The role of hydrogen in the luminescence-center-mediated Er excitation in Si rich SiO_2 with and without Si nanocrystals

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The road toward a viable silicon based light source

We have come a long way …

… but we're not there yet!

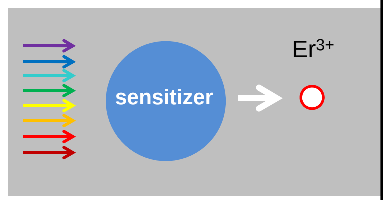
Introduction

Known : Er has small absorption cross-section and narrow absorption lines

⇒ strong and narrowband pump needed for gain

Solution: use sensitizer

- Si nanocrystals appear to be a good sensitizer:
  1) Large absorption cross section (> 10^{-16} cm^2)
  2) Broad absorption band ($E > E_{bg}$)
  3) Efficient energy transfer to Er (>55%)



Challenges

- Si nanocrystals introduce confined carrier absorption
- High T anneal appears to reduce density of active Er ions, resulting in low gain

New developments

Recent work: Savchyn et al. PRB **76**, 195419 (2007)

- Er excitation predominantly through isolated sensitizer (luminescence center)
- Cross section appears large (2-4x10^{-15} at 351nm)
- Relatively high C_{Er} seems possible
- No nanocrystals needed ⇒ no confined carrier absorption

Observations suggest:

- Nanocrystal passivation should not affect Er excitation
  (nanocrystals not the dominant excitation mechanism)

This study:

- Briefly recap arguments for luminescence-center (LC) mediated excitation
- **measure passivation-dependent photoluminescence properties**

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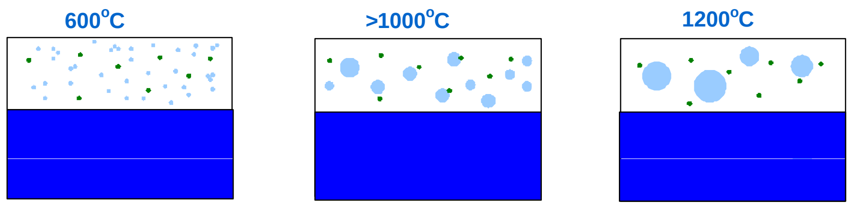
Sample preparation

1. Magnetron <u>co-sputtering</u> from Si, SiO_2 and SiO_2:Er_2O_3 targets onto Si

   Er: 0.63 at.% / **Si excess: 12 at.%** ; Thickness ~110nm

2. <u>Rapid thermal annealing</u> in N_2 for 100 sec at **T = 600 - 1200°C**

   activation of erbium to optically active Er^{3+} state
   nucleation of silicon atoms/clusters into nanocrystals.



3. <u>Passivation</u> in N_2:H_2 (95% : 5%) for 30 min at different T up to 600°C

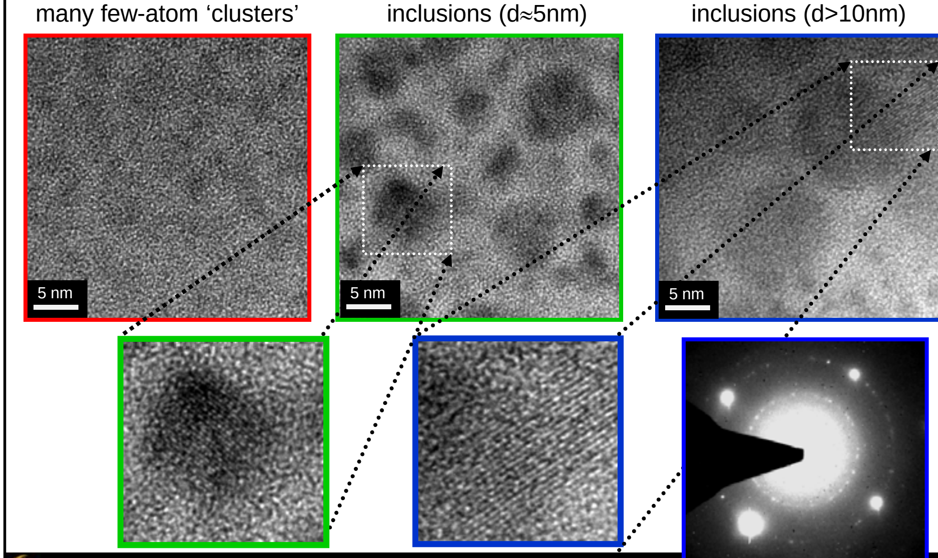
   passivates dangling bonds at Si-SiO_2 interface

Energy Filtered Transmission Electron Microscopy

T_{anneal} = 600°C
excess Si in SiO_2 :
many few-atom 'clusters'

T_{anneal} = 1000°C
small crystalline
inclusions (d≈5nm)

T_{anneal} = 1200°C
large crystalline
inclusions (d>10nm)



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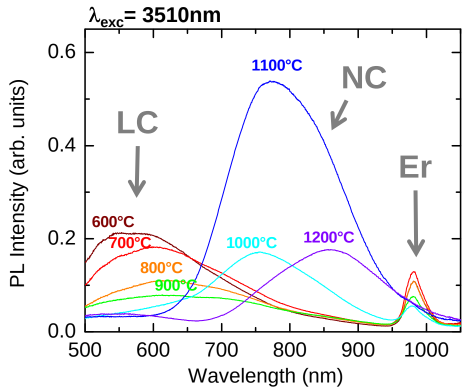
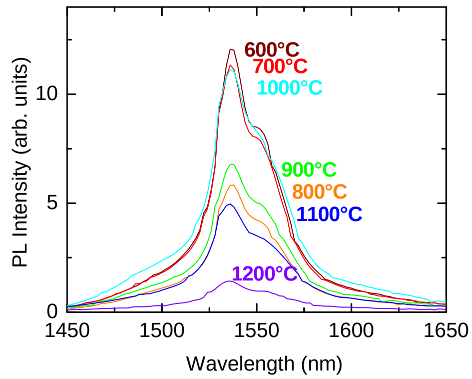
Photoluminescence vs. annealing temperature



Savchyn et al. PRB **76**, 195419 (2007)



Low annealing temperature:

- luminescence center emission with <80ns decay + Er PL at 981nm and 1535nm

High annealing temperature:

-Broad nanocrystal emission band with ~20 us decay + reduced Er PL

Samples with *entirely different microstructure* ⇒ Er excitation entirely different?

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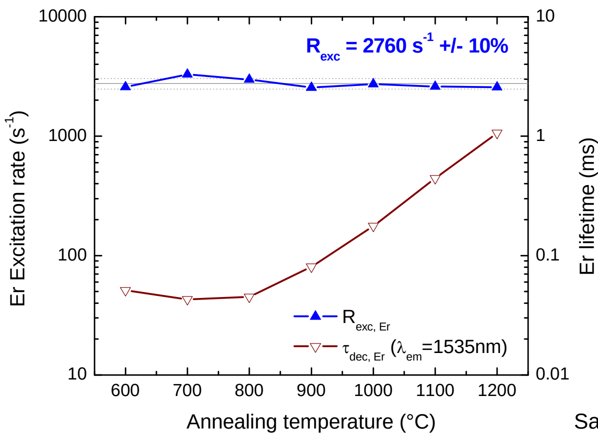
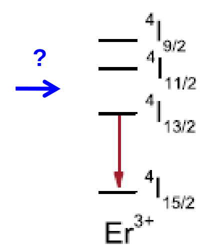
Er lifetime and excitation rate vs. T_{anneal}

Er rise and **decay time** at 1535nm measured for fixed pump; $R_{exc} = \tau_{rise}^{-1} - \tau_{decay}^{-1}$





Savchyn PRB **76**, 195419 (2007)

Er excitation rate constant within10% for all annealing temperatures **!**

Sensitizer unchanged ⇒ not extended crystal; likely (di)atomic scale structure

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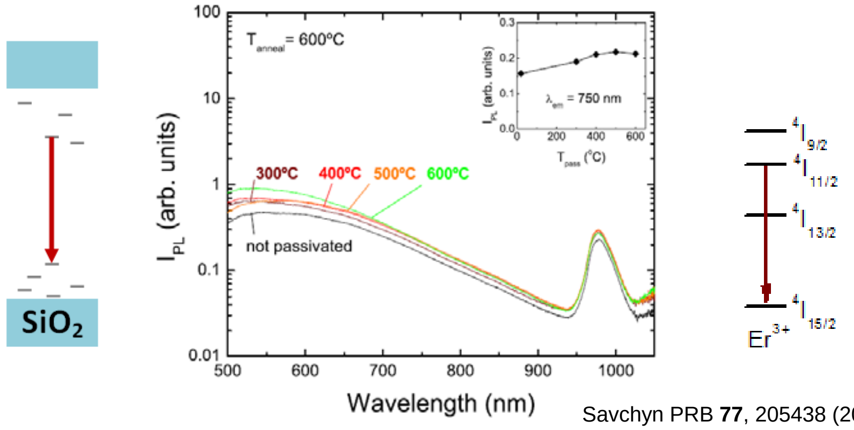
Low-temperature anneal – Passivation dependent PL

T_{anneal} **= 600°C**, Passivated at T_{pass} ≤ **600°C** (some additional annealing occurs)



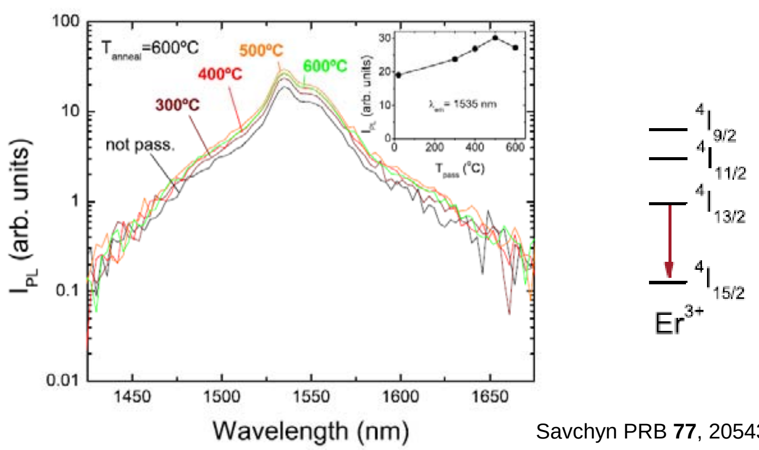
Savchyn PRB **77**, 205438 (2008)

No Si nanocrystals present ⇒ passivation has little effect on PL spectrum

Correlation between 980 emission and LC emission (note log scale)

Low-temperature anneal – Passivation dependent PL

T_{anneal} **= 600°C**, Passivated at T_{pass} ≤ **600°C** (some additional annealing occurs)



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Passivation also has little effect on Er PL spectrum at 1535nm

Similar small rise in Er related signal

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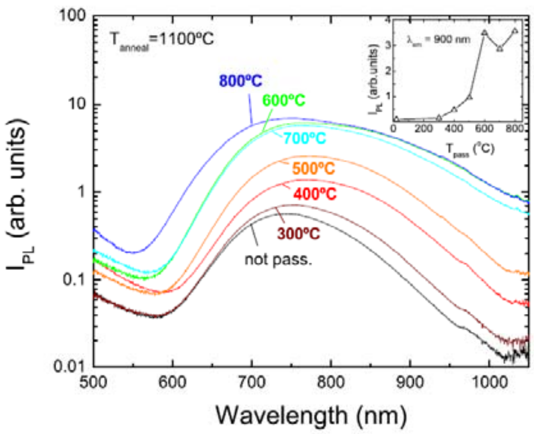
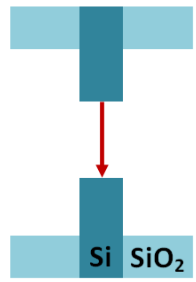
High-temperature anneal – Passivation dependent PL

T_{anneal} = 1100°C, Passivated at $T_{pass} \leq$ 800°C





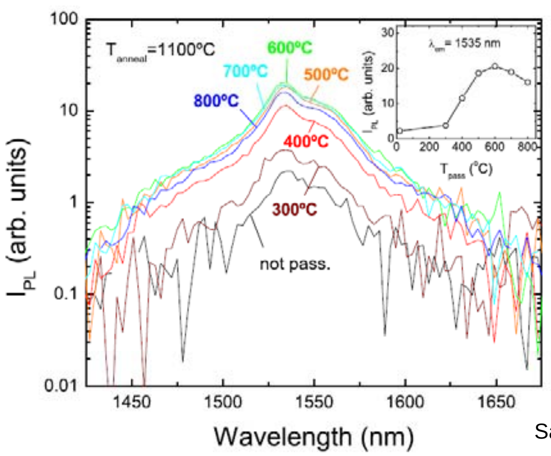
Savchyn PRB **77**, 205438 (2008)

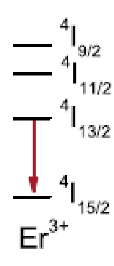
Passivation leads to significant increase of nanocrystal PL

Attributed to hydrogen termination of dangling bonds

High-temperature anneal – Passivation dependent PL

T_{anneal} = 1100°C, Passivated at $T_{pass} \leq$ 800°C





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Surprise: Er PL intensity at 1535nm is significantly improved by passivation

Paradox: LCs are dominant sensitizer **BUT** NC passivation is important for Er PL

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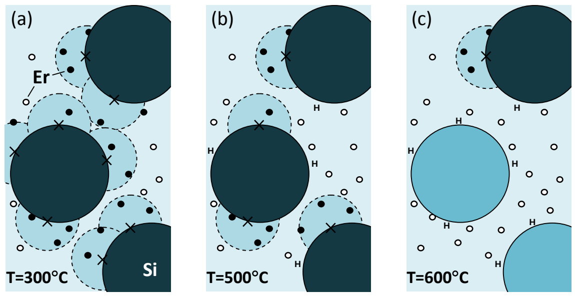
Resolution of the passivation paradox

- Luminescence centers are dominant excitation source
- Dangling bonds (x) affect Er emission or LC-mediated excitation



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(a) **Low T_{pass}** many DBs, nanocrystals inactive, most Er dark

(b) **Intermediate T_{pass}** fewer DBs, most nanocrystals inactive, some Er active

(c) **High T_{pass}** minimal DBs, most nanocrystals active, ~all Er active

Summary and conclusions

- Er excitation is luminescence center mediated
- Large effective absorption cross section at 351nm : $\sigma_{exc} = 2\text{-}4 \times 10^{-15}$ cm^2
- Cross-section does not depend on presence of Si nanocrystals
- The presence of nanocrystals with dangling bonds suppresses Er emission

Benefits over nanocrystal mediated excitation:

- Relatively high Er density seems possible
- No nanocrystals needed ⇒ no confined carrier absorption
- Low processing temperatures
- Reduced Mie scattering

⇒ **Luminescence center sensitized Er excitation is a promising candidate for a broad-band pumped gain medium at 1.53 um**

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