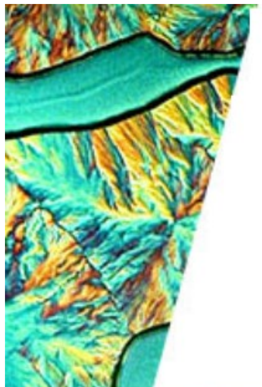
The OSA Photonic Detection Technical Group Welcomes You!



BENDING, TRAPPING AND SLOWING DOWN LIGHT BEAMS FOR HIGHLY EFFICIENT AND ULTRA-FAST PHOTODETECTION

19 August 2019 14:00 EST

OSA Photonic Detection Technical Group

Speaker:
Prof. M. Saif Islam
Chair – ECE Department
University of California, Davis

OSA Photonic Detection Technical Group

Committee 2019

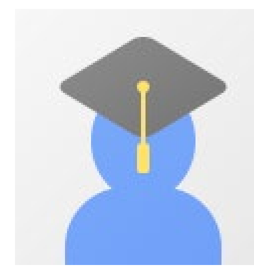
Girija Gaur
Chair
Kramer Levin Naftalis & Frankel

Achyut Dutta
Vice Chair
Founder, Banpil Photonics

Shuren Hu
Events Officer USA/Asia/EU
GlobalFoundries

Chi Xiong
Events Officer USA
IBM

Gabe Spalding
Member
Illinois Wesleyan University



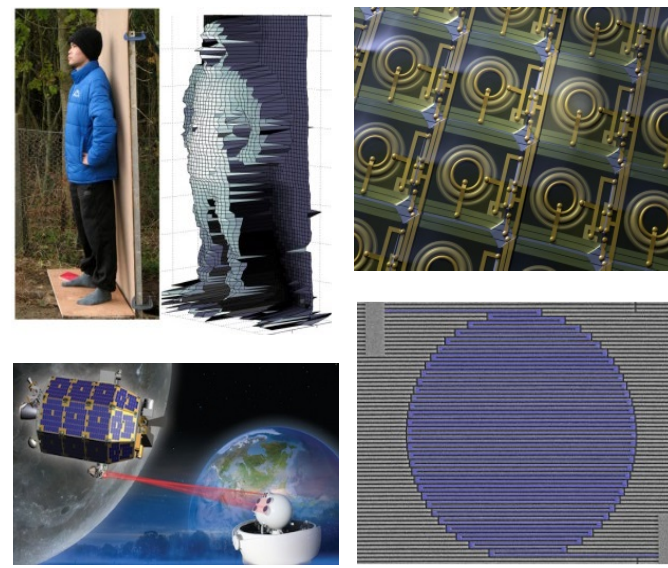
Rajan Jha
Events Officer India
IIT Bhubaneswar, India

OSA Photonic Detection Technical Group

About Us

The Photonic Detection technical group is part of the Photonics and Opto-Electronics Division of the Optical Society. This group focuses on the detection of photons as received from images, data links, and experimental spectroscopic studies to mention a few. Within its scope, the PD technical group is involved in the design, fabrication, and testing of single and arrayed detectors.

This group focuses on materials, architectures, and readout circuitry needed to transduce photons into electrical signals and further processing. This group's interests include: (1) the integration of lens, cold shields, and readout electronics into cameras, (2) research into higher efficiency, lower noise, and/or wavelength tunability, (3) techniques to mitigate noise and clutter sources that degrade detector performance, and (4) camera design, components, and circuitry.



OSA Photonic Detection Technical Group

Find us online

OSA Homepage
www.osa.org/PD

LinkedIn Group
www.linkedin.com/groups/Photonic-Detection-Technical-Group-8297763/about

Photonic Detection (PD)

This group involves the detection of photons as received from images, data links, and experimental spectroscopic studies to mention a few. Within its scope, it is involved in the design, fabrication, testing of single and arrayed detectors. Detector materials, structures, and readout circuitry needed to translate photons into electrical signals are considered by this group. Also included in this group is the integration of components such as lens, cold shields, and readout electronics into cameras. Research into higher efficiency, lower noise, and/or wavelength tunability is included here. Additionally, techniques to mitigate noise and clutter sources that degrade detector performance are within the purview of this group. In the imaging area, camera design, componentry, and circuitry are considered.

Webinar on Computational Deep Learning Microscopy

Time: 2:00pm - 3:00pm EDT, Thursday 21 March 2019

Register today for this free webinar hosted by the Photonic Detection Technical Group. Dr. Yair Rivenson will provide attendees with an overview of how the rapidly developing field of deep learning is impacting biomedical imaging and simplifying diagnostic work-flows. The presentation will be of interest to researchers interested in the cross-disciplinary fields of deep learning, photonic detection and biomedical optics including spectroscopy, holography, OCT, diffractive optics, tissue imaging, and bio-optics. The live webinar will be recorded for future viewing on demand. **Register Now >>**

Announcements

If you are a member of the Photonic Detection Technical Group and have ideas for activities and initiatives to help engage this community, please share them with the chair, Girija Gaur.

View OSA Technical Group webinars on-demand at any time or register for any of our upcoming webinars online. Each webinar is an hour long and features a technical presentation on a topic selected by your OSA Technical Groups.

Join our Online Community

LinkedIn

Work in Optics

Systems Engineer - Laser Spectroscopy | Opto-Knowledge Systems, Inc.
Fri, 09 Aug 2019 17:30:45 -0400

Search Jobs »

OSA Photonic Detection Technical Group

Technical Group Activities

- ***Special Sessions*** at OSA conferences such as CLEO and OFC.
- ***~4 Webinars*** for this year!
- Interactions with local sections and student chapters.
- Interactive community for bringing together researchers across inter-disciplinary fields for tackling advances in photonic detection technologies.
- Example: Panel discussion on ***Silicon Photonics for LiDAR and Other Applications*** at OFC 2019 which had great turn-out and a lot of interest!

Bending, Trapping and Slowing Down Light Beams
for highly-efficient and ultra-fast photodetection

M. Saif Islam, Hilal Cansizoglu, Yang Gao, S. Ghandiparsi, Cesar Bartolo-Perez, A. S. Mayet, E. P. Devine
Electrical and Computer Engineering, University of California, Davis, CA, 95618 USA

Nibir K. Dhar, US Army Night Vision and Electronic Sensors Directorate, Fort Belvoir, VA 22060 USA

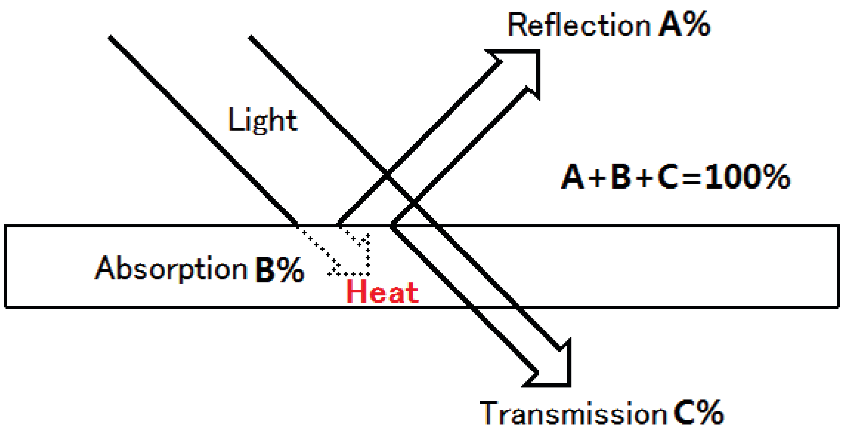
Aly F. Elrefaie and Shih-Yuan Wang, W&WSens Devices, Inc., 4546 El Camino, Los Altos, California, 94022 USA

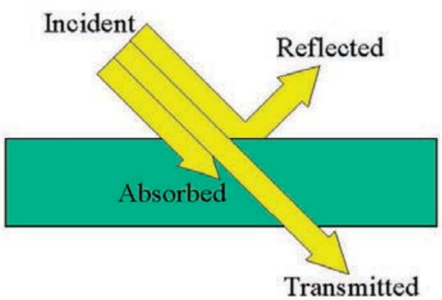
W&Wsens Devices, Inc.

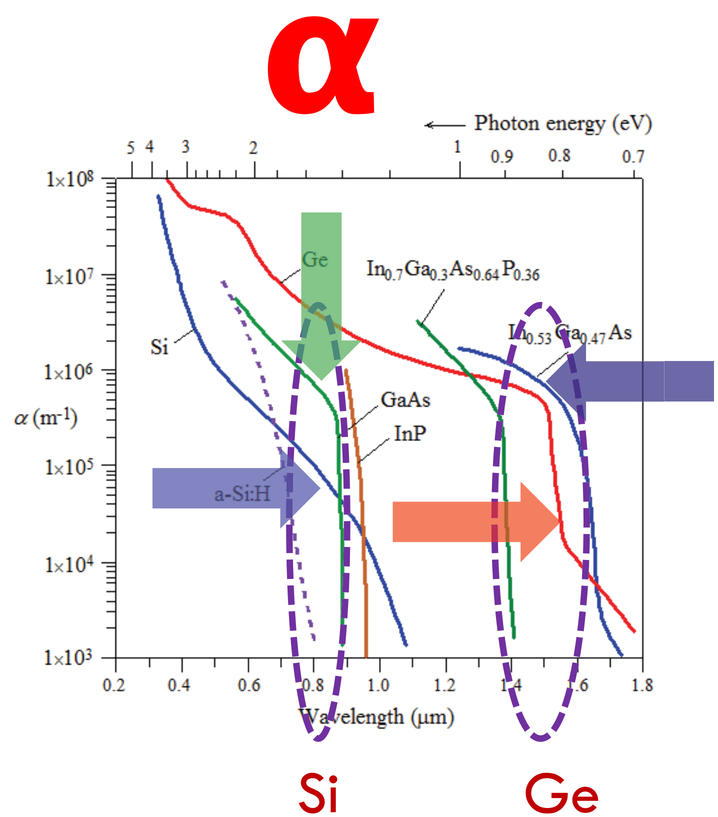
Outline

- How to make materials absorb more light than their natural limits
- Explore device applications
  - Detectors, sensors
  - Energy harvesting devices
- System level opportunities and CMOS integration

Light-Material Interaction

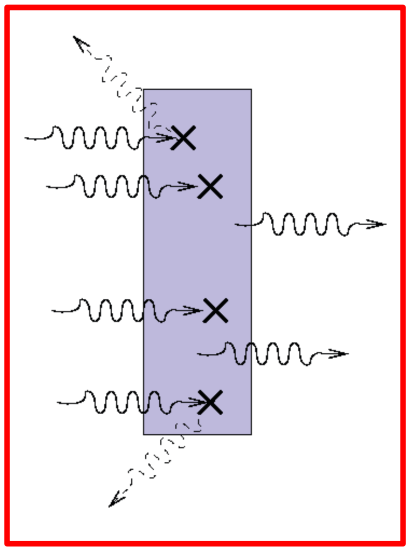




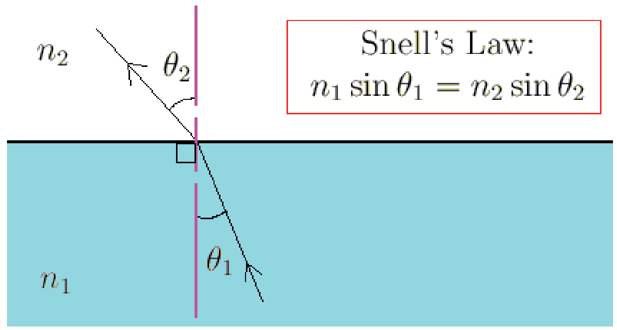


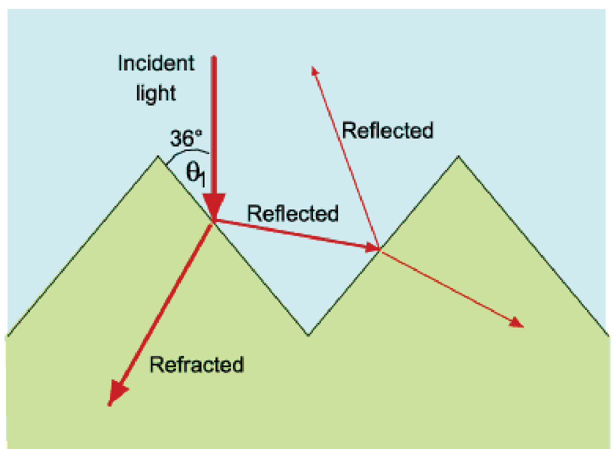
Surface Texturing for Light Trapping & AR

α



$\alpha_{enhanced}$





https://www.pveducation.org

$\alpha_{enhanced}$

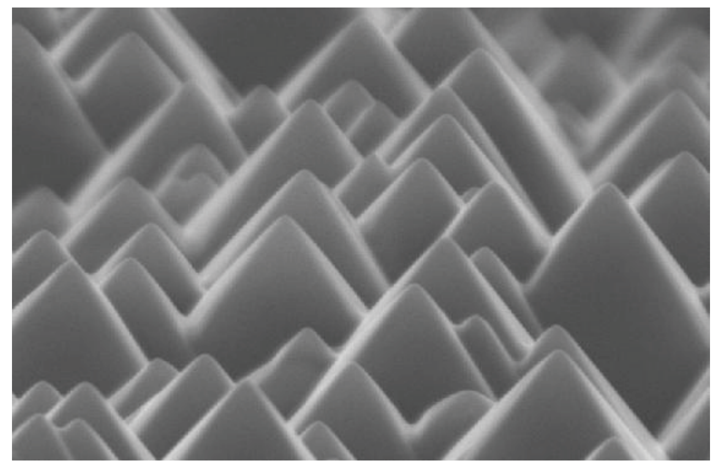


Image Courtesy: School of Photovoltaic & Renewable Energy Engineering, Univ of New South Wales.

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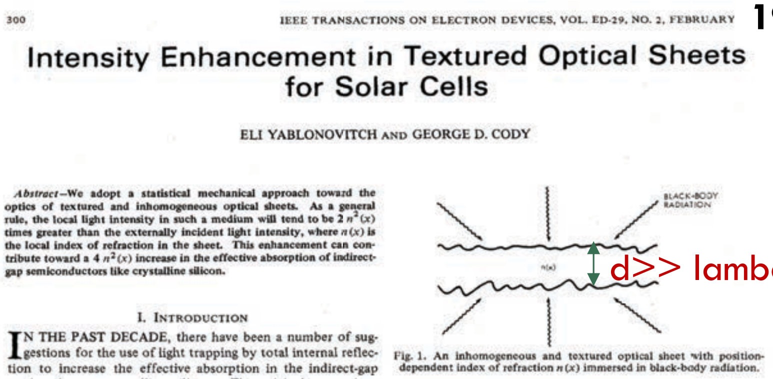
1982


300 IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. ED-29, NO. 2, FEBRUARY

Intensity Enhancement in Textured Optical Sheets for Solar Cells

ELI YABLONOVITCH AND GEORGE D. CODY

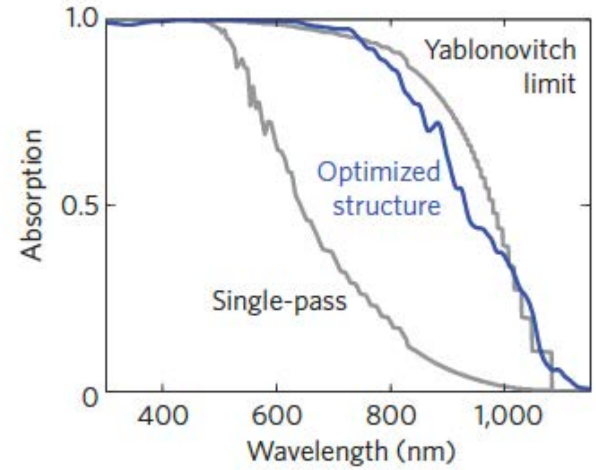
Abstract—We adopt a statistical mechanical approach toward the optics of textured and inhomogeneous optical sheets. As a general rule, the local light intensity in such a medium will tend to be $2n^2(x)$ times greater than the externally incident light intensity, where $n(x)$ is the local index of refraction in the sheet. This enhancement can contribute toward a $4n^2(x)$ increase in the effective absorption of indirect-gap semiconductors like crystalline silicon.

I. INTRODUCTION

IN THE PAST DECADE, there have been a number of suggestions for the use of light trapping by total internal reflection to increase the effective absorption in the indirect-gap

Fig. 1. An inhomogeneous and textured optical sheet with position-dependent index of refraction $n(x)$ immersed in black-body radiation.

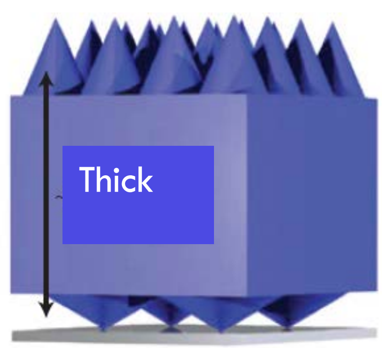
Blackbody radiation argument that is directly related to the modal structure of the solar cell



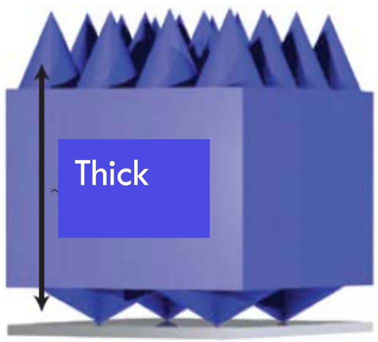
Wang , Fan and et. al *Nano Lett,* 2012

Single-pass absorption: $A = 1 - e^{-\alpha d} \approx \alpha d$

Total absorption: $\dfrac{\alpha d}{\alpha d + \frac{1}{4n^2}}$



Enhancement in absorption coefficient: $4n^2$



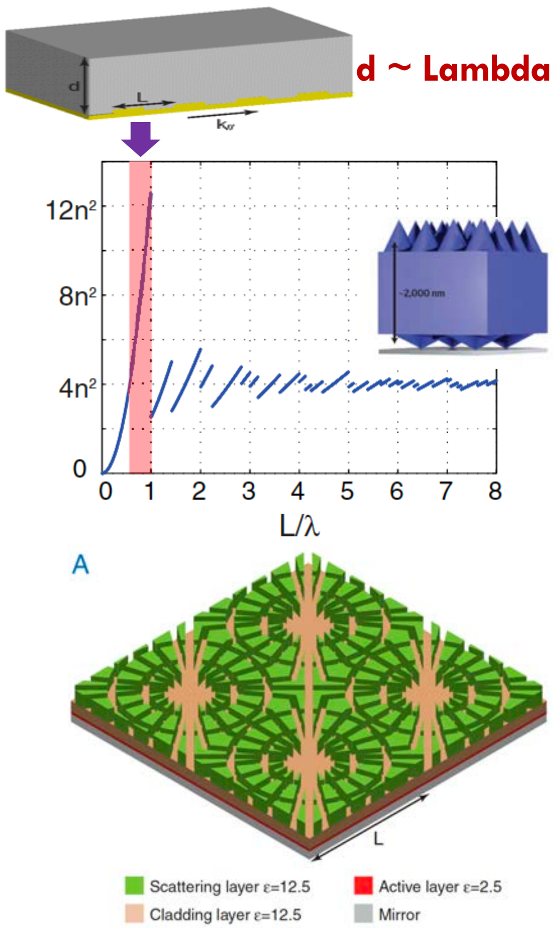
Enhancement in absorption coefficient: $4n^2$

$$\alpha_{enhanced} = \alpha \times 4n^2$$

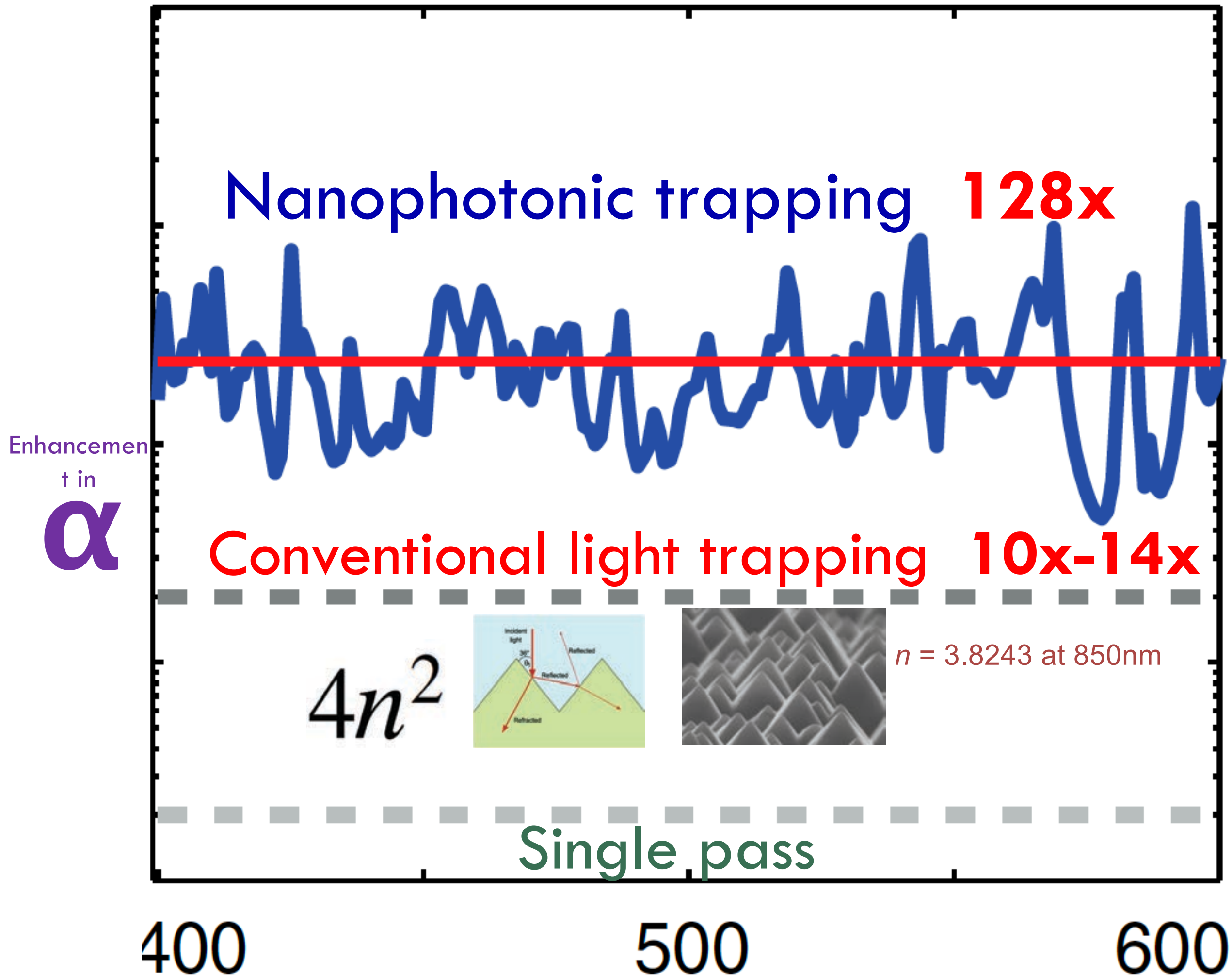
Fundamental limit of nanophotonic light trapping in solar cells

Zongfu Yu[1], Aaswath Raman, and Shanhui Fan[1]

Ginzton Laboratory, Stanford University, Stanford, CA 94305



PNAS | 2010 | vol107 | no. 41 | p17491



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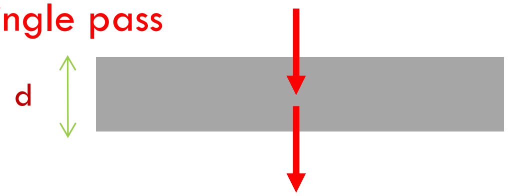
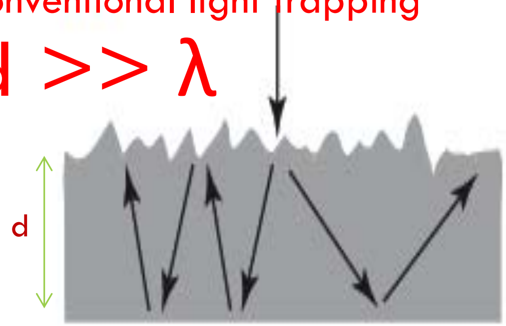
Enhancing Light-Material Interaction

Single pass



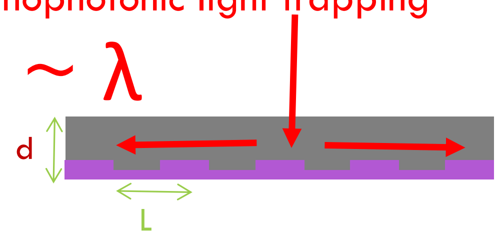
Conventional light trapping

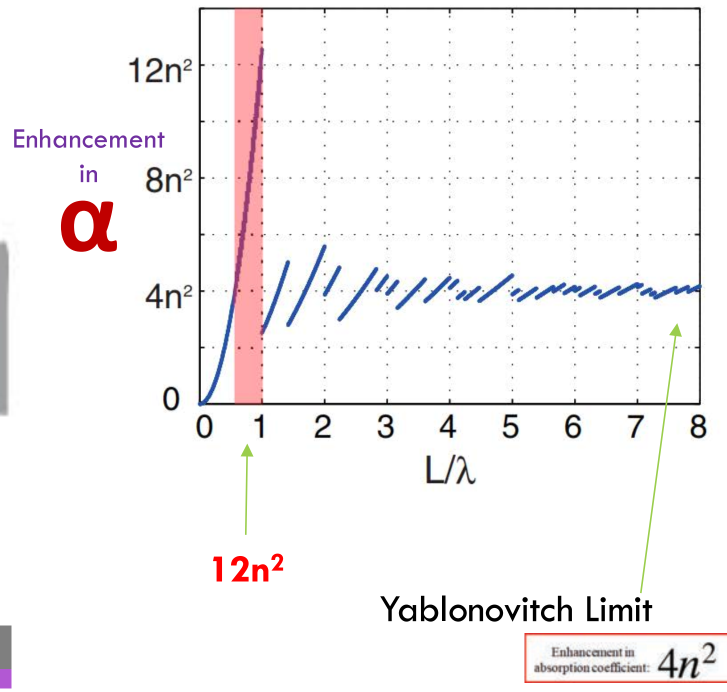
$d >> \lambda$

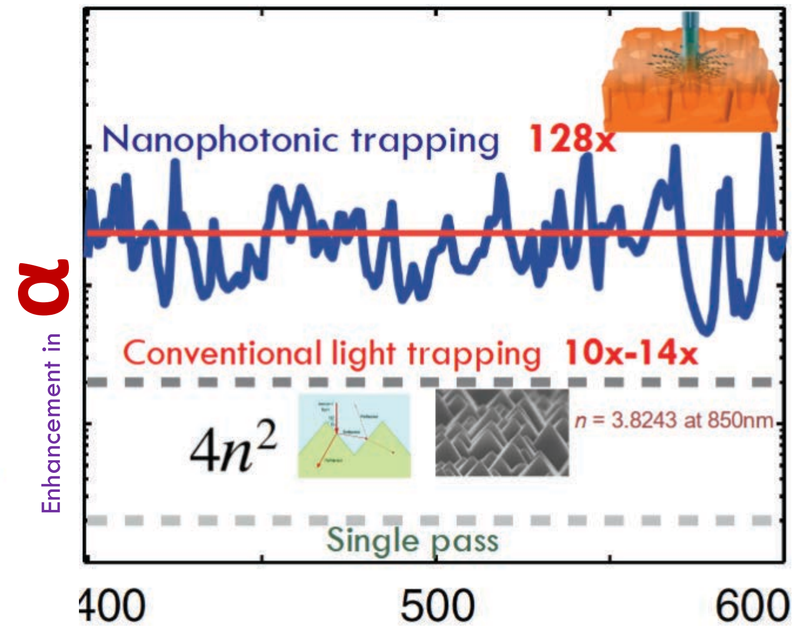


Nanophotonic light trapping

$d \sim \lambda$







Z. Yu, A. Raman, and S. Fan, "Fundamental limit of nanophotonic light trapping in solar cells," *Proc Natl Acad Sci U S A,* vol. 107, no. 41, pp. 17491-6, Oct 12 2010.

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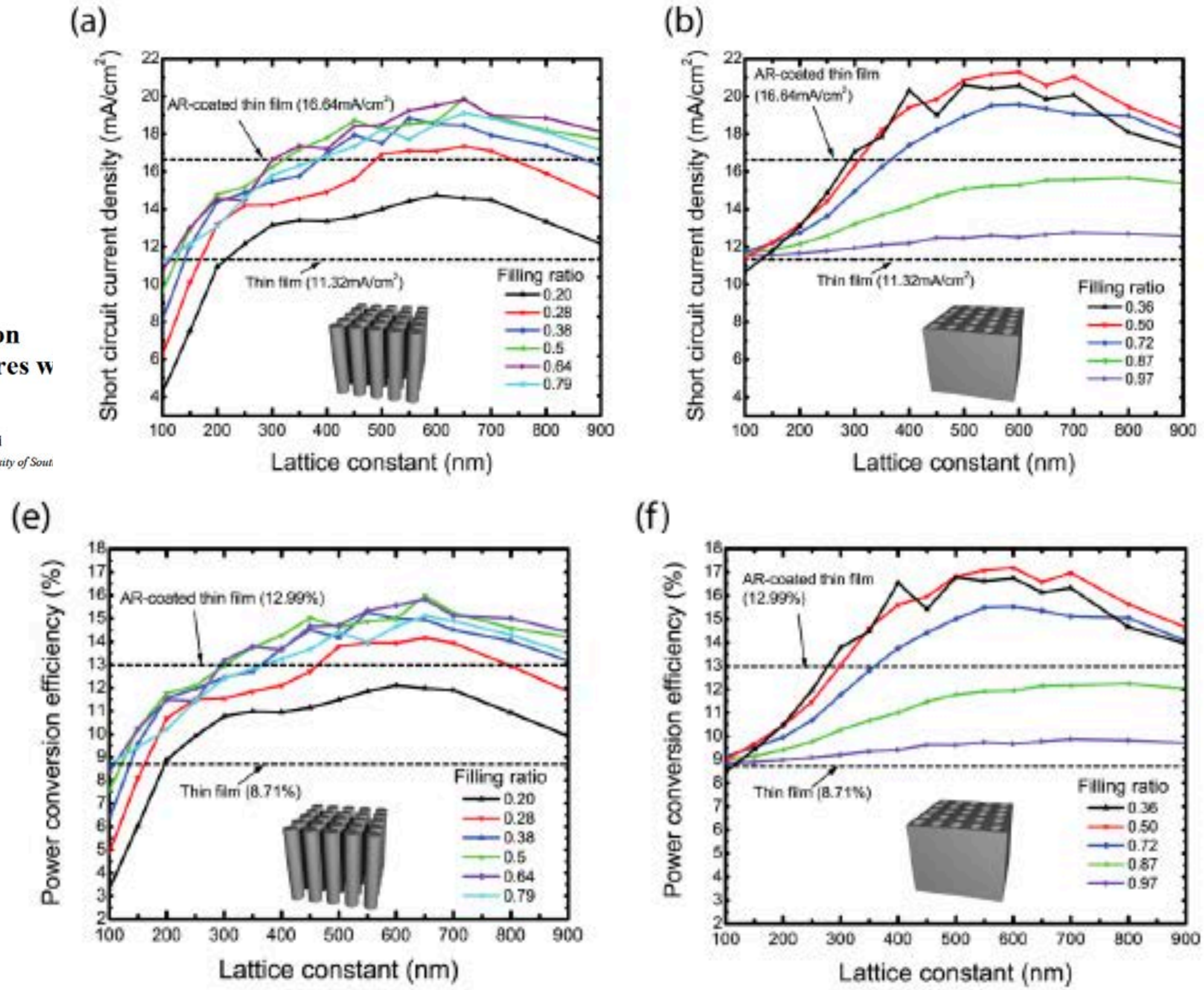
Experimental broadband absorption enhancement in silicon nanohole structures w optimized complex unit cells

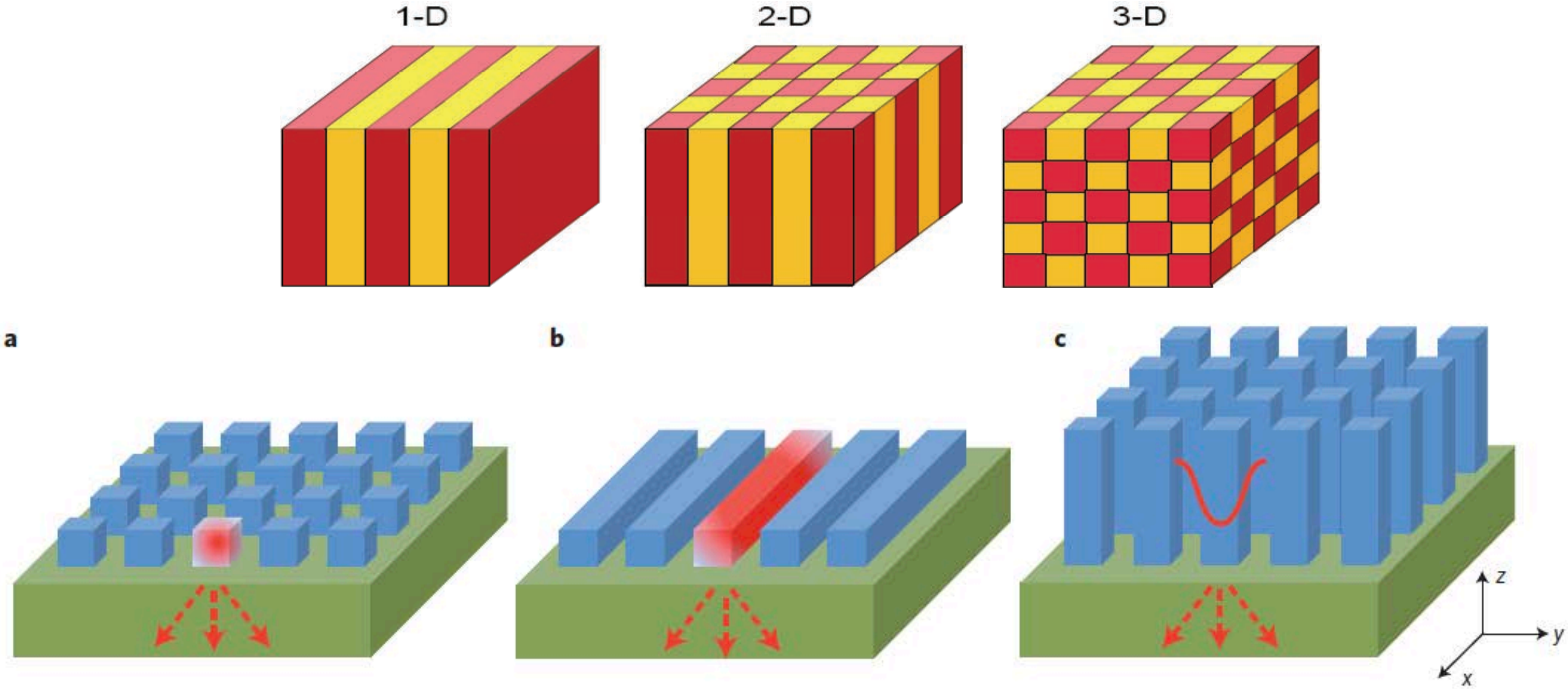
Chenxi Lin,* Luis Javier Martinez, and Michelle L. Povinelli

Ming Hsieh Department of Electrical Engineering and Center for Energy Nanoscience University of Sout California, Los Angeles, CA 90089, USA
*chenxil@usc.edu

2013



light-trapping Structures



NATURE MATERIALS | VOL 13 | MAY 2014

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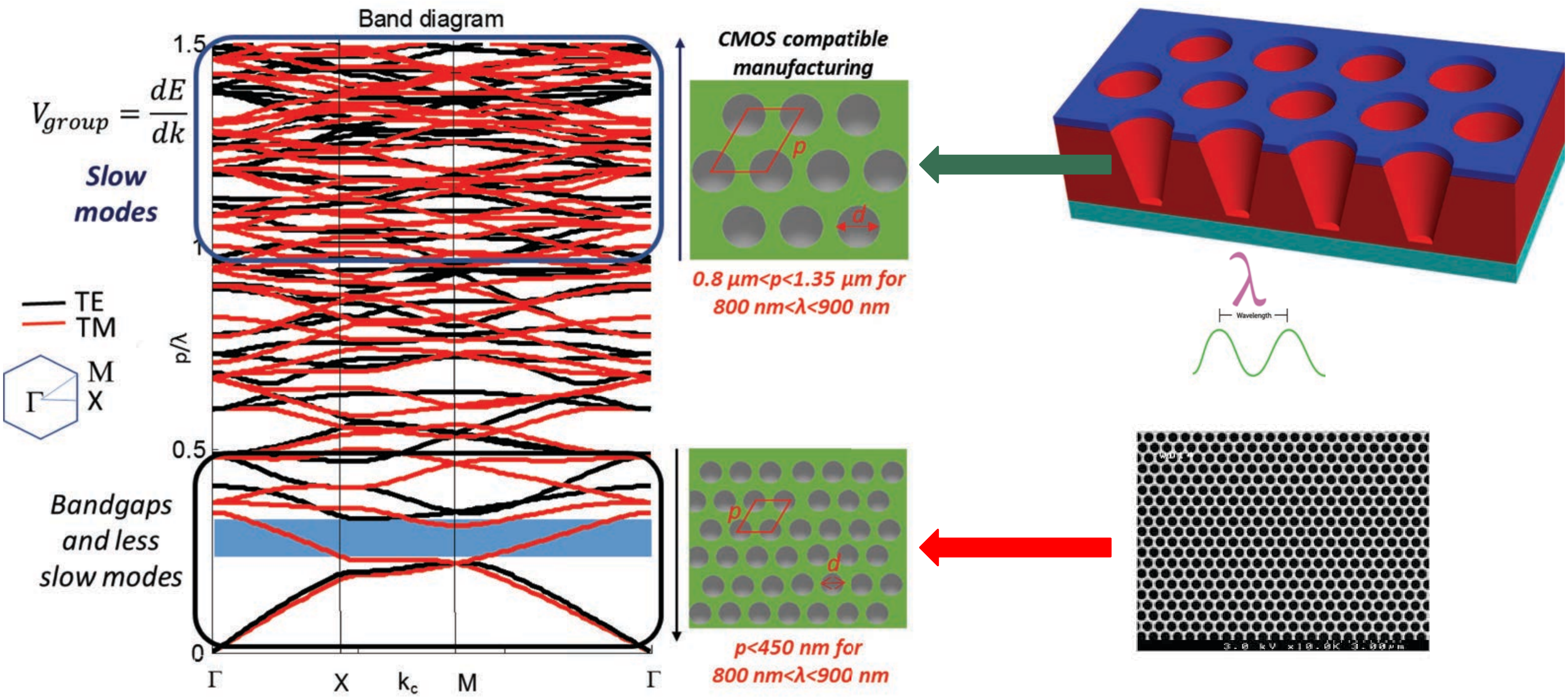
Slow Light and Guided Modes



Wave Optics Light Trapping Theory: Mathematical Justification and Ultimate Limit on Enhancement

KEN XINGZE WANG[1*], YU GUO[2], SHANHUI FAN[2†]

[1] School of Physics, Huazhong University of Science and Technology, Wuhan, Hubei 430074, China
[2] Ginzton Laboratory, Stanford University, Stanford, CA 94305, USA
[*] wxz@hust.edu.cn
[†] shanhui@stanford.edu

June 2019

Why Photons Need to be Trapped?

- Reduce cost for less abundant materials
- Improve cell efficiency with thin film (inhibit recombination)
- Using thinner absorbers in organic solar cells given their short exciton diffusion lengths of about 3 – 10 nm
- Higher open circuit voltage
- 2D materials for photonics

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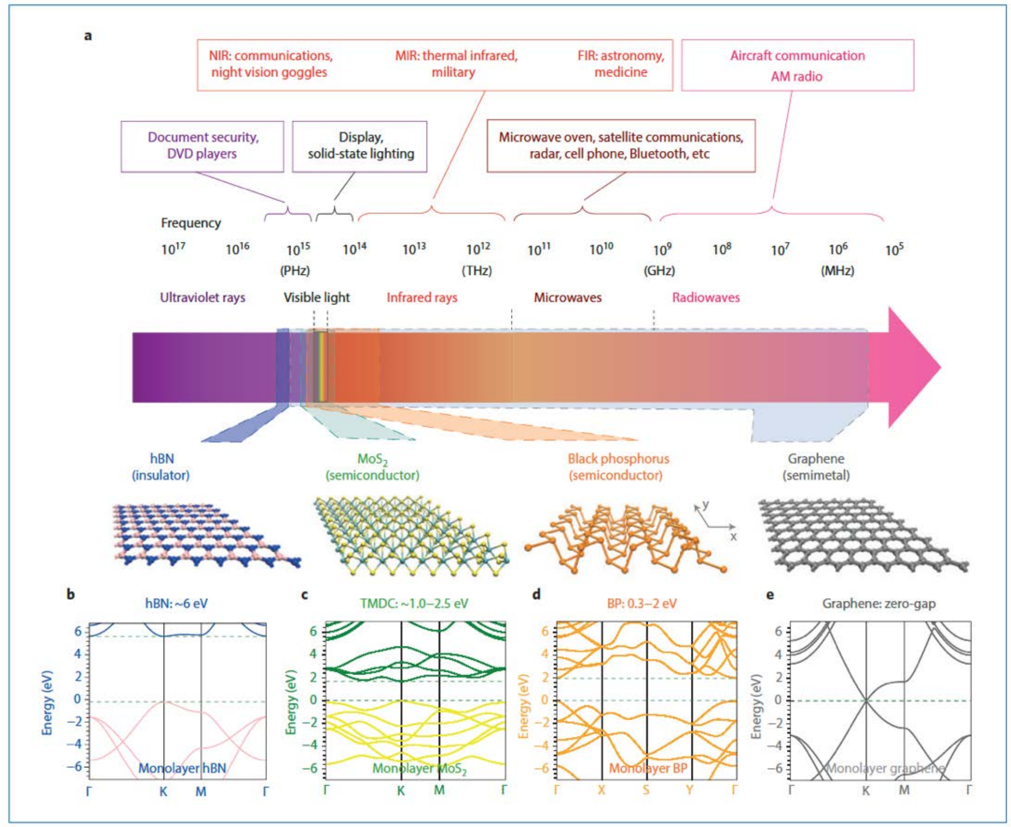
Opportunity: 2D Materials Photonics

- Broad spectrum from the far IR all the way to the UV
- Photo carrier lifetime is ~ps
- Graphene absorbs ~2% of the incident light over a



nature photonics
FOCUS | REVIEW ARTICLE
PUBLISHED ONLINE: 27 NOVEMBER 2014 | DOI: 10.1038/NPHOTON.2010.271

Two-dimensional material nanophotonics

Fengnian Xia[1*], Han Wang[2], Di Xiao[3], Madan Dubey[4] and Ashwin Ramasubramaniam[5]

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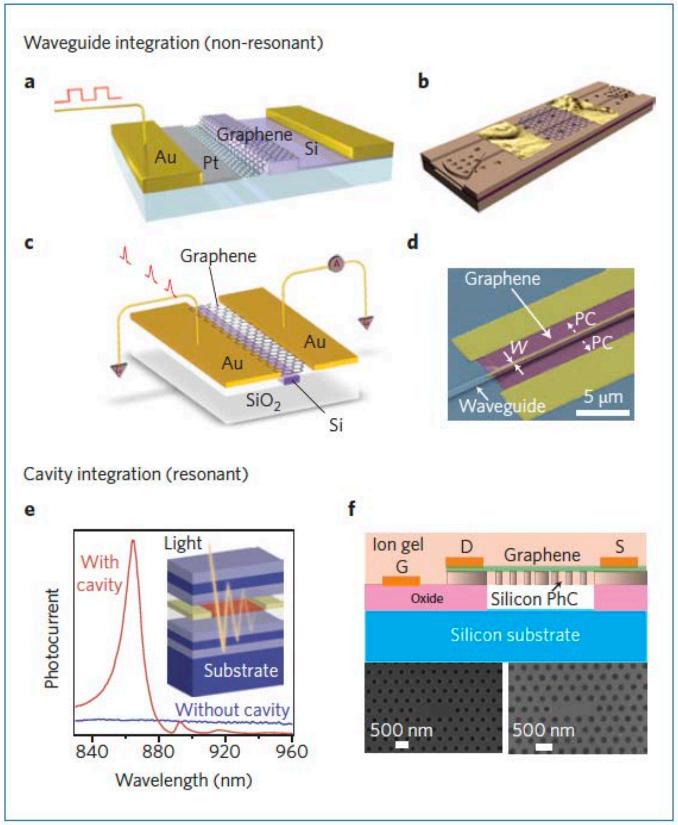
Challenge: Enhancing Absorption in 2D Materials

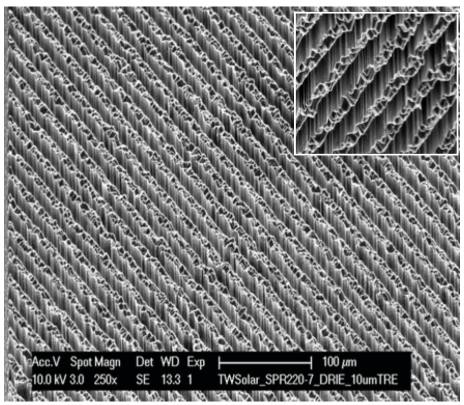
- Strongly localized incident light to graphene through plasmon excitation (energy loss in metals)
- Placing materials on waveguides
- Fabry-Pérot microcavity
- 2D PC defect cavities
- Dielectric gratings

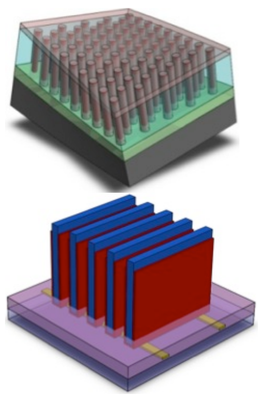
At specific frequencies only

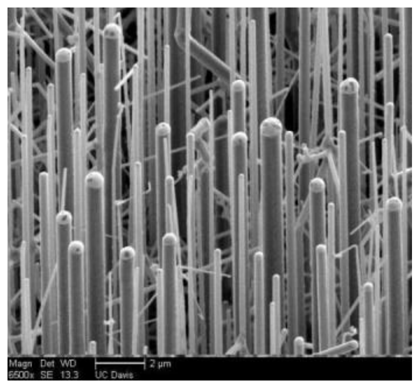


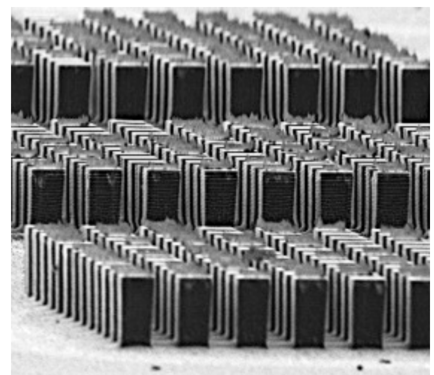
Ramasubramaniam, 2014

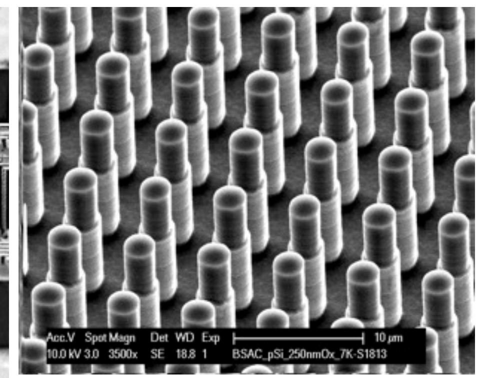
Micro/nano Wall (1D) and Pillars (2D) Enabled Diffraction for Light Trapping





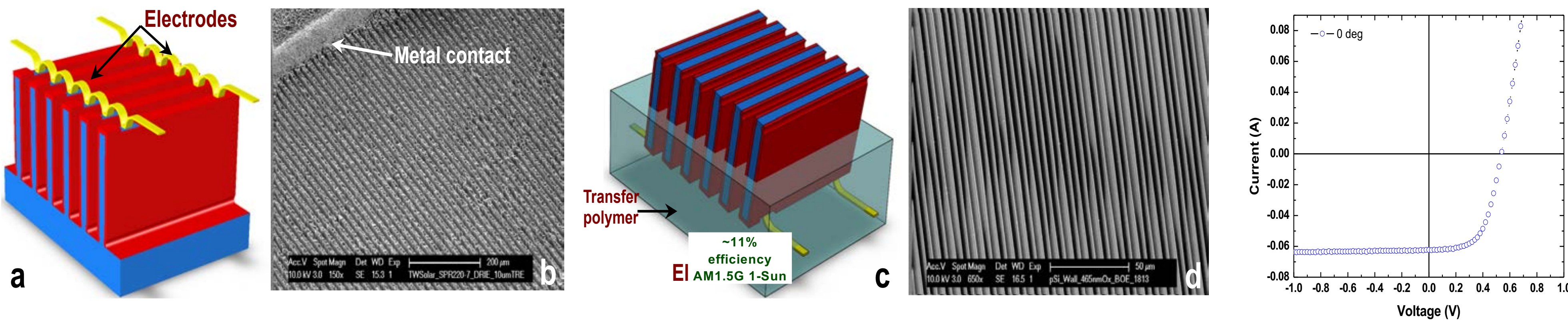






Phys. Status Solidi A 214, No. 3, 1600724 (2017)

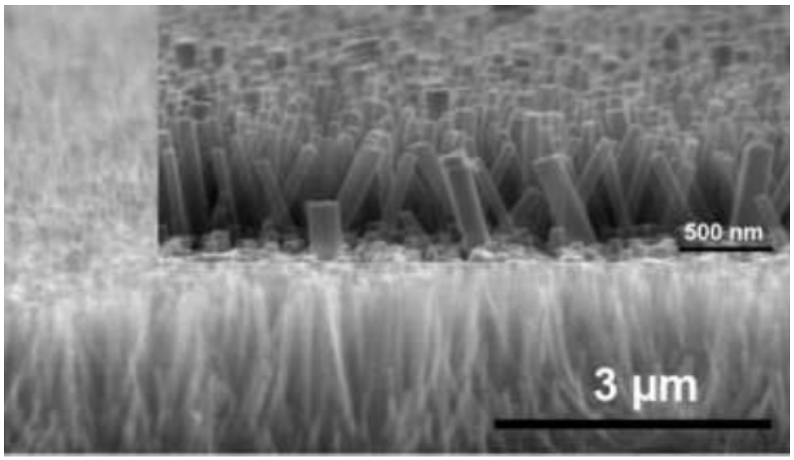
1D Periodic Diffraction: Micro/nano Wall Based PVs



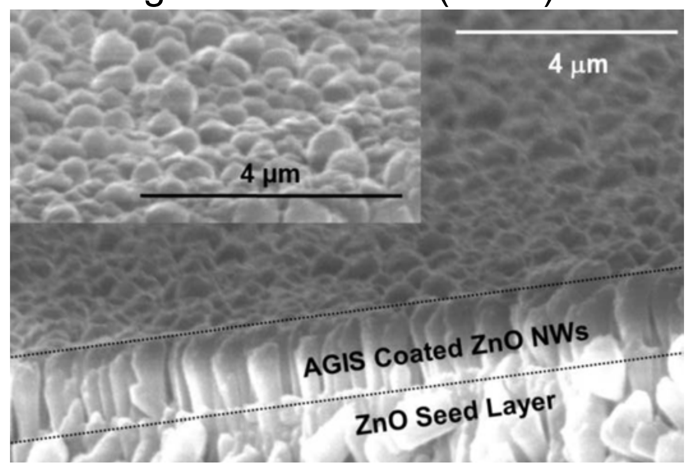
Phys. Status Solidi A 214, No. 3, 1600724, 2017

ZnO Nanowire Based PVs

ZnO Nanowires



ZnO Nanowires coated with AgGa0.5In0.5Se2 (AGIS)



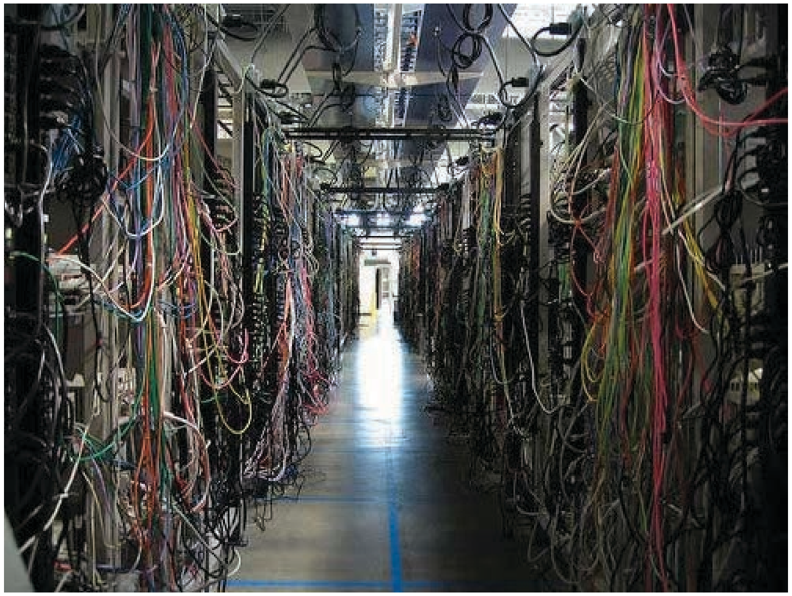
- Grow n-ZnO on anything
- Coat it with p-Chalcopyrite to form a junction ($AgGa_{0.5}In_{0.5}Se_2$ - AIGS/CIGS)

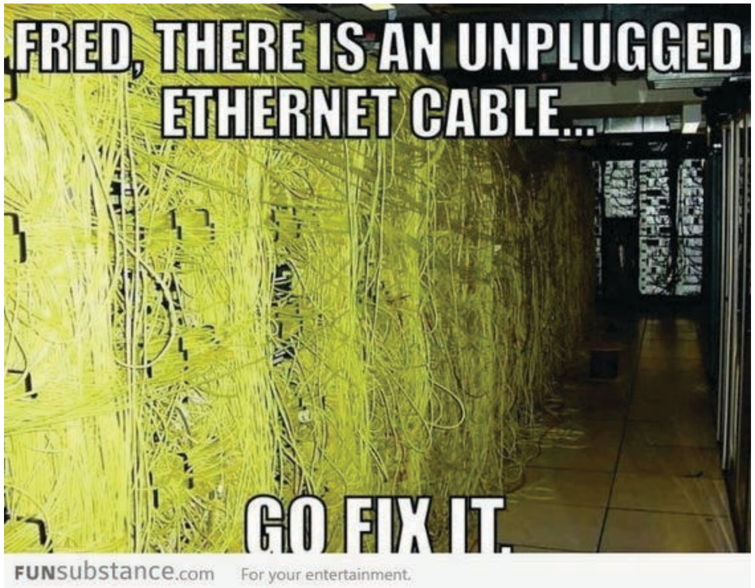
Islam, Materials Chemistry and Physics, 2013

Highly-efficient and ultra-fast photodetection

Data Center Cable Hell

- 1 channel/cable
- Short distance and signal needs to be amplified





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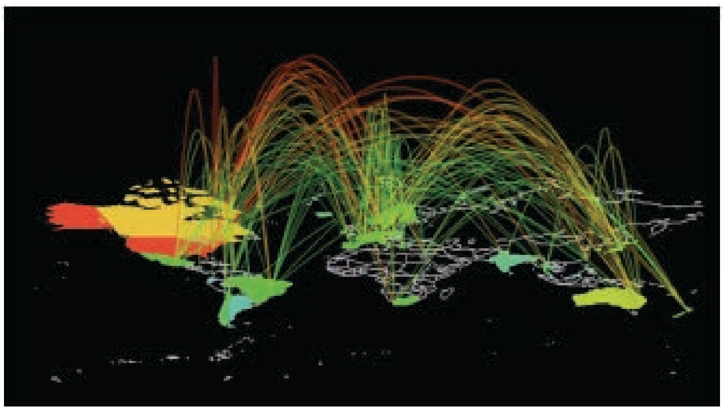
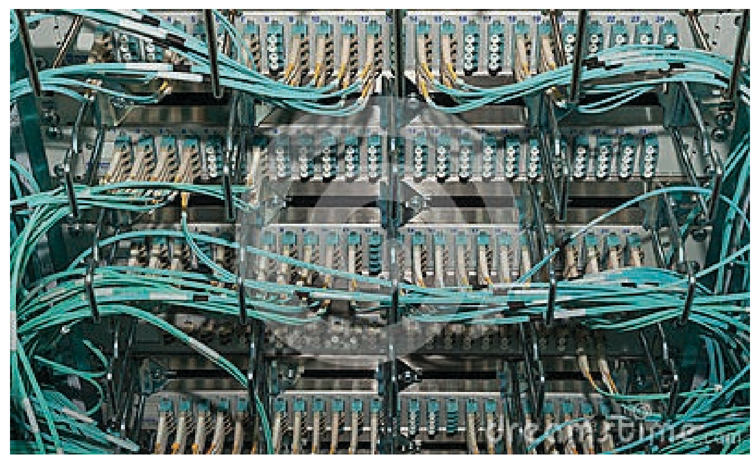
Optical Network Paradise

- Many channels per cable
- Higher speed 100+ Gbps
- Few meters to 10s of Km





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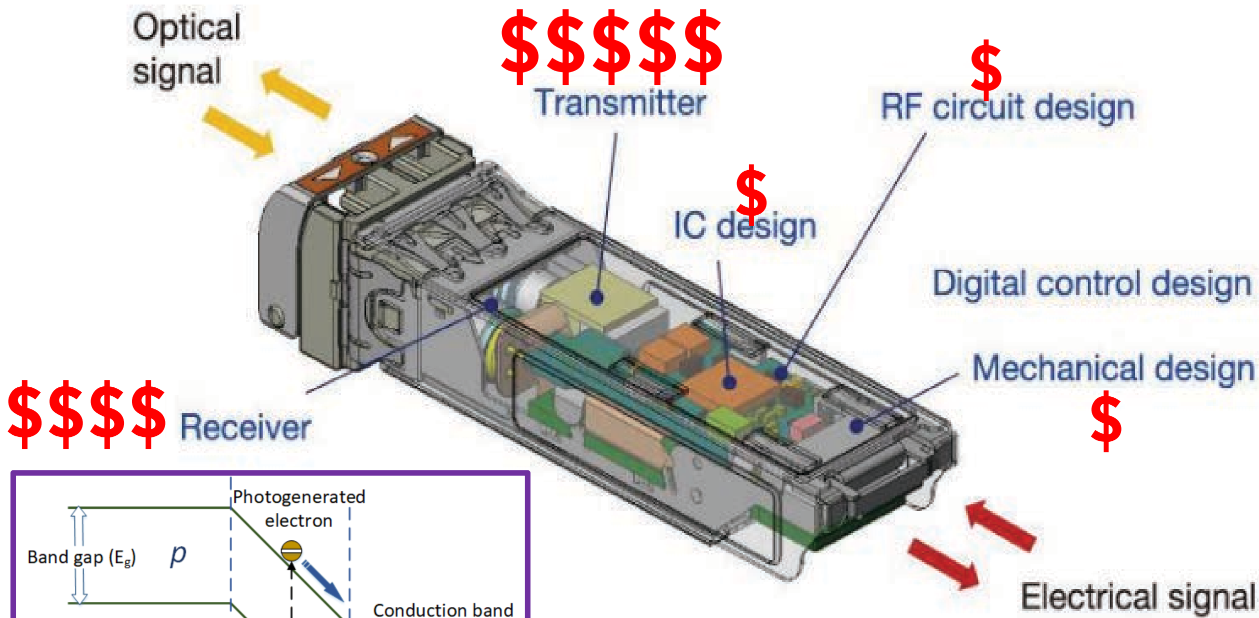
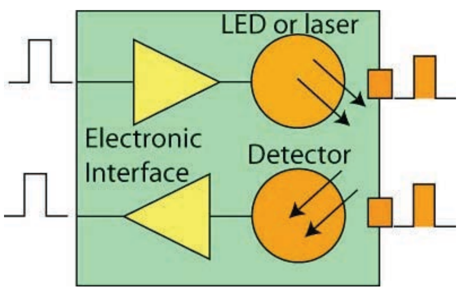
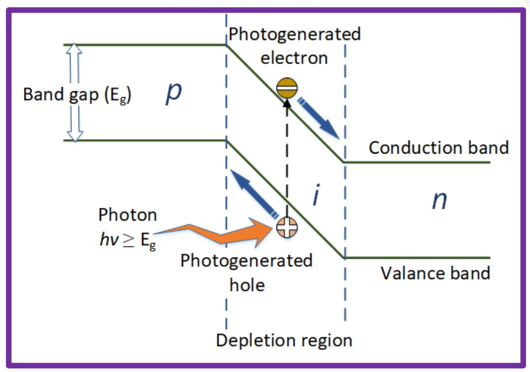
Fiber Optic Transceivers





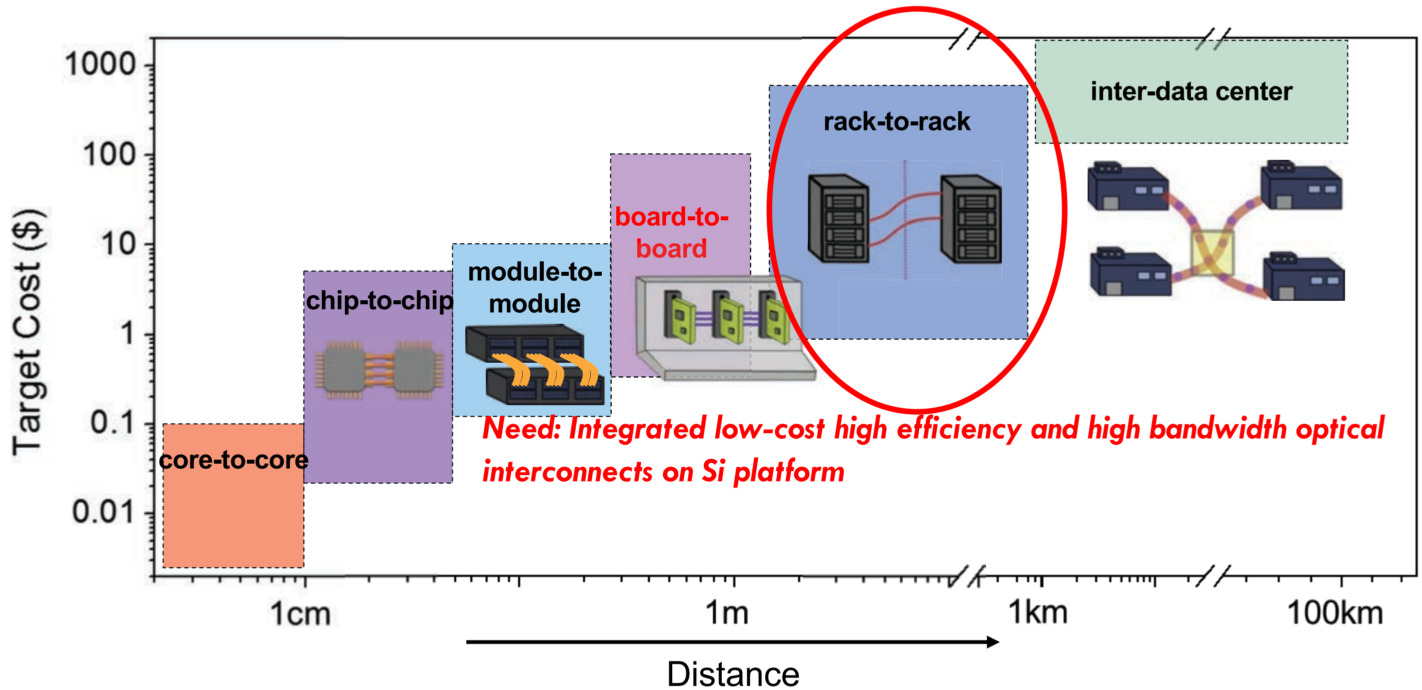


100 Gbps Fiber Cables

	Digi-Key Part Number	Manufacturer Part Number	Manufacturer	Description	Quantity Available	Unit Price USD	Minimum Quantity	Series	Part Status	Data Rate	Wavelength
	AFBR-89CDDZ-ND	AFBR-89CDDZ	Foxconn Optical Interconnect Technologies, Inc.	TXRX QSFP28 100GBPS 850NM	0 Standard Lead Time 8 Weeks	$656.25000	10 Non-Stock	-	Active	100Gbps	850nm
	AFBR-89CEDZ-ND	AFBR-89CEDZ	Foxconn Optical Interconnect Technologies, Inc.	TXRX QSFP28 100GBPS 850NM	0 Standard Lead Time 8 Weeks	$775.00000	10 Non-Stock	-	Active	100Gbps	850nm
Photo Not Available	AFBR-8422IDZ-ND	AFBR-8422IDZ	Foxconn Optical Interconnect Technologies, Inc.	CFP2 GEN2 SR10 TXCR	0 Standard Lead Time 10 Weeks	$1,625.00000	1 Non-Stock	-	Active	100Gbps	150nm
	516-3086-ND	AFBR-8420Z	Foxconn Optical Interconnect Technologies, Inc.	100G CFP2 SR10 TRANCEIVER MODULE	0	$1,875.00000	-	-	Not For New Designs	10.3125Gbps	850nm
Photo Not Available	AFBR-8422EDZ-ND	AFBR-8422EDZ	Foxconn Optical Interconnect Technologies, Inc.	CFP2 GEN2 ESR10 TXCR	0 Standard Lead Time 10 Weeks	$2,031.25000	1 Non-Stock	-	Active	100Gbps	550nm
	AFCT-8450Z-ND	AFCT-8450Z	Foxconn Optical Interconnect Technologies, Inc.	TXRX CFP 100GBPS	0 Standard Lead Time 10 Weeks	$5,160.00000	1 Non-Stock	-	Active	100Gbps	-

FOXCONN
Advancing Through Innovation

Current and Target Cost: Gbps Data



Current market is dominated by **GaAs/InGaAs** photodetectors

Target: To reduce cost from10s of dollars/Gbps to 1 dollar/Gbps and even to *$0.5/Gbps*

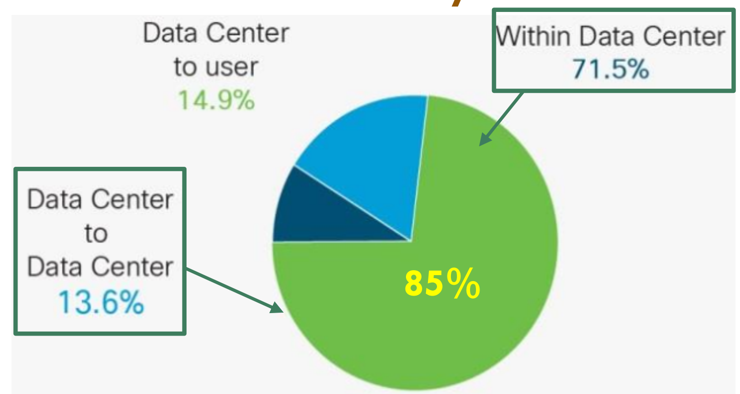
Refs:
Kachris, K. Kanonakis, and I. Tomkos, "Optical interconnection networks in data centers: Recent trends and future challenges," *IEEE Communications Magazine*, vol. 51, pp. 39-45, 2013
E. Agrell, M. Karlsson, A. Chraplyvy, D. J. Richardson, P. M. Krummrich, P. Winzer, *et al.*, "Roadmap of optical communications," *Journal of Optics*, vol. 18, p. 063002, 2016

Global traffic in datacenters

- 2 folds growth in 3 years
- 3 folds growth in 5 years (forecast)

Global datacenters' traffic growth (CISCO 2018)

Global data traffic by destination



Unprecedented pace of big data growth

- 90% of the world's data has been created in the last 2 years alone.
- Most companies only analyze 12% of the data they have.
- By 2020, there will be more than 50 billion smart connected devices in the world, collecting, analyzing and sharing data.
- Bad data costs the US $3.1 Trillion annually.
- AI's impact on marketing is growing, predicted to reach nearly $40 billion by 2025.
- IoT will save consumers and businesses $1 trillion a year by 2022.

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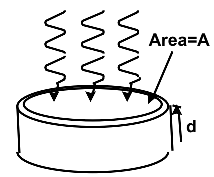
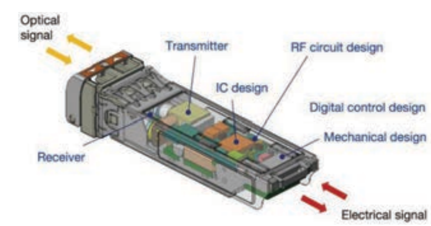
Evolution of Broadband High Power Photodetectors

Paradigm shift:
High-speed photodetectors with large absorption volume are desired

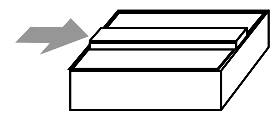
Surface-illuminated Photodetector (SIPD) — Limited frequency-efficiency product





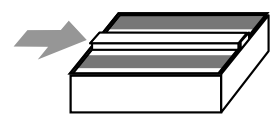
↓

Waveguide Photodetector (WGPD) — Limited by RC

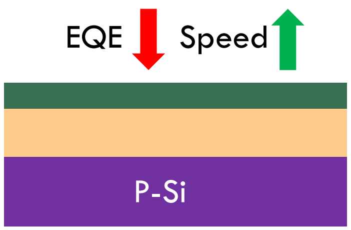


↓

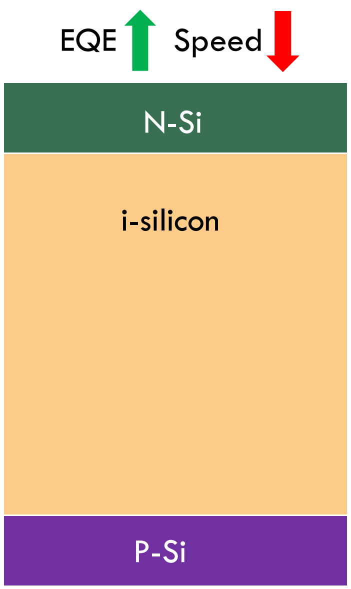
Traveling Wave Photodetector (TWPD) — Limited by velocity mismatch



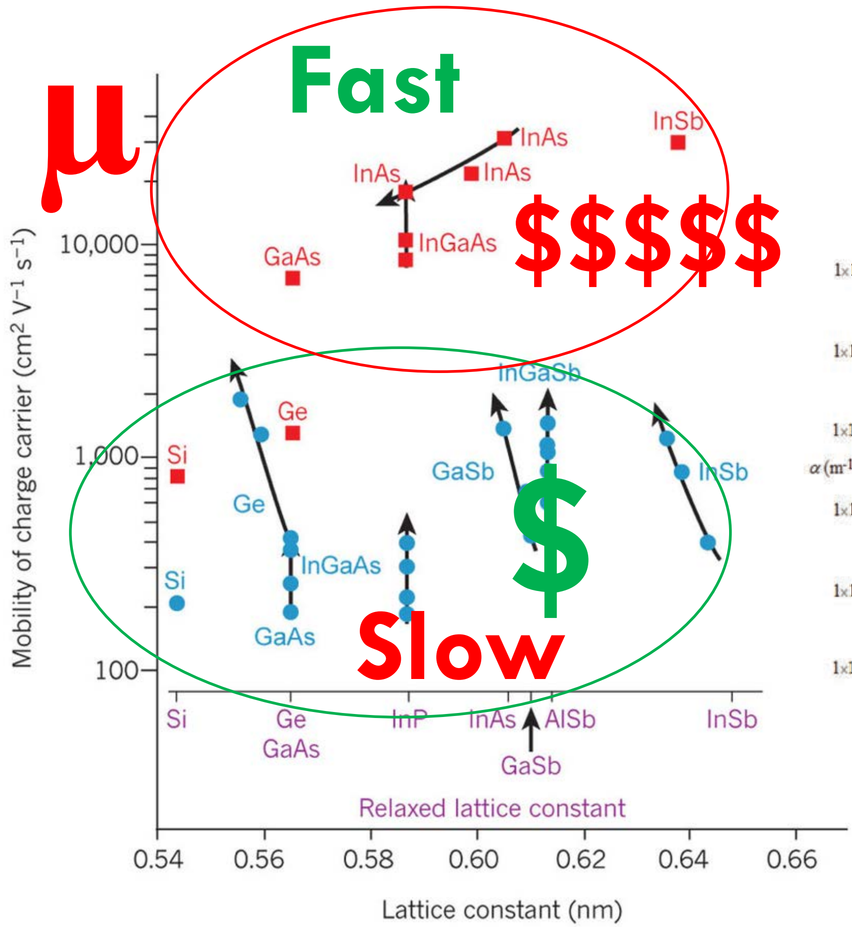
Photodiodes: Speed & Efficiency

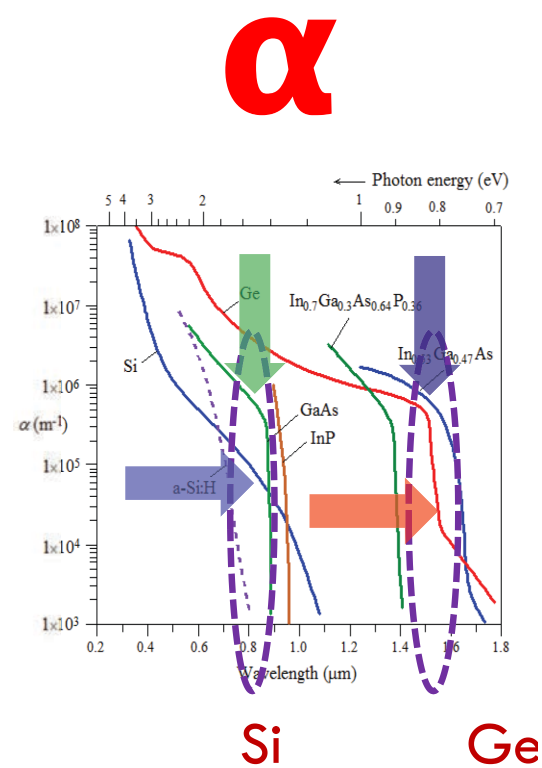


Fast Detector

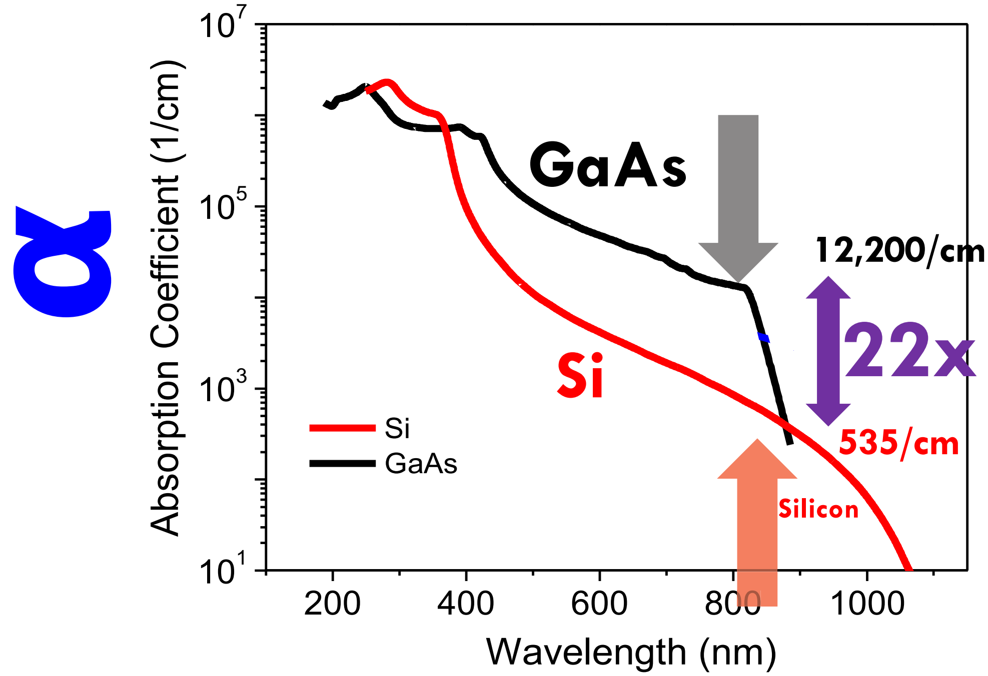


Slow Detector

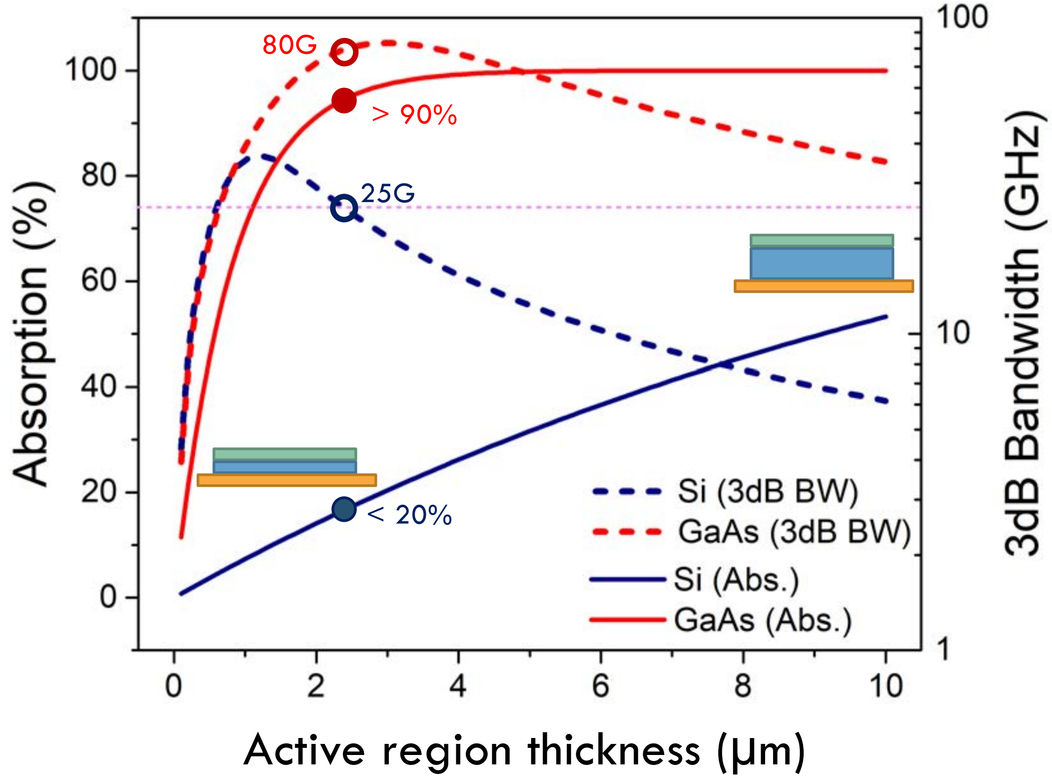




Silicon is a weak absorber close to band edge



High-speed and High-efficiency trade-off



Optical absorption:

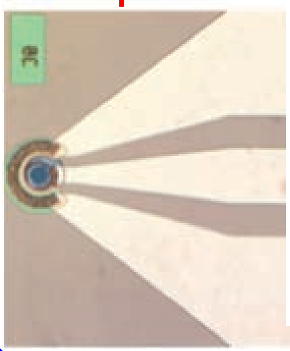
$$\eta = 1 - exp(-\alpha d)$$

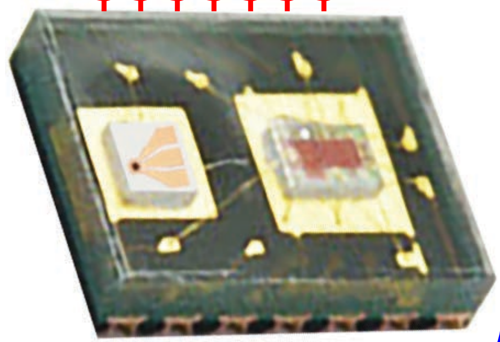
Photodiode 3dB bandwidth:

$$f_{3dB} = \frac{1}{\sqrt{(2\pi RC)^2 + (\frac{t_r}{0.44})^2}}$$

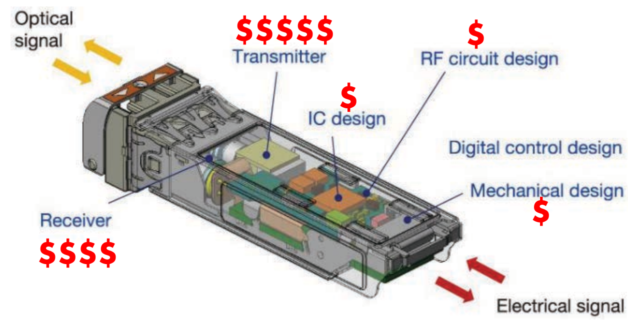
Fiber Optic Transceiver: Integration Challenge

$ $$$$$$$

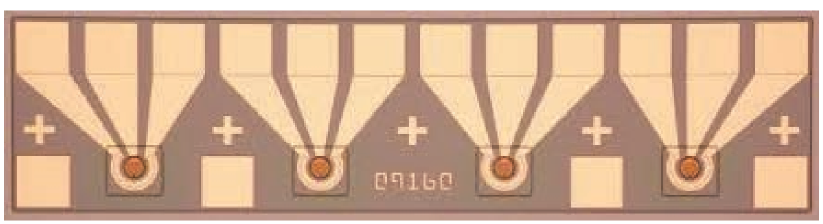


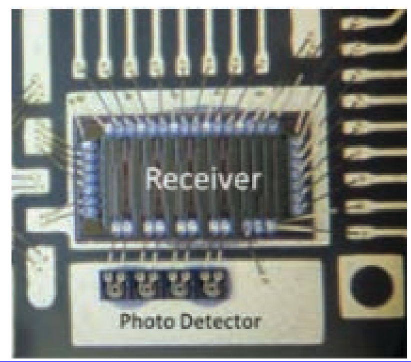


Single



4x1 Array





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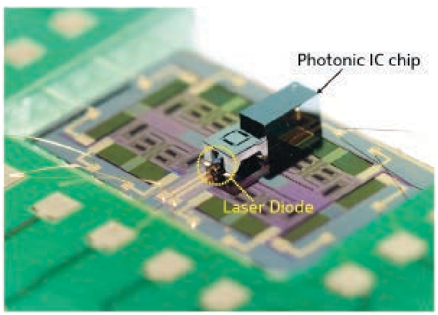
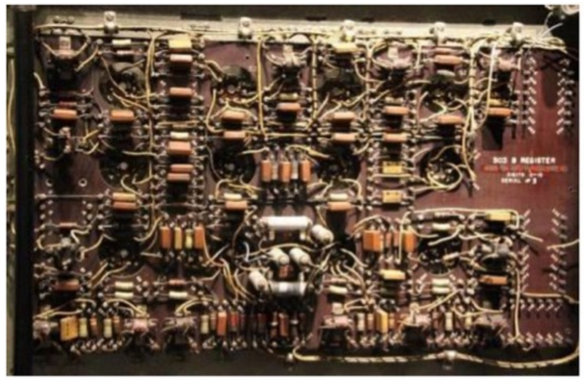
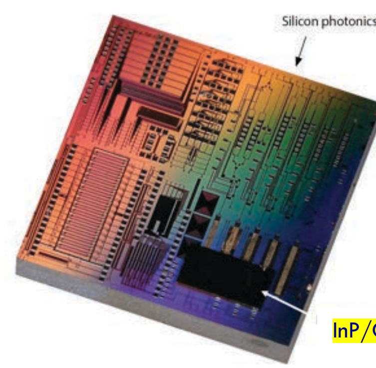
Hybrid Integration on Silicon





Whirlwind, MIT, 1952



1mm^2 of processes Intel chip: \$0.03

→ each PD/LD will be \$0.0003

What is the solution?

EQE ↑ Speed ↓

N-Si

i-silicon

Commercial Detector

P-Si

Increase absorption in Si α

Make silicon faster μ

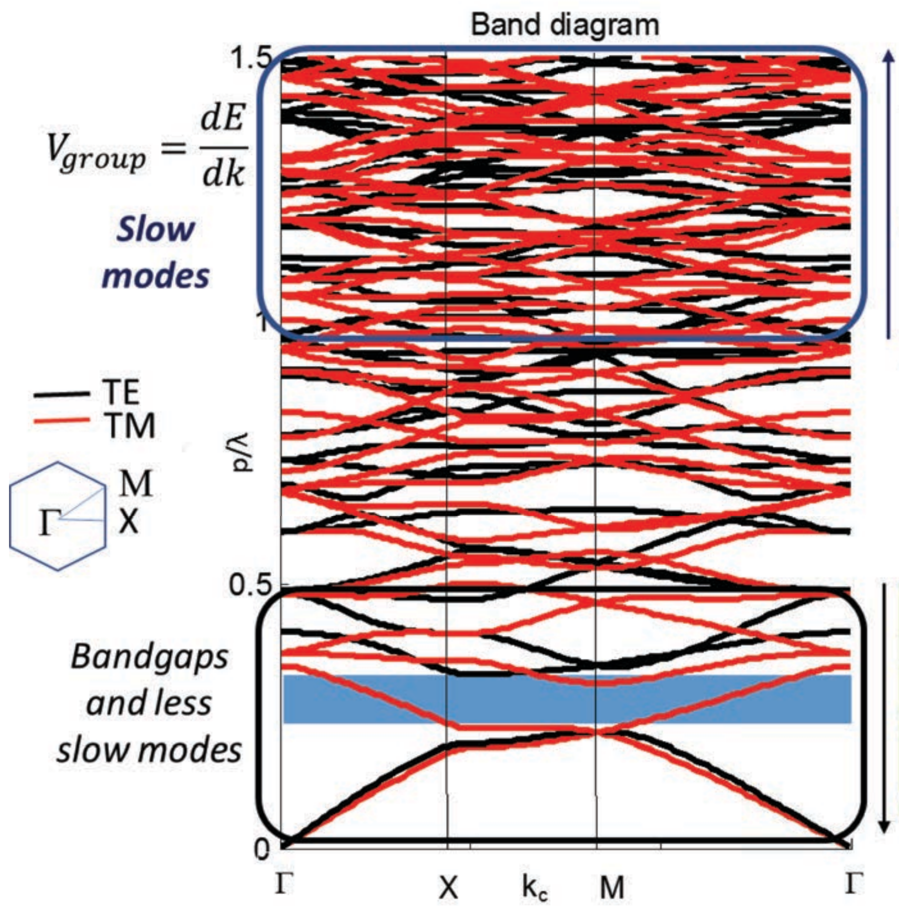
→

EQE ↓ Speed ↑

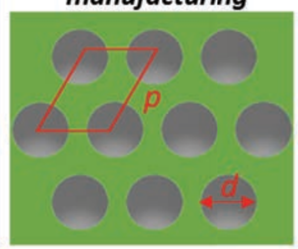
Fast Detector

P-Si

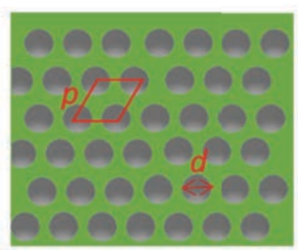
Slow Light and Guided Modes



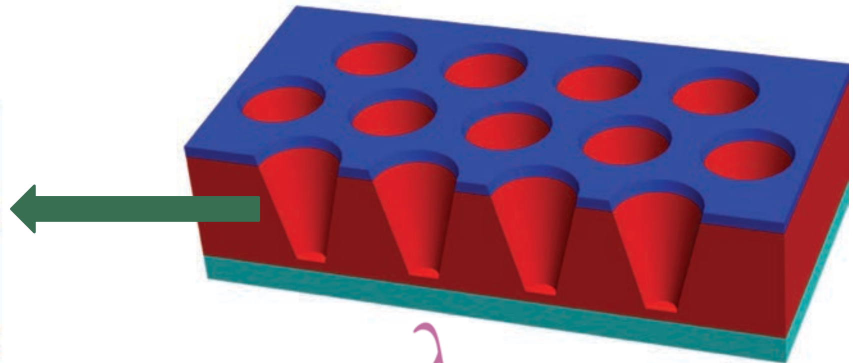
CMOS compatible manufacturing

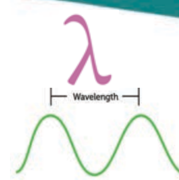


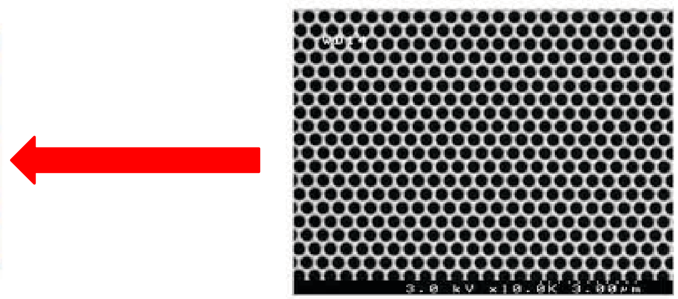
0.8 µm<p<1.35 µm for 800 nm<λ<900 nm



p<450 nm for 800 nm<λ<900 nm







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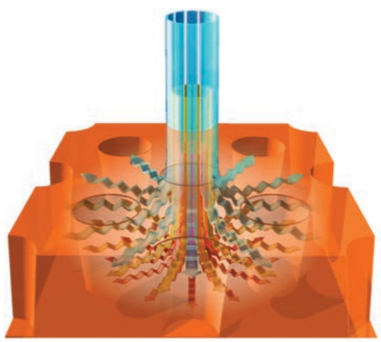
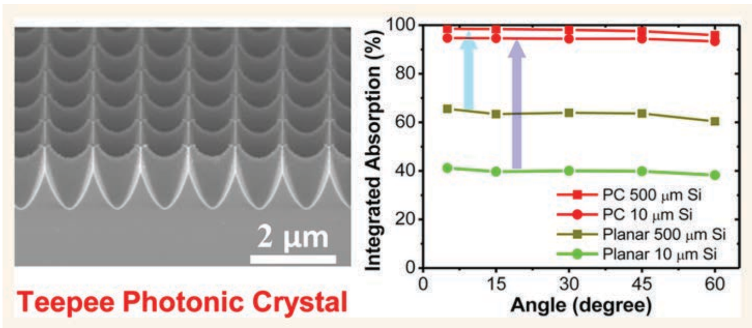
Innovative Approach: Parallel-to-interface Refractive Modes

- Photonic crystals (PC) enable flat absorption by exciting parallel-to-interface refractive (PIR) modes
- Light incident at nearly normal incidence is refracted into PC modes propagating nearly parallel to the air-PC interface
- PIR modes enables light trapping and harvesting
- PIR modes have **a long lifetime** and **slow group velocity** inside the PC. This increases the interaction time between light and materials.

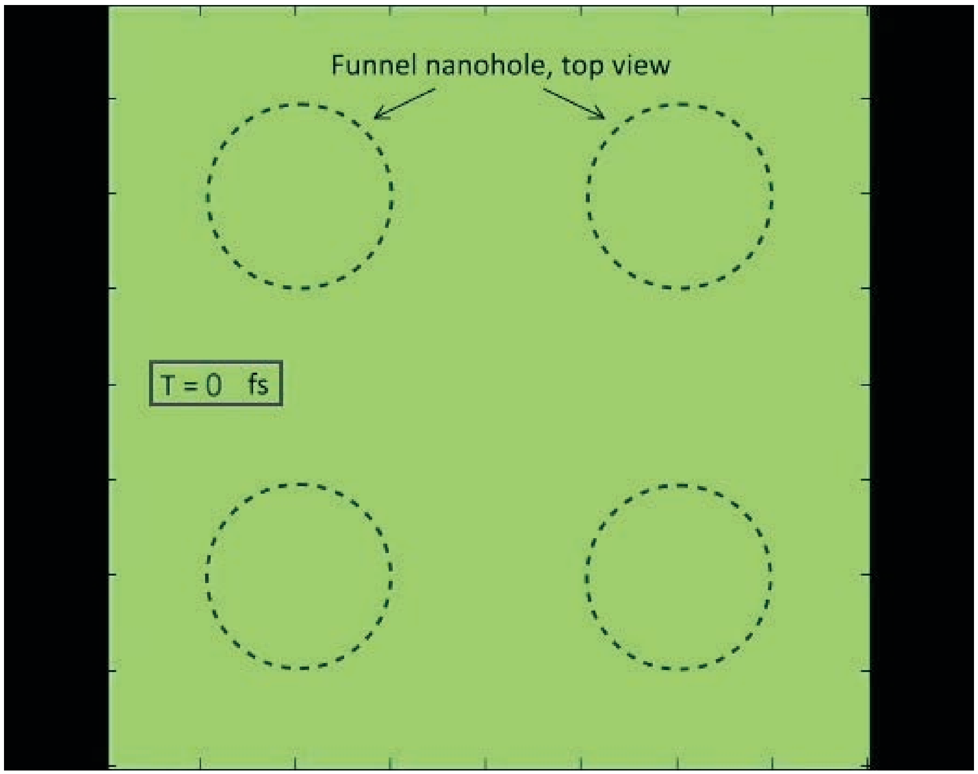


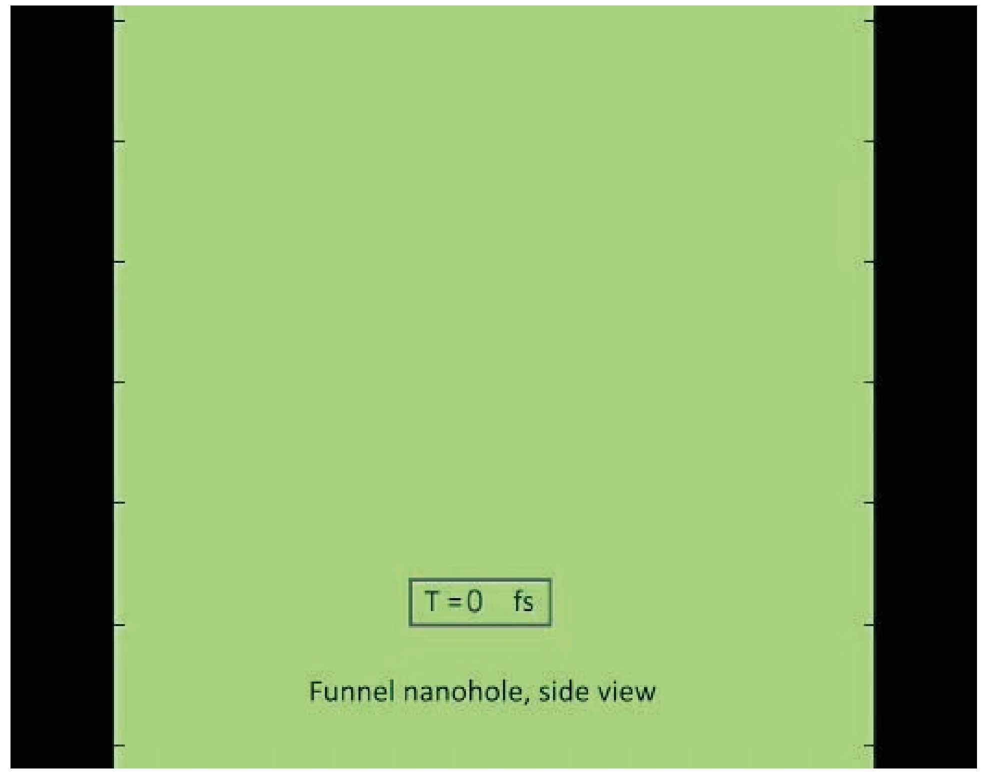
Gao, Cansizoglu, et. al; *Nature Photonics*, 11(5), p30, 2017



Sajeev John & Shawn-Yu Lin, 2016

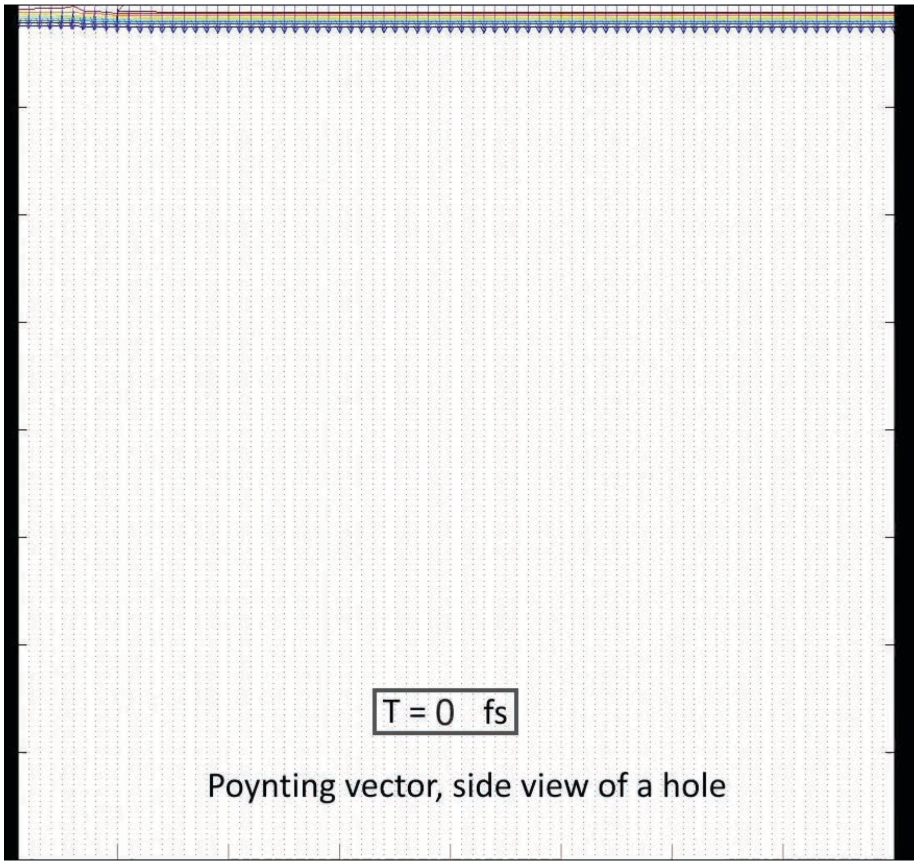
Light Bending & Trapping

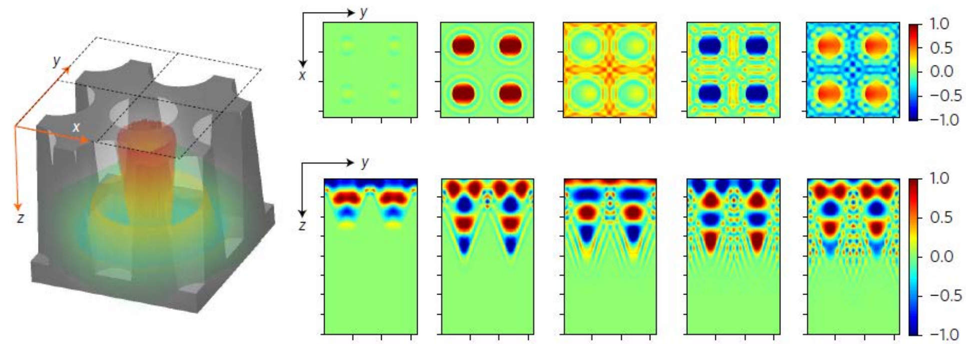




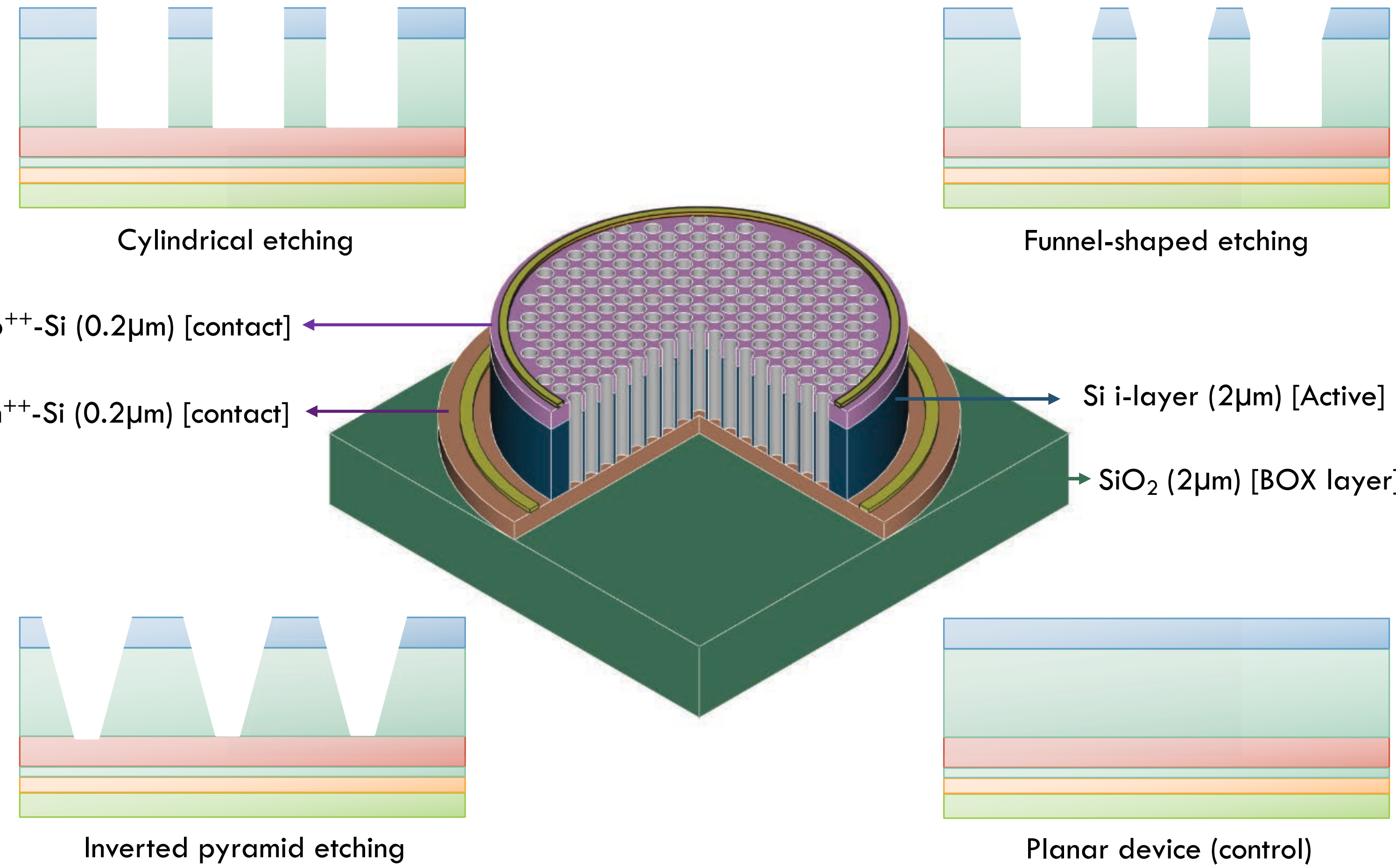
Y. Gao, H. Cansizoglu, K. G. Polat, S. Ghandiparsi, A. Kaya, H. H. Mamtaz, *et al.*, "Photon-trapping microstructures enable high-speed high-efficiency silicon photodiodes," *Nat Photon,* vol. 11, pp. 301-308, 05//print 2017.

Light bending at 90 degrees

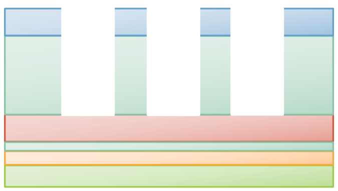




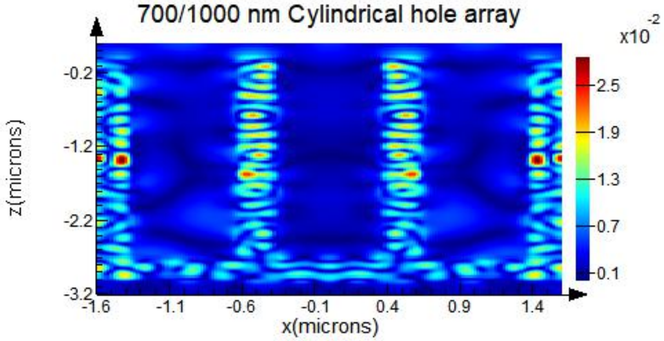
Parallel-to-interface Refractive Modes in a PIN photodiode

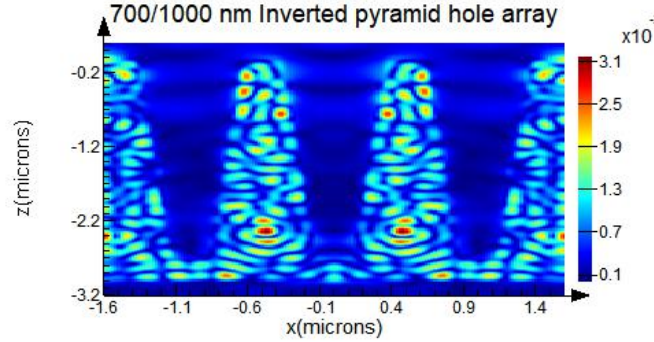


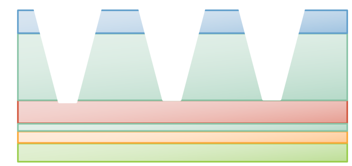
Parallel-to-interface Refractive Modes in a PIN photodiode



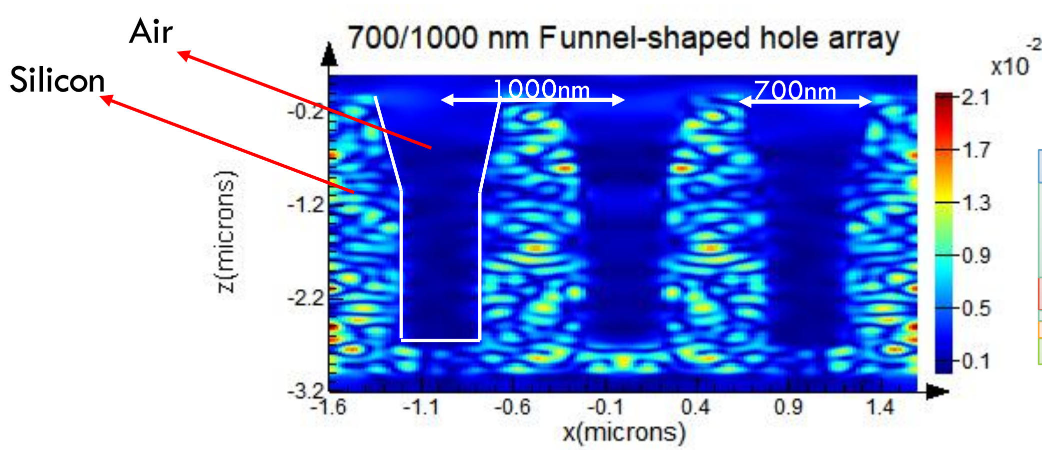
Cylindrical etching

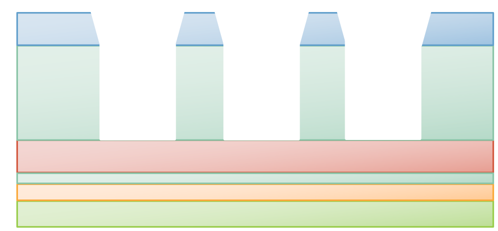






Inverted pyramid etching





Funnel-shaped etching

Y. Gao, et al., "Photon-trapping microstructures enable high-speed high-efficiency silicon photodiodes, " Nature Photonics, 11(5), 301-308 (2017).

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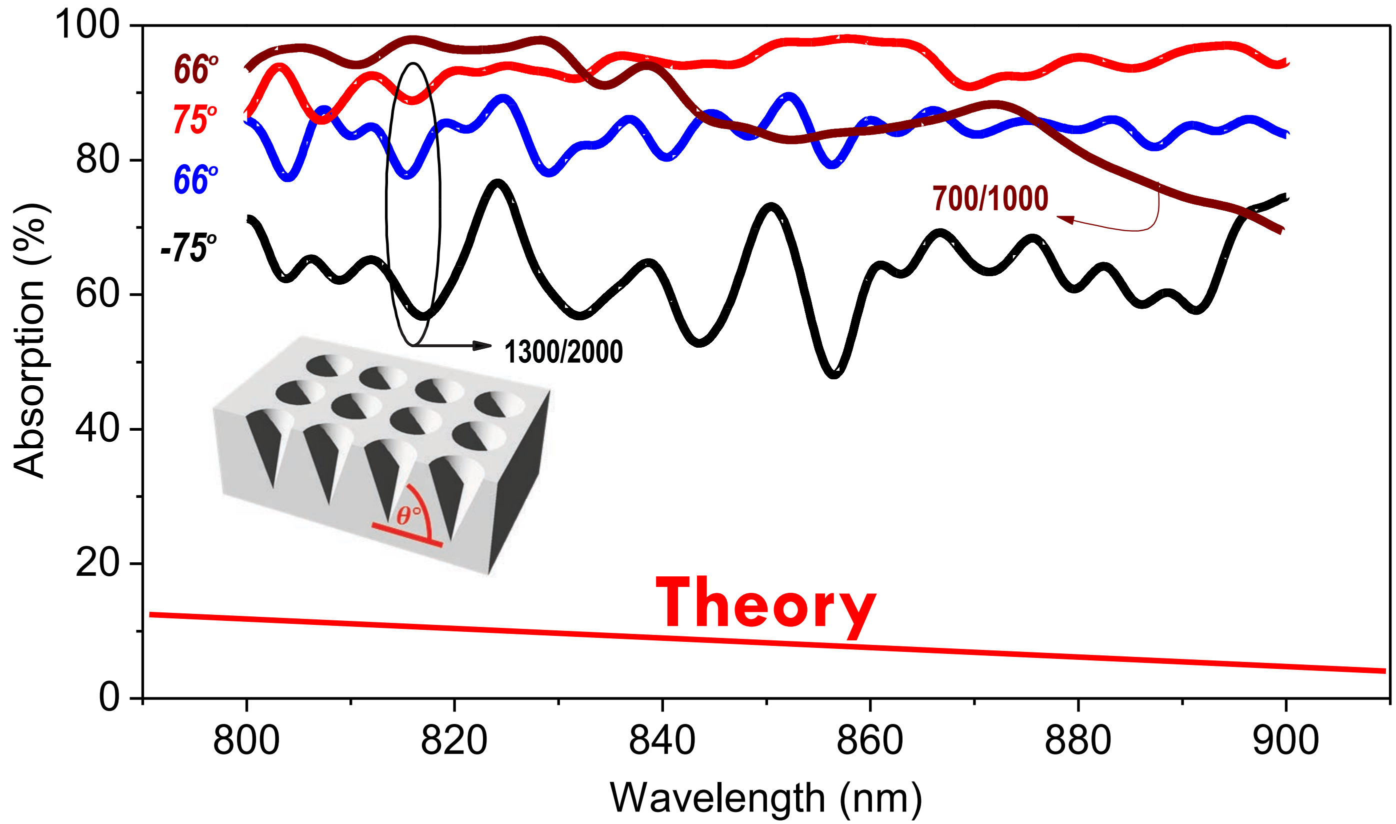
Absorption in 2μm Silicon



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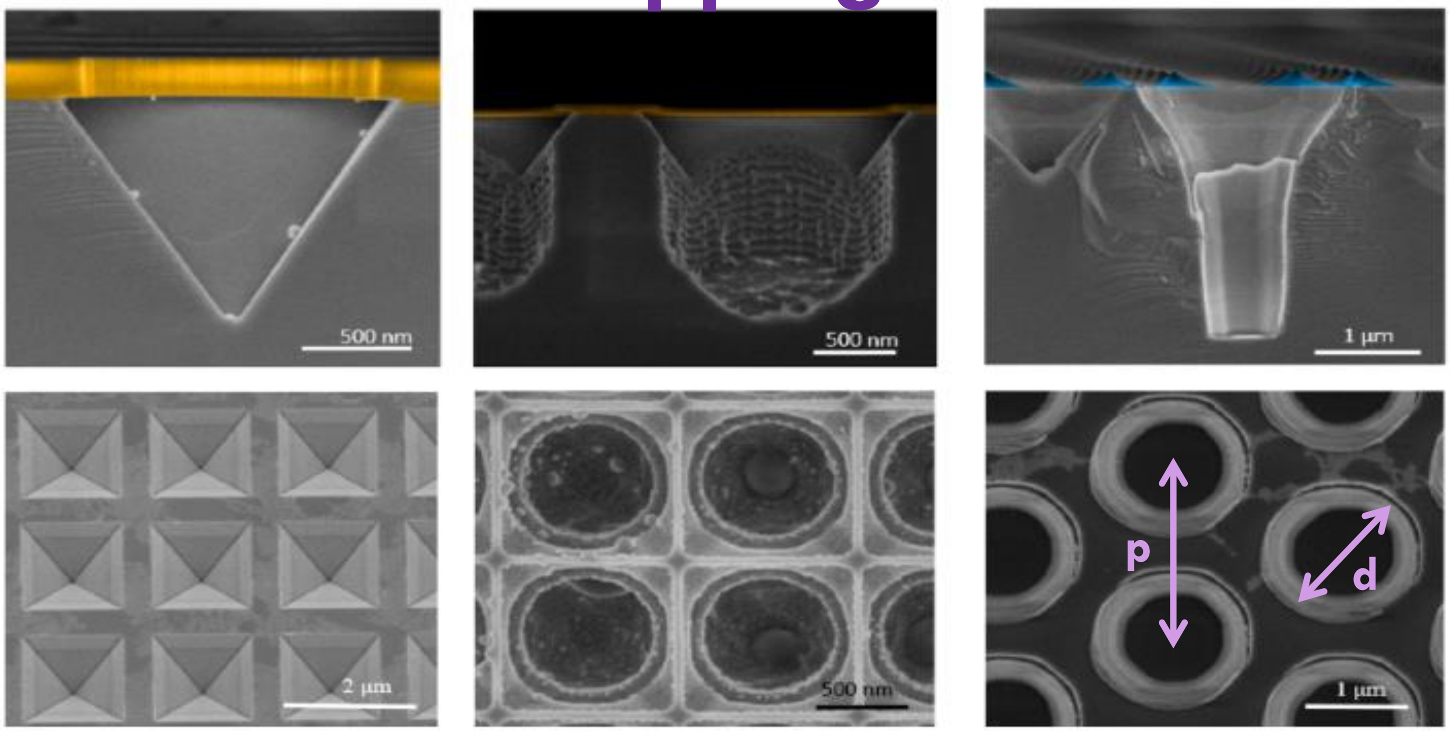
Photon Trapping Structures

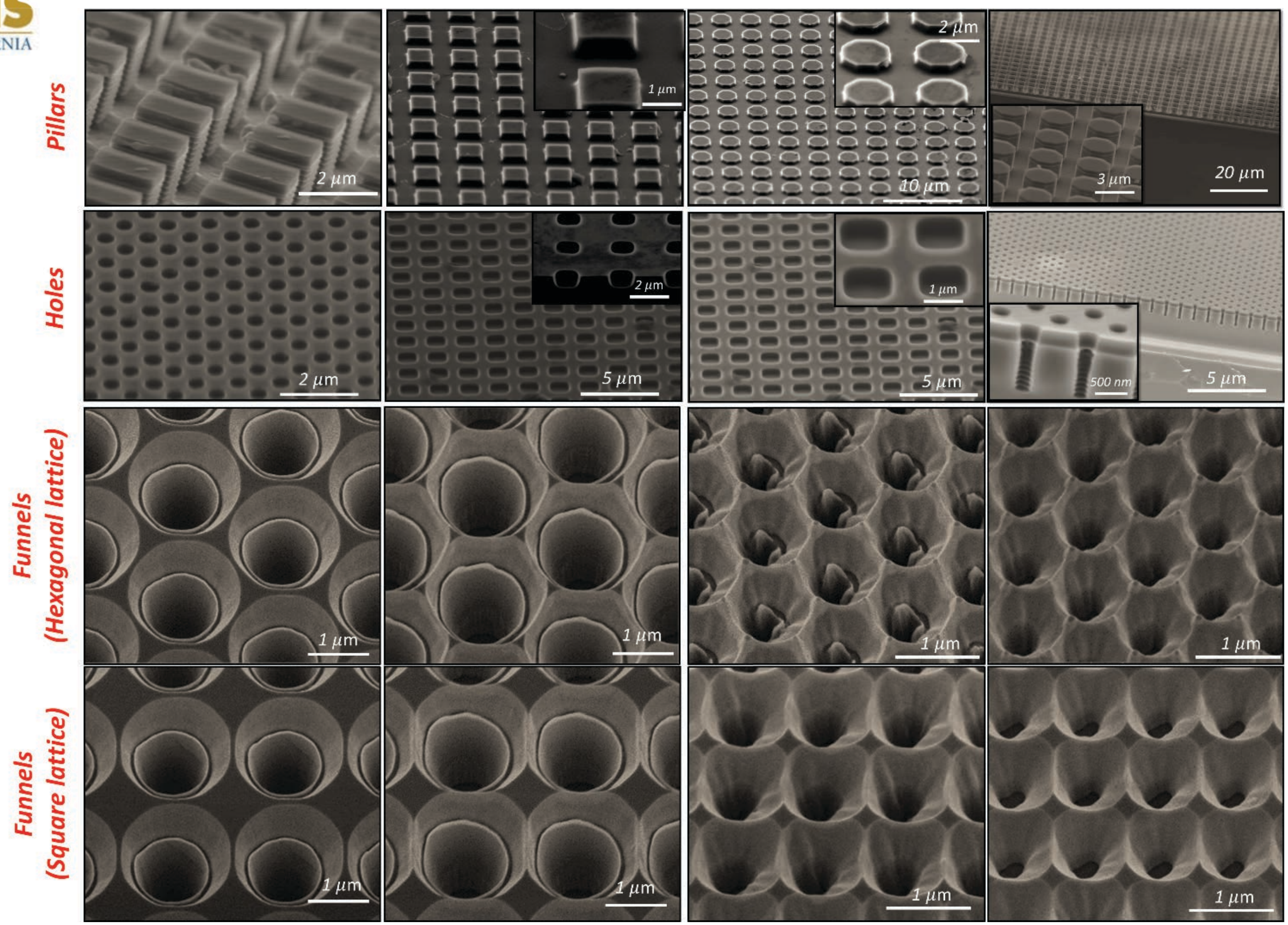


KOH wet etch

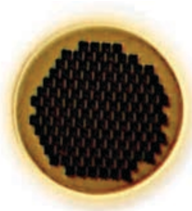
KOH wet etch followed by deep reactive ion etch (DRIE)

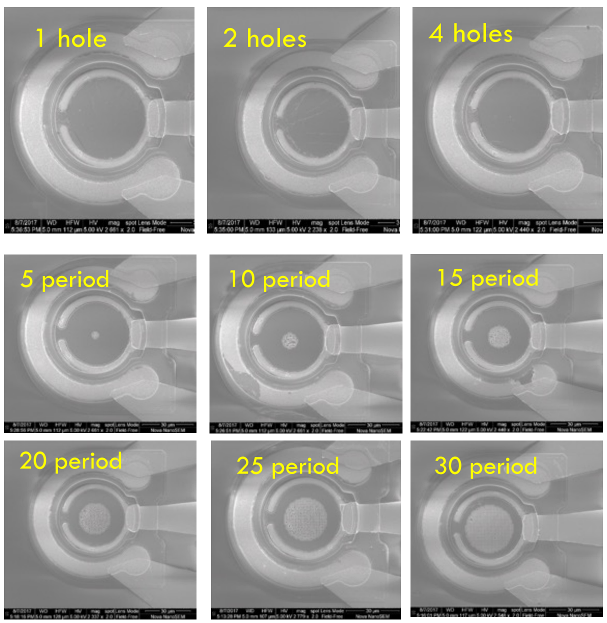
Reactive Ion Etch (RIE)

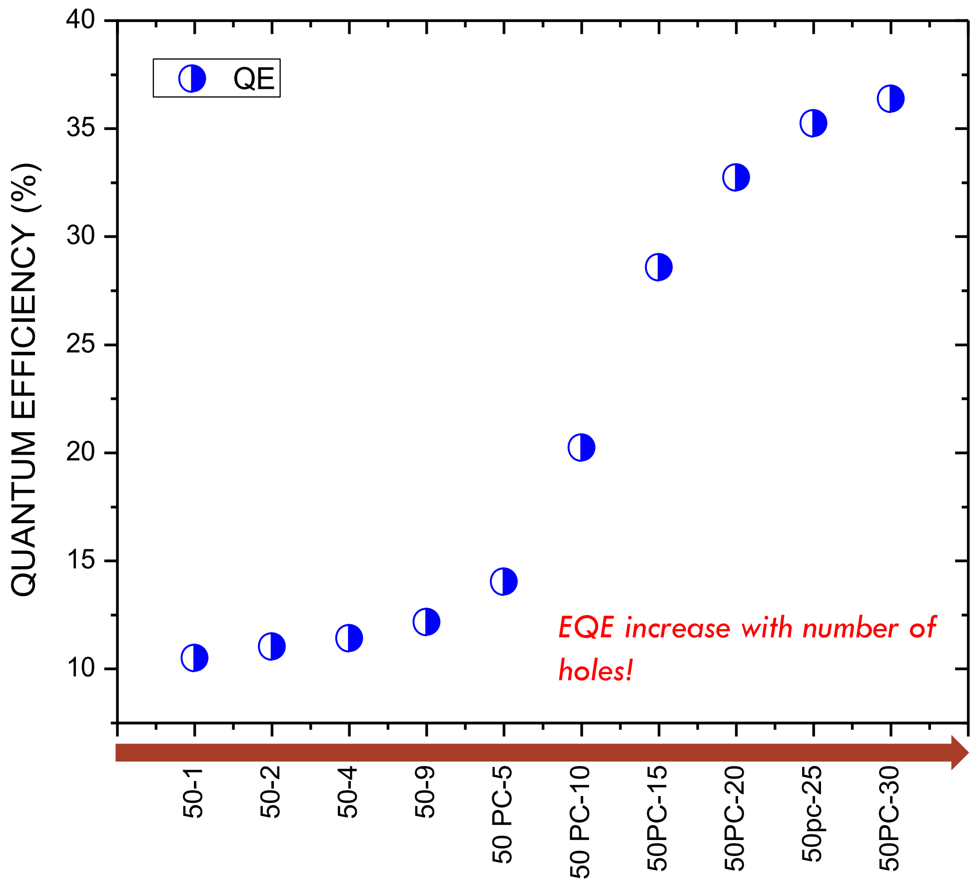
Y. Gao, H. Cansizoglu, S. Ghandiparsi, C. Bartolo-Perez, E. P. Devine, T. Yamada, *et al.*, "High Speed Surface Illuminated Si Photodiode Using Microstructured Holes for Absorption Enhancements at 900–1000 nm Wavelength," *ACS Photonics,* vol. 4, pp. 2053-2060, 2017.


Pillars
Holes
Funnels (Hexagonal lattice)
Funnels (Square lattice)
2 μm
1 μm
2 μm
10 μm
3 μm
20 μm
2 μm
2 μm
5 μm
1 μm
5 μm
500 nm
5 μm
1 μm

Photon Trapping in Different Number of Holes







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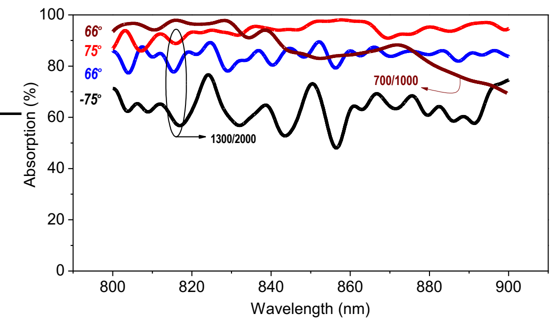
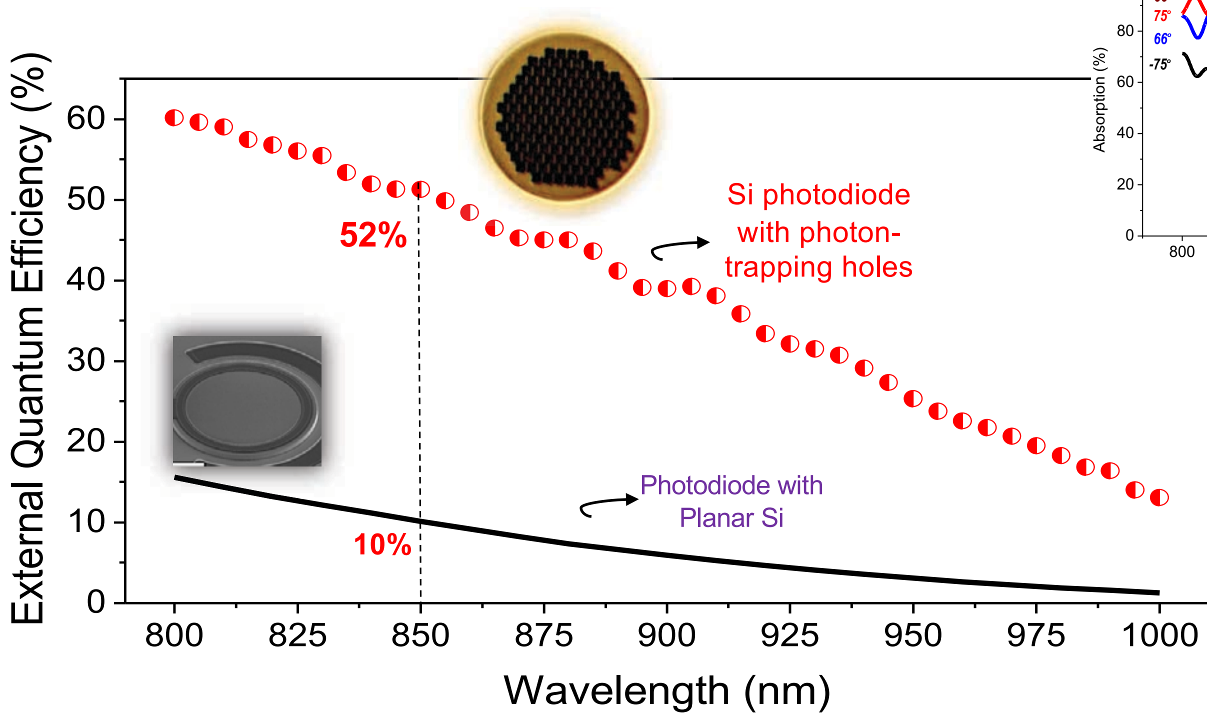
Measured Quantum Efficiency in Silicon Photodiodes

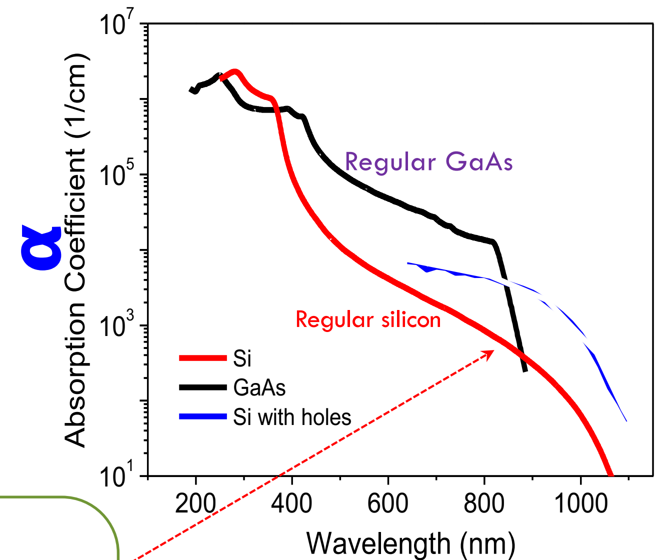


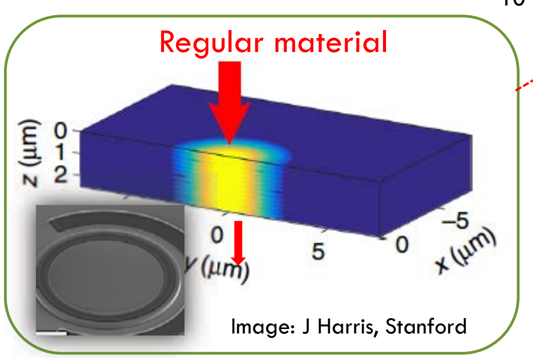


Gao, Cansizoglu, et. al; Nature Photonics, 11(5), p30, 2017

Enhancing α:

Improved Photon Materials Interactions

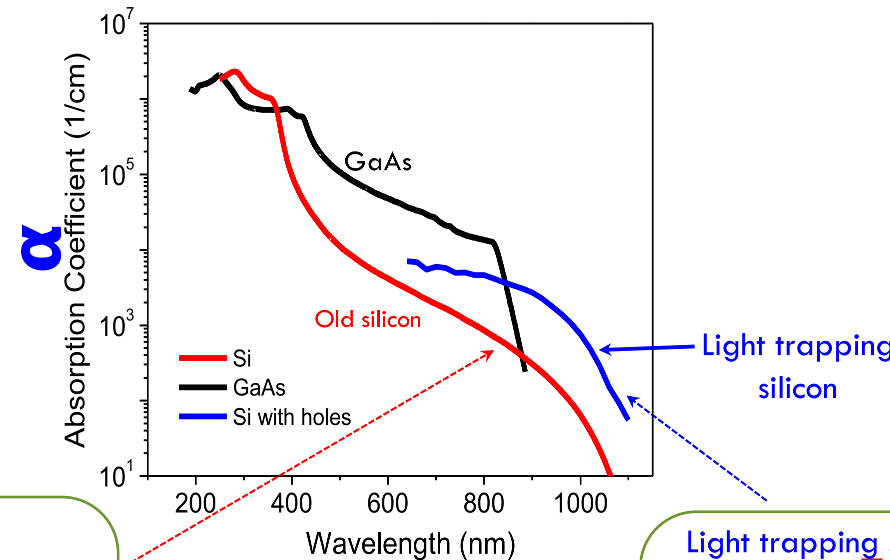


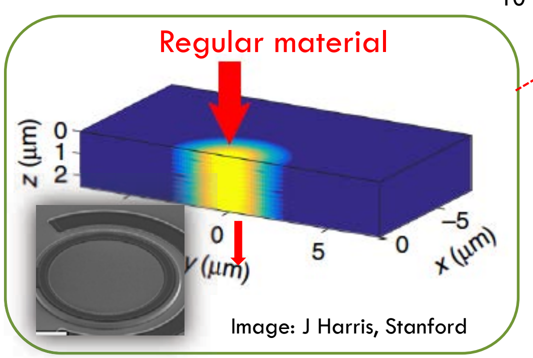


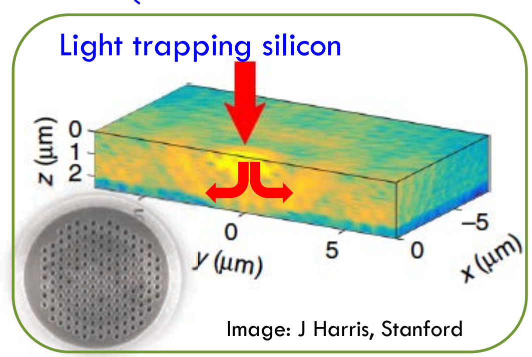
Gao, Y, et al. *ACS Photonics*, 4 (8), p2053 2017.
Gao, Y., *Nature Photonics*, 11(5), p301, 2017

Enhancing α:

Improved Photon Materials Interactions

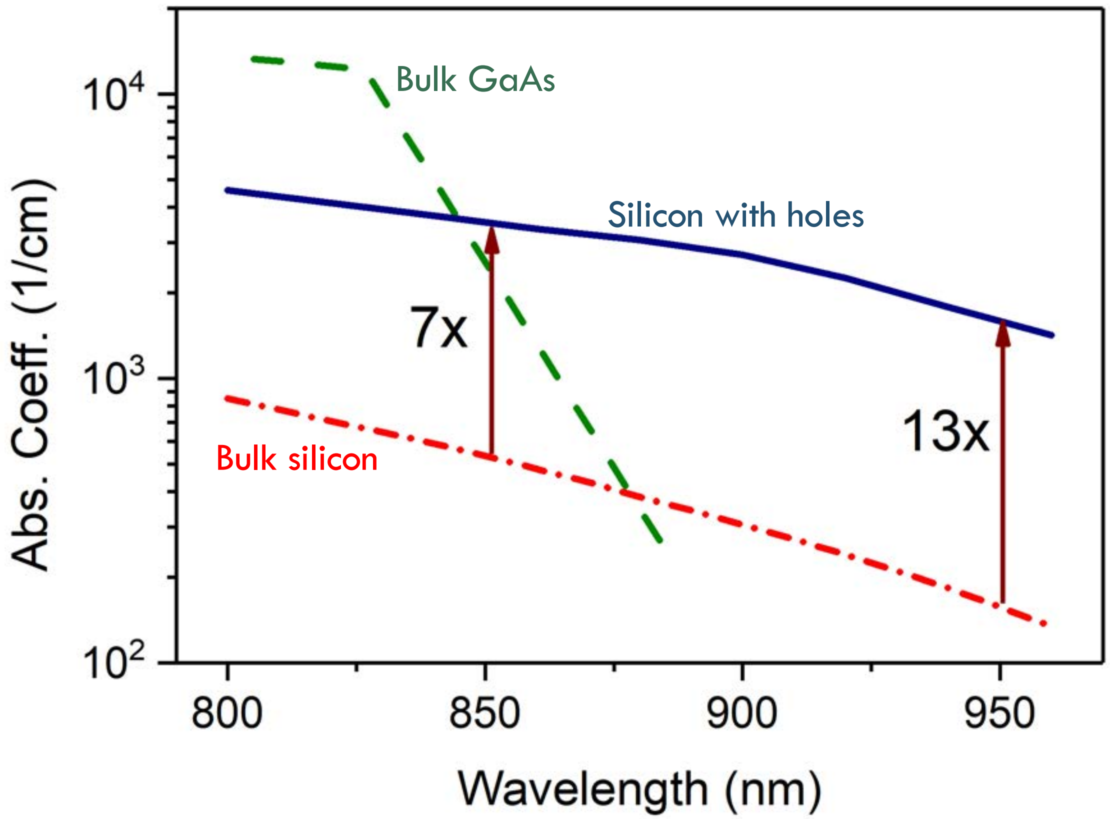






Gao, Y, et al. *ACS Photonics*, 4 (8), p2053 2017
Gao, Y., *Nature Photonics*, 11(5), p301, 2017

Enhanced Optical Absorption coefficient



$$\eta = 1 - exp(-\alpha_{eff} d)$$

S. Ghandiparsi, et al., "High-Speed High-Efficiency Photon-Trapping Broadband Silicon PIN Photodiodes for ShortReach Optical Interconnects in Data Centers ", Journal of Lightwave Technology, 2019 (Under review).

Capacitance Reduction by Holes

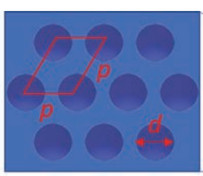
$$f_{3dB} = \frac{1}{\sqrt{(2\pi RC)^2 + (t_{tr}/0.44)^2}}$$

In a typical pin diode; $C = \varepsilon A/d$

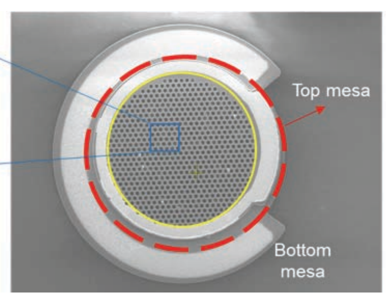
A is the junction area

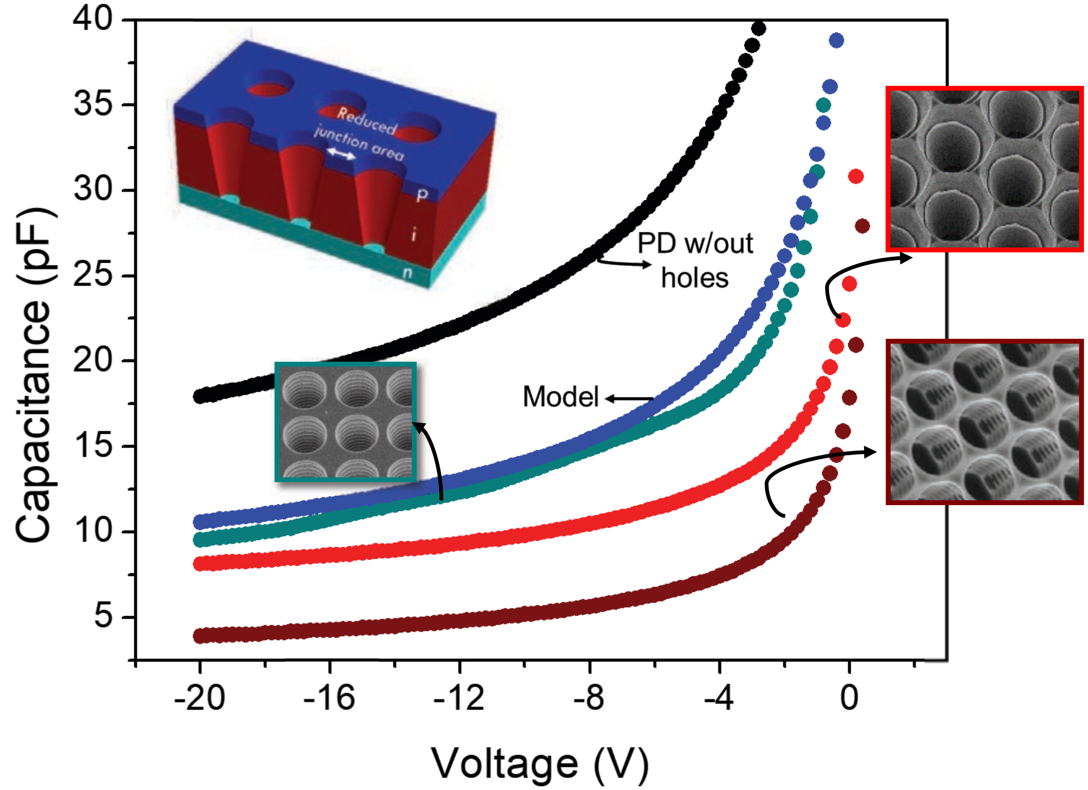
d is depletion layer width which is composed of *i*-layer

$$C_{PD\ with\ holes} = C_{PD\ (no\ holes)} - C_{PD\ (no\ holes)} \times R \times (AR)$$

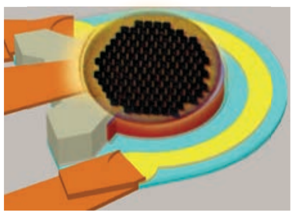


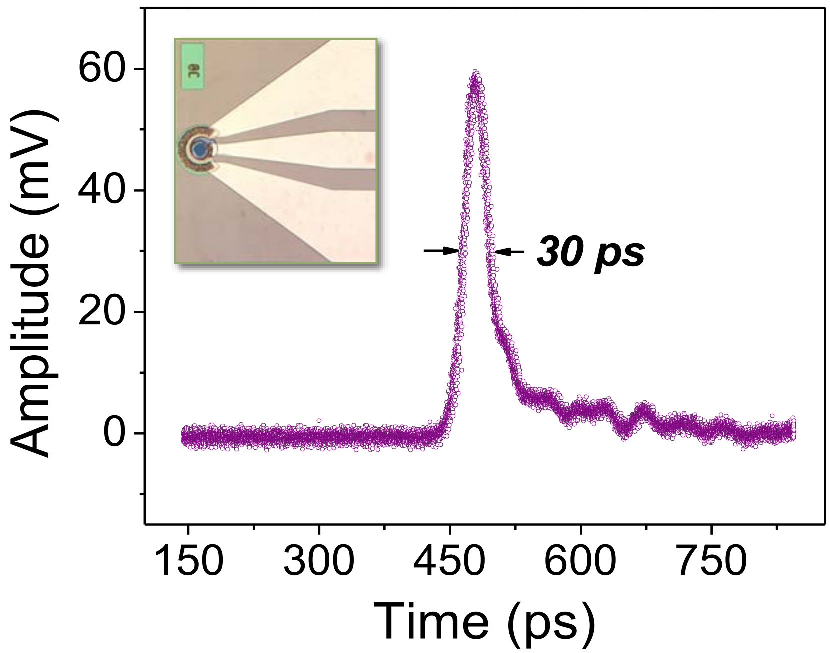
$$Air\ ratio\ (AR) = \frac{\pi(\frac{d}{2})^2}{p^2\sqrt{3}/2}$$

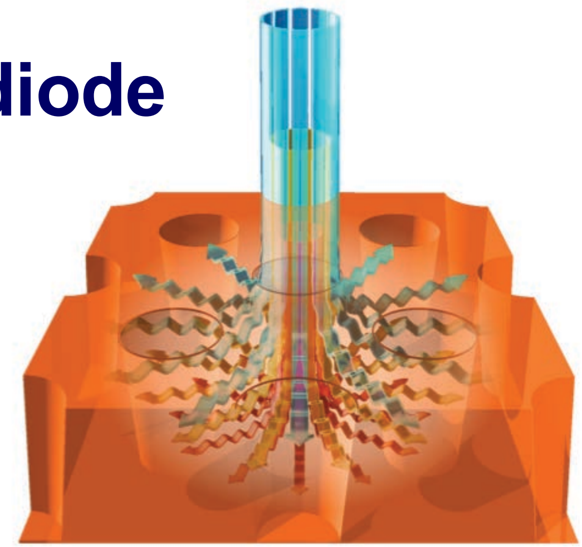


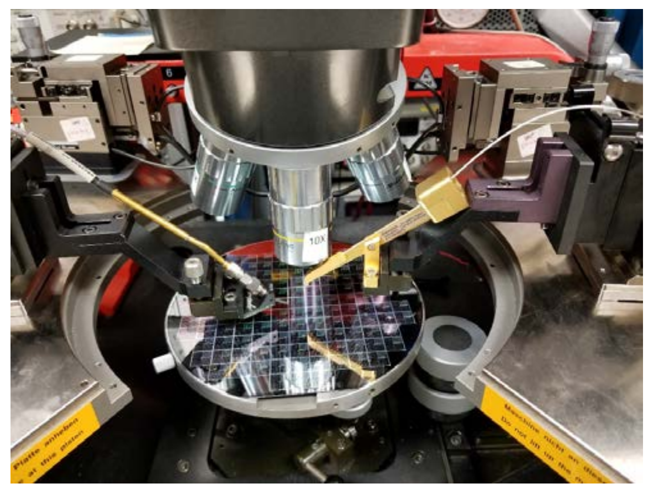


Ultra-fast Silicon Photodiode









Nature Photonics, 11(5), p301, 2017

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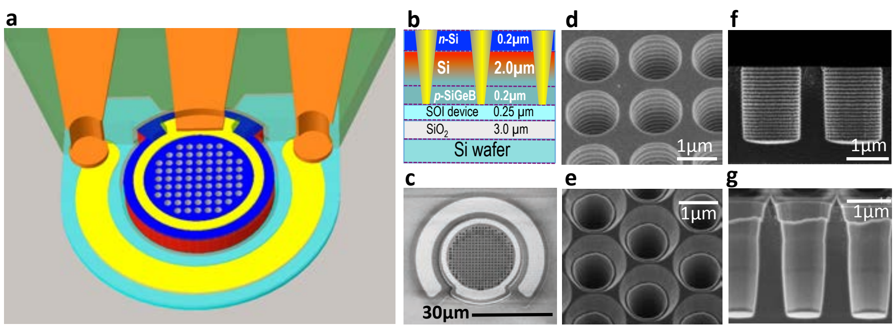
April 2017

nature photonics ARTICLES
PUBLISHED ONLINE: 3 APRIL 2017 | DOI: 10.1038/NPHOTON.2017.37

Photon-trapping microstructures enable high-speed high-efficiency silicon photodiodes

Yang Gao[1†], Hilal Cansizoglu[1†], Kazim G. Polat[1], Soroush Ghandiparsi[1], Ahmet Kaya[1], Hasina H. Mamtaz[1], Ahmed S. Mayet[1], Yinan Wang[1], Xinzhi Zhang[1], Toshishige Yamada[2,3], Ekaterina Ponizovskaya Devine[3], Aly F. Elrefaie[1,3], Shih-Yuan Wang[3] and M. Saif Islam[1*]



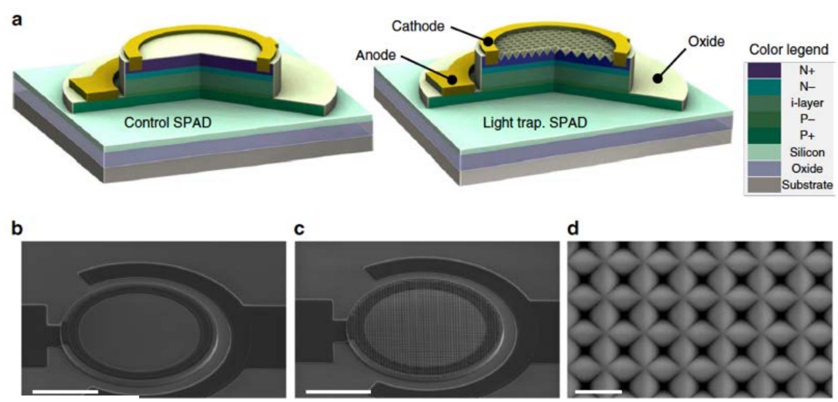
September 2017

nature COMMUNICATIONS

ARTICLE
DOI: 10.1038/s41467-017-00733-y OPEN

Silicon single-photon avalanche diodes with nano-structured light trapping

Kai Zang[1], Xiao Jiang[2,3], Yijie Huo[1], Xun Ding[2,3], Matthew Morea[1], Xiaochi Chen[1], Ching-Ying Lu[1], Jian Ma[2,3], Ming Zhou[4], Zhenyang Xia[4], Zongfu Yu[4], Theodore I. Kamins[1], Qiang Zhang[2,3] & James S. Harris[1]



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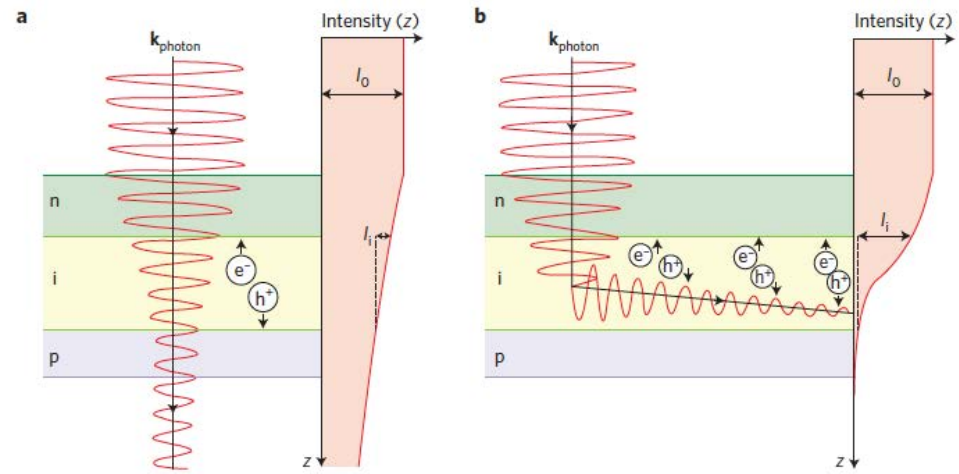
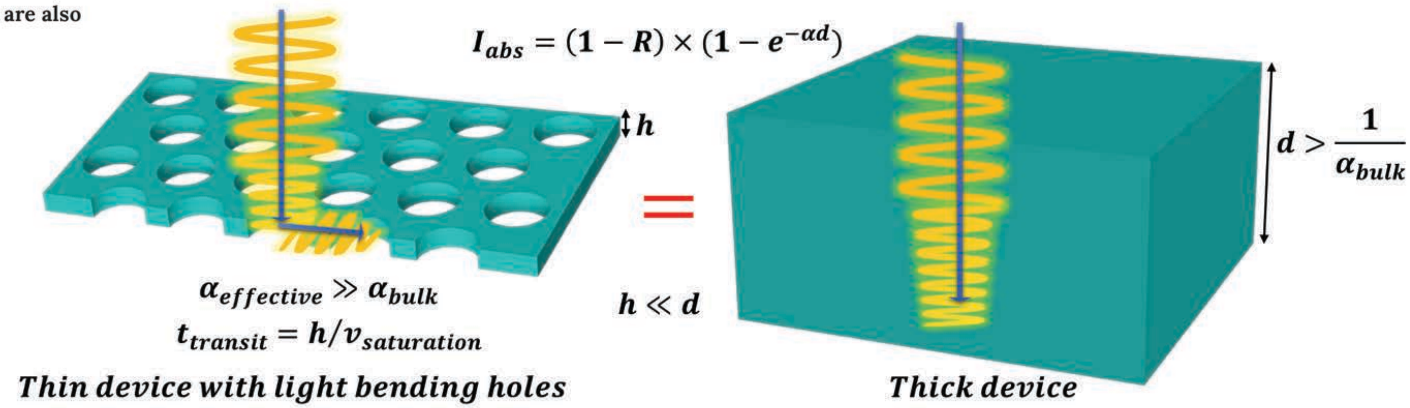
News and Views

Optoelectronics: Fast silicon photodiodes

Michael B. Johnston Department of Physics, University of Oxford

There is typically a compromise between speed and efficiency when designing silicon photodiodes. Now, researchers have exploited microstructuring to achieve fast and thin devices that are also efficient.





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June 2017

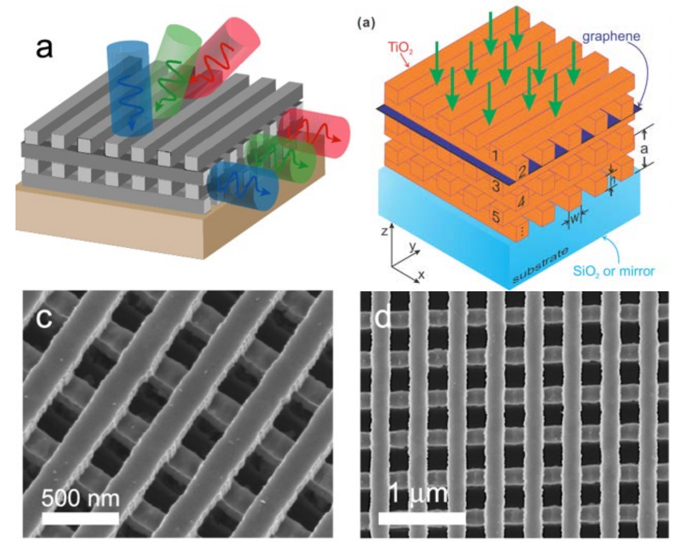
SCIENTIFIC REPORTS

OPEN

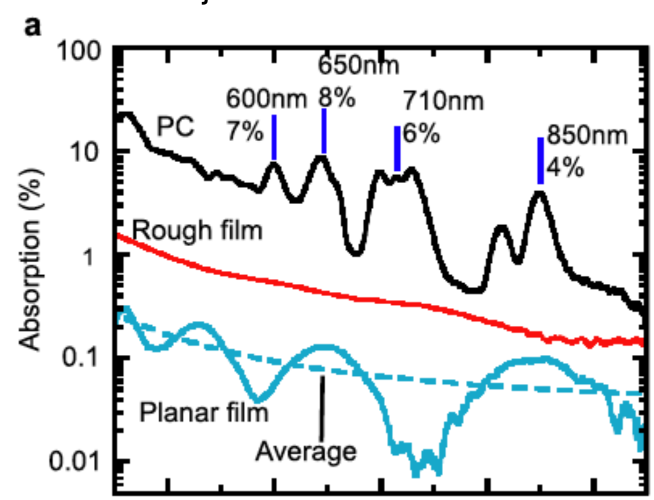
Effectively infinite optical path-length created using a simple cubic photonic crystal for extreme light trapping

Received: 19 October 2016
Accepted: 4 May 2017
Published online: 23 June 2017

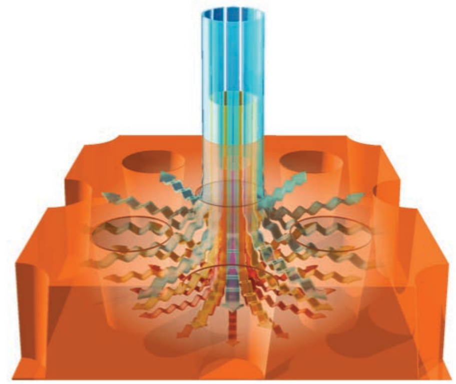
Brian J. Frey[1], Ping Kuang[1], Mei-Li Hsieh[2], Jian-Hua Jiang[3], Sajeev John[4] & Shawn-Yu Lin[1]

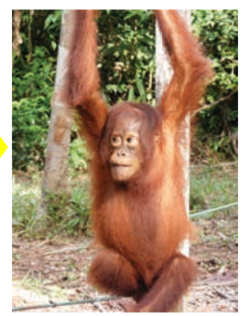


Sajeev John & Shawn-Yu Lin

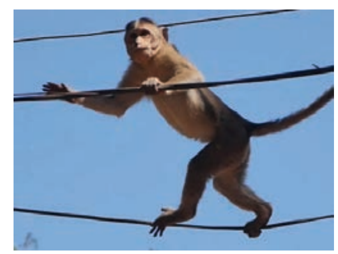


Same Material, but Faster and Higher Efficiency



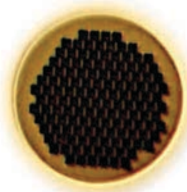


New Si

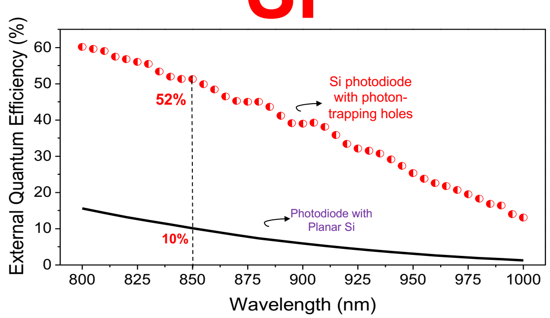


GaAs

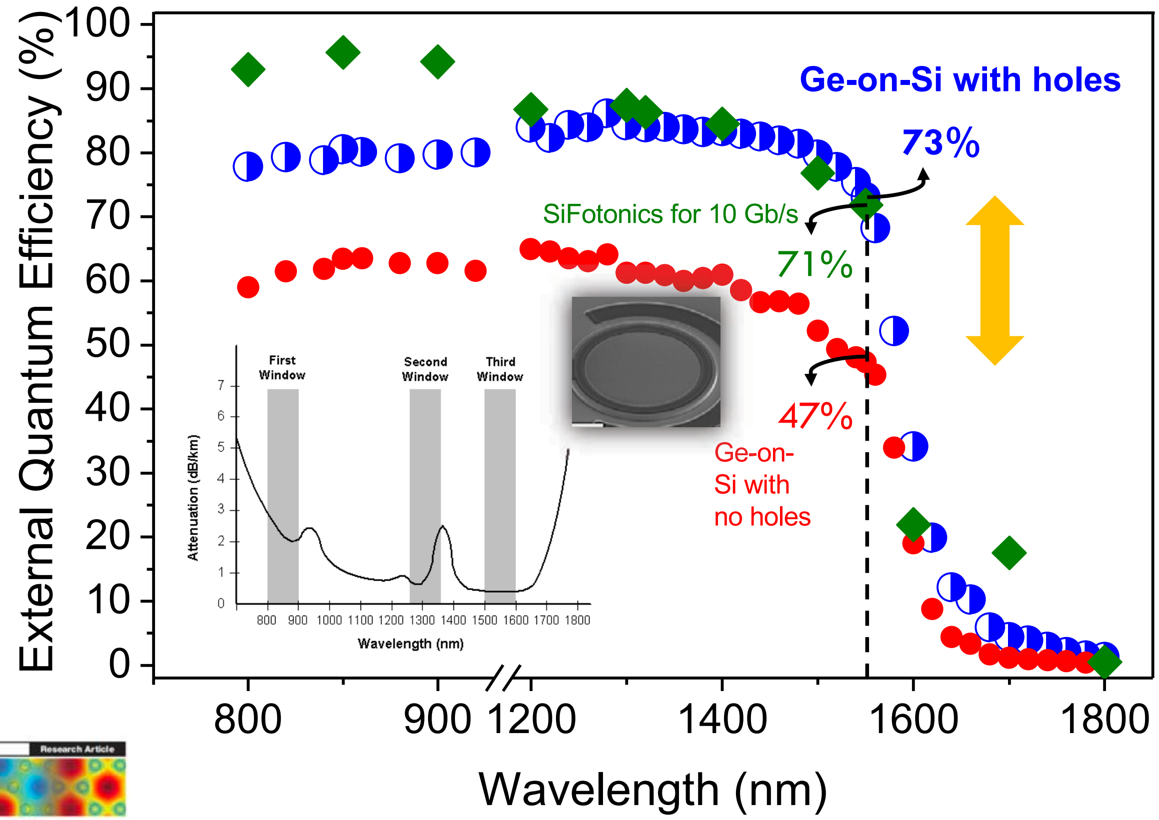
Wideband Efficiency Enhancement in Ge

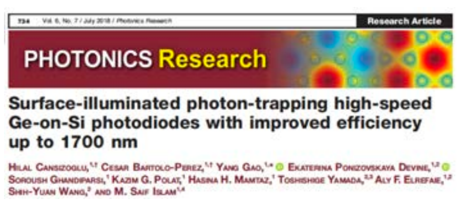


Si



Ge on Si




724 Vol. 6, No. 7 / July 2018 / Photonics Research — Research Article

PHOTONICS Research

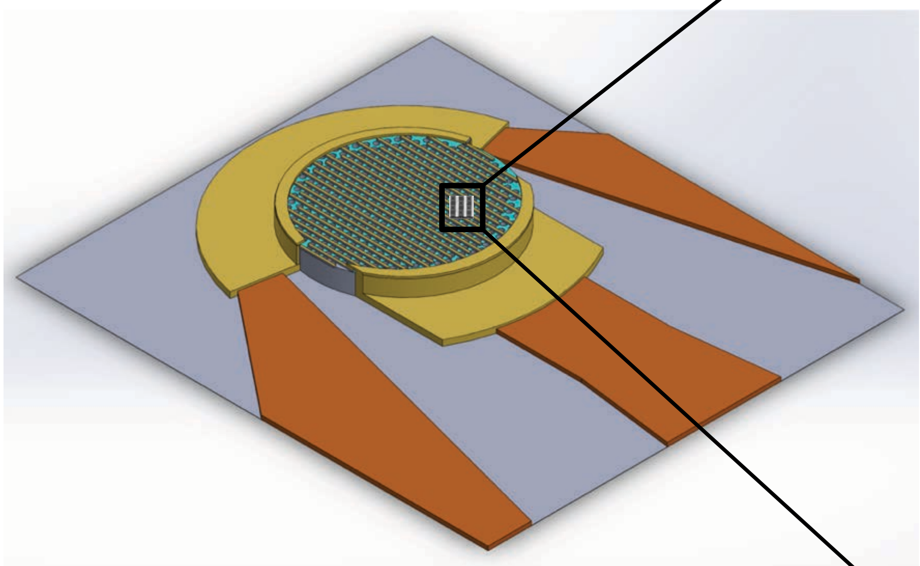
Surface-illuminated photon-trapping high-speed Ge-on-Si photodiodes with improved efficiency up to 1700 nm

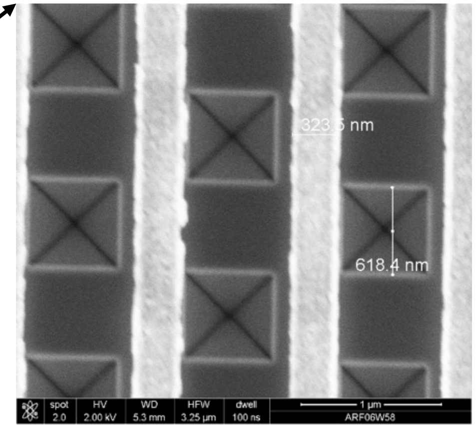
Hilal Cansizoglu, Cesar Bartolo-Perez, Yang Gao, Ekaterina Ponizovskaya Devine, Soroush Ghandiparsi, Kazim G. Polat, Hasina H. Mamtaz, Toshishige Yamada, Aly F. Elrefaie, Shih-Yuan Wang, and M. Saif Islam

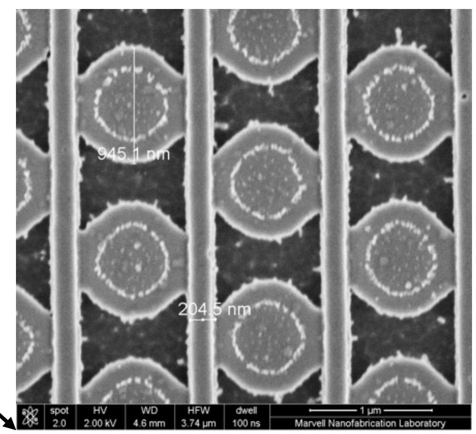
Gao et al., ACS Photonics, 4(8), p2053, 2017

Cansizoglu, Bartolo-Perez et al, *Photonics Research* 2018

Photon-Trapping in **Even Thinner Si**: With MSM PDs







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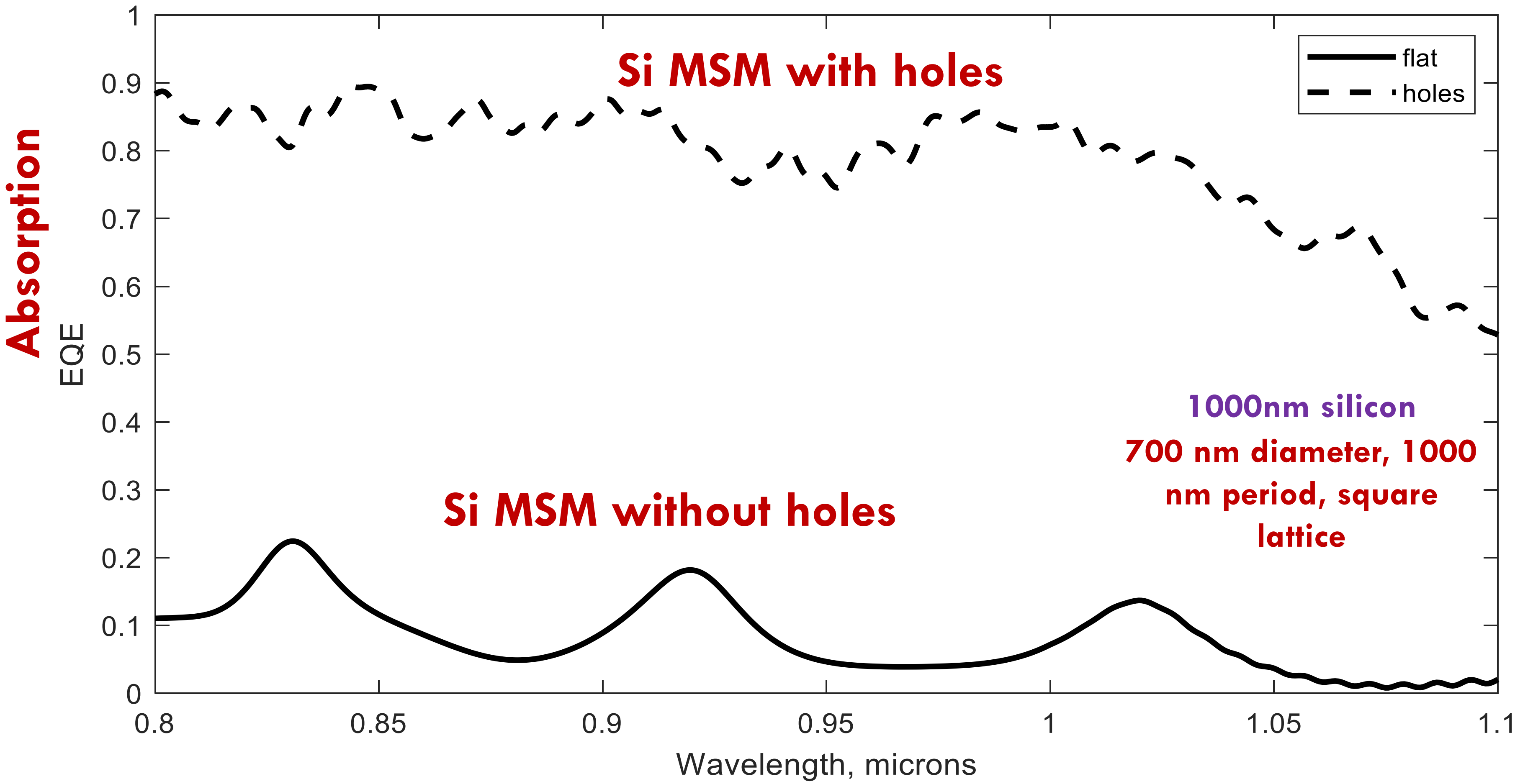
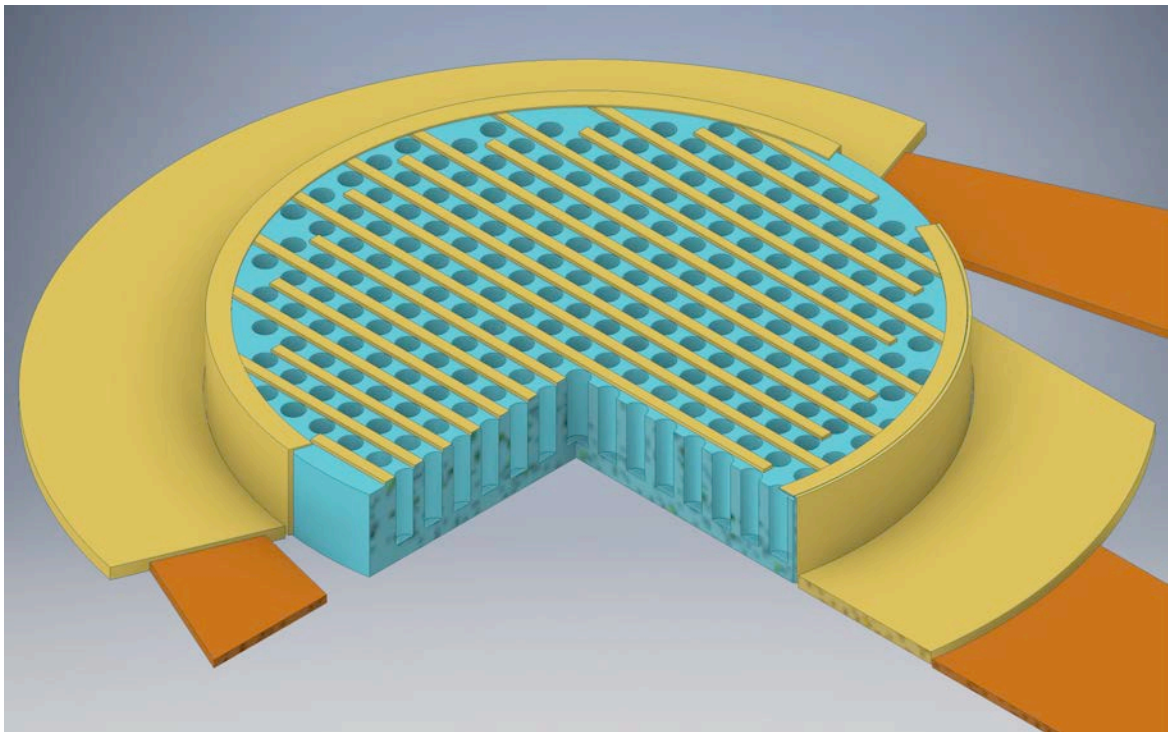
Si MSM: Integrated Holes Enhance Absorption



Photon-Trapping in Even Thinner Si : MSM PDs



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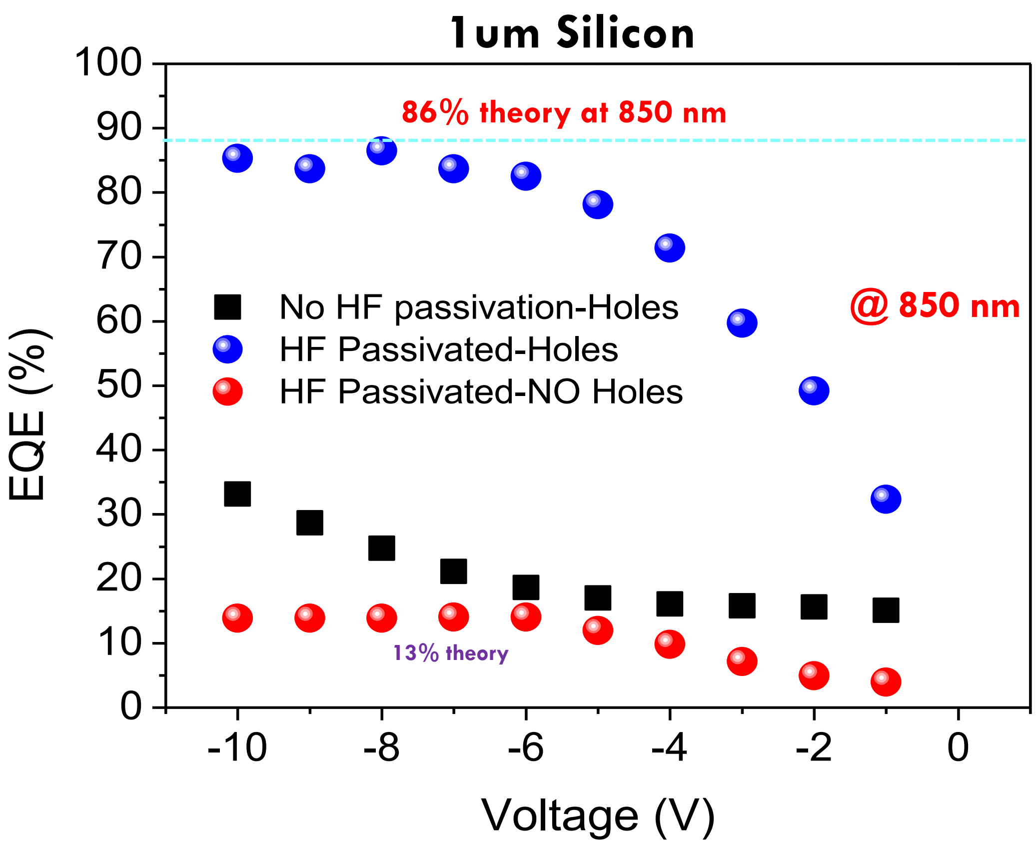
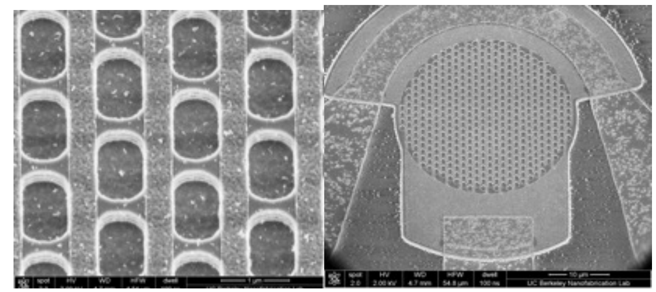
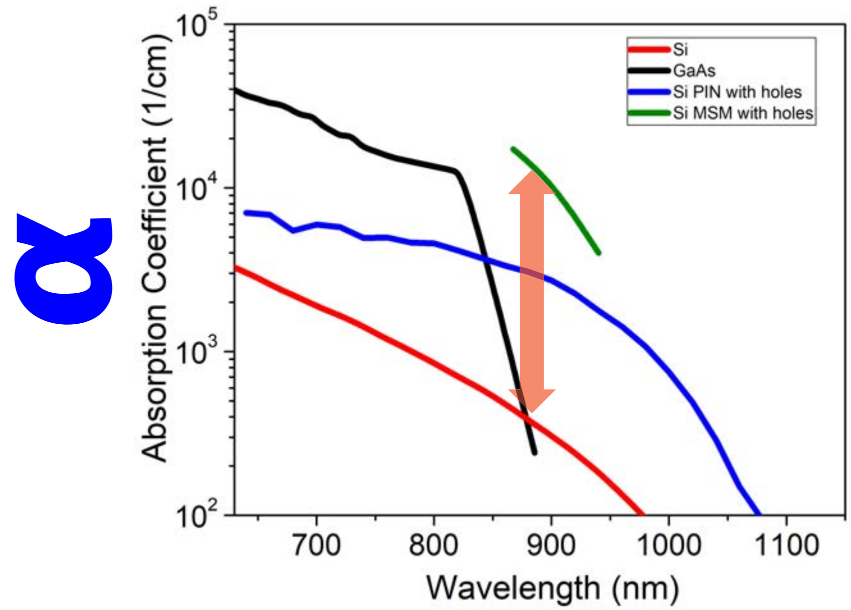
MSM Lateral Structure Experimental Results

SEM Images of MSM PD







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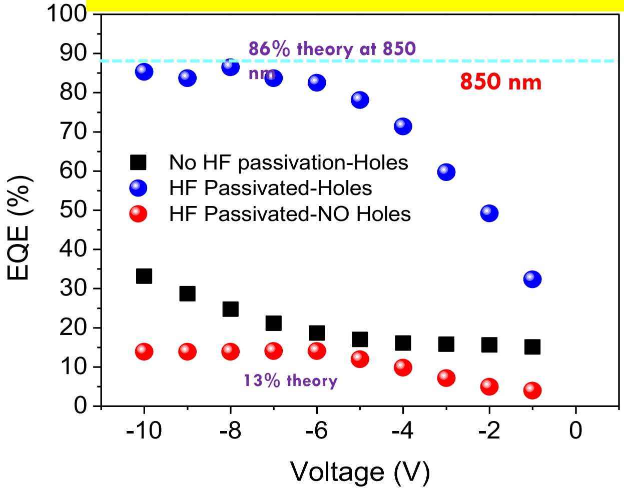
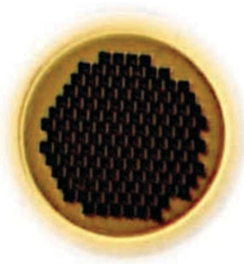
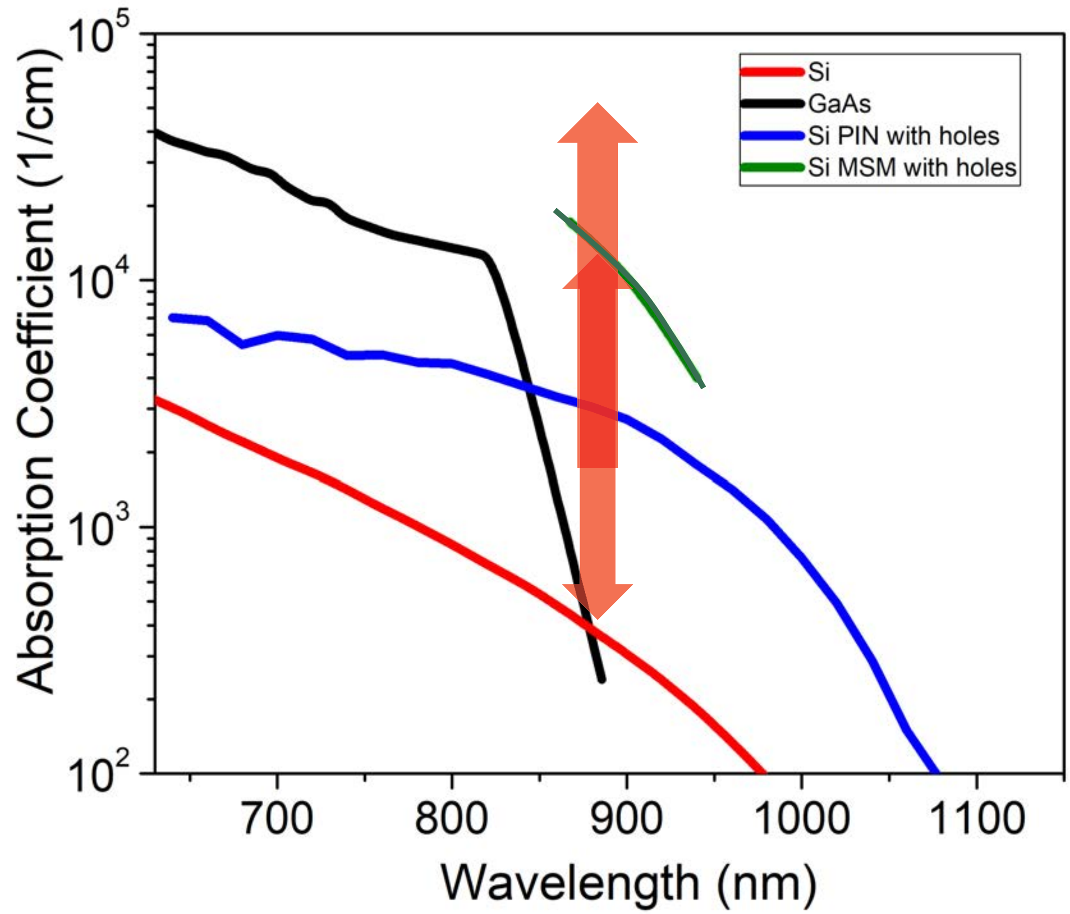
MSM Lateral Photodiode: Experimental Results

1 um GaAs → ~77%
Our um Si → 85% at 850 nm





α



α/cm of silicon

850nm, **α**= 535
905nm, **α**=272
940nm, **α** = 183

α/cm of holey silicon

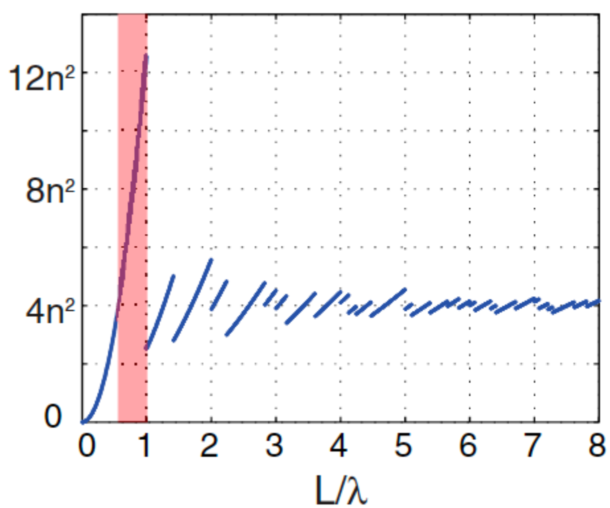
850nm, **α**= 18971	38x
905nm, **α**=11086	40x
940nm, **α** = 4004	22x

Fundamental limit of nanophotonic light trapping in solar cells

Zongfu Yu[1], Aaswath Raman, and Shanhui Fan[1]

Ginzton Laboratory, Stanford University, Stanford, CA 94305

PNAS | 2010 | vol107 | no. 41 | p17491

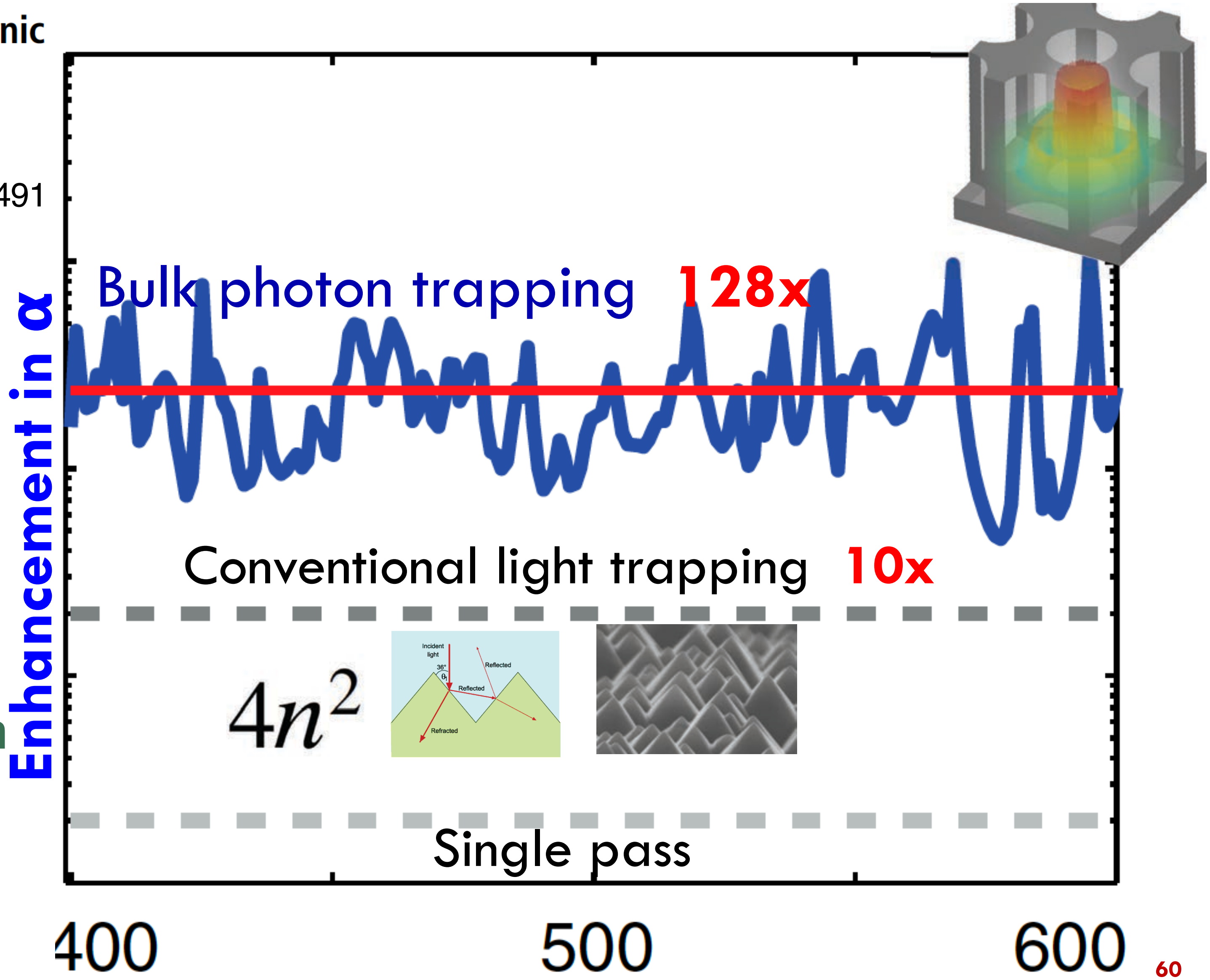


α/cm of holey silicon

850nm, **α**= 18971 38x

905nm, **α**=11086 40x

940nm, **α** = 4004 22x



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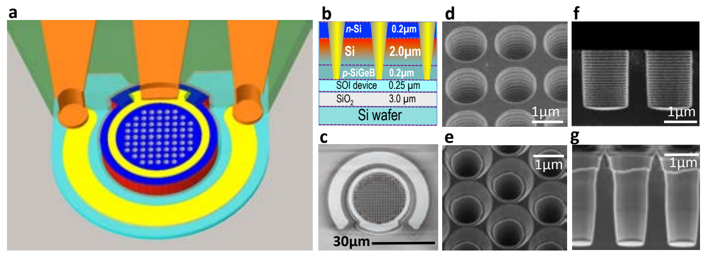
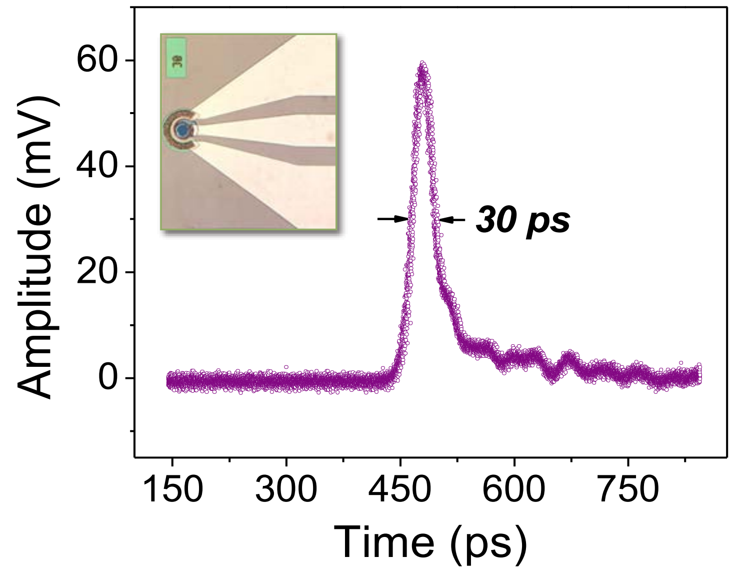
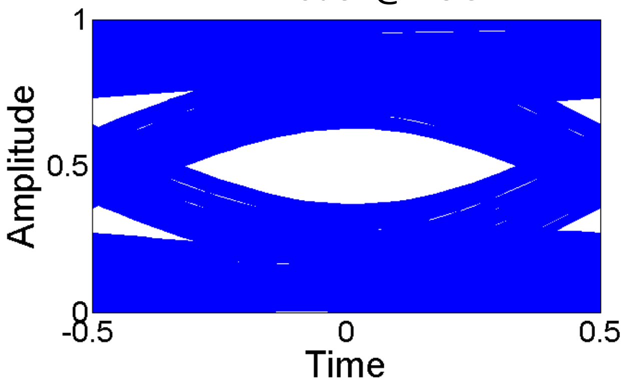
Ultra-fast 50Gb/s Silicon PDs

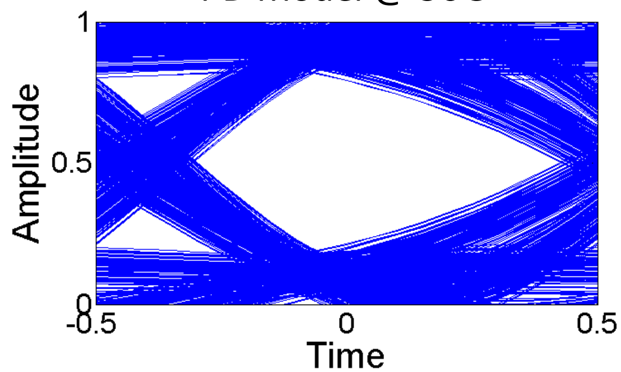




PD Model @ 25G

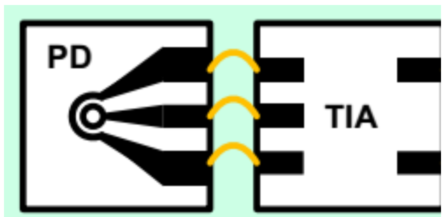


PD Model @ 50G

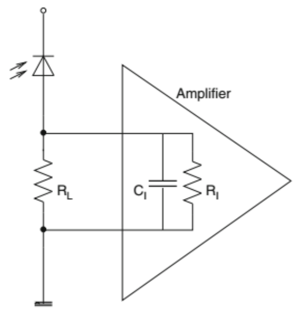


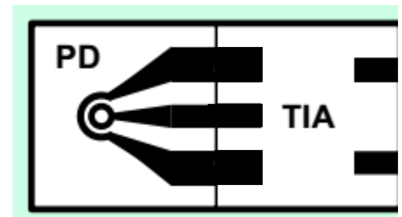
Saif Islam, University of California, Davis

Toward Integrated Receiver

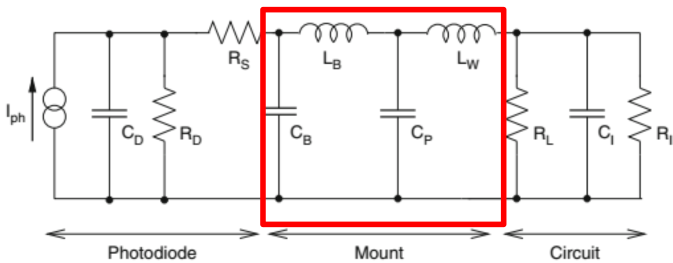


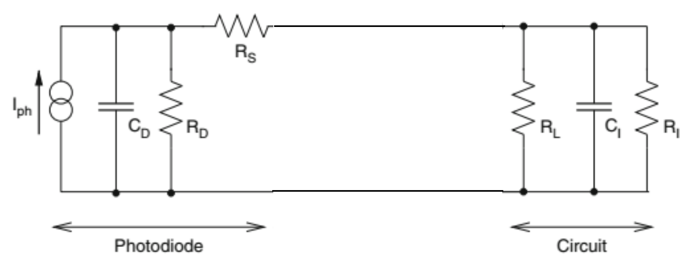
Wire-bonded EIC and PIC





On-chip integrated EIC and PIC





$$f_{3dB} = \frac{1}{2\pi\,(R_L||R_I)(C_j + C_b + C_p + C_I)}$$

$$f_{3dB} = \frac{1}{2\pi\,(R_L||R_I)(C_j + C_I)}$$

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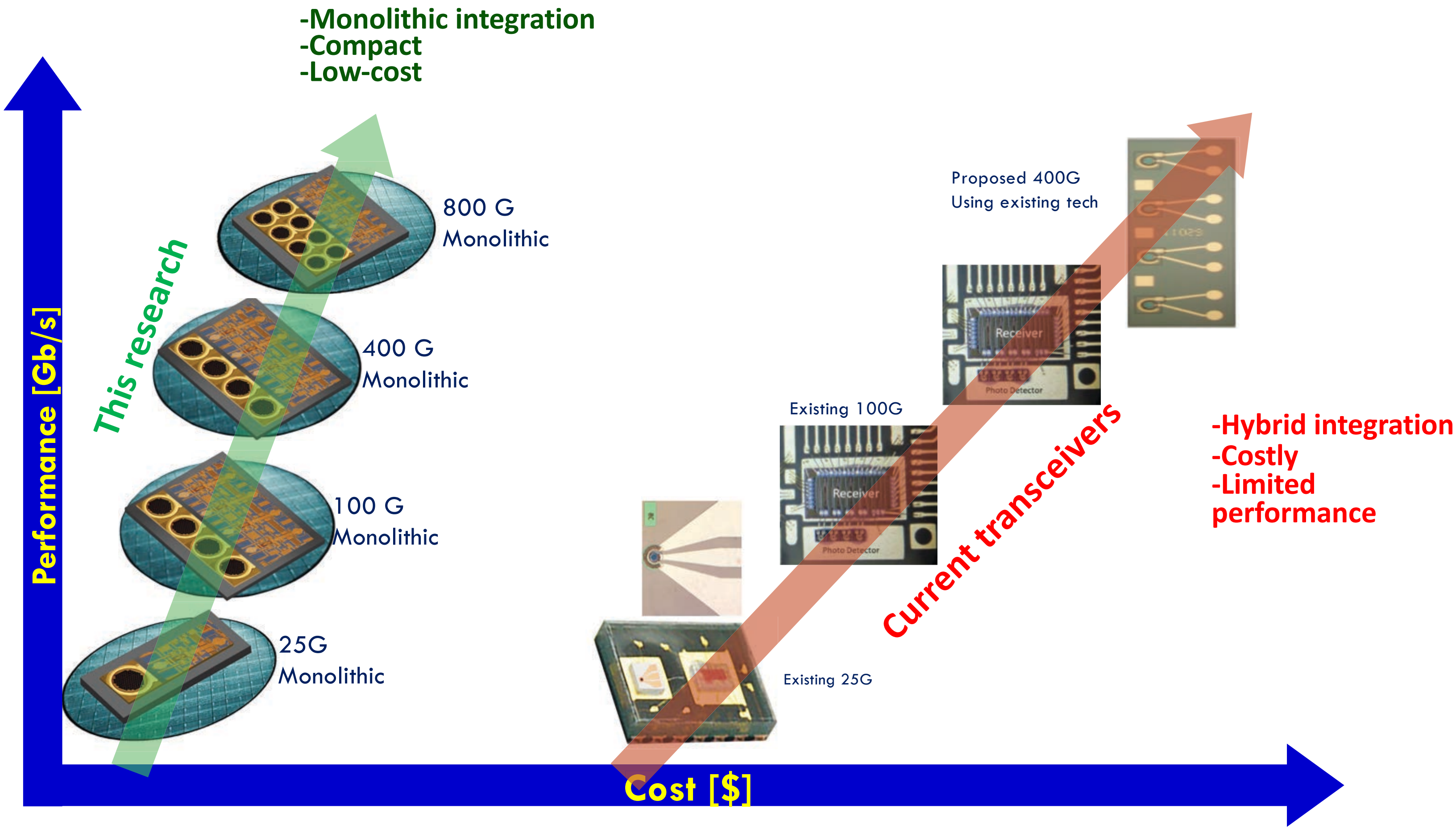
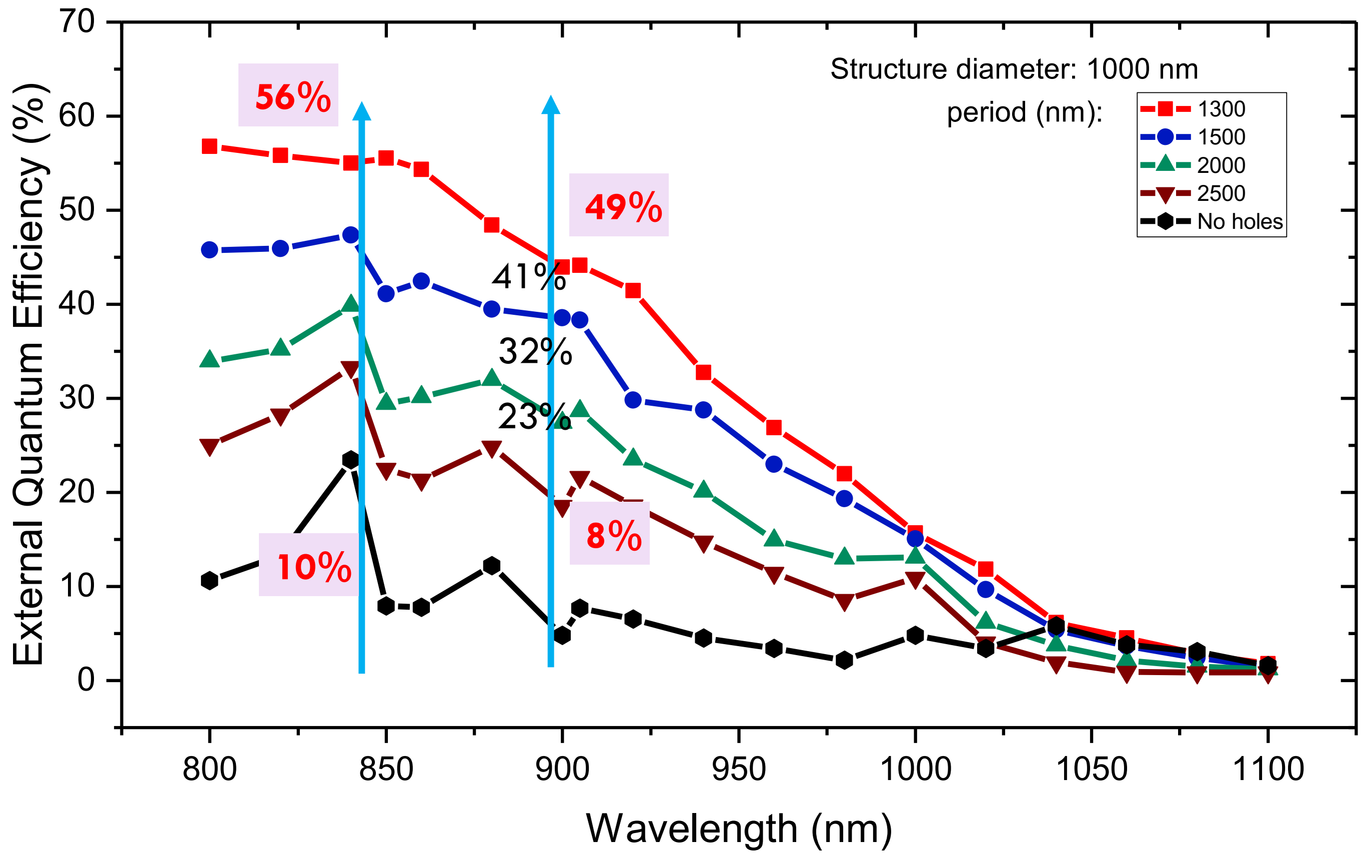
Ultrafast Si Transceivers for Data Centers

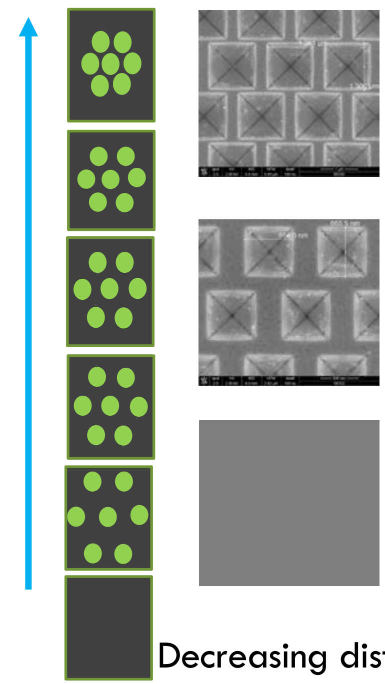


Thank you!

sislam@ucdavis.edu

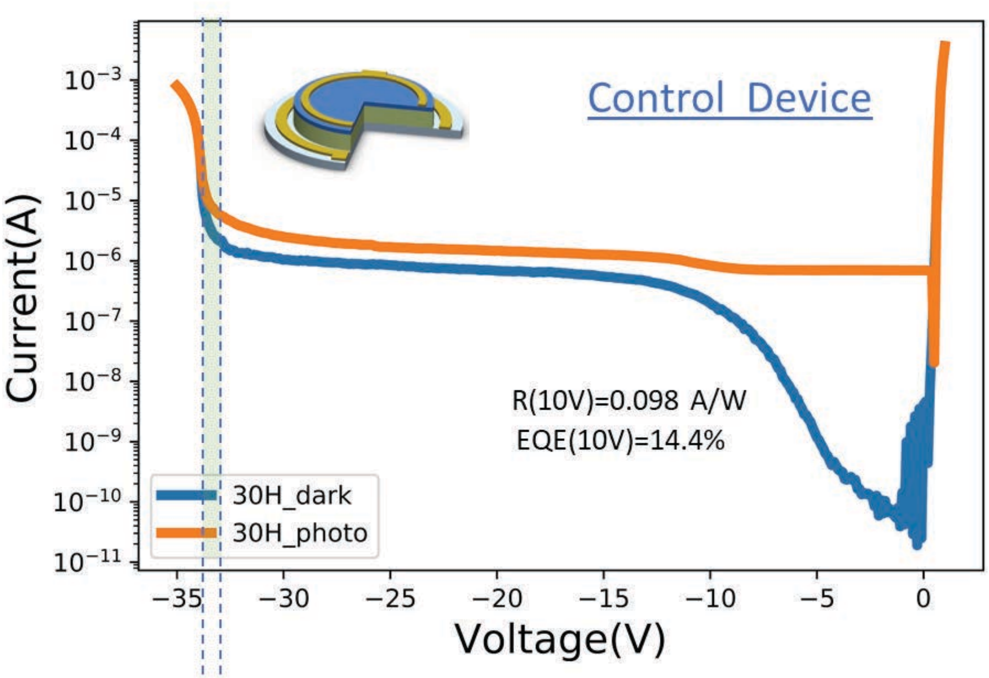
Broadband EQE on Si PDs

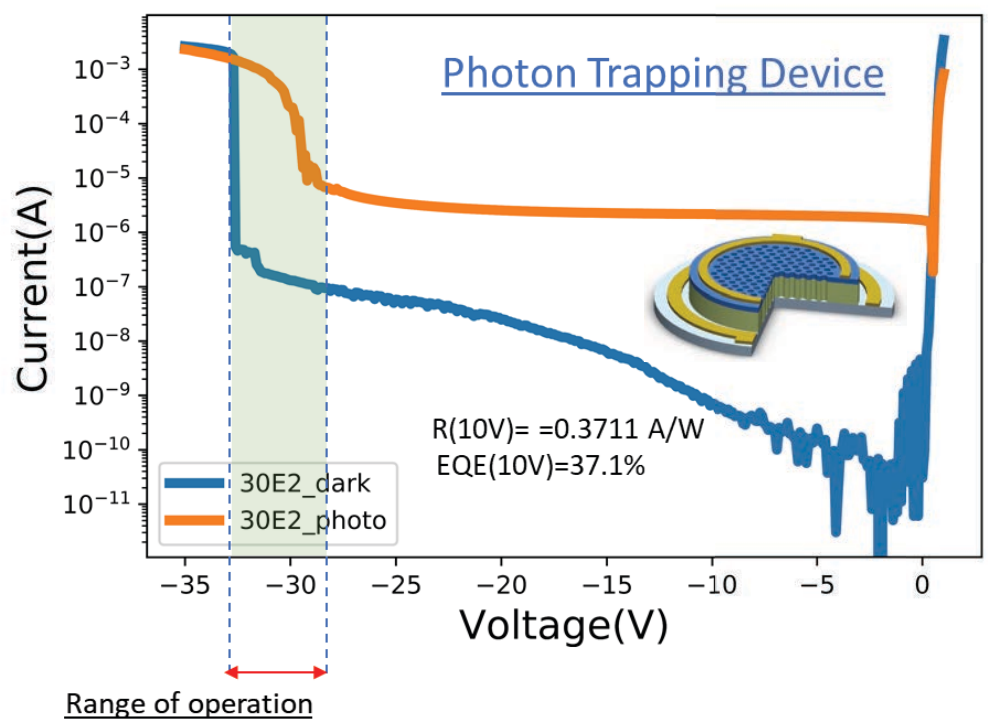




Decreasing distance between nanostructures

Photon trapping Si APD



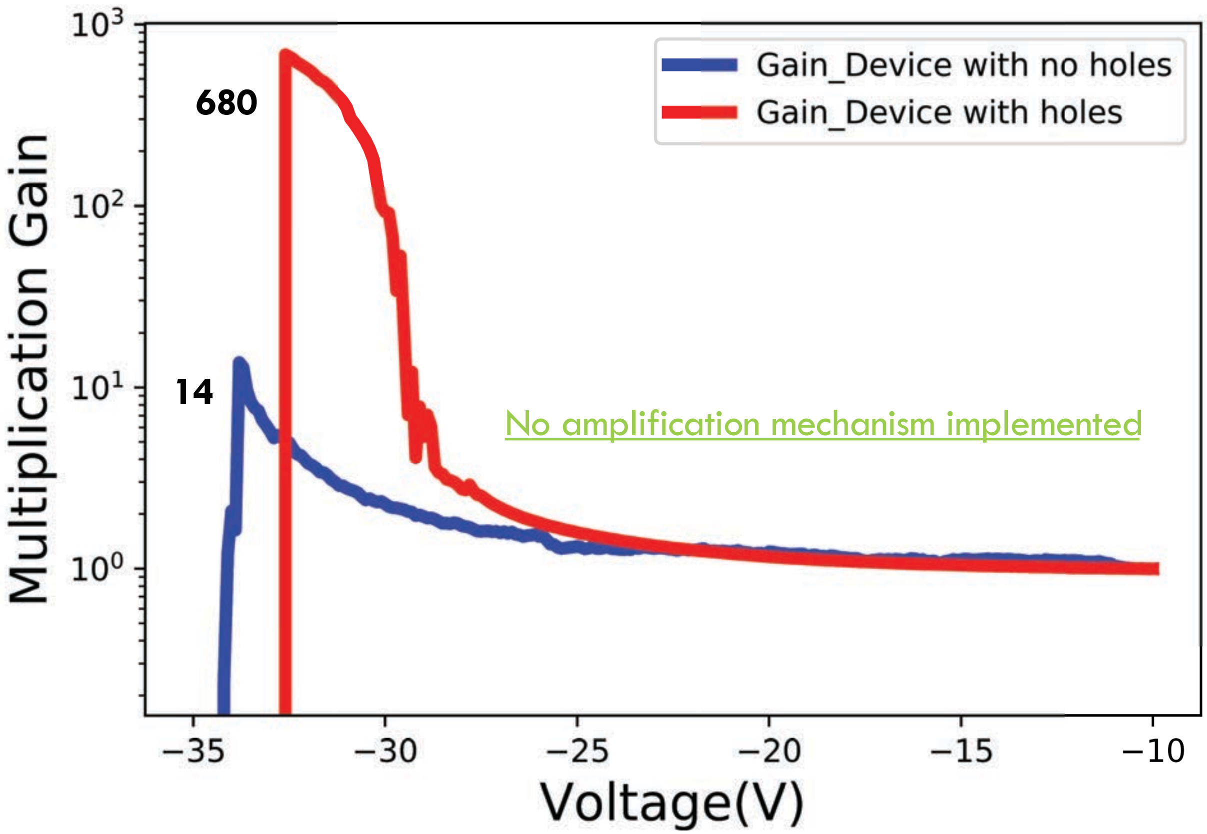


X

Experimental data obtained in SPAD photon trapping devices
Input power: 8.5μW
Laser: Calmar Laser 850nm
Device Diameter: 30 μm

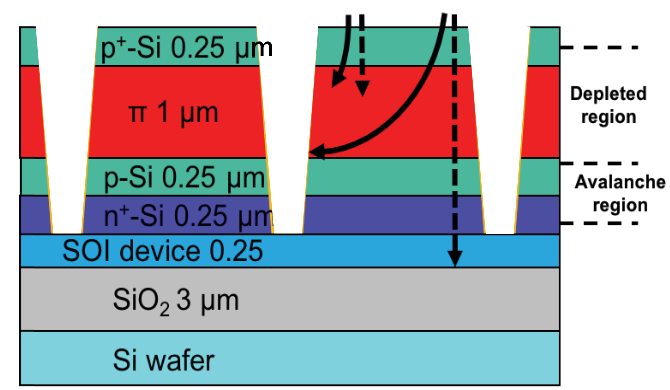
Gain in PD devices at 850nm

Experimental data obtained in SPAD photon trapping devices
Input power: 8.5μW
Laser: Calmar Laser 850nm
Device Diameter: 30 μm

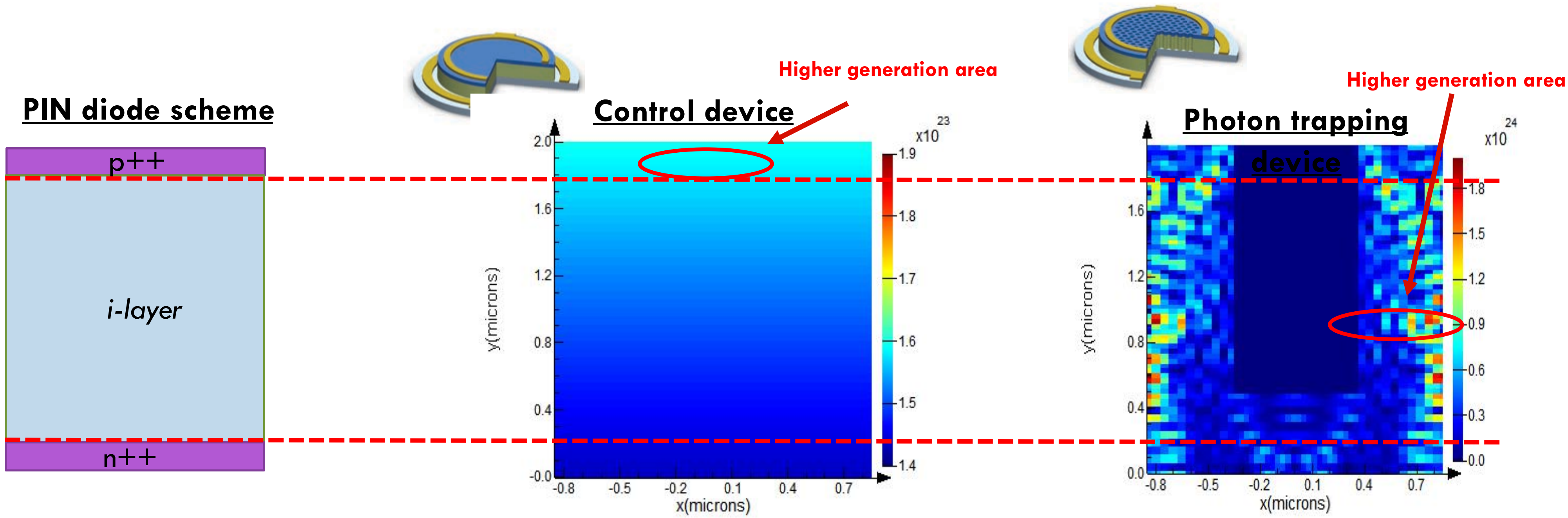


Goal: Obtain a gain of 10^6

Future electrical design:
Separate Absorption and Multiplication Layer (SAML)



Electron-hole generation profile



For silicon, we expect to have lower excess noise with electron injection

<u>Future work: Optical and electrical simulation must be coupled</u>

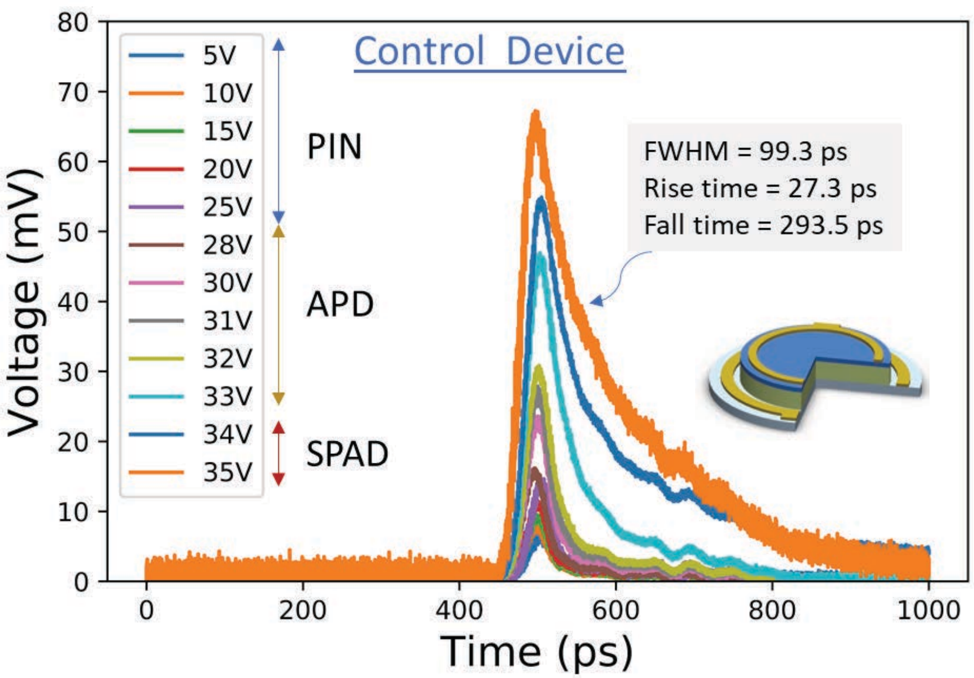
Speed of operation for Si-APD

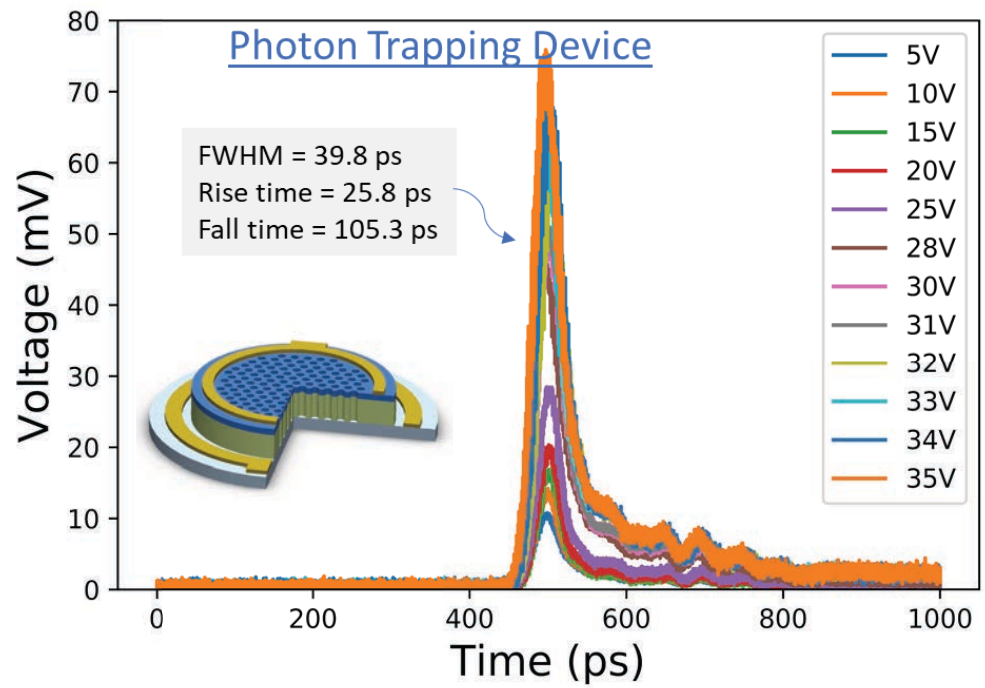
Experimental data obtained in SPAD photon trapping devices

Input power: 8.5µW

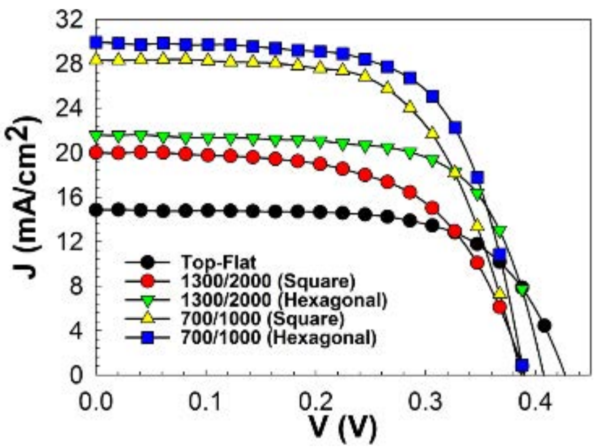
Laser: Calmar Laser 850nm

Device Diameter: 30 µm





Solar Cells with Holey Silicon



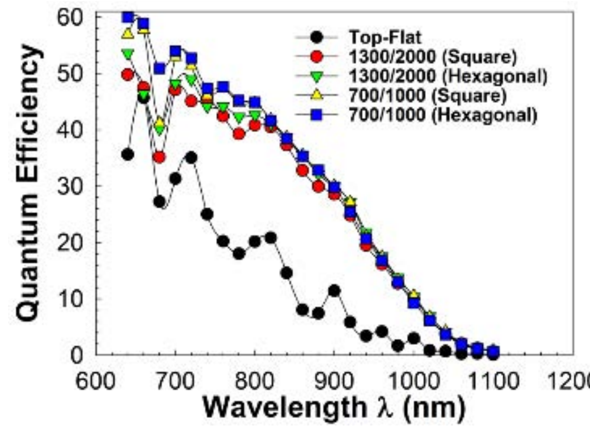


Table 1. The performance of SCs by designing with different lattice design size/period

Hole Size diameter/period	V_{oc} (V)	I_{sc} (mA)	FF (%)	Eff. (%)
Top-Flat	0.42	0.029	66.02	4.18
1300/2000 (Hexagonal)	0.40	0.042	67.98	5.97
700/1000 (Hexagonal)	0.38	0.059	66.07	7.69
1300/2000 (Square)	0.39	0.039	60.12	4.69
700/1000 (Square)	0.39	0.060	62.74	6.88

Future Work: System level design and simulation

- Design photodiode integrated with **TIA circuit**:
  - Find a convenient CMOS technology with required features.
  - Adopt the device structure with CMOS available features.

- Simulation:
  - Evaluate device performance integrated with TIA circuit.
  - Optimize the design based on simulation results.