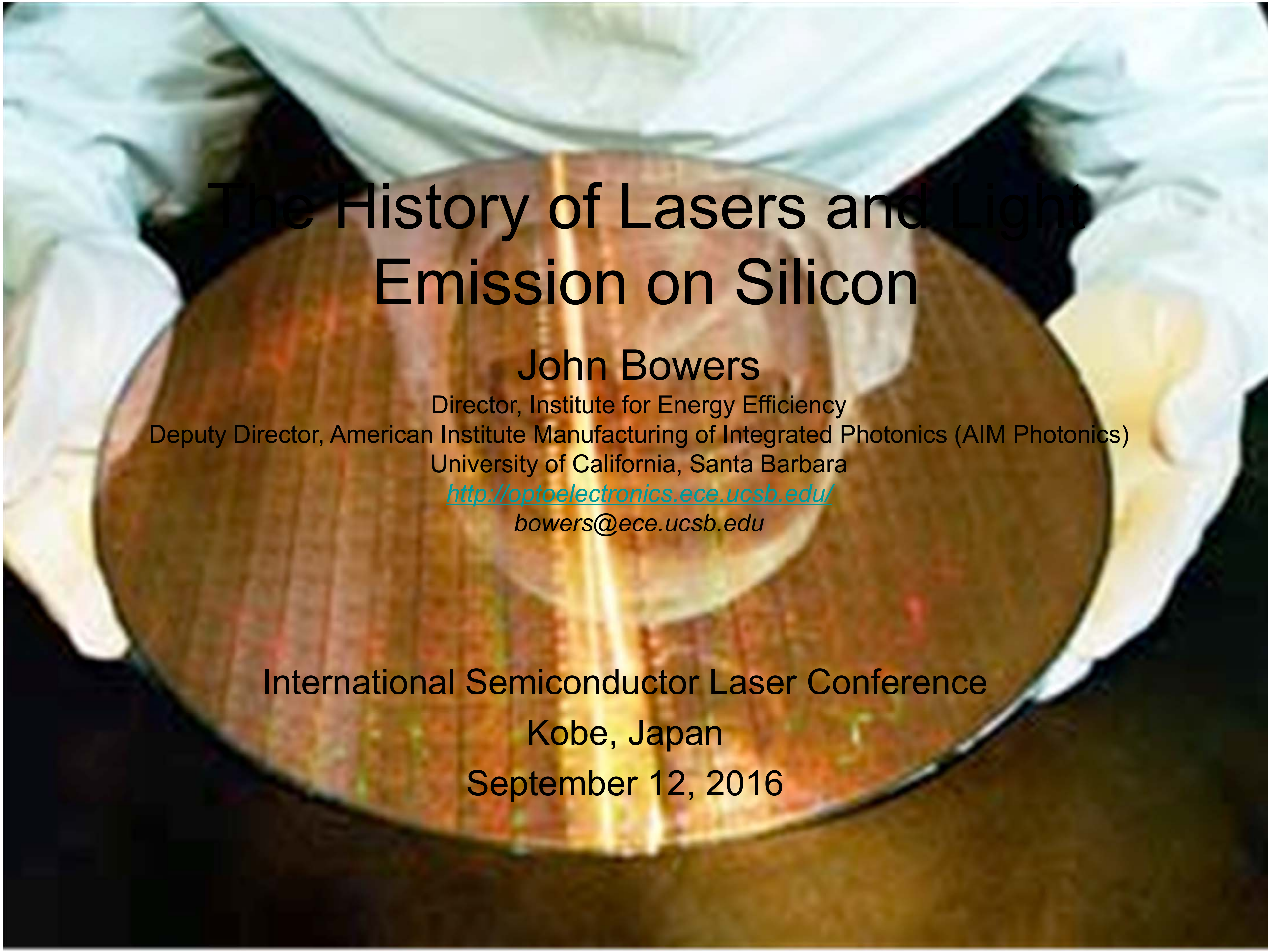

The History of Lasers and Light Emission on Silicon

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International Semiconductor Laser Conference

Kobe, Japan

September 12, 2016

Why use Silicon Substrates?

- Cheaper substrates
- Larger substrates (>300 mm)
- Large fabrication infrastructure (32 nm 300 mm fabs)
- Improved process control-critical for large scale integration.

Why use Silicon Substrates/Waveguides?

- Cheaper substrates
- Larger substrates (>300 mm)
- Large fabrication infrastructure (32 nm 300 mm fabs)
- Improved process control-critical for large scale integration.
- Lower loss waveguides: <0.3 dB/cm
- Reduced two photon absorption (100x less)
- Higher thermal conductivity (κ) of
  - Waveguides (Si has 30x higher κ than InGaAsP)
  - EAMs or PD Absorbers: Ge has 16x higher κ than InGaAs

UCSB

Why not use Silicon?

- Indirect band gap - inefficient for light emission
- Not electro-optic

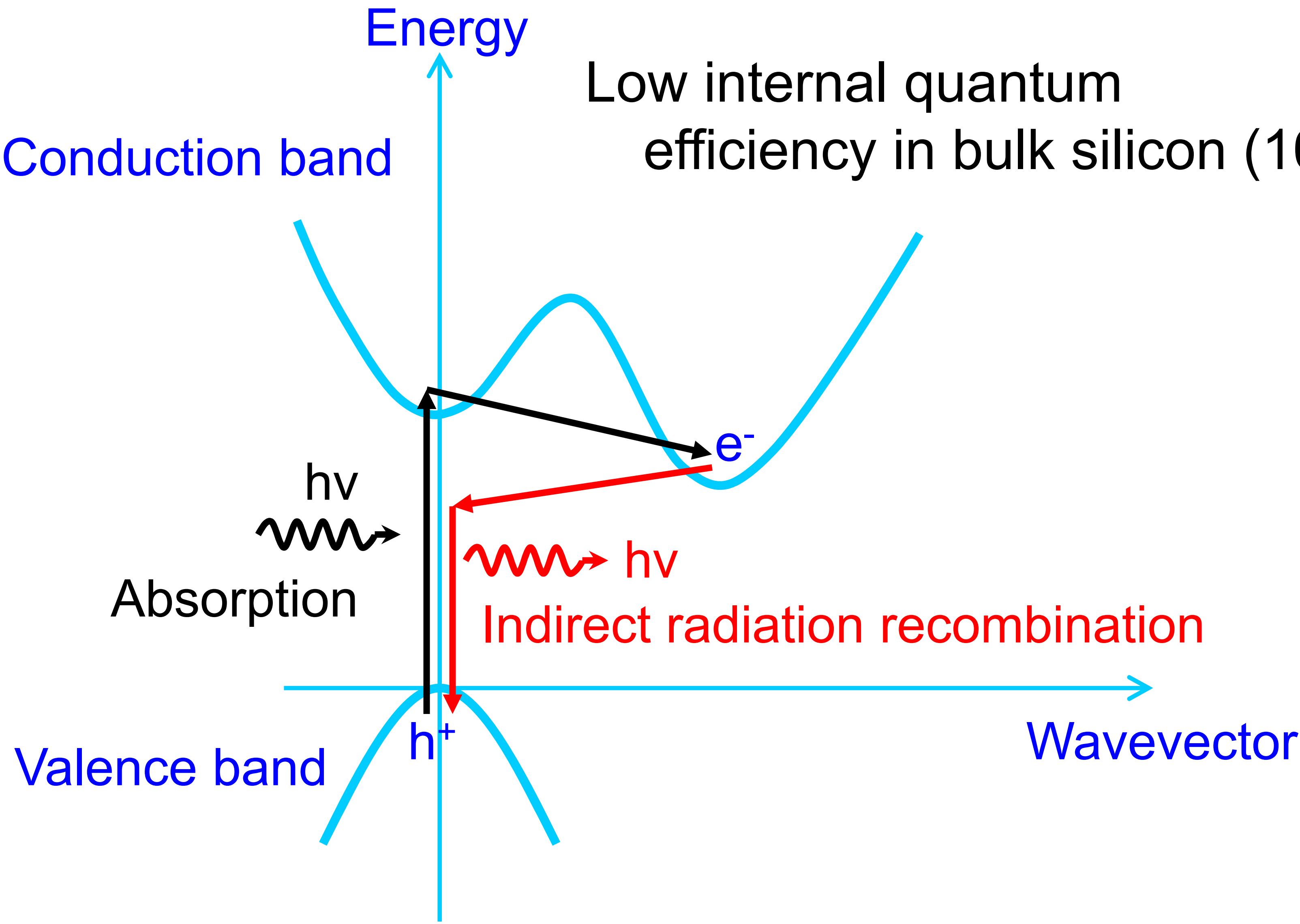
Why not use Silicon?

- Indirect band gap - inefficient for light emission
- Not electro-optic

Solvable problems

Silicon light emission – limits

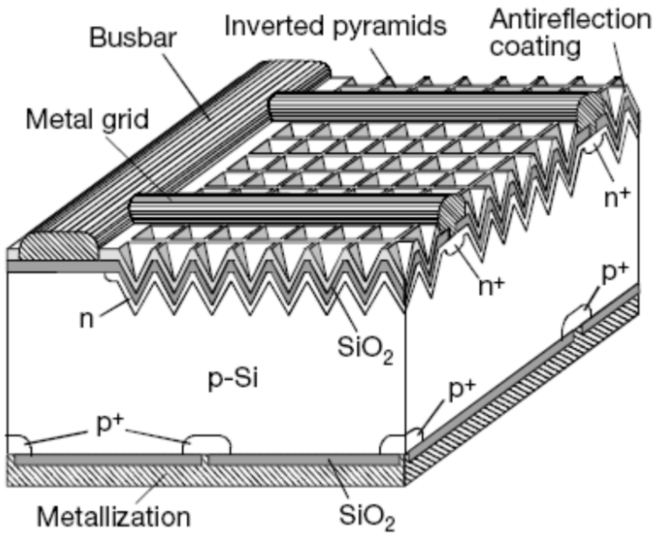
Low internal quantum efficiency in bulk silicon (10^{-6})

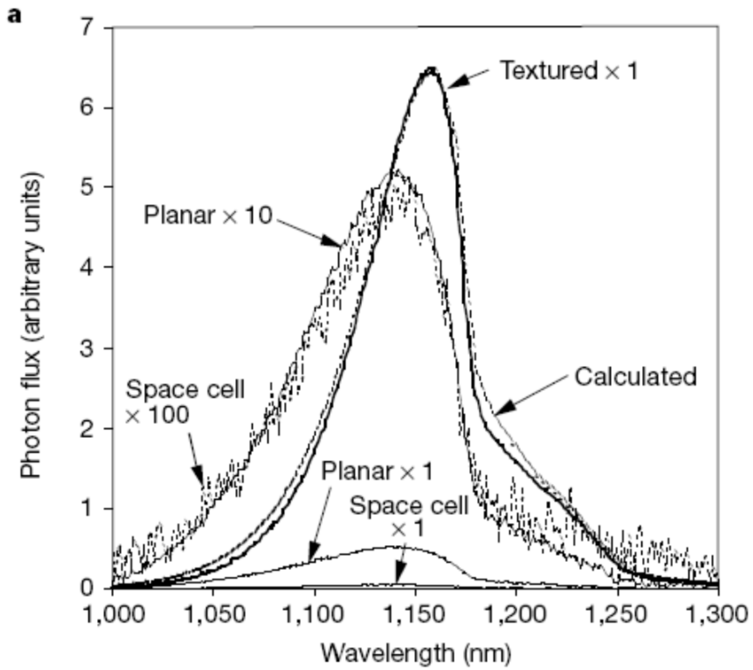


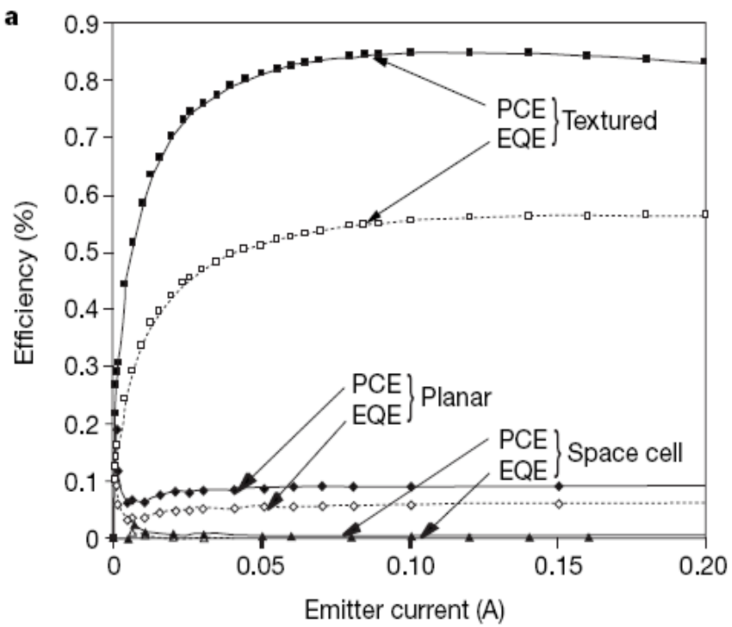
Silicon light emission – How?

- Bulk silicon
- Low dimension Silicon
  - Silicon nanocrystal
  - Periodic nanopatterned crystalline silicon
- Er dopants
- Raman laser (UCLA/Intel)
- Another material for gain (heterogeneous approach)
  - Epitaxial
    - Ge
    - GeSn
    - Quantum Dot
    - Pillars
  - Bonding
    - Dice level
    - Wafer level (BCB or Molecular)

Bulk silicon LED





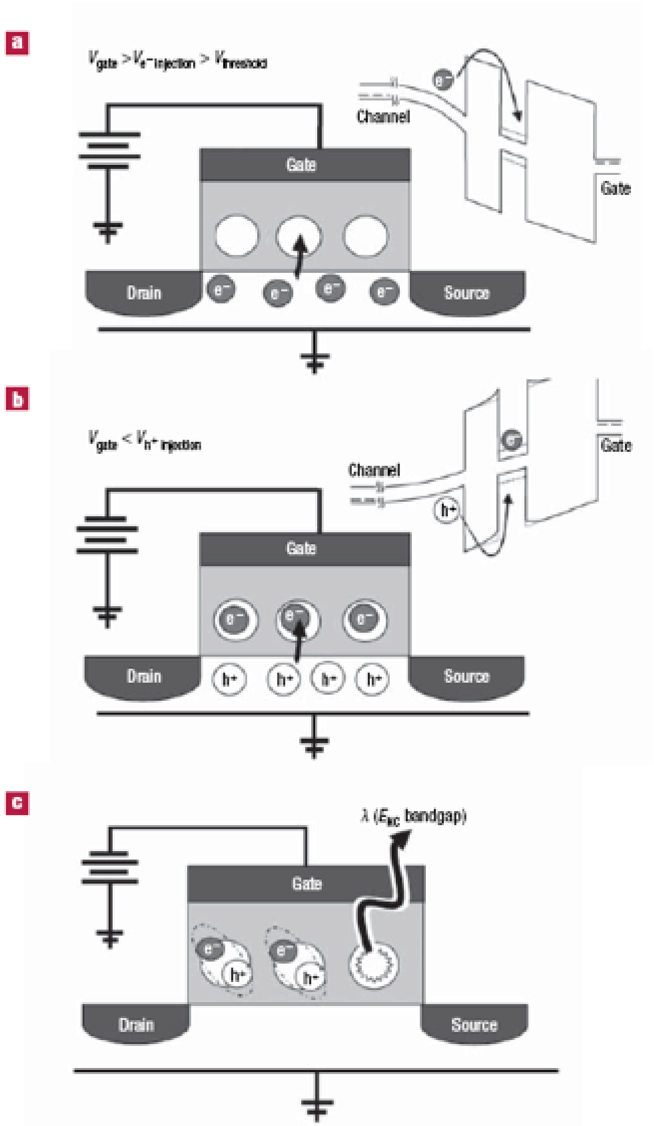


Solar cell forward bias

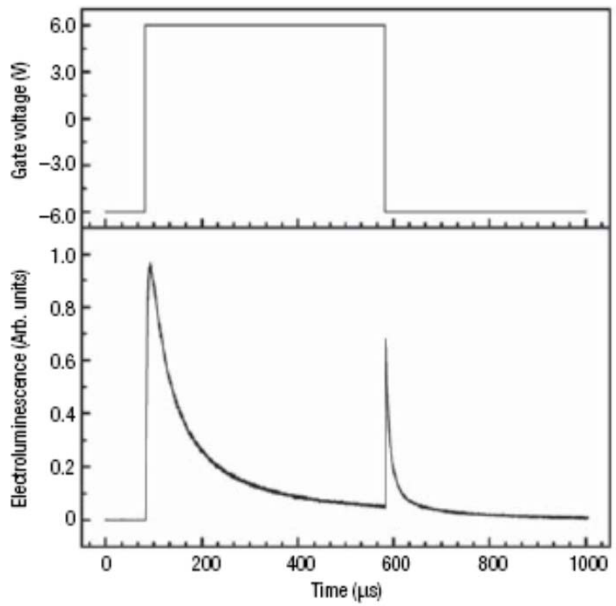
<1% external quantum efficiency

M. A. Green et al., Nature 412, 805 (2001).

Field effect electroluminescence

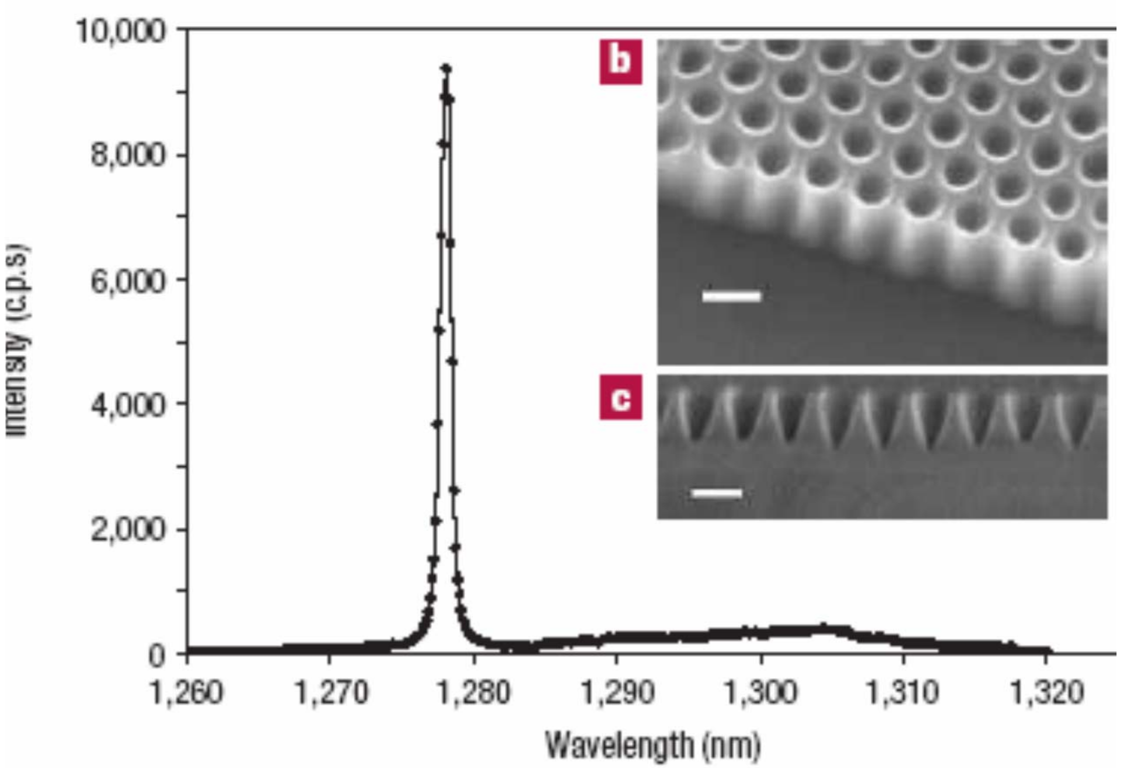


Sequential injection of electron and hole



R. J. Walters, G. I. Bourianoff, and H. A. Atwater, Nat. Mater. 4, 143 (2005).

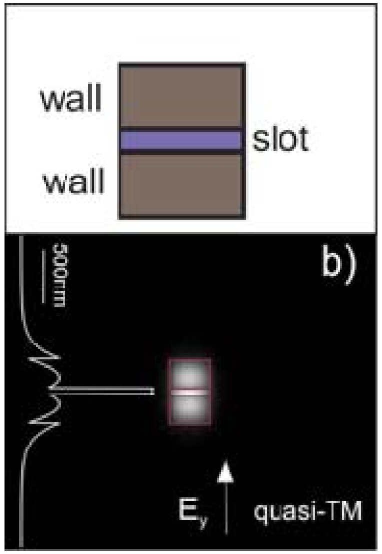
Nanopatterned Crystalline Silicon

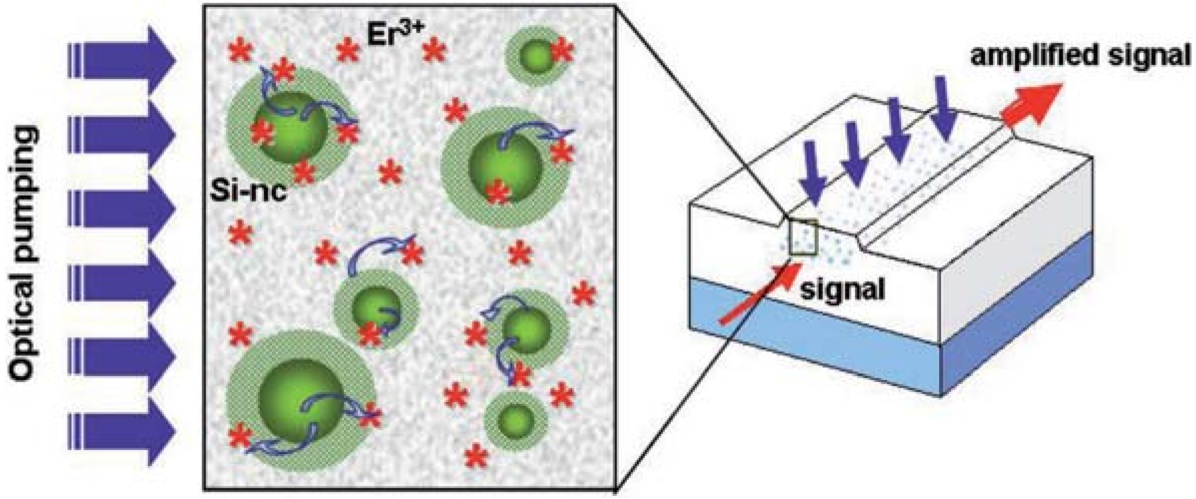


S. G. Cloutier, P. A. Kossyrev and J. Xu, Nat. Mater. 4, 887 (2005).

Silicon nanoclusters: waveguides

- Si-nc embedded in SiO_2 can provide optical gain (red wavelengths);
- Slot waveguides provide high SiO_2 confinement and small cross-section;
- Si-nc creates localization of injected carriers at luminescent centers (Er^{3+} for infrared)

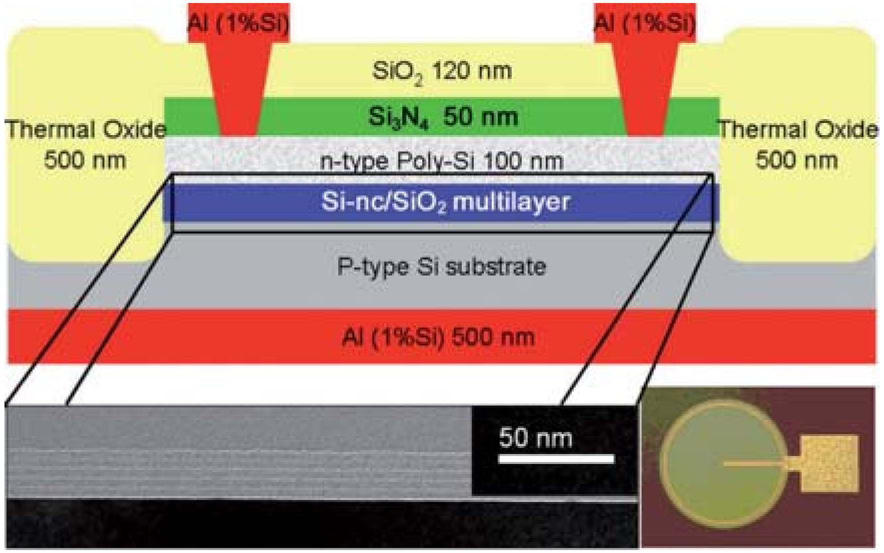


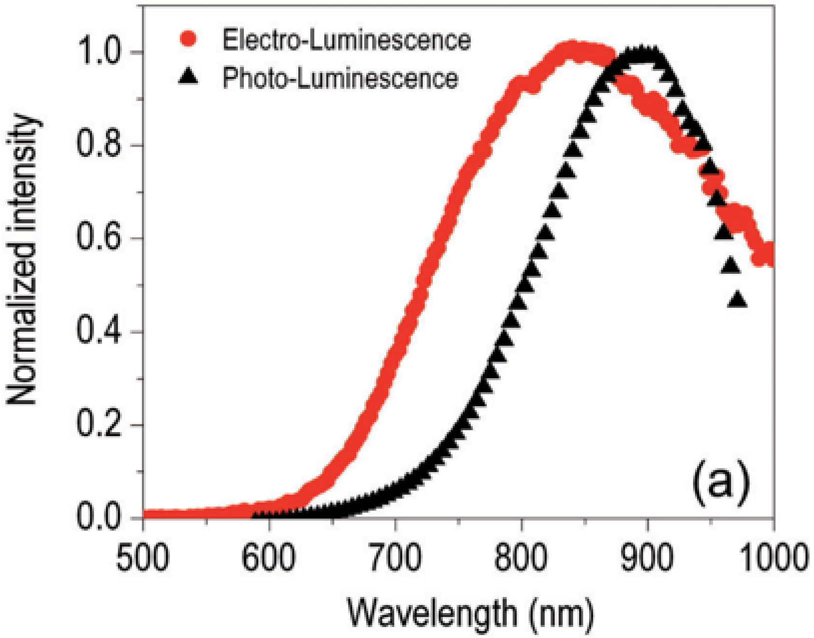


N. Daldosso and L. Pavesi, Laser & Photon. Rev. 3, 508 (2009).

Silicon nanoclusters: LED

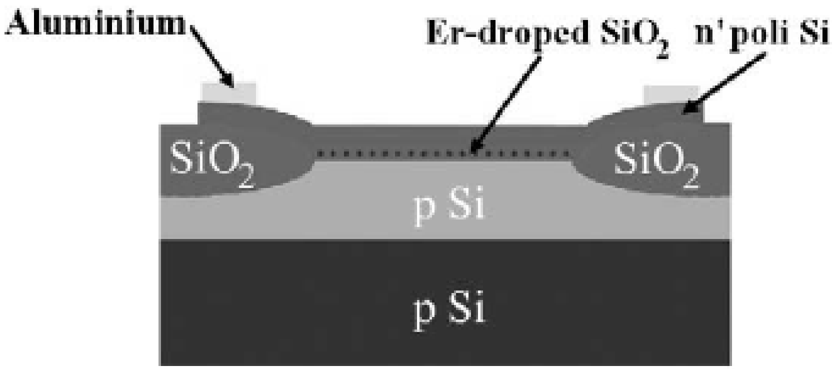
- EL power efficiency values for LED devices:
  - 0.01–0.03% for pure Si-nc;
  - 0.2–0.3% for rare-earth ion doped
- For high EL efficiency: bipolar injection needed
  - issue: electron tunneling barrier << hole barrier



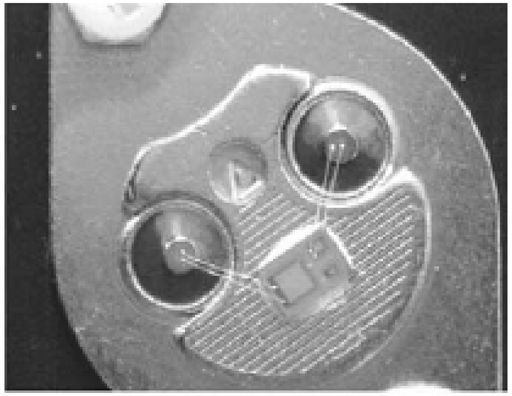


N. Daldosso and L. Pavesi, Laser & Photon. Rev. 3, 508 (2009).

Rare earth doped light emitting MOS



(a)



(b)

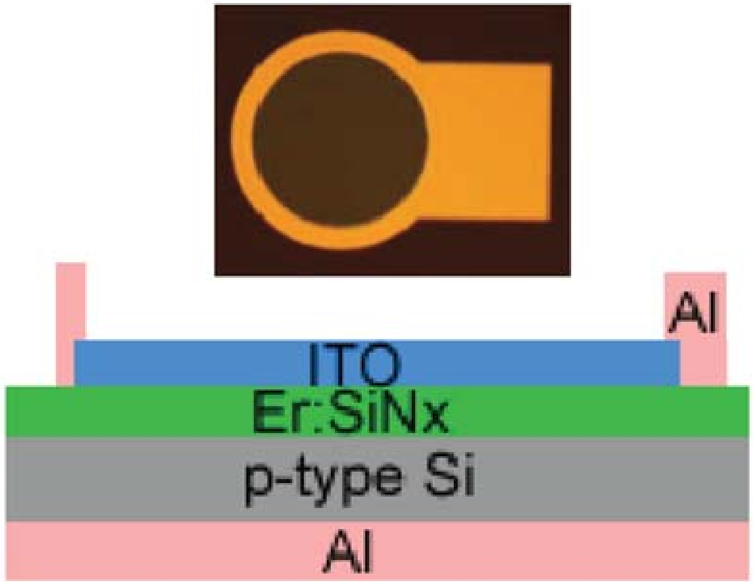
Table 1
Emission wavelength, cross-section and external quantum efficiency of MOS devices with rare-earth doped gate dielectric

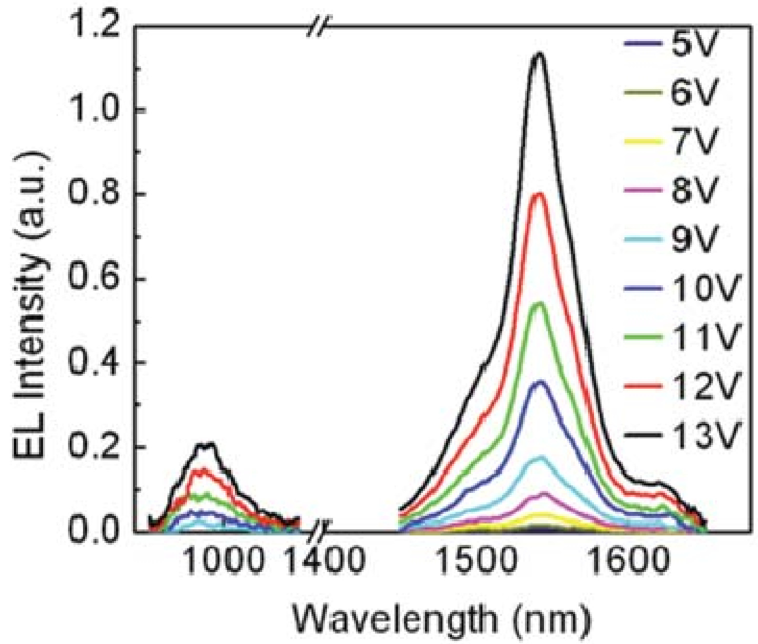
Rare earth	λ emission (nm)	σ (cm^2)	η_{ext} (%)
Erbium	1540	1×10^{-14}	10
Terbium	540	4×10^{-15}	10
Ytterbium	980	1×10^{-15}	0.1

M. E. Castagna et al., Materials Science and Engineering B 105, 83 (2003).

Use Er:SiN
Dal Negro (Boston Univ)

- EL centered at 1535 nm (Er $^4I_{13/2}$)
  - Small peak at 980 nm (Er $^4I_{11/2}$)

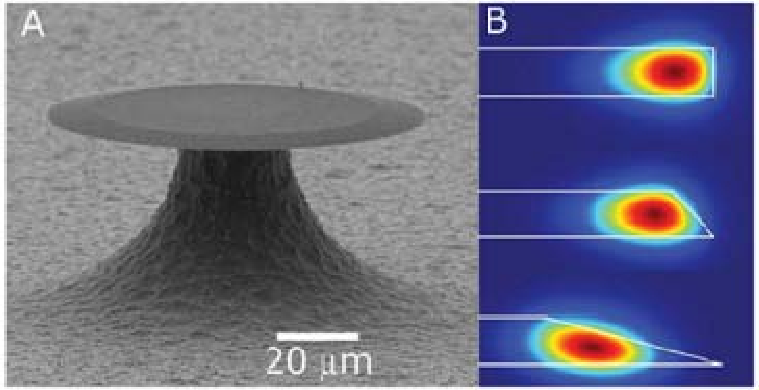


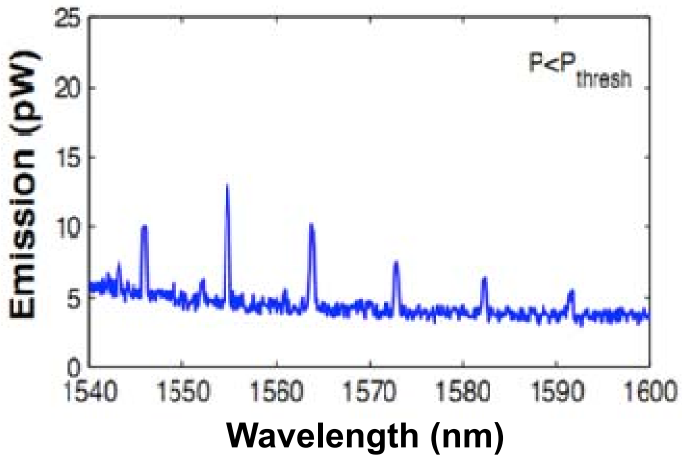


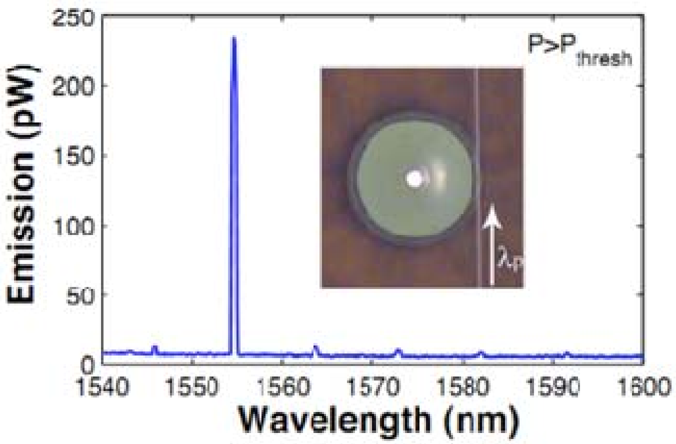
S. Yerci et al., Integrated Photonics Research, Monterey, CA (2010), PDIWI3.

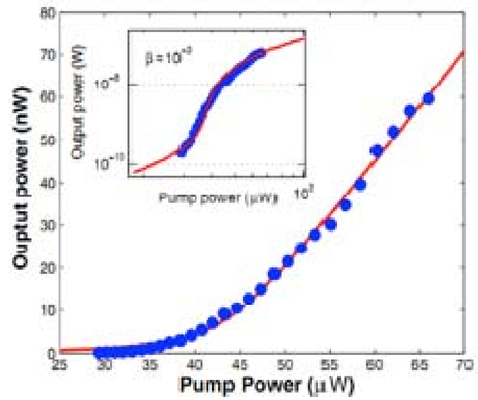
Er-doped microdisk laser on a silicon chip

- SiO_2 microdisk resonator on silicon;
- whispering gallery-type mode;
- $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition @ 1450 nm, lasing @ 1550 nm
- pump threshold 43 μW



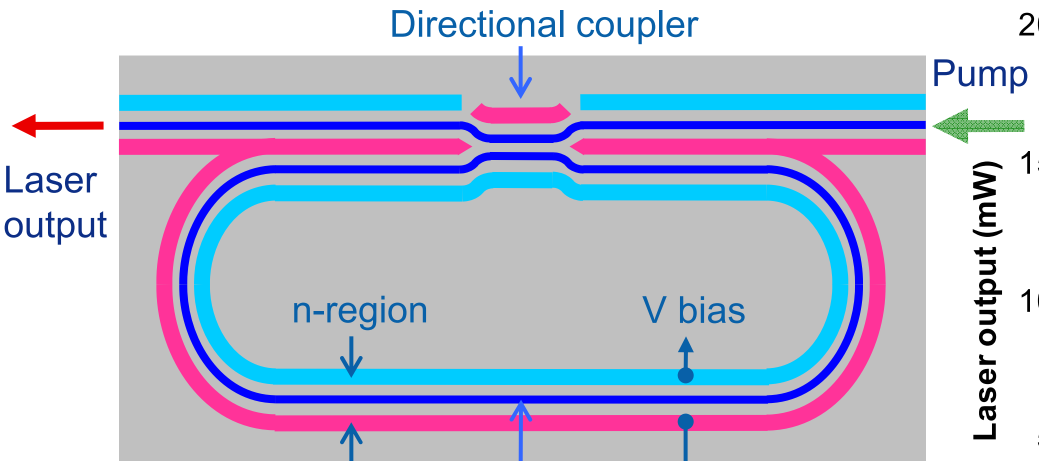


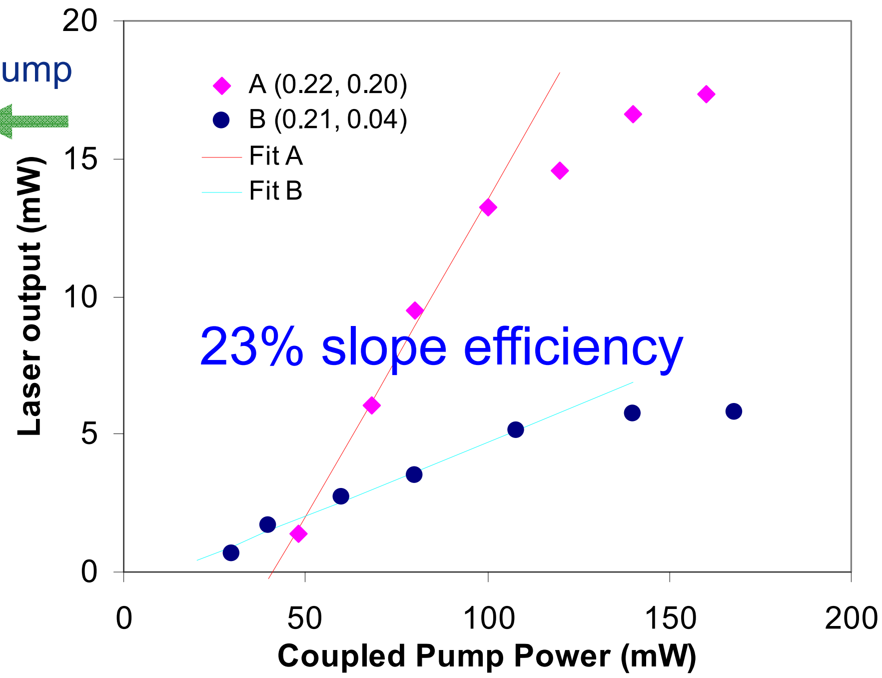


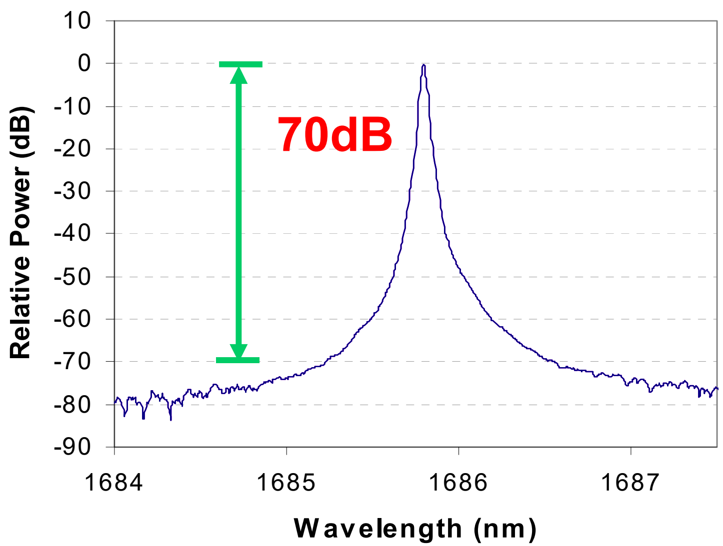


A. Schliesser et al., Phys. Rev. Lett. 97, 243905 (2006).

CW Ring Raman silicon laser







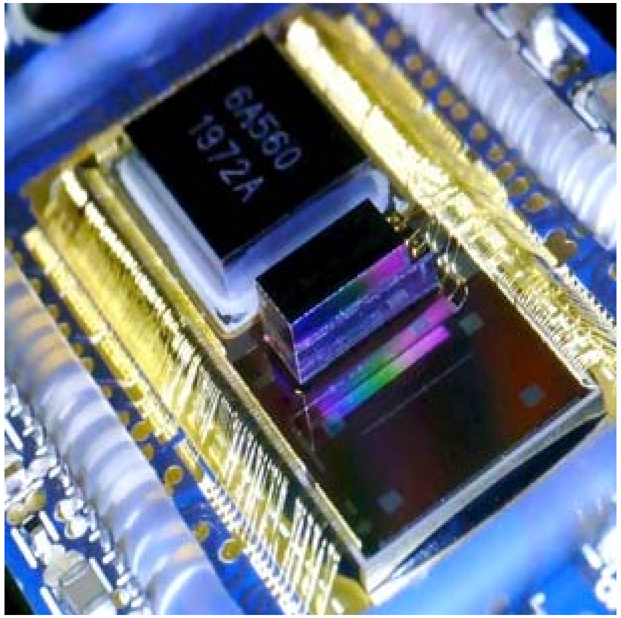
A pump laser is still needed

H. Rong et al., Opt. Express 14, 6705 (2006).

Heterogeneous Approaches: Use another material for gain

- Solder InP lasers to CMOS (Lightwire,Kotura, Luxtera)
- Epitaxial growth on Si substrate
  - Strained Germanium (MIT)
  - SiGeSn (AFRL, U. Mass., Arizona)
  - Quantum Dot (UCSB, UCL, HKUST, Michigan)
  - MOCVD nanopillars on Si (UC Berkeley)
- Process InP layers after CMOS (HELIOS)
- Bonded III-V layers on Si substrate
  - BCB (Ghent/IMEC)
  - Molecular (UCSB, Intel, Caltech, TIT, Hewlett Packard)

Luxtera: 4x26 Gbps PSM-4 Chipset & QSFP28 Module

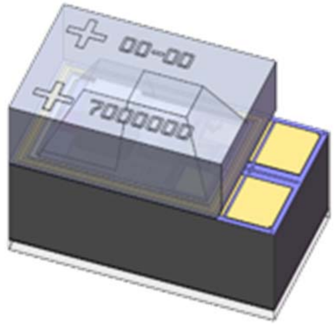


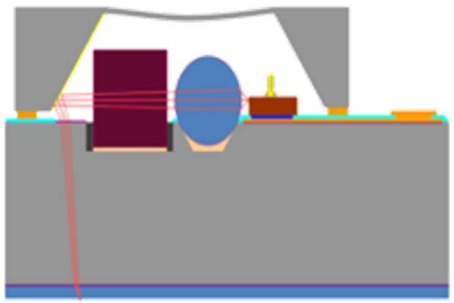
Si Photonics IC (based on 1310 nm library)

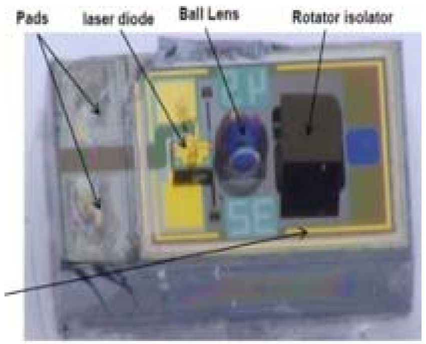
- MZI High Speed Modulators
- Ge High Speed Photodetectors
- Ge monitor PDs for control and monitoring
- BIST (Optical High-Speed loopback)
- Photonics assembly features

Single light source (1310 nm)

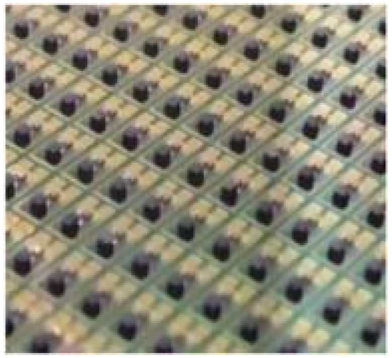
- Based on 1310 nm InP/InGaAsP DFB laser diode







Laser Module after Lid removed : Optical view



Flip Chip Assembly of III/V Components on Si

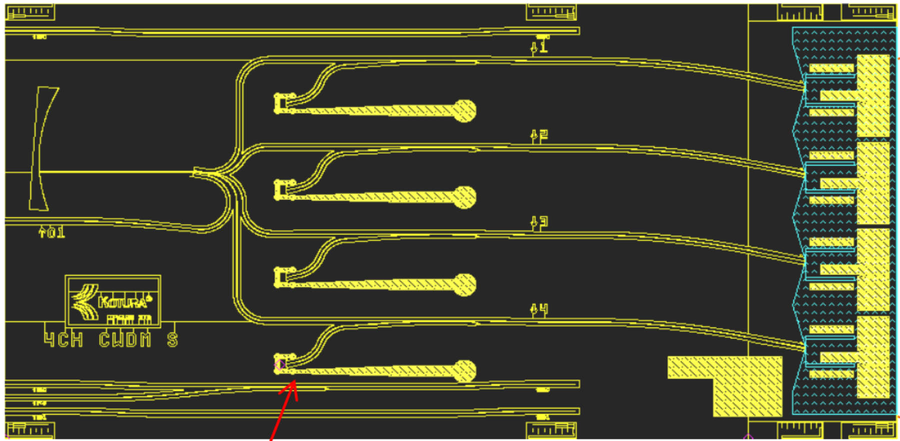
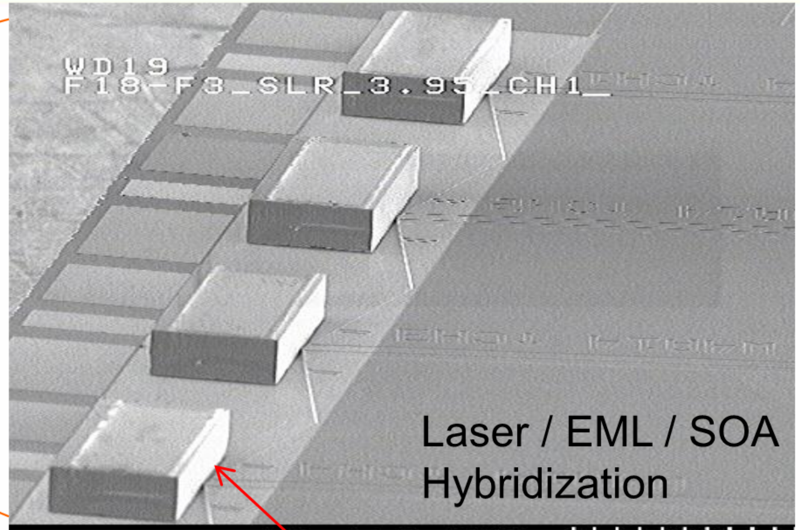
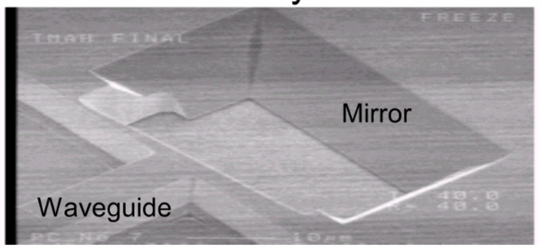
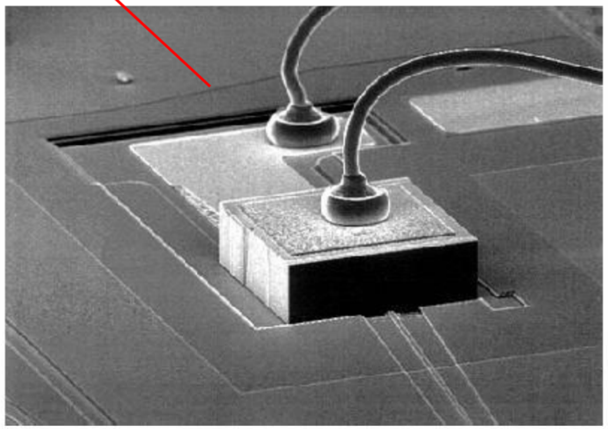


Photo-diode Hybridization

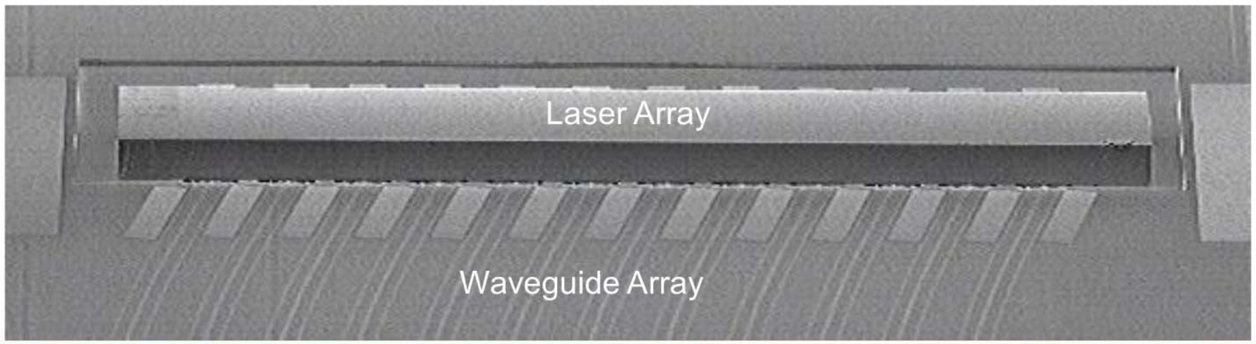




Coupling losses:
LD: 1.5-3dB
PD: 0.5-1dB
Back reflection:
<-45dB
3x3um Si WGs
used

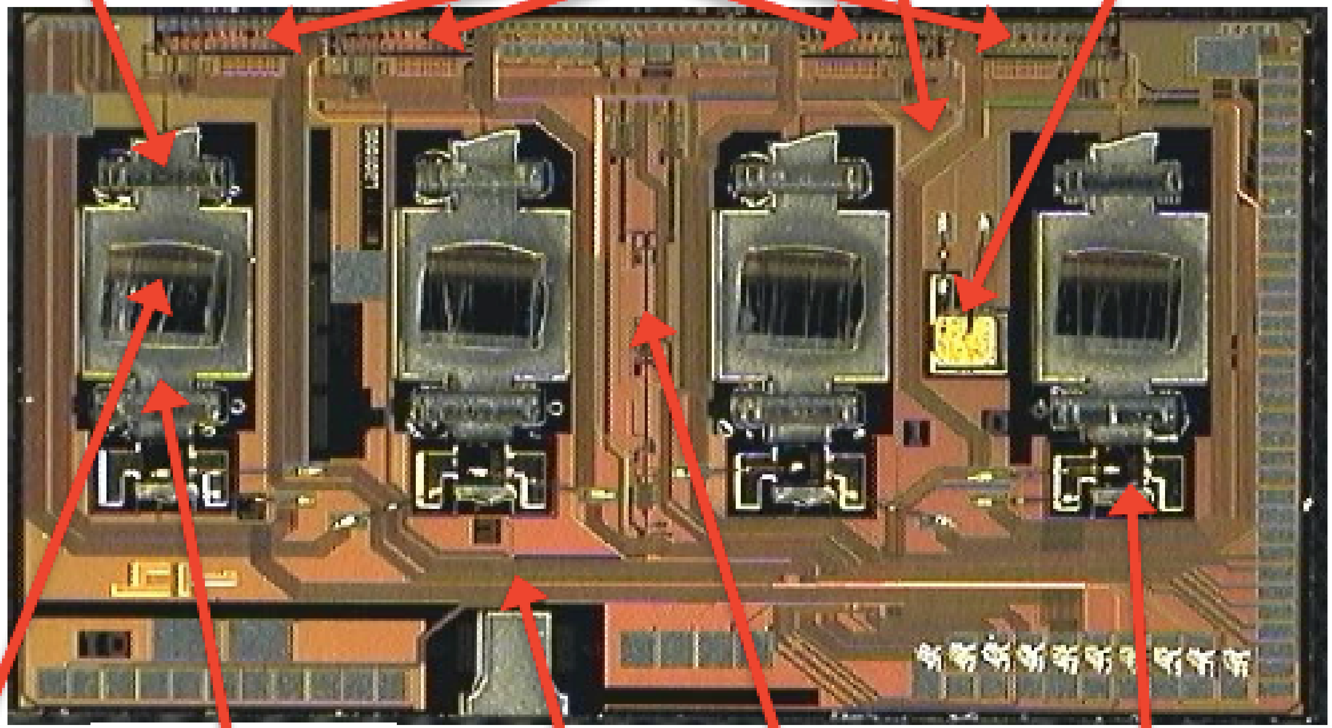


Mechanical features in Si interlock with III/V components for accurate positioning



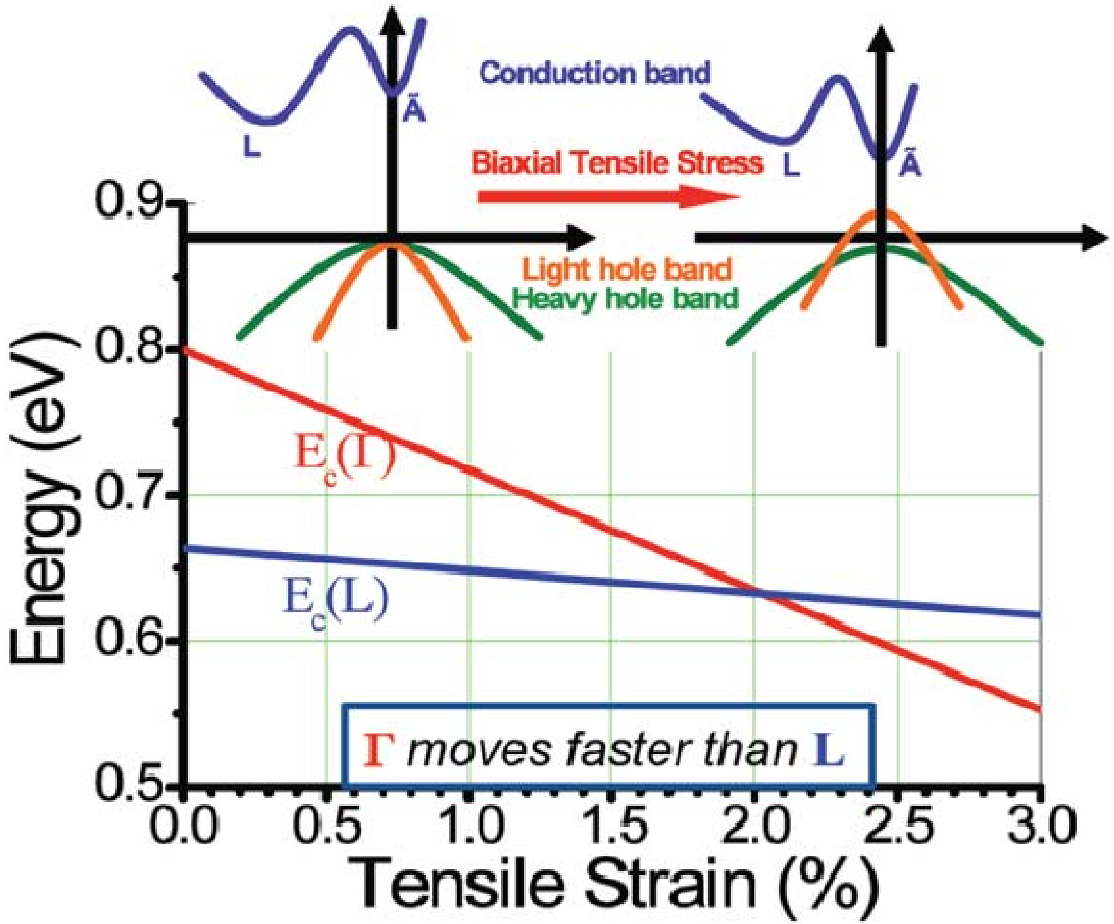
III/V chips (LD, EML, SOA, PD) can be flip chip attached on Si

Cisco: System in Package Integration of Lasers



" OFC2014 : Packaging and Reliability of CMOS Photonics", Angelo Miele & David Piede (CISCO CPAK 100G LR4 design)

Ge-on-Si: in-plane tensile strain

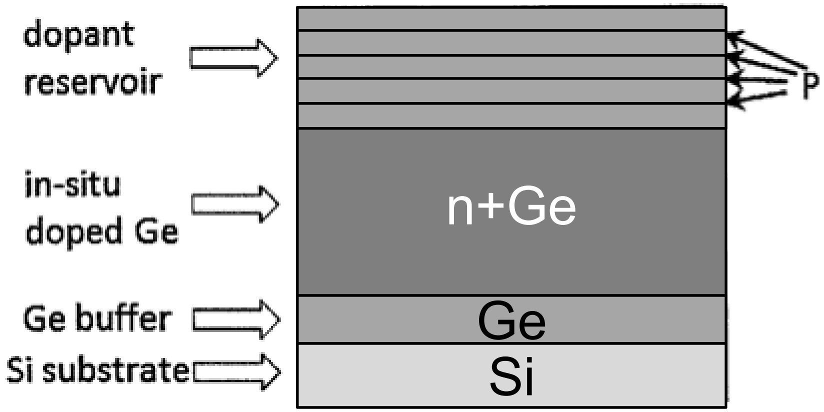


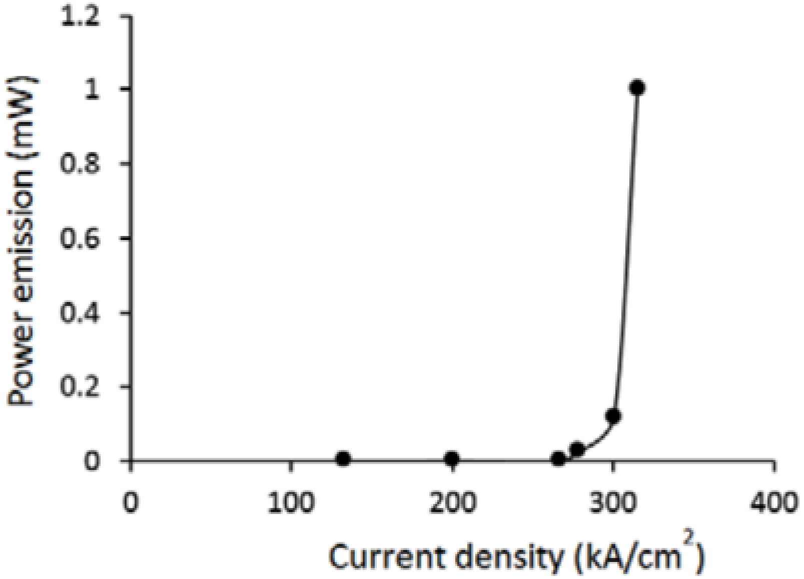
- Ge is pseudo-direct gap and compatible with CMOS.
- Tensile strain drives Ge towards direct gap behavior.

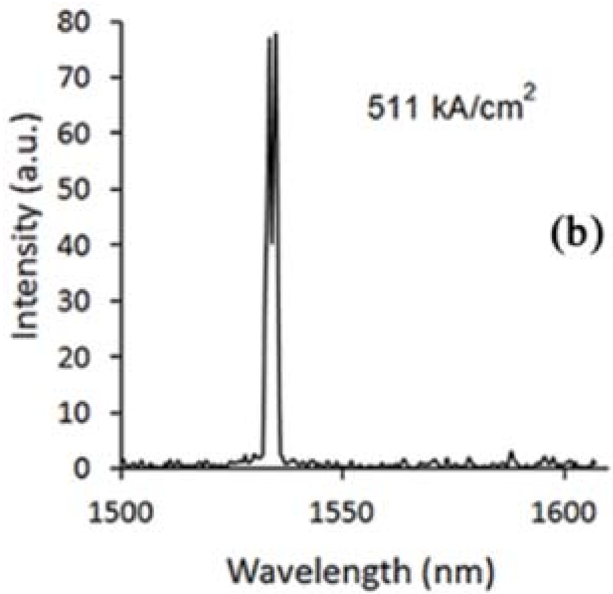
Slide courtesy of L. Kimmerling, MIT

Electrically pumped Ge-on-Si laser

- Pulsed operation at 15 C
- Threshold 280 kA/cm^2
- 1.7 V at threshold
- Threshold current: 0.6 A*
- Threshold power: 1 W*
- Output: 1 mW at 315 kA/cm^2
- Efficiency ~10^{-4}

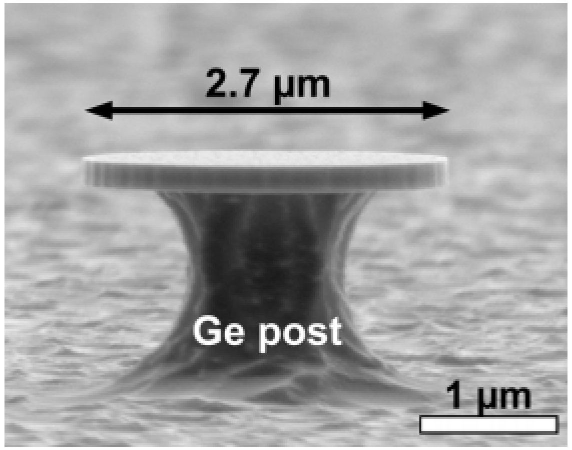


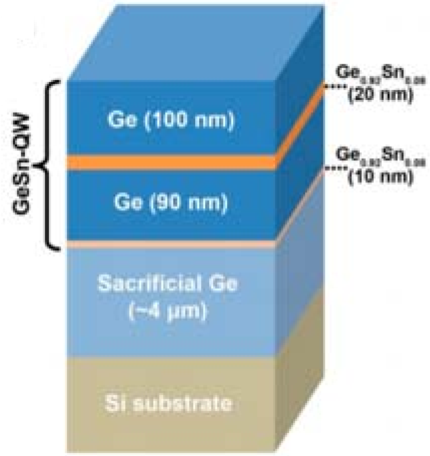




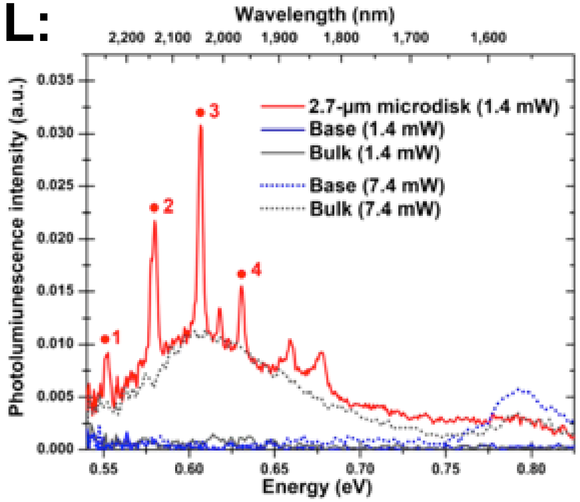
R. E. Camacho-Aguilera et al., Opt. Express 20, 11316 (2012) and J. Michel et al., OFC (2012).

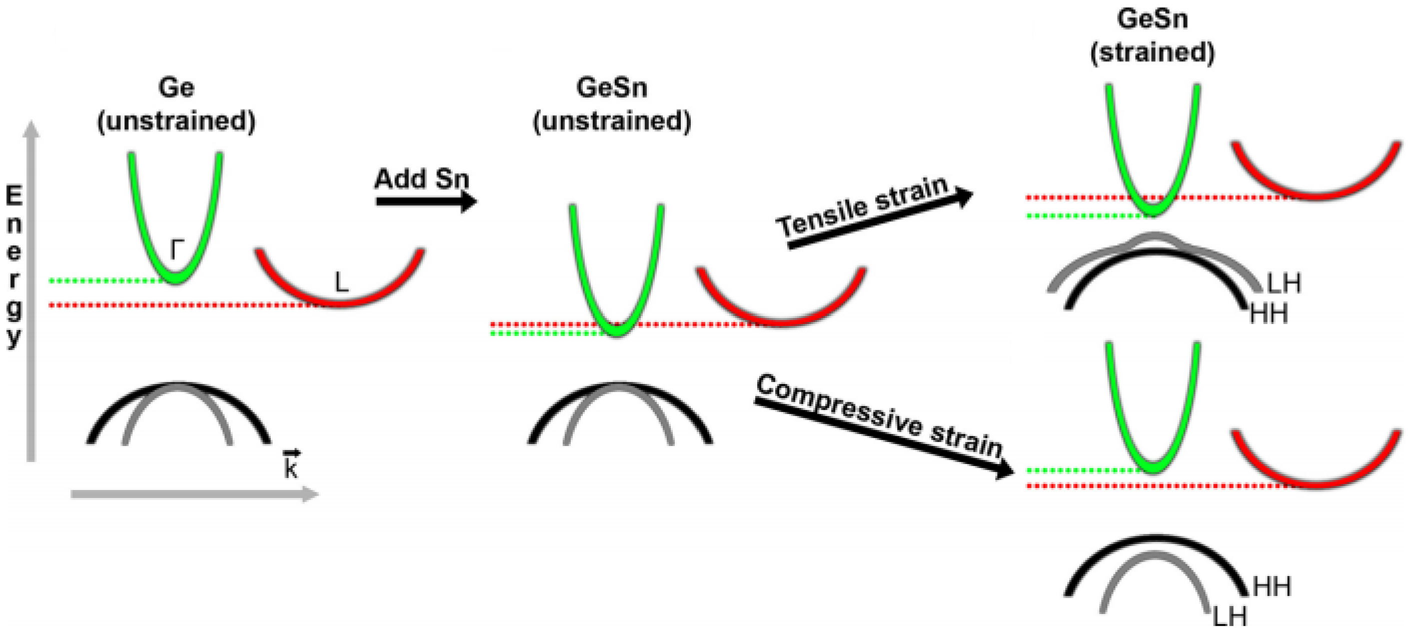
Pseudomorphic Ge/GeSn/Ge





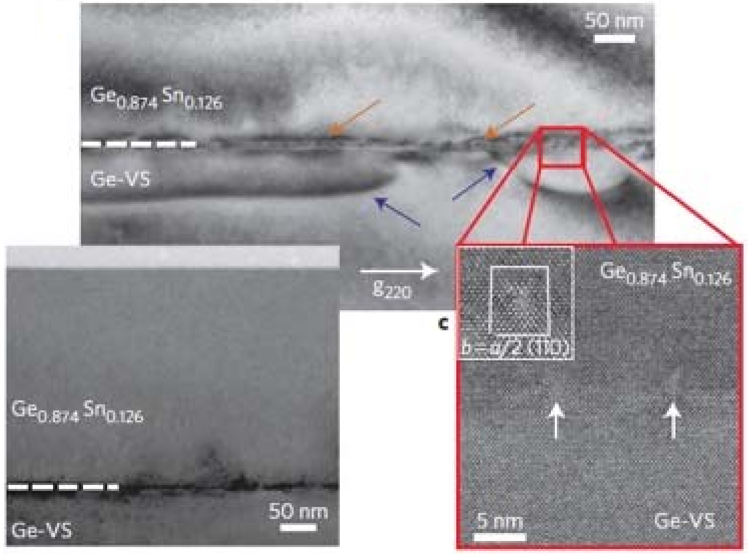
PL:

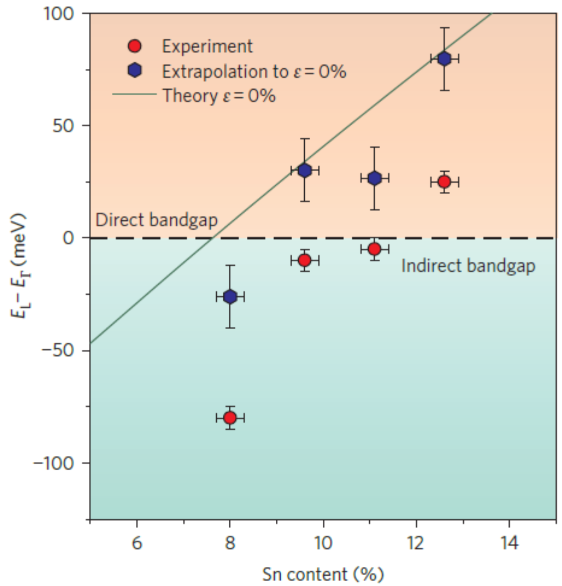




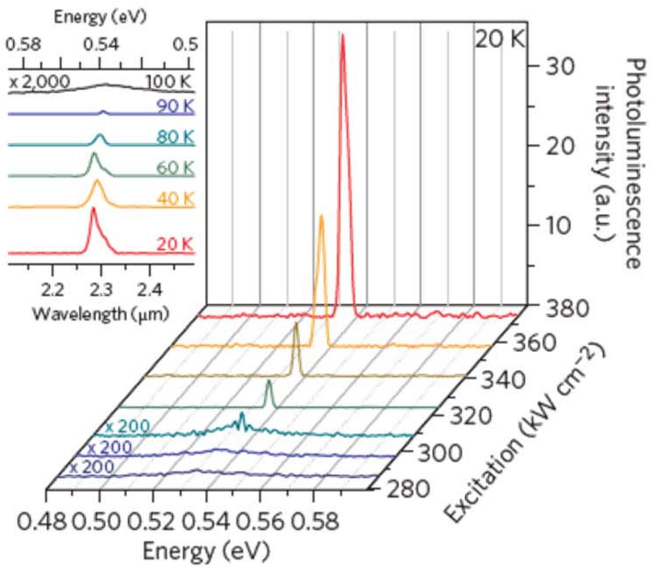
R. Chen et al., Nano Lett. 14, 37 (2014).

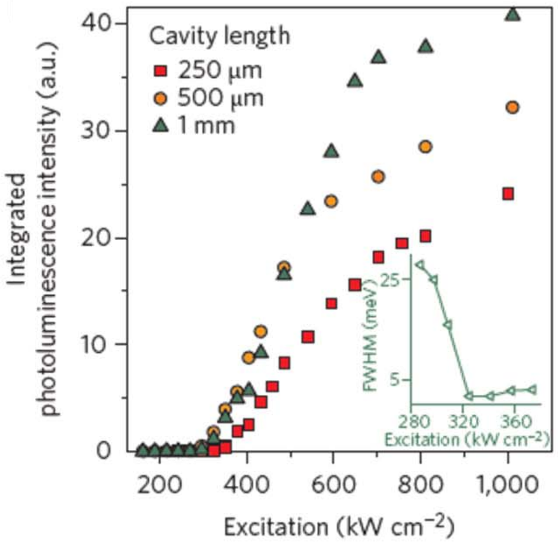
Lasing in direct-bandgap GeSn alloy grown on Si

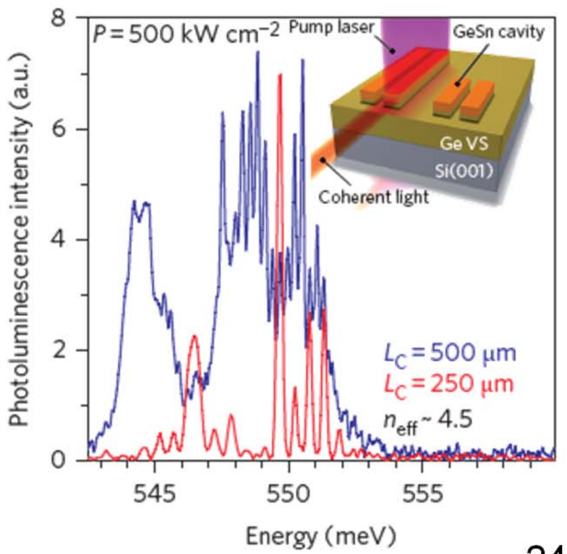




Optical pump

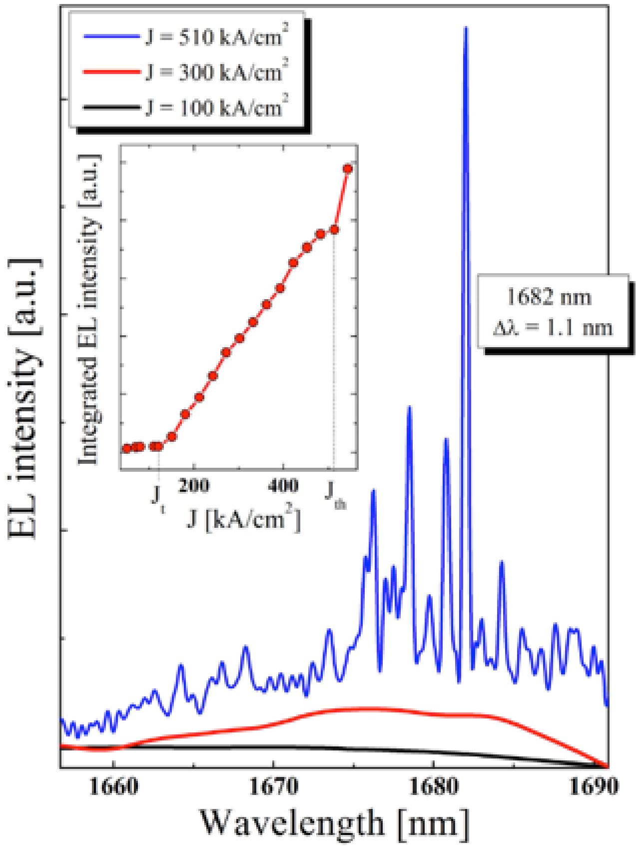


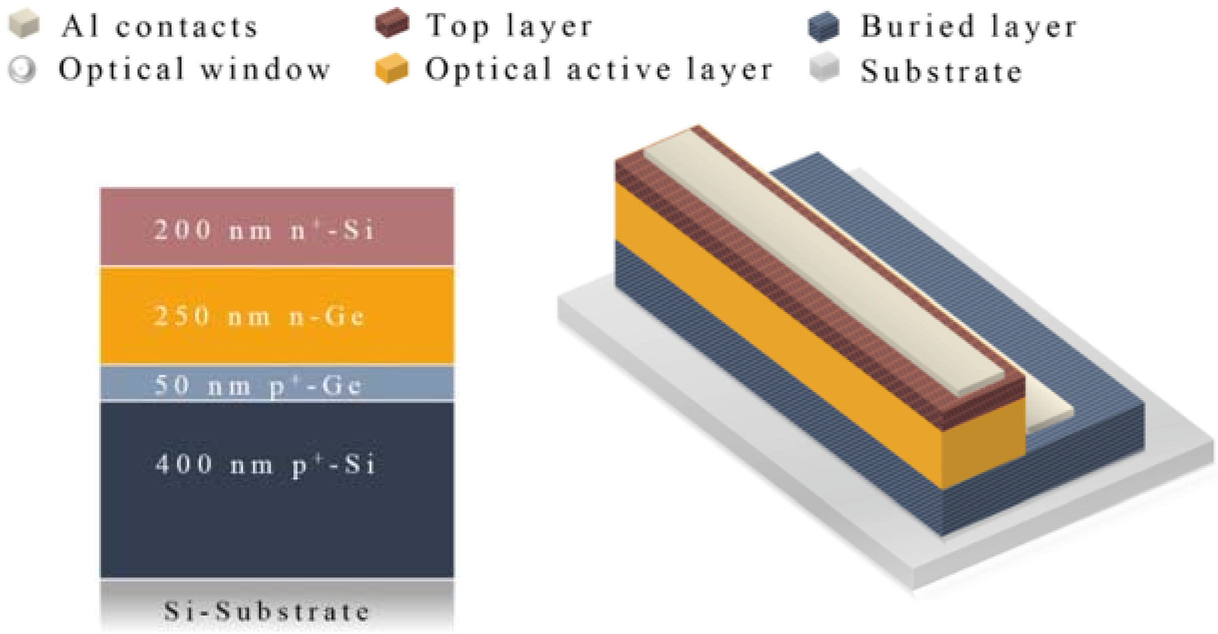


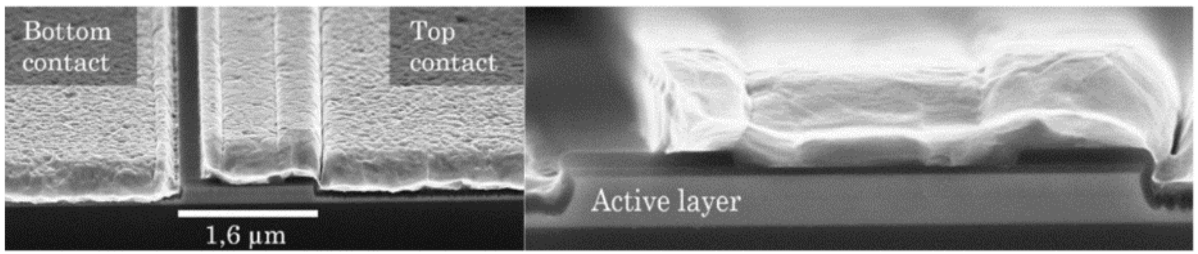


S. Wirths et al., Nat. Photon. 9, 88 (2015).

Electrically pumped lasing from Ge Fabry-Perot resonators on Si







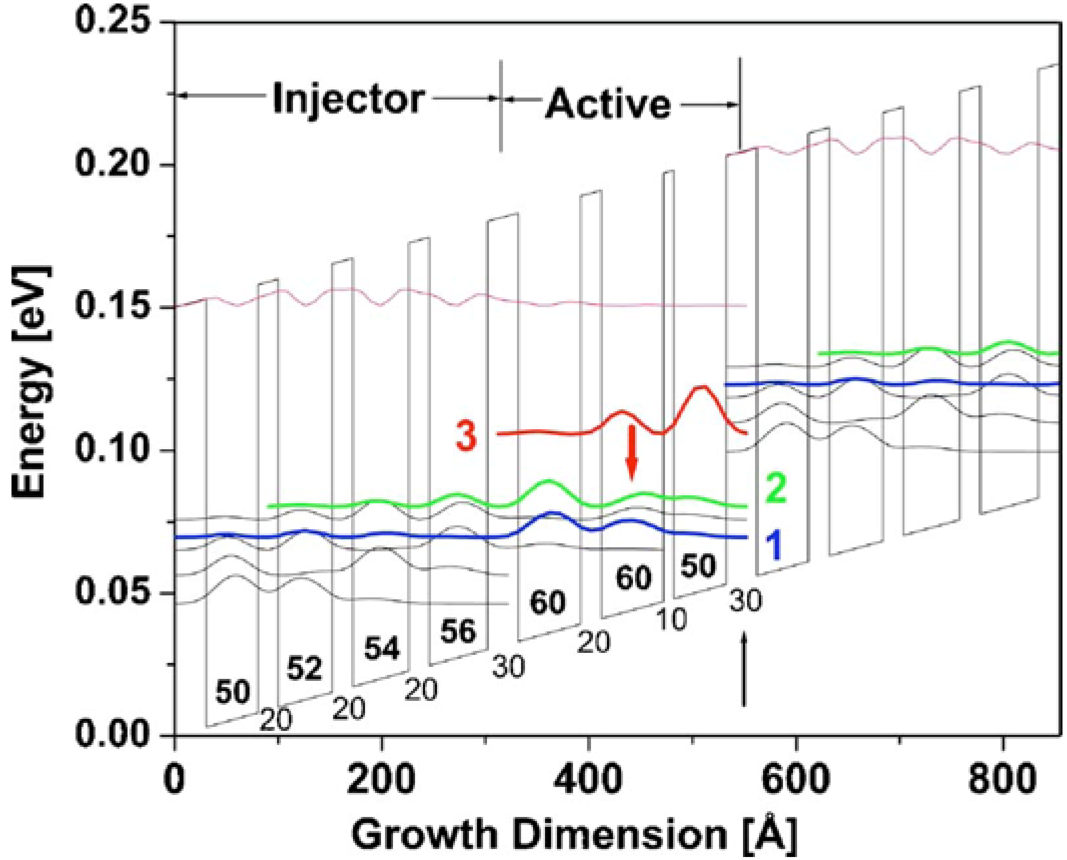
R. Koerner et al., Opt. Express 23, 14815 (2015).

n-i-n Intersubband Ge/SiGeSn QCL

Strain-free Ge/GeSiSn quantum cascade lasers based on *L-valley* intersubband transitions

G. Sun, HH. Cheng, J. Menendez, J. B. Khurgin, and R. A. Soref

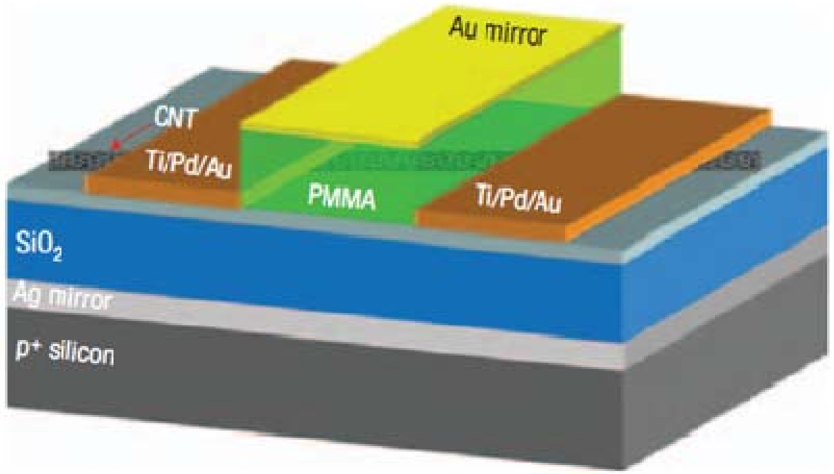
One Period of QCL showing design of Ge quantum wells and SiGeSn barriers. Wavefunctions and the 3-2 lasing transition are also shown.

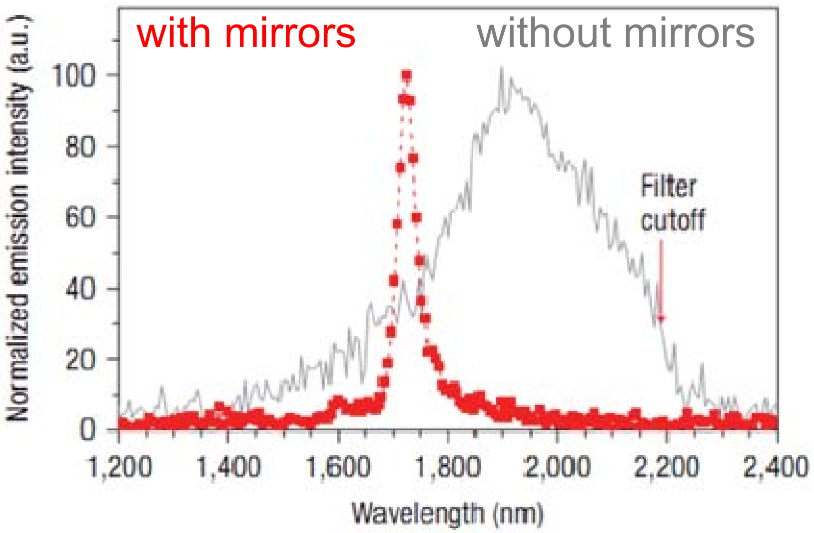


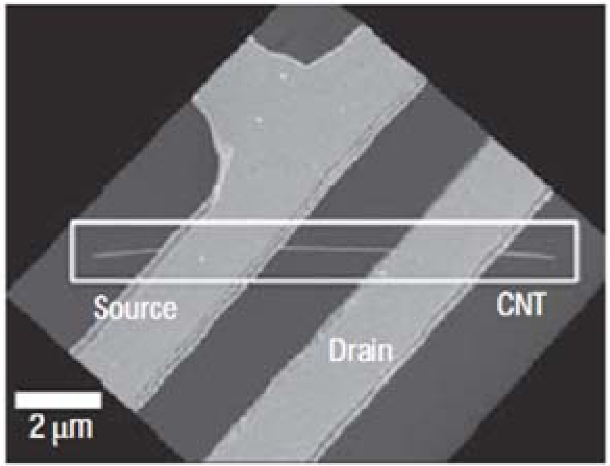
G. Sun et al., Appl. Phys. Lett. 90, 251105 (2007).

On-chip carbon nanotube emitter at IR wavelengths

- Current injection of nanotube transistor;
- Generally: CNT EL spectrum broad, non-directional;
- with λ/2 microcavity → narrow (~40nm) and directional spectrum @1.75 μm.







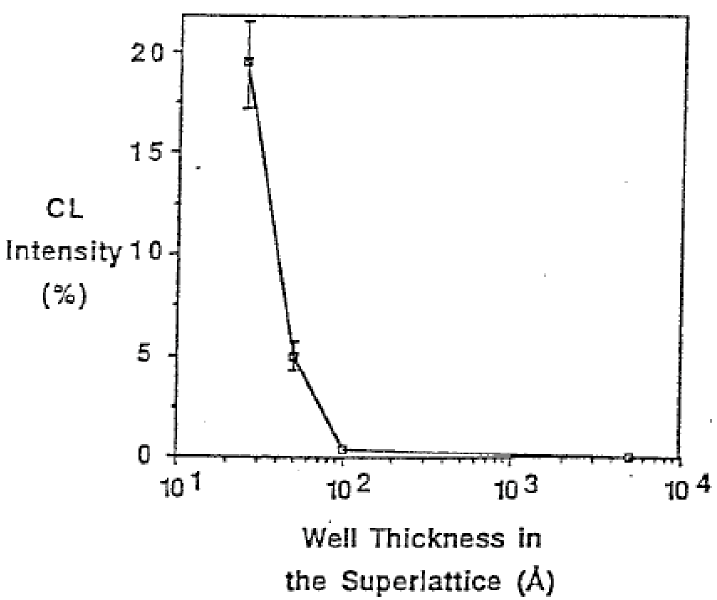
F. Xia et al., Nature Nanotechn. 4, 839 (2008).

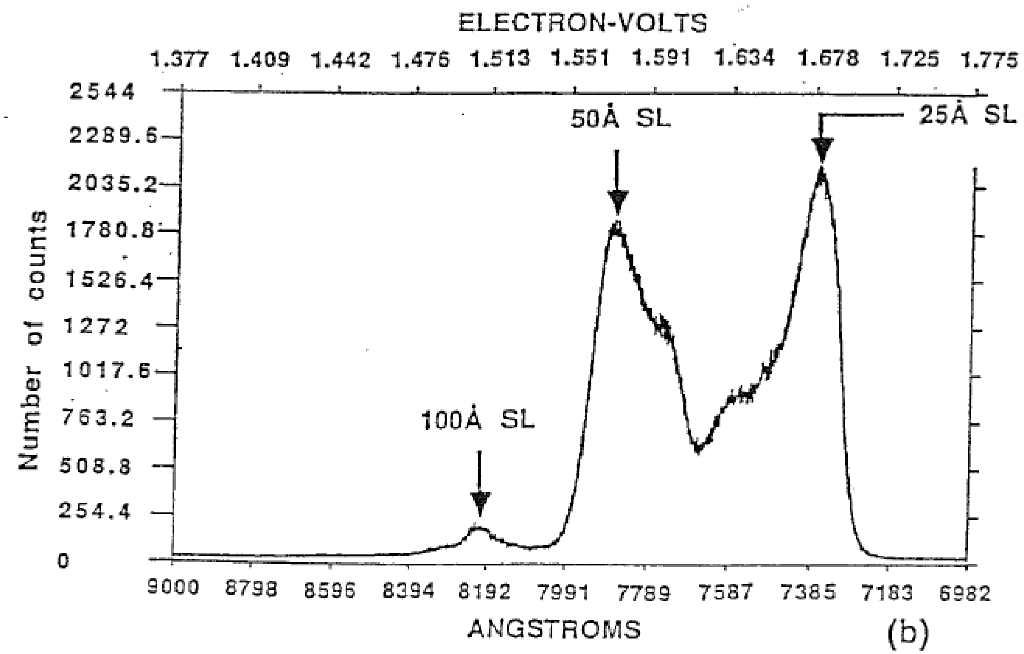
Epitaxial III-V Quantum Wells on Si

Quantum well: historically poor emission and poor lifetime. Two examples:

- Van der Ziel, et al. "Degradation of GaAs lasers…" APL (1987): 89-91. **8 sec lifetime**
- Liu, Petroff, Kroemer JAP 64 (1988):

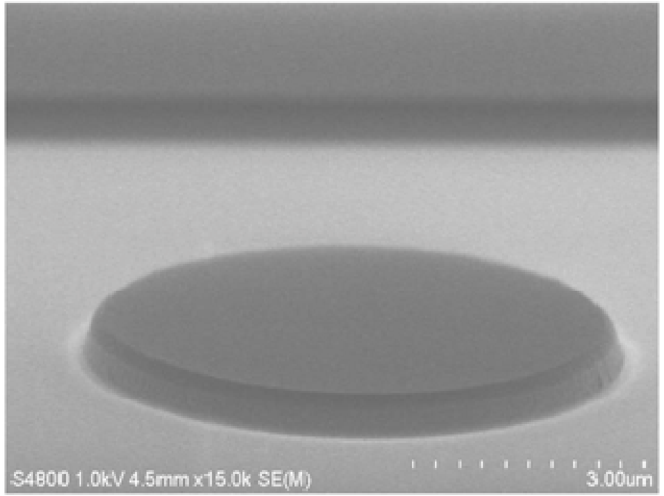
GaAs/AlAs Superlattices on Silicon

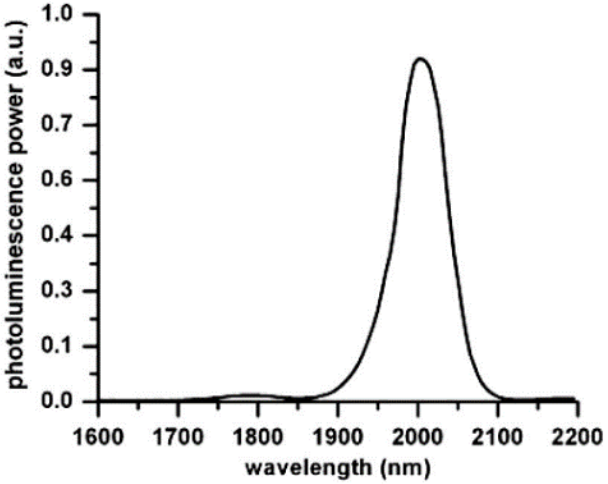


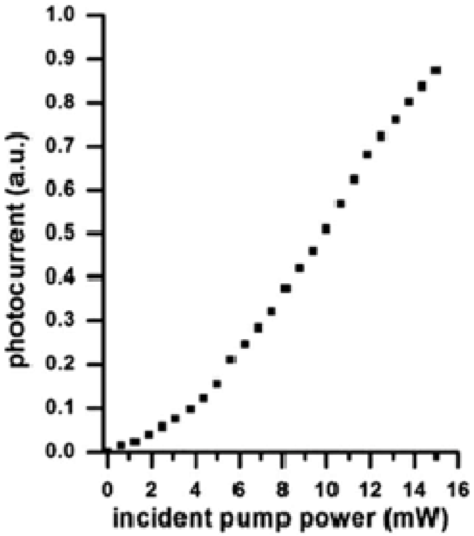


InGaSb QW microcylinder laser @ 2μm

- III-Sb monolithically grown on silicon substrate
  - interfacial misfit array to relieve lattice mismatch;
- 5-μm diameter disk
- RT lasing @ 2 μm;
- optical pumping @850 nm.





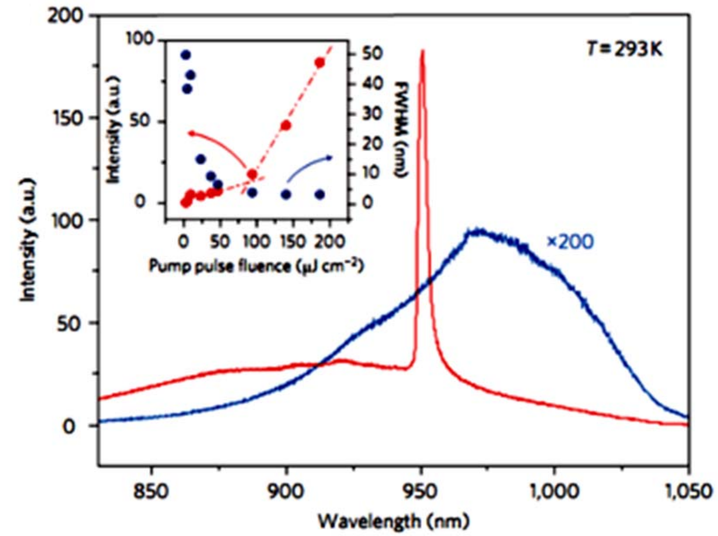


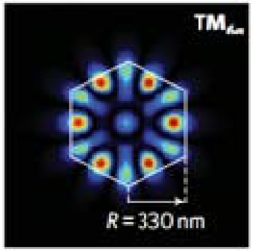
J. K. Yang and K. K. Berggren, J. Vac. Sci. Technol. B 25, 2025 (2007).

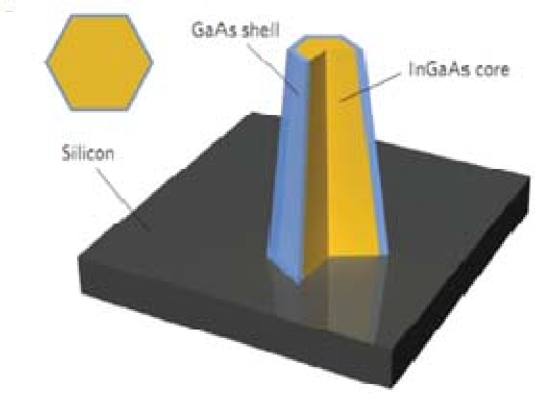
Nanolasers grown on silicon

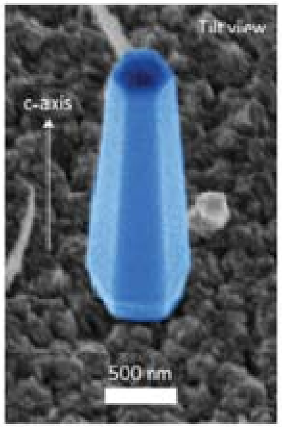
C. Chang Hasnain (UC Berkeley)

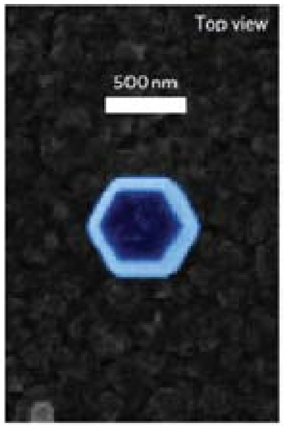
- III–V nanolaser grown on silicon;
- room-temperature operation;
- subwavelength volume;
- helically propagating cavity modes.

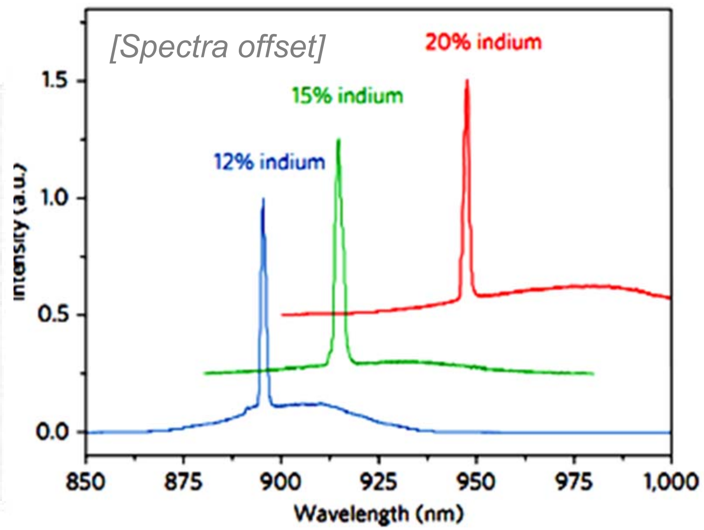








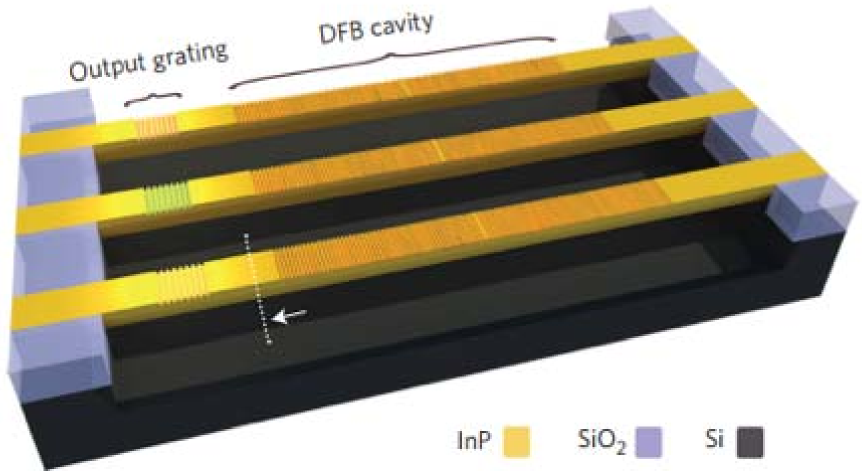


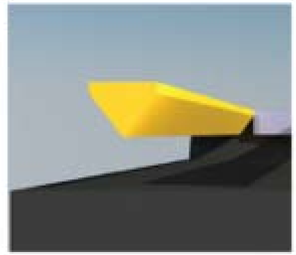


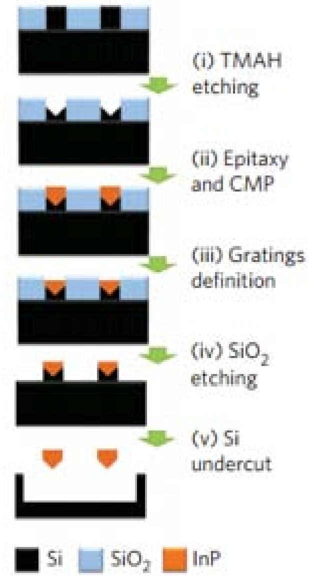
R. Chen et al., Nat. Photon. 5, 170 (2011).

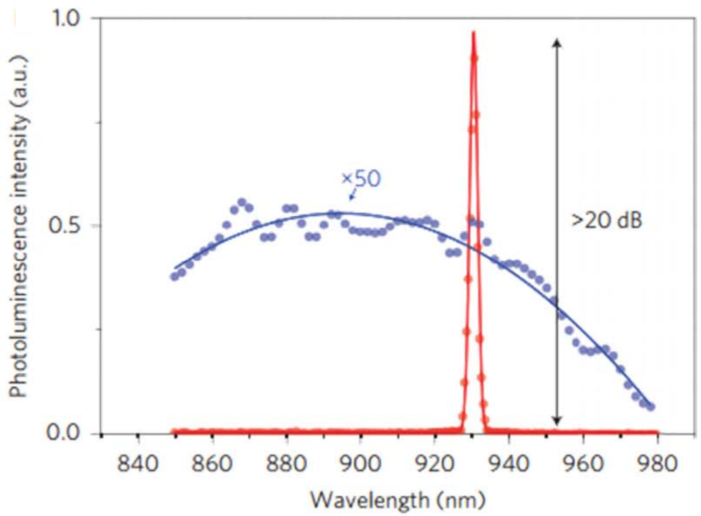
Room-temperature InP distributed feedback laser array directly grown on silicon

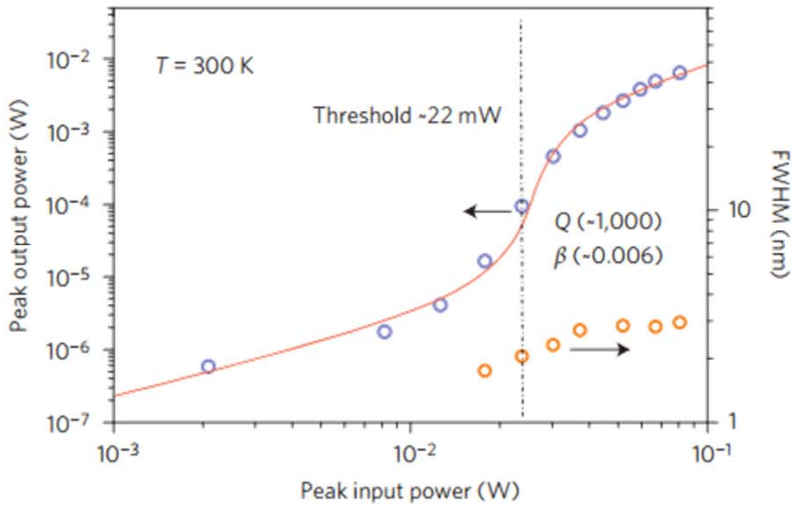
- Optically pumped
- Threading dislocations and anti-phase boundaries suppressed to <20 nm thick layer







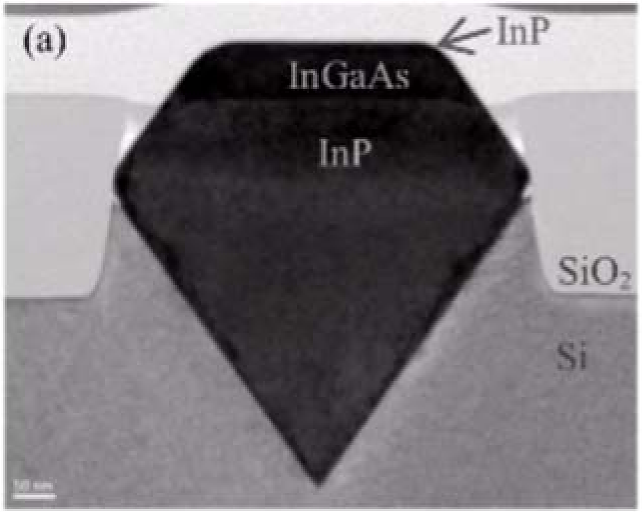


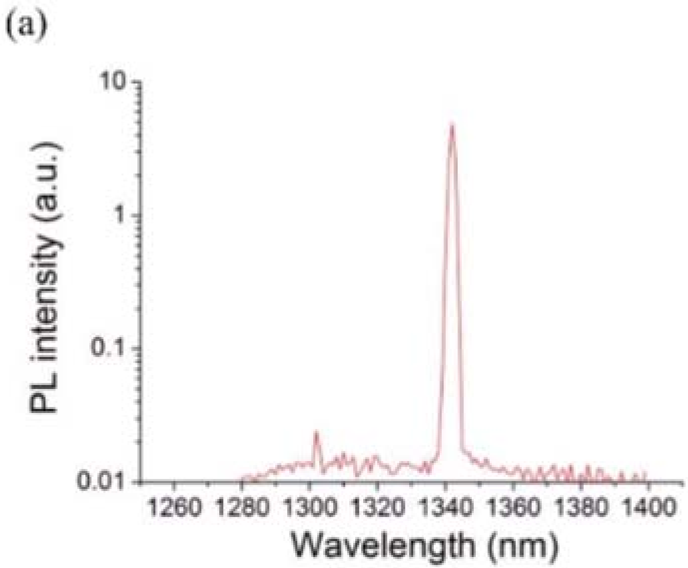


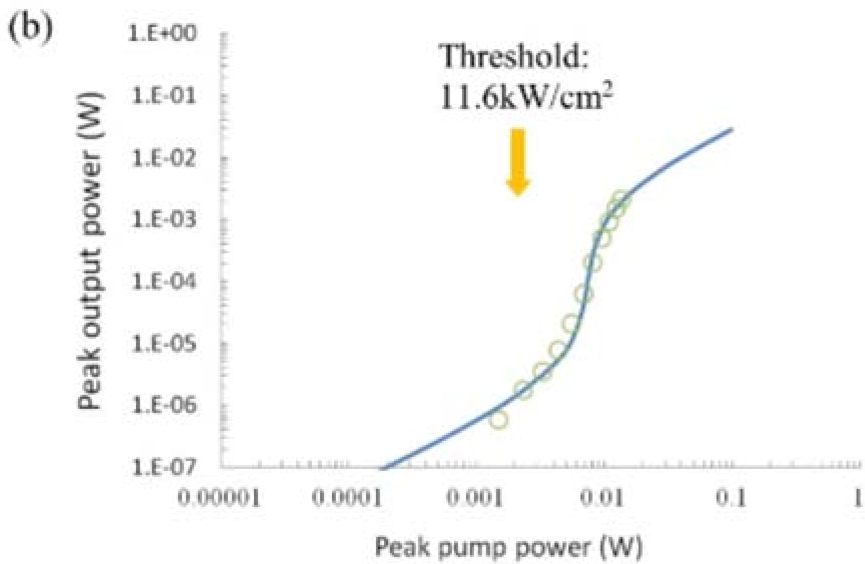
Z. Wang et al., Nat. Photon. 9, 837 (2015).

RT InGaAs/InP distributed feedback laser array directly grown on silicon at 1.3μm

- Prior technique further explored
- CMP→MOCVD overgrowth of InGaAs alloy



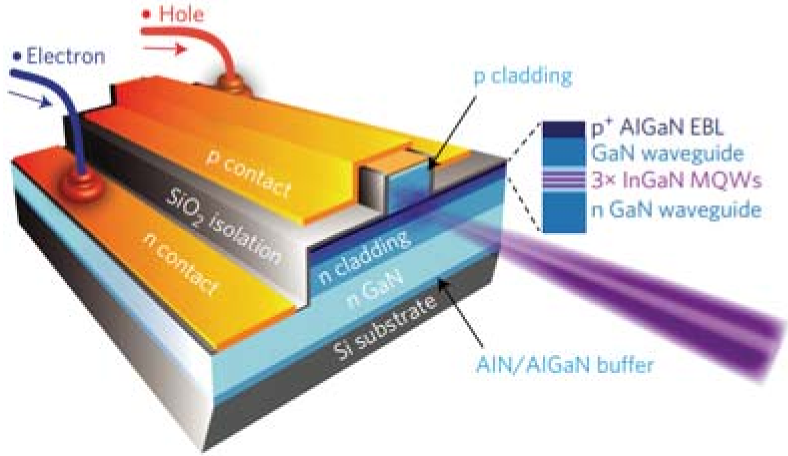


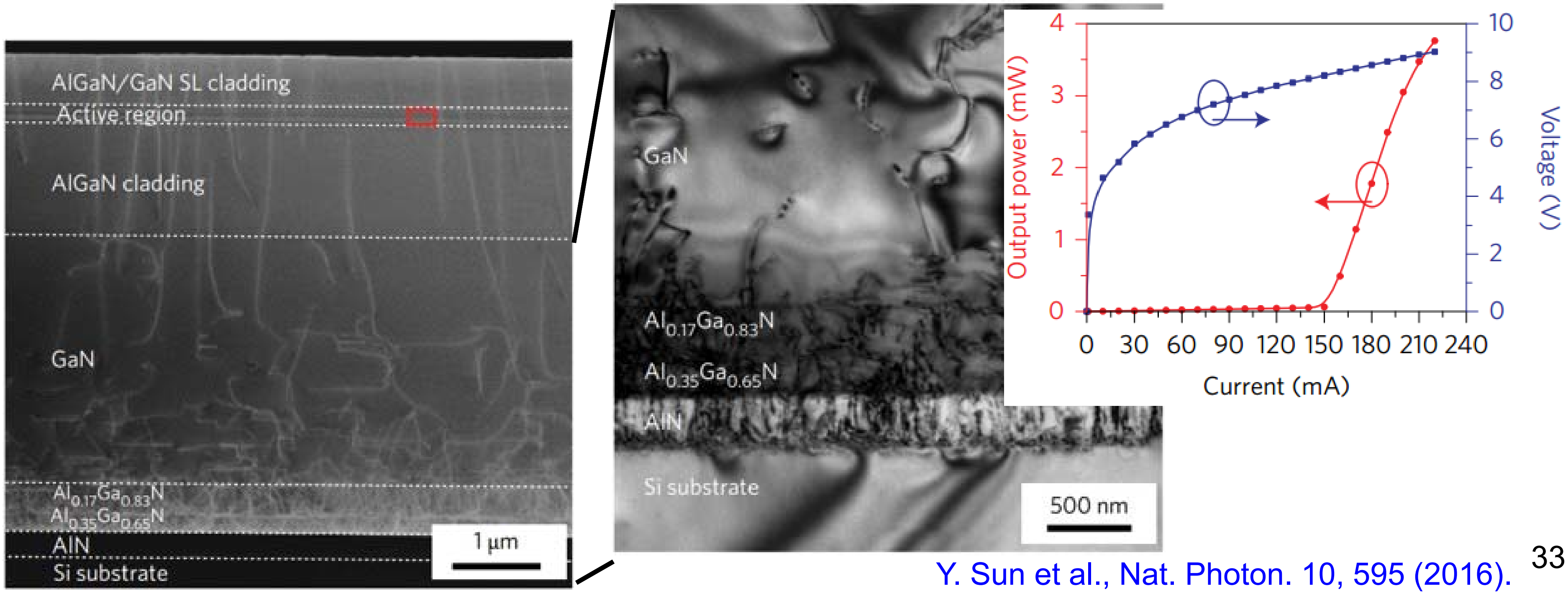


Z. Wang *et al.* CLEO (2016).

Room-temperature continuous-wave electrically injected InGaN-based laser directly grown on Si

- InGaN MQWs
- Key advance is using $Al_{0.35}Ga_{0.65}N/AlN$, then $GaN/Al_{0.17}Ga_{0.83}N$ to facilitate threading dislocation bending



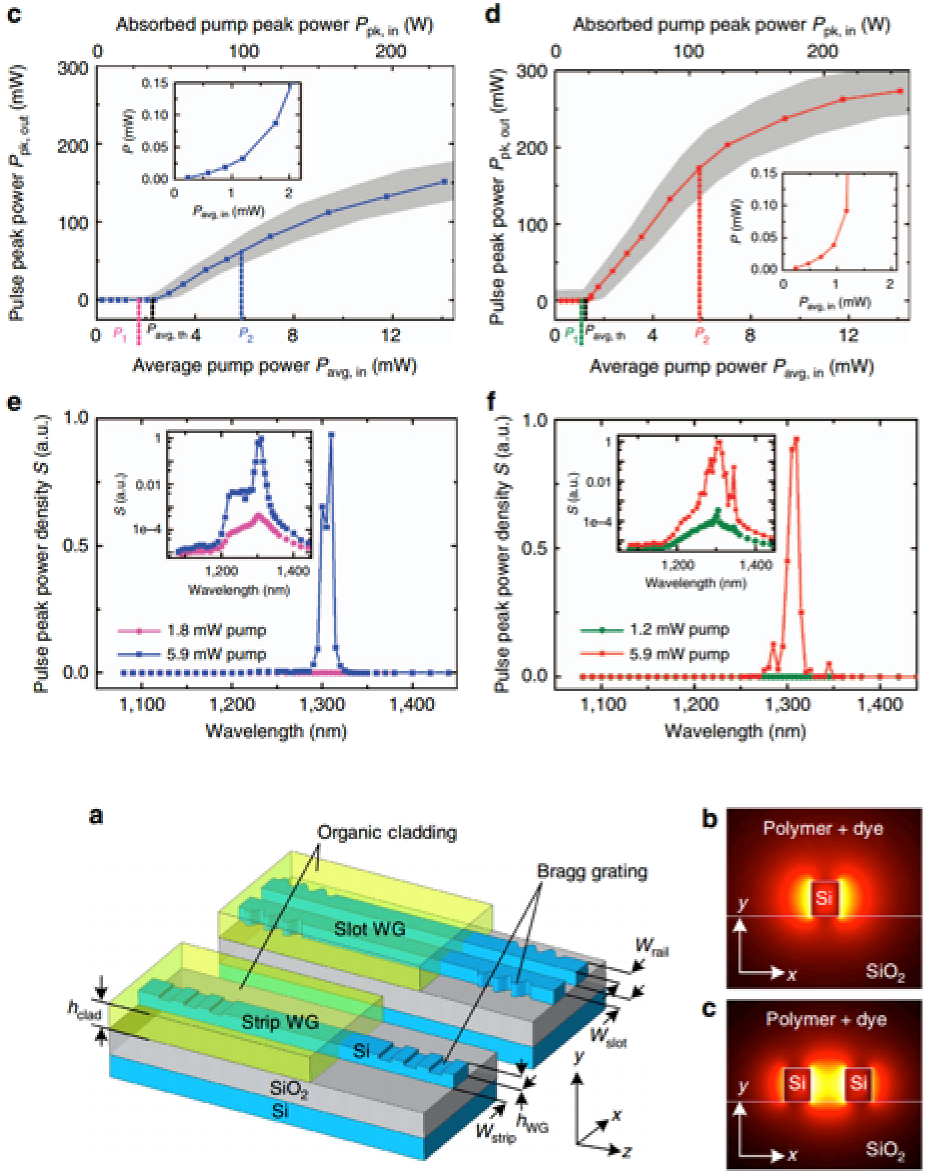


Y. Sun et al., Nat. Photon. 10, 595 (2016).

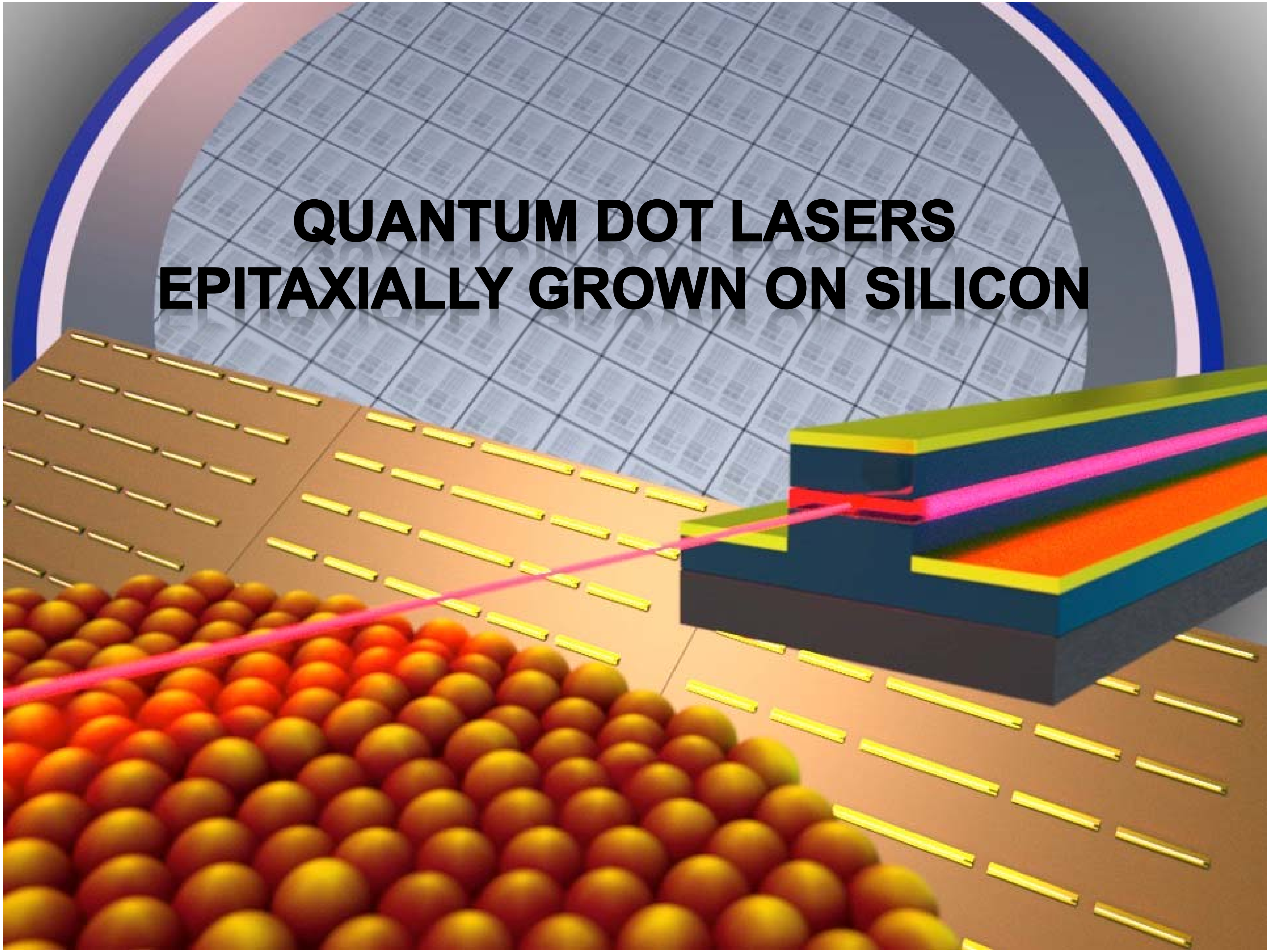
UCSB

Silicon Organic Hybrid Laser

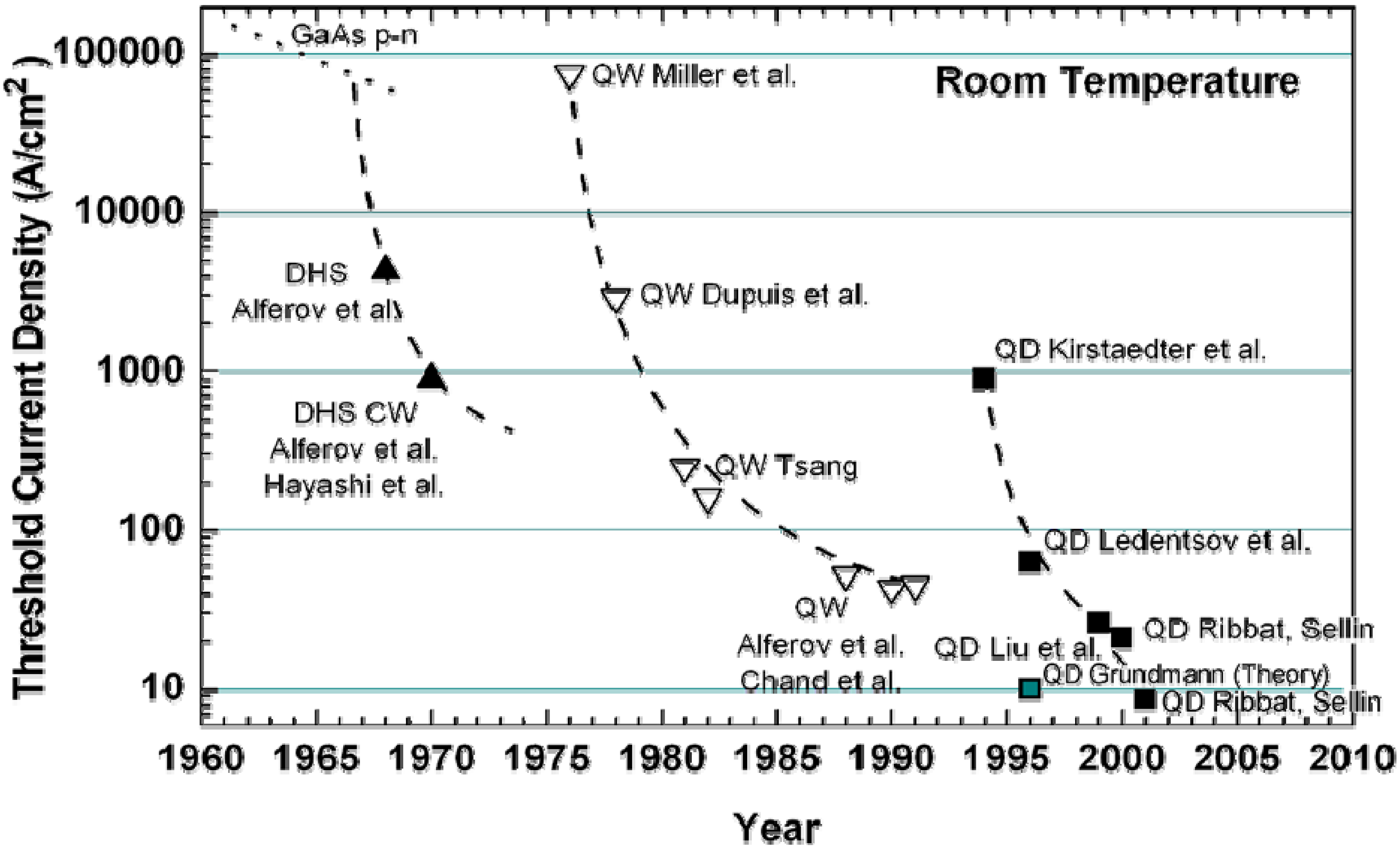
- Si slot and strip waveguides coated in IR26 doped PMMA
- Optical pumping achieves lasing at 1310 nm
- Threshold for strip, slot =2.3, 1.3 mW



D. Korn *et al*. Nat. Commun. 1(2016).


QUANTUM DOT LASERS
EPITAXIALLY GROWN ON SILICON

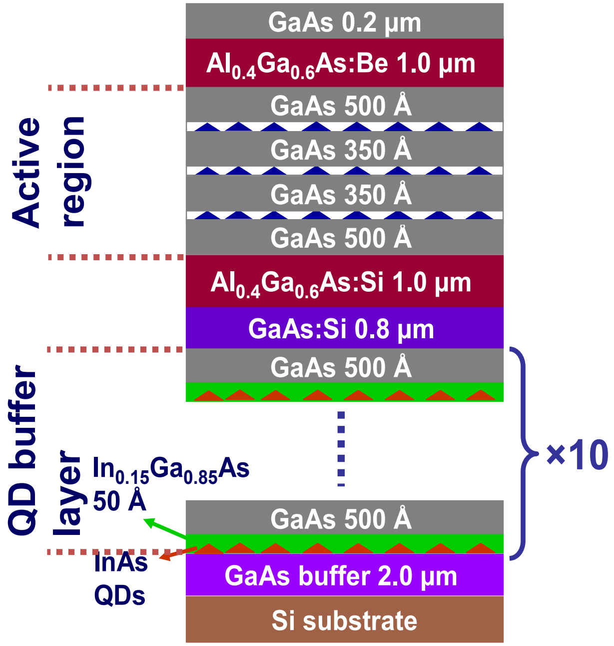
Threshold Current Densities of Semiconductor Lasers

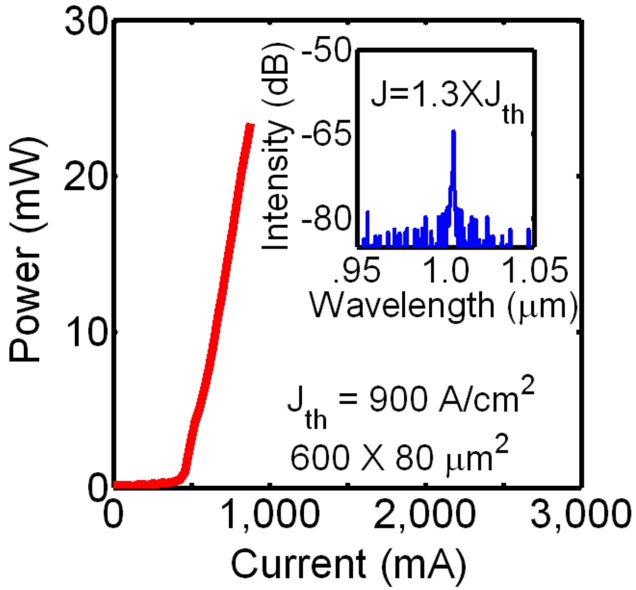


QD-lasers for lower thresholds

Survey of Quantum Dot Lasers on Silicon

- 1999 – First laser operation with $In_{.4}Ga_{.6}As$ QDs @ 1 µm. Pulsed at 80 K (Bhattacharya, University of Michigan)
- 2005 – RT Pulsed operation with $In_{.5}Ga_{.5}As$ QDs @ 1 µm (Bhattacharya, University of Michigan)

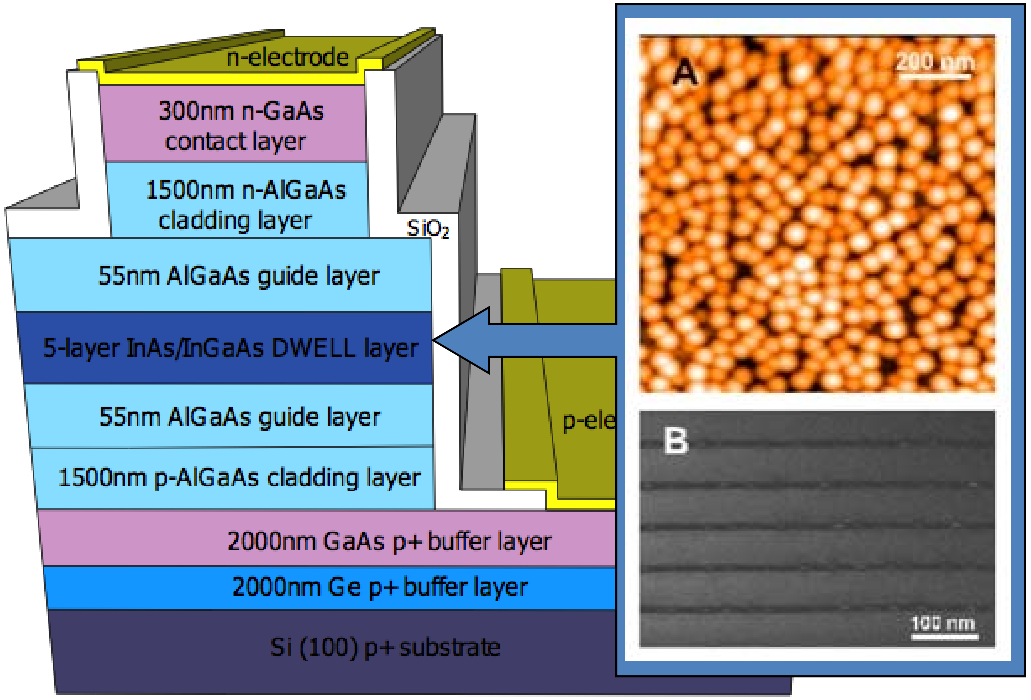


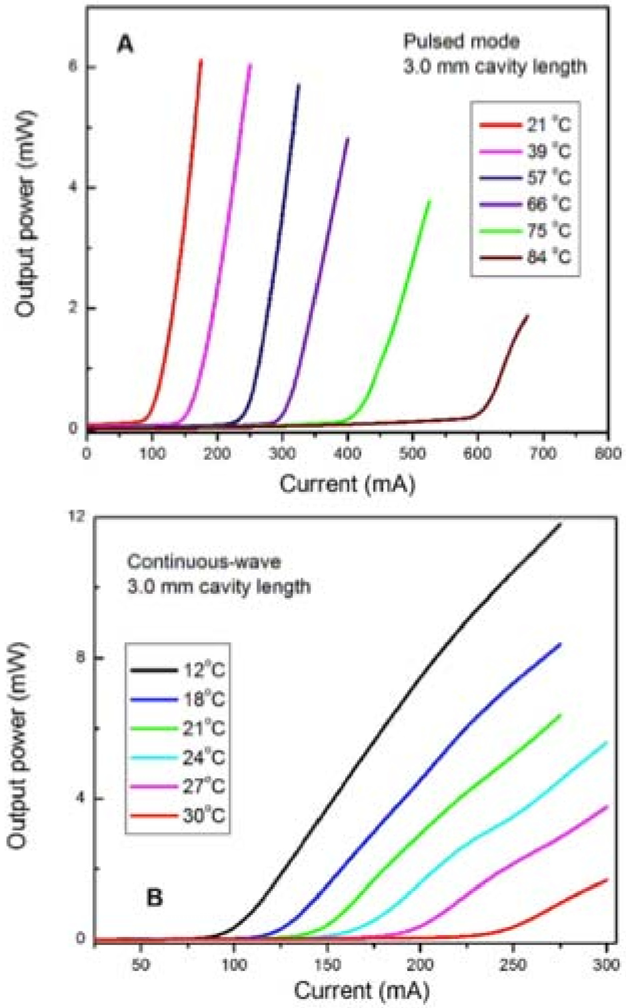


- **(001)-oriented Si substrates misoriented 4º towards [111] are used to eliminate the formation of antiphase domains and stacking faults at the GaAs/Si interface.**

Survey of Quantum Dot Lasers on Silicon

- 1999 – First laser operation with $In_{.4}Ga_{.6}As$ QDs @ 1 µm. Pulsed at 80 K (Michigan)
- 2005 – RT Pulsed operation with $In_{.5}Ga_{.5}As$ QDs @ 1 µm (Michigan)
- **2011 – First RT CW operation with InAs QDs @ 1.3 µm (Huiyun Liu's group at UCL)**
- Thresholds:
  - 63.4 A/cm^2 pulsed (44.3 mA for 3.5mm x 20 um)
  - 163 A/cm^2 CW (114 mA for 3.5mm x 20 um)
- CW lasing up to 30 °C



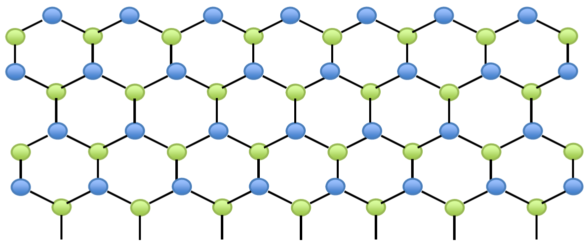


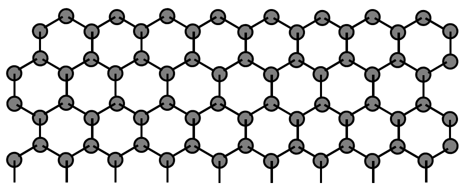
(A. Lee et al. Opt Express, **20,** 2012)

III-V Laser Growth on Silicon

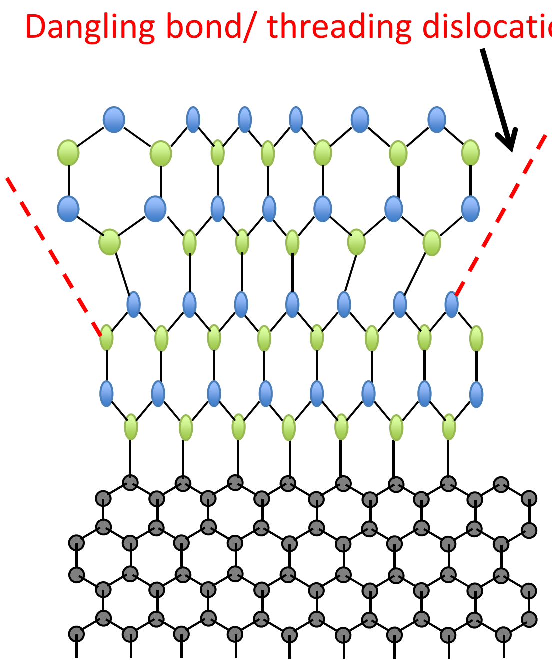
- Polarity, lattice & thermal expansion mismatch between silicon and III-Vs result in high dislocation densities
  - High thresholds (or no lasing), and poor reliability for QW lasers.

Bulk GaAs: a=0.565 nm

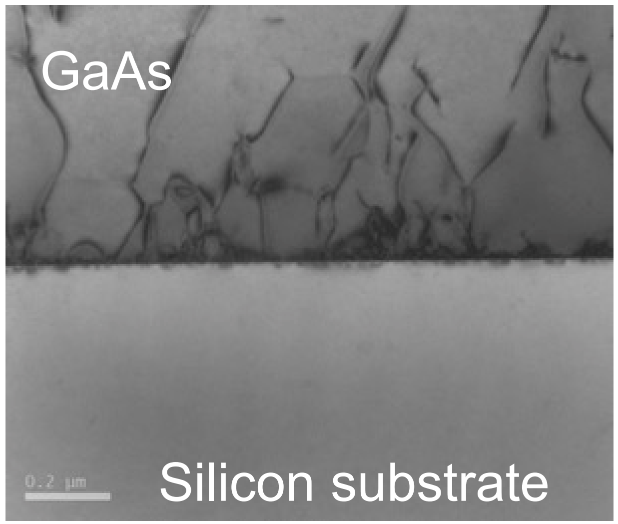




Bulk Si: a=0.543 nm



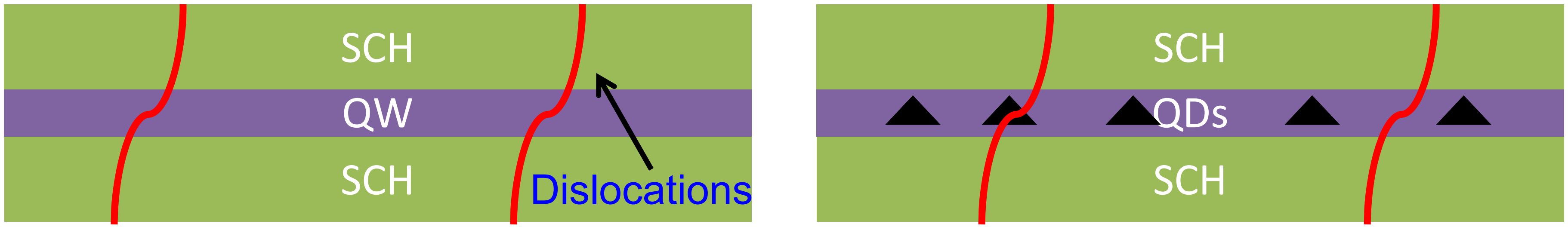
Si substrate



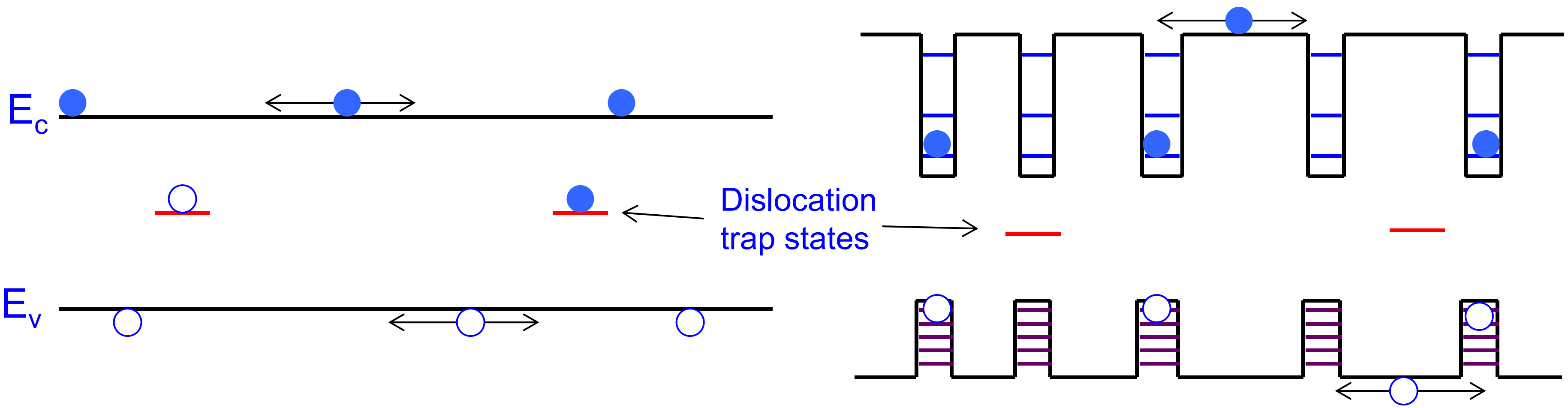
Solution: Use Quantum Dots

1991 – “Semiconductor Structure for Optoelectronic Components with Inclusions” (Jean Gerard & Claude Weisbuch), U.S. Patent No. 5,075,742

- 3D confinement provided by quantum dots prevents carriers from migrating to dislocations.

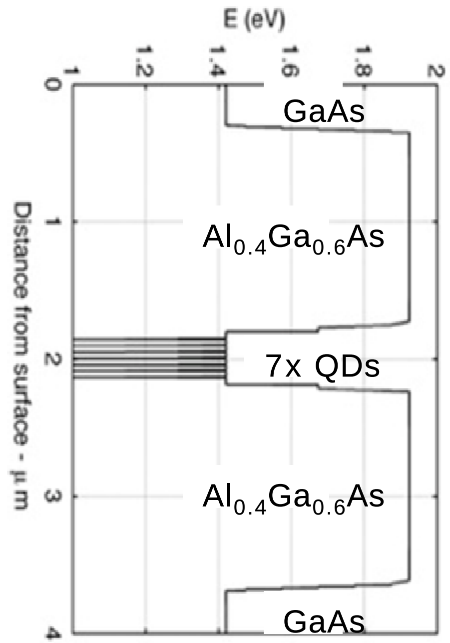


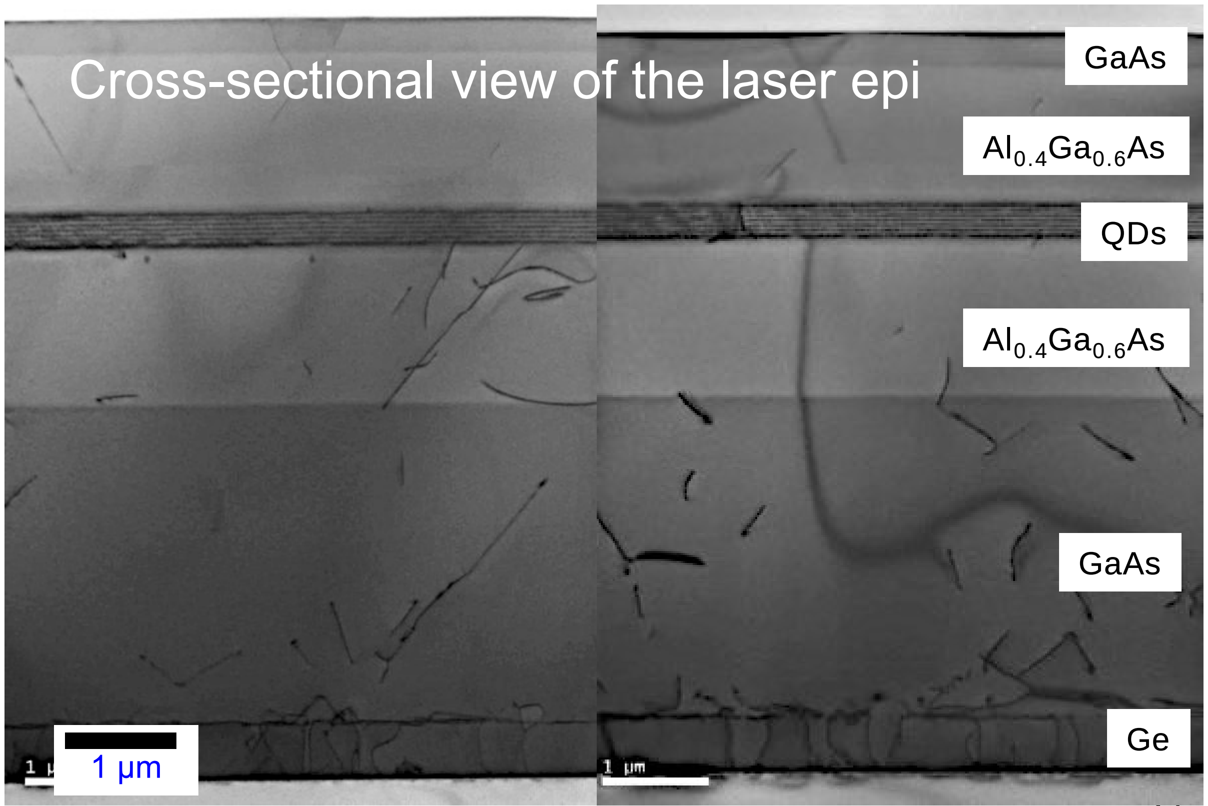
In-plane band diagram:



GRINSCH QDLs on Ge/Si

- TEM images of unprocessed laser material
- $>10^8$ cm^{-2} dislocation density in the QD active region



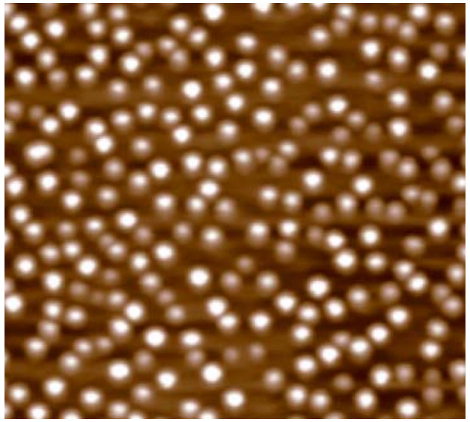


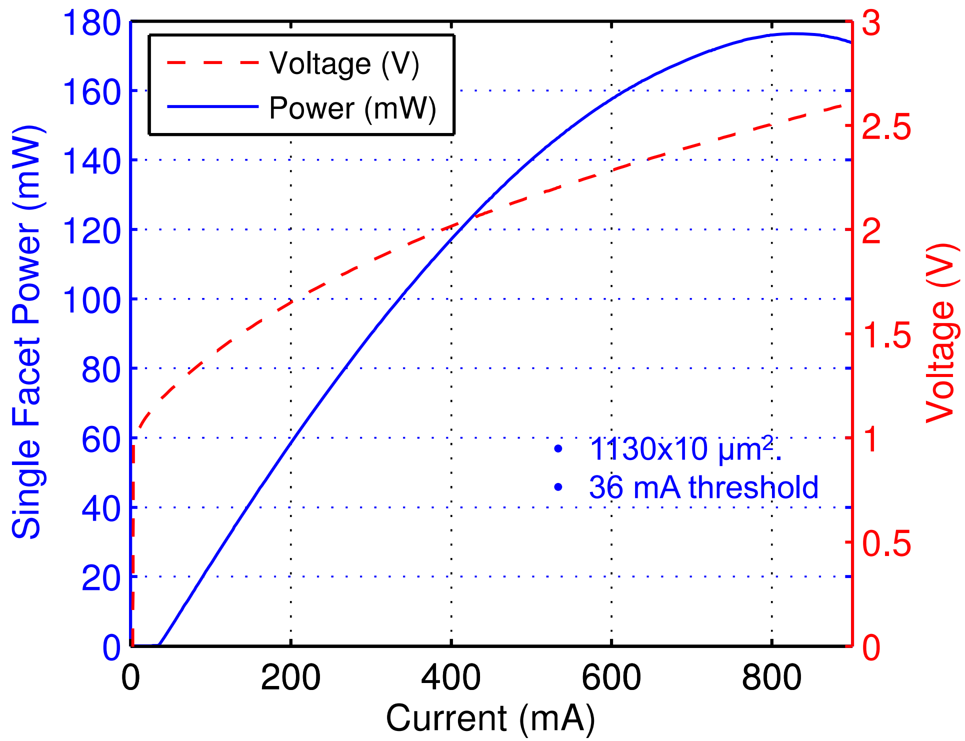
(100) Si 6º [111]

UCSB

High Output Powers

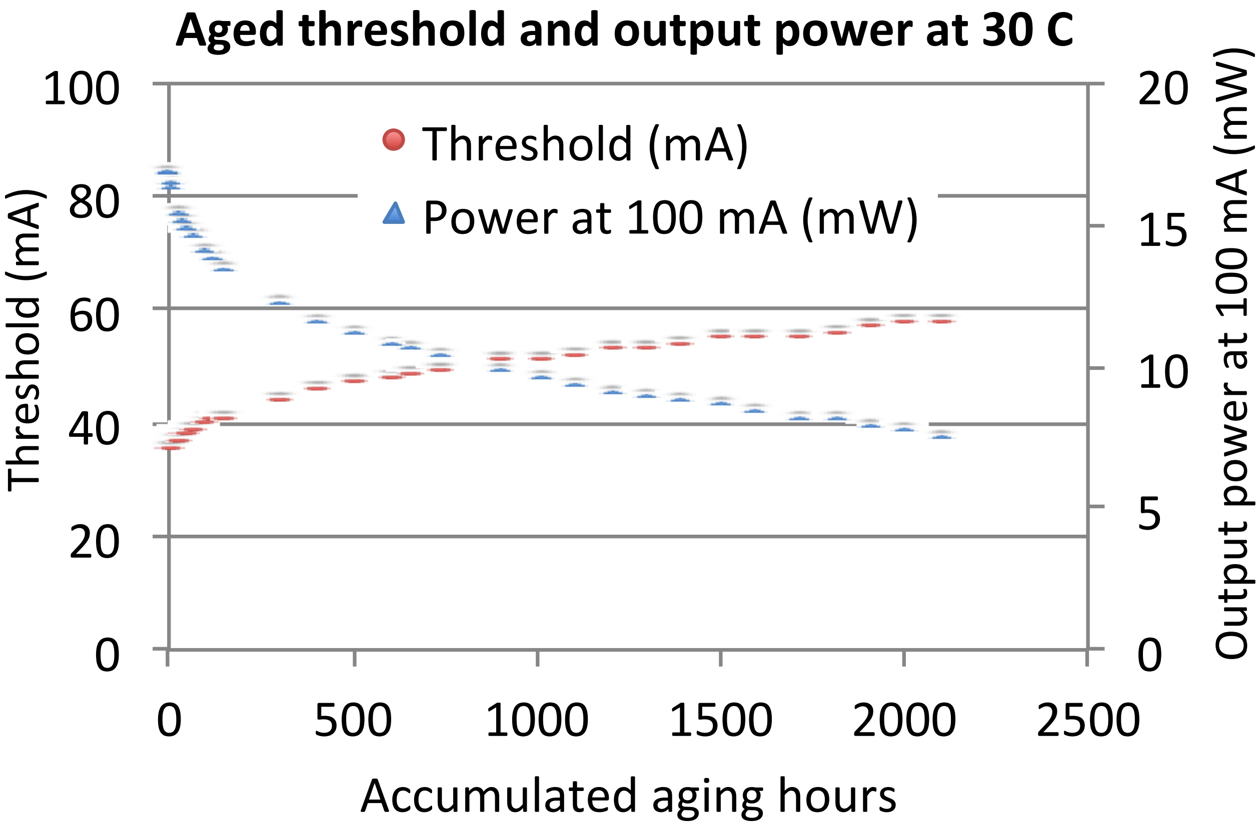
- Stranski Krastanov Quantum Dot Growth
- Low CW threshold (150 A/cm^2)
- CW powers over 100 mW routinely achieved.
- Nearly 180 mW maximum CW single side output power at 20 ^{o}C
- 33% differential efficiency and 18% WPE (at 150 mA)
- CW lasing to 119 C



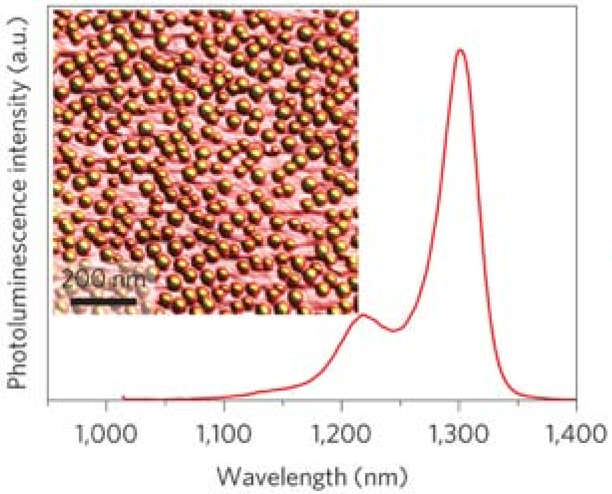


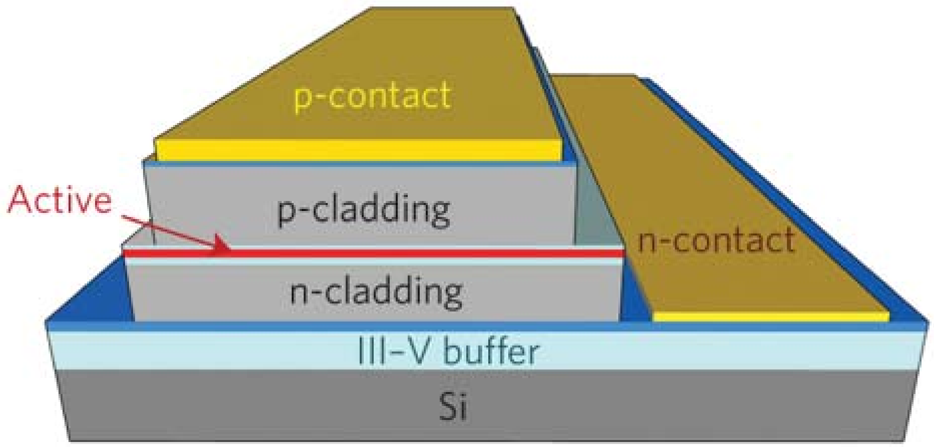
Reliability Studies of QD lasers on Silicon

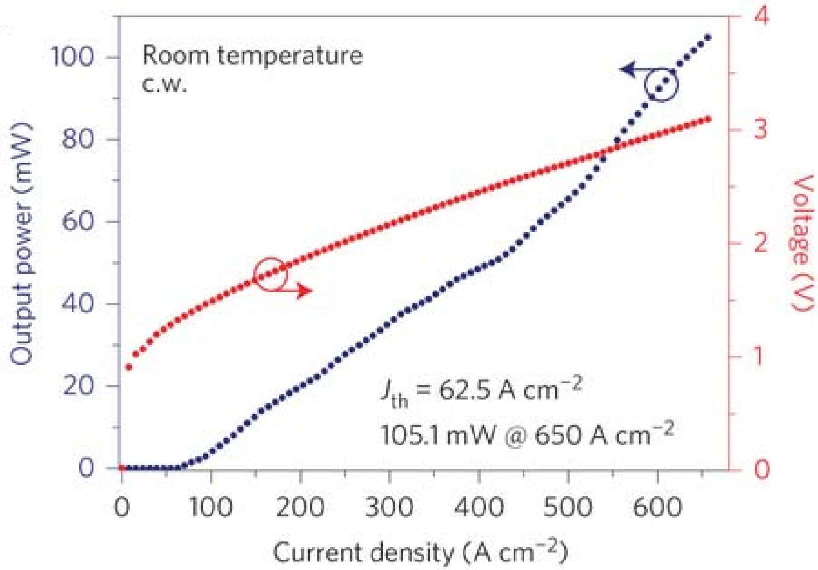
- Lattice mismatch causes dislocations, which have limited quantum well laser reliability on Si.
- Over **2100 hours** of continuous operation
- **>26x** improvement over best reported lifetime for GaAs laser on Si
- Not yet adequate for real applications

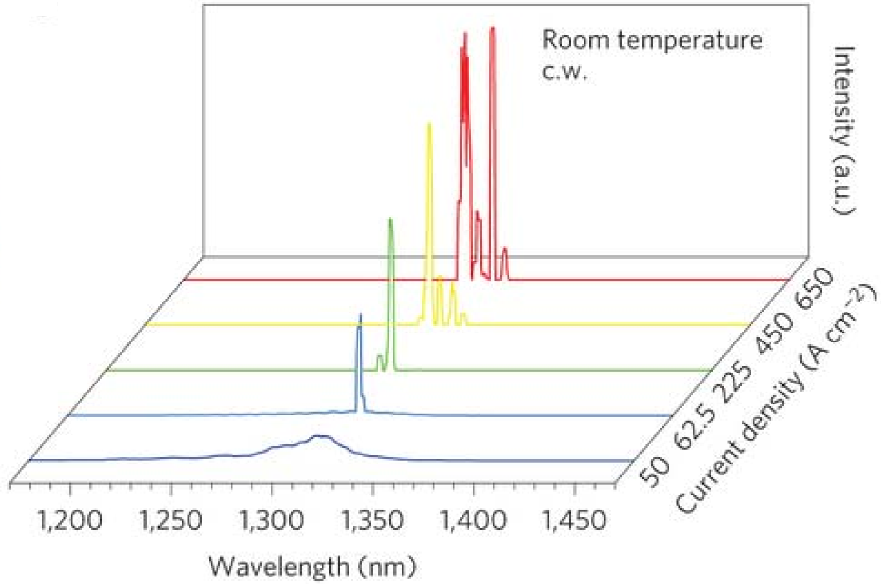


UCL: Electrically pumped continuous-wave III–V quantum dot lasers on silicon







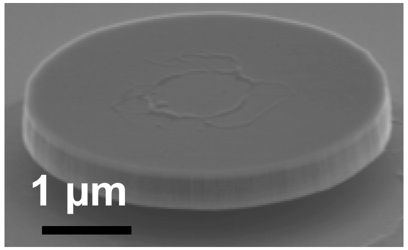


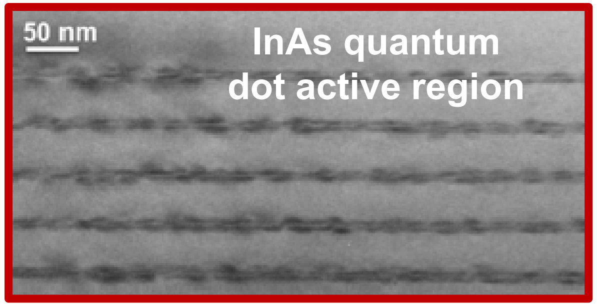
S. Chen et al., Nat. Photon. 10, 307 (2016).

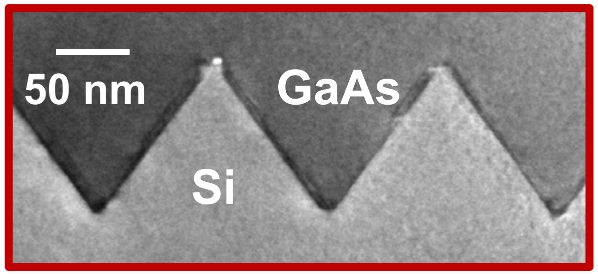
Quantum dot microdisk lasers on (001) silicon

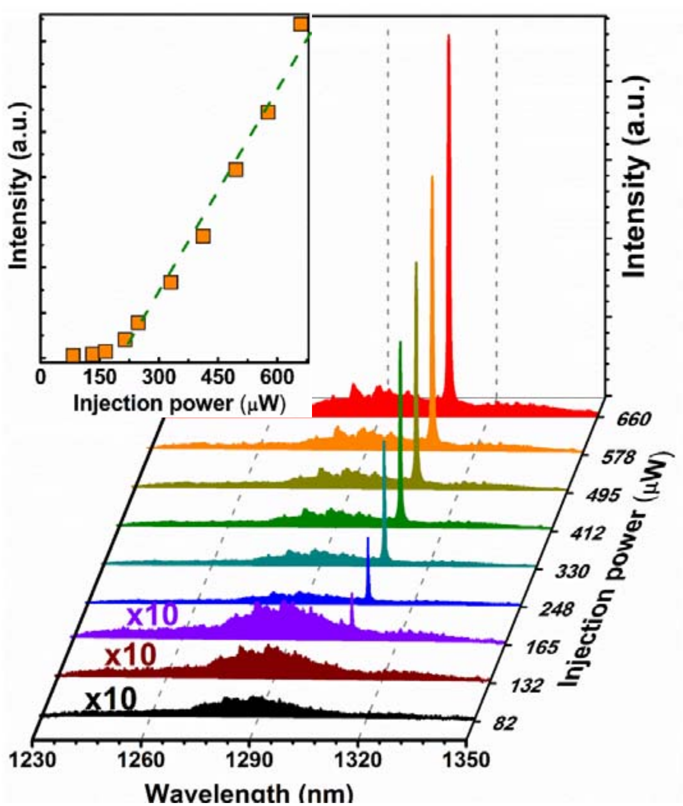
HKUST, UCSB, Harvard

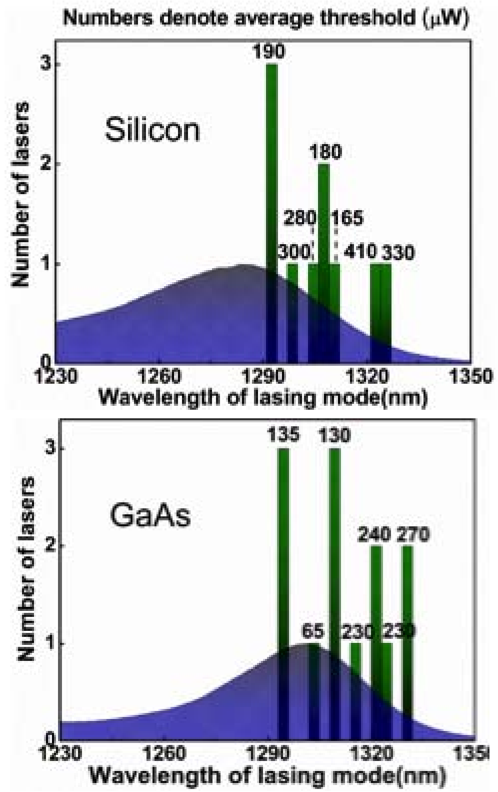
- GaAs grown on v-groove patterned Si to filter defects **(no Ge, no offcut)**
- 4 um microdisk resonators with air cladding
- **Room temperature continuous wave lasing** observed with average thresholds of 250 uW for devices on Si substrate compared to 180 uW for devices on GaAs











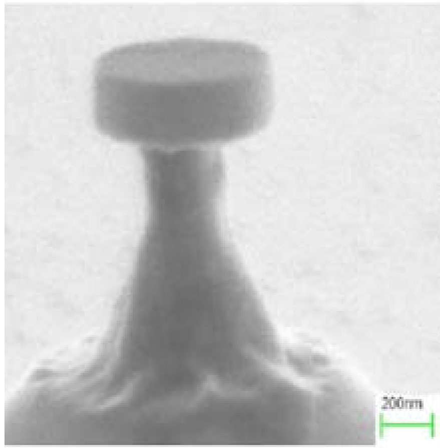
Y. Wan, Q. Li, A. Y. Liu, A. C. Gossard, J. E. Bowers, E. L. Hu, K. M. Lau, "1.3 µm room temperature InAs quantum-dot micro-disk lasers directly grown on (001) silicon," Optics Letters 2016

Sub wavelength quantum dot microdisk lasers on (001) silicon: HKUST, UCSB, Harvard

- Dense integration
- Low power consumption

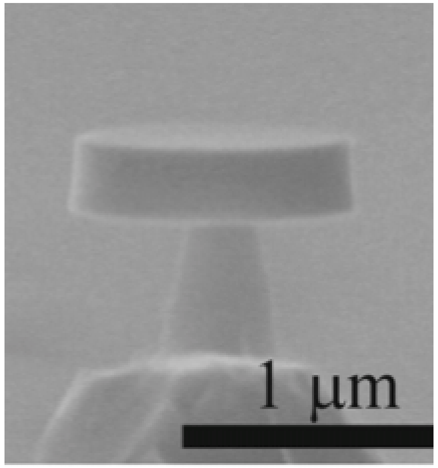
- High radiation loss
- Limited gain medium

0.86 μm/ 10 K / pulse



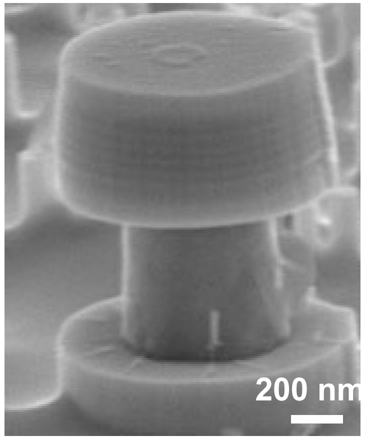
Song et al. 2009

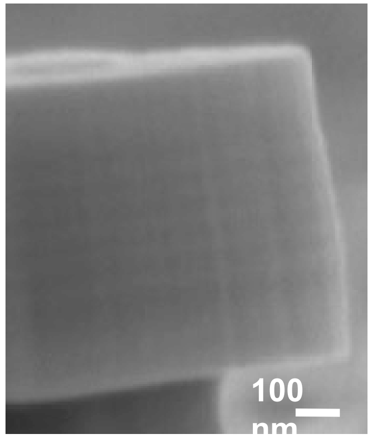
1.3 μm/ 300 K /CW



Kryzhanovskaya et al. 2015

1.2 μm/ 10 K /CW





Kei May Lau et al., ThA7 ISLC 2016

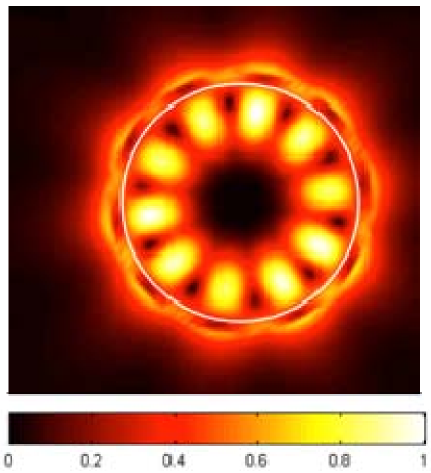
Limited results on GaAs

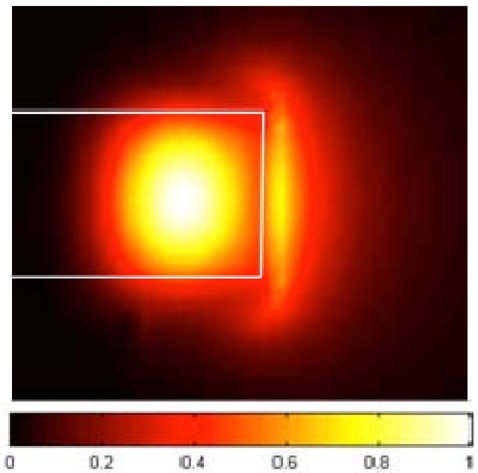
First results on Si

Y. Wan, Q. Li, A. Y. Liu, W. W. Chow, A. C. Gossard, J. E. Bowers, E. L. Hu, K. M. Lau, "Sub-wavelength InAs quantum dot micro-disk lasers grown on exact Si (001) substrates," Applied Physics Letters 2016

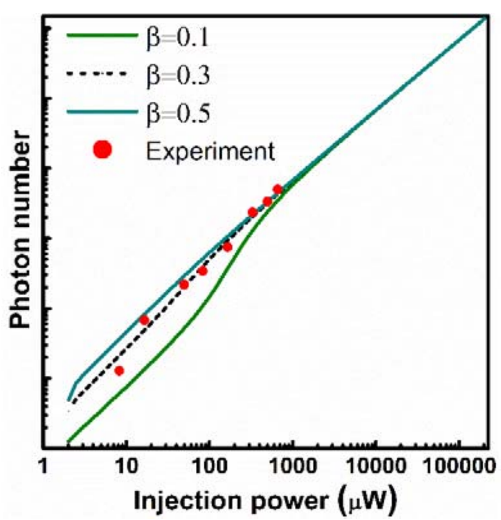
Subwavelength microdisk lasers on (001) Si

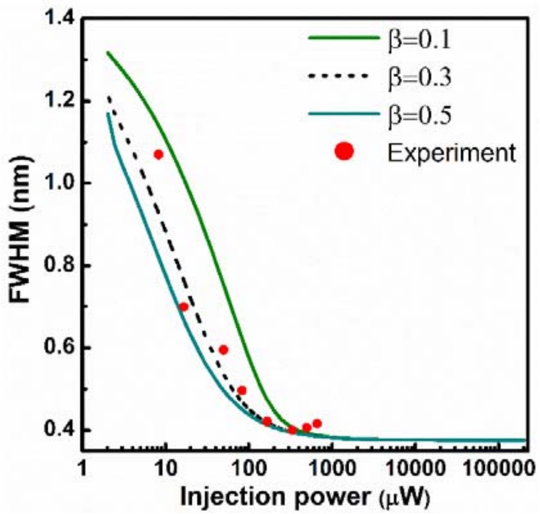
- The lasing mode was identified to be $TE_{1,5}$ according to FDTD simulation





- The spontaneous emission factor (β) was extracted to be 0.3 by fitting the experimental data to a semiconductor cavity-QED model



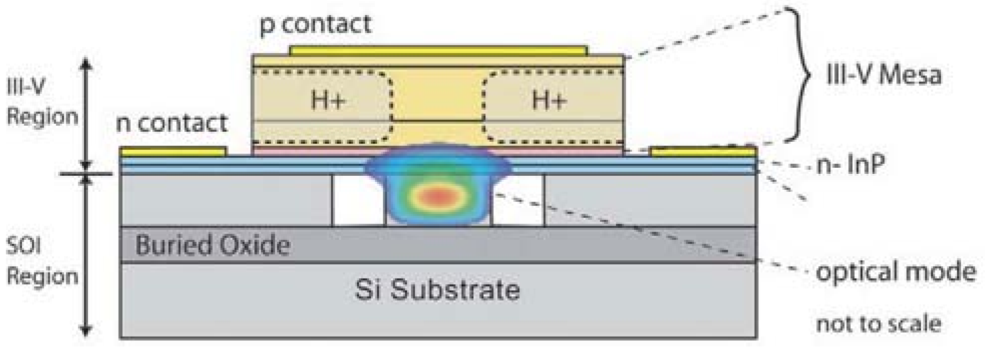


Y. Wan, Q. Li, A. Y. Liu, W. W. Chow, A. C. Gossard, J. E. Bowers, E. L. Hu, and K. M. Lau, " Sub-wavelength InAs quantum dot micro-disk lasers epitaxially grown on exact Si (001)substrates", *Applied Physics Letters,* Vol. 108, 221101, May 2016

Bonding for Heterogeneous Si Photonics

Bonding for Heterogeneous Si Photonics

- Multiple material systems
- CMOS compatible process
- Efficient light coupling with Si WG

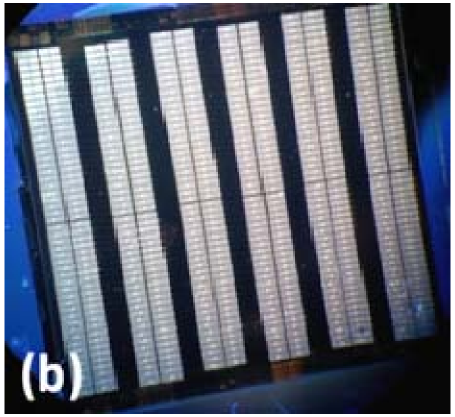


Full set of device library

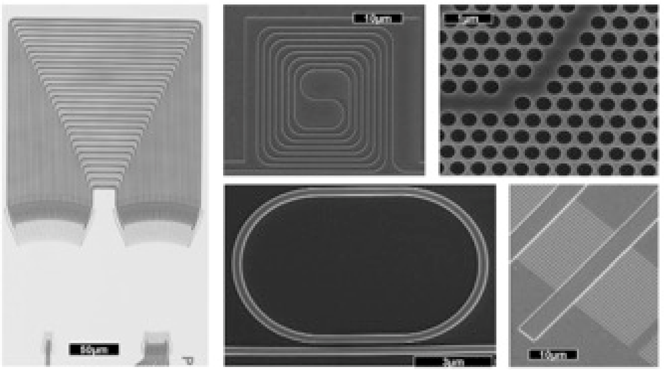
- DFB, TLD, MLL, MZM, EAM Si_3N_4 …

A.W. Fang, H. Park, R. Jones, O. Cohen, M. J. Paniccia, and J. E. Bowers, "A Continuous Wave Hybrid AlGaInAs-Silicon Evanescent Laser," PTL, 18 (10), 1143-1145, May 15, 2006

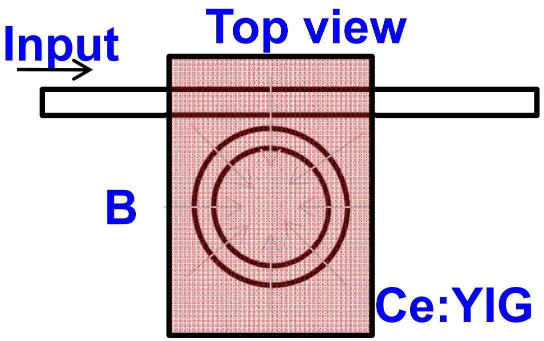
InP



Silicon



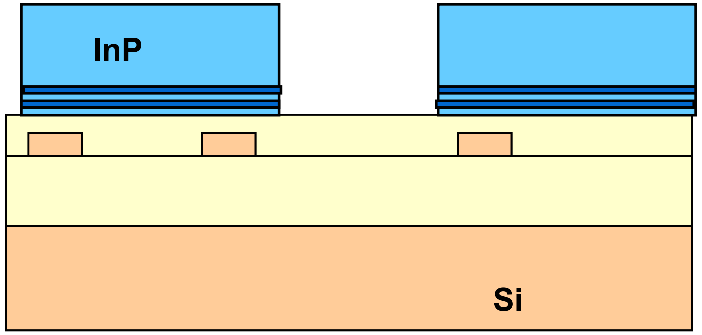
Ce:YIG Isolator

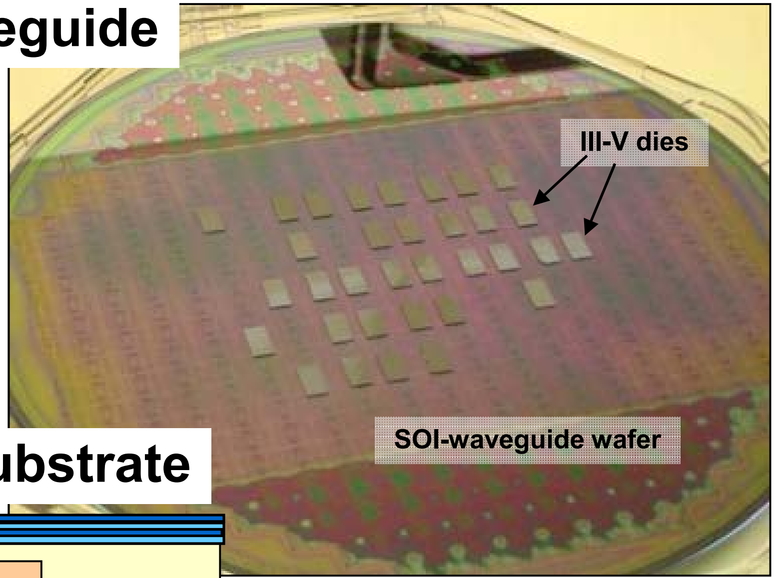


Ce:YIG

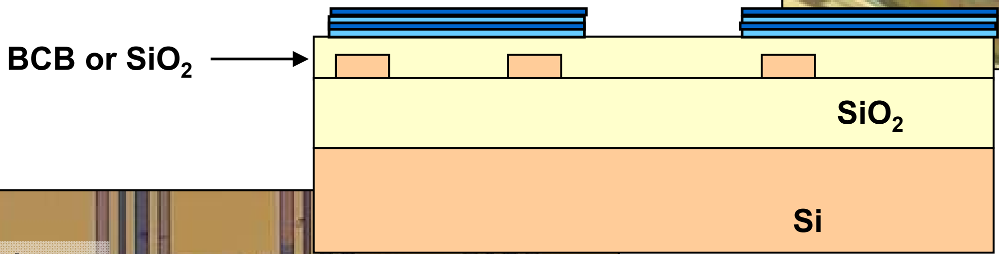
Heterogeneous integration

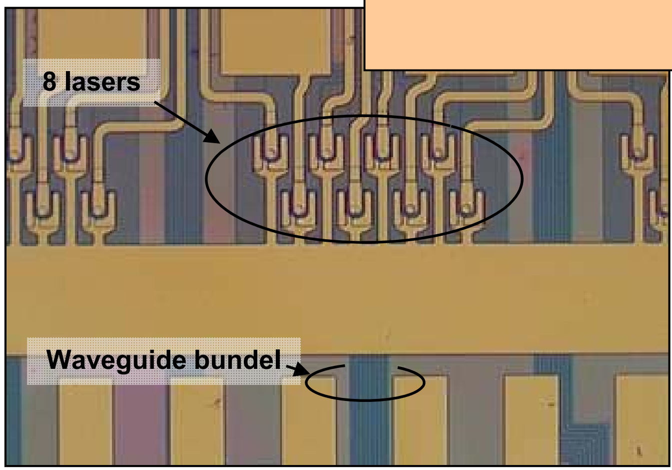
Step 1: Bond InP-dies on SOI waveguide



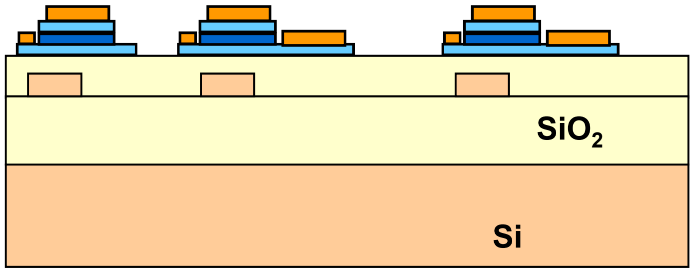


Step 2: Remove substrate



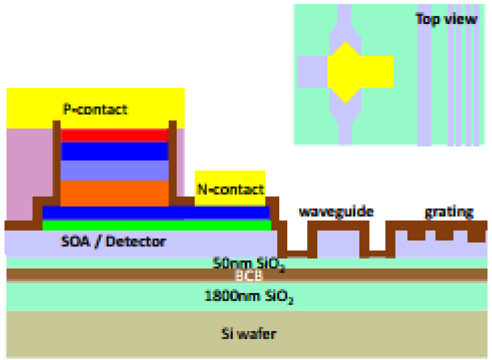


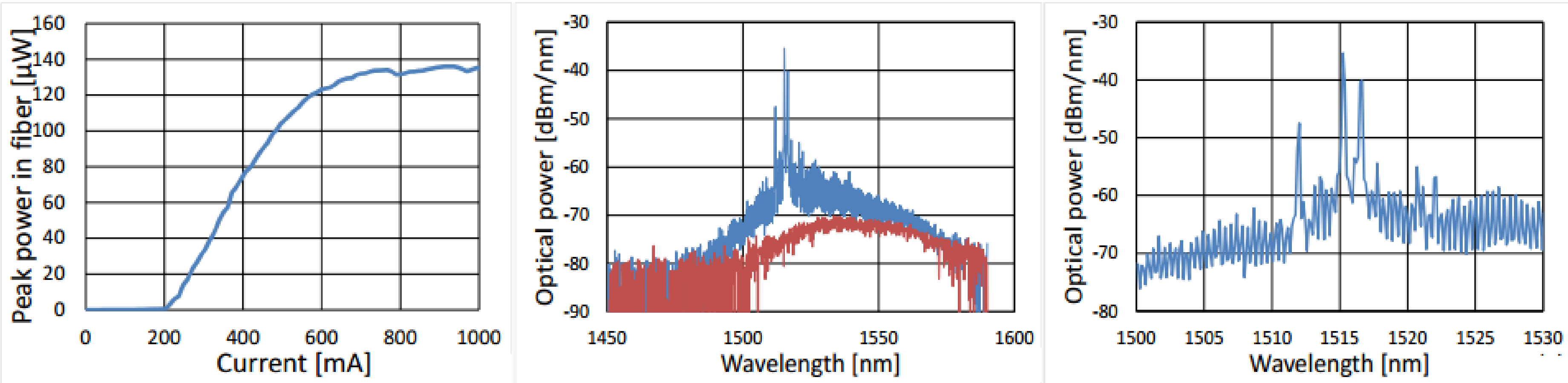
Step 3: Process lasers <u>at wafer scale</u>



Heterogeneous integration with BCB

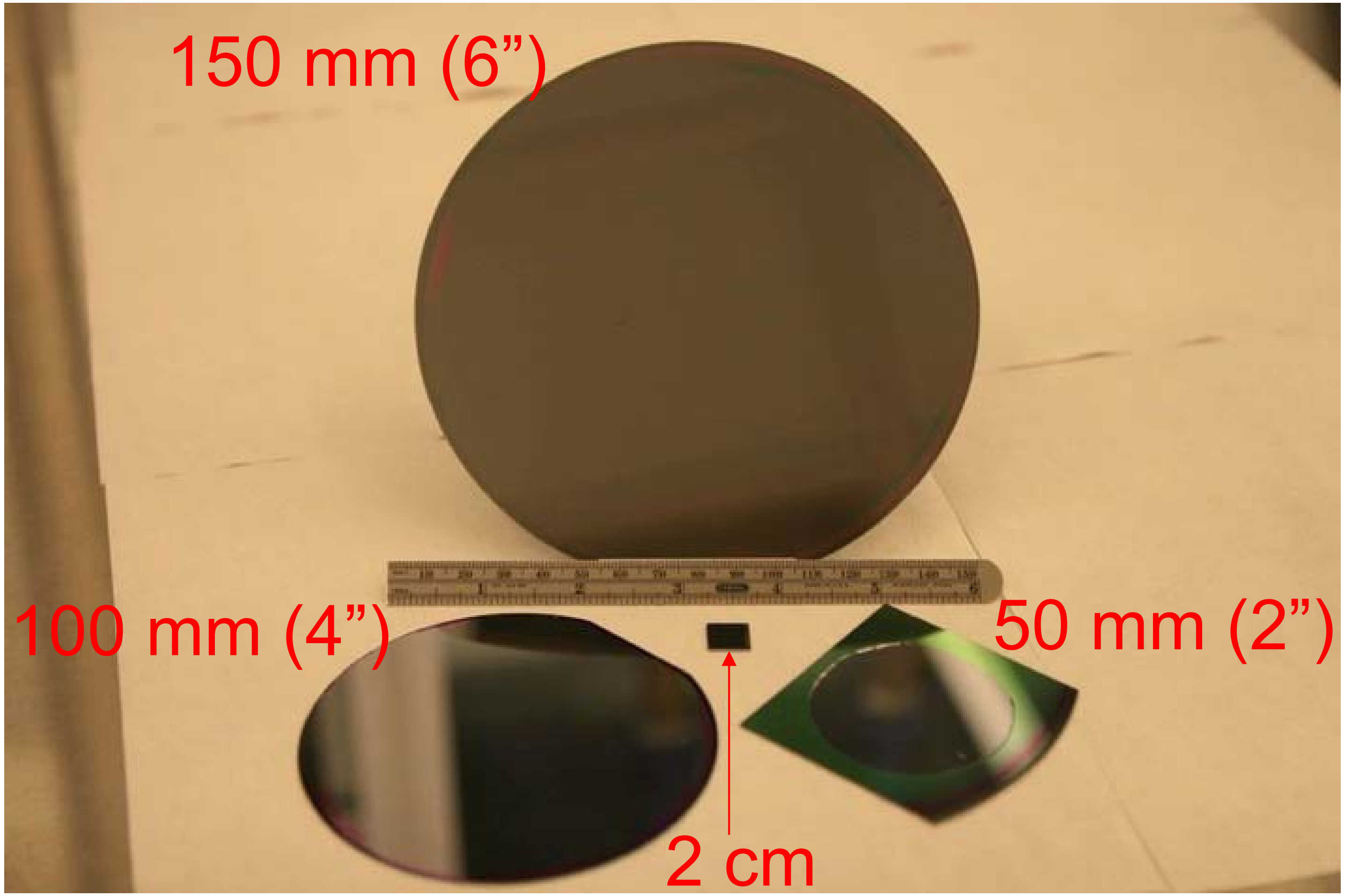
- InP membrane on Si (IMOS)
- Bond SiO_2 to SiO_2 with BCB
- <1 mW on chip at 700 mA
- Threshold current of 200 mA
- COBRA Research Institute





Y. Jiao et al., Integrated Photonics Research, Boston, MA (2015), IM4B.3.

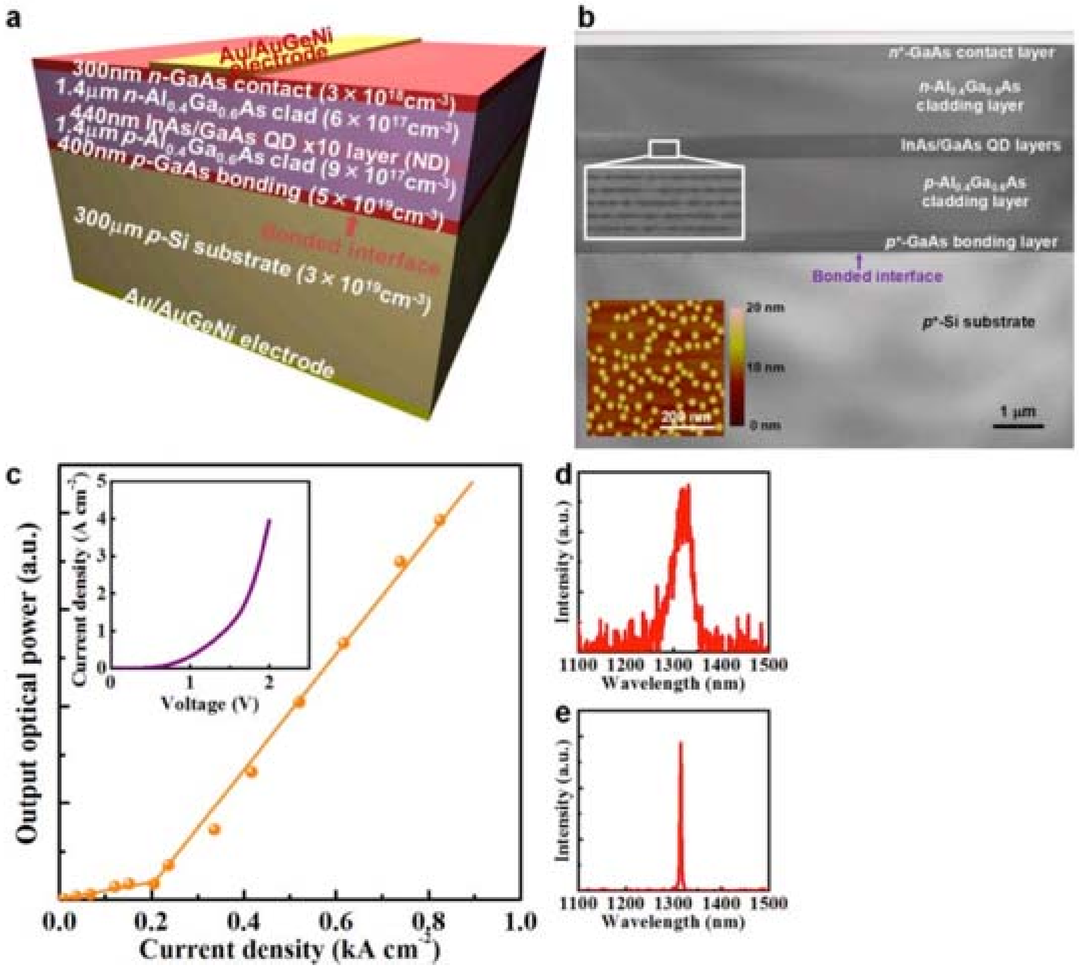
Direct Bonded Wafers



These wafers have patterned optical waveguides on SOI with 2 micron GaInAsP layer on top.
Oxygen plasma enhanced bonding: 300 C, 30 minutes

D. Liang et al., Materials 3, 1782 (2010).

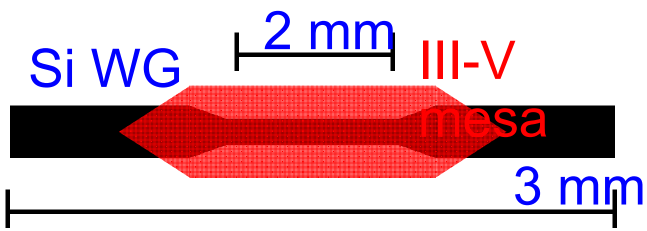
Quantum Dot Lasers on Si by Direct Fusion Bonding



- First 1.3 μm quantum dot lasers on Si with current injection across bonded GaAs/Si interface
- Direct wafer bonding without metal or oxide mediation
- 2 nm amorphous interlayer at the bonding interface
- Threshold: **205 A/cm^2** pulsed at room temperature (for 2.1mm x 100 μm device).

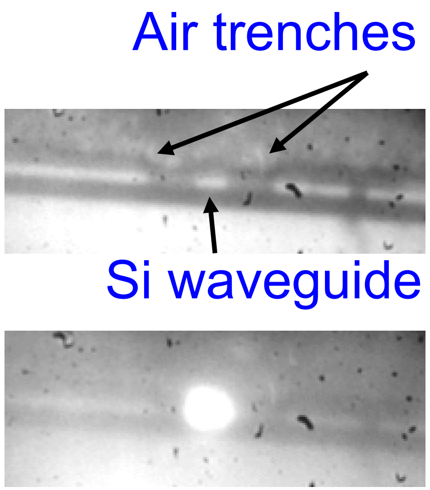
Tanabe, Katsuaki, Katsuyuki Watanabe, and Yasuhiko Arakawa. "III-V/Si hybrid photonic devices by direct fusion bonding." *Scientific reports* 2 (2012).

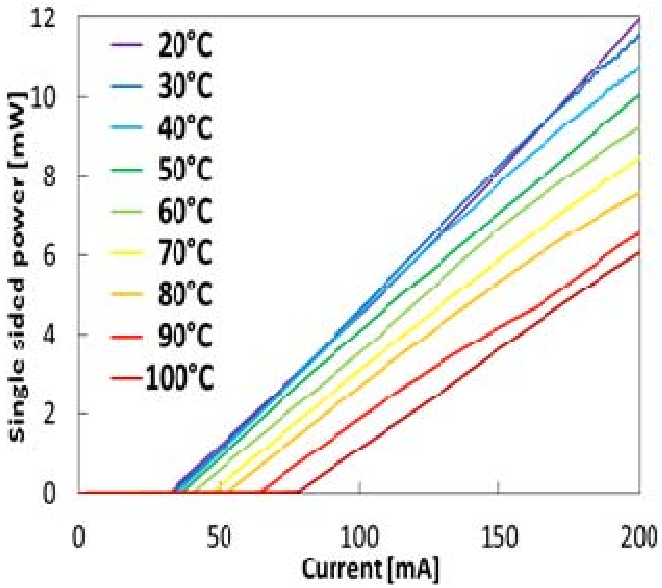
Wafer bonded QD laser on Si
HPE

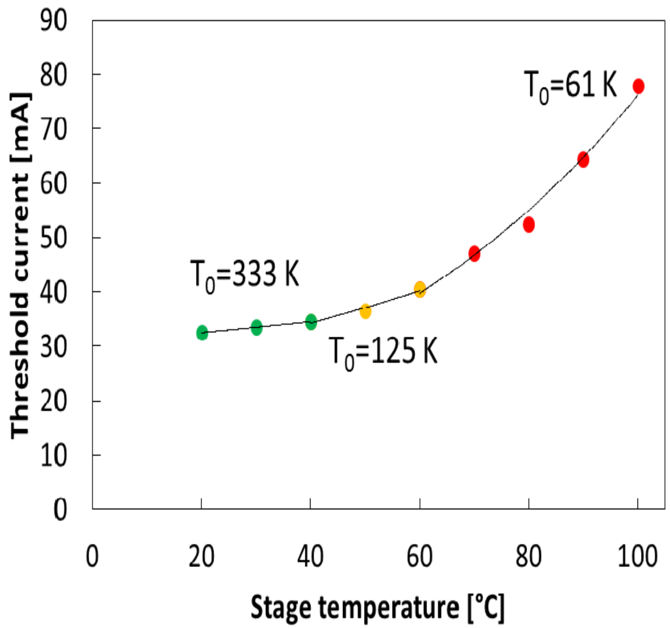


Kurczweil et al… HPE
ThA5 Thursday 9:30 am

6 µm wide mesa, Γ_{QD}=55%

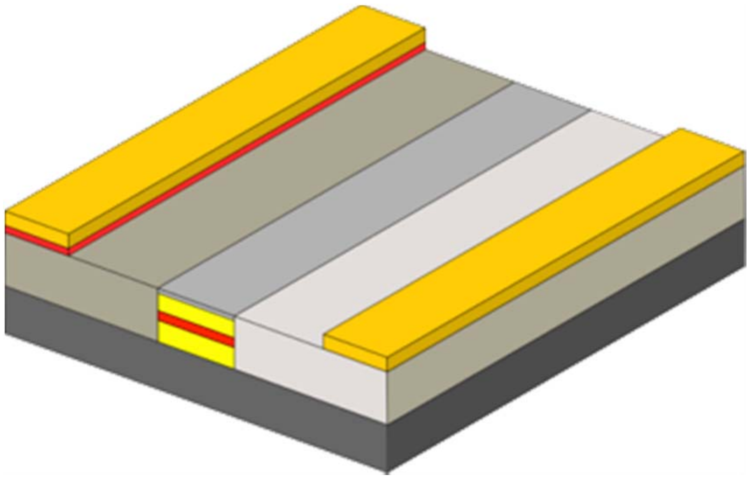




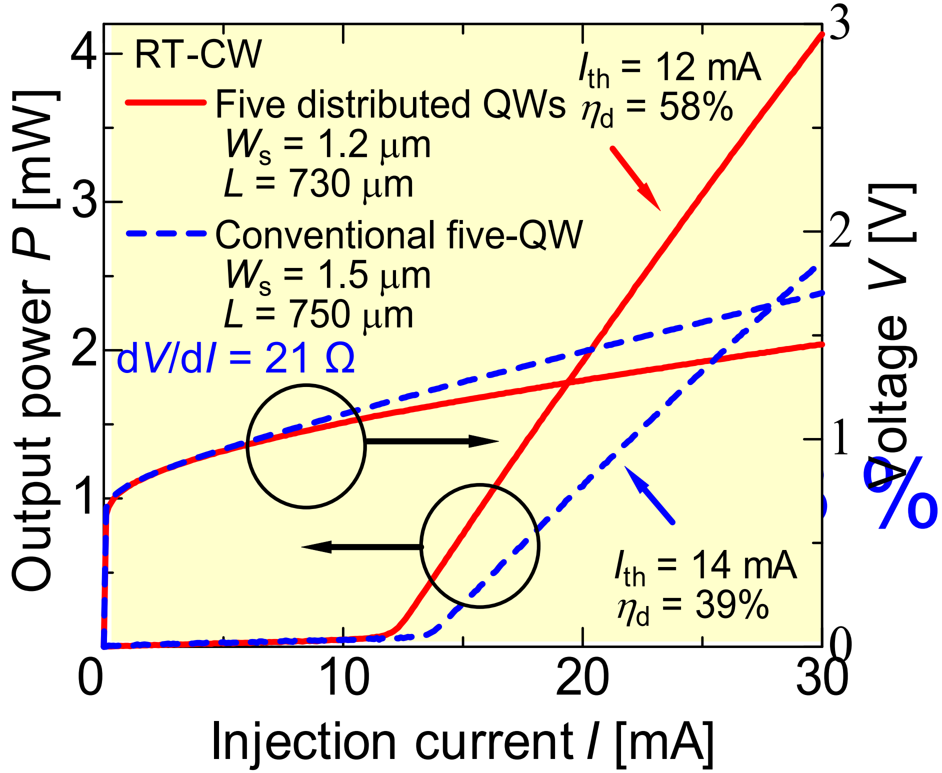


Membrane Lasers: Arai TIT

Arai Plenary Tuesday 8:45 am



BCB Bonding
Single mode lasers

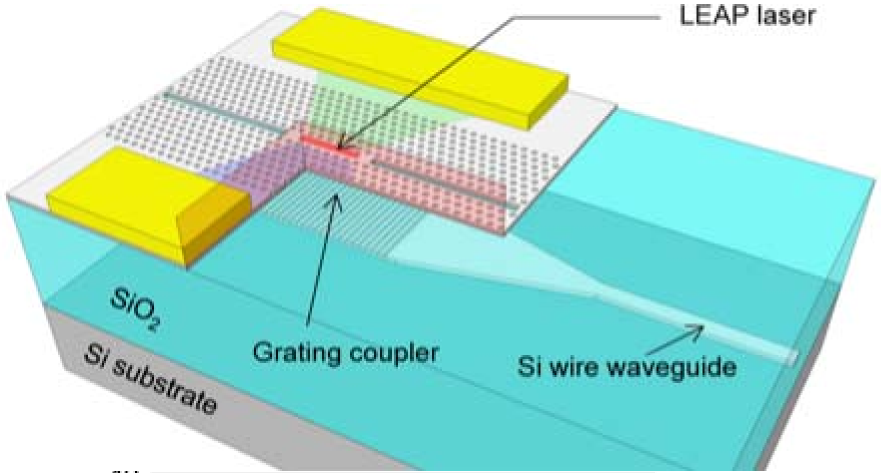


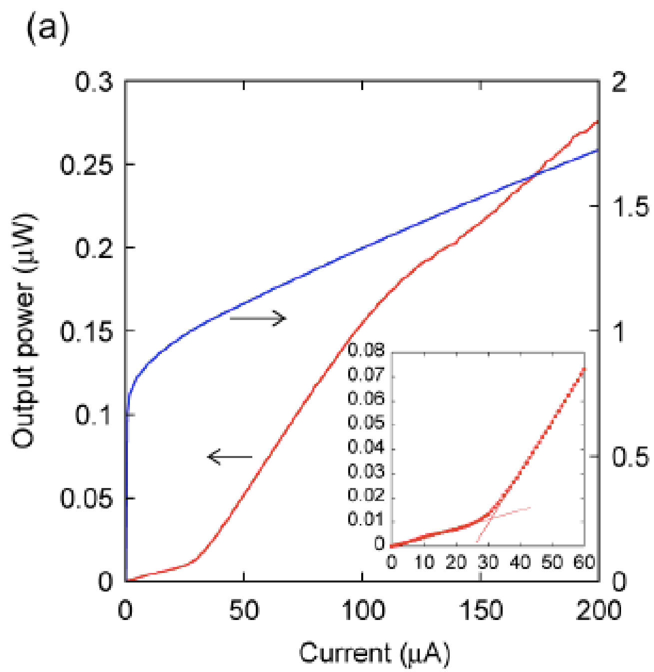
I_{th} = 12 mA, η_d = 58%
dV/dI = 21 Ω (@I = 12 mA)

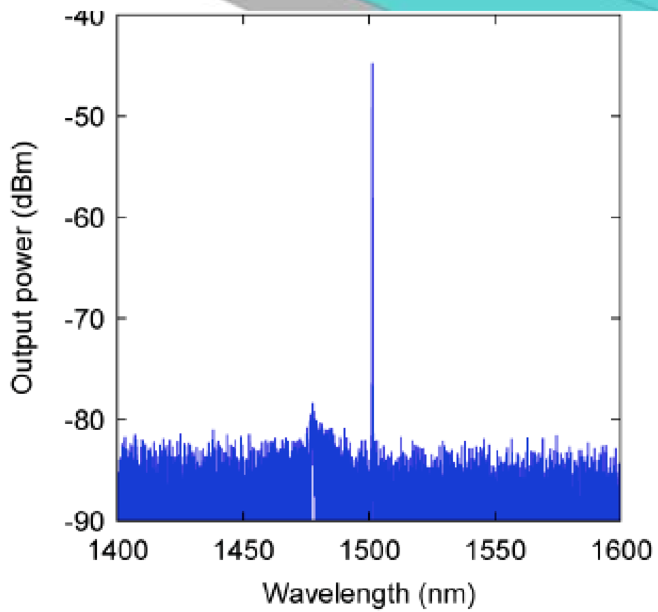
(M. Futami et. al, IEEE PTL, vol. 24, no. 11, p. 888, June 2012.)

NTT: LEAP Laser on Si

LEAP: lambda-scale embedded active-region photonic-crystal
Photonic crystal lateral confinement
Strong SiO2 vertical confinement
Low threshold: 42 uA!
Low total output power
Single mode operation





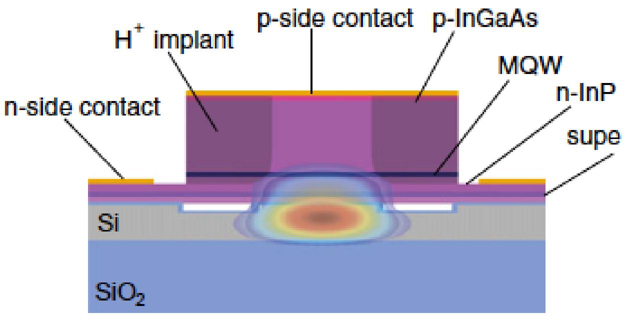


K. Takada et al. Optics Express (2015).

High-coherence semiconductor lasers based on integral high-*Q* resonators in hybrid Si/III-V platforms

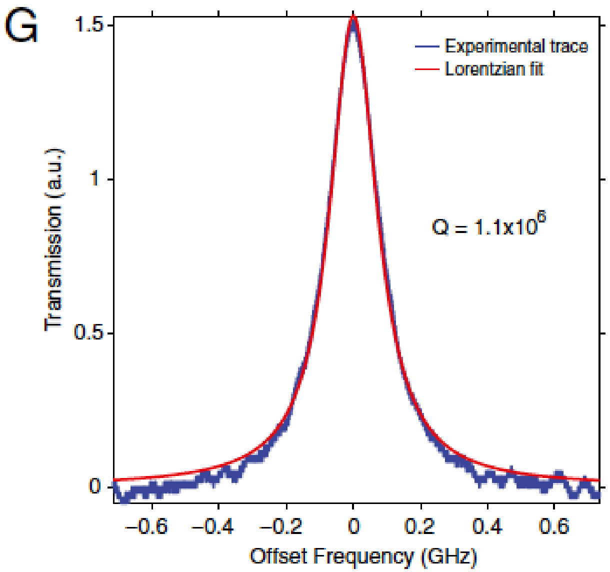
Christos Theodoros Santis[1], Scott T. Steger, Yaakov Vilenchik, Arseny Vasilyev, and Amnon Yariv[1]

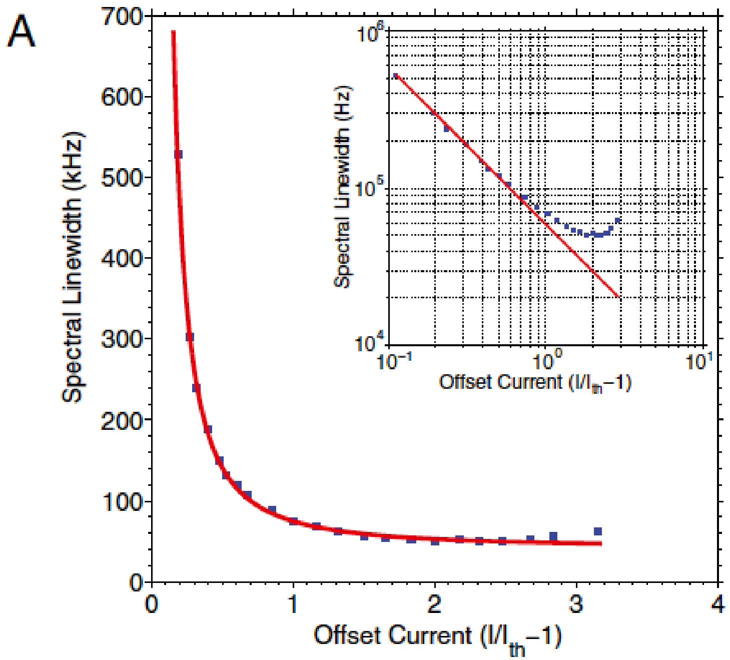
Yariv Plenary Tuesday 8 am



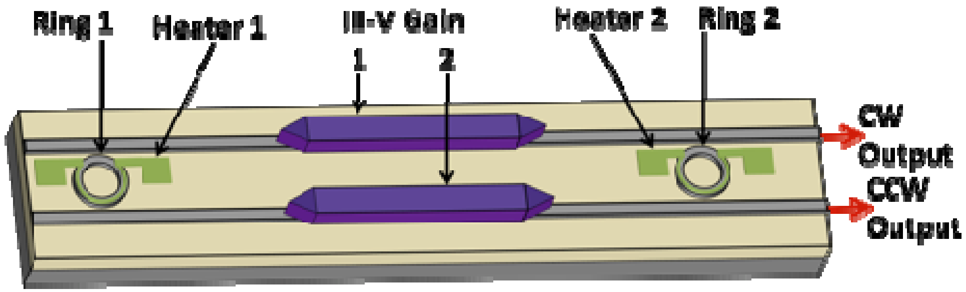
$$(\Delta\nu)_{laser} = \frac{2\pi h\nu_o^3\mu(1+\alpha^2)}{Q^2 P}$$

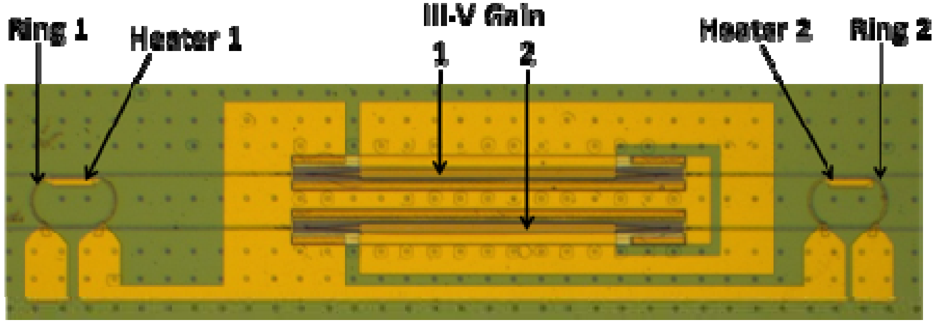
High Q (1 million)
1 kHz linewidth

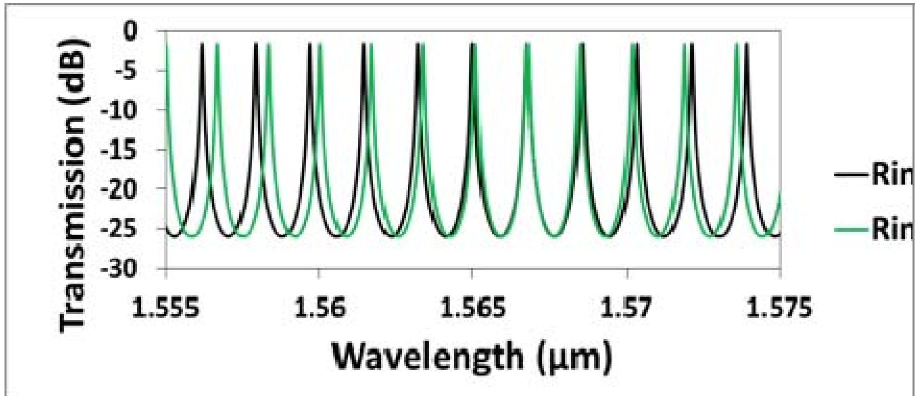


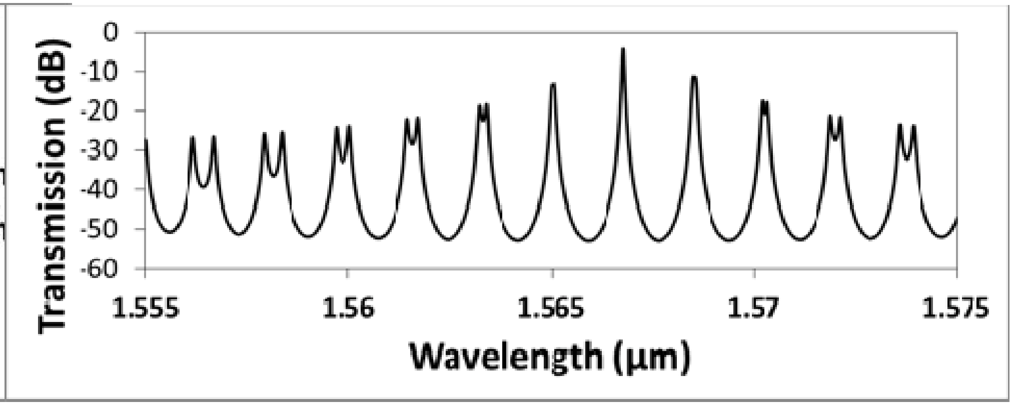


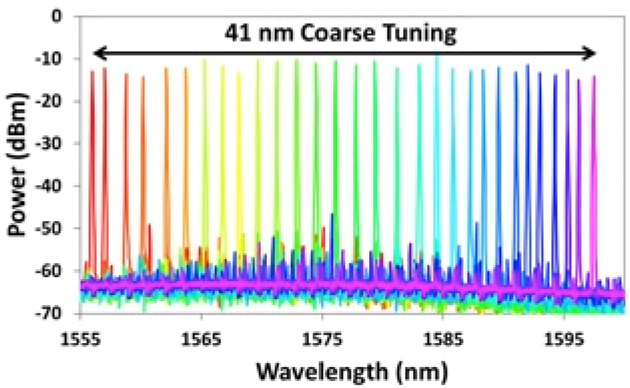
Widely Tunable Vernier Ring Laser

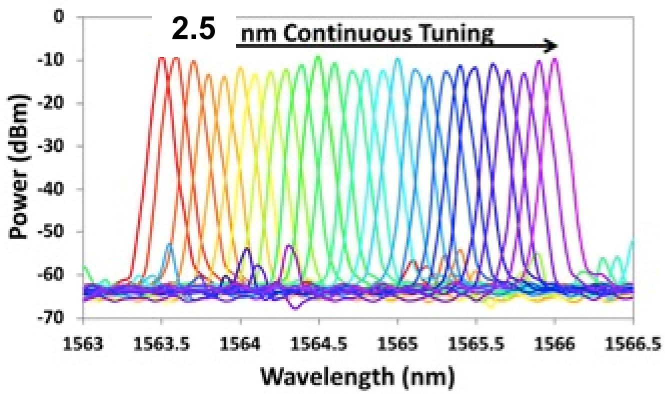






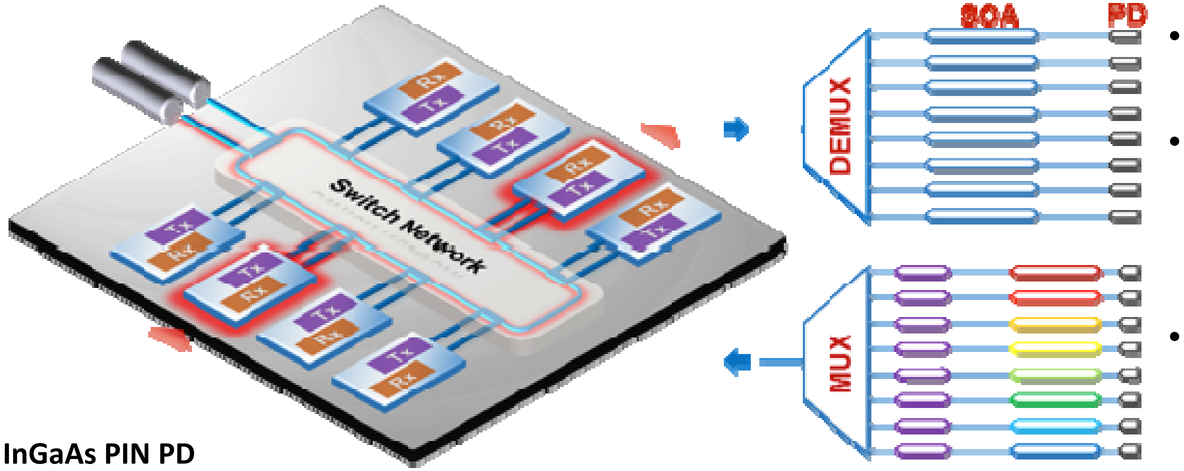




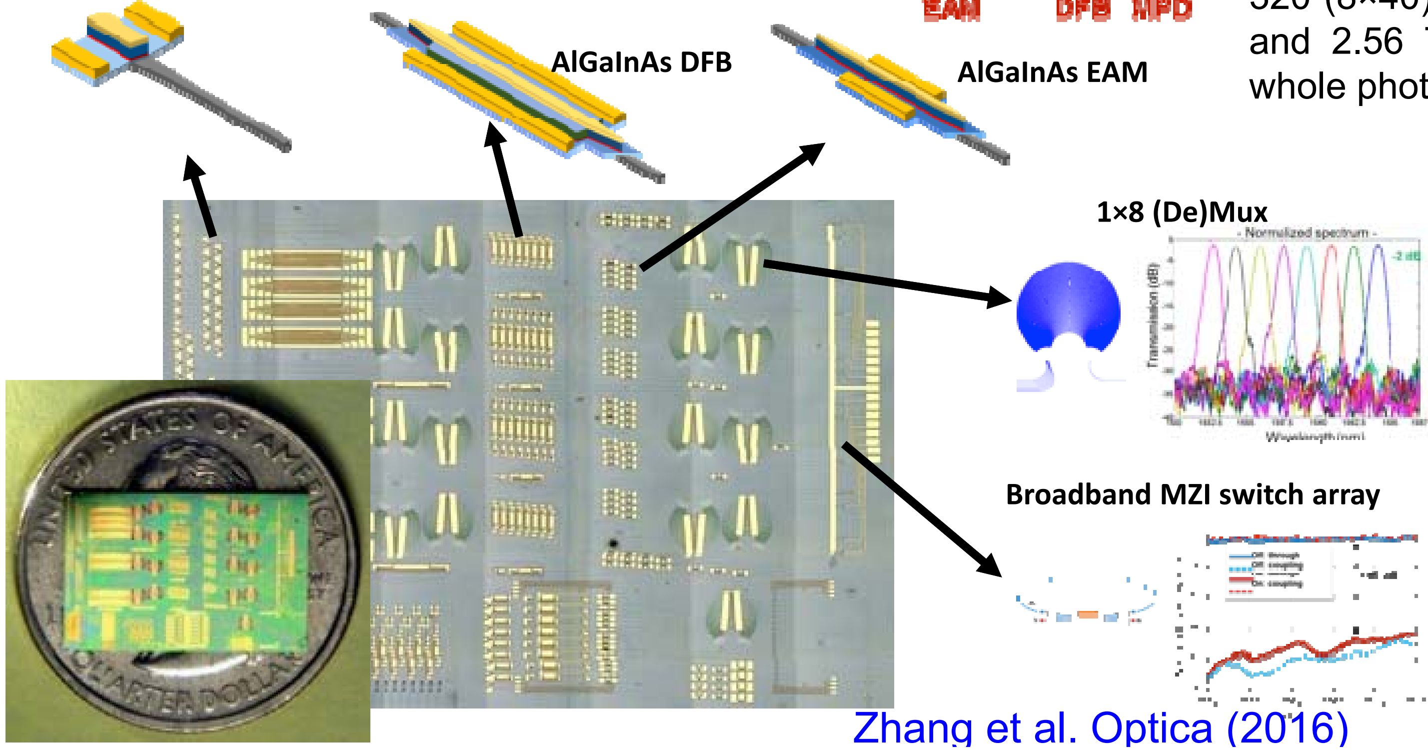


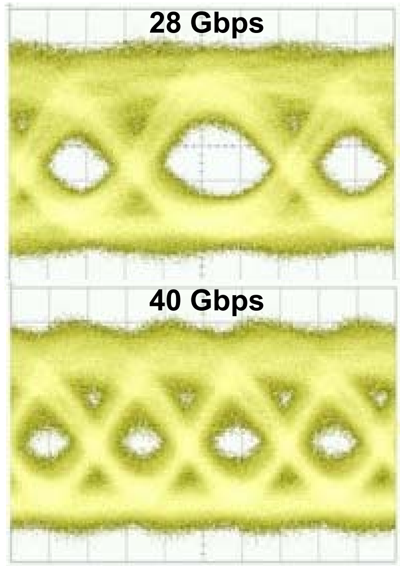
J. C. Hulme, J. K. Doylend, and J. E. Bowers, "Widely tunable Vernier ring laser on hybrid silicon," Opt. Express **21**, 19718-19722 (2013)

Heterogeneously-integrated WDM Network-on-Chip UCSB



- Fully integrated WDM transceiver network
- Compact footprint with 300+ active units (48 DFB, 93 EAM, 67 PD) and 120+ passive units (7 AWG, 1X15 MZI switch) in single chip;
- Data rate of 40 Gbps per wavelength channel, showing a potential large capacity of the transceiver array, with 320 (8×40) Gbps per transceiver node, and 2.56 Tbps (8×320 Gbps) for the whole photonic circuit.



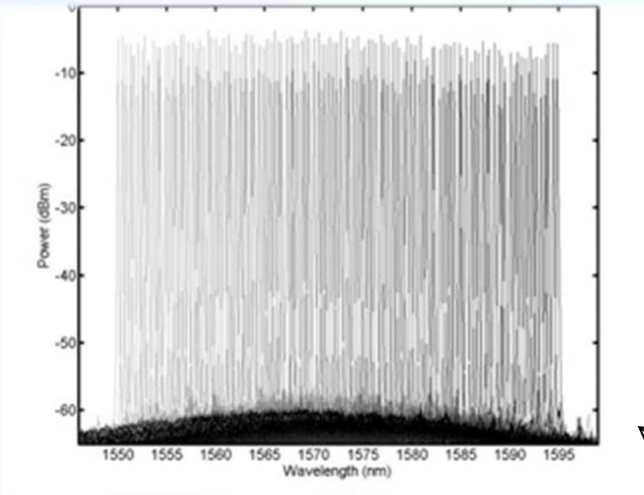


Zhang et al. Optica (2016)

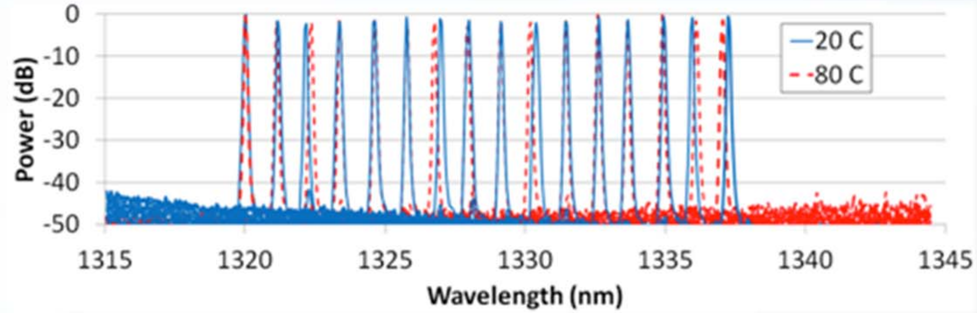
Aurrion PIC Integration

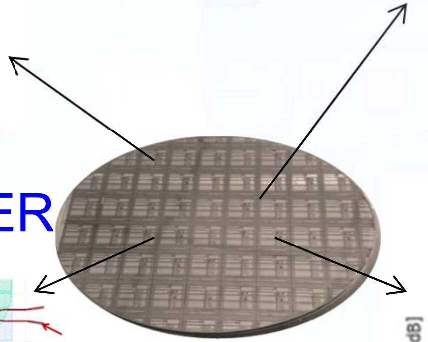
Brian Koch *et al.*, OFC Postdeadline 2013

Telecom Tunable Lasers

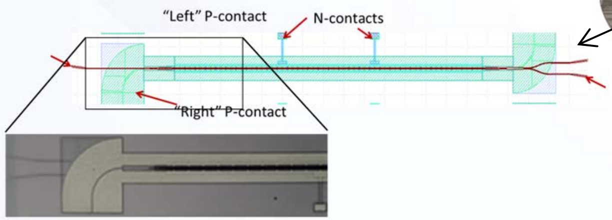


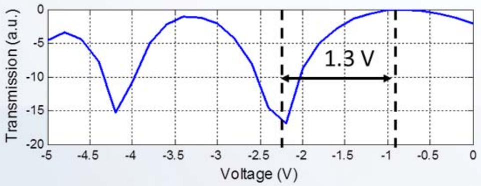
Datacom uncooled WDM laser arrays

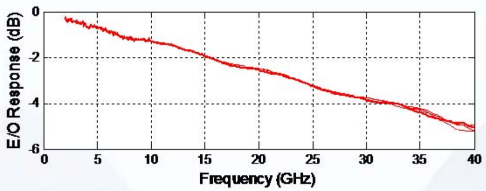


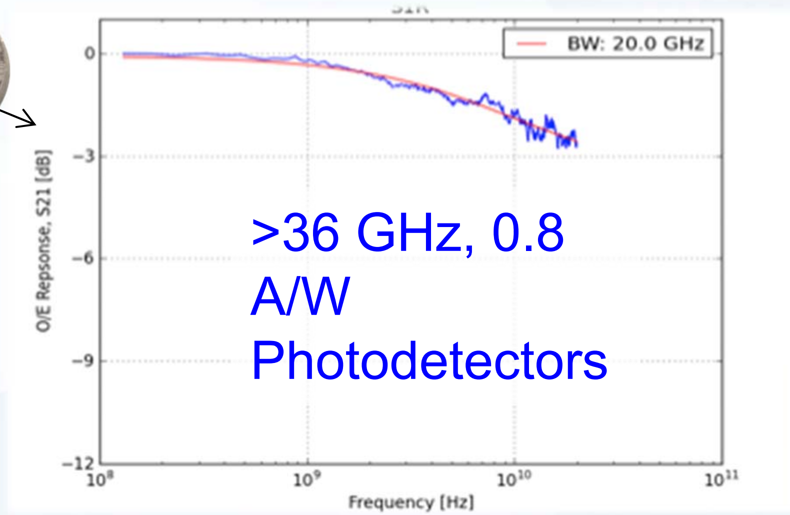


Modulators: 23 GHz, >15 dB ER









>36 GHz, 0.8 A/W Photodetectors

aurrion

Aurrion acquired by Juniper Networks in August, 2016

Intel is shipping heterogeneous PICs in high volume production for 100 Gbps

Intel® Silicon Photonics Products

These optical transceivers enable high-bandwidth connections reaching up to 2km over single-mode fiber, based on industry standards at 100G for switch, router, and server use.

100G PSM4 QSFP28 Optical Transceiver

Features up to 2km reach on parallel single-mode fiber, and is designed to be compliant with 100G PSM4 MSA, QSFP28, and CAUI-4 specifications.

Read the product brief ›

100G CWDM4 QSFP28 Optical Transceiver

Features up to 2km reach on duplex single-mode fiber, with high speed and low-power consumption. Designed to be compliant with 100G CWDM4 and CLR4 MSA, QSFP28, and CAUI-4 specifications.[3]

Read the product brief ›

Summary

- Complicated, high performance PICs are being commercialized on silicon substrates (Intel, Acacia, Juniper Networks, Mellonix, Oracle,…)
- Lasers on silicon are here at low cost.
- Highest level of integration on silicon: >400 elements on chip, including 64 low threshold lasers on chip
- Fully integrated reconfigurable photonic network for chip-level interconnection, total capacity up to 2.56 Tbps