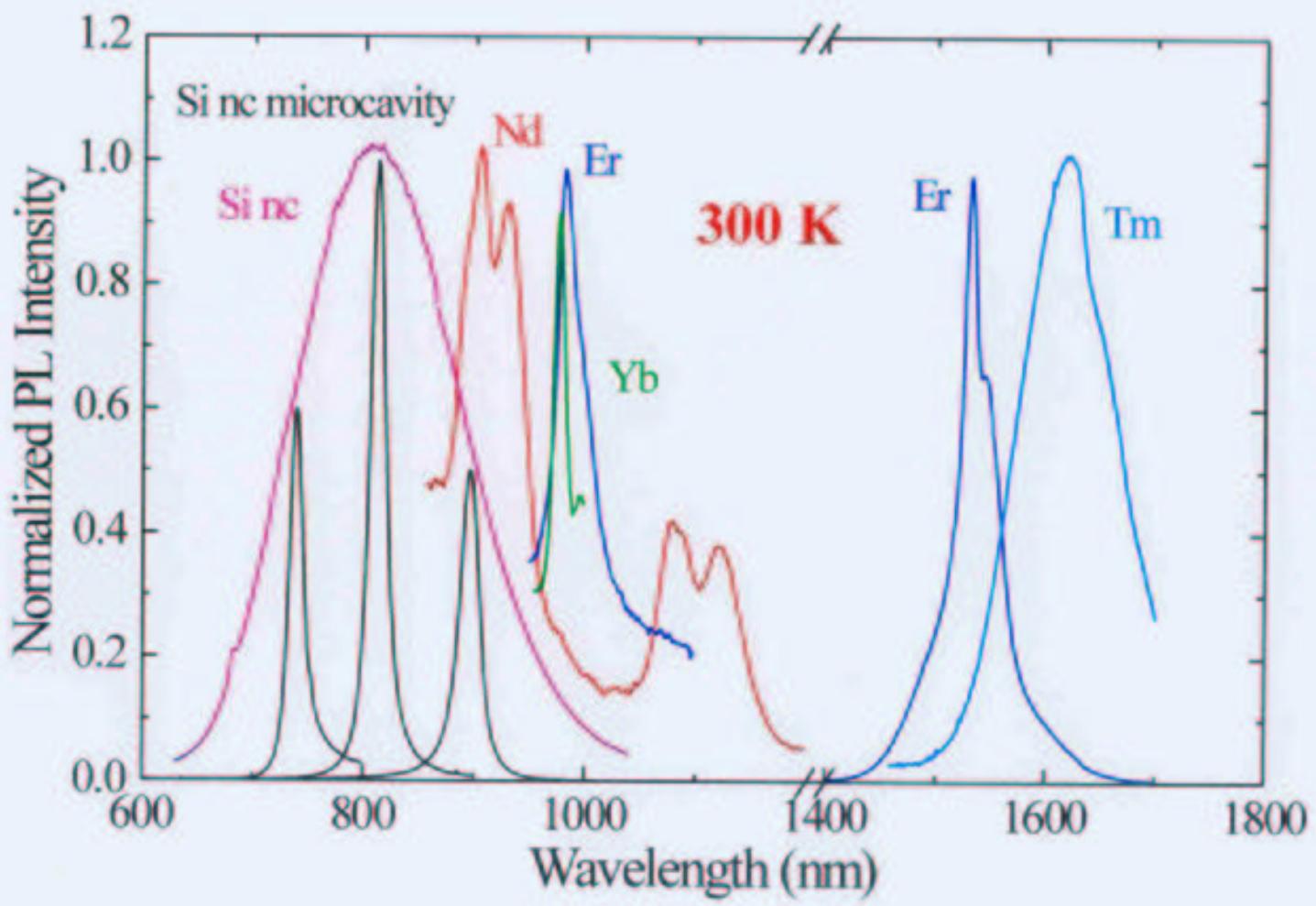
$$R = \tau_{\text{on}}^{-1} - \tau^{-1} = \sigma \phi$$



$$\sigma_{\text{EL}} = 1 \times 10^{-14} \text{ cm}^2$$

$$(\sigma_{\text{PL}} = 1 \times 10^{-16} \text{ cm}^2)$$

The colorful world of Si nanostructures



CONCLUSIONS

Si nanocrystals represent a very promising system to realize an efficient Si-based light source:

- Si nc exhibit a strong and tunable room temperature luminescence;
- Si nc exhibit optical gain;
- spectral purity and luminescence intensity can be strongly improved by realizing Si nc-based microcavities;
- Si nc can be electrically pumped to obtain room temperature operating devices.