Hybrid III-V Silicon Quantum Dot and Quantum Well Lasers

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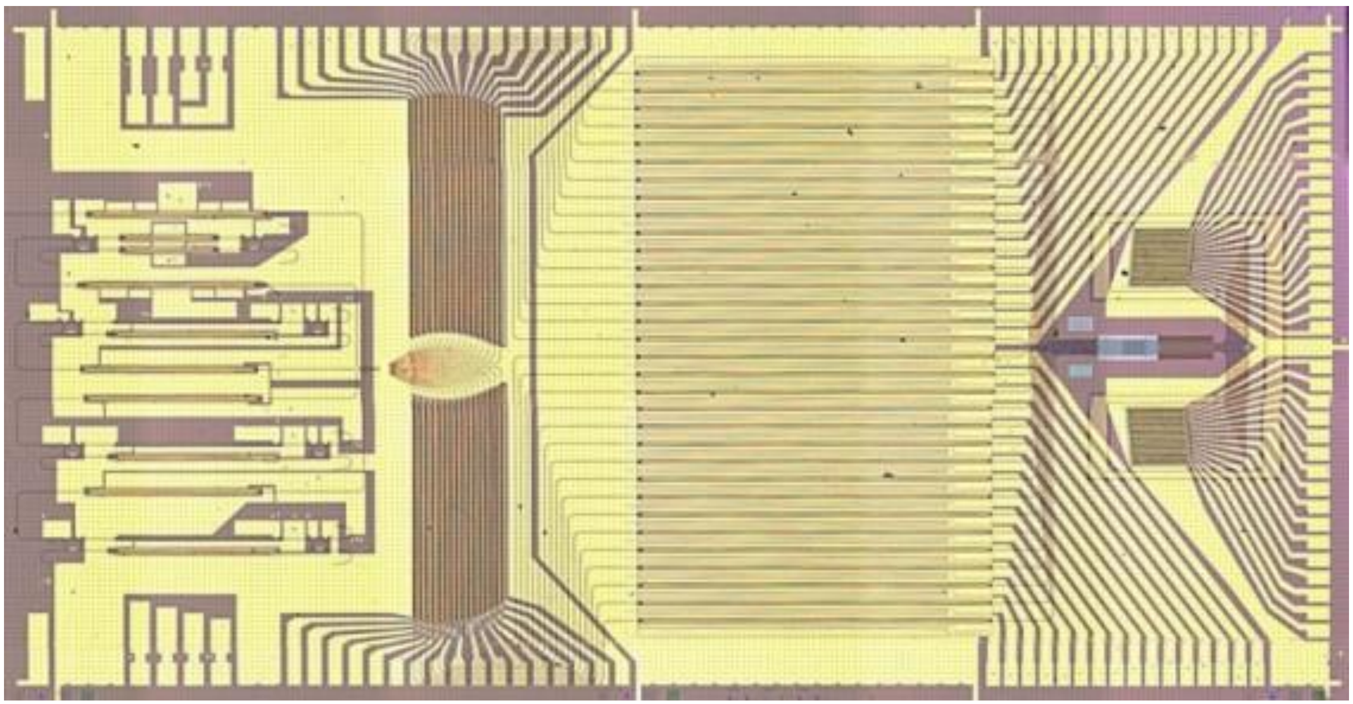
Director, Institute for Energy Efficiency
University of California, Santa Barbara
http://optoelectronics.ece.ucsb.edu/

UCSB: Jared Bauters, Daoxin Dai, Mike Davenport, Art Gossard, Martijn Heck, Jared Hulme, Alan Liu, Jon Peters, Daryl Spencer, Sudha Srinivasan



4 tunable lasers, 4x32 splitter, 32 amplifiers, 32 phase shifters, 32 grating emitters, 32 photodetectors

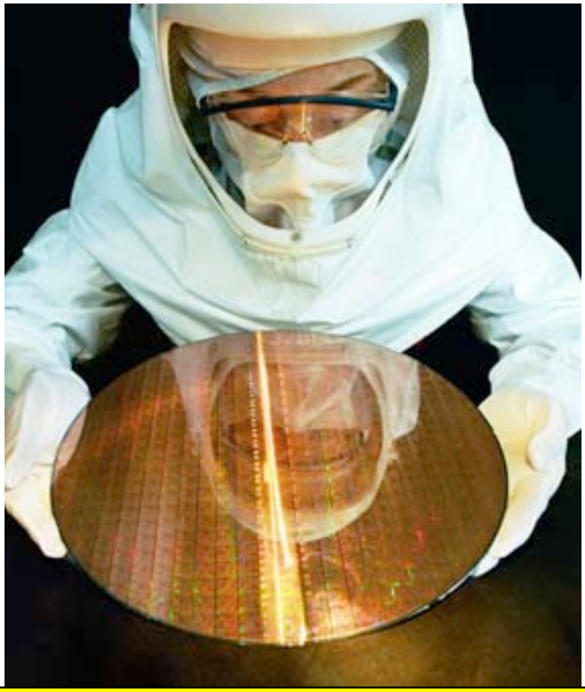
Research supported by Josh Conway and Jag Shah at DARPA MTO

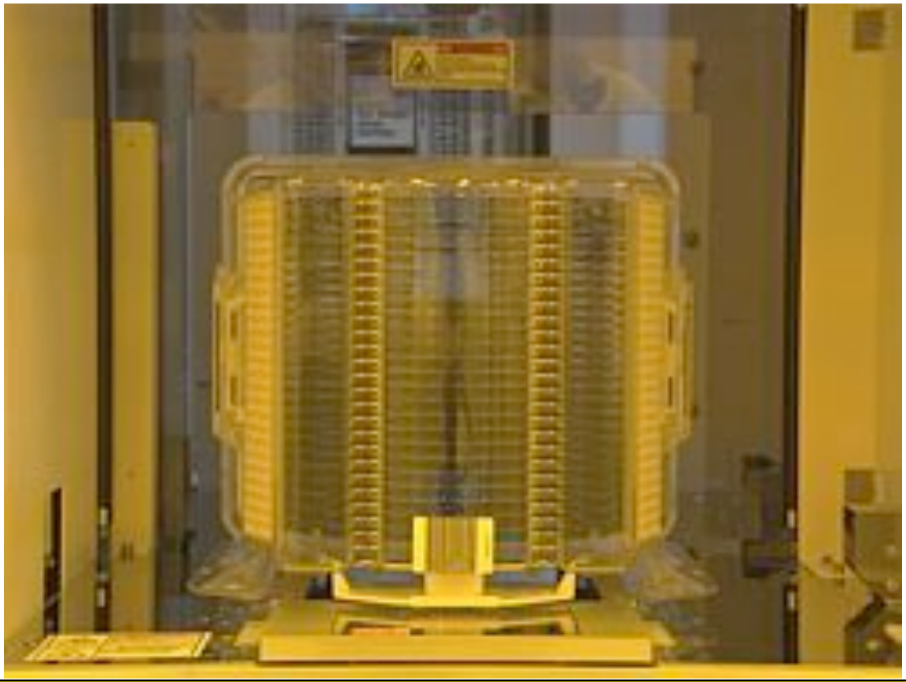
Outline

- Silicon Photonics
- Lasers on Silicon
  - Er doped
  - Patterned
  - Ge
  - Bonded
  - Epitaxially grown
- Quantum dot lasers
- Tunable Lasers
- Integration
- Commercialization
- Future
- Summary

What is Silicon Photonics?

- Making photonic integrated circuits on Silicon using CMOS process technology in a CMOS fab
- Merging photonics and CMOS





The issue is not InP or GaAs versus Si. The issue is

1) Scaling photonics to high levels of integration with improved performance and better process control at low cost.
2) Solving electrical interconnect limits in Data centers, Supercomputers and ICs with higher capacity, lower cost optical interconnects

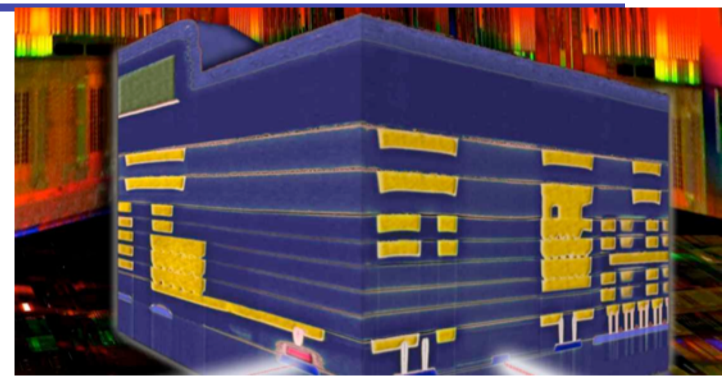
2014: Silicon Photonics Participants

Silicon Photonics Companies	Silicon & Systems Co's	Silicon Photonics Foundries
LIGHTWIRE	CISCO	ST
KOTURA	IBM	IBM
Caliopa silicon photonics	ORACLE	GLOBALFOUNDRIES
aurrion	intel	imec
LUXTERA	Mellanox TECHNOLOGIES	MOSIS
RANOVUS	TeraXion	A*STAR Institute of Microelectronics
	HUAWEI	OpSIS
		PETRA
		cea leti

This is not exhaustive list

Numerous Silicon Photonics Entrants
Across Start-ups, Products, Foundries and Research

Why Silicon Photonics?

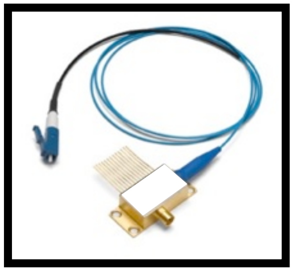


Cross-sectional view of an IBM Silicon Nanophotonics chip combining optical and electrical circuits
Vlasov et al. IEDM postdeadline

- Integrate photonics with electronics
  - Same wafer
  - Bump bonding of silicon PIC with silicon IC
    - Same coefficient of thermal expansion
  - 3D stacking
- Reduce cost by going to larger diameter wafers (300 mm)
  - InP limited by wafer breakage to 100 mm diameter
- Reduce cost by sharing VLSI facility with electronics
- Improve yield by taking advantage of silicon process development
- Volume driver: Solve IC interconnect bottleneck (from 4 Tbps to 1 Pbps). Optical transmitters/receivers on processors, memories, switches.

Bringing Si Manufacturing to the Laser

Lasers



Very high bandwidth

Long dista

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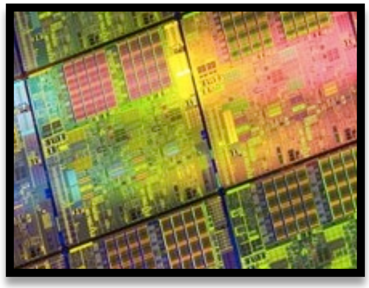
electrical i

InP Photonic Integrated circuits

Si Manufacturing



High volume, low cost

Highly integrated

Scalability

Six Generations

Silicon Photonic Integrated circuits

Year of Production	1995	1998	2001	2004	2007	2010	2013	2016
DRAM 1/2 Pitch (nm)	270	190	130	90	65	43	32	22
Wafer Size (mm)	150	200	200	200	300	300	300	450

UCSB

Needs

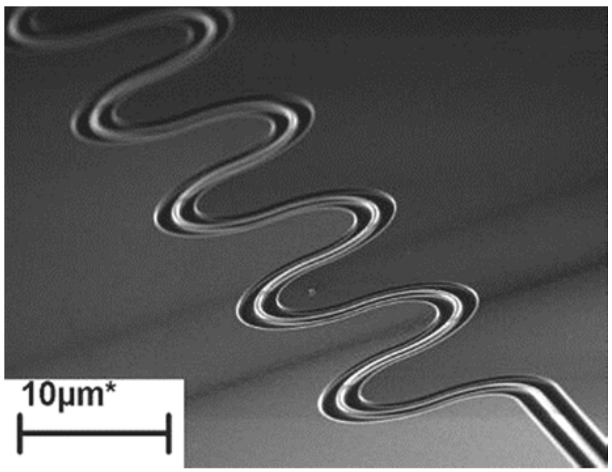
- What is needed is a photonics platform for interconnects and switching that is scalable to
  - Low power
  - High capacity
  - Low cost
  - High volume
  - High yield
  - High reliability

Silicon Photonic Components

- Passives
  - Low loss waveguides
  - Splitters
  - Wavelength selective combiners/splitters
  - Isolators/Circulators
  - Comb generators
- Actives
  - Lasers (Pump and single frequency)
  - Modulators
  - Switches
  - Amplifiers
  - Photodetectors

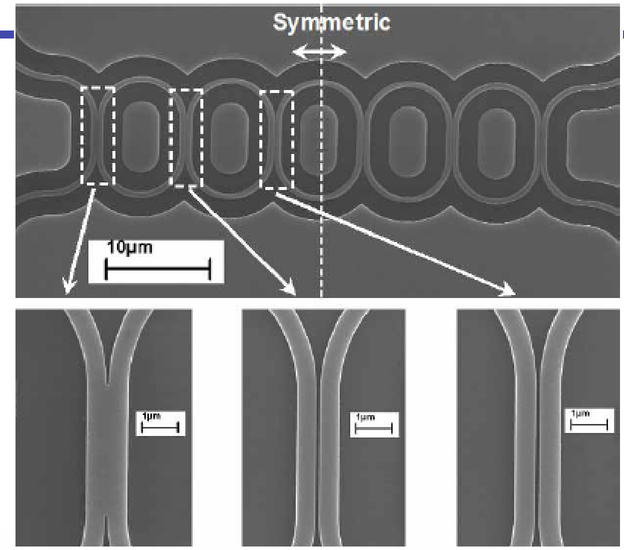
Superior Passive Si Photonic Devices

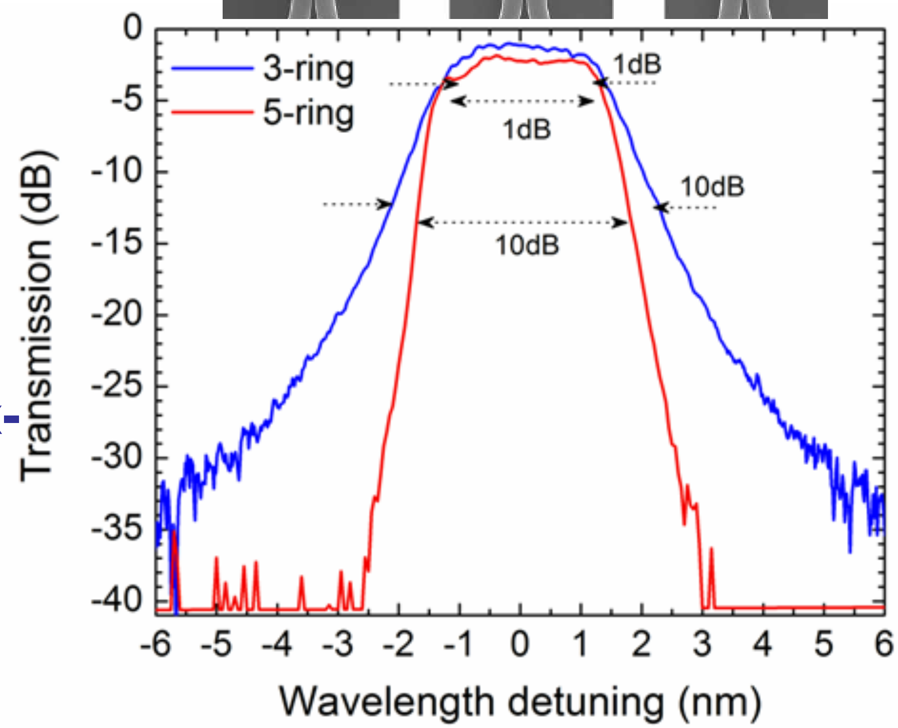
Si/SiO2 High index contrast:
- **Small wires**
- **Small passive devices**
- **High coupling loss**
- **High propagation loss**



Example of losses for high-index-contrast "wire" waveguides:
- **For 6.5 mm radius bends, losses are 0.0043 dB per 180º turn**

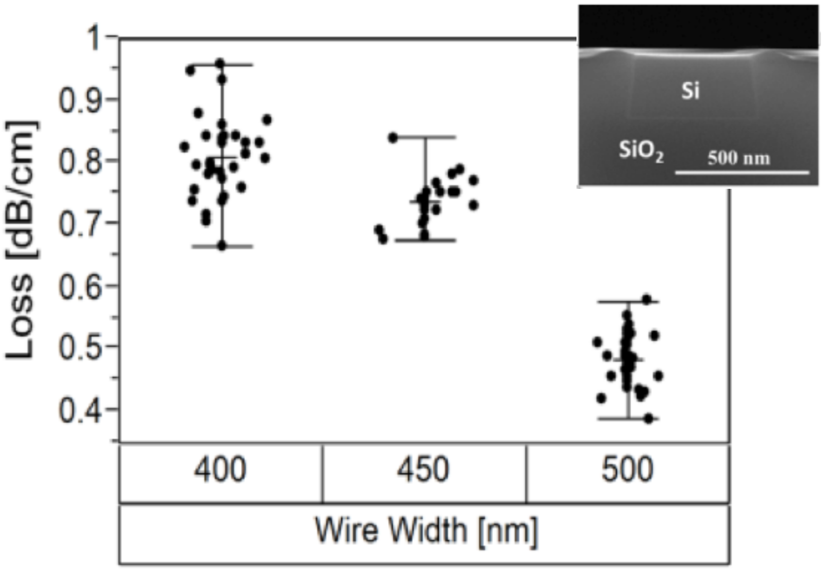
Source: Y. Vlasov, IBM



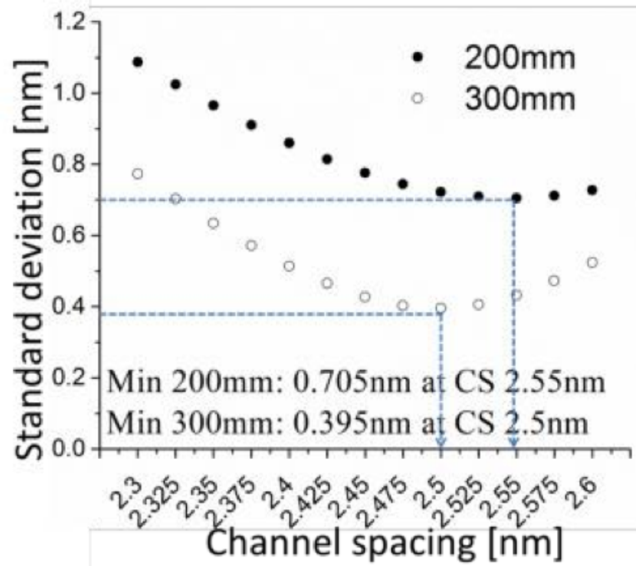


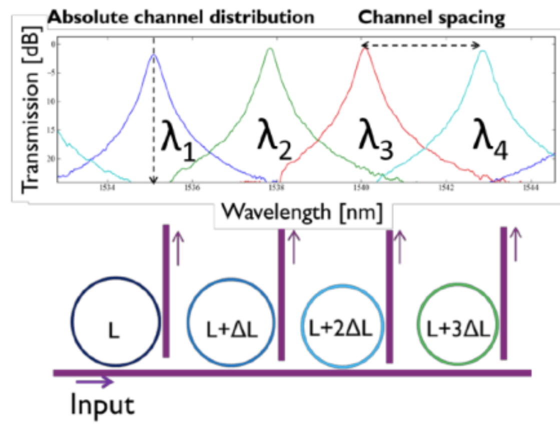
Move to 193nm immersion lithography, 300mm wafers

Lower loss waveguides



More uniform channel spacing in ring demux





Also:

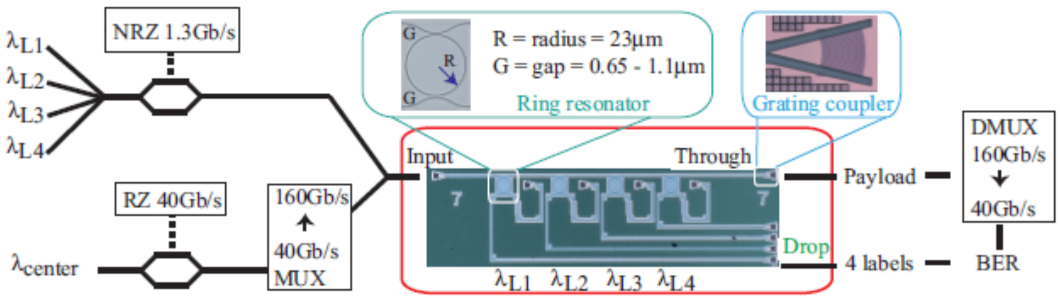
- < 0.15dB/cm loss in ridge waveguides
- <2dB/cm loss in slot waveguides

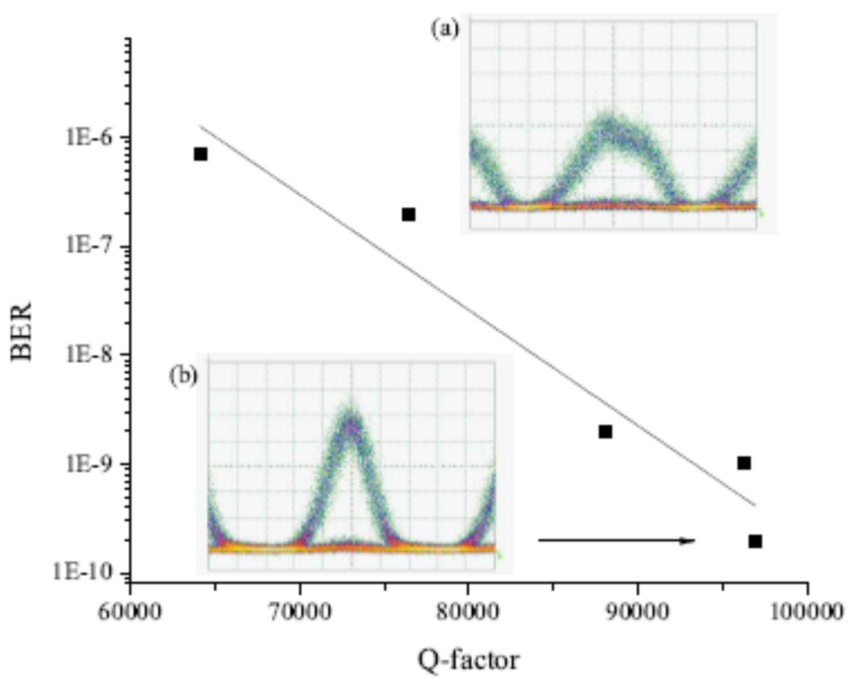
S. Selvaraja e.a., OFC '14

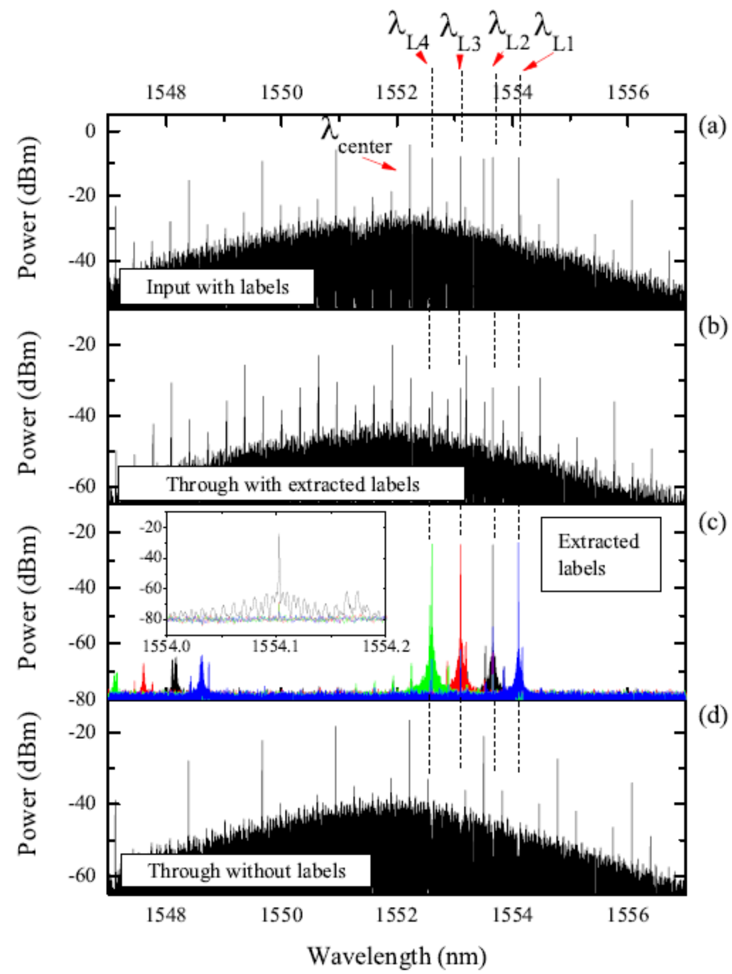
Selvaraja e.a. 17th OptoElectronics and Communications Conference (OECC 2012)

P. De Heyn, PhD Thesis UGent, May '14

A four in-band label extractor for 160 Gb/s optical packets







De Heyn e.a., IEEE JLT, 2014

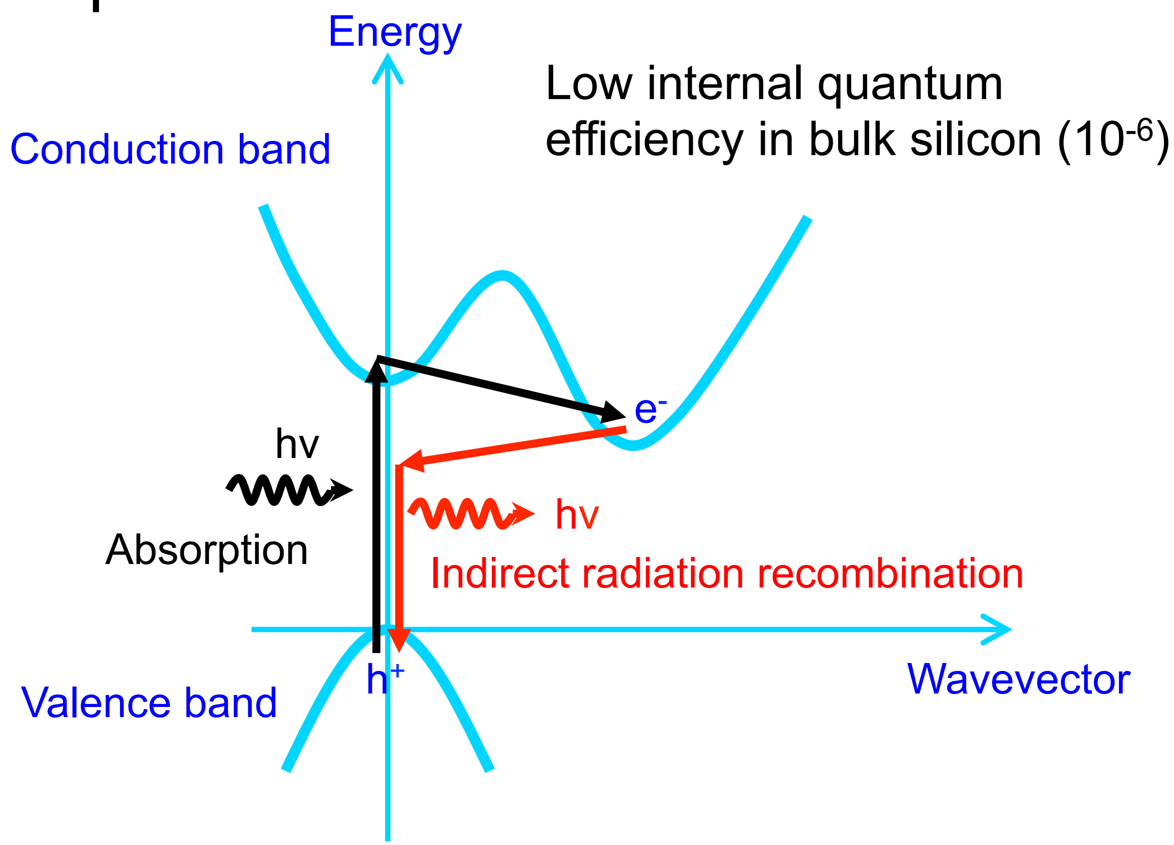
(collaboration with TU/e)

Silicon Photonic Components

- Passives
  - Low loss waveguides
  - Splitters
  - Wavelength selective combiners/splitters
  - Isolators/Circulators
  - Comb generators
- Actives
  - Lasers (Pump and single frequency)
  - Modulators
  - Switches
  - Amplifiers
  - Photodetectors

Silicon light emission – limits

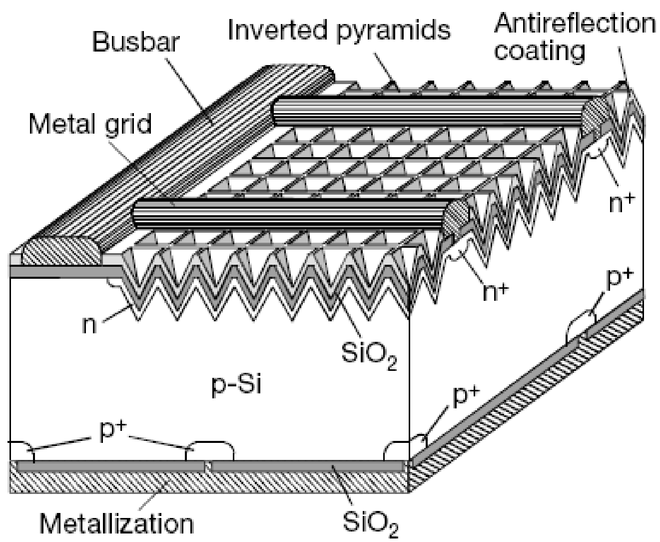
- Indirect band gap - inefficient for light emission
- Auger recombination
- Free carrier absorption

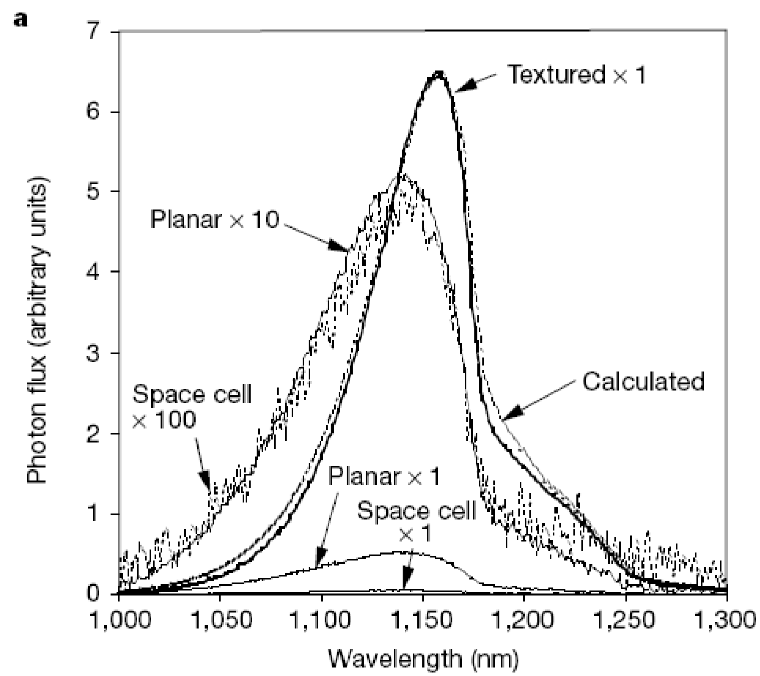


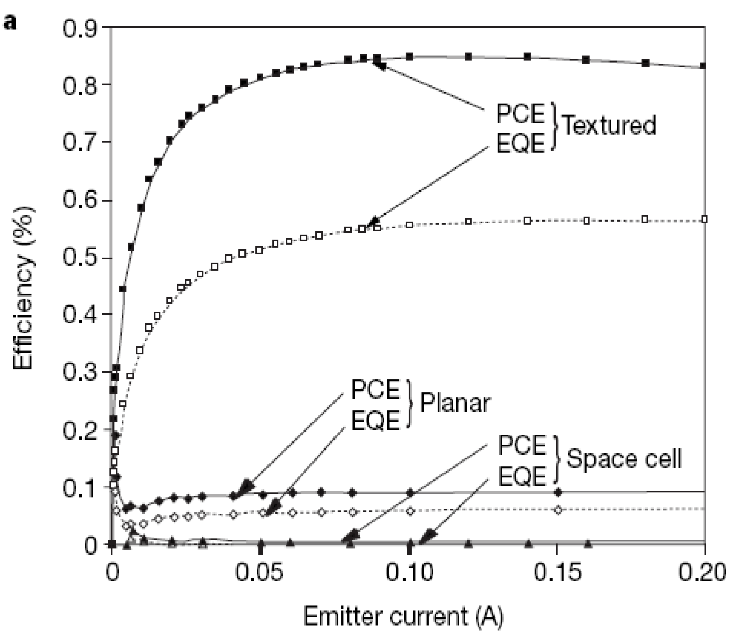
Silicon light emission – How?

- Bulk silicon
- Low dimension Silicon
  - Silicon nanocrystal (Pavesi, …)
  - Periodic nanopatterned crystalline silicon (Jimmy Xu)
- Er dopants (Dal Negro,…)
- Raman laser (Noda, Kyoto, UCLA, Intel)
- Another material for gain (hybrid approach)
  - Epitaxial
    - Ge
    - GeSn
    - Quantum Dot
    - Pillars
  - Bonding
    - Dice level
    - Wafer level (BCB or Molecular)

Bulk silicon LED





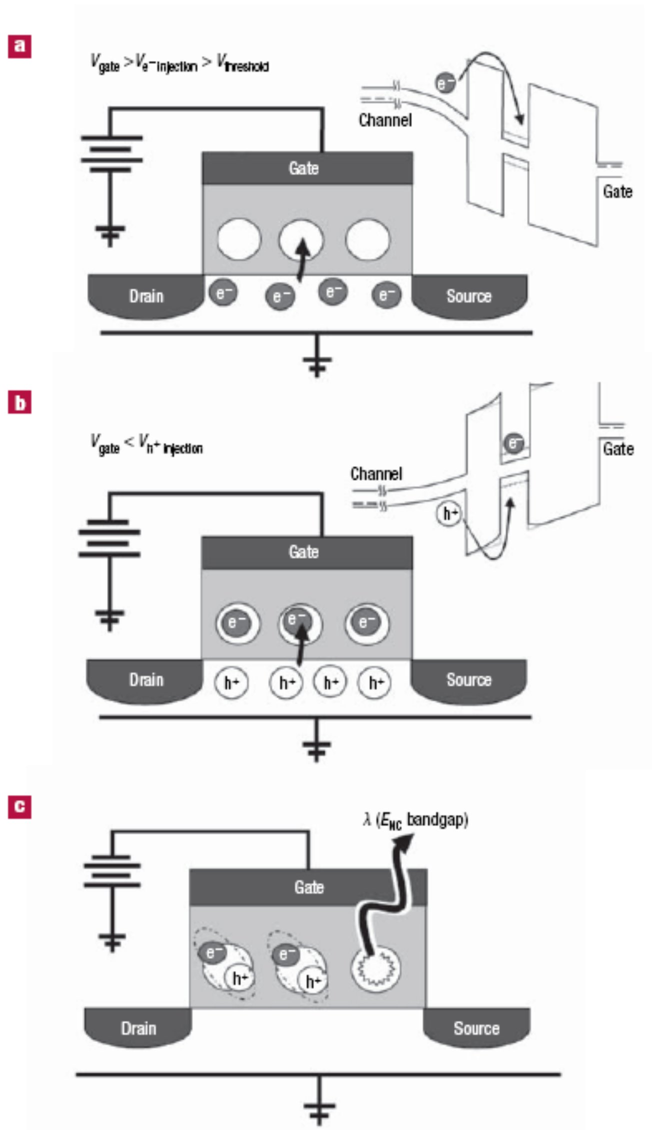


Solar cell forward bias

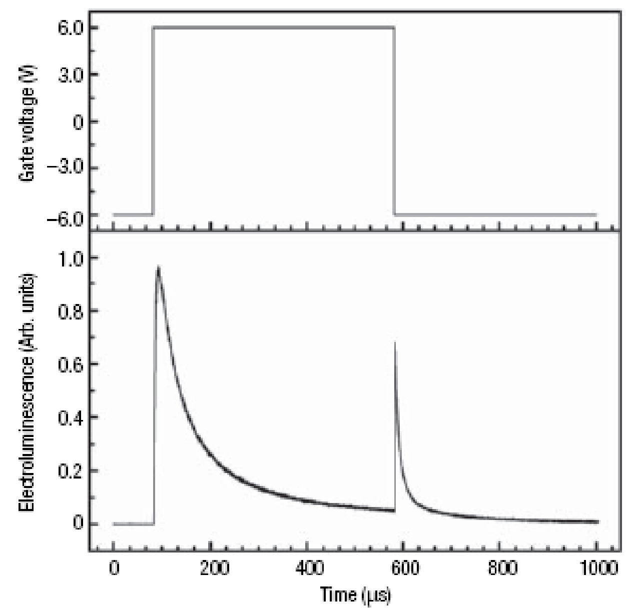
~1% external quantum efficiency

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

Field effect electroluminescence

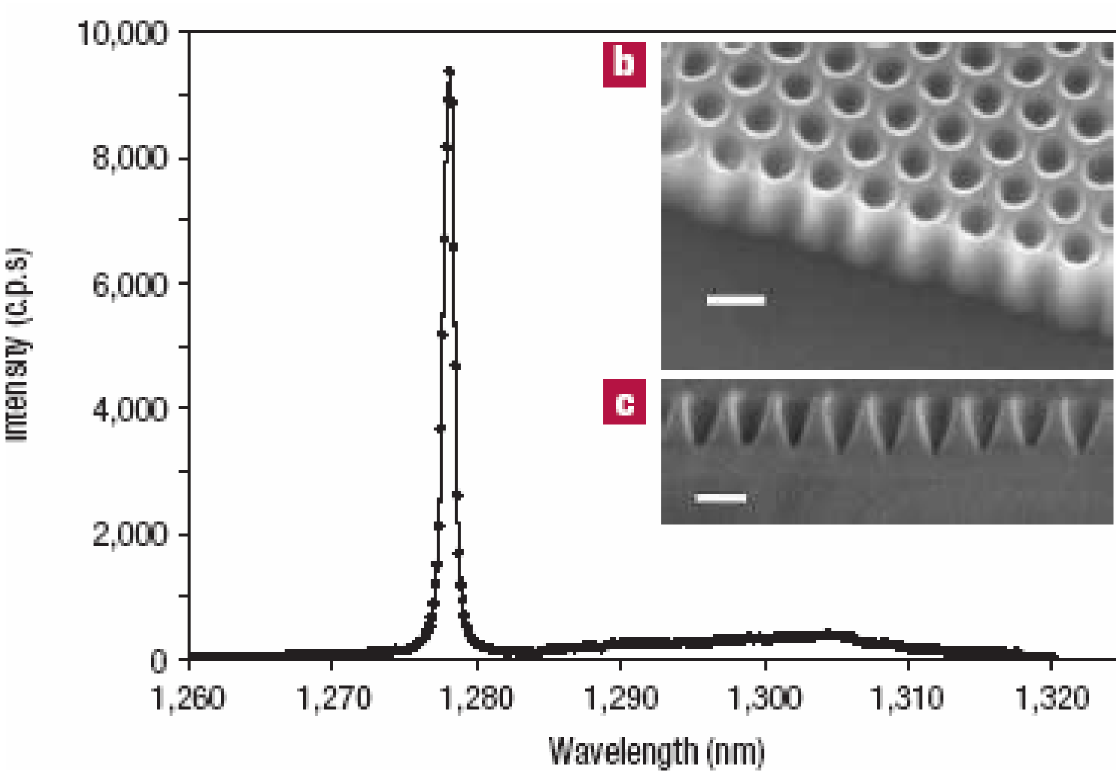


Sequential injection of electron and hole



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

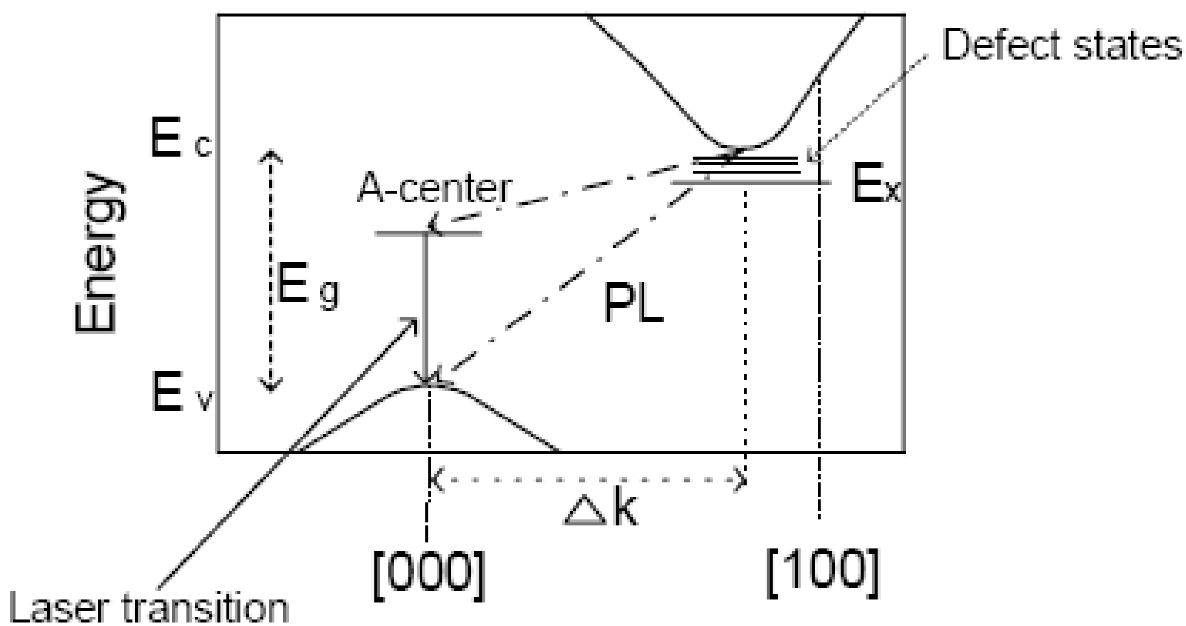
Nanopatterned Crystalline Silicon



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

Emission mechanism

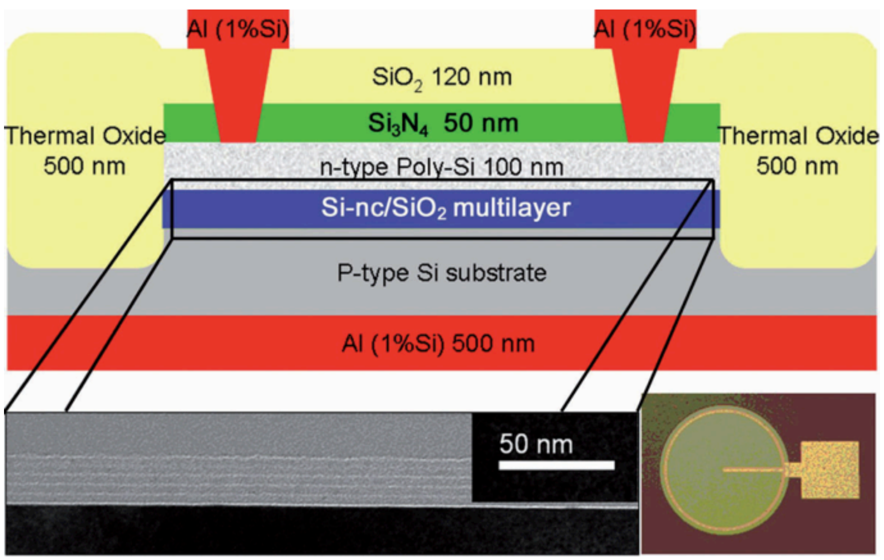
Nano-patterning creates a densely packed array of Emissive Structural Deformation (ESD) zones in the side-wall region of the nano-holes

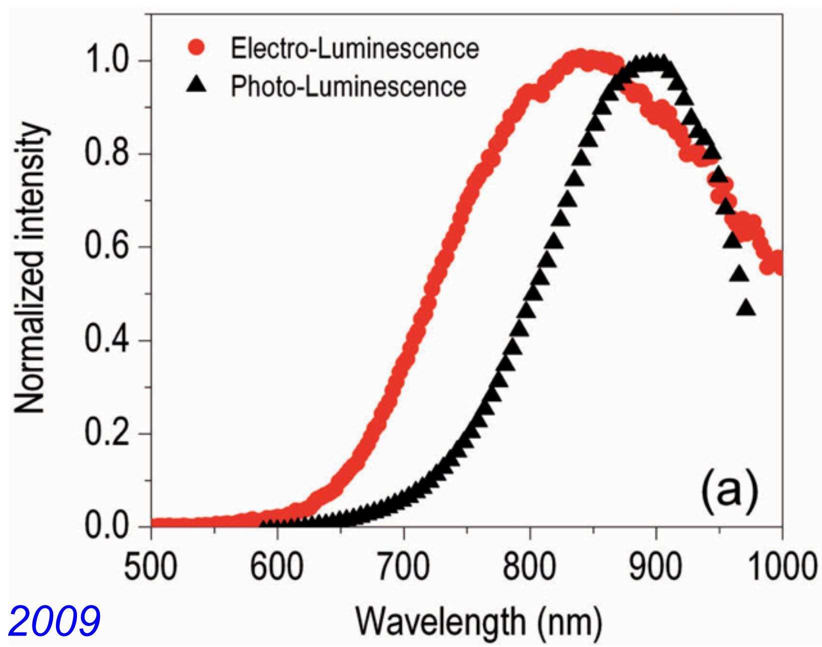


J. Xu, IEEE International Conference on Group IV Photonics, Ottawa, Canada (2006), FA1.

Silicon nanoclusters: LED

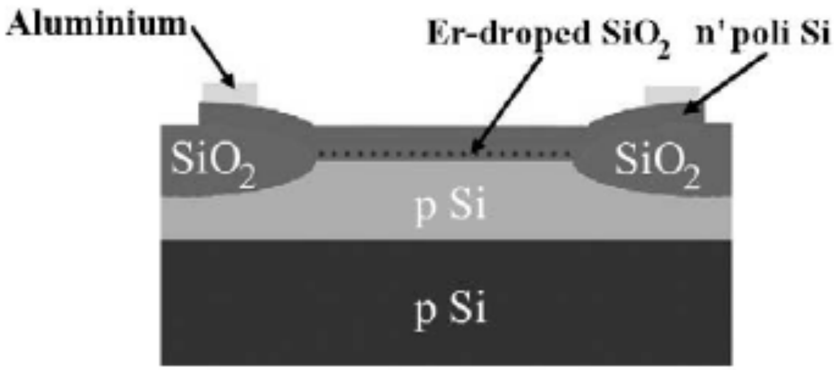
- EL power efficiency values for LED devices:
  - 0.01–0.03% for pure Si-nc;
  - 0.2–0.3% for rare-earth ion doped
- For high EL efficiency: bipolar injection needed
  - issue: electron tunneling barrier << hole barrier





N. Daldosso and L. Pavesi, Laser & Photon. Rev., 2009

Rare earth doped light emitting MOS



(a)

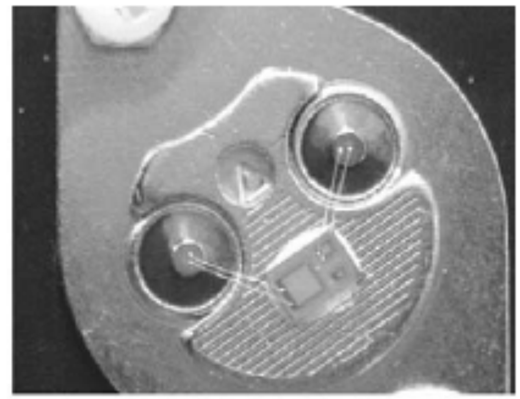

(b)

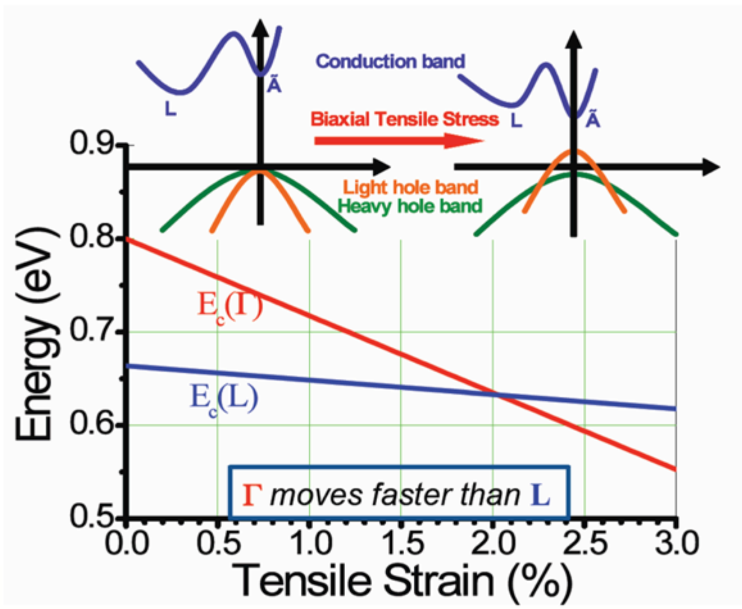
Table 1
Emission wavelength, cross-section and external quantum efficiency of MOS devices with rare-earth doped gate dielectric

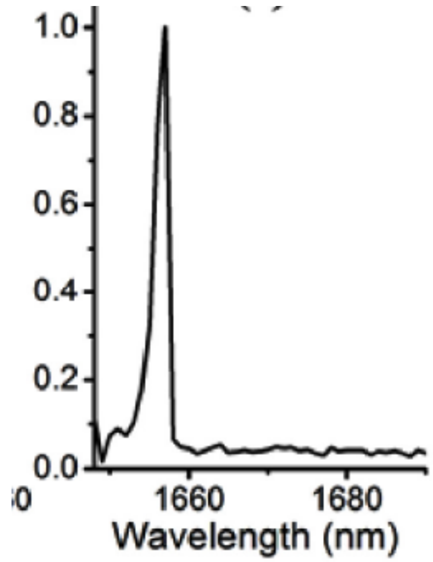
Rare earth	λ emission (nm)	σ (cm^2)	η_{ext} (%)
Erbium	1540	1×10^{-14}	10
Terbium	540	4×10^{-15}	10
Ytterbium	980	1×10^{-15}	0.1

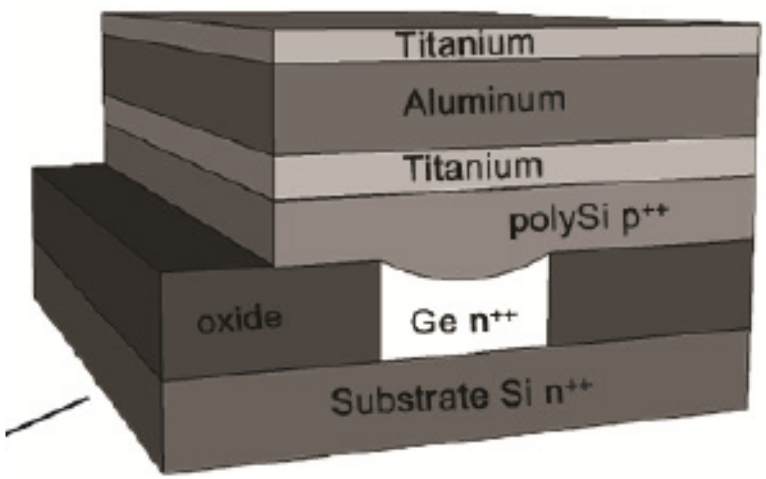
M.E. Castagna *et al*., Materials Science and Engineering B 105, 83 (2003)

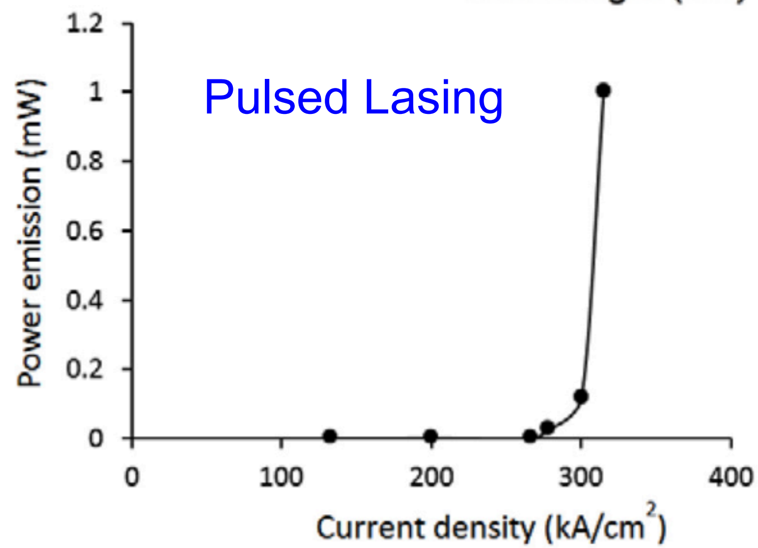
An electrically pumped germanium laser

Rodolfo E. Camacho-Aguilera,[1] Yan Cai,[1] Neil Patel,[1] Jonathan T. Bessette,[1] Marco Romagnoli,[1,2] Lionel C. Kimerling,[1] and Jurgen Michel[1,*]







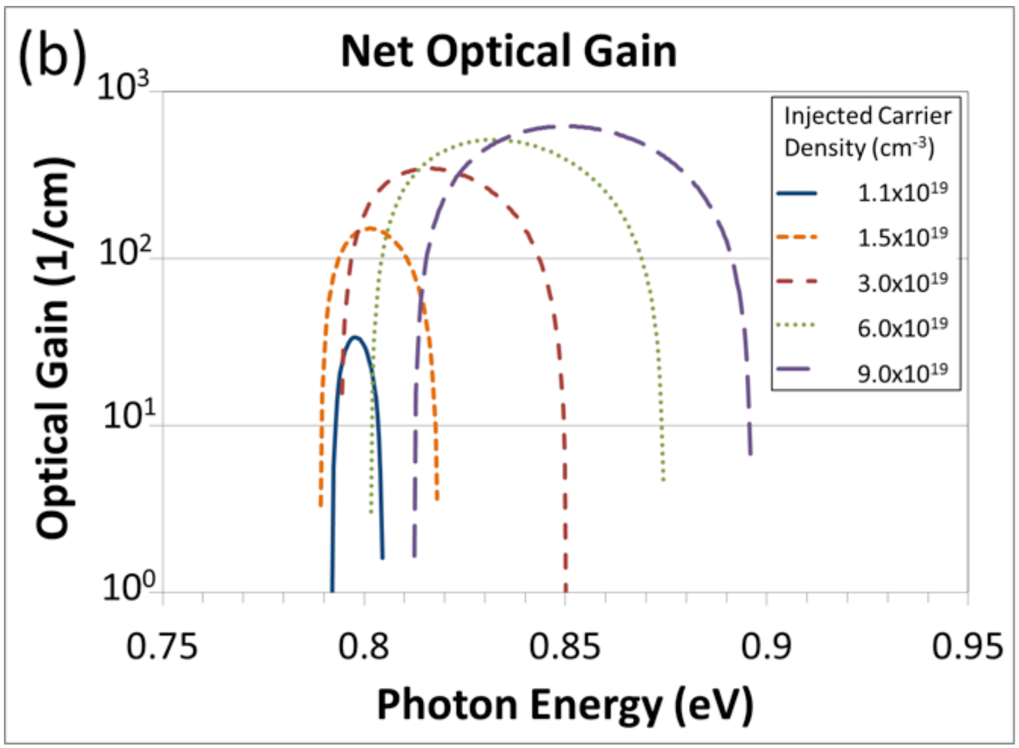


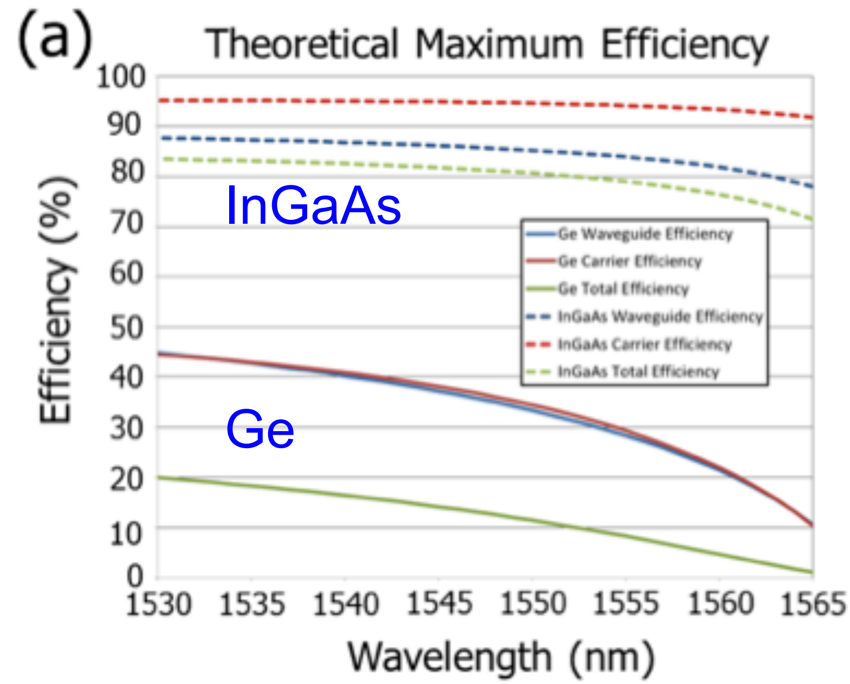
UCSB

Theoretical efficiency of electrically pumped, strained Ge lasers

David C. Nielsen,[1,*] and J. Scott Rodgers,[2]

[1]*Booz Allen Hamilton, 3811 N Fairfax Dr, Arlington, VA 22203, USA*
[2]*Defense Advanced Research Projects Agency, 675 N. Randolph St., Arlington VA. 22203, USA*
[*]*nielsen_david@bah.com*



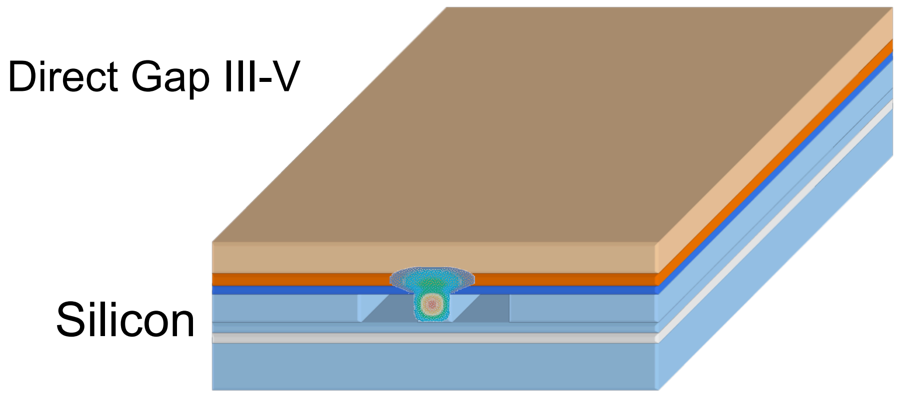


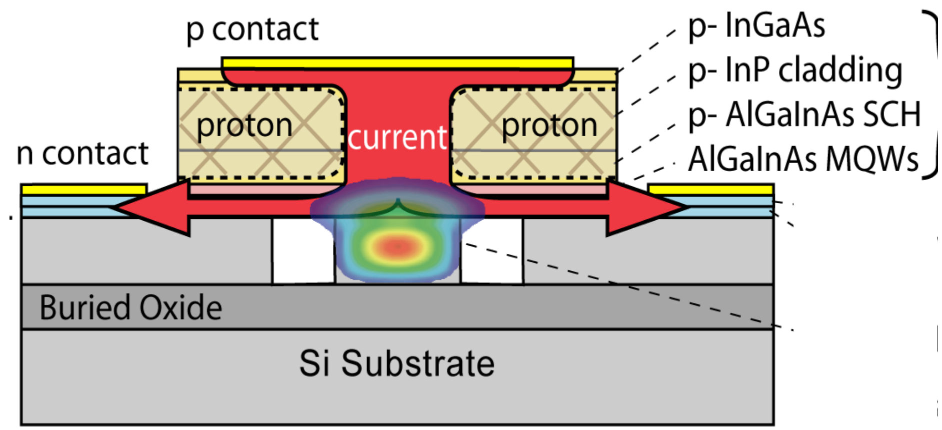
Heterogeneous Integration

Quantum Well (UCSB, Ghent, Caltech, Tokyo Inst. Of Tech, Intel, HP, Aurrion)

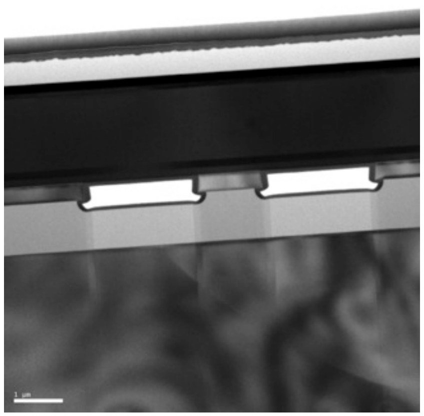
Quantum Dot (Univ. Tokyo, UCSB)

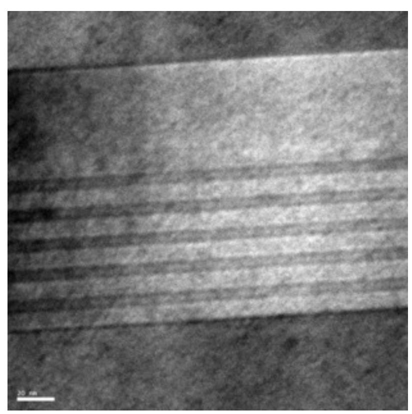
Hybrid Silicon Photonics

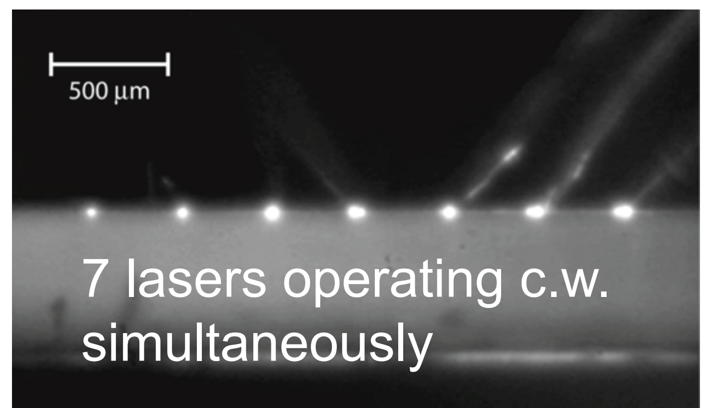




- Optical gain from III-V Material
- Efficient coupling to silicon passive photonic devices
- No bonding **alignment** necessary: suitable for high volume CMOS
- All back end processing low temperature (<350 C)





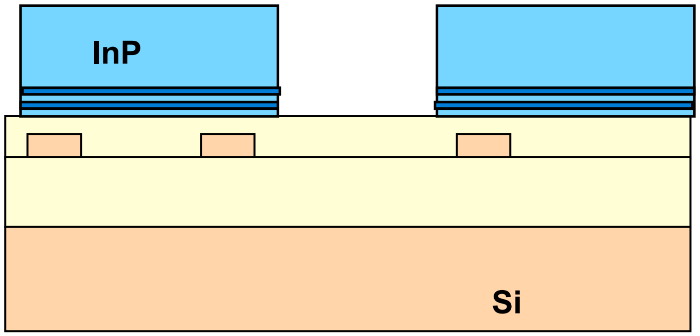


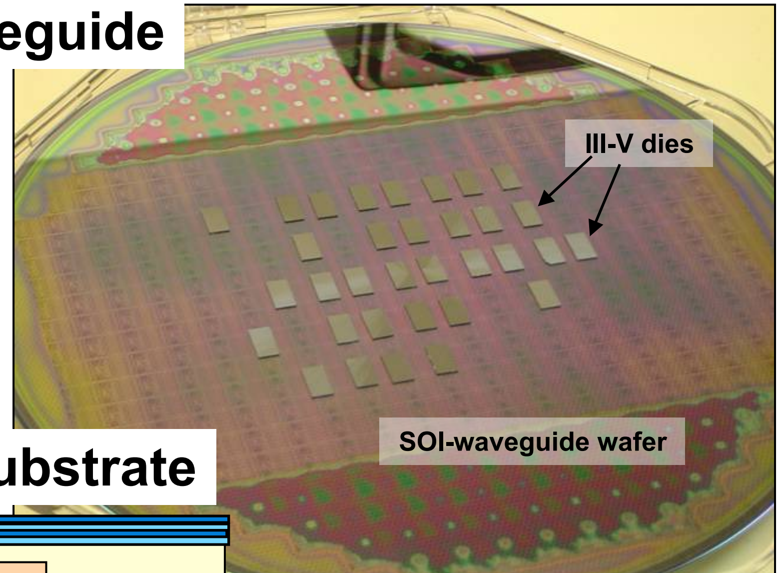
A.W. Fang, et al., “A Continuous Wave Hybrid AlGaInAs-Silicon Evanescent Laser,” IEEE Photonics Technology Letters, 18 (10), 1143-1145, May 15, 2006

Heterogeneous integration

UCSB, Intel, HP, Ghent, TIT, Caltech

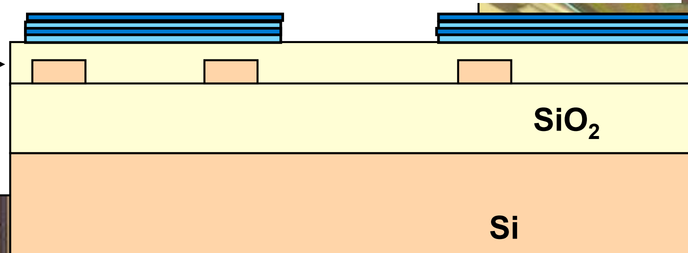
Step 1: Bond InP-dies on SOI waveguide

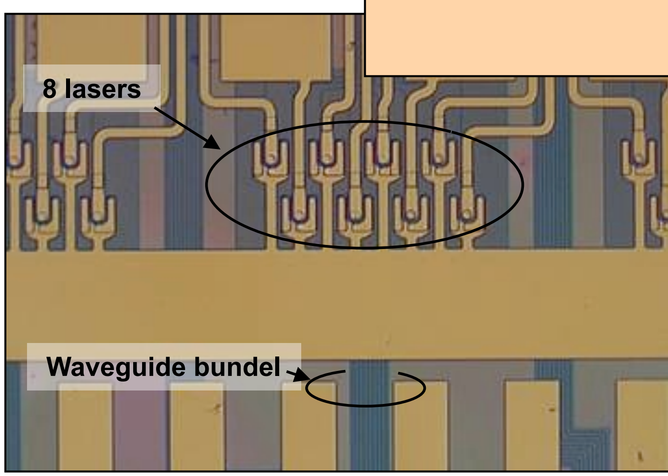




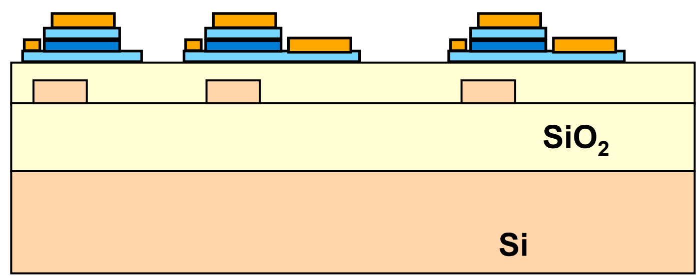
Step 2: Remove substrate

BCB or SiO_2





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

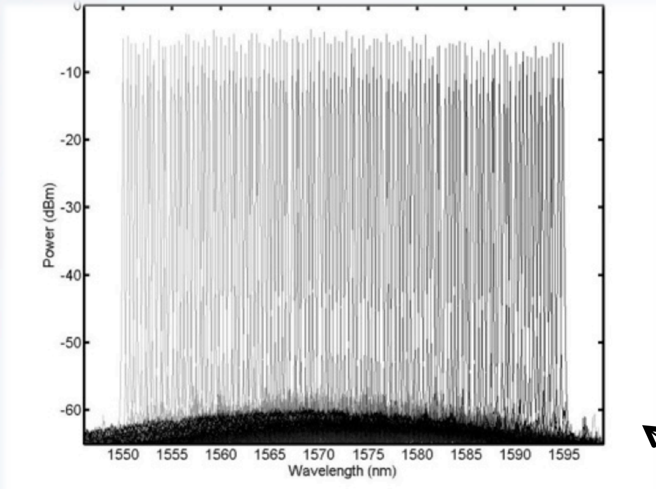


IMEC/Ghent

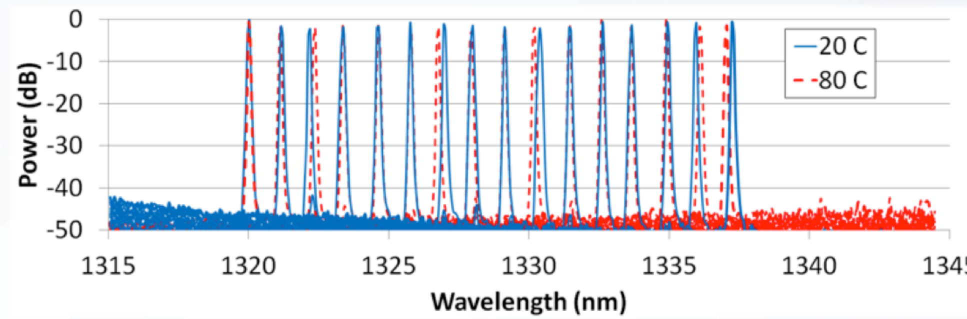
Aurrion PIC Integration

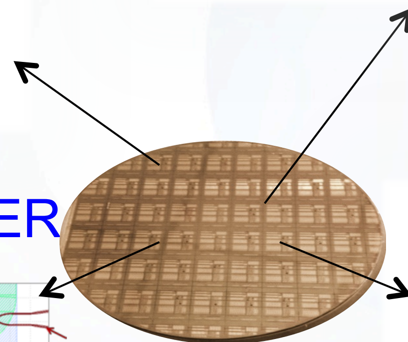
Brian Koch *et al.*, OFC Postdeadline 2013

Telecom Tunable Lasers

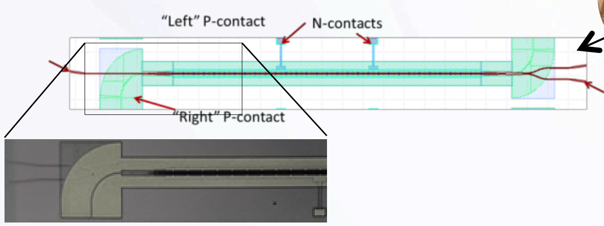


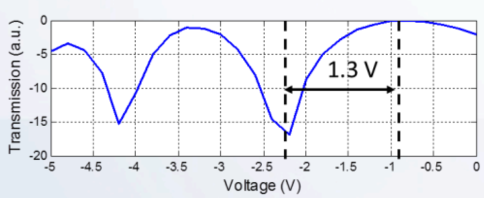
Datacom uncooled WDM laser arrays

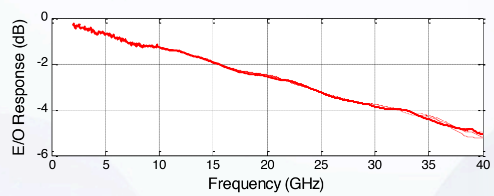


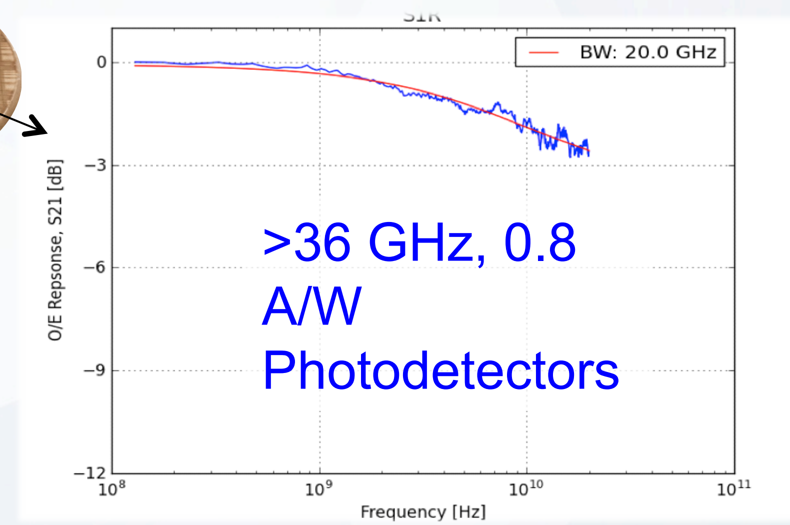


Modulators: 23 GHz, >15 dB ER









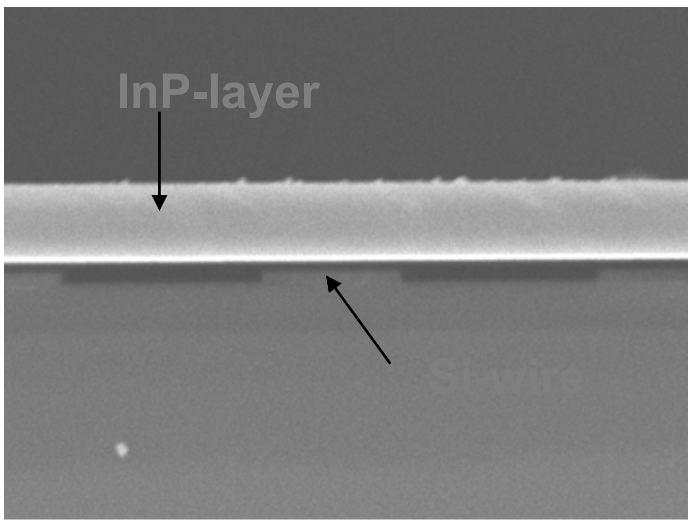
>36 GHz, 0.8 A/W Photodetectors

aurrion

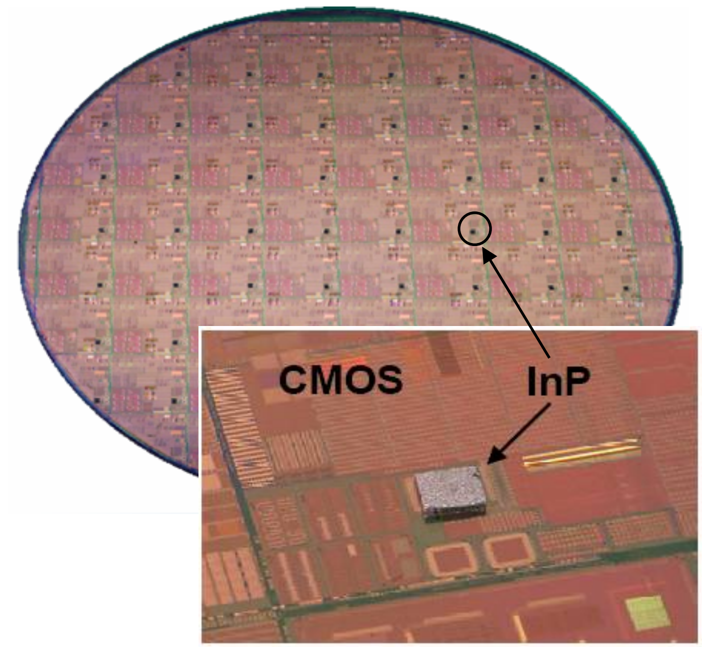
Heterogeneous integration

Two alternatives for the die-to-wafer bonding process

- Adhesive layer bonding
  - Planarization and bonding in single step (IMEC-Ghent University)
  - Ultra-thin bonding layers (sub 200nm demonstrated) [1]



- Molecular bonding
  - InP on SOI-waveguides (UCSB, Intel, Hewlett Packard, Caltech, TIT, CEA-LETI, TRACIT) [2,3]



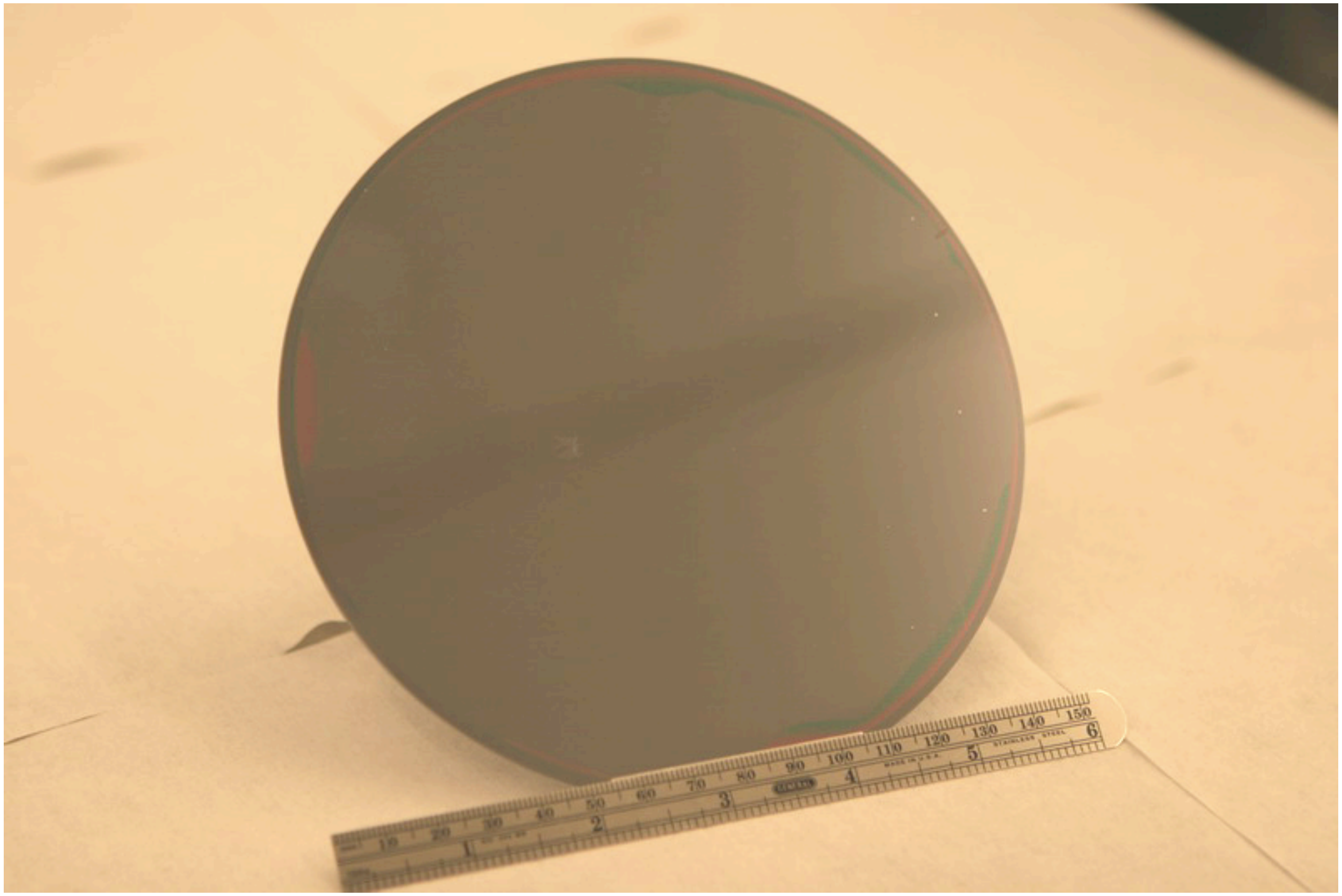
[1] G. Roelkens et al., “Adhesive Bonding of InP/InGaAsP Dies to Processed Silicon-On-Insulator Wafers using DVS-bis-Benzocyclobutene”, J. Electrochem. Soc., Volume 153, Issue 12, pp. G1015-G1019 (2006)

[2] D. Liang, G. Roelkens, R. Baets, J. E. Bowers , "Hybrid Integrated Platforms for Silicon Photonics," Materials , 3 (3), 1782-1802 , March 12 , 2010

[3] M. Kostrzewa et al., 'InP dies transferred onto silicon substrate for optical interconnects application ', Sensors & Actuators A 125 (2006) 411-414

Quantum Well Epi on 150 mm Silicon

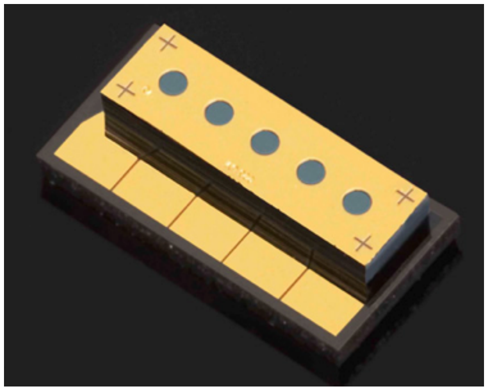
Oxygen Plasma Enhanced Molecular Bonding



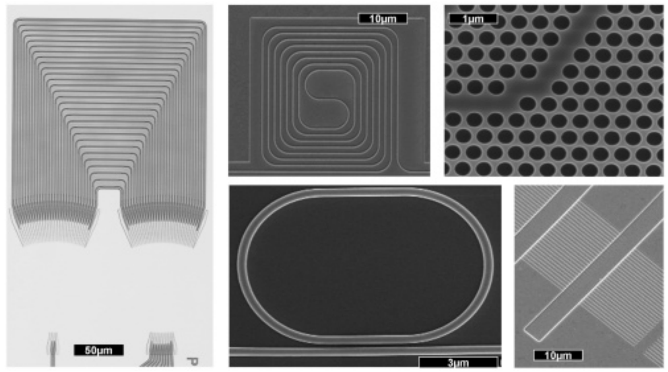
UCSB

Heterogeneous Integration of 6 Photonic Platforms

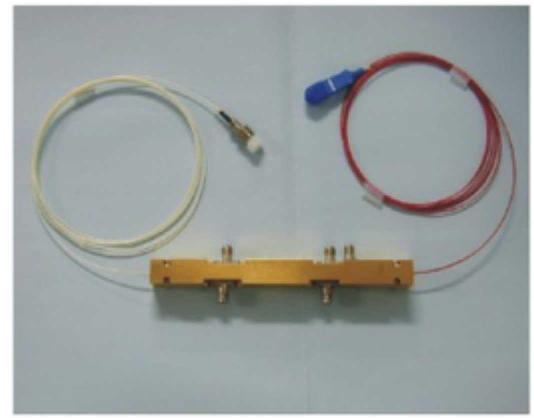
GaAs



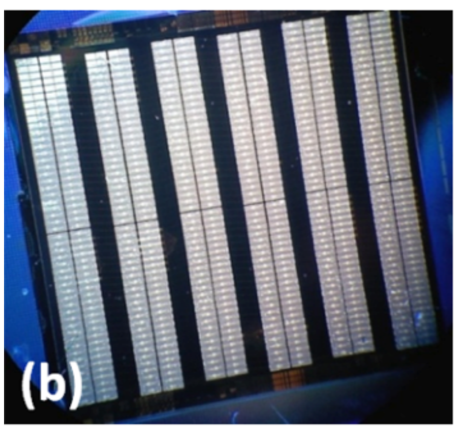
Silicon



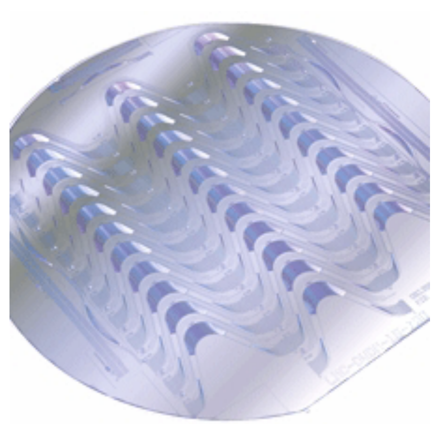
$LiNbO_3$



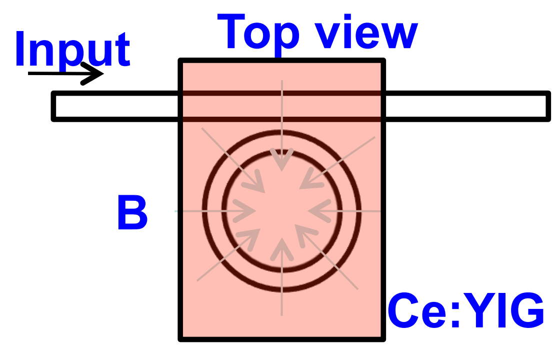
InP



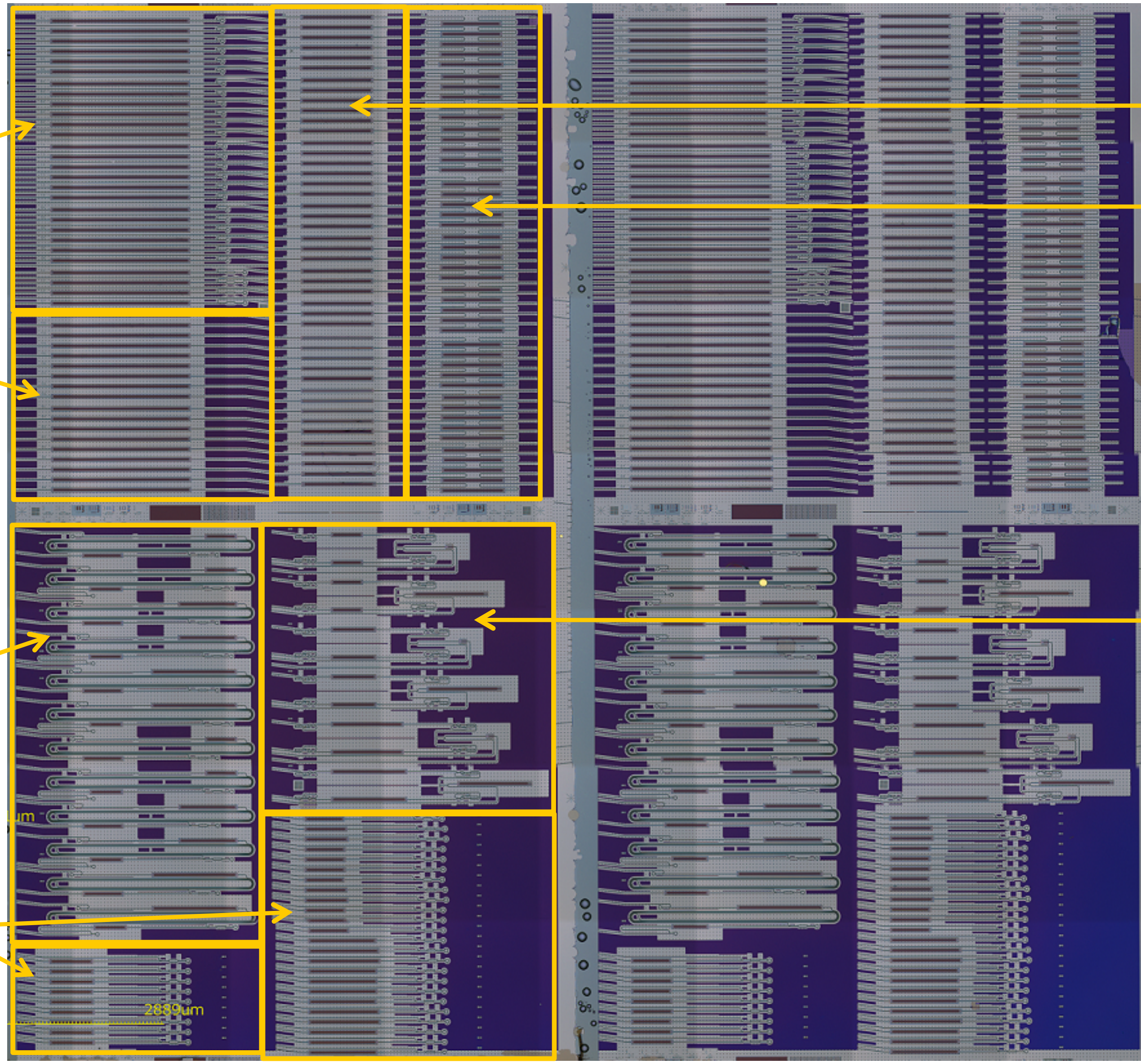
SiN/SiON/SiO2



Ce:YIG Isolator

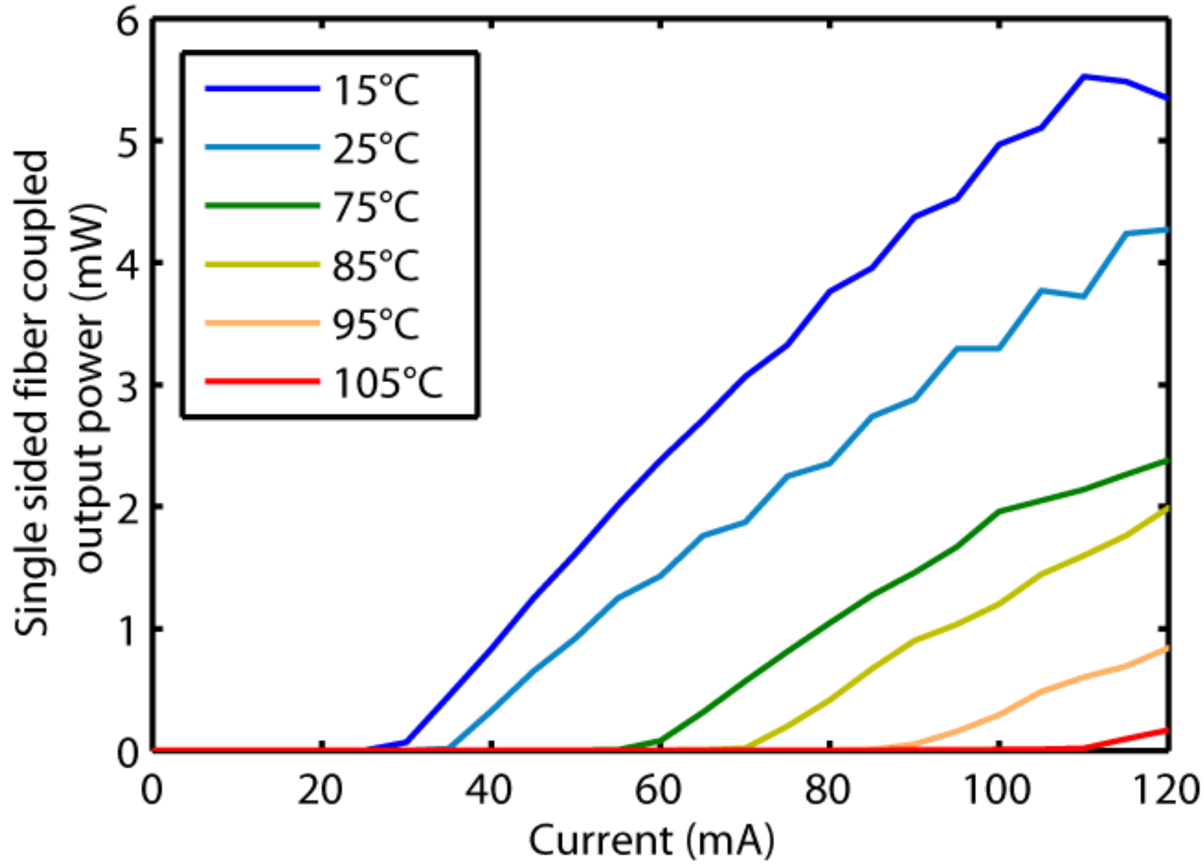


UCSB Shuttle Run



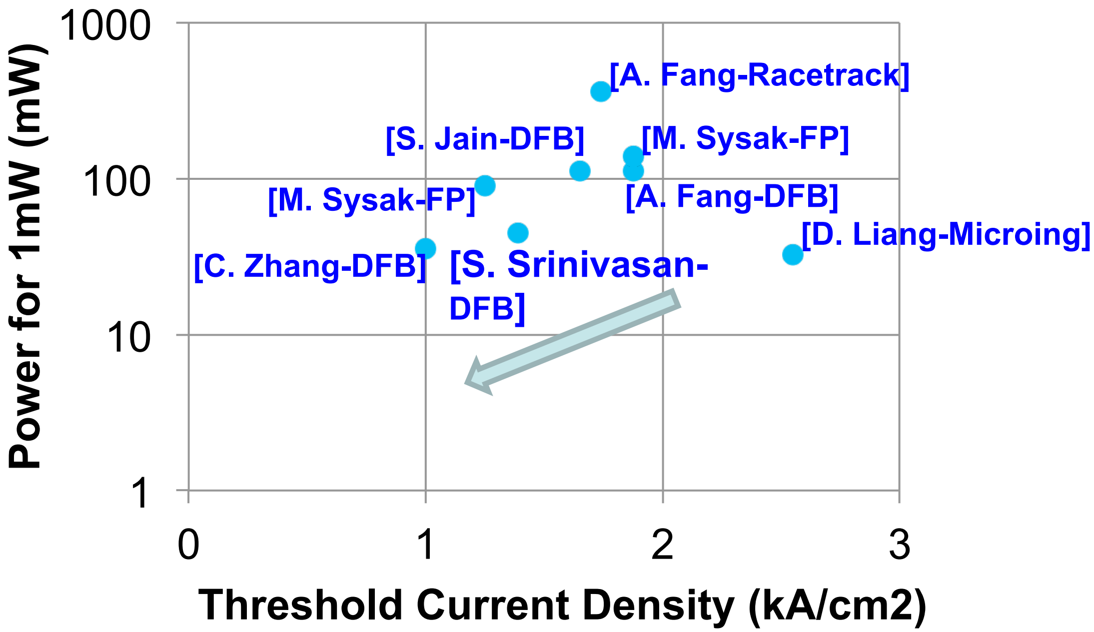
Hybrid Silicon Quantum Well Lasers
105 C CW 1310 nm laser

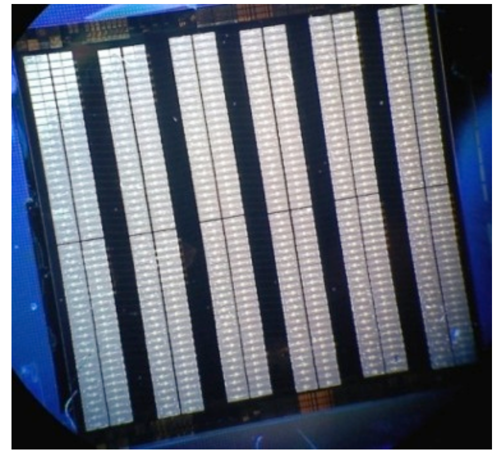
- Max fiber coupled output power: 5.5 mW/facet
- T_0: 80 °C
- Injection efficiency: 52 %



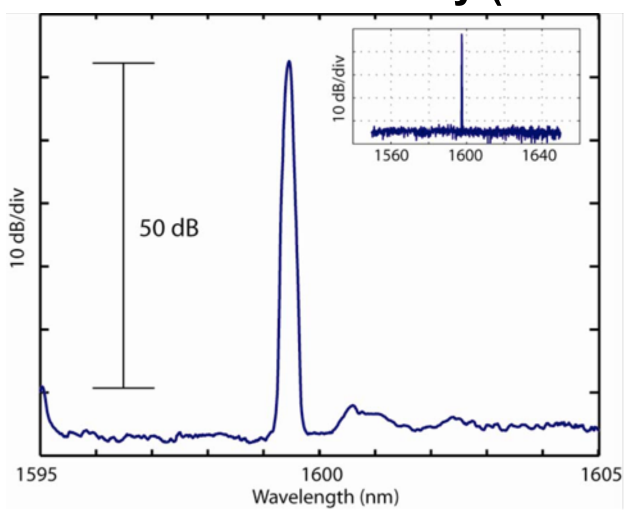
Chang et al., Optics Express 15(18), 11466, August (2007).

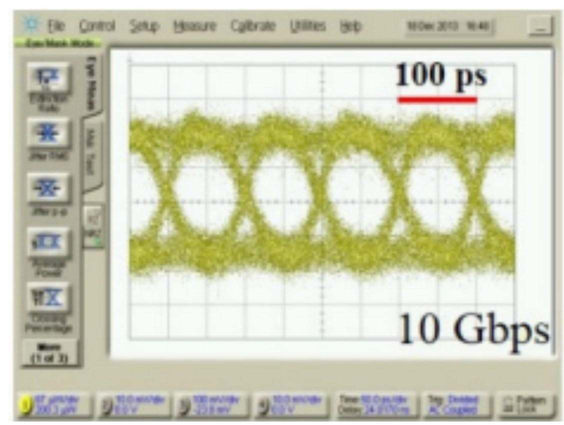
DFB Quantum Well Hybrid Silicon Lasers





Chip showing 300 DFB lasers with yield >95%



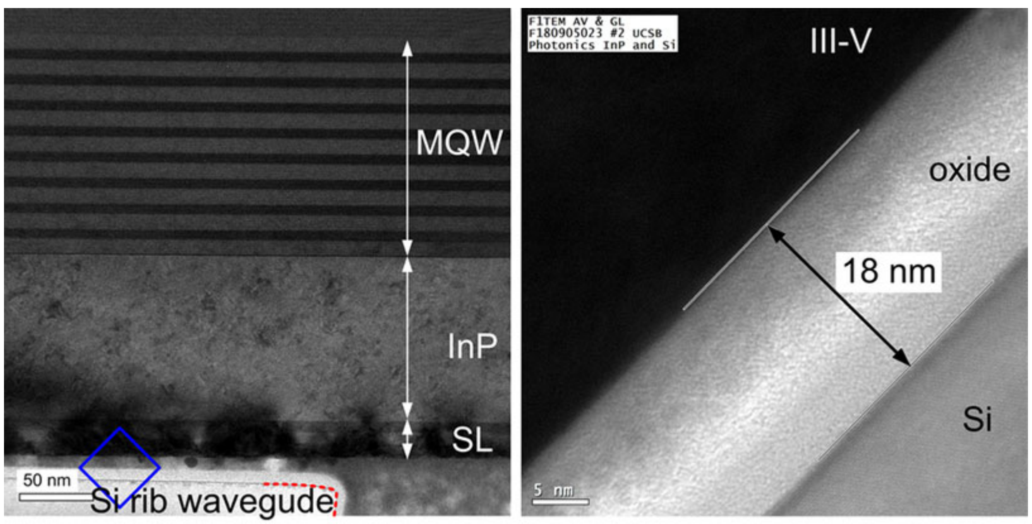


10Gbps direct modulation of a 200μm DFB laser

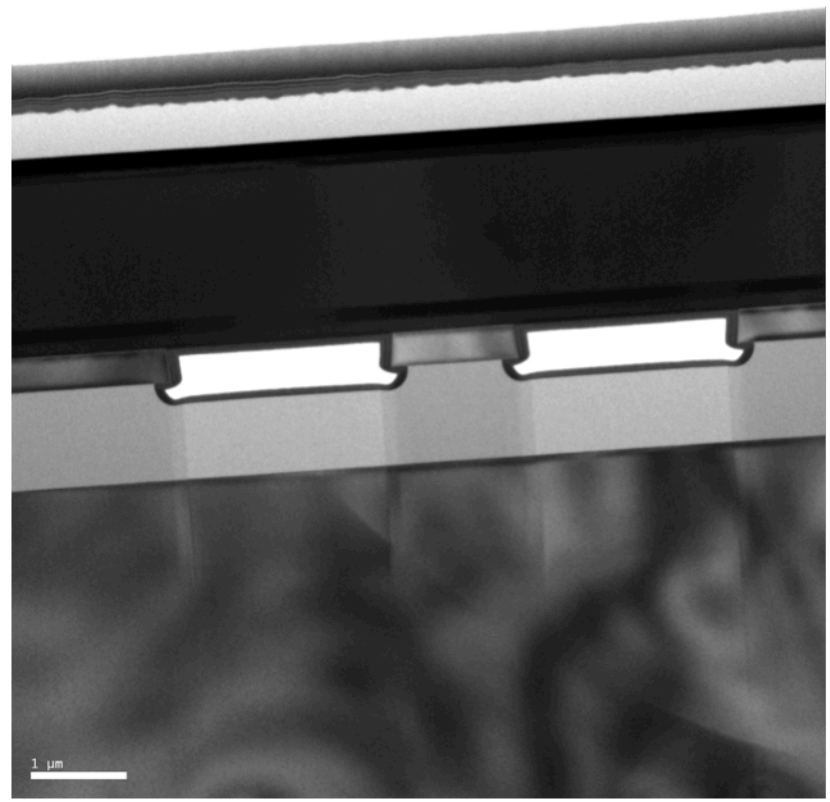
C. Zhang, et al. "Low threshold and high speed short cavity distributed feedback hybrid silicon lasers", Optics Express 2014

Aging: Bonded III-V on Si

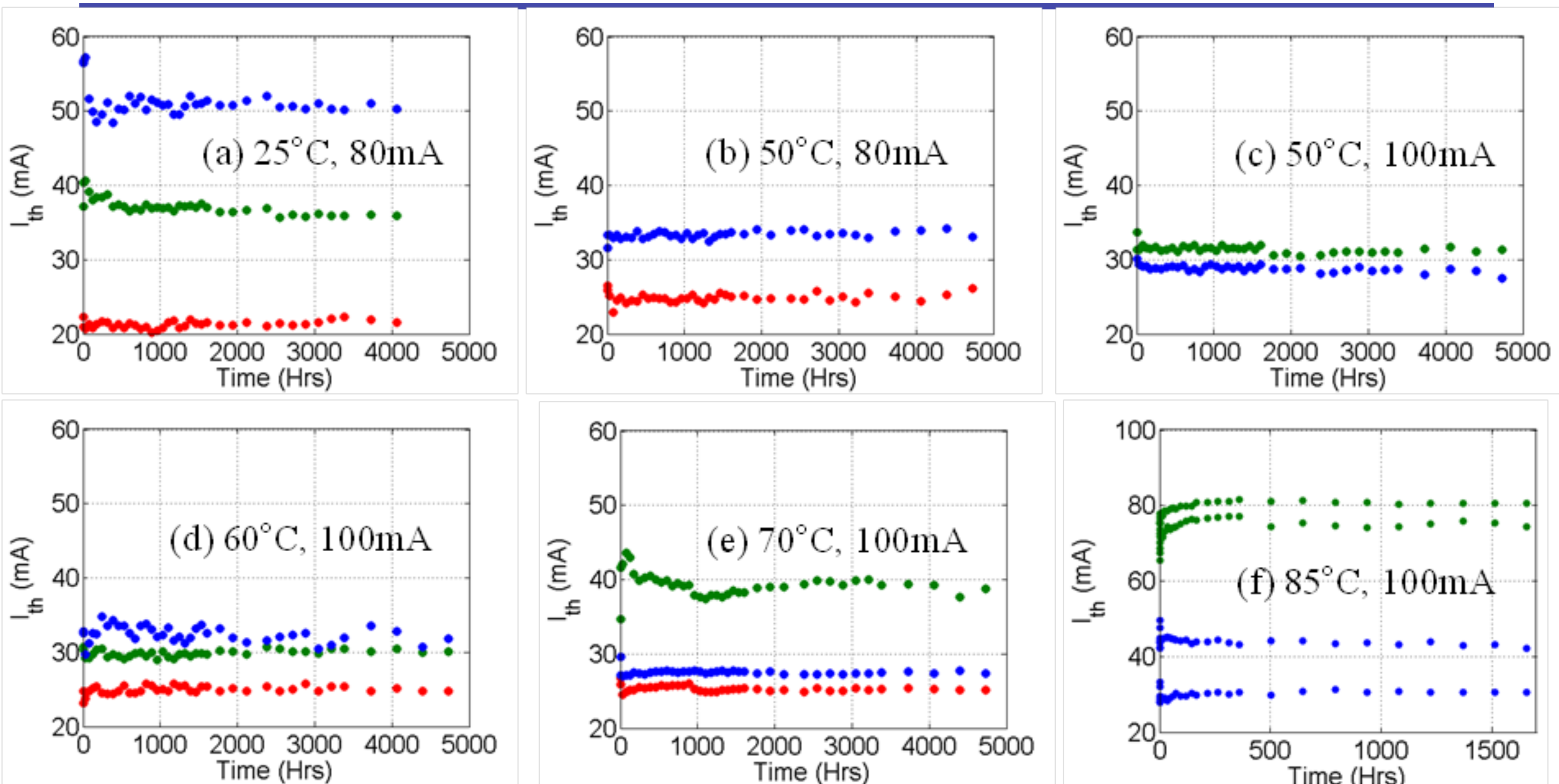
- Epitaxial growth on InP or GaAs followed by bonding to Si results in edge dislocations, which are not problem for laser lifetime.



a   b



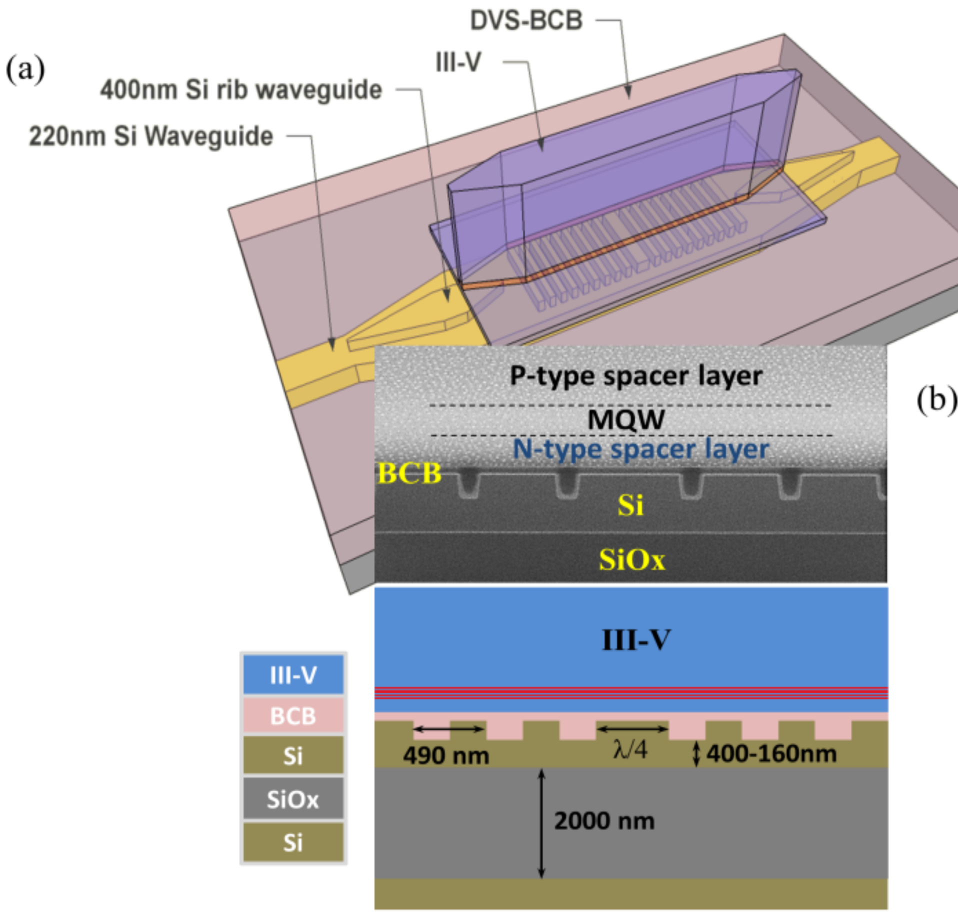
Temperature Dependence of DFB Aging

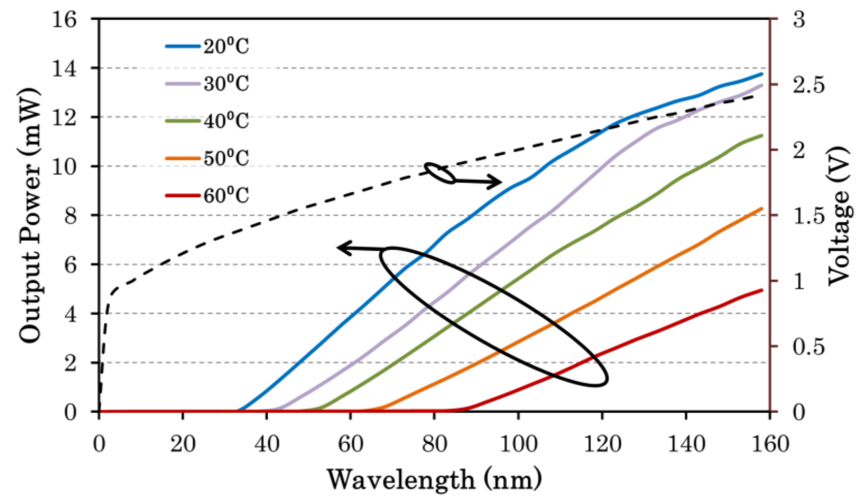


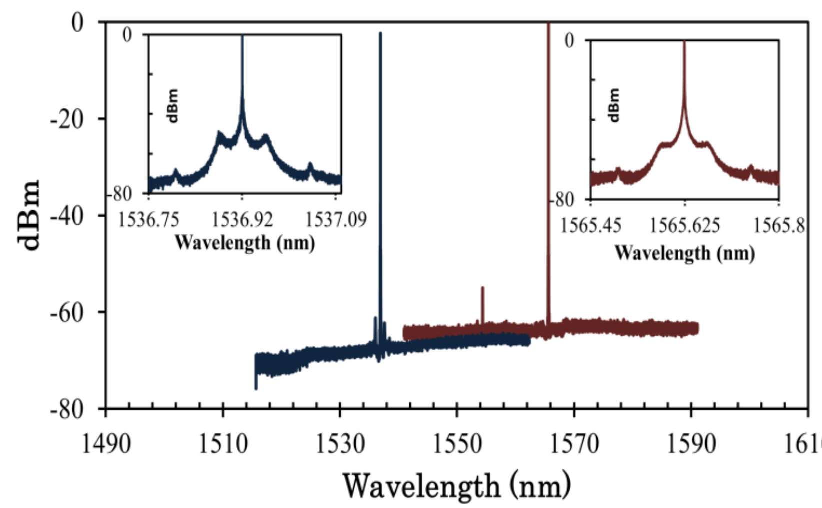
Time to reach 50% degradation in threshold current at 70°C is >40,000hrs

S. Srinivasan and J.E. Bowe
lasers," International Semiconductor Laser Conference (ISLC) 2012 , San Diego, 2012

DFB-type hybrid lasers



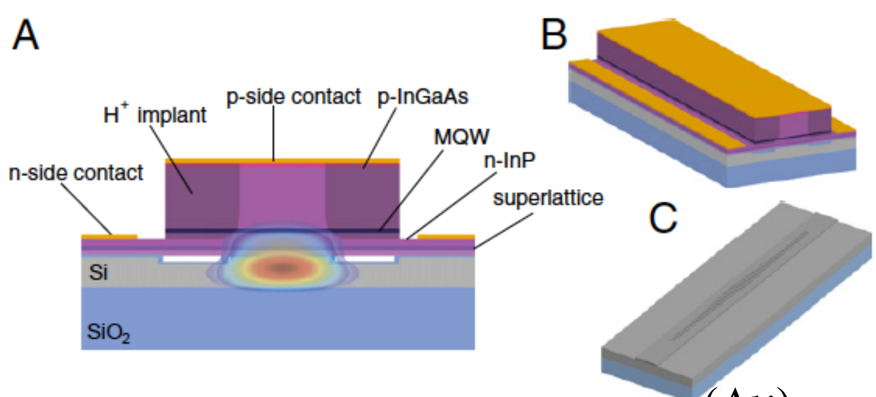


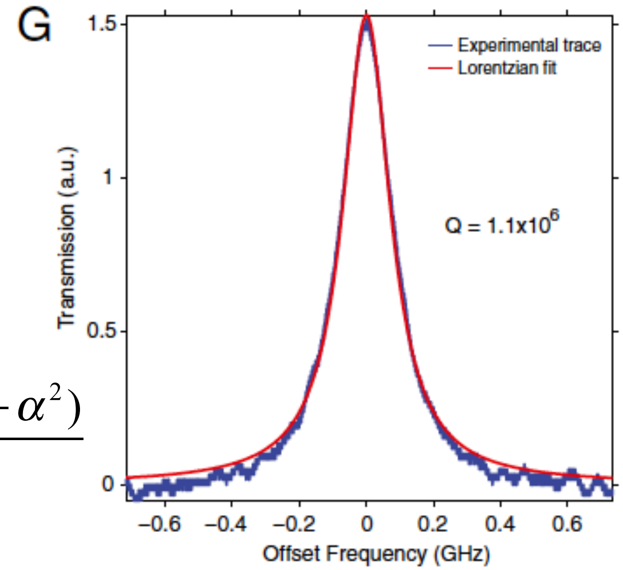


Keyvaninia, Opt Lett. 2013

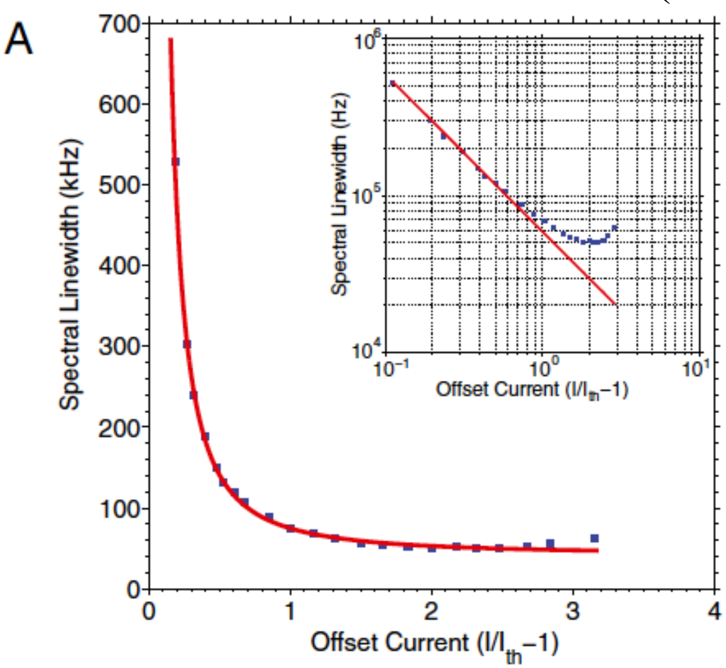
High-coherence semiconductor lasers based on integral high-*Q* resonators in hybrid Si/III-V platforms

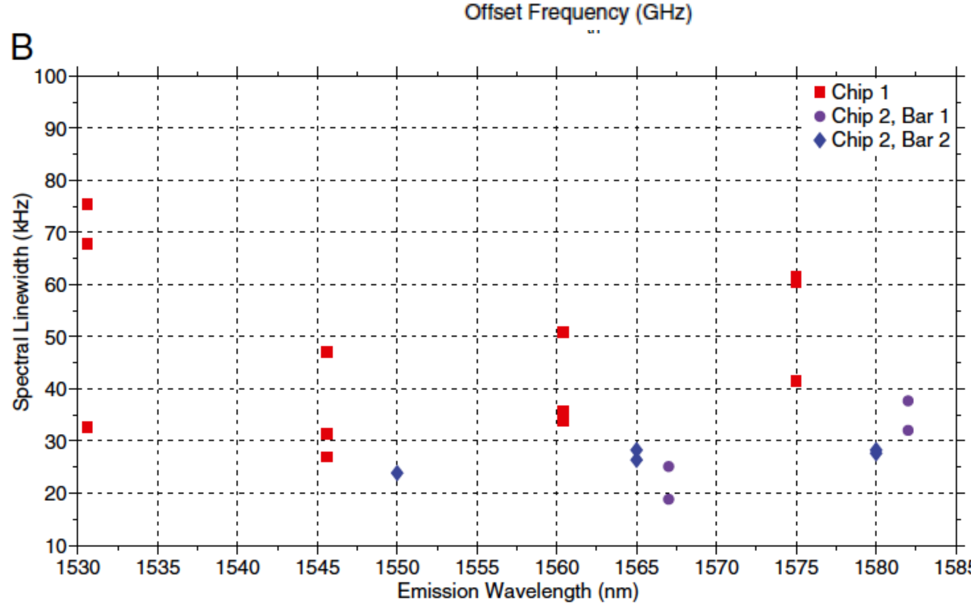
Christos Theodoros Santis[1], Scott T. Steger, Yaakov Vilenchik, Arseny Vasilyev, and Amnon Yariv[1]





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





LCI Membrane DFB Lasers

12:00 MB2 – "GaInAsP/InP Lateral-Current-Injection Membrane DFB Laser Integrated with GaInAsP Waveguides on Si Substrate"

Daisuke Inoue, Jieun Lee, Takuo Hiratani, Yuki Atsuji, Tomohiro Amemiya, Nobuhiko Nishiyama, Shigehisa Arai, *Tokyo Institute of Technology, Japan*

A lateral-current-injection membrane DFB laser integrated with GaInAsP waveguides and a detector was fabricated by butt-joint regrowth technique. As a result, a threshold current of 700 μA under room-temperature CW condition was obtained.

BCB Bonding

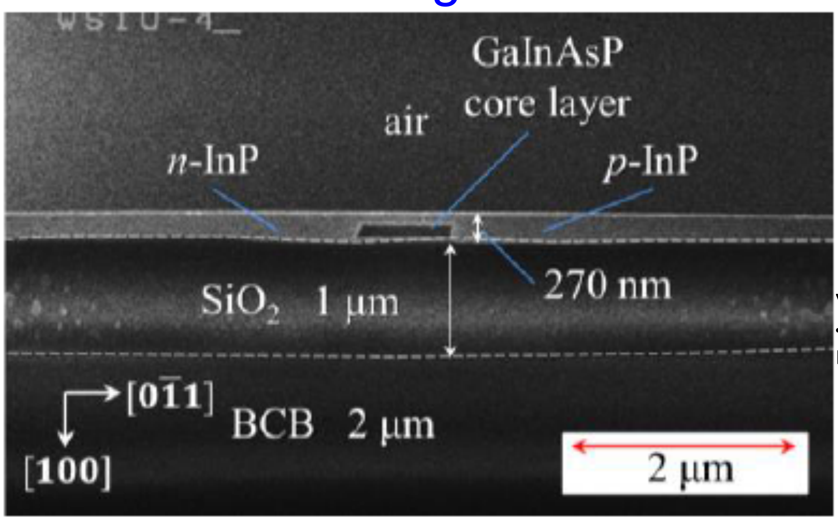
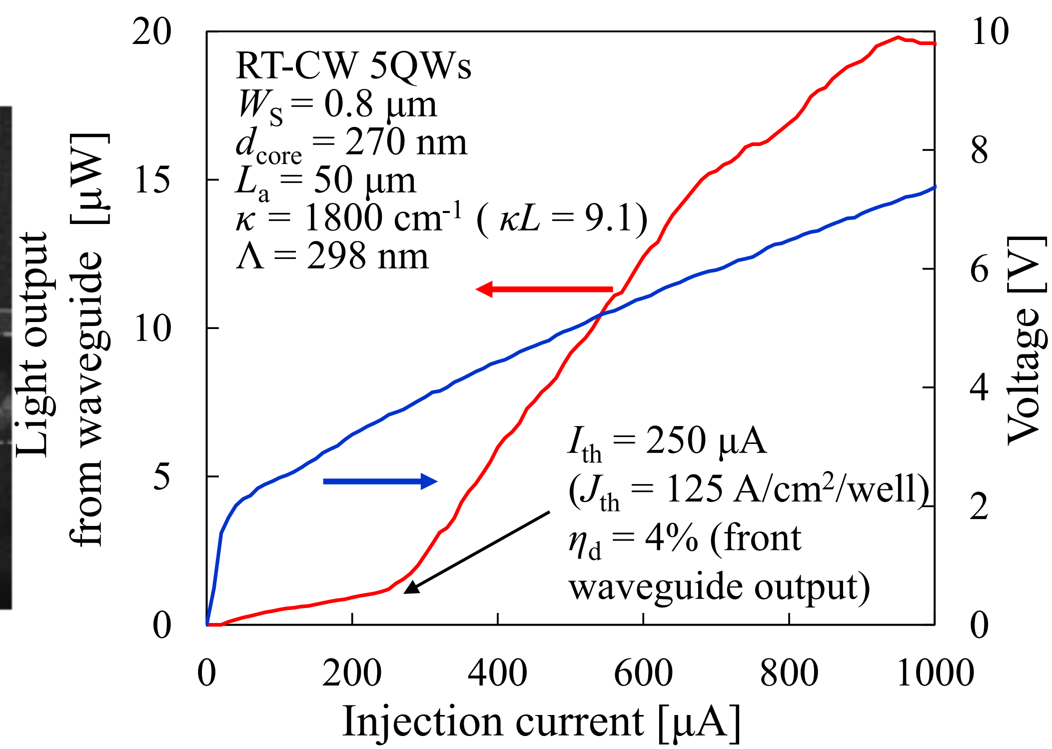


Fig. 2 A SEM image of cross sectional of GaInAsP

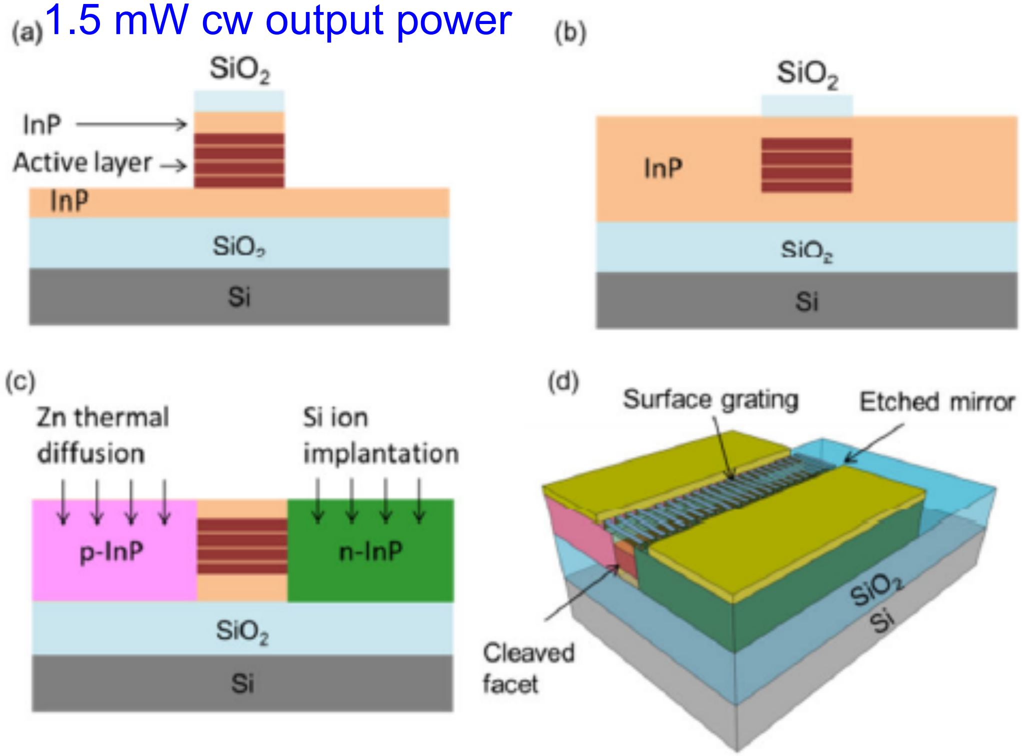


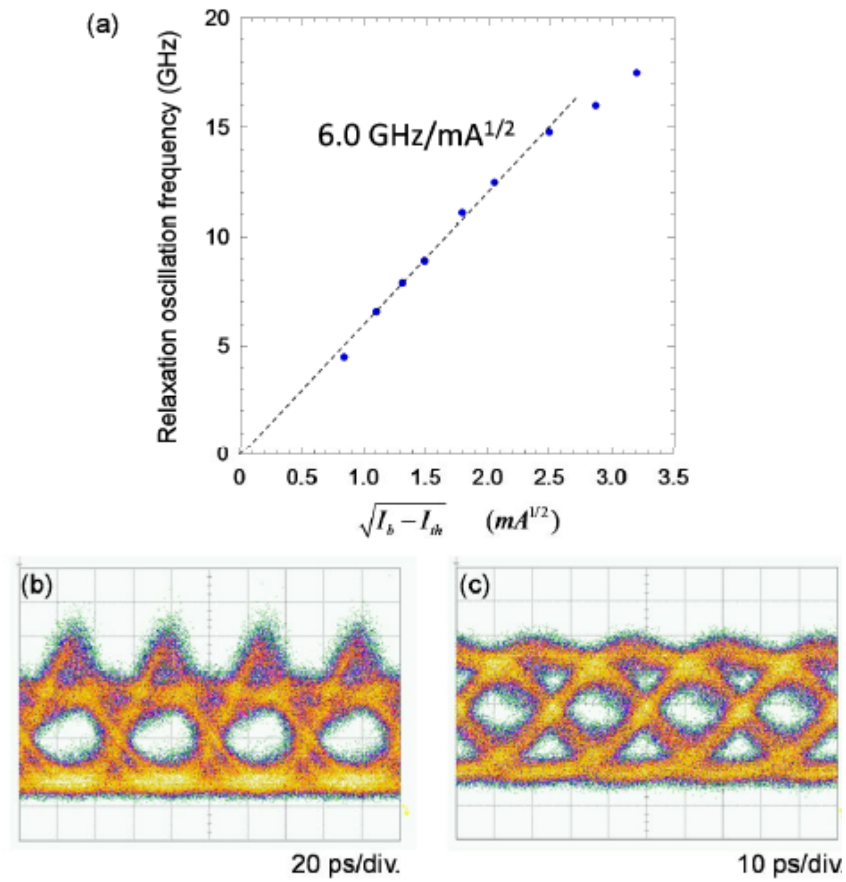
40-Gbit/s Direct Modulation of Membrane Buried Heterostructure DFB Laser on SiO_2/Si Substrate

Shinji Matsuo, Takuro Fujii, Koichi Hasebe, Koji Takeda, Tomonari Sato, and Takaaki Kakitsuka

NTT Photonics Laboratories, NTT Corporation

Bonded with oxygen plasma assisted bonding.
Then regrown with MOCVD.
1.5 mW cw output power

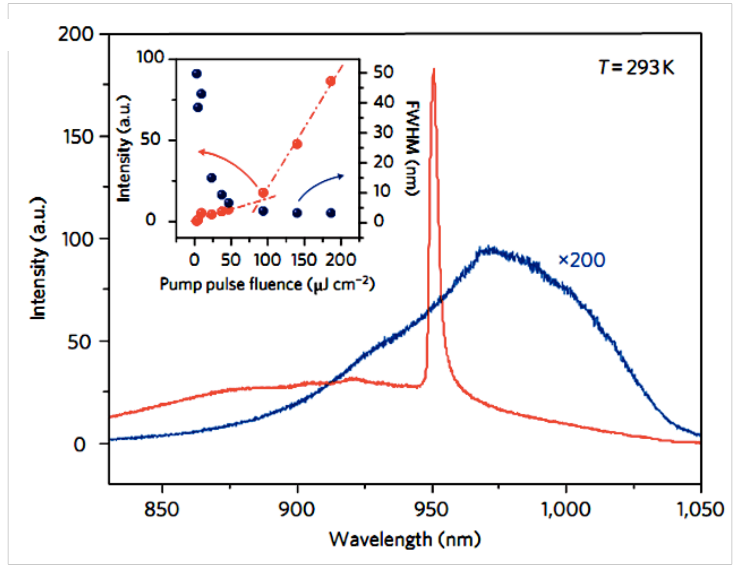


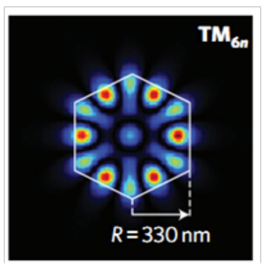


40 Gbit/s

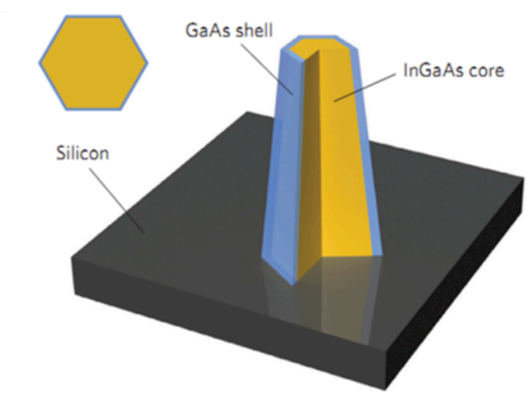
Nanolasers grown on silicon
C. Chang Hasnain (UC Berkeley)

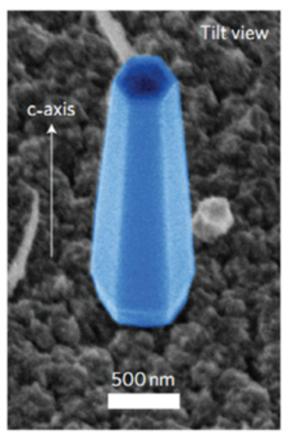
- III–V nanolaser grown on silicon;
- room-temperature operation;
- subwavelength volume;
- helically propagating cavity modes.

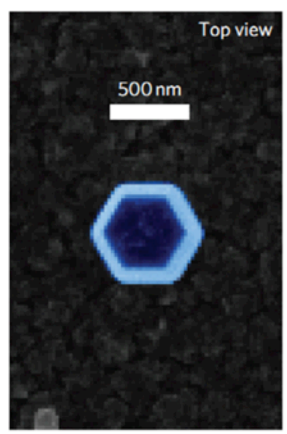


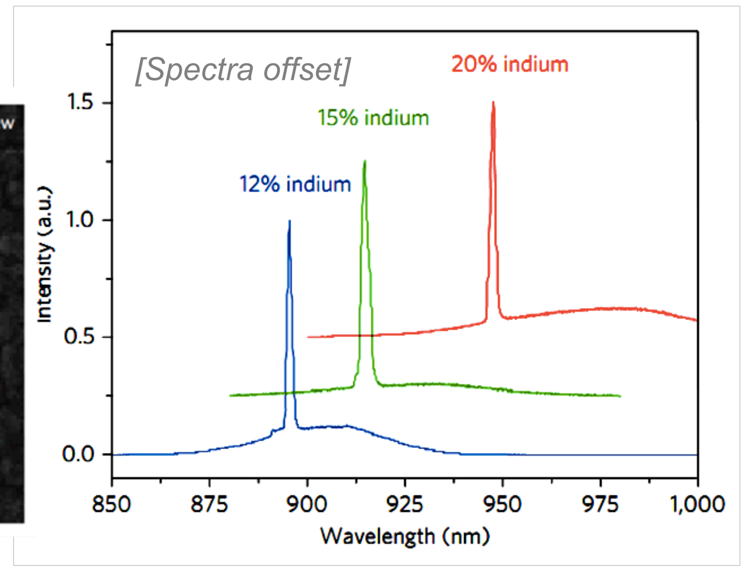


R. Chen et al.,
Nat. Photon. 2011



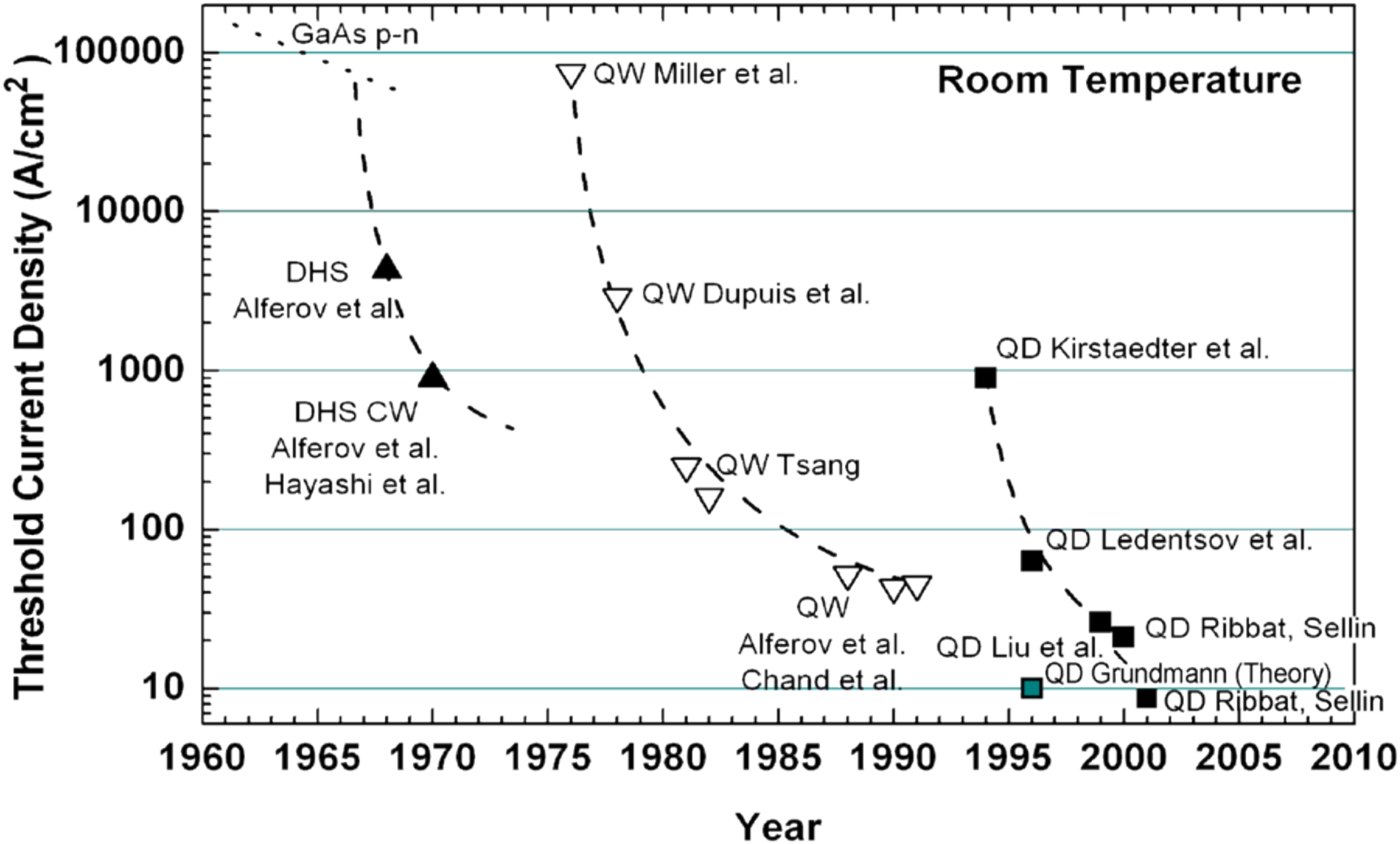






Quantum Dot Lasers

Threshold Current Densities of Semiconductor Lasers



QD-based photonic devices are less power hungry

Early work on quantum dot lasers

Theoretical work

• The first proposal :	Arakawa (1982)
• Reduced temperature dependence:	Arakawa (1982)
• Higher speed modulation :	Arakawa, Yariv (1984)
• Zero-a-parameter, low-chirping :	Arakawa, Yariv (1984)
• Lower threshold current density :	Asada/Suematsu (1986)
• p-doping:	Arakawa (1982, 1991)
• Tunneling injection:	Arakawa (1992)

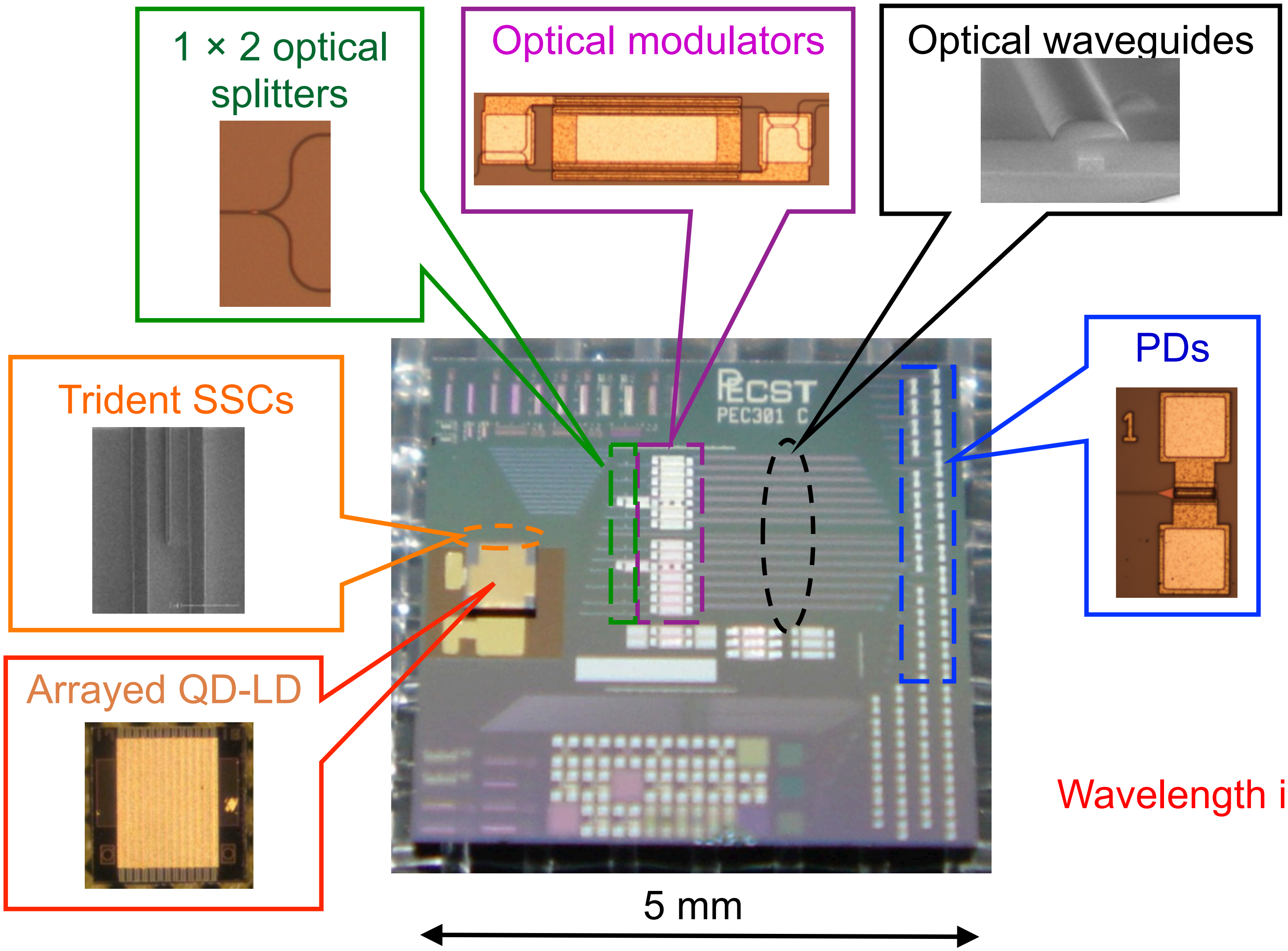
$$f_r = \frac{1}{2\pi}\sqrt{\frac{\left(\frac{\partial g}{\partial n}\right)\uparrow}{\tau_P} S}$$

$$\Delta\nu = (1+\alpha^2)\Delta\nu_{St} \quad \left(\alpha = \frac{\partial\chi_R/\partial n}{\partial\chi_I/\partial n}\right) \longrightarrow 0$$

High magnetic field experiment up to 30Tesla

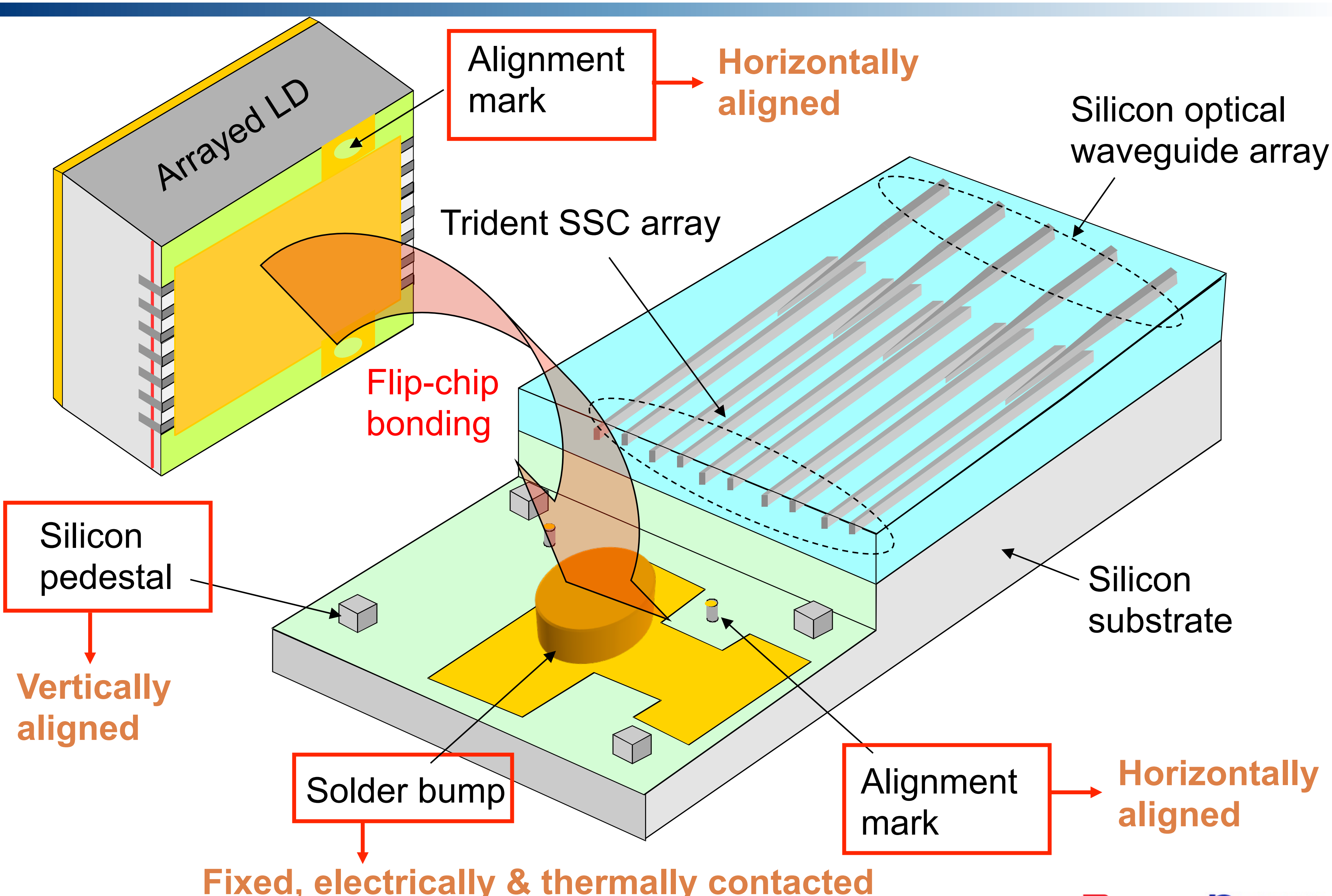
Enhanced modulation speed	Arakawa, Vahala, Yariv (1984-86)
Reduced a-parameter	Arakawa, Vahala, Yariv (1984-86)

QD lasers on silicon optical interposers



Wavelength is 1.3mm.

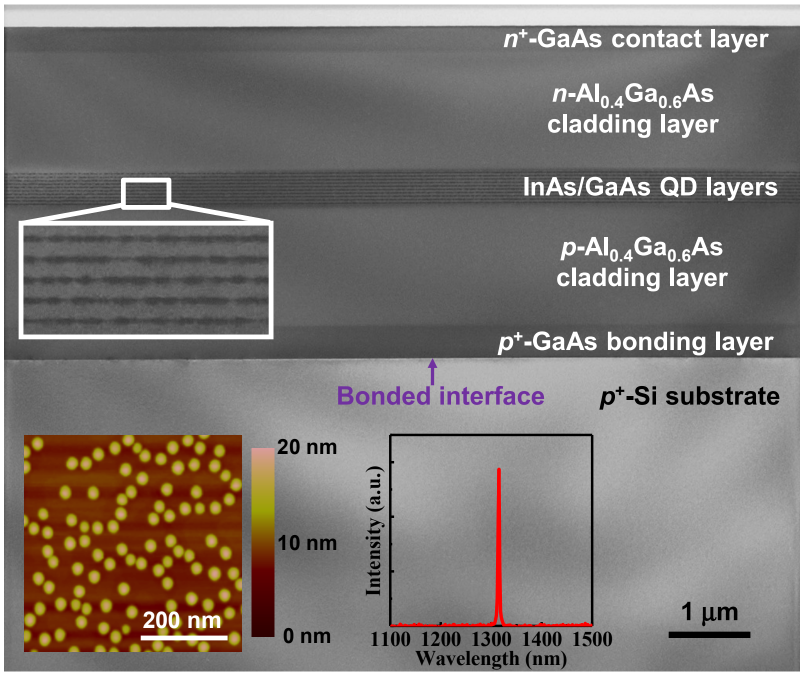
Hybrid QD laser array on silicon by flip-chip bonding



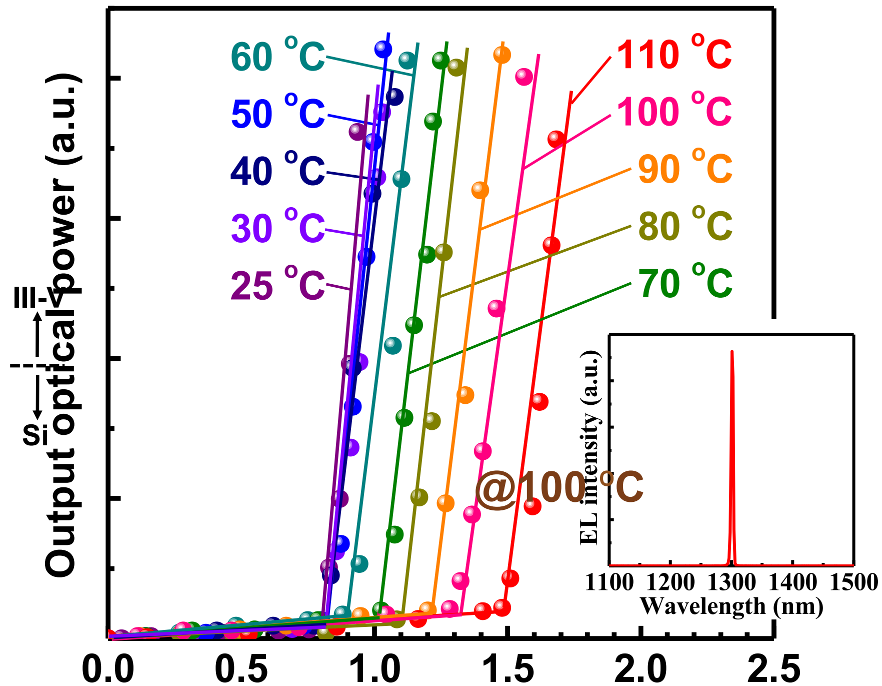
THE UNIVERSITY OF TOKYO

PECST PETRA

Hybrid QD laser on silicon by wafer bonding technique



K. Tanabe et al, Sci. Rep. ***2****, 349 (2012)*



- Lasing at telecom *O*-band 1.3 mm (GS transition of InAs QDs)
- Realized lasing operation at over 100 ºC

K. Tanabe et al, Appl. Phys. Express 6, 082703 (2013)

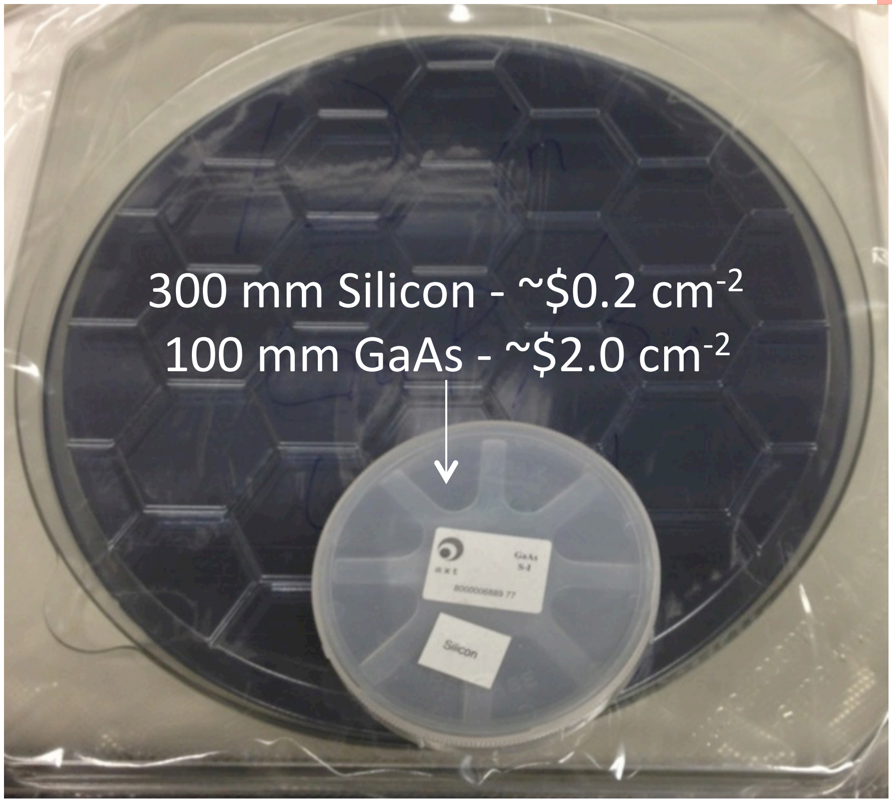
THE UNIVERSITY OF TOKYO

PECST PETRA

III-V Laser Growth on Silicon

Table 1. Approximate growth substrate minimum cost and maximum size [1]

	InAs	*InP*	*GaAs*	*SOI*	*Si*
Substrate Cost ($/cm^2)	18.25	4.55	1.65	1.30	0.20
Maximum size (mm)	76	150	200	450	450



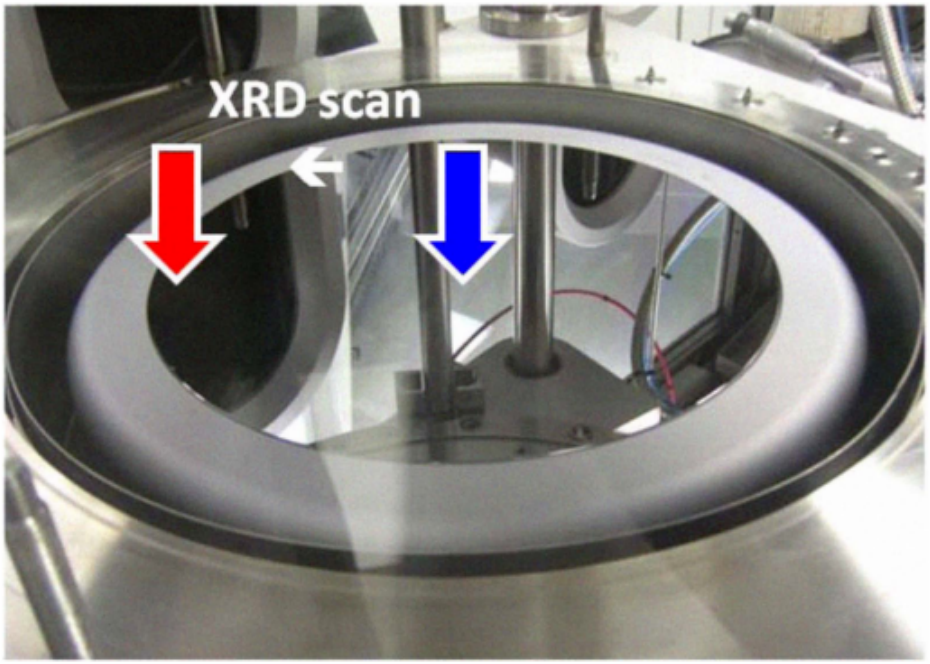
(Courtesy of Dr. Jordan Lang, Yale)

- CMOS processing of photonics is already happening, yet high cost and small size of III-V wafers remains an issue.
- **Goal:** Grow III-V lasers on larger and cheaper silicon substrates without sacrificing laser performance for lower cost and higher throughput.

[1] Bowers, John E., et al. "A Path to 300 mm Hybrid Silicon Photonic Integrated Circuits." OFC 2014

III-V growth on 300 mm Silicon Wafers

GaP on 300 mm Silicon by NAsP III/V GmbH using MOVPE (AIXTRON CRIUS CCS reactor)



B. Kunert *et al.* *69th Device Research Conference,* Santa Barbara (2011)

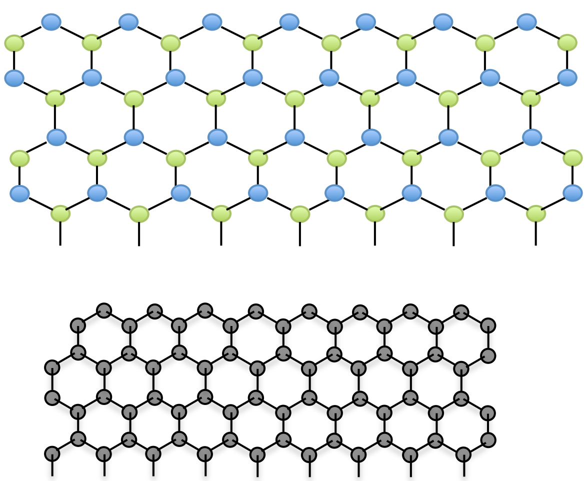
World's 1st 12" GaAs on Si epiwafer by IQE, using MBE (Veeco Gen-2000 reactor).

(Courtesy of Amy Liu, IQE Inc.)

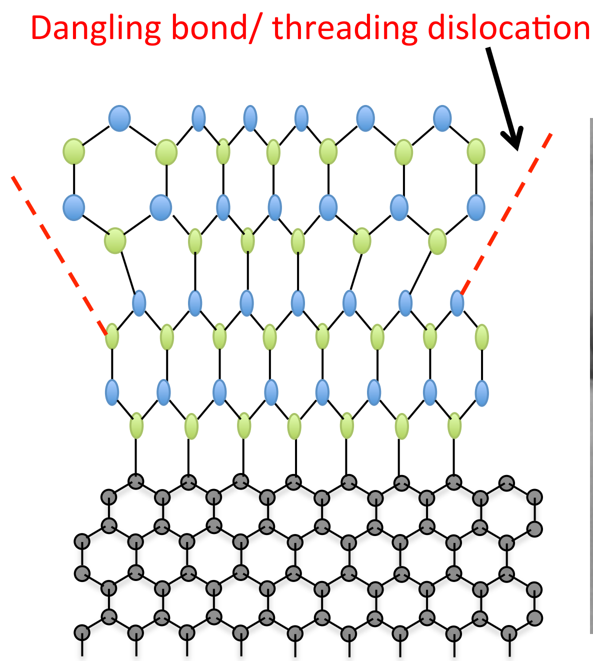
III-V Laser Growth on Silicon

- 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.

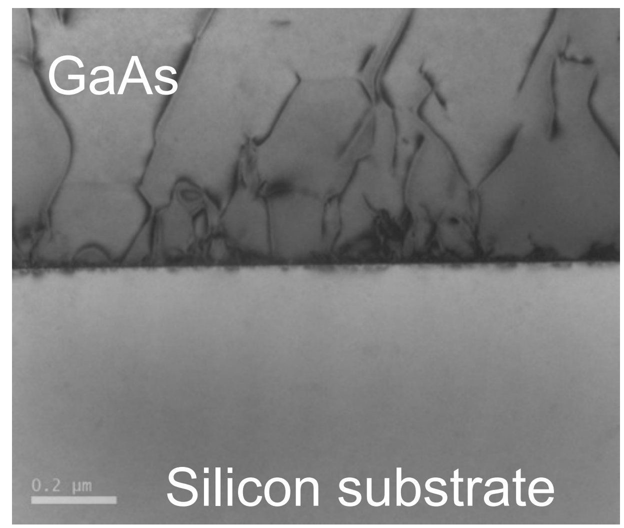
Bulk GaAs: a=0.565 nm



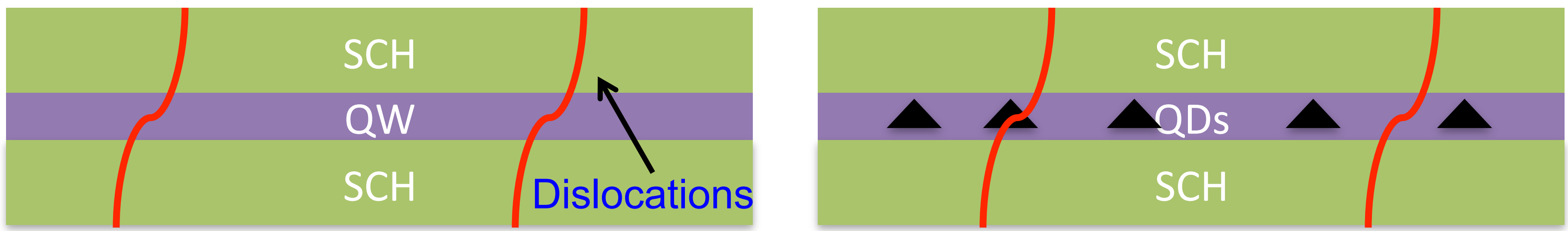
Bulk Si: a=0.543 nm



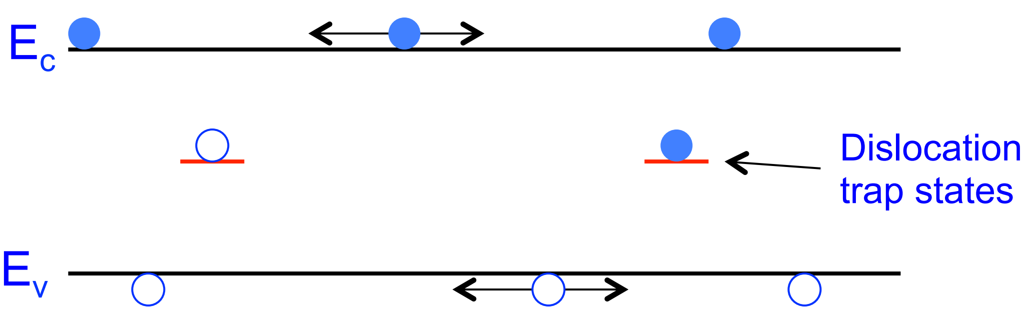
Si substrate



Solution: Use Quantum Dots!



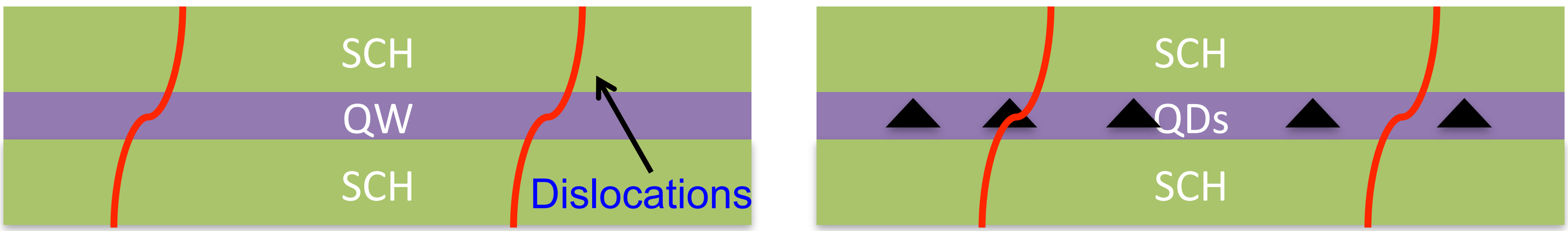
In-plane band diagram:



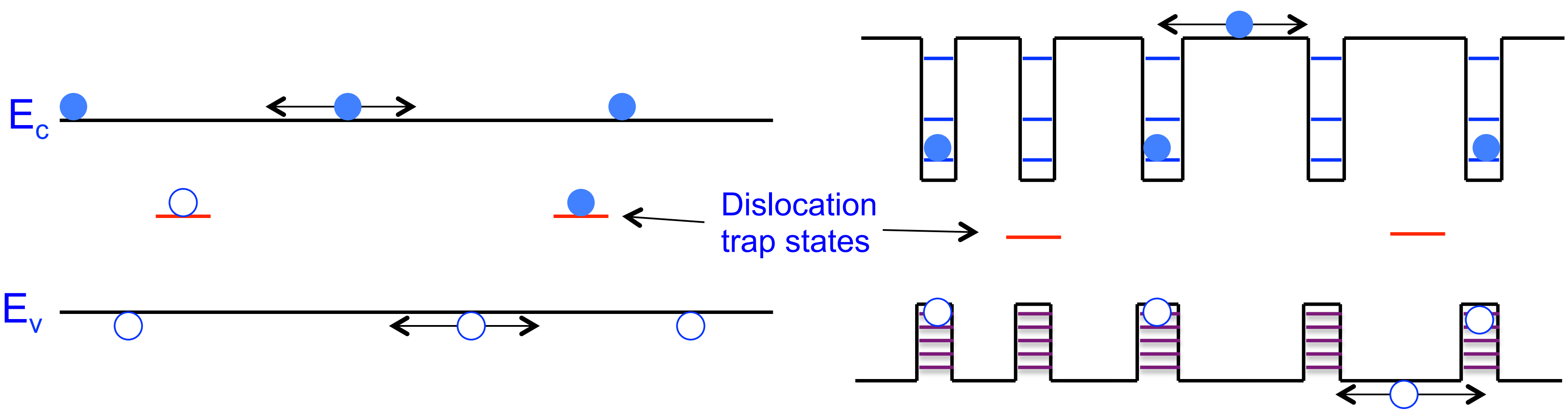
Solution: Use Quantum Dots!

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.

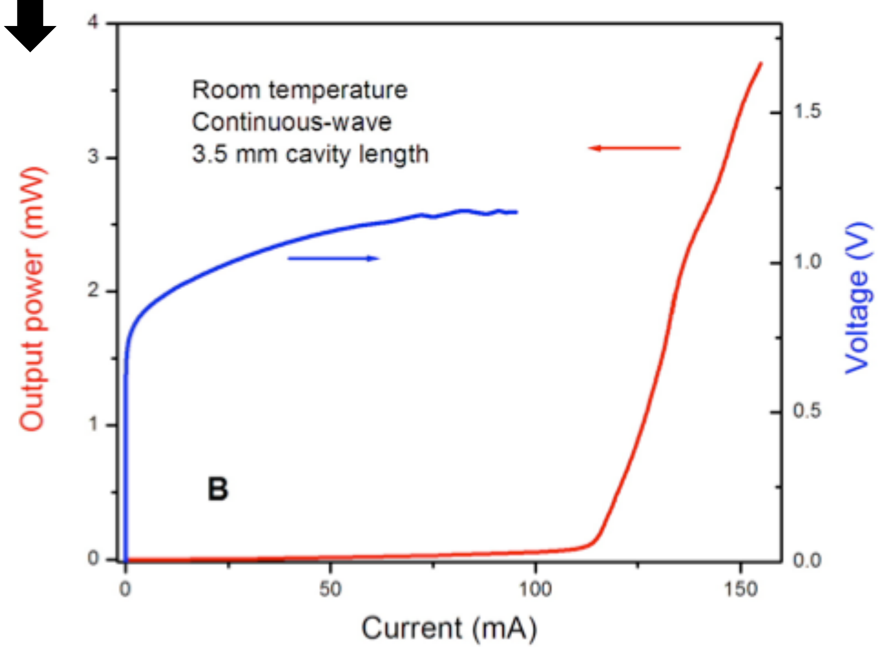


In-plane band diagram:

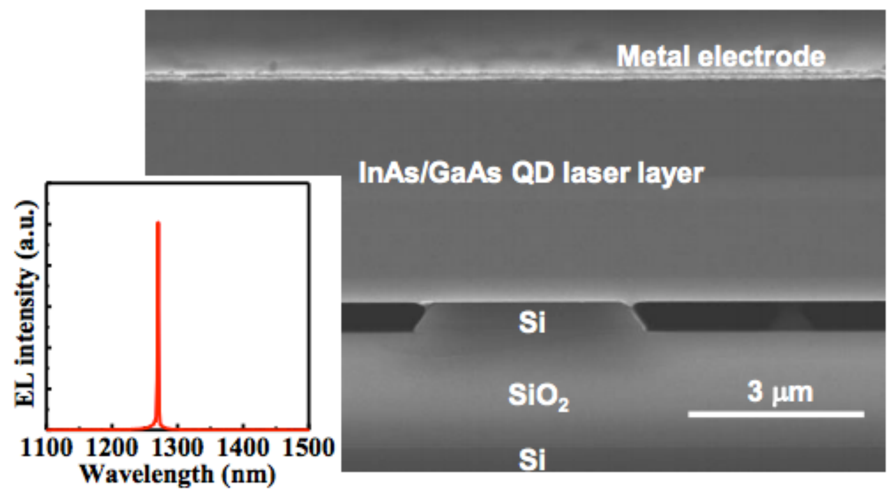


History of Quantum Dot Lasers on Silicon

- 1991 – "Semiconductor Structure for Optoelectronic Components with Inclusions" (Jean Gerard & Claude Weisbuch), U.S. Patent No. 5,075,742
- 1999 – First laser operation with $In_{.4}Ga_{.6}As$ QDs on Si@ 1 µm. Pulsed at 80 K (Michigan)
- 2000 – RT CW operation of quantum-dot like laser on Si @ 0.854 µm (Nagoya IT)
- 2005 – RT Pulsed operation with $In_{.5}Ga_{.5}As$ QDs on Si@ 1 µm (Michigan)
- 2011-Present – RT Pulsed & CW operation with wafer bonded InAs QDs on Si (U. of Tokyo)
- 2011-Present – RT Pulsed & CW operation with InAs QDs on Si & Ge/Si @ 1.3 µm (UCL)

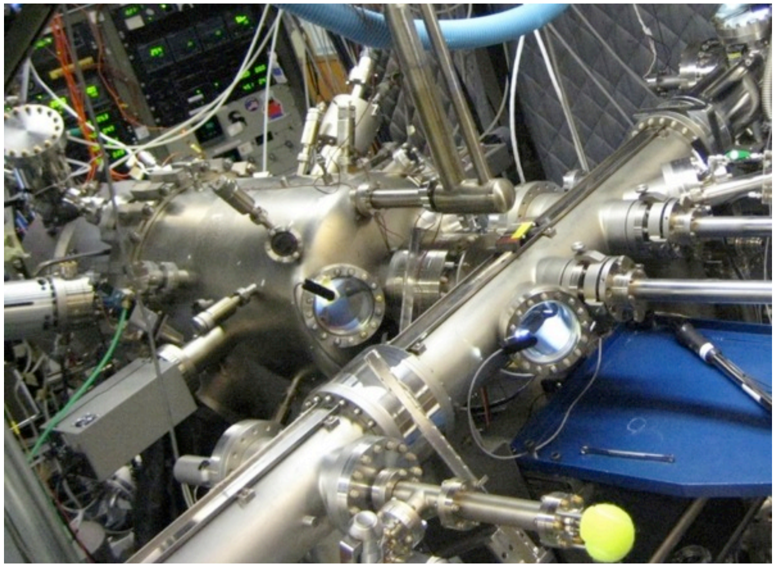


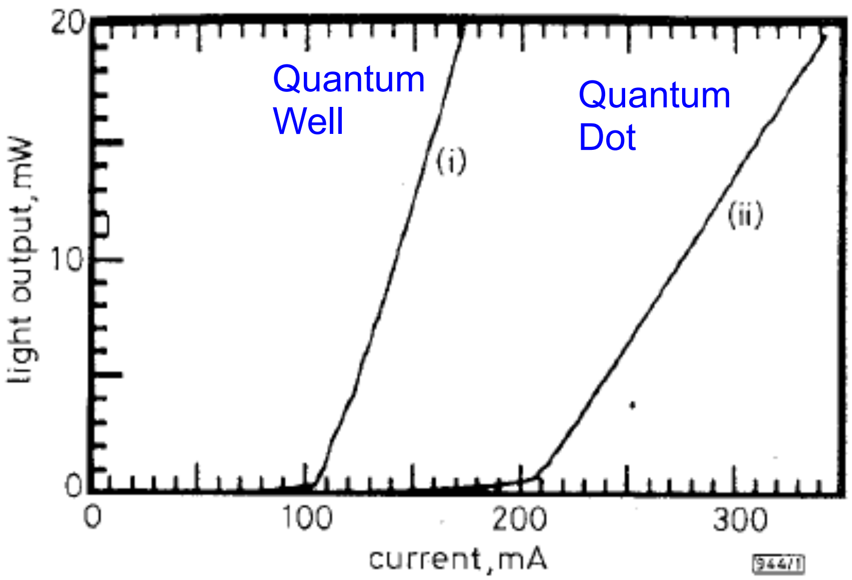
Lee, Andrew, et al. "Continuous-wave InAs/GaAs quantum-dot laser diodes monolithically grown on Si substrate with low threshold current densities." Optics express 20.20 (2012): 22181-22187.



Tanabe, Katsuaki, and Yasuhiko Arakawa. "1.3 µm InAs/GaAs Quantum Dot Lasers on SOI Waveguide Structures." CLEO: Science and Innovations. Optical Society of America, 2014.

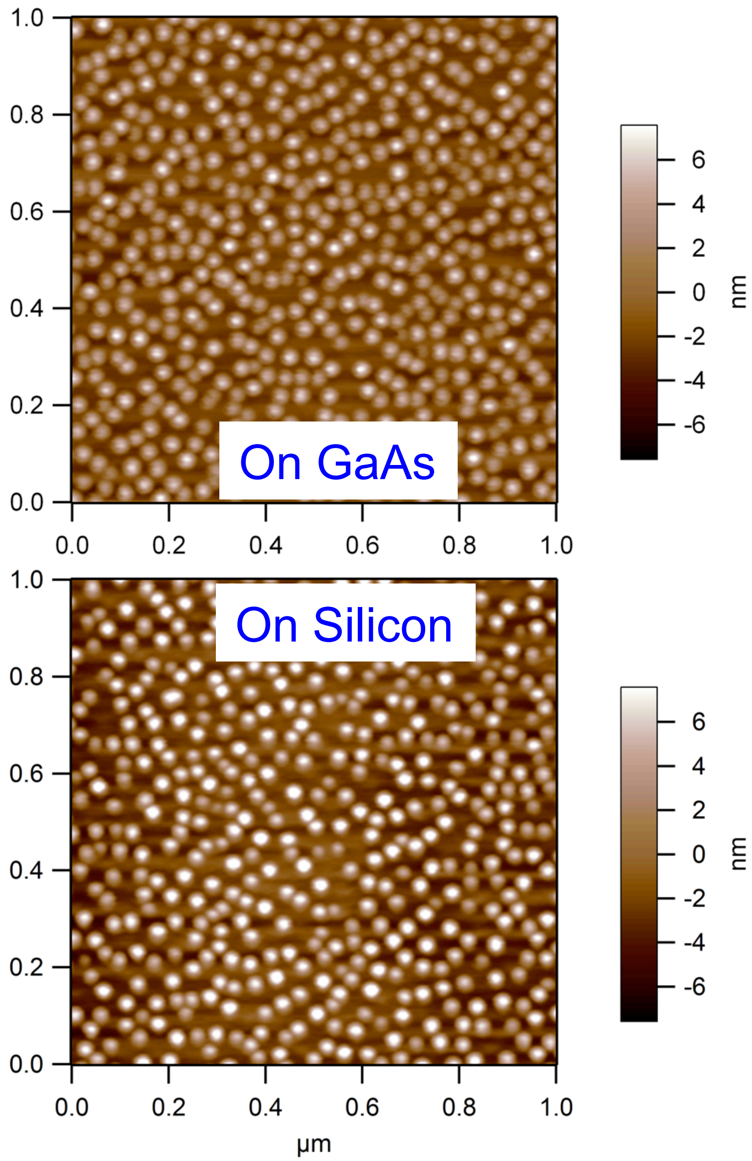
UCSB Quantum Dot Growth



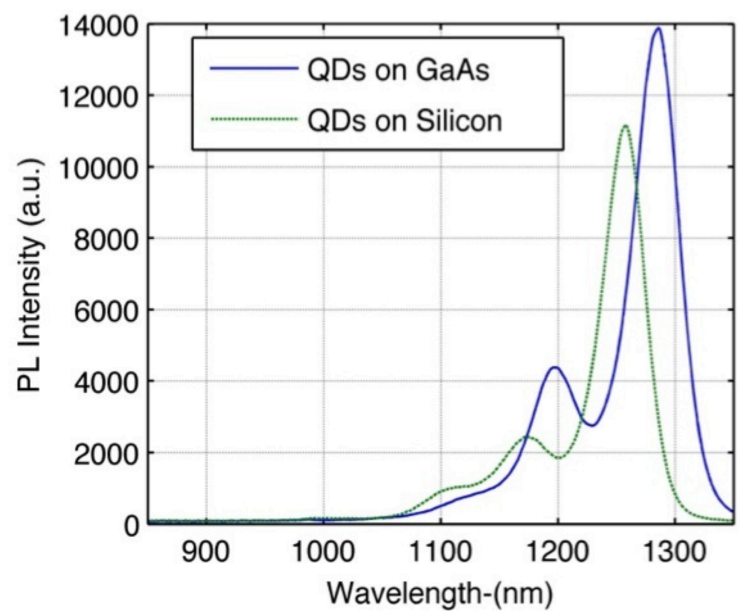


- 1993 – First ever self assembled InGaAs quantum dots reported by D. Leonard, S. Denbaars, P. Petroff et al. *(Appl. Phys. Lett.* ***63)***
- 1995 – First 1.3 µm photoluminescence from InGaAs by R. Mirin, A. C. Gossard, J. E. Bowers et al. *(Appl. Phys. Lett.* ***67****)*
- 1996 - R. P. Mirin, A. Gossard, and J. E. Bowers, "Room Temperature Lasing From InGaAs Quantum Dots," Electronics Letters, 32 (18), 1732,
- 2014 – High Performance continuous wave 1.3 µm quantum dot lasers on silicon by A. Y. Liu, A. C. Gossard, J. E. Bowers et al. *(Appl. Phys. Lett* ***104****)*

MBE growth of InAs Quantum Dots



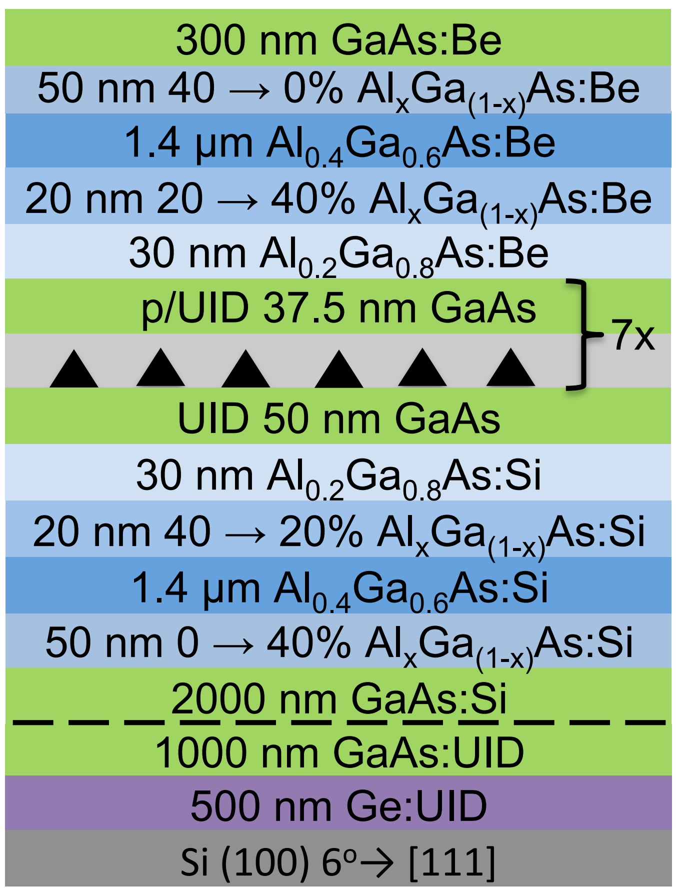
- InAs/GaAs self assembled quantum dots by Stranski-Krastanov layer/island growth mode
- Average quantum dot density: **~5x10^{10} cm^{-2}**
- PL peak around 1285nm on GaAs and 1255nm on Si
  - 47nm/35 meV PL linewidth

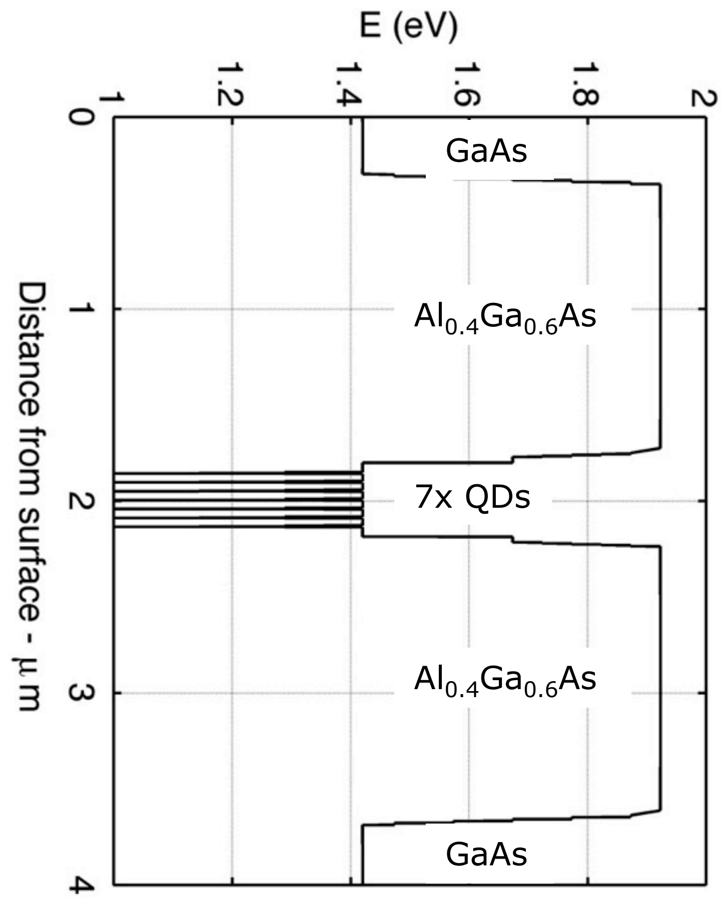


- A. Y. Liu *et al*, "MBE growth of P-doped 1.3 µm InAs quantum dot lasers on silicon". *J. Vac. Sci. Technol. B.* 2014

GRINSCH QDLs on Ge/Si

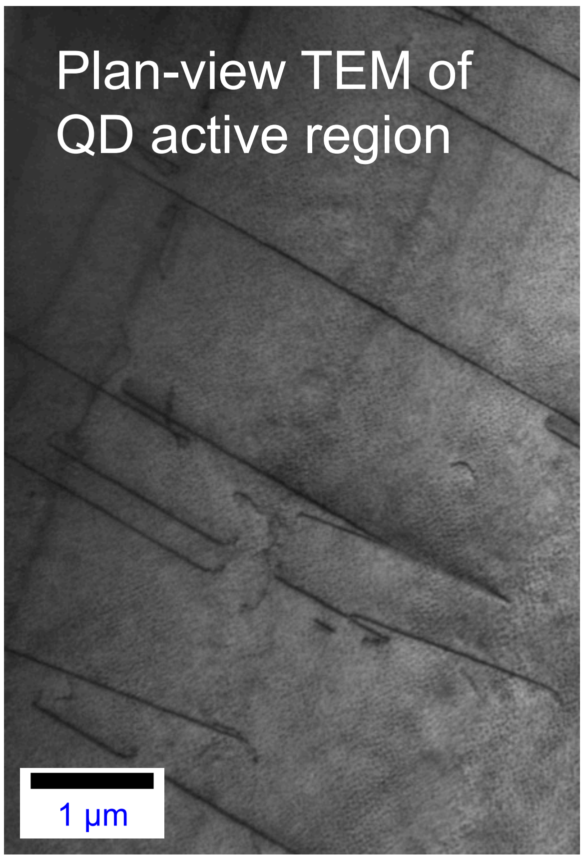
- Two graded index separate confinement heterostructure (GRINSCH) lasers were grown on GaAs-on-Ge-on-Si virtual substrates provided by IQE Inc.
- In one wafer, the QD barrier layers were p-doped with beryllium to improve T_0.

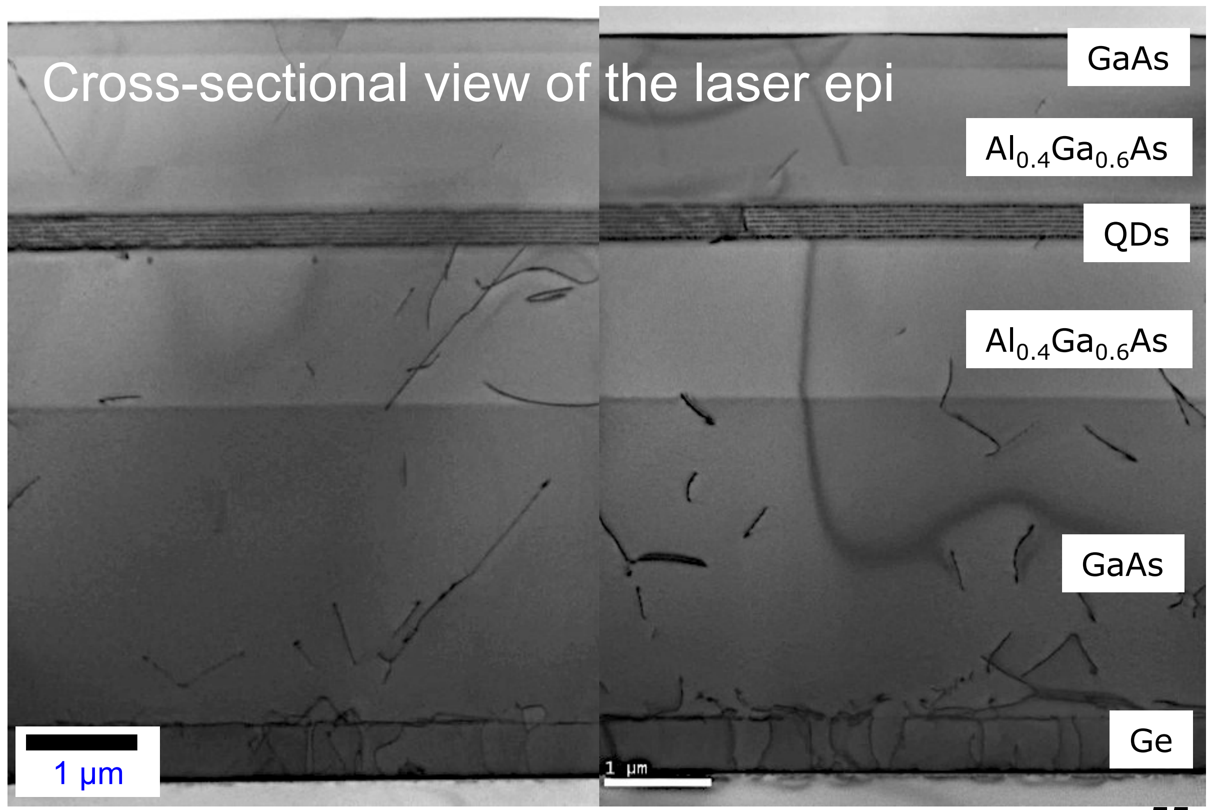




GRINSCH QDLs on Ge/Si

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





GRINSCH QDLs on Ge/Si

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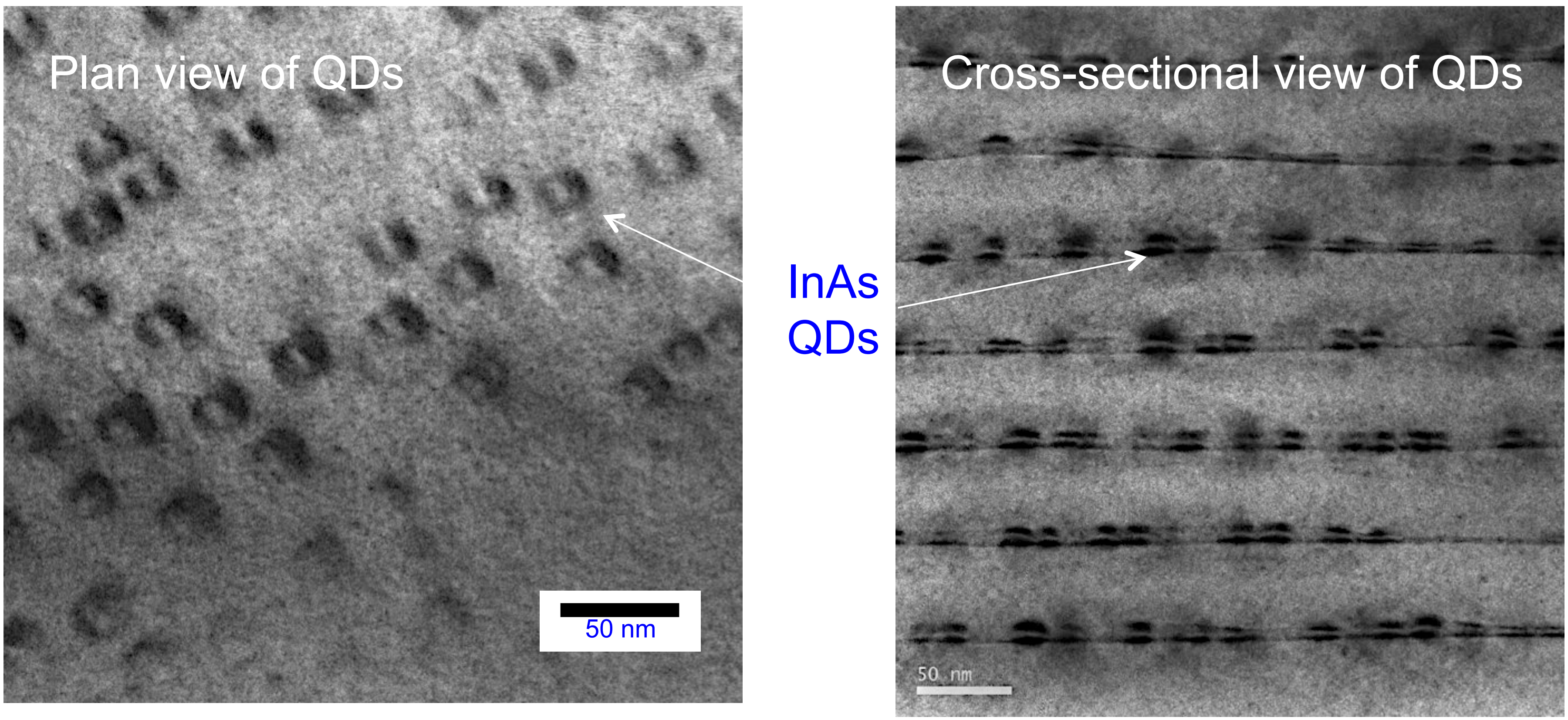
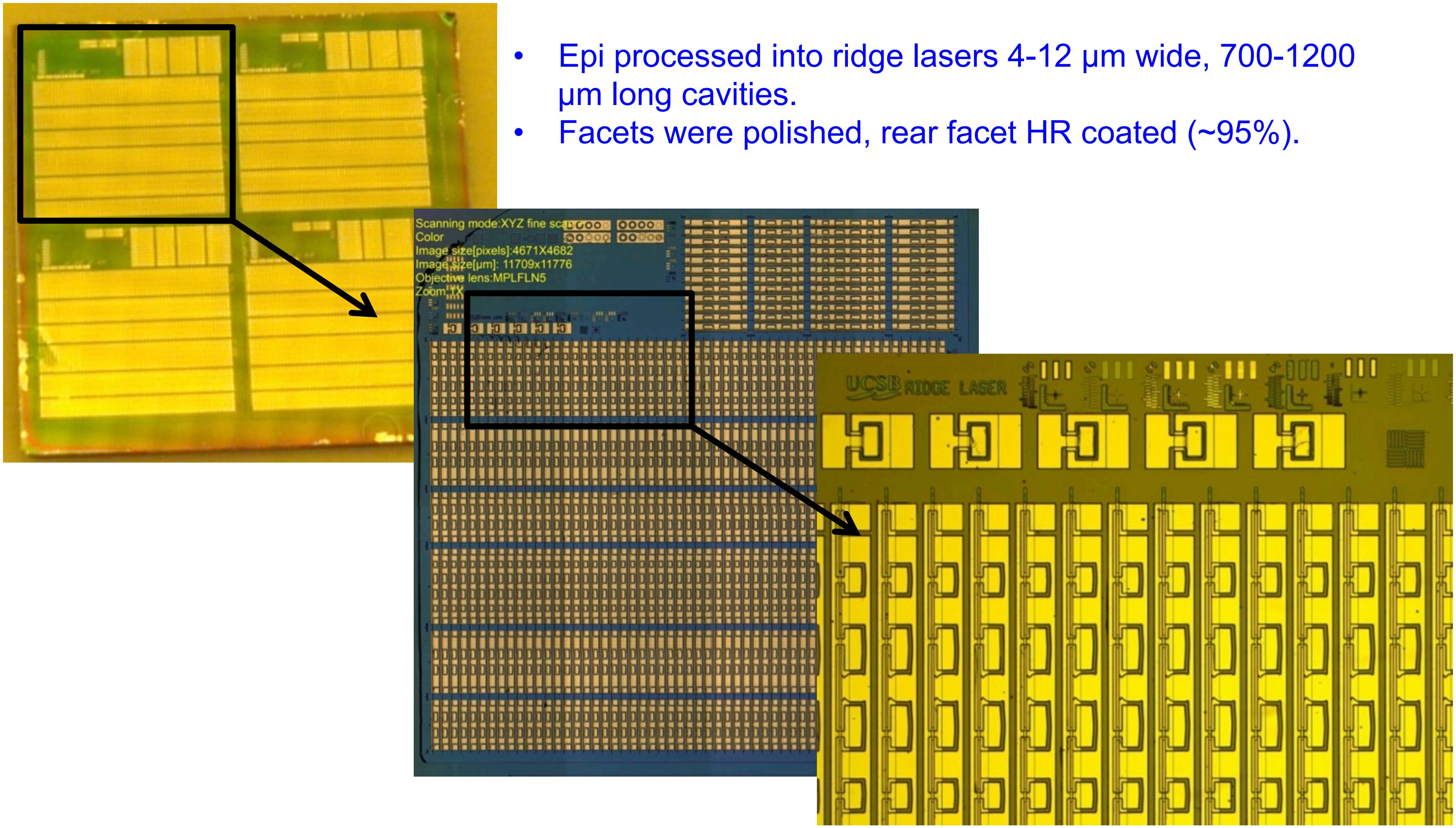


UCSB

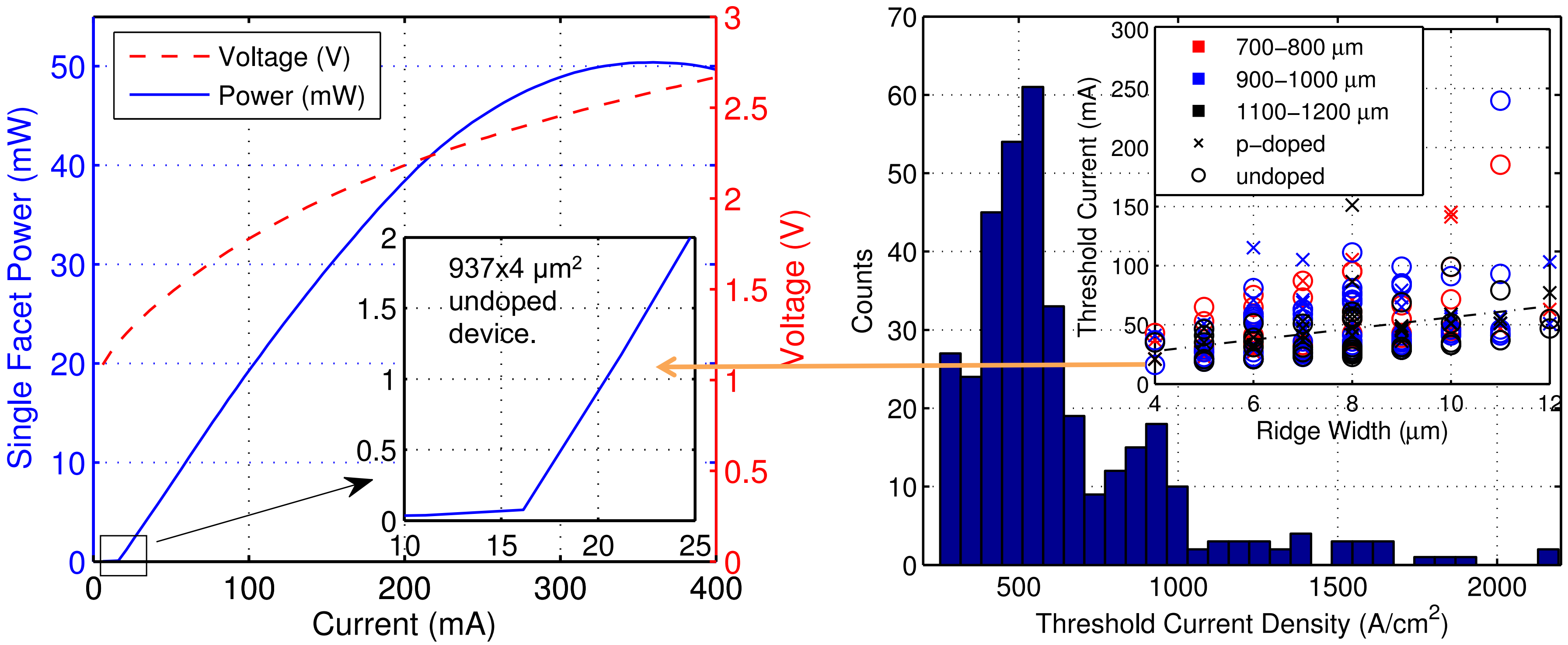
Device Fabrication



- Epi processed into ridge lasers 4-12 μm wide, 700-1200 μm long cavities.
- Facets were polished, rear facet HR coated (~95%).

Continuous Wave Threshold Data

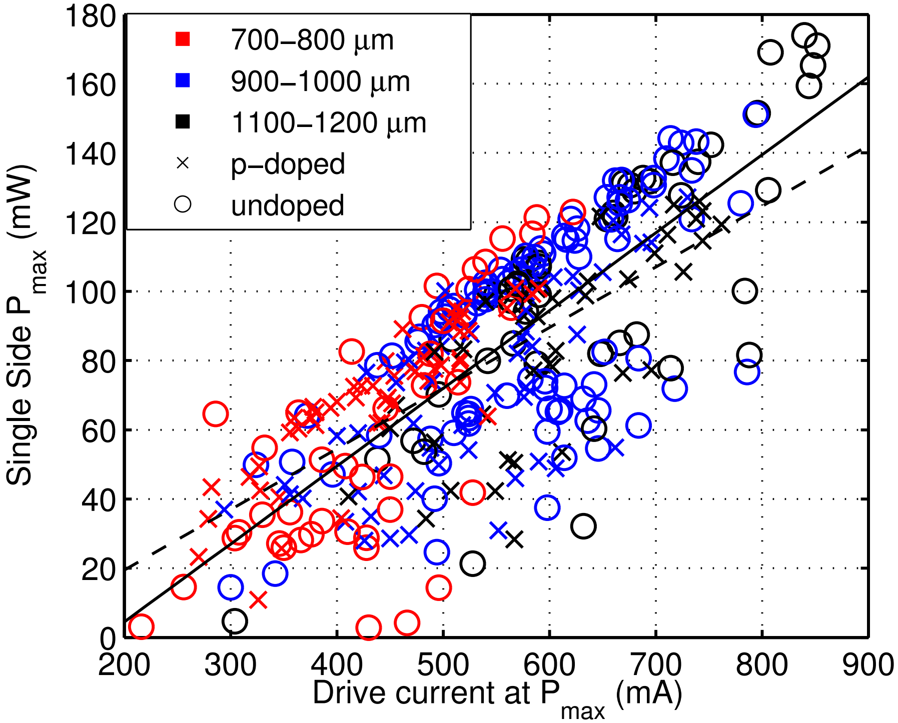
- Over 300 working lasers measured from two wafers.
- Uniform threshold current densities across die/wafers.



Liu, Alan Y., et al. "High performance continuous wave 1.3 μm quantum dot lasers on silicon." Applied Physics Letters 104.4 (2014): 041104.

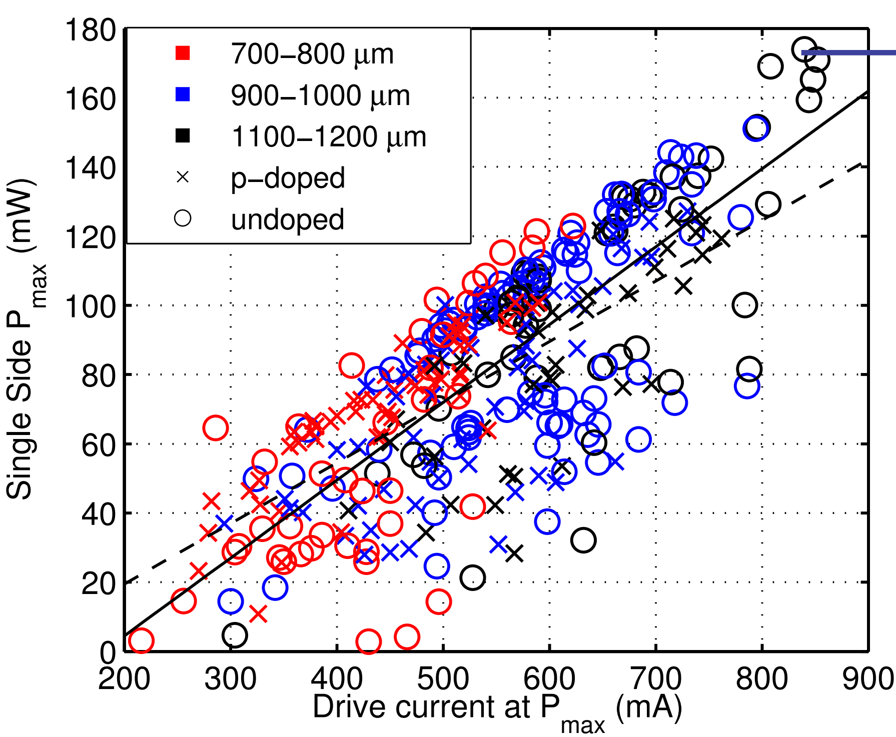
Output powers

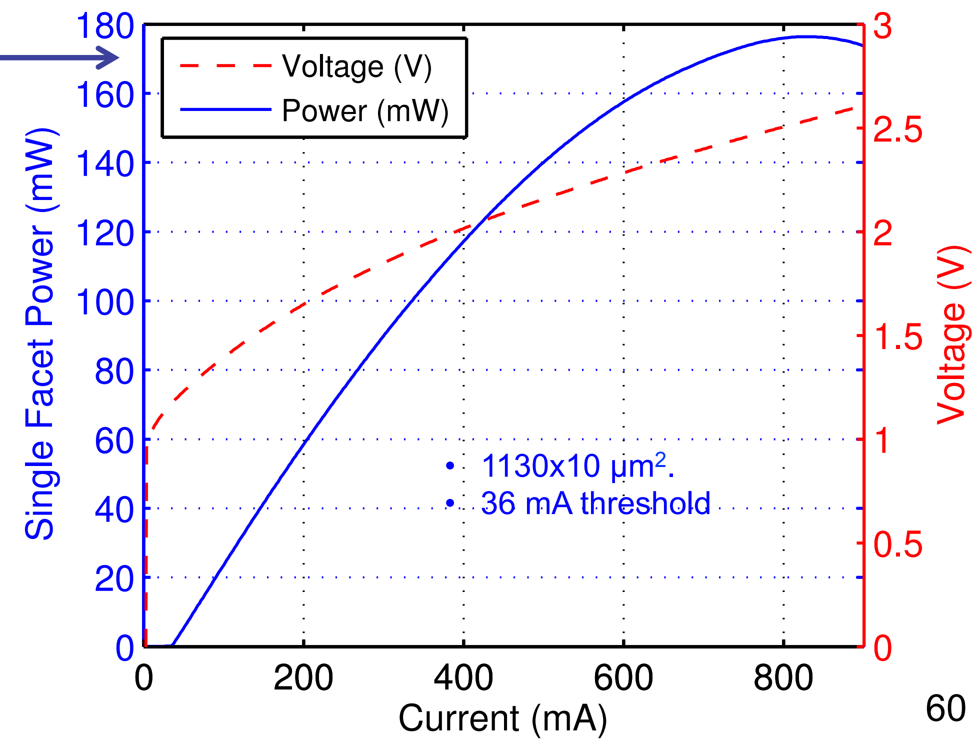
- CW powers over 100 mW routinely achieved.



Output powers

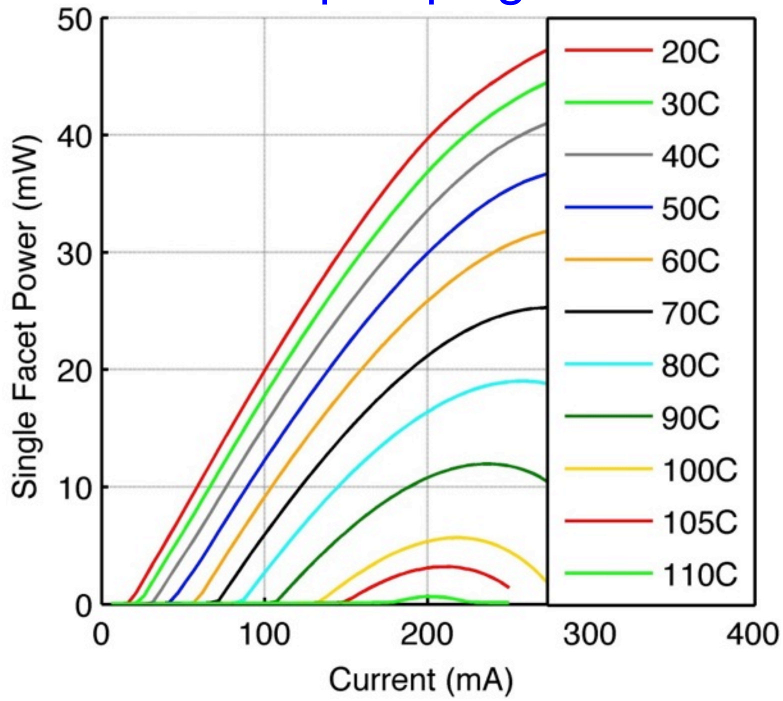
- CW powers over 100 mW routinely achieved.
- Nearly 180 mW maximum CW single side output power at 20 °C from HR coated 1130x10 μm² intrinsic active region (undoped) device.
  - 33% differential efficiency and 18% WPE (at 150 mA)





High Temperature Performance

Without p-doping

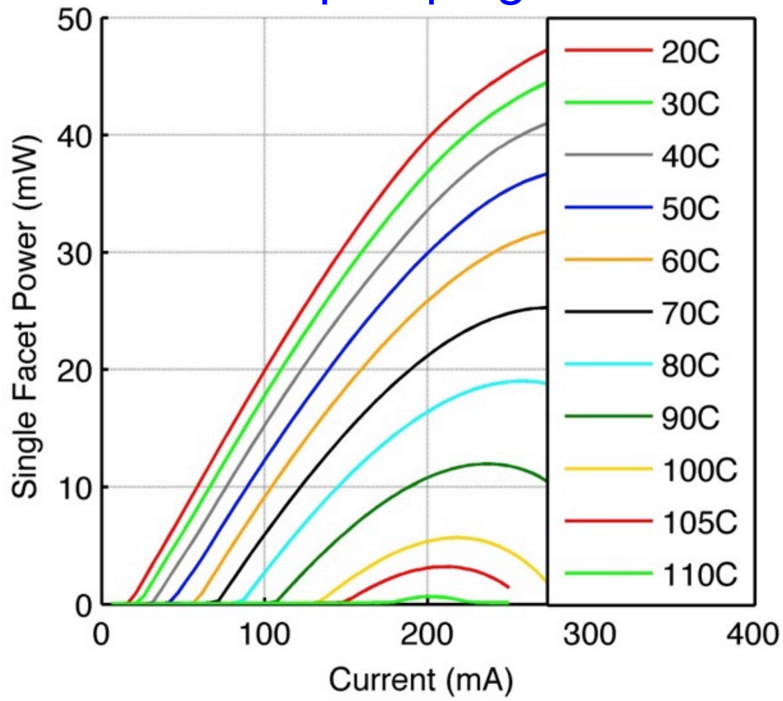


[1] Alexander, Ryan R., et al. "Systematic study of the effects of modulation p-doping on 1.3-μm quantum-dot lasers." Quantum Electronics, IEEE Journal of 43.12 (2007): 1129-1139.

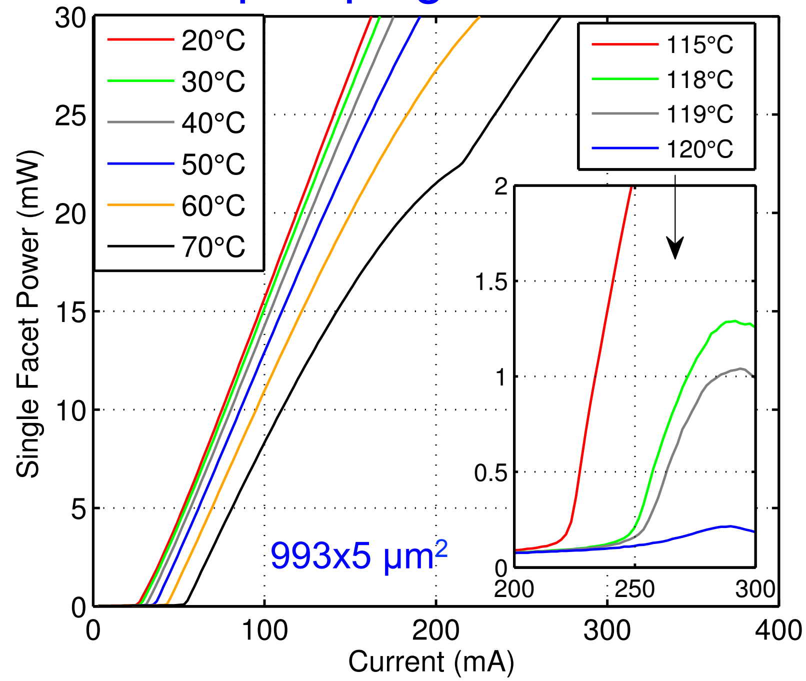
High Temperature Performance

- P-doping the active region improves thermal performance.[1]
- Continuous wave lasing up to 119°C
    - (dual state lasing at high currents/temperatures).

Without p-doping



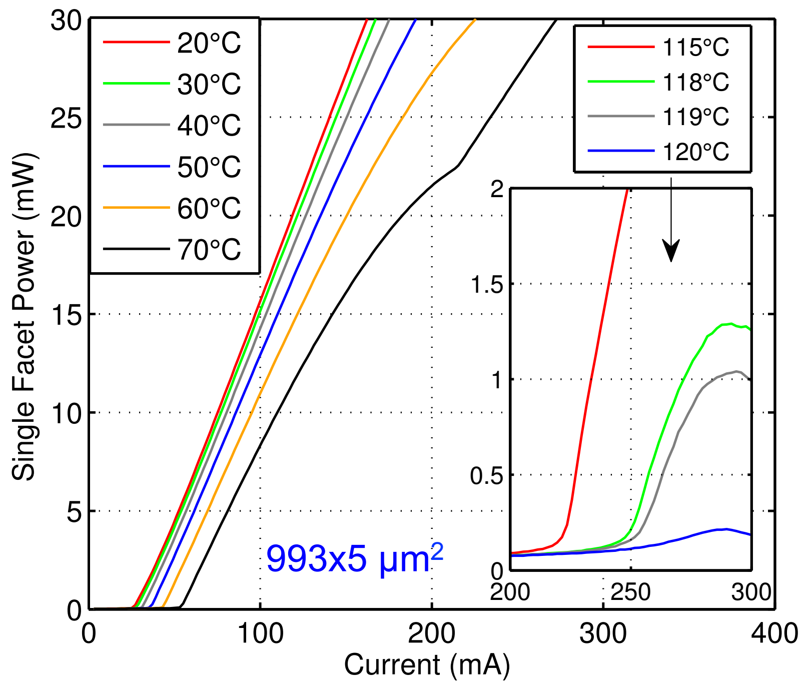
With p-doping

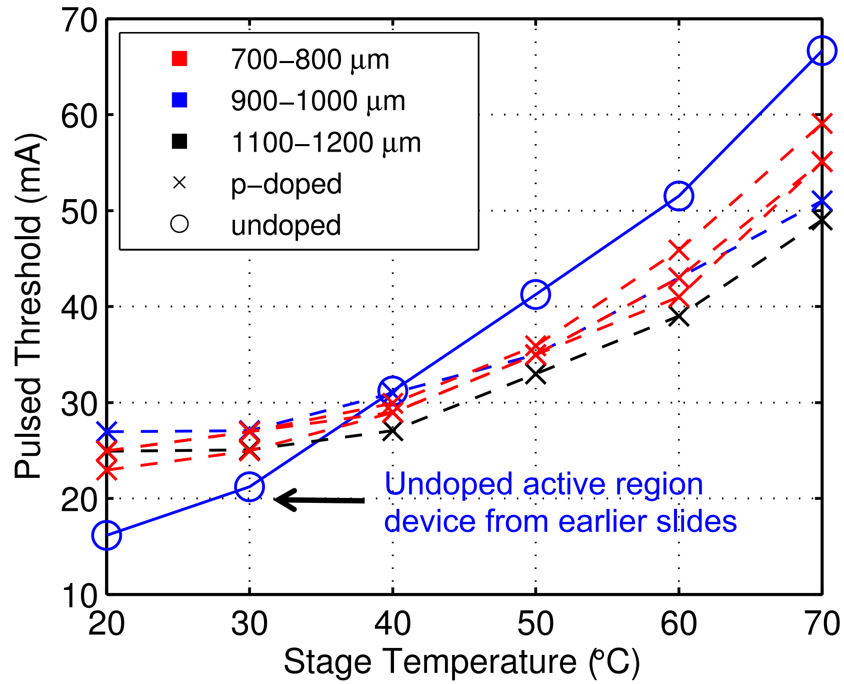


[1] Alexander, Ryan R., et al. "Systematic study of the effects of modulation p-doping on 1.3-μm quantum-dot lasers." Quantum Electronics, IEEE Journal of 43.12 (2007): 1129-1139.

High Temperature Performance

- P-doping the active region improves thermal performance.[1]
- Continuous wave lasing up to 119^{o}C
  - (dual state lasing at high currents/temperatures).
- T_0 of 100-200 K from 20-40^{o}C.

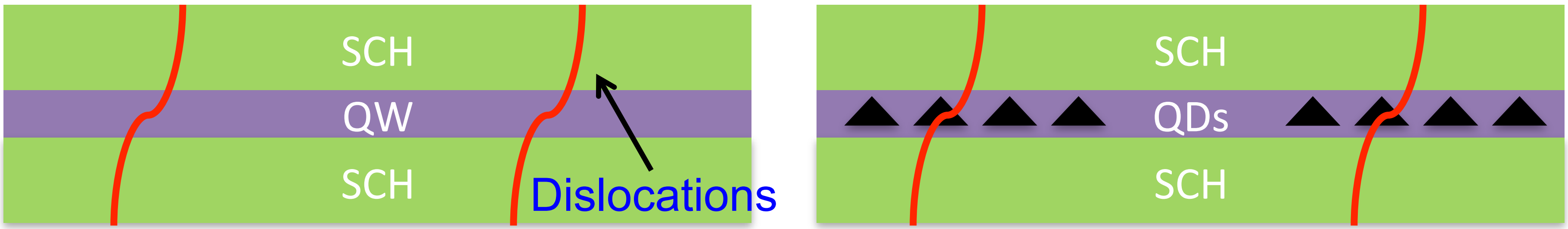


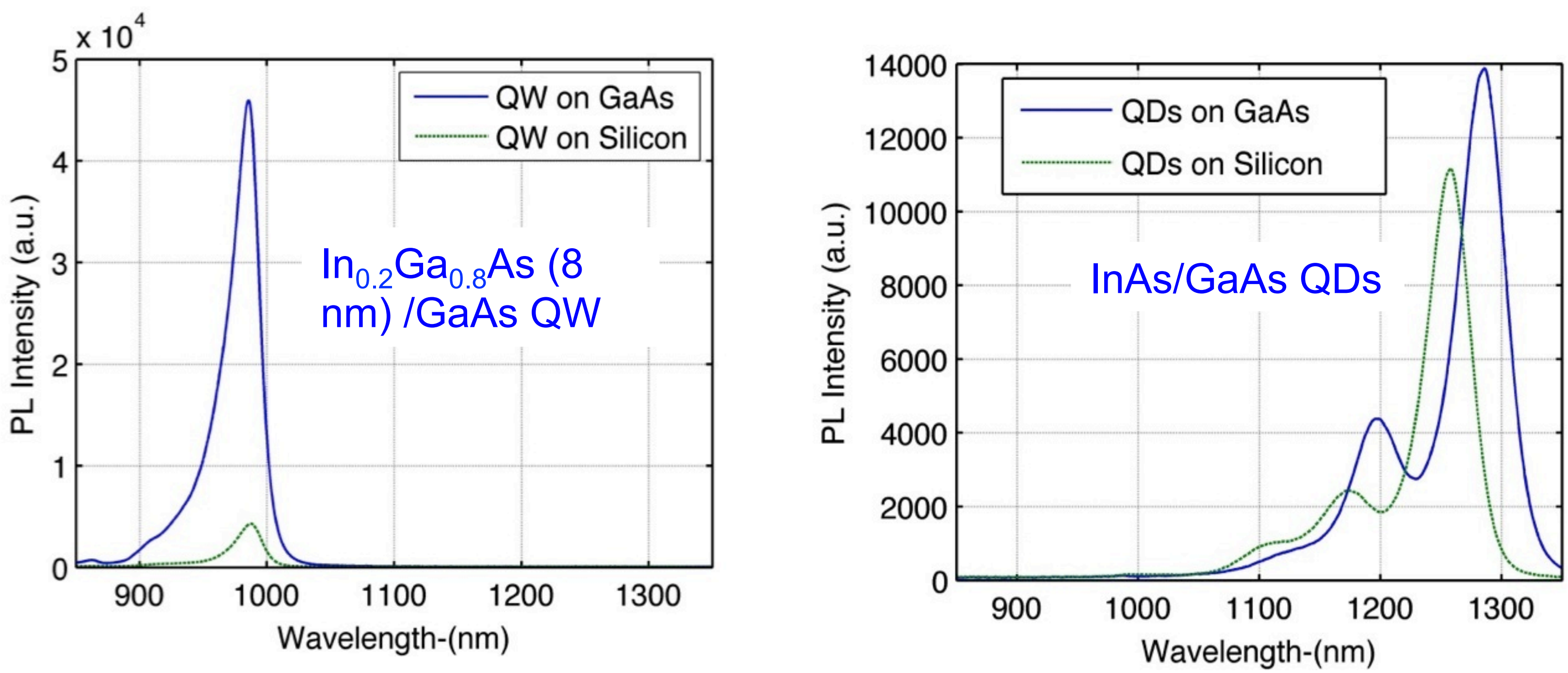


[1] Alexander, Ryan R., et al. "Systematic study of the effects of modulation p-doping on 1.3-μm quantum-dot lasers." Quantum Electronics, IEEE Journal of 43.12 (2007): 1129-1139.

QD vs QWs on silicon

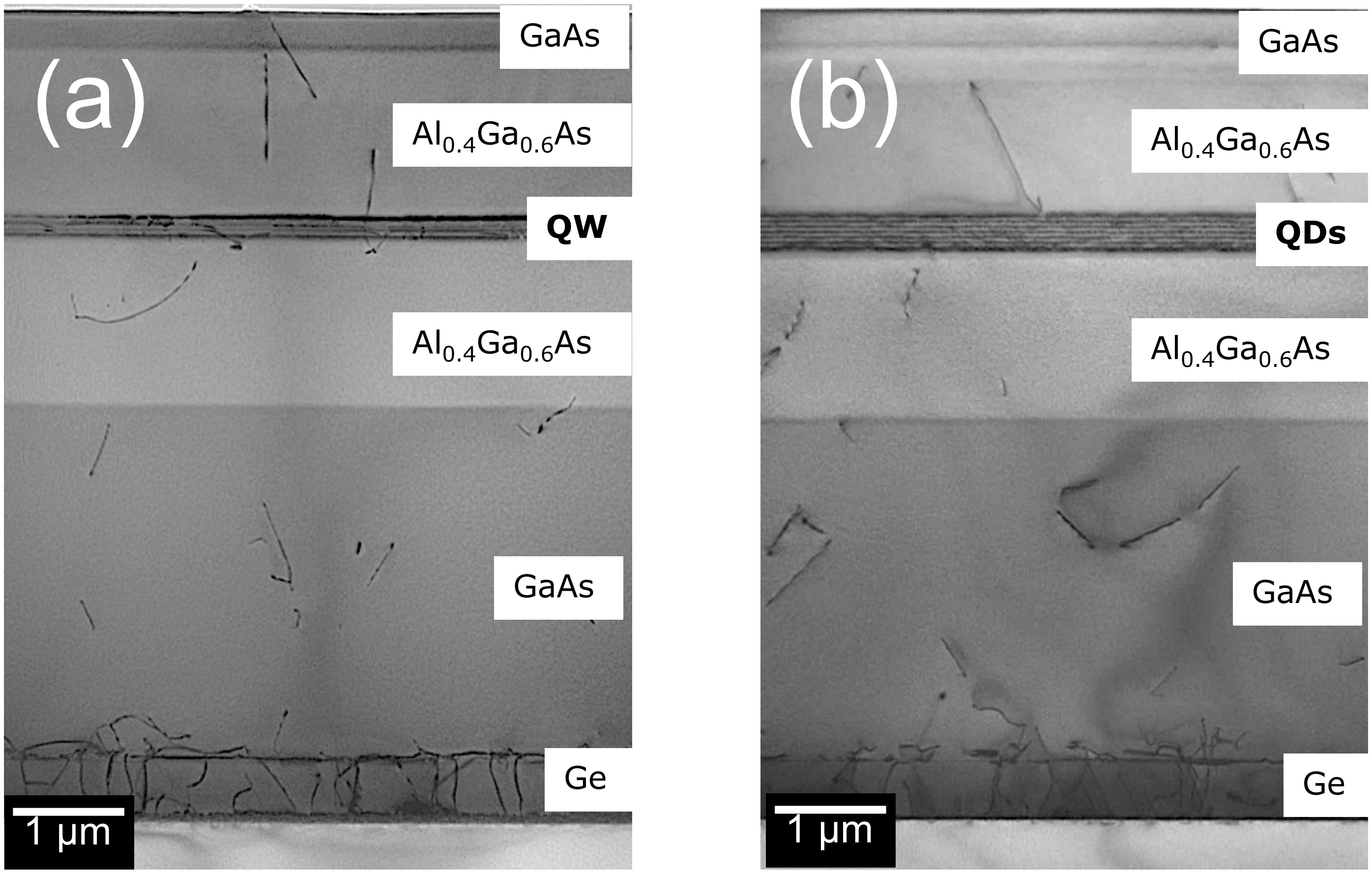
Direct comparison: Grow on both substrates; first quantum dots, then quantum wells Fabricate together





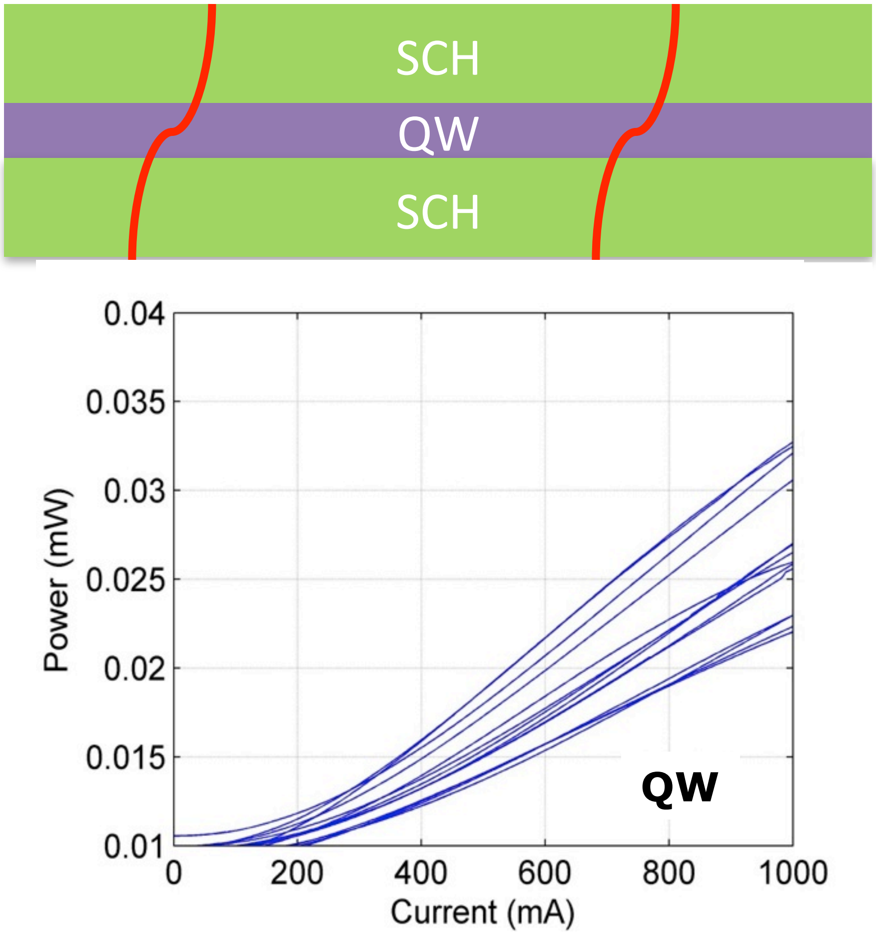
QD vs QWs on silicon

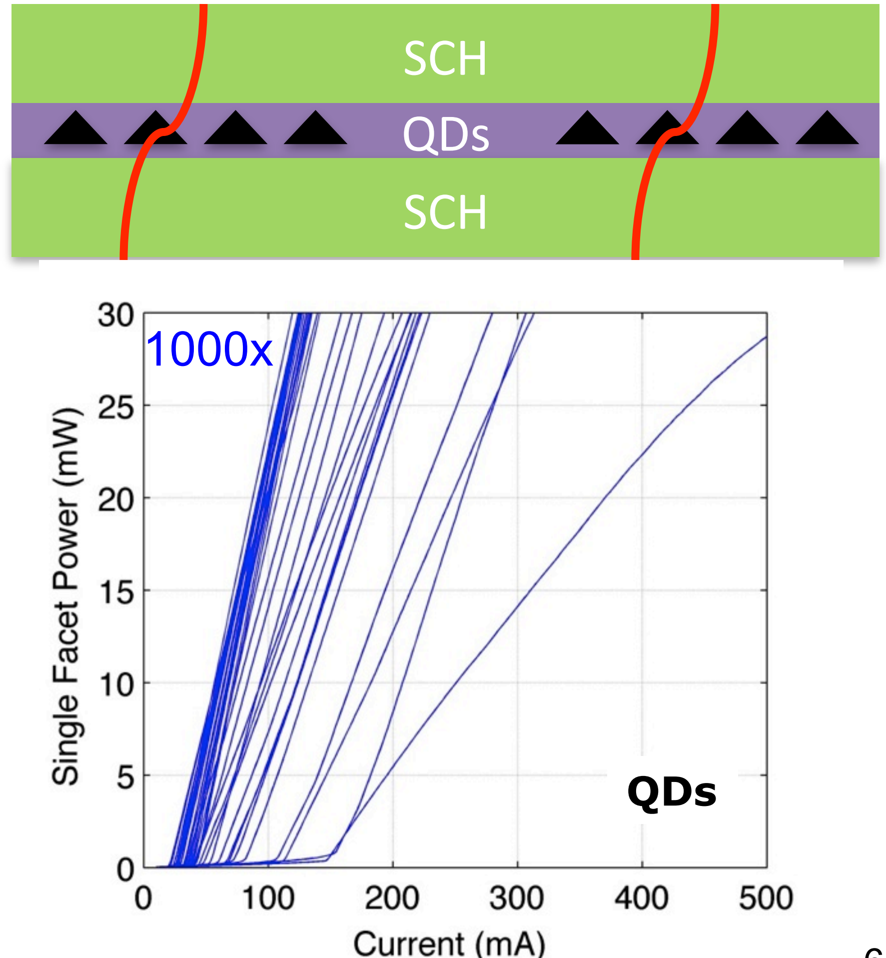
- An $In_{0.2}Ga_{0.8}As$ (8nm)/GaAs (3x) QW laser was grown for comparison.
- Substrate, epi stack, device design, and fabrication all identical. Only difference is active region type (QW vs QD)
- Similar dislocation density by TEM.



QD vs QWs on silicon

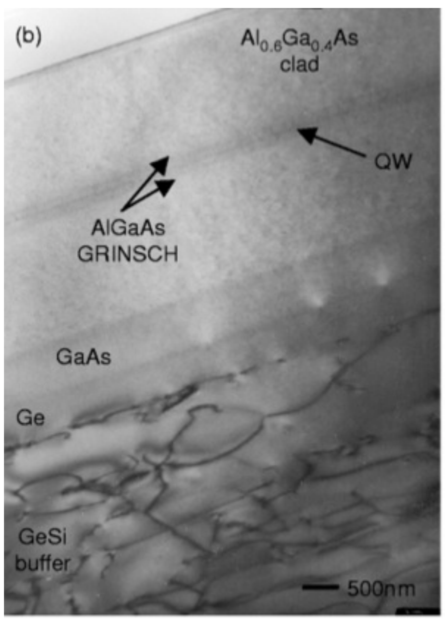
- No lasing for QWs on Si (all LEDs).
  - Reference QW lasers on GaAs worked fine.

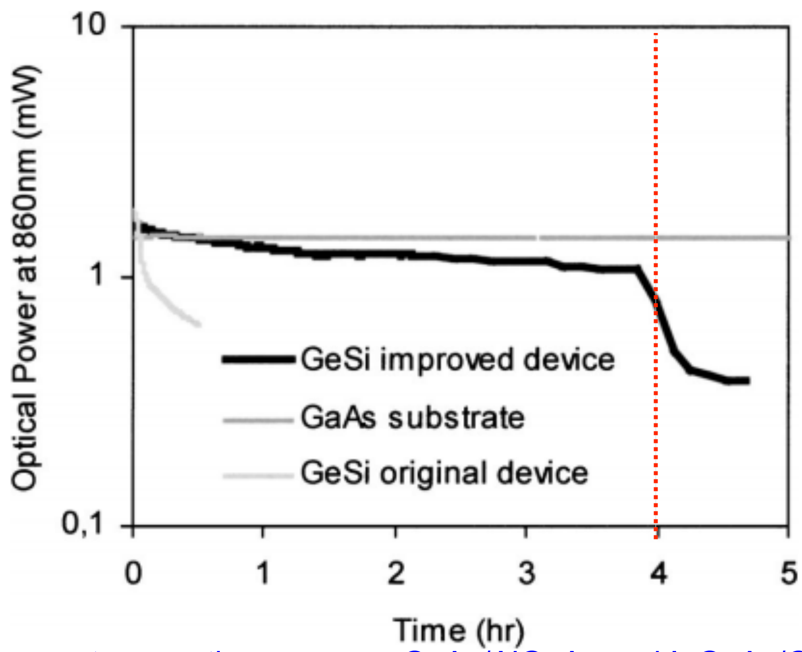




Lifetimes of Previous GaAs based lasers on Silicon

- GaAs based lasers are very sensitive to defect density and susceptible to failure by recombination enhanced defect reactions (REDR)[1][2]
- First GaAs lasers on silicon had lifetimes of ***~10 seconds*** (RT, pulsed) (1987) [3]
- Longest lifetime reported for GaAs based laser on Si (853 nm) is 80 hours (RT, CW) (2000) [4]
- GaAs/AlGaAs laser on Ge/Ge_xSi_{1-x}/Si substrates: 4 hours at (RT, CW) (2003) [5]





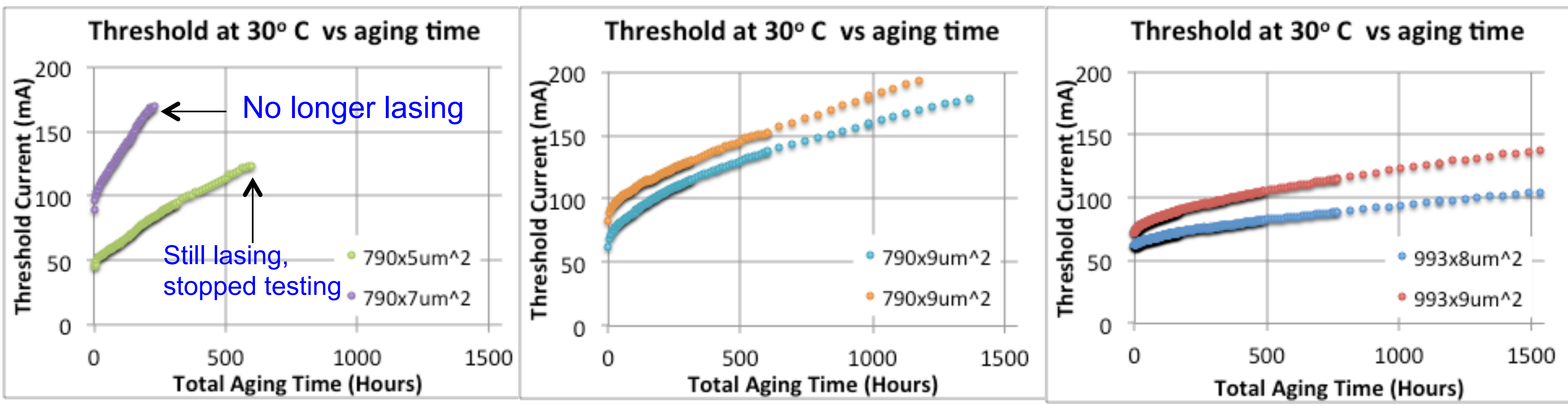
[5] Groenert, Michael E., et al. "Improved room-temperature continuous wave GaAs/AlGaAs and InGaAs/GaAs/AlGaAs lasers fabricated on Si substrates via relaxed graded GeSi buffer layers." Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures 21 (2003): 1064.

Reliability Studies of QD lasers on Silicon

UCSB

- Stress conditions: 30°C continuous wave under constant 100 mA injection current (~1.25-3x $I_{th}(0)$, ~1-20 mW initial output power)
- Degradation monitored by periodic light-current-voltage (LIV) sweeps at 30 °C

Increasing cavity size/decreasing current density

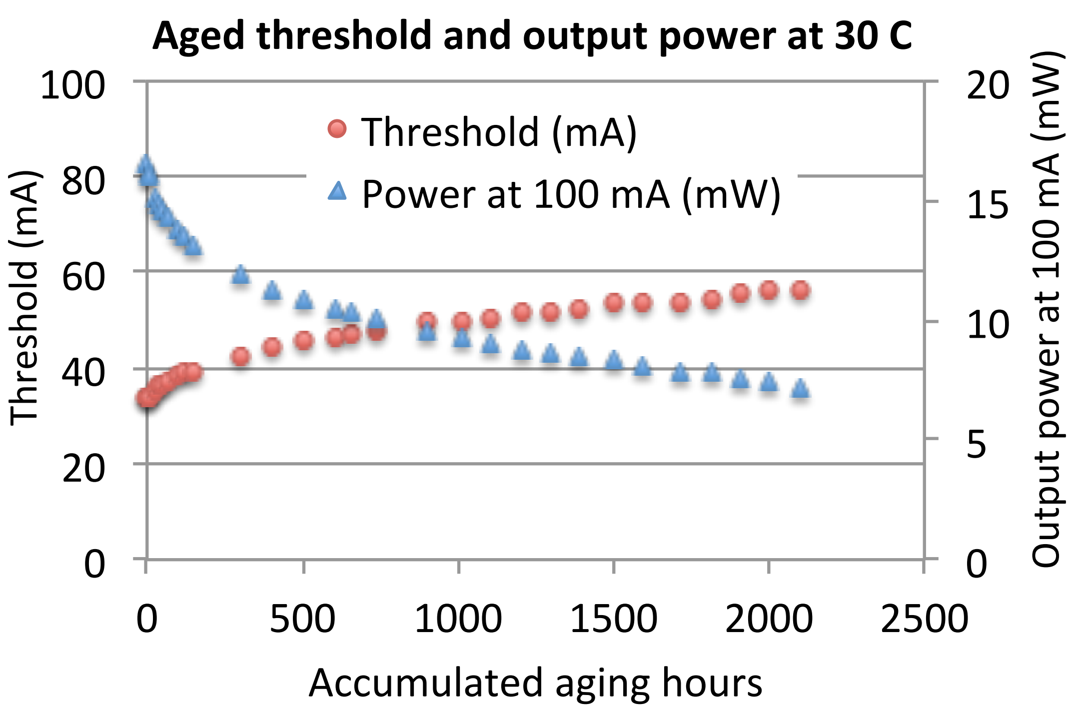


J=1.8-2.5 kA/cm^2 | J=1.4 kA/cm^2 | J=1.1-1.2 kA/cm^2

UCSB

Reliability Studies of QD lasers on Silicon

- Stress conditions: 30°C continuous wave under constant 100 mA injection current (~1.25-3x $I_{th}(0)$, ~1-20 mW initial output power)
- Degradation monitored by periodic light-current-voltage (LIV) sweeps at 30 °C
- Over **2100 hours** of continuous operation (testing stopped)
    - **>26x** improvement over best reported lifetime for GaAs laser on Si:
    - (2100 hours at 30°C, 2 kA cm^{-2} vs 80 hours at RT, 1.3 kA cm^{-2})
- No catastrophic failures observed.



Heterogeneously Integrated Quantum Well Transmitters

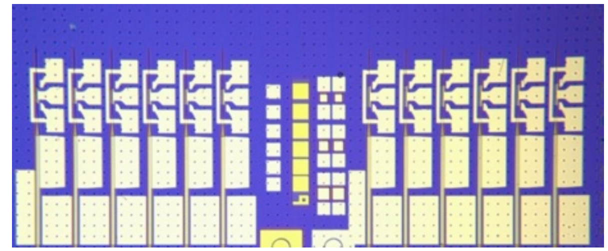
Modulators

Photodetectors

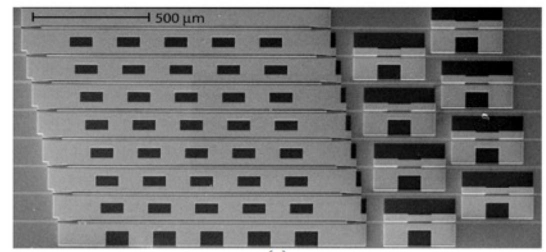
Integrated Transmitters

Active Elements needed for PICs

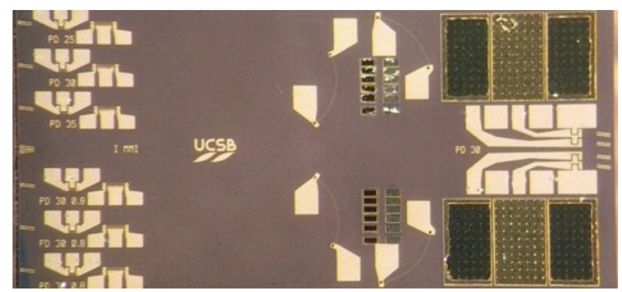
- Range of components for PICs:
  - Lasers
  - Modulators
  - Amplifiers
  - Photodetectors
- Integration
- High yield
- Good reliability



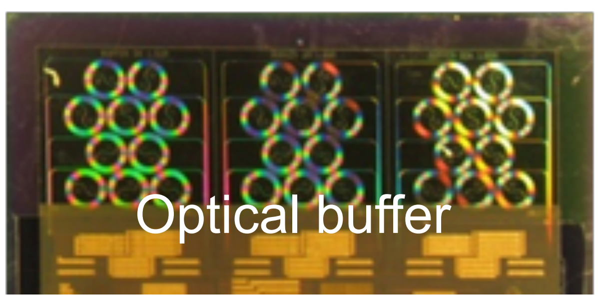
DFB/EAM/PD Array



Optical preamplifier PD array



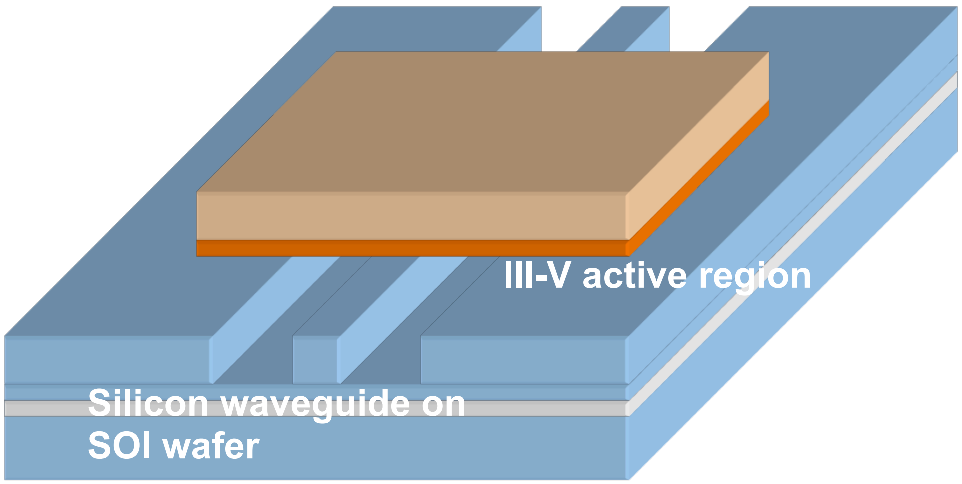
DQPSK Receiver

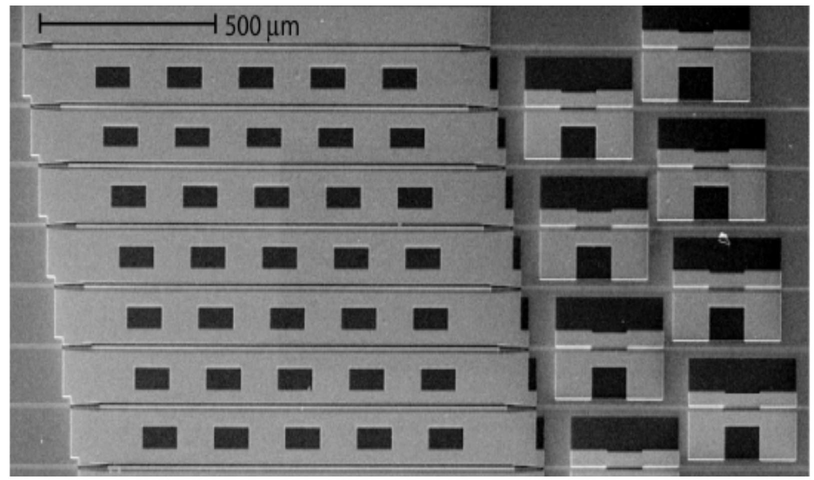


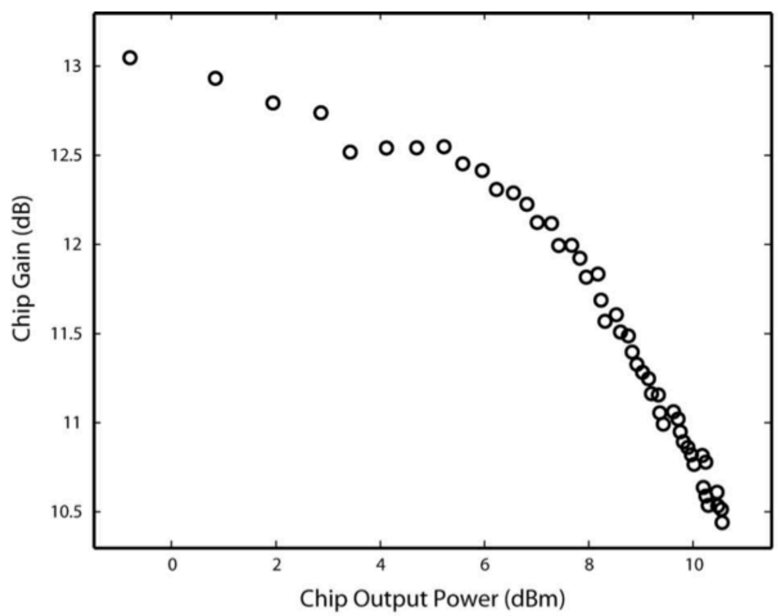
Optical buffer

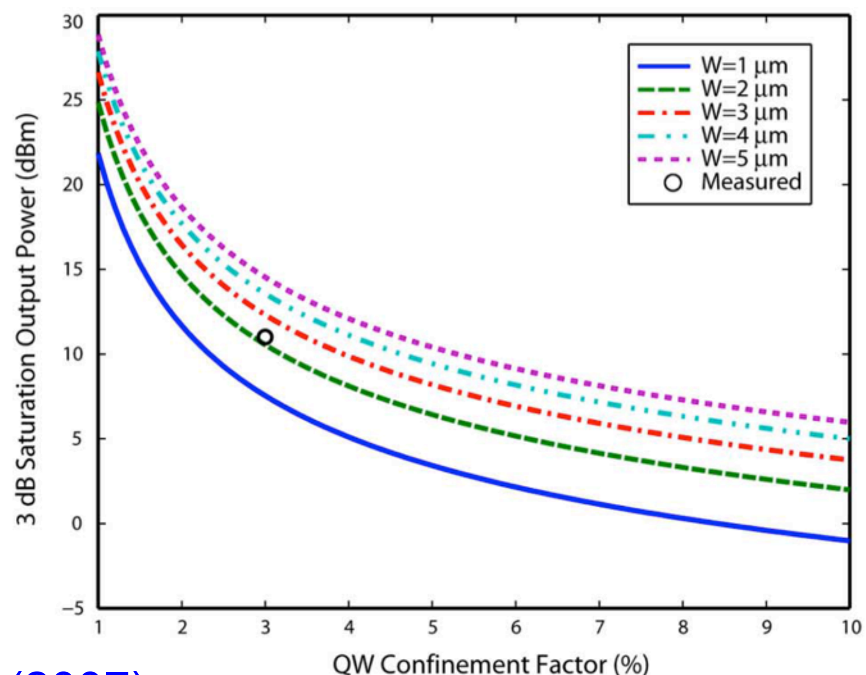
A Hybrid AlGaInAs–Silicon Evanescent Amplifier

Hyundai Park, *Student Member, IEEE*, Alexander W. Fang, *Student Member, IEEE*, Oded Cohen, Richard Jones, *Member, IEEE*, Mario J. Paniccia, *Senior Member, IEEE*, and John E. Bowers, *Fellow, IEEE*





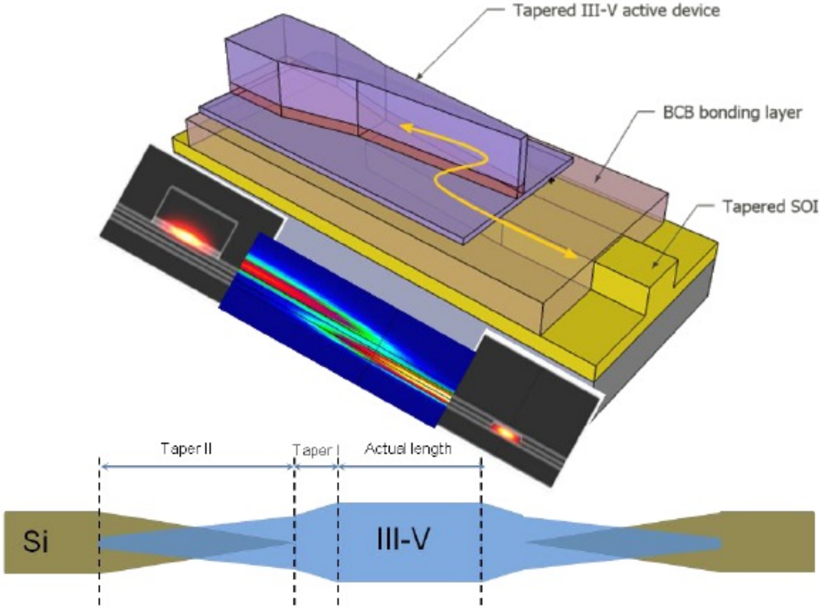


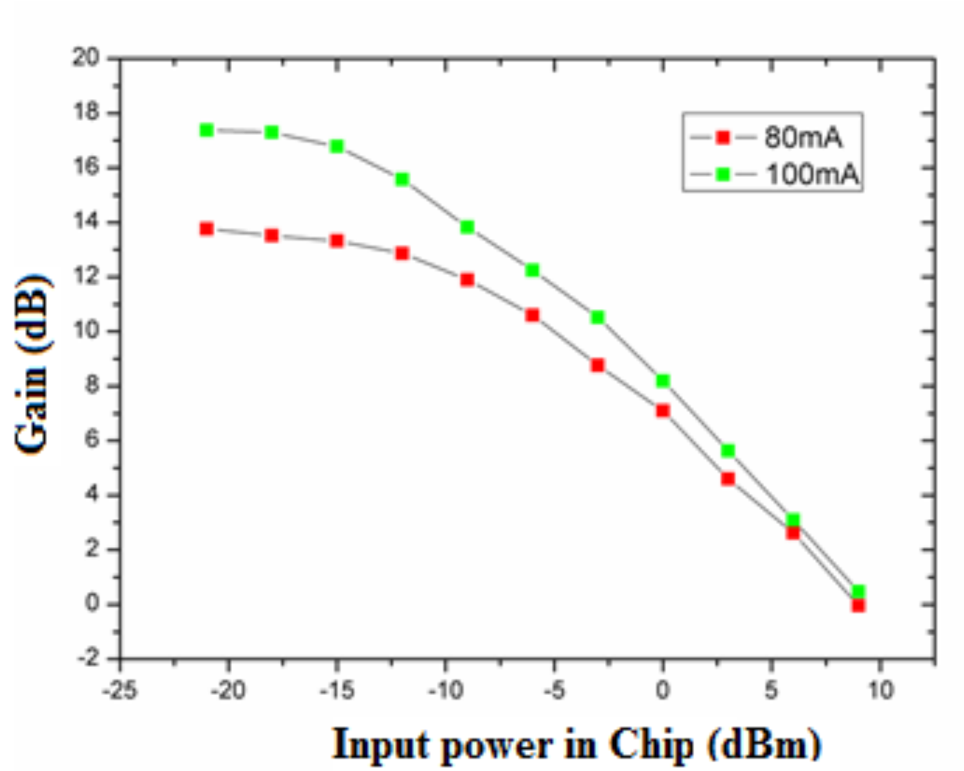


(b)

H. Park et al., PTL, 19(4), 230, February (2007).

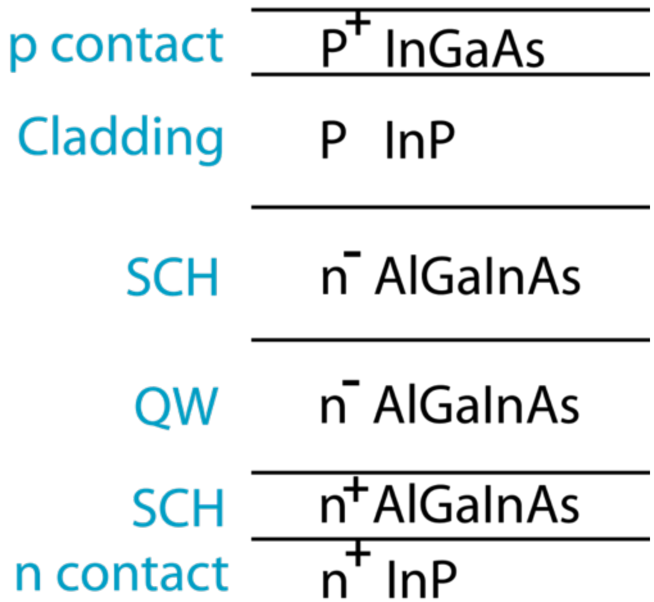
III-V on silicon optical amplifiers

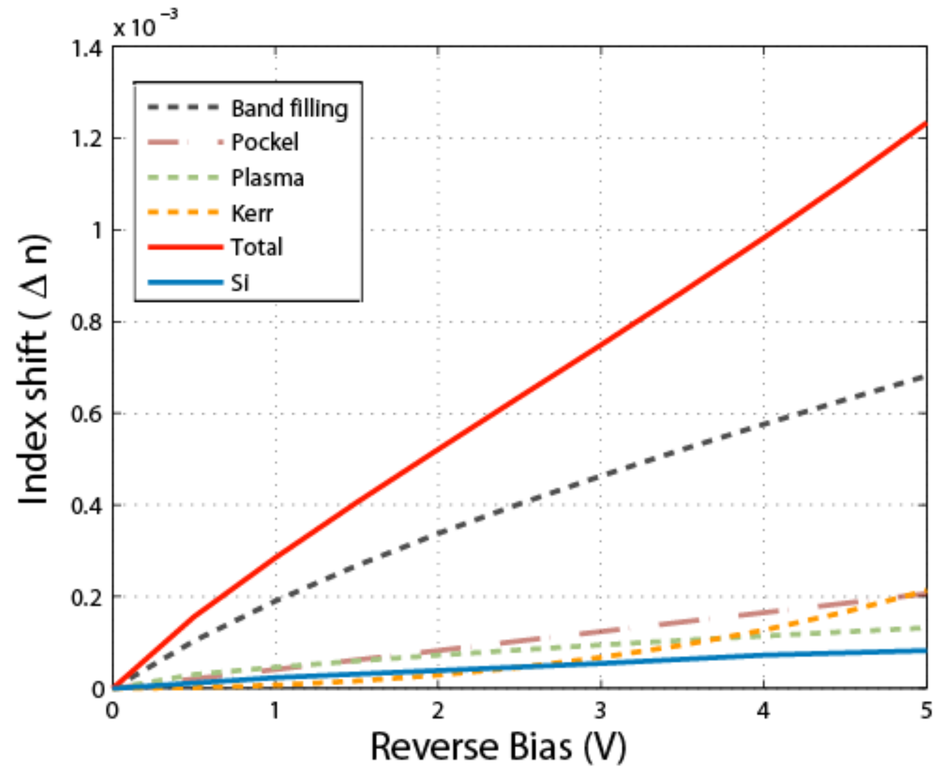




18dB small signal gain for 100mA drive current

Hybrid Silicon Switch: Use III-V Material





>10x

Si = Plasma +….

III-V = Plasma + BF + Pockels + Kerr +….

* Silicon phase shift is calculated from "High speed optical modulation based on carrier depletion in a silicon waveguide," A. Liu et. Al, Opt. Express, 15 (2), 2007

Hybrid Silicon MZMs

2008	2009	2011	2013~2014

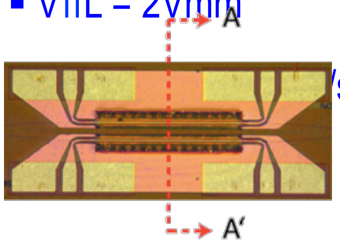
Gen 1 Hybrid silicon MZM:

- AlGaInAs QW
- Coplanar waveguide
- QW undercut

Performance:

- 8 GHz bandwidth
- VπL = 2Vmm

/s



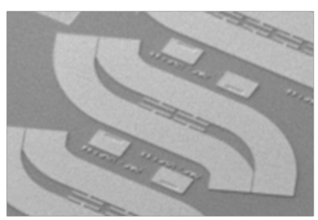
H. Chen, et al., OE 16(25), 20571(2008)

Gen 2 Hybrid silicon MZM:

- Capactively-loaded slot line
- Electric-isolation by Implantation
- Push-pull operation

Performance:

- ~12.5 GHz bandwidth
- 11 dB ER @ 25 Gb/s

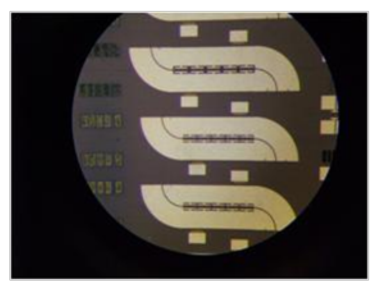


Gen 3 Hybrid silicon MZM:

- Improved implantation profile
- Improved contact resistance
- Improved MMI

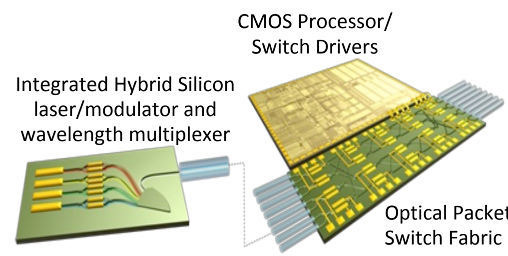
Performance:

- 27 GHz bandwidth
- 11 dB ER @ 40 Gb/s



Application:

- large scale non blocking optical switch array
- Vector-modulated Tx

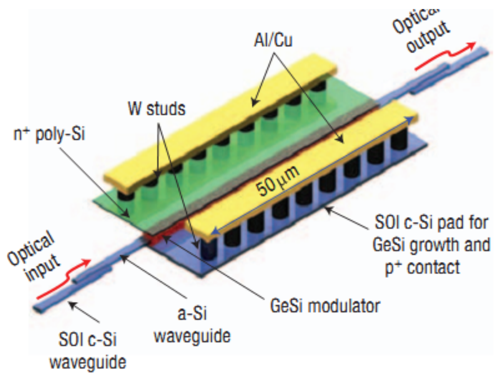


L. Chen et al., Photonic J. 2011

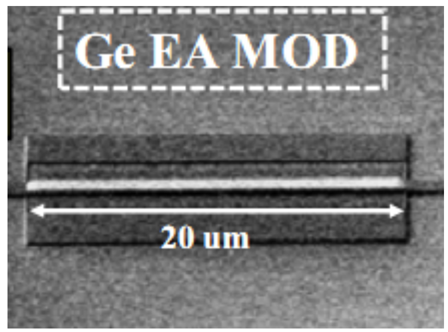
H. Chen, et al., OE 18(2)), 1070(2010) H. Chen, et al., OE 19(2)), 14552011)

EAM

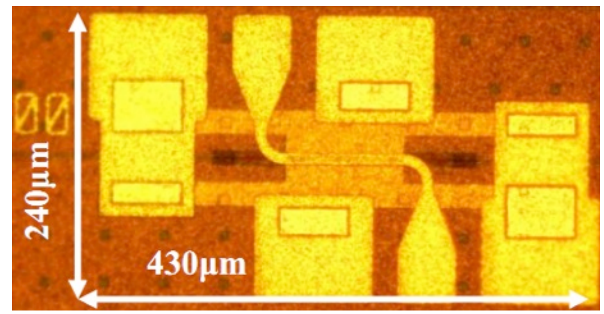
$$T = \exp\left(-\alpha_0 L - \underbrace{\alpha(V)}_{\text{voltage-controlled loss}} L \right)$$



Liu, et al., Nat. Photonics, 2, 433-437, 2008



Lim, S*STAR, OFC OWQ2, 2011



Tang, et al., OE, 19(7), 5811-5816 (2011)

Group	f_{3dBe} [GHz]	Len [µm]	ER [dB|V_{pp}|Gb/s]	Type	Note
Liu, MIT, 2008	1.2	50	--	GeSi	Frank-Keldysh
Rong, Stanford, 2010	13	30	0.53|2.5|3.125	GeSi/Si	QCSE, λ=1408nm
Tang, UCSB, 2011	74	100	9.8|2|50	AlGaInAs	QCSE, hybrid
Lim, A*STAR, 2011	--	100	--|--|1.25	Ge	FK, λ=1600nm

UCSB

Hybrid Si Electroabsorption Modulators

2008 | 2011 | 2012 | 2013-2014

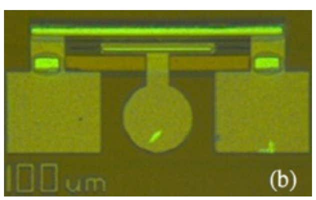
Gen 1 Hybrid silicon EAM:

- AlGaInAs QW
- Lumped electrode
- QW undercut

Performance:

- >16 GHz bandwidth
- sub-voltage operation

(250μm)



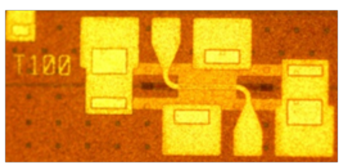
Y. Kuo, et al., OE 16(13), 9936 (2008)

Gen 2 Hybrid silicon EAM:

- Distributed electrode
- Electrically-isolated taper
- Improved contact resistance

Performance:

- ~42 GHz bandwidth
- 9.8 dB ER @ 50 Gb/s



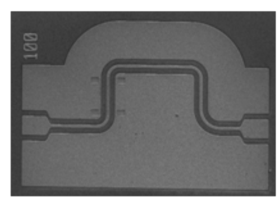
Y. Tang, et al., OE 19(7)), 5811(2011)

Gen 3 Hybrid silicon EAM:

- New epitaxy design for 1300 nm
- Segmented electrode
- Gradually-doping p-InP

Performance:

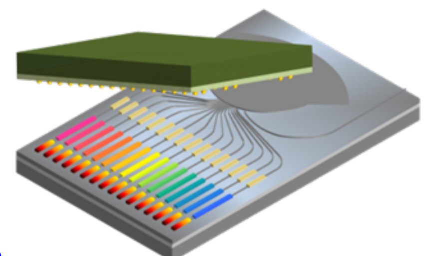
- bandwidth > 67 GHz
- modulation efficiency > 5 dB/V
- power consumption < 1mW/Gb/s
- transmission distance > 10km



Y. Tang, et al., OE 20(10), 11529(2012)

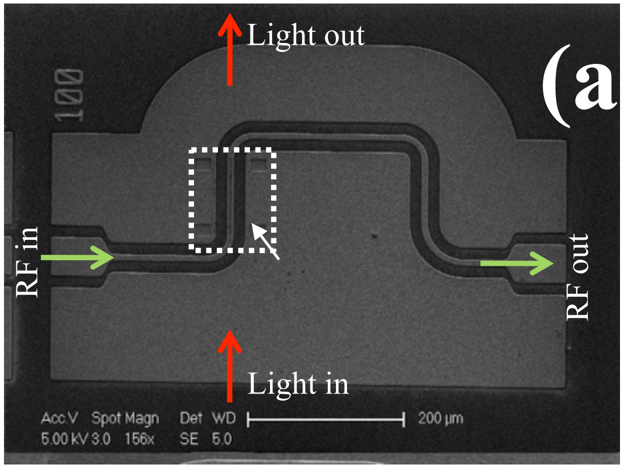
Gen 4 Hybrid silicon EAM:

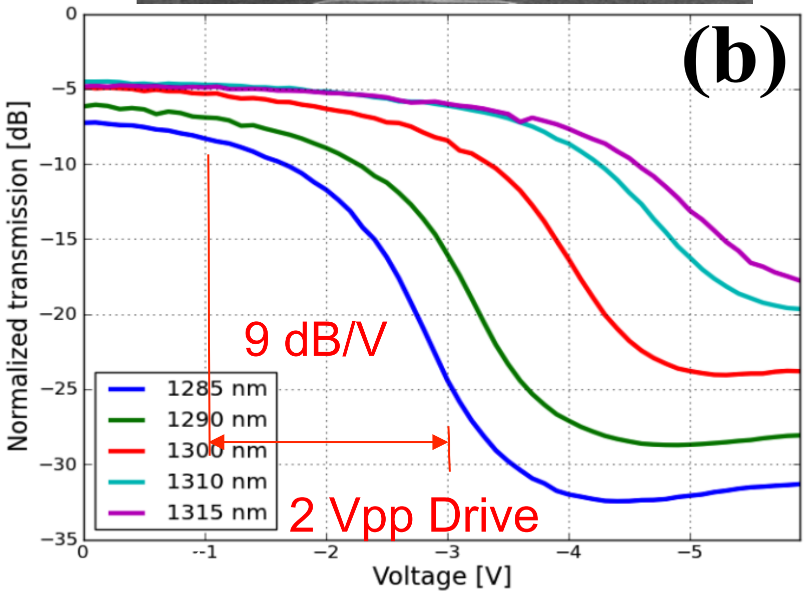
- 1x16 EML Array+Mux
- <1pJ/bit @ 25Gb/s

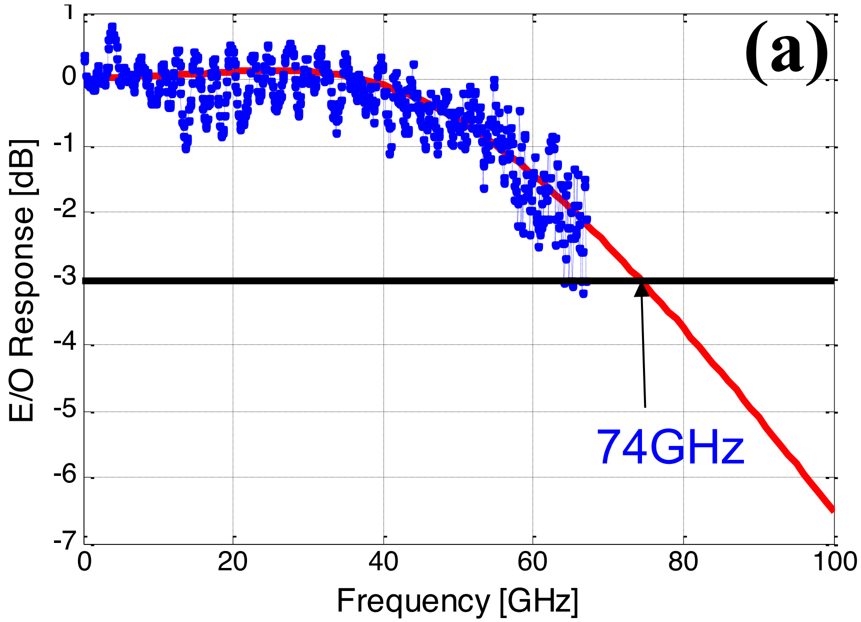


Hybrid Silicon HSEAM

- Segmented electrode
- Length: 100 µm
- >67 GHz Bandwidth



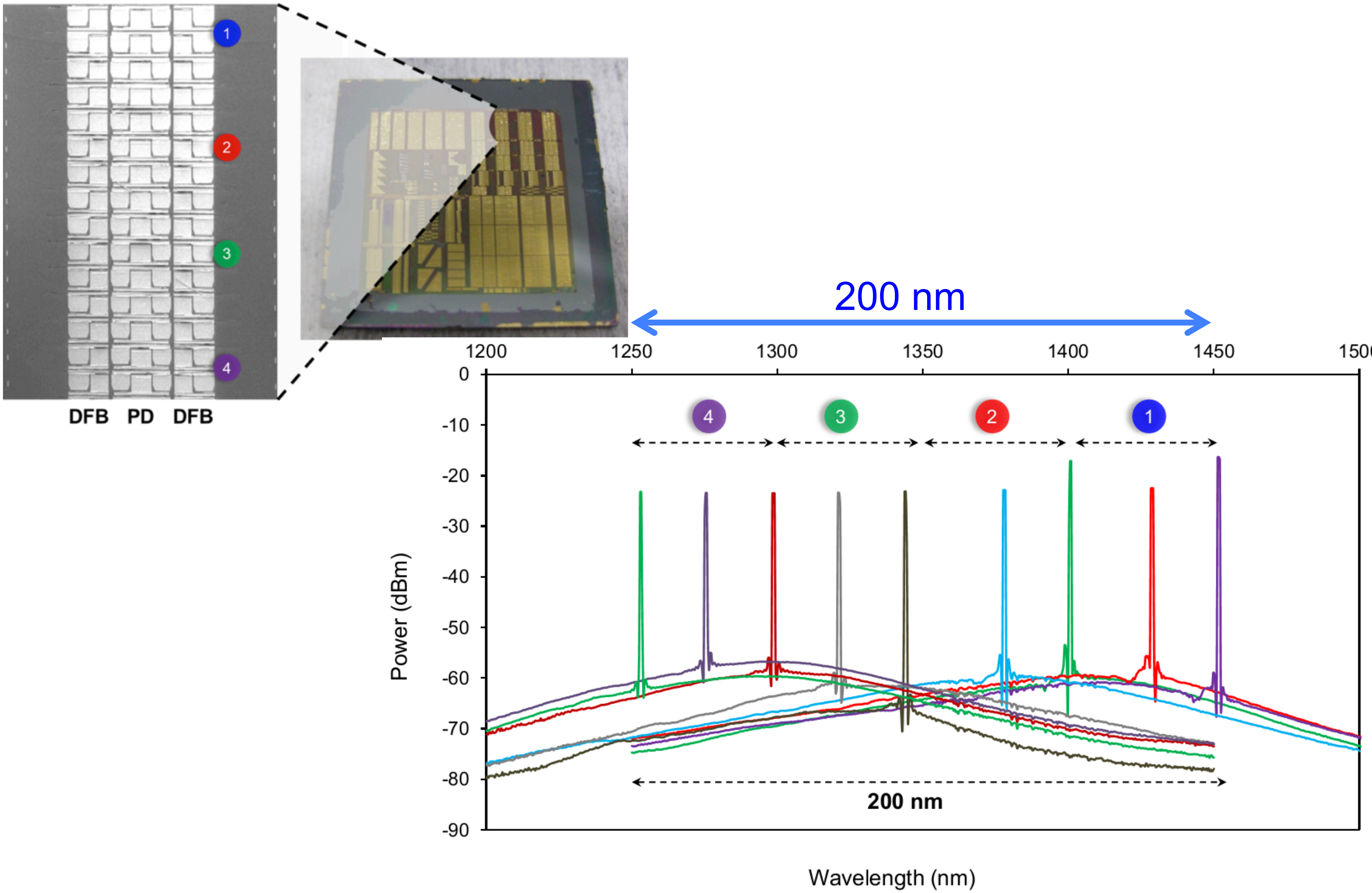




330 fJ/bit

Tang, Peters, Bowers OFC Postdeadline 2012

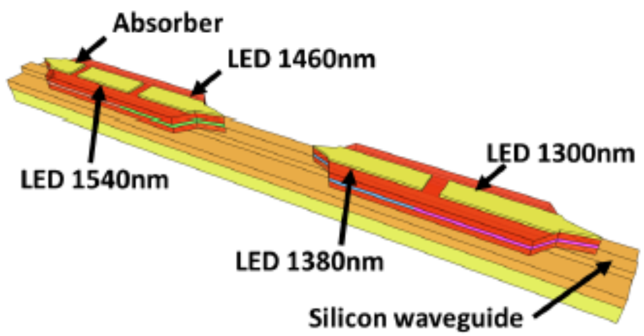
Integrated Transmitters

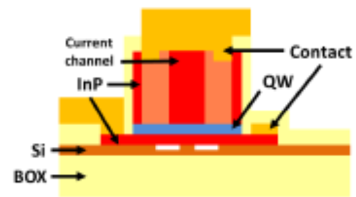


Heterogeneously integrated III-V on silicon multi-bandgap superluminescent light emitting diode with 290nm optical bandwidth

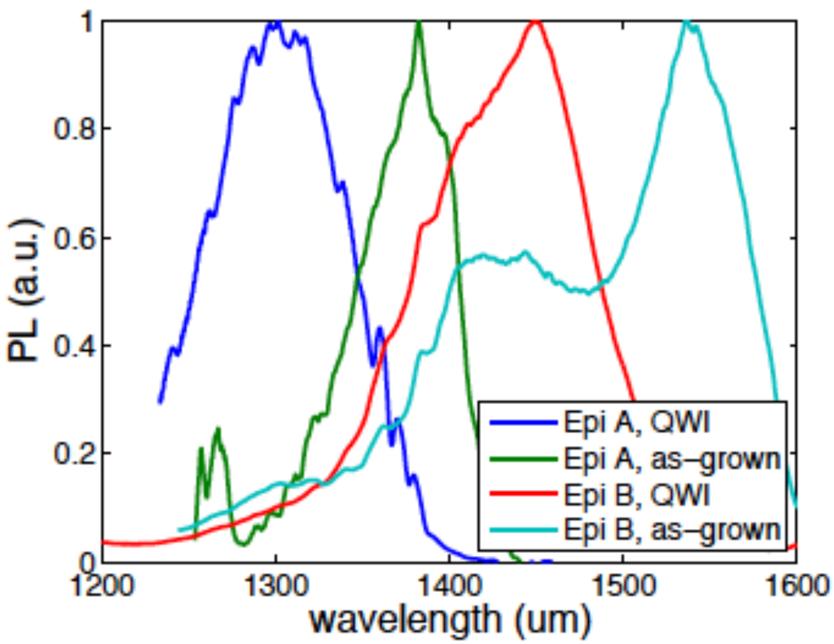
Optics Letters 2014

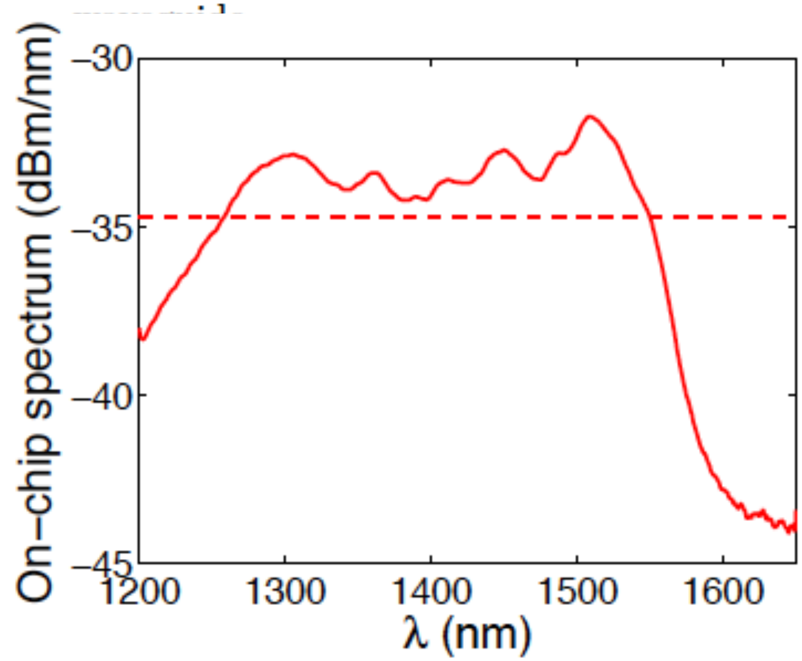
A. De Groote,[1,2,*] J.D. Peters,[1] M.L. Davenport,[1] M.J.R. Heck,[1] R. Baets,[2] G. Roelkens,[2] and J.E. Bowers[1]





(b) Cross section of the III-V on silicon

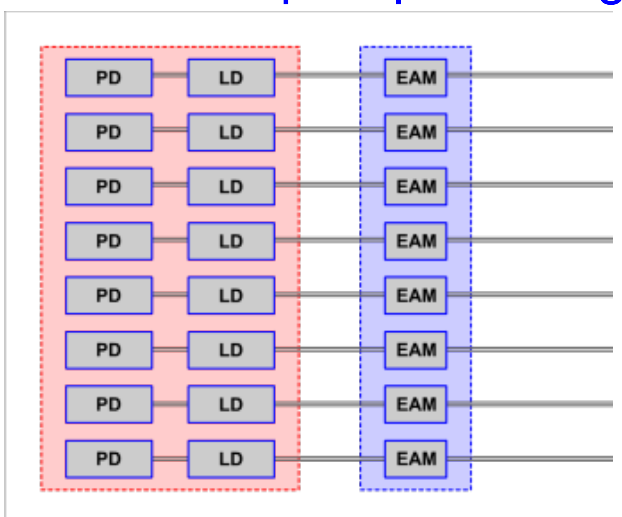


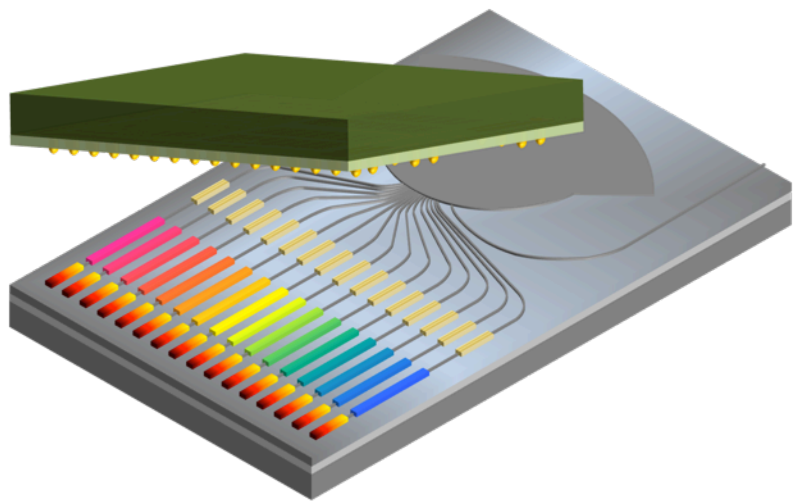


Integration of DFB and EAM on hybrid silicon platform

Low power, high speed, integrated photonic transmitter based on hybrid silicon platform

- High capacity optical interconnects between processors and memory.
- Low power optical transmitters with high impedance modulators Integrate arrays of lasers with arrays of modulators to reduce the power required for off-chip lasers.
- Flip chip bonding with CMOS driver chip *

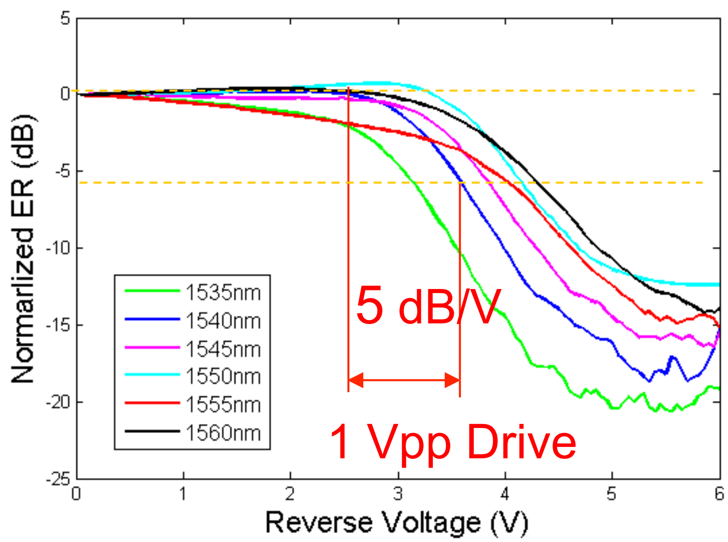




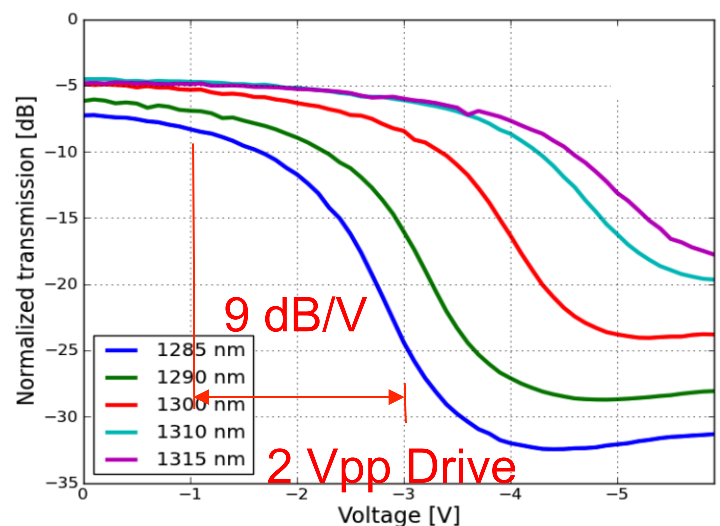
Hybrid Silicon Electro-absorption Modulators

	C-band Lumped EAM	O-band Lumped EAM
Wavelength [nm]	1550	1300
Active Length [µm]	100	100
Bandwidth [GHz]	18	30
ER [dB/1V]	> 5	> 9
Footprint [μm^2]	55×220	210×310
Insertion Loss	3	5
Current under bias [mA]*	< 0.1	~ 0.1

C-Band



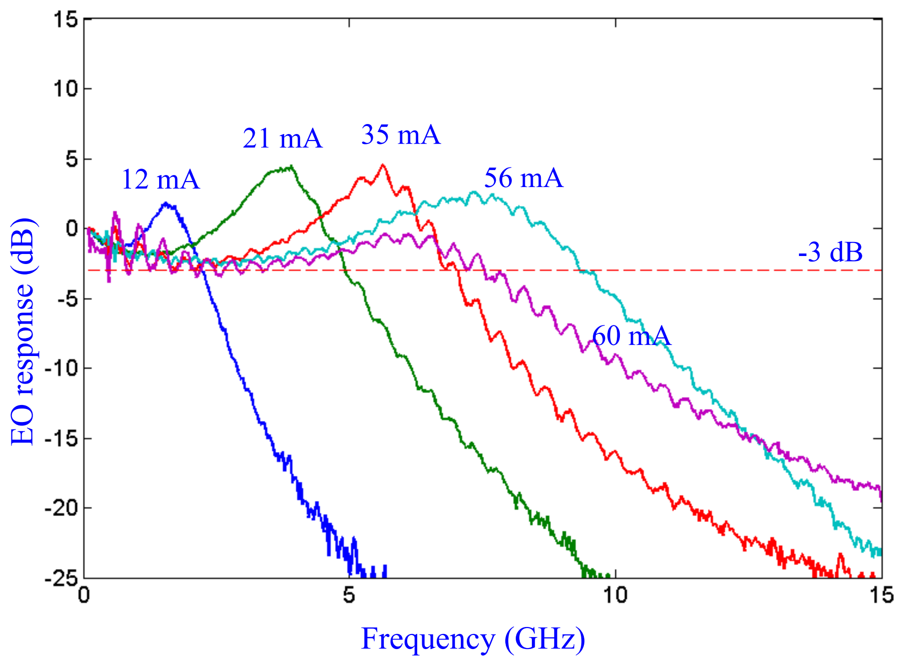
O-Band

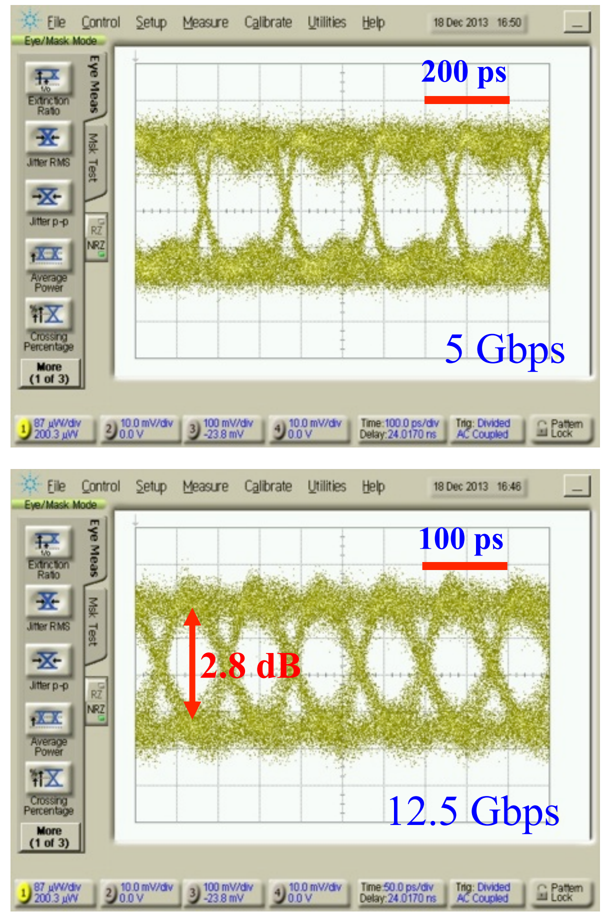


YB Tang, 2012

Direct modulation of short cavity DFB

- Maximum 3 dB bandwidth is about 9.5 GHz
- The slope of f_r curve is about 1.185 GHz/mA$^{1/2}$
- Open eye diagrams up to 12.5 Gbps.





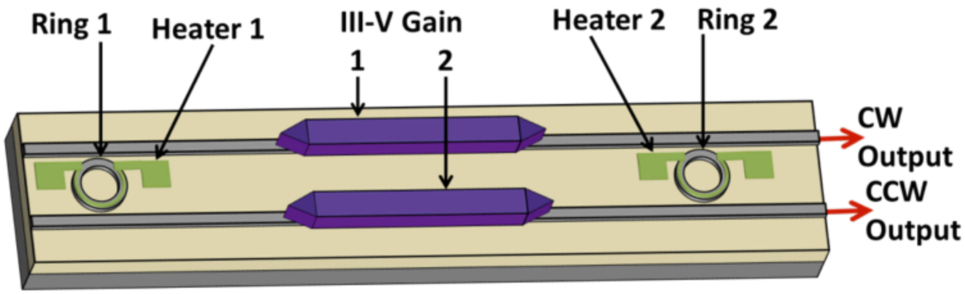
C Zhang, 2014

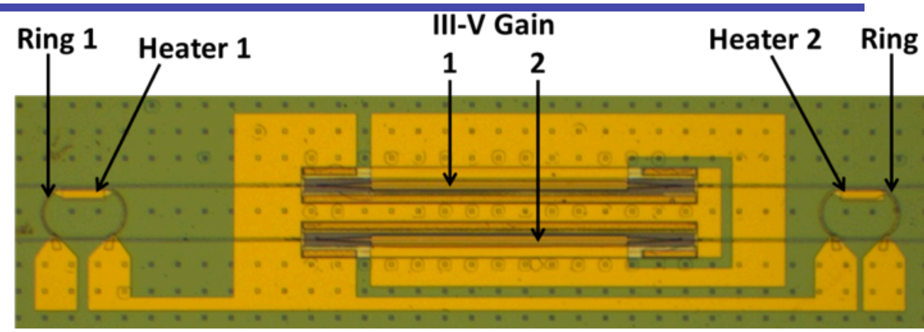
Tunable Lasers

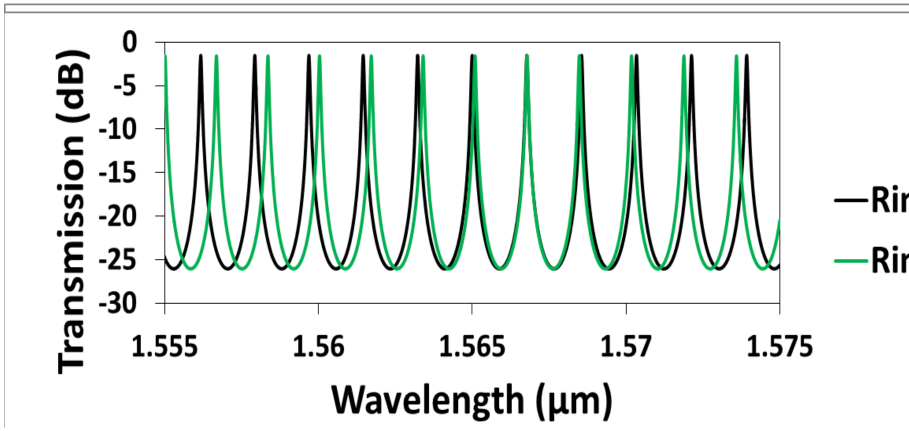
UCSB

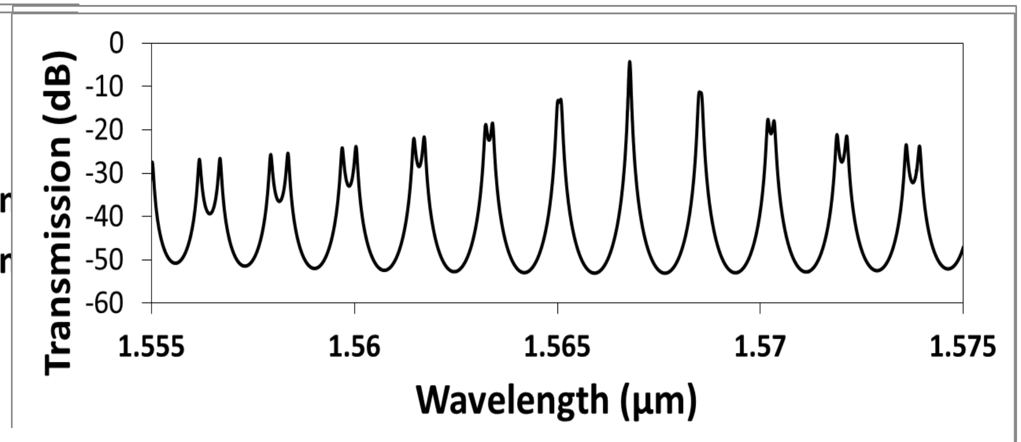
Ghent

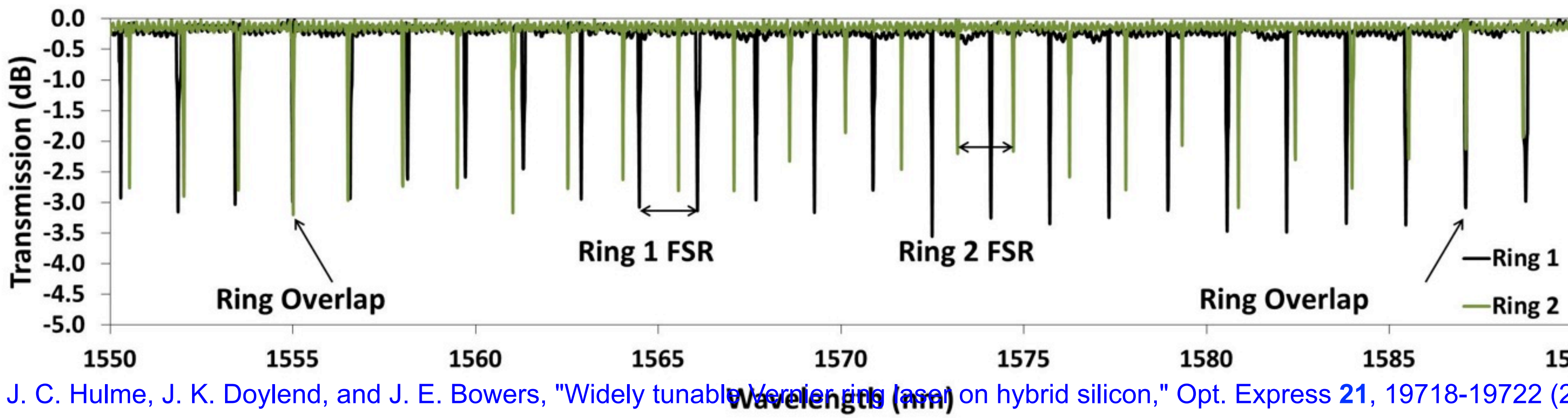
Widely Tunable Vernier Ring Laser





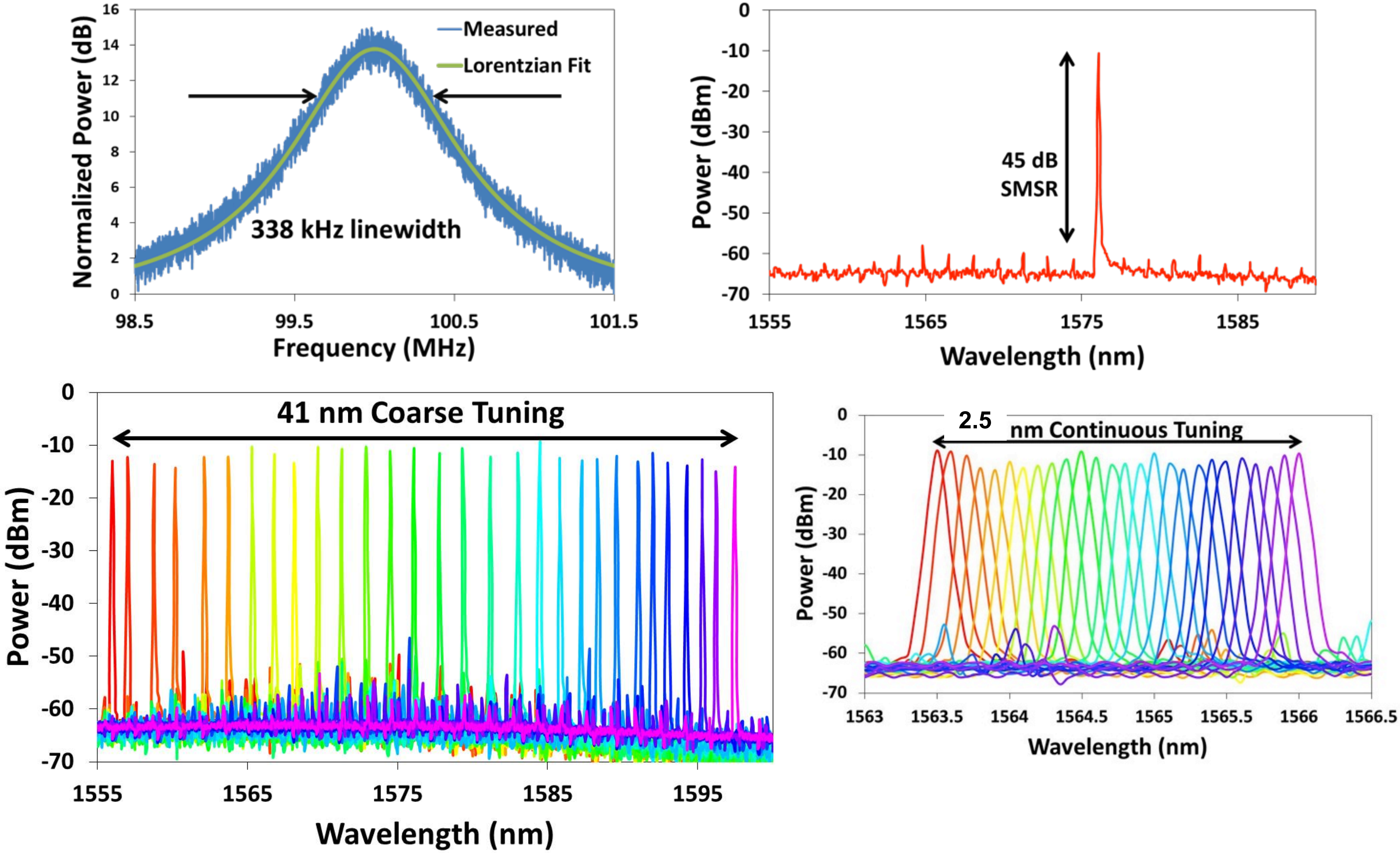






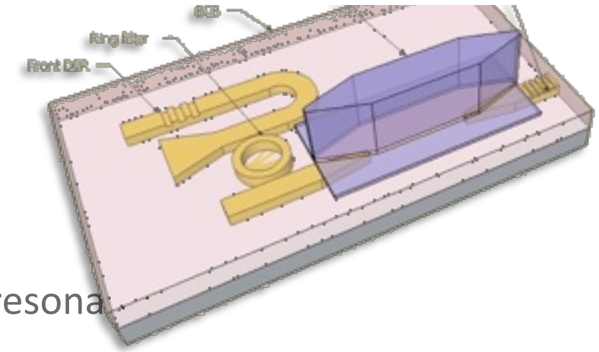
J. C. Hulme, J. K. Doylend, and J. E. Bowers, "Widely tunable Vernier ring laser on hybrid silicon," Opt. Express **21**, 19718-19722 (2013)

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)

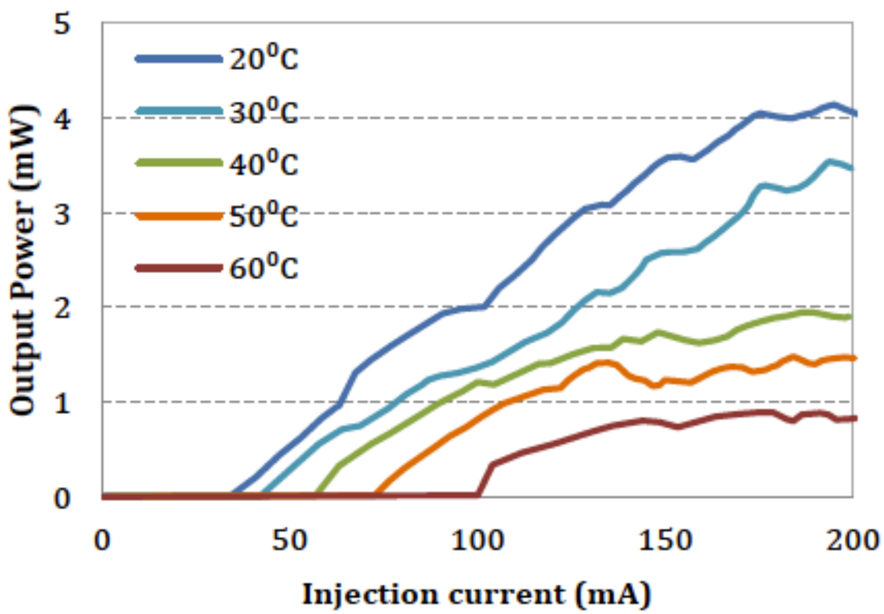
III-V/Si extended cavity laser

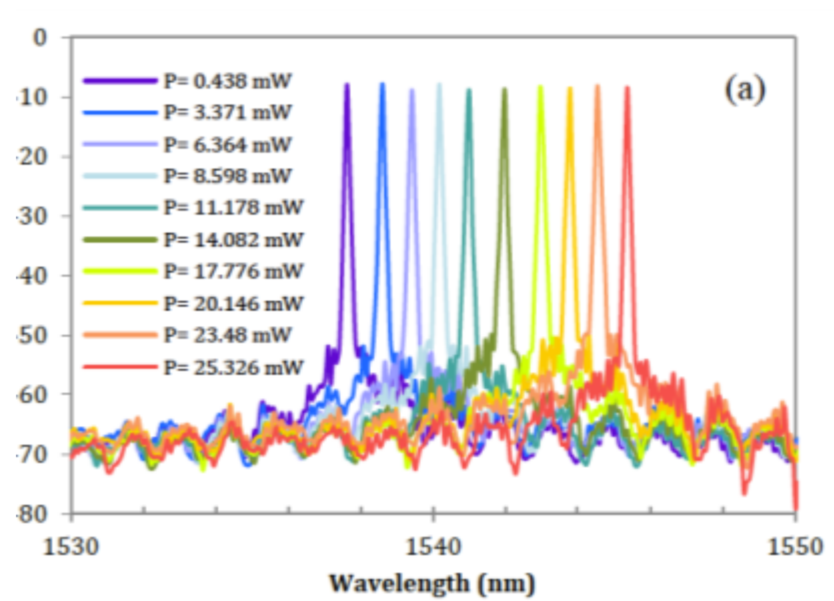


III-V/silicon tunable laser

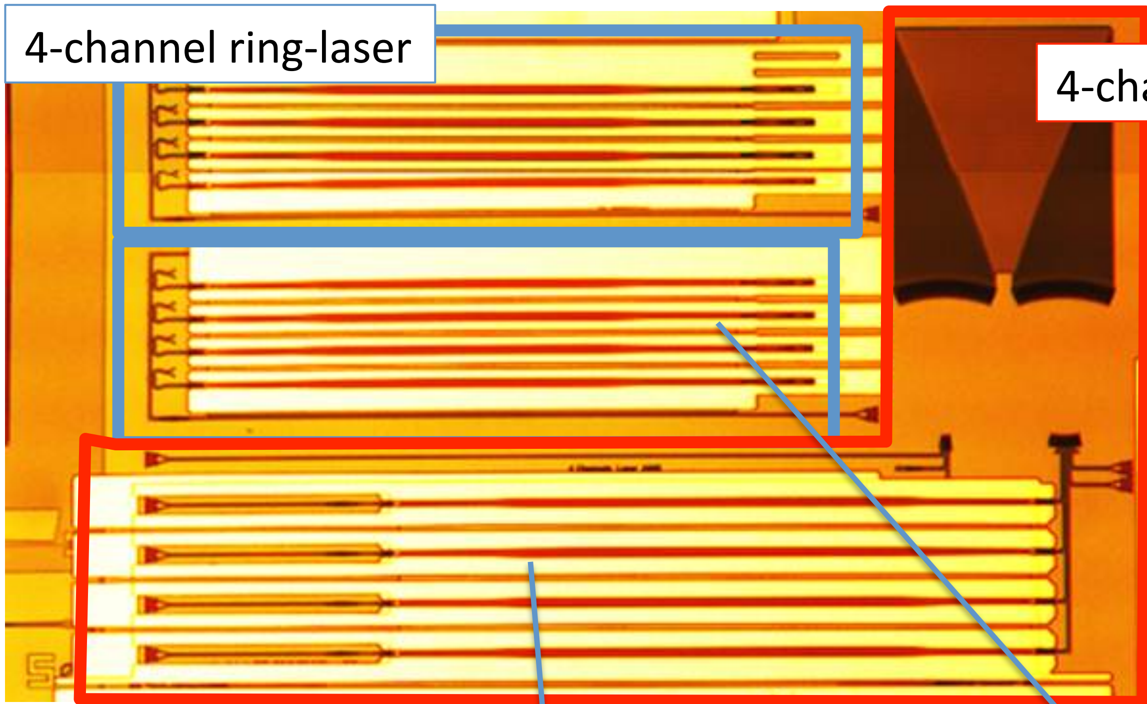
- 8nm tuning range, based on thermo-optic tuning of silicon ring resona
- > 40dB SMSR
- threshold of 35mA
- 4mW optical output power
- co-integrated with 10G silicon electro-optic modulator

•Realized in EU-project HELIOS (jointly with CEA-LETI, III-V labs)

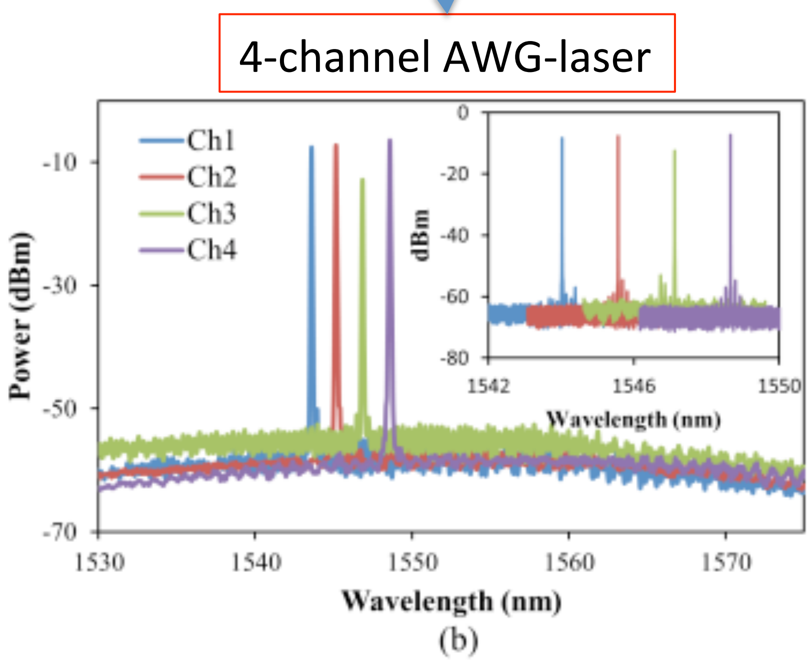


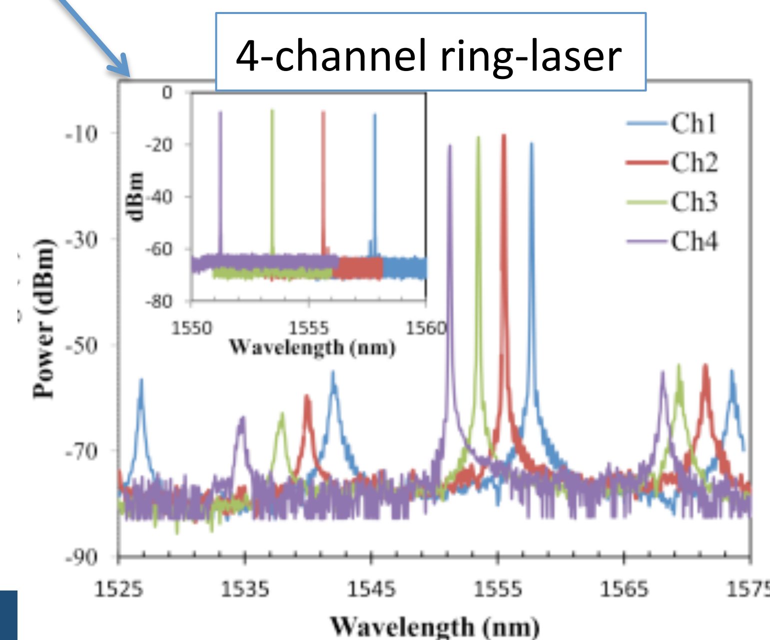


Keyvaninia, Opt Express 2012



Keyvaninia, Opt Express 2013





Integration

2D Scanners

Triplexers

Buffer Memories

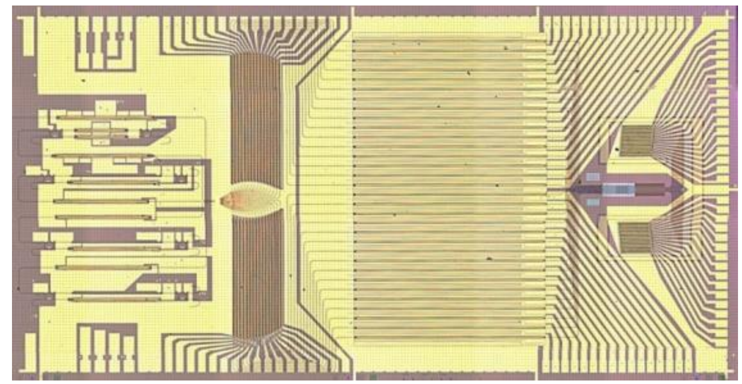
Mode Locked Lasers

UCSB

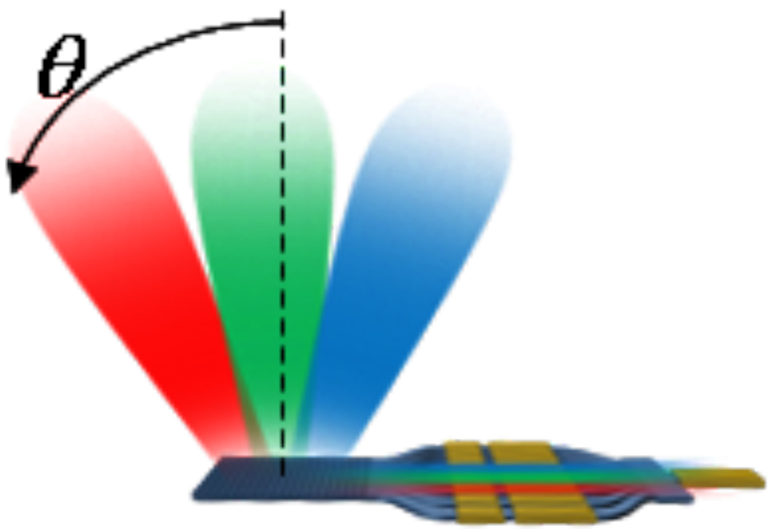
Fully Integrated hybrid silicon free-space beam steering source using a tunable laser phased array

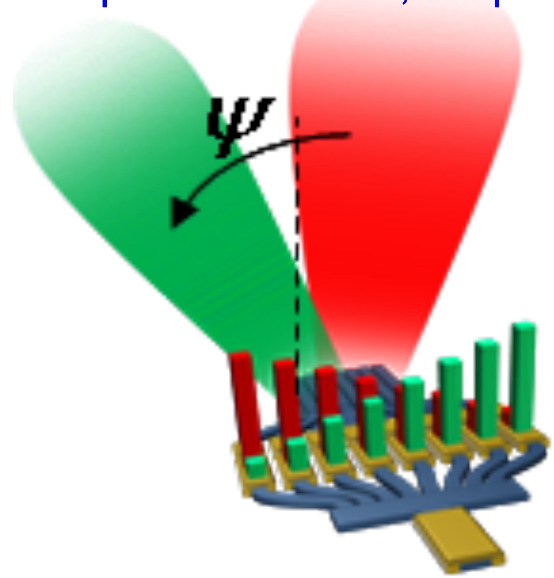
2D Scanning with
- Tunable laser and grating for θ
- Phased array emitter for ψ

Scaling: N+1, not N^2!



4 tunable lasers, 32 amplifiers,
32 phase shifters, 32 photodetectors



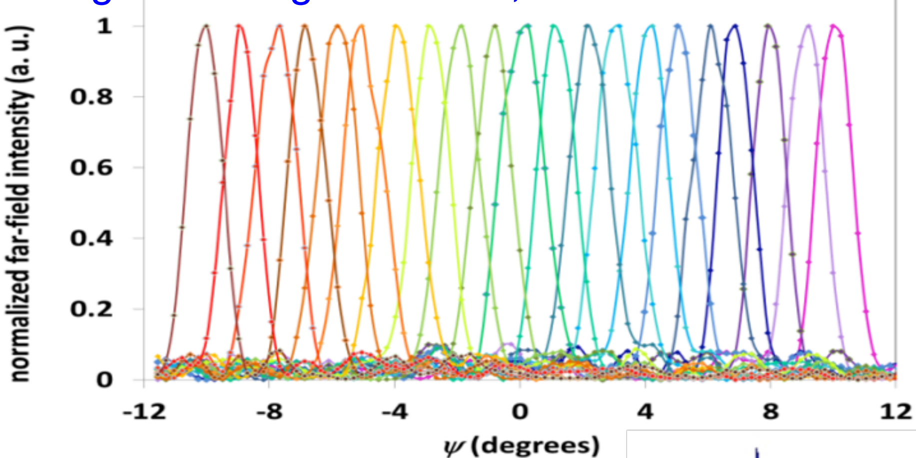


1 (wavelength)

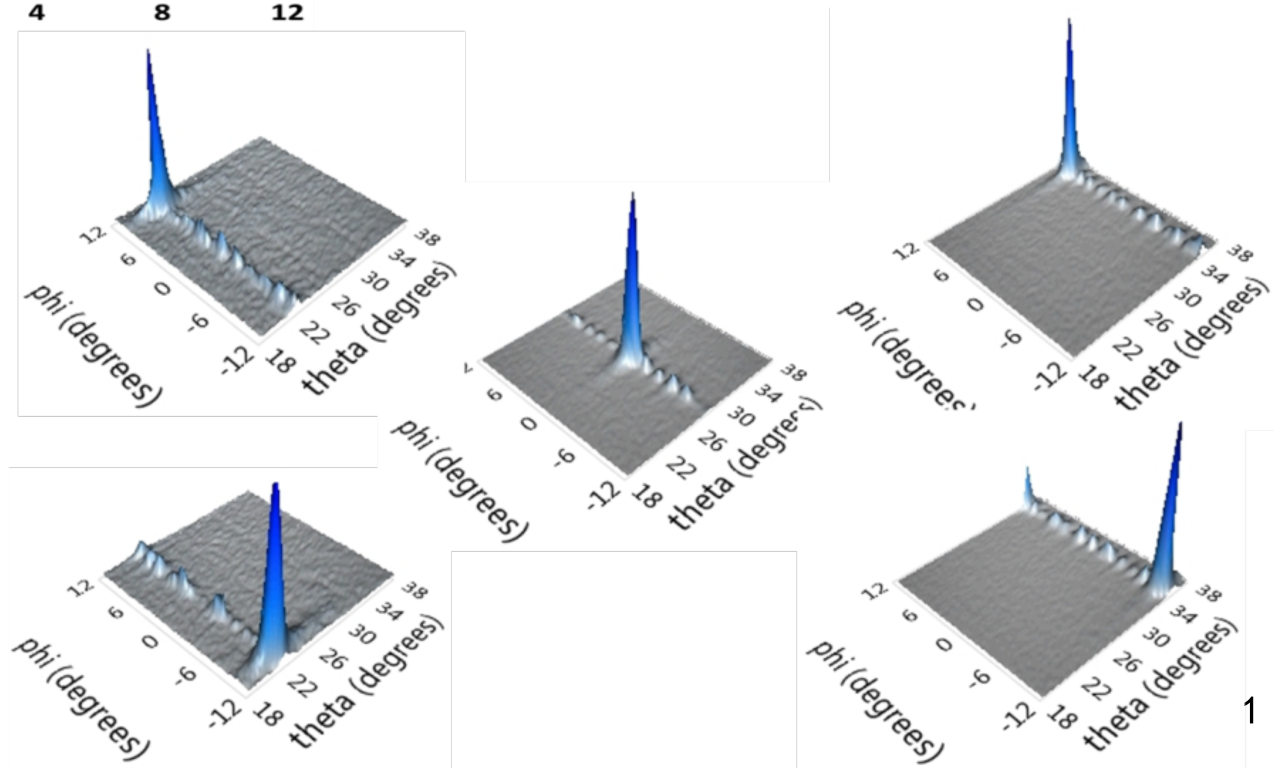
N (number of emitters)

2D Beam Scanning

1° angular tuning resolution, 1.6° FWHM beam width



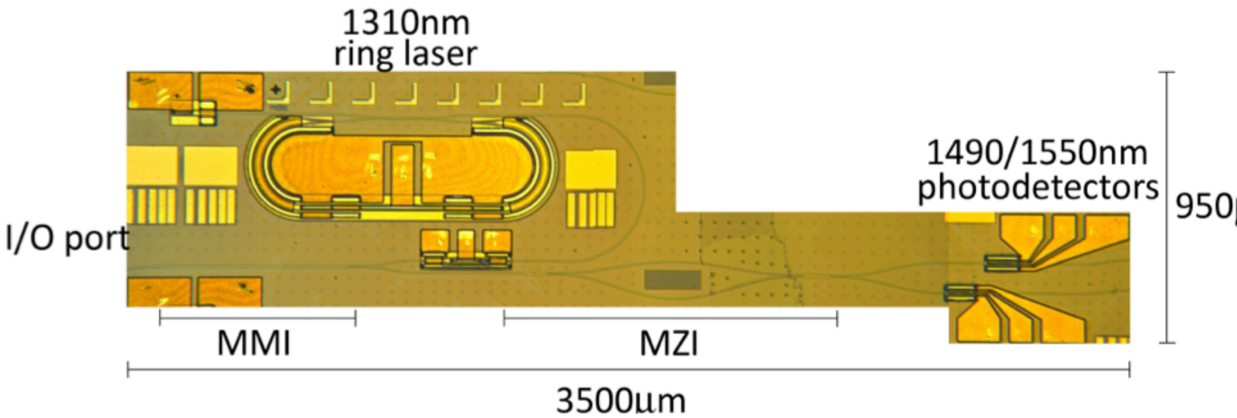
- Beam angle can be arbitrarily chosen within a 20° x 14° window

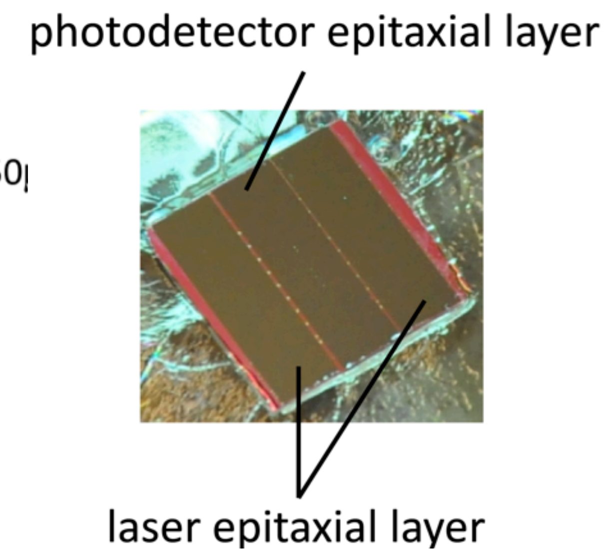


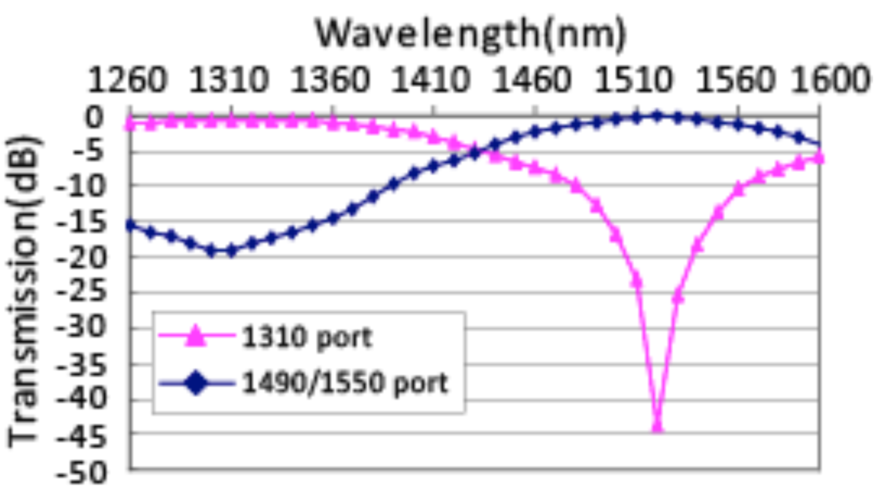
Doylend *et* al., SPIE 2013.

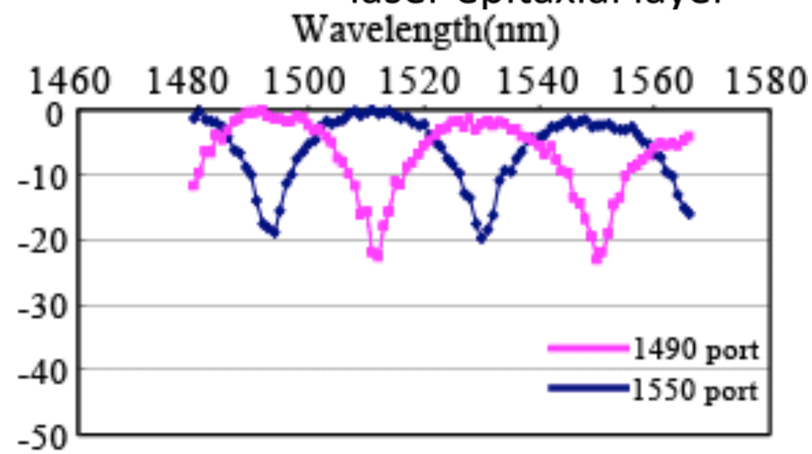
Hybrid Silicon Triplexers

Laser, 1310/1500 nm MUX MMI, MZI 1550/1490 MUX, PDs integrated





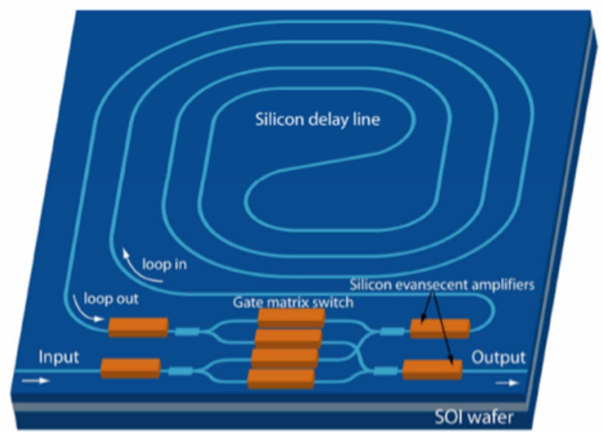


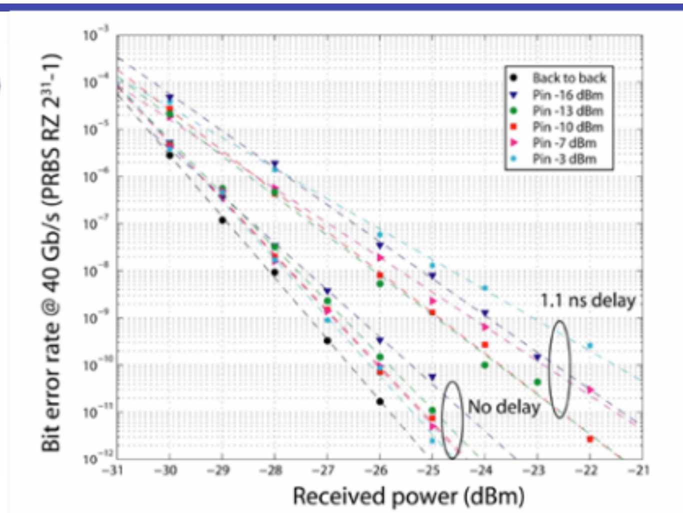


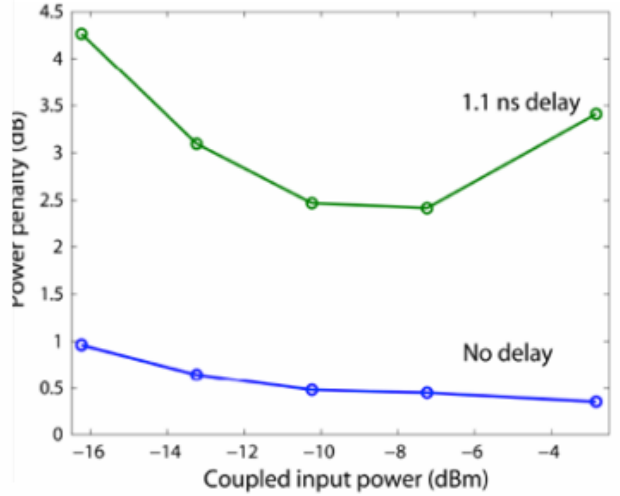
Chang et al. OFC 2010

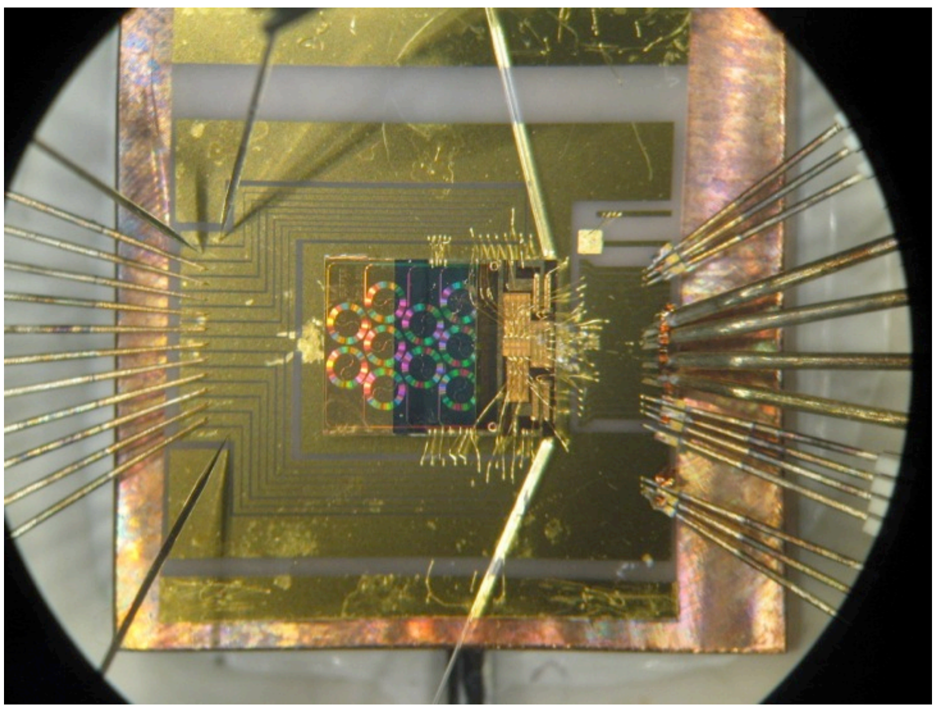
UCSB

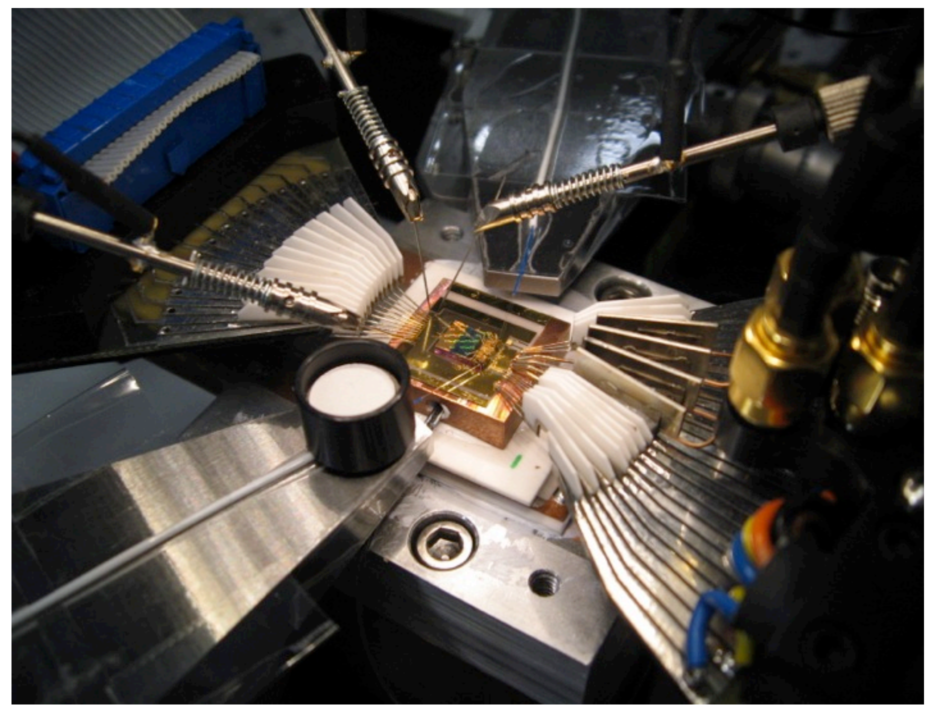
Optical Buffer Memory



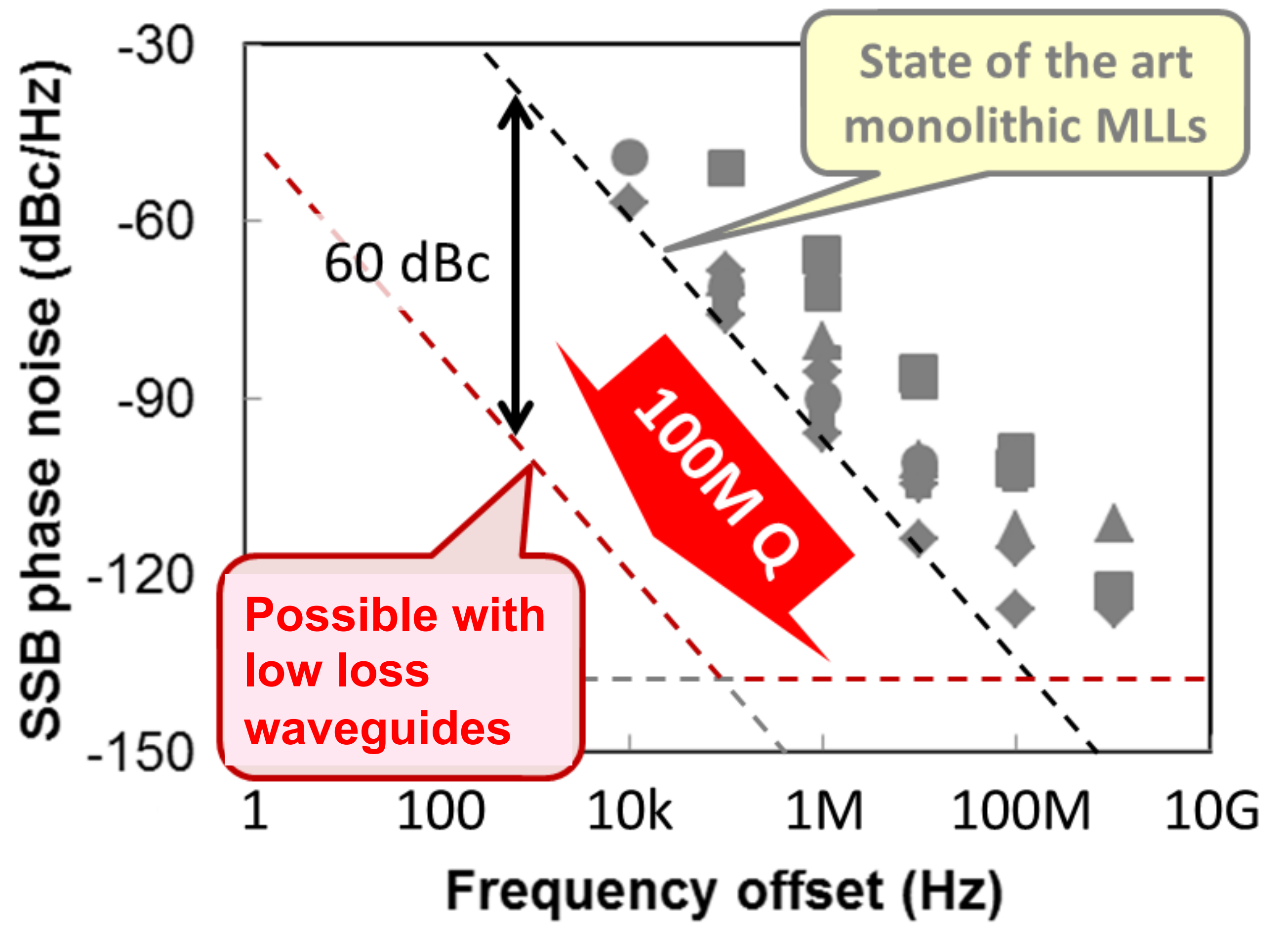






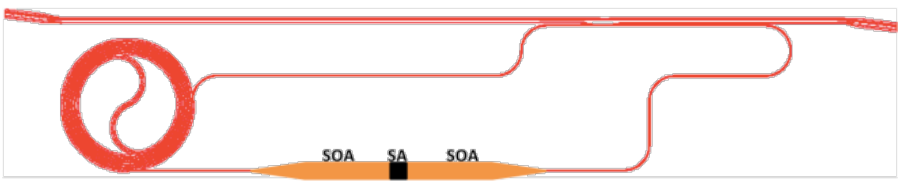


Lower Loss Waveguides for Low Jitter Mode Locked Lasers

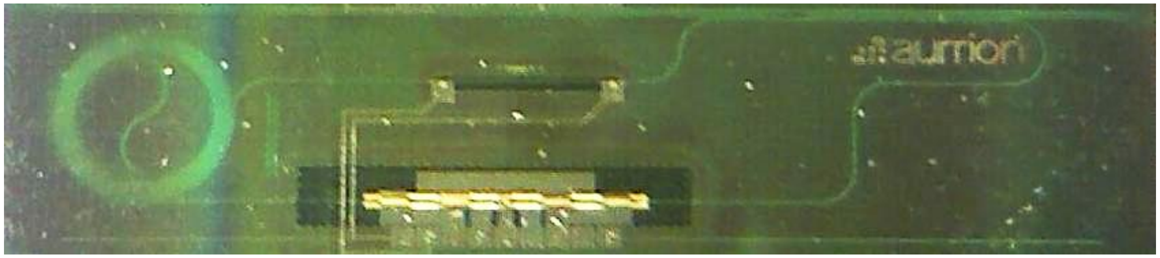


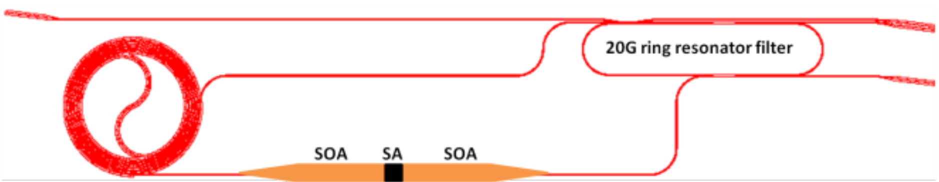
Mode Locked Laser Stabilization by Harmonic ML and Integration of Long Cavities

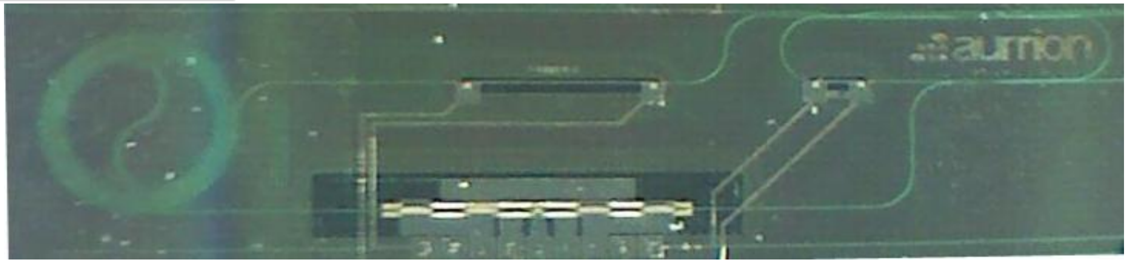
- Longer cavities for low phase noise
- Harmonic mode locking for high frequencies
- Multiple pulses in the cavity are not well coupled
- Intracavity etalon to stabilize



4cm cavity length

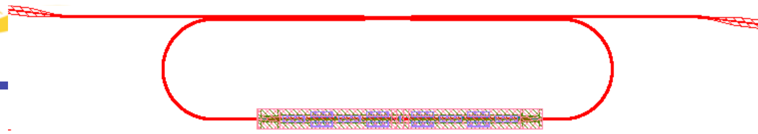


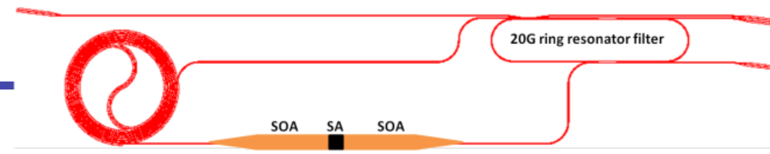




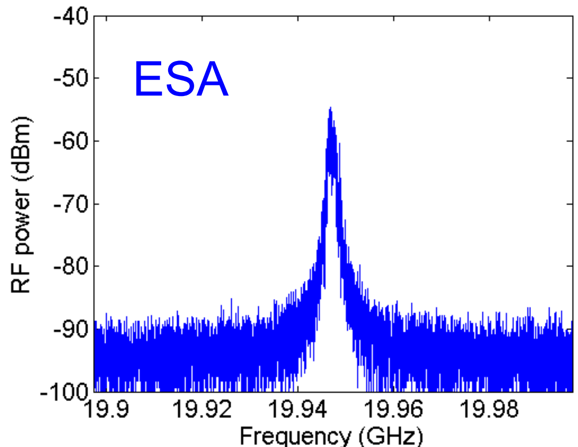
Sudha Srinivasan: Th3A.4. 2:00-2:15 PM – "Suppression of supermode noise in a harmonically mode-locked hybrid silicon laser using an intra-cavity filter."

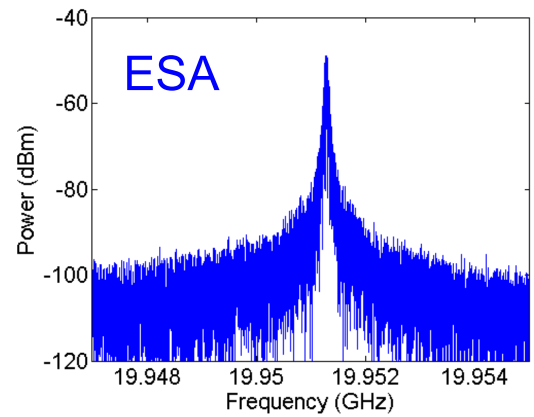
Passive Locking – comparison





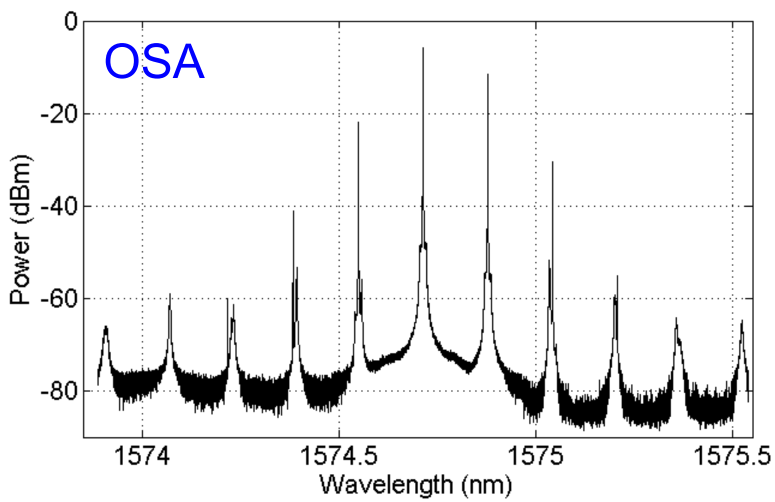
20G cavity – 188mA, 0 V

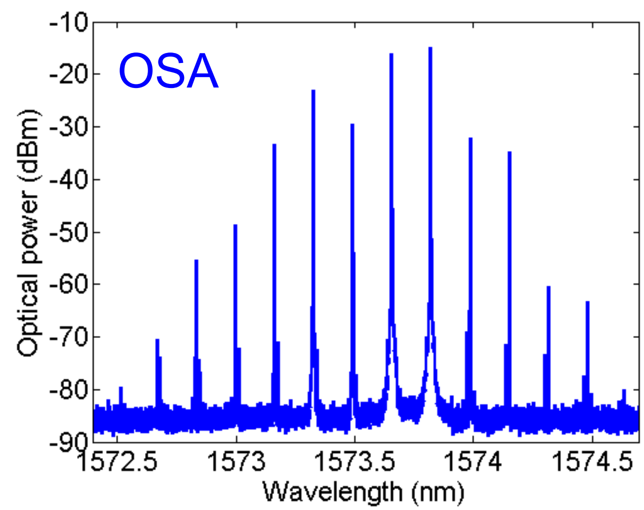




2G cavity with filter -220mA, -0.5V

Linewidth improvement – 1.5MHz → 52kHz (30x)





SOA lengths 900mm and 1.4mm respectively.
Absorber length 50mm in both cases

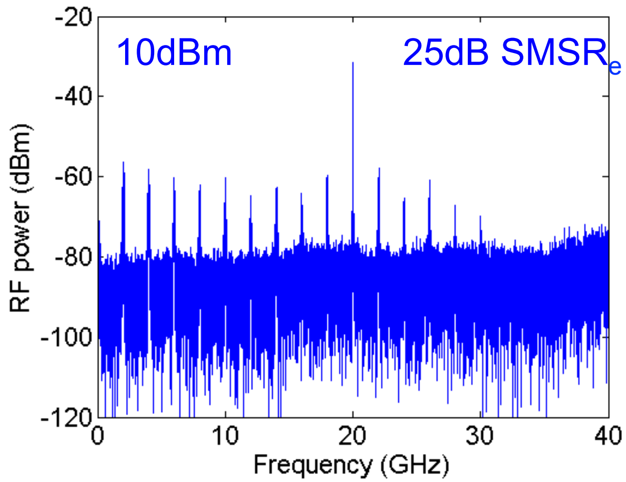
Srinivasan et al. JSTQE 2013

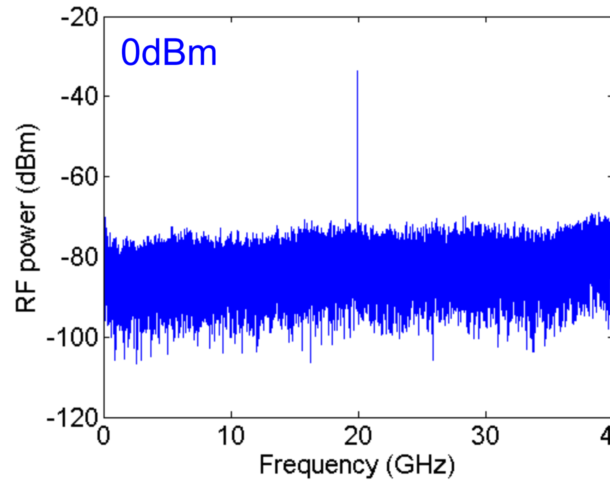
Hybrid locking – comparison

Without Filter

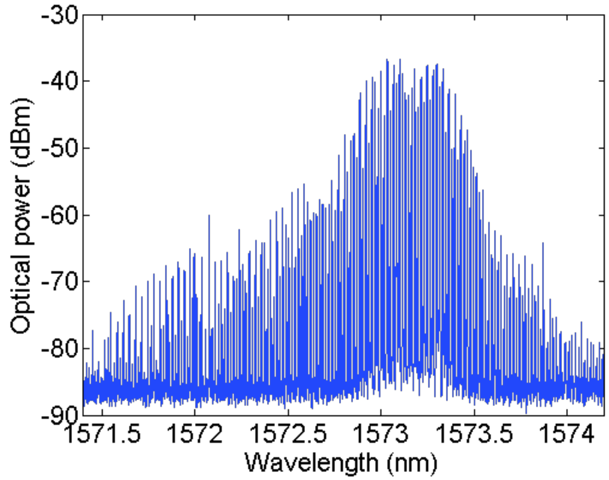
With Filter

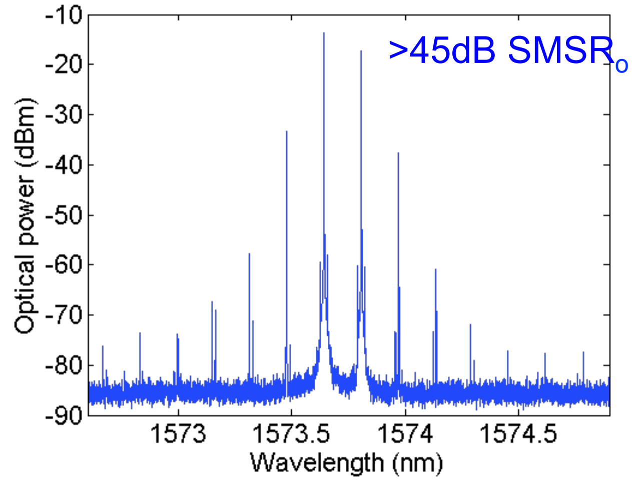
Electrical spectrum





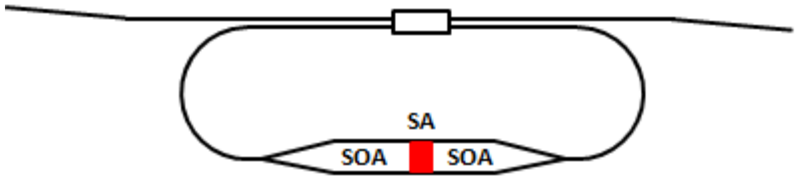
Optical spectrum



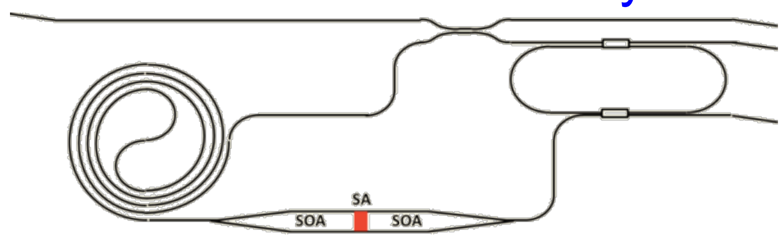


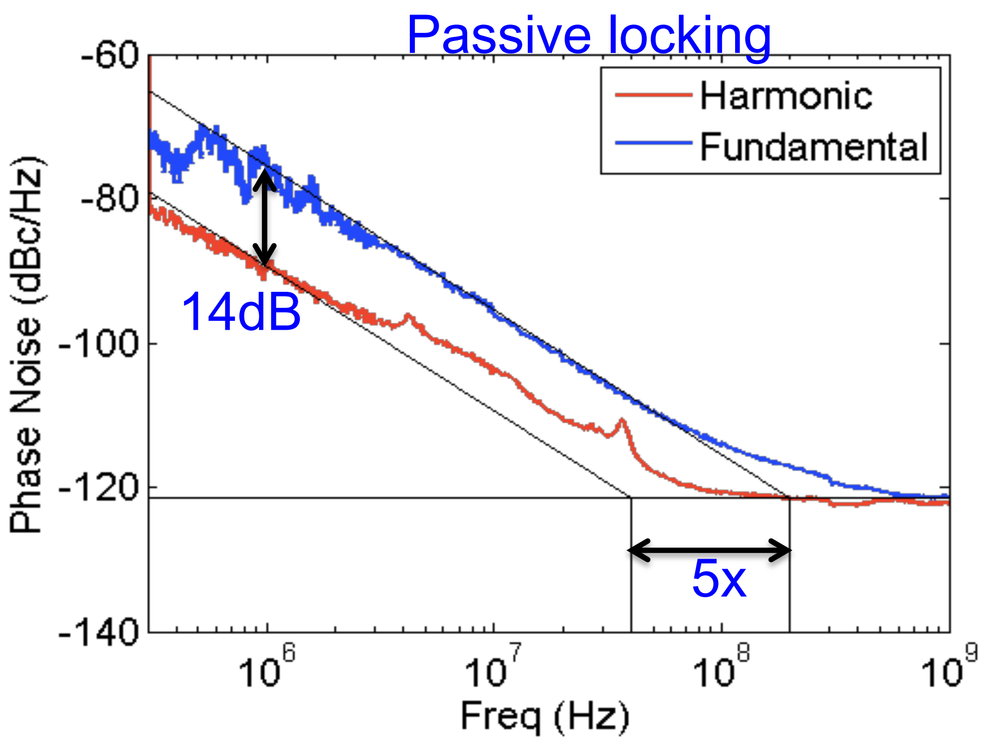
Advantage of Long Laser Cavity

Fundamental cavity



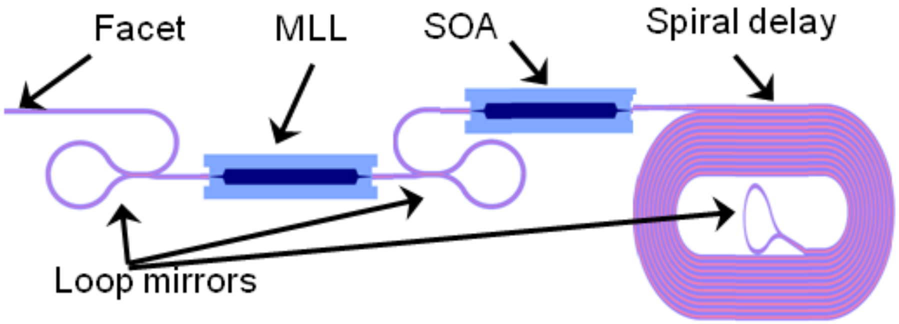
Harmonic cavity

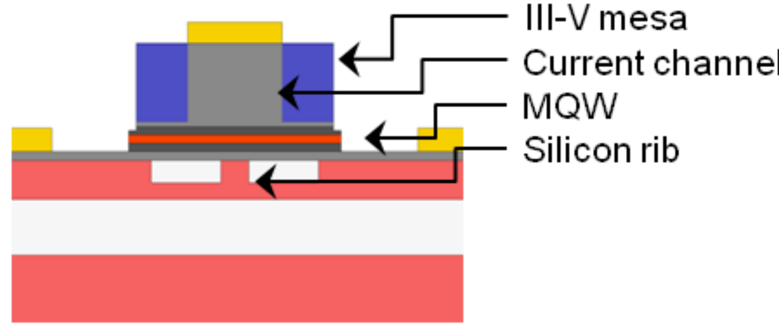




UCSB

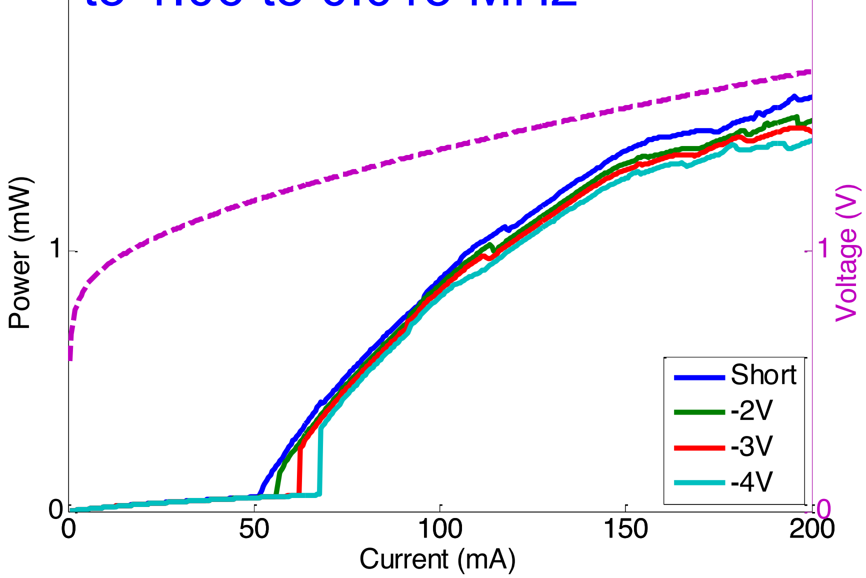
Integrated Feedback Stabilized Mode-Locked Laser

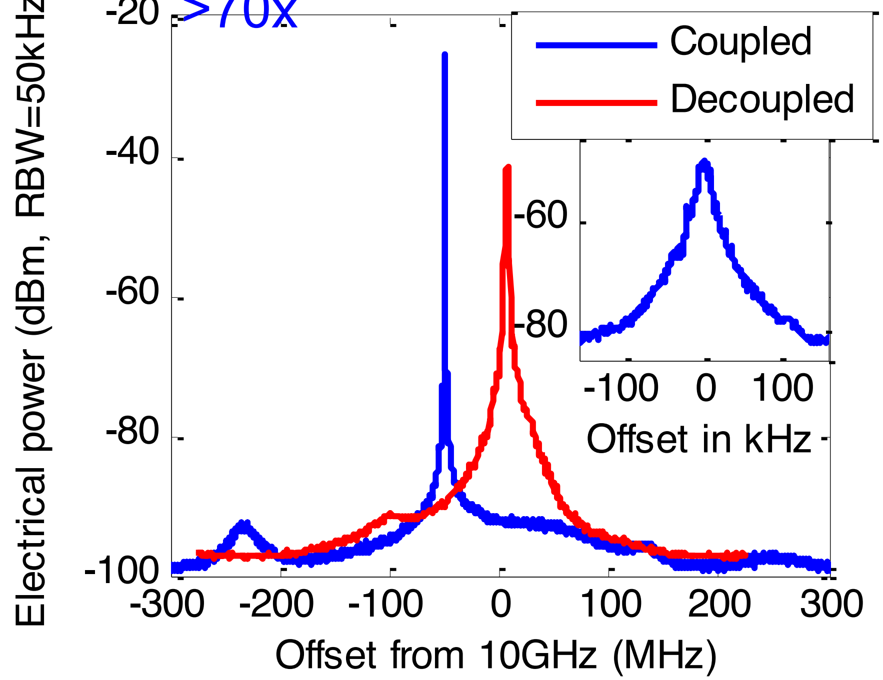




- Passive mode locking at 10 GHz
- Microwave linewidth reduction from to 1.06 to 0.015 MHz

RF Linewidth reduction >70x





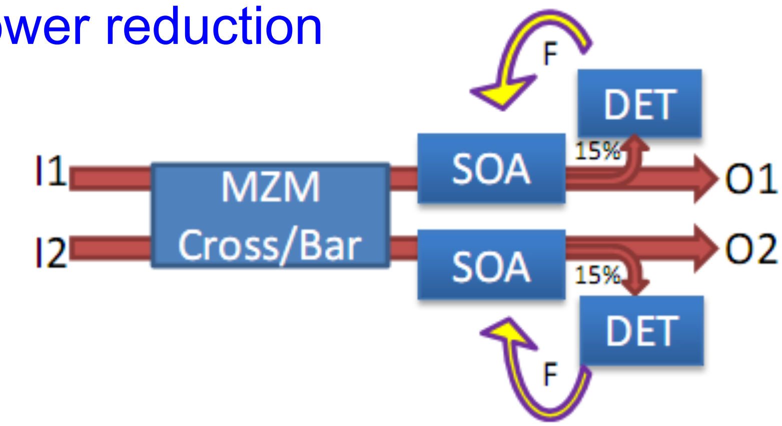
Davenport et al. OFC 2014

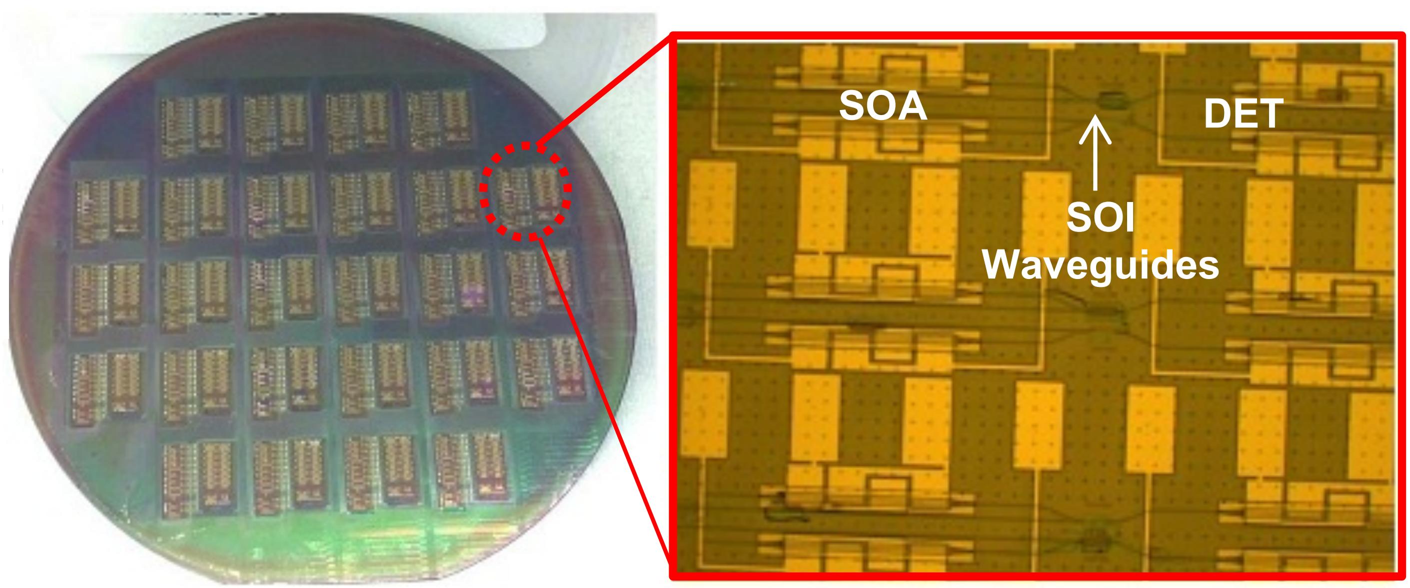
Integration with Electronics

CMOS Integration in Photonic IC

Chen et al. OFC and Communications Magazine (2013)

- "Smart Photonics" – Integrated electronic w/ photonic ICs
- Avoid driving 50Ω terminations Power reduction
- Self-calibration
- Active feedback control

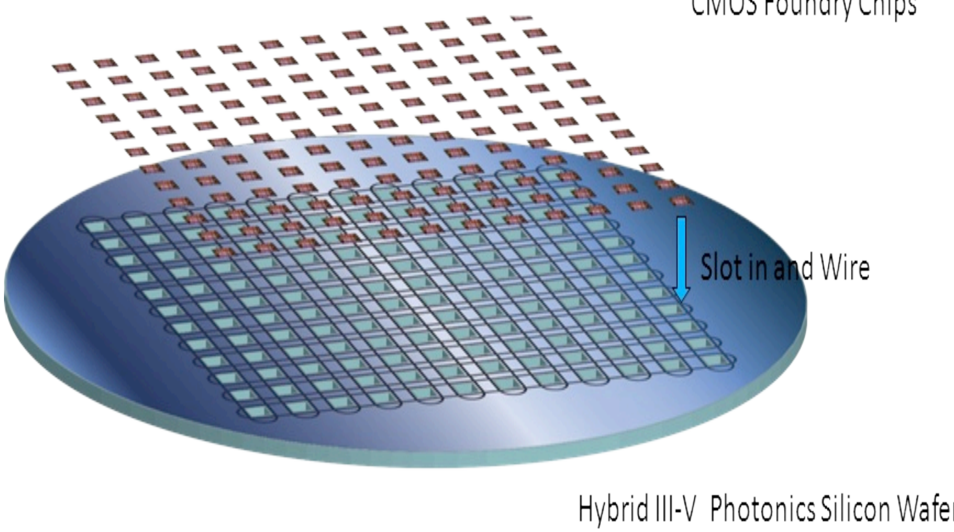


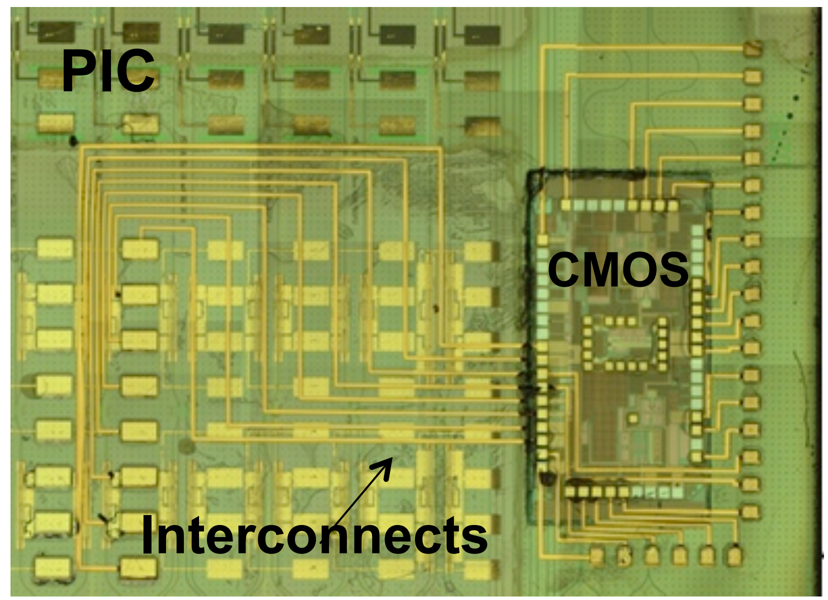


Hybrid Silicon PIC from Aurrion

CMOS Integration in Photonic IC
(with Theogarajan)

- "Smart Photonics" – Integrated electronic w/ photonic ICs
- Avoid driving 50Ω terminations
- Self-calibration
- Active feedback control

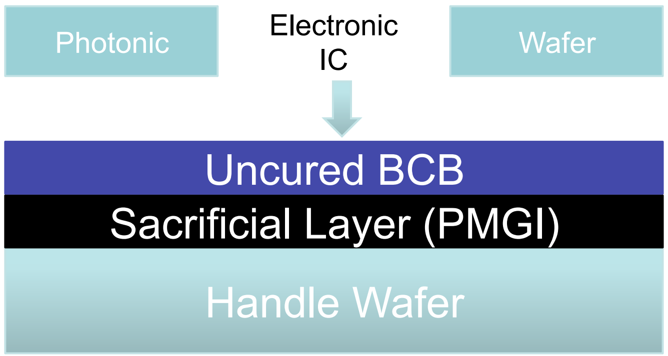




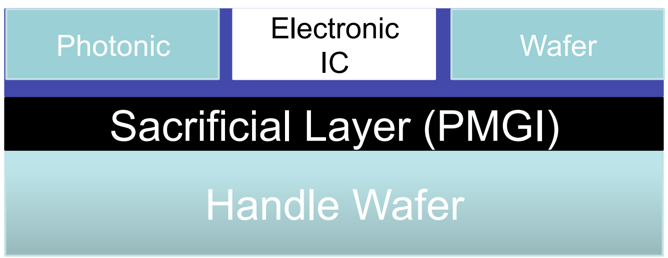
Chen et al. OFC 2013

Electronic-Photonic Integration

RDL First Process to ensure surface flatness



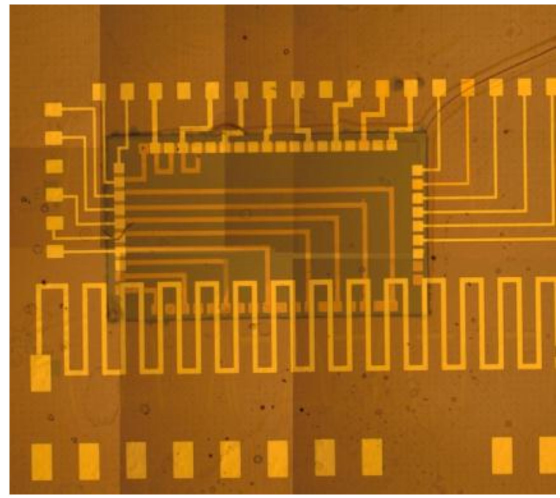
Place Etched Photonic Chip and Electronic IC



Release assembly from Sacrificial layer

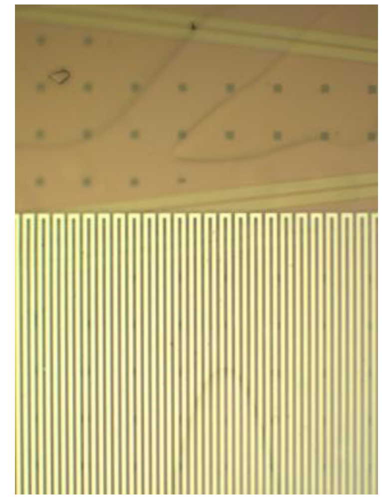
Etch electrical pad access and wire

20µm pitch and density

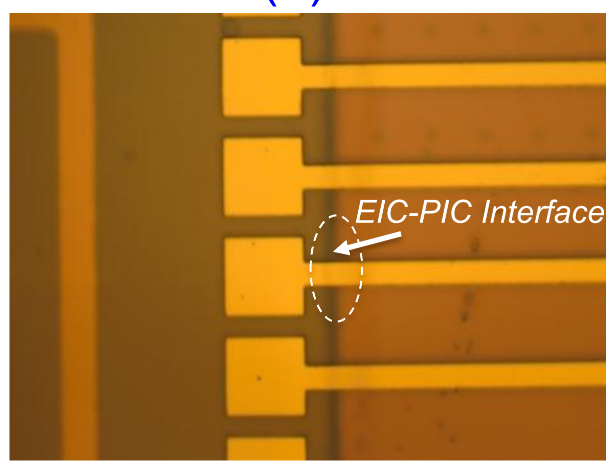


(a)

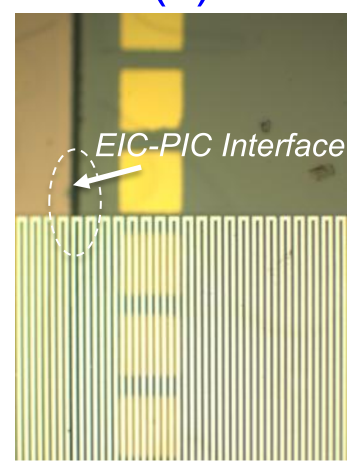
5µm pitch and density



(c)



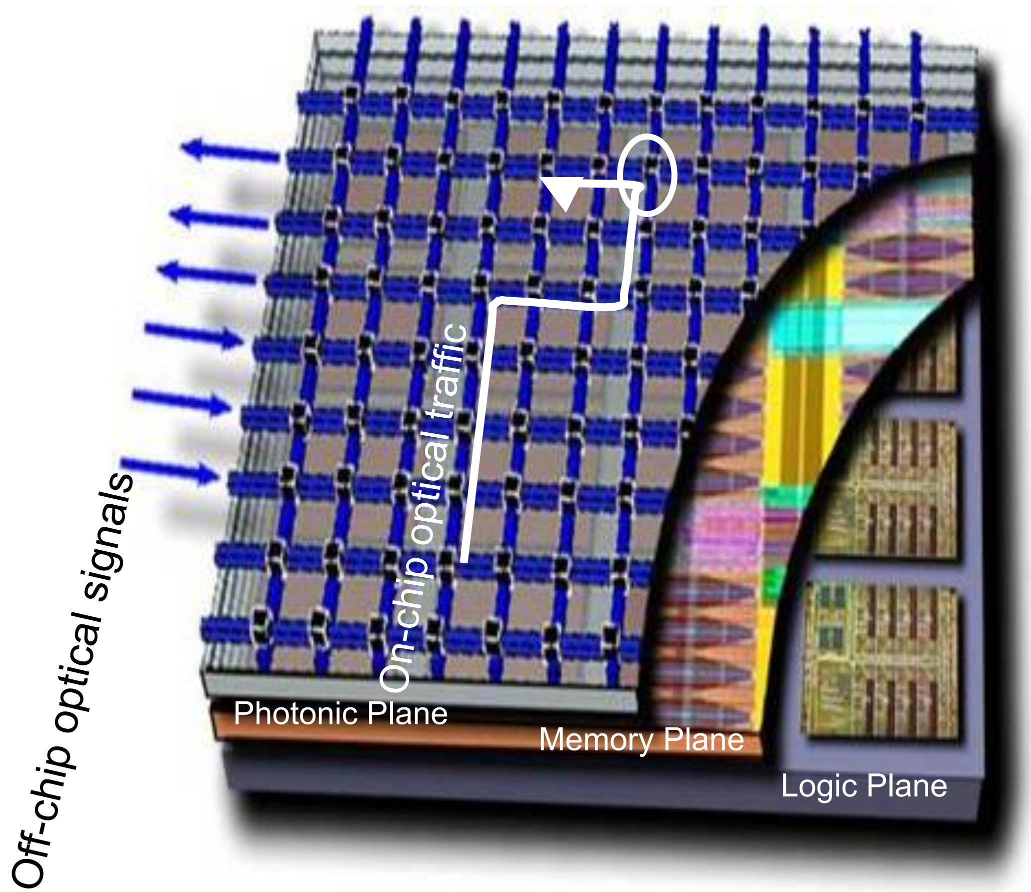
(d)



(d)

Network on a Chip: Optical Interconnects

- 3D layer stacking will be prevalent in the 22nm timeframe
- Intra-chip optics can take advantage of this technology
- Photonics layer (with supporting electrical circuits) more easily integrated with high performance logic and memory layers
- Layers can be separately optimized for performance and yield



Kash, “Photonics in Supercomputing: the Road to Exascale,” IPNRA, 2009

Commercialization

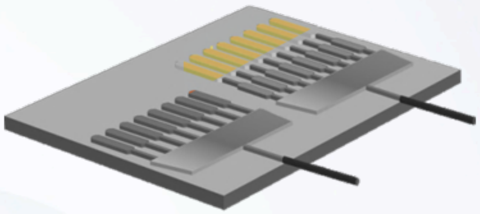
Aurrion

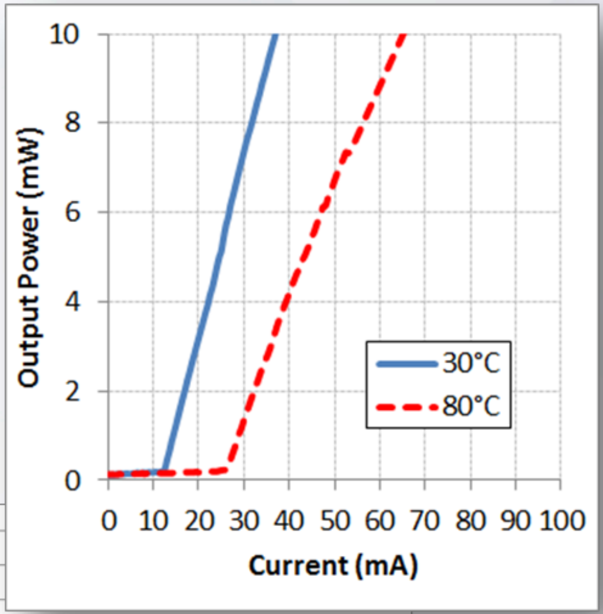
Intel

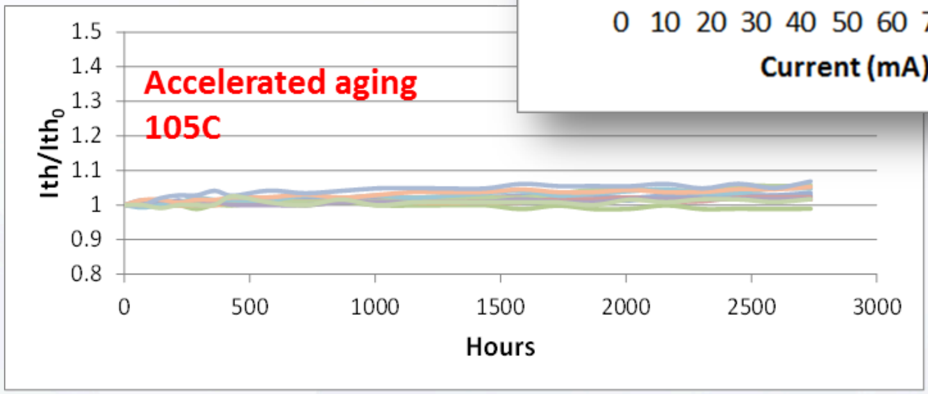
Hewlett Packard

Integrated Lasers

- **III-V gain integrated on silicon waveguides**
- **High power/High efficiency**
  - >25% at 30C
  - 15% at 80C
  - >20mW

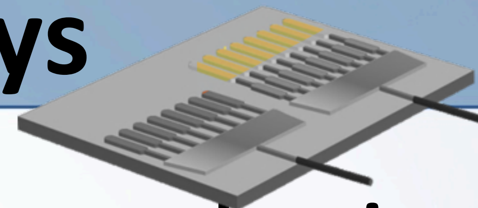




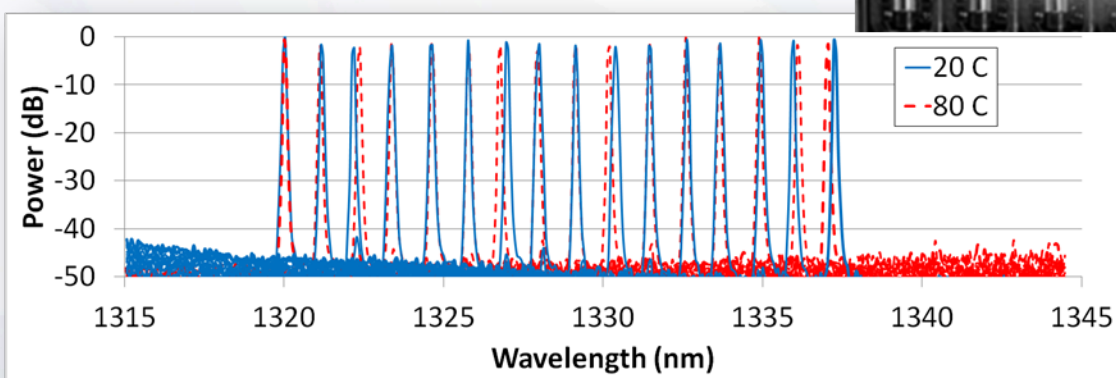


aurrion

WDM Laser Arrays



- **High yield integrated laser breaks cost barrier**
  - Large WDM arrays processed in parallel
- **Uncooled operation**
  - Wavelength-locking across temperature (20-80C) without a TEC
  - 200GHz (or 800GHz) grid

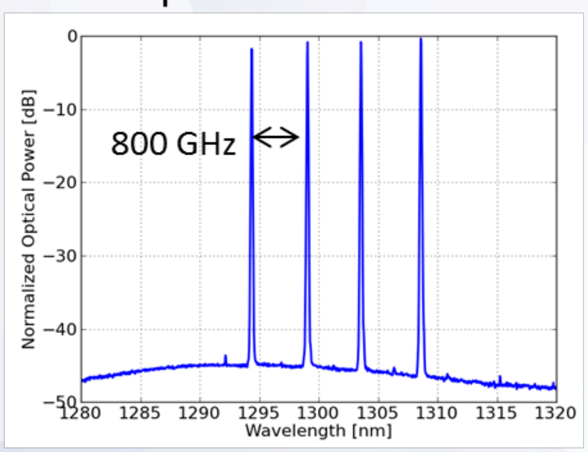


100G PIC Links

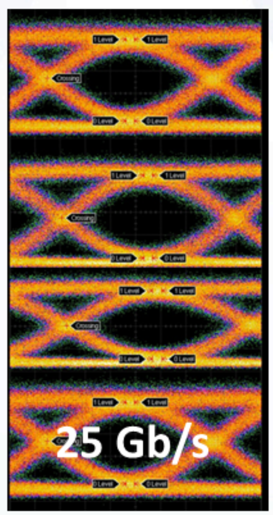
100G WDM Tx PIC

100G WDM Rx PIC

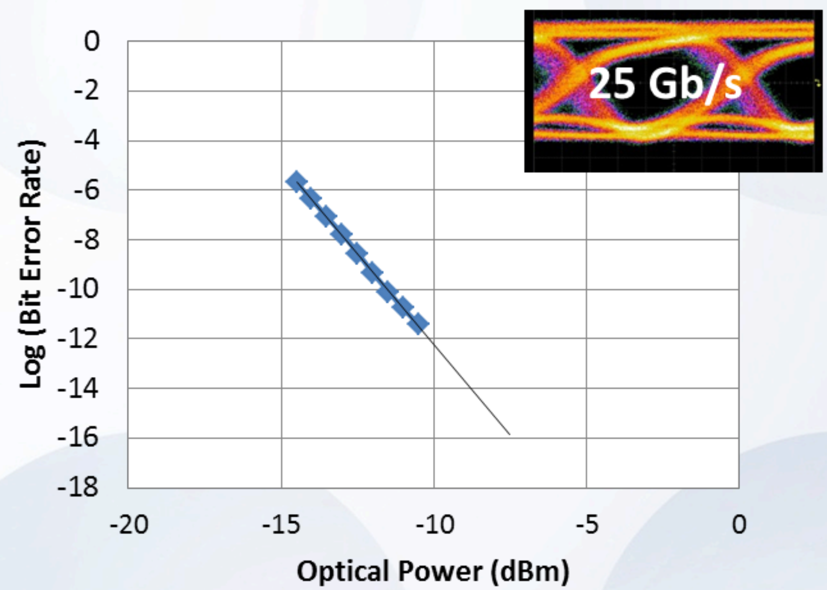
Laser Spectrum



Tx Eye Diagrams

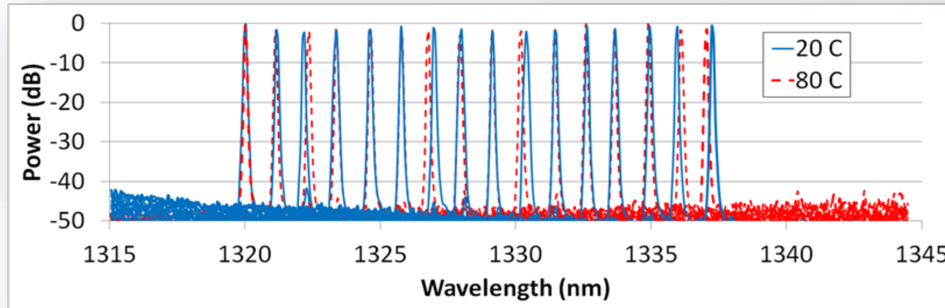


Rx Eye Diagram

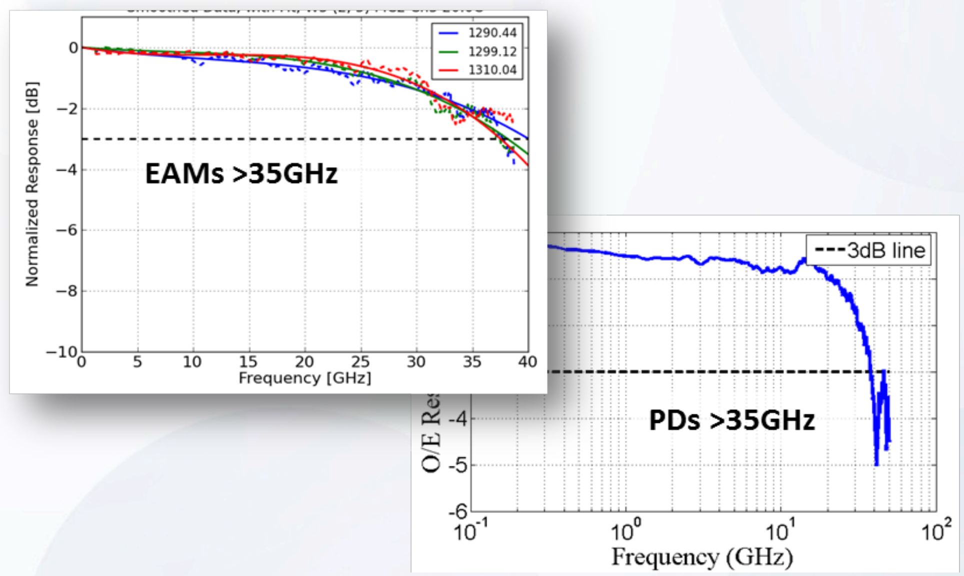


Scaling to 400G+

- **Uncooled 16x laser arrays on silicon demonstrated**
  - Locked to 200GHz grid from 20-80C = no TEC required

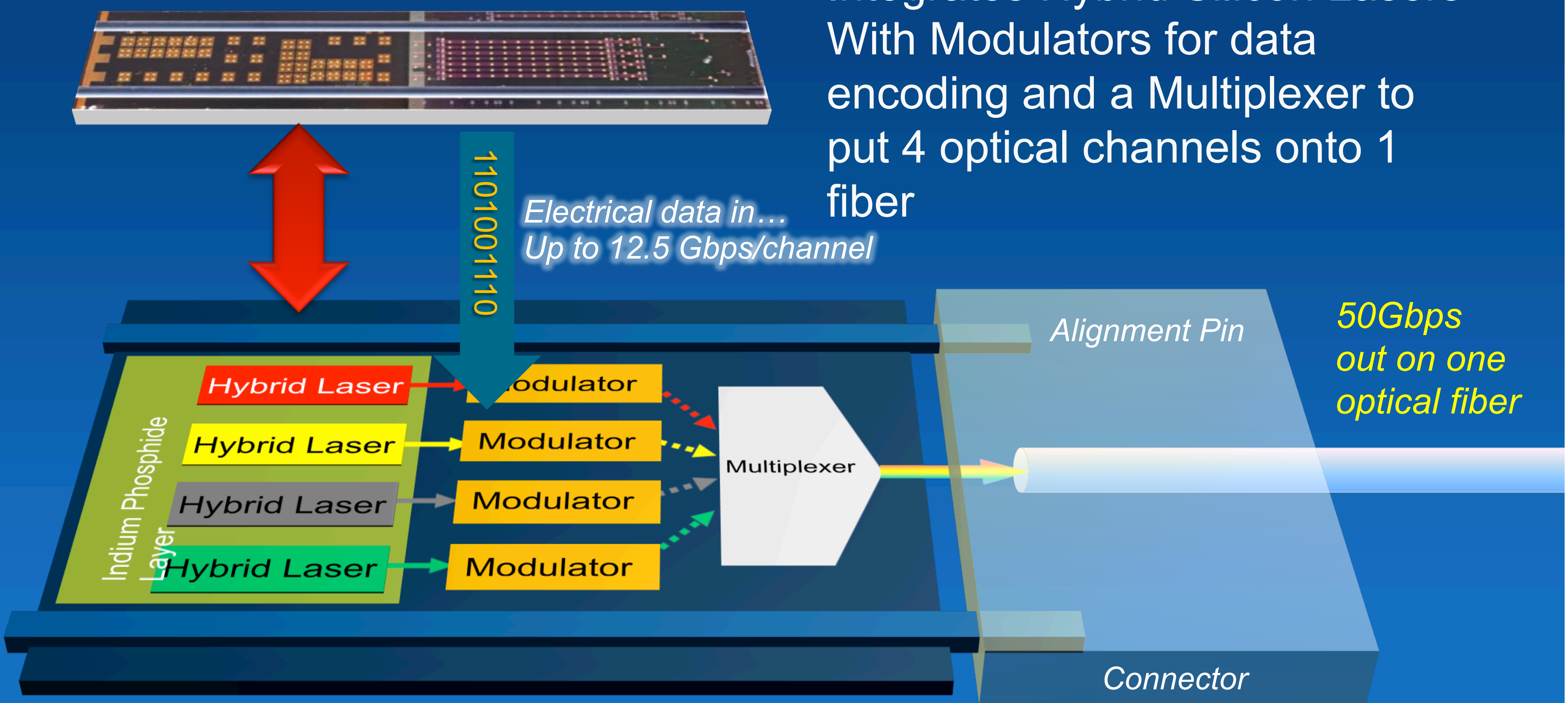


- **3dB bandwith of EAMs & PDs >37 GHz**
  - Supports 50Gb/s



Integrated Transmitter Chip

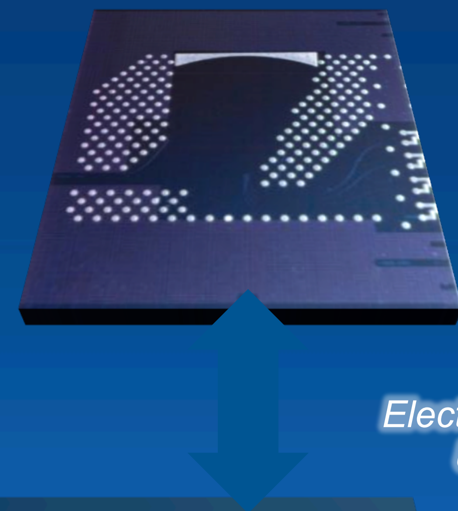
Integrates Hybrid Silicon Lasers With Modulators for data encoding and a Multiplexer to put 4 optical channels onto 1 fiber

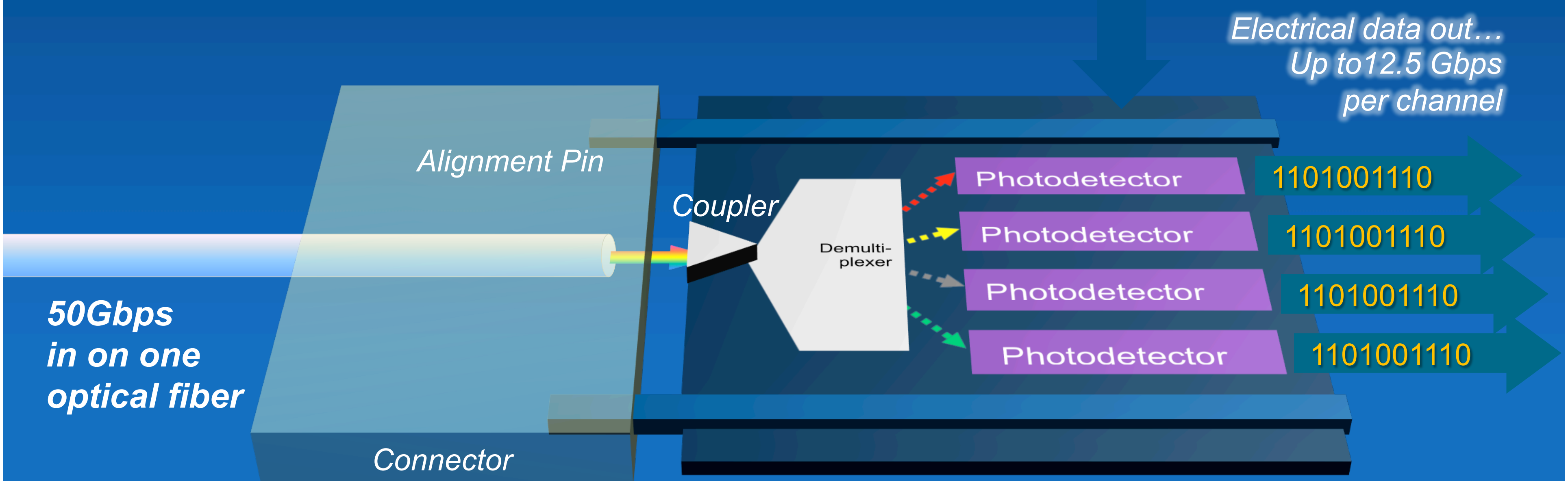


Parallel channels are key to scaling bandwidths at low costs

Integrated Receiver Chip

Integrates a coupler to receive incoming light with a demultiplexer to split optical signals and Ge-on-Si photodetectors to convert photons to electrons





Receives 4 optical channels at 12.5Gbps and converts to electrical data

Jan 2013 OCP – Facebook announcement

Frank Frankowsky
FB VP R&D

Justin Rattner
Intel CTO

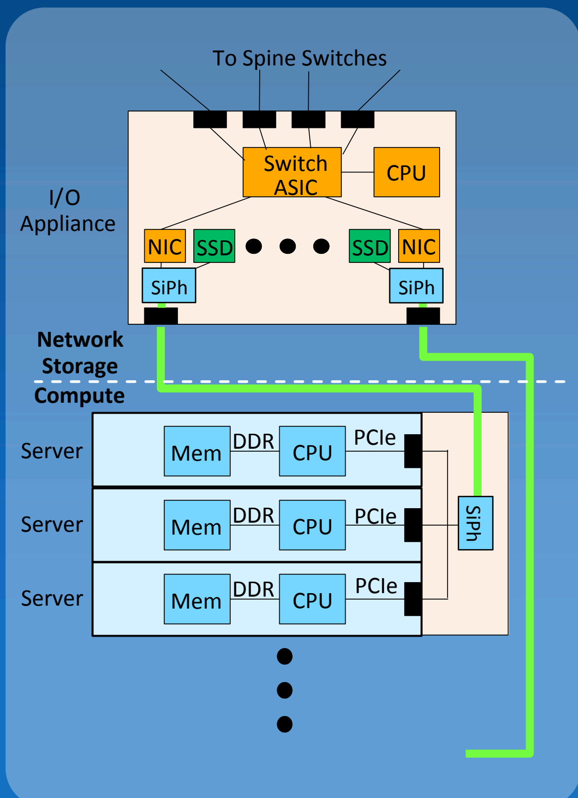
Andy Bechtolsheim
Arista: Founder and CEO
Sun: Founder and CTO

Announced at Facebook's Open Compute Summit

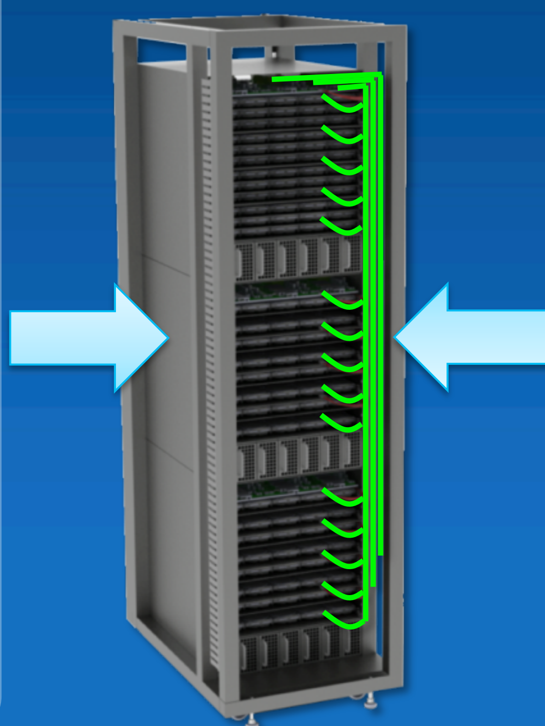
1. Intel is working with Facebook and Quanta to define a new class of server architectures
2. First architecture is disaggregation
3. Intel has sampled it's 100G photonic modules

Photonics in the Rack

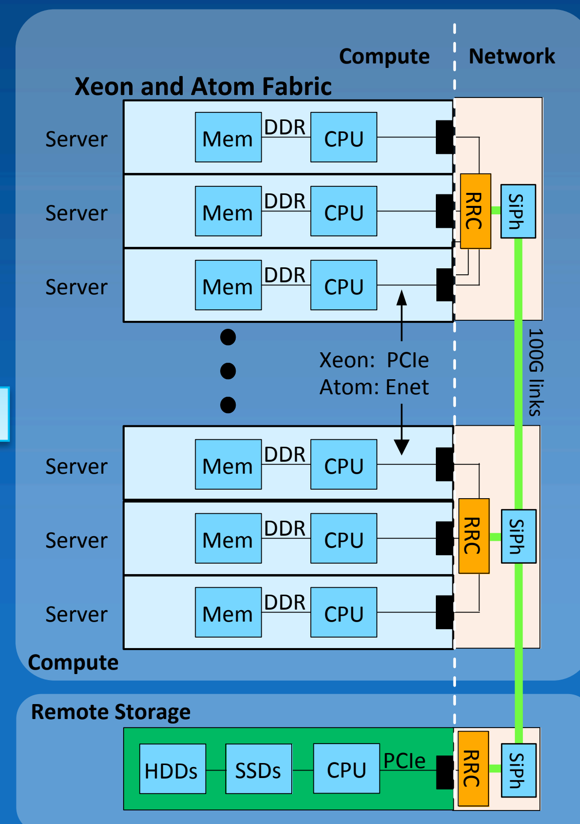
Network & Storage move
into TOR Switch



Optical Rack



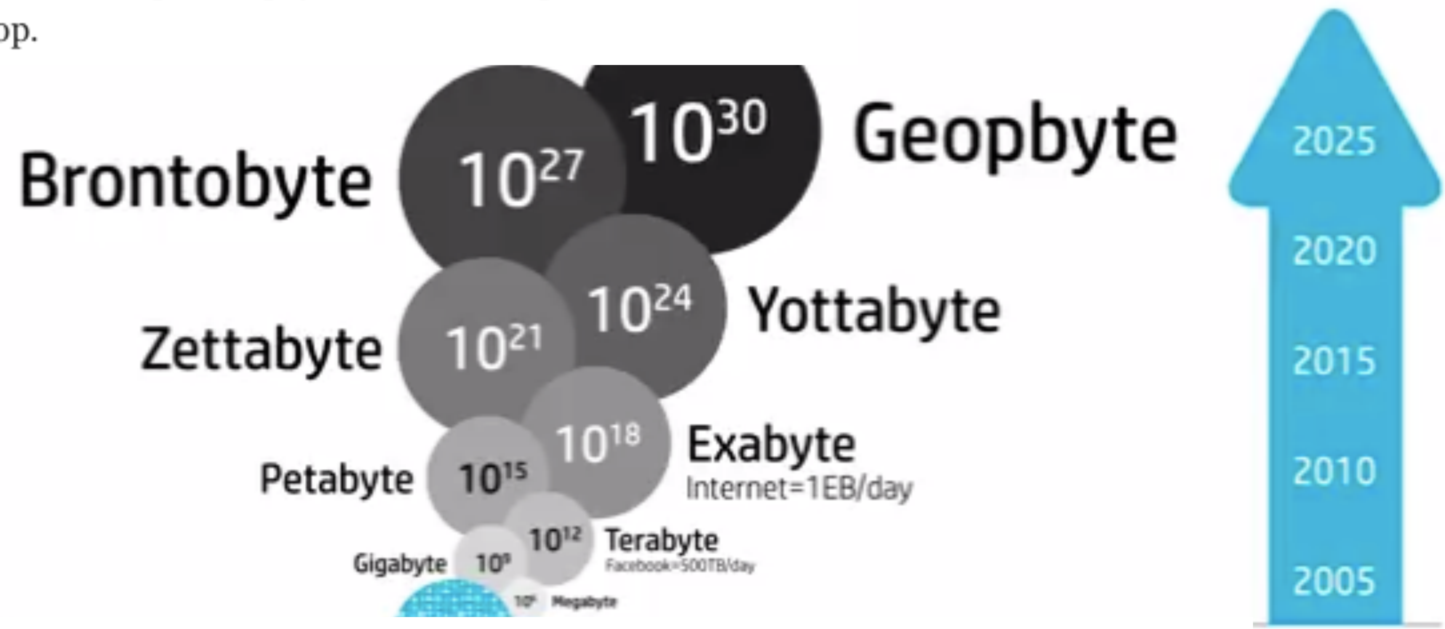
TOR Switch distributed
into Servers



Architecture offers flexible solutions and multiple Value Propositions

Hewlett Packard: “The Machine”

The Machine started to take shape two years ago, after Fink was named director of HP Labs. Assessing the company’s projects, he says, made it clear that HP was developing the needed components to create a better computing system. Among its research projects: a new form of memory known as memristors; and silicon photonics, the transfer of data inside a computer using light instead of copper wires. And its researchers have worked on operating systems including Windows, Linux, HP-UX, Tru64, and NonStop.

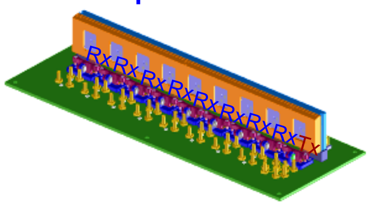


HP’s proposed silicon photonics would also be a big deal. HP, Intel (INTC), and others have been struggling to shrink speedy fiber-optic equipment enough to replace cheap, proven copper wiring inside a computer. In theory, fiber could also replace Ethernet cables and link entire racks of servers together.

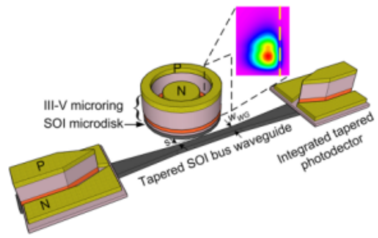
Supercomputing: HP photonics technologies

Active cable

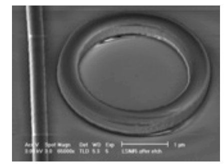
Optical bus



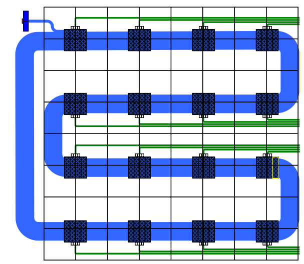
Hybrid microring laser



Silicon PIC



On-chip interconnect

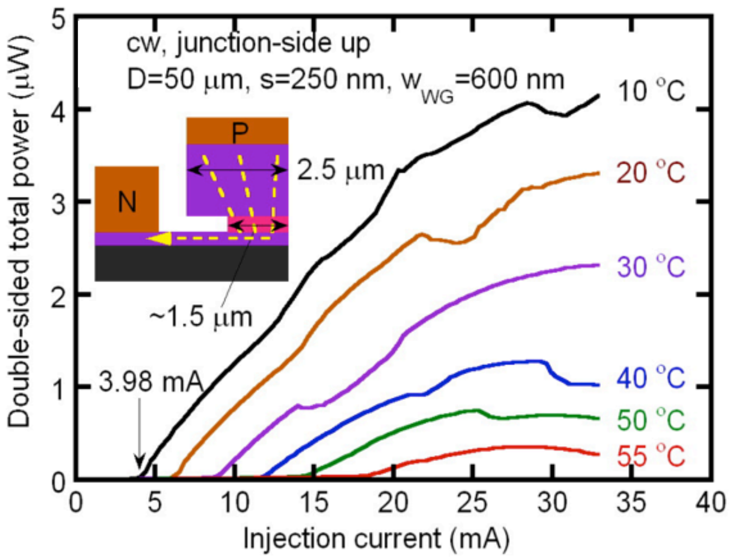


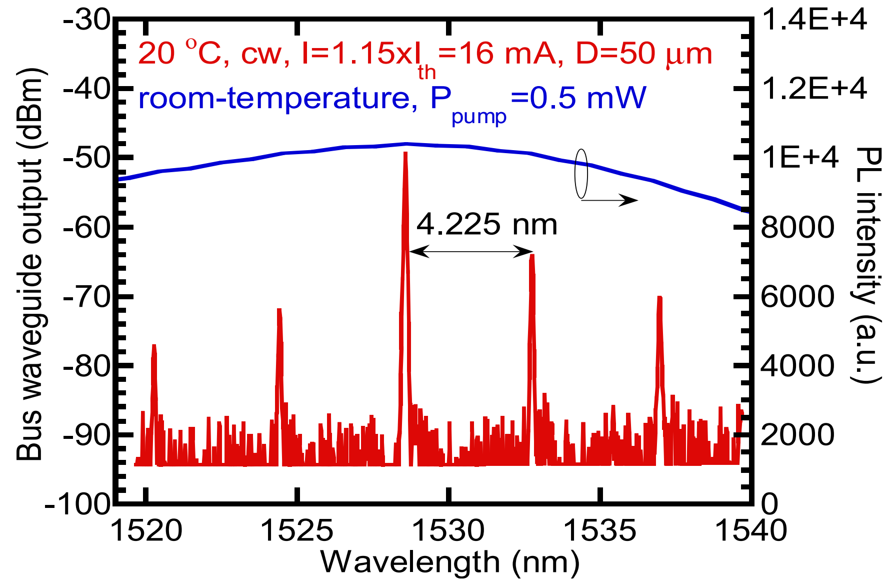
Now → 1 Year → 3 Years → 5 Years → 7 Years → 10 Years

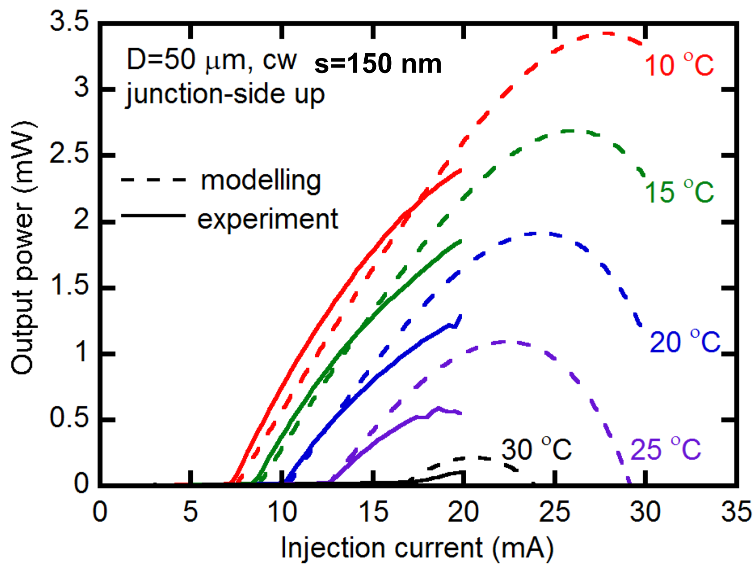
Single wavelength → CWDM → DWDM

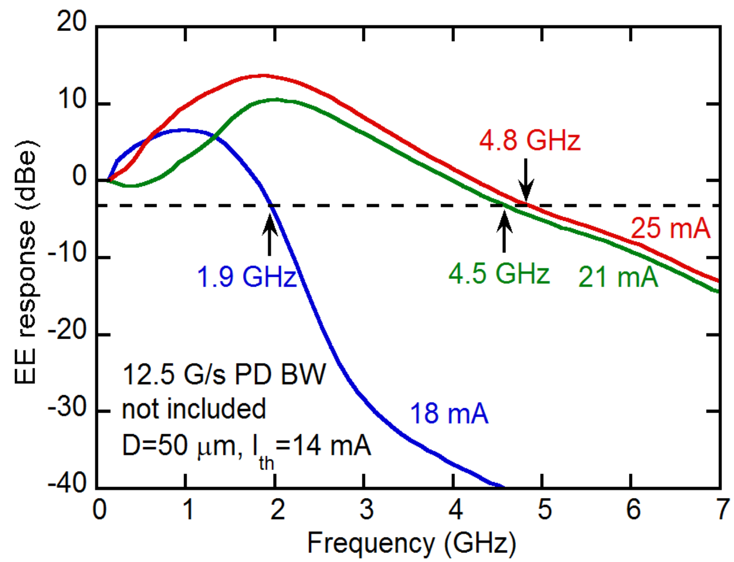
100 pJ/bit → >.1 pJ/bit

Device (50 mm) typical performance

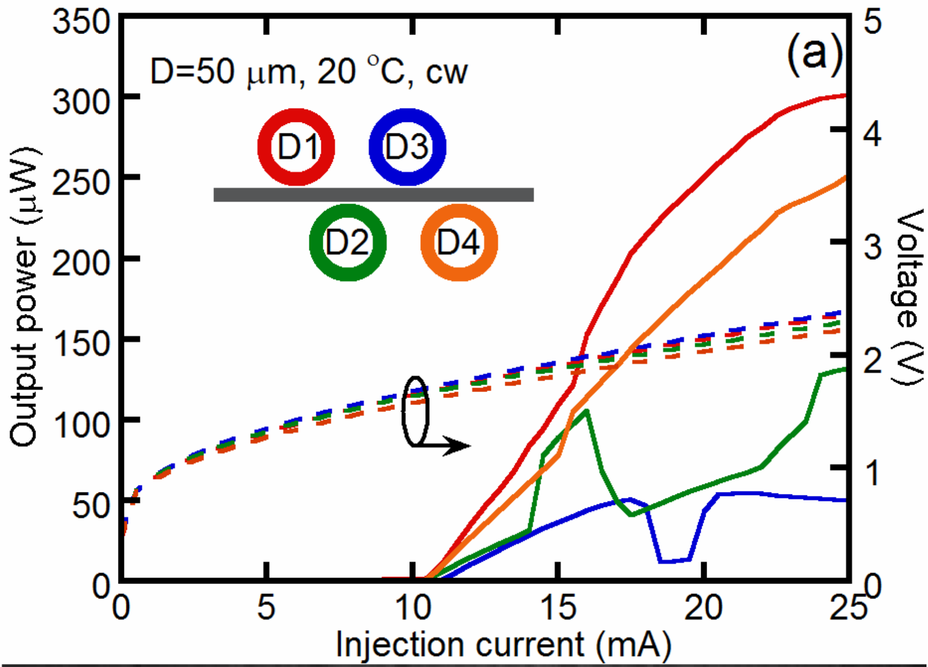


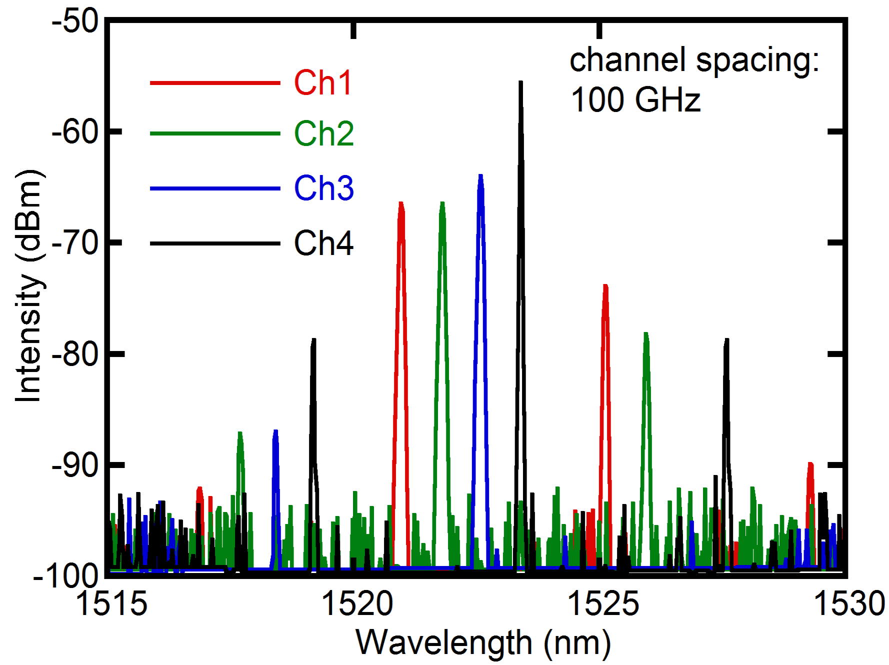


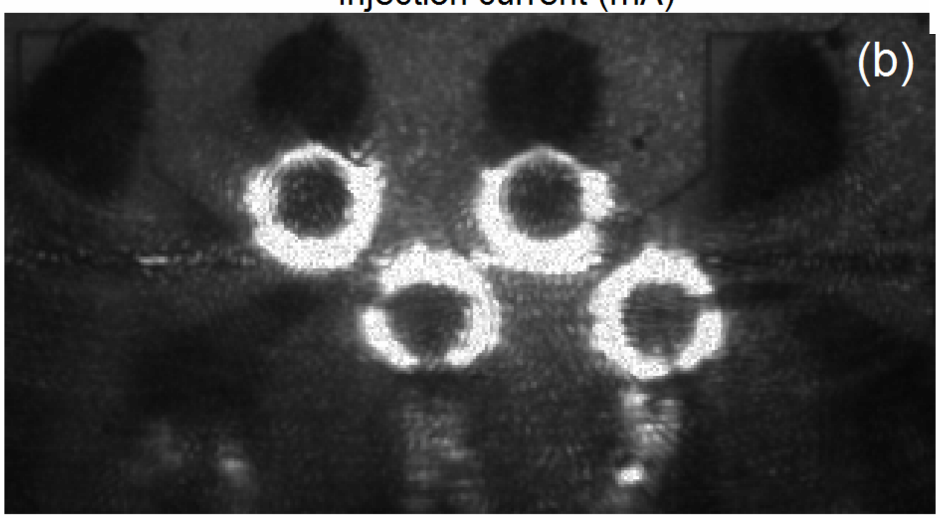




4-channel microring laser array







- Lasing wavelength was fine tuned by injection current.

The Future of Hybrid Silicon Photonics

Key focus areas:

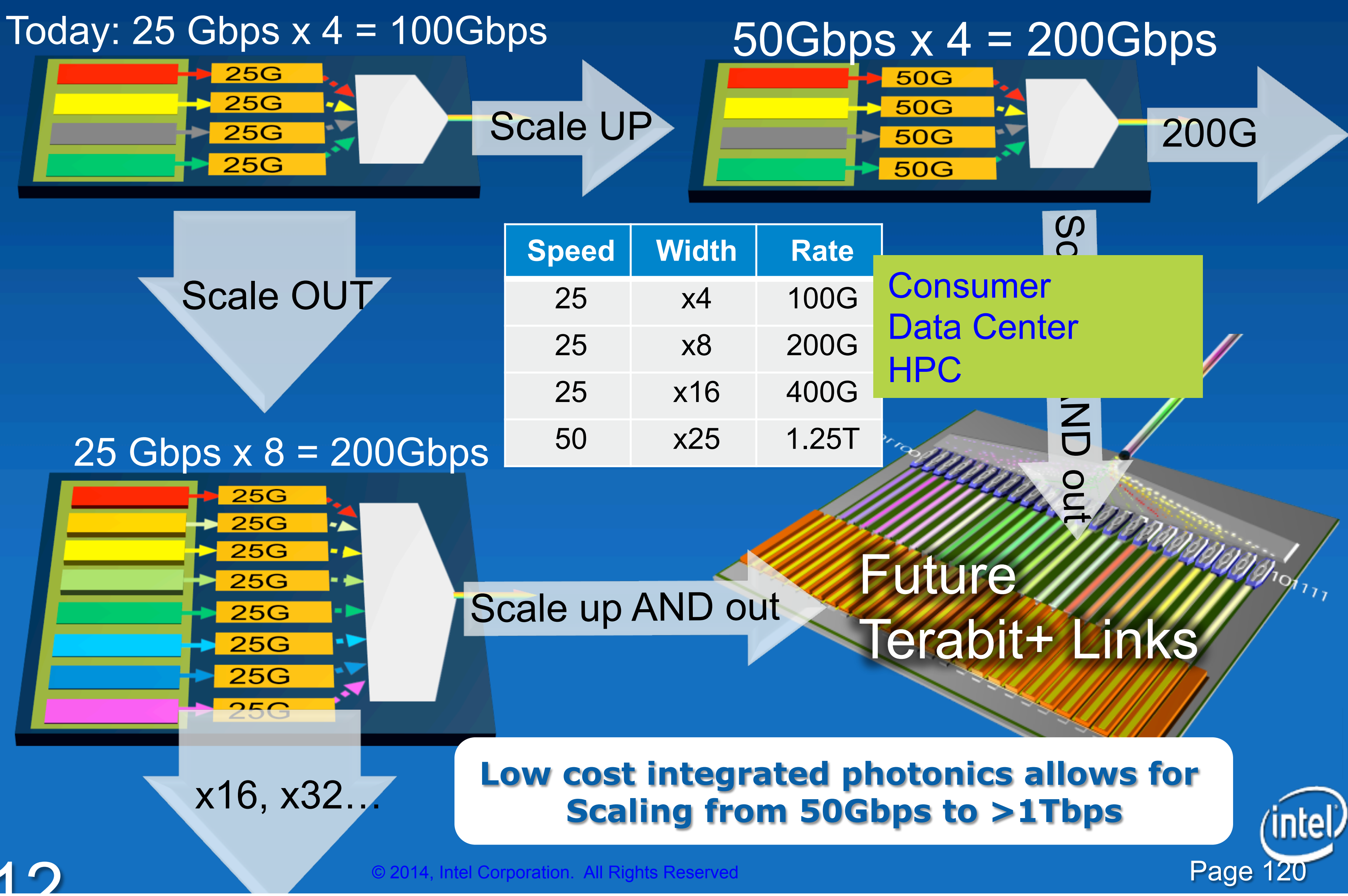
1) Bandwidth/speed

- 25G today moving to 100G
- Also need to be thinking >1Tbps +

2) Power

- CMOS voltages scaling below .9V
- How do you drive your devices?
- How do you reduce overall power consumption ?
- Exascale targeting <1mW/Gbps (total I/O)

The Path to Tera-scale Data Rates

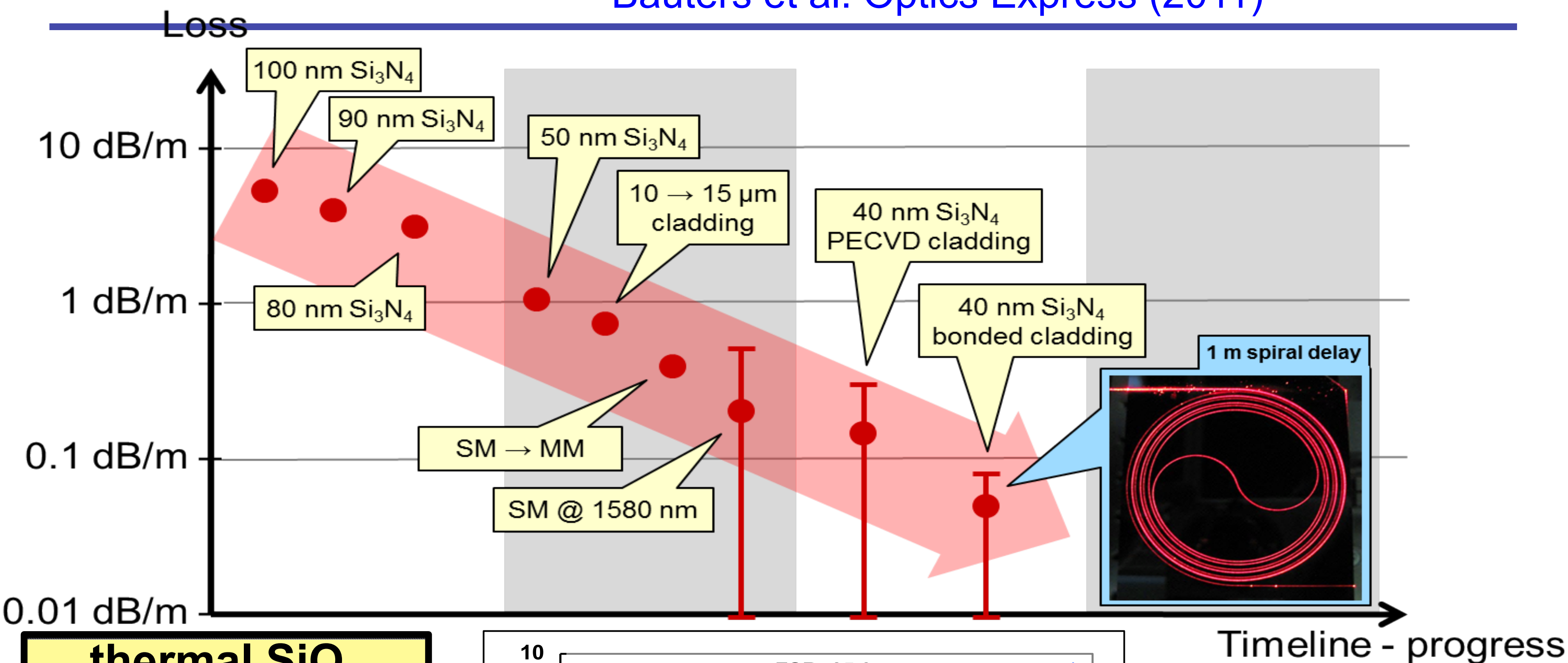


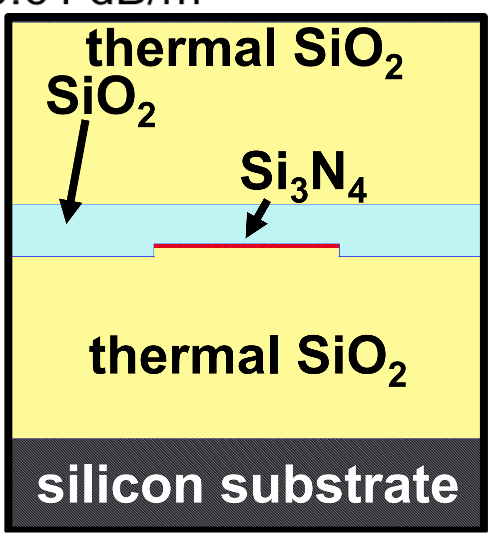
Speed	Width	Rate
25	x4	100G
25	x8	200G
25	x16	400G
50	x25	1.25T

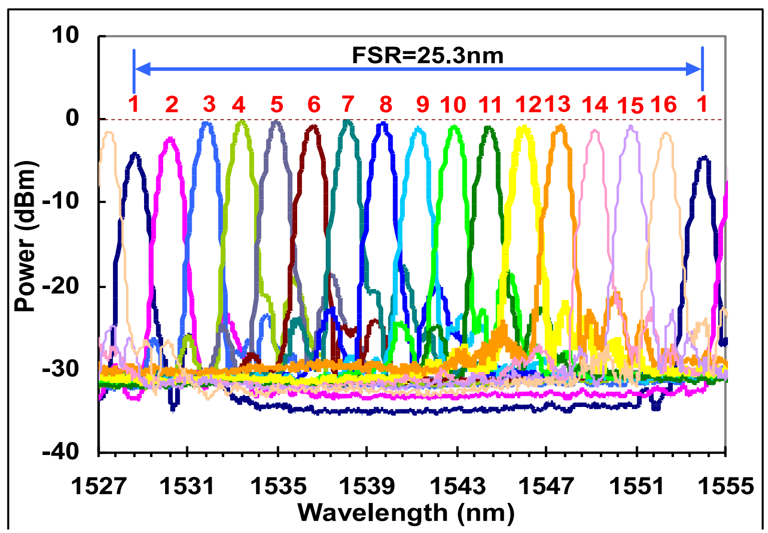
Low cost integrated photonics allows for Scaling from 50Gbps to >1Tbps

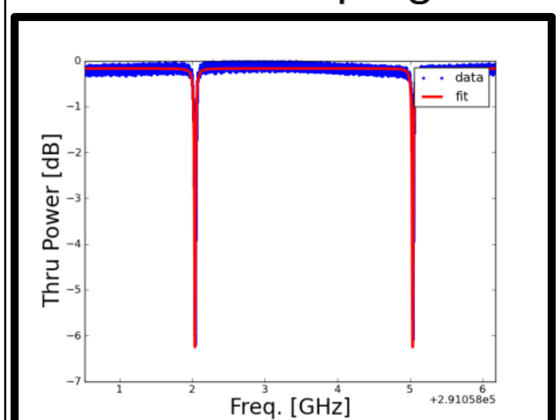
Path to Ultralow Loss Waveguides

Bauters et al. Optics Express (2011)







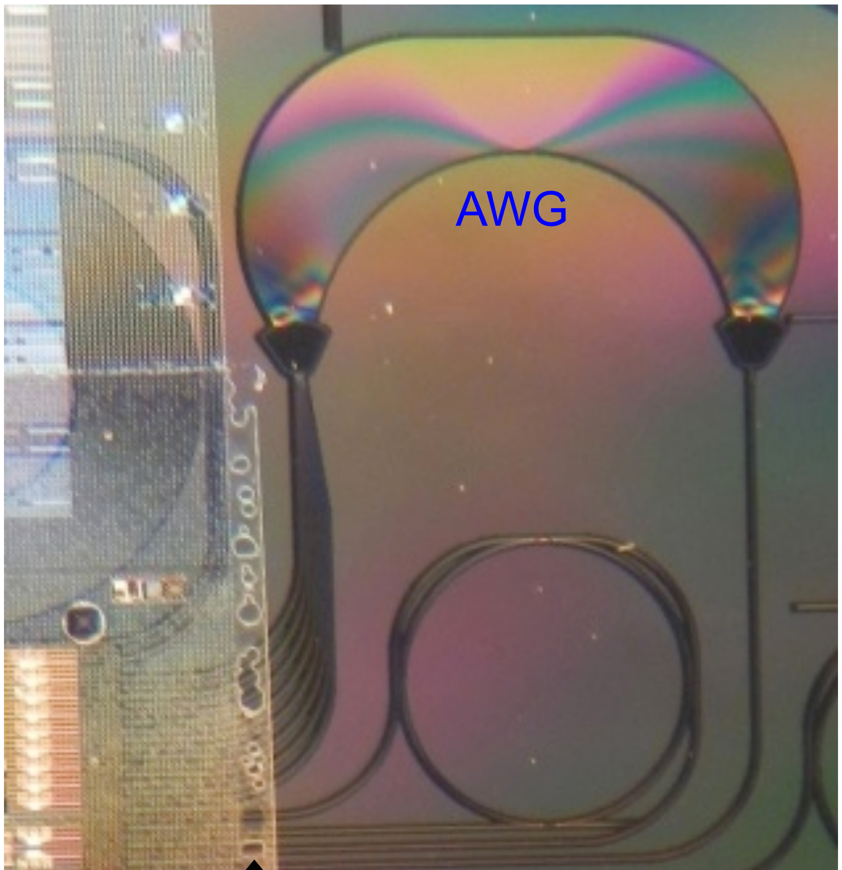


High Q Resonators (80Millio

Integration of Ultralow loss waveguides with hybrid silicon: 400 Gbps (8x50 Gbps) Receiver

Davenport et al., OFC Postdeadline (2013)

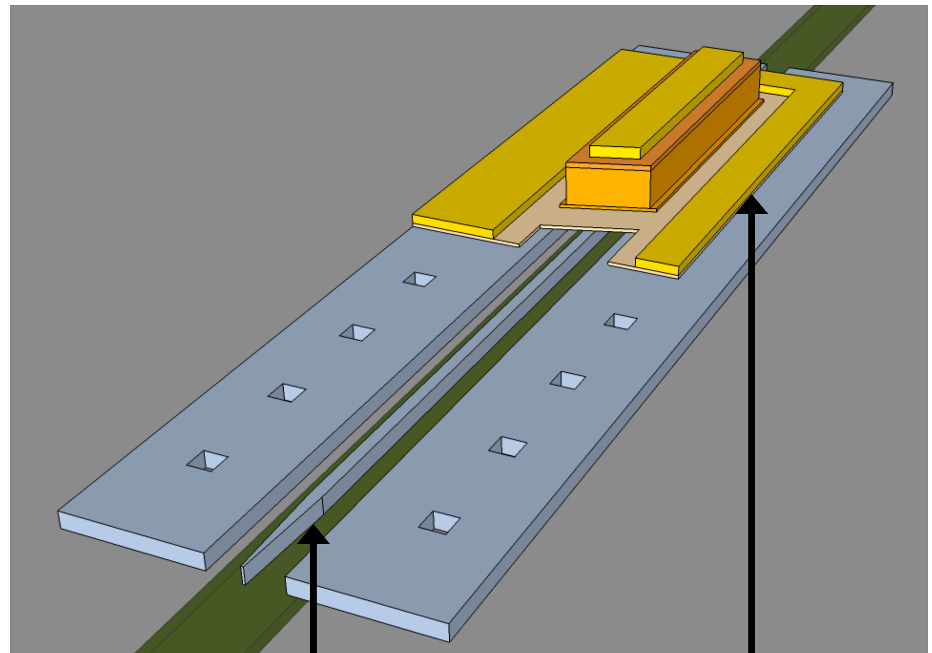
Micrograph of completed device



Detector array

Input waveguide

Detector schematic

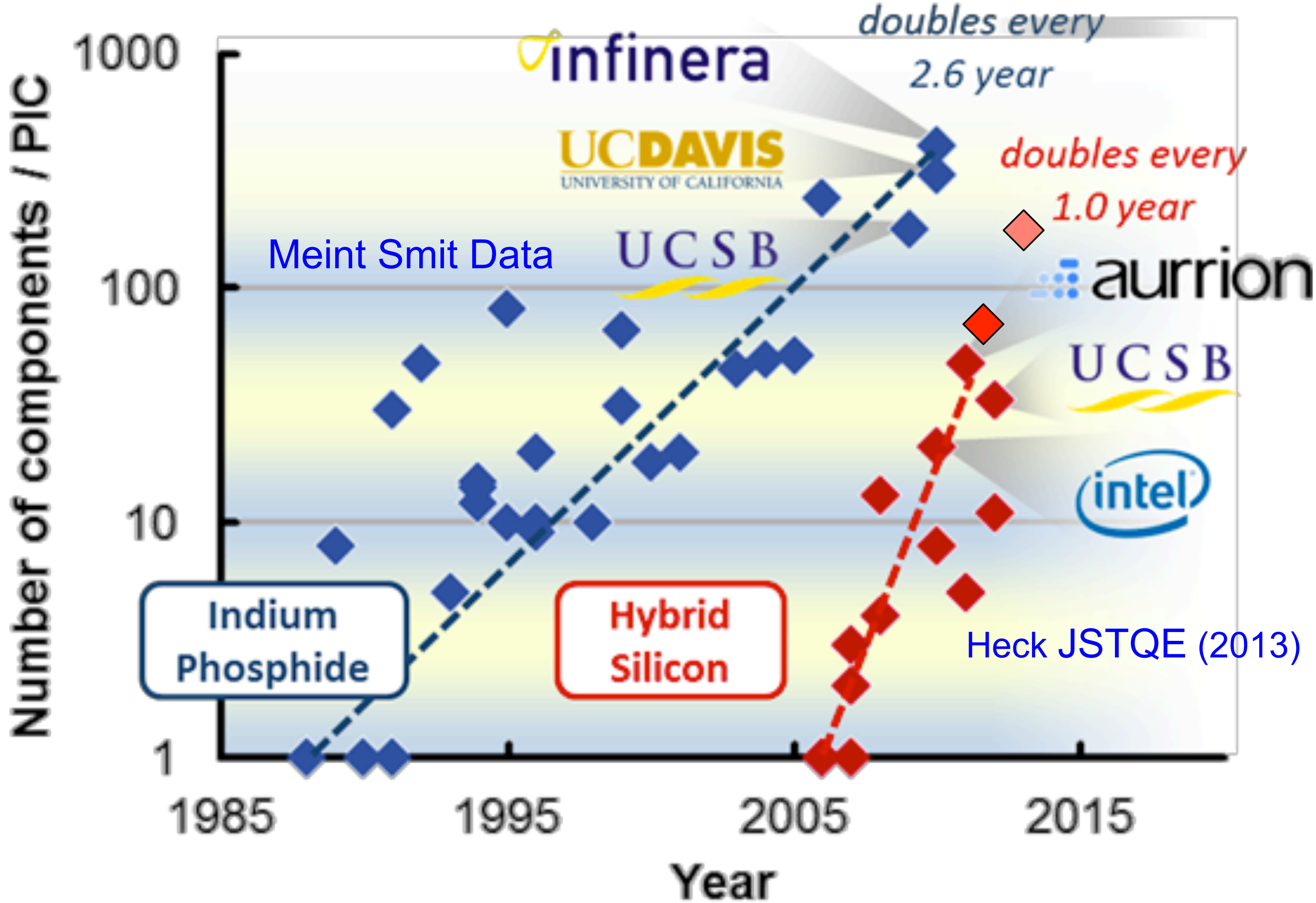


Si3N4 waveguide

Si waveguide and taper

Hybrid Si/InGaAs photodetector

Photonic Integration



Hybrid Silicon Record Performance

- 2013 Narrowest DFB linewidth: **18 kHz** Yariv et al. (Caltech)
- 2011 Lowest waveguide loss on silicon: **0.04 dB/m** Jared Bauters et al.
- 2012 Highest level of integration: **160 devices** Jared Hulme et al.
- 2012 Best reliability: >**40,000 hours at 70C** Srinivasan et al.
- 2012 Highest laser yield: **99%** Srinivasan et al.
- 2012 Fastest Si modulator: **74 GHz** Tang et al.
- 2013 Highest receiver capacity: **400 Gbit/s** Piels et al.
- 2013 Largest laser array bandwidth**: > 200 nm** Jain et al.
- 2014 Largest LED bandwidth: **>200 nm** DeGroote et al.(Ghent and UCSB)
- 2014 Highest temperature**: 119C** Alan Liu et al.
- 2014 Highest power: **180 mW** Alan Liu et al.

Acknowledgements

UCSB:

Former students and postdocs: Alex Fang, Jared Bauters, Hui Wen Chen, Daoxin Dai, Jon Doylend, Martijn Heck, Sid Jain, Geza Kurzveil, Brian Koch, Di Liang, Hyundai Park, Molly Piels, Paolo Pintus, Matt Sysak, Yongbo Tang**,** Jason Tien

Present students: Jock Bovington, Mike Davenport, Jared Hulme, Alan Liu, Jon Peters, Daryl Spencer, Alex Spott, Eric Stanton, Sudha Srinivasan, Chong Zhang

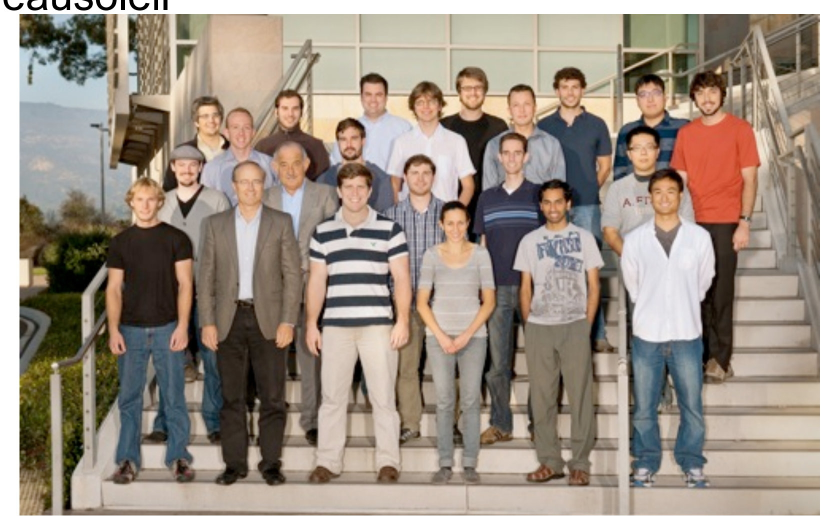
Colleagues: Rod Alferness, Dave Auston, Dan Blumenthal, Larry Coldren, Nadir Dagli, Steve Denbaars, Art Gossard, Herb Kroemer, Chris Palmstrom, Mark Rodwell, Adel Saleh, Luke Theogarajan

Intel : Richard Jones, Yimin Kang, Mario Paniccia, Matt Sysak

Aurrion: Alex Fang, Greg Fish, Rob Guzzon, Eric Hall, Brian Koch, Erik Norberg, Anand Ramaswamy, John Roth, Dan Sparacin

Hewlett Packard: Di Liang, Geza Kurzveil, Ray Beausoleil

Slides: Roel Baets, Tom Koch



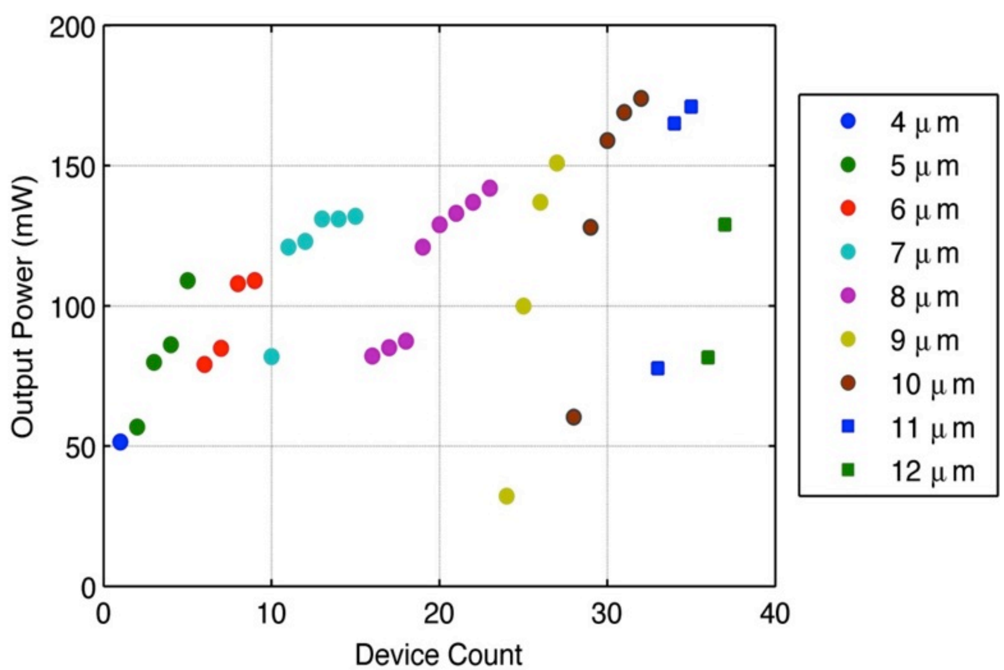
Summary

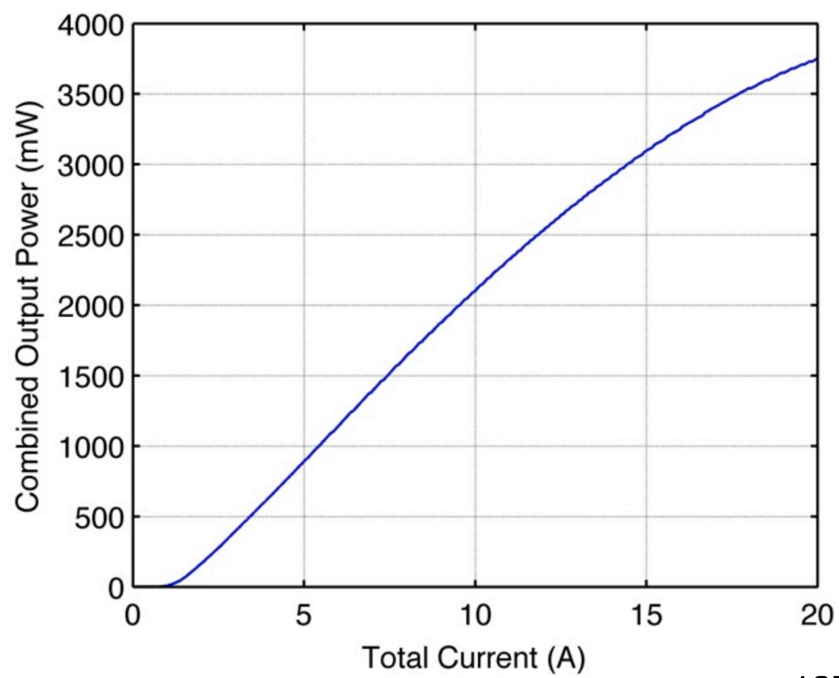
- III-Vs layers on Silicon have key advantages for
  - Low threshold, high power lasers
  - High gain amplifiers
  - High speed modulators
  - Electronics

- Integration is essential for size, weight, power and cost reduction and improved yield and reliability
- Photonics can allow lower power and higher capacity for
  - Sensors
  - Data communication and switching

Output powers

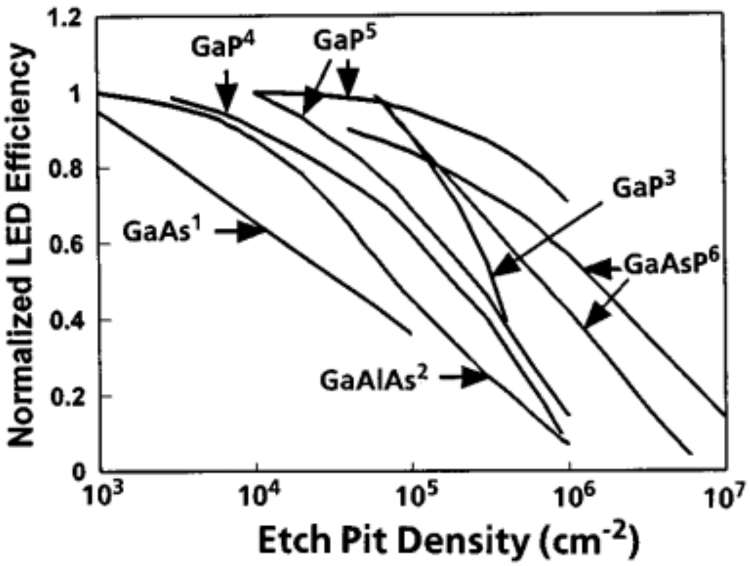
- Highest yielding laser bar: 37/55 working devices (62%, the rest lost due to facet polishing imperfections and metallization shorts)
- One bar numerically summed (e.g. ignoring thermal cross talk):
  - >3.5 watts of combined CW power at 20 ^{o}C.

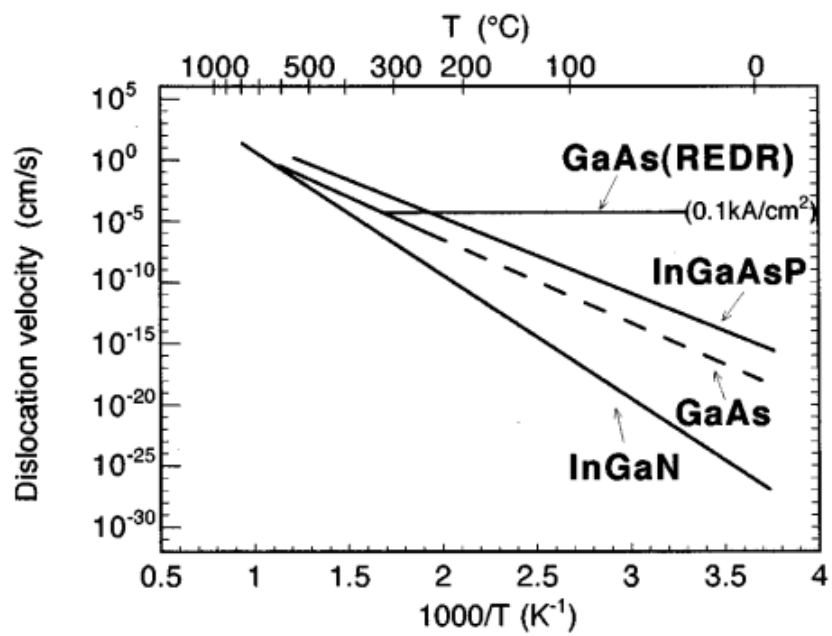




Lifetimes of Previous GaAs based lasers on Silicon

- GaAs based lasers are very sensitive to defect density and susceptible to failure by recombination enhanced defect reactions (REDR)[1][2]

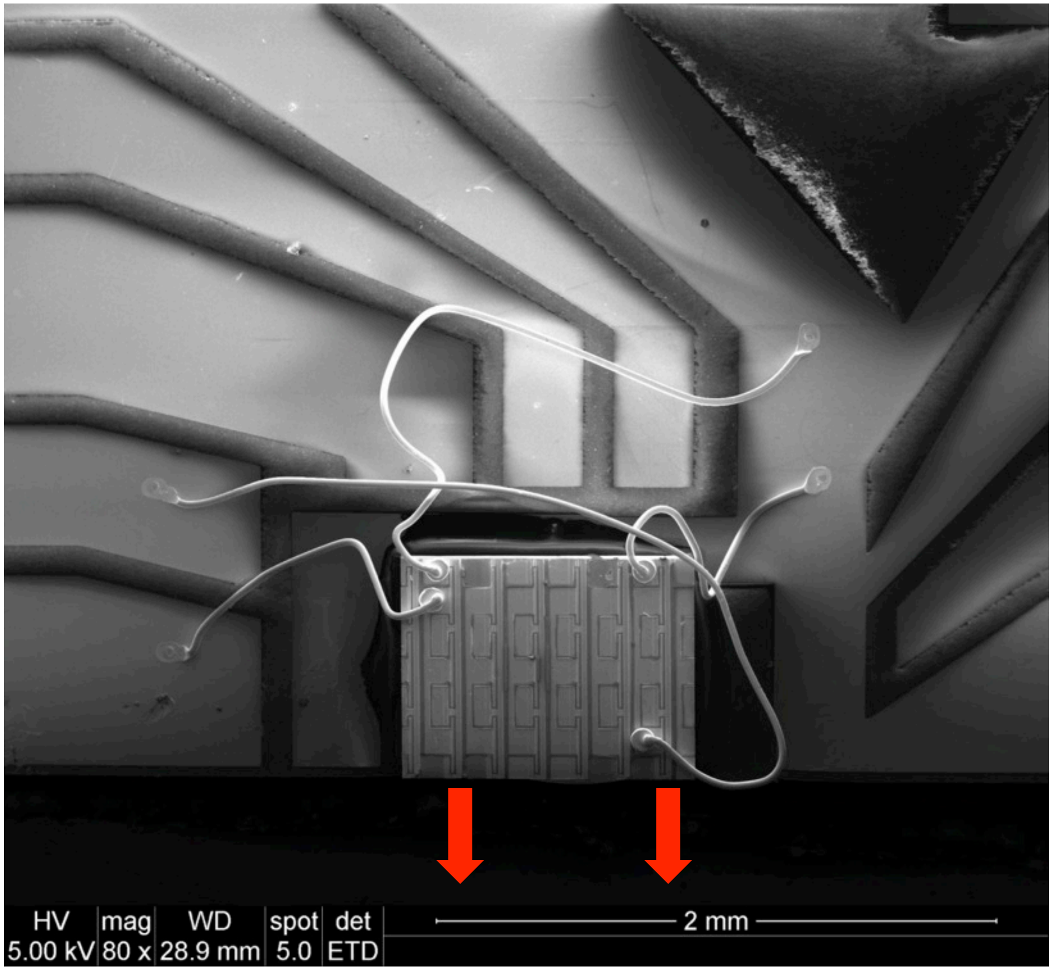




[1] Lester, S. D., et al. "High dislocation densities in high efficiency GaN-based light-emitting diodes." Applied Physics Letters 66.10 (1995): 1249-1251.
[2] Sugiura, Lisa. "Comparison of degradation caused by dislocation motion in compound semiconductor light-emitting devices." Applied physics letters 70.10 (1997): 1317-1319.

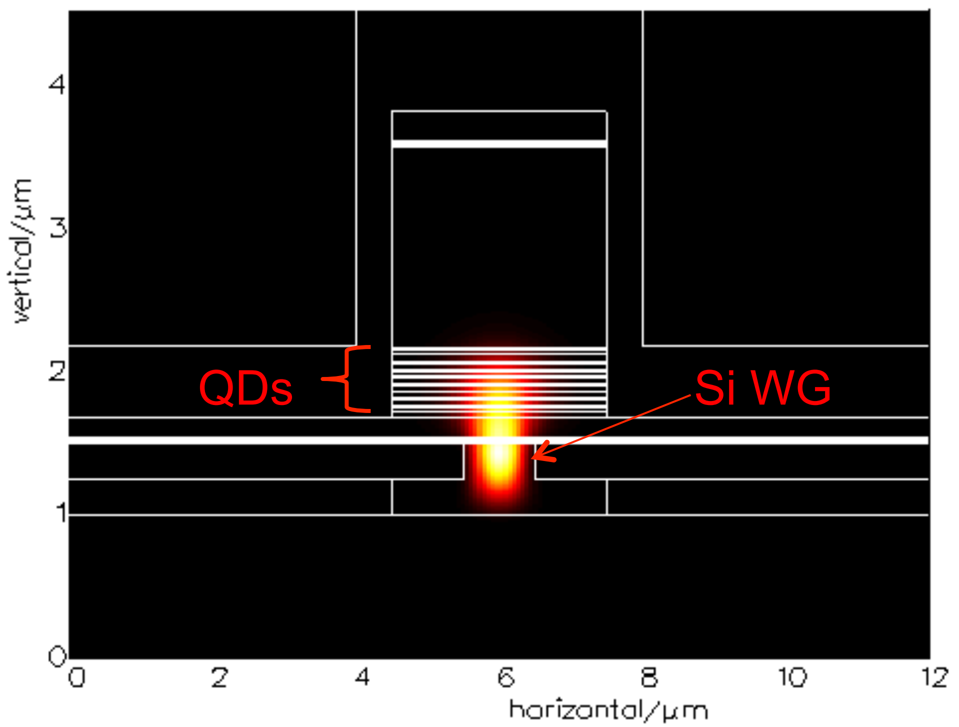
Reliability Studies of QD lasers on Silicon

- Stress conditions: 30°C continuous wave under constant 100 mA injection current (~1.25-3x $I_{th}(0)$, ~1-20 mW initial output power)
- Degradation monitored by periodic light-current-voltage (LIV) sweeps at 30 °C



Quantum Dot Summary

- Repeatable high performance quantum dot lasers on silicon demonstrated
  - Low thresholds (16 mA)
  - CW output power ~180 mW (previous record on silicon: 45 mW)
  - CW lasing up to 120 ^{o}C (previous record on silicon: 105 ^{o}C)
  - T_0 100-200K from 20-40 ^{o}C
  - >2100 hours operation under aging at 30^{o}C & 100 mA.
- **Quantum dot lasers are a promising light source for silicon photonics**



Lifetimes of Previous GaAs based lasers on Silicon

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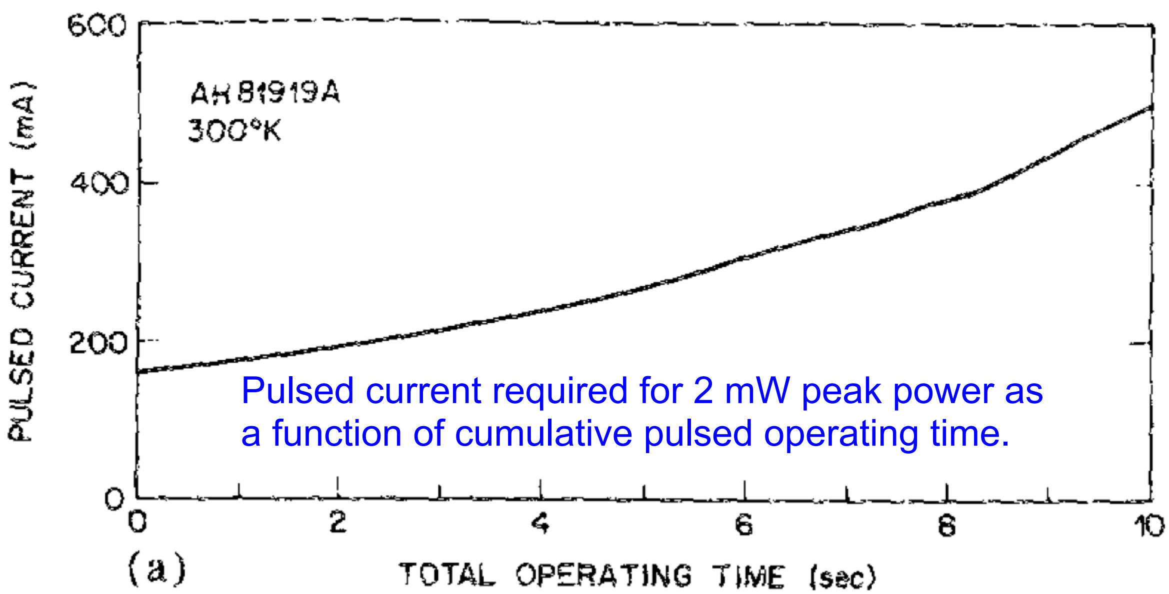
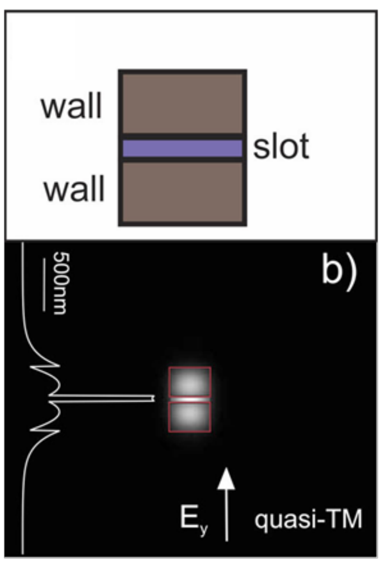
- First GaAs lasers on silicon had lifetimes of ~***10 seconds*** (RT, pulsed) (1987) [3]

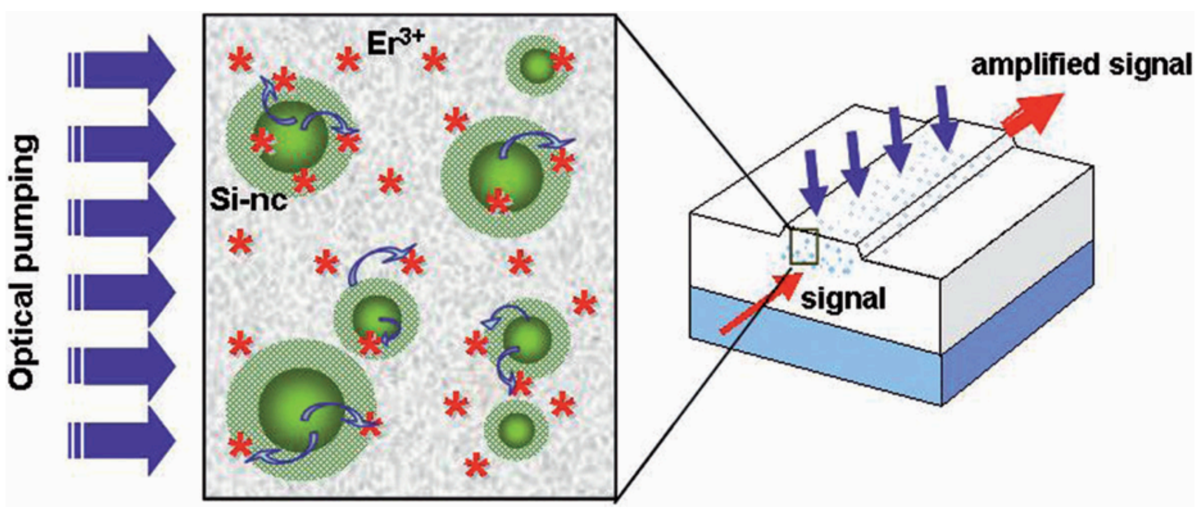


[3] Van der Ziel, J. P., et al. "Degradation of GaAs lasers grown by metalorganic chemical vapor deposition on Si substrates." Appl. Phys. Lett. **51** (1987): 89-91.
[4] Kazi, Zaman Iqbal, et al. "First Room-Temperature Continuous-Wave Operation of Self-Formed InGaAs Quantum Dot-Like Laser on Si substrate Grown by Metalorganic Chemical Vapor Deposition." Japanese Journal of Applied Physics **39** (2000)

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., 2009

Lifetimes of Previous GaAs based lasers on Silicon

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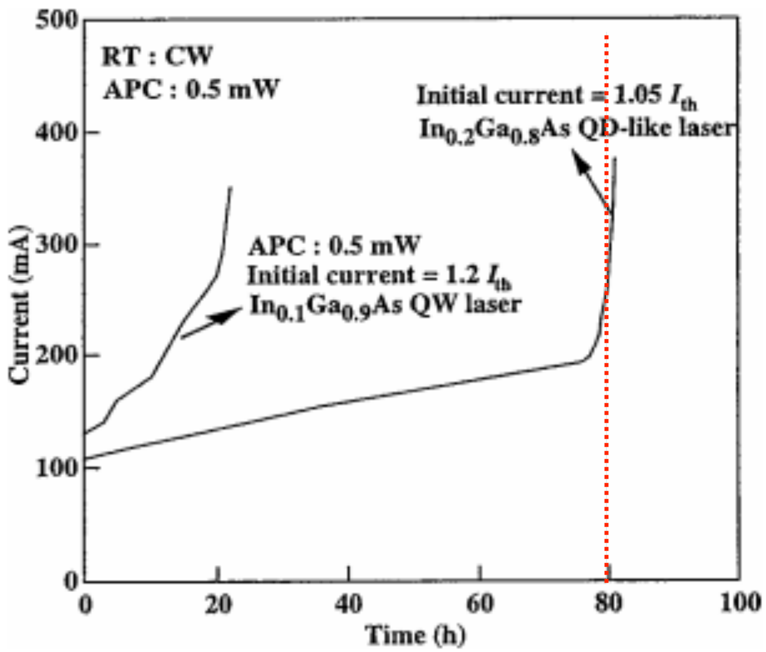
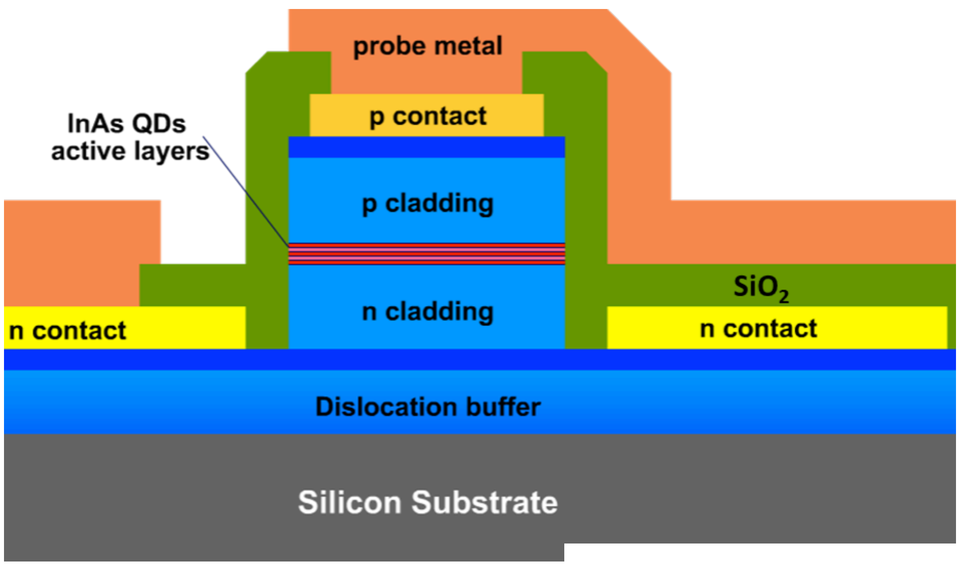
- First GaAs lasers on silicon had lifetimes of ~***10 seconds*** (RT, pulsed) (1987) [3]
- Longest lifetime reported for GaAs based laser on Si (853 nm) is 80 hours (RT, CW) (2000) [4]

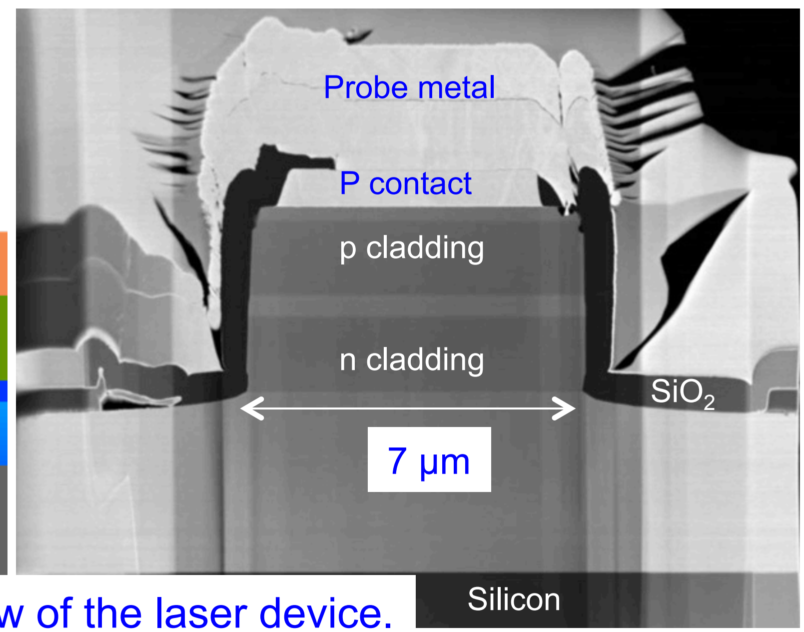


[3] Van der Ziel, J. P., et al. "Degradation of GaAs lasers grown by metalorganic chemical vapor deposition on Si substrates." Appl. Phys. Lett. **51** (1987): 89-91.
[4] Kazi, Zaman Iqbal, et al. "First Room-Temperature Continuous-Wave Operation of Self-Formed InGaAs Quantum Dot-Like Laser on Si substrate Grown by Metalorganic Chemical Vapor Deposition." Japanese Journal of Applied Physics **39** (2000)

Device Fabrication

- Epi processed into ridge lasers 4-12 μm wide, 700-1200 μm long cavities.
- Facets were polished, rear facet HR coated (~95%).

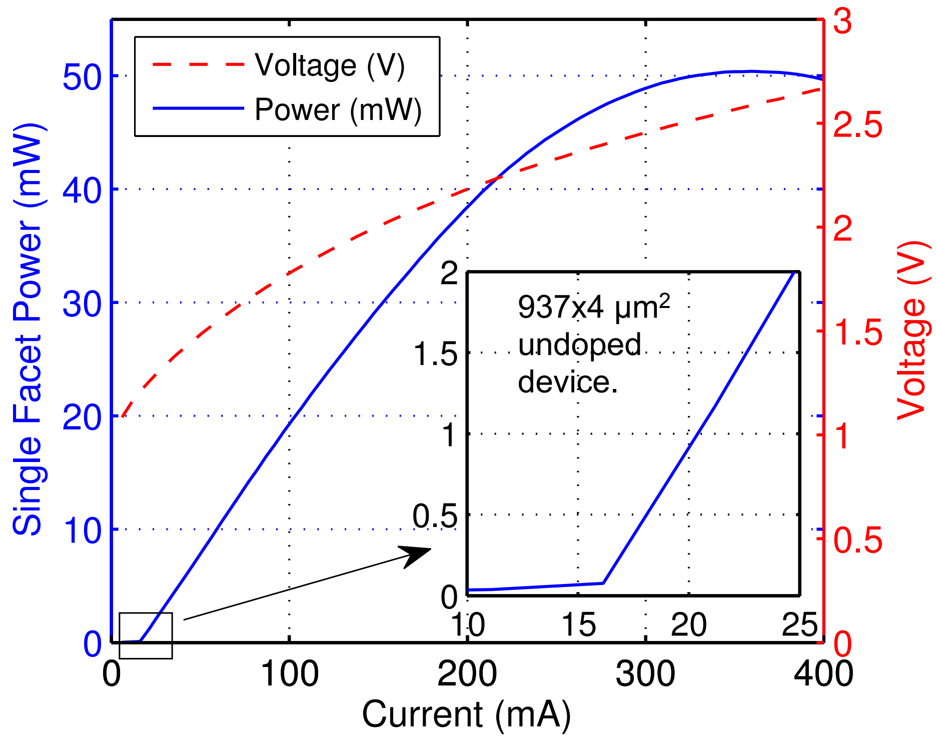


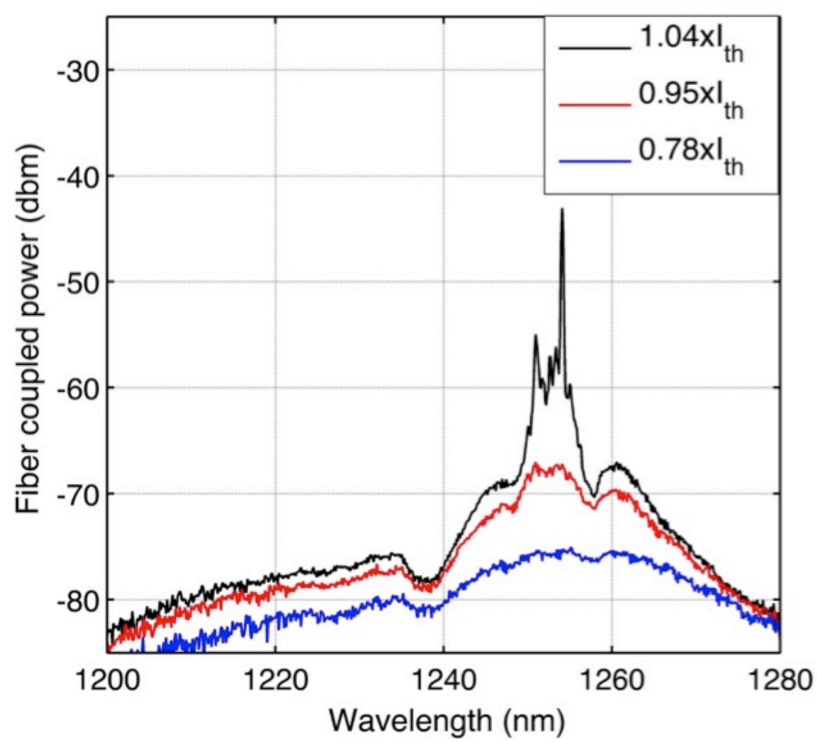


Cross sectional view of the laser device.

Continuous Wave Threshold Data

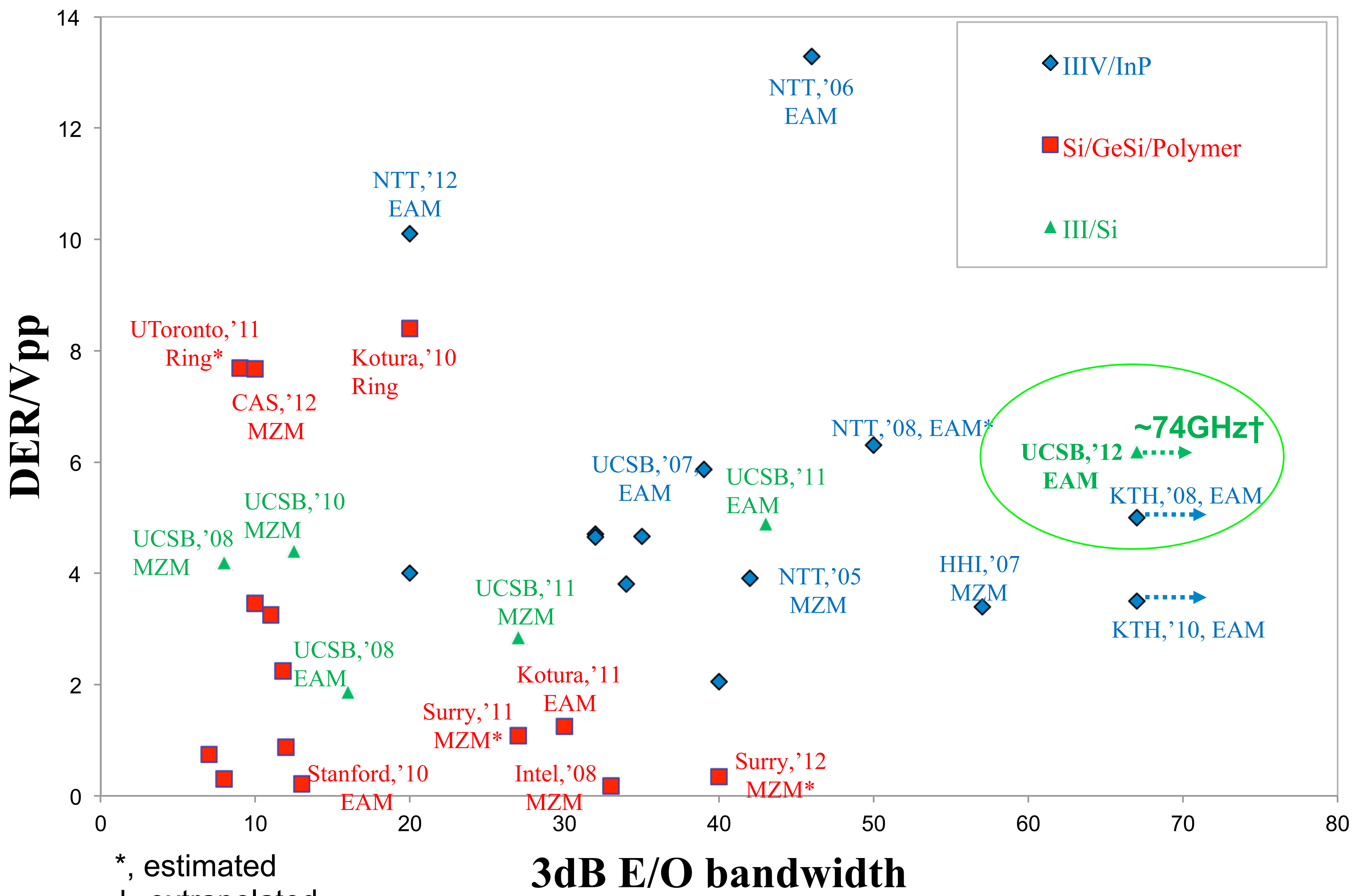
- Lowest CW threshold at 20 °C is 16 mA for an HR coated 937x4 μm^2 device with an intrinsic active region (undoped).
- Greater than 50 mW output power from same device.





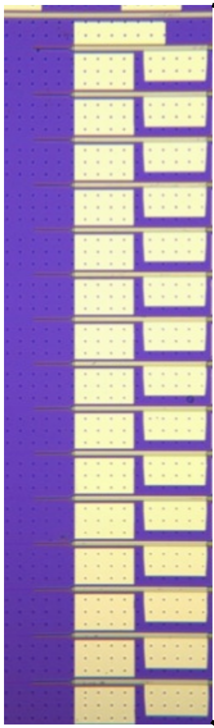
Liu, Alan Y., et al. "High performance continuous wave 1.3 μm quantum dot lasers on silicon." Applied Physics Letters 104.4 (2014): 041104.

Modulator Survey

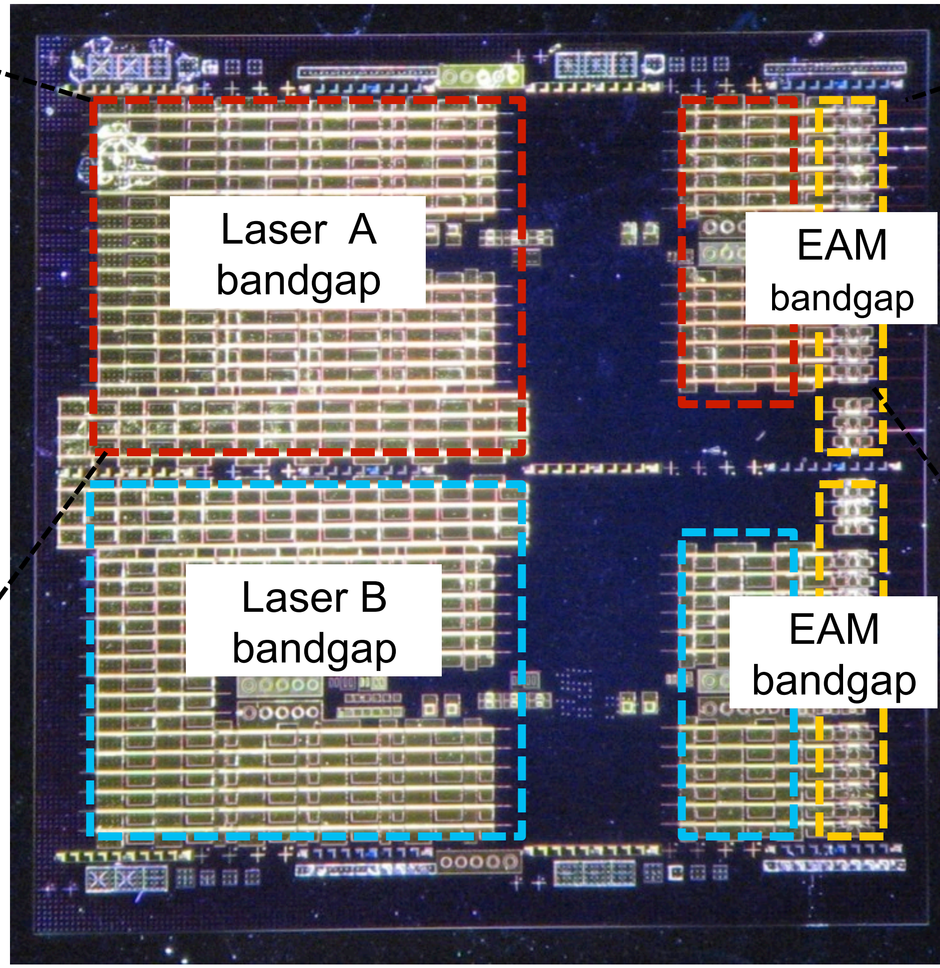


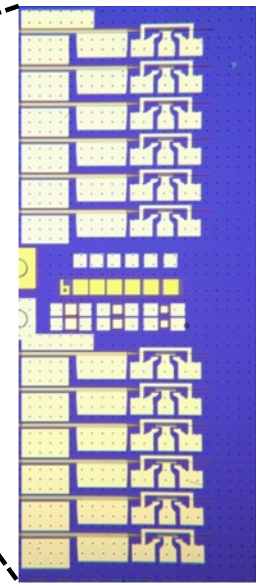
*, estimated
†, extrapolated

QWI to Integrate DFBs and EAMs



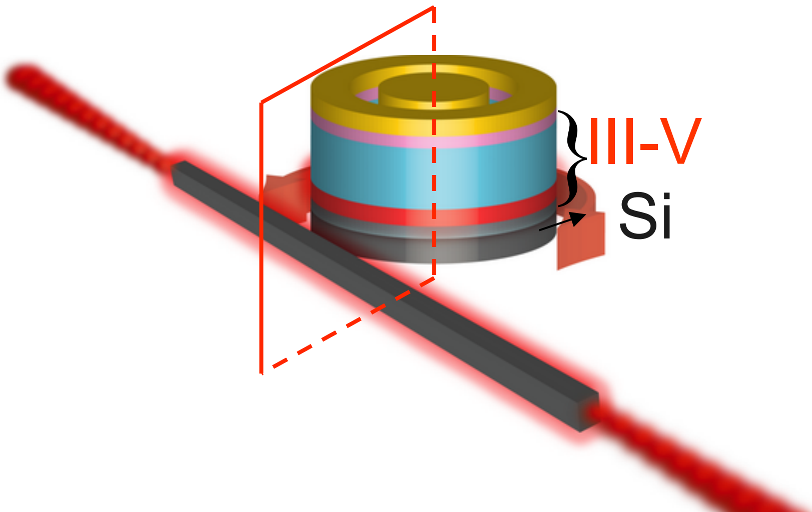
16 DFB/PD laser array





8 Integrated PD-DFB-EAM

Hybrid silicon microring laser



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Confinement: MQW: 5.5%; silicon: 52%