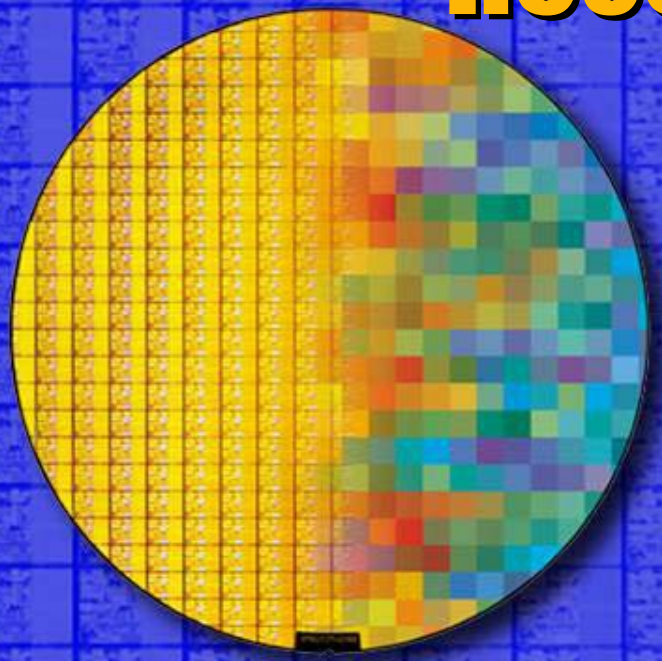
Silicon Photonics Opportunity, Applicatoins & Recent Results

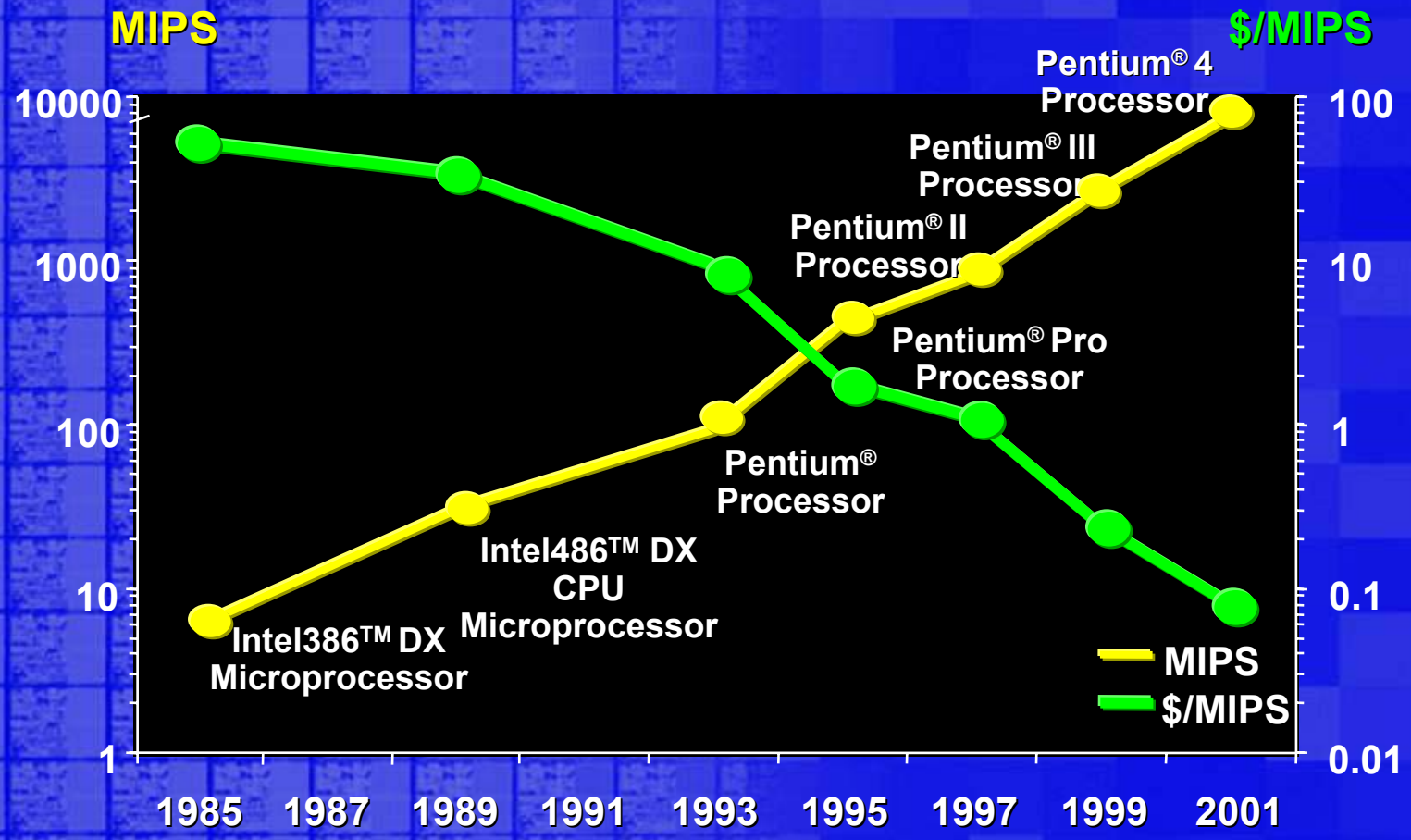


Mario Paniccia,
Director Photonics Technology Lab
Intel Corporation

Agenda

- Opportunity for Silicon Photonics
- Copper vs optical
- Recent advances
- Intels SP Research
- Recent results
  - Intel's Silicon Laser
- Summary

ELECTRONICS: Moore's Law Scaling



Integration & increased functionality

Volume economics – faster, better, cheaper

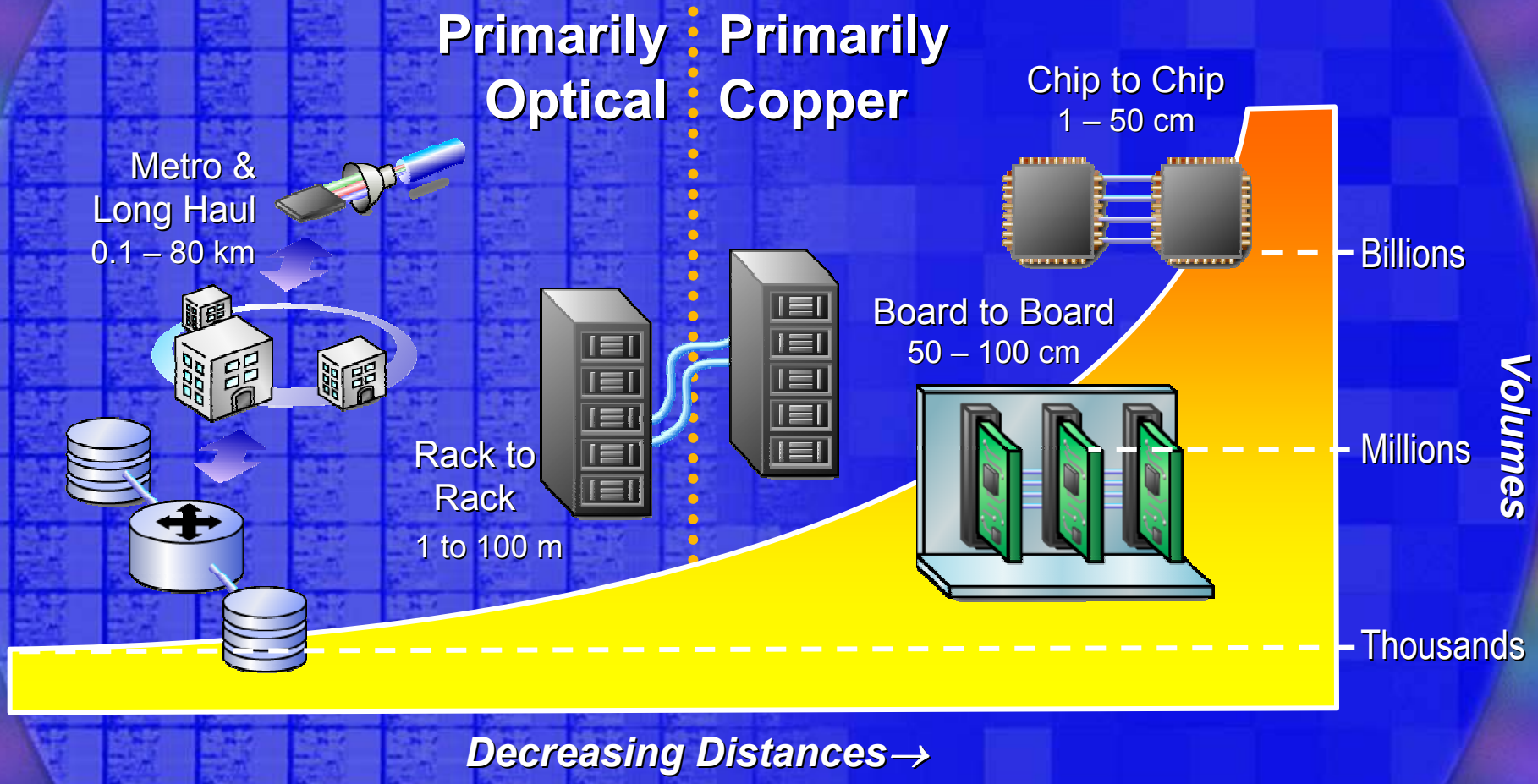
The Opportunity of Silicon Photonics

- Take advantage of enormous ($ billions) CMOS infrastructure, process learning, and capacity
  - Available tools: litho requirements typically >90nm
  - Draft continued investment going forward
- Potential to integrate multiple optical devices
- Micromachining could provide smart packaging
- Potential to converge computing & communications

Industry standard silicon manufacturing processes could enable integration, bring "volume economics" to optical.

To benefit from existing infrastructure optical wafers *must* run alongside product.. i.e CMOS fabrication compatible..

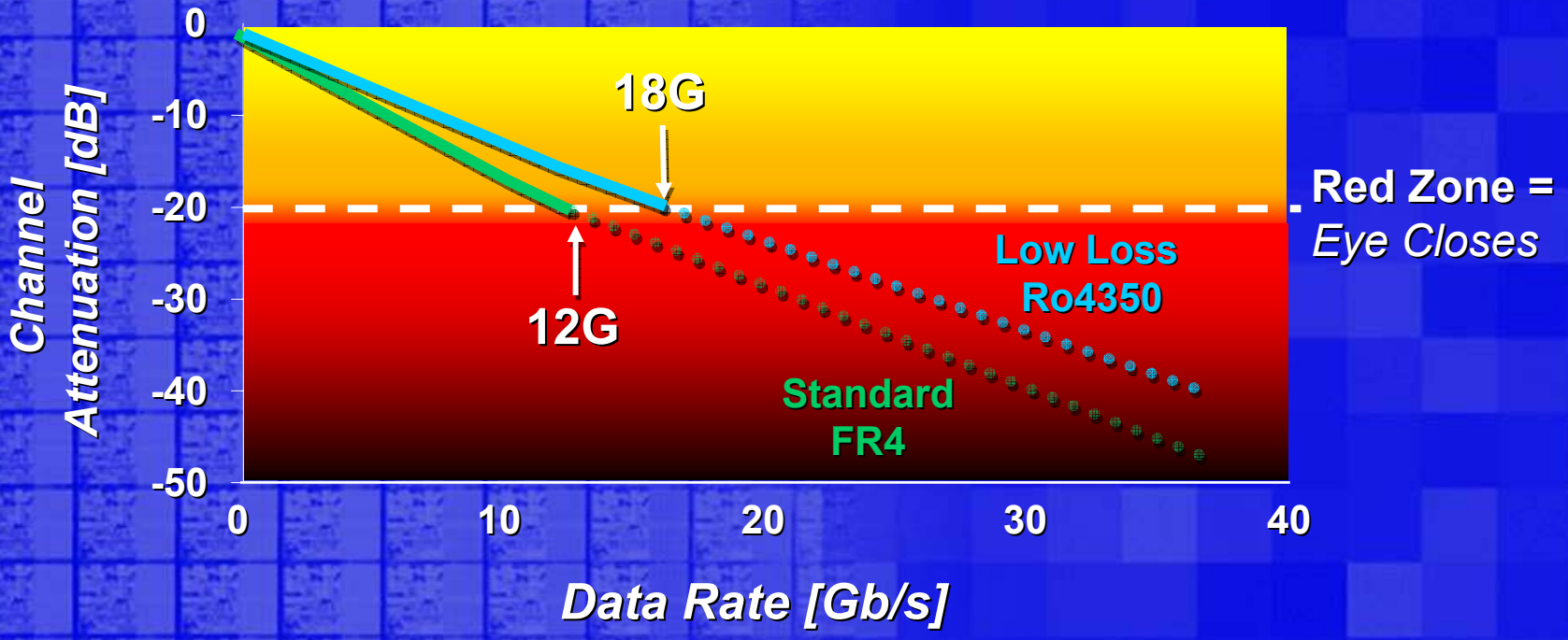
Today's High Speed Interconnects



Need to drive volume economics to drive optical closer to chip

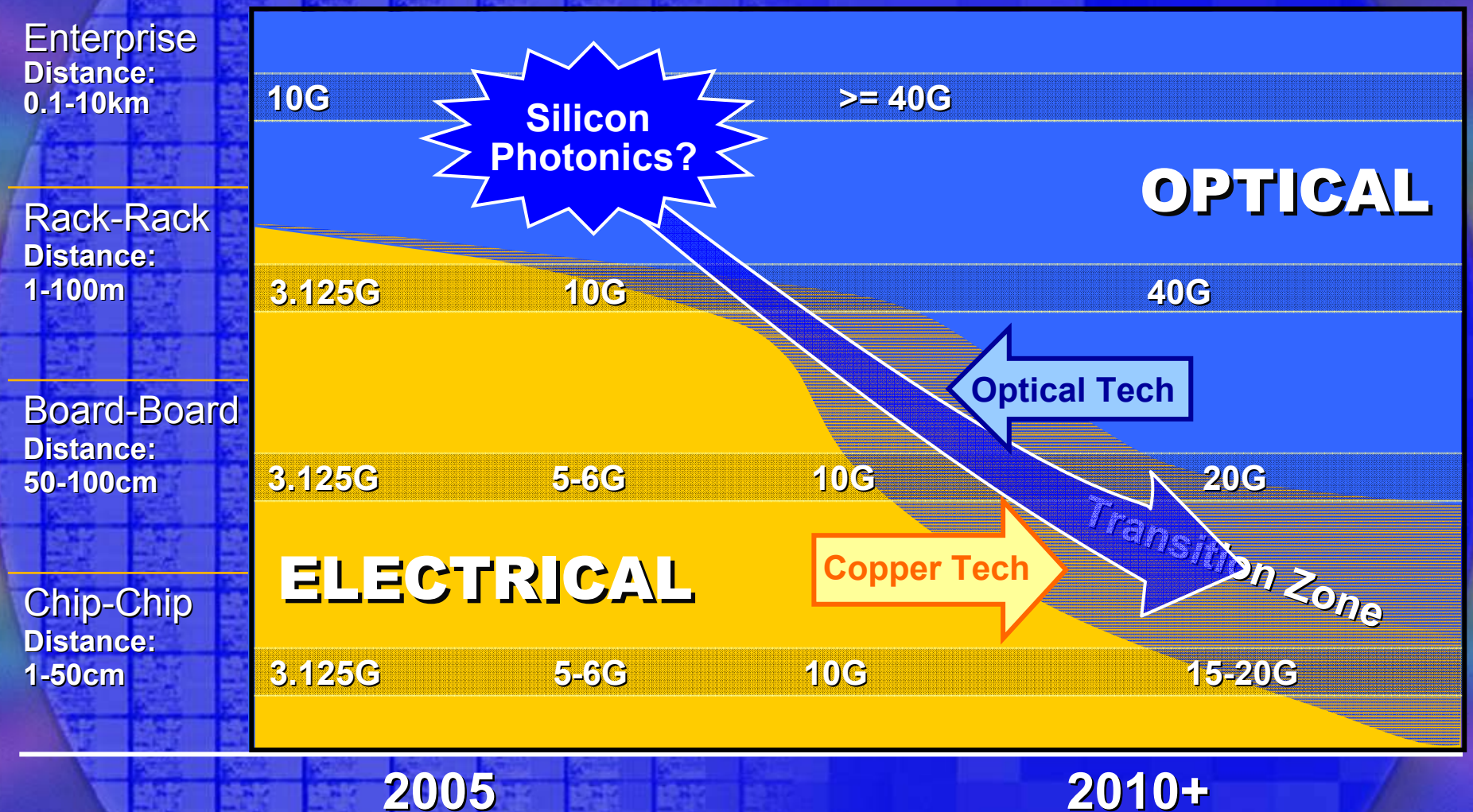
Copper Approaching Limits

Simulation of 20” channel transmitter w/ equalization



Copper scaling more challenging.
Headroom getting squeezed.

Electrical to Optical



Transition driven by cost

The Photonic Dilemma

- Fiber has much more bandwidth than copper
- However, it is much more expensive…..

Photonics: *The technology of emission, transmission, control and detection of light (photons) aka fiber-optics & opto-electronics*

Today: *Most photonic devices made with exotic materials, expensive processing, complex packaging*

Silicon Photonics Vision: *Research effort to develop photonic devices using silicon as base material and do this using standard, high volume silicon manufacturing techniques in existing fabs*

Benefit: Bring volume economics to optical communications

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- Recent advances
- Intels SP Research
- Recent results
  - Intel's Silicon Laser**
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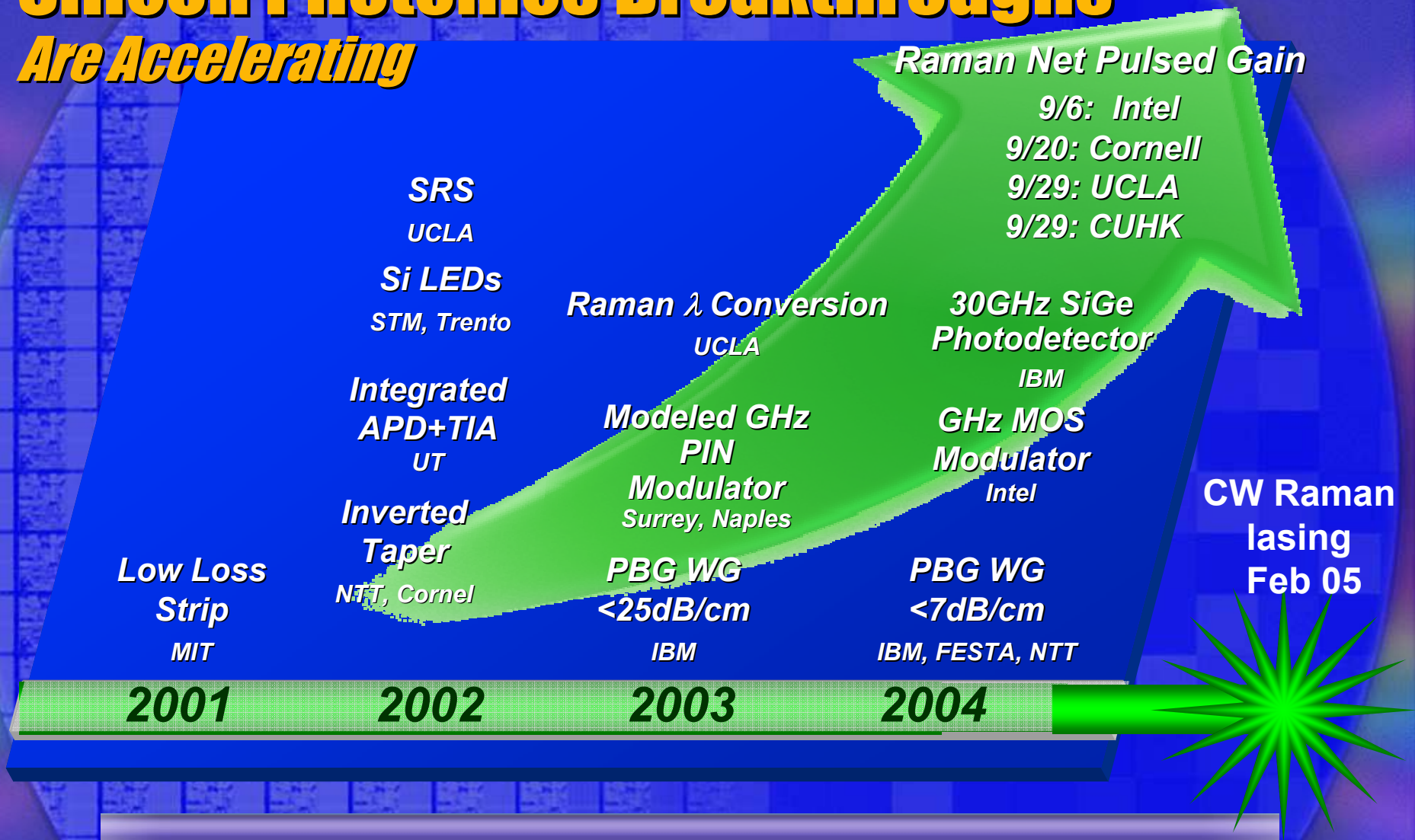
Silicon Pro's and Cons

+ Transparent in 1.3-1.6 µm region
+ CMOS fabrication compatibility
+ Low cost
+ High-index contrast – small footprint

– No electro-optic effect
– No detection in 1.3-1.6 µm region
– High index contrast – coupling
– Lacks efficient light emission

Silicon will not win with passive devices..
Must produce active devices that add functionality

Silicon Photonics Breakthroughs *Are Accelerating*



Progress In Recent Years Is Accelerating still not there…

Agenda

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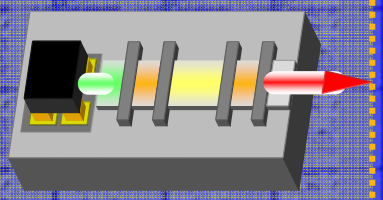
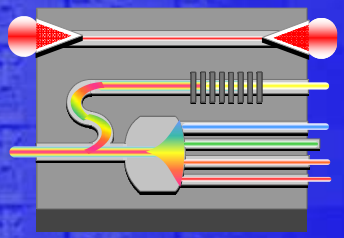
Intel's Silicon Photonics Research

1. Develop photonic building blocks in silicon

1) Light Source

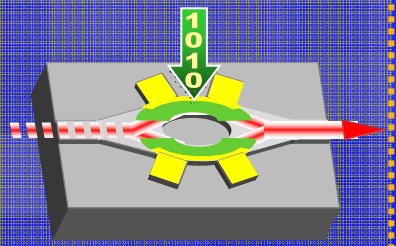


2) Guide Light



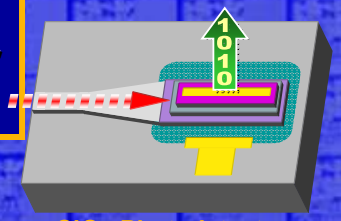
Waveguides devices

3) Modulation



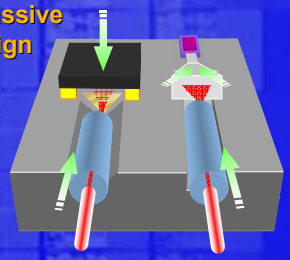
First Continuous Silicon Laser *(Nature 2/17/05)*

4) Photo-detection

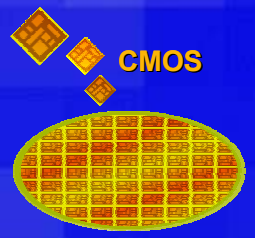


SiGe Photodetectors

5) Low Cost Assembly



6) Intelligence

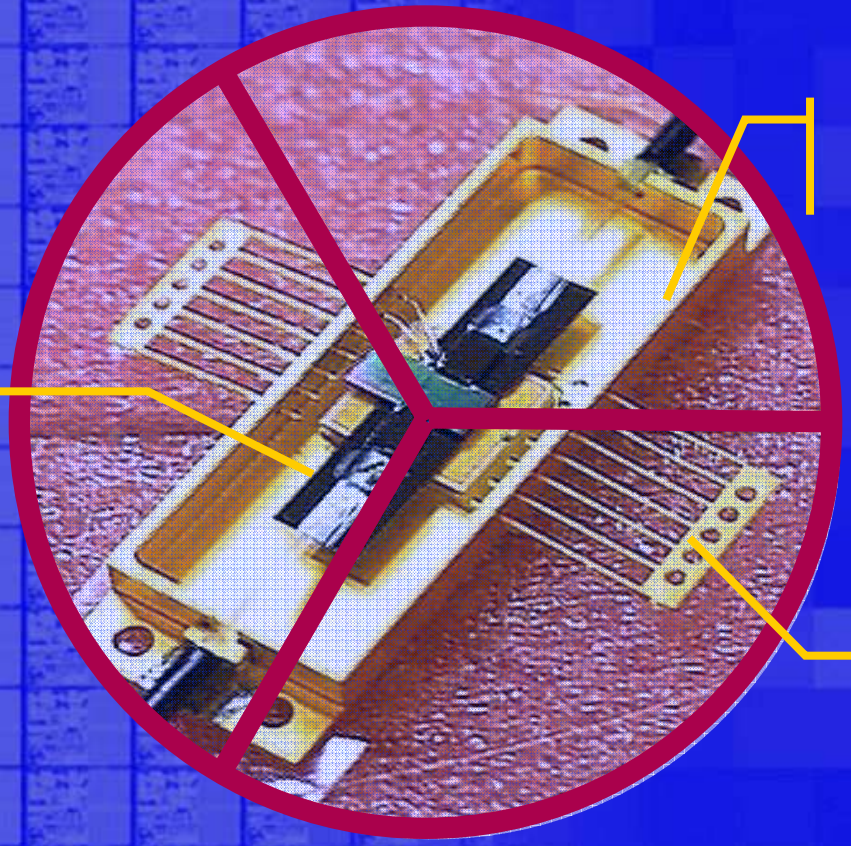


1GHz *(Nature '04)*
4 Gb/s *('05)*

First Prove that silicon is viable material for photonics

Packaging

Approximate Optical Product Cost Breakdown

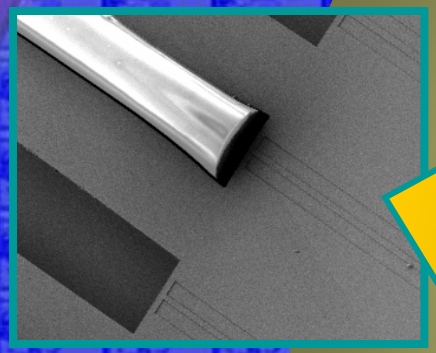


In addition to device costs, packaging and testing costs must drop with to enable high volume photonics

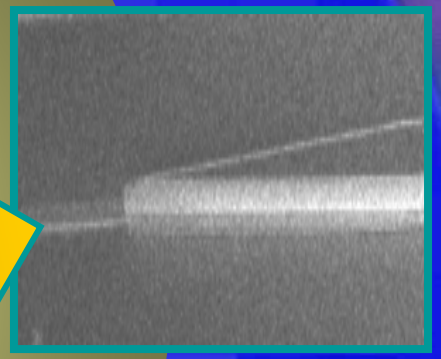
Micromachining for Packaging

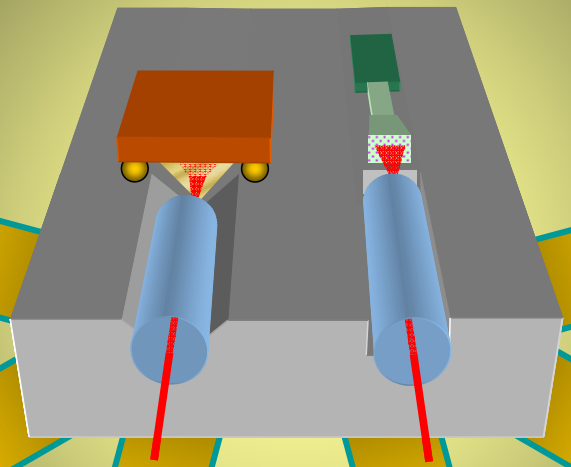
Use standard pick and place technologies along with litho defined silicon micro-machining

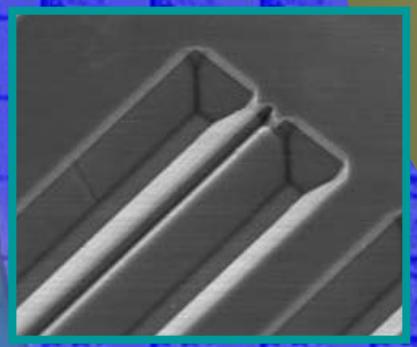
U-Grooves



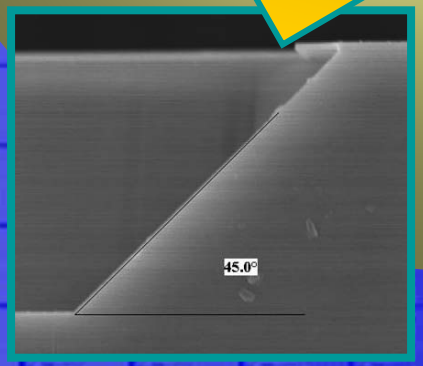
Tapers



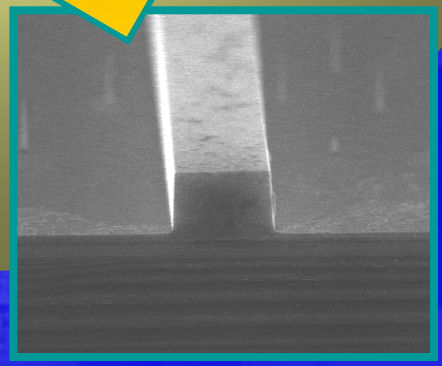




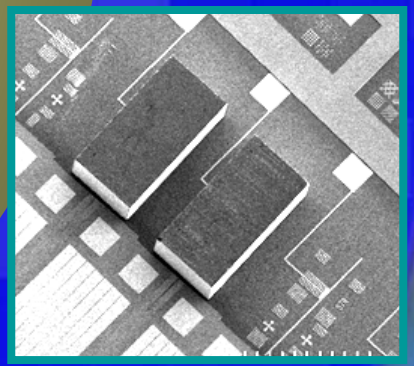
V-Grooves



45° Mirrors



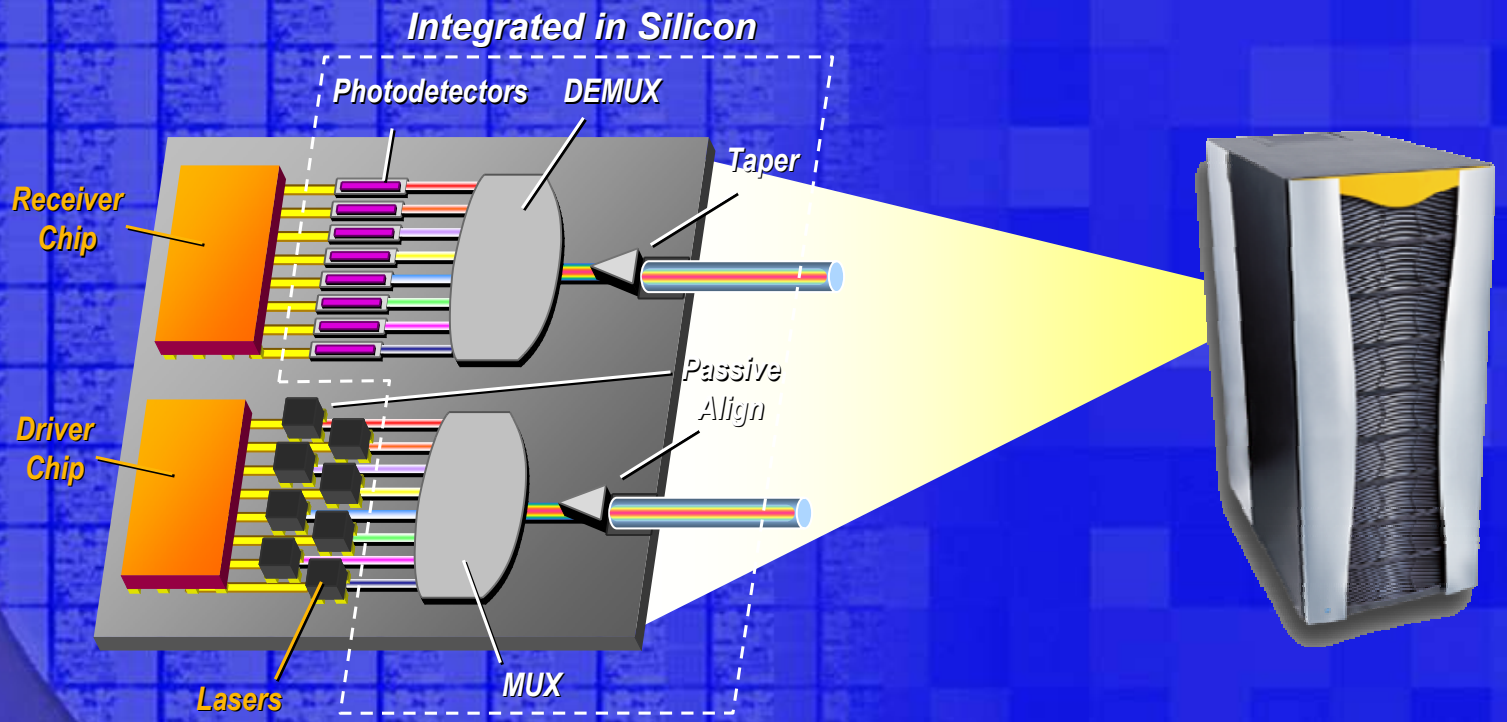
Facet Preparation



Laser Attach

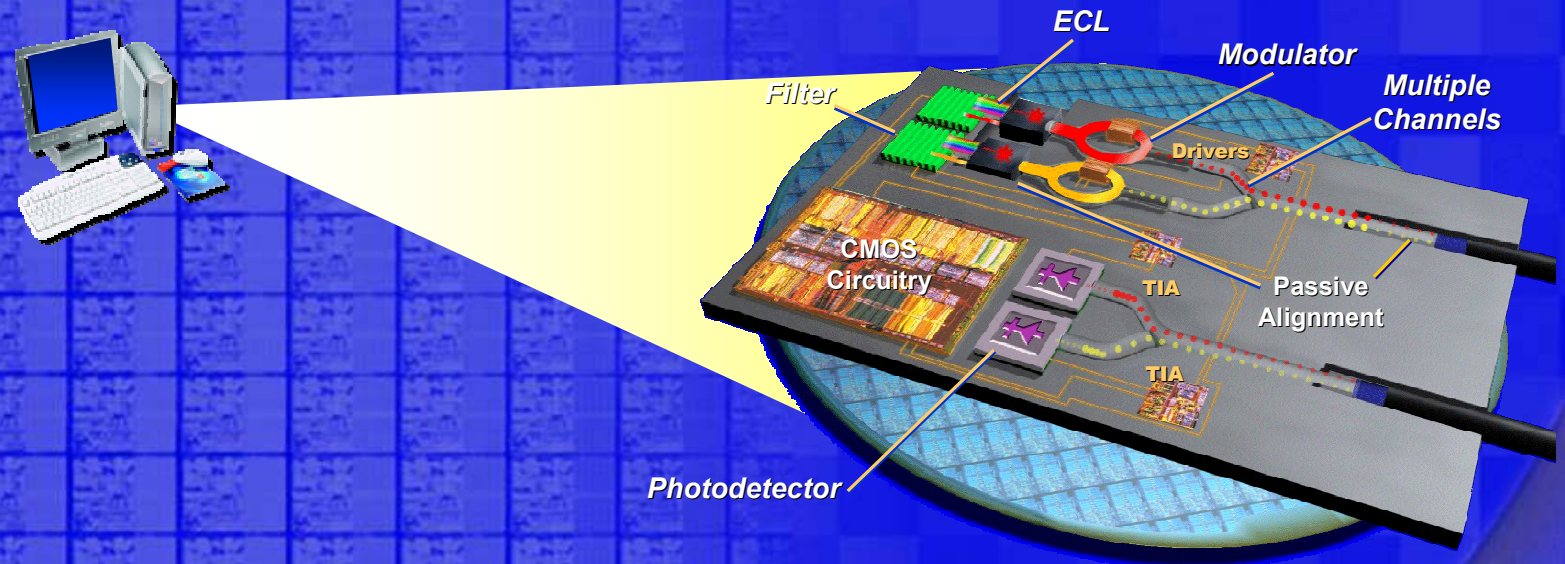
Intel's Silicon Photonics Research

1. Develop photonic building blocks in silicon
2. Integrate increasing functionality directly onto silicon



Intel's Silicon Photonics Research

1. Develop photonic building blocks in silicon
2. Integrate increasing functionality directly onto silicon
3. Long term explore monolithic integration

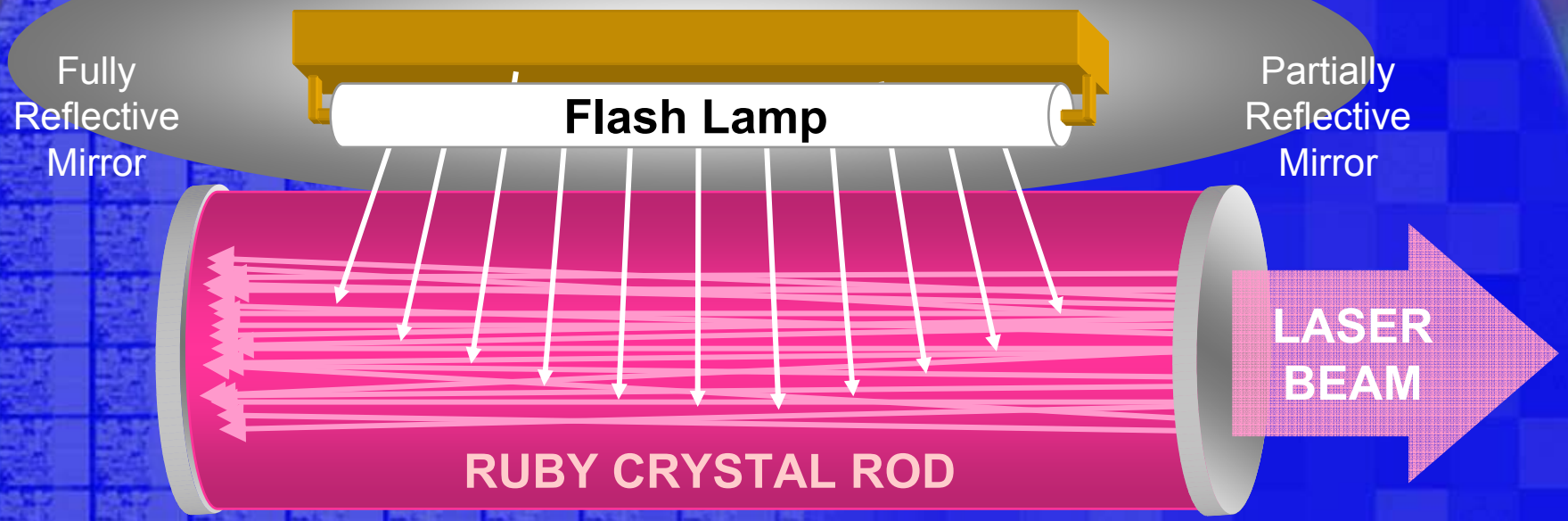


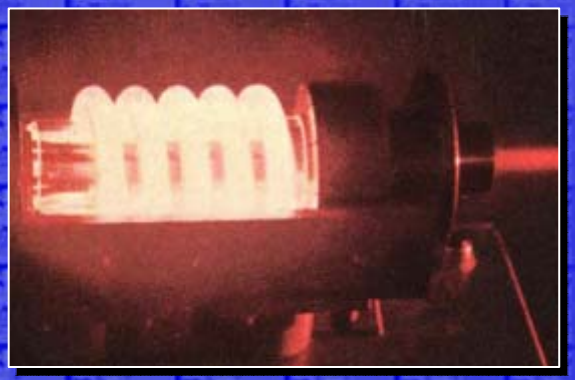
SILICON LASER

What we announced on Feb 17th

The First Laser

Developed by Ted Maiman, published in *Nature*, August 6, 1960.
this ruby laser used a flash lamp as an optical pump





Raman: (Historical Note)

Raman Effect or Raman Scattering: ***A phenomenon observed in the scattering of light as it passes through a transparent medium; the light undergoes a change in frequency and random alteration in phase due to a change in rotational or vibrational energy of the scattering molecules.***

- Discovered a material effect that is named after him
  - ***Nature*** **published his paper on the effect on March 31, 1928**
  - **He received the Nobel prize in 1930 for his discovery**
- The first laser using the Raman effect was built in 1962
- **Today Raman based amplifiers are used throughout telecom**
  - **Most long distance phone calls will go through a Raman amplifier**

Venkata Raman – Biography

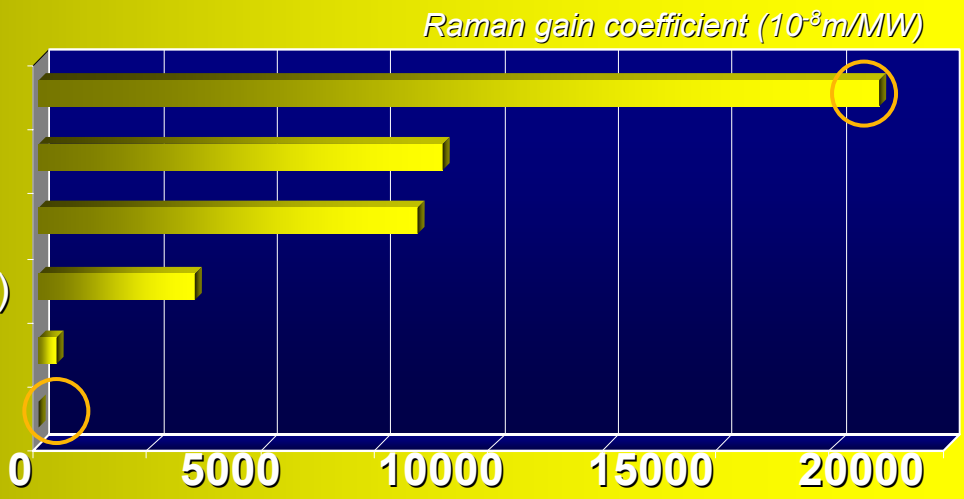
Chandrasekhara Venkata Raman was born at Trichinopoly in Southern India on November 7th, 1888. His father was a lecturer in mathematics and physics so that from the first he was immersed in an academic atmosphere. He entered Presidency College, Madras, in 1902, and in 1904 passed his B.A. examination, winning the first place and the gold medal in physics; in 1907 he gained his M.A. degree, obtaining the highest distinctions.

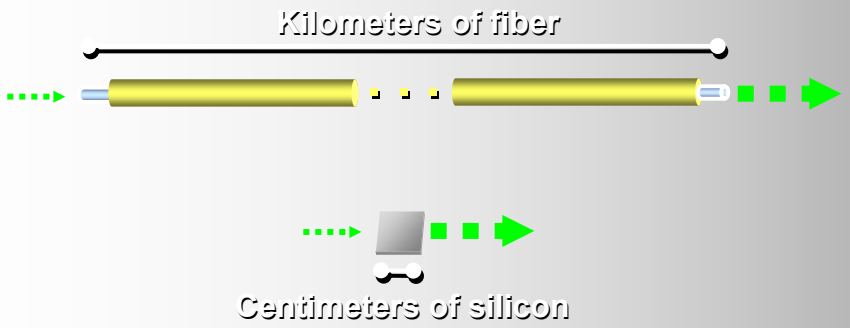
Typical Raman Amplifier

The Raman Effect

Materials

- **Silicon**
- Indium Antimonide (III-V)
- Quartz
- Lithium Niobate (used for modulators)
- Diamond
- Glass Fiber (Raman lasers/amps)



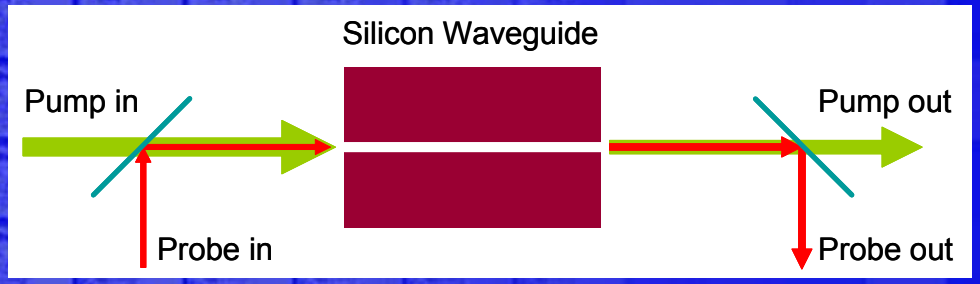


The Raman effect is 10,000 times stronger in silicon than in glass fiber

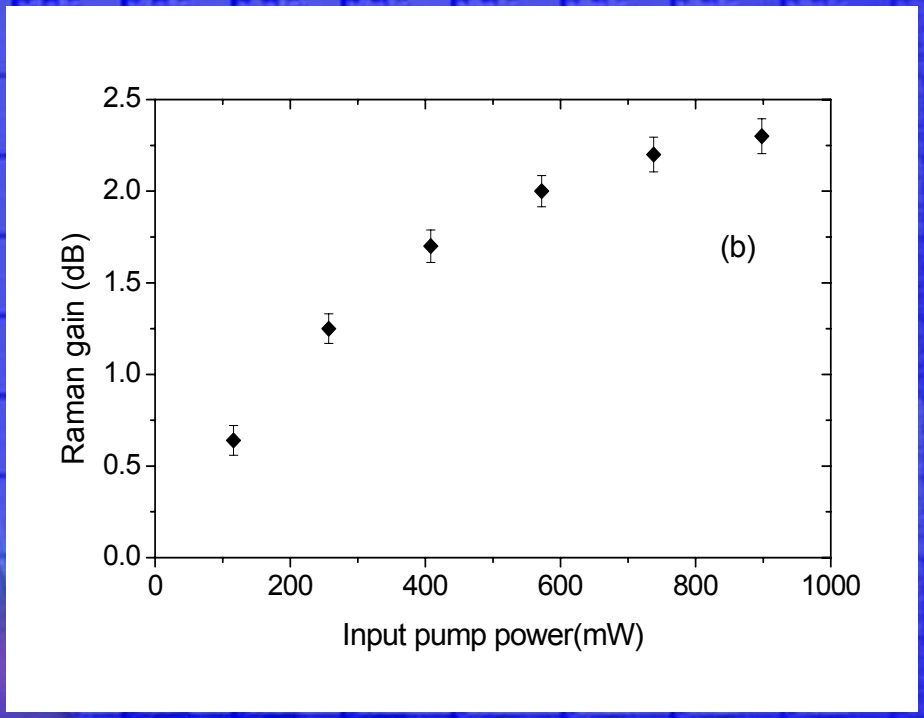
This allows for significant gain in centimeters instead of kilometers

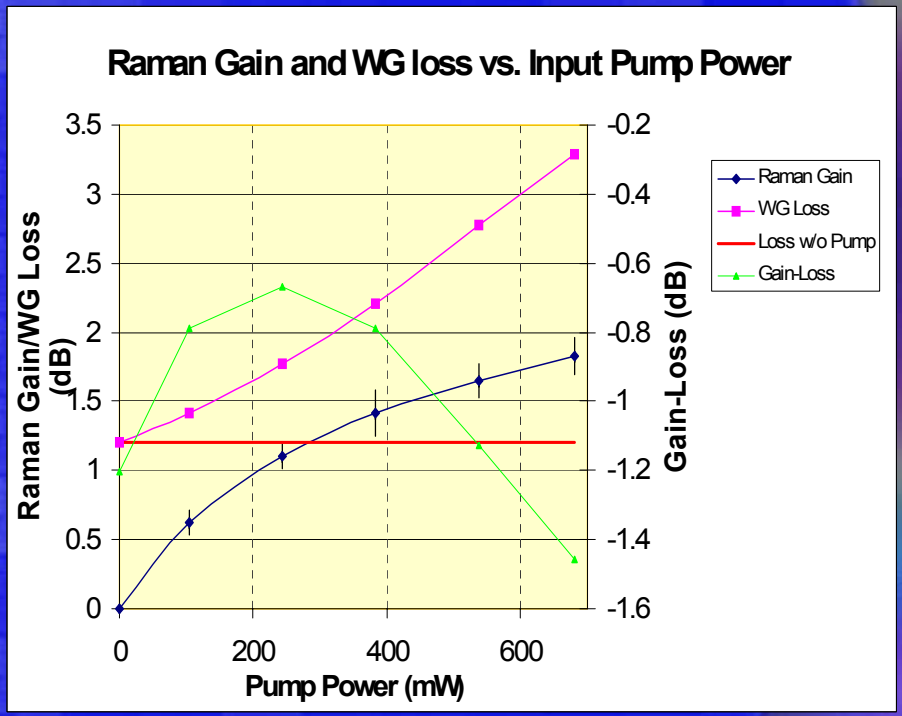
Fabrication of low-loss silicon waveguides is challenging

Raman Gain in Silicon



Pump/probe experiment

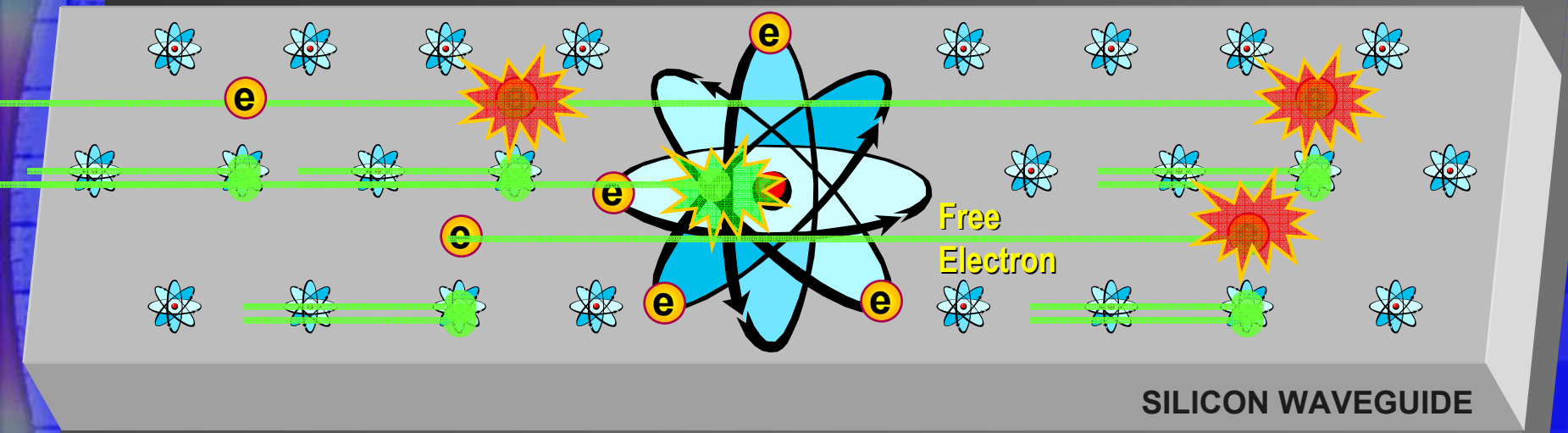




CW Gain Saturation due to TPA induced FCA

Two Photon Absorption

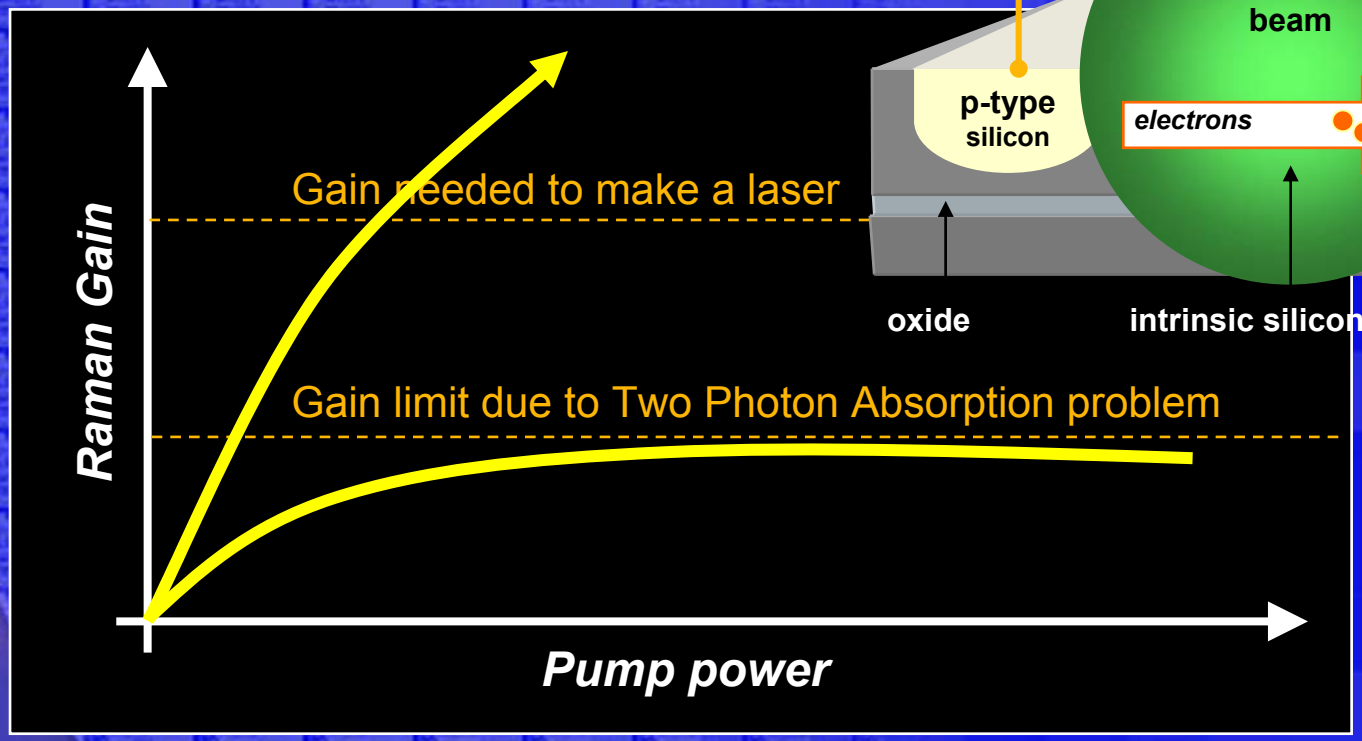
In silicon, one infrared photon doesn't have the energy to free an electron

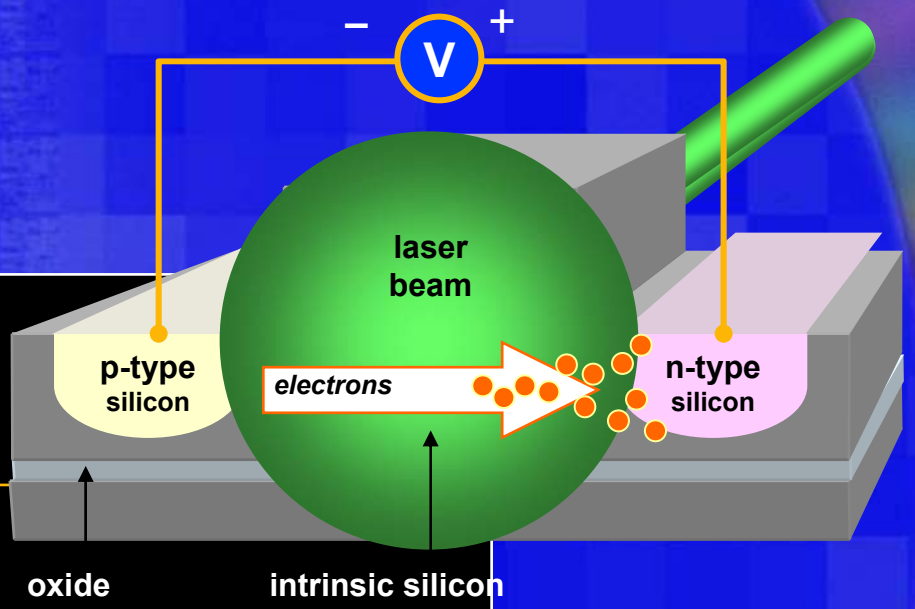


But, occasionally, *two* photons can knock an electron out of orbit.

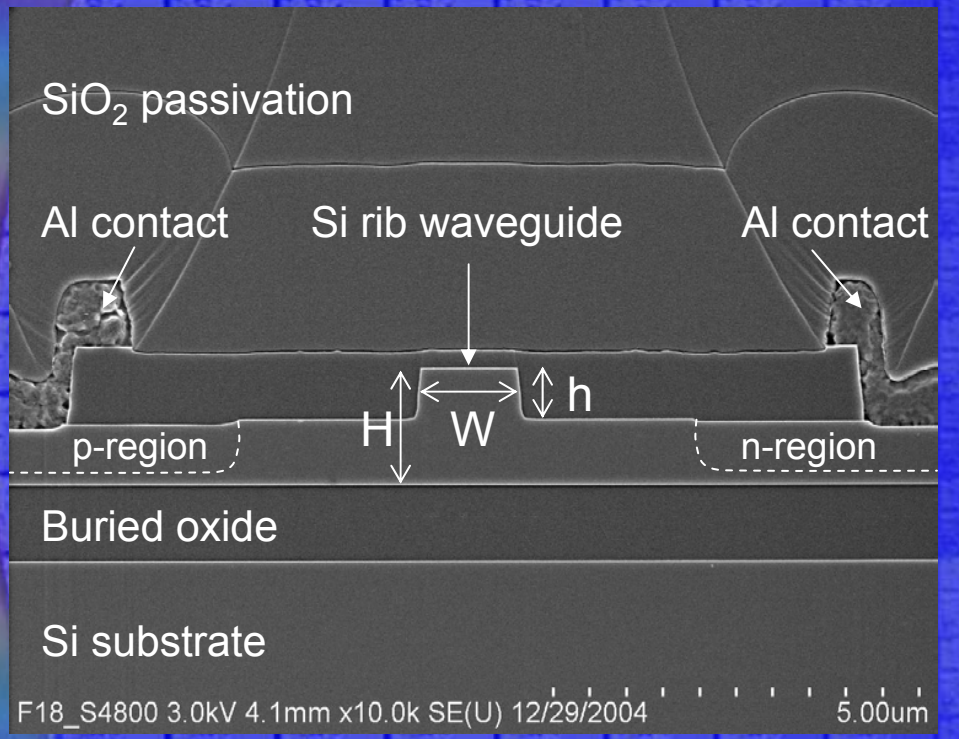
Free electrons *absorb individual photons and cancel Raman gain*

Overcoming TPA induced FCA

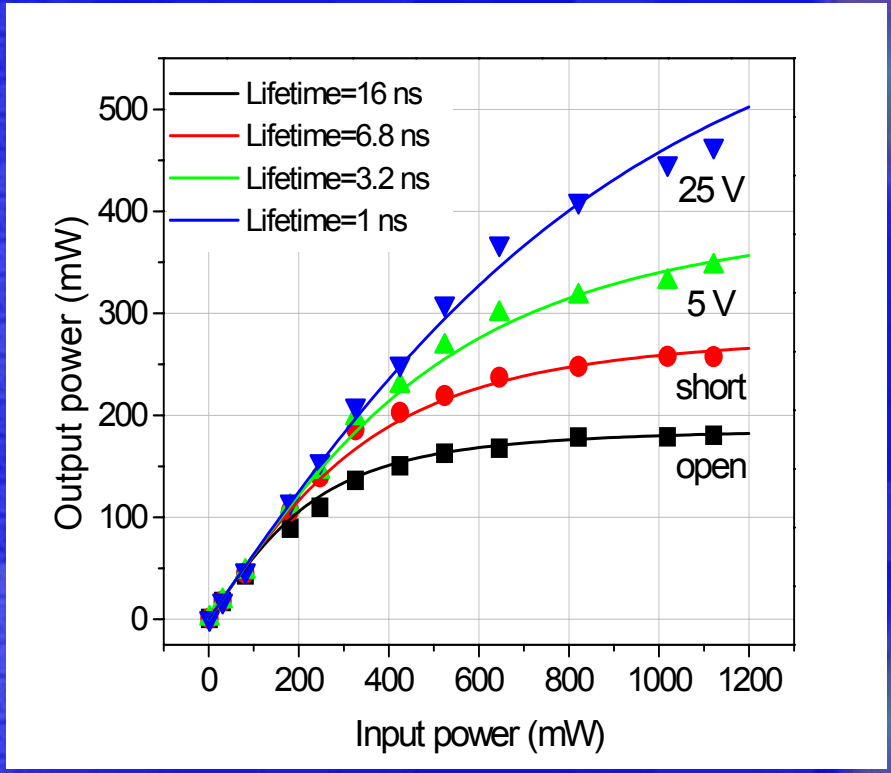




Effective Carrier lifetime reduction



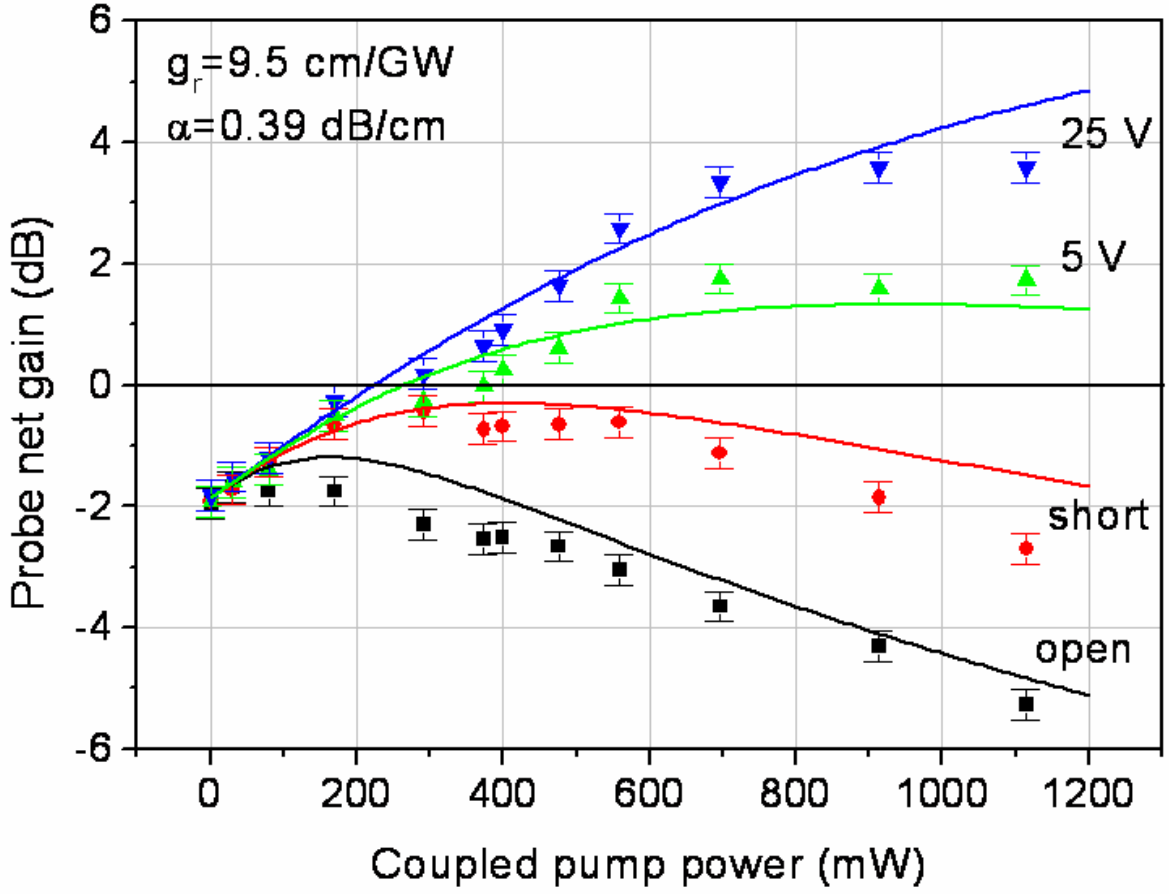
PIN Cross-section



TPA coeff ~ 0.5 cm/GW, α 0.39 dB/cm,
FCA cross sect 1.45e-17 cm^2 @ 1550 nm.
The lifetime is used as a fitting parameter

CW gain vs. reverse bias voltage

WG= ~1.5um by 1.5um

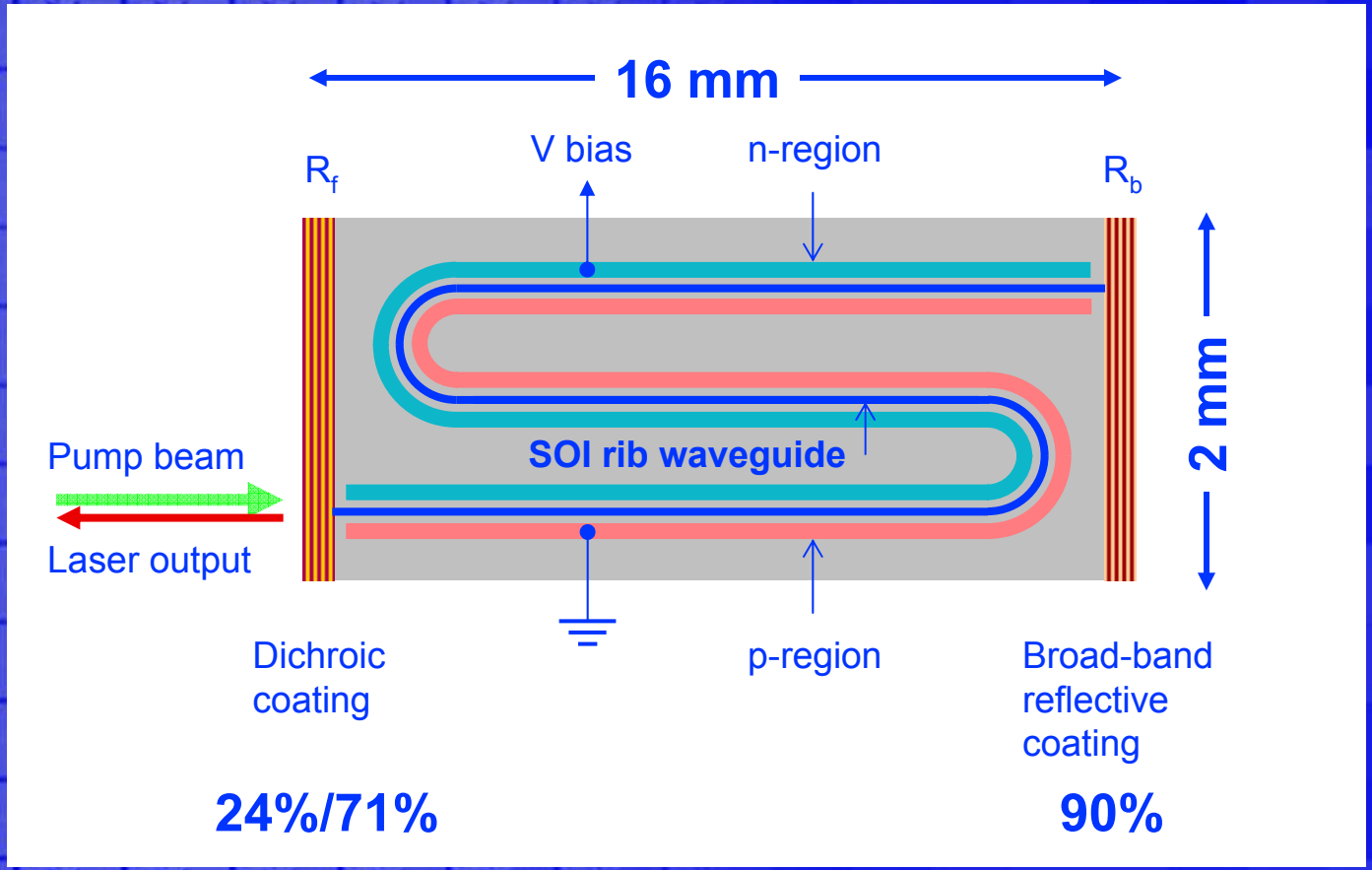


NET GAIN

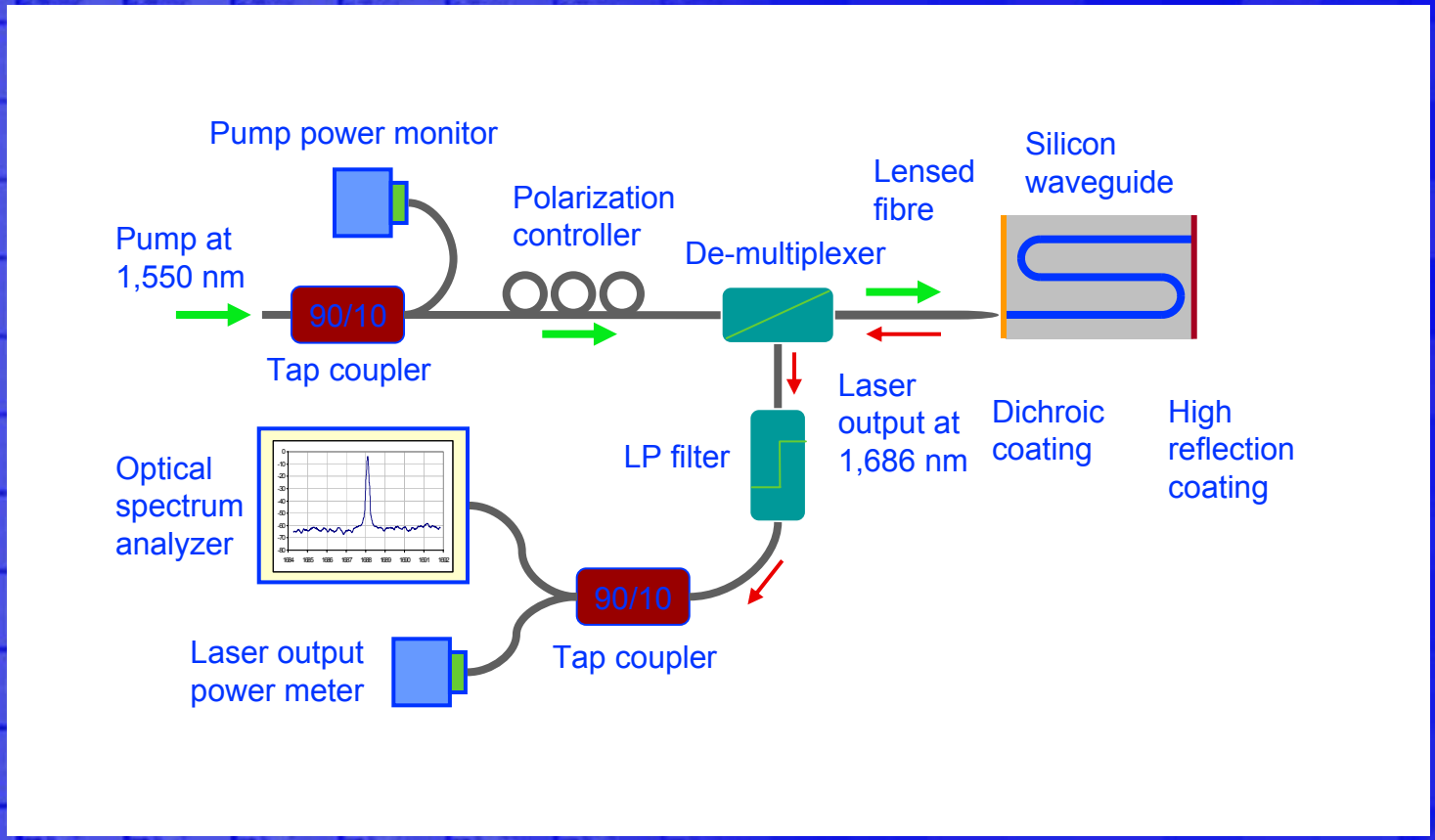
NO NET GAIN

Pump λ=1550 nm Signal λ=1686 nm

With gain can build Laser:
Silicon Waveguide Cavity



Experimental setup



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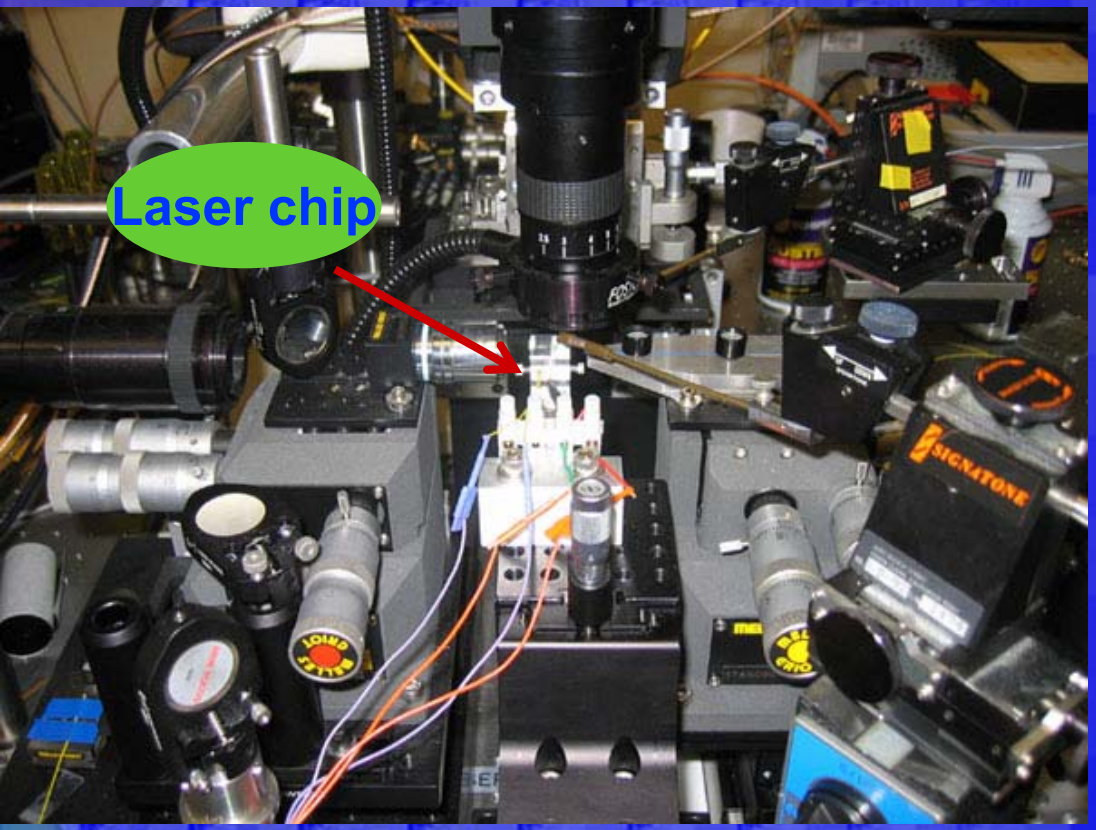
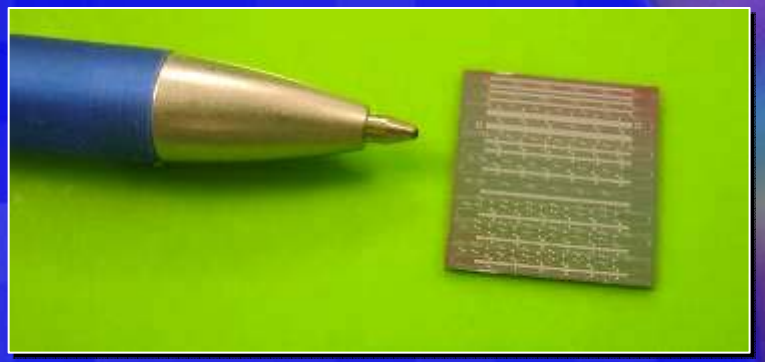
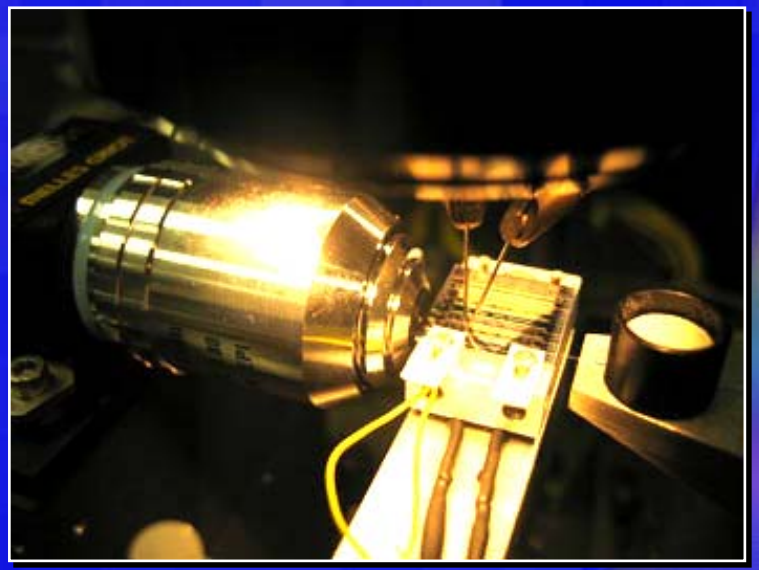


Test chip with 8 laser WG's

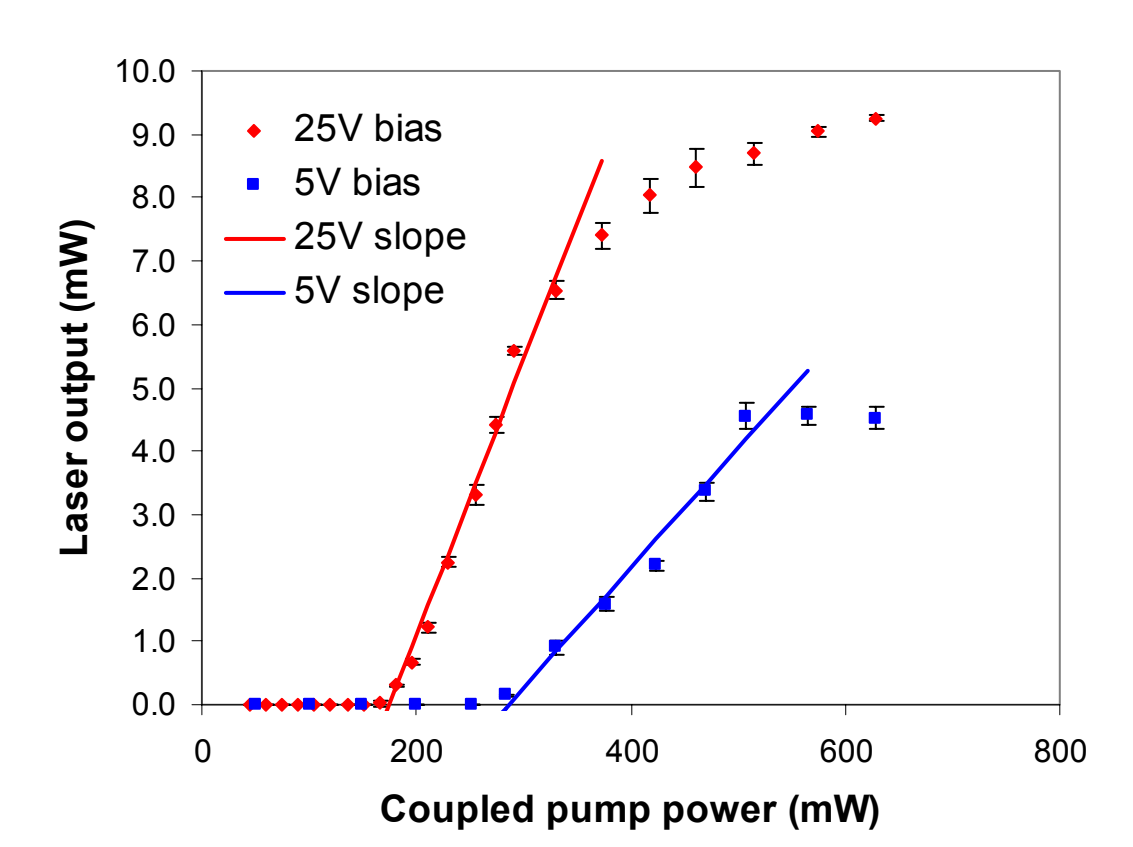




Typical Lasing Criteria

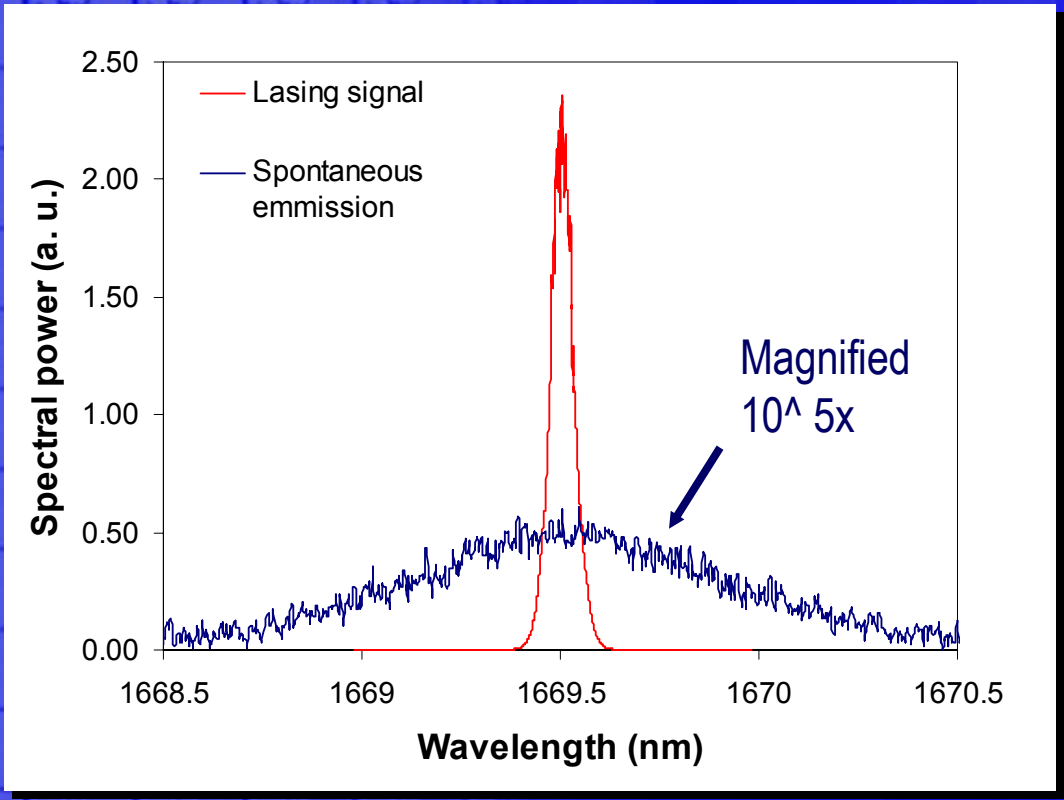
- Threshold behavior:
  - rapid growth in output power when gain > loss
- Spectral linewidth narrowing:
  - Coherent light emission

Threshold, Efficiency, and PIN effect



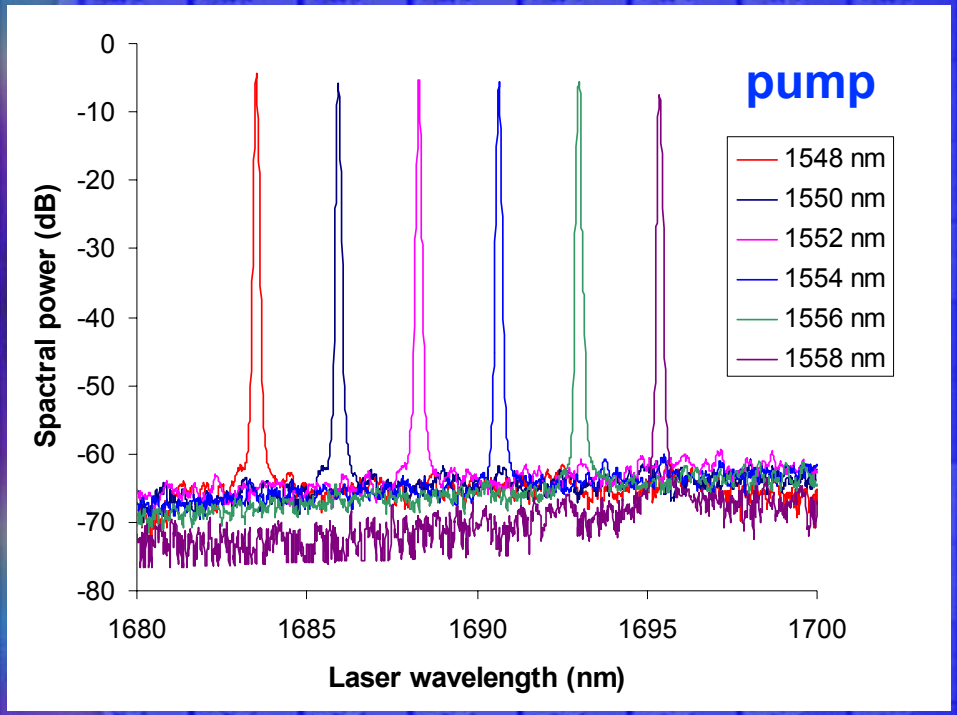
Laser turns on at threshold, when gain per pass in cavity becomes greater than the loss.

Spontaneous emission vs. laser spectrum

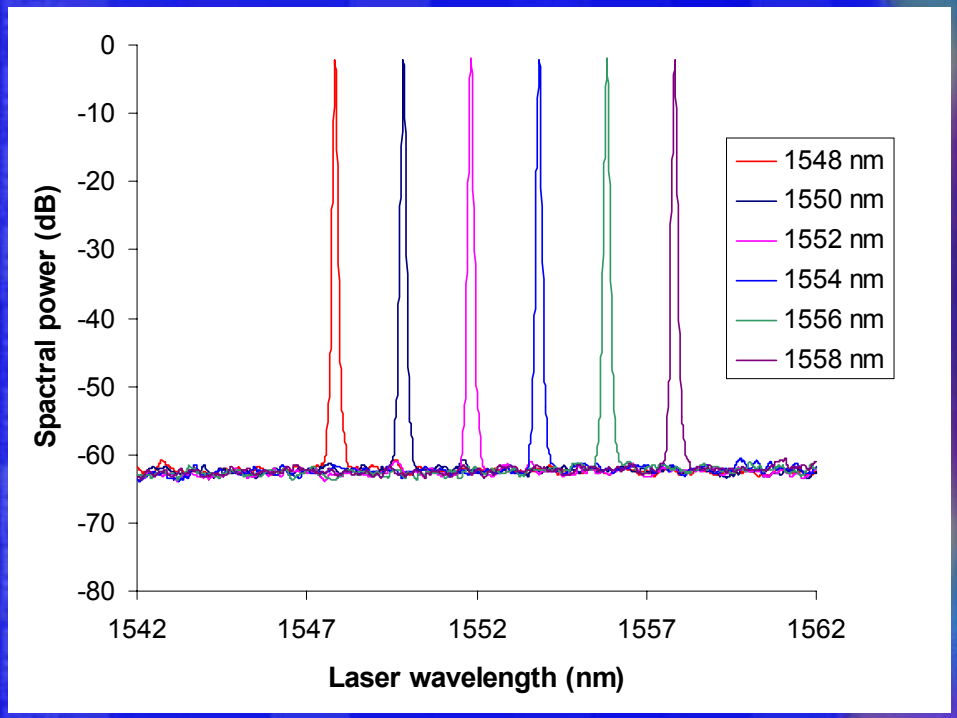


When lasing, the spectrum becomes much more narrow and much higher in power.

Wavelength tuning (comparison)



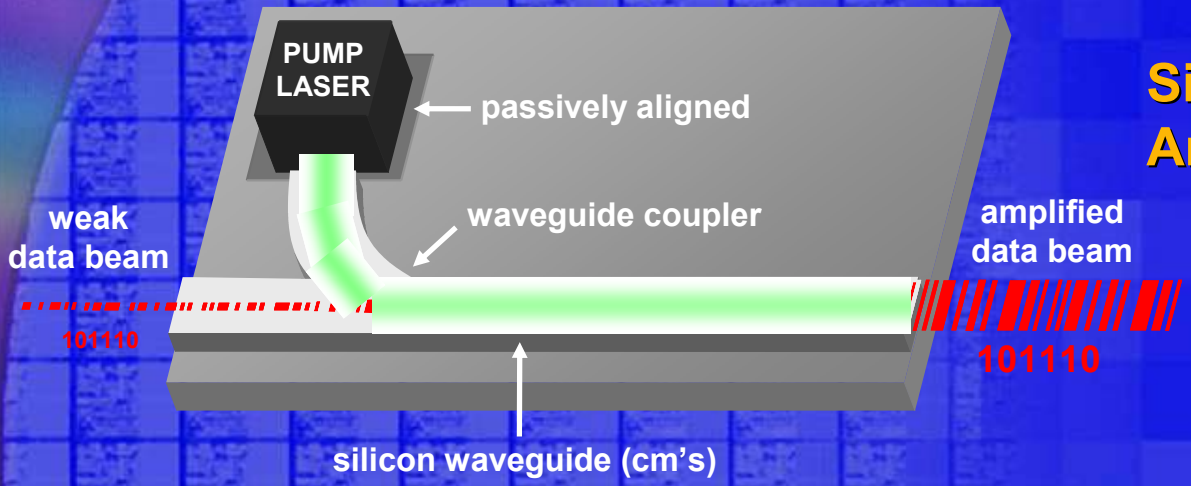
Silicon Raman laser



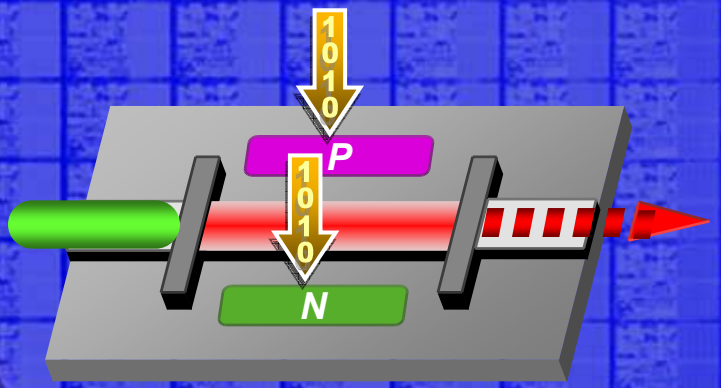
Commercial ECDL

Potential Applications

Communications Applications

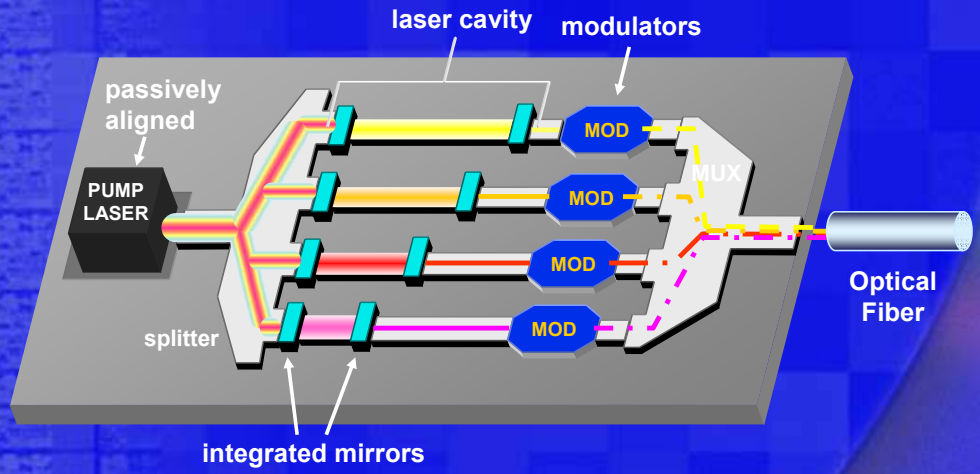


Si Raman Amplifier



Si Raman Modulator

Si Multi-Channel Transmitter

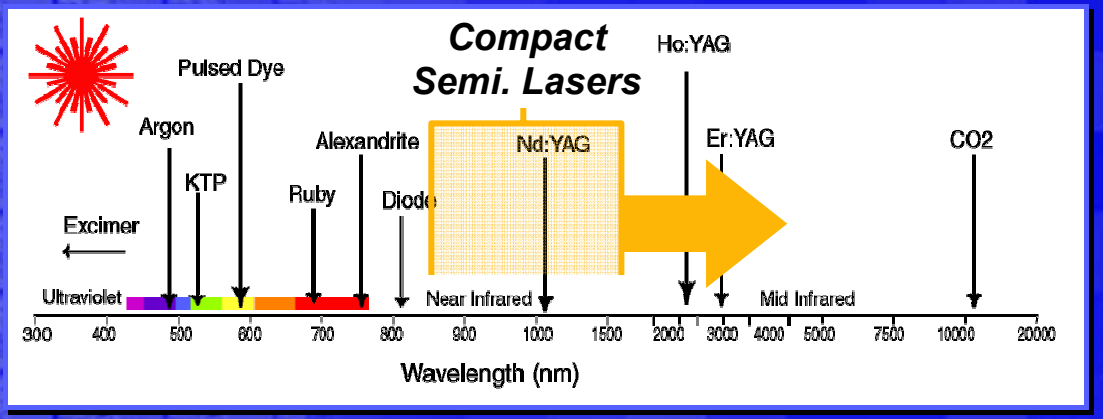


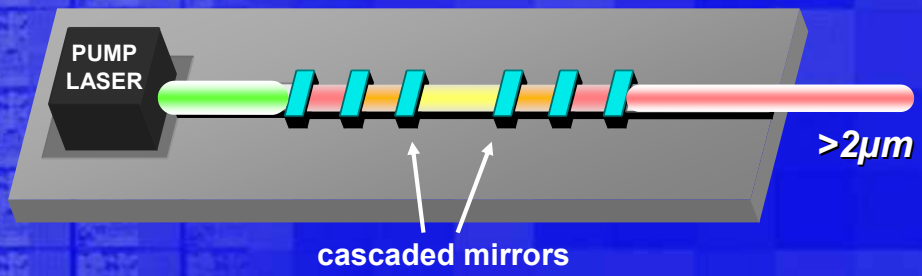
Covering the Gaps

2.1μm Ho:YAG laser

2.9μm Er:YAG laser

- Different wavelengths require different types of lasers
- Mid-Infrared very difficult for compact semiconductors
- Raman Lasers could enable lasers at these wavelengths
- Applications in sensing, analysis, medicine, and others





Could enable lasers for a variety of applications

intel

*Third p

Summary

Long term true convergence opportunities are with silicon

B/W will continue drive conversion of optical into interconnects

Tremendous progress from research community

- Need to continue pushing & improving performance

Research breakthrough with CW silicon laser

Integration is next set of challenges

In order to benefit Technologies must be CMOS fabrication compatible to benefit from HVM & infrastructure

Silicon will not win with individual devices, but with integrated modules that bring increased total functionality & intelligence at a lower cost

BACKUP

Benefits of Integration

- *Photonic Integration:*
  - ✓ Reduction in interfaces – lower loss
  - ✓ Reduction in size
  - ✓ Simpler assembly, testing, packaging
  - ✓ Cost
- *Optoelectronic Integration:*
  - ✓ Reduce parasitics, improved high-freq performance
  - ✓ Further size, testing, packaging reductions
  - ? Cost

Integration is only useful if integrated device has benefit (functionality, cost, performance) over discrete devices

CMOS Integration Challenges

- Film topology
- Coupling to fiber
- Contaminating the fab
- Yield metrology
- Thermal budgets
- Heat dissipation
- Complexity / yield

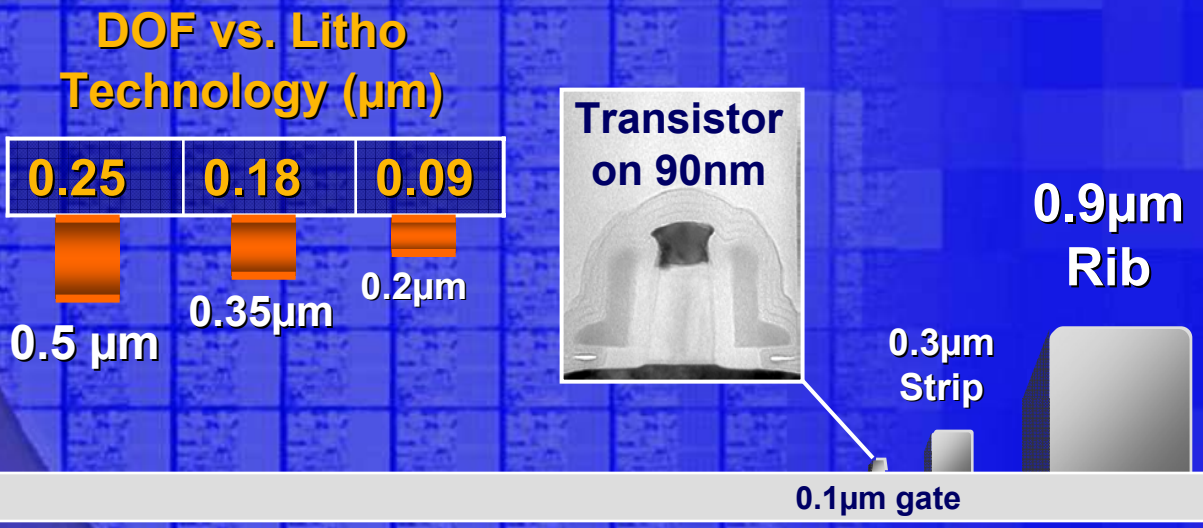
Optoelectronic Integration

To benefit from existing infrastructure optical wafers must run alongside product, introducing additional pragmatic challenges

Surface Topology: Litho vs DOF

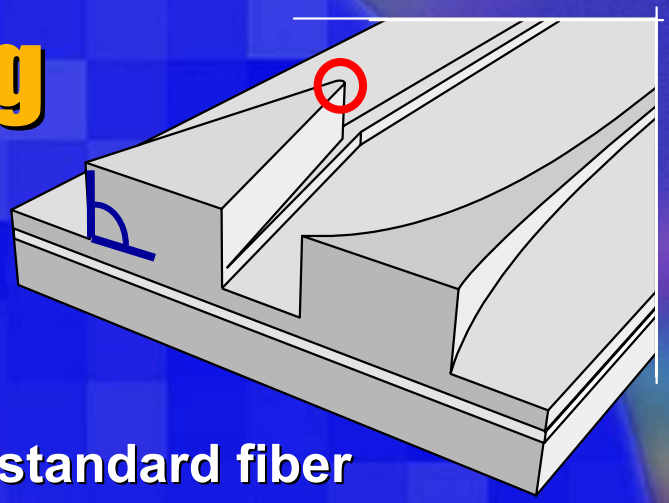
- Depth of focus (DOF) shrinks as litho improves
- Many optical devices are much taller than transistors

For 0.18µm and better, topology exceeds DOF
New planarization techniques required for advanced litho

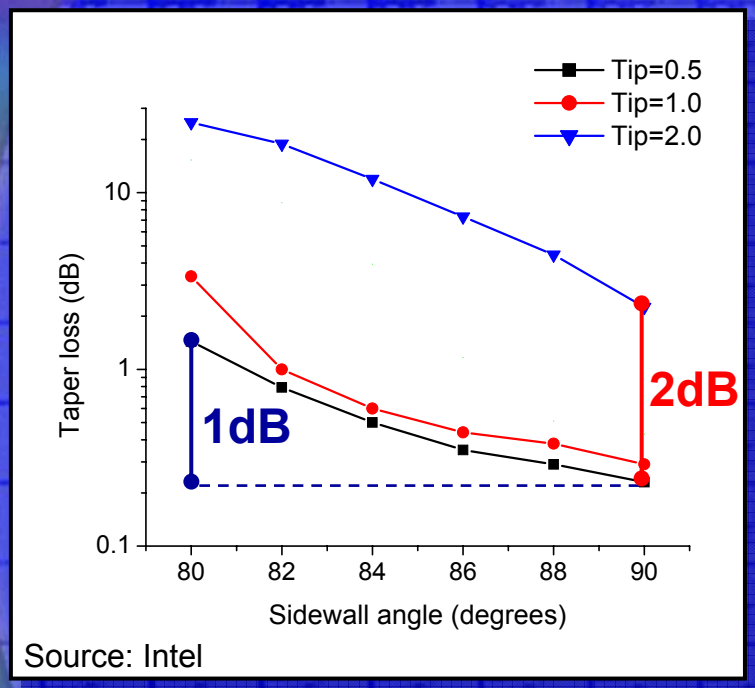


8µm Taper

Fiber Coupling



Taper from (W x H):
10 x 8 μm to 2.5 x 2.3 μm
Assume zero roughness



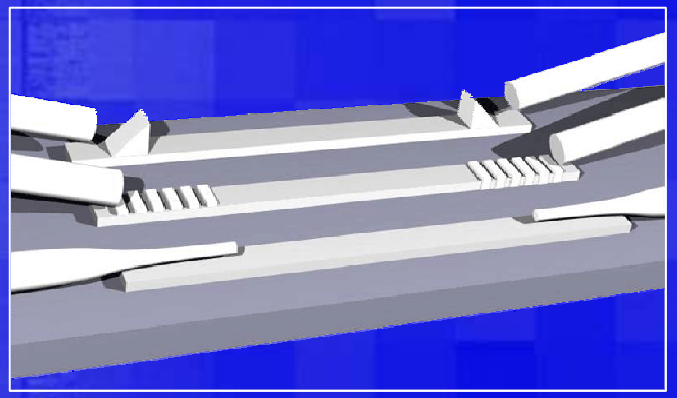
Source: Intel

- Coupling from standard fiber to Si waveguides requires special structures (tapers, gratings, etc).
- For wedge tapers, etch angle as well as the tip lithography impact loss.
- Sidewall roughness is also a factor

Getting light from fibers into silicon waveguides will require couplers. For certain structures litho and etch parameters must be carefully controlled.

Yield Metrology

- CMOS fabs monitor thousands of parameters across wafer in line
- Tight control – e.g. CMOS gate width held to 10's of angstroms
- *Significant per-wafer cost savings* from screening out yield early



- In-line wafer level optical probing is very immature
- Most optical device testing is performed after wafer dicing

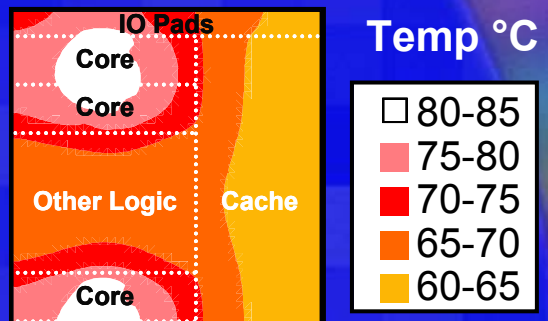
To truly gain from HVM processing, automated & non-destructive techniques for probing optical devices at the wafer level must be developed

Opto-Electronic Integration (cont)

Thermal:

For optoelectronic integration , optical devices must tolerate heat generated by CMOS circuits.

Simulated multi-core thermal map



Process compatibility:

@ 10Gb/s CMOS IC's need 90nm technology
Silicon Photonic devices may only need ~.25um

Yield:

Typical industry IC yields are high, but the process windows are extremely tight.
Tweaks to enable opto-electronic integration may effect IC yield

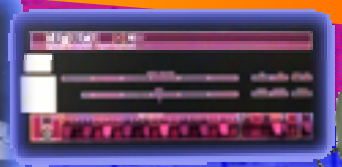
Trade off of yield and process compexity will determine if opto-electrical integration valuable

Animation

Click in box while in slide show mode to start

Click outside animation box after animation

Extending and Expanding Moore's Law



Discrete SSI LSI VLSI

EXTENDING

EXPANDING

Sensors

Mechanical

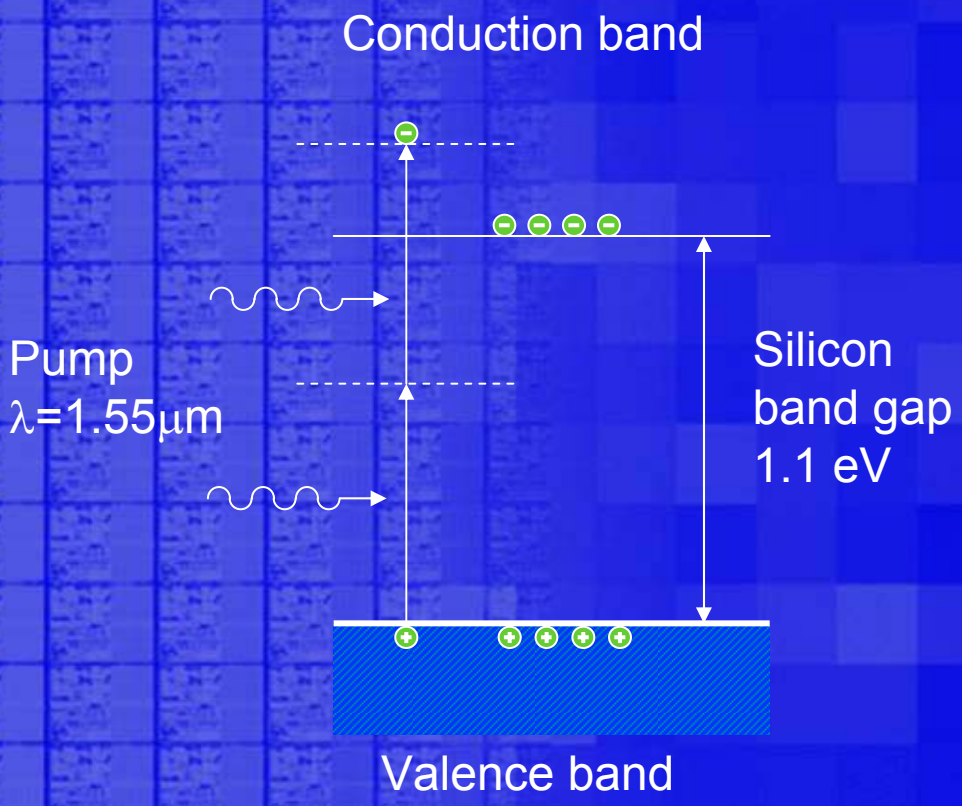
Biological

Fluidics

Wireless

Optical

Two Photon Absorption in Silicon



Two photons can simultaneously hit an atom
Combined energy enough to kick free an electron