Silicon Laser – impossible possibility

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Outline

- **Overview & Key findings**
- **I. Silicon Laser Feasibility**
  - *Edge-emission spectra*
  - *Optical Gain*
  - *Threshold and Stimulated Emission*
  - *Spectral and Spatial Coherence*
- **II. Establishing Principles**
  - *The A-centers*
  - *Phonon-Localization and Enhanced Radiative Recombination*
  - *Photocurrent Spectroscopy*
  - *High-Resolution TEM Analysis*
- **Summary**

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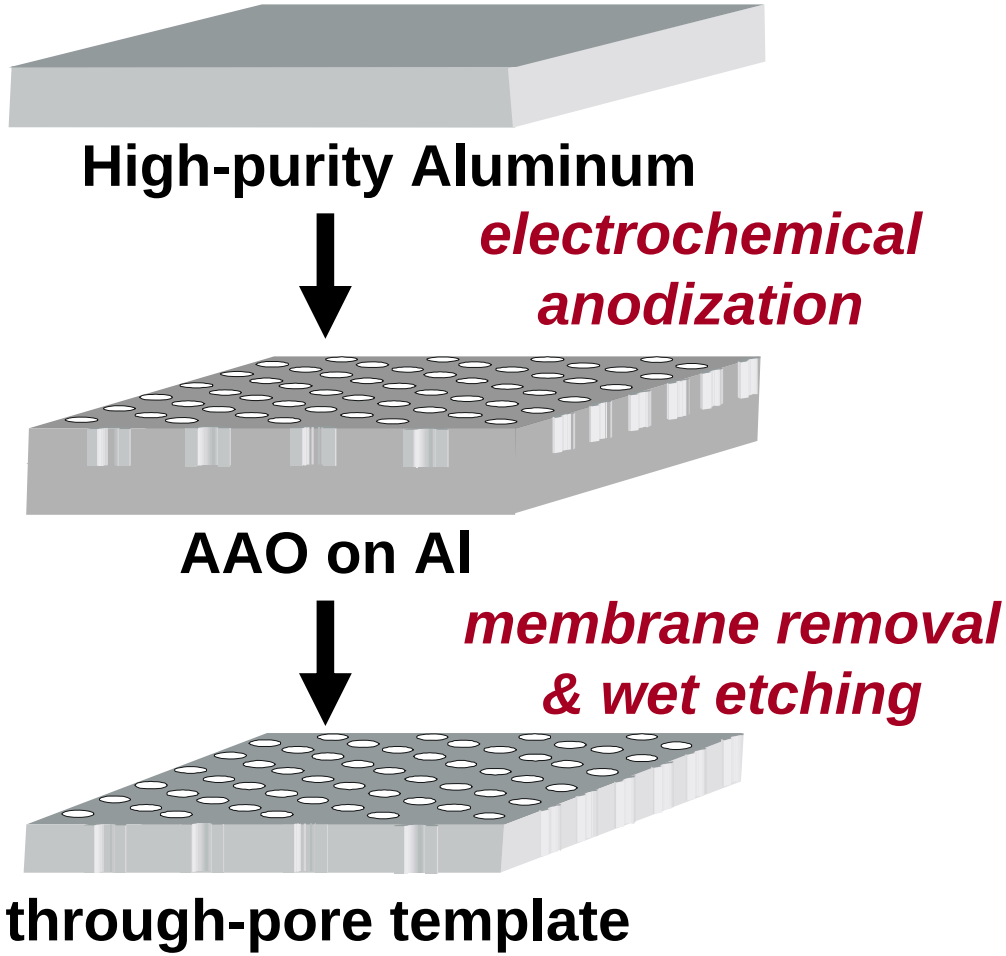
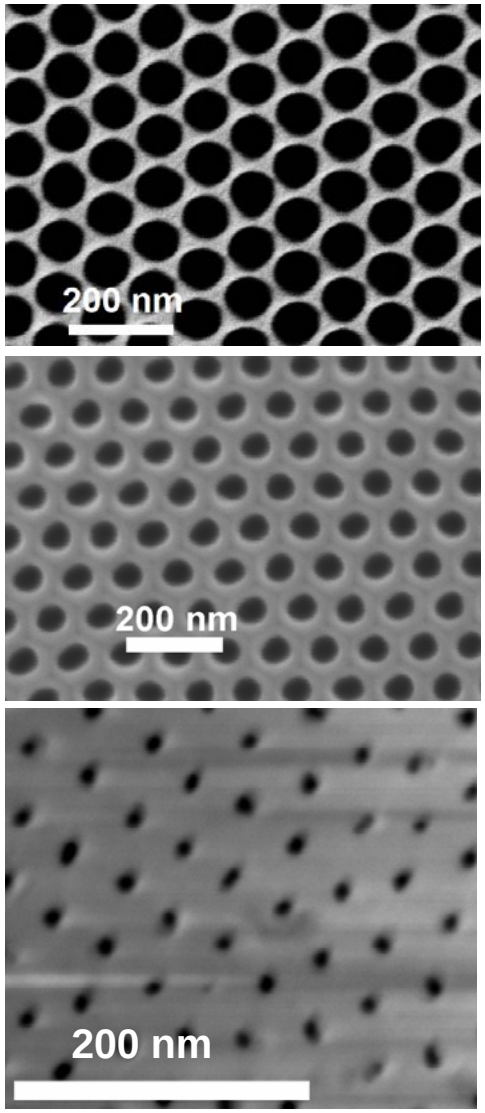
Fabrication, Nonlithographic, Control





- *Large-field sub-50 nm feature remains a challenge for lithography*
- *A non-lithographic and but controllable approach.*
- *Highly-ordered and uniform array template, and*

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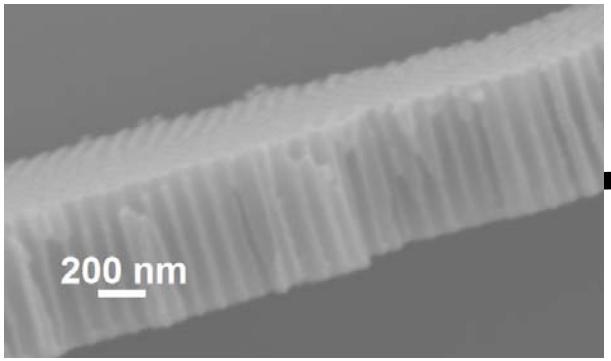
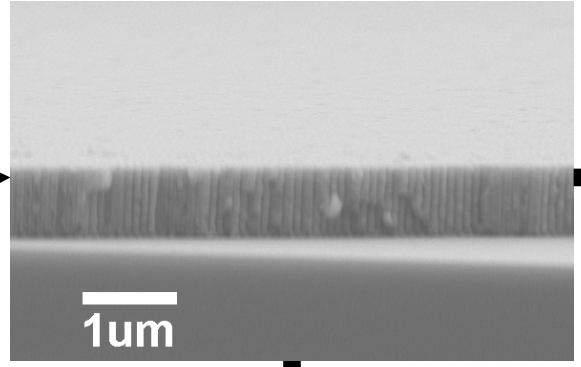
Fabrication 2nd step: Pattern Transfer

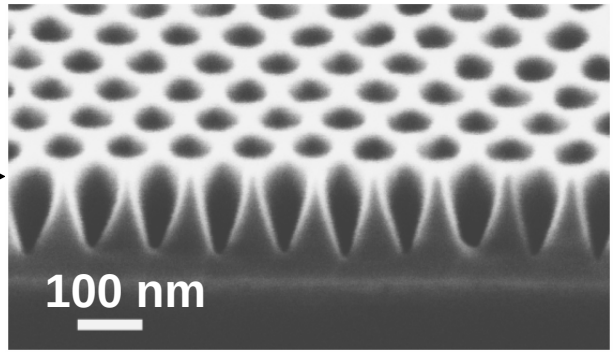
Free-standing AAO nanopore template

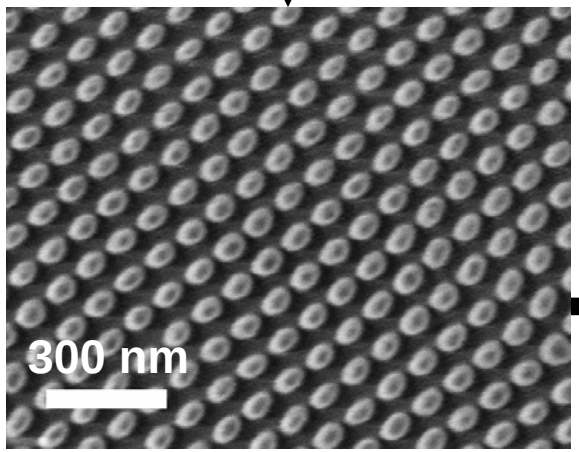


Deposition atop SOI substrate

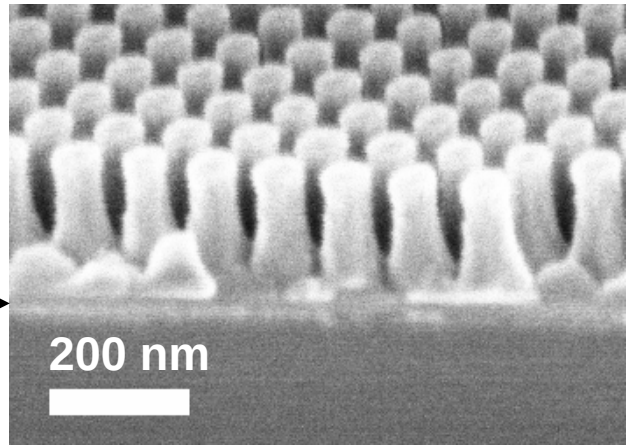


RIE pattern transfer and AAO removal



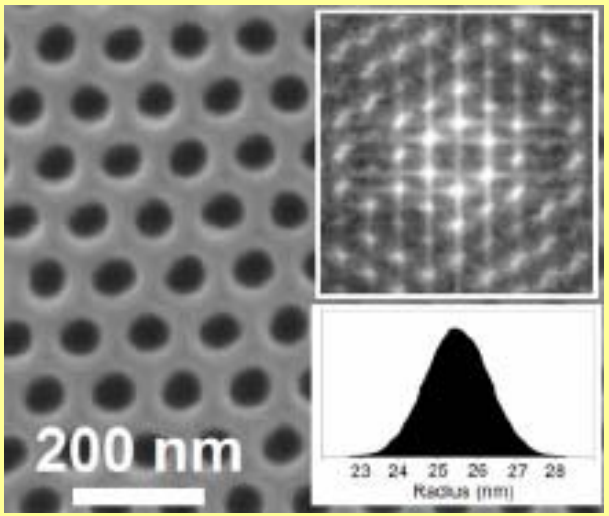


Metal evaporation and AAO removal



RIE pattern transfer

The AAO mask



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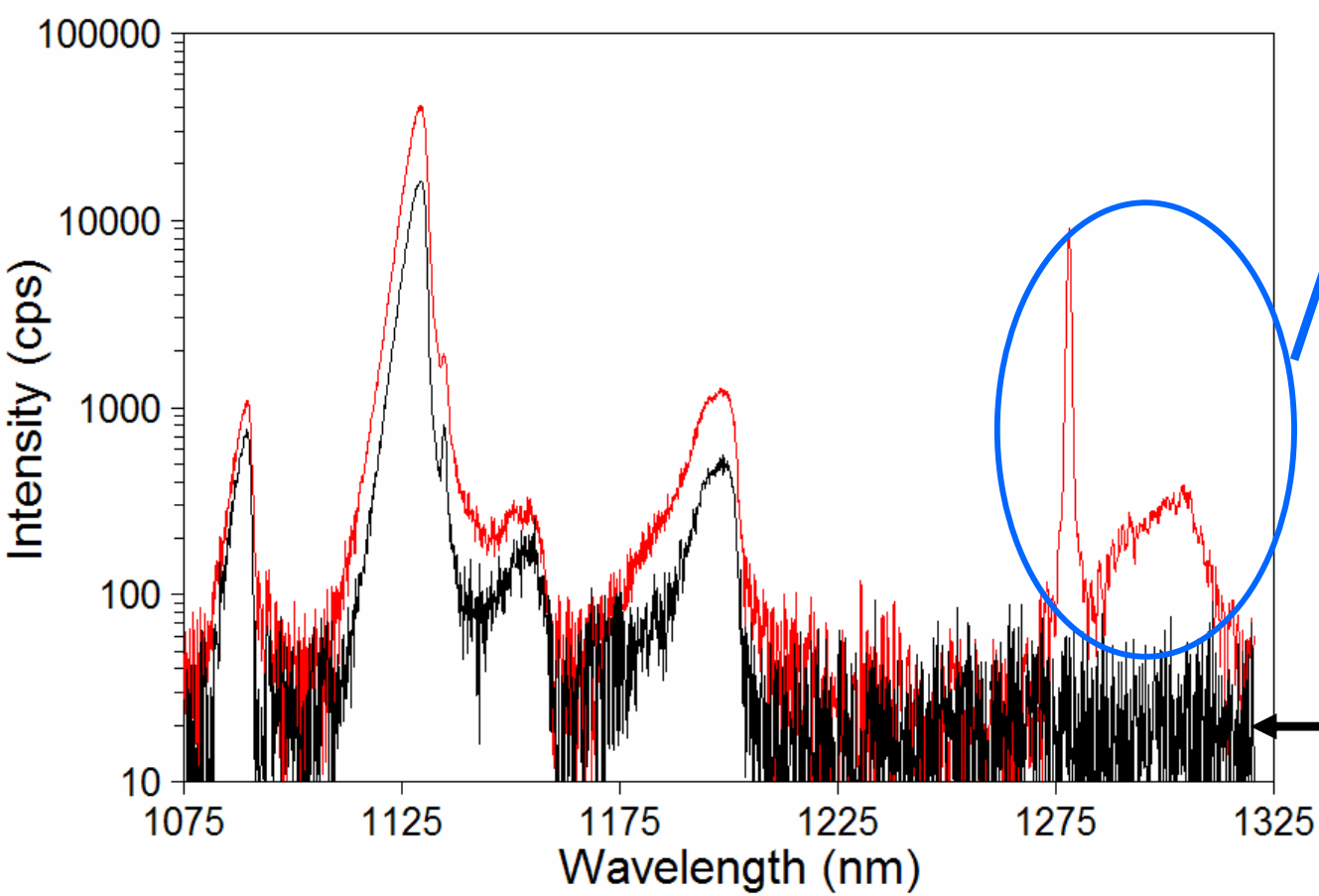
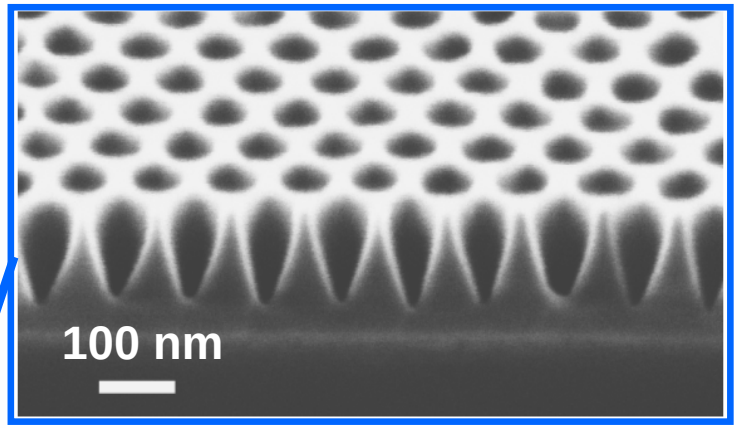
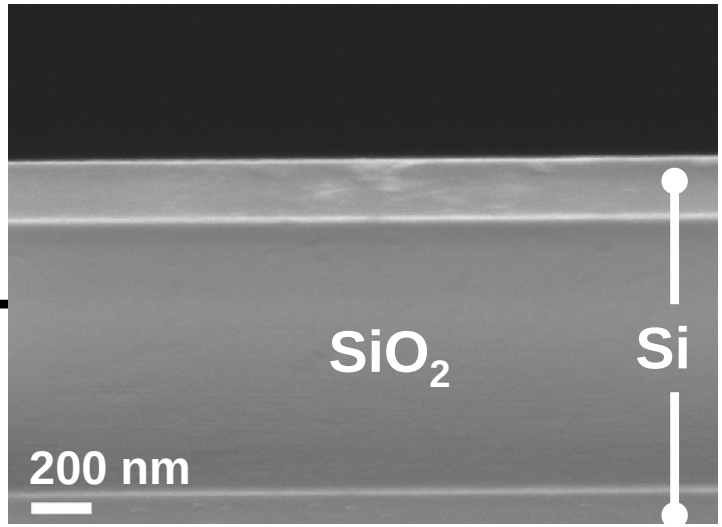
Silicon Laser Feasibility







- ***No such sub-bandgap emission was observed from reference un-patterned SOI samples, or bulk silicon.***

S.G.Cloutier, P.A.Kossyrev and J.M.Xu, Nature Materials, 4, 887-891, 2005
S.G.Cloutier and J.M.Xu, Condensed Matter Archives, Arxiv cond-mat/0412376, 2004

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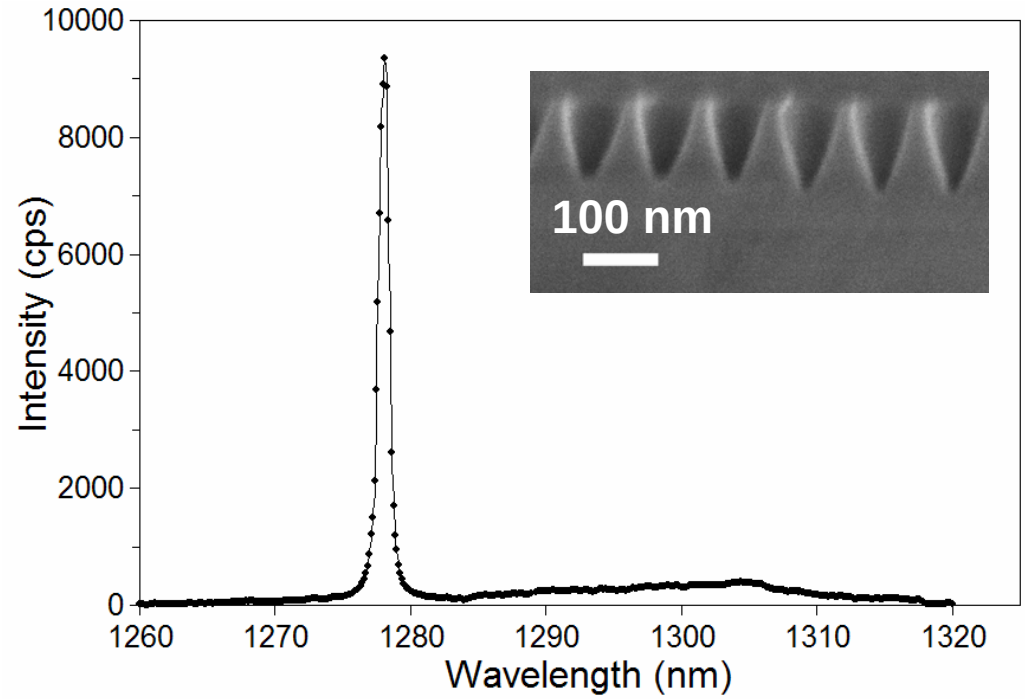
Key Findings: Emission Properties



- ***Emission observed in the nano-patterned SOI samples, not in "controls"***
- ***Net optical gain coefficient up to 260 cm^{-1} at 1278 nm and 10 K .***
- ***Threshold transition, linewidth narrowing and gain transition, all confirming Amplified Stimulated Emission.***
- ***Linewidth Narrowing, Resonant cavity feedback modes and narrow far-field emission angle, measures of spectral and spatial coherence respectively.***

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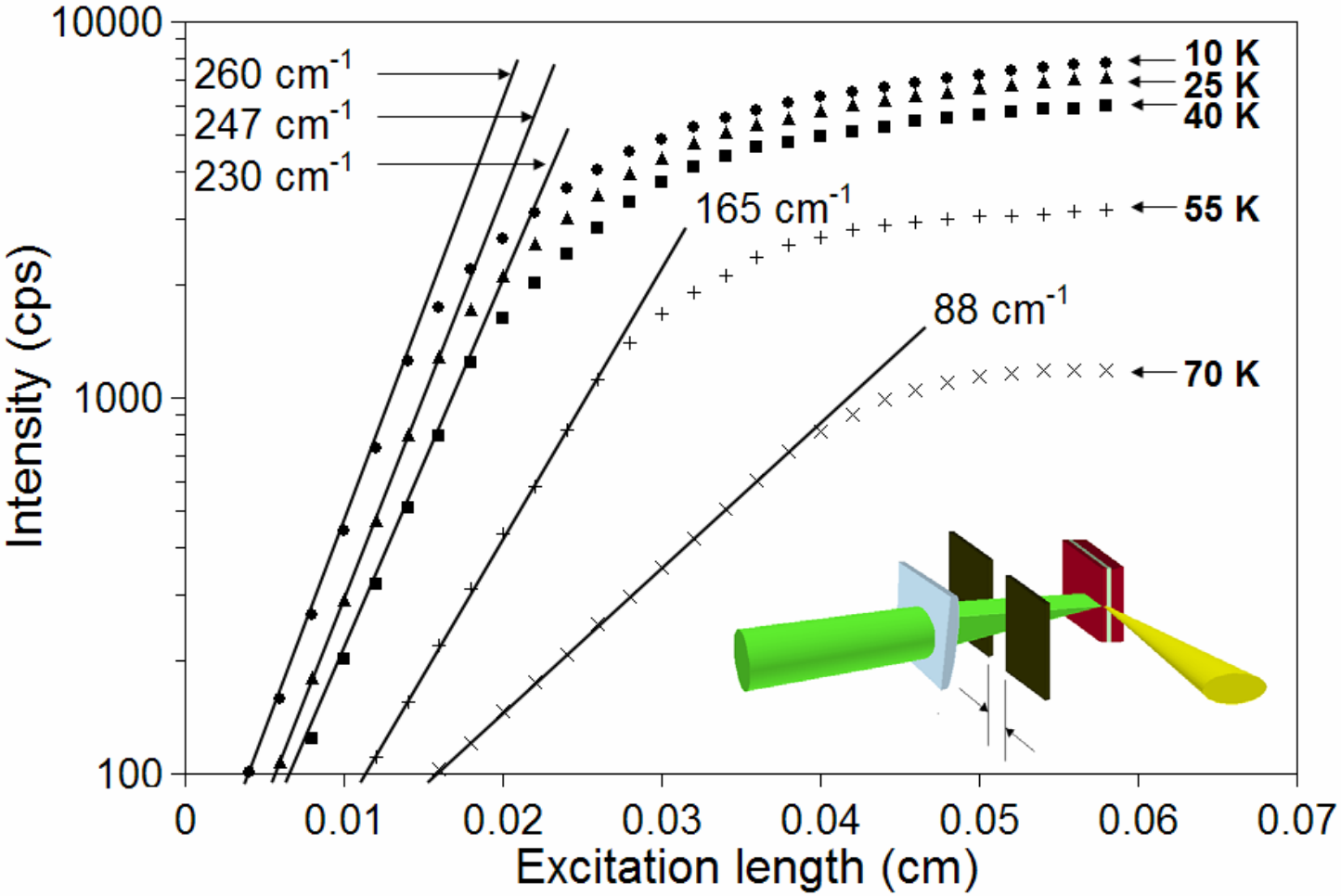
Optical Gain Measurements



Net optical gain coefficient (G):

$$G = \Gamma g - \alpha$$

$$G = \frac{\ln(P_{i+1} / P_i)}{L_{i+1} - L_i}$$

Shaklee, J. Lumin. **7**, 284 (1973)

The measured gain coefficients appear surprisingly large, but has a short saturation length.

S.G.Cloutier, P.A.Kossyrev and J.M.Xu, Nature Materials, 4, 887-891, 2005
S.G.Cloutier and J.M.Xu, Condensed Matter Archives, Arxiv cond-mat/0412376, 2004

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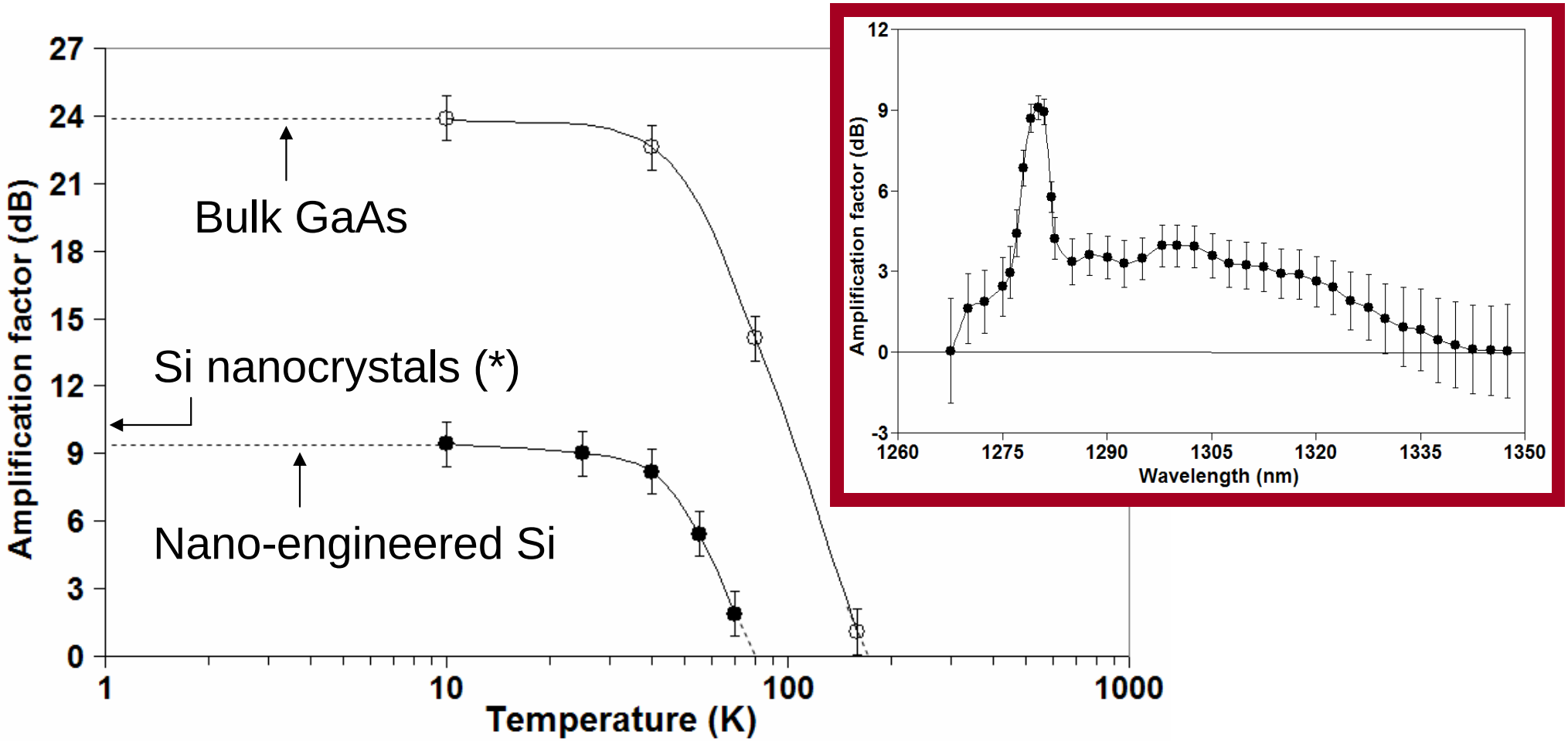
Optical Gain Measurements

The associated total amplification factor turns out to be quite reasonable.

$$A_{(dB)} = 4.434 \text{ x } G \text{ x } L_S$$



(*) L. Pavesi *et al.*, Nature 408, 440 (2000)

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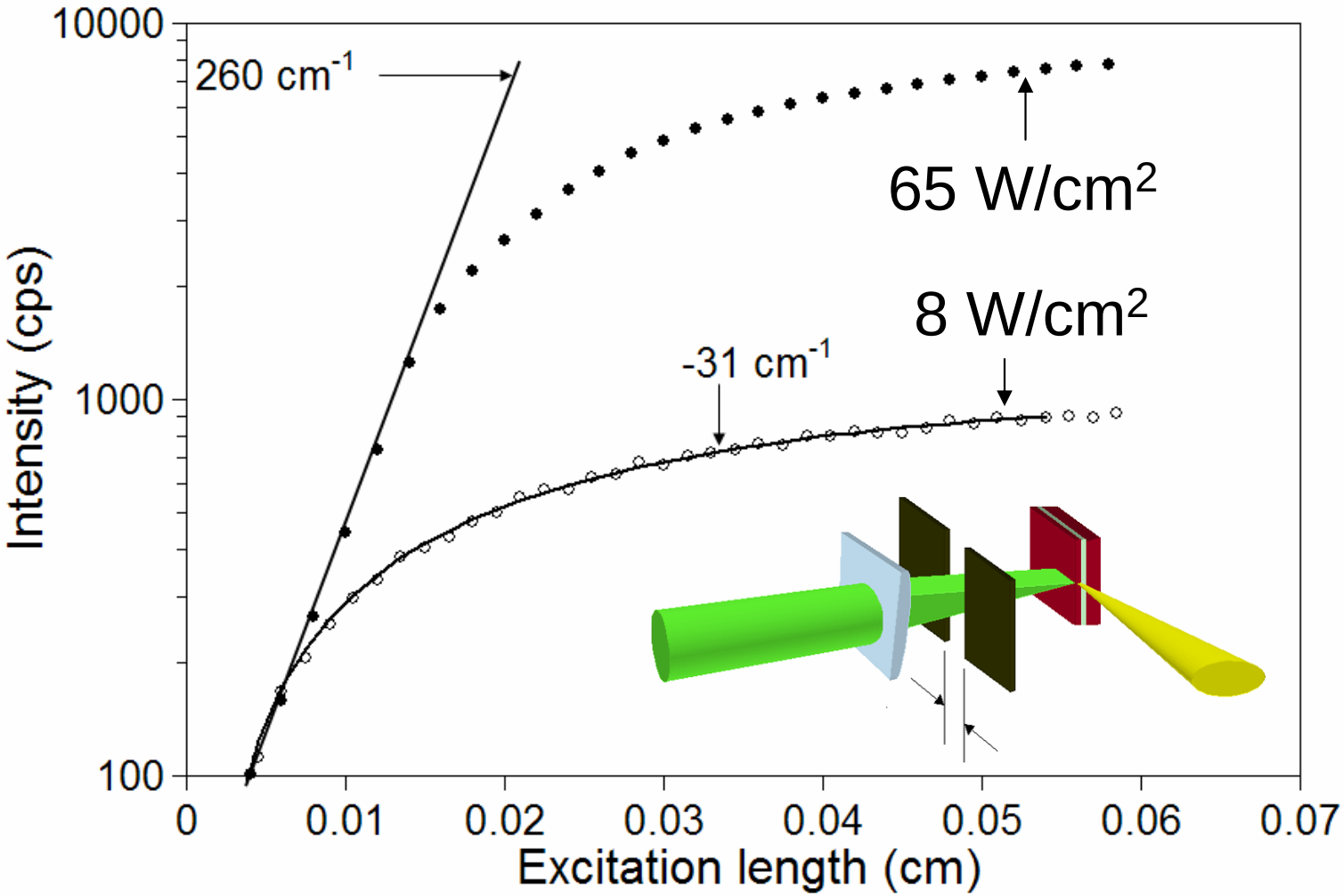
Optical Gain and Stim. Emission



By increasing the pump power density, the net gain coefficient goes from negative (propagation loss dominated) to positive (gain), a clear indicator of stimulated emission.

S.G.Cloutier, P.A.Kossyrev and J.M.Xu, Nature Materials, 4, 887-891, 2005

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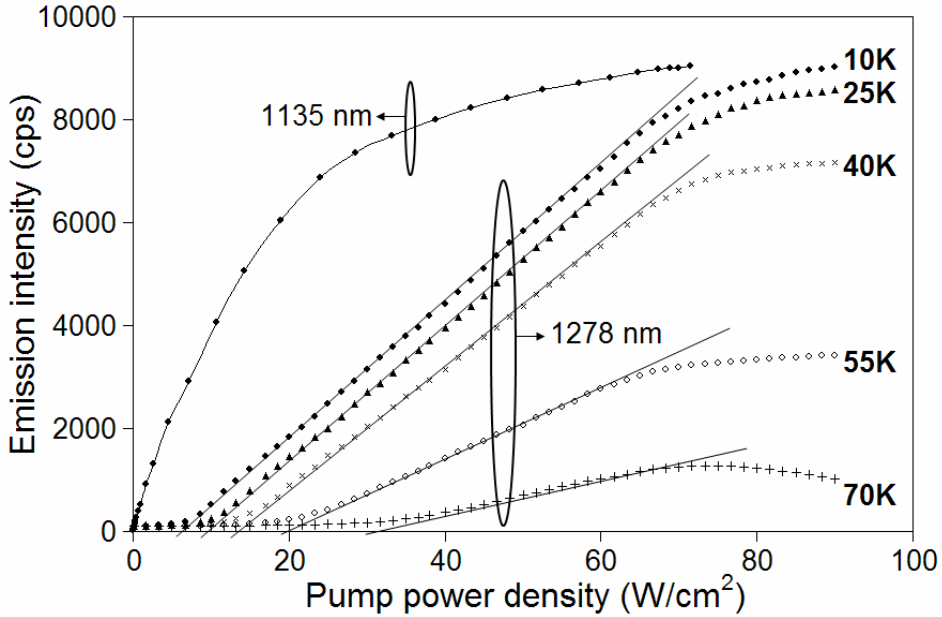
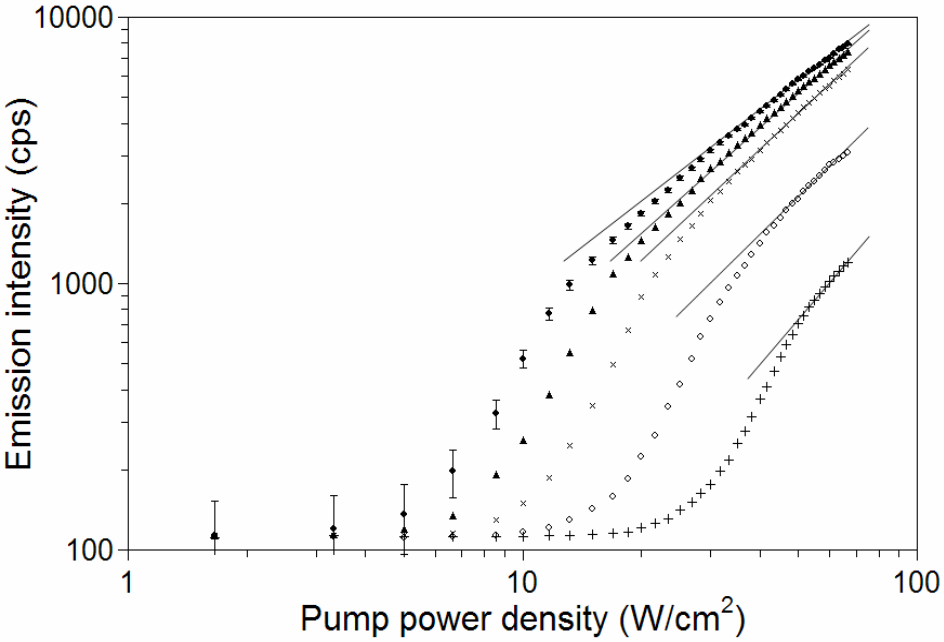
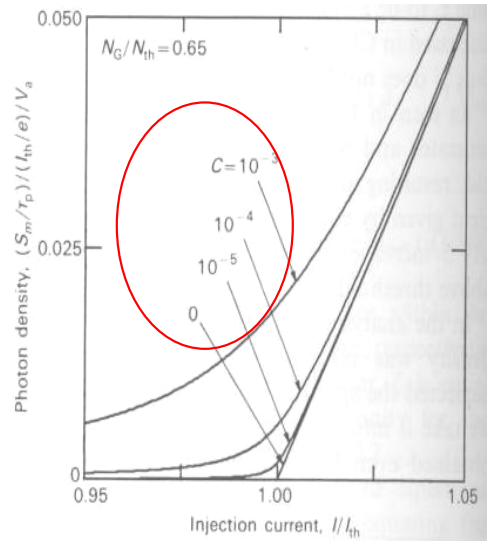
Stimulated Emission

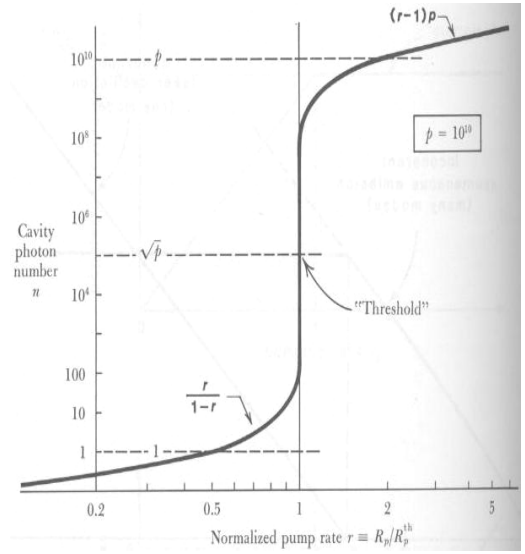




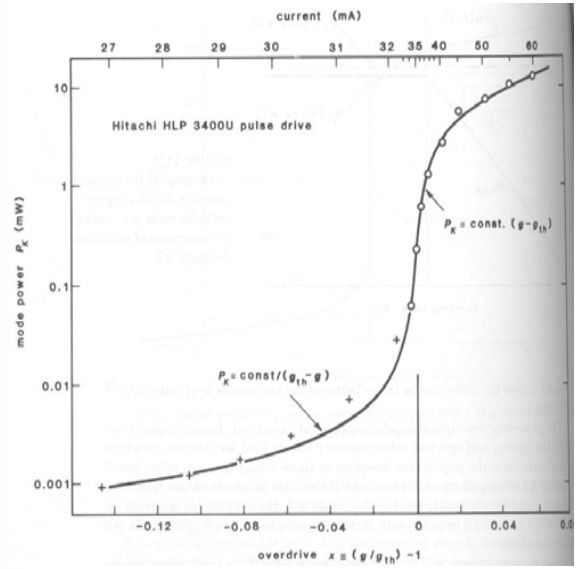
Suematsu, (1994)



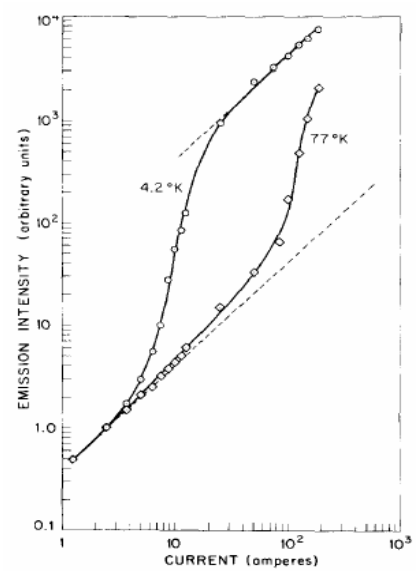
Siegman, Laser (1986)



Theory



Siegman, Laser (1986)



Quist, APL **1**, 91 (1962)

Experiment

S.G.Cloutier, P.A.Kossyrev and J.M.Xu, Nature Materials, 4, 887-891, 2005
S.G.Cloutier and J.M.Xu, Condensed Matter Archives, Arxiv cond-mat/0412376, 2004

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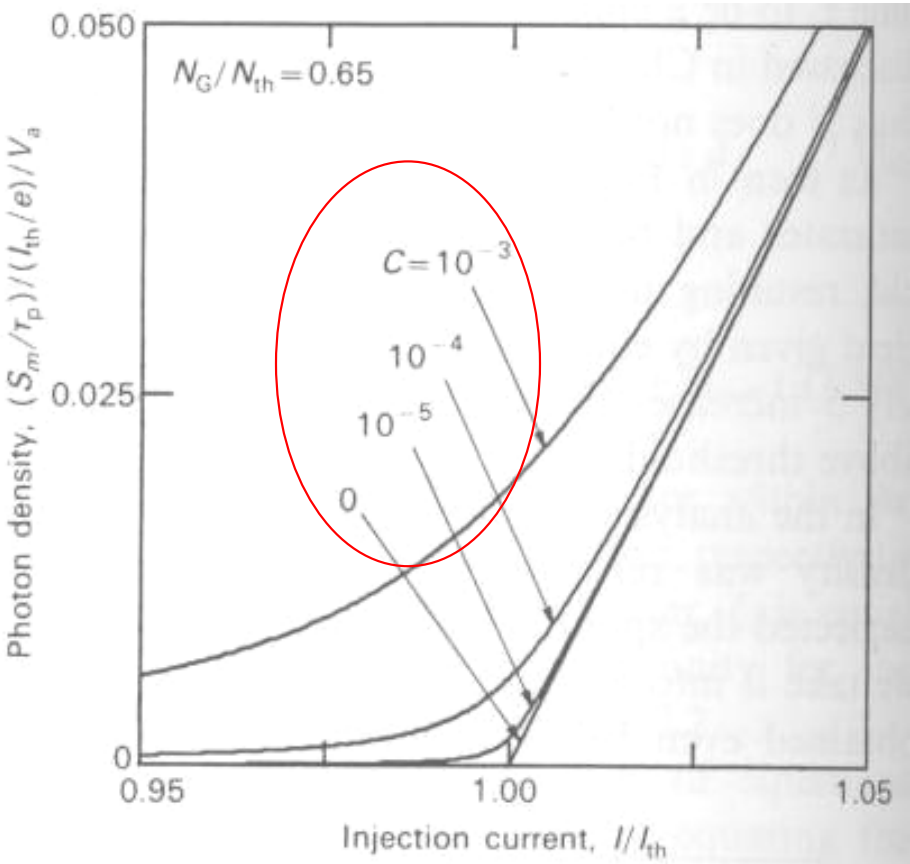
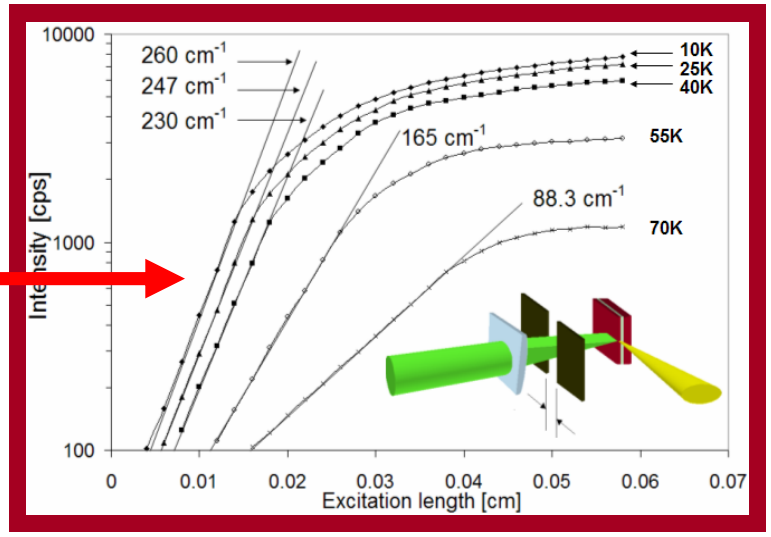
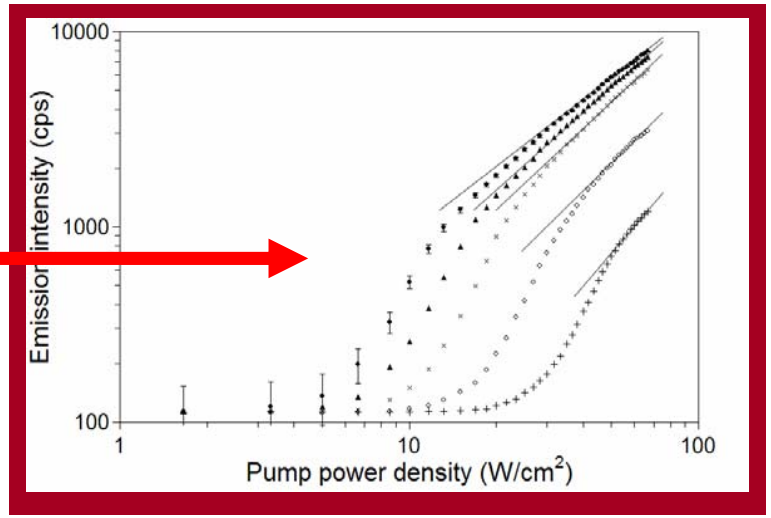
Stimulated Emission



Suematsu, *Handbook of semiconductor lasers* (1994)
Dingle, APL **19**, 5 (1971)





The exponential evolution (threshold) region indicates a transition from a spontaneous to a stimulated emission dominated regime.

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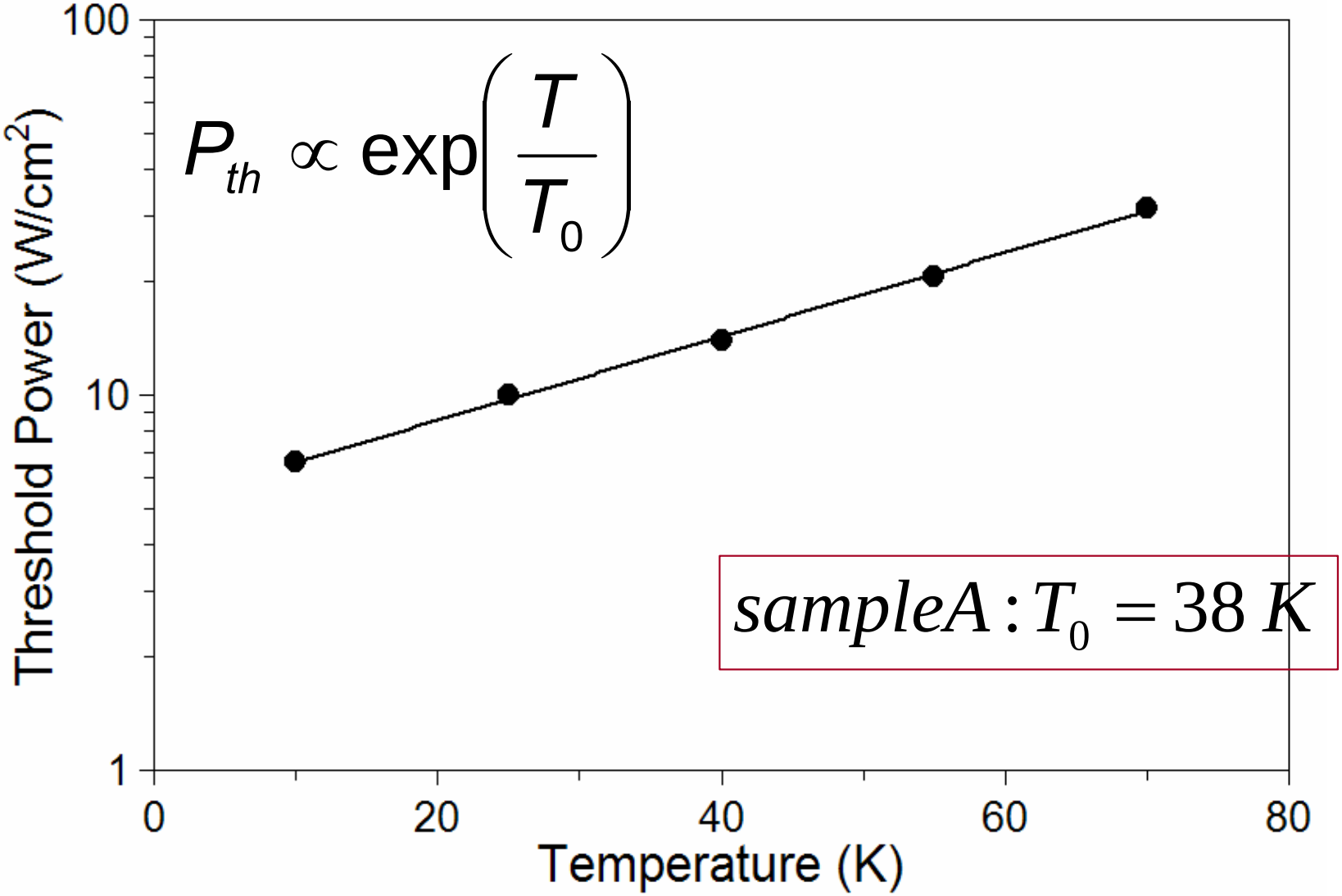
Stimulated Emission



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Stimulated Emission

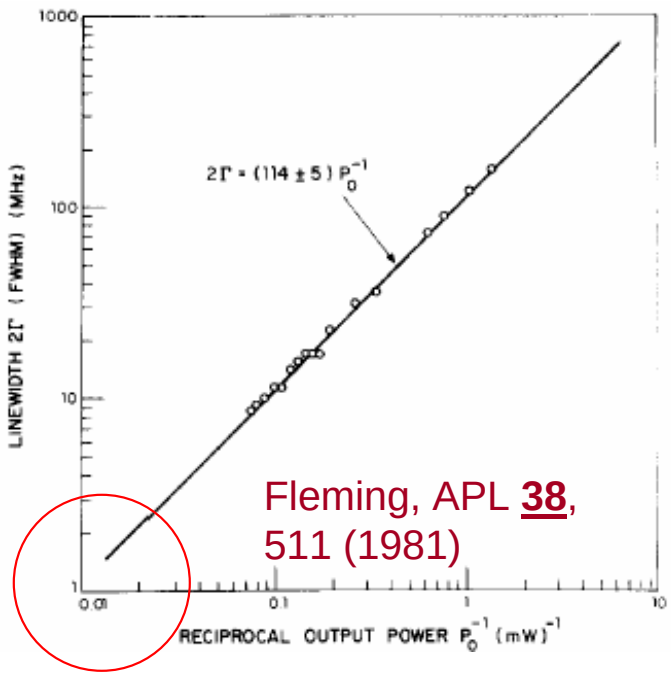
Schalow-Townes criterion

Theory

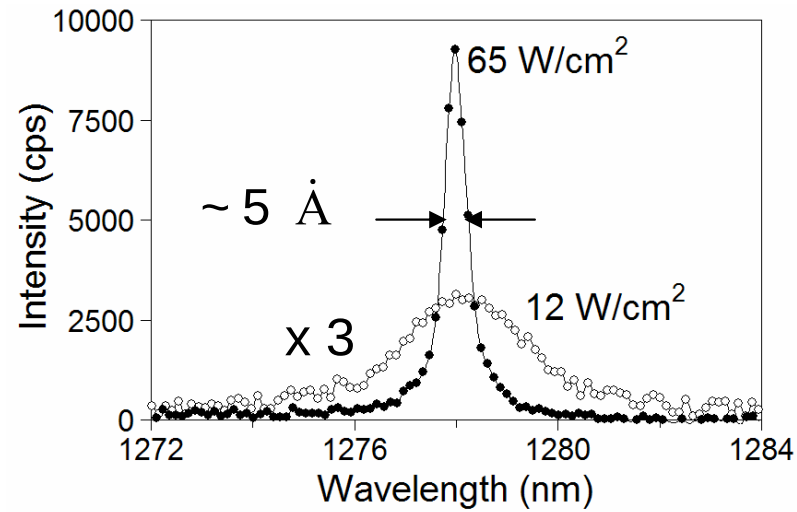
$$\Delta f = \frac{v_g^2 \, h\nu \, g \, n_{sp} \, \alpha_m (1+\alpha^2)}{8\pi P_0}$$

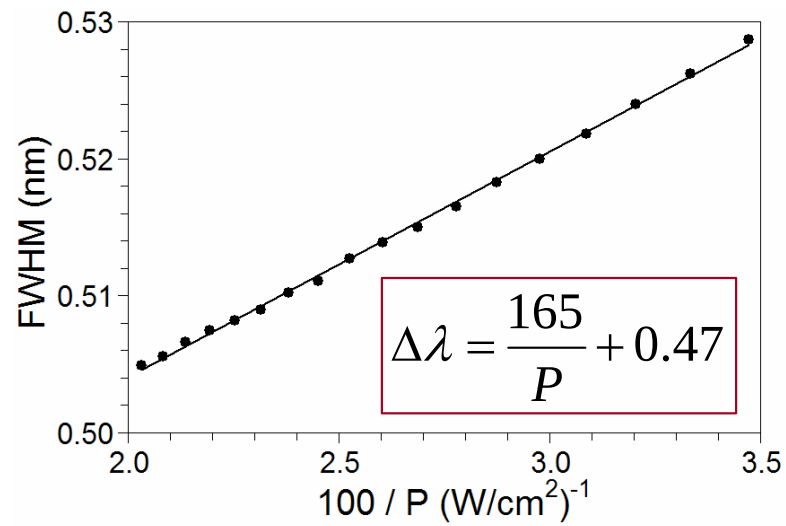
Henry, IEEE J.Quant.Elec. **QE-18**, 259 (1982)

Experiment



Fleming, APL **38**, 511 (1981)





The linear reciprocal-power linewidth evolution (Schalow-Townes relation) also indicates a stimulated emission dominated regime.

S.G.Cloutier, P.A.Kossyrev and J.M.Xu, Nature Materials, 4, 887-891, 2005
S.G.Cloutier and J.M.Xu, Condensed Matter Archives, Arxiv cond-mat/0412376, 2004

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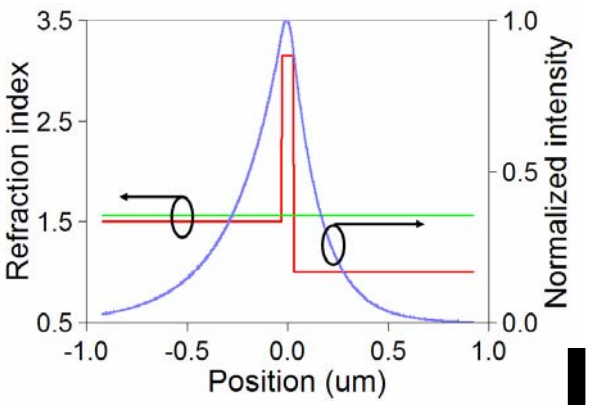
Spectral Coherence

Interference&Cavity modes

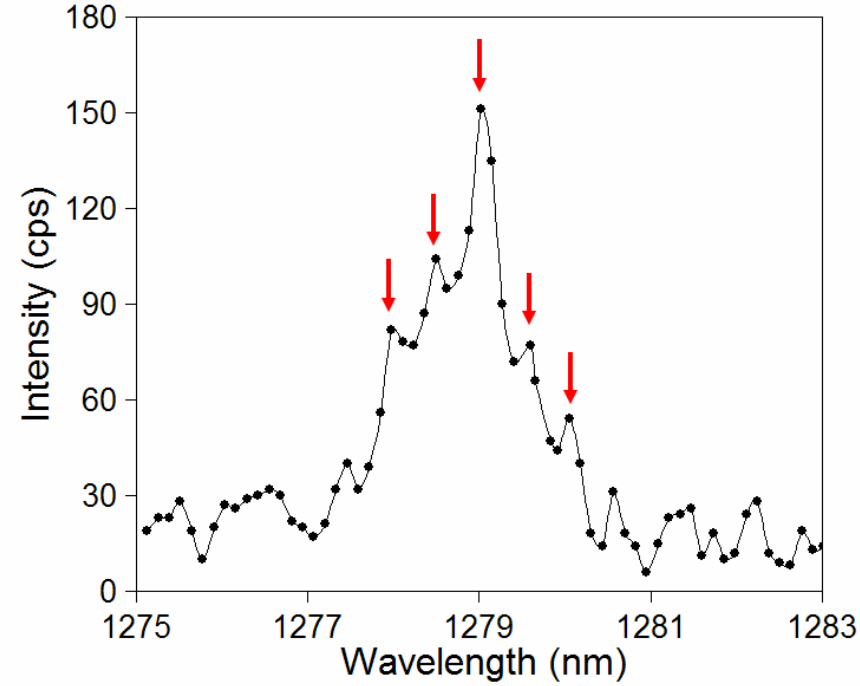
$$n_{eff} \cdot L_C = 1.565 \pm 0.050 \text{ mm}$$

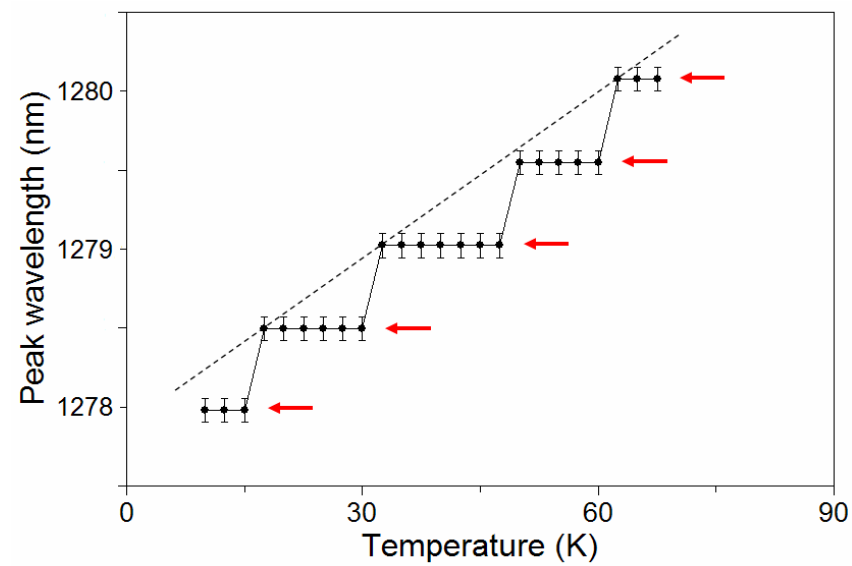


$$n_{eff} \approx 1.564$$

$$L_C^{calc} = 1.00 \pm 0.10 \text{ mm}$$

$$L_C^{meas} = 1.00 \pm 0.03 \text{ mm}$$





S.G.Cloutier, P.A.Kossyrev and J.M.Xu, Nature Materials, 4, 887-891, 2005

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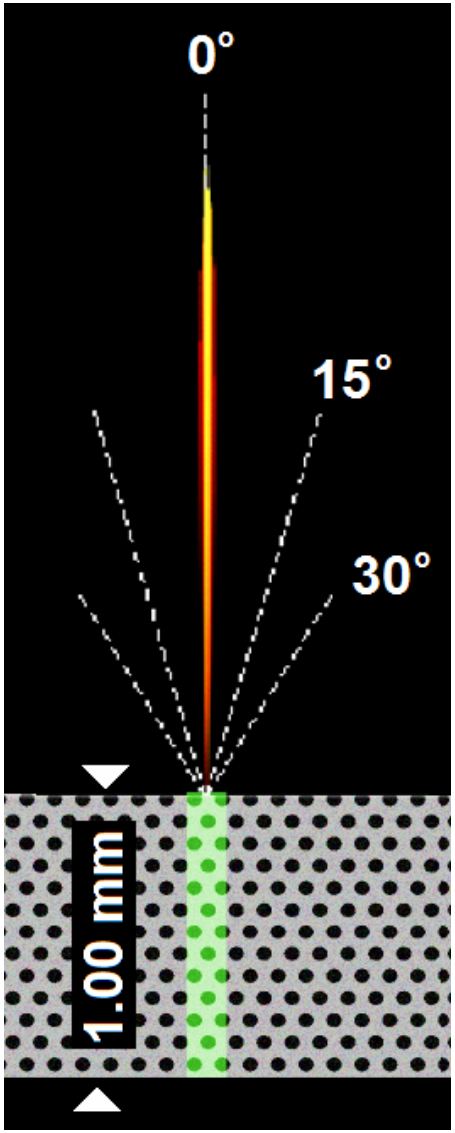
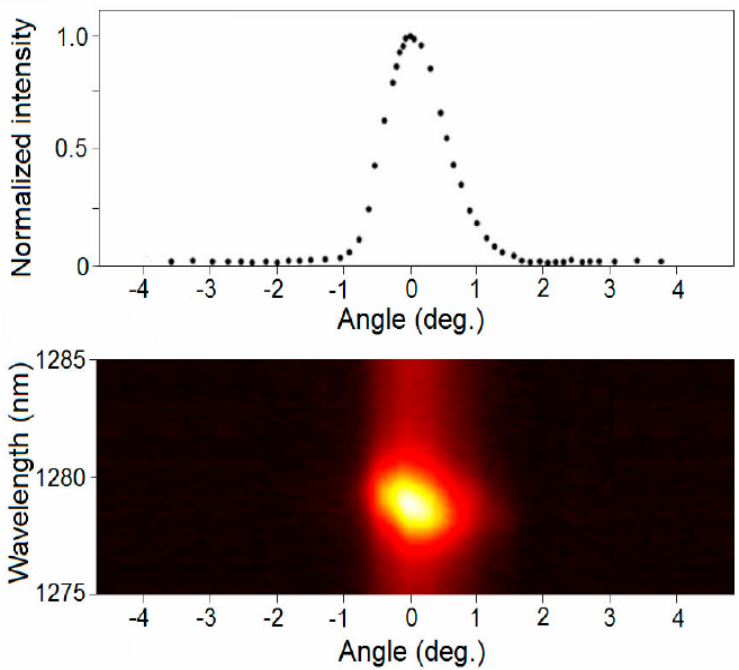
Spatial Coherence

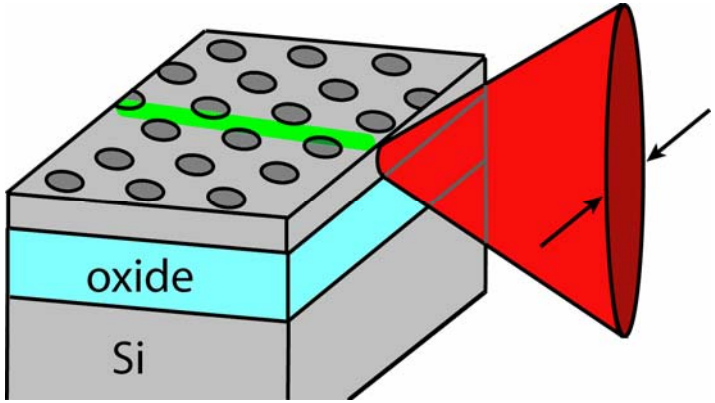
Far-field angular distribution intensity profile

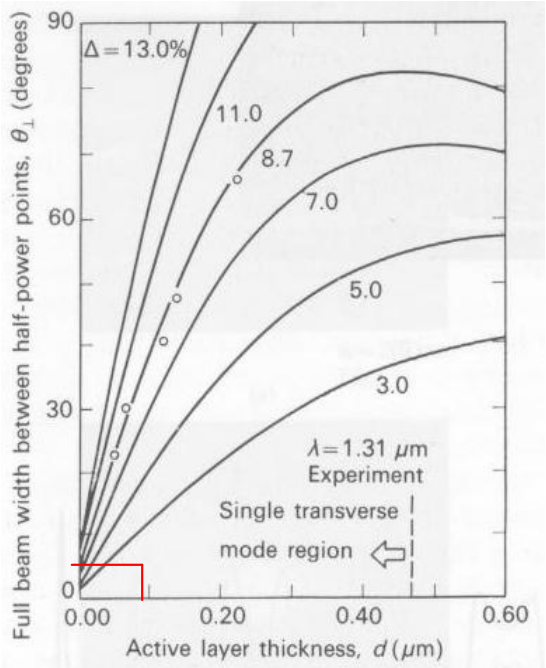




$$\Delta\theta \approx 1.1 \pm 0.1^{o}$$

$$\Delta \approx 1\%$$





Suematsu, (1994)

S.G.Cloutier, P.A.Kossyrev and J.M.Xu, Nature Materials, 4, 887-891, 2005

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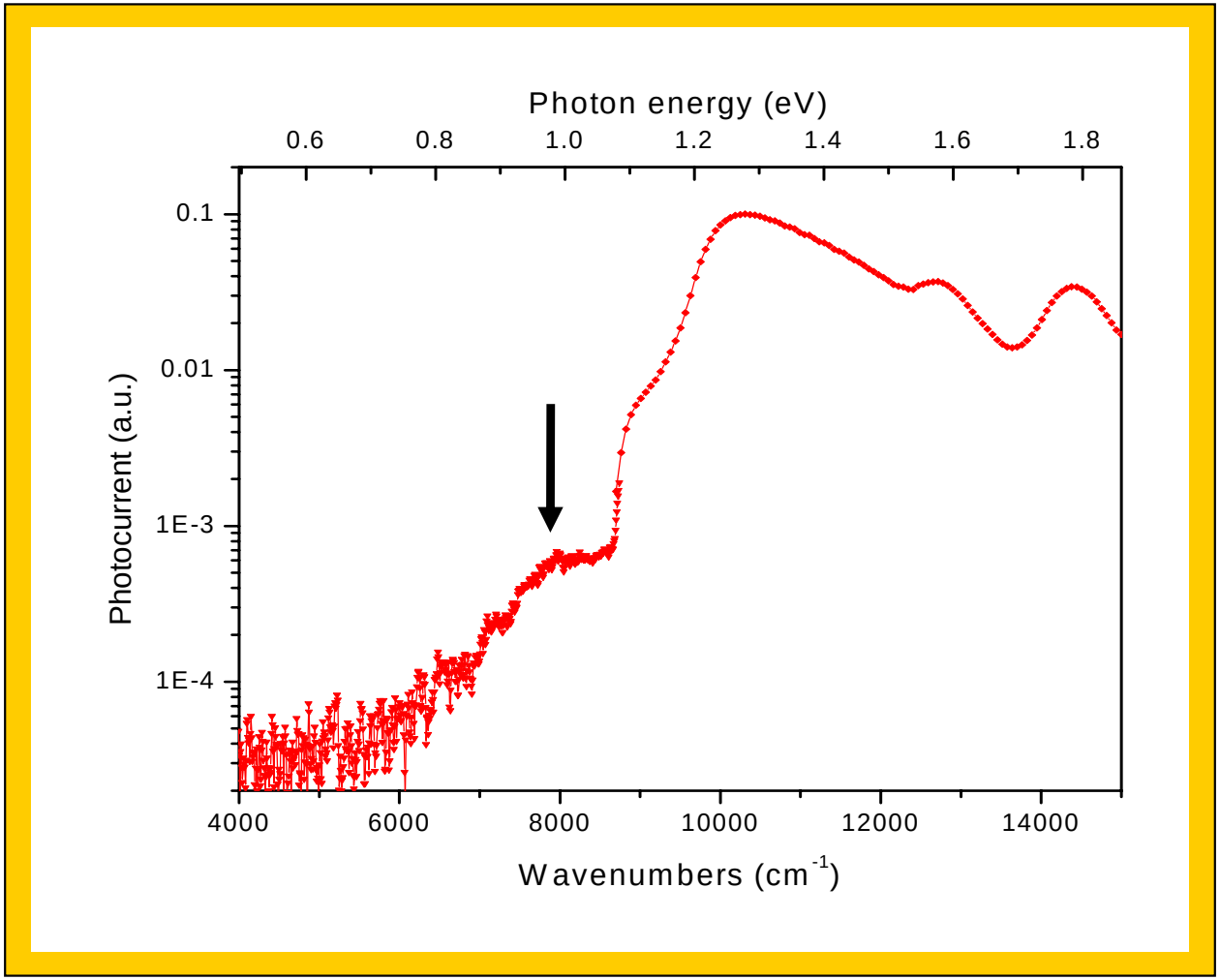
Key Findings: Underlying Physics

- ***The photocurrent spectroscopy reveals the presence of activated sub-bandgap states, in agreement with that inferred from PL and ASE spectra.***



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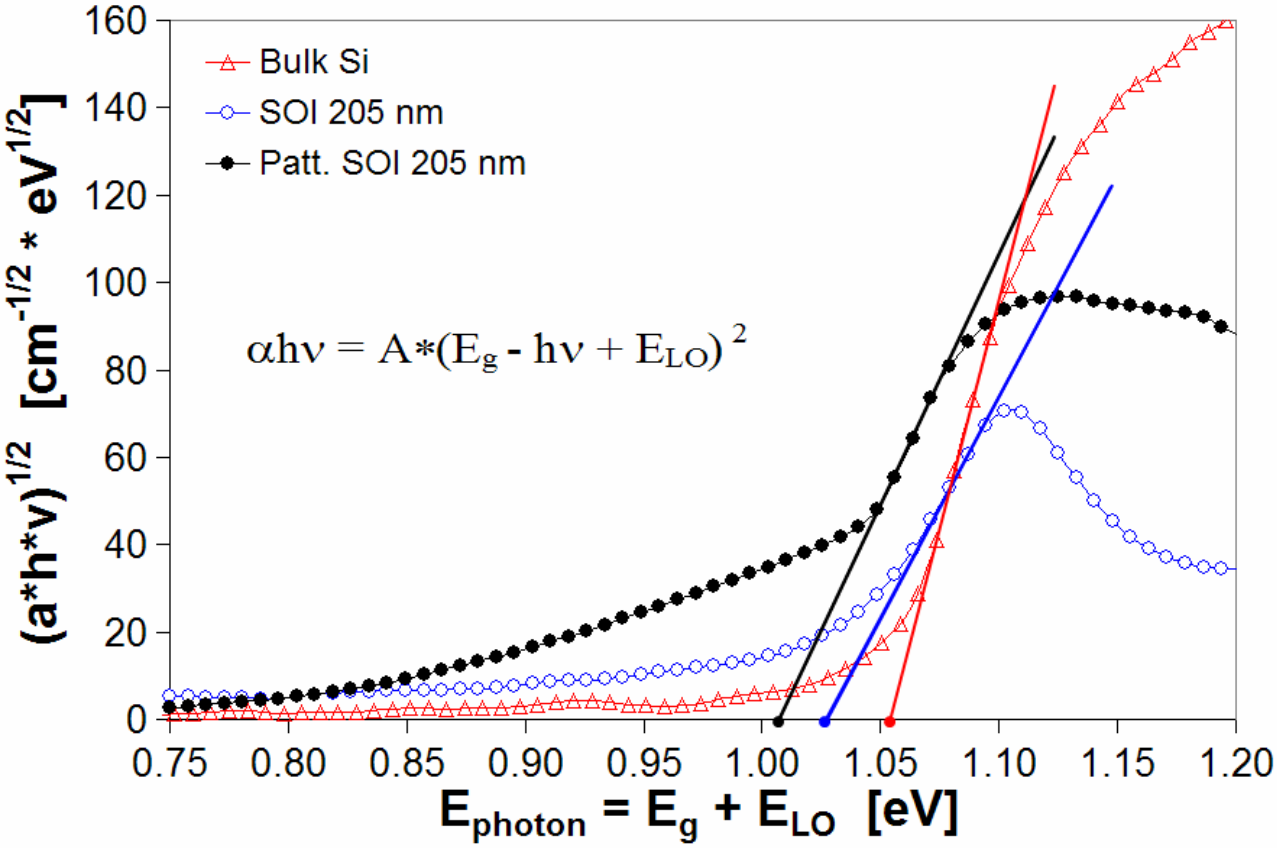
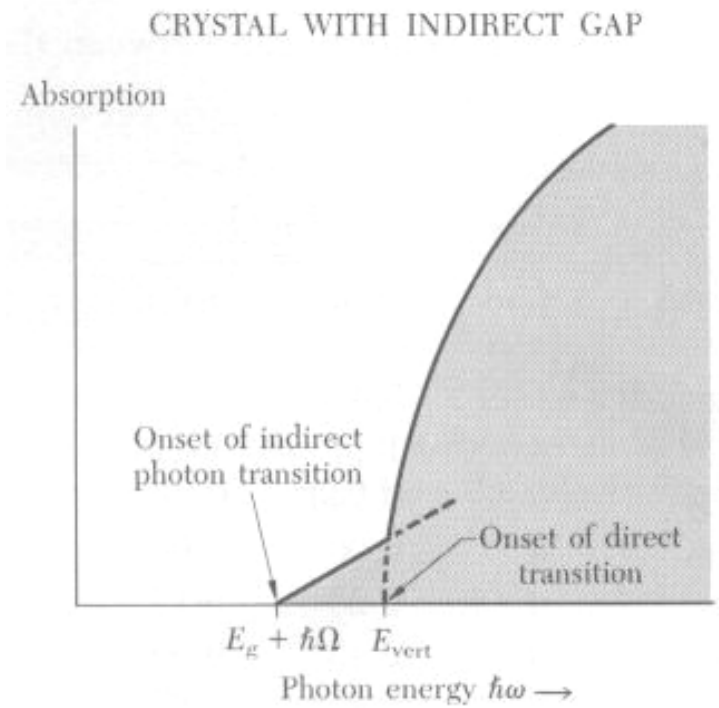
Photocurrent Spectroscopy





Kittel, Intr. to Solid State Physics

- ***Phonon-absorption tail in nanopatterned vs un-patterned SOI confirms the results from Raman and photoluminescence spectroscopy measurements.***
- ***Smaller E_{LO} (phonon-localization / strains) and/or E_g (strains) are observed in our structures.***
- ***We know for sure we have phonon-localization. What about strains?***

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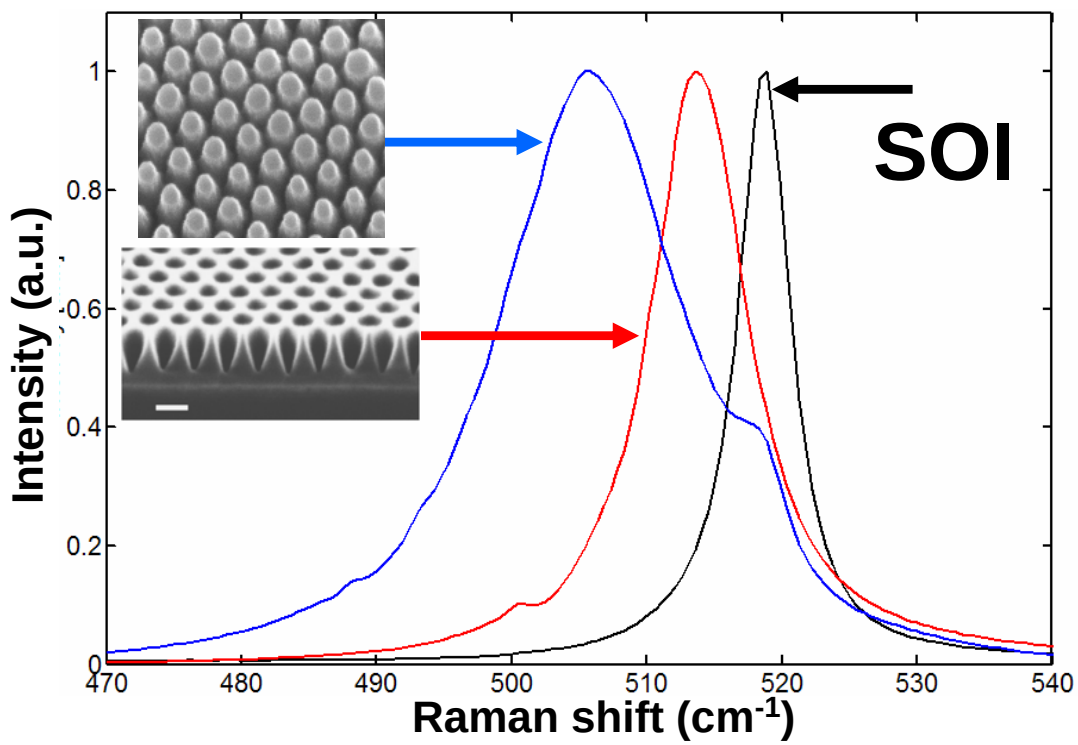
Operation mechanism, underlying Physics

- ***Photoluminescence spectroscopy, Activation energy and TEM point to silicon vacancies as one mechanism involved.***

- ***Raman, Photocurrent and Photoluminescence spectroscopy have also identified phonon-localization effects as another contributing factor.***



- ***TEM and Photocurrent spectroscopy confirm the presence of strains.***

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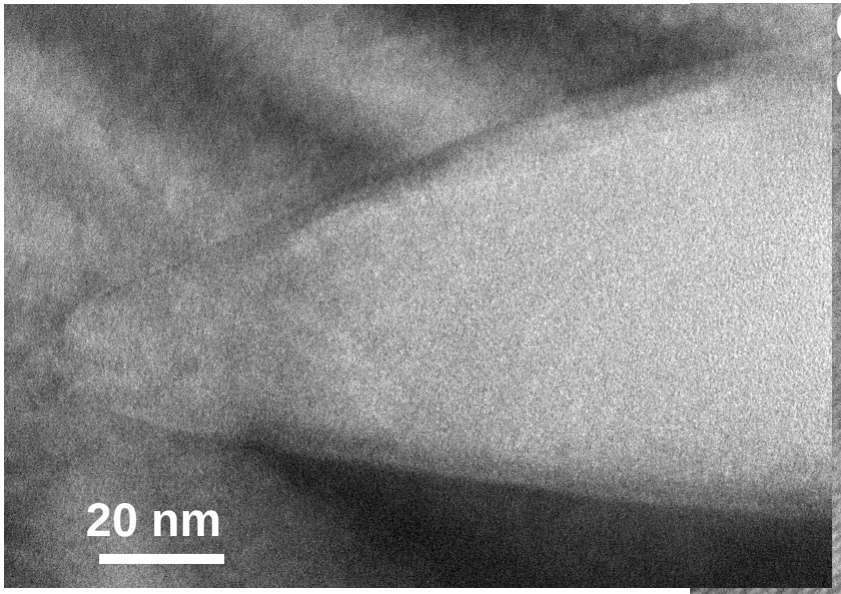
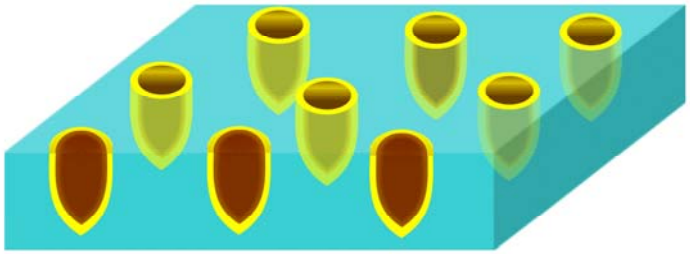
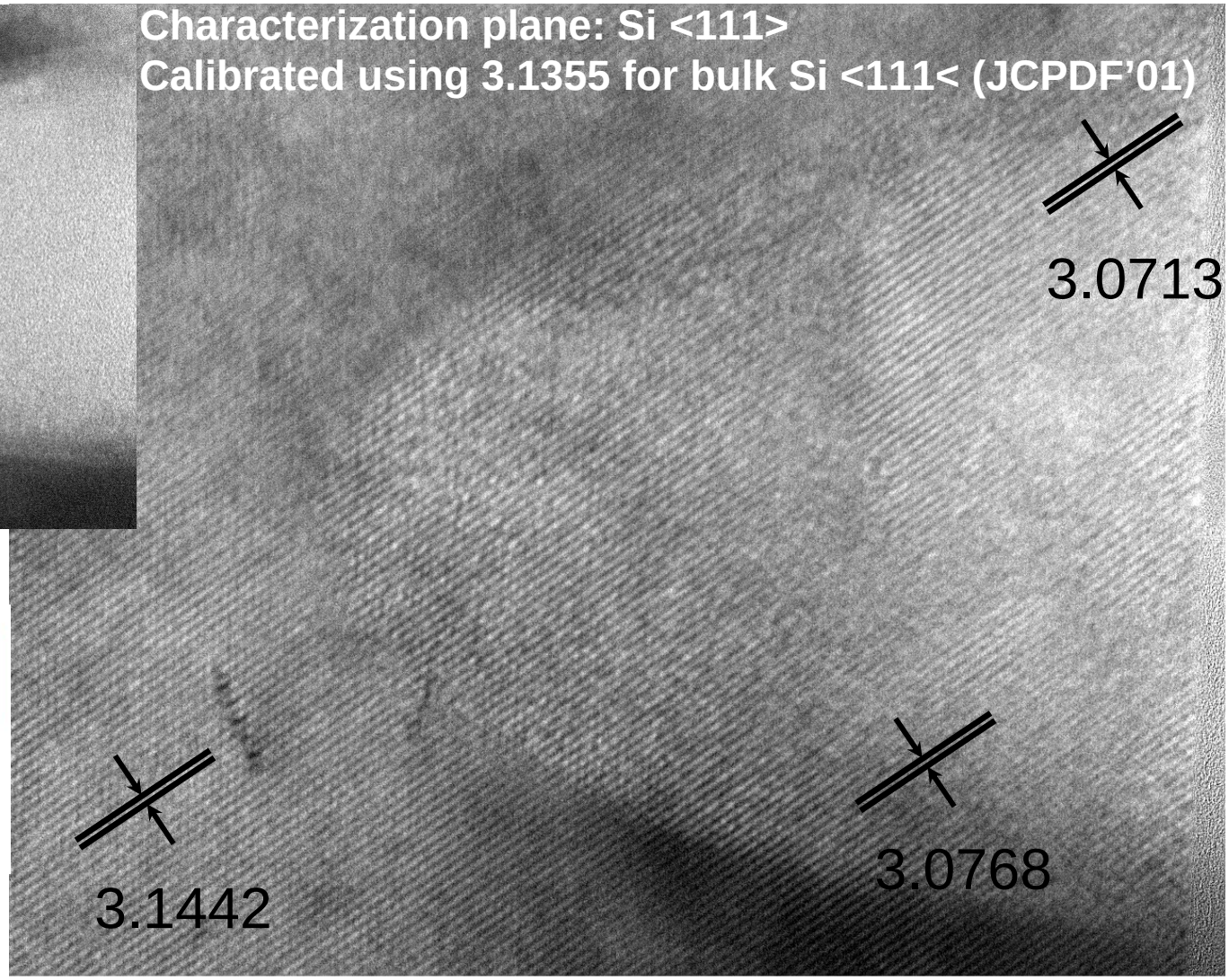
Key Findings: TEM direct observation of Strains







- ***Lattice constant change ~ 2.2 % (3.14A → 3.07A)***
- ***Suggests significant compressive strains in the wall structure***

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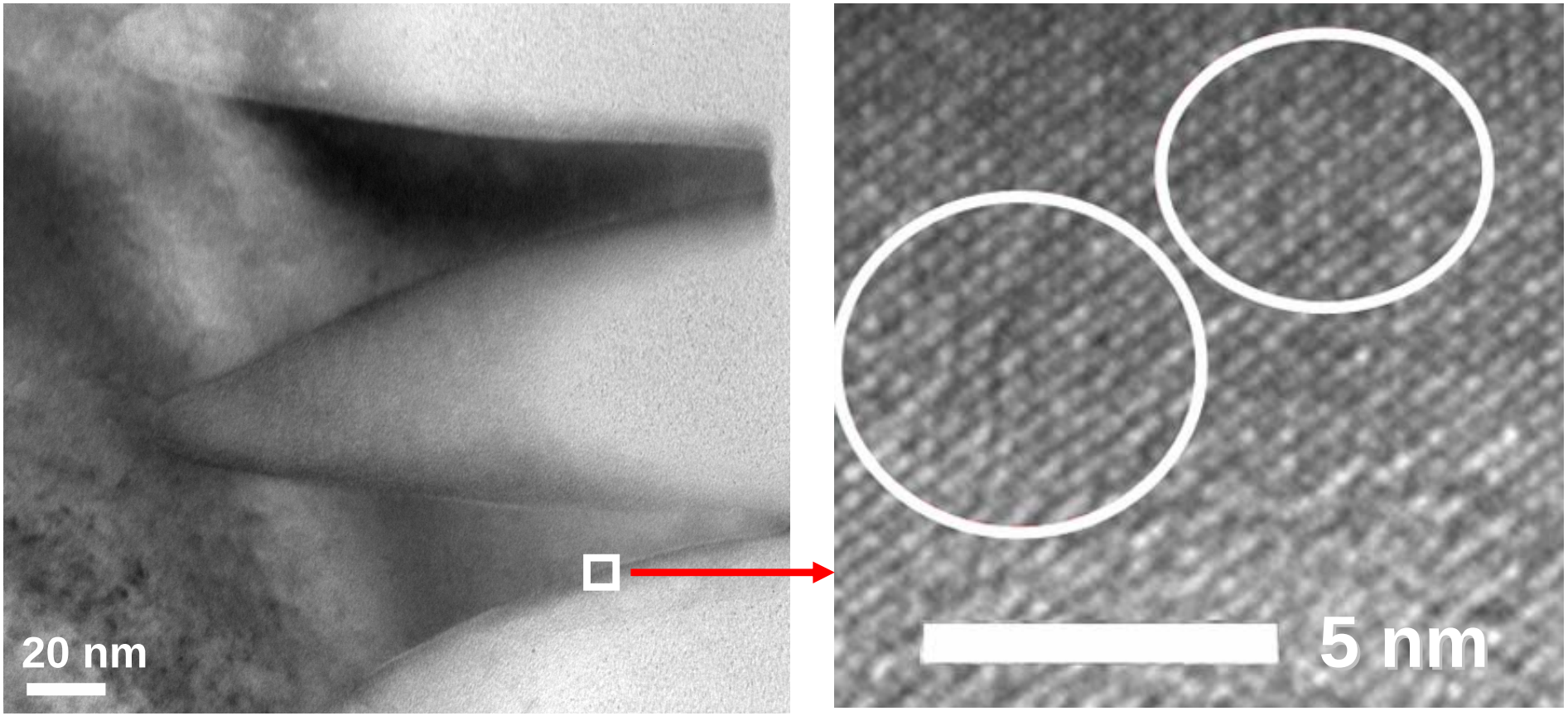
High-Resolution TEM



- ***We clearly observed silicon vacancies (A-centers) in the surface layer.***
- ***TEM also showed the presence of significant (~2.2%) compressive strains.***

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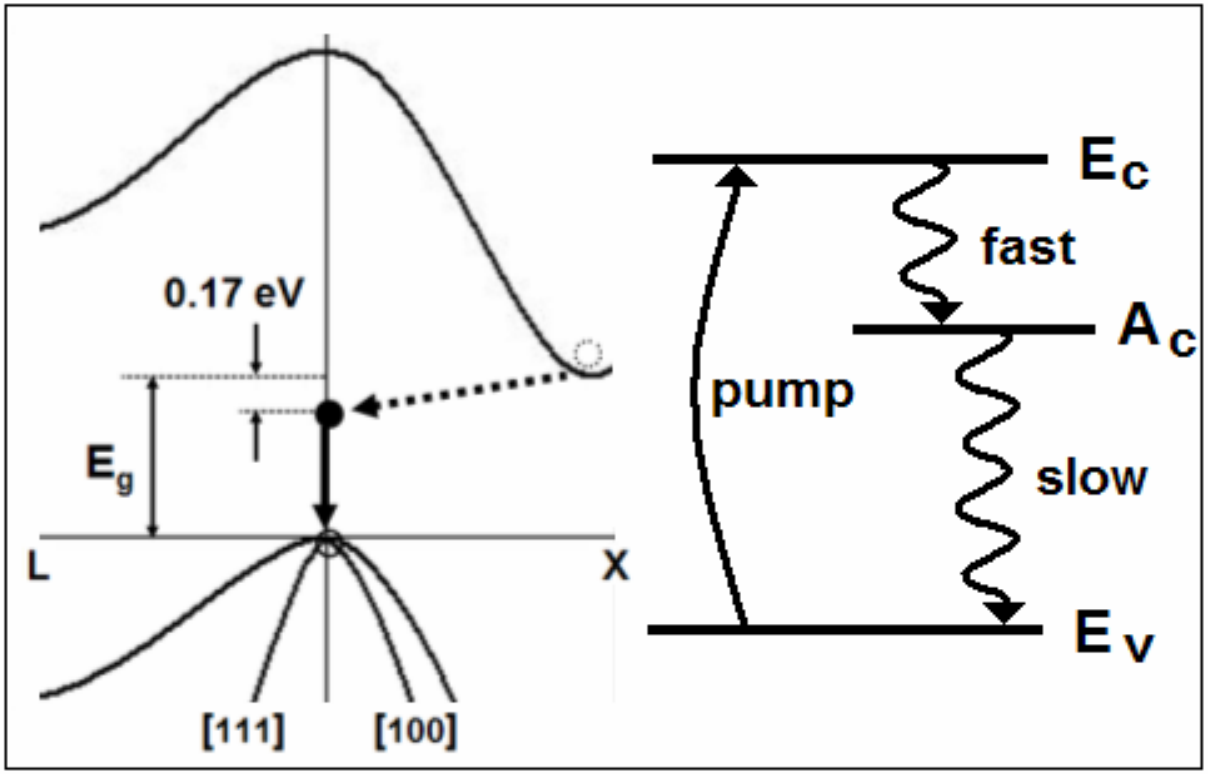
Investigating the Underlying Physics



- ***The A-type optical centers allow a fast filling then direct (phononless) recombination between trapped electrons and free holes, permitting population inversion.***
- ***Further enhanced by strain induced band narrowing and the SOI***

Spry, Phys. Rev. **175**, 1010 (1968)

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Enabling Mechanisms for Laser Action

- *A-centers mediated phononless (direct) recombination between trapped electrons and free holes.*

- *High volume density of gain zones (A-center zones) (4-6 nm in the anti-dot surface shell).*

- *Minimized optical loss due to the High degree of uniformity in the nanopatterning.*

- *Minimum material losses due to:*
  - *strong A-centers localization.*
  - *bandgap narrowing due to strain in the anti-dot shell.*
  - *breaking of the phonon k-selection rule .*
  - *SOI electrical and optical blocking.*
  - *others to be investigated: symmetry-breaking, dielectric localization, etc…*

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Summary

- *Enhanced light emission through nano-scale alteration of bulk crystalline-silicon.*

- *Demonstrated Light Amplification by Stimulated Emission of Radiation at 1278 nm (with spatial and spectral coherence).*

- *Identified the most likely origin as A-center mediated phononless (direct) recombination*

- *Identified other additional possible contributing factors: phonon-confinement, e-h localization, strains, symmetry-breaking, dielectric and SOI confinement, etc…*

- *Control of the pore sizes and spacing as well as the degree of uniformity and ordering of the AAO mask, with similar emission properties.*

- *Continuing optimization of fabrication, approaches, processes*

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Enabling Mechanisms for Laser Action

- *A-centers mediated phononless (direct) recombination between trapped electrons and free holes.*

- *High volume density of gain zones (A-center zones) (4-6 nm in the anti-dot surface shell).*

- *Minimized optical loss due to the High degree of uniformity in the nanopatterning.*

- *Minimum material losses due to:*
  - *strong A-centers localization, phonon localization, electron localization.*
  - *bandgap narrowing due to strain in the anti-dot shell.*
  - *breaking of the phonon k-selection rule .*
  - *SOI electrical and optical blocking.*
  - *others to be investigated: symmetry-breaking, dielectric localization, etc…*

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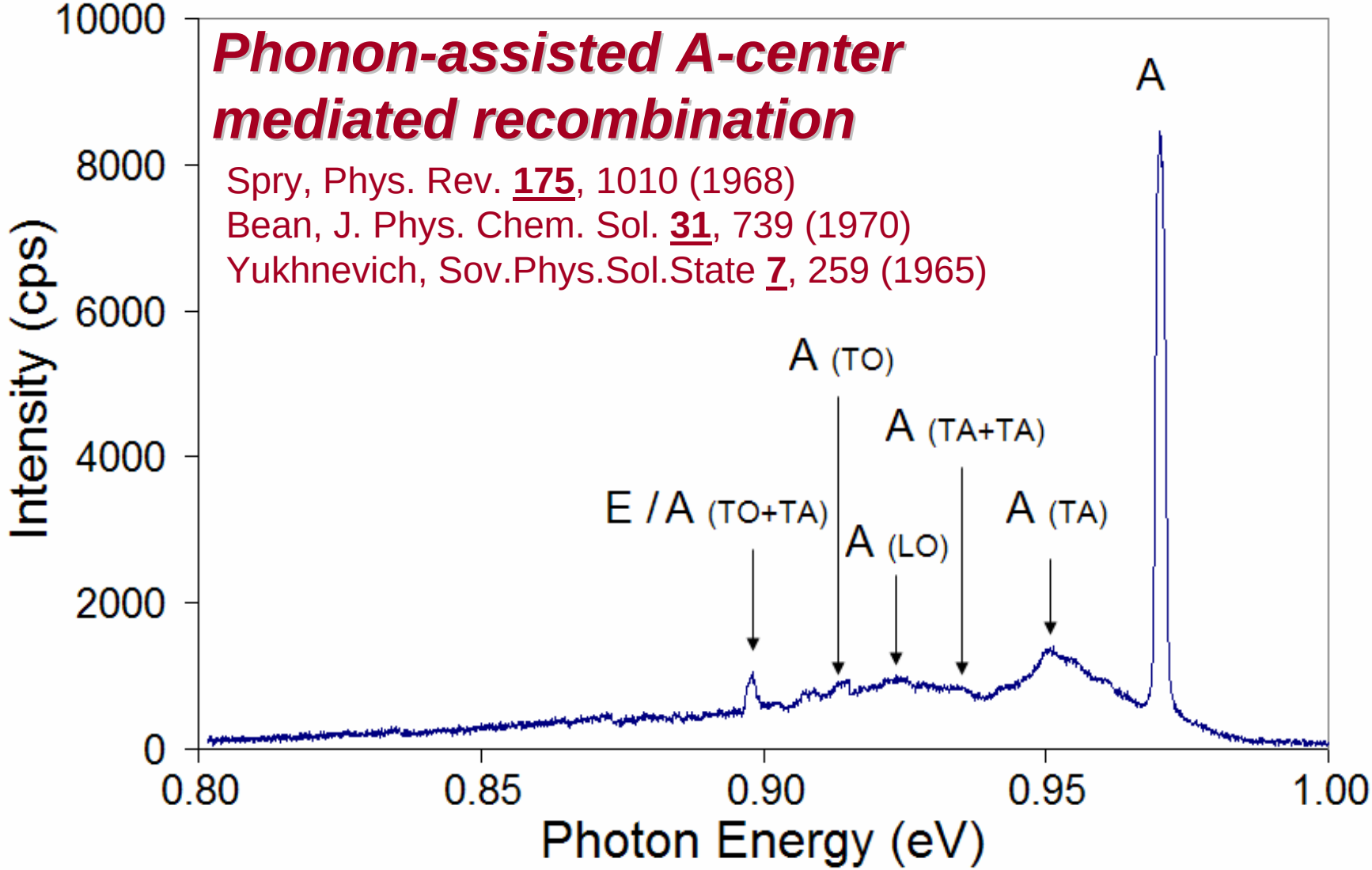
The A-center mechanism



- ***The high-resolution photoluminescence spectrum shows the lower-energy phonon-assisted recombination bands from the A-center states***

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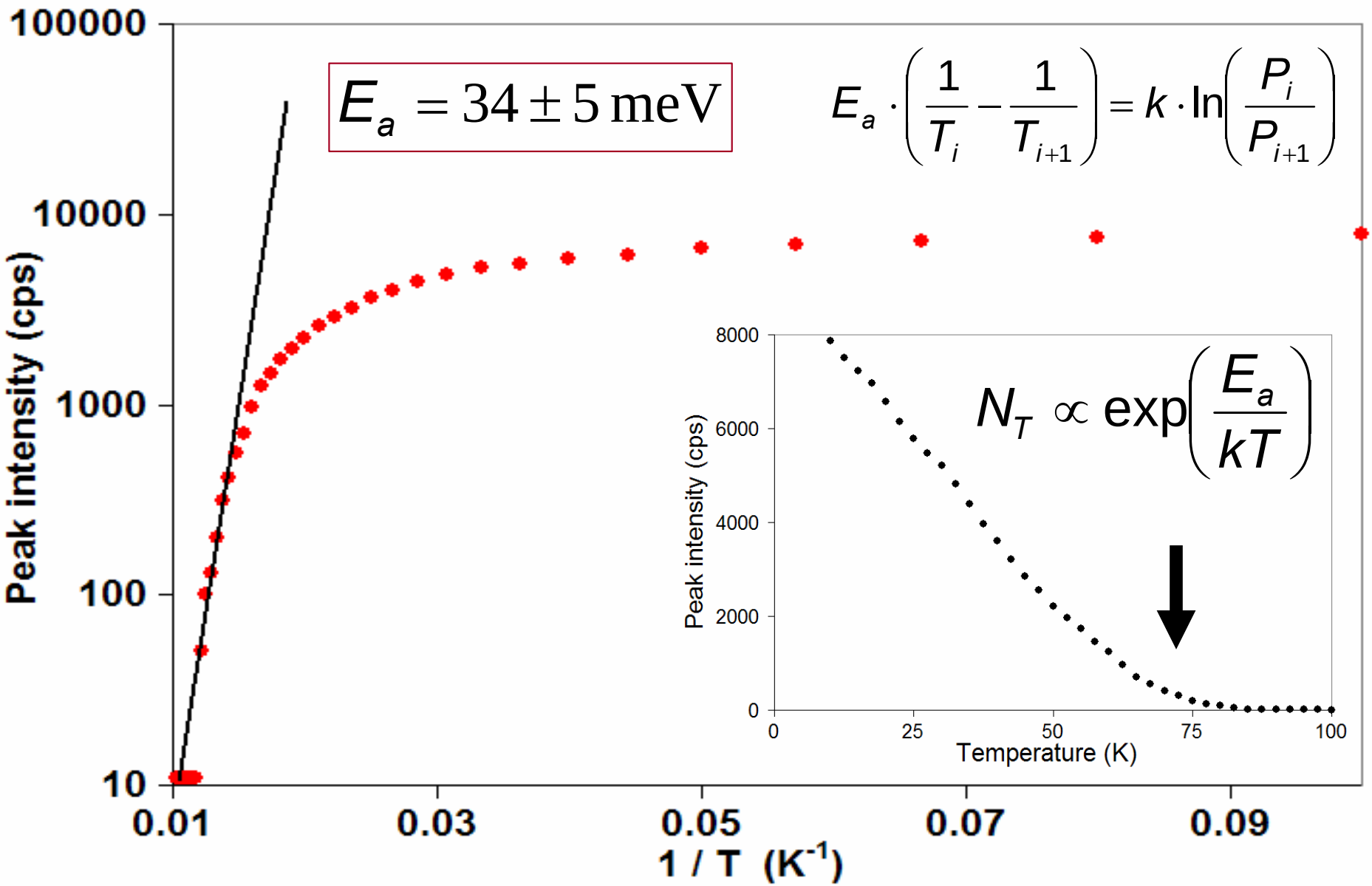
The A-center characteristics



Characteristic Process Activation Energy matches previous reports on A-centers.

Jones, Jour. Appl. Phys. **44**, 5402 (1973)

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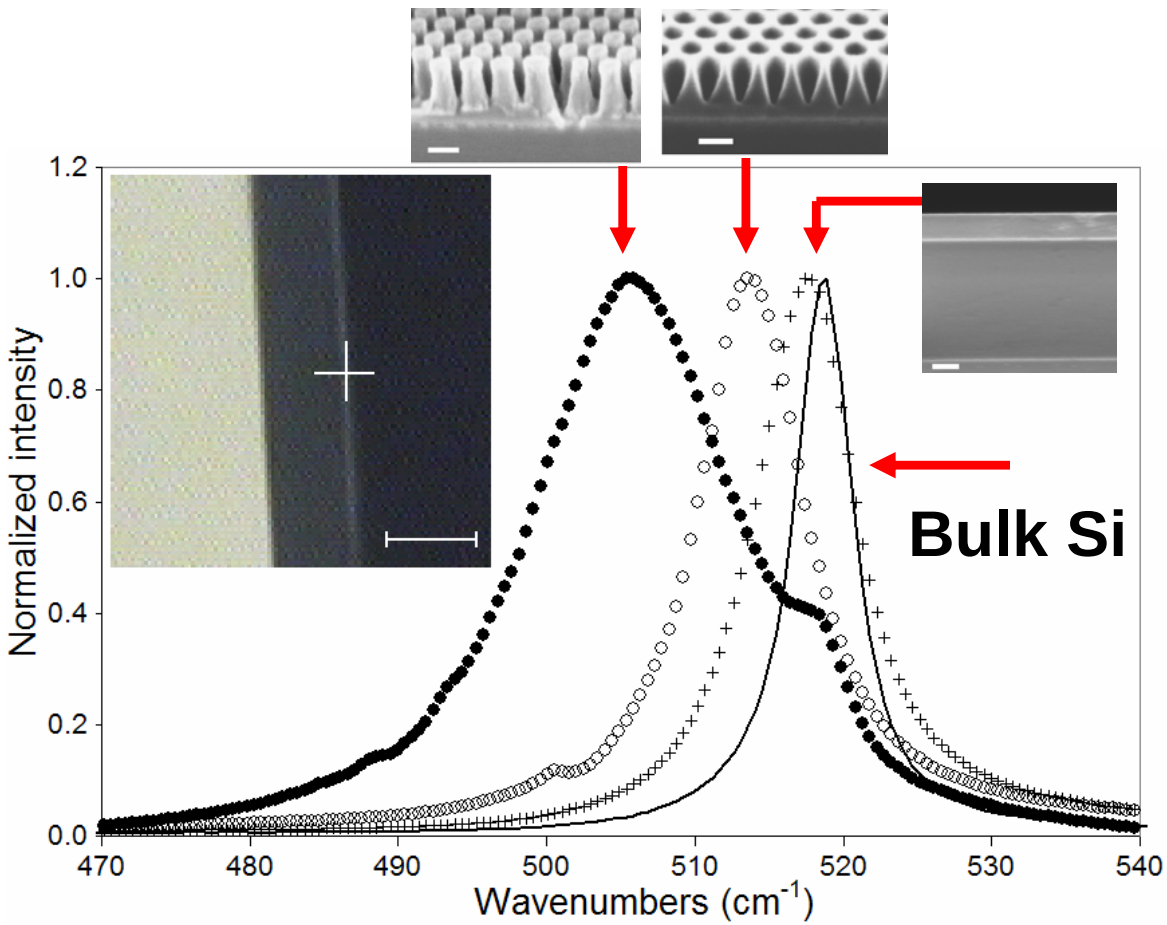
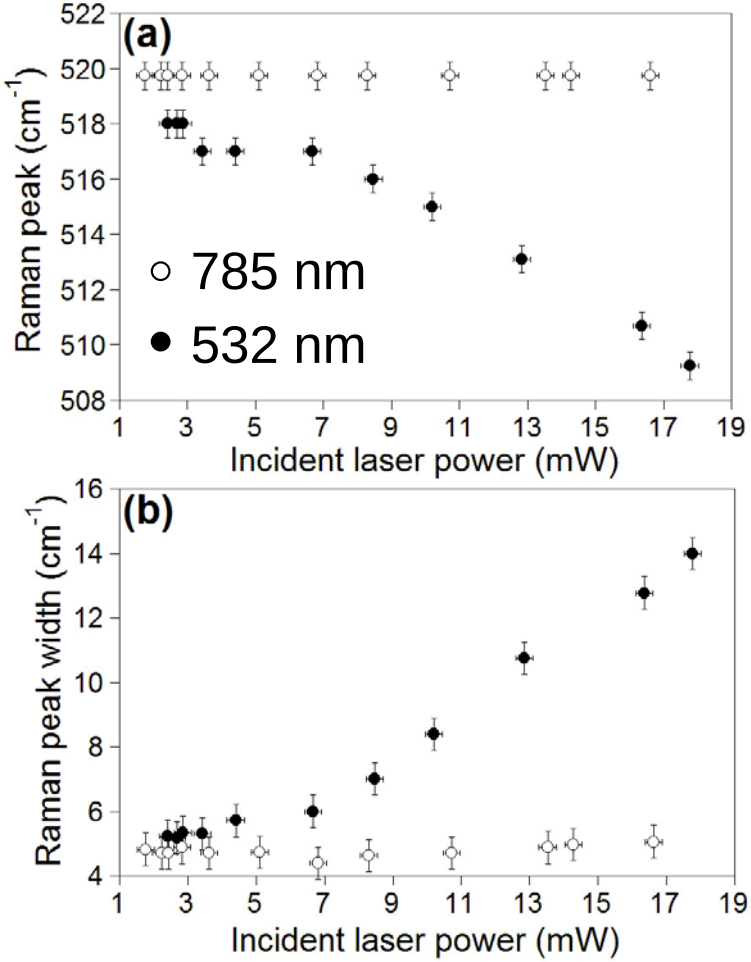
Raman spectroscopy: Phonon-localization





- ***Reminiscent of phonon-confinement effects in low-dimensional silicon structures. But the pore array feature size as fabricated is 10x the measured 4nm***
- ***Phonon-localization effects should enhance radiative recombination in silicon by breaking the k-selection rule imposed by the indirect band-structure.***

S.G.Cloutier, R.S.Guico and J.M.Xu, Appl. Phys. Lett., 87, 222104, 2005

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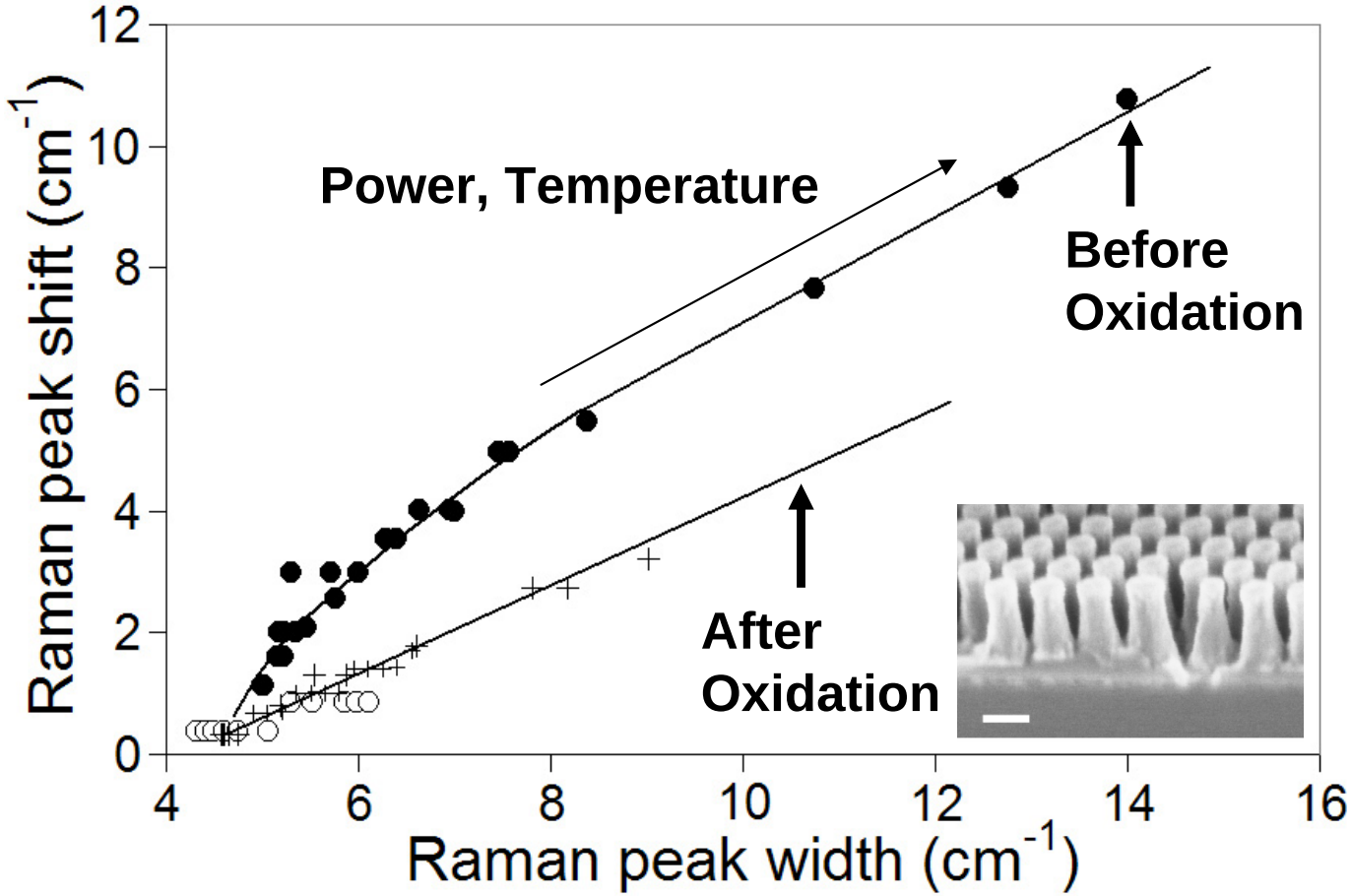
Phonon-Spectroscopy



- ***The nonlinear evolution at low pump power (or temperature) is a clear indicator of phonon-localization effects. But where in the structure???***

- ***A short thermal oxidation (4-6 nm) removed completely this nonlinear region such that the shift-width evolution becomes purely linear as in original SOI. Therefore, localization seems to occur at the silicon pillar surface!***

S.G.Cloutier, R.S.Guico and J.M.Xu, Appl. Phys. Lett., 87, 222104, 2005

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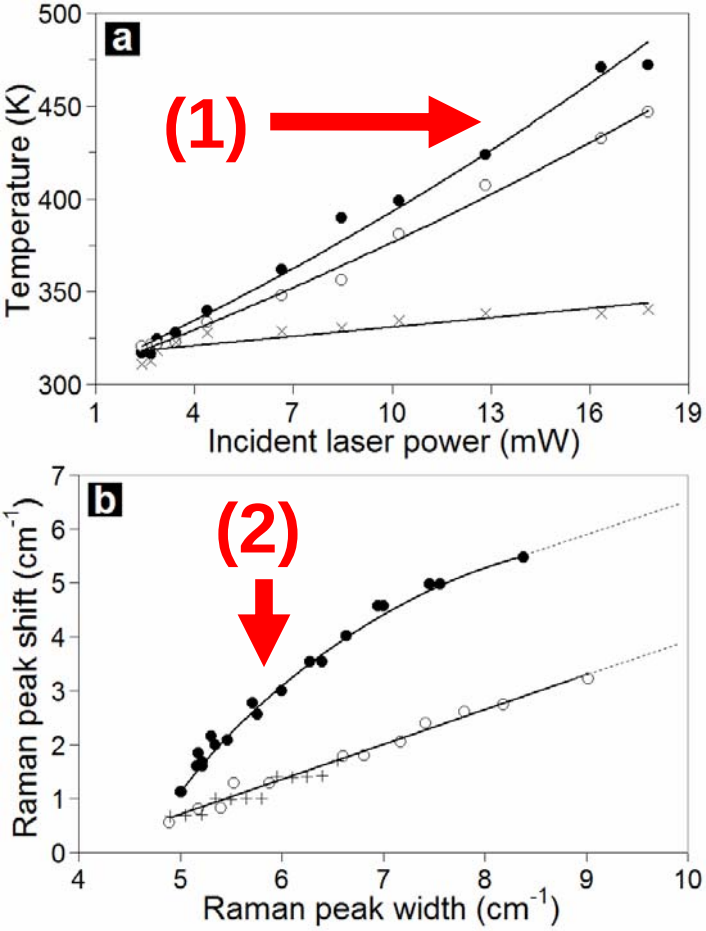
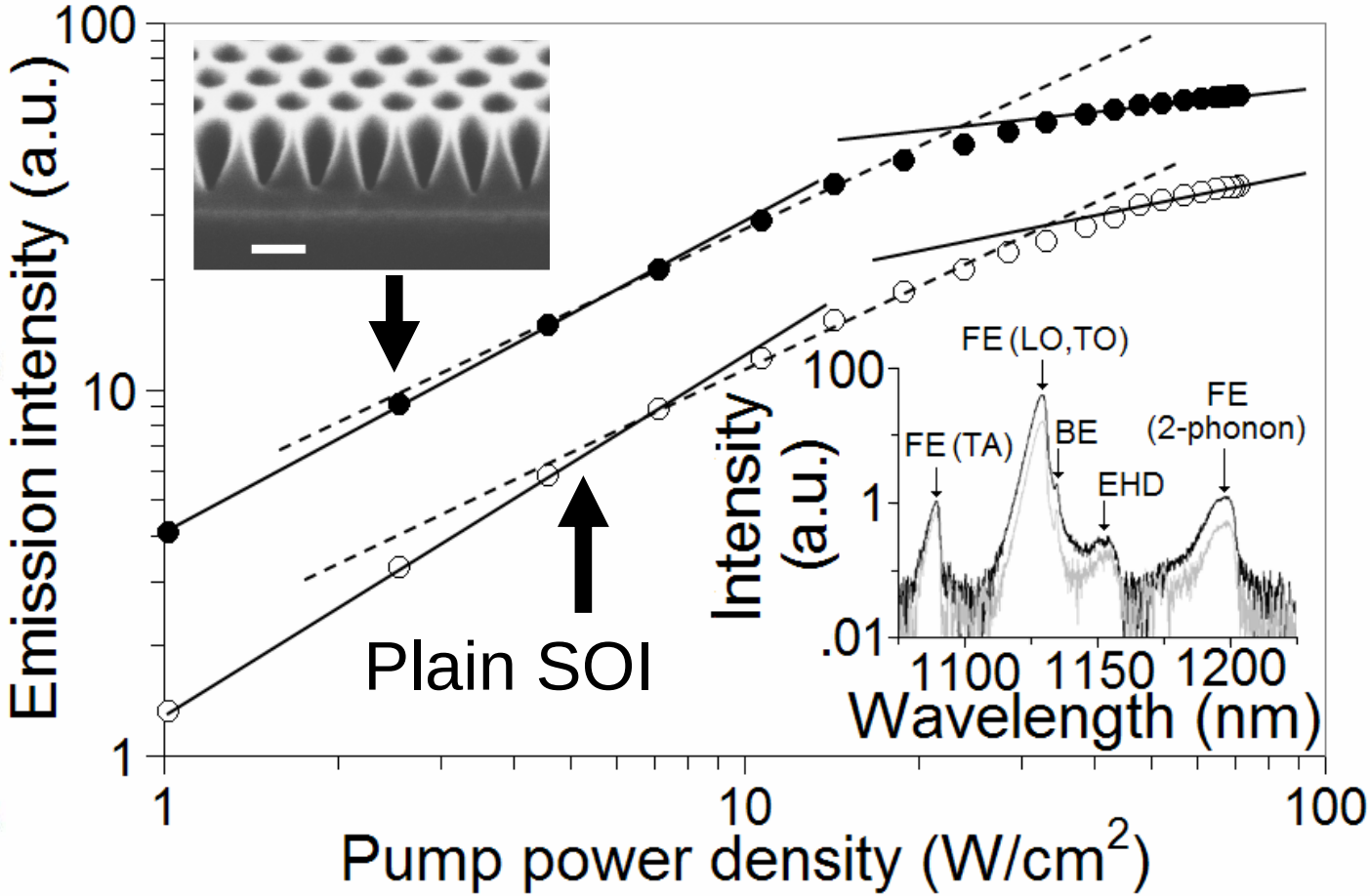
Enhanced Radiative Recombination





As expected:

(1) More laser heating in nano-patterned SOI vs un-patterned SOI (High Power).

(2) Also more radiative recombination due to a relaxation of the phonon-selection rule that prevails in bulk silicon (Low Power).

I. Schnitzer *et al.*, APL **63**, 2174 (1993)

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