Rare-earth doped nano-cluster silicon for silicon based photonic applications

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Outline

- Si based photonics: Needs? Breakthrough?
- Silicon nanostructures and limitations
- Rare earth ions for optical dopants in Si based photonics
- The advantages of nc-Si over bulk semiconductor for RE-doping
- The effect of exciton-RE coupling on backtransfer
- Efficient luminescence: optical amplification on visible non-resonant source
- Broad luminescence from co-doped RE system: RE-RE interaction and its control
- The expansion of luminescence to ‘real’ visible from RE-doped nc-Si
Fast but expensive

Broadband network: ‘Backbone’

- Every home user want broadband
- Optical backbone level: fast but too bulky and expensive for home network
- The need development of low-cost, high-performance integrated optoelectronic devices

We need

- To miniaturize the equipment & To reduce the costs of the optical hardware

→ Integrated Optical Circuit (IOC)

: Chip integrated with several photonic capabilities such as light sources, photodetectors, optical filter & waveguides

High speed home-network?

Example of IOC (Polman, Nature Mat.)

Si photonics lab. (KAIST)
Si micro-photonics

Si: promising candidate for micro-photonics
- Predominant material for electronic circuit and devices
- In addition, optically and electrically important related compound
  $\rightarrow$ Si, SiO$_2$, SiN$_x$ and SiC
- The combination of well-developed infrastructure for Si and photonics

Key to success: ‘to siliconize’
- Various examples

![1GHz modulator by Intel](image)
All ready to open Si photonic Era?

→ Still need a few key breakthrough: LIGHT EMISSION!!!

- Si: is not efficient light emitter

Teach silicon New tricks!!!
Silicon nano-structure

Training strategy: Si nanostructure
- Quantum confinement:
  - Increases the bandgap from 1.14 to 2-3 eV
- Physical confinement of electron-hole pairs:
  - Radiative transition rates are improved
- Physical isolation from quenching centers:
  - Increased luminescence efficiency

Some fruitful results
E.g., Optical amplification from nc-Si (Pavesi Nature)

Limitations of nc-Si
- Broad luminescence from even a single nc-Si (Valenta APL 2002)
- Awkward luminescence position (generally near infrared)
  - Very strong Stokes shift – hard to exceed 2.0 eV (Wolkin PRL 1999, Puzder JCP 2002)
  - Luminescence cannot be tuned down to IR range
    - Difficult to use telecommunication window of silica fiber
Rare earth ions

Intra-4f transition from lanthanide series rare earth metals

- Incomplete 4f shells: Ce: [Xe].4f1.5d1.6s2 ~ Yb: [Xe].4f14.6s2

How to overcome

Limitations of nc-Si

- Broad luminescence
- Awkward luminescence position
- High pump for lasing

Using RE ions

- Stable, atomic transition with environment insensitive luminescence positions
- Various visible to infrared luminescence
- Originally parity forbidden – allowed due to crystal field: long luminescence lifetimes and ease of population inversion in addition to multi level system

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**Silicon-rich silicon oxide (SRSO)**
- 2-4 nm nc-Si embedded inside RE-doped SiO$_2$.
- Fabricated by depositing a-SiO$_x$ (x<2) and annealing to precipitate nc-Si.
- nc-Si size controlled by controlling the excess Si content.
- Stochastic control over ‘nc-Si’ – RE coupling.
- Rapid & dense formation of nc-Si.

**Sample deposition**
- By ECR-PECVD
- Flowing O$_2$, SiH$_4$ and Ar gases
- Concurrent sputtering of RE targets

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**TEM image**
- Sample deposition
  - By ECR-PECVD
  - Flowing O$_2$, SiH$_4$ and Ar gases
  - Concurrent sputtering of RE targets
This presentation

• The advantages of SRSO films for RE-doping
• Photonic Implications of RE-doped SRSO
• The extension of luminescence window of RE-doped Si nano-cluster by co-doping of impurity
RE excitation via excitons in Si nanoclusters

1.54 µm Er PLE spectra → similar with absorption spectra of NanoSi

- Very efficient: effective excitation cross-section ~$10^{-18}$ cm$^2$ for Er for nc-Si
  (c.f, 2 X 10^{-21} cm^2 for silica)
- Continuous excitation cross section: broad band excitation.
  (c.f. direct optical absorption)

General for RE-doped semiconductor host
Problems of bulk semiconductor for RE doping

De-excitation processes

- Reversibility of physics: Efficient excitation ↔ Efficient de-excitation

Thermal quenching
- Energy backtransfer of excited RE ions

De-excitation of Auger effects
- Always exist even at 0 K
- Serious decrease in both excitation and quantum efficiency Population inversion is difficult

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The advantages of nc-Si for RE-doping: compared to bulk semiconductor,

• Efficient luminescence
  → Lack of all possible de-excitation path including backtransfer and Auger quenching (Seo et al. 1999 APL)

The lack of de-excitations of nc-Si: the origins

Backtransfer:
→ Bandgap: increases thermal barrier between RE and excitons and known to be predominant factor for ‘backtransfer;
→ Wide bandgap of nc-Si: the reason for the suppression of thermal quenching?
  :Contrarily, strong thermal quenching of wide bandgap matrix (e.g, GaP:Nd)

Auger effect:
→ Auger effect has no relation with bandgap
→ The reason for the suppression of Auger effect?
The advantages of nc-Si for RE-doping

What is different?

- Nc-Si: inhomogeneous structure
  → RE ions can be located in SiO₂ matrix, nc-Si, the interface between SiO₂ and nc-Si
  → Various couplings may exist between excitons and RE ions

Thus exciton-RE coupling strength

- Determines Not only excitation of RE ions but also RE de-excitations such as Auger effect and backtransfer
**Exciton–RE coupling strength:**
Probing by Nd luminescence of Nd–doped SRSO films

**Nd$^{3+}$ luminescence**
- 0.9 um ($^{4}F_{3/2} \rightarrow ^{4}I_{9/2}$) and 1.1 um ($^{4}I_{11/2}$)
  - within c-Si and nc-Si luminescence range
  - Sensitive probe of the interaction between nc-Si and RE ions

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The lack of backtransfer

- $t_{Nd}(T) \rightarrow 40 \, \text{us with} \, T$ (cf. Nd-doped silica-based thin films)
- The reason of 3 folds decrease of Nd PL intensity
  - not backtransfer but exciton dissociation

Only ~ 200 meV difference between nc-Si luminescence and Nd$^{3+}$ excitation energy

- Not sufficient to suppress backtransfer (cf. bulk GaAs:Nd)
- Even GaP ($E_g=2.26$ eV) shows > 10 folds thermal-quenching of Nd$^{3+}$ luminescence

GaP:Nd (Taniguch et al. APL, 1991)
Weak couplings induce weak backtransfer

Kik’s
- $W_{BT}(T) = W_0 \exp(-E_0/kT)$

Takahei’s
- $W_{BT}(T) = W_0 (n_q)^p \exp(-2n_q s)$
  
  $n_q = \left[ \exp(h\omega/kT) - 1 \right]^{-1}$

**Analysis of temperature quenching of with**

- Kik’s (Thermal dissociated) and Takahei’s (Multi-phonon relaxed) model
- Different physical basis but similar dependence on $E_0$ and $W_0$

\[ W_{BT}(T) = W_0 \times f(E_0, T) \]  
\($W_0$: coupling prefactor)\]

**Identical simulated results fit by both models with similar fitting value**

- $E_0 \sim 100$ meV and $W_0 \sim 1-10 \times 10^5$ sec$^{-1}$
- Much smaller than $W_0 \sim 10^9$ sec$^{-1}$ for Er-doped bulk Si
The separation of RE from nc–Si

**Different from bulk semiconductor**
- Weak coupling between exciton and RE: responsible for suppression of backtransfer
- Slight separation of RE from nc-Si
  → Weakens the interaction between nc-Si and RE (Kimura et al.)
  → Uniqueness of nanocluster

**This exciton-RE couplings are**
Still strong enough for efficient excitation of RE
Weak enough for suppression of de-excitation

**The suppression of de-excitation by Auger process and backtransfer**
→ High concentration of excited RE ions at given pump power
→ Imply optical amplification!!!
Optical amplification pumping with LED Array

1.54 um signal enhancement even pumped by commercial blue LED array

→ Commercially viable
Further extension bandwidth using RE-doped SRSO

Utilizing advantages of nc-Si sensitizing

**Advantages:**
- Sensitized by nc-Si
- Dual pumping (Er and Tm) with single- broad source
- Simple scheme: Reduction in coupling loss
Broad and flat 1.4–1.9 µm luminescence from Er and Tm co-implanted SRSO

**PL Spectra**

- Er and Tm PL intensities increase with increasing RE content:
  - PL intensity was limited by available RE
- Tm co-doping: quenches Er PL intensity and PL lifetimes
- Er co-doping: has no effect on Tm luminescence
  - Er and Tm interact – but how?

**PL Decay traces**

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Interaction between Er and Tm: Co-operative up-conversion of Tm\(^{3+}\)

- Almost exact agreement with experimental result → verifying interaction model
- Er-Tm interaction: Need to be minimized

PL Decay traces

RE PL intensity as function of pump power
Control of Er–Tm interaction by spatial separation

- Er luminescence increases with increase in layer thickness
- The interaction between Er and Tm
  → Can be successfully minimized by spatial separation
- Judicious control and design of nc-Si size and RE distribution
  → Enabling efficient luminescence minimizing undesired degradation

Alternating SRSO:Er/ SRSO:Tm layers

PL intensity (a.u.)
Wavelength (µm)

005 sec
015 sec
030 sec
060 sec
180 sec
SRSO:Er+Tm (24)

MRS
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The realization of visible RE luminescence

Up to date, most RE-doped SRSO:
→ Investigated and demonstrated for photonics application in infrared range

And, need of the expansion to other wavelength:
RE ions for visible luminescence: implication for Si photonics
• Visible luminescence:
  → Open the feasibility of Si based full color display unit
• Can be detected with Si photo-diodes
  → Applicable inter-chip communication using polymer fiber

HOWEVER,
The optical transition of oxide capped nc-Si
→ Strong Stokes shift limits below 2 eV
→ Difficult to excite RE onto visible 4f transition

In order to realize visible RE luminescence from SRSO
• The need of wide bandgap (blue-white)
  → by suitable impurity incorporation other than oxygen

(Puzder, JCP)
Candidate of wide bandgap: 1. C-doped SRSO

(Seo et al. APL 2004)

C-doping into SRSO

- Significantly increases blue-white luminescence
- Excitons in C-rich nc-Si is responsible strong visible luminescence
  - Only Si-C bonds exists among C related bonds
  - The dependence of Si content & anneal temp.: very similar to those of C free SRSO
- Can be utilized as wide bandgap material host for visible RE luminescence
Green luminescence from Tb-doped SRSO:C

The details will be found in L.6.8

(Seo et al. APL 2004, in press)

The enhancement of Tb$^{3+}$ luminescence by co-doping of C

- C doping:
  - Increases the number of high energy excitons (which can efficiently excite Tb ions)
  - Strongly enhances Tb$^{3+}$ luminescence

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Candidate of wide bandgap: 2. Si rich Si nitride

Wavelength tuning by Si content
• Strong visible covering from RED to BLUE
  → Can be also utilized as host matrix of RE for visible RE luminescence? YES
Green Tb luminescence is also possible from Tb-doped SRSN. The sharp strong visible RE luminescence from nc-Si based wide bandgap such as SRSO:C and SRSN:

→ Can be used for other RE ions (Eu, Er, Tm, Pr, and Sm)
→ Feasibility of RGB display pixel integrated on single Si chip
Summary & Conclusion

- **Advantages of nc-Si over bulk semiconductor for RE doping**
  - Separation of RE from carriers: suppress the de-excitation
  - But still holding benefit of nc-Si: efficient excitation cross-section

- **Photonic implication of advantages of nc-Si**
  - Suppression of de-excitations and efficient luminescence: optical gain from nc-Si sensitized Er-doped waveguide amplifier
  - Exciton mediated excitation: simultaneously exciting two different RE ions & pumping with non-resonant visible source

- **The expansion of luminescence band to visible from nano-cluster Si**
  - Suitable impurities can increase optical transition
  - Strong green luminescence can be accomplished from Tb-doping
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