ACTIVE, Si-BASED PHOTONIC BANDGAP AND MICROPHOTONIC STRUCTURES BASED ON RARE EARTH DOPED HYDROGENATED AMORPHOUS Si ALLOYED WITH CARBON

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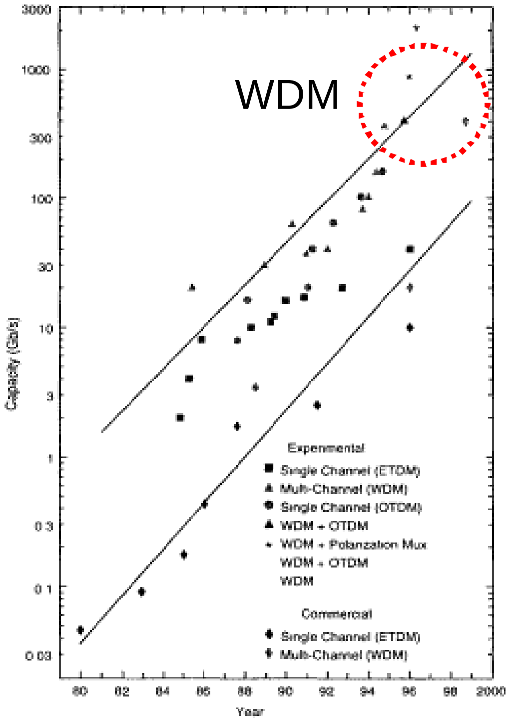
Outline

- **Si based microphotonics**
- **a-Si:H:C as a viable material for Si-based microphotonics**
- **Er-doped a-Si:H:C**
  - **Structural properties**
  - **Optical properties**
- **Microphotonics using a-Si:H:C**
  - **Photonic crystal**
  - **Microdisk**
- **Conclusion**

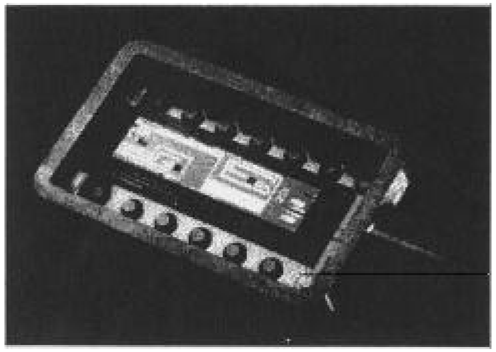
Introduction

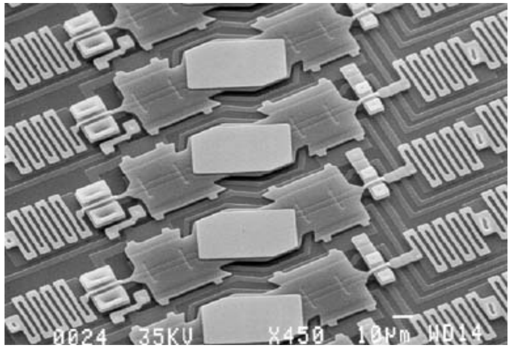
- **Photonics: the next “killer” application (X100/10yrs)**

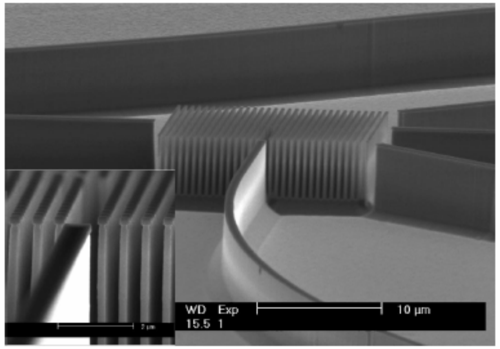


… but based on unsustainable manufacturing processes

- **Si microphotonics**
  - Microphotonics based on Si and Si-compatible processes
  - Bringing the astronomical Si processing infrastructure and know-how to photonics
  - Si itself is an excellent optical material with high transparency in the infra-red region and chemical/mechanical strength
  - But lack of optical activity limit its use to passive devices







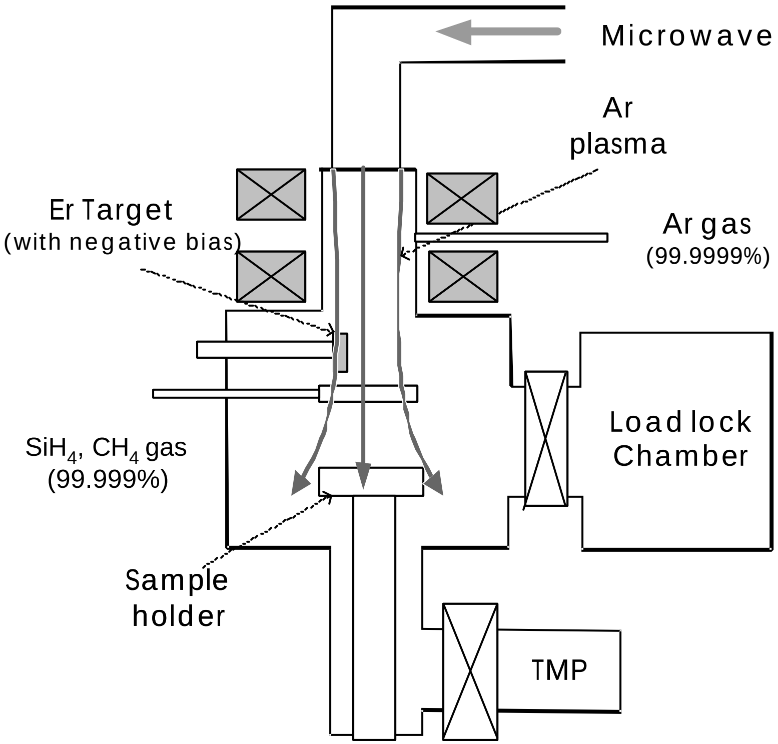
… because if you can do it with silicon, you MUST do it with silicon

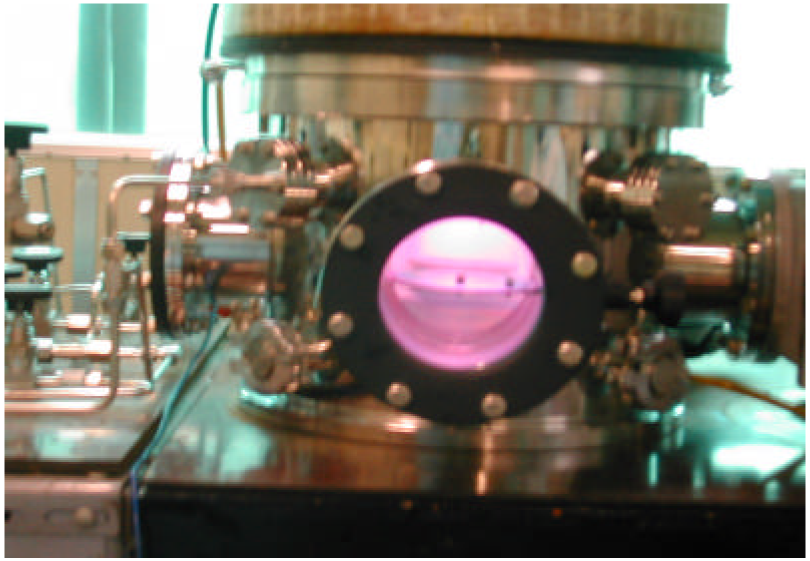
Hydrogenated amorphous Si and SiC (a-Si:H and a-Si:H:C)

- **a-Si:H: Low-cost alternative to crystalline Si**
  - Large area, low-cost deposition on optical substrates (quartz, glass)
  - Highly transparent in the infra-red region (< 3dB cm^{-1} Peuzin, Opt. Comm 1984)
  - Variable refractive index for added freedom in design
  - Very smooth surface and compatibility with the standard Si processes for smooth sidewalls
  - Low-temperature deposition allows photonics fabrication to be a back-end process

- **a-Si:H:C**
  - Isovalent impurity with Si: for small carbon concentration (< 40% of Si), very similar to a-Si:H in terms of material and electronic structure
  - Mature material – used frequently in high-efficiency solar cells
  - Larger bandgap than a-Si:H
  - Carbon demonstrated to be an activating ligand for Er (Michel, PRB 1991)

Deposition of the Er-doped a-Si:H:C





- **ECR-PECVD of SiH_4 and CH_4 with concurent sputtering of RE**
  - No metalorganic precursor needed → no organic contamination
  - Substrate: Corning 1737 glass
  - Base pressure: 1×10^{-7} torr   Dep. Pressure: 1×10^{-4} torr
  - Microwave power: 400W   Dep. Temp: 250 ℃

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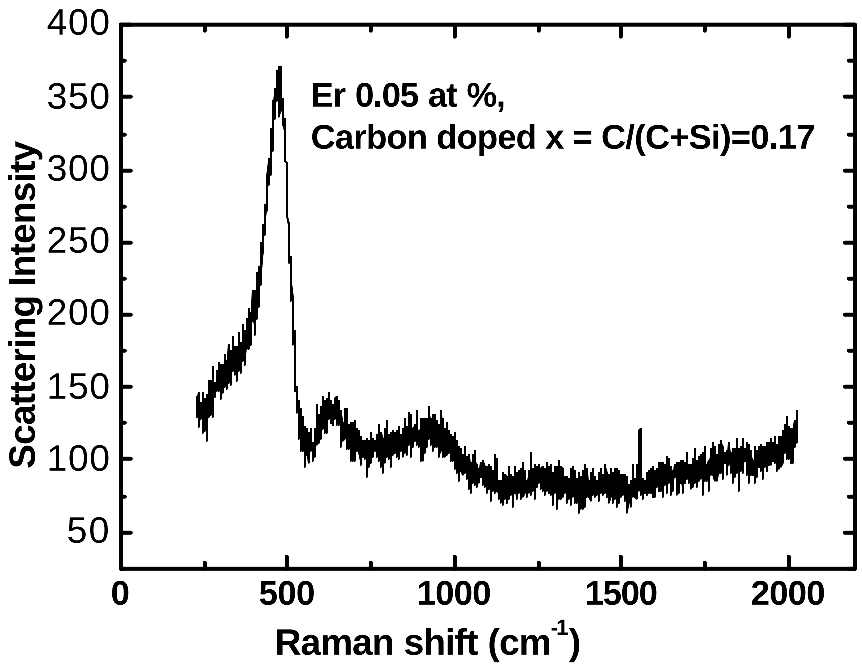
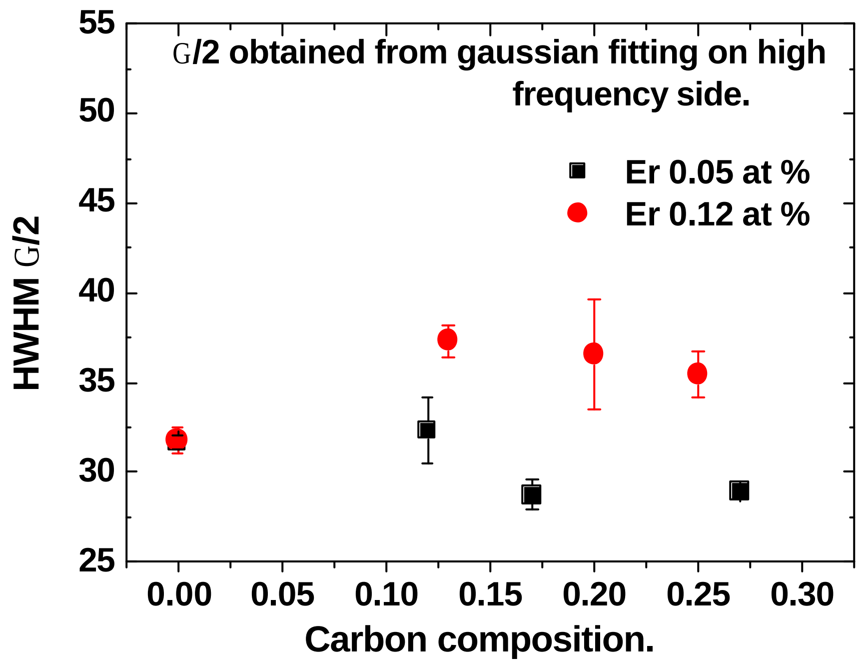
Results

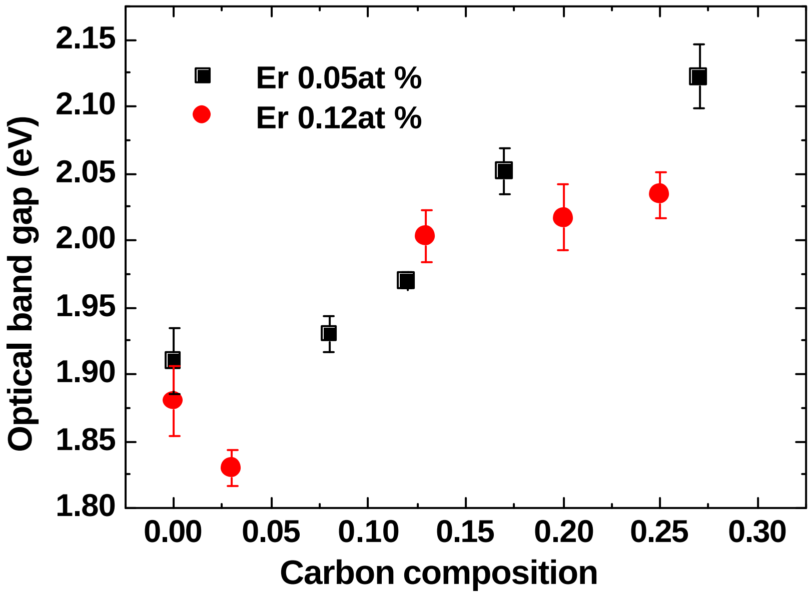
- **Material structure**

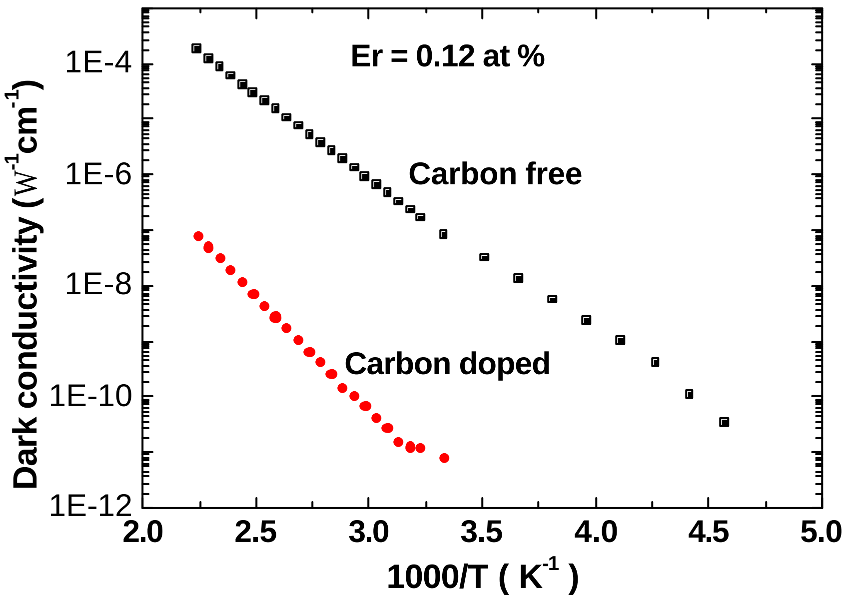




- **Raman spectra of Er-doped a-Si:H:C**
  - Strong Si-Si bond (300-600 cm^{-1}), weak Si-C bond (600-1000 cm^{-1}), but no C-C bond (1300-1600 cm^{-1}) ➔ No carbon clustering, with carbon mostly in CH_2 and CH_3 form
  - $\Gamma/2$ value of 32 cm^{-1} ➔ good short range order with little bond angle distortion
  - Carbon co-doping dos not increase $\Gamma/2$ value ➔ carbon does no induce structural disorder

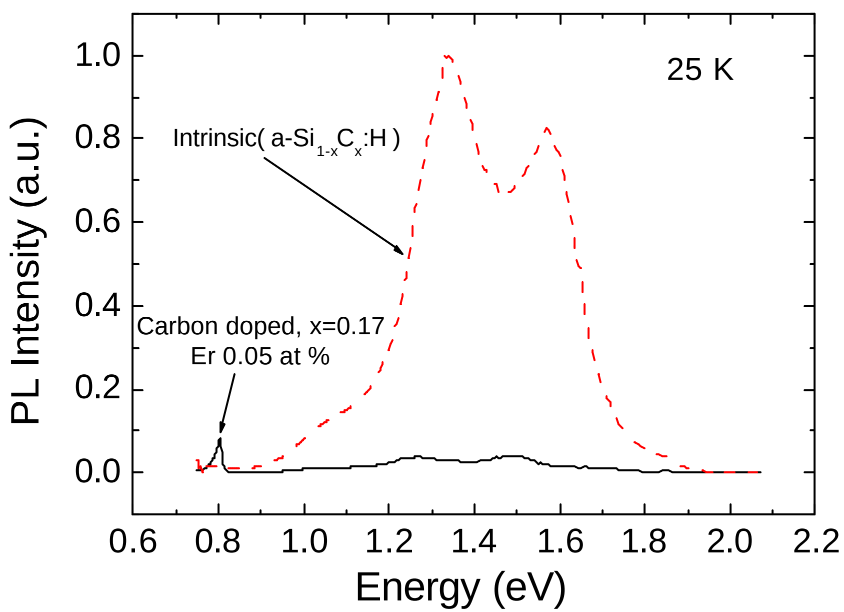
- **Electronic structure**

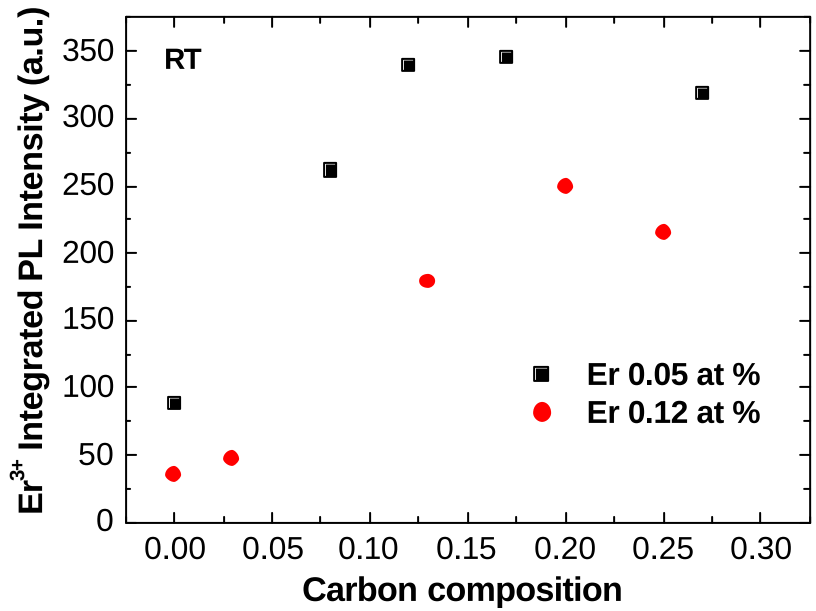




- **Effect of carbon co-doping:**
  - Carbon co-doping Increases the optical bandgap (Tauc gap) irrespective of Er concentration
  - Carbon co-doping strongly reduces the dark conductivity while retaining semiconducting behavior, consistent with the larger bandgap

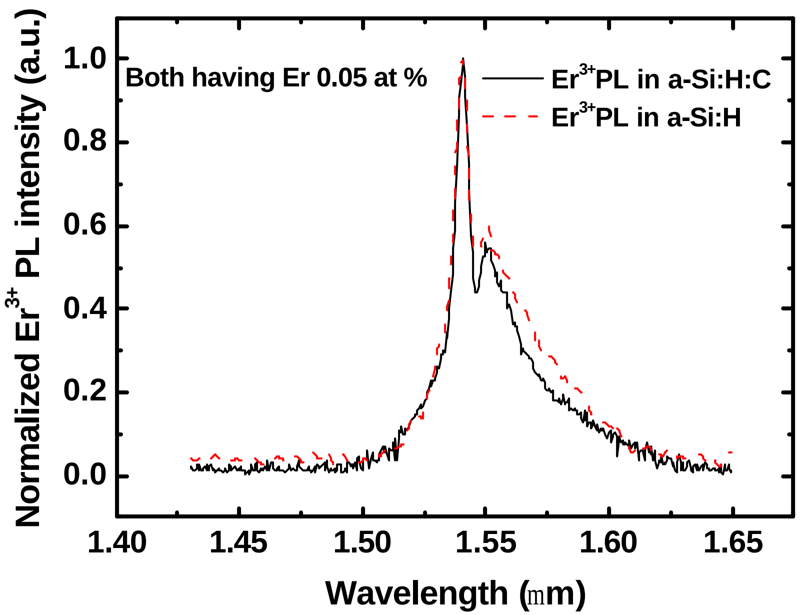
- **Photoluminescence**

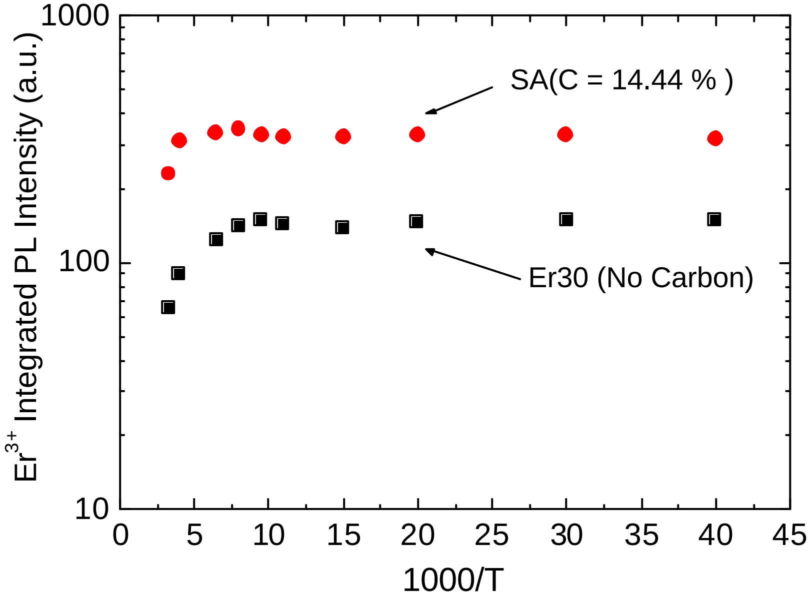




- **Photoluminescence using 477 nm line of Ar laser**
  - Er doping nearly completely quenches the intrinsic a-Si:H:C luminescence (peaks in the a-Si:H:C PL are optical artifacts due to multiple reflection in the film)
  - Er PL intensity is much weaker than the a-Si:H:C PL intensity
  - Up to 4fold increase in the RT Er PL intensity by C co-doping!

- **Cont'd**

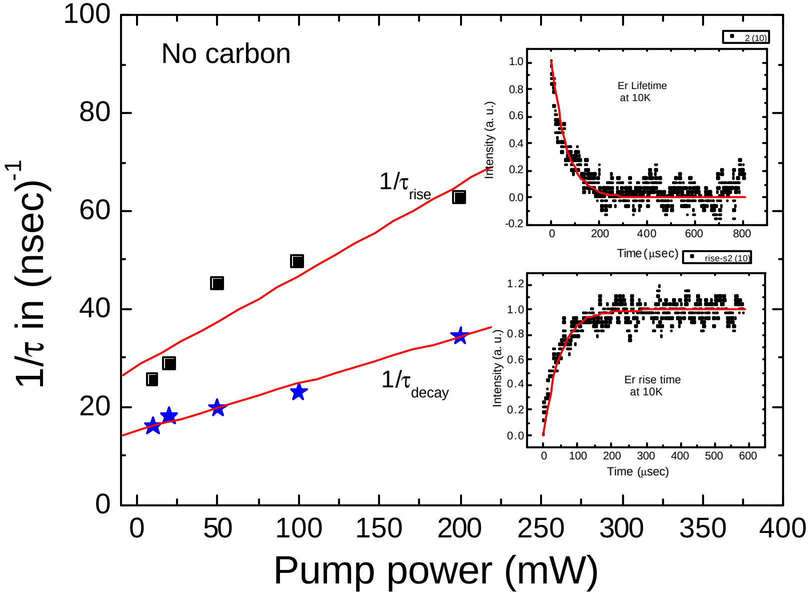


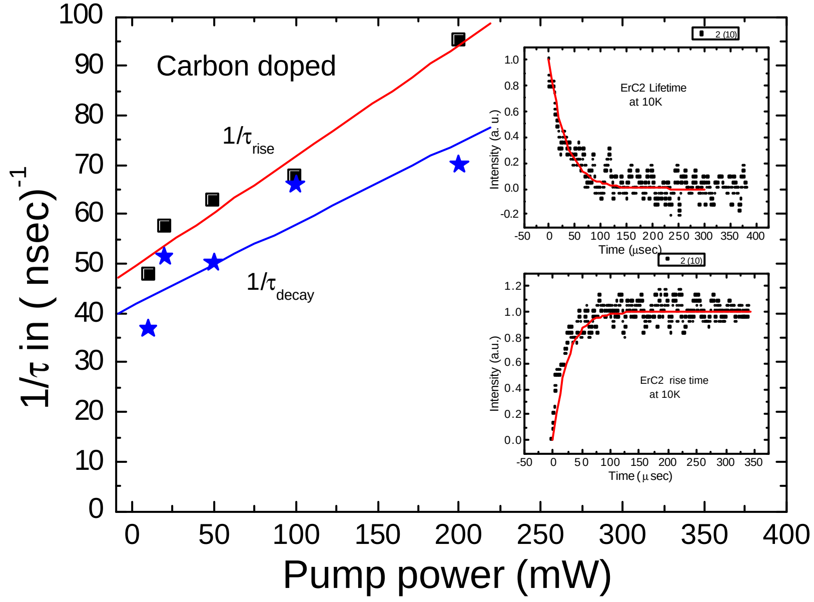


- **Carbon co-doping**
  - Has only small effect on Er^{3+} PL spectrum
  - Reduces temperature quenching from 50 to 30 %

Discussion

- **Effects of carbon on Er^{3+} luminescence**
  - Gettering of carbon by Er: No change of Er^{3+} PL spectra ➔ likely not critical
  - "Activation" of Er by carbon: 2 fold PL increase upon 100 fold increase in C ➔ likely not critical
  - Matrix – Er interaction?



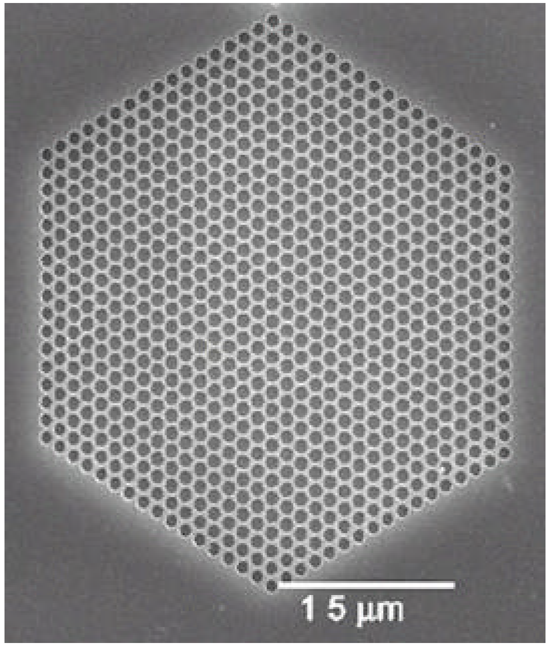


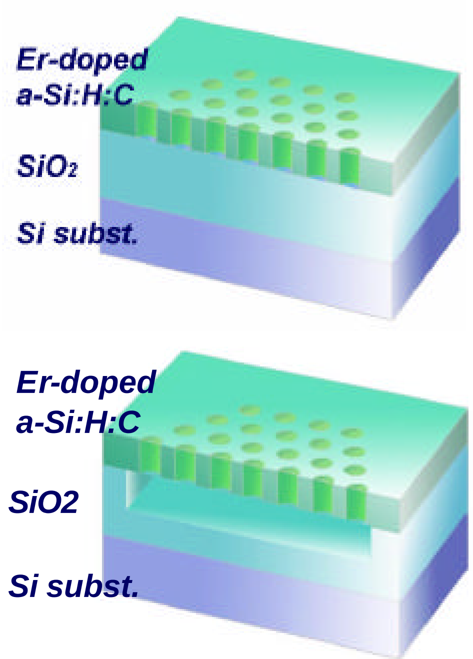
- **Time resolved measurements of luminescence rise and decay**
  - Difference in slope gives effective excitation cross section: $1\pm0.5\times10^{-15}$ cm^{-2} for both carbon-free and carbon doped film

  ➔ The most important effect of carbon co-doping is suppression of temperature quenching

Microphotonics using a-Si:H:C:Er

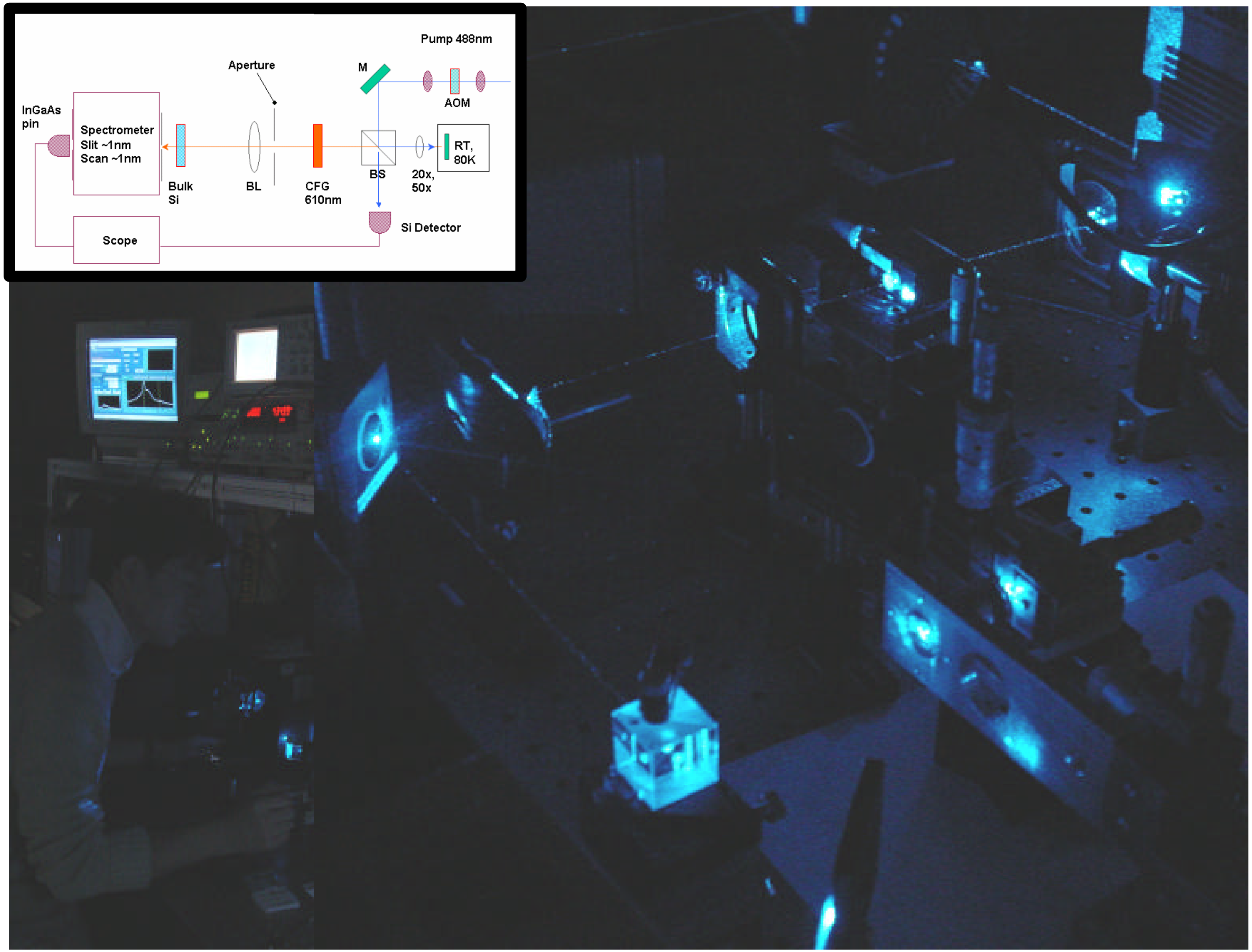
- **2D slab photonic crystal using Er-doped a-Si:H:C**
  - a-Si:H:C: sufficient refractive index contrast for photonic crystal
  - a-Si:H:C:Er → active, Si-based photonic crystal!



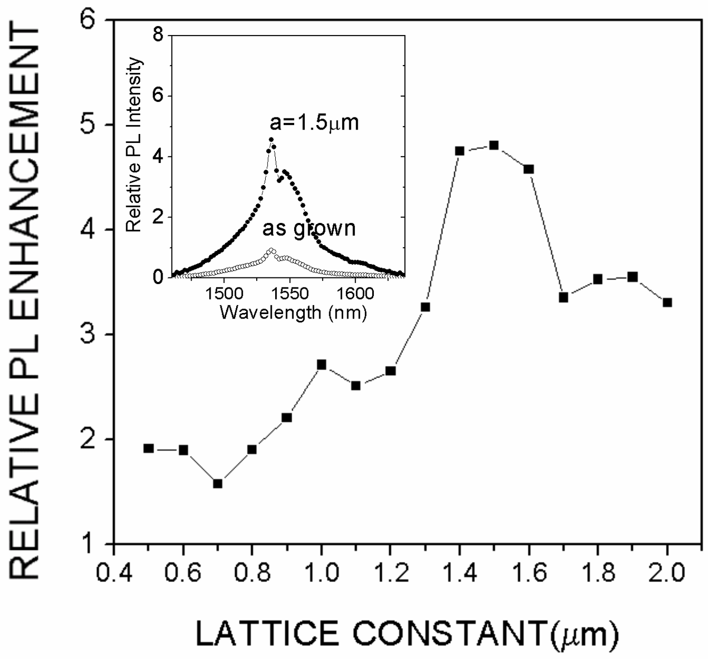


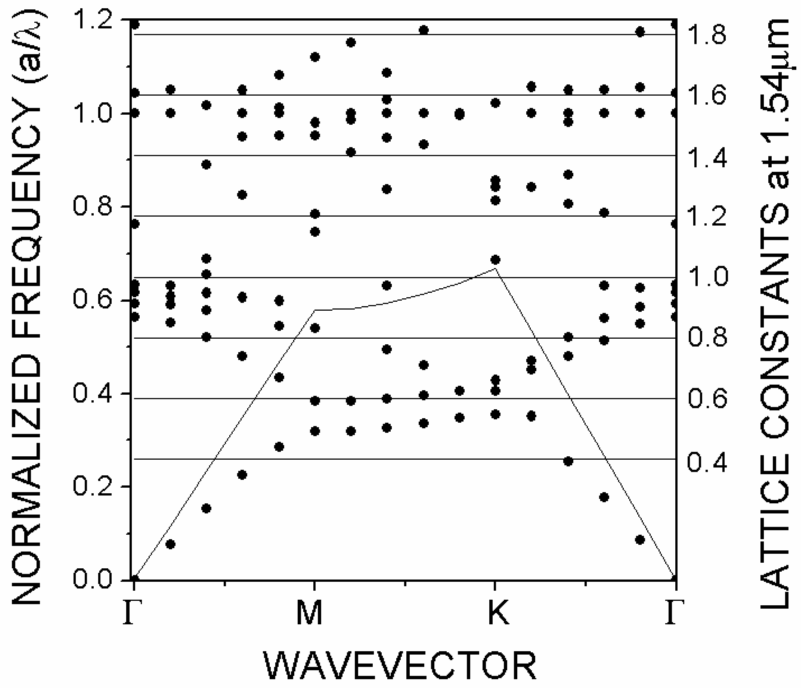
- 0.5 μm thick Er-doped a-Si:H:C on 5 μm thick thermal oxide
- Triangular lattice of holes with r/a fixed at 0.3
- Au + PMMA → E-beam litho → Ion milling → RIE → plasma ashing + mask removal
- Free-standing structure formed by BOE etching of SiO_2 layer

Experimental setup



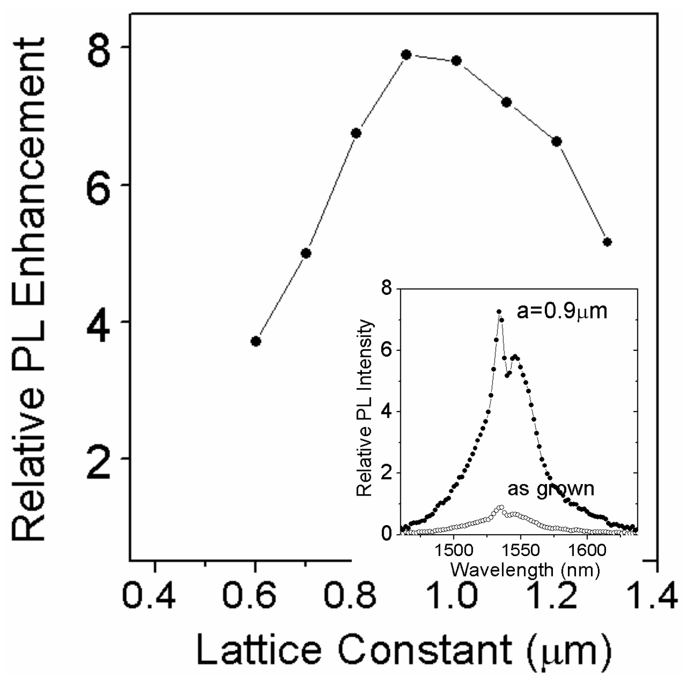
- **Enhanced light extraction from photonic crystal: oxide clad structure**
  - Strong coupling of in-plane radiation with vacuum mode

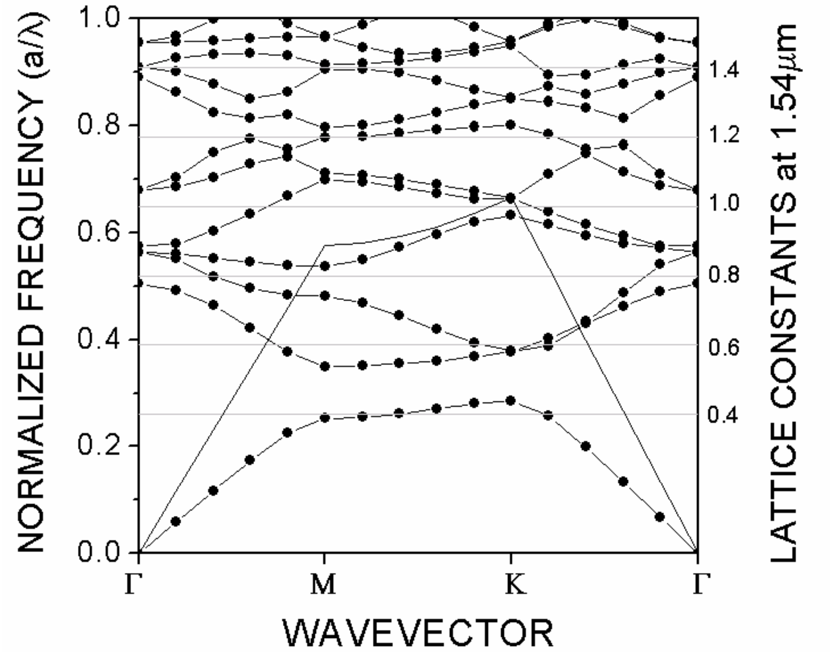




- 3D FDTD calculation of photonic bands
- 5 fold relative PL enhancement near normalized frquency of 1 at room temperature

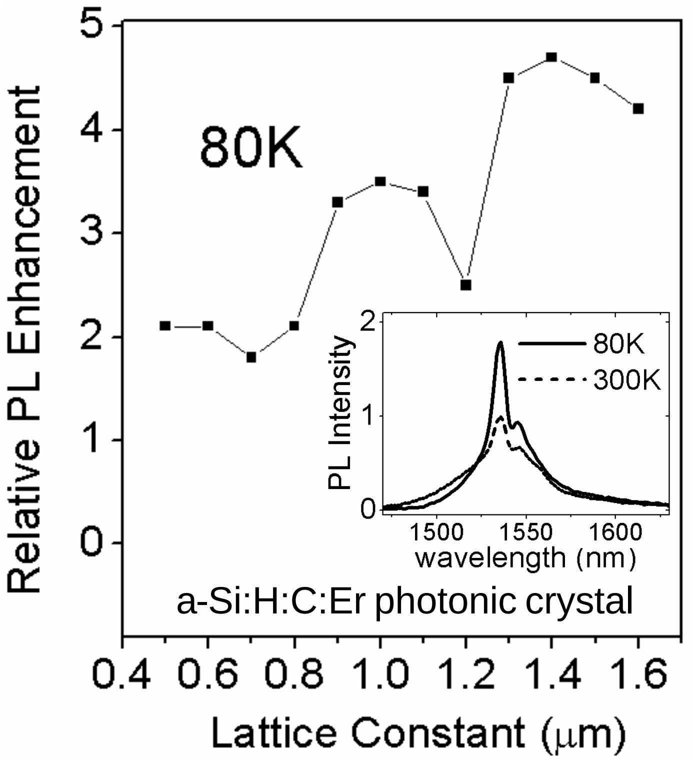
- **Enhanced light extraction from photonic crystal: free-standing structure**
  - Stronger coupling of in-plane radiation with vacuum mode

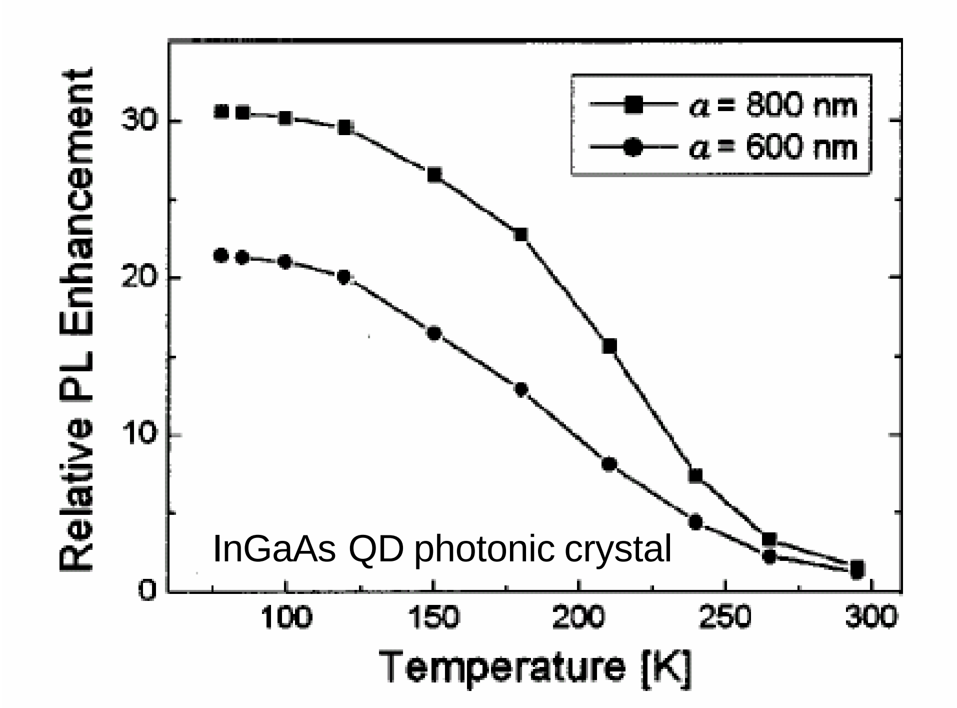




- 3D FDTD calculation of photonic bands
- Full bandgap for TE-like mode observed
- 8 fold relative PL enhancement near normalized frquency of 0.6

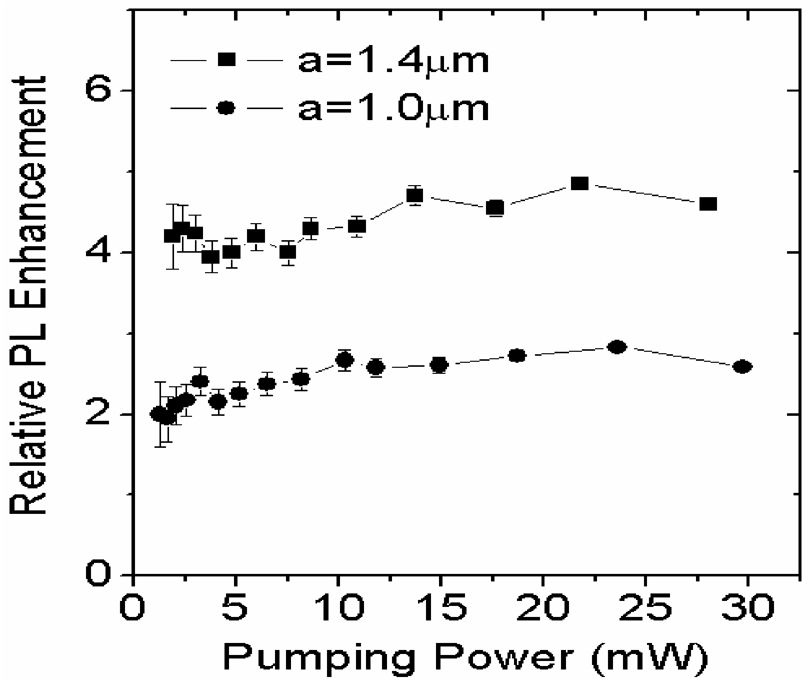
- **Advantage of using Er-doped a-Si:H:C**
  - Insensitivity to temperature





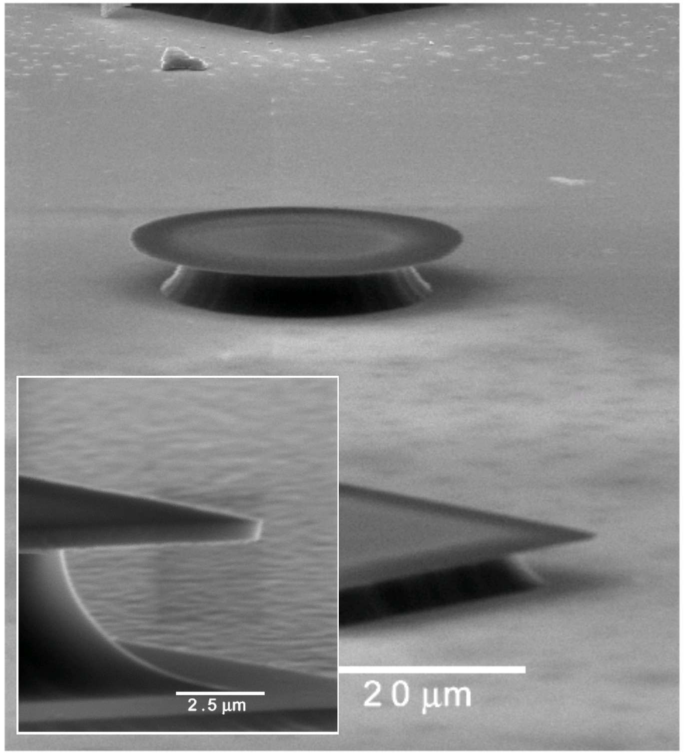
- Near complete independence of extraction efficiency on temperature, quite unlike that observed for III-V compound semiconductor-based photonic crystals
- Slight hump near 0.6 due to change in PL shape

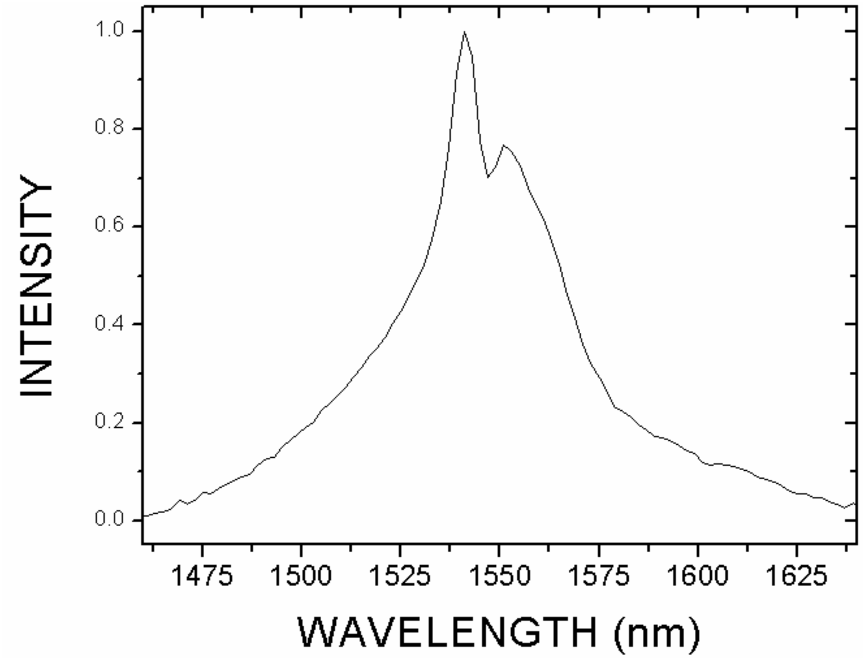
- **Advantage of using Er-doped a-Si:H:C**
  - Insensitivity to pump power



- Near independence of the extraction efficiency on the pump power, quite unlike that observed for III-V compound semiconductor-based photonic crystals
- Surface recombination nearly negligible for Er^{3+} luminescence from a-Si:H:C ➔ consequence of an atomic transition excited via trapped carriers

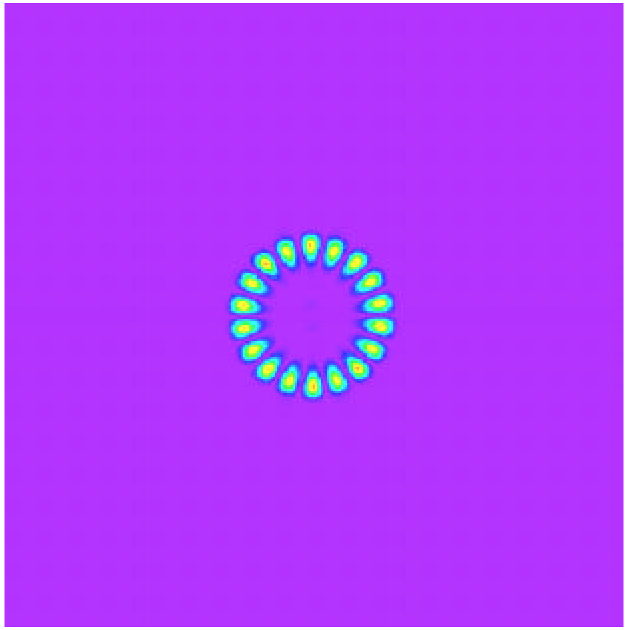
- **Microdisk resonator based on Er-doped a-Si:H:C**

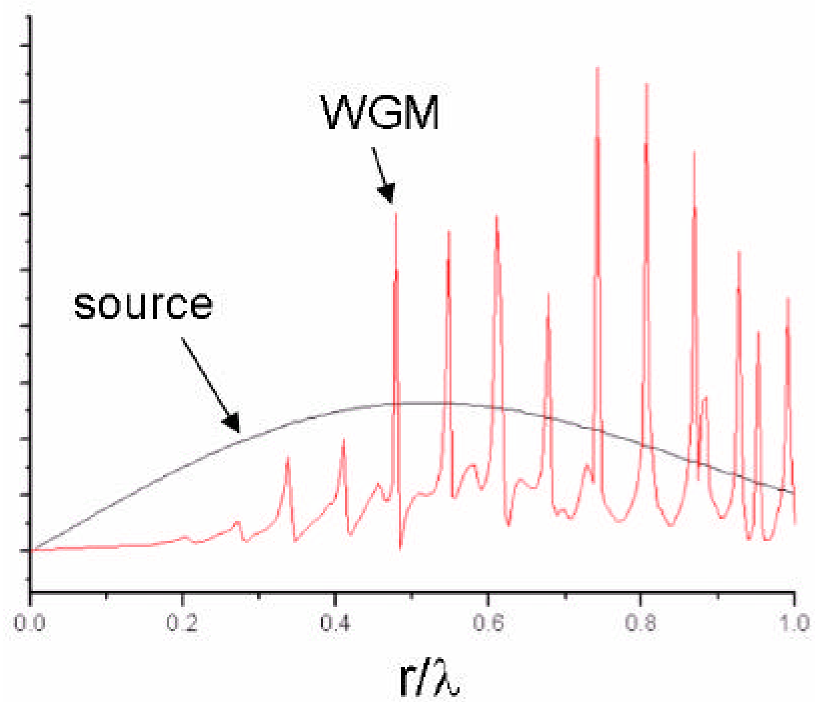




- Microdisks with smooth wall and edges formed by optical litho and BOE etch
- Er^{3+} optical activity unaffected by lithography and etching

- **Expected modes in fabricated microdisks**





- Whispering gallery modes for 10 μm microdisk: mode spacing of only 6 nm ➔ too low S/N ratio to observe mode vertically
- For a microdisk with moderate Q of 10^5, the lifetime of WGM is 80 ps ($T = Q/(2\pi(\lambda/c))$) ➔ it will travel for 1 cm!

Conclusion

- **Er-doped a-Si:H:C demonstrated as a viable material for active, Si based microphotonics**
- **Carbon co-doping results in 4-fold increase in RT Er^{3+} PL intensity without adversely affecting material or electronic structure of the material.**
- **2D slab photonic crystal based on Er-doped a-Si:H:C demonstrated**
  - **Up to 8-fold increase in the relative PL extraction efficiency**
  - **Near complete insensitivity to the environmental factors**
- **Microdisks based on Er-doped a-Si:H:C demonstrated**
  - **Process-insensitive Er^{3+} PL demonstrated**

Acknowledgment

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