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Enterprise

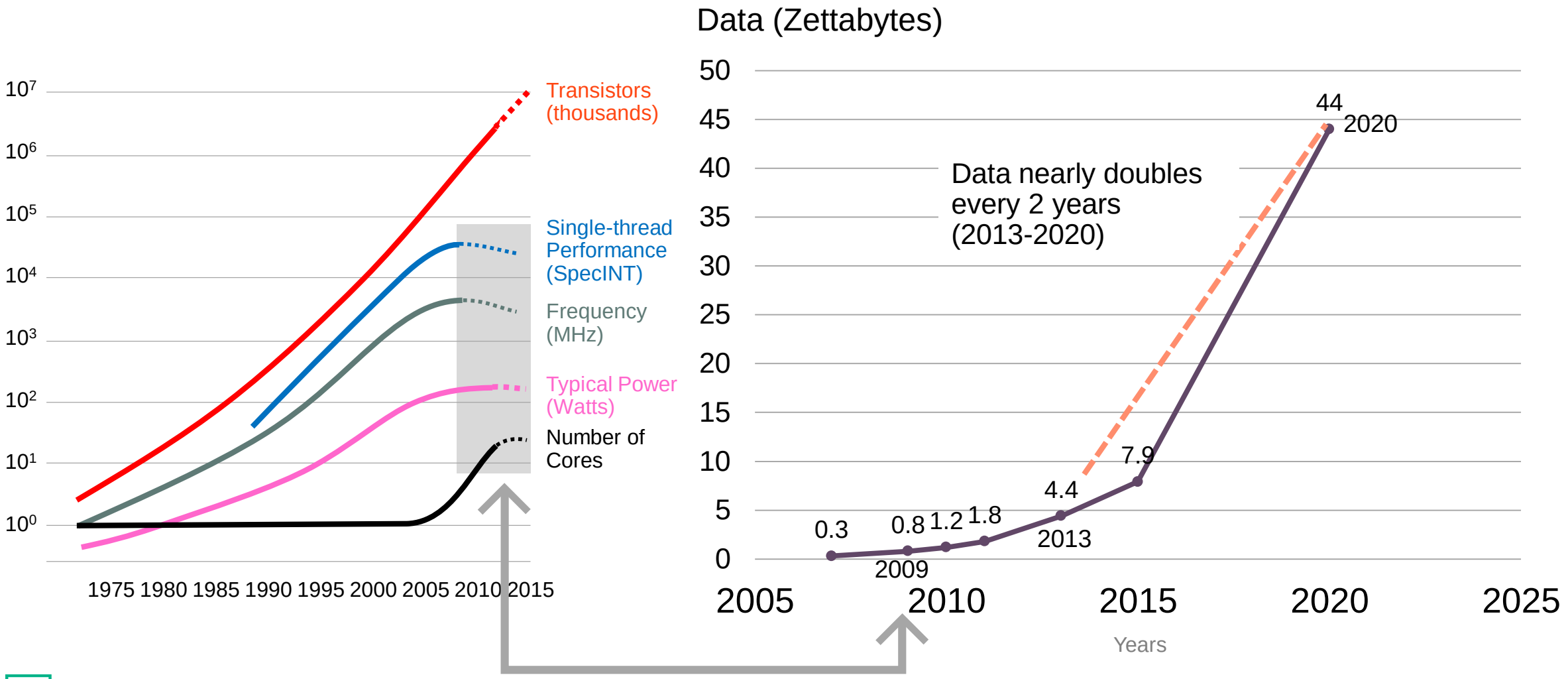
Integrated Photonic Interconnect Reliability for Datacom Applications

Di Liang

Large-Scale Integrated Photonics (LSIP) Group
Hewlett Packard Labs

The end of cheap hardware

Compute is not keeping up



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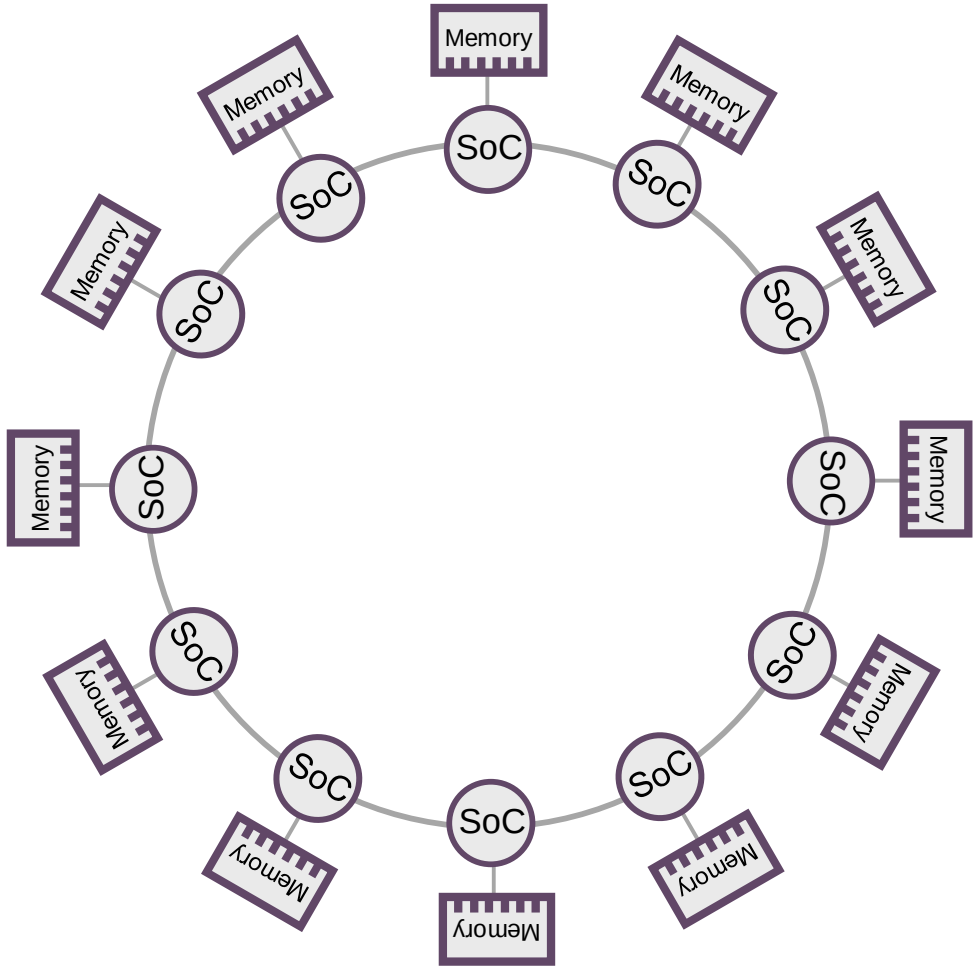
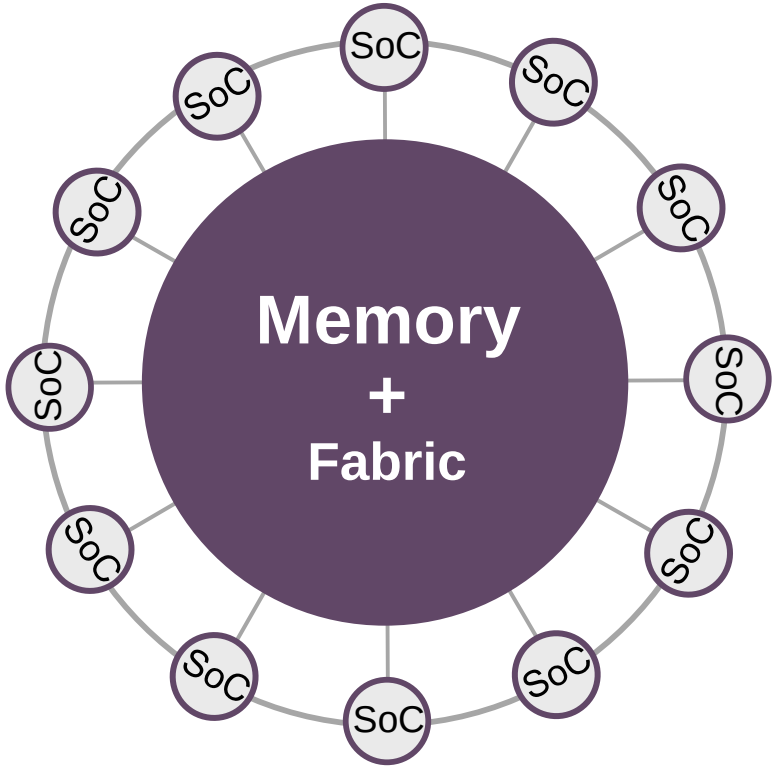
Memory-driven computing

"The Machine"

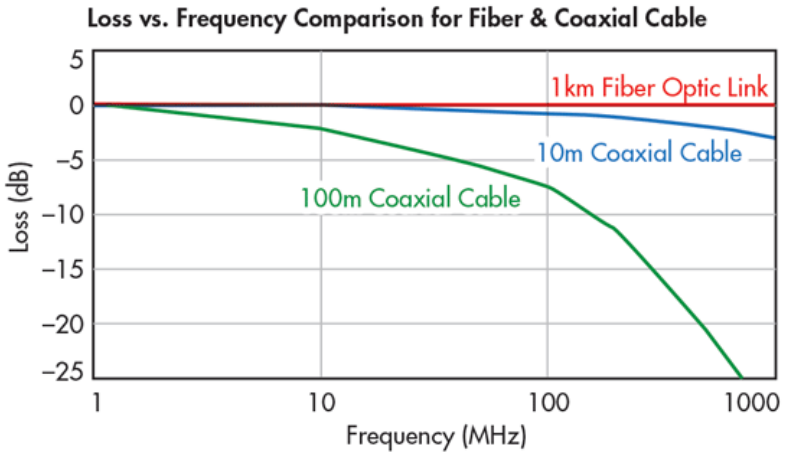


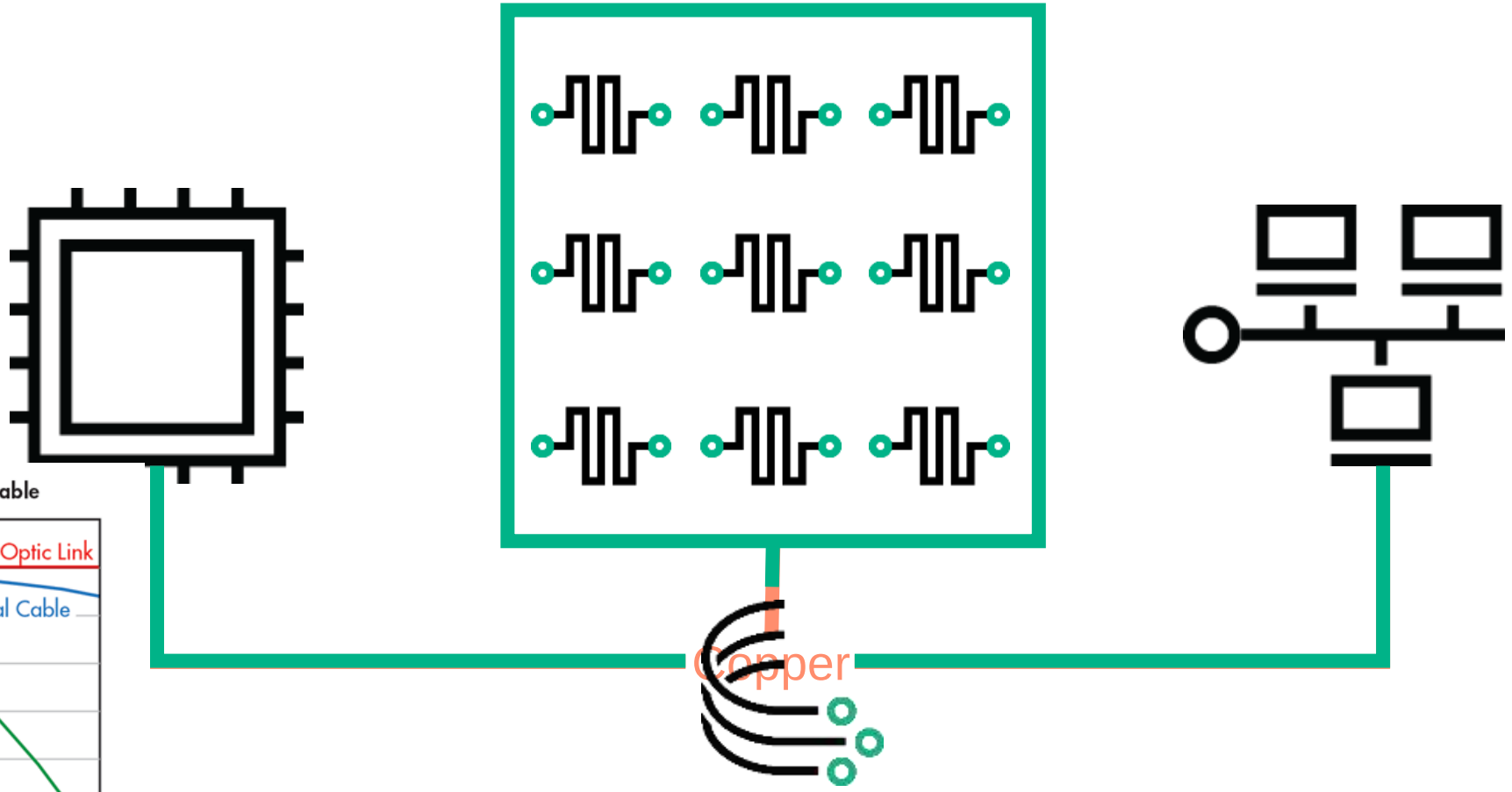
From processor-centric computing…



…to Memory-Driven Computing

Moving data in “The Machine” with photons … from now on





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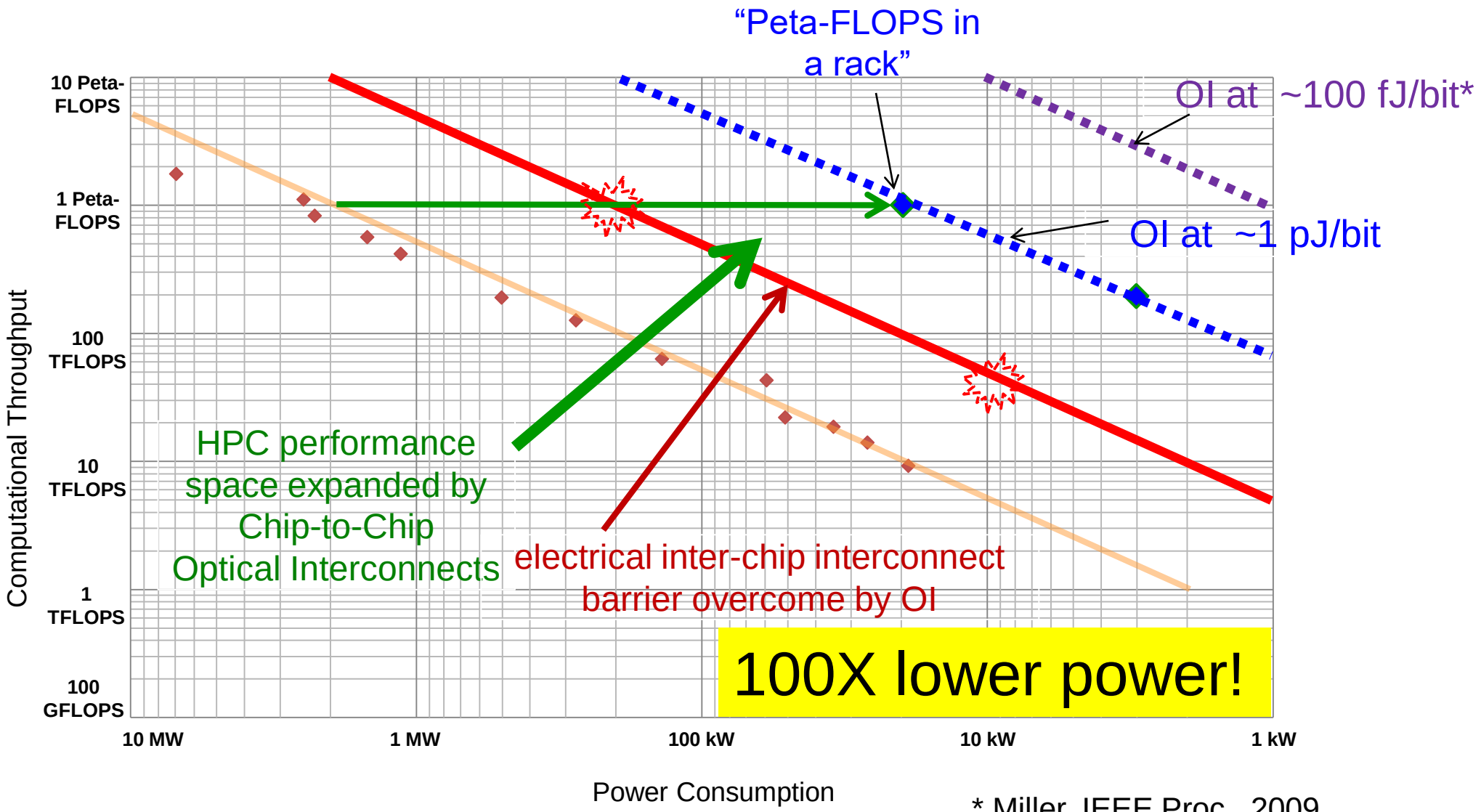
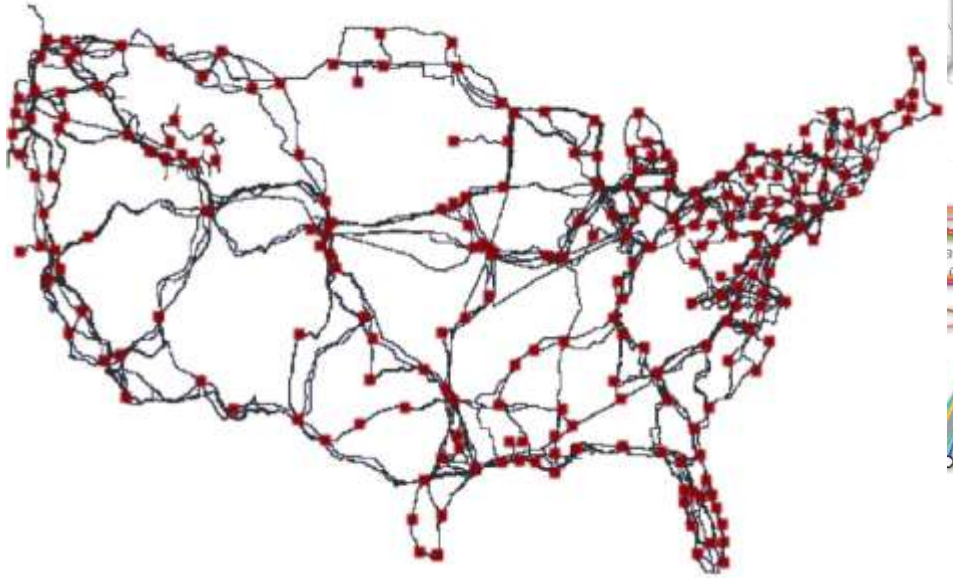
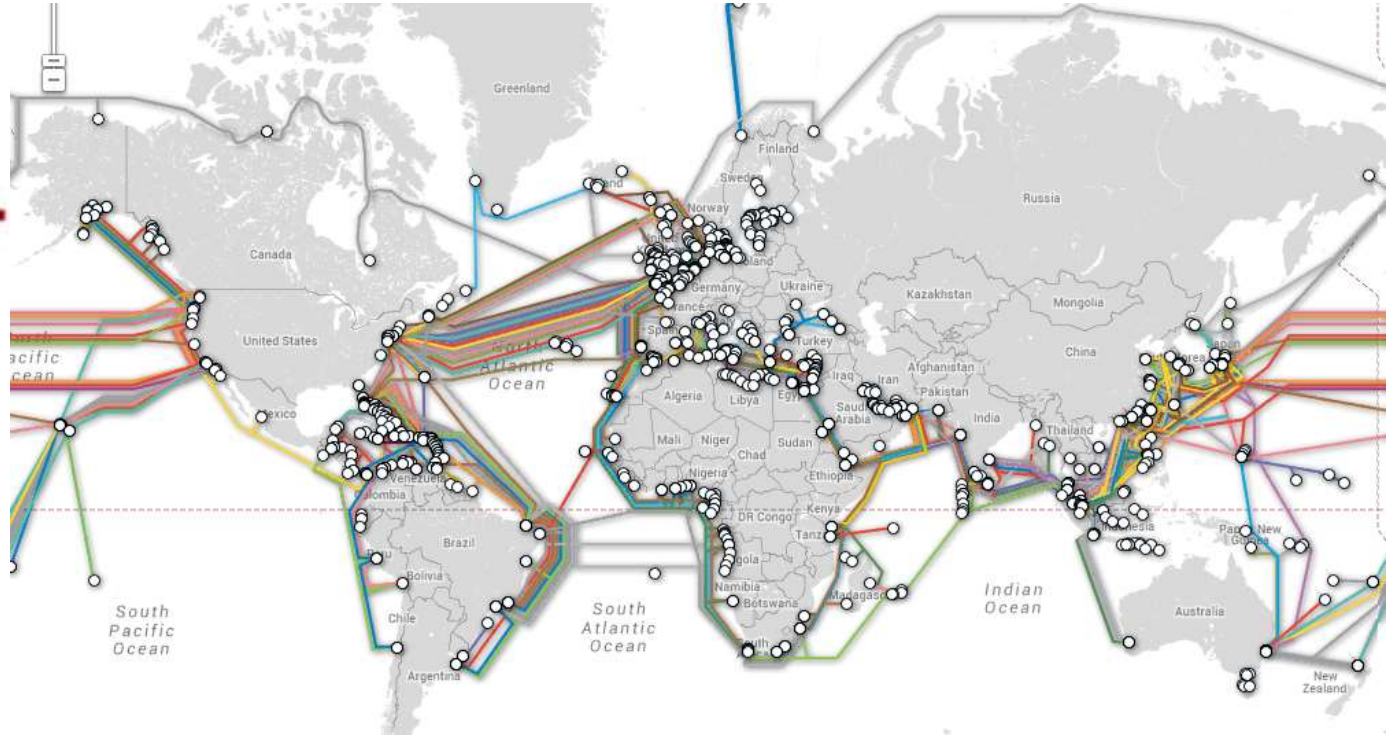
Electrical vs. optical interconnect



* Miller, IEEE Proc., 2009

Moving data around the world with photons … for decades

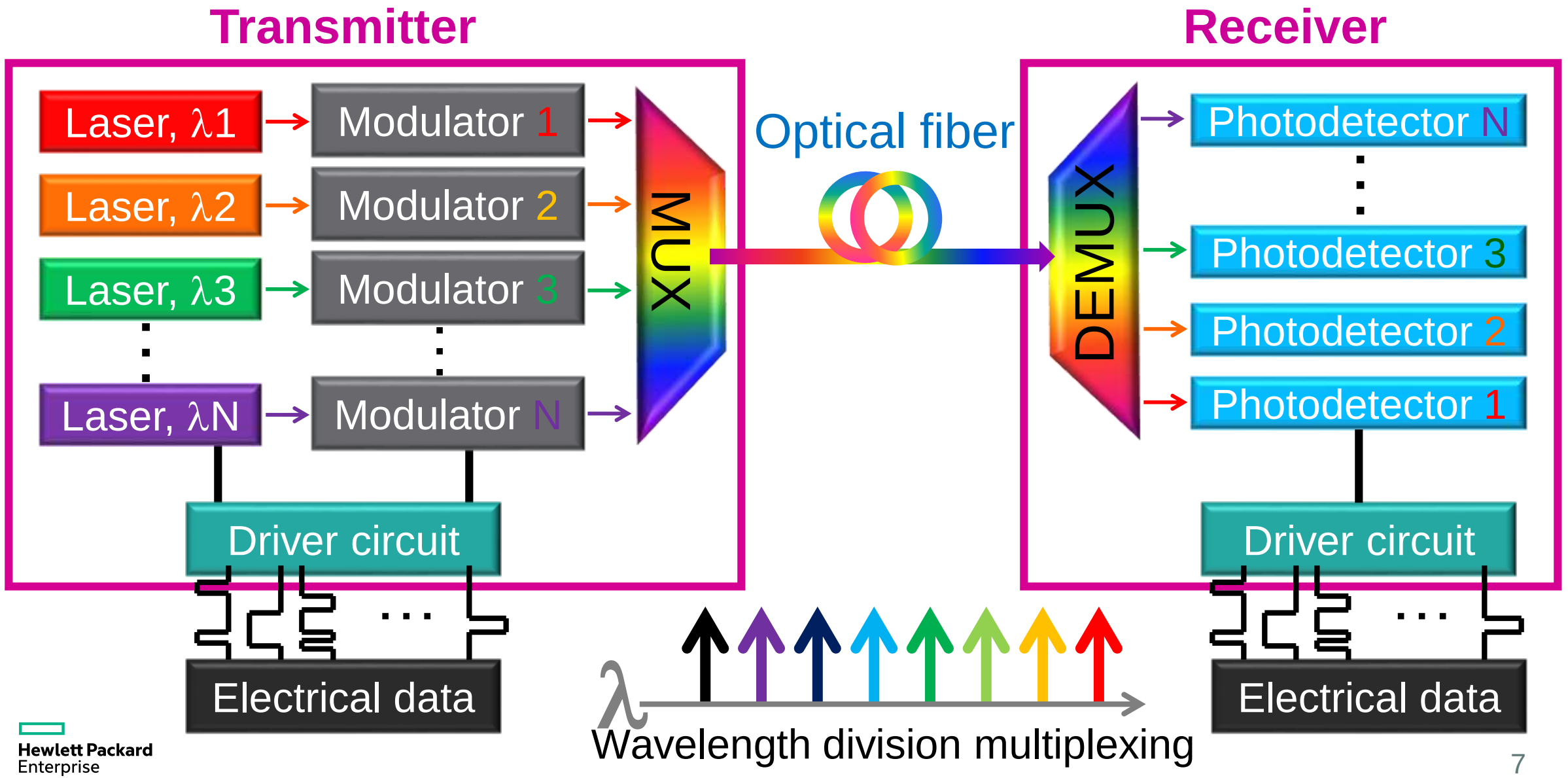




- 1960-70: invention of **optical fiber**, development of GaAs **diode lasers**
- 1970-80: 1st generation of commercial fiber-optic network
- 1980- post 1990s: 2nd, 3rd generations of network
- 2017: KDDI Research and Sumitomo Electric set record (**10.16 Petabit/s**, multi-core fiber, SDM)

http://cdn.theatlantic.com/static/mt/assets/international/Screen%20Shot%202013-07-16%20at%2011.17.56%20AM.png
http://www.theatlantic.com/international/archive/2013/07/the-creepy-long-standing-practice-of-undersea-cable-tapping/277855/
http://www.govtech.com/network/Comcast-Launches-Plan-to-Take-on-Gig-Internet-Providers.html

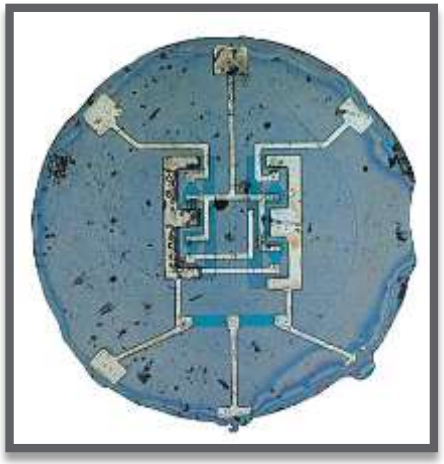
Carry multiple data channels in different color of light streams



Microelectronic integration vs. photonic integration

Silicon

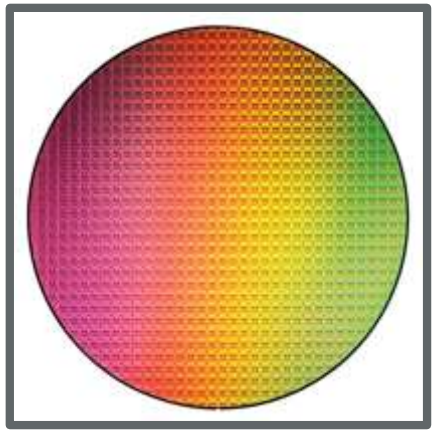
1959



First Silicon IC (Noyce)

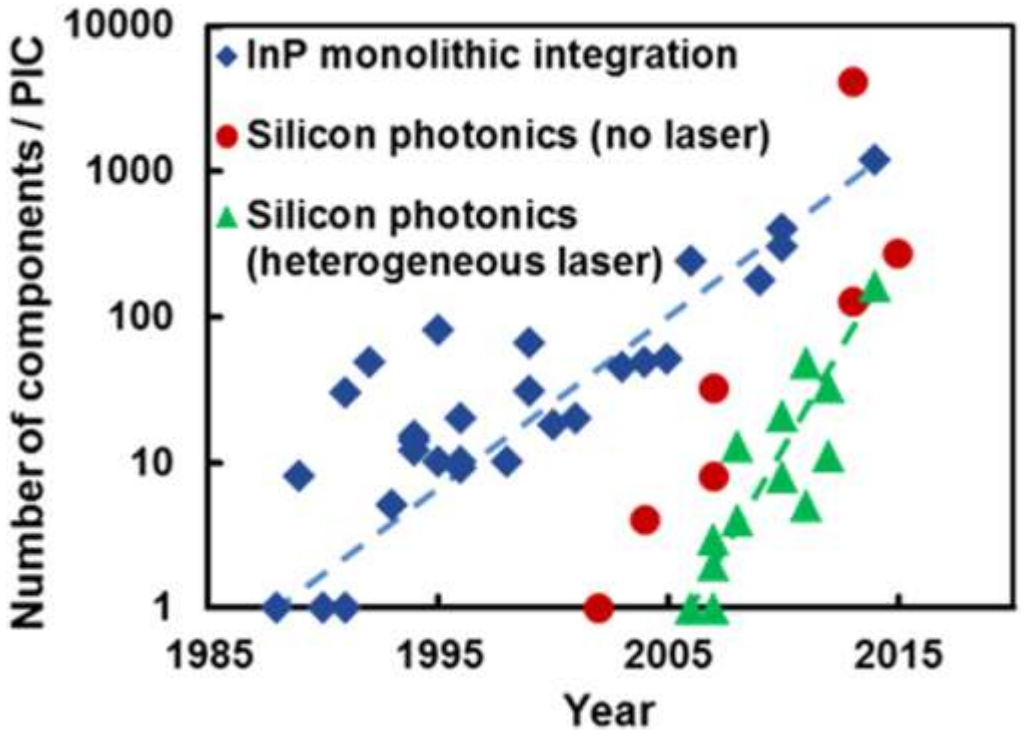
~50 years

Today



Billions of Transistors

Courtesy: Rattner (Intel)



Heck, JSTQE **19**, 6100117(2013)

- Microelectronic integration: device size, wafer scale, manufacture technique
- Photonic integration: functionality, material and fabrication compatibility

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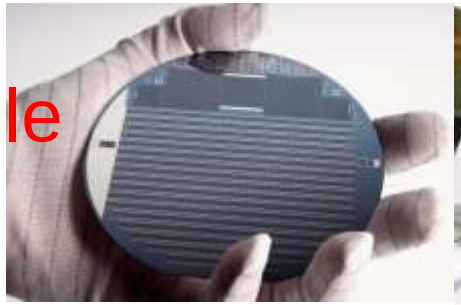
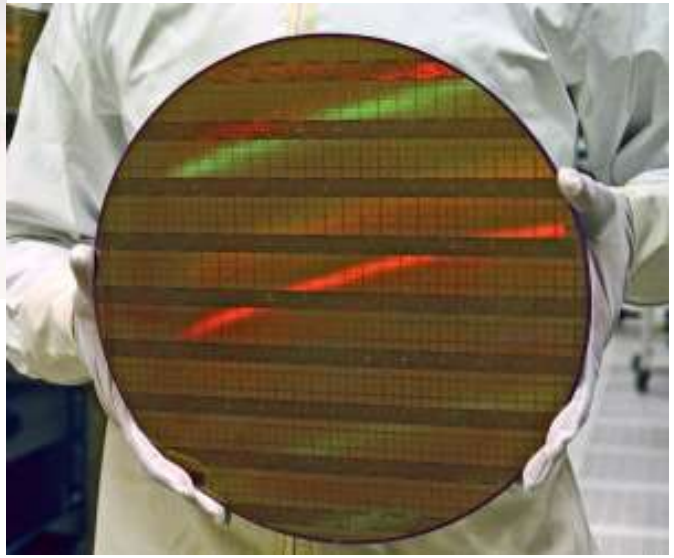
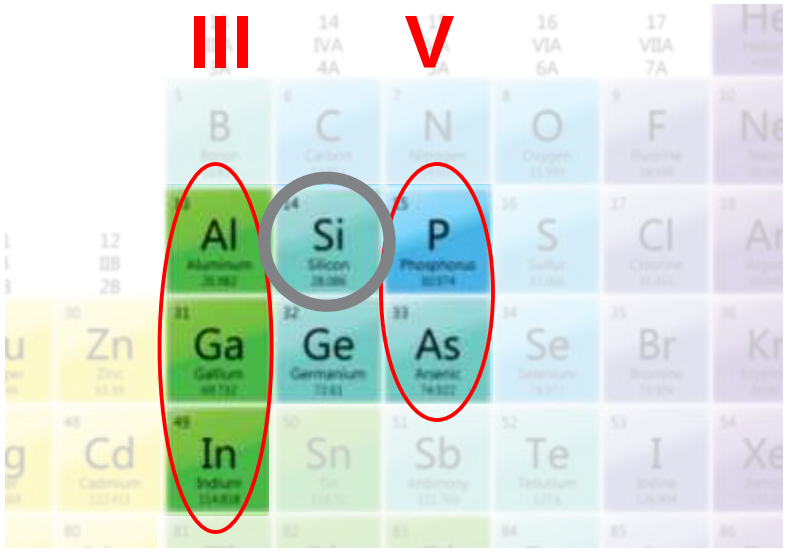
How to build low-cost photonic integrated circuits (PICs)?

>$1000/module

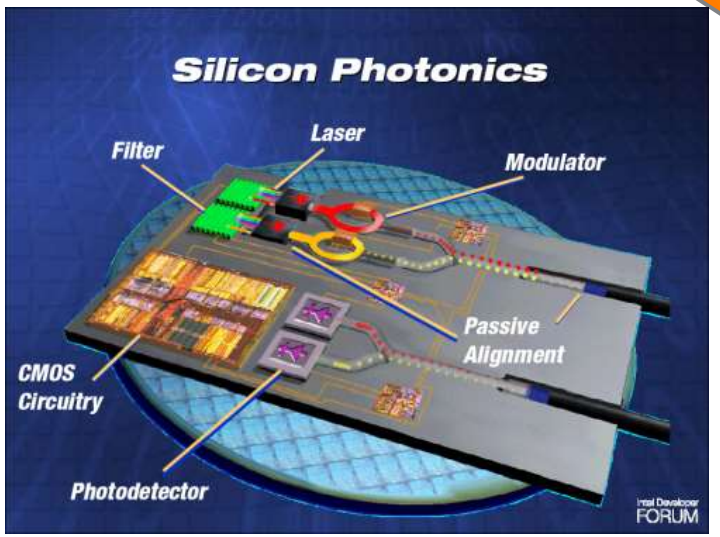


III-V
2, 3, 4 inch





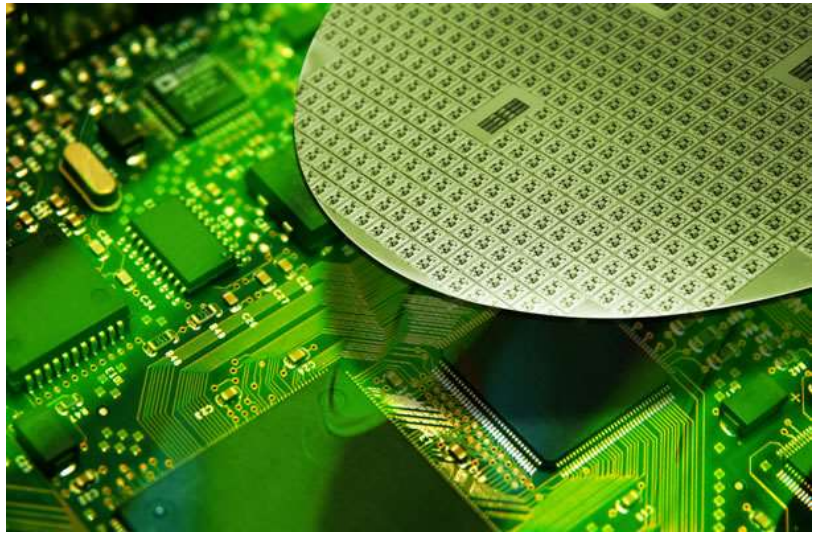
Courtesy: Intel



Silicon
12, 18 inch

<$1/module

$/chip



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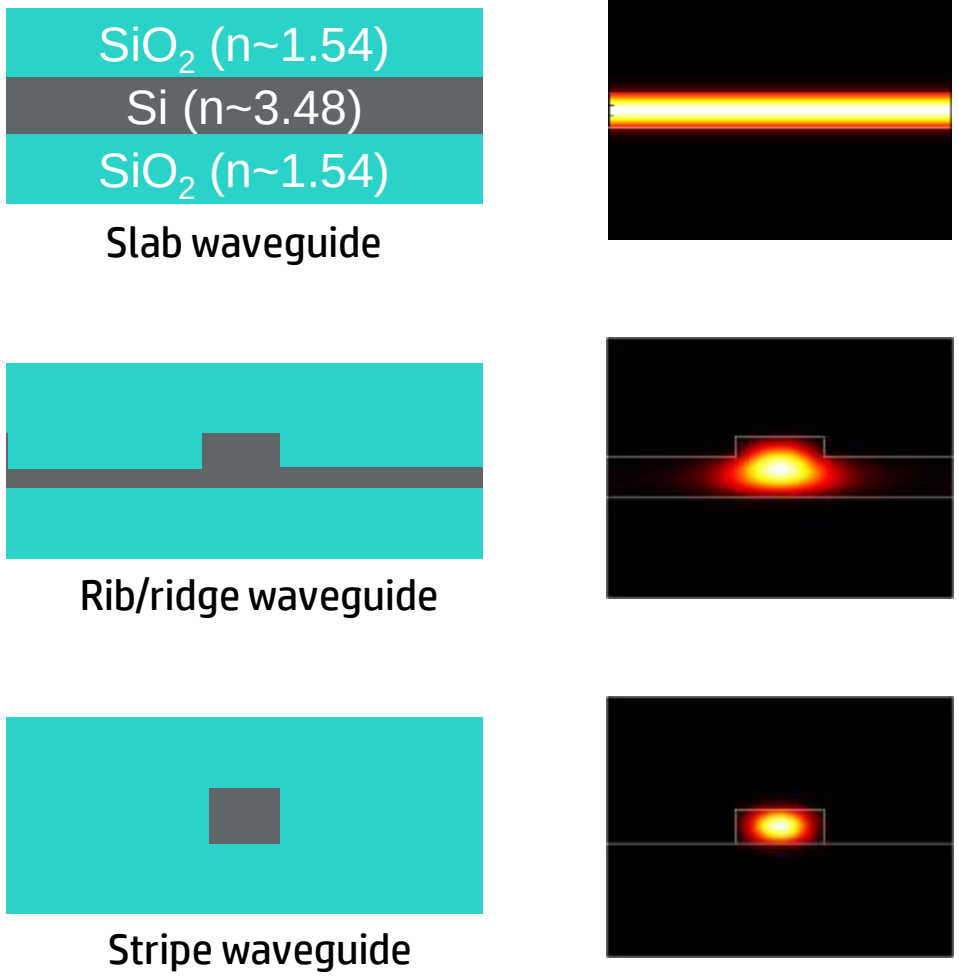
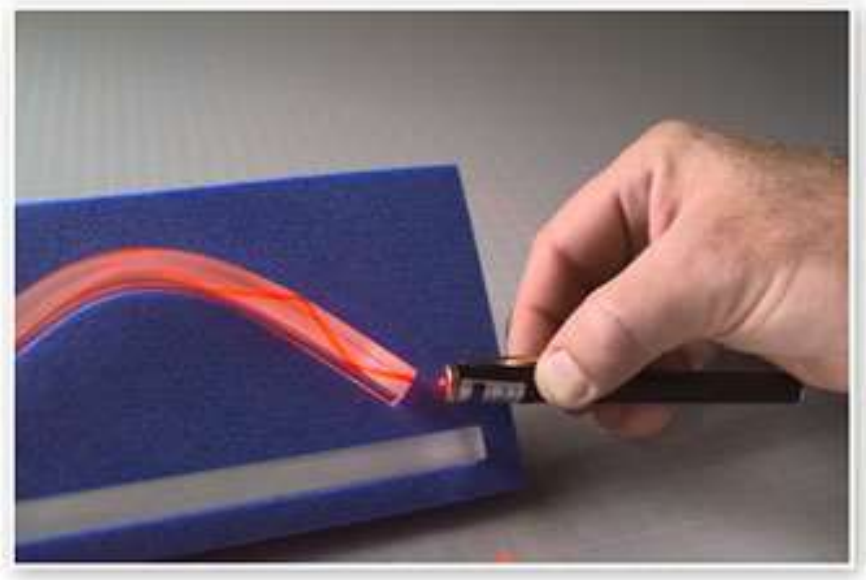
http://sciencenotes.org/printable-periodic-table/
http://www.evgroup.com/images/content/78745/multi-junction_concentrator_solar_cell.jpg
http://www.bit-tech.net/news/hardware/2012/07/10/intel-invests-asml/1

Basic planar waveguide structure on silicon

Waveguide cross-section



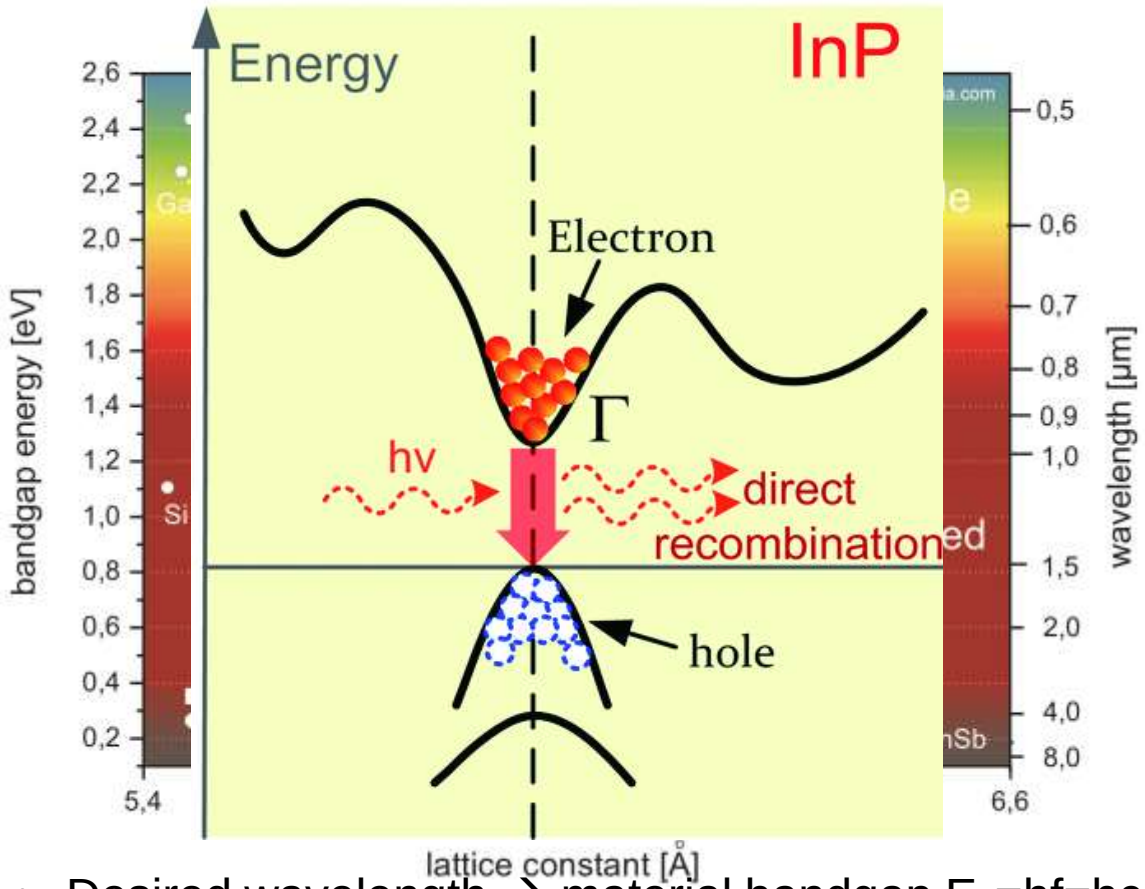


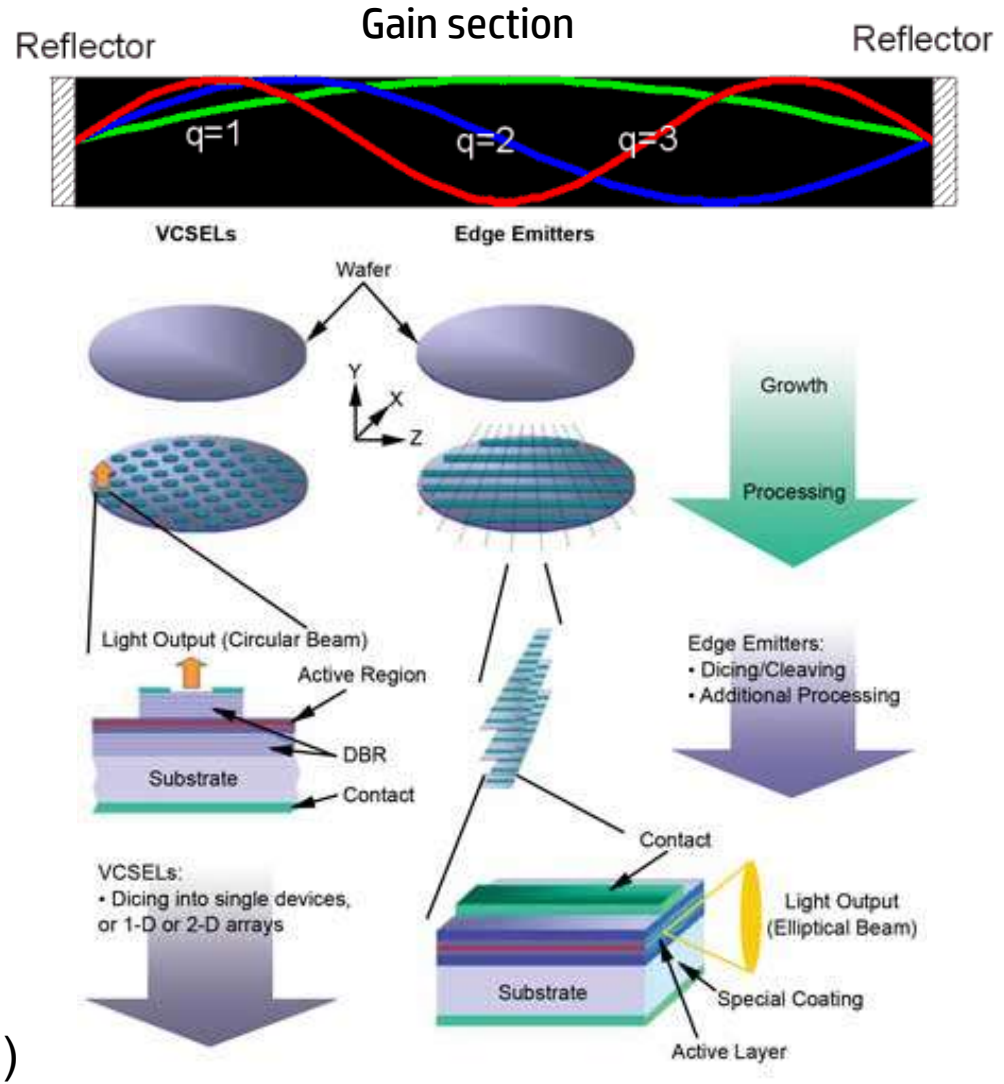
– Larger index contrast $\Delta n = n_{core} - n_{cladding}$

- smaller single-mode waveguide
- better mode confinement ➔ smaller bending loss
- higher scattering loss if sidewall is rough

http://i-fiberoptics.com/laser_detail.php?id=1305

Light source: diode lasers



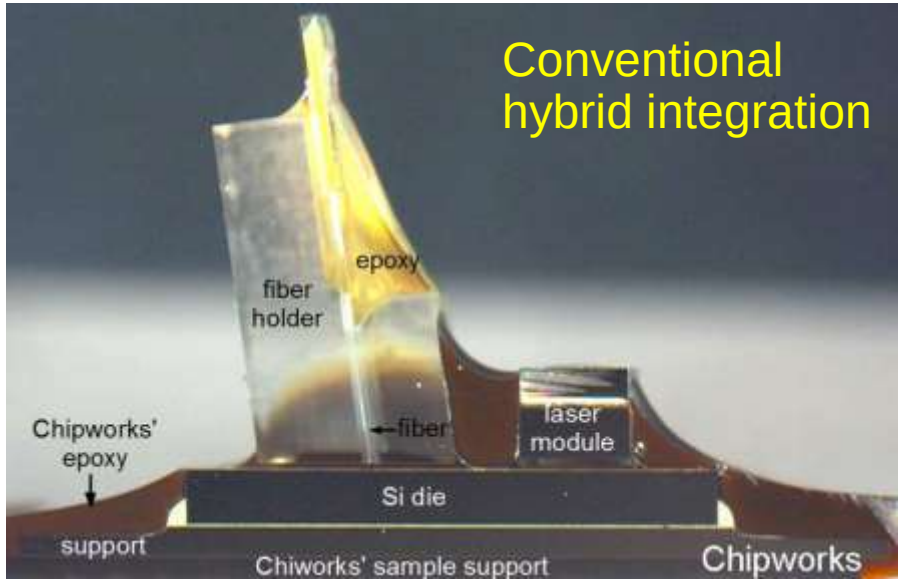


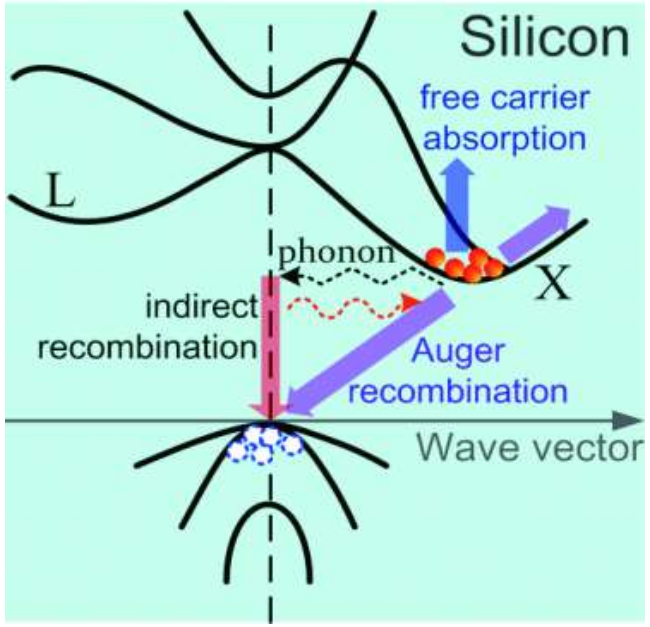
- Desired wavelength → material bandgap $E_g=hf=hc/\lambda$
- Direct bandgap material
- Difficult to manufacture (purity, fabrication, reliability …)

Optical gain inside a resonator

http://lab.frumania.com/
http://www.photonics.com/Article.aspx?AID=49950
http://www.princetonoptronics.com/technology/technology.php

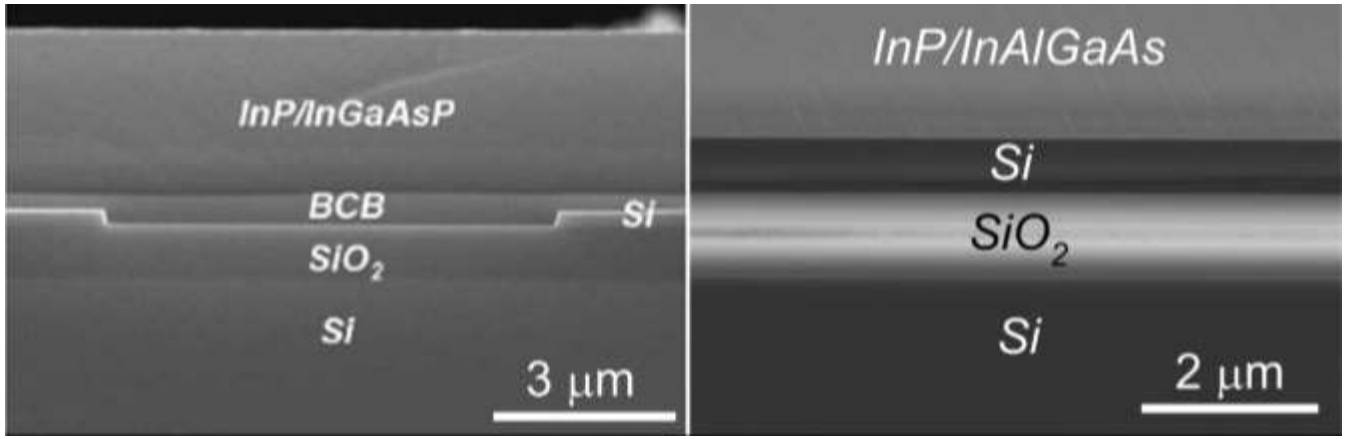
Integrating lasers/lasing materials on silicon





Monolithic integration

Heterogeneous integration



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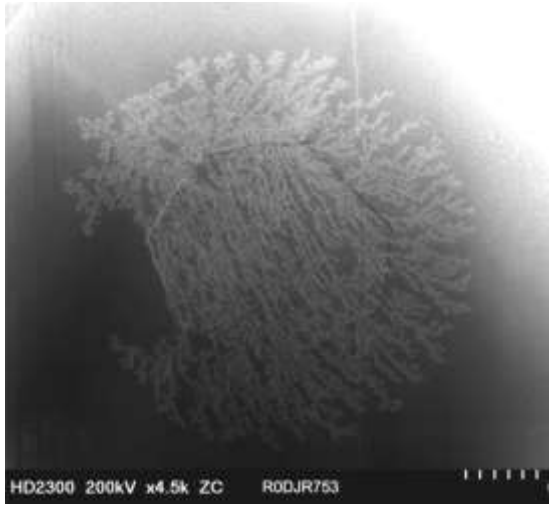
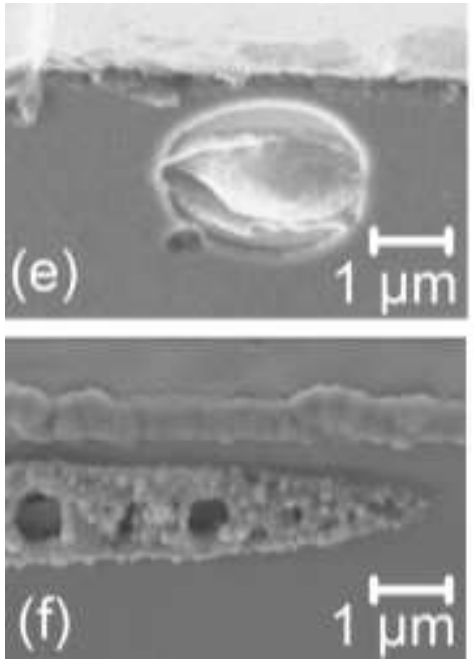
http://www.semiconductor-today.com/news_items/2016/jun/ucsb_200616.shtml

Reliability issues in diode lasers

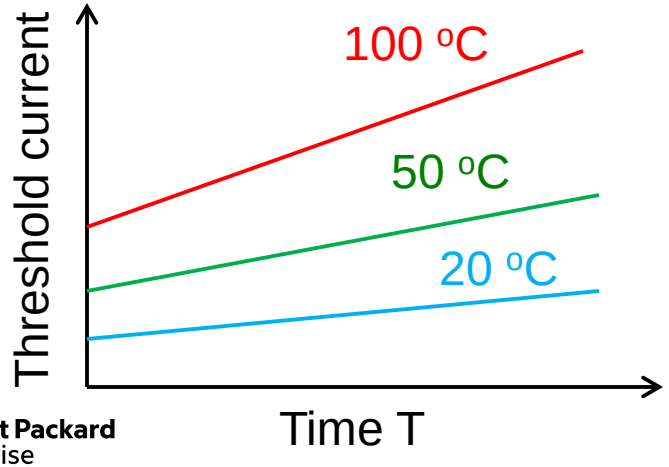
– Typical diode laser degradation modes:
  – Active region – crystalline defects, operation
  – Mirror facets – impurity, crystalline defects
  – Carrier lateral confinement – crystalline defects
  – Ohmic contacts – fabrication, packaging
  – Electrical overstress and electrostatic discharge – packaging, handling
  – Mechanical stability – packaging, operation condition, environment

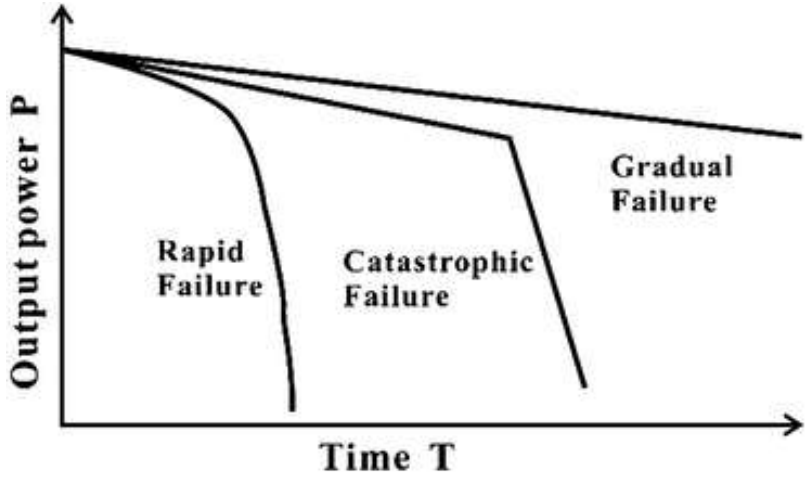


Courtesy of R. Herrick (Intel)



Hempel, CLEO (2011)





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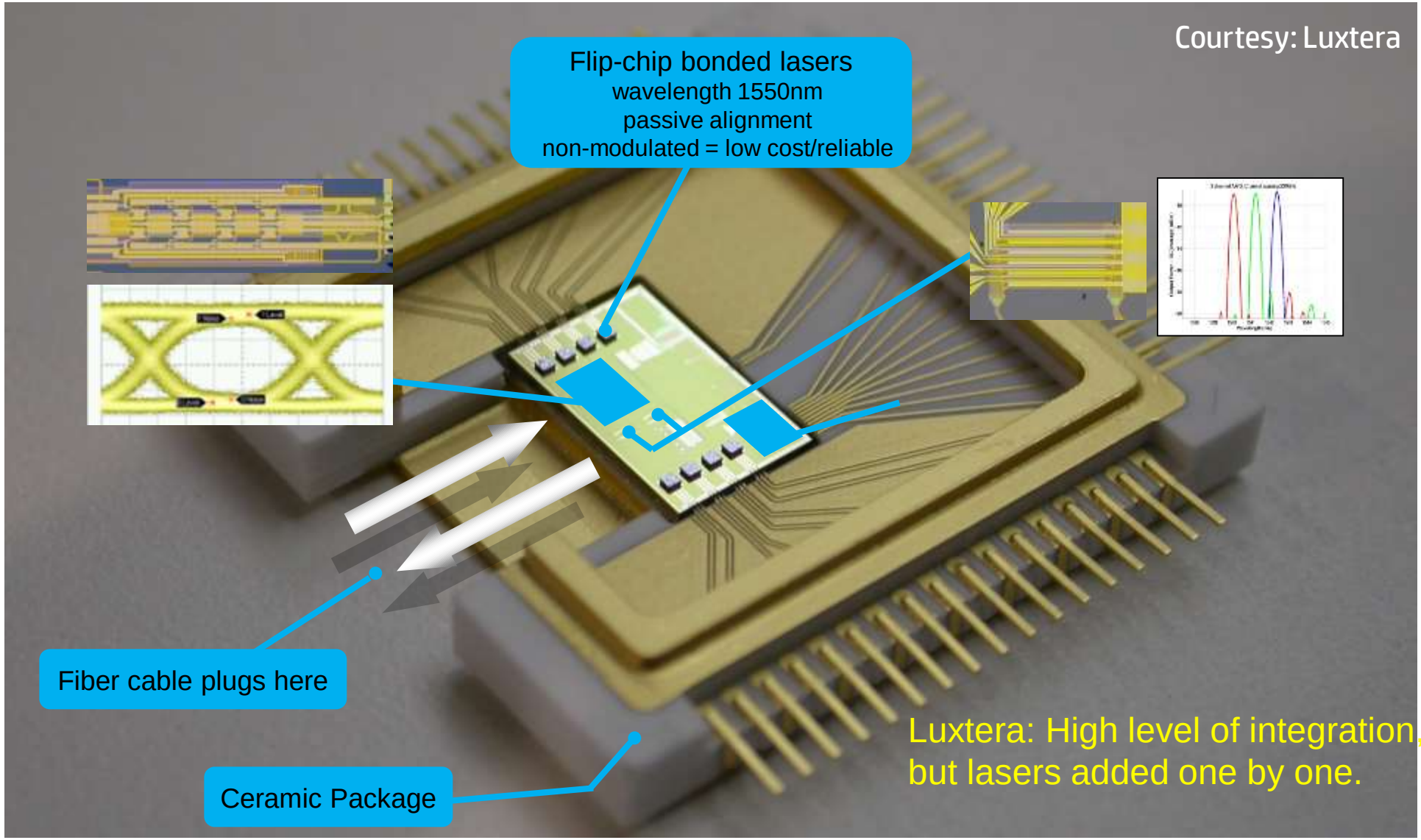
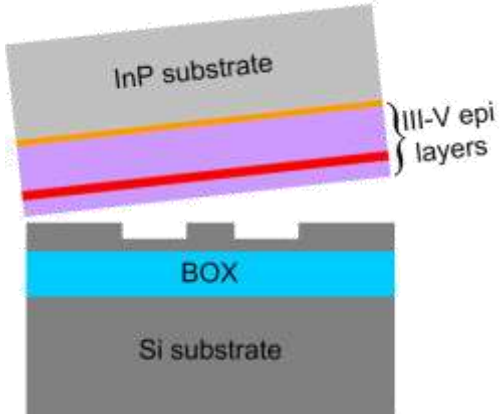
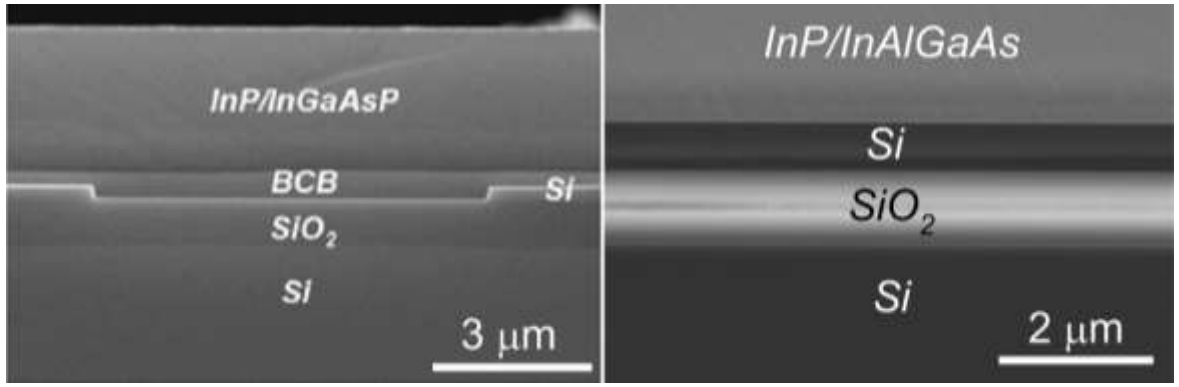
Conventional hybrid integration

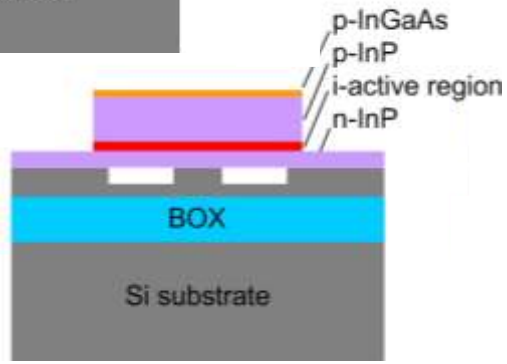


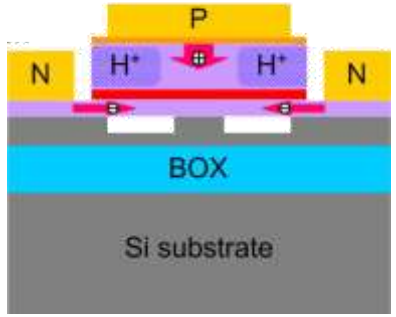
Heterogeneous integration

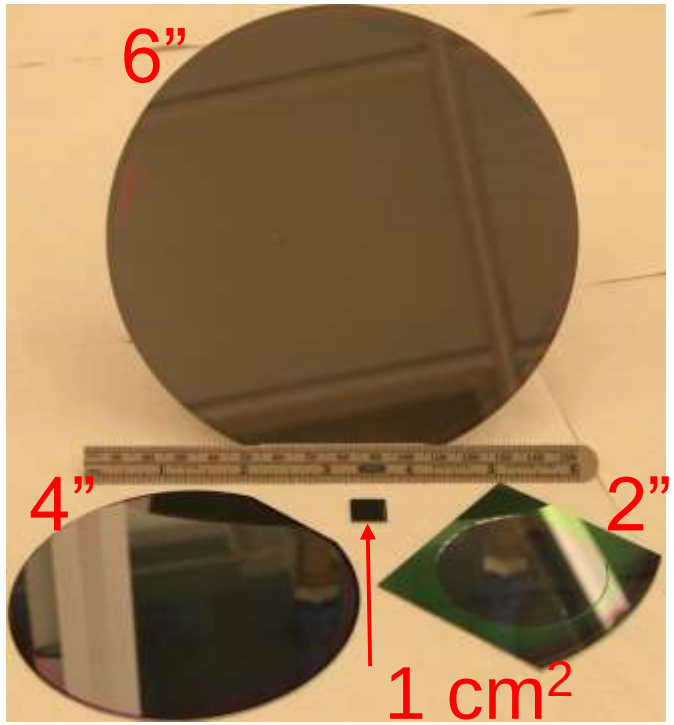


Park, OE, **12**, 9460 (2005)
Fang, OE, **14**, 9203 (2006)
Roelkens, OE, **14** 8154 (2006)

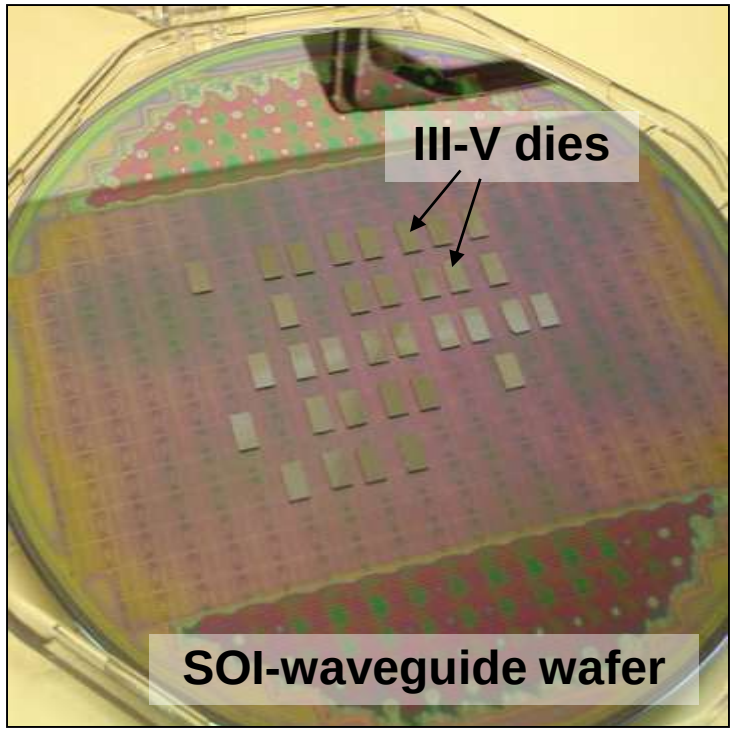








Liang, ESSL 1**2**, H101 (2009)



Fedeli, AOT **2008**, 412518 (2008)

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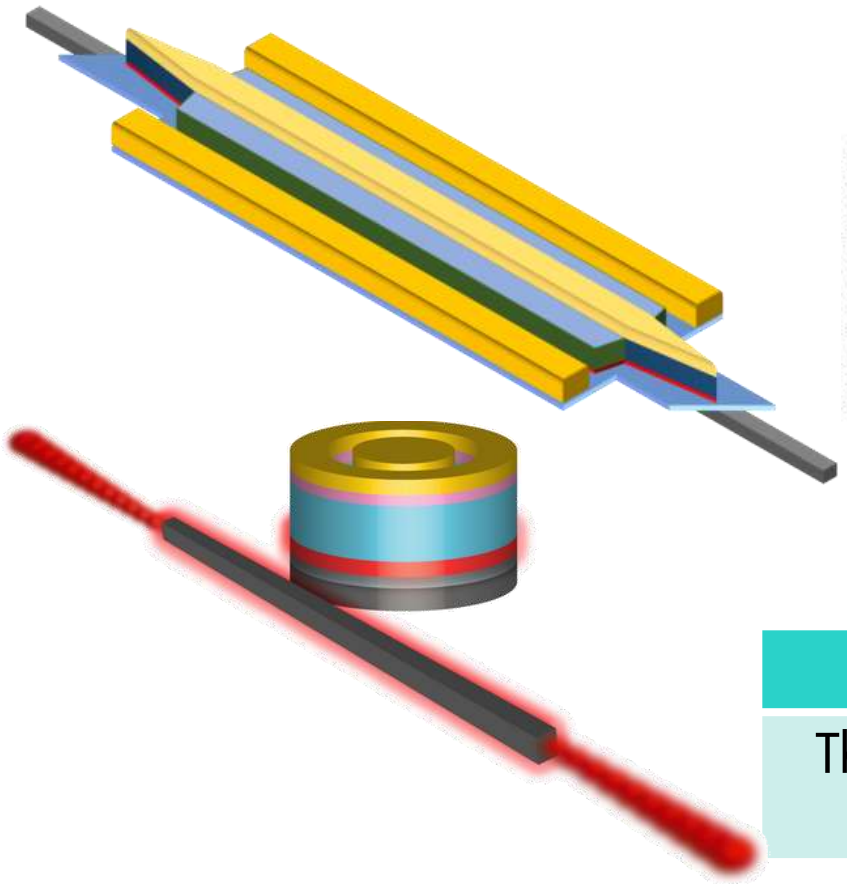
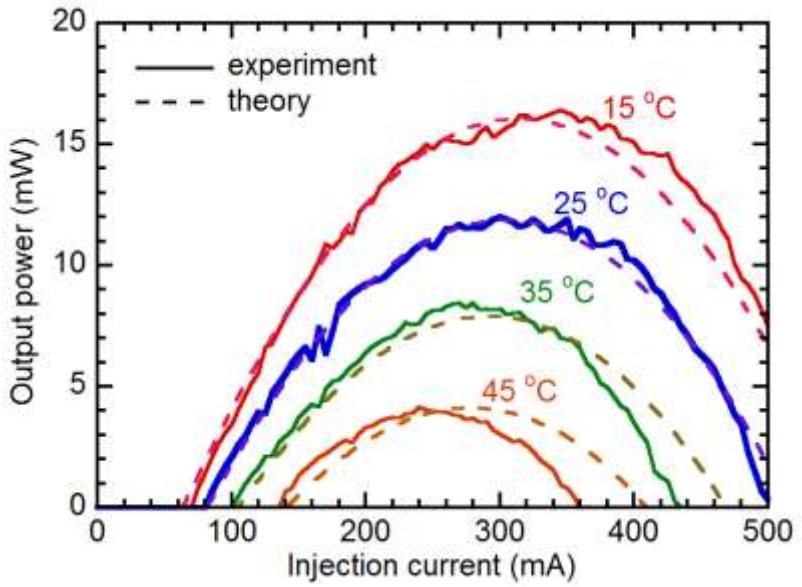
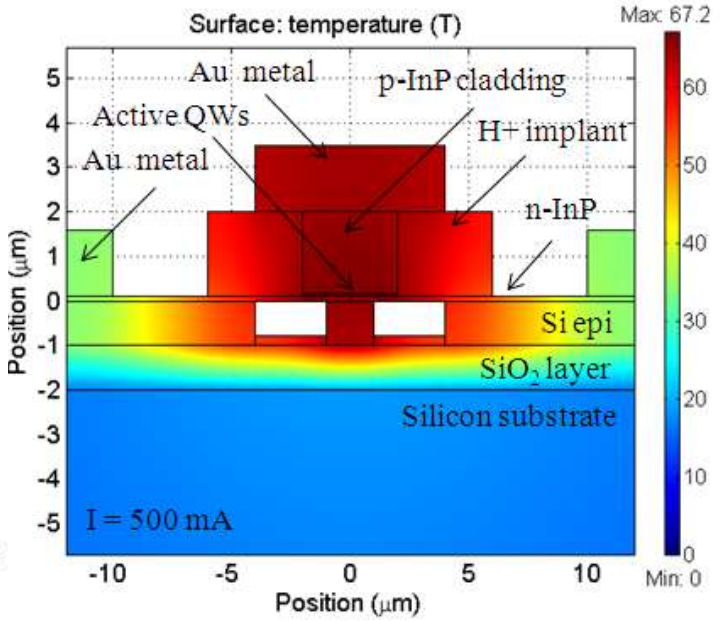
A major performance bottleneck: thermal management







Material	InP	Si	SiO_2	Au
Thermal conductivity (W/m-K)	70	130	1.3	317

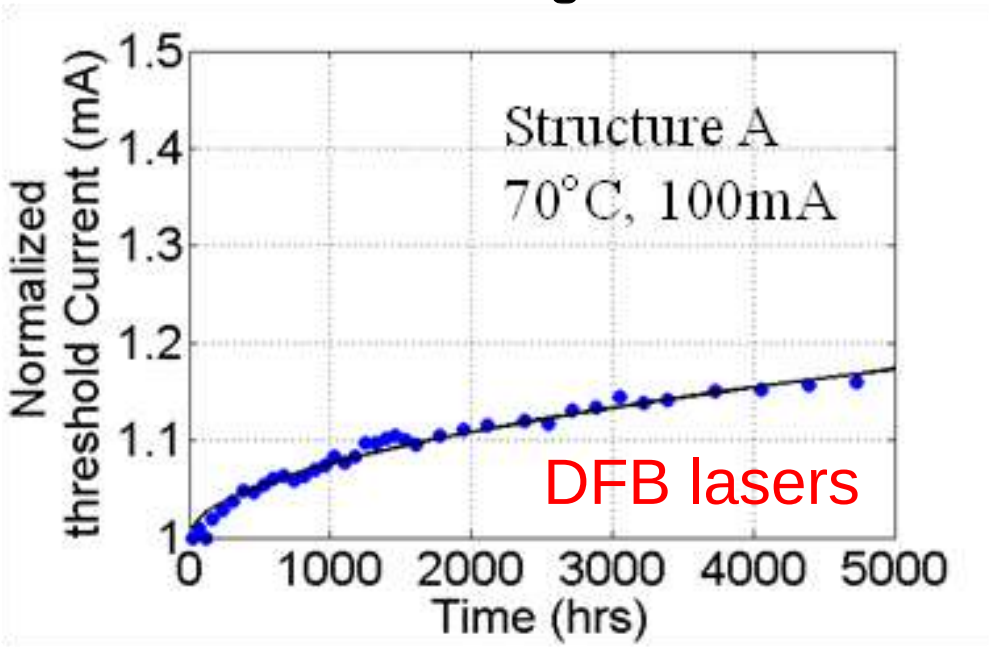
Sysak, OE **15**, 15041 (2007)
Liang, PJ **3**, 580 (2011)

Reliability studies on heterogeneous lasers

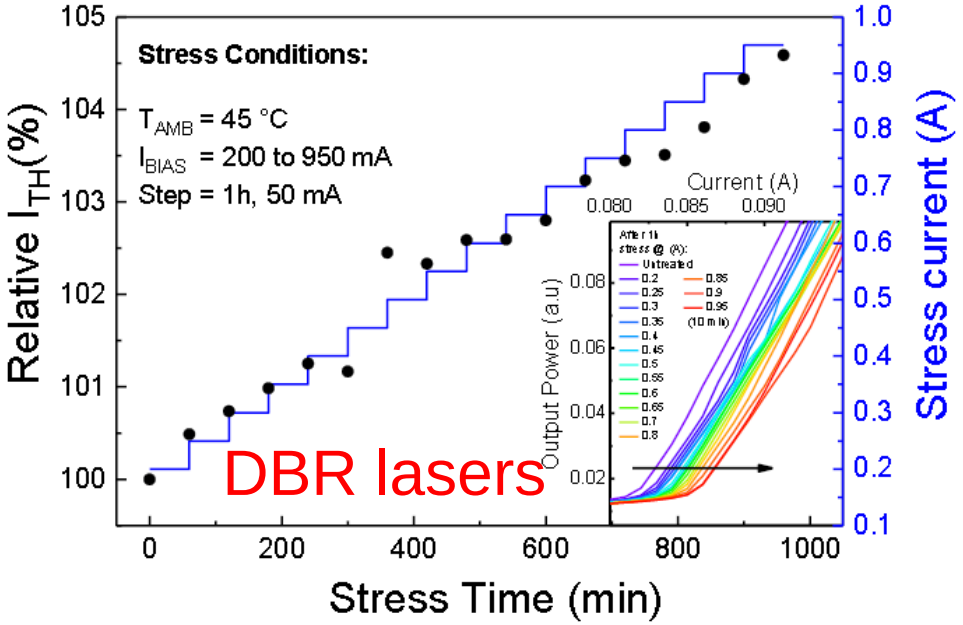
- DFB lasers: estimated 50% degradation in threshold current at 70 °C for ~40000 hrs
- DBR lasers: degradation likely from impurity diffusion towards the active region.

$$I_{th}/I_{th}(0) = 1 + at^m$$

$$MTTF = \left(\frac{0.5}{a}\right)^{1/m}$$



Srinivasan, JSTQE **19**, 1501305 (2013)



Buffolo, Proc. SPIE **10537**, 105370X (2018)

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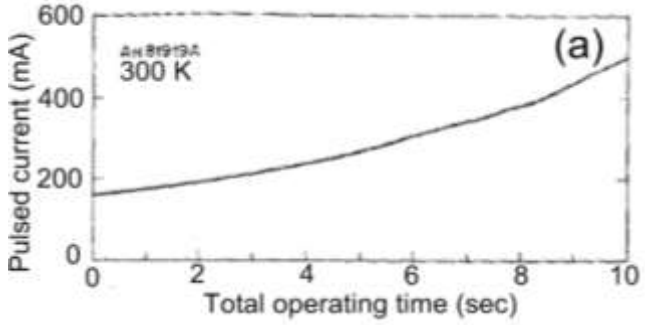
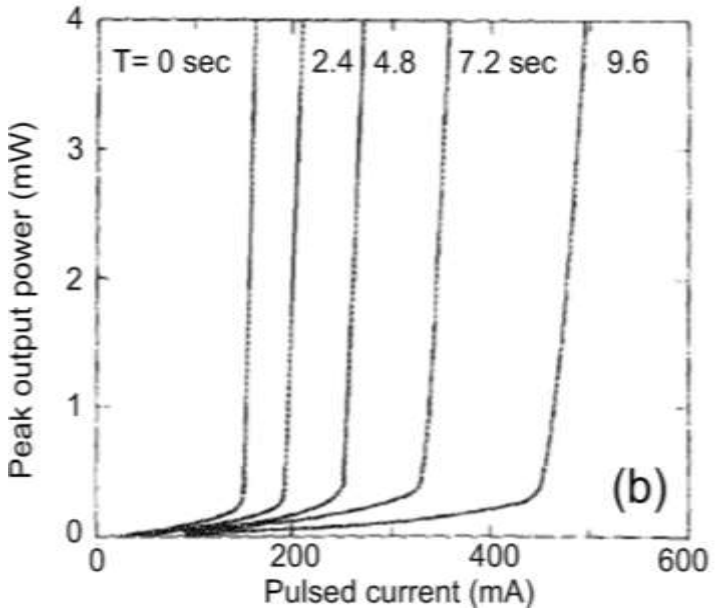
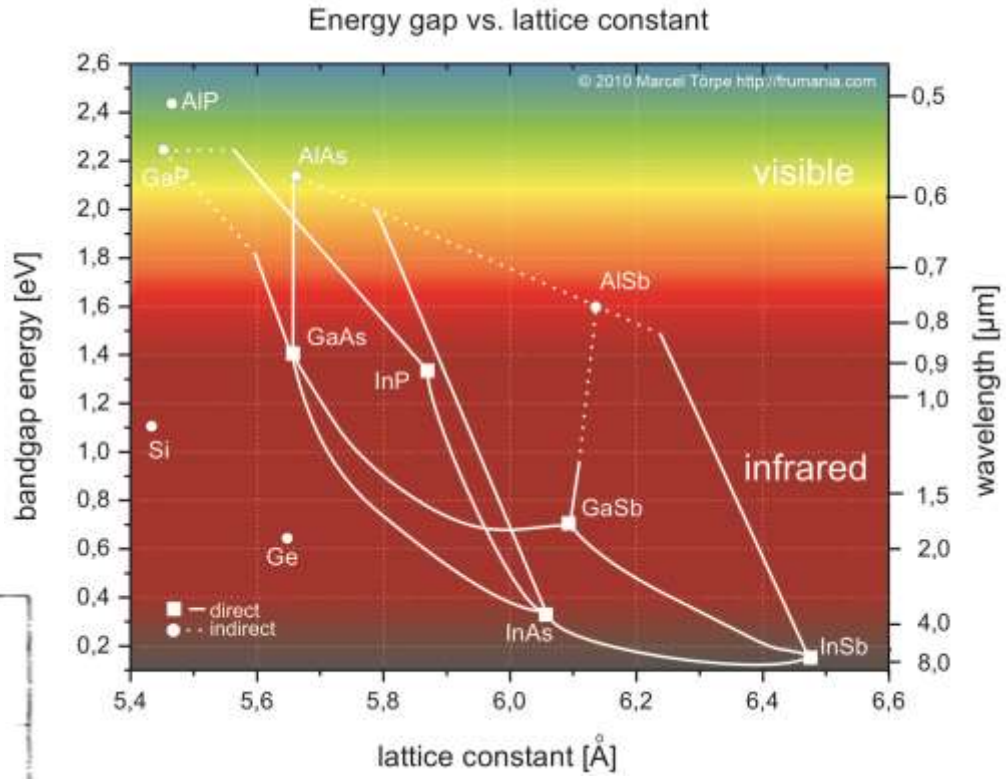
Monolithic integration

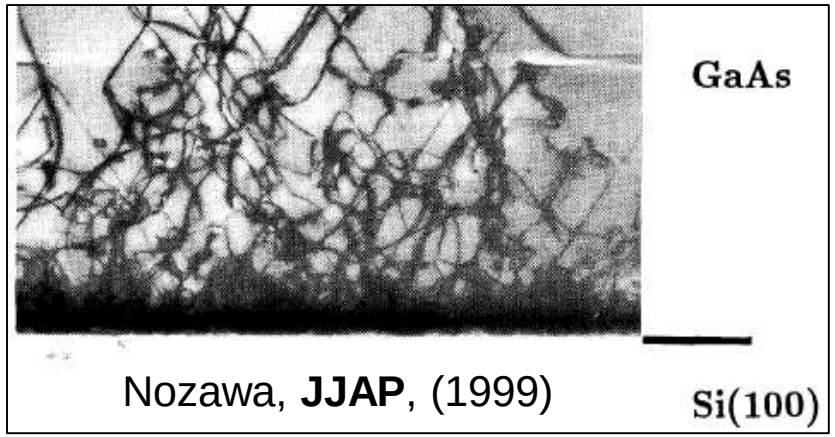
–Main challenges:
  – Lattice mismatch (~4-8% for GaAs, InP vs. Si)
  – Anti-phase domains, stacking faults
  – Mismatch of thermal expansion coefficient



van der Ziel, APL **51**, 89 (**1987**)







Nozawa, **JJAP**, (1999)

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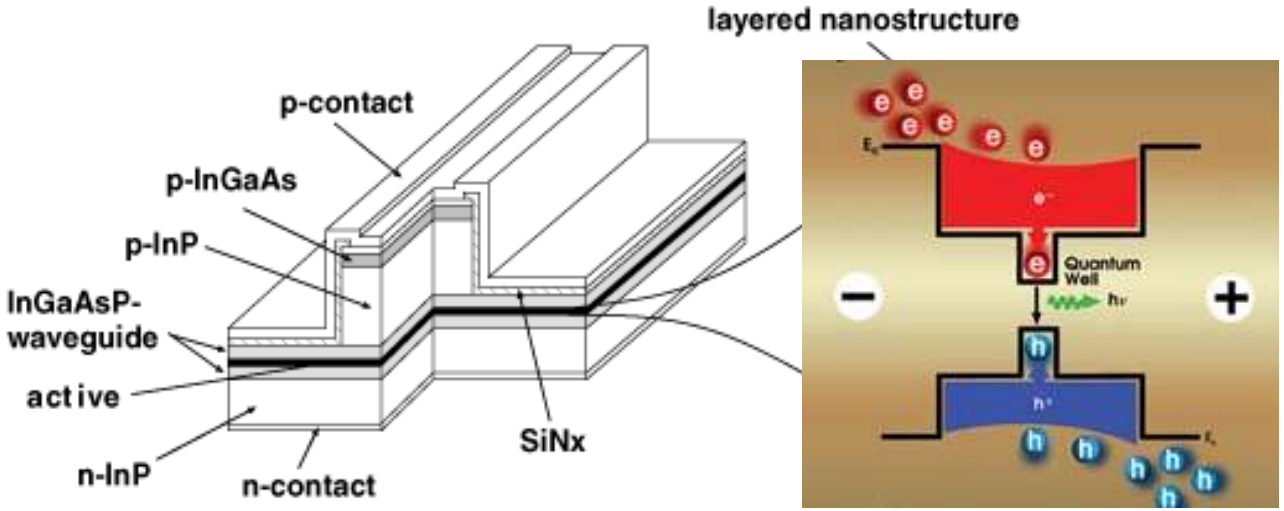
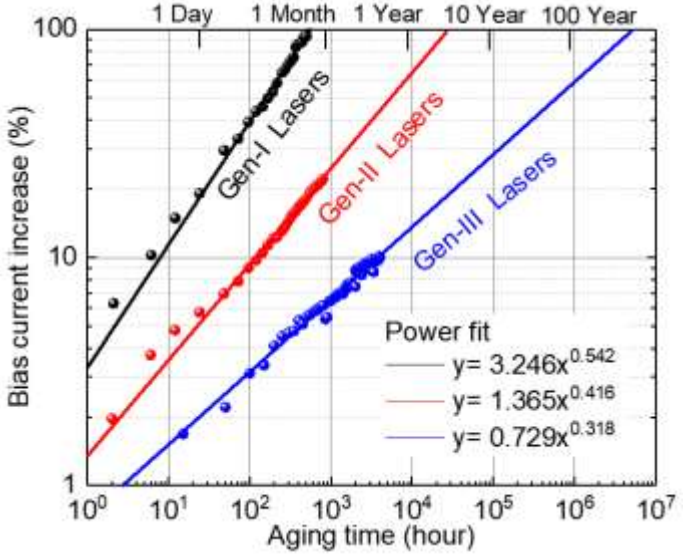
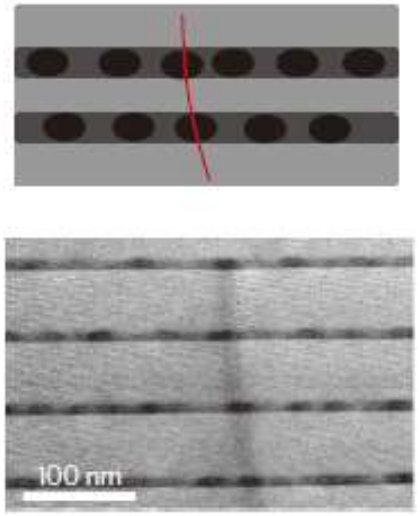
Growing defect-tolerant active region: quantum dot

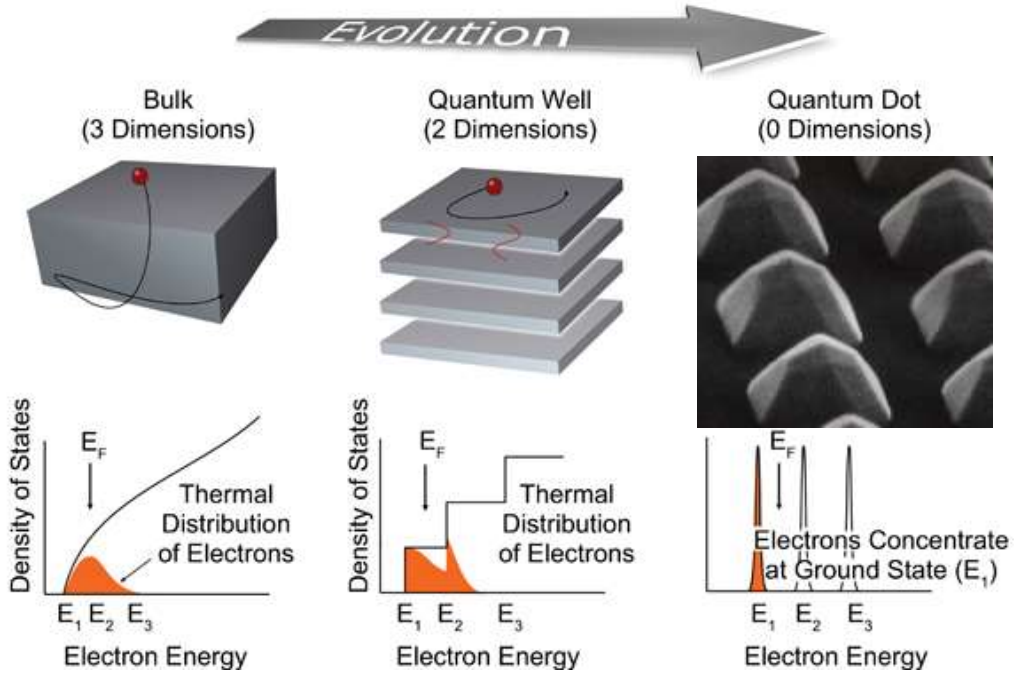


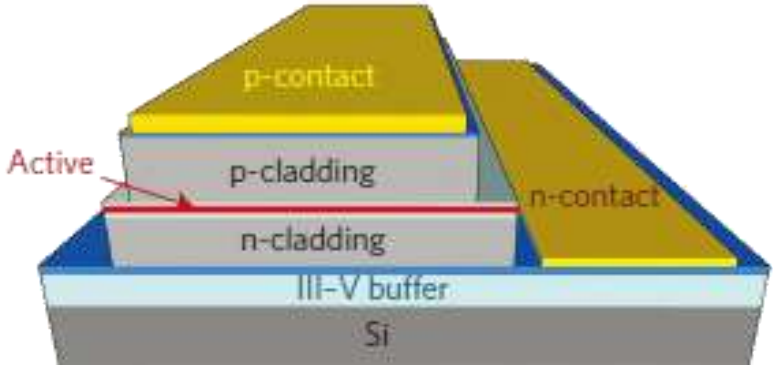
Defect density: 3E8, 7E7, 7E6 /cm^2



Jung, ACS Photonics **5**, 1094 (2018)



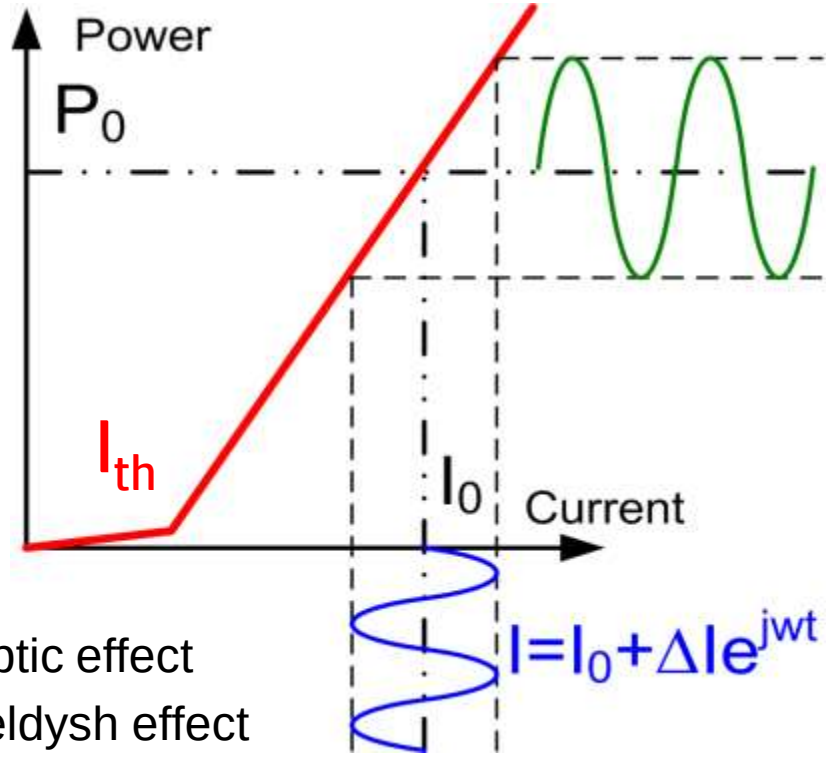




Chen, Nat. Photon. **10**, 307 (2016)

Optical signal modulation

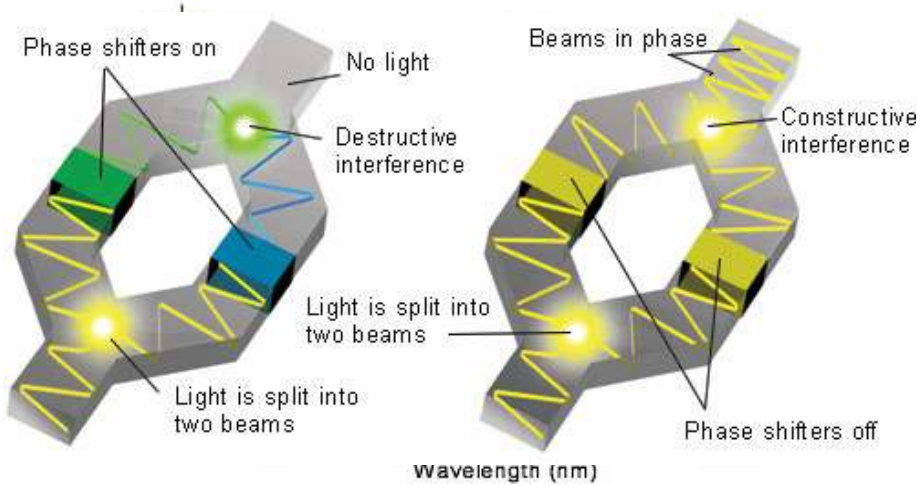
Diode laser
direct modulation



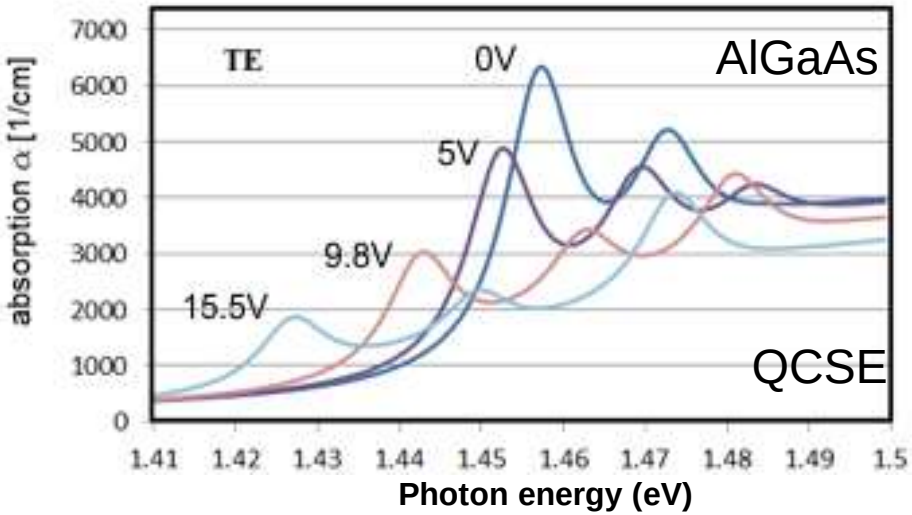
– Electro-optic effect
- Franz-Keldysh effect
- Pockels effect
- Kerr effect
- Band-filling effect
- Quantum-confined Stark effect (QCSE)
- **Plasma dispersion effect**

External modulation

a. Phase (index) modulation



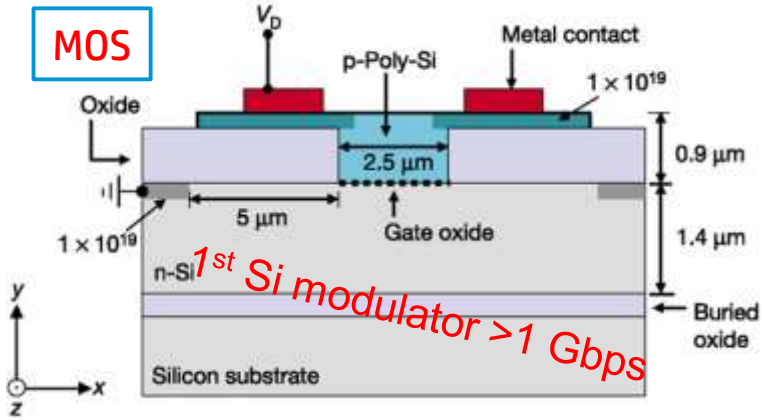
b. Amplitude (loss) modulation



http://spectrum.ieee.org/semiconductors/design/the-silicon-solution
http://www.photond.com/images/products/harold/eam/algaas_validation.gif

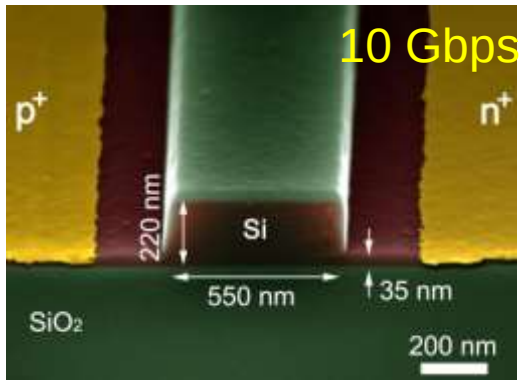
Silicon modulators

MOS

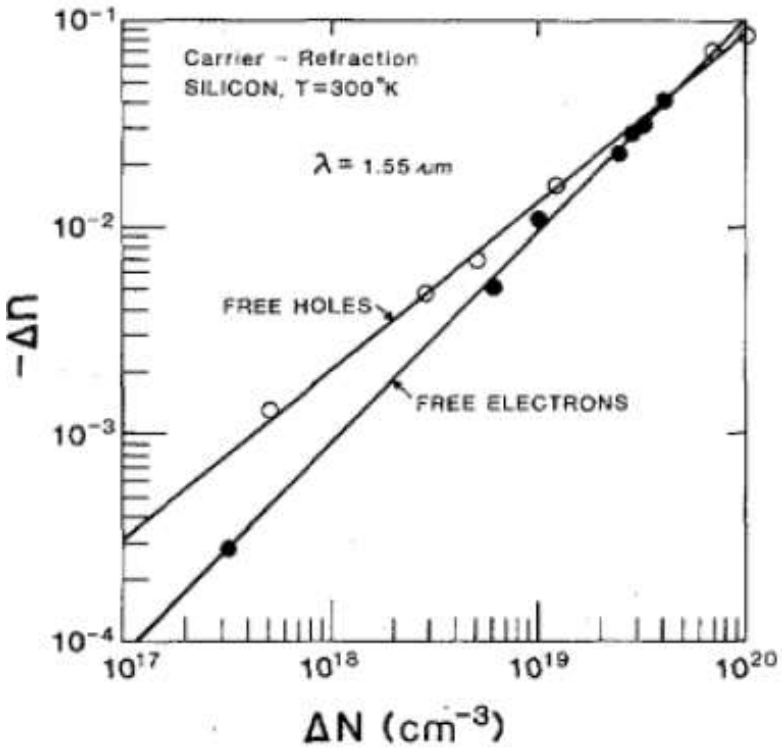


Liu, Nature **427**, 615 (2004)

Injection



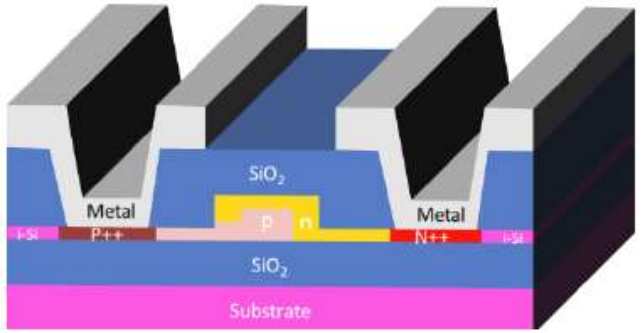
Green, OE **15**, 17106 (2007)



Sorel, JQE **QE-23**, 123 (1987)

Depletion

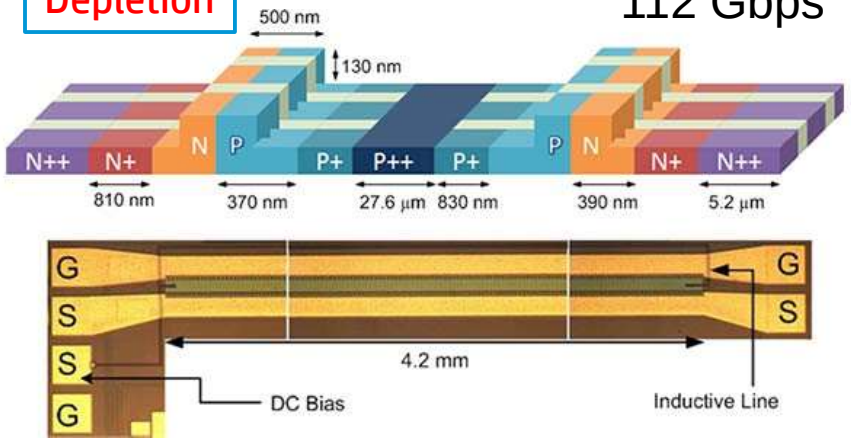
40 Gbps



Gardes, OE **19**, 11804 (2011)

Depletion

112 Gbps



Samani, PJ **7**, 7901413 (2015)

$$\Delta n = \frac{-q^2\lambda_0^{\,2}}{8\pi^2 c^2 n\varepsilon_0}\left(\frac{\Delta N_e}{m_{ce}^*}+\frac{\Delta N_h}{m_{ch}^*}\right)$$

$$\Delta\alpha = \frac{q^3\lambda_0^{\,2}}{4\pi^2 c^3 n\varepsilon_0}\left(\frac{\Delta N_e}{m_{ce}^{*\,2}\mu_e}+\frac{\Delta N_h}{m_{ch}^{*\,2}\mu_h}\right)$$

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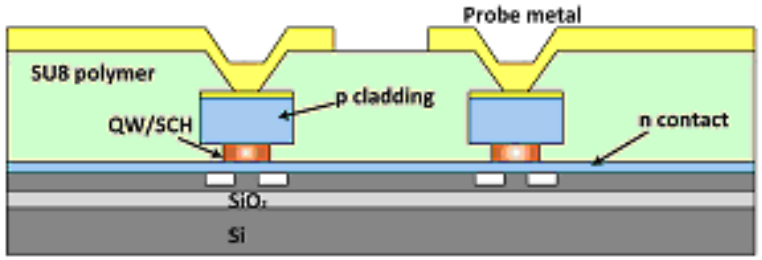
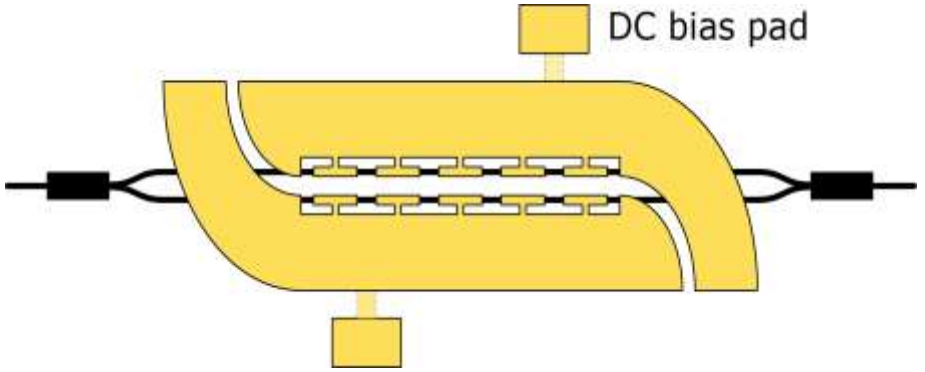
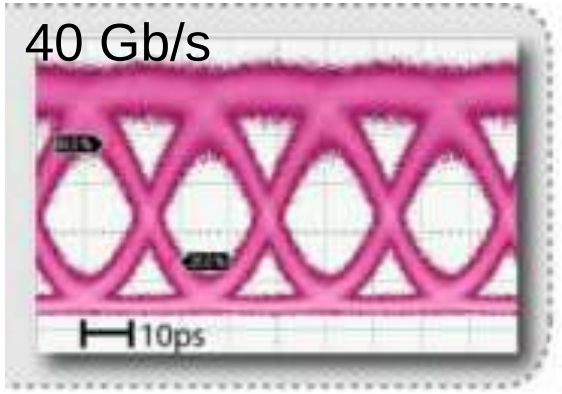
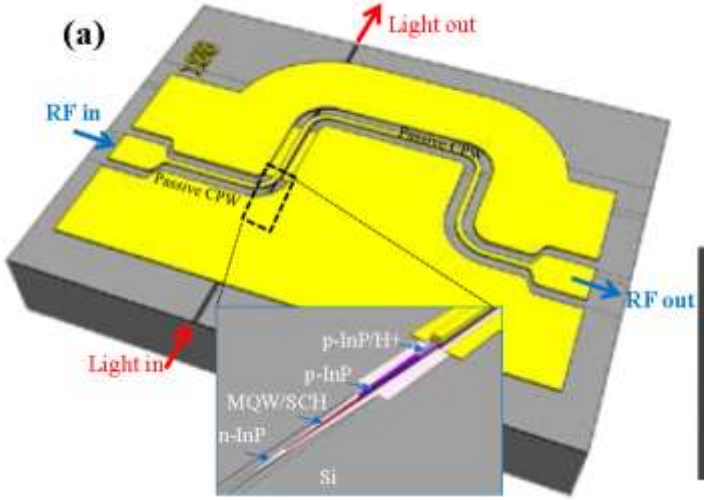
Heterogeneous silicon modulators

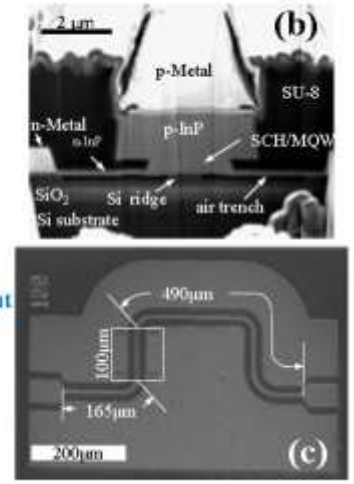


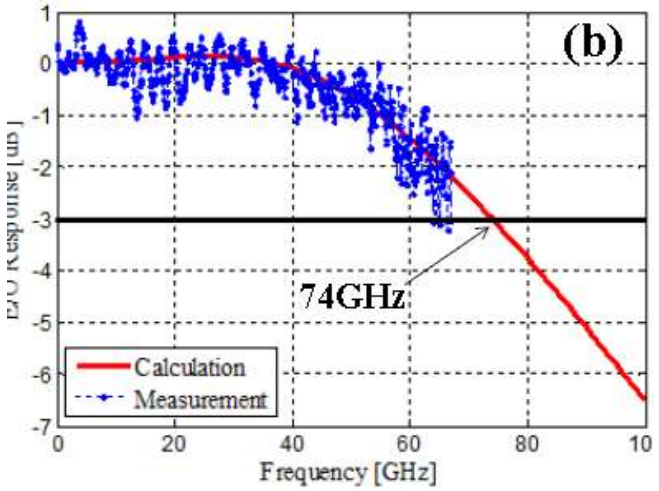


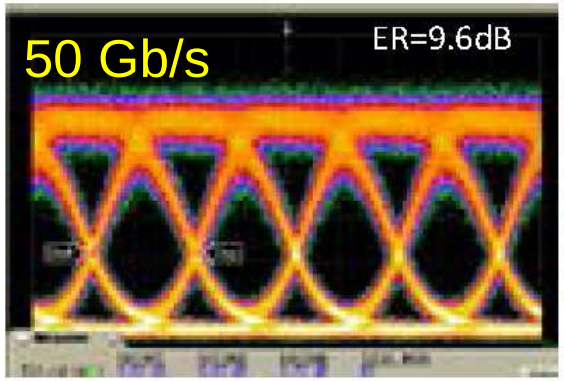


Chen, OE **19**, 1455 (2011)









Tang, OE **20**, 11529 (2012)

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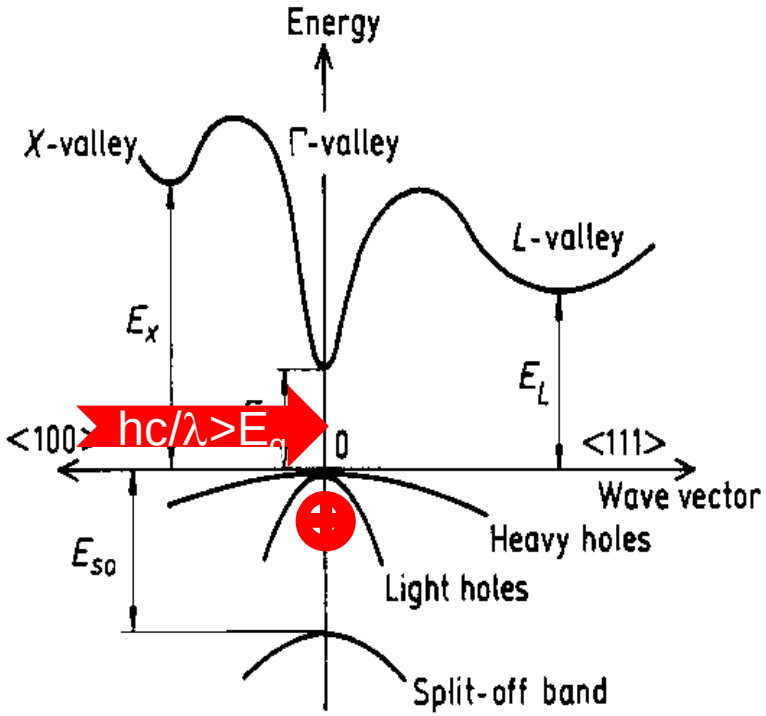
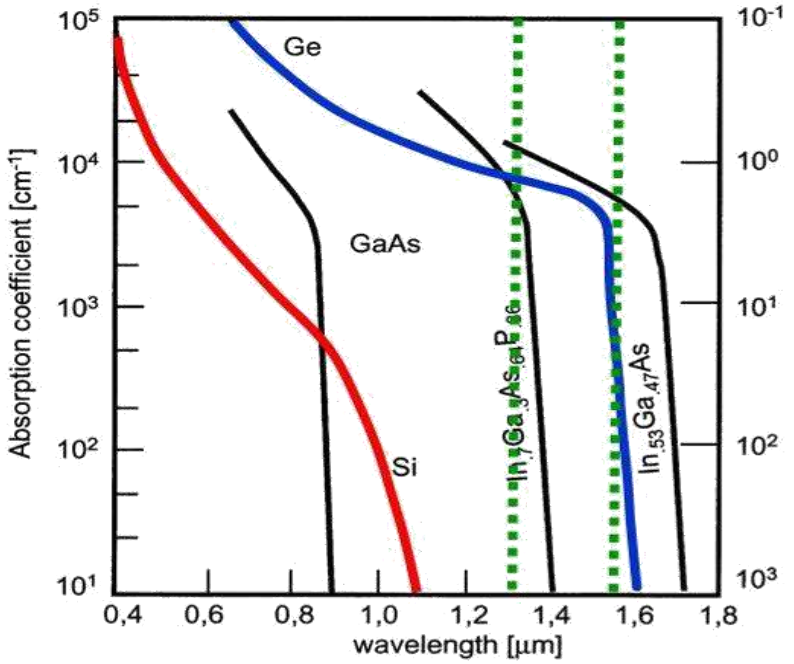
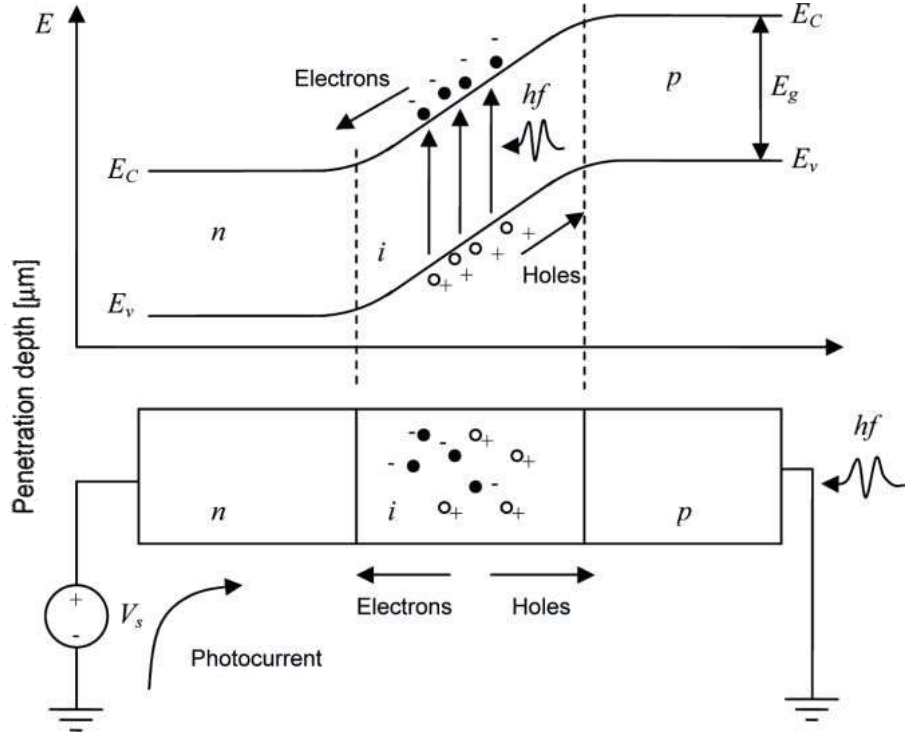
Photodetection

InGaAs band diagram

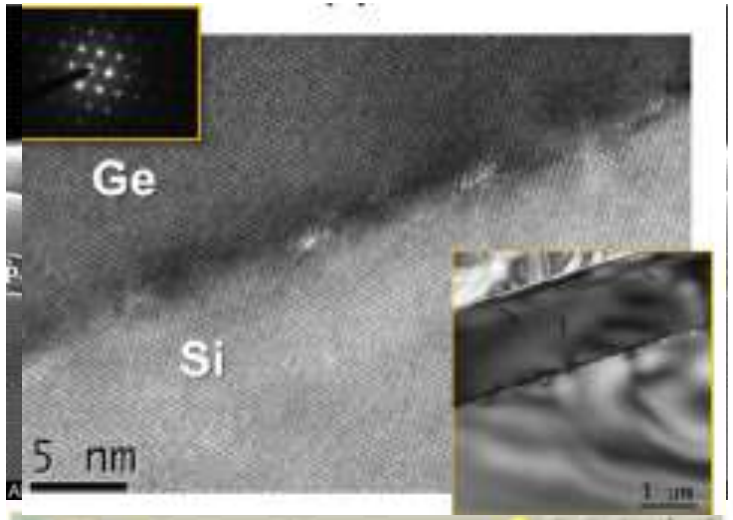


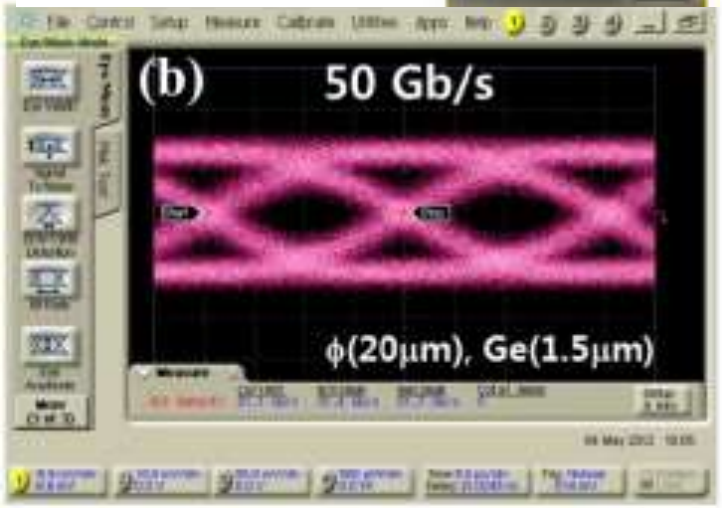




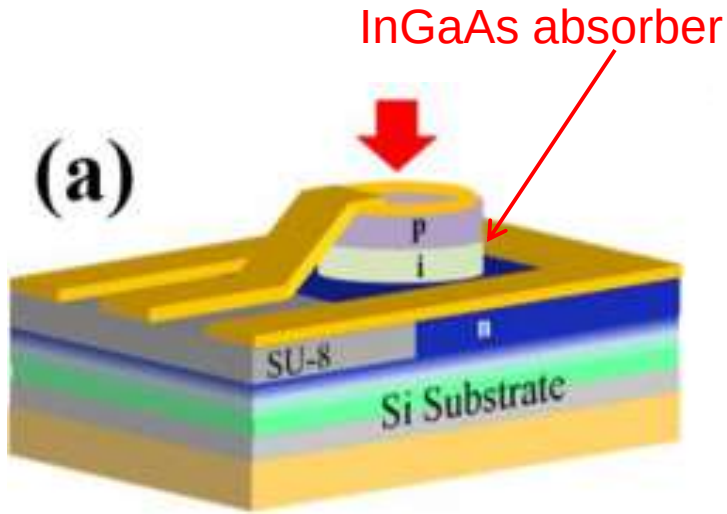
http://www.ioffe.ru/SVA/NSM/Semicond/GaAs/Figs/421.gif
http://link.springer.com/chapter/10.1007%2F978-1-4419-0304-4_6/fulltext.html#Fig6_1_176711_1_En

Silicon-based photodetectors

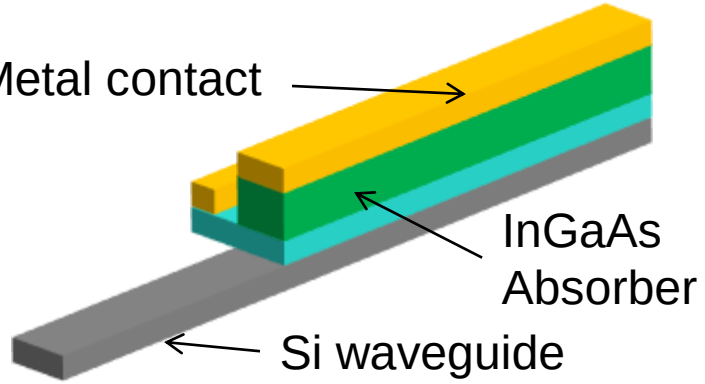




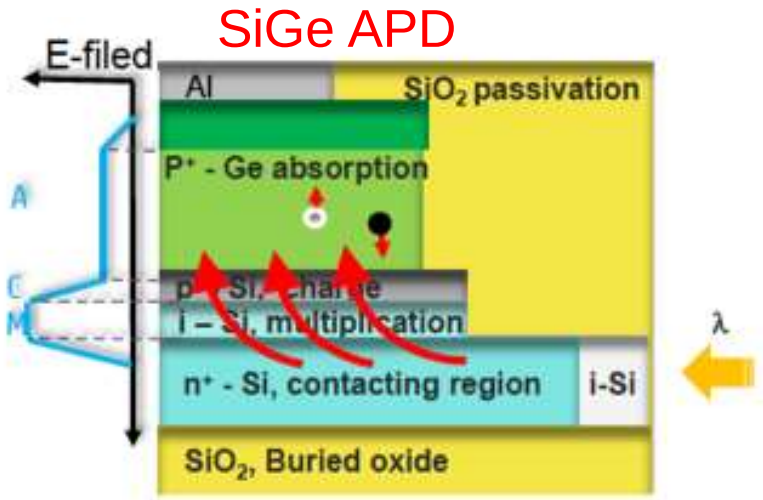
Kim, OE **21**, 30716 (2013)



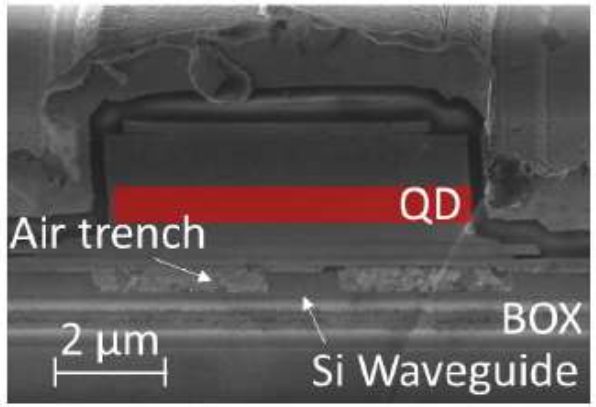
Sun, OE **26**, 13605 (2018)



Kurczveil, OI (2016)



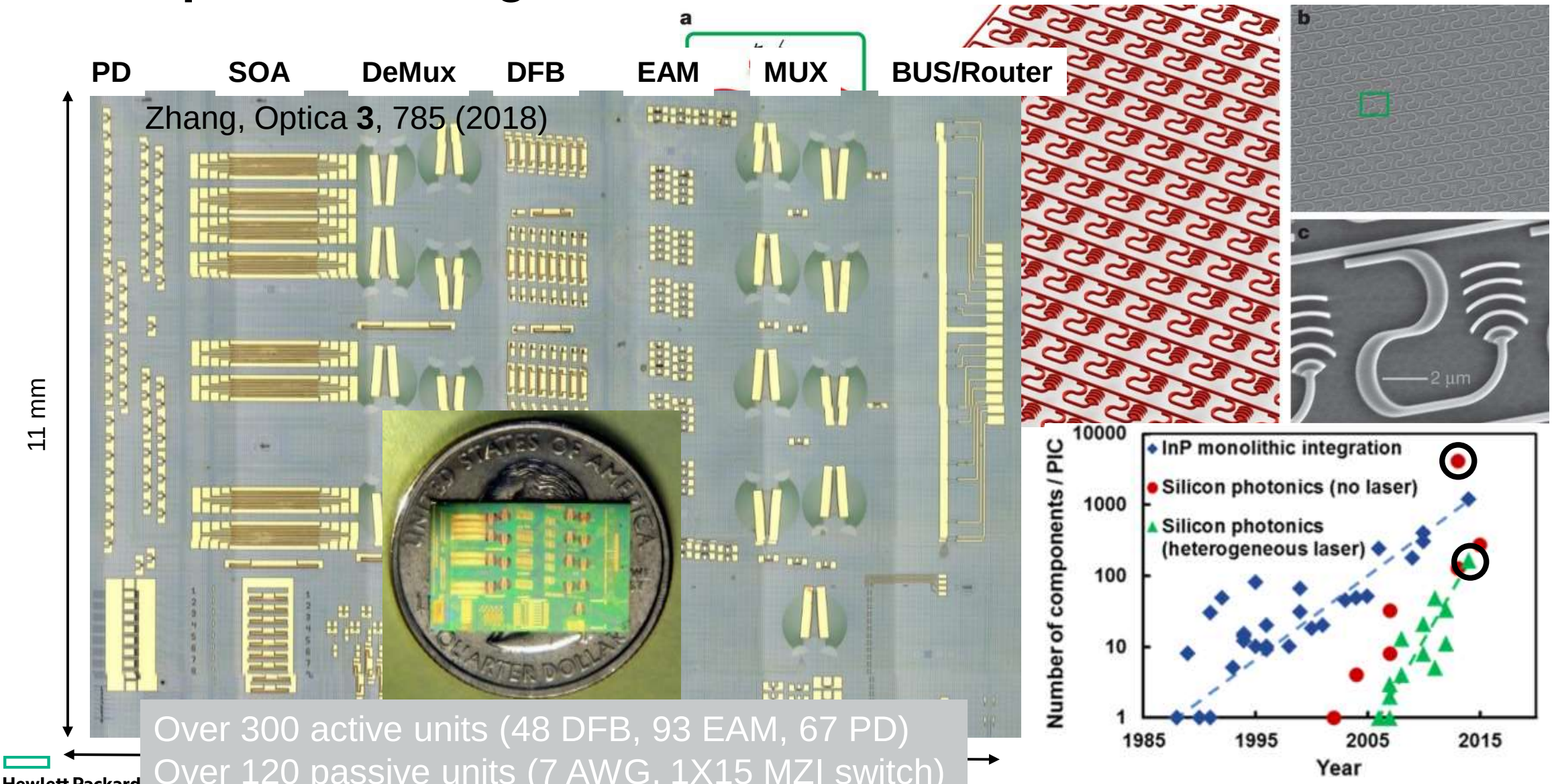
Huang, Optica **3**, 793 (2016)



Tossoun, DRC (2018)

Silicon photonic integration

Sun, Nature 439, 195 (2013)



Over 300 active units (48 DFB, 93 EAM, 67 PD)
Over 120 passive units (7 AWG, 1X15 MZI switch)

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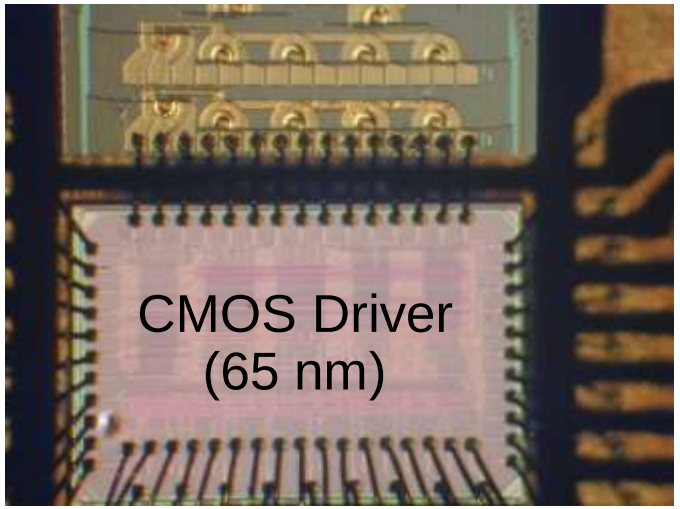
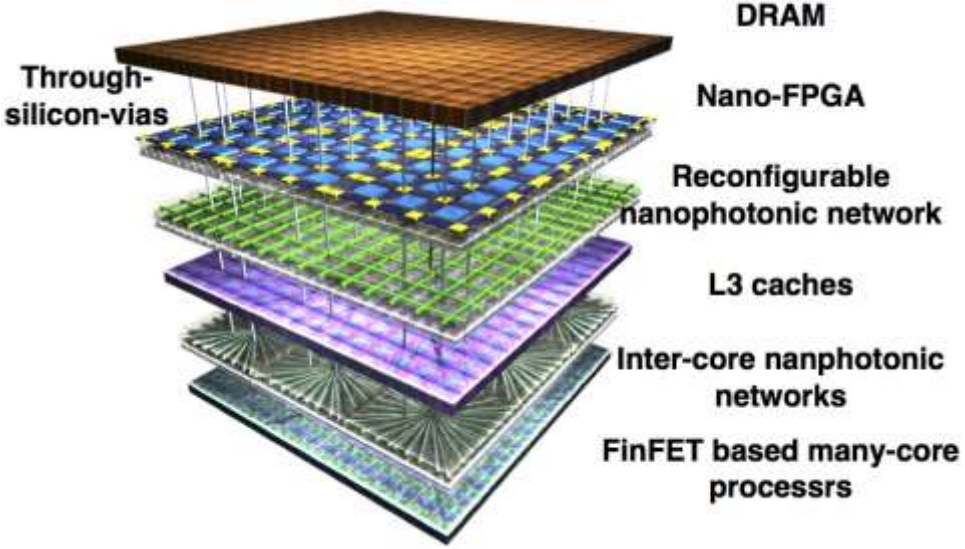
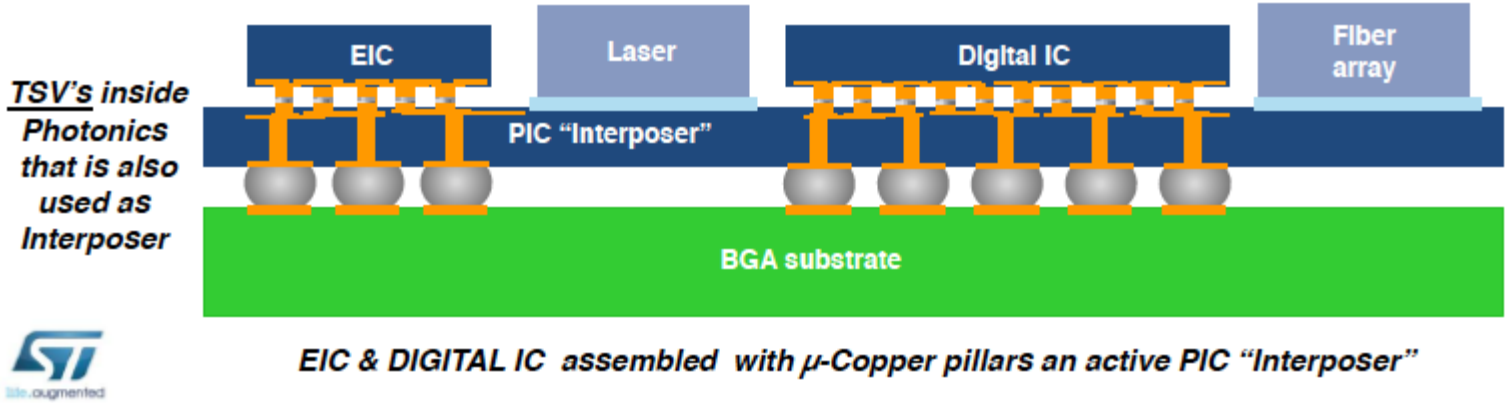
Silicon photonics - electronics hybrid integration

2D, 2.5D and 3D integration schemes

Optical Transmitter







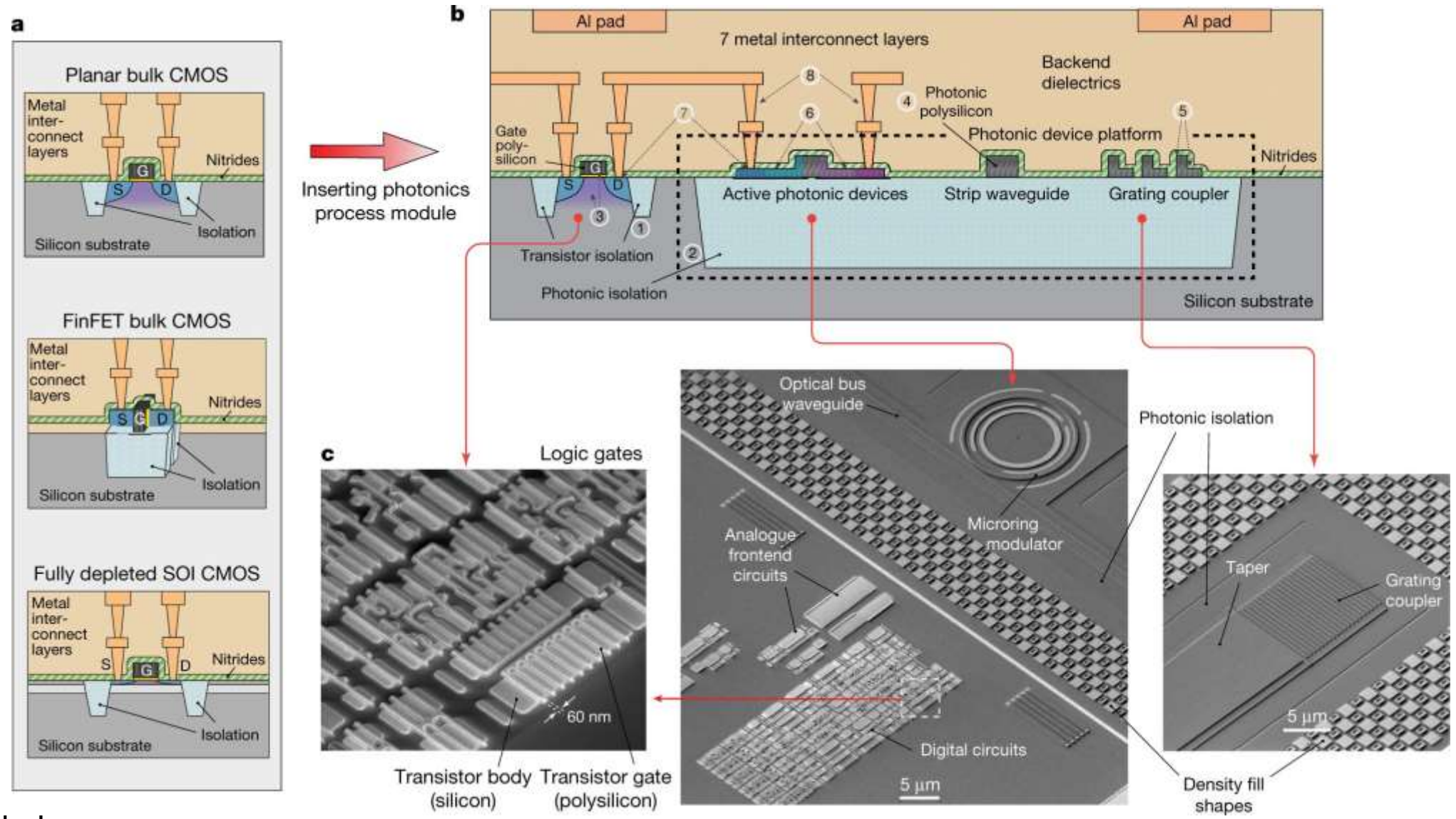
EIC & DIGITAL IC assembled with μ-Copper pillars an active PIC "Interposer"

– 2D integration
  – Simple, mature
  – Limited bandwidth
– 2.5D integration
  – High speed, low power consumption
  – Fabrication, thermal management
– 3D integration
  – Largest bandwidth, smallest footprint
  – Thermal management, system design, reliability

Hewlett Packard Enterprise

https://www.3dincites.com/2014/01/lessons-learned-trenches-3d-ic-manufacturing-sensor-applications/
https://www.colorado.edu/engineering/gwol/SiliconPhotonics.html

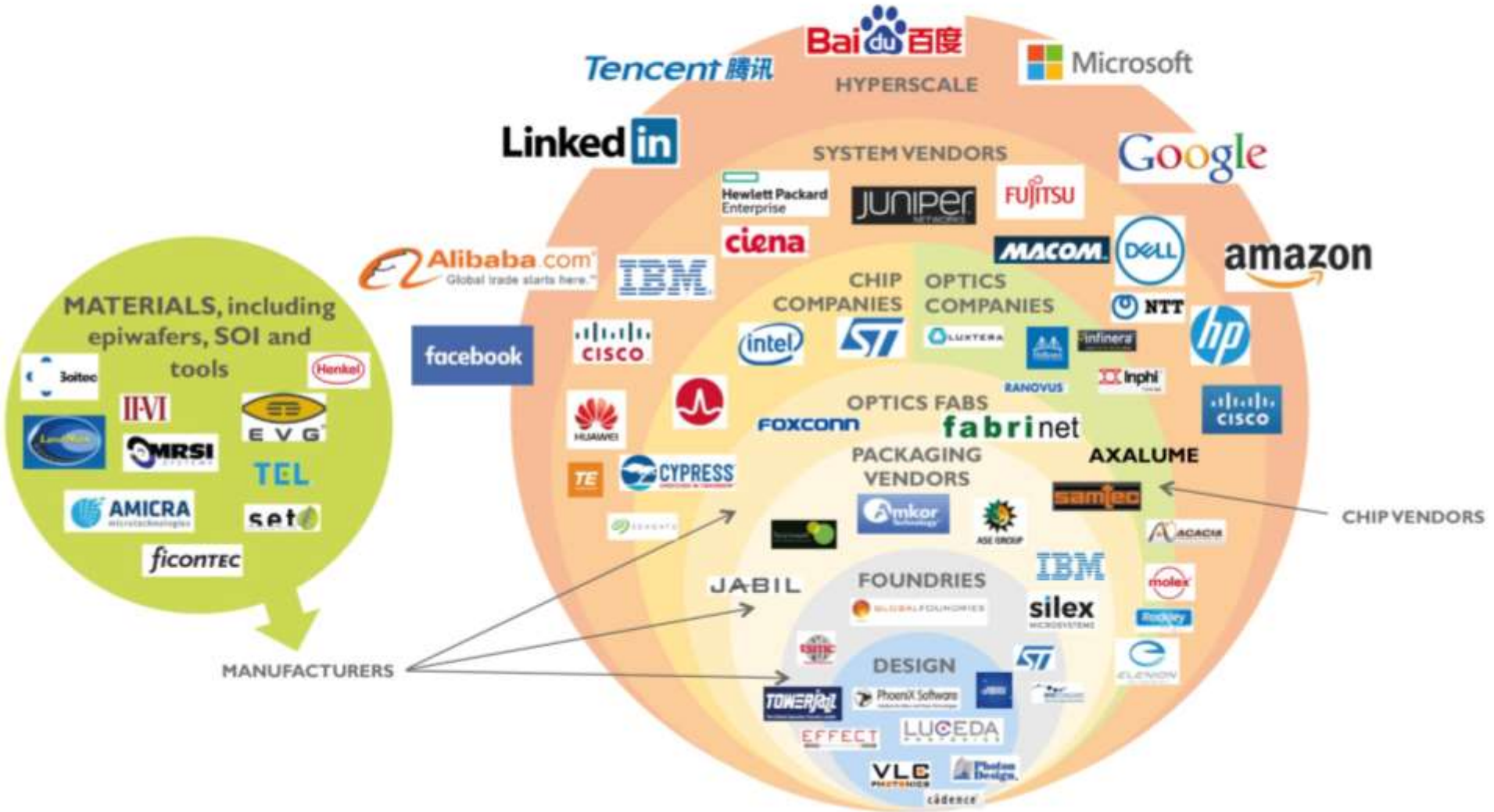
Silicon photonics - electronics monolithic integration



Atabaki, Nature **556**, 349 (2018)

Si Photonics: ecosystems & stakeholders in 2017

(Source: Silicon Photonics 2018 report, Yole Développement, January 2018)



http://www.yole.fr/iso_album/illus_si_photonics_ecosystem_yole_jan2018.jpg

Summary

– Key factors in photonic integration: functionality, material and fabrication compatibility

– Silicon photonic building blocks getting mature and complete in past 15 years

– On-chip laser: still primary R&D component and reliability determining factor

– Photonics – electronics integration: a challenging balance of bandwidth – thermal management – cost

– Silicon photonic ecosystem: vertical integration presently; open and horizontal integration necessary

– Helps needed from EDA community
  – Advanced active photonic component simulation (Optical, electrical, thermal)
  – Packaged module level simulation (Optical, electrical, thermal, mechanical)
  – Reliability simulation of III-V and Ge components on silicon and integrated chips