Emerging Interconnect Technologies

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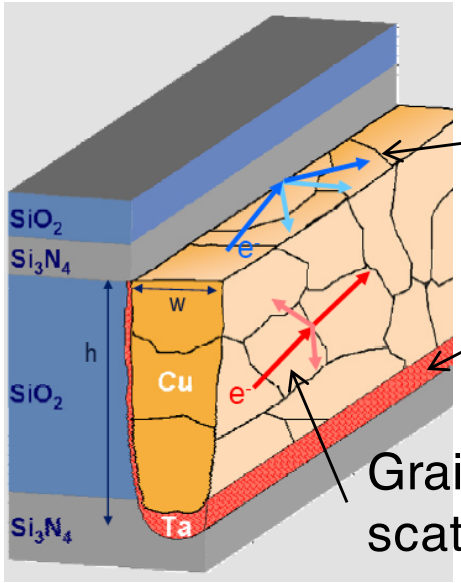
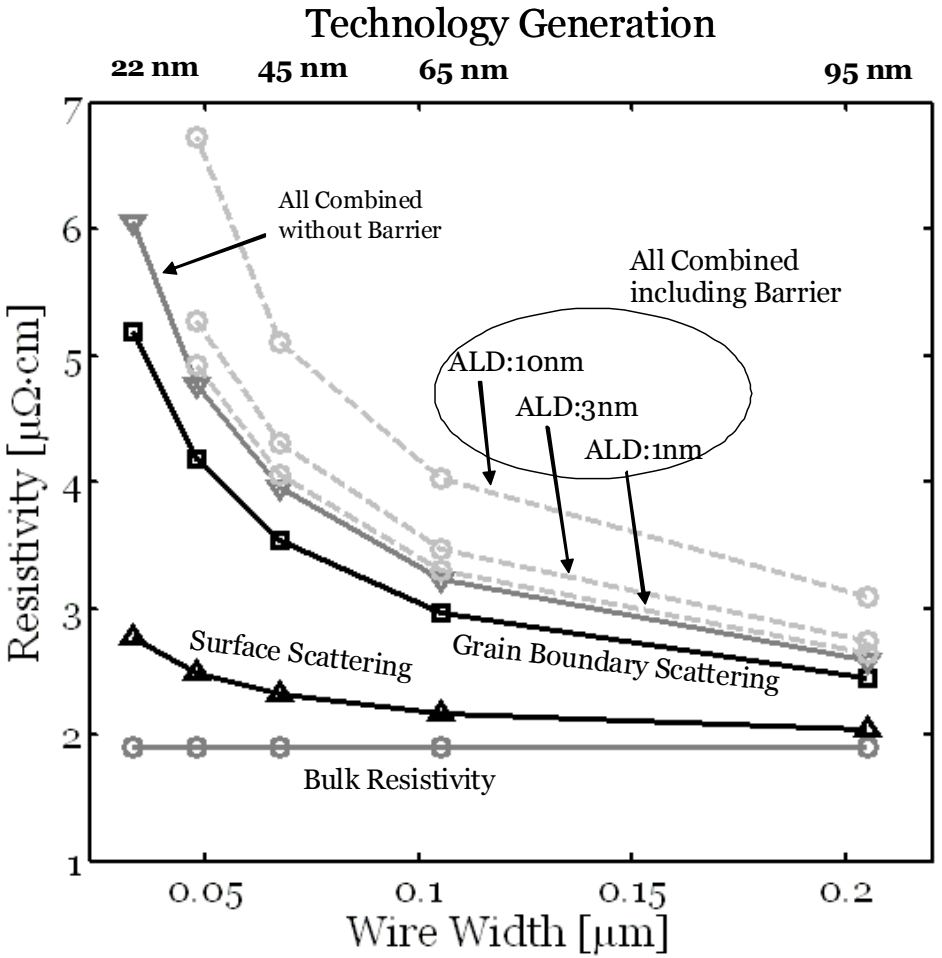
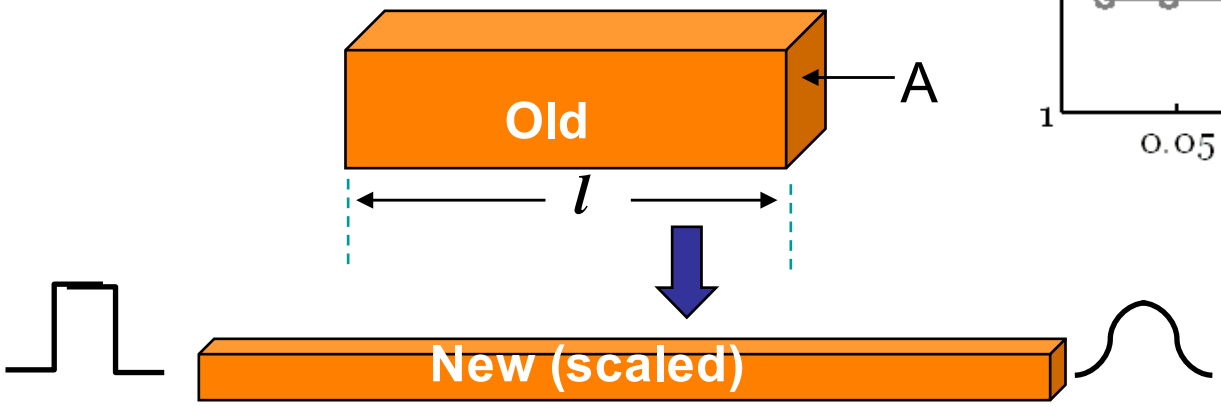
Outline

- Scaling limits of interconnects
  - ➢ Alternatives to Cu
- Performance simulations
  - Cu, CNT, optical interconnects
- Technology for novel optical interconnects
- 3-D integration
- Summary

Effect of Scaling on interconnect performance







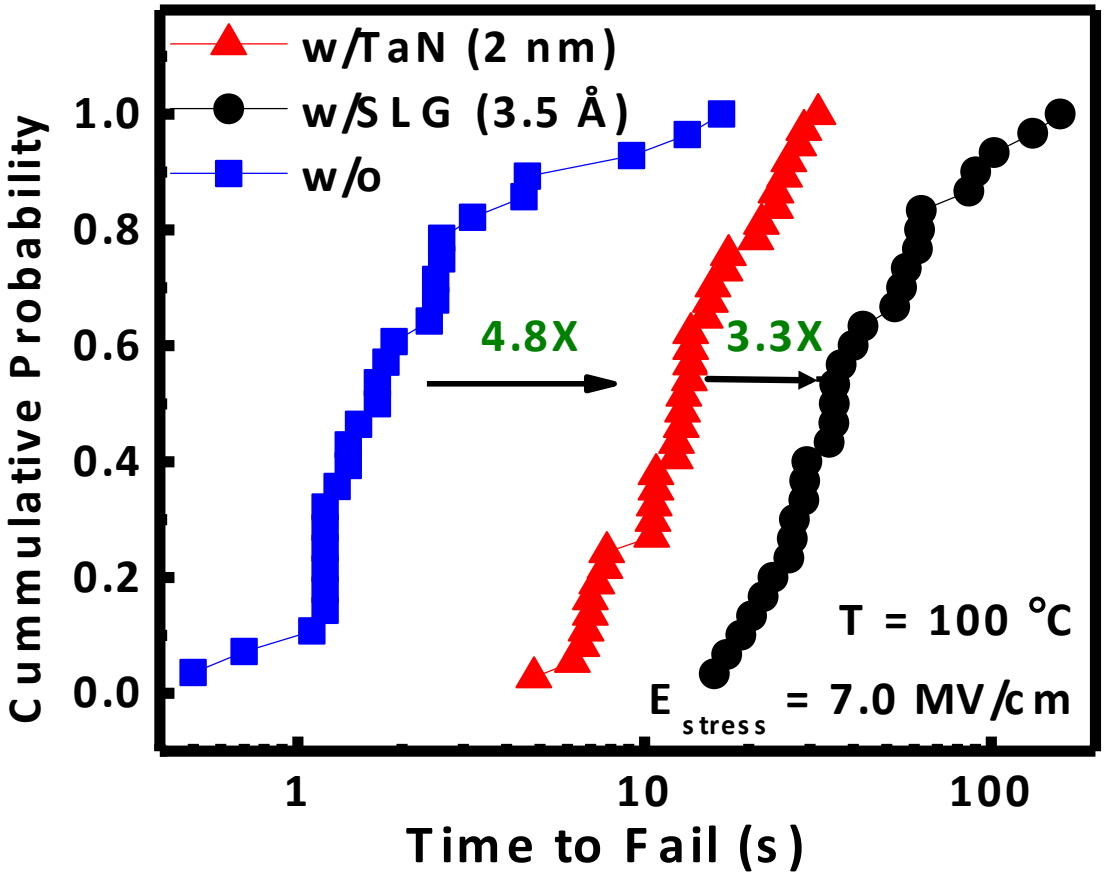
Bit rate $\propto A/l^2$

Delay $\propto l^2/A$

Power dissipation $\sim CV^2f$

K.-H. Koo and K. C. Saraswat, in Nanoelectronic Circuit Design, Springer, 2011, pp. 377-408

Graphene vs. TaN Barrier for Cu

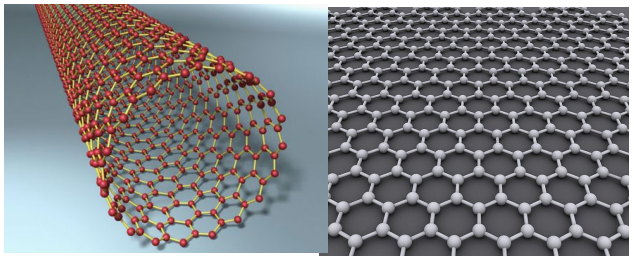


L. Li … H.-S. P. Wong, *Symp. VLSI Tech.* 2015
L. Li … H.-S. P. Wong, *ACS Nano* 2015

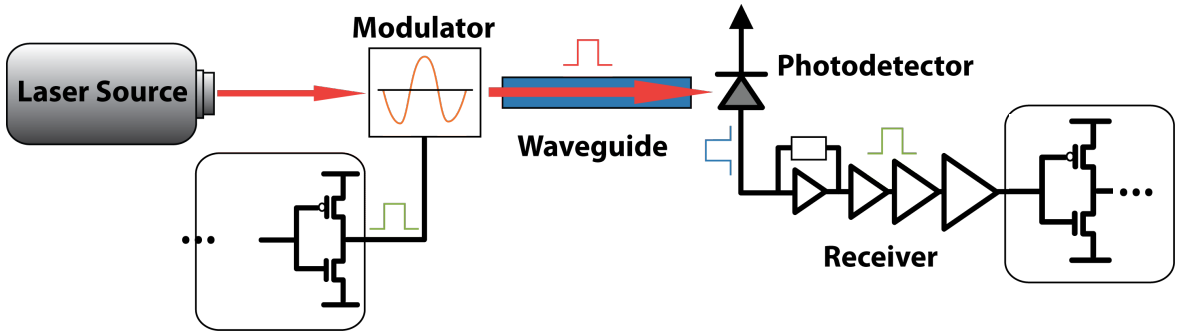
Thinner barrier: 3.5 Å single layer graphene is better than 2 nm TaN

How can we improve interconnect performance?

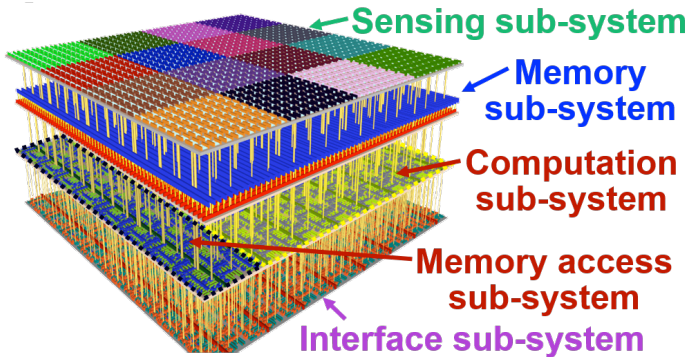
- Carbon nanotubes/ Graphene



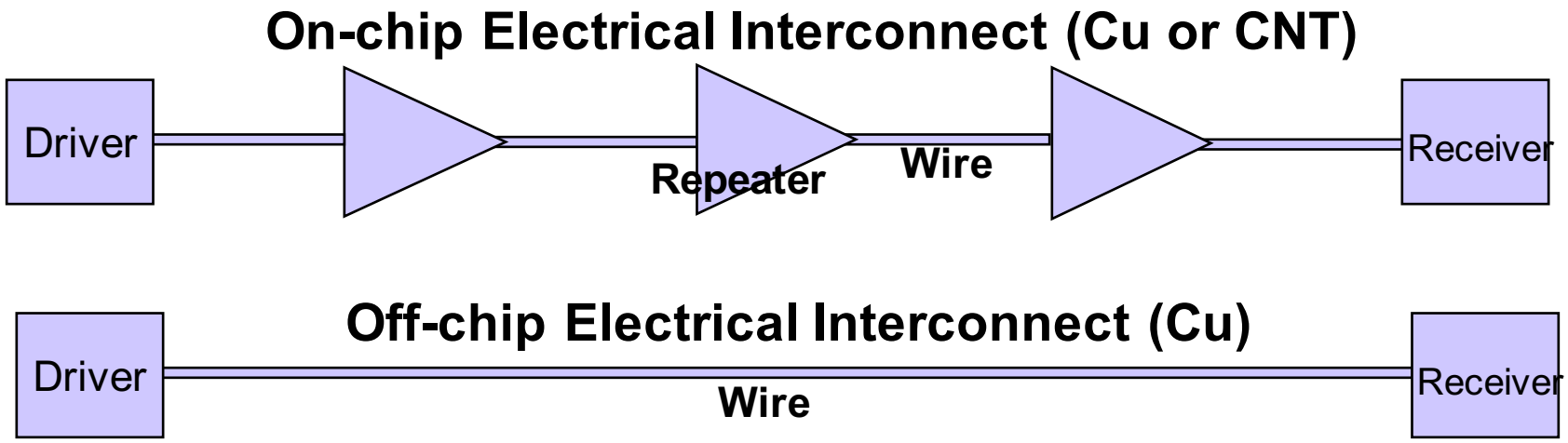
- Optical interconnects



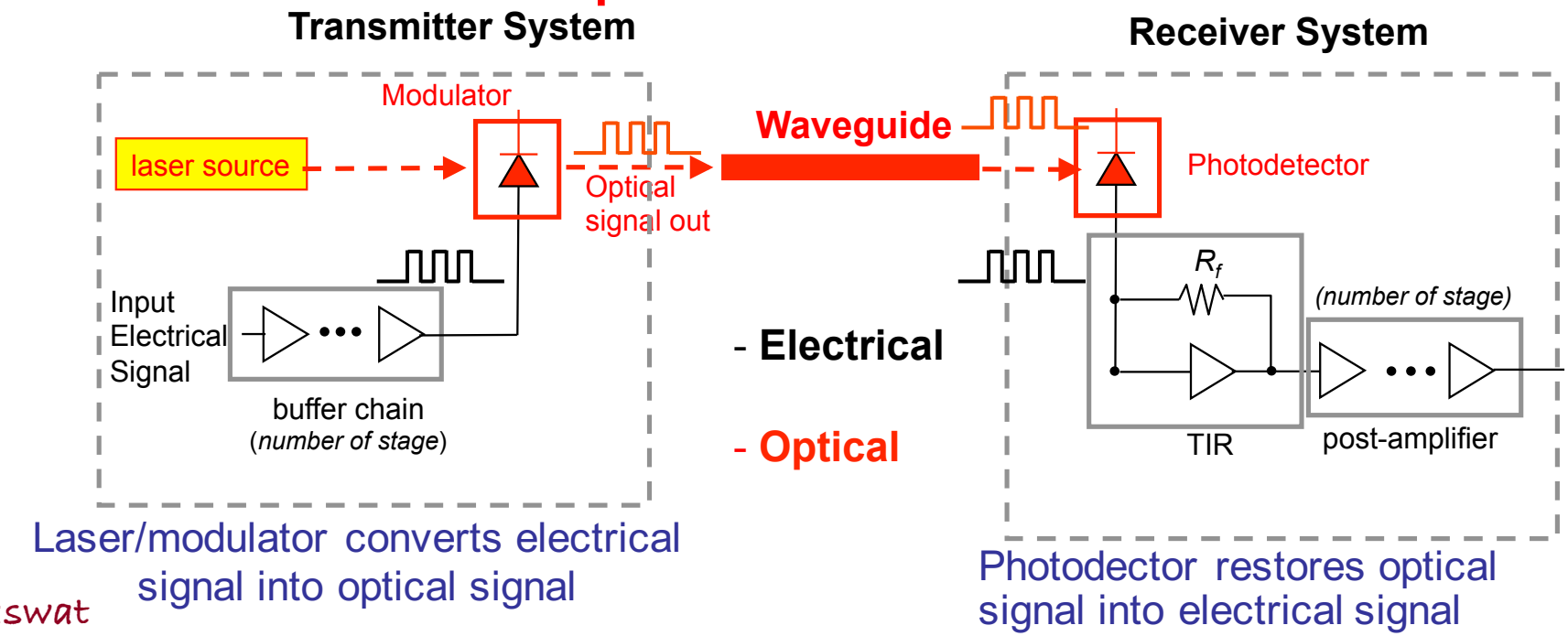
- 3D



Optical & Electrical Wires: Schematic



Optical Interconnect

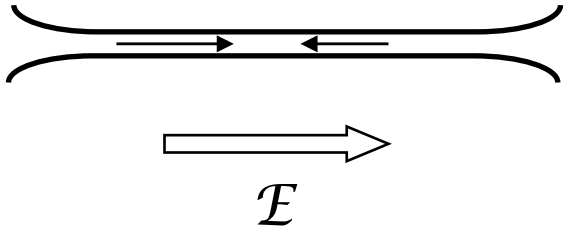


Laser/modulator converts electrical signal into optical signal

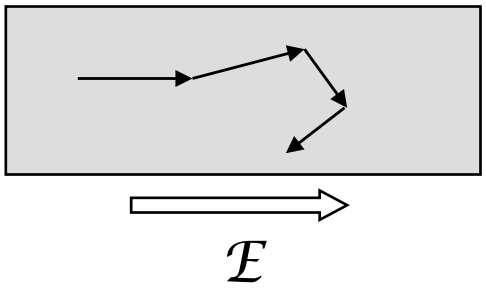
Photodector restores optical signal into electrical signal

Carbon Nanotubes

1-D conductors:



3-D conductors:

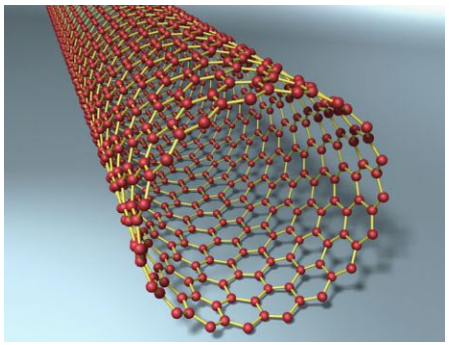


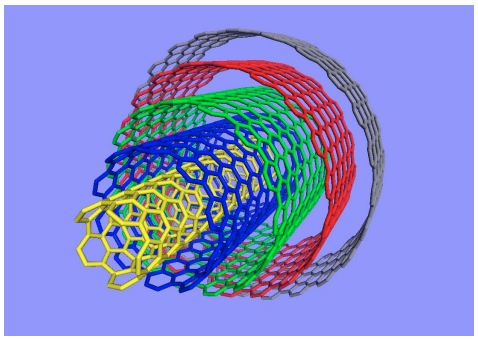
Quantum Wires:

- 1D system with limited density of states. Hence quantum effects play an important role in determining the values of R, L and C
- Mean free paths as large as 1.6μm.

Conventional wires :

- Backscattering through a series of small angle scatterings.
- Mean free paths ~ 30nm.



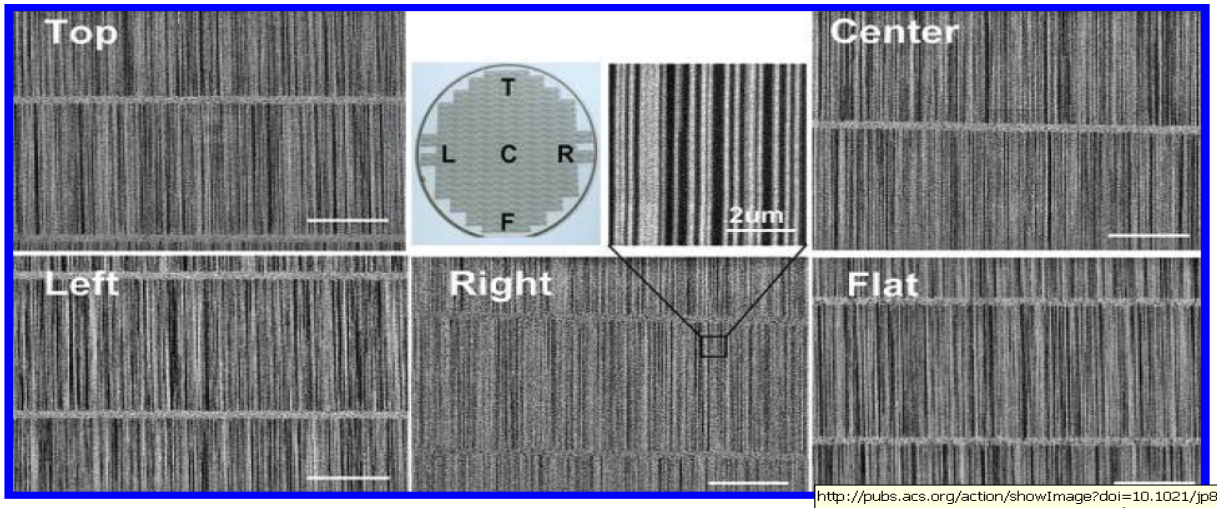


Potential Candidates for GSI Interconnects.

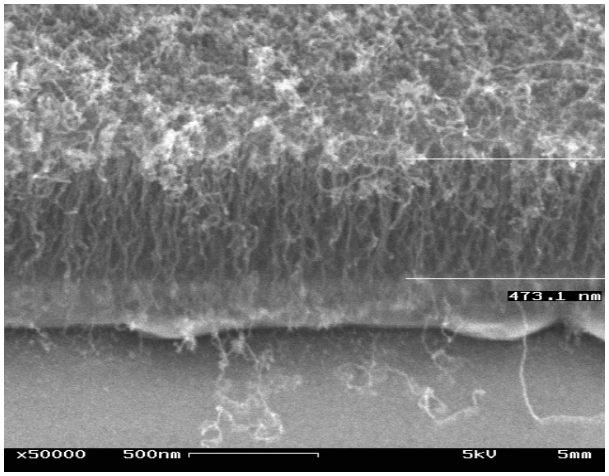
Formidable Task: Dense Bundles of SWNTs

Horizontal Growth for Interconnects

Y. Nishi and H.-S. Philip Wong (Stanford)



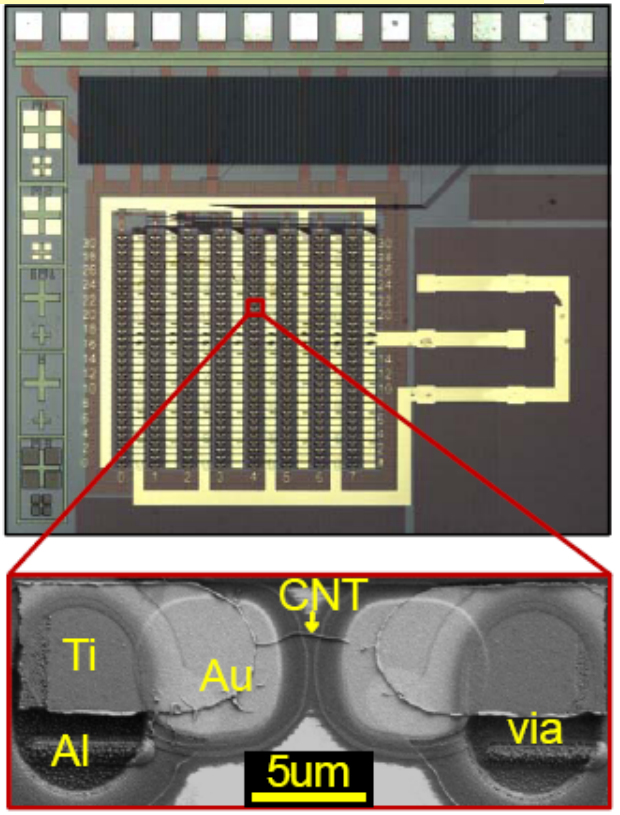
Vertical Growth



C.V. Thompson, MIT

256-Element CNT Ring Oscillator

H.-S. Philip Wong (Stanford)

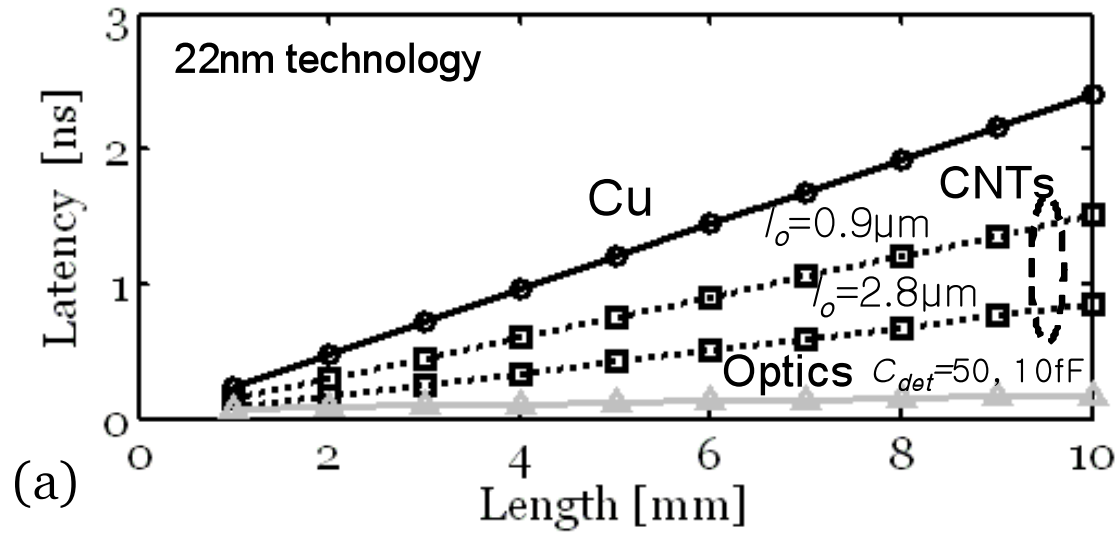


Promising progress in creating aligned isolated SWNTs by transferring SWNTs grown on sapphire to other substrates

Potential reliability performance comparison

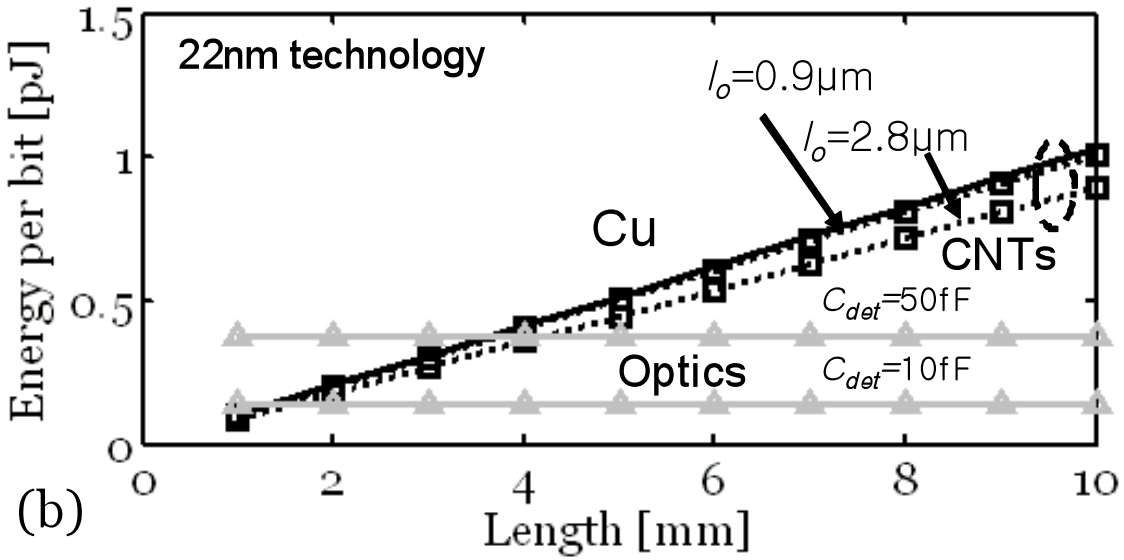
- **Good thermal conductivity**
  - Graphene: $4.84\times10^{3} \sim 5.30\times10^{3} W/mK$
  - CNT: $1.75\times10^{3} \sim 5.80\times10^{3} W/mK$
  - Copper: $385\ W/mK$
- **High breakdown current**
  - Graphene: $\sim 10^{8}\ A/cm^{2}$
  - CNT: $\sim 10^{9}\ A/cm^{2}$
  - Copper (EM threshold): $\sim 10^{7}\ A/cm^{2}$

Latency and Energy/bit vs. Wire Length



(a)

- Cu, CNT: small wire width → more repeaters, wire capacitance → latency ↑
- CNTs are favorable for shorter wires
- Optics favorable for longer wires

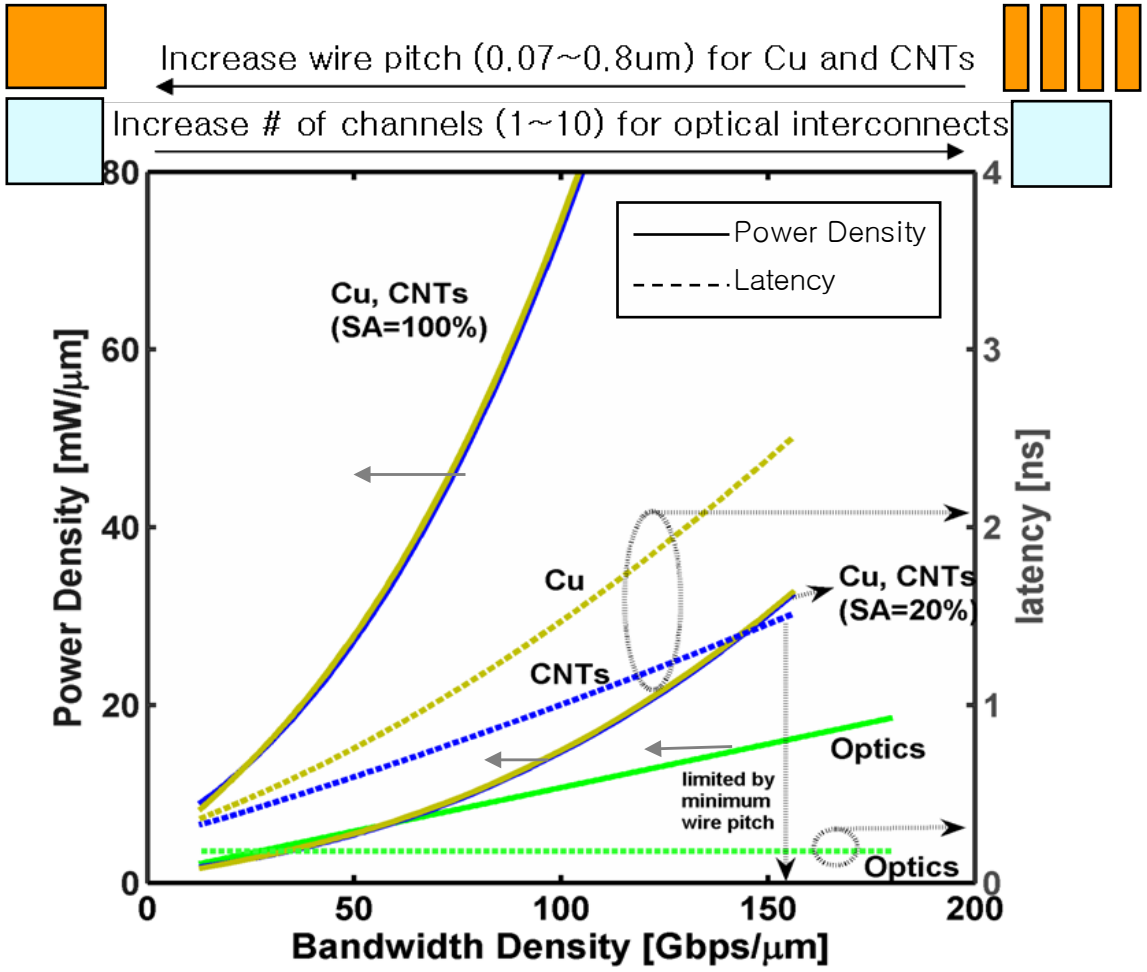


(b)

- Cu, CNT: small wire width → Energy per bit decreases as wire pitch is scaling (CV^2)
- CNTs is favorable for shorter global wire
- Optics: transmitter receiver power ↓
- Optics favorable for longer wires

Koo, Kapur and Saraswat, IEEE Trans. Electron Dev., Sept. 2009

Comparison Study: Global Interconnect CNTs, Cu, Optics



- BW density

Cu and CNTs: f_{clk} / $pitch_{wire}$

Optics: no. of wavelength of WDM

- Power density

Cu & CNTs (non-linear):

Cap and wire pitch

Optics (linear):

no. of wavelength

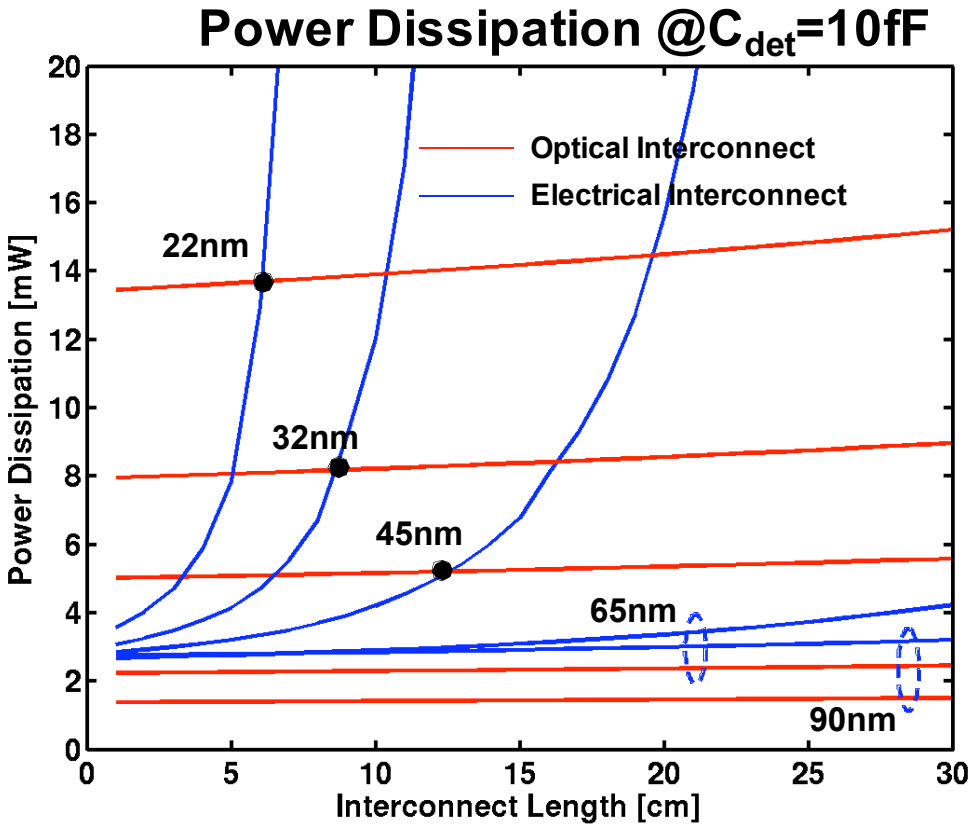
channel

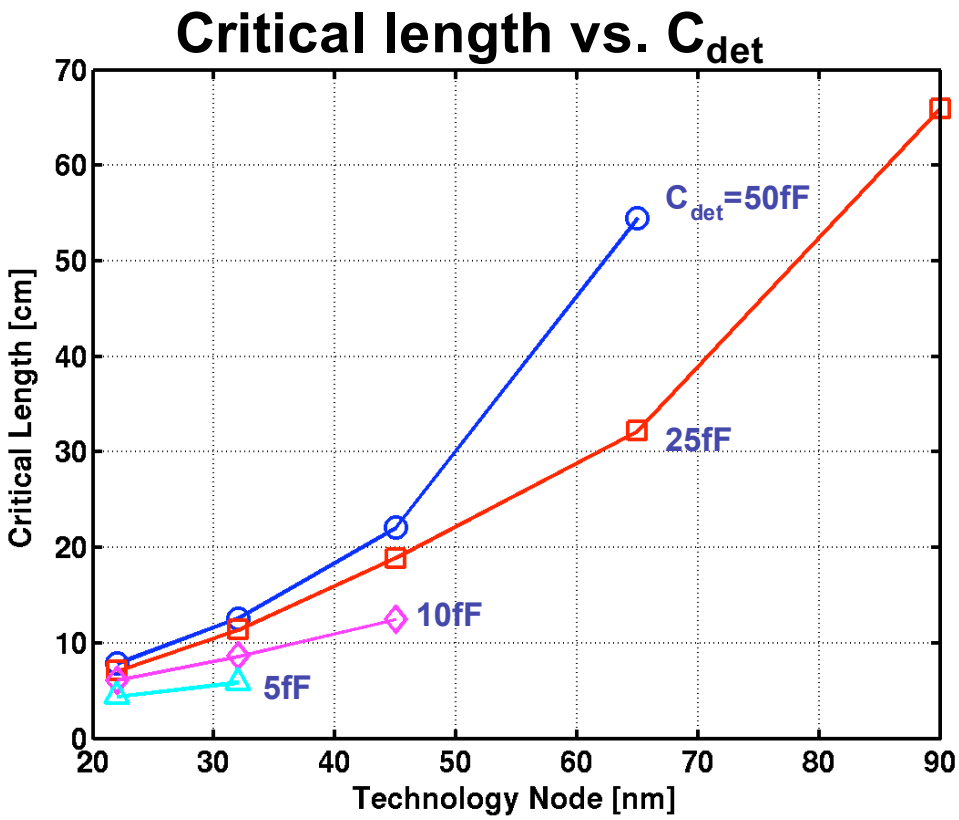
- Latency

Optics < CNTs < Cu

Koo, Kapur and Saraswat, IEEE Trans. Electron Dev., Sept. 2009

Off-Chip Interconnect Performance: Electrical vs. Optical

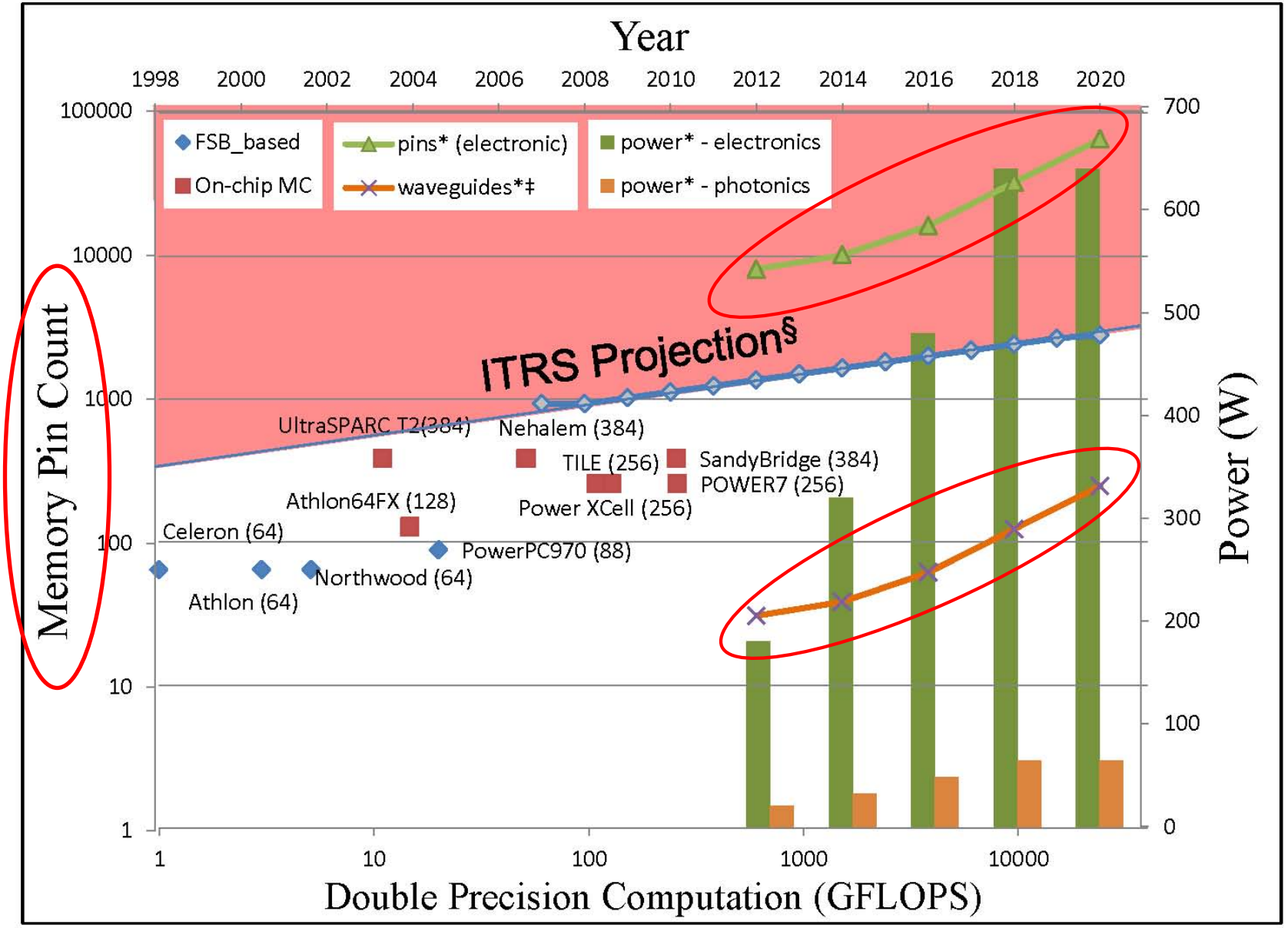




- Beyond certain length optical I/O is more power efficient
- Critical length decreases at higher bit rate & lower detector capacitance
- Beyond 32nm Technology node critical length < 10cm

Cho, Kapur and Saraswat, IEEE IITC, June 2005

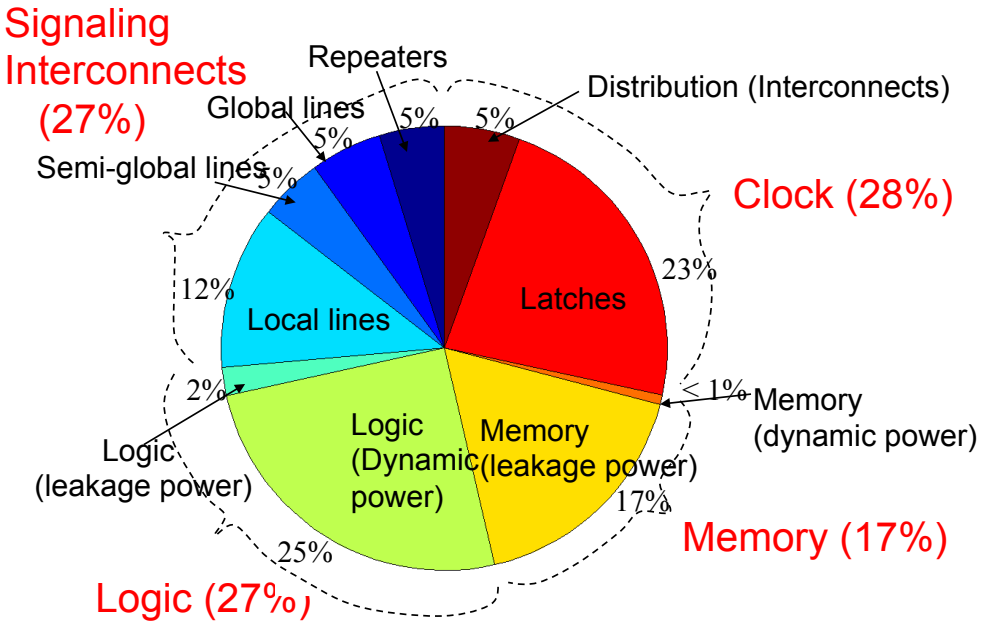
Why Really Photonics?



Source: Keren Bergman, Columbia University

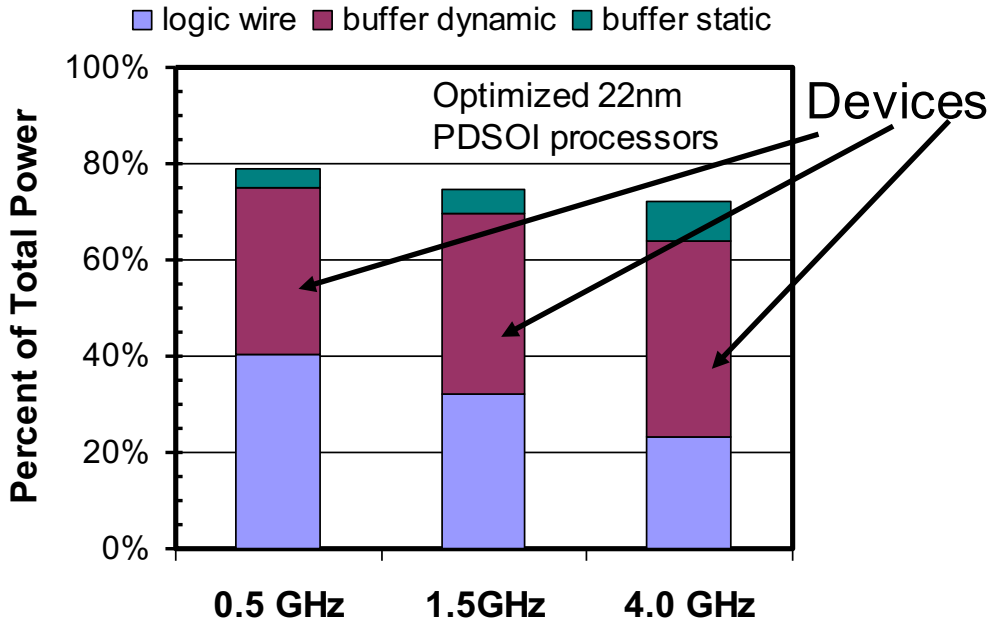
Communication Dominates Power

On-Chip Power Breakdown 50nm node



More than half the power can be attributed to interconnects

Chandra, Kapur and Saraswat, IEEE IITC, June 2002



70-80% of total logic power is for communication

- Need proper consideration of wires!!

Wilfried Haensch, (IBM) Data Abundant Systems Workshop, Stanford Univ., April 2014

Why Off-chip Photonic Interconnects

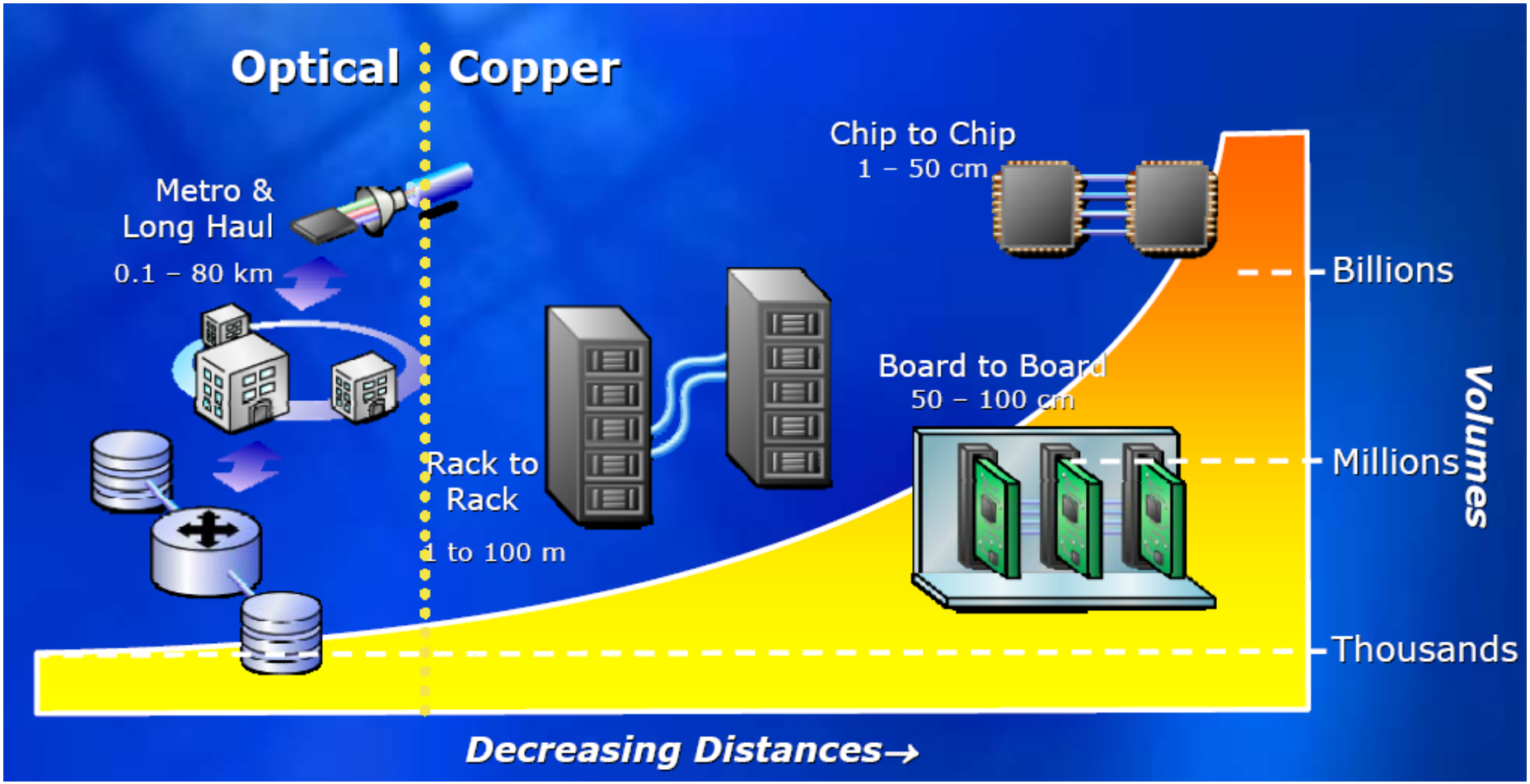
Copper wires

Optical Interconnects

- Copper wires are reaching physical limits
- Photonic interconnects offer the solution for the future

The Interconnect Problem

"For the long term, material innovation with traditional scaling will no longer satisfy performance requirements. Interconnect innovation with optical, RF, or vertical integration … will deliver the solution" (ITRS)

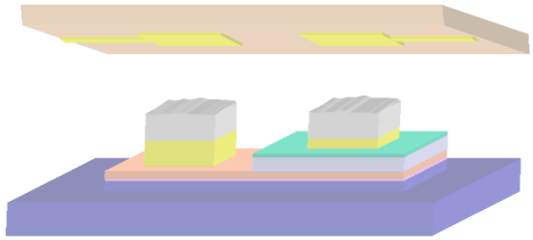


Source: Intel

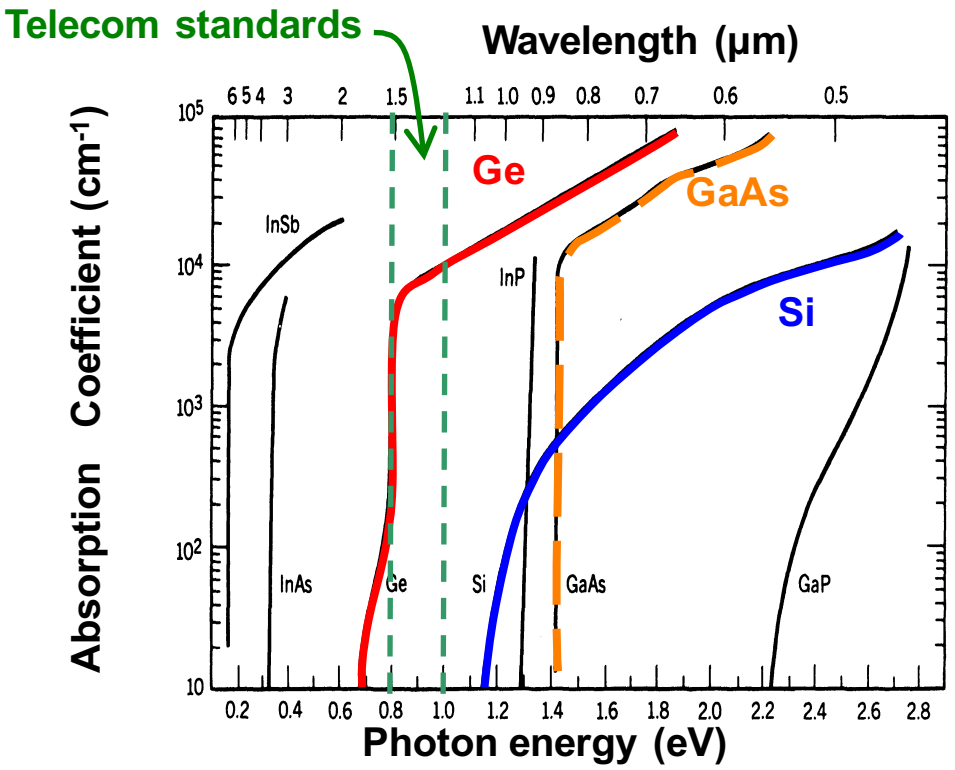
Material Options for Optical Interconnects

- **What are the right optical devices to use?**
  - Need to be cheap, available in large numbers
  - Compatible with CMOS
- **Silicon devices are a long shot**
  - Need 3D heterogeneous integration
- **Flip bond III-V to Si CMOS**
  - Current process
  - Cost, resources, yield?
- **How about germanium?**
  - Bandgap ideal for λ = 1.5 μm
  - Can be monolithically integrated on Si
  - Becomes direct bandgap material by straining or adding tin

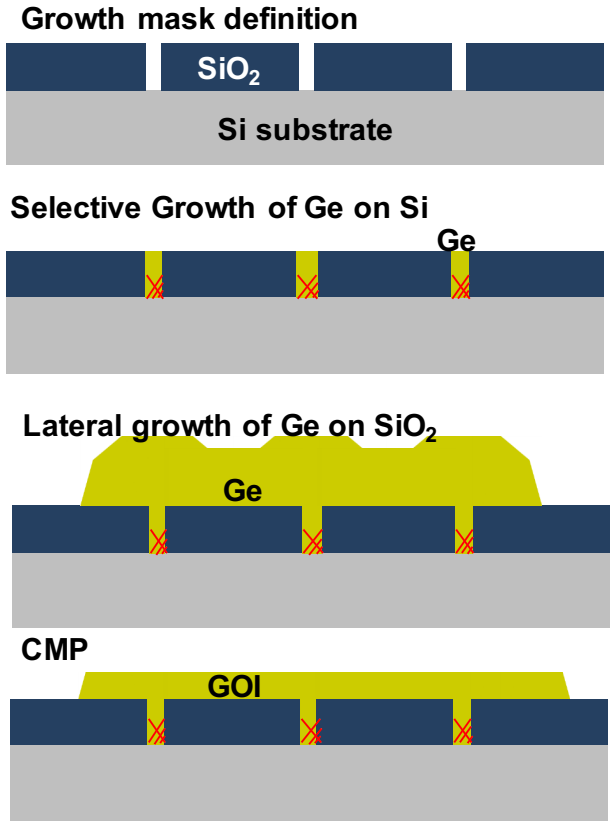
Si CMOS chip with gold bonding pads



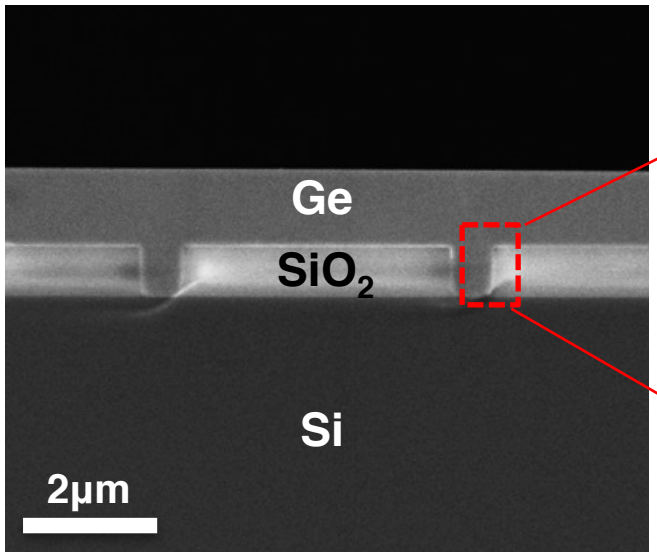
GaAs optoelectronic chip with indium flip-chip bumps



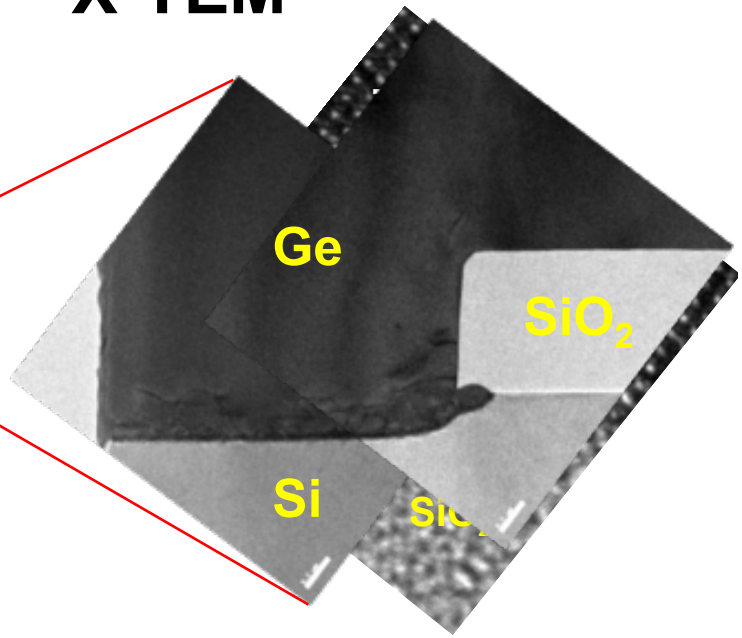
Selective and Lateral Overgrowth of Ge on SiO_2



SEM



X-TEM

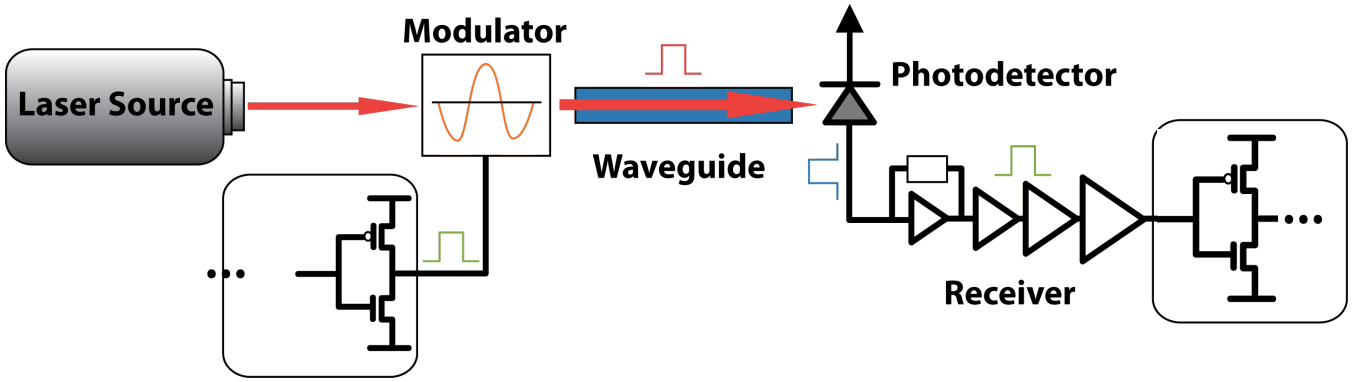


400°C deposition + 800°C H_2 anneal + 600°C deposition

- **Lateral Ge growth on SiO_2 window achieved**
- **Dislocation density of Ge on SiO_2 < 10^6 cm^{-2} (same thickness Ge on Si: 1×10^8 /cm^2)**
- **Surface RMS roughness ~0.4 nm after CMP**
- **Ge is ~0.2% tensile strained due to thermal mismatch with Si**

Ju Hyung Nam…….K. Saraswat, J. Crystal Growth, April 2015

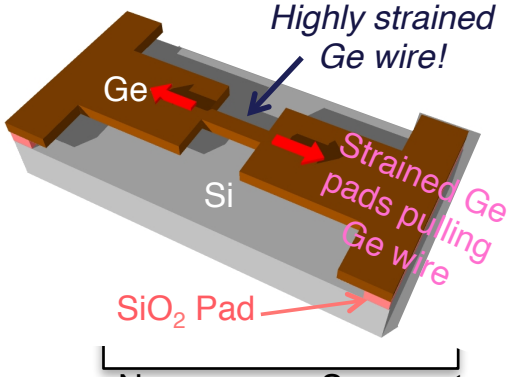
Si Compatible Photonic Interconnect



Laser/modulator converts electrical signal into optical signal

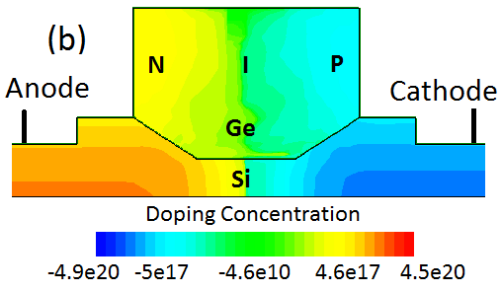
Photodector restores optical signal into electrical signal

Laser



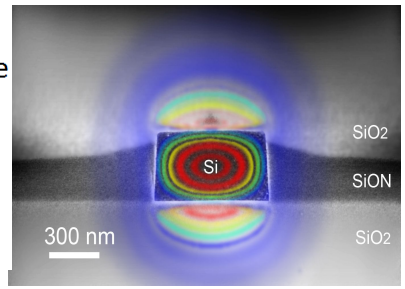
Nam……..Saraswat, Nano Letters, June 11, 2013.

Modulator

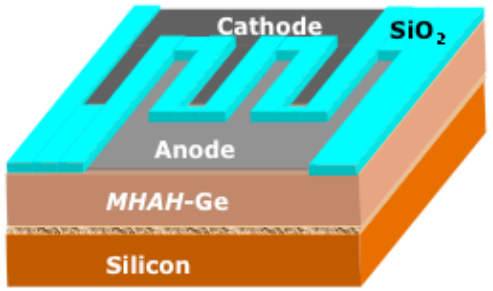


Gupta……..Saraswat, OFC, March 2015

Waveguide



Detector

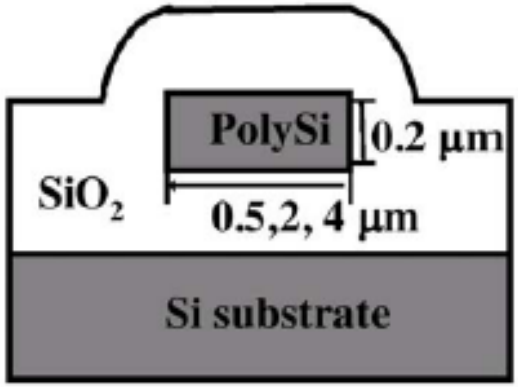


Okyay…….. Saraswat, Optics Lett. 2006

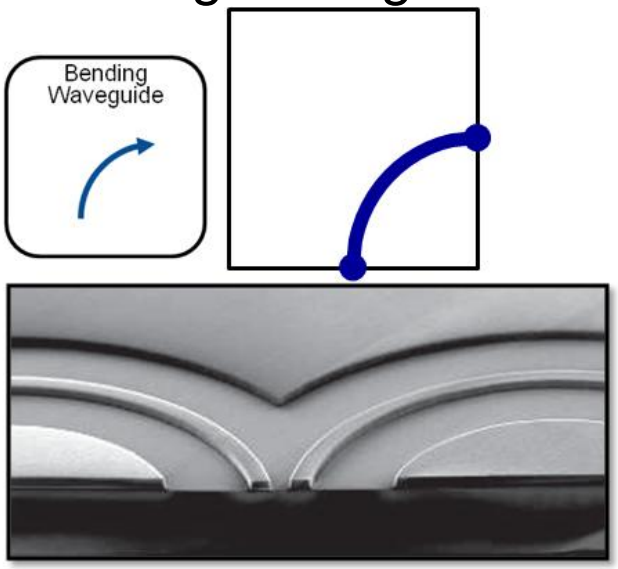
- Germanium devices can be monolithically integrated on silicon
- Laser is the only missing component

Technology for Optical Interconnects on Silicon: Optical Transmission Media

Waveguides

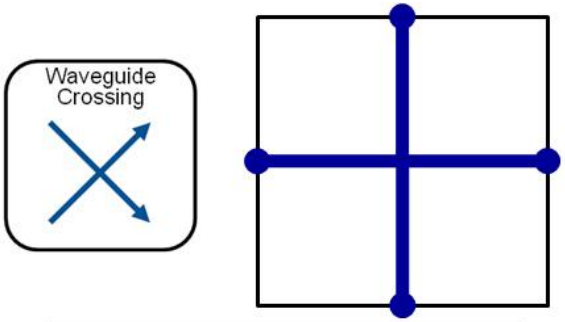


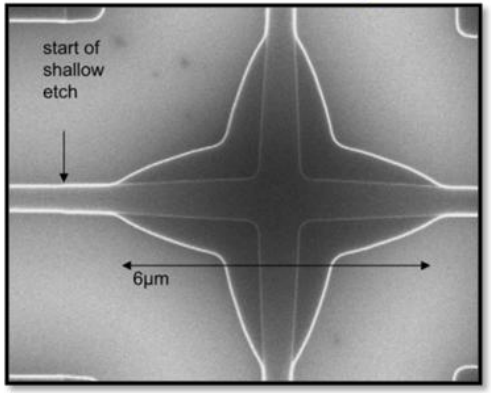
Bending Waveguides



[F. Xia *et al.*, Nature Photonics, 2006]

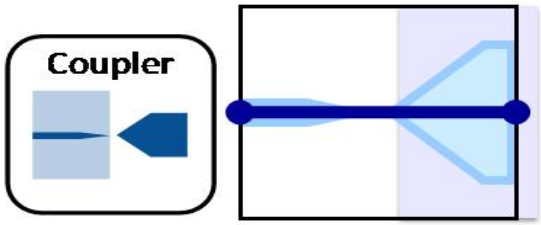
Waveguide Crossings

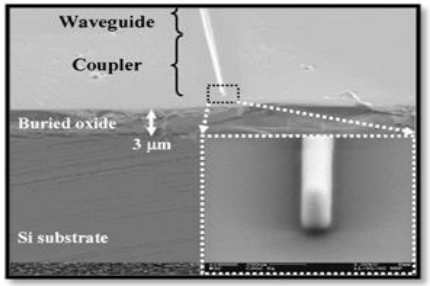




[W. Bogaerts *et al.*, Optics Letters, 2007]

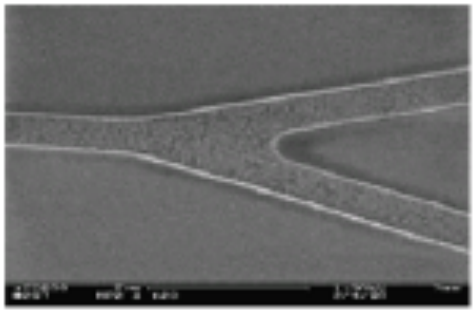
Couplers





[V. Almeida *et al.*, Optics Letters, 2003]

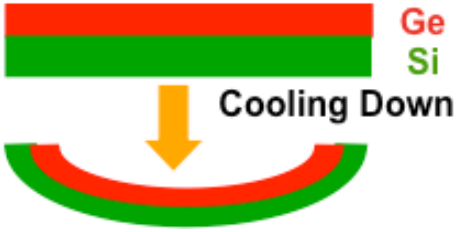
Splitter

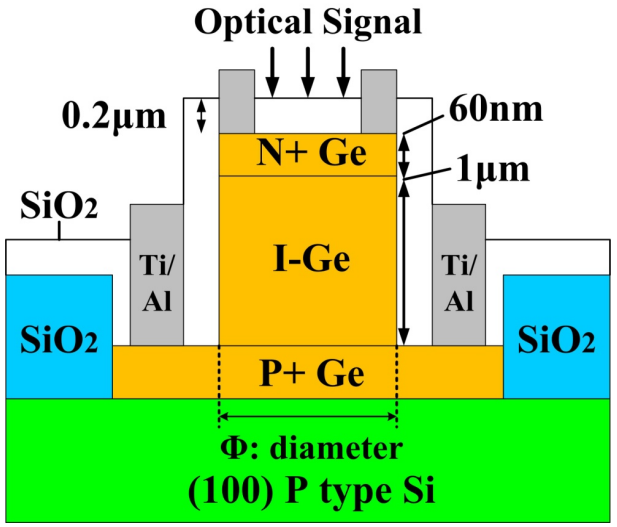


(Kimmerlingr, MIT)

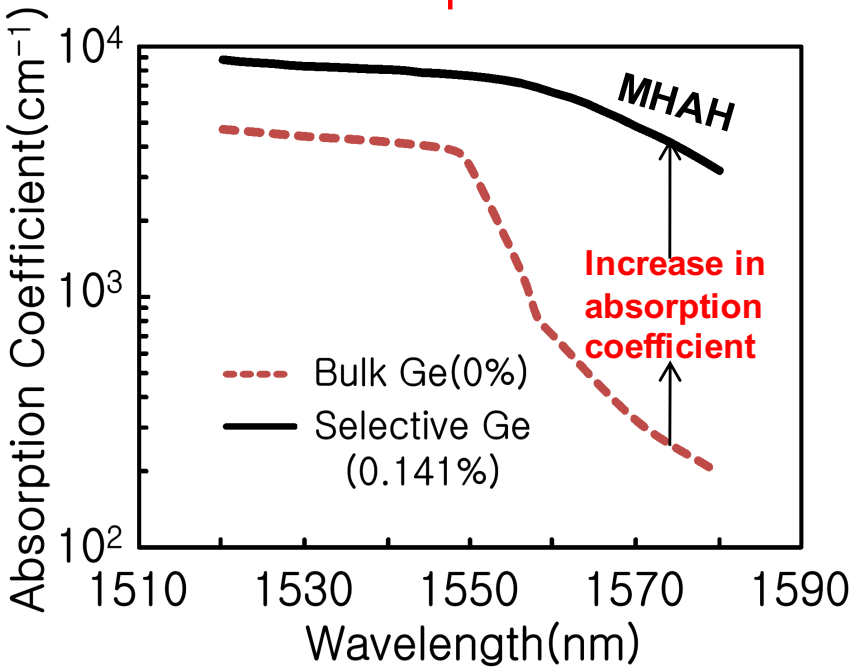
High Efficiency Ge p-i-n Photodetectors on Si

Biaxial Tensile Strain





Photoresponse

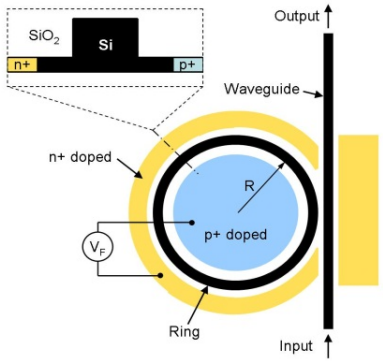


- Ge grown on Si by **M**ultiple **H**ydrogen **A**nneal and **H**eteroepitaxy (MHAH) Technique
- Ge film complies with Si substrate on cooling down resulting in tensile strain => bandgap reduces
- Detector efficiency improves at 1550nm due to tensile stress
- Dark Current high

Hyun-Yong Yu,…..... K. Saraswat, IEEE Electron Dev. Lett., Nov. 2009.

Optical Modulator

Electro-optic Modulators

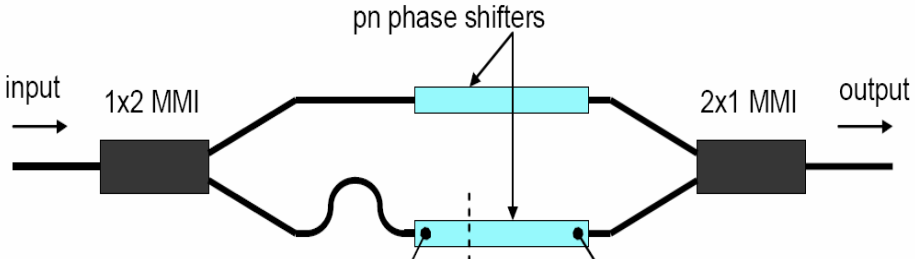


- Index change
- Weak mechanism
- High Q
- Temperature tuning

Lipson (Cornell)

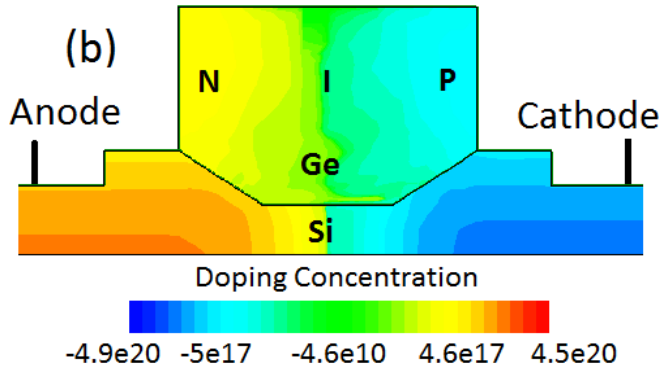
Mach-Zehnder Modulators

- Phase shift effect in waveguides
- Large size and power consumption



Electro-absorption Modulators

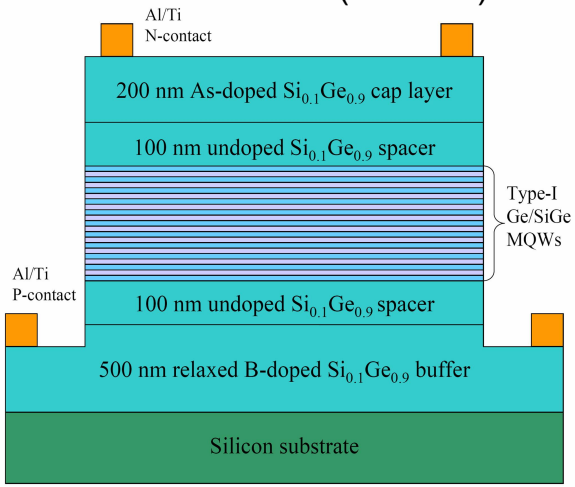
Saraswat (Stanford)



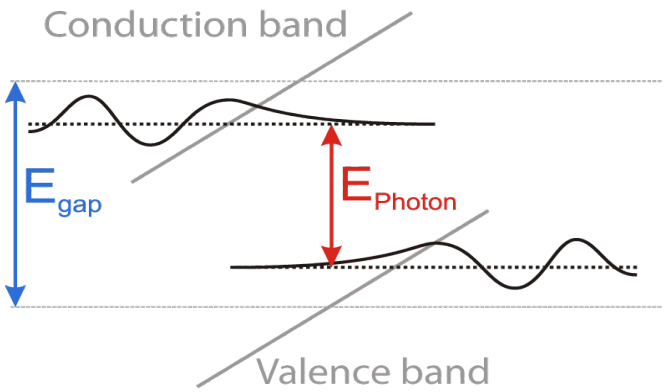
- Franz-Keldysh effect in bulk material

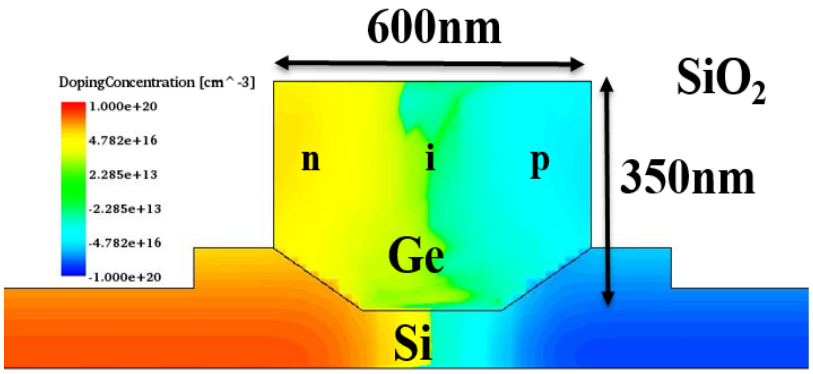
QCSE Ge/SiGe Modulator

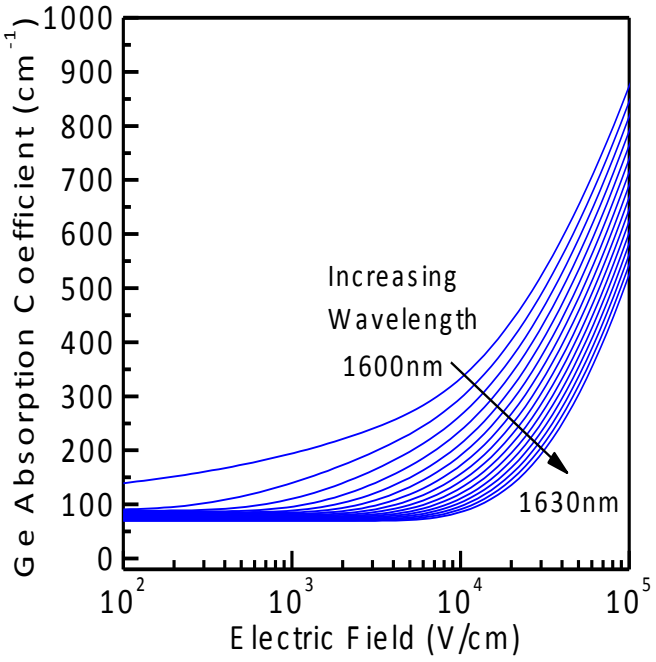
Harris and Miller (Stanford)

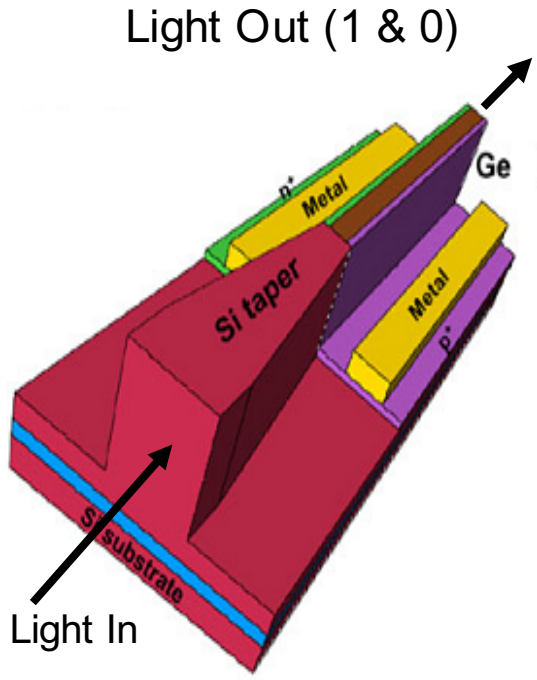


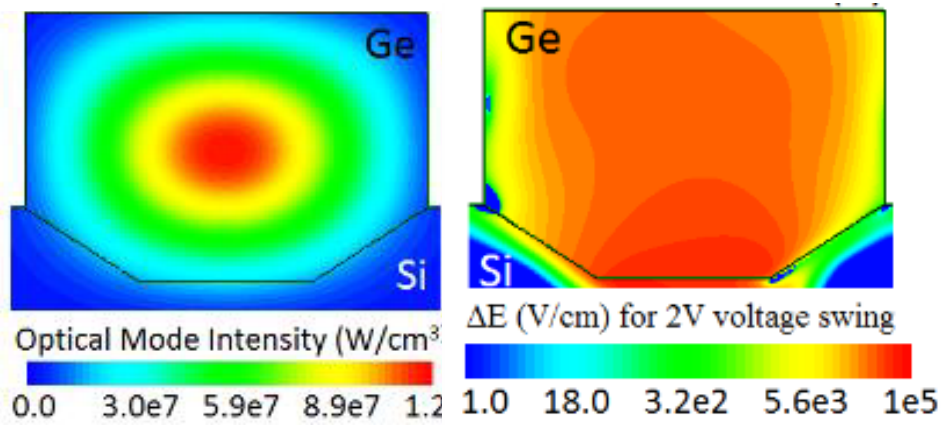
Ge/Si Electro-Absorption Franz-Keldysh Effect Modulator









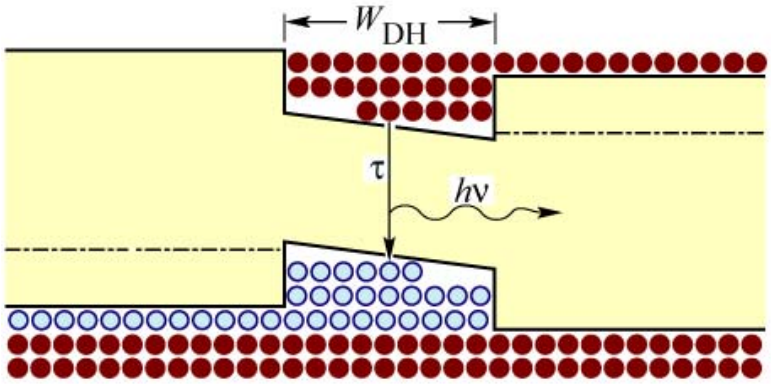


In the presence of an electric field, the conduction and valence bands of a semiconductor tilt. Application of an electric field leads to overlap in valence and conduction band wave functions, and hence optical absorption, at energies below the semiconductor bandgap.

S. Gupta……..K. Saraswat, OFC, Los Angeles, Paper No. Tu2A.4, March 2015

Structure Needs for Efficient Lasing

Heterojunction



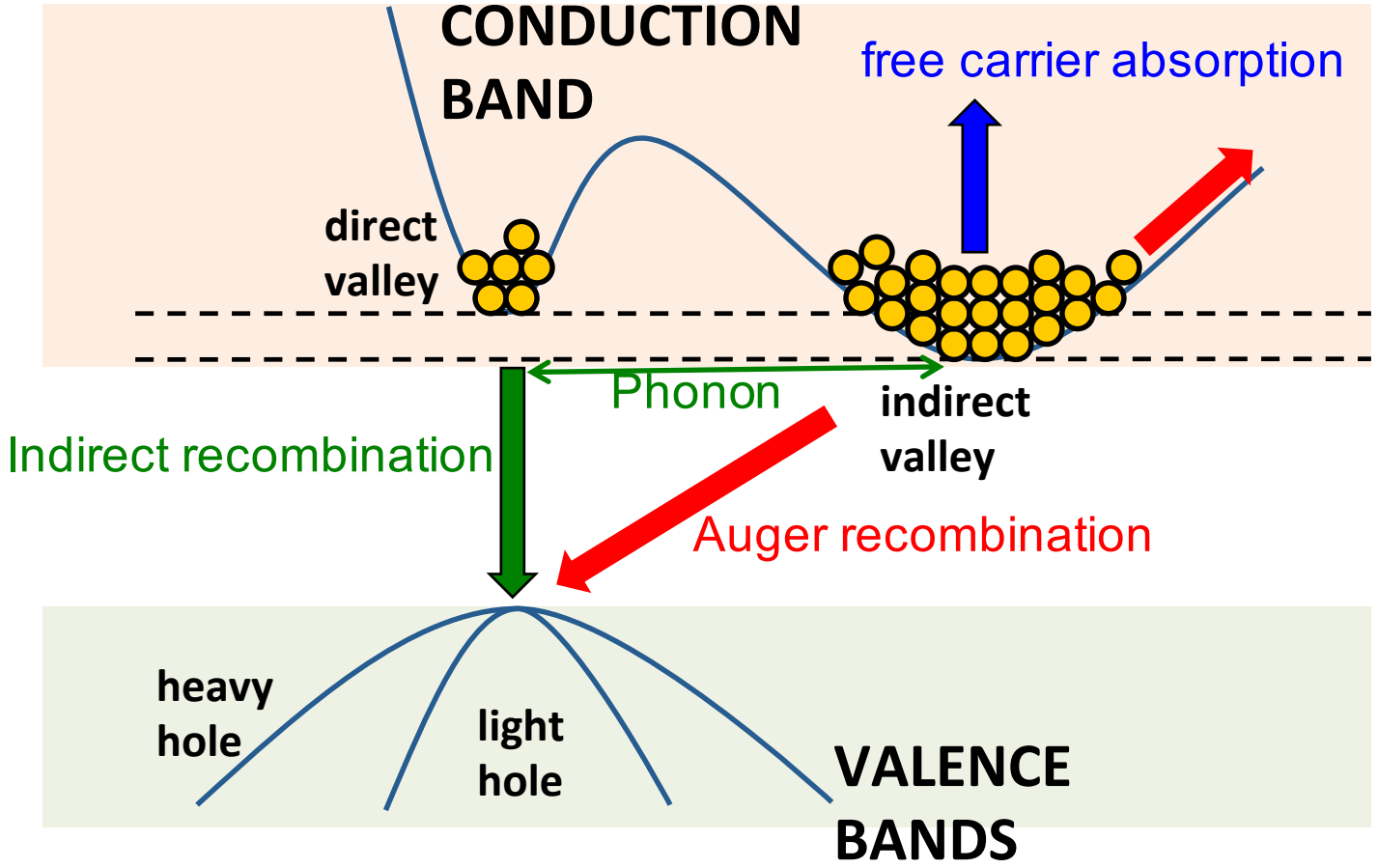
For efficient laser

- Direct bandgap cavity
- Hetrojunction quantum well for carrier confinement

E. F. Schubert, Light Emitting Diodes (Cambridge Univ. Press)

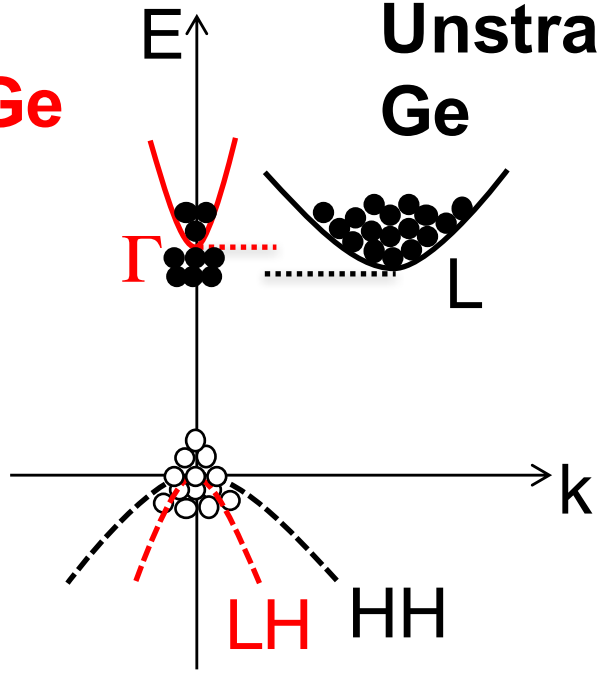
Engineering Ge for light emission- Doping

- N-type doping can be used to fill electrons into the L valley upto the level of Γ valley
- But it is difficult to heavily dope Ge n-type
- Increases free carrier absorption and auger recombination
- Inefficient light emission

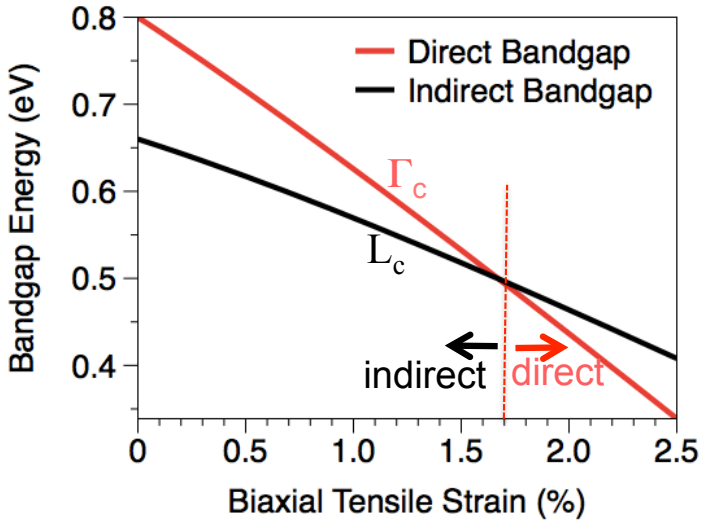


Engineering the Ge band structure for light emission: Strain

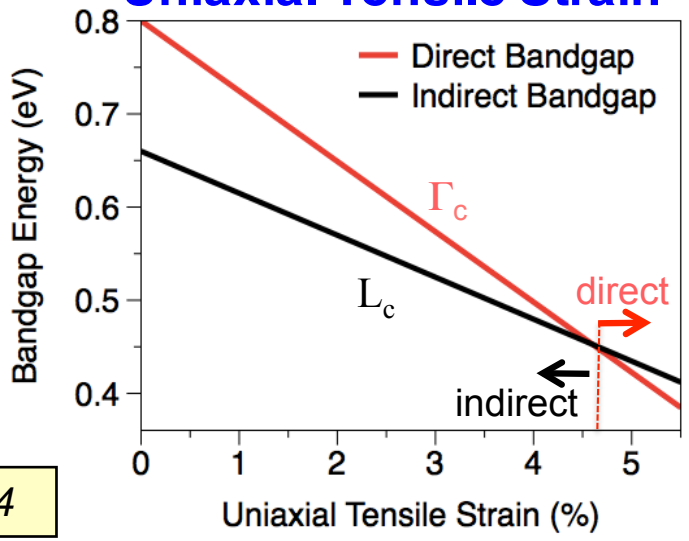
Strained Ge



Biaxial Tensile Strain



Uniaxial Tensile Strain



>1.7% biaxial tensile strain or

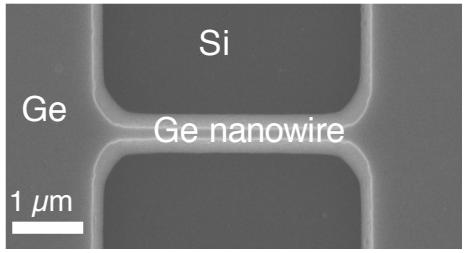
> 5% uniaxial tensile strain

turns Ge into a direct bandgap material, making light emission possible

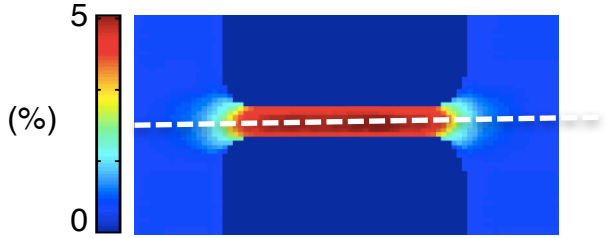
Sukhdeo,……. Saraswat, Photonics Research, 2014

Heterostructure in a Single Material: Strained Ge

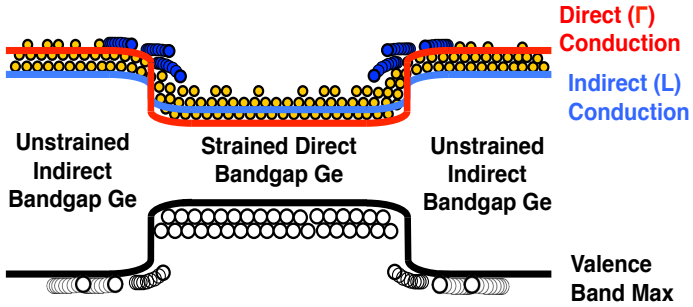
SEM



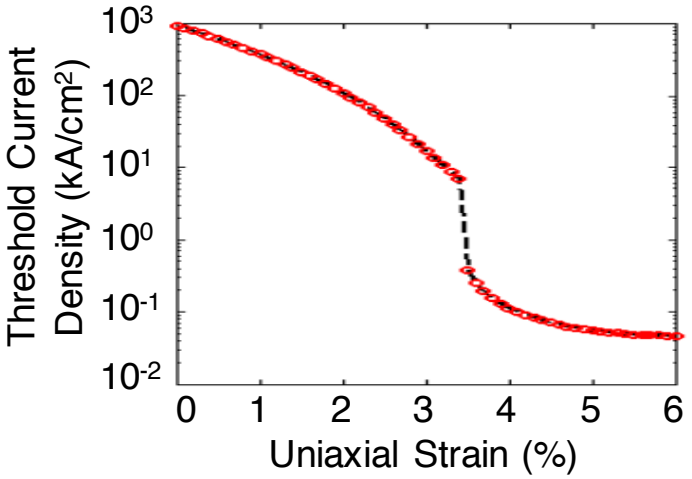
2D Strain Distribution



Band Diagram



Threshold Current Simulations



- Strain can be tunable with geometry
- Heterostructure created due to reduction in bandgap of strained Ge
- Direct bandgap cavity and hetrojunction quantum well in single material

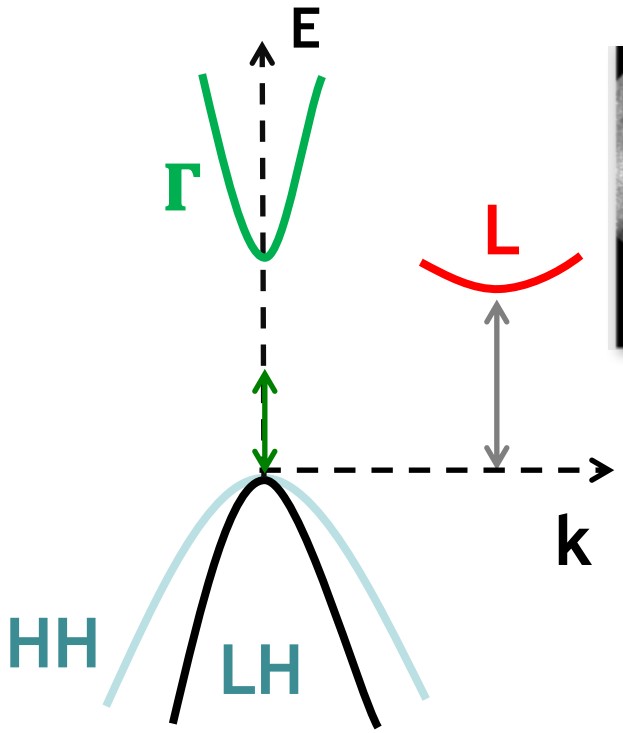
Nam, Saraswat, et al., Nano Letters, June 11, 2013.

Engineering the Ge band structure by alloying with tin for GeSn CMOS and photonics

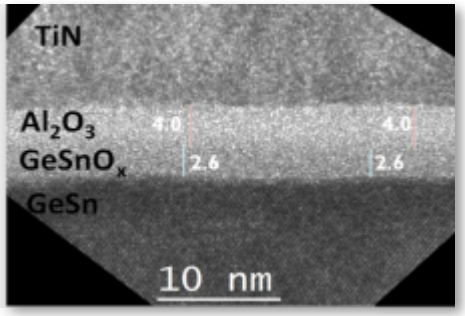
14 Si Silicon 28.0855 — 5.43 Å

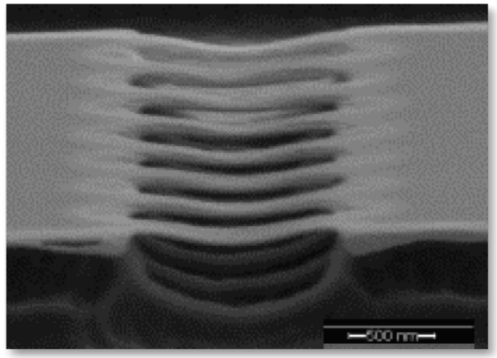
32 Ge Germanium 72.63 — 5.65 Å

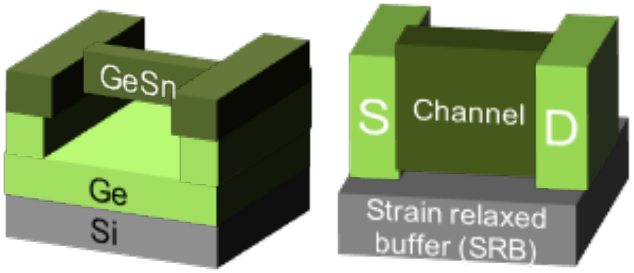
50 Sn Tin 118.710 — 6.49 Å



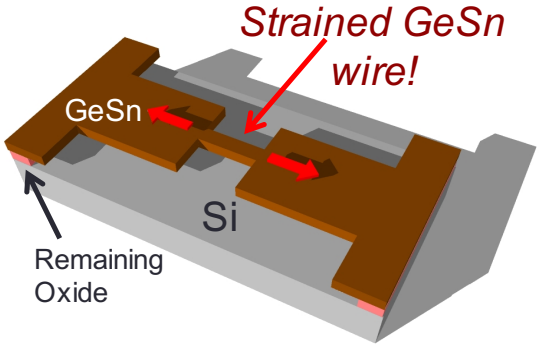
$Ge_{1-x}Sn_x$



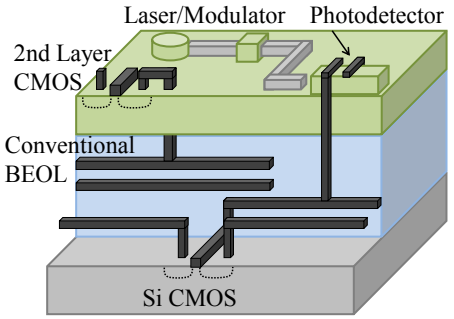




Strain engineering in FinFETs



Si-compatible Laser

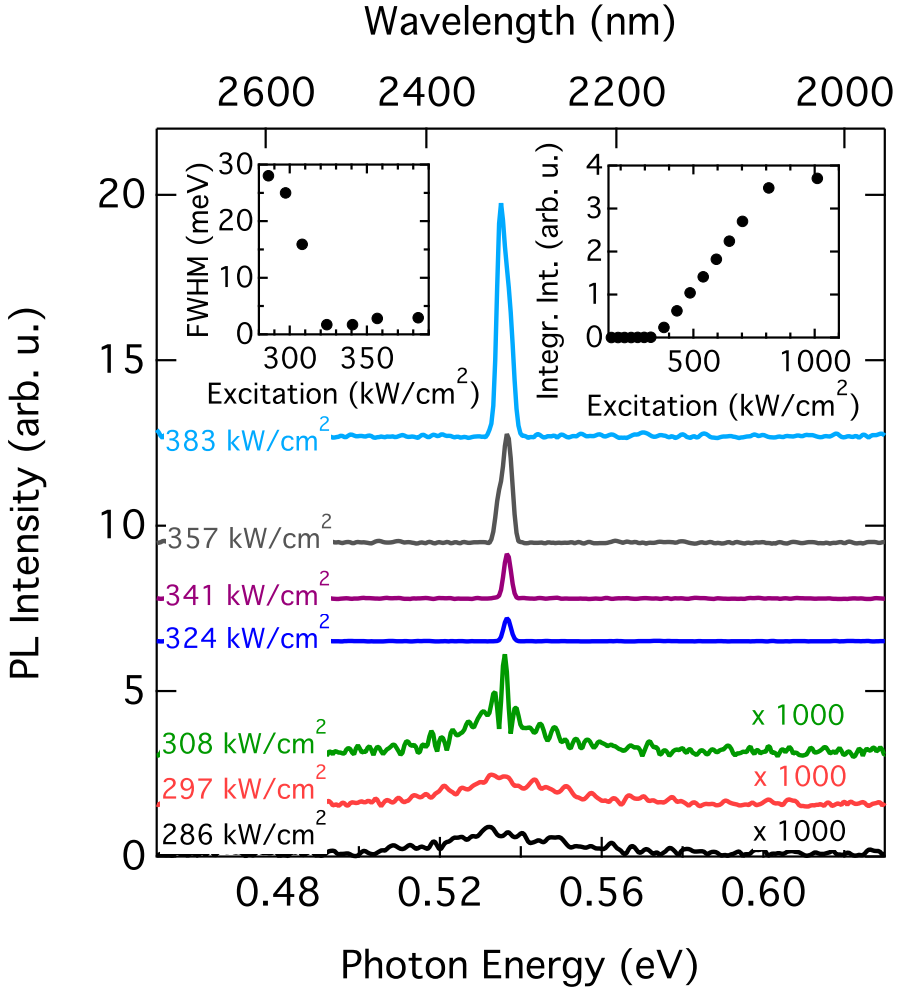


At ~ 7 Sn% $Ge_{1-x}Sn_x$ becomes direct band gap!

Gupta, Yeo, Takagi, Saraswat, et al., MRS Bulletin, Aug 2014

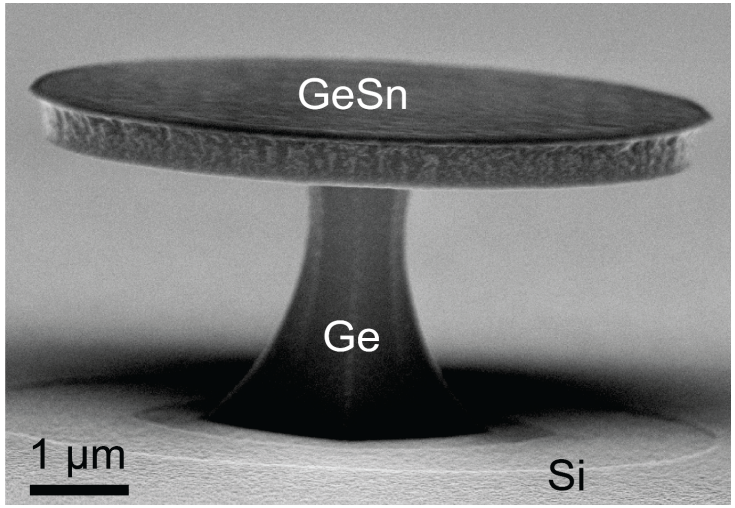
3-D IC: CMOS, Photonics co-integration

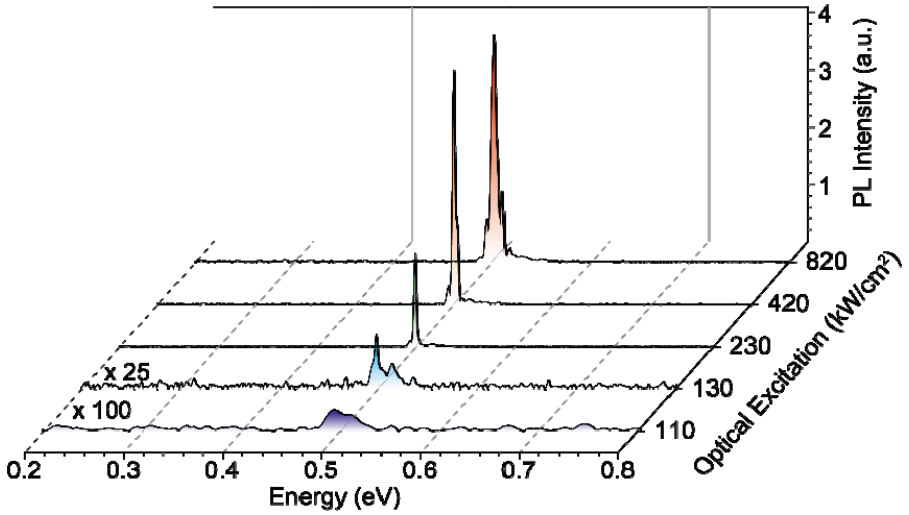
Demonstration of Optically Pumped GeSn Laser



- Lasing emission spectra measured from the facet of a 5 μm x1 mm long Fabry-Perot waveguide $Ge_{0.87}Sn_{0.13}$ cavity under optical pumping at 20 K.
- More work needed for room temperature laser

Direct Bandgap GeSn Microdisk Laser on a Si-Platform

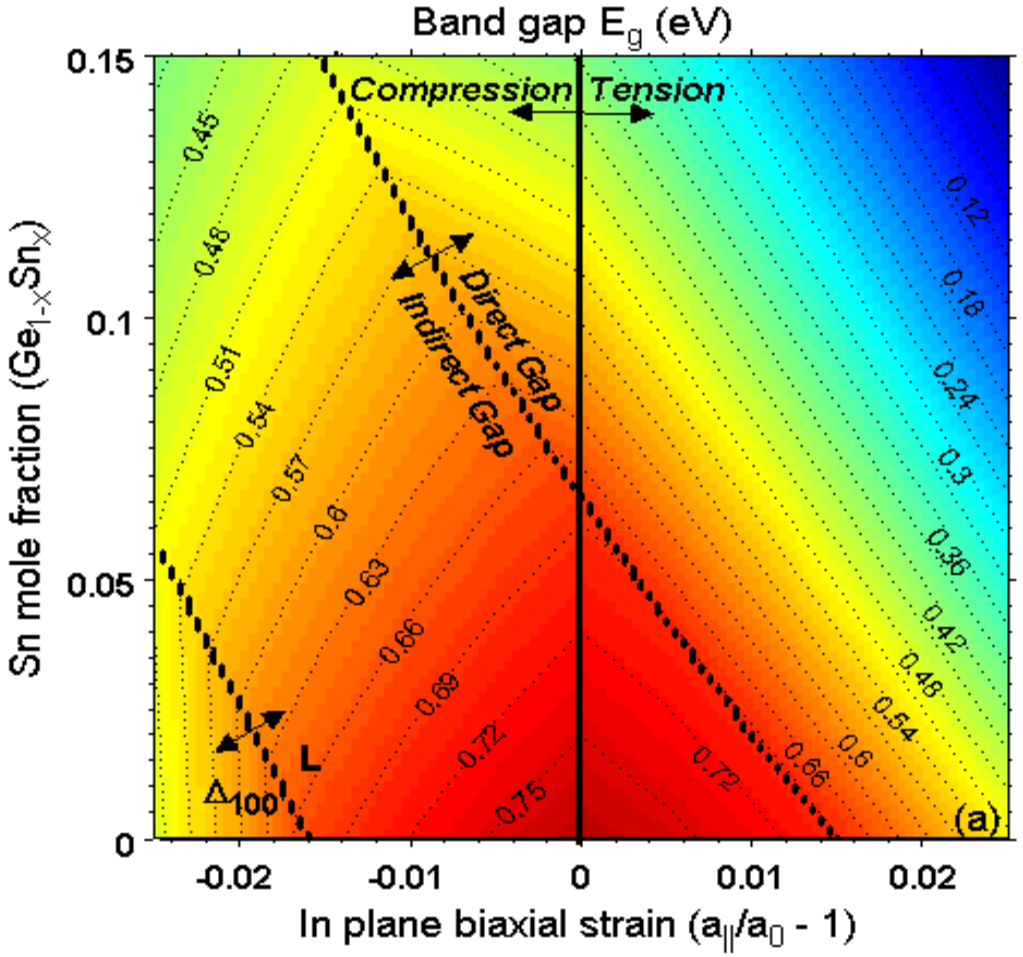




- Power-dependent PL spectra of an 8 μm diameter $Ge_{0.875}$ $Sn_{0.125}$ microdisk at 50 K.
- More work needed for room temperature laser

S. Wirth, et al., IEEE IEDM, Dec. 2015

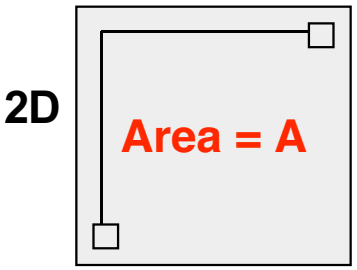
Multiple Knobs to Turn for Direct-Gap: Strained GeSn



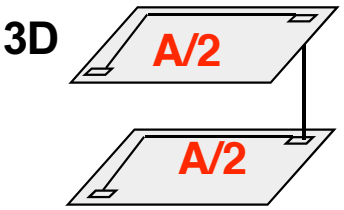
- A combination of alloying Ge with Sn and strain can also give us a direct bandgap material
  - Efficiency would be comparable to present III-V lasers

Gupta, Magyari-Köpe, Nishi, Saraswat, J. Appl. Phys. **113**, 073707 (2013)

3-D Integration: Motivation

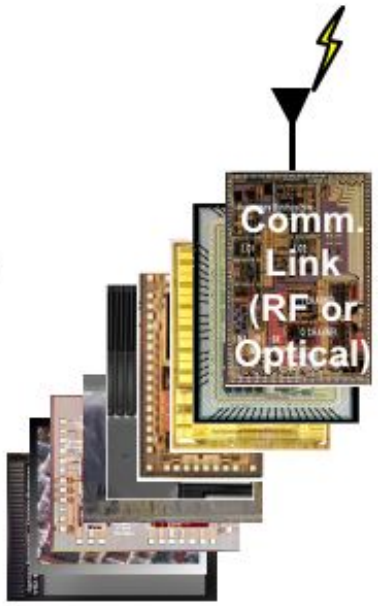


Very Long Wire

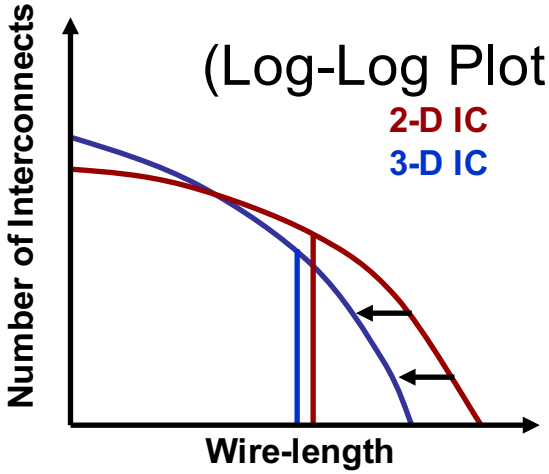


Shorter Wire

2-D System



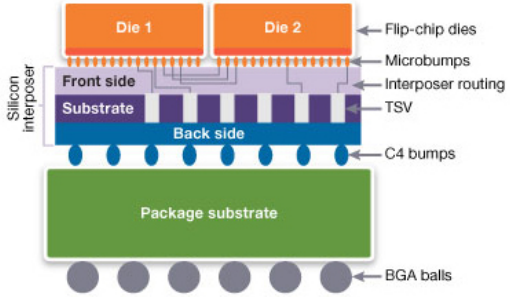
3-D System

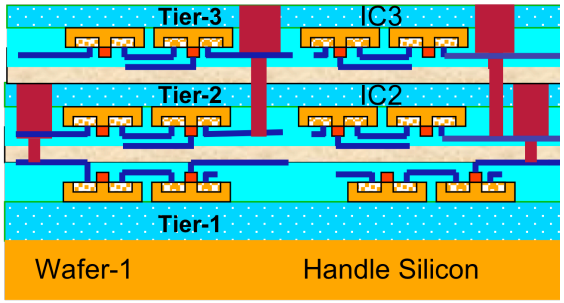


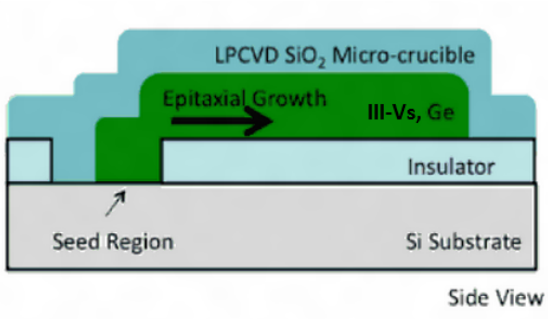
- Reduce Chip footprint
  - ➢ Improved form factor
  - ➢ Interconnect length ⬇ and therefore R, L, C ⬇
    - – Delay reduction
    - – Power reduction
    - – Higher bandwidth
- Integration of heterogeneous technologies possible, e.g., memory & logic, sensors, optical I/O

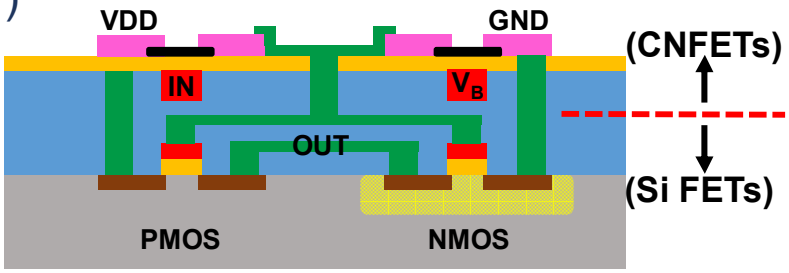
Technology to Fabricate 2.5D/3D ICs

- **2.5D packaging** (mature technology)
  - Wire bonded
  - Bump
  - vertical interconnect density < 20/mm or 400/mm^2
- **3D bonding/TSV** (emerging technology)
  - Die stacking
  - wafer stacking
  - vertical interconnect density < 40,000/mm^2
- **3D crystallization** (near future technology)
  - Epitaxial growth
  - Laser melting and crystallization
  - Seeded crystallization
  - Liquid phase crystallization
  - vertical interconnect density < 25M/mm^2
- **3D self assembled devices** (future technology)
  - Si and Ge nanowires
  - Carbon nanotubes
  - Organic semiconductors

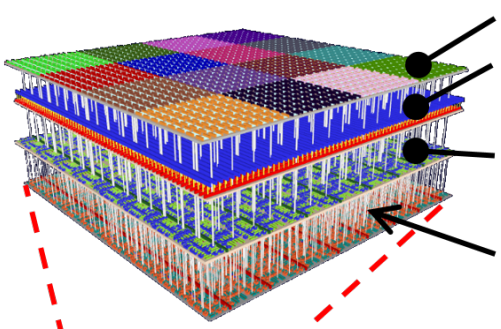


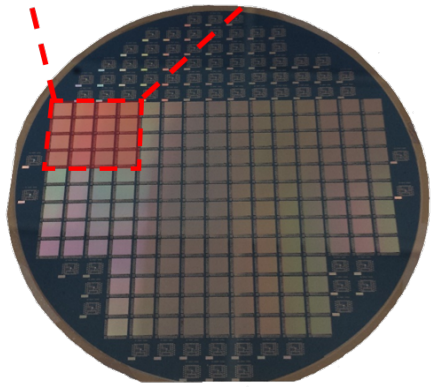


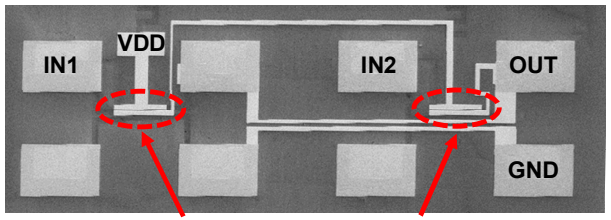


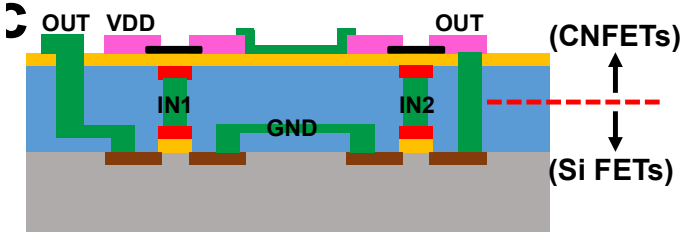


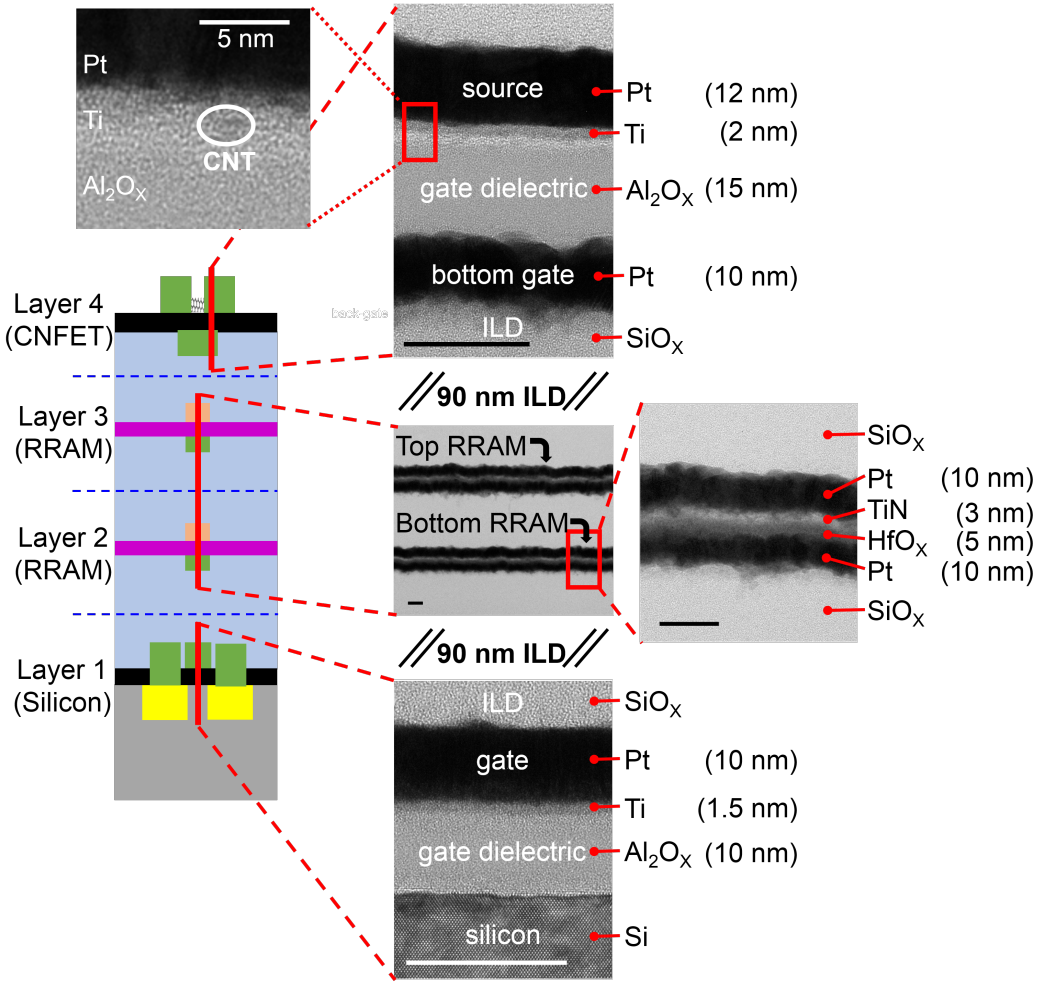
Monolithic 3D Integration of Si MOSFETs with RRAMs and CNTFETs





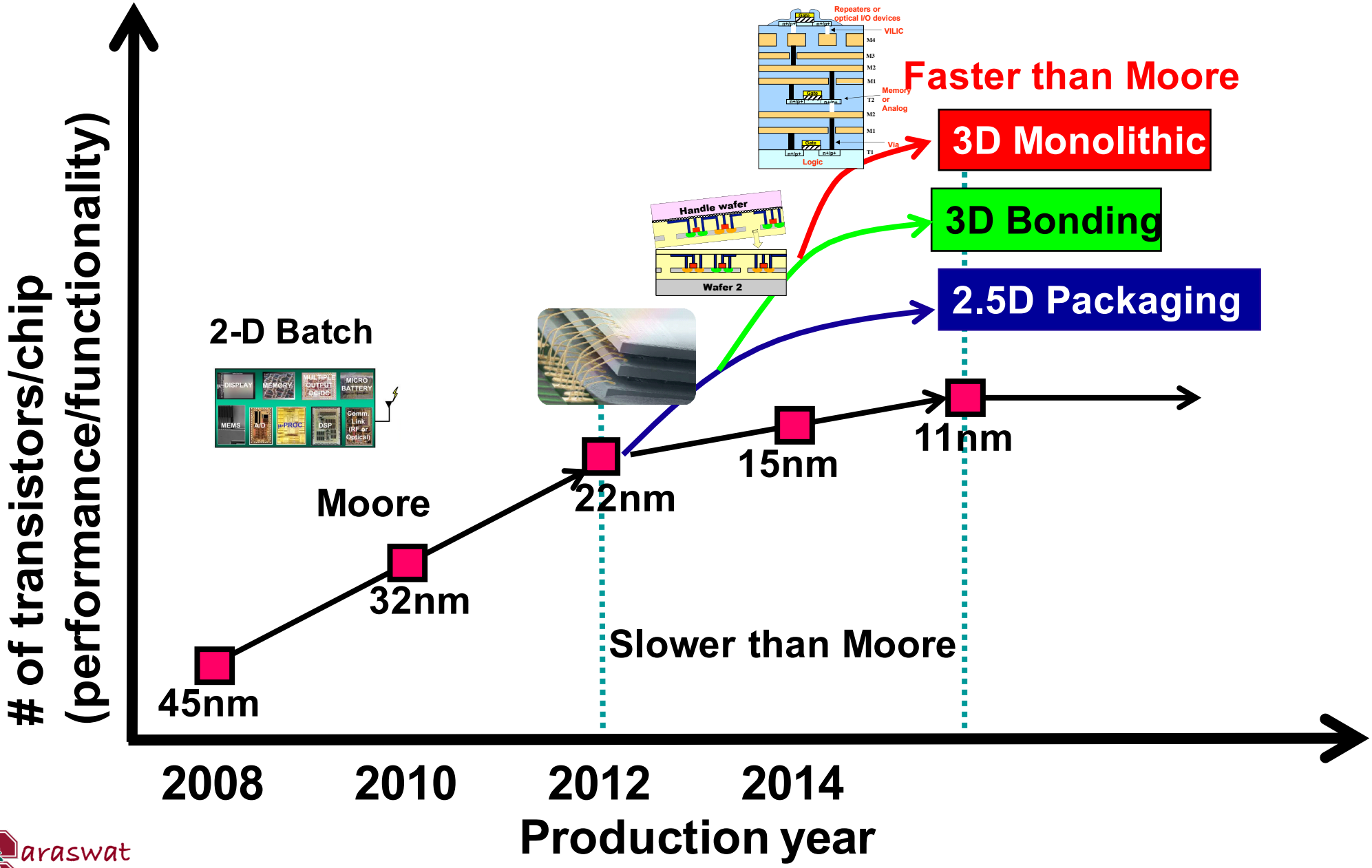




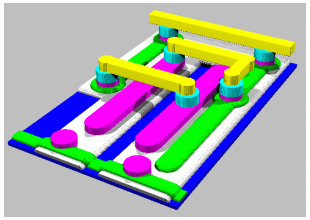


Max Shulaker, et al., IEDM, December 2014, VLSI Symp. 2014

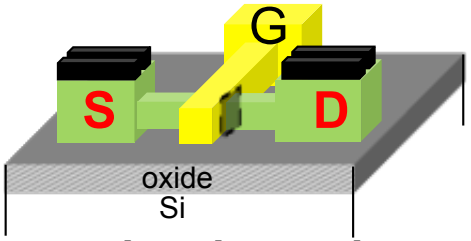
Heterogeneous 3D Integration Faster than Moore



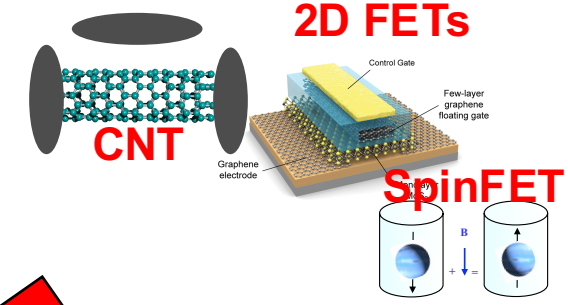
Future Systems will Require Heterogeneous 3D Integration on a Si Platform



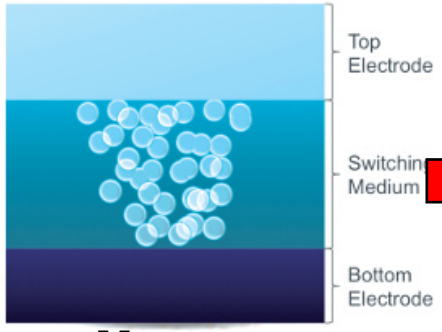
Metal interconnect



Conventional transistors

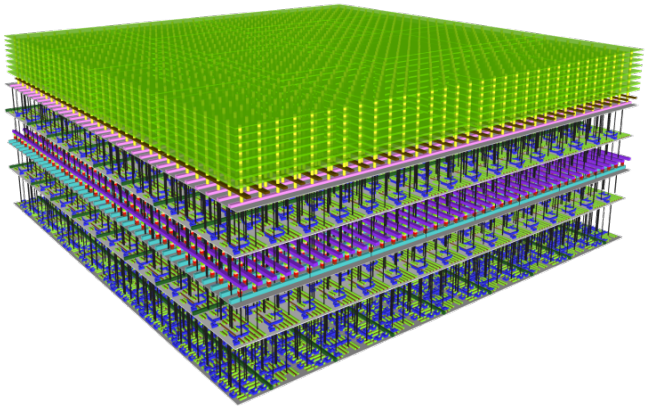


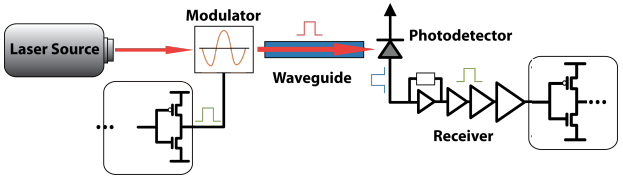
Novel transistors



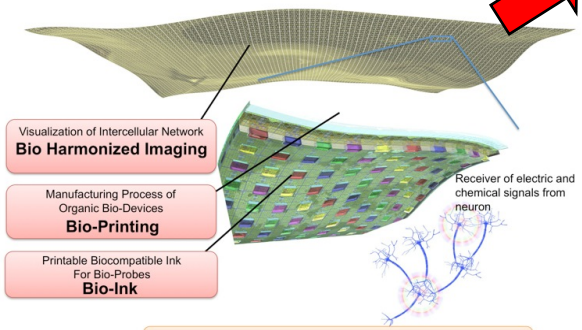
Memory

3D System

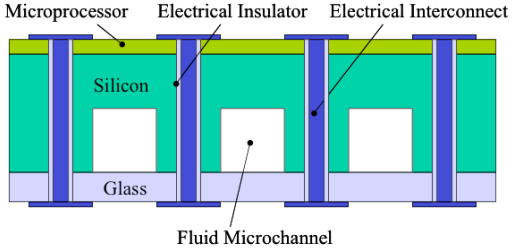




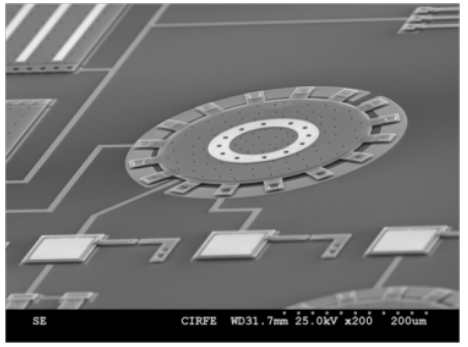
Photonics



Bio devices



Heat Transfer



MEMS/Sensors

Conclusion

- ☹ Cu resistivity increases as technology scales down. This will be a bottleneck of future high-performance chip.
- ☺ CNTs have a significant advantage over Cu wires especially for local interconnects
- ☺ Optical links have smallest latency and energy per bit for longer global interconnects requiring higher band width
- ☺ 3D heterogeneous integration will keep the Moore's law going for awhile.

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