Silicon photonics:

a new technology platform to enable low cost and high performance photonics

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Outline

- Silicon Photonics
- State of the art
- Silicon Photonics for lab-on-a-chip
- NanoSilicon photonics
- Conclusion

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The experts look ahead

Cramming more components onto integrated circuits

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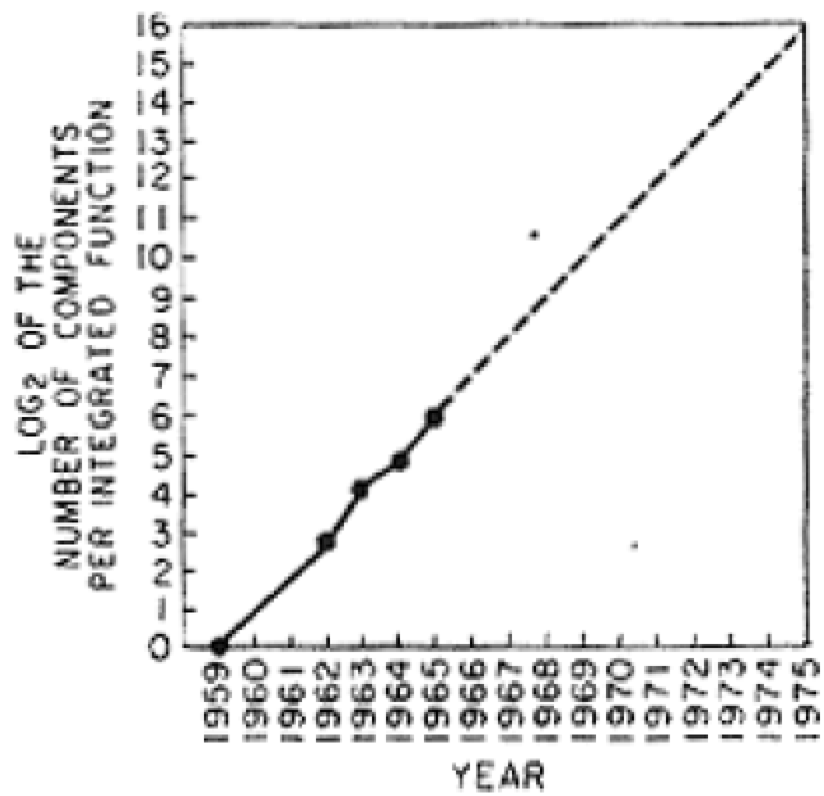
By Gordon E. Moore

Director, Research and Development Laboratories, Fairchild Semicondu division of Fairchild Camera and Instrument Corp.

Electronics, Volume 38, Number 8, April 19, 1965



The experts look ahead

Cramming more components onto integrated circuits

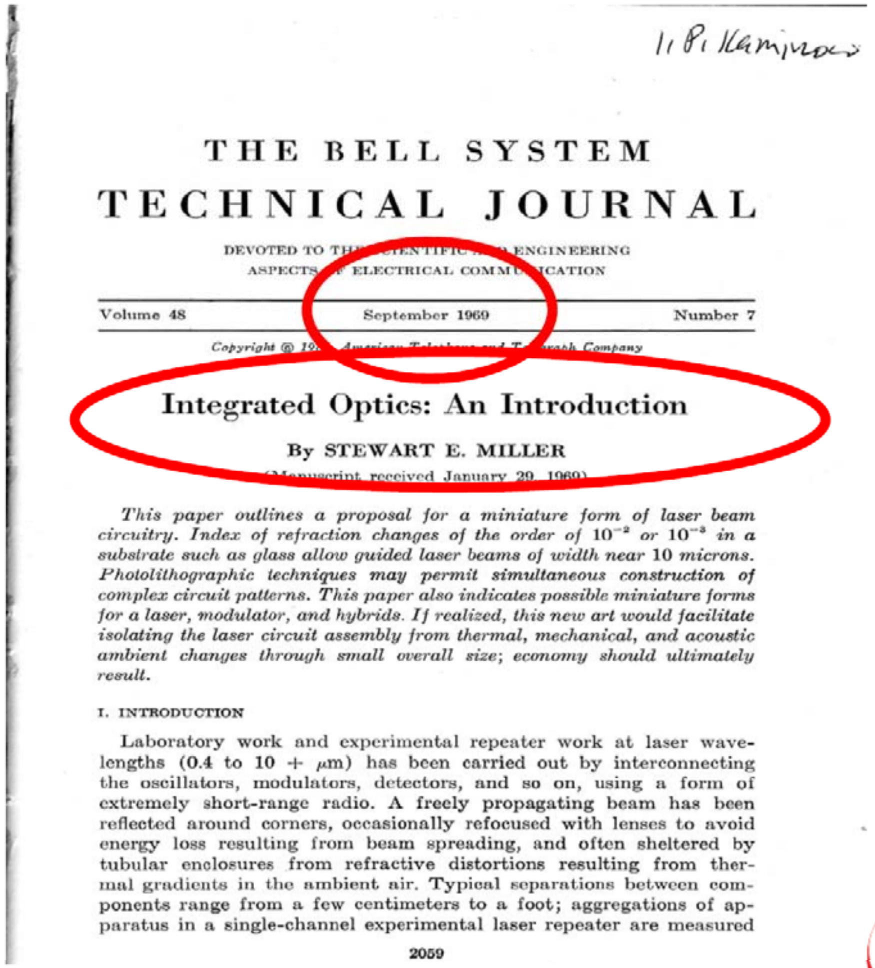
With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore
Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

Objective: reduce the cost per single transistor

Birth of the PIC Concept

"There is a conviction that the new miniaturized optical circuitry will prove useful… We must wait a while longer to find out how useful this new technology will become."



THE BELL SYSTEM
TECHNICAL JOURNAL

DEVOTED TO THE SCIENTIFIC AND ENGINEERING
ASPECTS OF ELECTRICAL COMMUNICATION

Volume 48 | September 1969 | Number 7

Integrated Optics: An Introduction

By STEWART E. MILLER

(Manuscript received January 29, 1969)

This paper outlines a proposal for a miniature form of laser beam circuitry. Index of refraction changes of the order of 10^{-2} or 10^{-3} in a substrate such as glass allow guided laser beams of width near 10 microns. Photolithographic techniques may permit simultaneous construction of complex circuit patterns. This paper also indicates possible miniature forms for a laser, modulator, and hybrids. If realized, this new art would facilitate isolating the laser circuit assembly from thermal, mechanical, and acoustic ambient changes through small overall size; economy should ultimately result.

I. INTRODUCTION

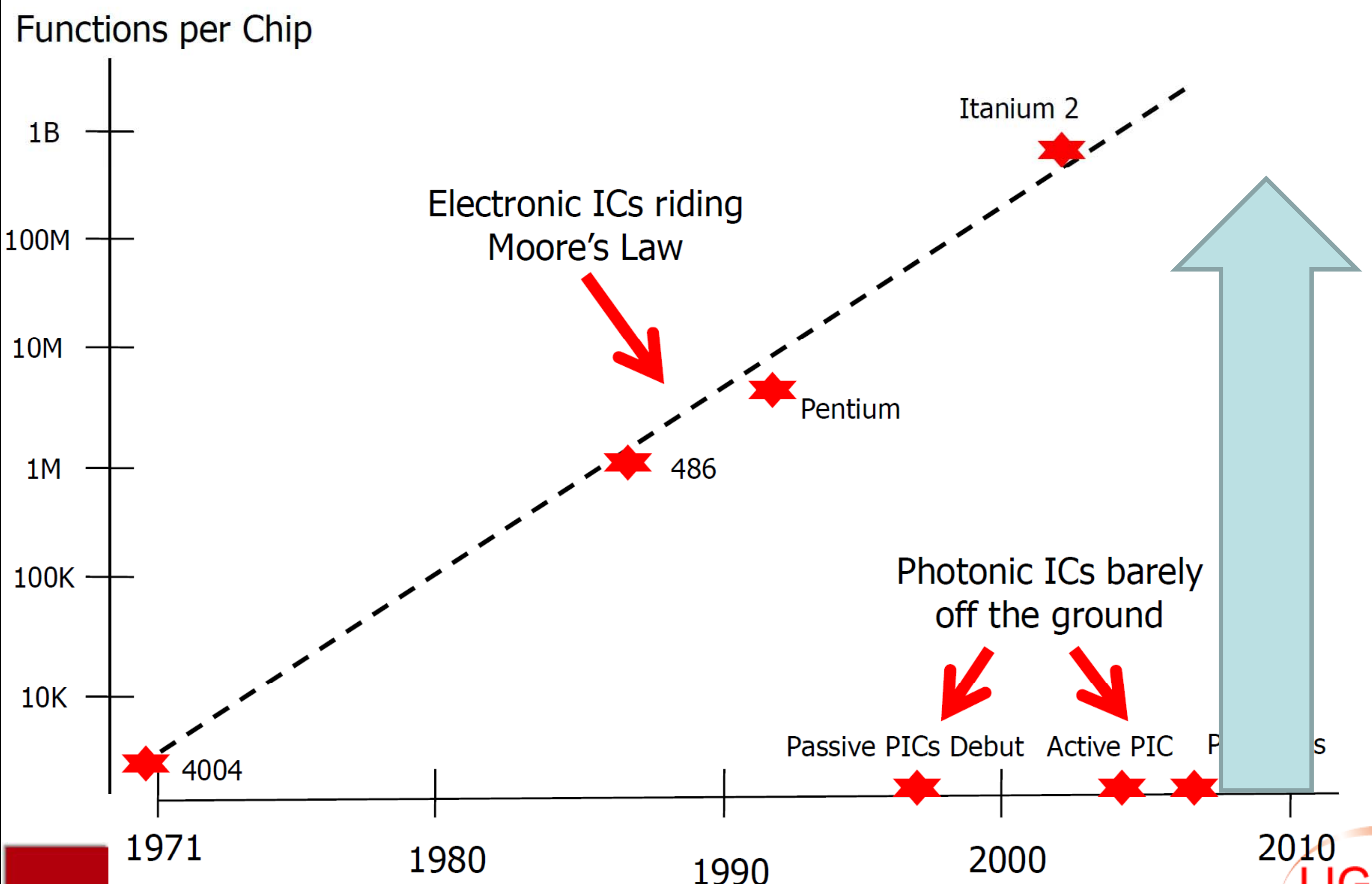
Laboratory work and experimental repeater work at laser wavelengths (0.4 to 10 + μm) has been carried out by interconnecting the oscillators, modulators, detectors, and so on, using a form of extremely short-range radio. A freely propagating beam has been reflected around corners, occasionally refocused with lenses to avoid energy loss resulting from beam spreading, and often sheltered by tubular enclosures from refractive distortions resulting from thermal gradients in the ambient air. Typical separations between components range from a few centimeters to a foot; aggregations of apparatus in a single-channel experimental laser repeater are measured

HEAVY READING

LIGHT READING

29 January 1969

Comparing Technology Progress



Sources: Intel and Heavy Reading, 2008

HEAVY READING

LIGHT READING

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Technology Comparison: Optics vs. ICs

Technologies	Semiconductor IC	Optical Components
Repeatable building block	Transistors	None (LD, PD, Mod, Filter, Isolator…)
Uniform material base	Silicon	None (InP, GaAs, Si…)
Dominant manufacturing process	CMOS	None (Hybrid, monolithic, active, passive…)

Source: J. P. Morgan

No standardized technology for optical components manufacturing

OKI

Oki, Network Solutions for a Global Society

Technology Comparison: Optics vs. ICs vs. Silicon Photonics

Technologies	Optical Components	Semiconductor IC	Silicon Photonics
Repeatable building block	None (LD, PD, Mod, Filter, Isolator…)	Transistors	LD,PD, microrings, ….
Uniform material base	None (InP, GaAs, Si…)	Silicon	Silicon
Dominant manufacturing process	None (Hybrid, monolithic, active, passive…)	CMOS	CMOS

Source: J. P. Morgan

No standardized technology for optical components manufacturing

Silicon photonics

Photonic devices produced within standard silicon factory and with standard silicon processing

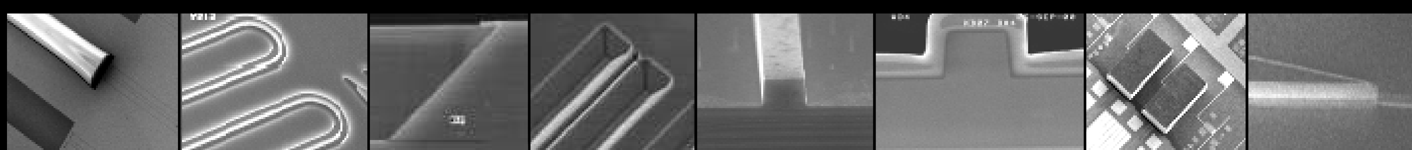
Silicon pro's and cons

- Transparent on 1.3-1.5 μm
- CMOS compatibility
- Low cost
- High index contrast, small footprint

- No electro-optic effect
- No detection in 1.3-1.5 μm region
- High index contrast coupling
- Lacks efficient light emission

The Opportunity of Silicon Photonics

- Enormous ($ billions) CMOS infrastructure, process learning, and capacity
  - Draft continued investment in Moore's law
- Potential to integrate multiple optical devices
- Micromachining could provide smart packaging
- Potential to converge computing & communications



To benefit from this optical wafers must run alongside existing product.
CMOS PHOTONICS

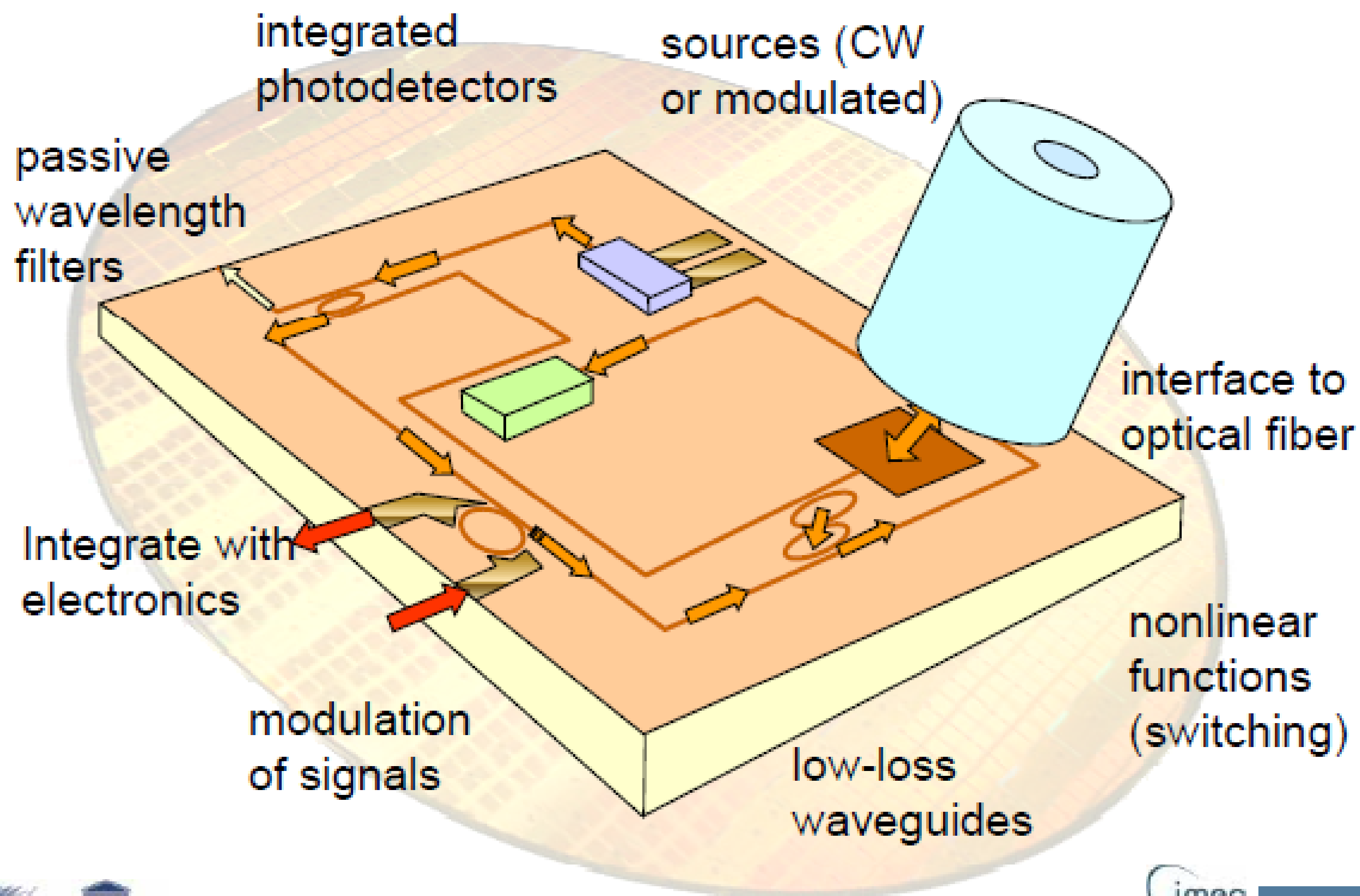
Cost = paradigm change

- 200 mm Si wafer has 125,000 - 0.5 mm sized dies
- Cost processed CMOS wafers $2,000,000
- Cost per die: $16
- Laser size: 10x100 microns.
- Cost per laser: $ 0.064
- This is just like estimating the cost of transistors. They are free. Only the PIC cost matters.
- Emphasis is moved from components to the system

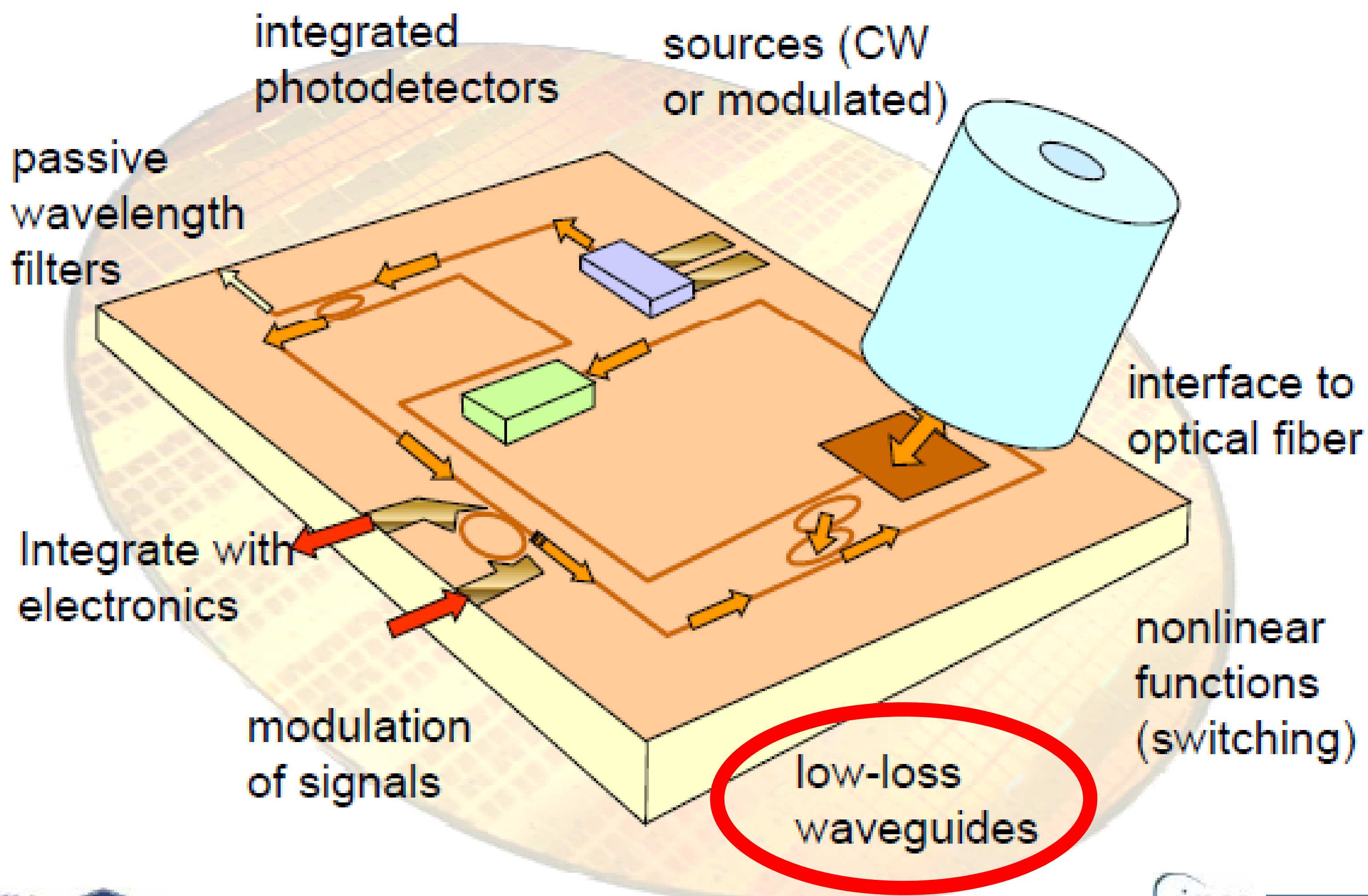
Silicon photonics

Basic building blocks

Funtions to be integrated



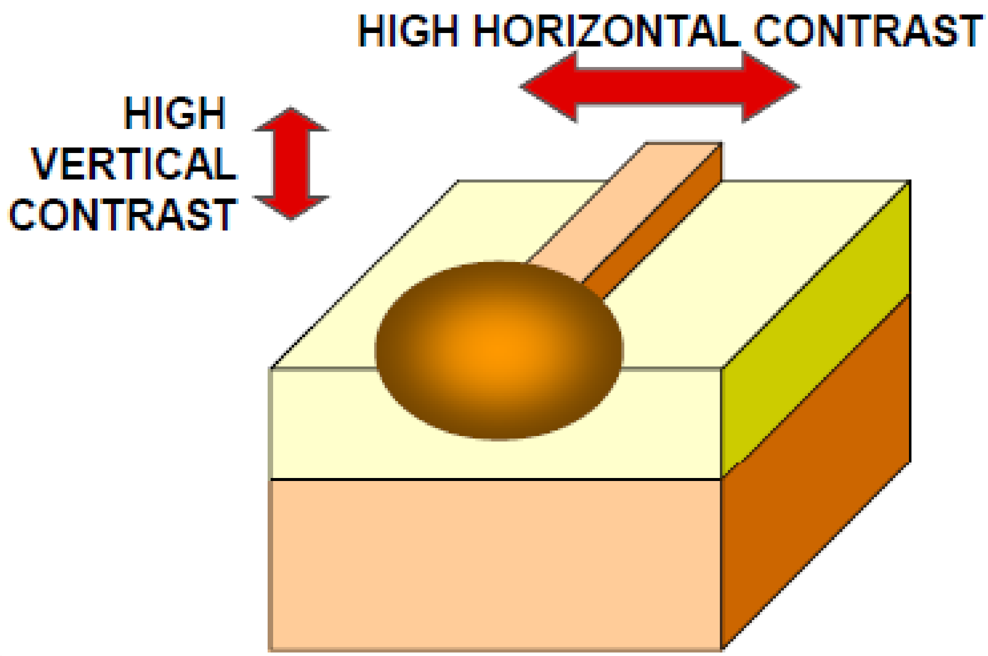
Funtions to be integrated



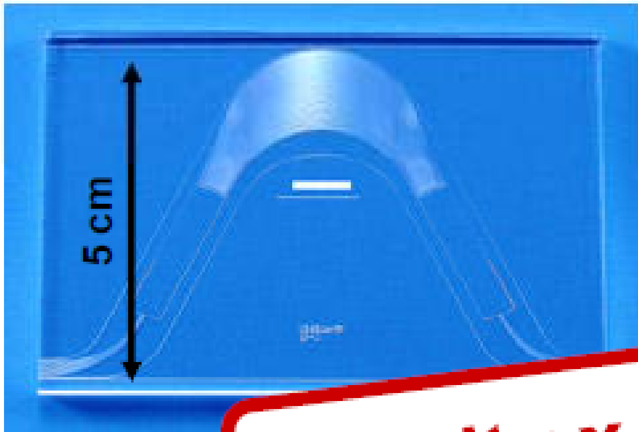
SOI Photonic Wires

High-contrast waveguide

- Large index contrast: 3.45 to 1.45
- Submicron cross section: 450 × 220nm^2
- Sharp bends (R ~2-3µm)



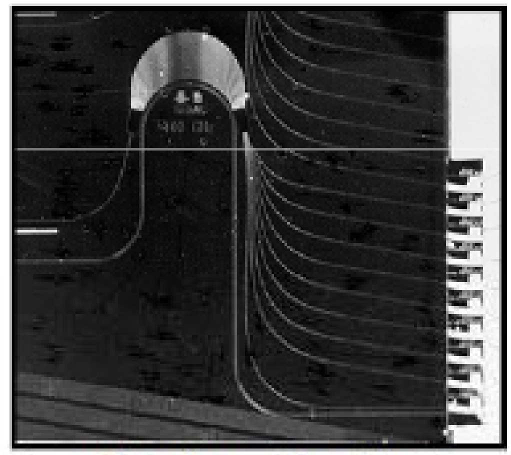
Larger-scale integration



Low Contrast - Fiber Matched
(silica or polymer based)
Bend Radius ~ 5 mm
Size ~ several cm^2

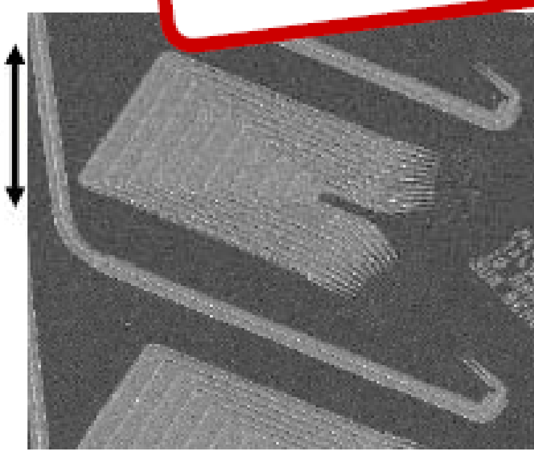
Density x 10^6

5 mm



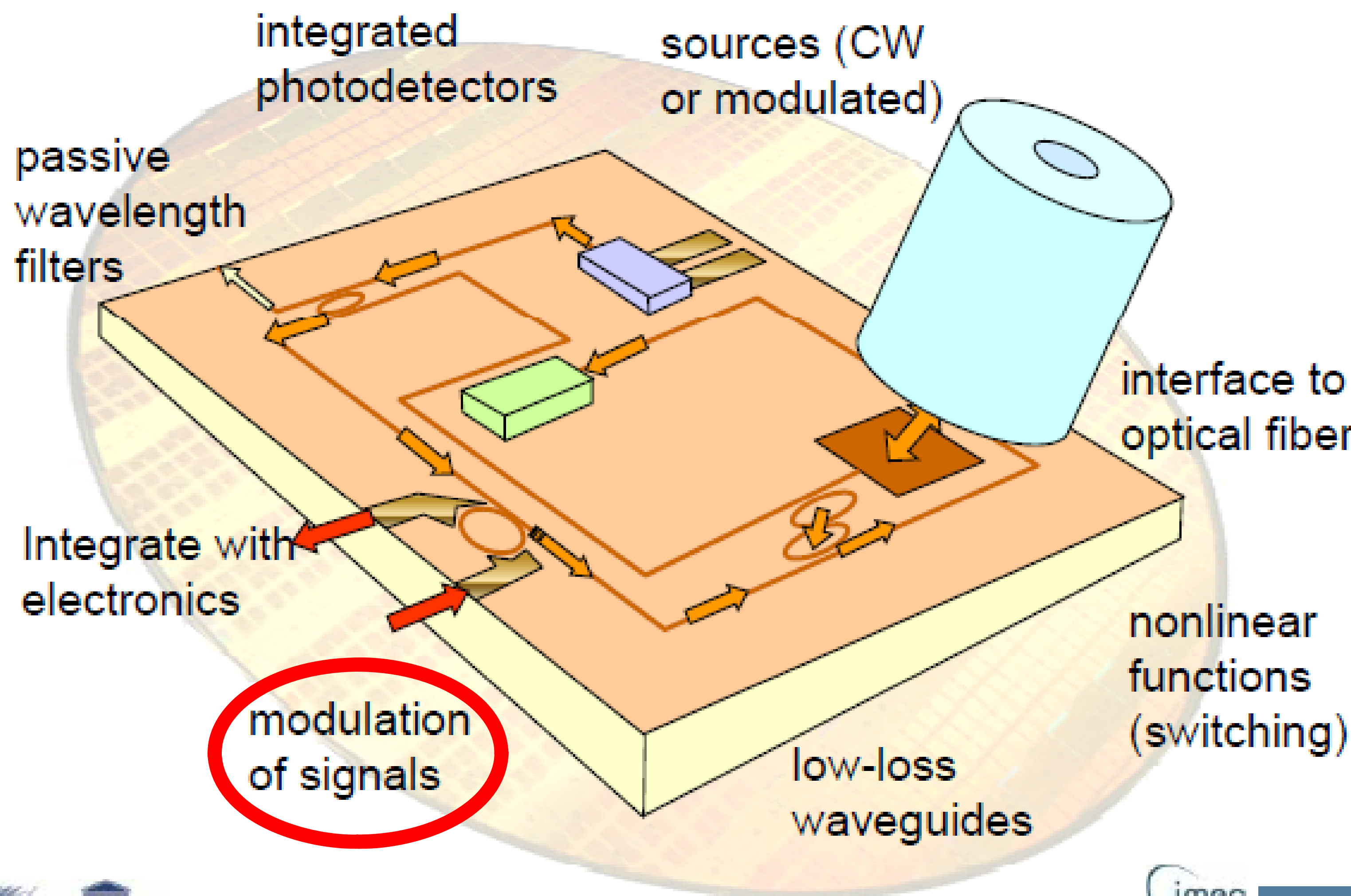
Medium Contrast
(InP-InGaAsP)
Bend Radius ~ 500µm

50 µm



Ultra-high Contrast
(Silicon on Insulator)
Bend Radius < 5µm

Funtions to be integrated



Modulator

- Because of its crystal structure, silicon is not a useful conventional electro-optic material
- Because of its indirect bandgap, silicon has no near bandgap nonlinearities
- Thermo-optical effect is strong but slow

The only effect that is left is the free carrier or Drude effect

$$\Delta n = -\left[8.8 \mathrm{x}\, 10^{-22}\,\Delta N + 8.5 \mathrm{x}\, 10^{-18}\,(\Delta P)^{0.8}\right]$$

$$\Delta \alpha = \left[8.5 \mathrm{x}\, 10^{-18}\,\Delta N + 6.0 \mathrm{x}\, 10^{-18}\,(\Delta P)\right]$$

R.A. Soref and B.R. Bennett, IEEE JQE 23, 123 (1987)

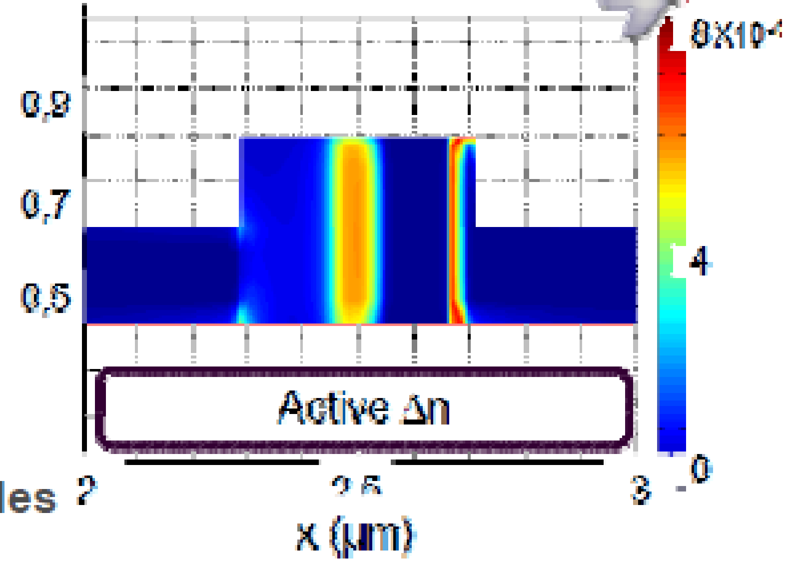
Example: depletion modulator

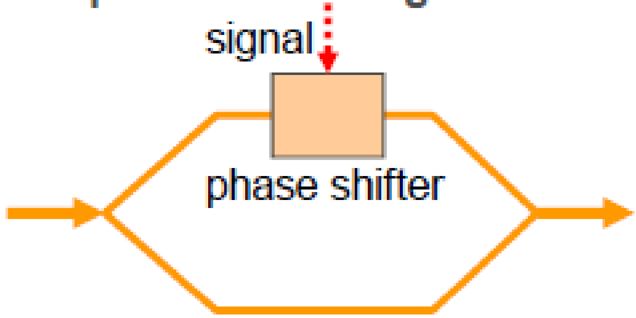
Complex multi-doping profile

- Larger index change
- Lower RC

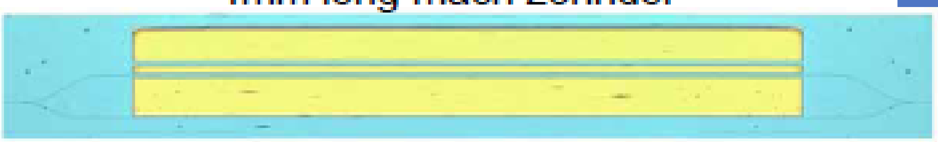
But

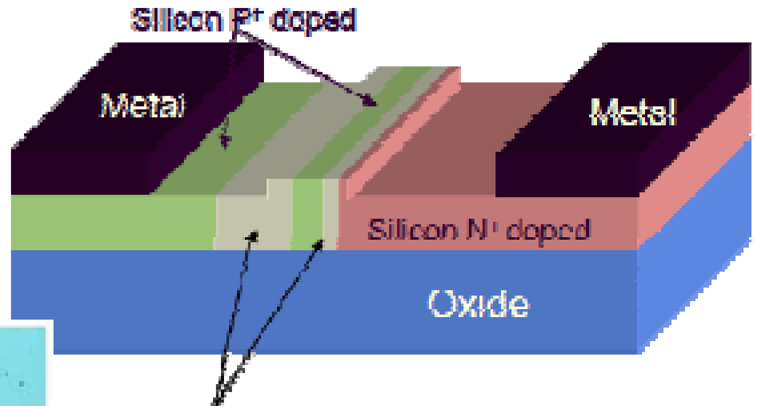
- Still a long device (4mm)
- Requires travelling wave electrodes



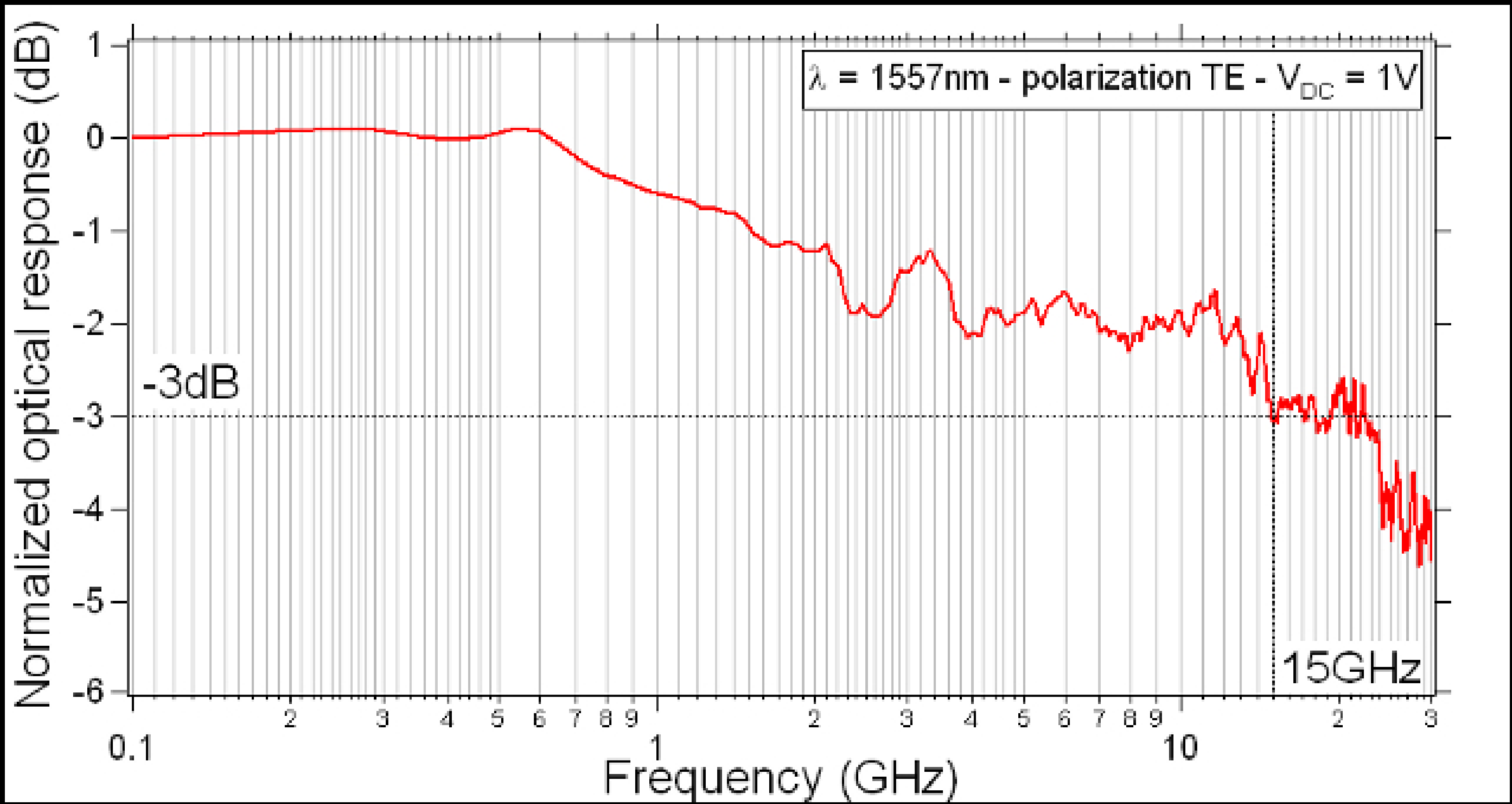


4mm long mach zehnder



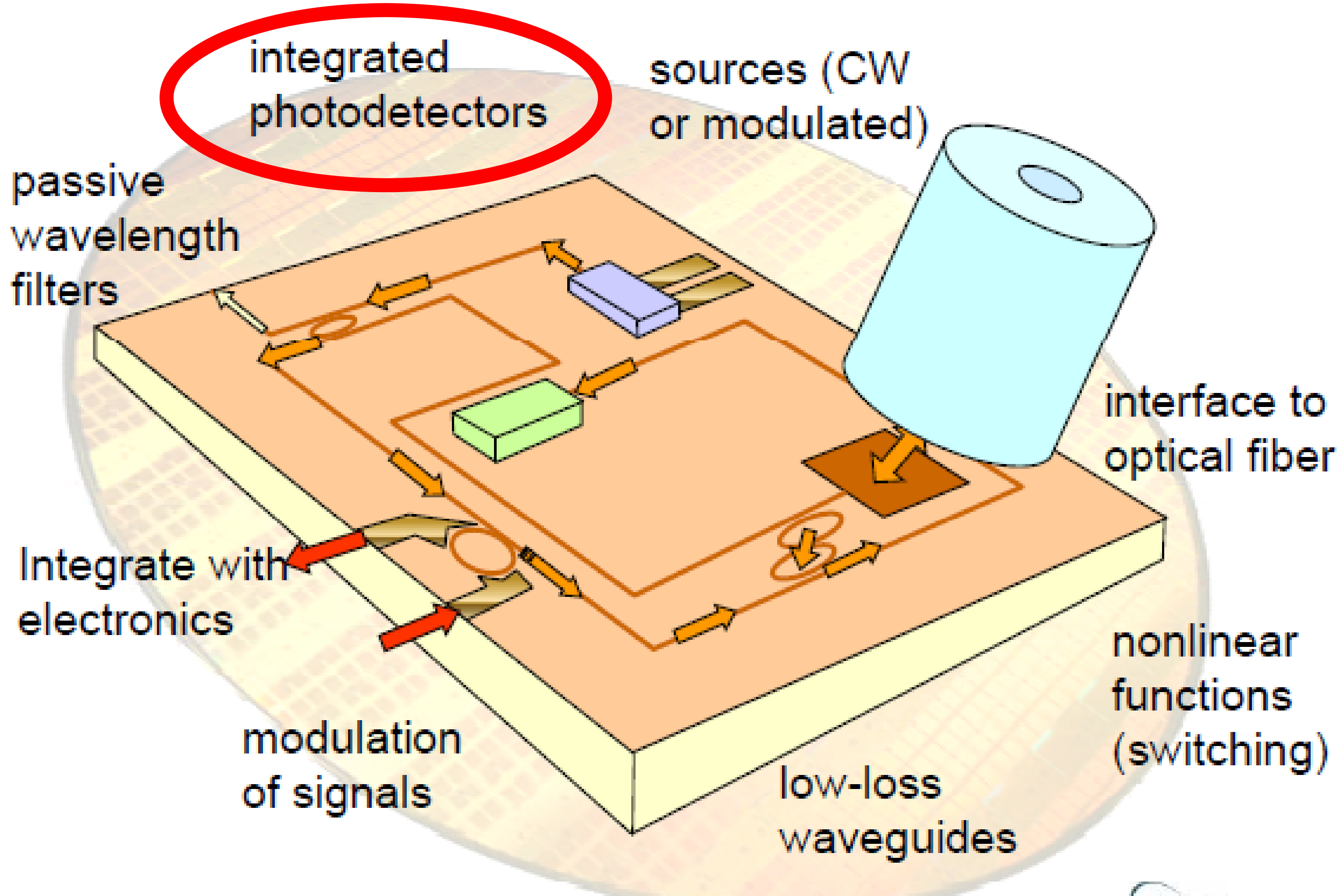


D. Marris-Morini, OpEx 16 (2008)



λ = 1557nm - polarization TE - V_{DC} = 1V
Normalized optical response (dB)
Frequency (GHz)
-3dB
15GHz
1
0
-1
-2
-3
-4
-5
-6
0.1
2
3
4
5
6
7
8
9
1
10

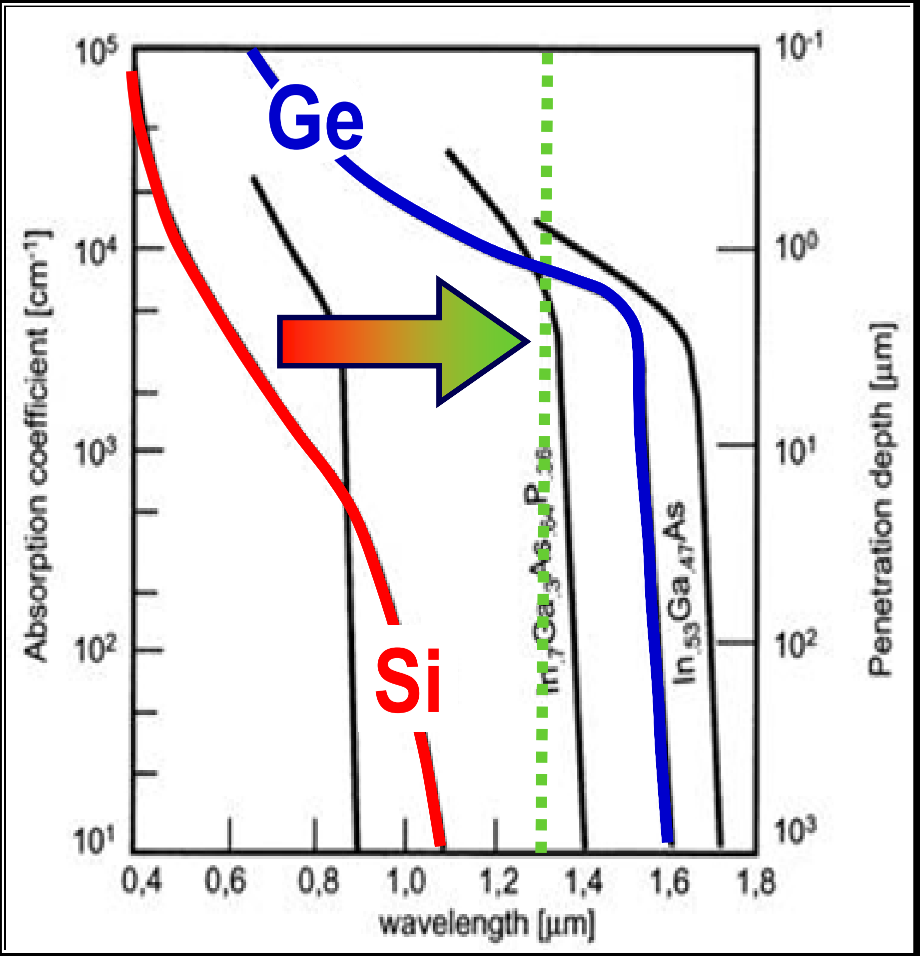
Funtions to be integrated



Photodetection

- **Silicon does not absorb IR well**

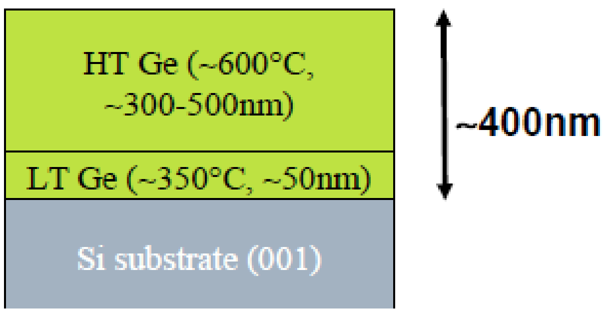
→ Use hybrid approach
→ Use SiGe or strained Ge
→ Use damaged silicon



Germanium growth

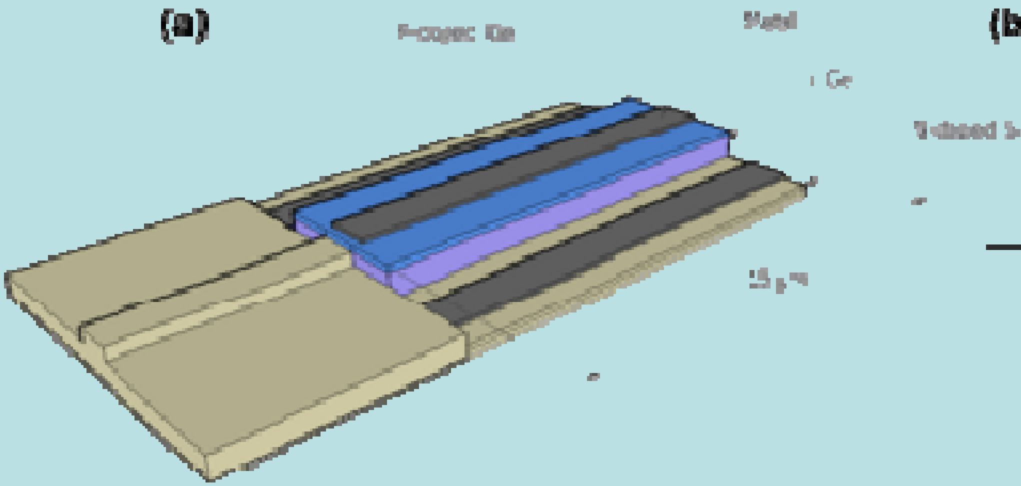
- Two-step growth process:
  - Direct growth of Ge on Si using a low temperature (~350°) CVD process
    ⇒ thin (a few 10nm) highly-dislocated Ge layer
  - Growth of a thick Ge layer (a few 100nm) at a higher temperature (~600°)
    ⇒ high quality Ge absorbing layer

- Thermal annealing to reduce the dislocation density

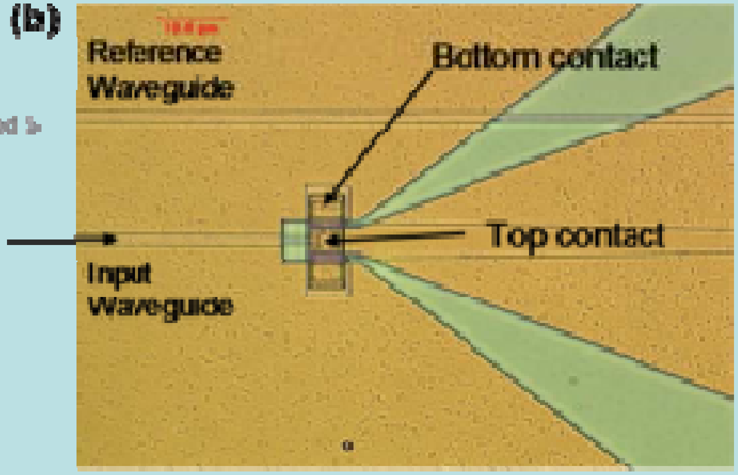


Ge photodector

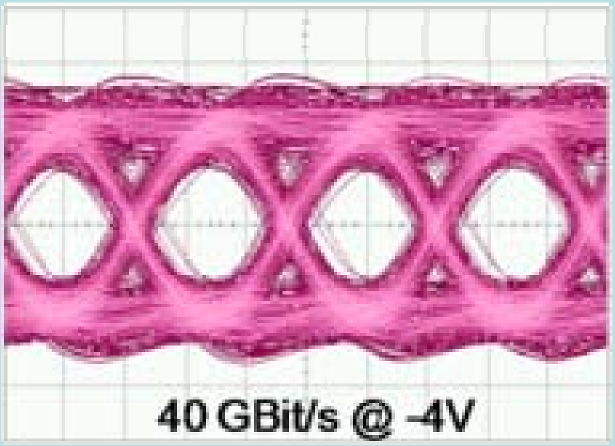
(a)



(b)

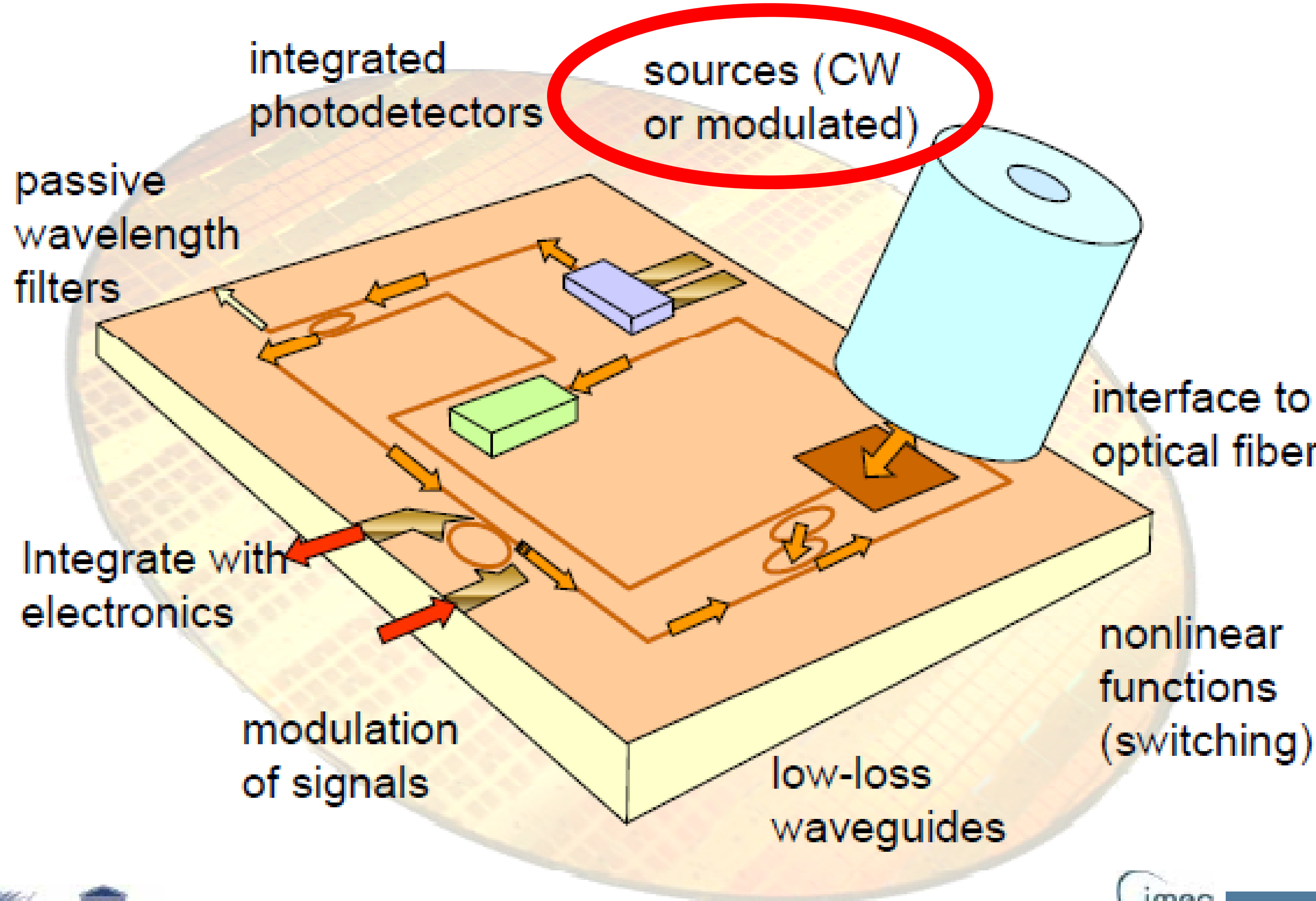


(c)



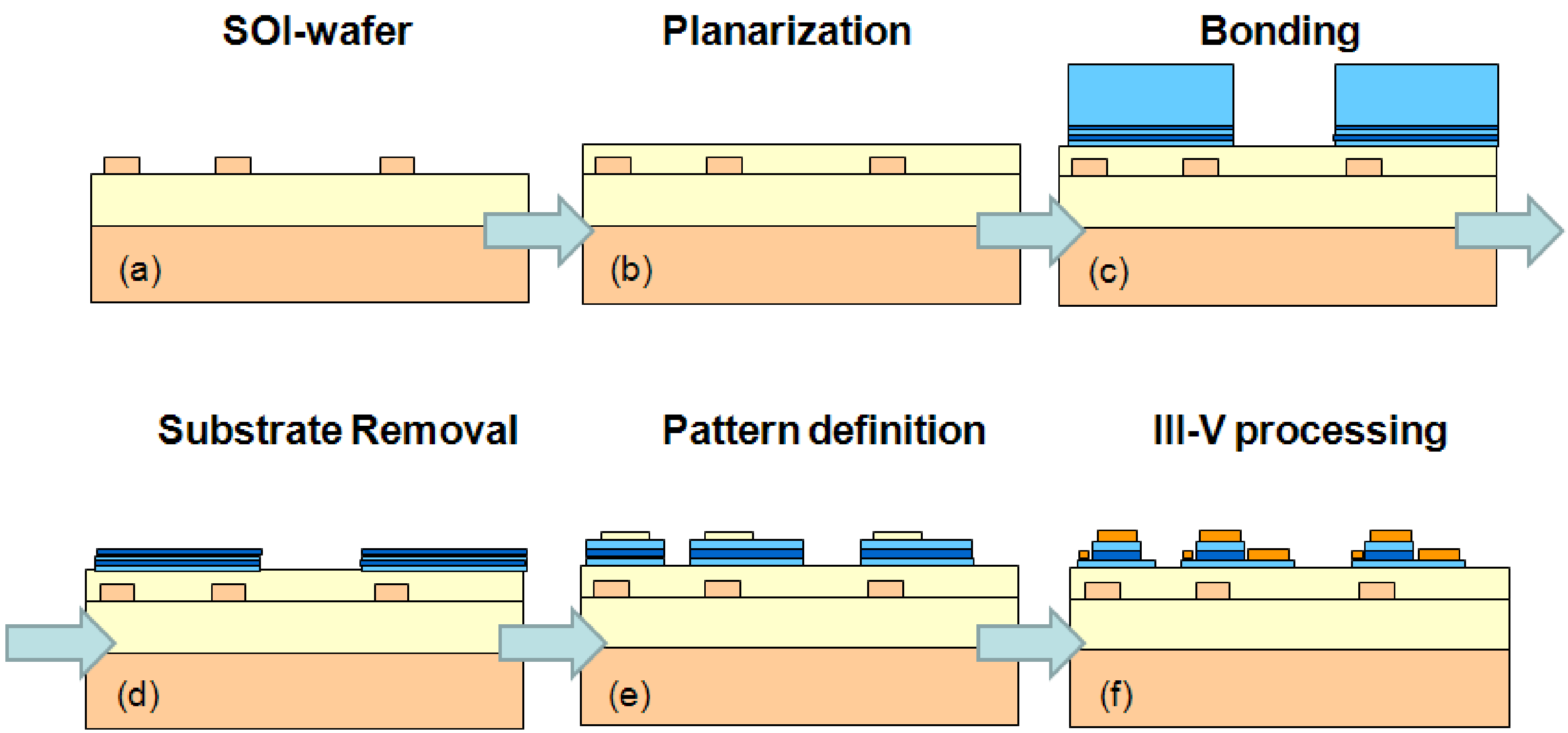
IEF-LETI

Funtions to be integrated

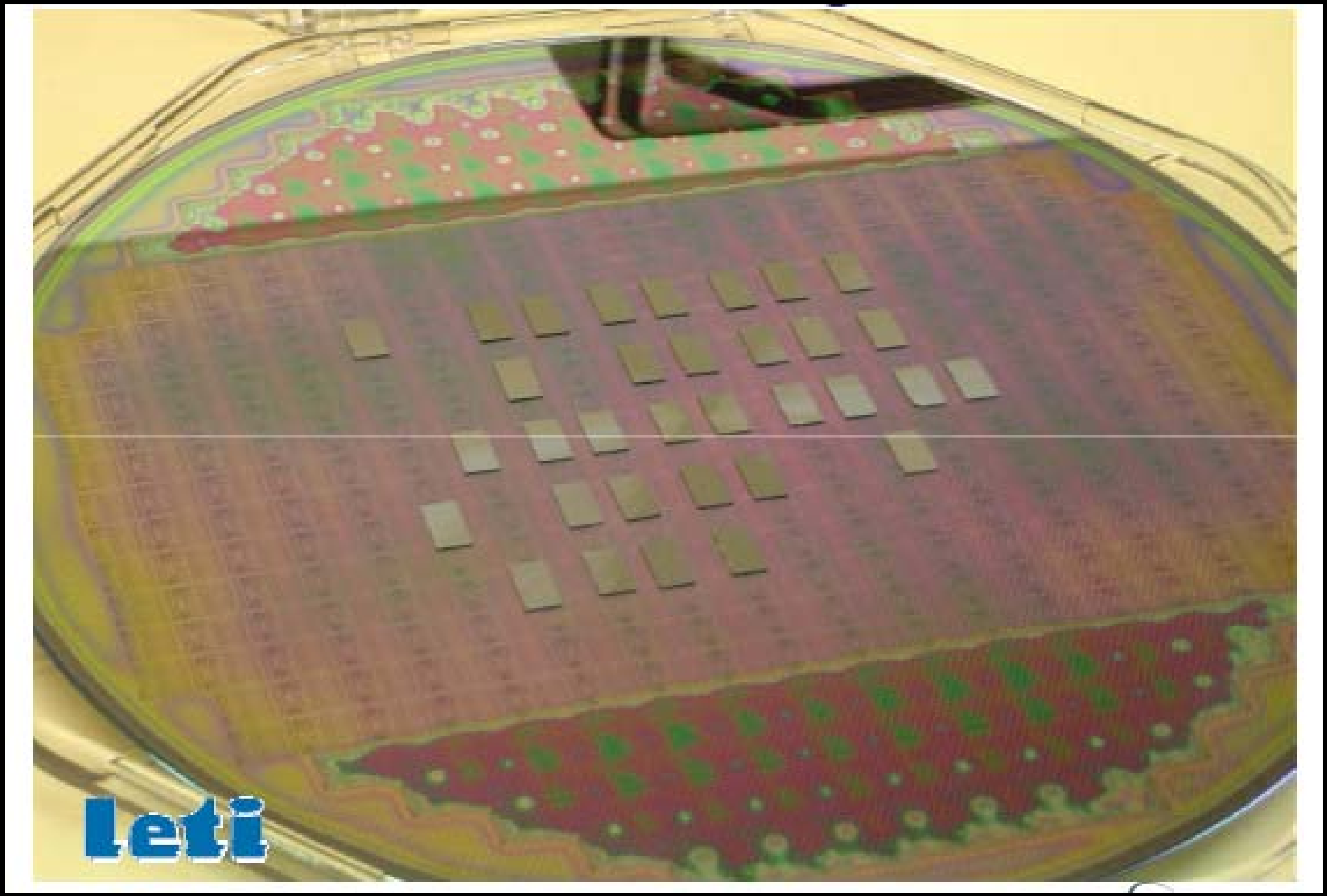


III-V heterogeneous integration for the laser source

Integration Scheme

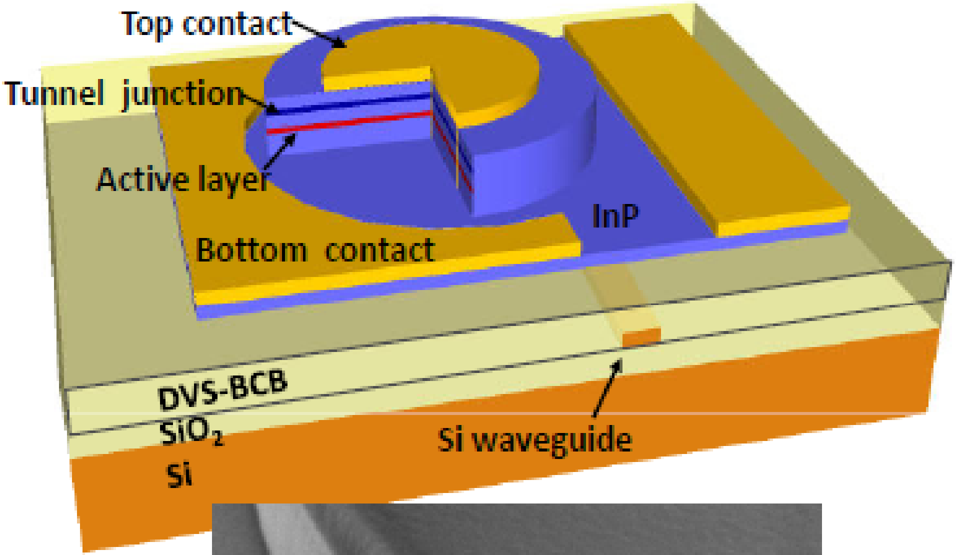


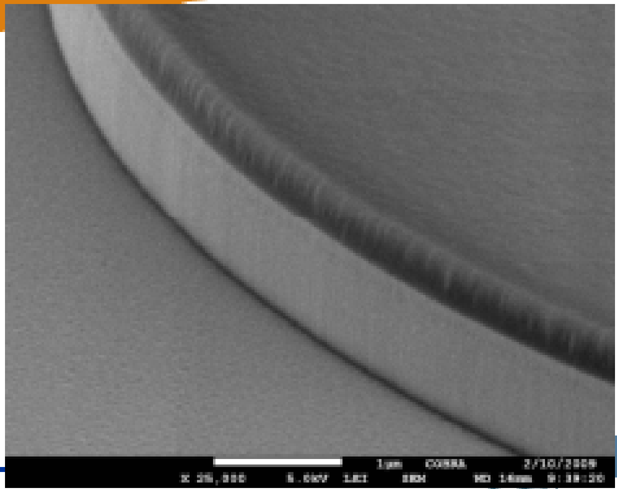
III-V heterointegration for the laser source



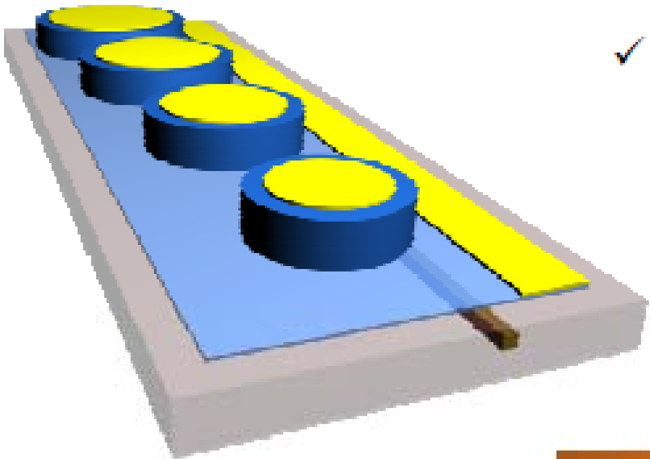
InP microdisk laser

- 7.5 um diameter
- 600 nm height
- Adhesive bonding
  (BCB ~ 250 nm)
- Evanescent coupling
to Si Waveguide

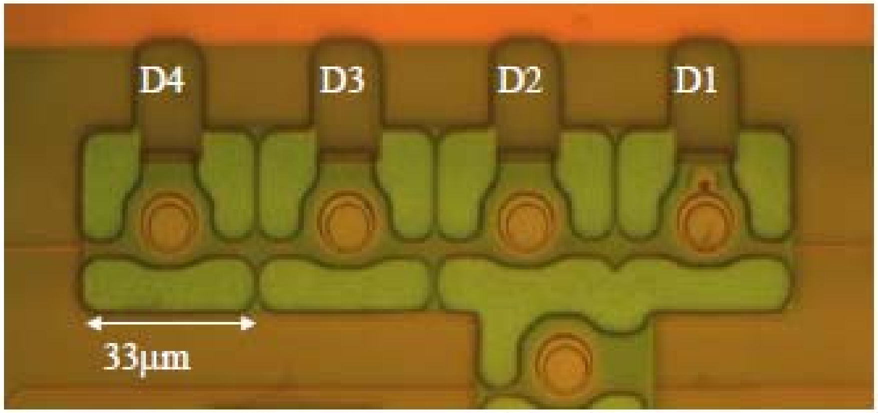




Multi-wavelength Laser



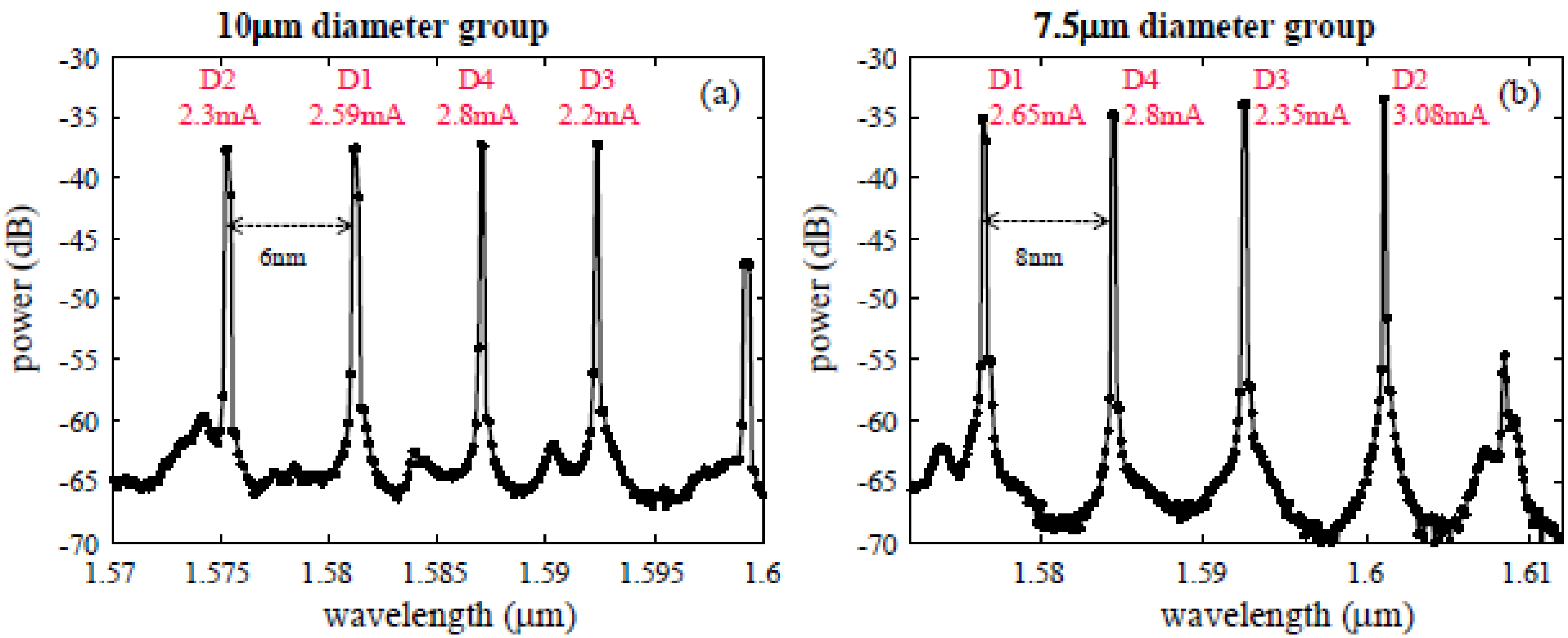
- ✓ Several (4) microdisks with different diameters are cascaded on one bus SOI waveguide.



J. Van Campenhout, L. Liu, et al, PTL **20**, 1345, (2008).

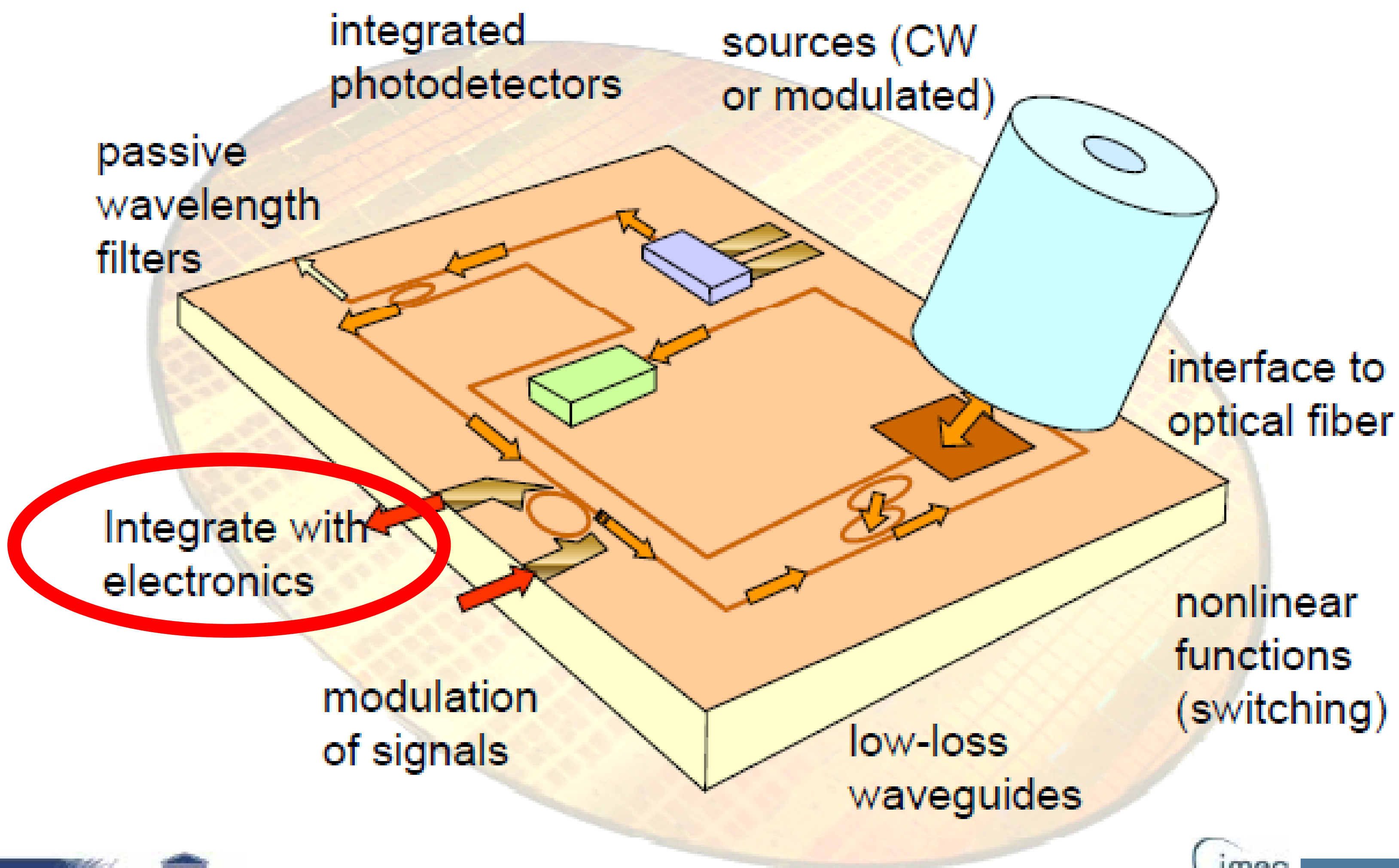
Multi-wavelength Laser

- Uniform peak power was obtained by adjusting the driving current of each individual disk laser.



J. Van Campenhout, L. Liu, et al, PTL 20, 1345, (2008).

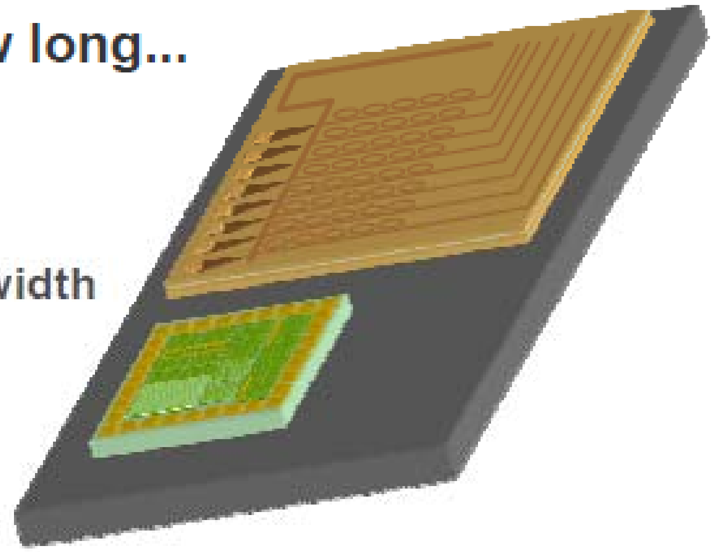
Funtions to be integrated



Co-packaging?

Works for now, but for how long...

- limited integration density
  - edge vs. area
- long distance = lower bandwidth



Integrate photonics with CMOS in a more scalable way

Where should we integrate the photonics layer ?

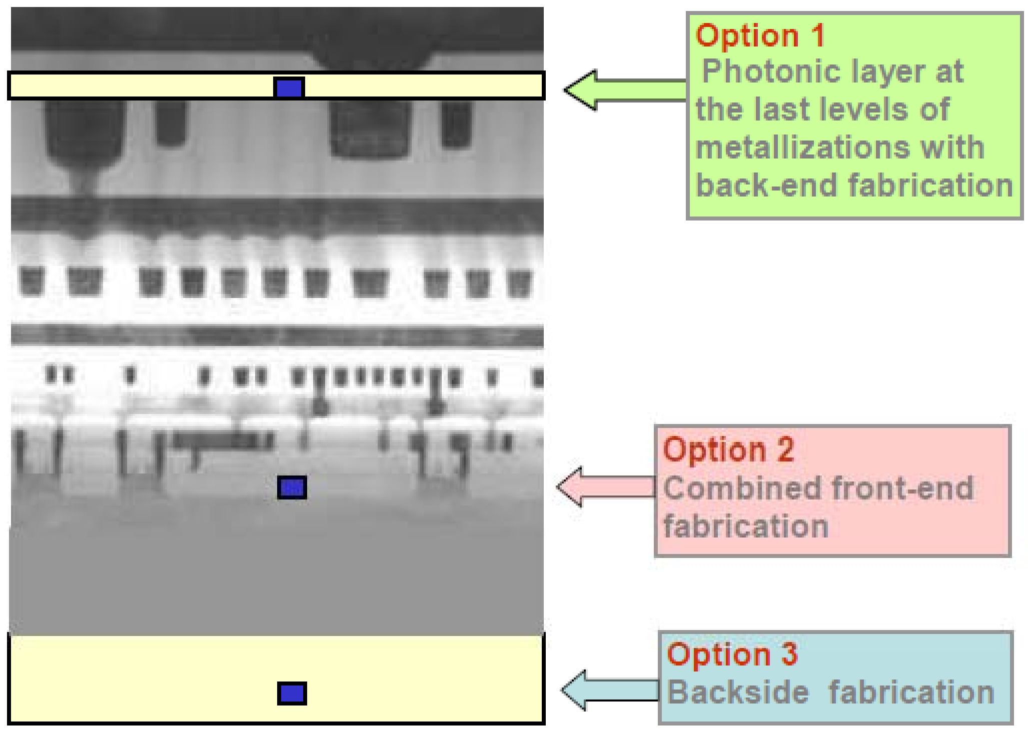
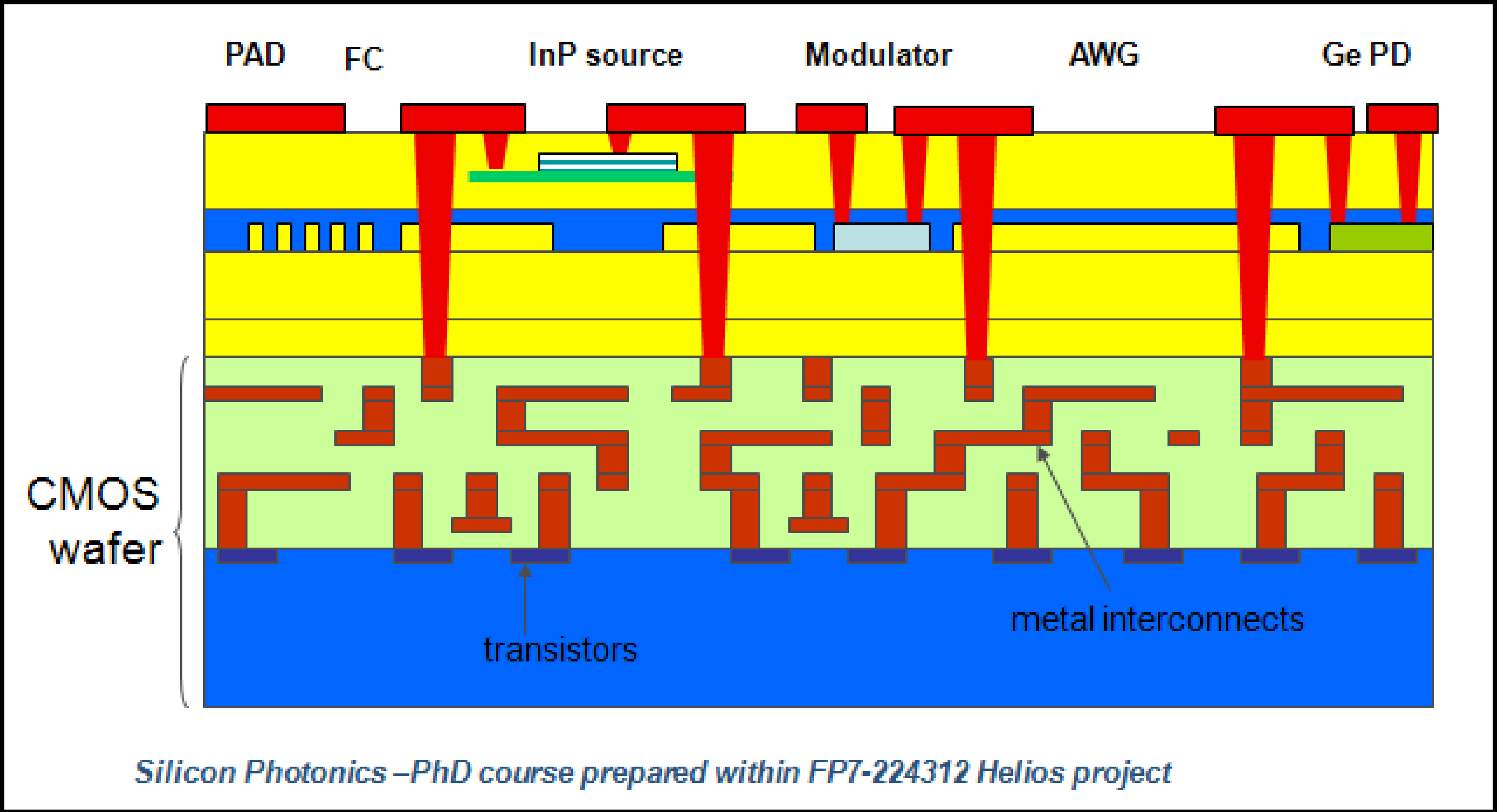


Figure 1: Different options for integrating the photonic layer addressed by the Helios project

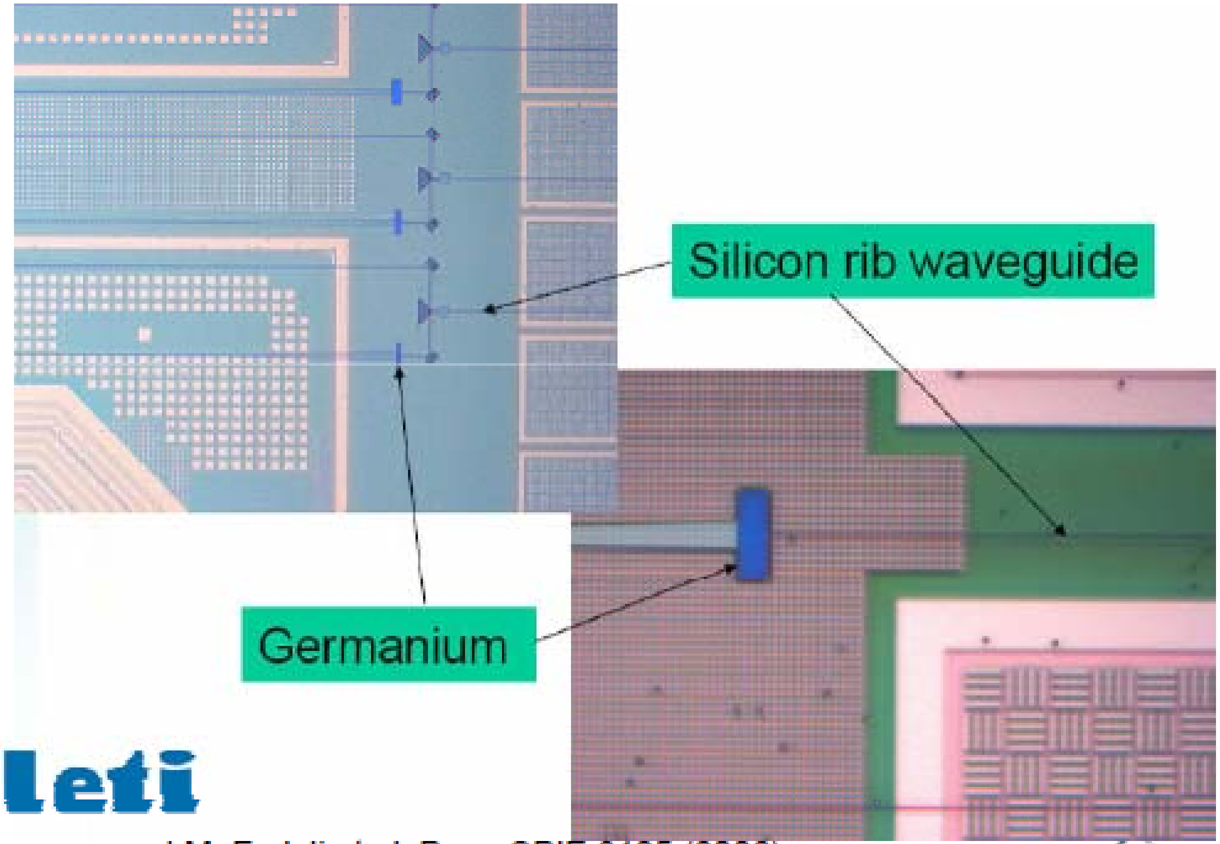
Options 1


PAD
FC
InP source
Modulator
AWG
Ge PD
CMOS wafer
transistors
metal interconnects
Silicon Photonics –PhD course prepared within FP7-224312 Helios project

Options 1

CMOS + Photonics wafer bonding

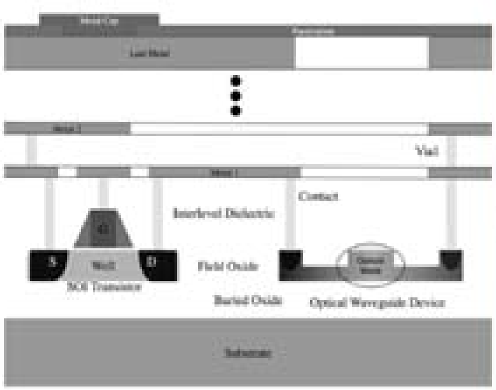
Photonics wafer on top of CMOS wafer

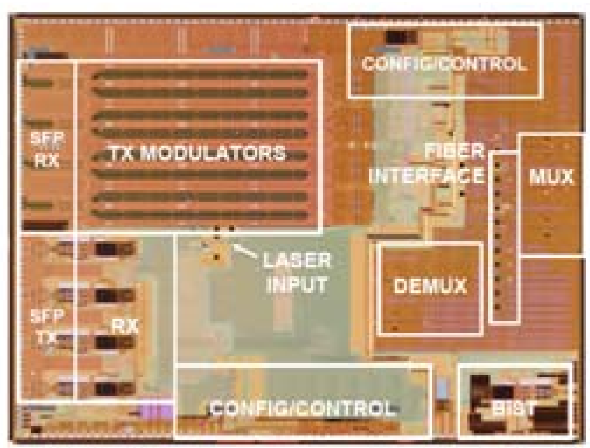


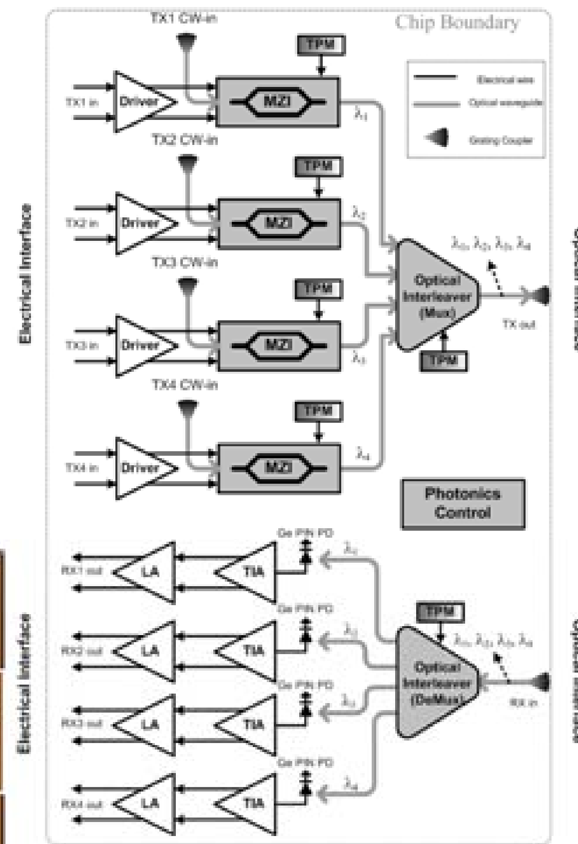
J.M. Fedeli et al. Proc. SPIE 6125 (2006)

Option 2: Luxtera approach

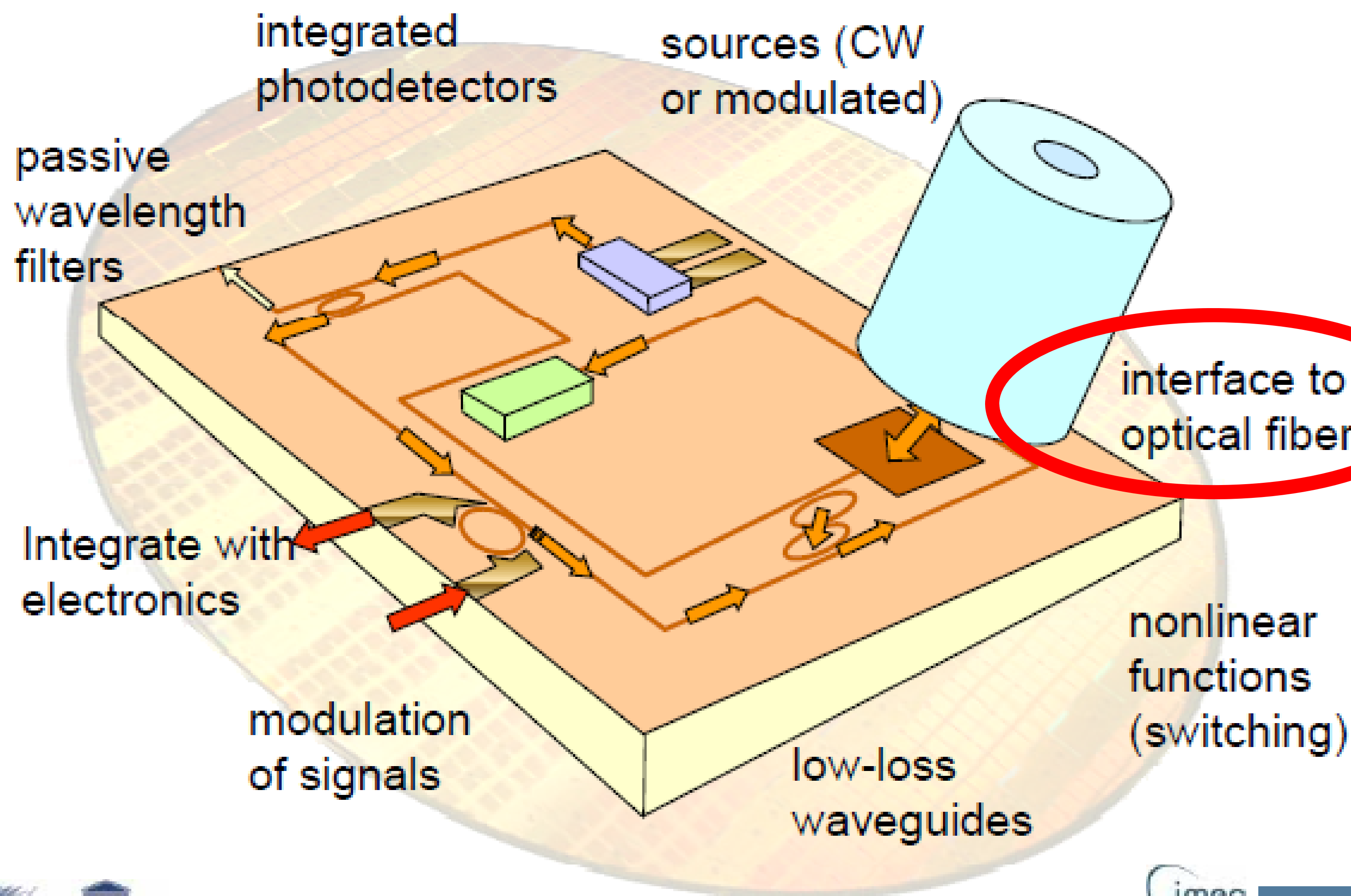
- Proprietary SOI CMOS 130nm technology
- Proprietary library for IC design
- Flip chip bonded lasers or external WDM lasers
- Surface gratings fiber couplers
- MUX and DEMUX with controlled MMI
- 10Gb/s modulator based on lateral Si depletion
- 20GHz Ge photodetectors
- Electronic control of optical devices





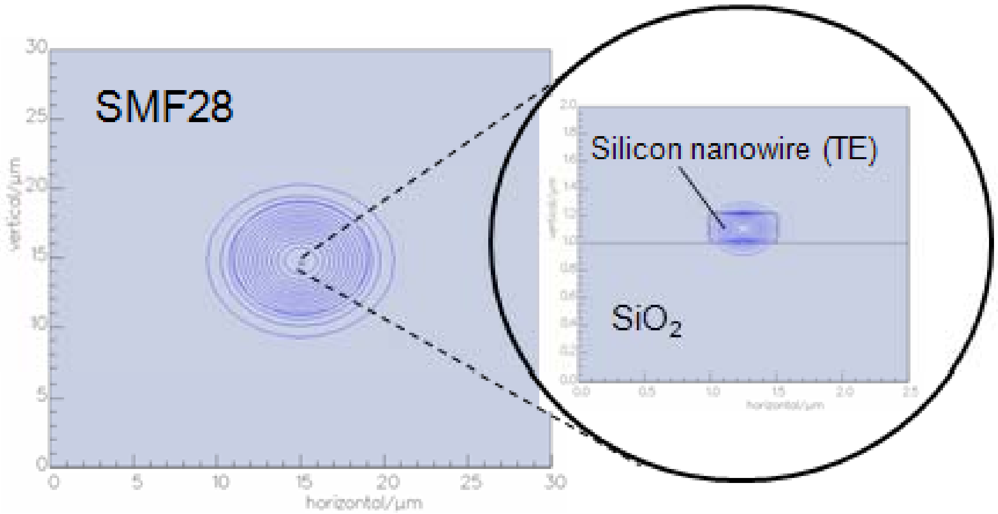


Funtions to be integrated



Major obstacle in silicon photonics

MFD of fiber and waveguides do not match

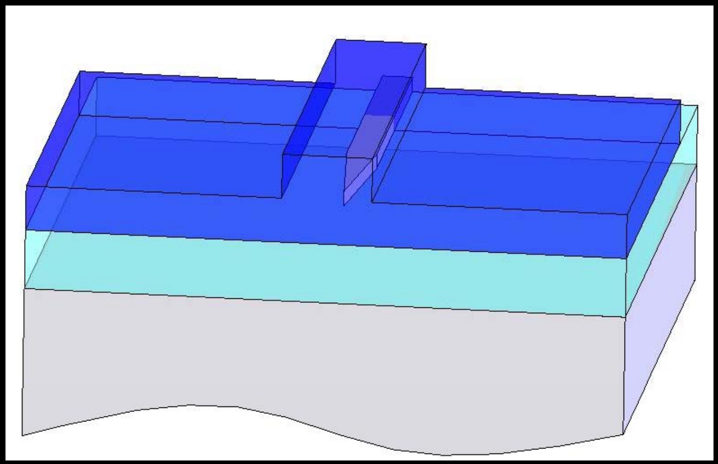


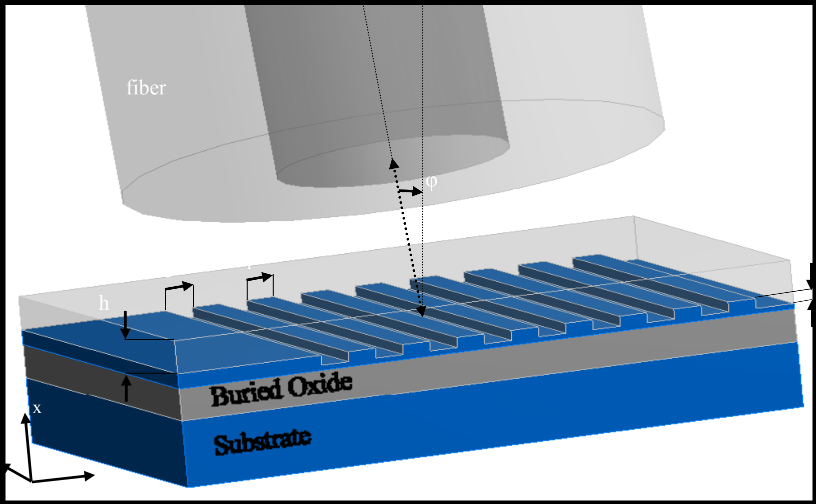
This requires

Spotsize conversion structures

Lateral coupling

Vertical coupling

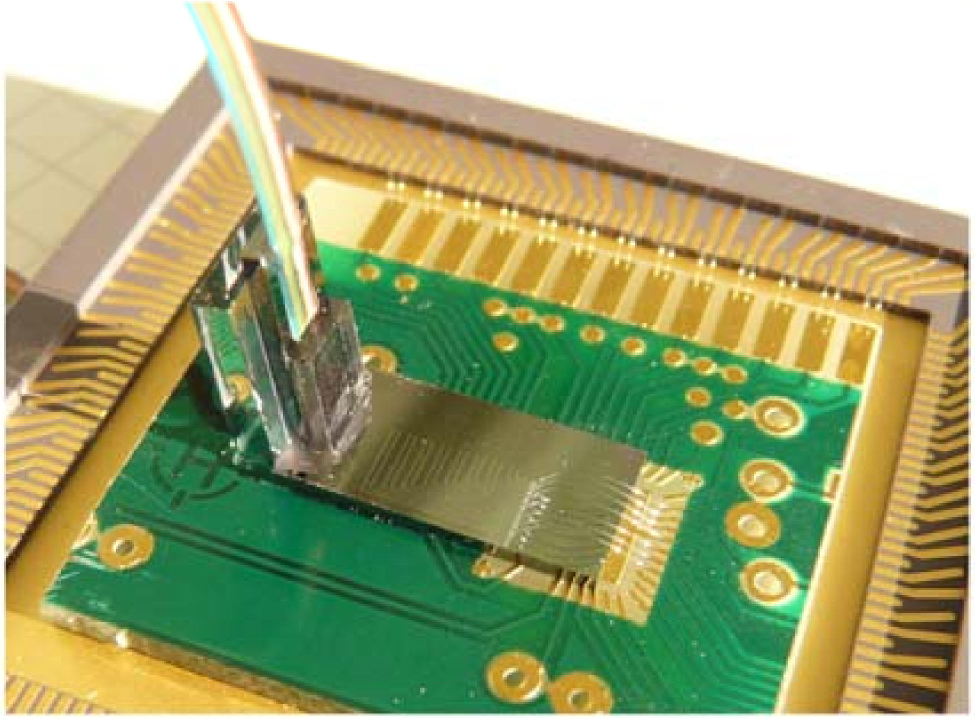




- typically based on inverted tapers
- spotsize: ~3 µm

- typically based on gratings
- spotsize: ~ 10 µm

Example - g-Pack



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University of St Andrews

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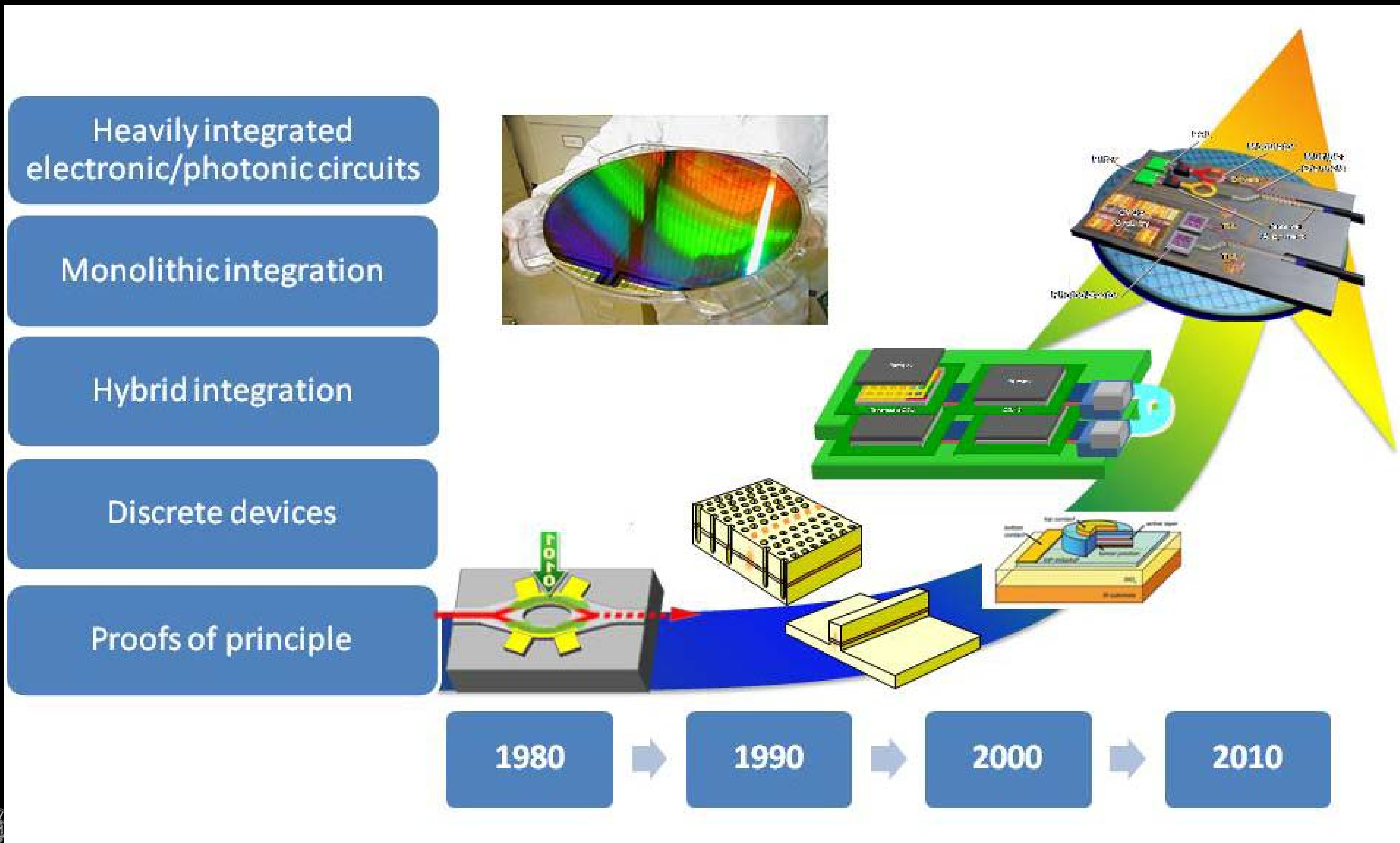
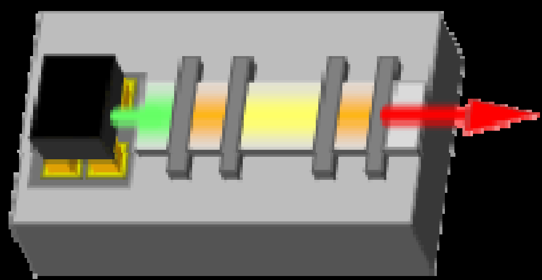
- Silicon Photonics for lab-on-a-chip
- NanoSilicon photonics
- Conclusion

Explosion of silicon photonics

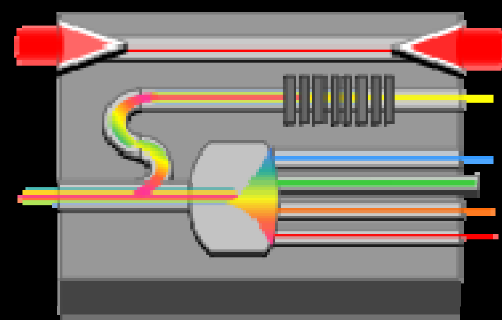


From Building Block Research

1) Light Source

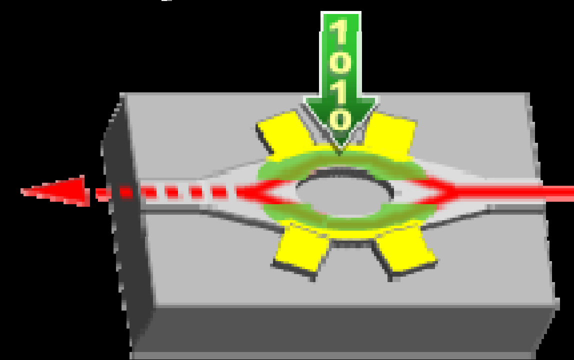


2) Guide Light

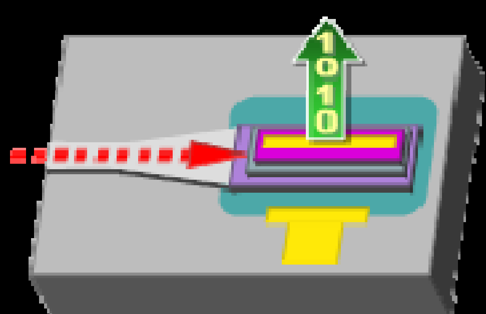


Waveguides devices

3) Modulation

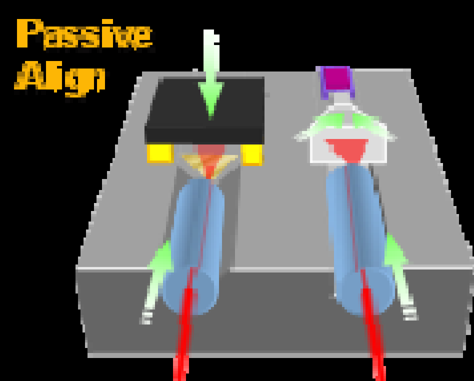


4) Photo-detection

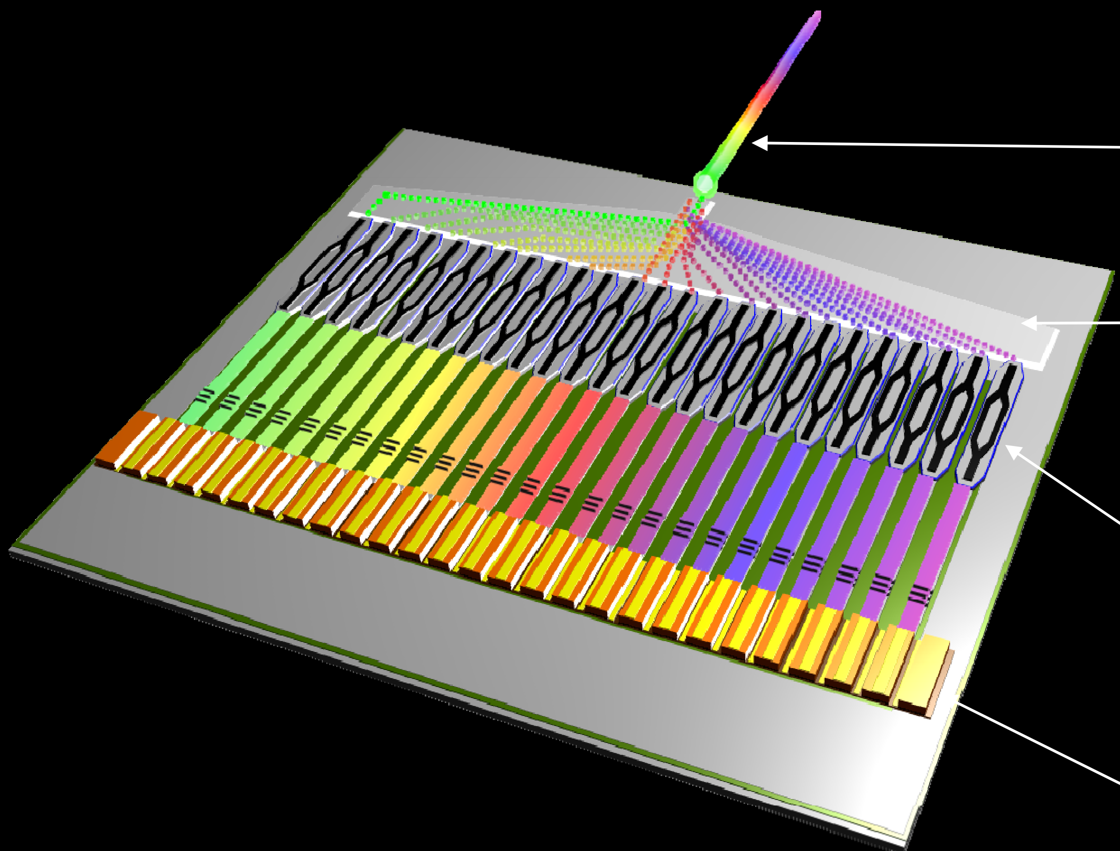


SiGe Photodetectors

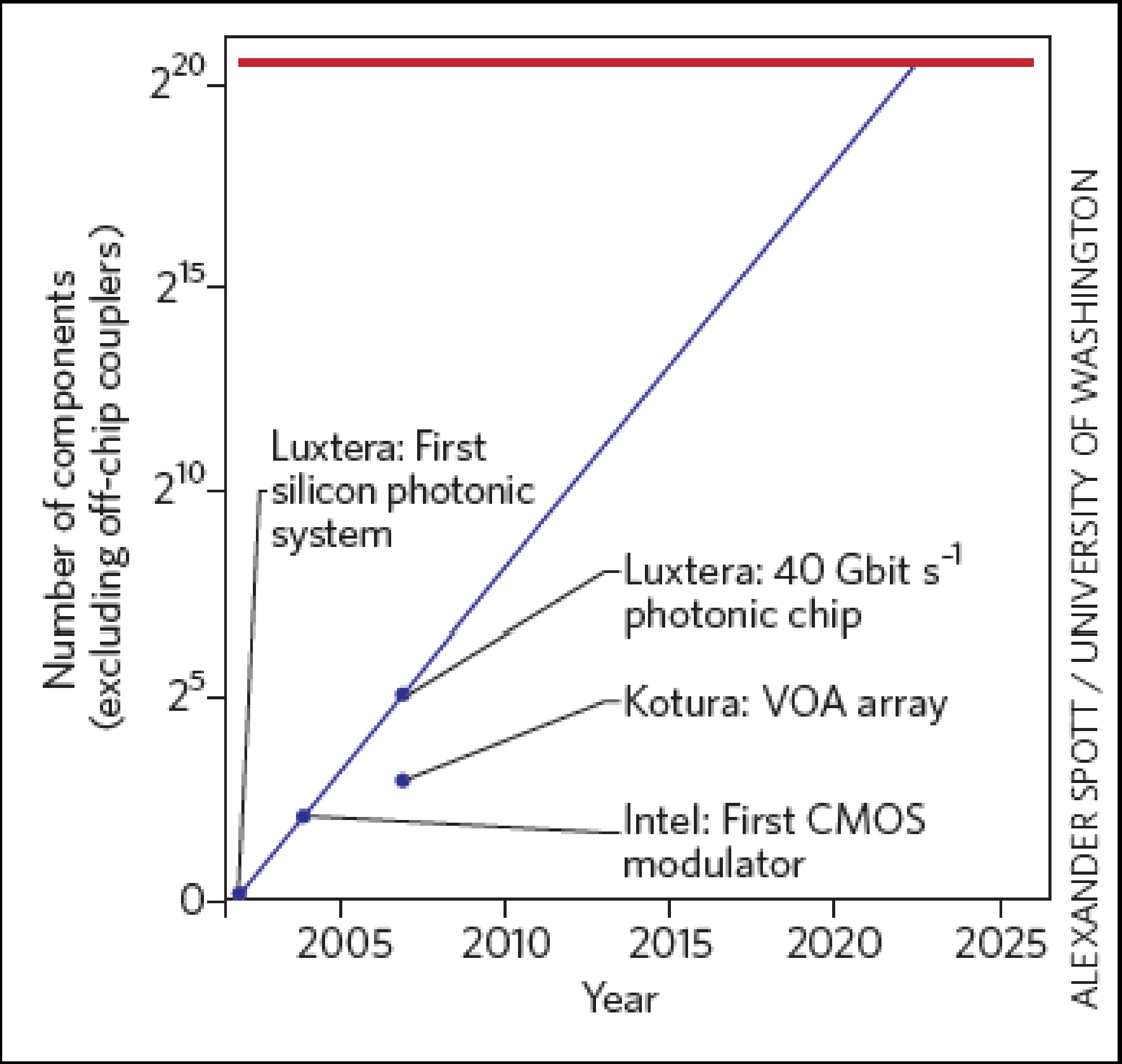
5) Low Cost Assembly



To Large scale integration



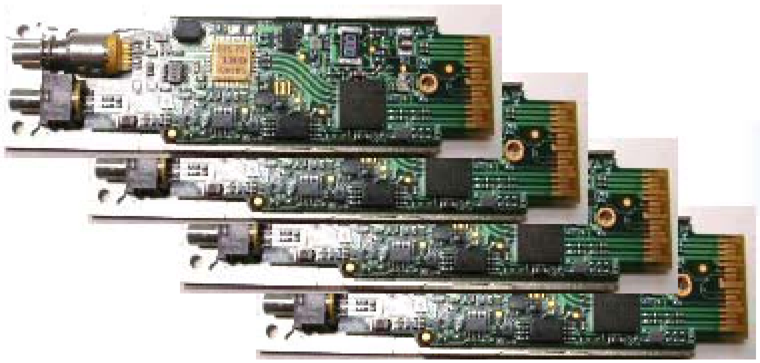
A future integrated 1 Tb/s optical link on a single silicon chip

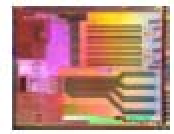


2^{20}
2^{15}
2^{10}
2^{5}
0
Number of components (excluding off-chip couplers)
Luxtera: First silicon photonic system
Luxtera: 40 Gbit s^{-1} photonic chip
Kotura: VOA array
Intel: First CMOS modulator
2005
2010
2015
2020
2025
Year
ALEXANDER SPOTT / UNIVERSITY OF WASHINGTON

CMOS Photonics Commercialization at Luxtera

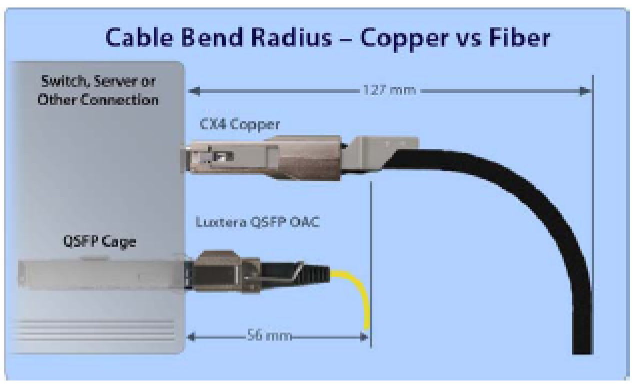
Functionality of Four SFP+ 10Gb Transceivers on a single CMOS Die





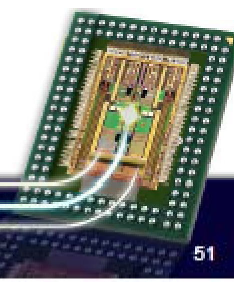
"Blazar"
40Gb Cable

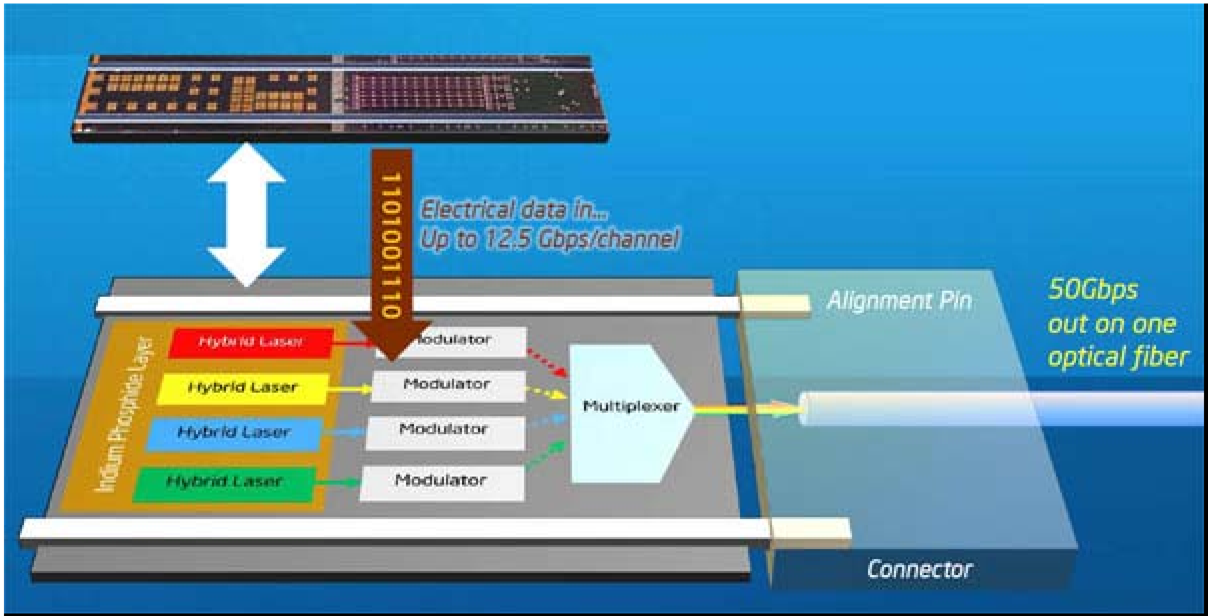
Optics is now price-competitive with copper!



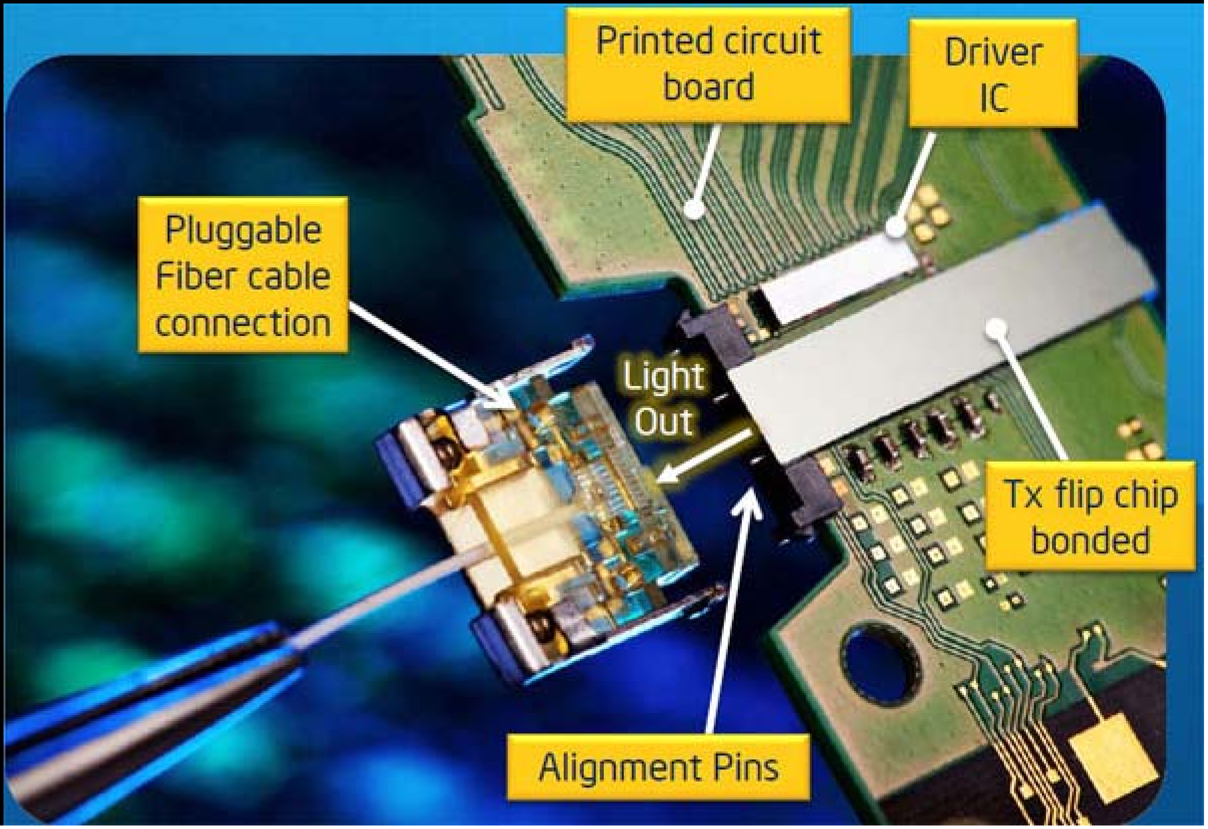
Benefits of optics maintained:

- 20% higher density
- 40% smaller bend radius
- 85% lighter cable
- 600% longer reach





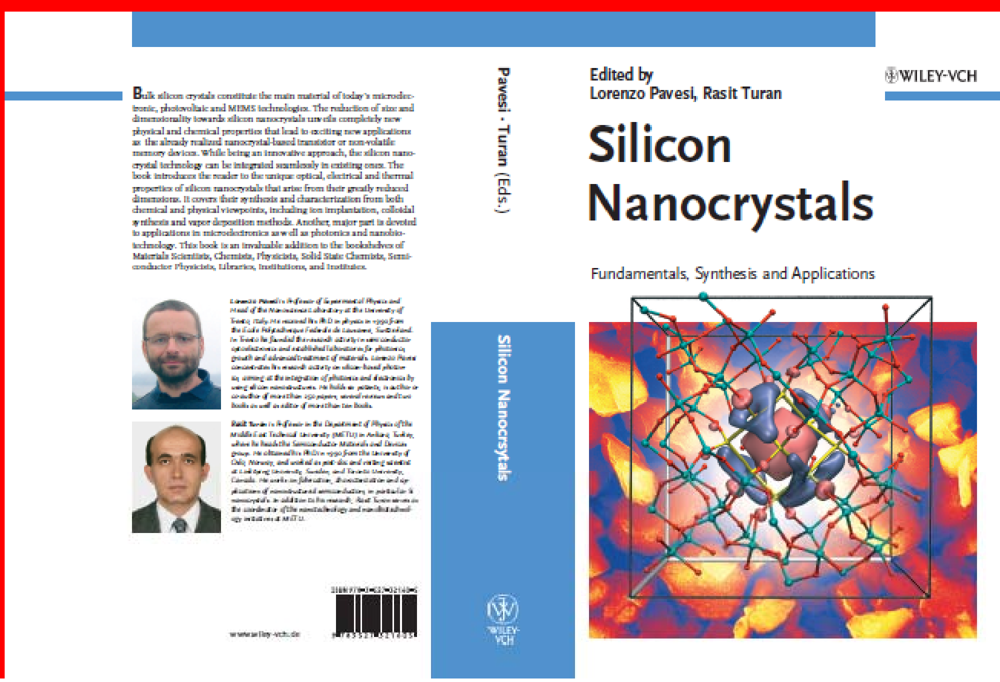
Silicon Photonic Link
50Gbps
Multichip approach
Driver 45 nm CMOS
Photonic 90 nm CMOS

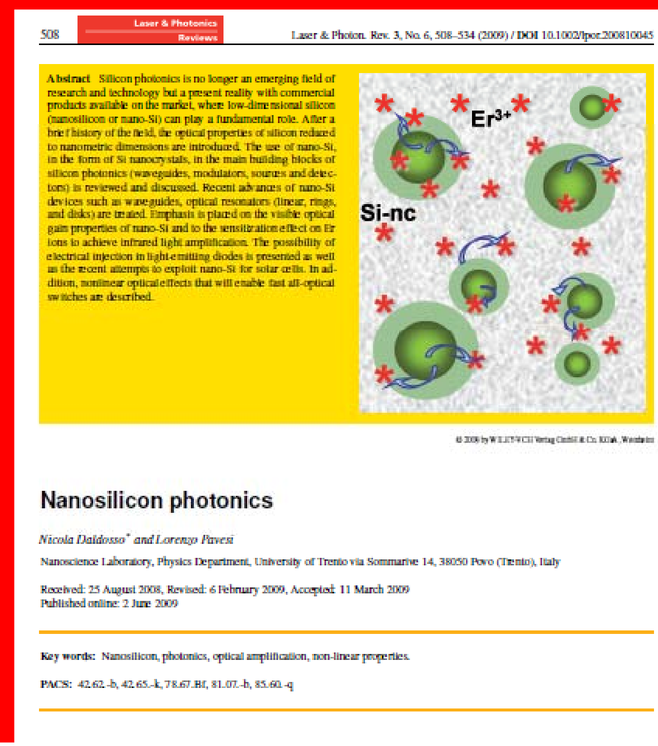


Outline

- Silicon Photonics
- State of the art
- Silicon Photonics for lab-on-a-chip
- NanoSilicon photonics
- Conclusion

Nanosilicon photonics:
a platform where silicon nanoclusters enable new functionalities in silicon photonics





508 Laser & Photonics Reviews Laser & Photon. Rev. 3, No. 6, 508–534 (2009) / DOI 10.1002/lpor.200810045

Abstract Silicon photonics is no longer an emerging field of research and technology but a present reality with commercial products available on the market, where low-dimensional silicon (nanosilicon or nano-Si) can play a fundamental role. After a brief history of the field, the optical properties of silicon reduced to nanometric dimensions are introduced. The use of nano-Si, in the form of Si nanocrystals, in the main building blocks of silicon photonics (waveguides, modulators, sources and detectors) is reviewed and discussed. Recent advances of nano-Si devices such as waveguides, optical resonators (linear, rings, and disks) are treated. Emphasis is placed on the visible optical gain properties of nano-Si and to the sensitization effect on Er ions to achieve infrared light amplification. The possibility of electrical injection in light-emitting diodes is presented as well as the recent attempts to exploit nano-Si for solar cells. In addition, nonlinear optical effects that will enable fast all-optical switches are described.

Nanosilicon photonics

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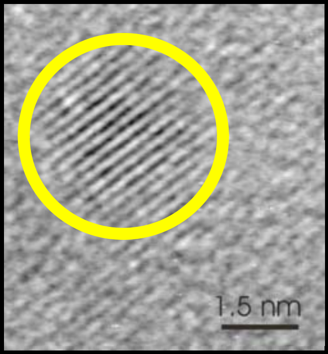
Key words: Nanosilicon, photonics, optical amplification, non-linear properties.

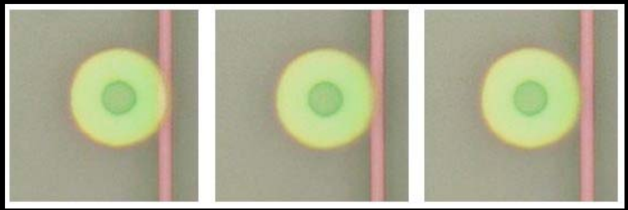
PACS: 42.62.-b, 42.65.-k, 78.67.Bf, 81.07.-b, 85.60.-q

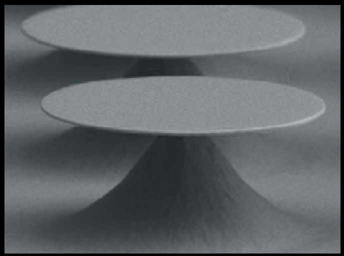
Silicon Nanophotonics

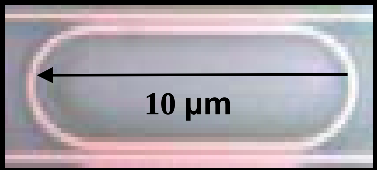
- Confine carriers on nanoscale dimensions



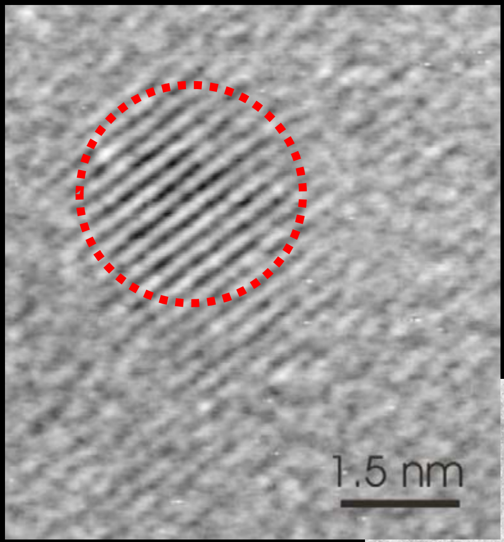
- Confine photons on nanoscale dimensions

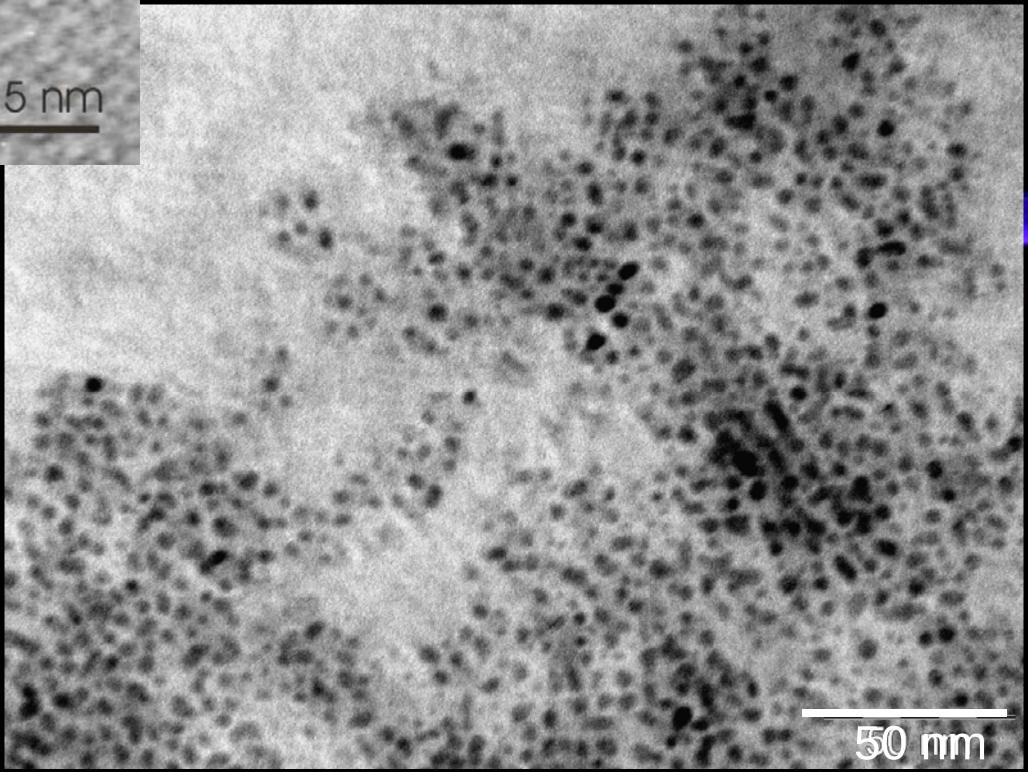


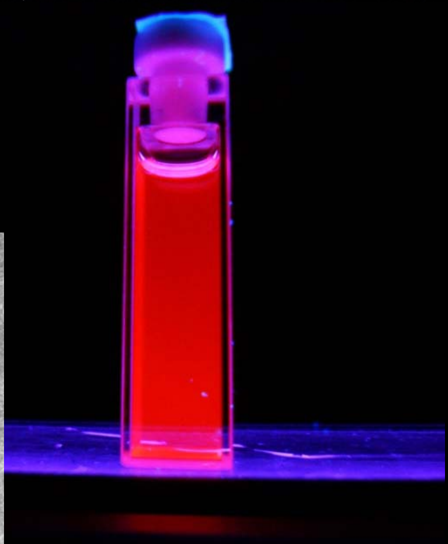




Silicon quantum dots







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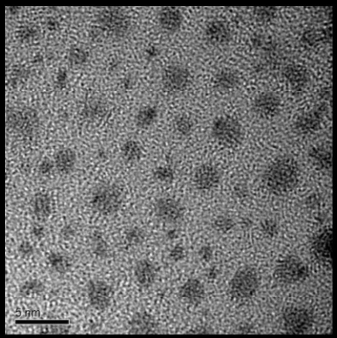
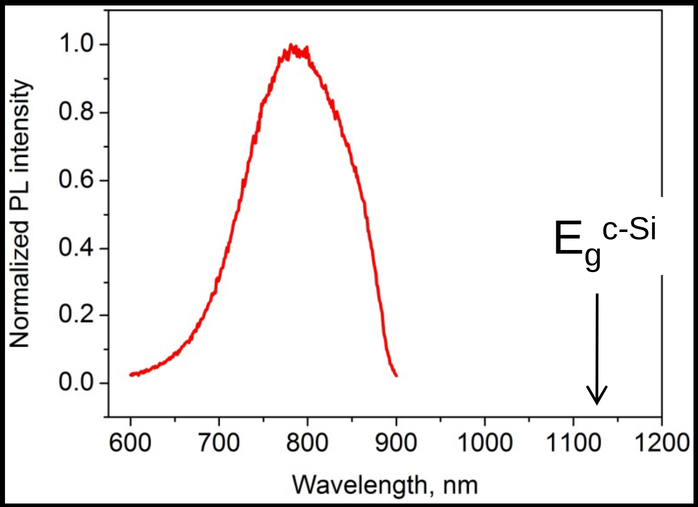
Silicon quantum dots





Bulk Silicon:
Indirect band-gap

inefficient light emitter

Nanocrystalline-Si:
Direct-gap due to QCE
Strong visible light emission

Optical gain in silicon nanocrystals

L. Pavesi*, L. Dal Negro*, C. Mazzoleni*, G. Franzò† & F. Priolo†

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Optical gain in silicon nanocrystals

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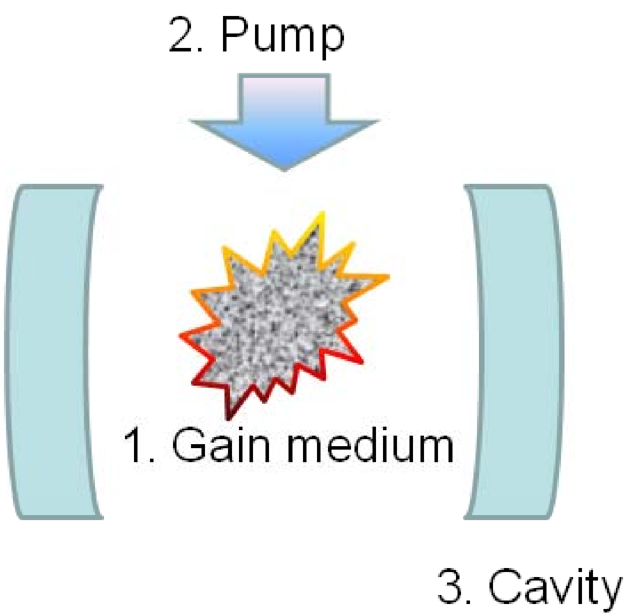
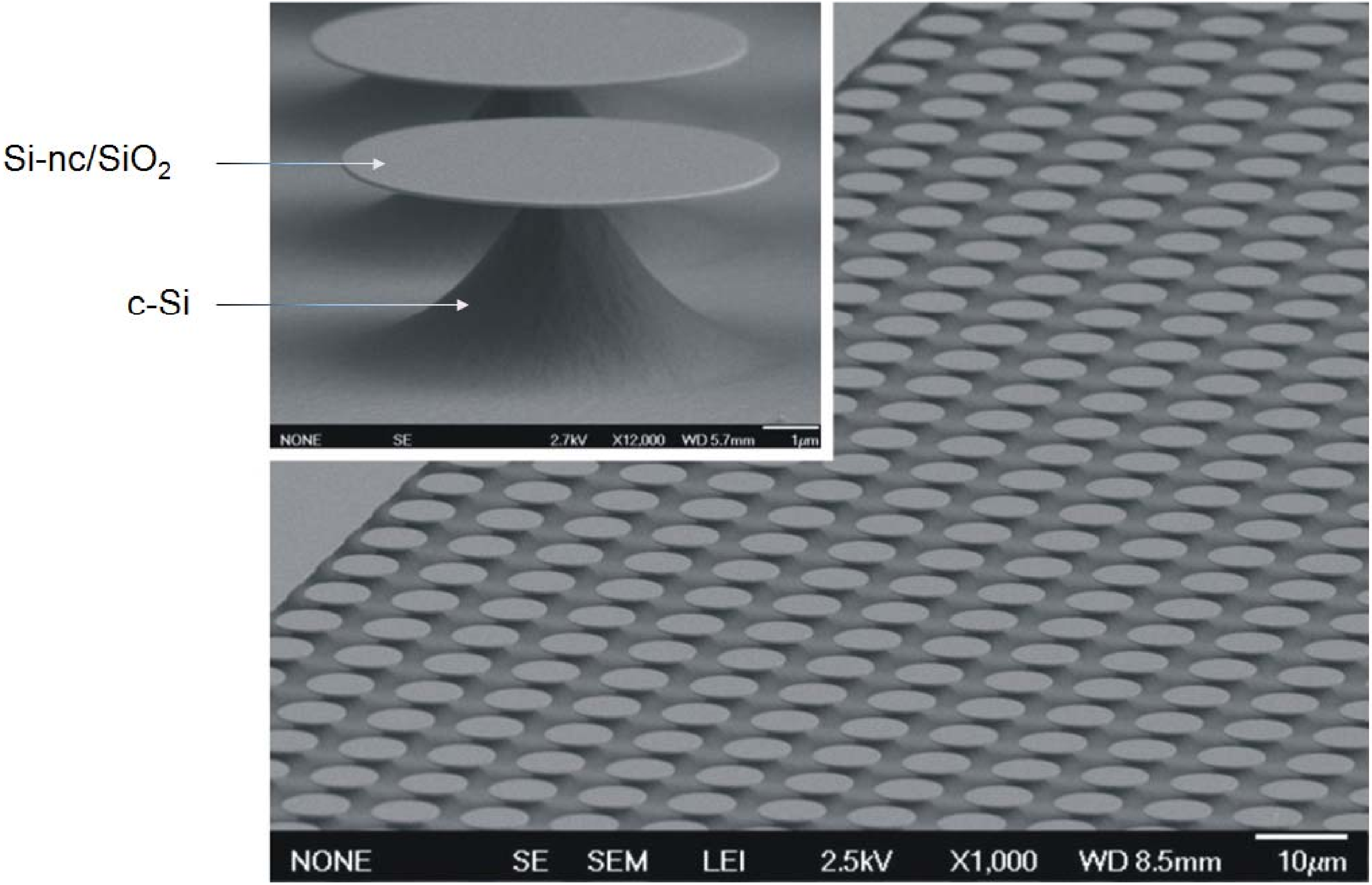
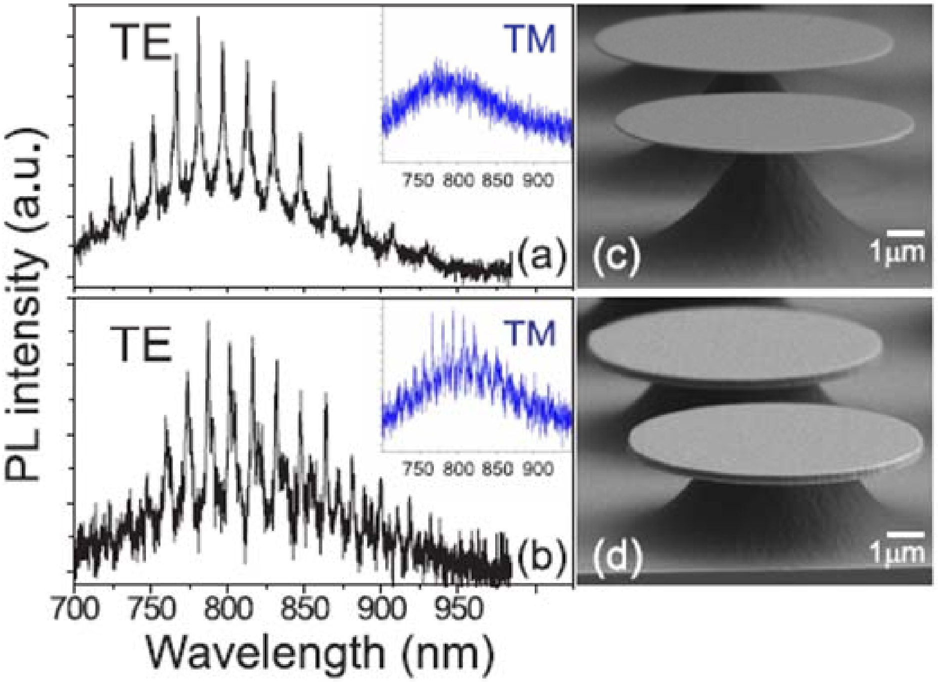
→ **Silicon laser ?**

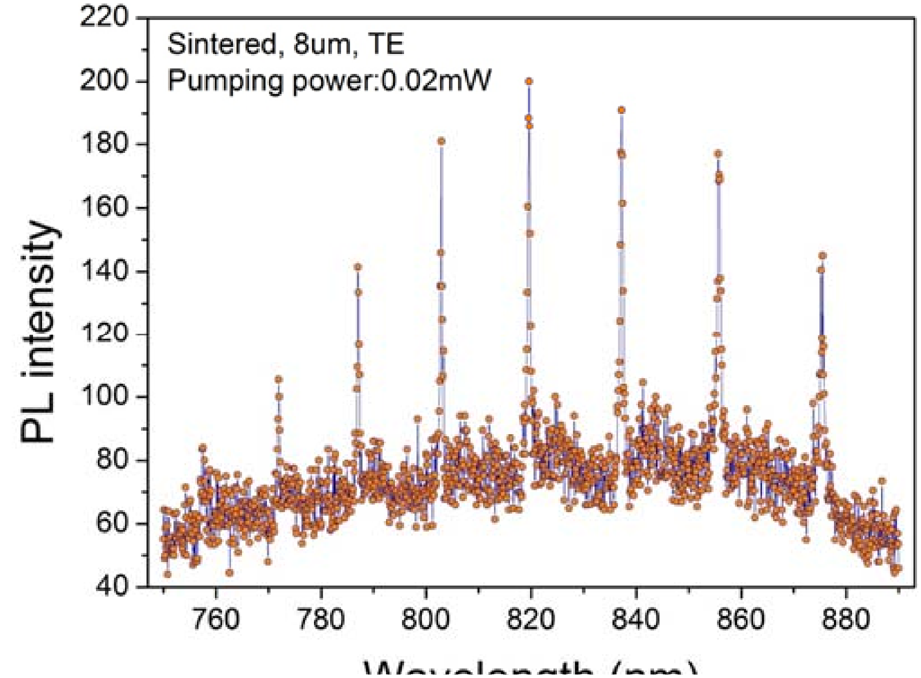


e.g., a **Whispering-gallery mode resonator**

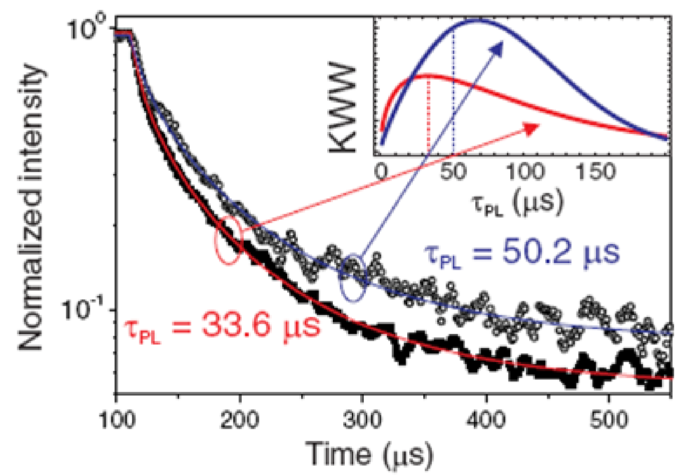
Si QD's in 2D whispering-gallery resonators





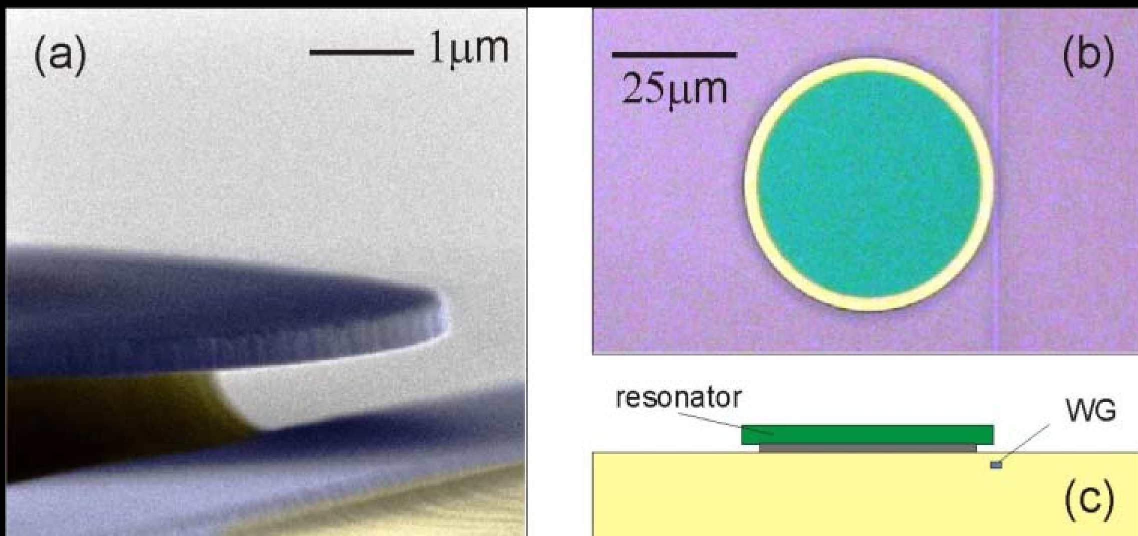


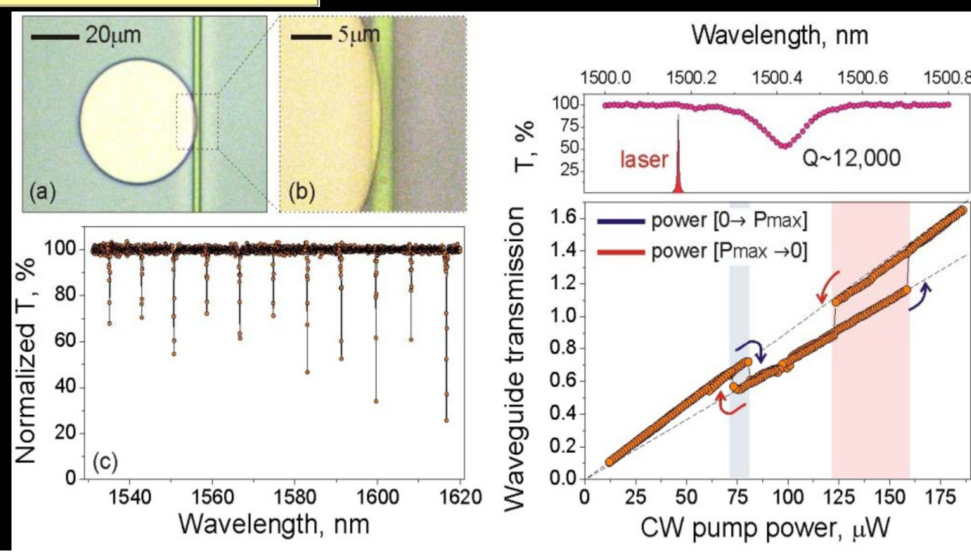
Purcel effect



M. Ghulinyan, D. Navarro-Urrios, A. Pitanti, Alberto Lui, Georg Pucker, L. Paves
OPT. EXPRESS **16**, 13218-13224 (2008)

Integration of microdisk with a waveguide





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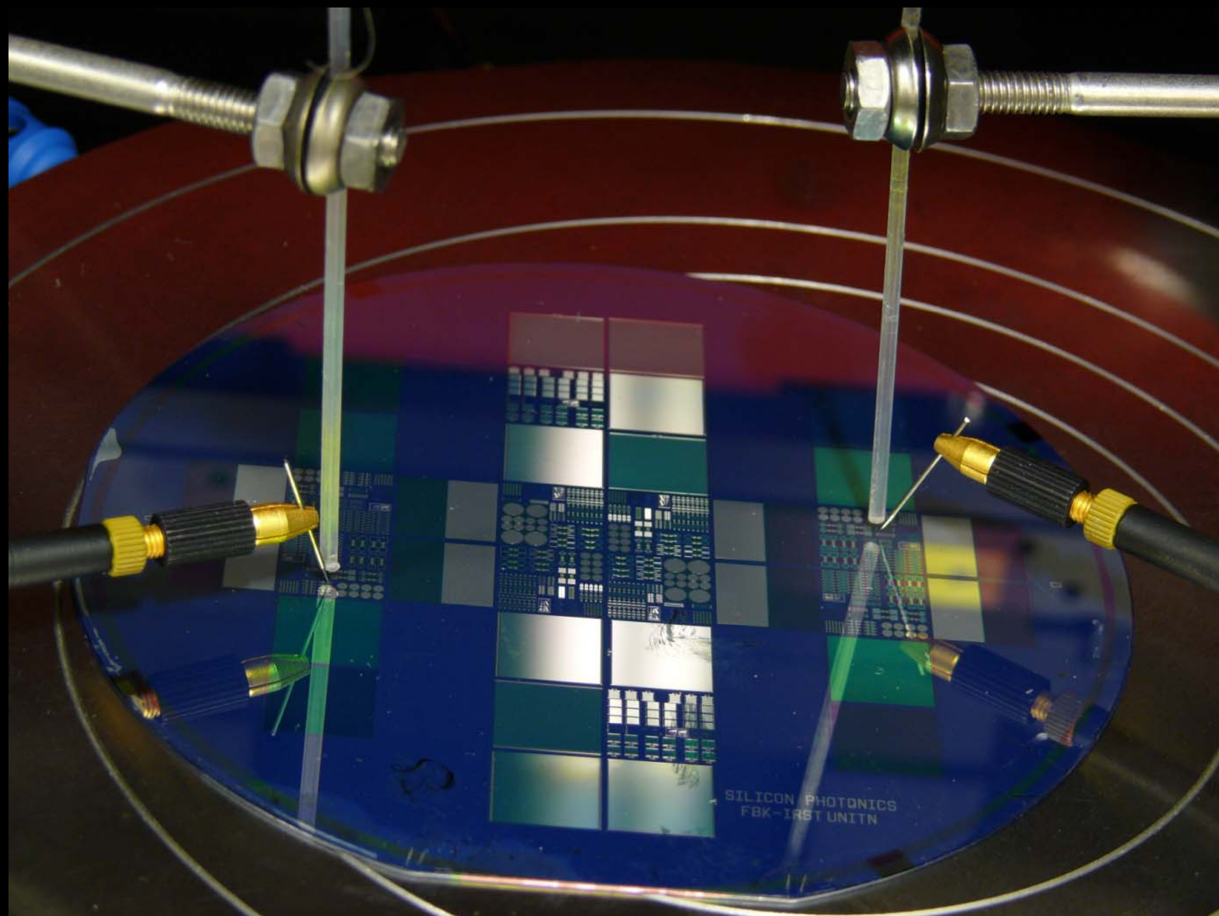
pHotonics ELectronics functional Integration on CMOS

THE all SILICON TRANSCEIVER



Marconi, Anopchenko

pHotonics ELectronics functional Integration on CMOS

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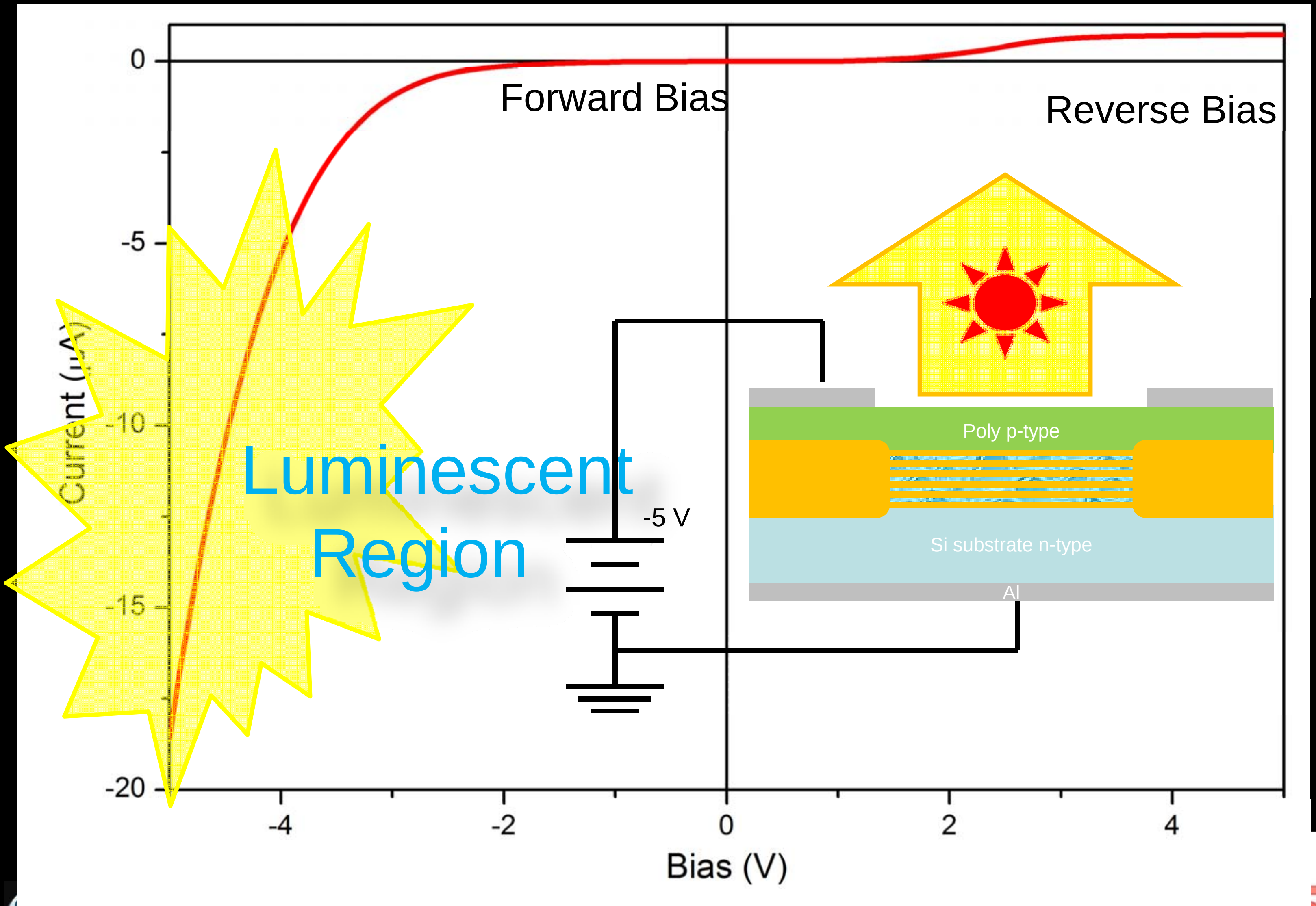

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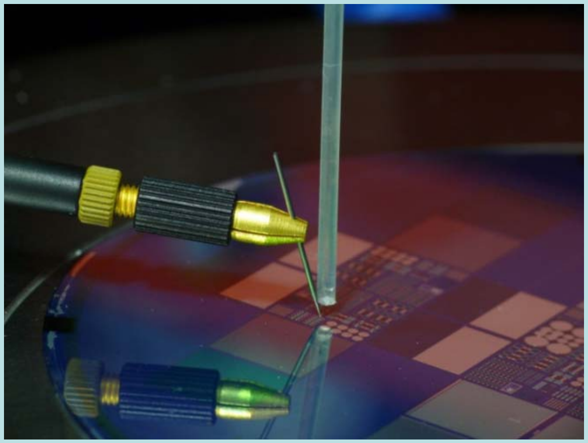

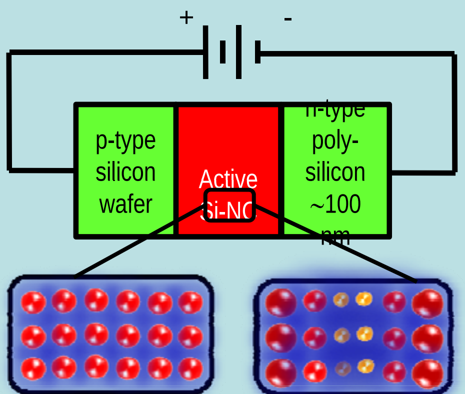

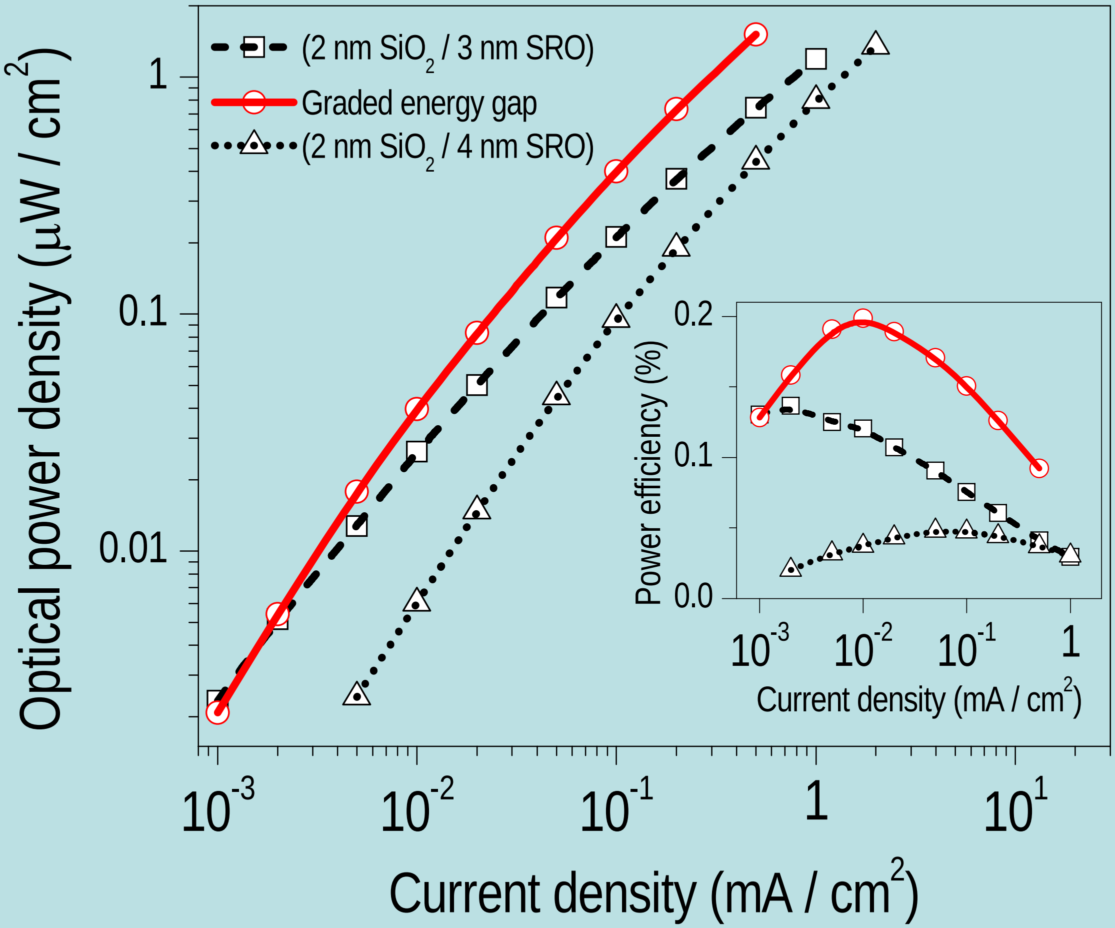

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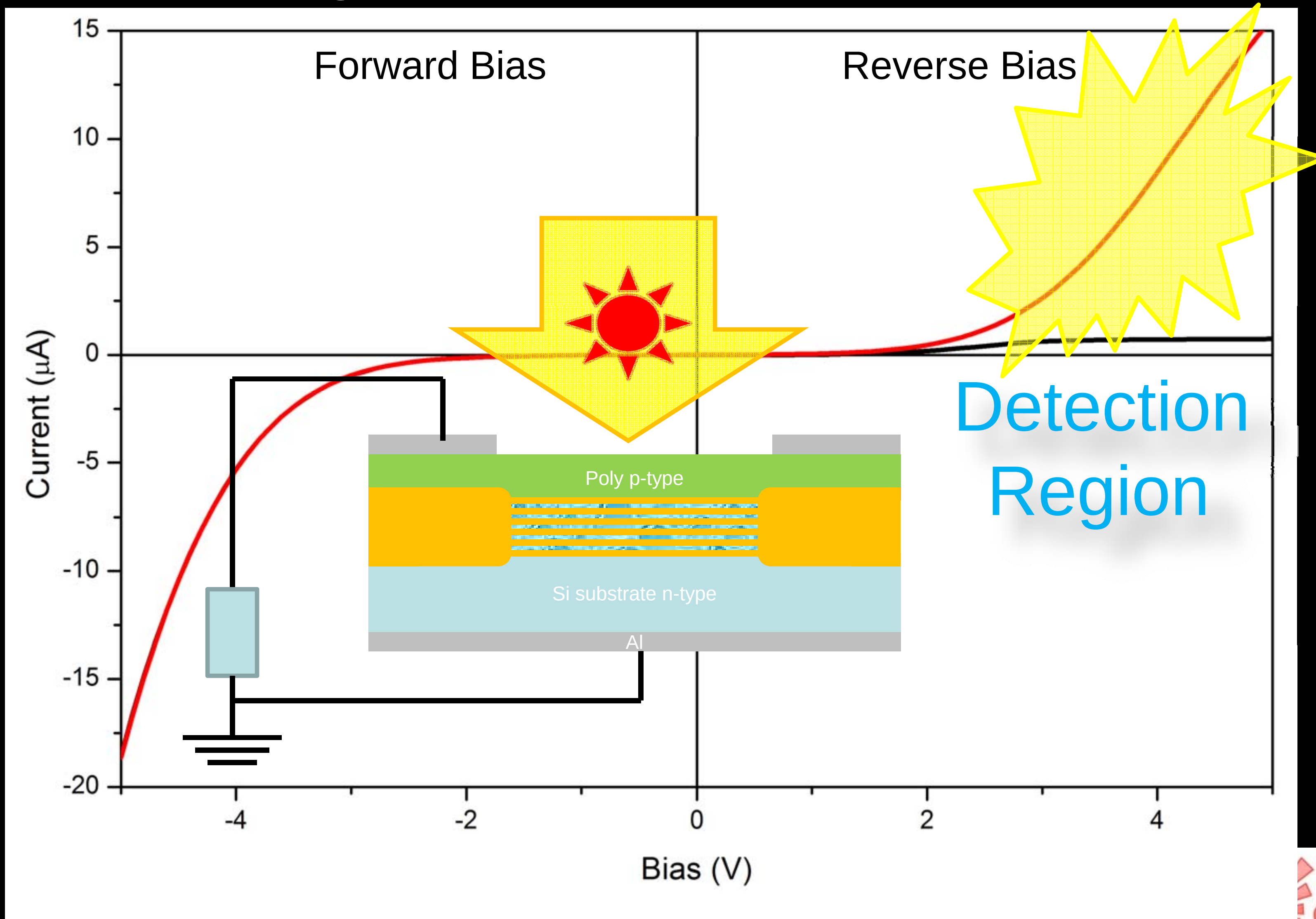

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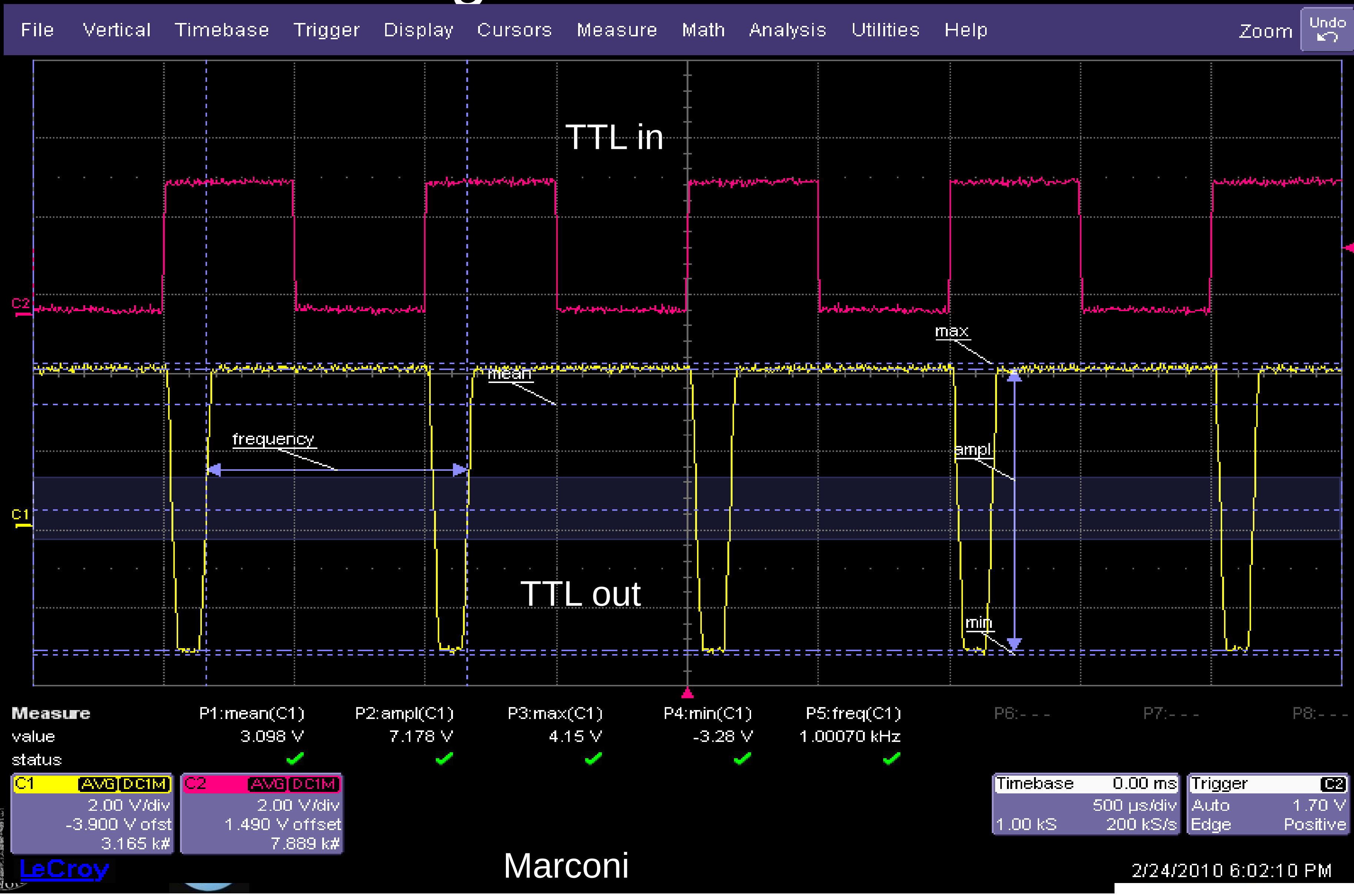


Marconi

All optical switching with silicon nanocrystals

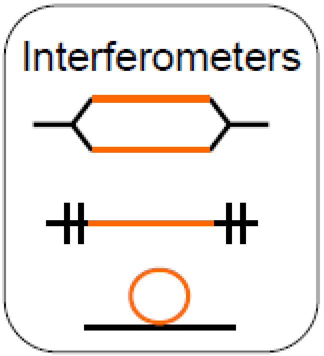
$$n = n_0 + n_2\, I$$

$$\alpha = \alpha_0 + \beta\, I$$

Refractive index variation

Effective index variation of the guided optical mode

Phase variation



Optical intensity variation

Comparison to other nonlinear materials

Silica → $n_2 = (1.54 \times 10^{-16})\ cm^2/W$ [3,4]

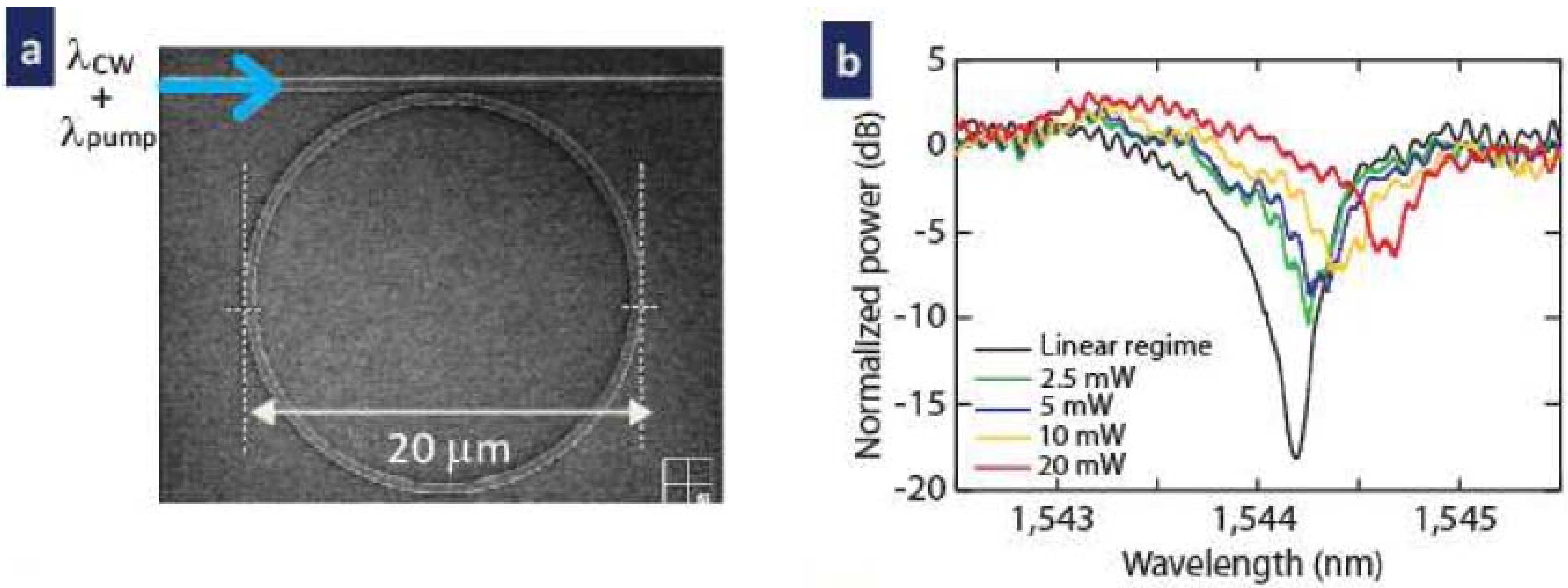
Bulk Silicon → $n_2 = (4.5 \times 10^{-14})\ cm^2/W$ [3,4]

GaAs → $n_2 = (1.59 \times 10^{-13})\ cm^2/W$ [5]

Si-ncs → $n_2 = (2 \div 8 \times 10^{-13})\ cm^2/W$ [present work]

[3] Handbook of Nonlinear Optics
[4] Adair R. et al., Physical Review B, 39, 3337, (February 1989).
[5] M. Dinu et al., Applied Physics Letters, 82, 2954 (2003).

All optical switching



Si nanocrystals activated slot waveguides

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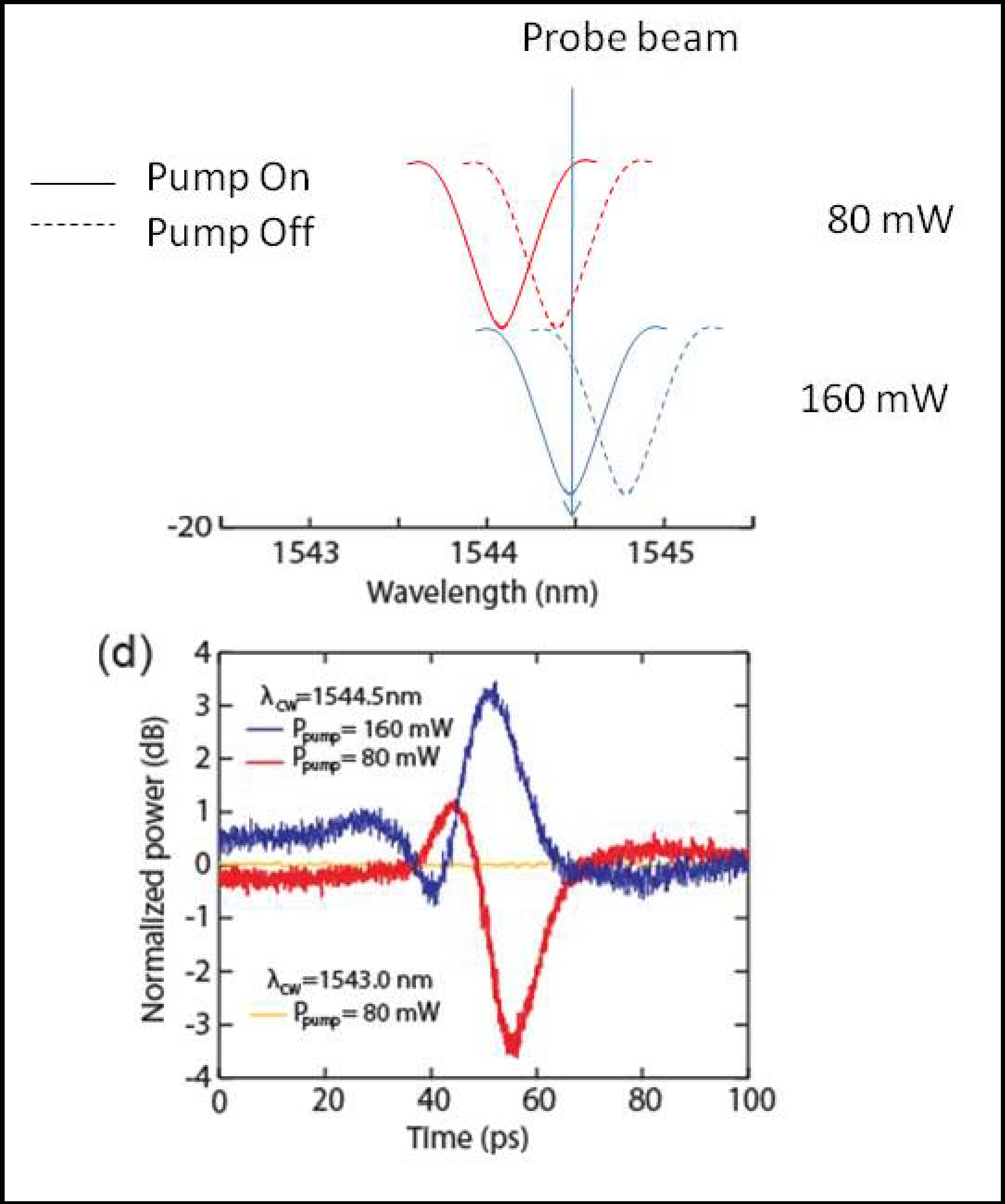
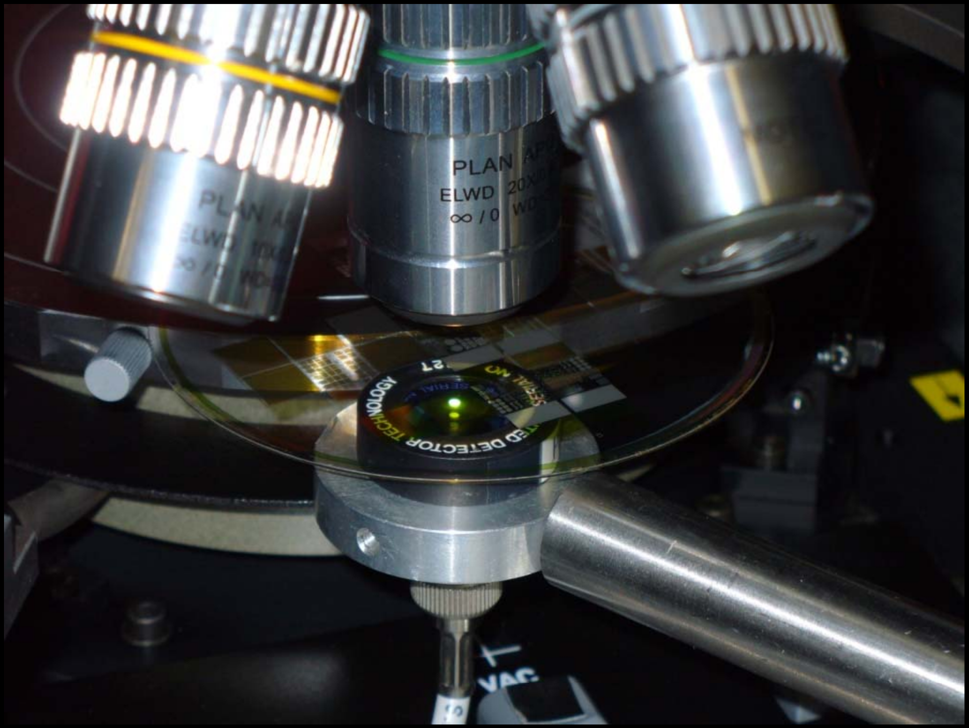
A. Martinez et al. Nanoletters (2010)



A. Martinez et al. Nanoletters (2010)

Improved photovoltaic efficiency by applying novel effects at the limits of light-matter interaction



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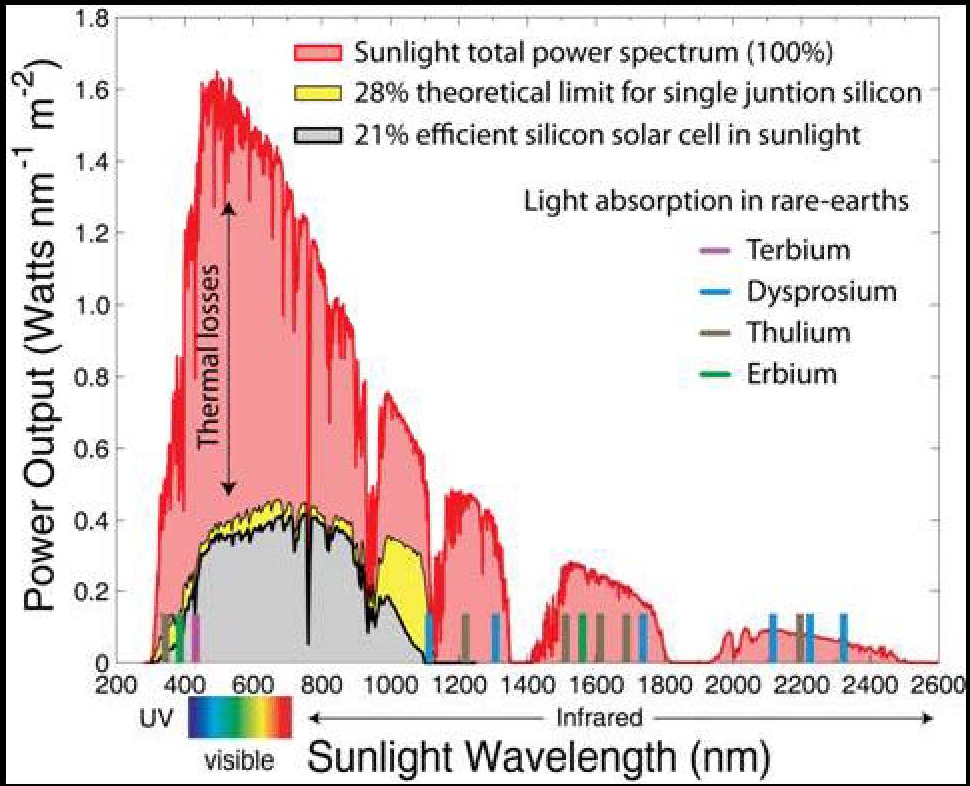
Improved photovoltaic efficiency by applying novel effects at the limits of light-matter interaction

Photon electron energy conversion	**32.9%**
Unabsorbed energy loss	18.7%
Heat loss	46.8%
Other losses	1.6%

OPTOI MICROELECTRONICS

lima

Improved photovoltaic efficiency by applying novel effects at the limits of light-matter interaction



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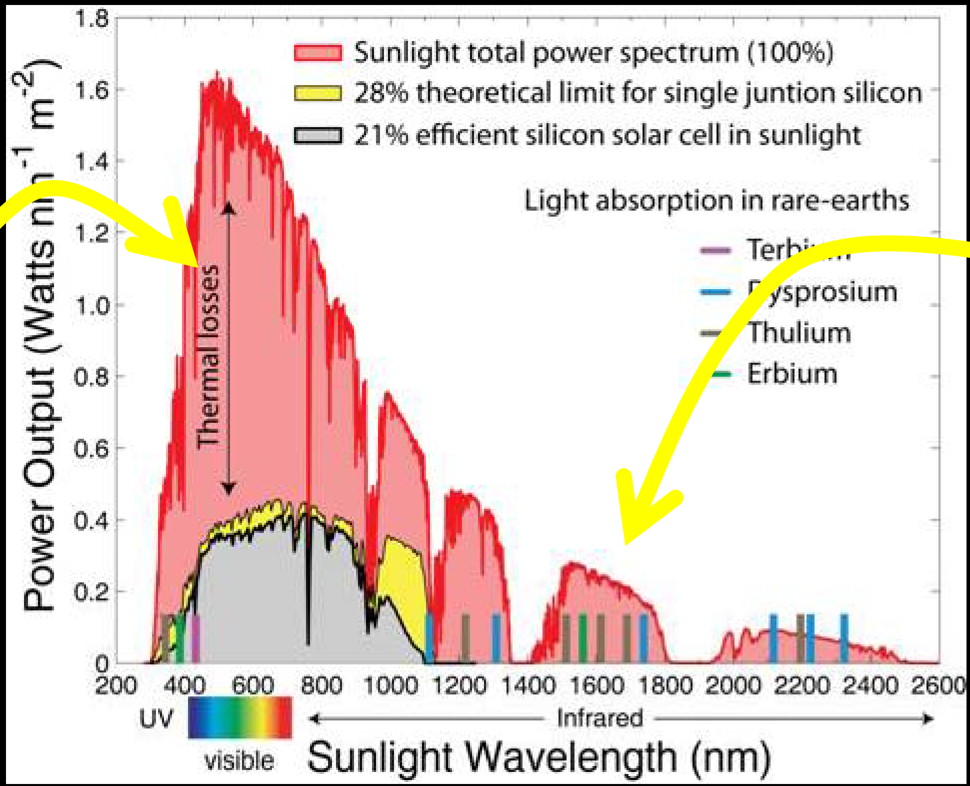
Improved photovoltaic efficiency by applying novel effects at the limits of light-matter interaction

downshifter



Secondary carrier generation

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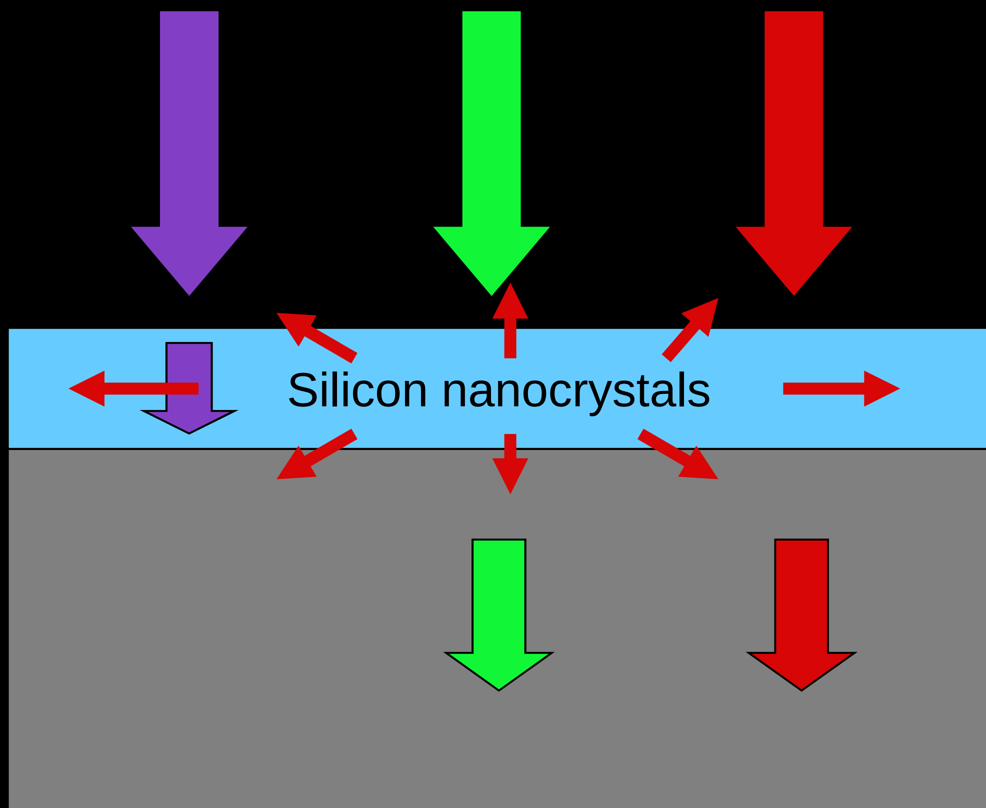
Improved photovoltaic efficiency by applying novel effects at the limits of light-matter interaction

downshifter



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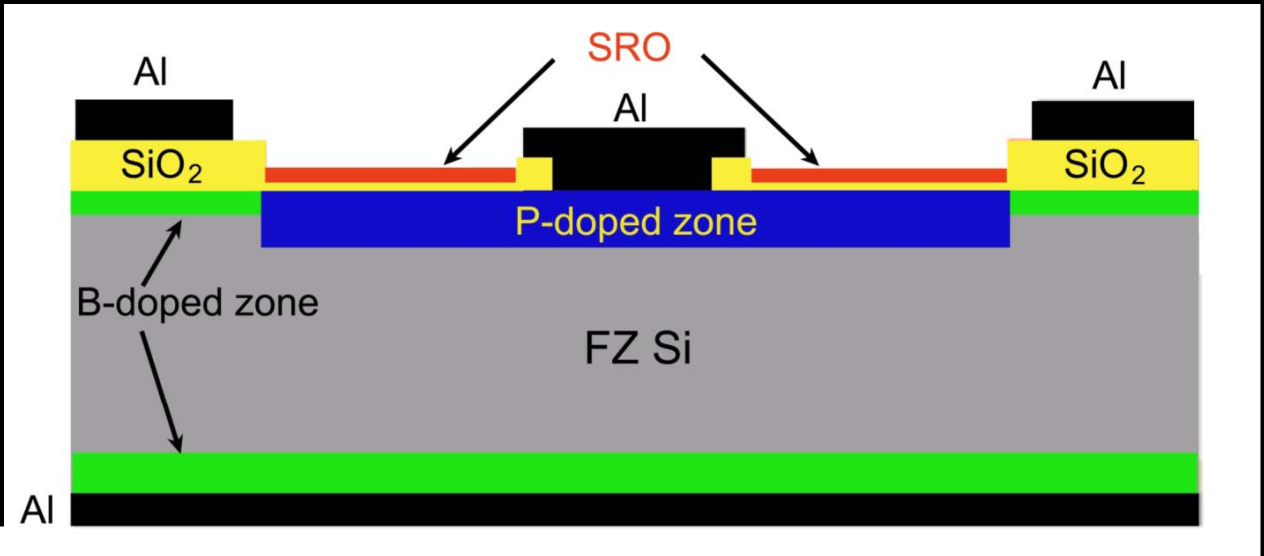
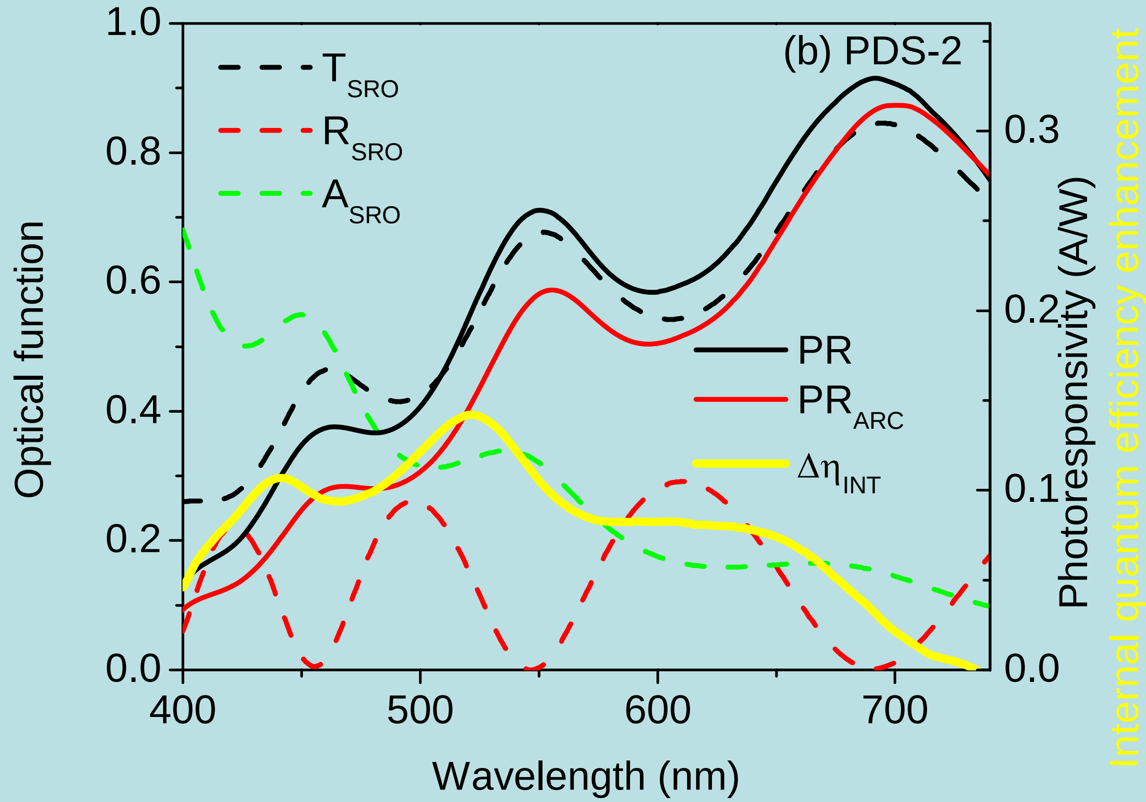
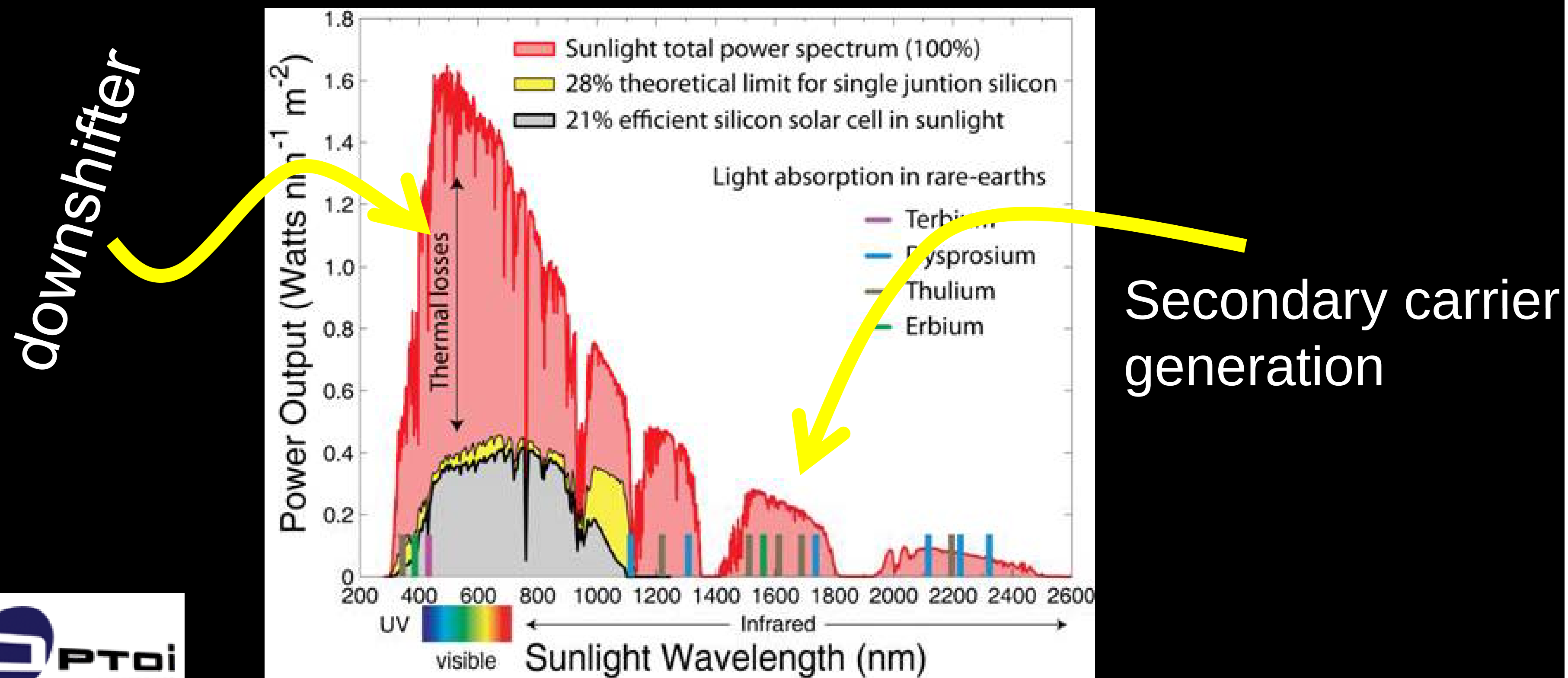


Ryan, Anopchenko, Marconi – APP FBK



A maximum enhancement of the internal quantum efficiency of 14%

Improve photovoltaic efficiency by applying novel effects at the limits of light-matter interaction



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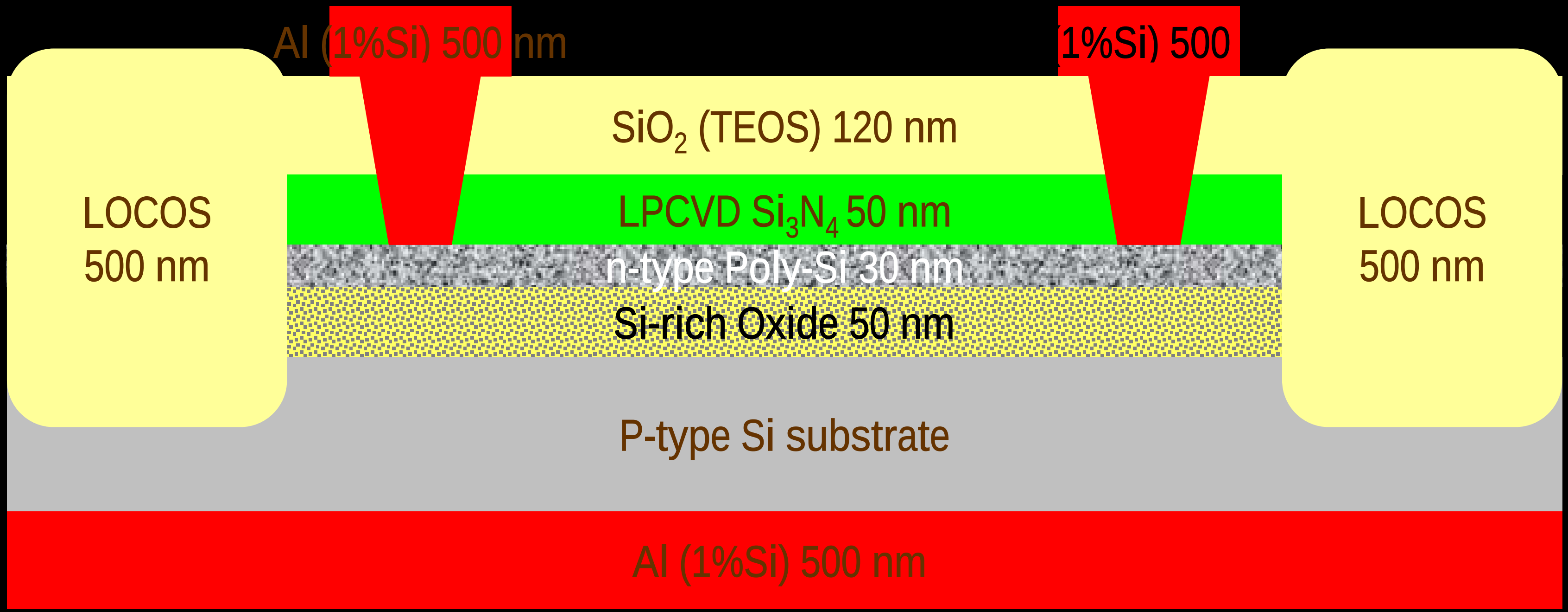
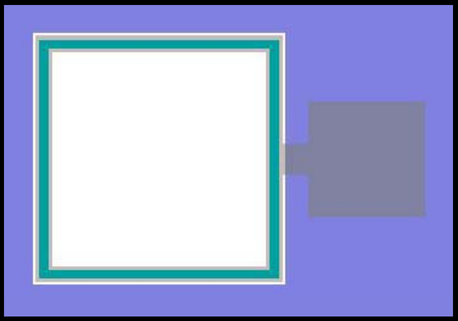
Cross section of the device



Device area = 320 μm X 320 μm



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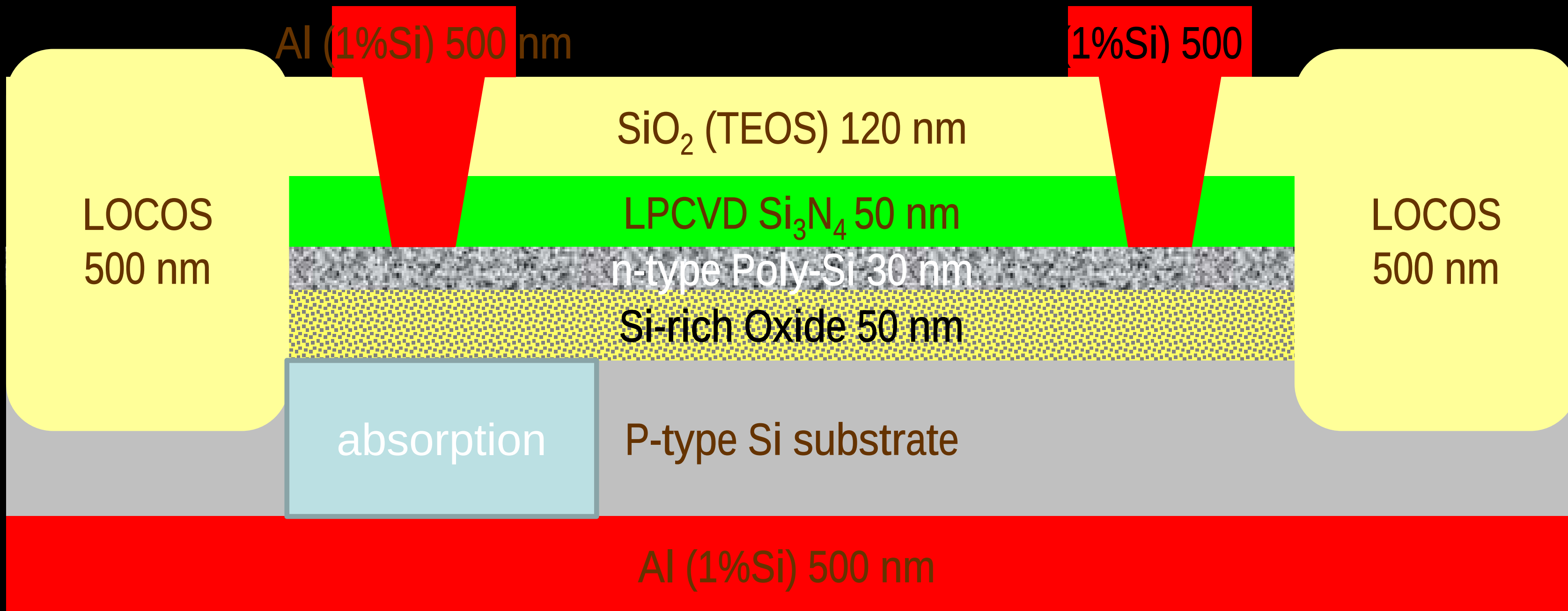
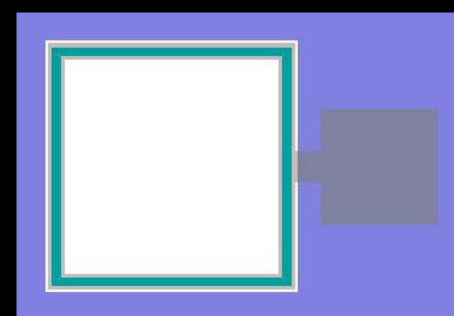
Cross section of the device





Device area = 320 μm X 320 μm

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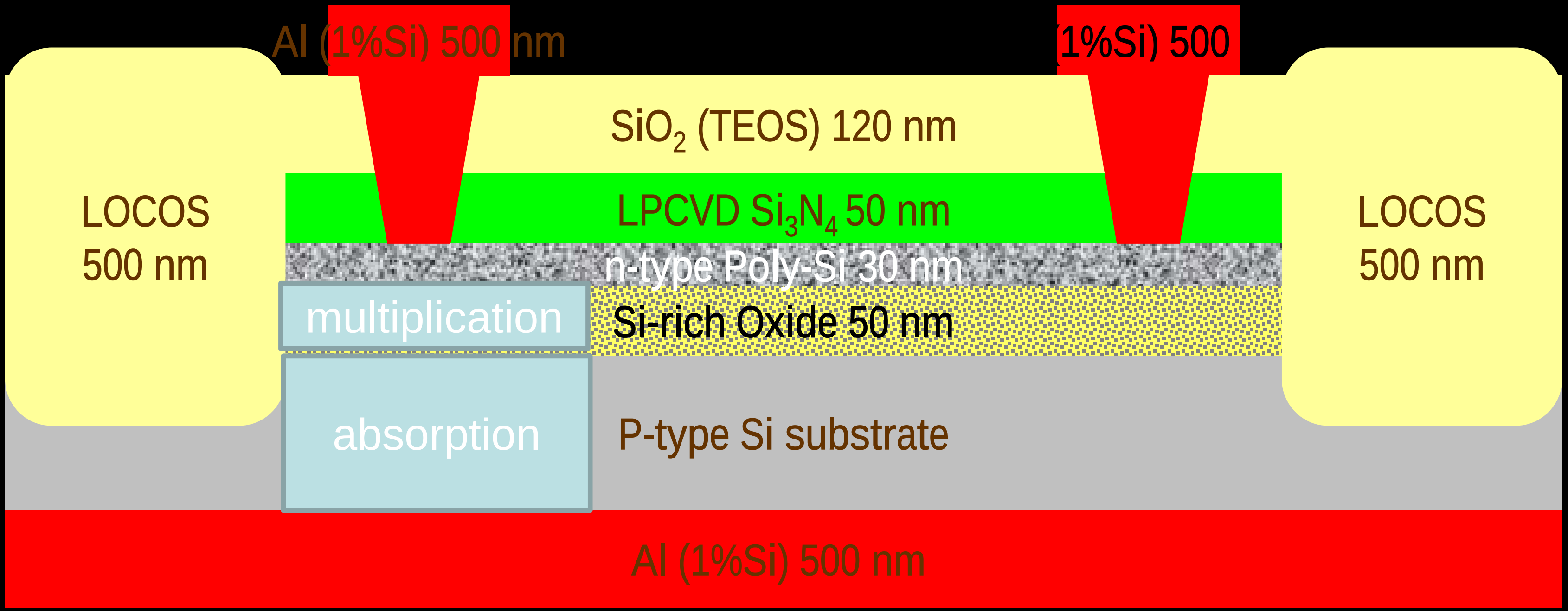
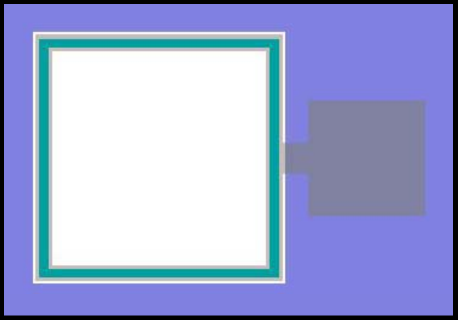
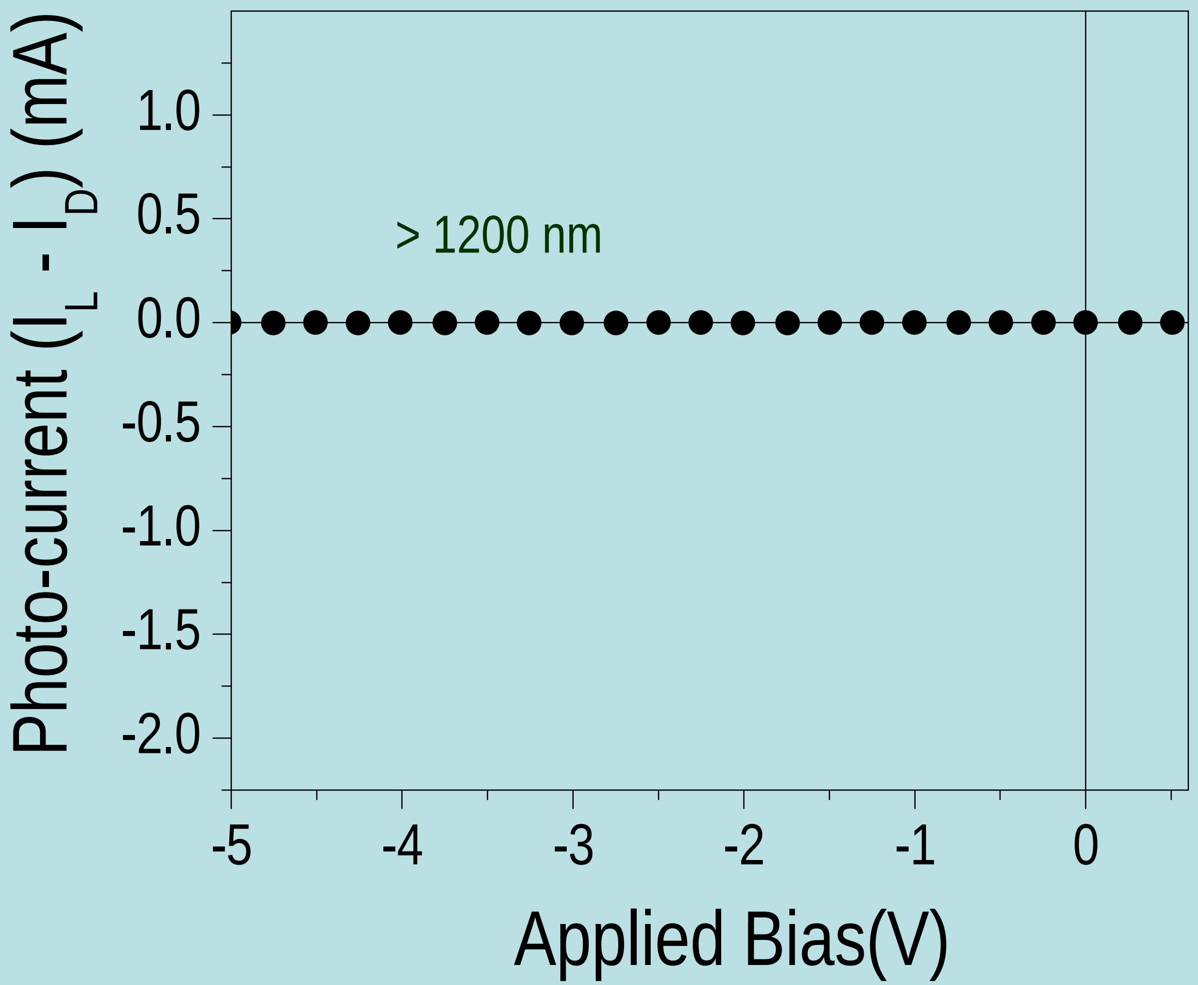
Cross section of the device



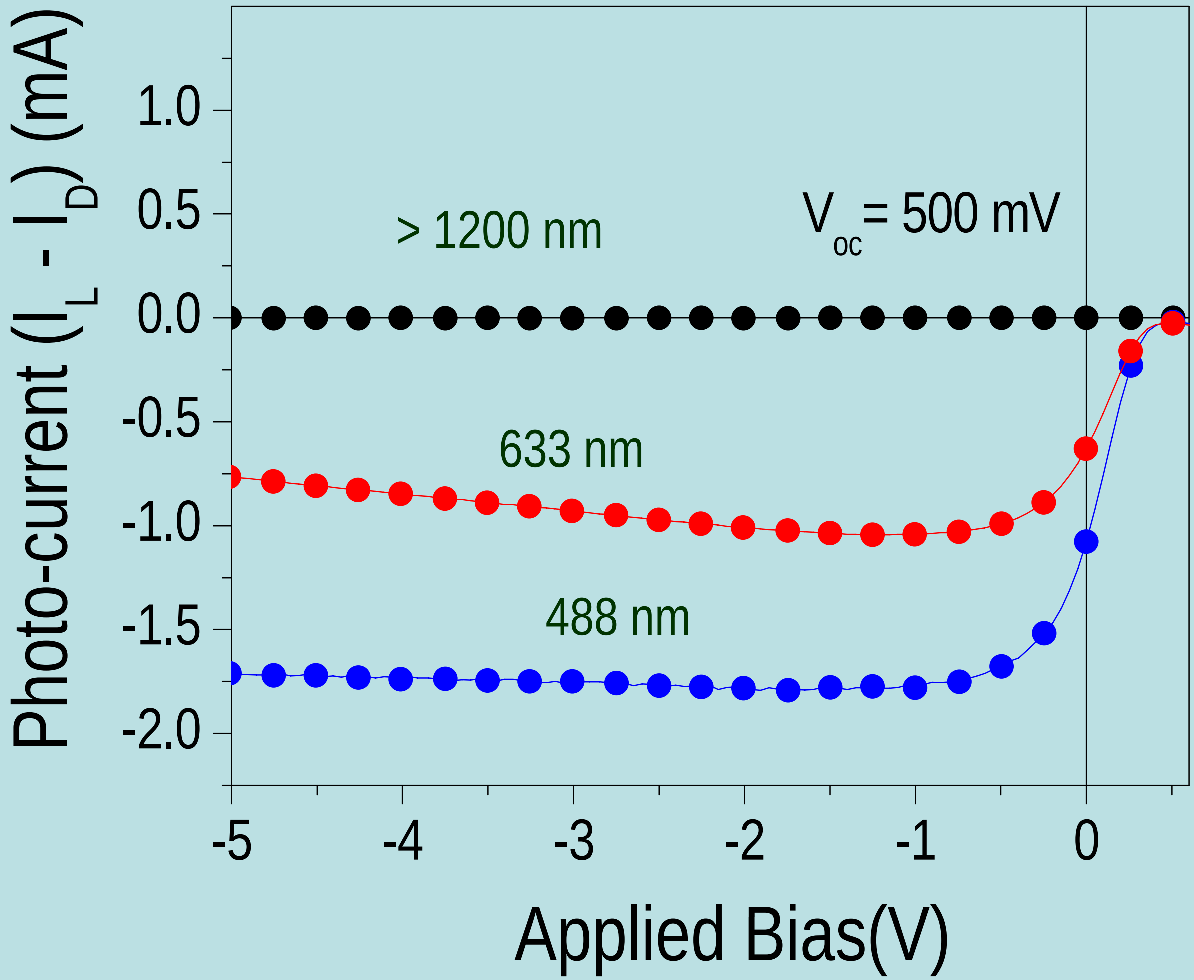


Device area = 320 μm X 320 μm

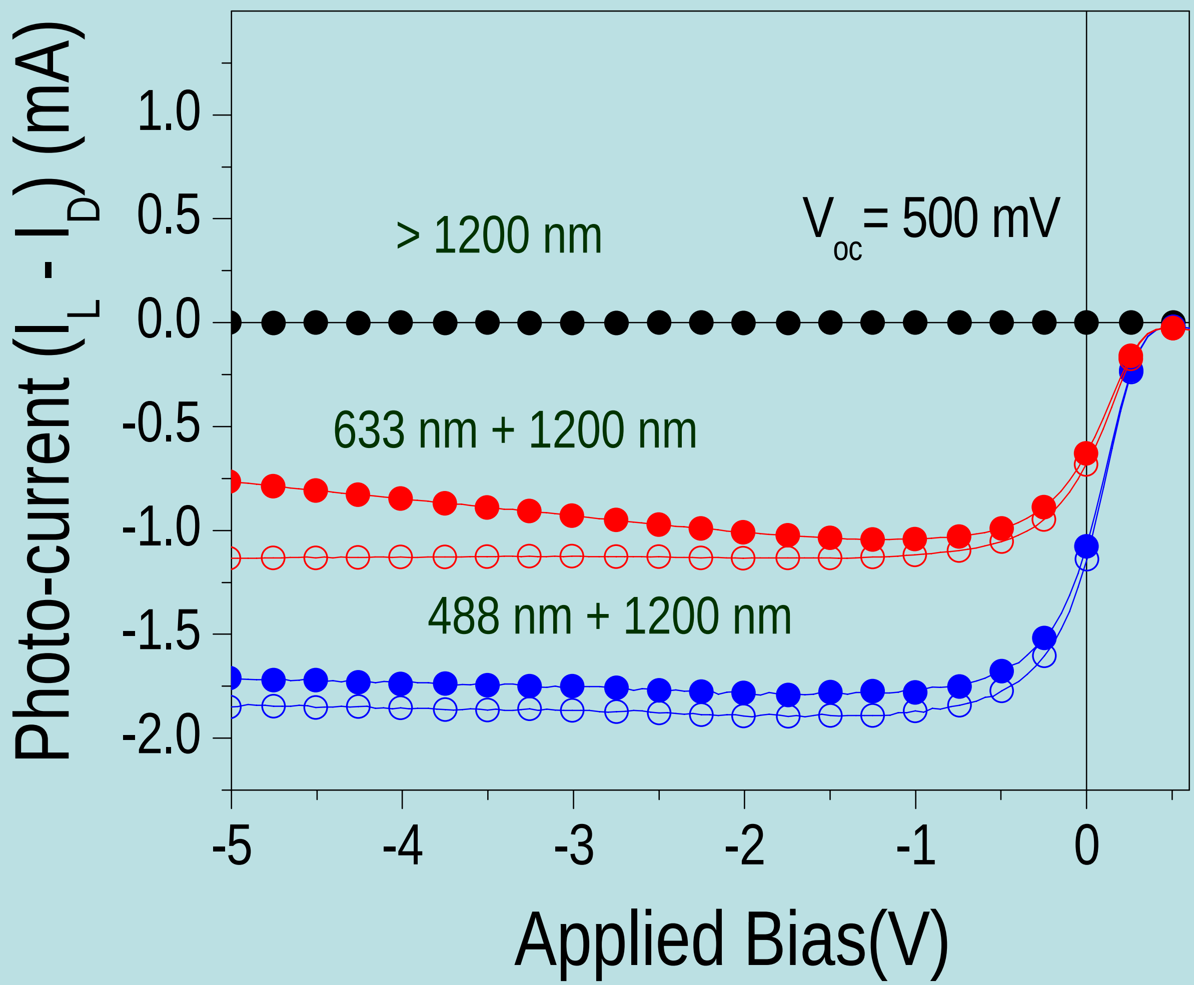
IR response in Γ3N



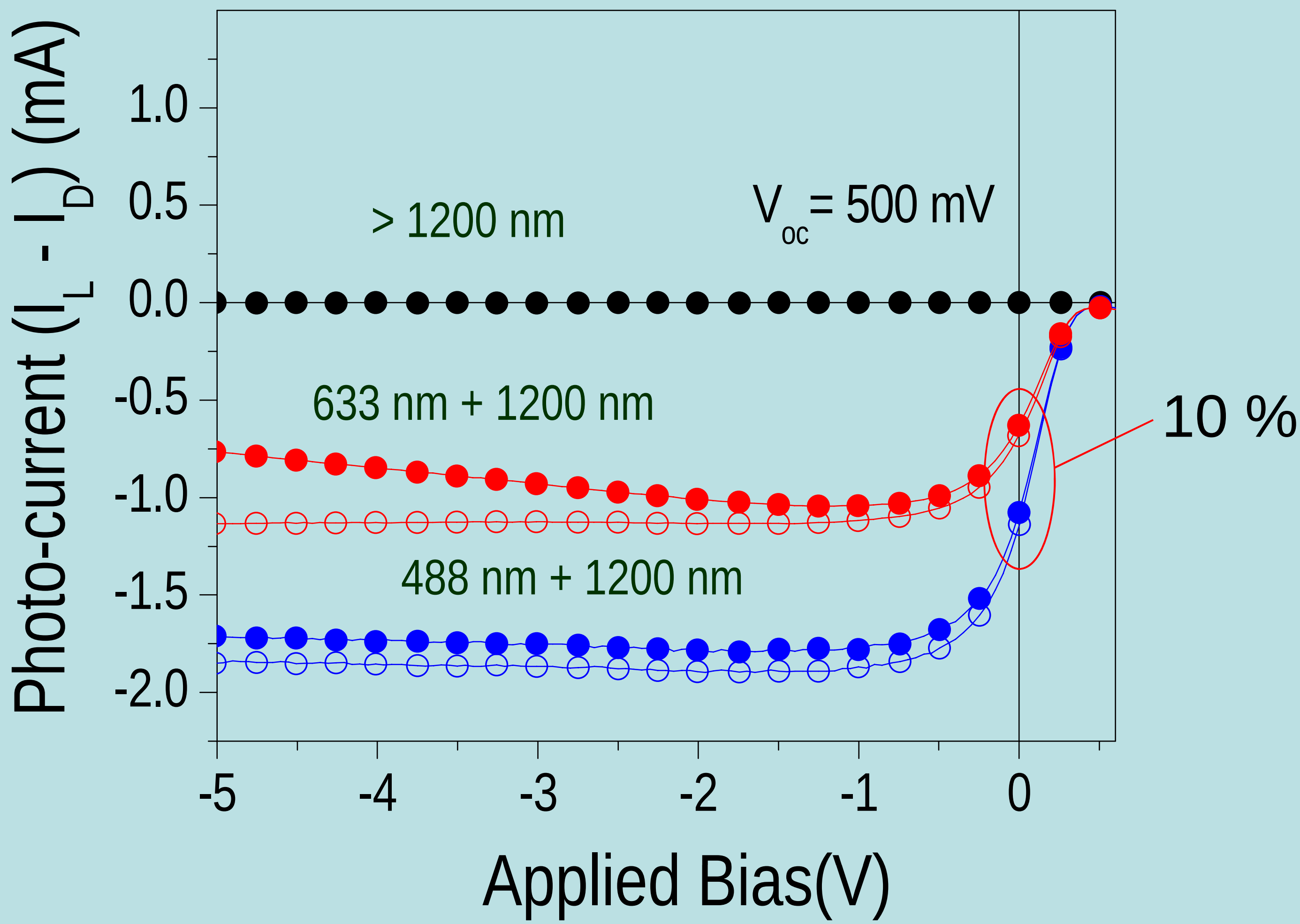
IR response in Γ3N



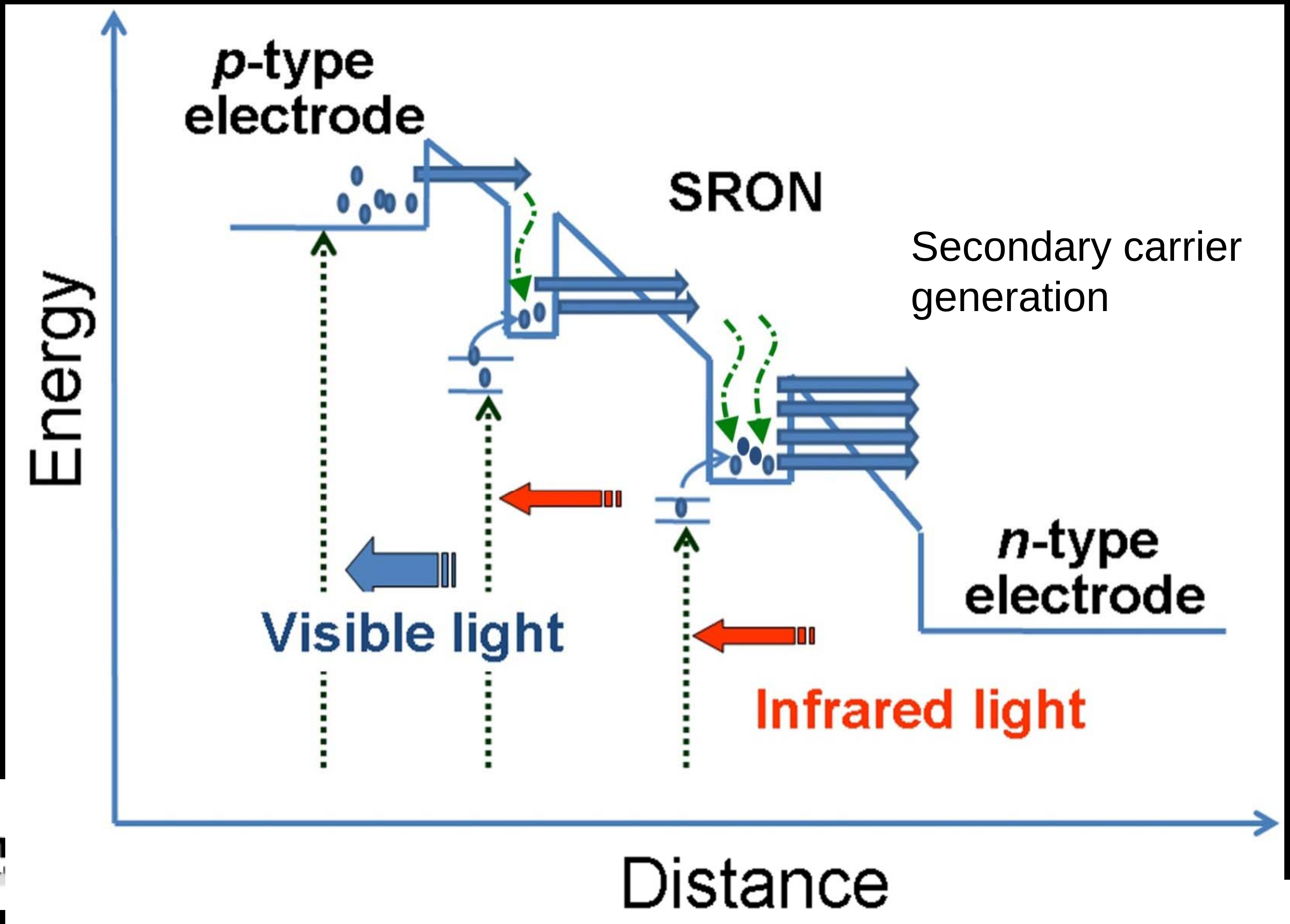
IR response in Γ3N



IR response in Γ3N



Solar cell with an internal gain mechanism



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Outline

- Silicon Photonics
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Conclusions:

- Silicon photonics is a mature technology
- Silicon photonics allows fabricating thousands of photonic components in a single chip
- Silicon photonics merges electronics and photonics to enable novel functionalities
- Silicon photonics is not only bulk Silicon (nanosilicon, strained silicon, silicon/germanium, germanium, ….)
- Silicon photonics is not only optical communication is much more

Bottom line:

- Each time the market catches size Silicon is the solution
- If you may want to compete with silicon, do not! Silicon will always make it

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HELIOS

pHotonics ELectronics functional Integration on CMOS

Silicon photonics course

prepared by the HELIOS consortium

Download the course on http://www.helios-project.eu/Download/Silicon-photonics-course

Acknowledgments

- EC: Helios, LIMA, Wadimos, Positive
- PAT: Gopsi, Naomi
- MAE: Italy-turkey, mexico, romania
- HCSC project and OptoI
- ITPAR

Acknowledgments