Si Sensitization of Er-doped SiO_2 for Low Thermal Budget CMOS Compatible Sources Operating at 1.54 um

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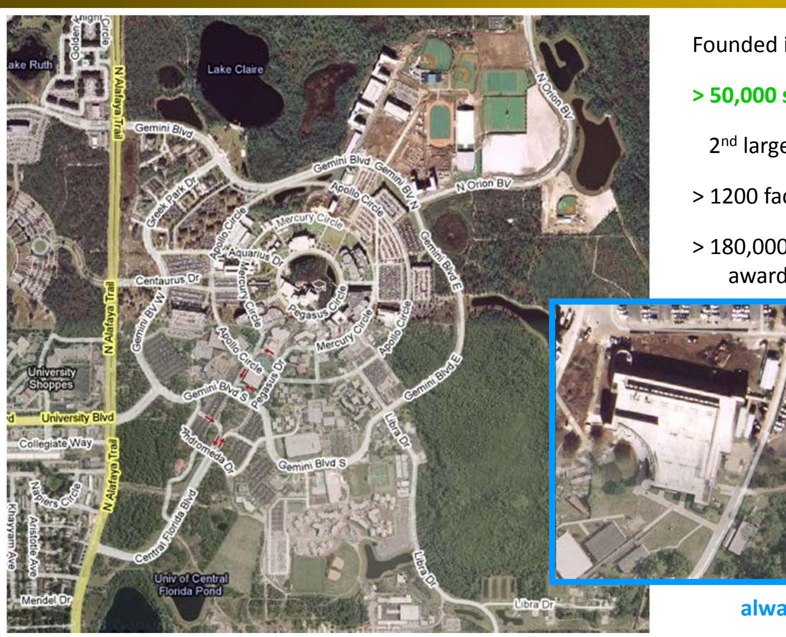
ECCS

UCF –outgrowing Google Maps



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> 50,000 students

2nd largest in USA

> 1200 faculty

> 180,000 degrees awarded

CREOL: always evolving

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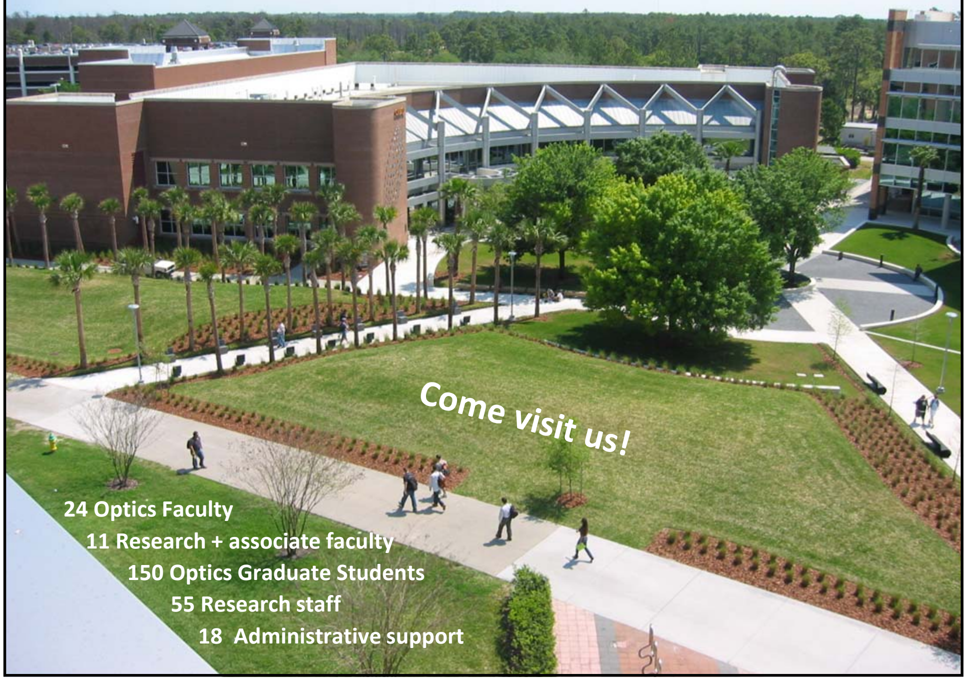

Outline

Introduction

- Si sensitization for Er doped silicon photonics

Experiments :

- origin of Si sensitization – Si nanocrystals?
- effective excitation cross-section – processing dependent?
- excitation wavelength dependence – broadband pump possible?
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- optimum C_{Si} in low temperature process samples – modified?

Summary / outlook

Problem and Solution

Challenge CPU's are getting increasingly complex

Interconnect bottleneck increased number of transistors:

- size reduction of integrated circuits
- tighter packing of the interconnects
- increase of parasitic capacitance
- signal propagation delay

Solution Partly replace electronic interconnects with optical interconnects

Any approach must be 'cheap' → use existing techniques from industry:

Optical interconnect technology must be silicon compatible

Ideally: no 'uncommon' materials, no 'uncommon' fabrication methods

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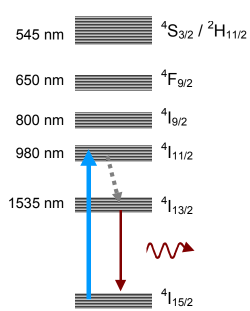
Er doped silica based gain media

Lanthanide Series	58 Ce 4f2	59 Pr 4f3	60 Nd 4f4	61 Pm 4f5	62 Sm 4f6	63 Eu 4f7	64 Gd 4f7	65 Tb 4f9	66 Dy 4f10	67 Ho 4f11	68 Er 4f12	69 Tm 4f13	70 Yb 4f14	71 Lu 4f14
Actinide Series	90 Th 6d2	91 Pa 5f2	92 U 5f3	93 Np 5f4	94 Pu 5f6	95 Am 5f7	96 Cm 5f7	97 Bk 5f8	98 Cf 5f10	99 Es 5f11	100 Fm 5f12	101 Md 5f13	102 No 5f14	103 Lr 5f14

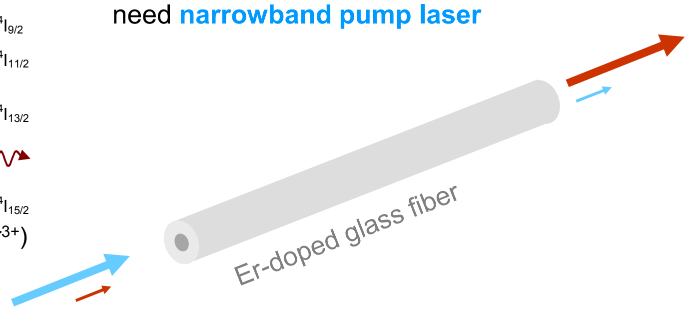


Erbium (Er^{3+})

sharp 4f energy levels

parity forbidden ⇒ $\sigma_{abs} \approx$ **10^{-21} cm^2**

need **narrowband pump laser**



For integration into Si photonics, preferably avoid use of pump laser

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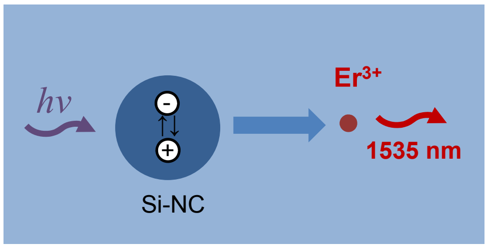
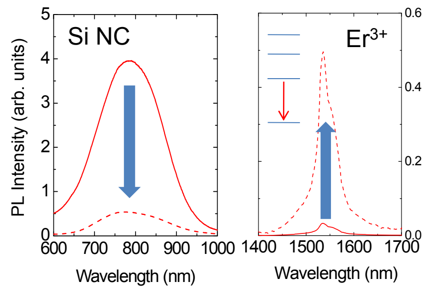
Silicon compatible light source – Si sensitized Er^{3+}

Late 1990's : exciting discovery: Er + **Si nanocrystals** in SiO_2 → coupling





Si NC present ⇒ non-resonant Er excitation possible

Increase C_{Er} ⇒ silicon NC emission reduced, Er emission enhanced

Increase of Er^{3+} effective absorption by 4 – 6 orders of magnitude

⇒ Spectacular effect, could influence photonics and optics significantly

Question: what makes a good sensitized gain medium?

The ideal sensitized Er doped gain medium

Erbium properties

- High concentration of optically active Er
- High concentration of sensitized Er ions
- High Er emission efficiency / Er lifetime

Sensitizer properties

- High pump absorption coefficient
- High power efficiency (small quantum defect)
- Large fraction of sensitizers coupled to Er
- High energy transfer efficiency

Other requirements

- Low processing temperatures
- High intrinsic transparency at 1.5 um
- Stable operation up to at least T_{CPU} = 100 °C

This is a very demanding set of requirements – **optimization challenging**

Si sensitized Er: a multi-dimensional challenge

End goal: high gain coefficient (assuming N_{Er} is optically active Er)

$$\gamma_{max} \approx [2 f_{sens} - 1] \sigma_{Er} N_{Er,tot}$$

f_{sens} is the *fraction of active Er ions that is sensitized*, must be > ½

Typically measured: photoluminescence intensity

$$I_{Er} \propto \frac{\tau_2}{\tau_{rad}} \sigma_{sens} \eta_{Si \to Er} f_{Si} N_{Er,tot} f_{sens}$$

f_{Si} is the *number of sensitizers per Er ion* (may be <1)

Challenge: all terms marked in green depend on **C_{Si}, $N_{Er,tot}$, T_{anneal}**

⇒ Optimization of PL intensity "makes no sens"

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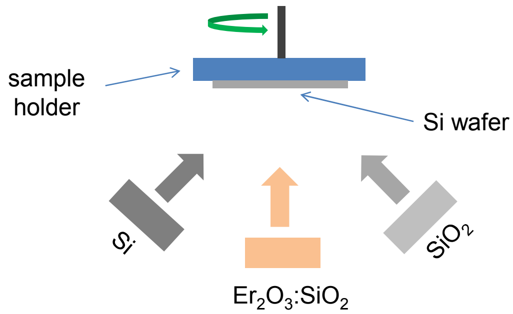
Sample Preparation – magnetron sputtering

Co-sputtering from Si, SiO_2 and Er_2O_3:SiO_2 targets



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Dr. Kevin R. Coffey

Multiple source materials ⇒ can make almost any sample composition

Here: deposit mostly SiO_2, add some Er, and add extra Si ('excess Si')

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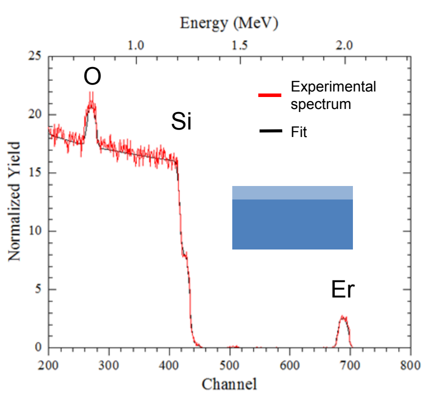
Sample analysis: Rutherford Backscattering Spectrometry

Irradiate sample with fast He ions, monitor energy of backscattered ions



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Fitting the RBS spectra gives thickness and composition

- thin film of Er-doped Si-rich SiO_2 (thickness 110 nm) on Si substrate
- Si excess: 12 at.%, Er: 0.63 at.% remainder: SiO_2 $Si_{12}Er_{0.63}[SiO_2]_{87}$

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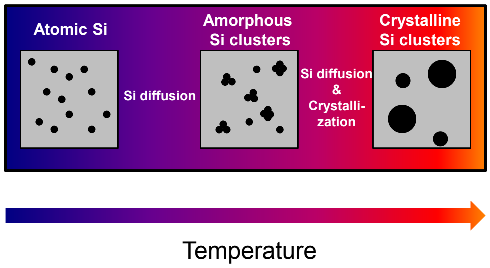
Sample Processing

Heat samples at 600-1200°C in N_2 for 100 s:

- removal of defects affecting Er emission efficiency
- formation of Si NCs at T > 1000°C




CREOL cleanroom

Heat at 500°C in forming gas (N_2:H_2 = 95%:5%) for 30min ('passivation'), saturates dangling bonds


NanoPhotonics and Near-field Optics Lab

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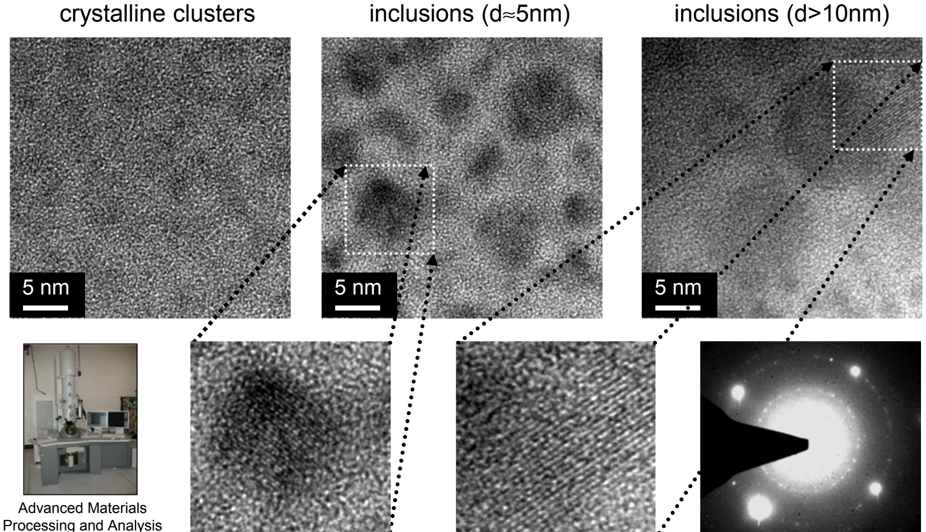
Transmission Electron Microscopy

T_{anneal} = 600°C	T_{anneal} = 1000°C	T_{anneal} = 1200°C
no clear evidence of crystalline clusters	small crystalline inclusions (d≈5nm)	large crystalline inclusions (d>10nm)



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Phys. Rev. B **76**, 195419 (2007)

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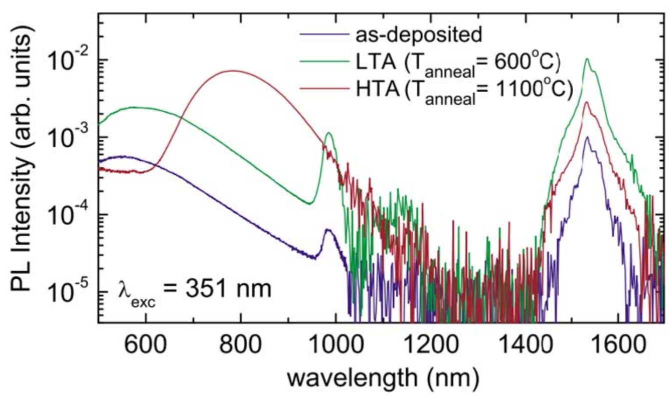
PL Measurements



Surprising result: No Si NCs – Er sensitization present
NC formation ⇒ Er emission *reduced*

Question: what is exciting Er? First, look at excitation cross-section

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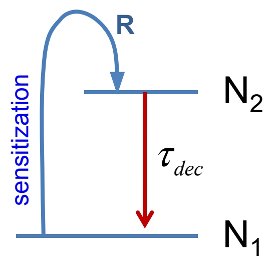
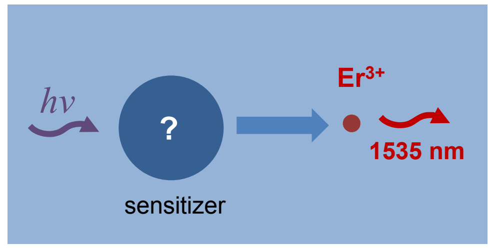
Er Excitation Cross Section

Study excitation mechanism → Study the excitation cross section σ_{Er}





Sensitized excitation occurs at a rate R (s^{-1}), given by $R = \sigma_{Er} \cdot \phi$

$$R = \sigma_{Er}\varphi = \frac{1}{\tau_{rise}} - \frac{1}{\tau_{dec}}$$

Time dependent signal can provide information on R and thus on σ_{Er}

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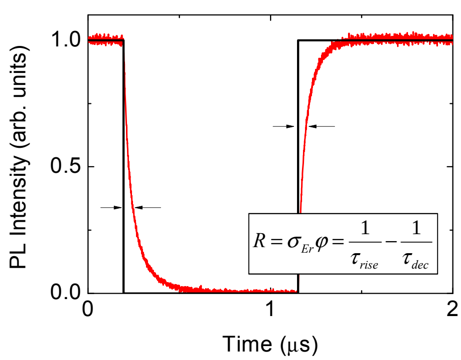
Er^{3+} Decay Time vs T_{anneal}

Microstructure - from Si excess atoms (T < 1000°C) to NCs (T ≥ 1000°C)



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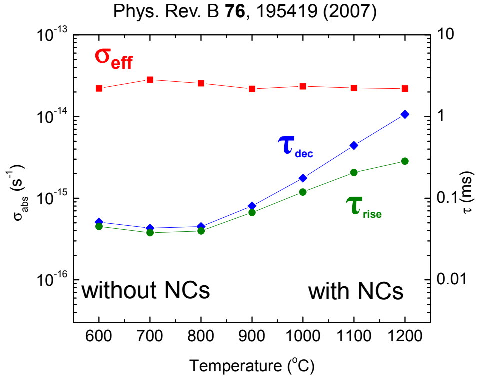

Effective Er^{3+} excitation cross section (σ_{Er}) vs T: ~ constant

Cross-section remarkably insensitive to NC formation

Si NCs – not the dominant source of Er^{3+} excitation

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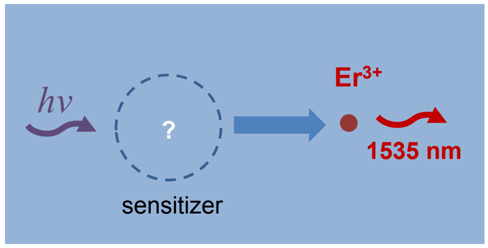
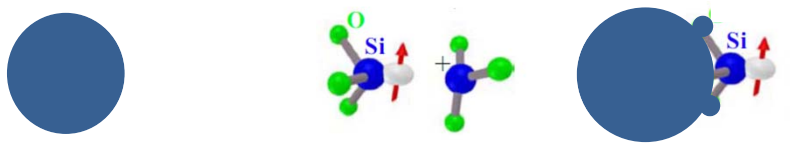
Sensitizer candidates





Excitons in Si nanocrystals?
Possible, weak contribution

E' centers?

Surface states?

Results suggest: finely distributed **Si excess** needed for Er^{3+} sensitization

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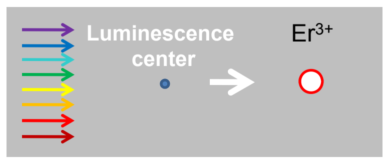
Gain vs λ_{exc}

Er-related gain at 1535 nm: $$\gamma = \sigma_{em}\frac{\sigma_{Er}(\lambda)\varphi\tau_{dec}-1}{\sigma_{Er}(\lambda)\varphi\tau_{dec}+1}N_{Er}(\lambda)$$

σ_{Er} (λ)– excitation cross section of Er → defines threshold pump power

N_{Er} (λ)– density of sensitized Er ions → defines maximum achievable gain



Goal: - study the dependence of σ_{Er} and N_{Er} on the excitation wavelength

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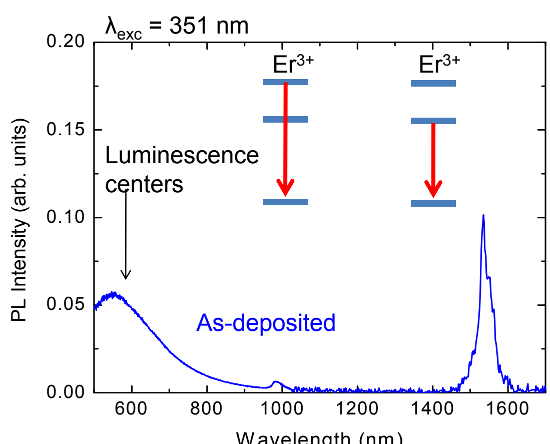
Photoluminescence Spectra (room temperature)



Appl. Phys. Lett. **95**, 231109 (2009)

Perform excitation spectroscopy of VIS bands and Er band at 1.5 um

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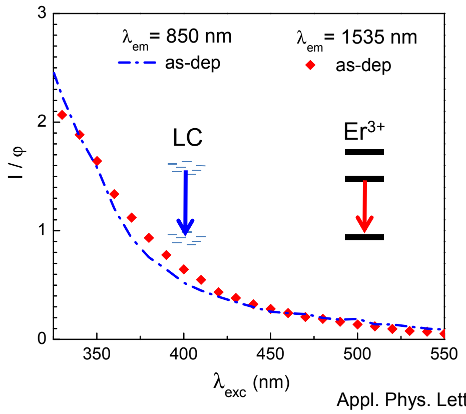
Excitation Spectra of Er and Luminescence Centers

Indirect excitation of Er in as-deposited samples



Appl. Phys. Lett. **95**, 231109 (2009)

Shape of the excitation spectrum :

$$\frac{I_{Er}}{\varphi} \propto \sigma_{Er}(\lambda_{exc}) \times N_{Er}(\lambda_{exc})$$

σ_{Er} – Er excitation cross section

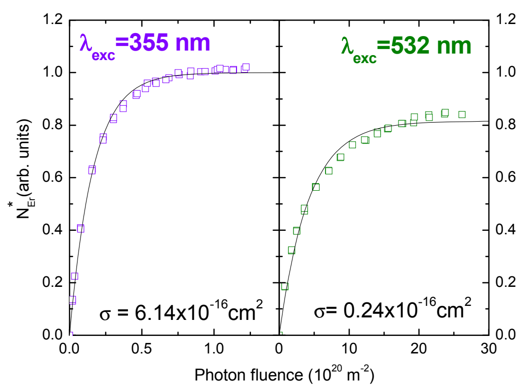
N_{Er} – density of sensitized Er ions

Correlation between LC and Er emission → sensitization due to LCs

Question: do **σ_{Er}** or **N_{Er}** dominate the shape of excitation spectra?

σ_{Er} and N_{Er} vs Excitation Wavelength – LTA sample

Pulsed excitation, PL immediately after pulse: $I_{Er}(\varphi) \propto N^*_{Er} = N_{Er}(1 - e^{-\sigma_{Er}\varphi})$



T_{anneal}=600°C:

$$\frac{\sigma_{Er}(355nm)}{\sigma_{Er}(532nm)} \approx 26$$

$$\frac{N_{Er}(355nm)}{N_{Er}(532nm)} \approx 1.2$$

Appl. Phys. Lett. **95**, 231109 (2009)

⇒ **$\sigma_{Er}(\lambda)$** – changes strongly with λ_{exc} , **$N_{Er}(\lambda)$** relatively constant

$$\gamma = \sigma_{em} \frac{\sigma_{Er}(\lambda)\varphi\tau_{dec} - 1}{\sigma_{Er}(\lambda)\varphi\tau_{dec} + 1} N_{Er}(\lambda)$$

➡ Similar maximum gain for different λ_{exc}

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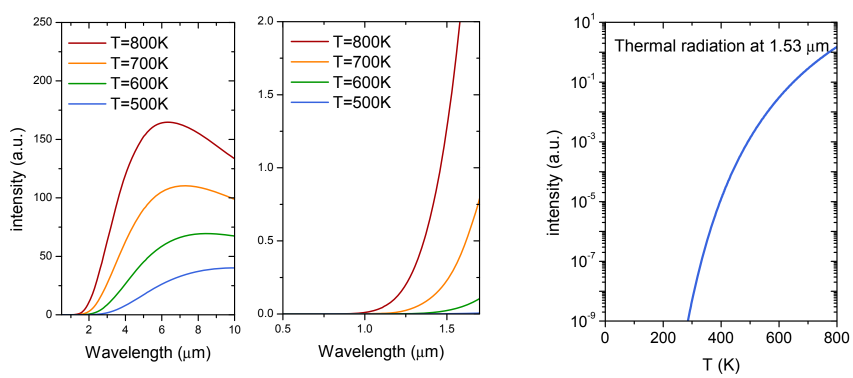
Measuring Er PL at elevated temperatures

Initial concern: thermal radiation could overshadow Er PL

$P_{thermal} \propto T^4$ ⇒ T up from 300 K to 600 K ⇒ P only 16x higher

Surprise: Ge detector saturates at T> ~250 °C



⇒ Estimate off by ~ 10,000,000.. Measure up to 200°C

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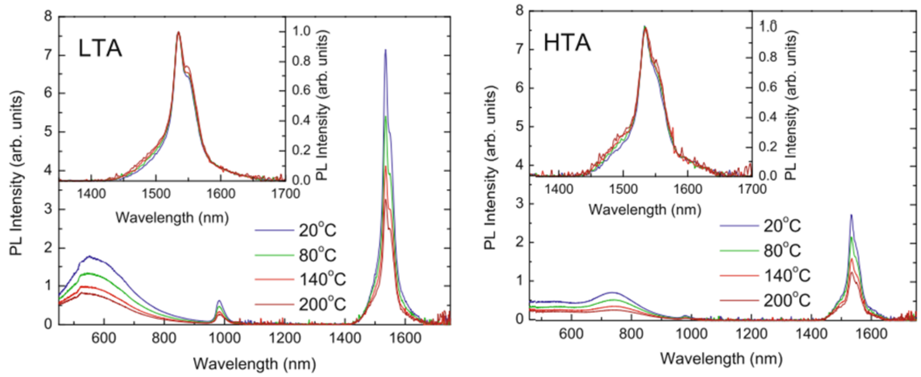
PL spectra vs. T – Low temperature anneal

Opt. Mat. **32**, 1274 (2010)



Both LTA and HTA samples: only small thermal broadening of Er PL

Peak intensity drops significantly as T increases to 200°C (~factor 2)

⇒ Investigate origin of peak PL reduction

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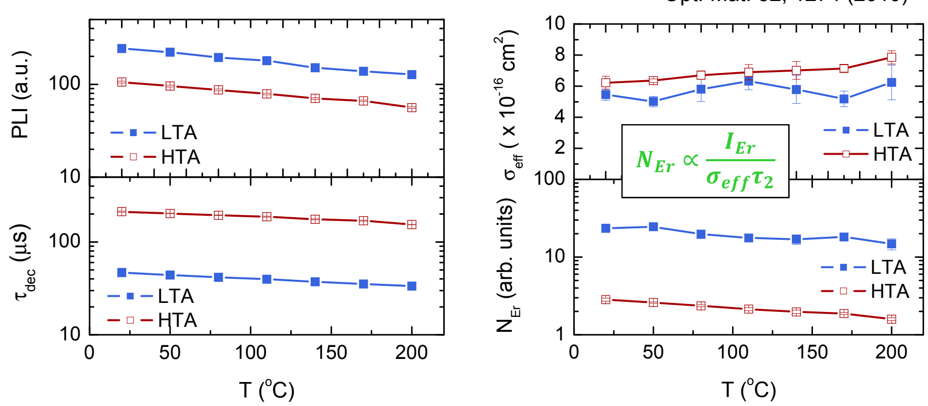
PL vs. sample temperature

Monitor PLI, τ, σ vs. T ⇒ determine N_{Er} vs. T

Opt. Mat. **32**, 1274 (2010)



Low temperature processed samples have:

- Higher PLI, shorter lifetime, similar cross-section, much higher N_{Er}
- Surprise: N_{Er} appears to depend on T

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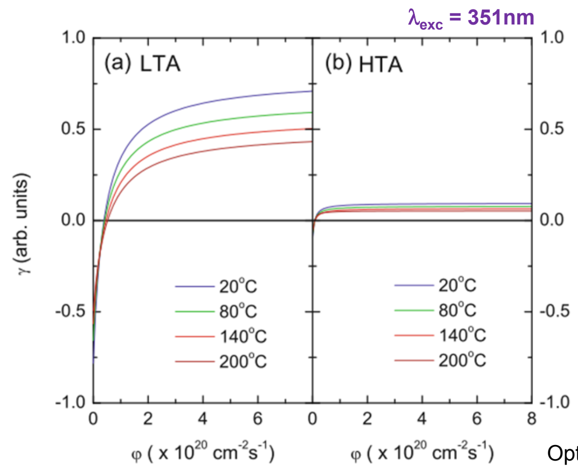
Temperature dependent gain

Estimate $\gamma(T)$, ignoring α_{BG}, upconversion, unsensitized Er contribution



Opt. Mat. **32**, 1274 (2010)

Low temperature processed samples requires **higher pump power**,

provides **larger gain**, exhibits **relatively stable gain** vs. T

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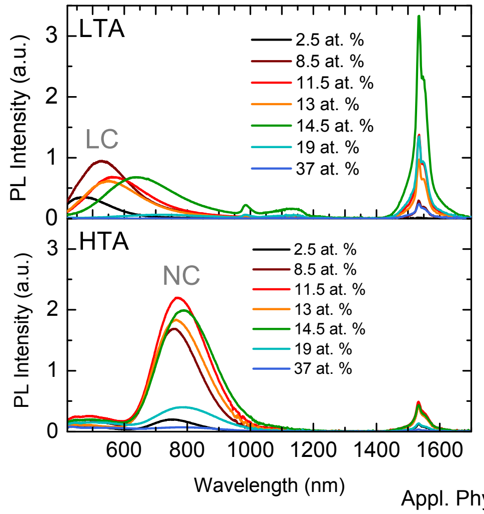
Photoluminescence vs. Si concentration



LTA samples:

Max. Er PL at

C_{SiE} = 14.5 at.%

HTA samples:

Max. Er PL at

C_{SiE} = 11.5 at.%

Appl. Phys. Lett. **97**, 201107 (2010)

Surprise: LC spectrum affected by C_{SiE} : LC-LC coupling?

High temperature anneal ⇒ significant drop in PL Er for almost all C_{SiE}

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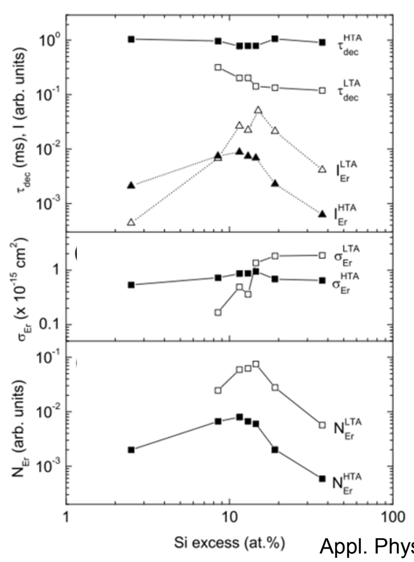
Determination of N_{Er} vs. C_{SiE}



Lifetimes τ_{dec}

Er emission intensity I_{Er}

Effective Er cross-section σ_{Er}

Concentration of sensitized Er

$$N_{Er} \propto \frac{I_{Er}}{\sigma_{eff}\tau_{dec}}$$

Appl. Phys. Lett. **97**, 201107 (2010)

Highest N_{Er} in LTA samples, for C_{SiE} 14.5 at.% ⇒ **max Er related gain**

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Er-doped Si-rich SiO_2: with NCs vs without NCs

Parameter	with NC	without NC
• High concentration of sensitized Er ions	No	Yes
• Low ground state absorption at 1.5 µm	No	Yes
• Low confined carrier absorption at 1.5 µm	No	Yes
• Low scattering	No	Yes

→ Use Er-doped Si-rich SiO_2 annealed at low temperature (< 1000°C) for device fabrication

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Outlook and Future Research

Is this the end? (no)

- Study host-induced optical absorption at 1.54 μm
- Determine the absolute fractions of sensitized Er ions
- Determine the optimal excitation geometry of the devices
- Fabricate and test waveguide devices based on Er-doped Si-rich SiO_2

Longer term:

- Investigate different rare earths, different sensitizers
- Investigate for different goals (phosphors, biomarkers)

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