NANOCRYSTAL SENSITIZED, Er DOPED SILICA AS THE MATERIAL BASIS FOR GAIN-PROVIDING, ACTIVE Si-BASED MICROPHOTONICS

Hak-Seung Han, Se-Young Seo, Joo-Yeon Sung, Yong-Seok Choi, Y. H. Lee, and Jung H. Shin

Dept. of Physics
Korea Advanced Institute of Science and Technology (KAIST)
373-1 Kusung-Dong, Yusung-Gu, Daejeon, Korea
Outline

• Si microphotonics
• nc-Si sensitized rare earth ions as the material basis
  • Physics of luminescence
  • Importance of nanoscale control for RE luminescence
• Applications
  • Amplifiers
  • Microphotonic
• Conclusion
Si microphotonics

- Si microphotonics
  - Microphotonics based on Si-based materials and Si-compatible processes

- Why? Because if you can do it with silicon, then you MUST!

  ![Image 1](https://example.com/image1)
  ![Image 2](https://example.com/image2)
  ![Image 3](https://example.com/image3)

  Bookham Technologies
  DeDood et al.

- Low cost, large-area, optical-quality substrates with chemical and mechanical strength
- Availability of astronomical Si processing knowledge and infrastructure

- But for true Si microphotonics, we need Si-based, optically active material capable of providing gain
Achieving optical activity in Si
nc-Si sensitization of RE ions

- Si Nanocrystal sensitization

- Excitation of 4f electrons by electron-electron interaction
  - Direct, efficient excitation of 4f electrons via short-range electron-electron interaction
  - nc-Si only need to generate carriers – control over size can be relaxed
  - Only need to generate photocarriers – control over pump wavelength not necessary
  - Luminescence from rare earth ions → efficient (>50%) luminescence with very long luminescence lifetimes (>ms at room temperature for Er)
Deposition of the nc-Si sensitized core layer

- ECR-PECVD of SiH₄ and O₂ with concurrent sputtering of RE
  - No metalorganic precursor needed → Any RE material can be used!
  - No ligand contamination
  - Plasma condition suitable for nc-Si formation
Deposited nc-Si : Er films

- Silicon-rich silicon oxide (SRSO) (Shin, APL 1998)
  - 2-4 nm NanoSi embedded inside RE-doped SiO$_2$.
  - Fabricated by depositing a-SiO$_x$ (x<2) and annealing to precipitate NanoSi.
  - NanoSi size controlled by controlling the excess Si content.
  - Stochastic control over NanoSi – Er coupling.
  - Amenable to rapid, mass-production.

- Si/SiO$_2$ superlattice (SL) (Shin, APL 1999)
  - Alternating layers of nm-thin NanoSi and Er-doped SiO$_2$ layers.
  - Fabricated by depositing a-Si/SiO$_2$:Er layers and annealing to precipitate NanoSi.
  - NanoSi size controlled by Si layer thickness.
  - Sub-nm control over NanoSi size and NanoSi – RE coupling.
Optimizing the Er luminescence from Er-doped SRSO

- Dependence of Er\(^{3+}\) luminescence properties on anneal temperature, anneal time, and film composition

- Optimum condition: Si 34-35 at.\%, 950-1050\(\Sigma\) C anneal for at least 5 min
- High-quality nc-Si precipitation without Er precipitation
- As little excess Si as possible
Critical parameters

- **NanoSi: NanoSi size less than 3 nm**
  - **Strong quantum confinement effect**: increases the bandgap of NanoSi to reduce back-transfer of energy from Er to nc-Si (temperature dependence)
  - **Larger surface/volume ratio**: faster trapping of free carriers by the surface
  - **Greater oscillator strength**: faster decay of excitons for faster excitation of Er → less than 3 nm required to reduce transfer time to < 10 μsec range
  - **Small volumetric fraction**: need to put Er inside SiO₂ matrix

- **Separation of Er from direct contact with nc-Si**
  - Carrier-mediated excitation without de-excitation (Si/SiO₂ interface: 1-2nm)

- **Not too large of Er/nanoSi ratio**
  - Strong nc-Si/Er interaction and long Er luminescence lifetime
Measuring the optical gain

- Top-pumped waveguide amplifier based on nc-Si sensitization

- SRSO film fabricated to specifications:
  - 2-3 nm NanoSi, 0.03 at. % Er
  - 9 msec Er3+ luminescence lifetime – the longest ever reported from NanoSi – based material

- Ridge-type single mode waveguide fabricated
  - Using PMMA mask and wet-etching using BOE
  - \( n = 1.46 \) (NanoSi provides the refractive index contrast)
Experimental Setup

• Top pumping using 477 nm line of an Ar laser

• 1 cm long waveguide, top-pumped with Ar laser
  • Usually 477 nm line to ensure that pumping occurs via NanoSi only
  • Waveguide very lossy due to experimental nature of the fabrication steps

• External signal from 1300 and 1535 nm DFB lasers coupled into the waveguide using lensed fibers (small signal, < 40 dBm)
- White light absorption, complemented with McCumber theory
- $6 \pm 1$ dB/cm absorption $\Rightarrow$ $1-2 \times 10^{-19}$ cm$^2$ absorption cross section at 1535 nm
Demonstration of optical gain

Transmitted 1300 nm signal, pump off

Transmitted 1535 nm signal, pump off
Demonstration of optical gain

Transmitted 1300 nm signal, pump on

Transmitted 1535 nm signal, pump on
Gain figures and the advantage of nc-Si sensitization

• $\sigma$ (emission cross section) $1-2\times10^{-19}$ cm$^2$ (x100 over that in SiO$_2$)
  - In agreement with P.G. Kik’s data (Kik et. al, JAP ’01) of $\geq 8\times10^{-20}$ cm$^2$

• $\Gamma$ (excitation cross section) $\geq 2\times10^{-17}$ cm$^2$ (x$10^4$ over that in SiO$_2$)
  - In agreement with Priolo and A. J. Kenyon ($2\times10^{-17}$ cm$^2$ and $7\times10^{-17}$ cm$^2$)

• SE = 14 dB/cm → twice the absorption, indicating near full Er inversion
  - At pump powers achievable with commercial GaN LEDs

• Internal gain > reported scattering loss of nc-Si
  - With better processing, full external gain achievable
Applications: PBG

- Photonic bandgap promises unprecedented capability to manipulate light
  - Periodic modulation of refractive index to create “bandgaps” for photons
  - Only possible route for ultra-high density optical integration down to the wavelength scale

- Advantages of nc-Si:RE for Si-based PBG
  - Photonic bandgap requires high refractive index contrast: can’t use glass
  - Active PBG requires optically active material: so far limited to III-V materials
  - Atomic transition: insensitive to surface effects
• Active, Si-based PBG using Er-doped Si/SiO$_2$ superlattice
  • Requires both high refractive index and efficient Er luminescence

Wafer

<table>
<thead>
<tr>
<th>PMMA</th>
<th>writing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au 400 Å</td>
<td>milling</td>
</tr>
<tr>
<td>SiO$_2$</td>
<td>RIE</td>
</tr>
<tr>
<td>Er-Si/SiO$_2$ 4000 Å</td>
<td>PC slab</td>
</tr>
<tr>
<td>Si$_3$N$_4$ 5000 Å</td>
<td></td>
</tr>
<tr>
<td>Si substrate</td>
<td></td>
</tr>
</tbody>
</table>

• Slab-type 2D PBG using Si$_3$N$_4$ sacrificial layer
• Triangular lattice of air holes in Er-doped Si/SiO$_2$ SL
  • $n \sim 2.5$ with max. Er PL

- Full bandgap for TE-like mode with a good Er$^{3+}$ luminescence properties
- 100% increase in extraction efficiency using PBG on silica substrate
- Complete insensitivity to processing, pump power, and temperature – advantage of using inner-shell transition

$r/a=0.3$

$Y = a + bX + cX^2$

$a = -0.35(0.12)$
$b = 0.70(0.20)$
$c = -0.07(0.08)$
Applications: microdisk

- Superlattice or SRSO microdisk on Si posts produced using either e-beam lithography or standard optical lithography followed by wet chemical etching
- Optical lithography allows production of massive arrays of microdisks
• Er PL intensity and lifetime unaffected by the entire fabrication process
• Expected WGM mode spacing: 6 nm ➞ too low S/N ratio to distinguish from the top
• A microdisk with a modest Q of $10^5$: mode travel of 1 cm!
Conclusion

• nc-Si sensitized Er demonstrated as a viable material for active, Si based microphotonics
• Optical gain demonstrated, and parameters relevant for achieving it identified
• 2D slab photonic crystal based on nc-Si sensitized Er demonstrated
• Microdisks based on nc-Si sensitized Er demonstrated

Acknowledgment

This work was supported in part by National Research Laboratory project by the Minstry of Science and Technology in Korea.