

W&Wsens Devices Inc.

Revolutionizing Optical Connectivity

www.wwsensdevices.com

Patent Owner, W&Wsens - Ex. 2021, p. 1

Key investment highlights

- ✓ **Disruptive photo detection technology with a simple structure for easy CMOS monolithic integration**
- ✓ **Addresses massive and fast growing markets (data center, LiDAR)**
- ✓ **Anticipated 50% cost reduction of ROSA package (25% cost reduction to entire transceiver package)**
- ✓ **Strong IP portfolio - 5 US issued patents with 159 claims, 1 China allowed patent with 69 claims, 15 patents pending between US, EU, China, Japan and Korea**

W&Wsens intellectual property portfolio

Patent Highlights

- Enhancement of sensitivity and high speed response with microstructure holes
- Monolithic integration of photodetectors and electronics
 - Compatible CMOS / BiCMOS process
- Avalanche photodiode with multiplication region in silicon
 - Low noise

United States Issued Patents

[Patent No: 9,496,435 B2](#) Date Issued 11.15.2016 – 31 claims

[Patent No: 9,525,084 B2](#) Date Issued 12.20.2016 – 28 claims

[Patent No: 9,530,905 B2](#) Date Issued 12.27.2016 – 30 claims

[Patent No: 9,818,893 B2](#) Date Issued 11.14.2017 – 30 claims

United States Allowed Patents

[US 2018/0102442 A1](#) Date published 4.12.2018 – 40 claims

United States Published Patents

[US 2017/0194522 A1](#) Date published 7.6.2017

[US 2018/0102442 A1](#) Date published 4.12.2018

[US 2019/0019899 A1](#) Date published 1.17.2019

International / EU Published Patents

[WO 2014/190189 A9](#) Date published 11.27.2014

[WO 2016/081476 A1](#) Date published 5.26.2016

[WO 2017/112747 A1](#) Date published 6.29.2017

[WO 2019/018846 A2](#) Date published 1.24.2019

[EP 3000134 A4](#) Date published 1.4.2017

[EP 3221895 A4](#) Date published 8.15.2018

[EP 3411906 A1](#) Date published 12.12.2018

China Allowed Patents

[CN 105556680 A](#) Date published 5.4.2014 – 69 claims

China Published Patents

[CN 107078145 A](#) Date published 8.18.2017

[CN 109155340 A](#) Date published 1.4.2019

Japan Published Patents

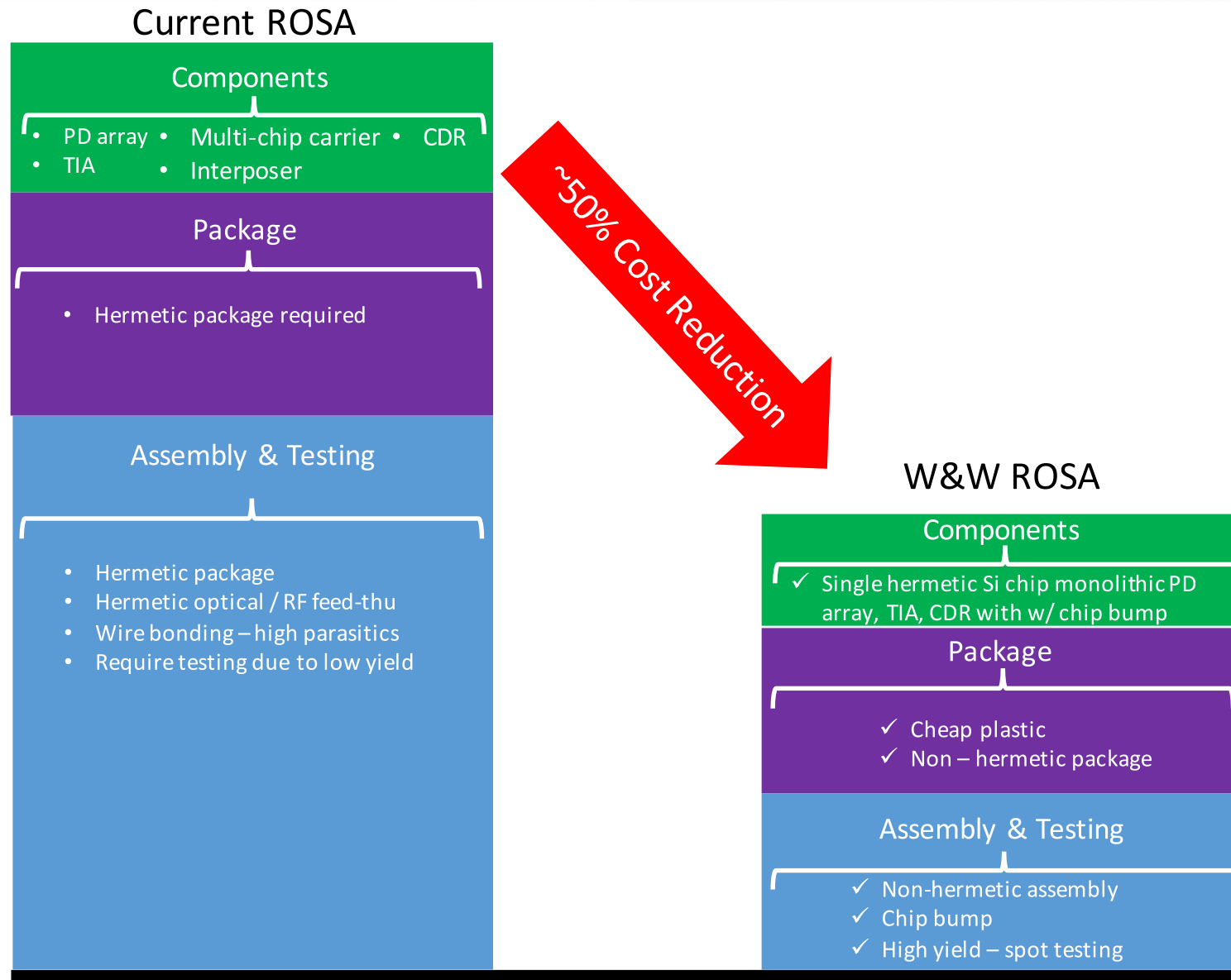
[JP 2016-526295 A](#) Date published 9.1.2016

[JP 2018-508970 A](#) Date published 3.29.2018

Korea Published Patents

[KR 10-2016-0039150](#) Date published 10.2016

ROSA Cost Reduction with Monolithic Integration



Key applications

Core focus



Data Center Interconnect

*Short reach → long haul networks
See slide 6-15 for details*



LiDAR

*Advanced Driver Assist Systems (ADAS)
See slide 16-21 for details*

Additional



Plastic Optical Fiber

*Automotive and
Aeronautics*



Fiber-to-Home

*Possibly first cost-competitive
solution*



Customer Electronics

*Active Optical Cable
(AOC) 4K + TV*

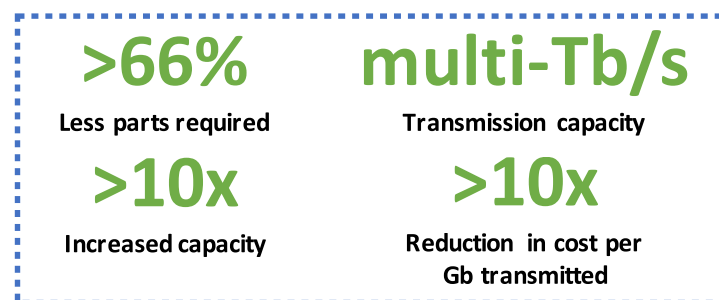
W&W Data Center

A Division of W&Wsens Devices Inc.

Solutions For The Next Generation

Technology differentiation of W&W photodetectors in data center interconnect

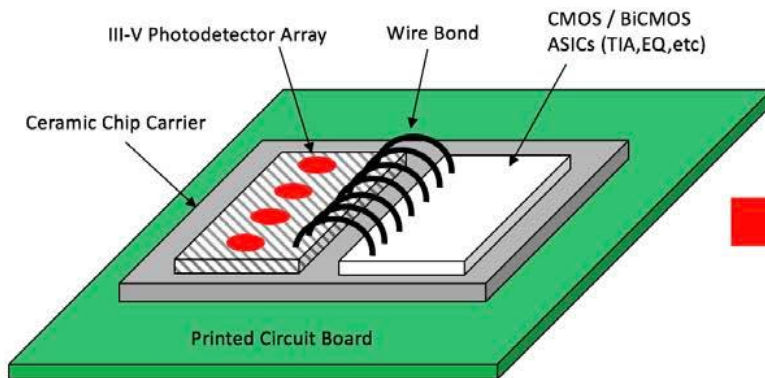
- ✓ Disruptive microstructure holes technology for photon trapping
 - Much higher sensitivity / speed and thinner photodetectors (PD) (1 μ m vs. 20 μ m used currently)
 - Enables all-silicon structure (instead of GaAs)
- ✓ Monolithic integration with CMOS / BiCMOS
 - Reduction of capacitance and inductance parasitics from wire bonding
 - PD and laser array with front-end transceiver mounted directly on PCB
- ✓ Simple assembly dramatically reduces packaging costs
 - Average cost of < \$0.10 per Gb Tx-Rx vs. \$2-10 in best-in-class solutions today
 - Significantly easier alignment of optical lenses with photodetector reducing cost
- ✓ Array size not limited by packaging complexity
- ✓ Ability to connect almost unlimited number of channels vs. current limitation of 48 channels in best-in-class solutions
 - Higher number of channels allows for increased aggregated data rate while maintaining low power consumption
- ✓ Ability to receive 25-50 Gb/s per channel
- ✓ Ability to drive multi-Tb/s vs. 480 Gb/s in top-rated solutions
- ✓ Ability to extend wavelength using Ge-on-Si photodetector / avalanche photodetector (APD) / single photon avalanche photodetector (SPAD)
- ✓ Allows for λ of 850nm – 1620nm



Simple CMOS monolithic integration for DCI

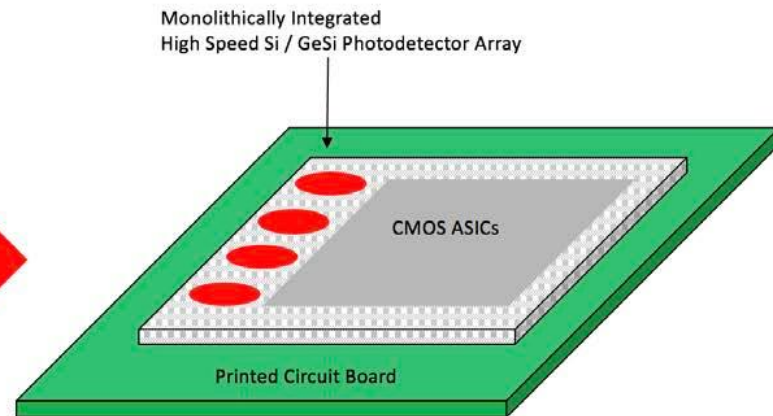
DCI Applications

Existing Optical Receiver (3 components on PCB)



Addressable Wavelengths & Data Rate
Wavelengths: 850nm, 1350nm, 1550nm
Data Rate: 25Gb/s (Quad PD = 100Gb/s
50Gb/s PAM4 (8PDs = 400Gb/s at 1350nm)

Optical Receiver With W&Wsens PD (1 component on PCB)



Decrease parts - 3 parts to 1
Decrease of assembly time
Increase profit margin

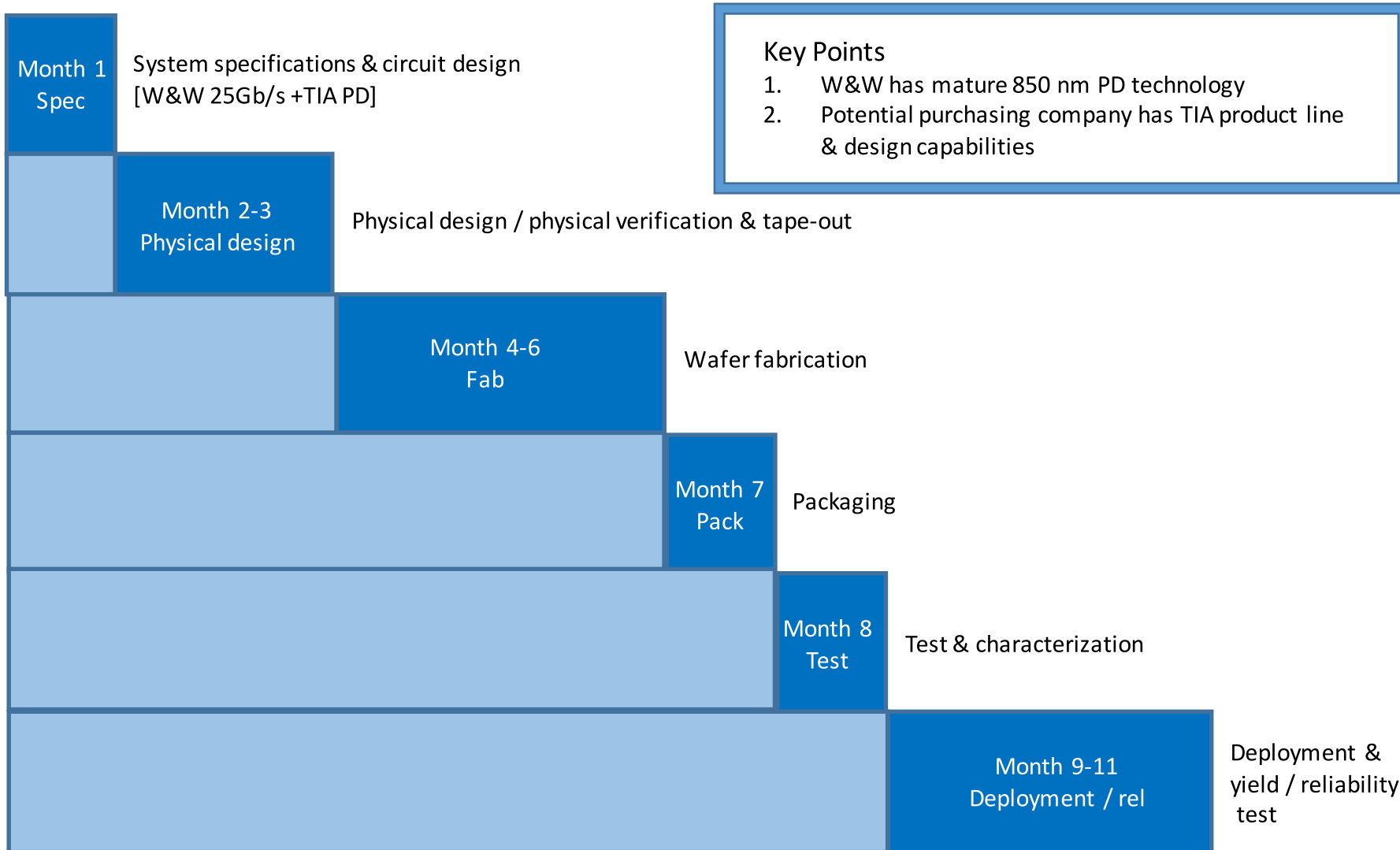
Time-to-Market

Monolithic Integrated 25 Gb/s 850 nm / 1310 nm PD



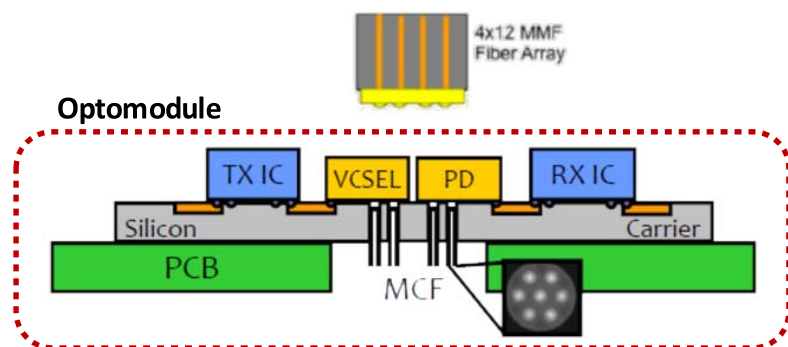
Time-to-Market

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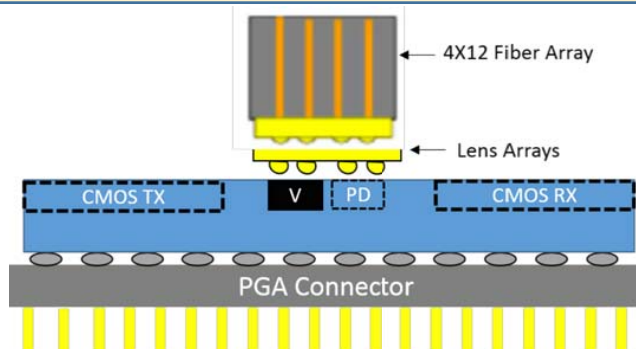
Application examples

Example 1 – Comparison to IBM



IBM On Board Optomodule

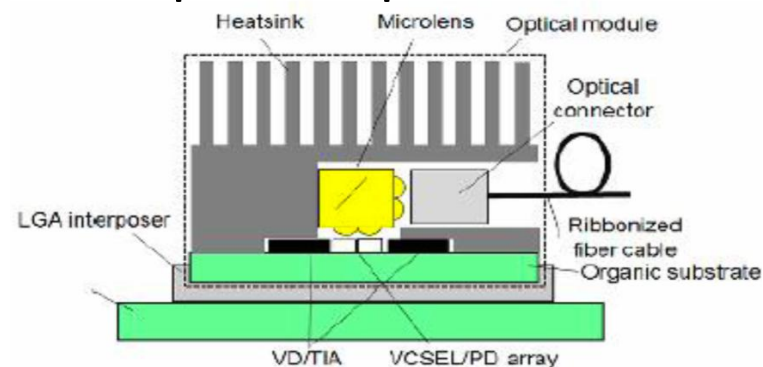
- 4-Fiber (24 core) optical transceiver



W&Wsens Devices On Board Optical Module

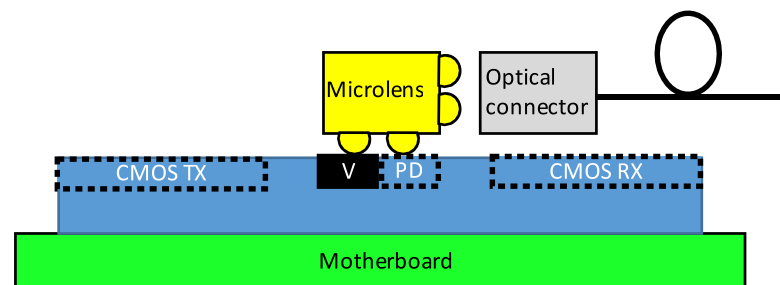
- Monolithically integrated Optochip with VCSEL array fluidic self-assembled 48 channel (480 Gb/s)
- 4 parts (IBM) vs. 1 part (W&Wsens)

Example 2 – Comparison to Finisar



TE Connectivity / Finisar On Board Parallel Optic Transceiver Module

- 12.5Gb/s x 24 channels (300Gb/s)



W&Wsens Solution:

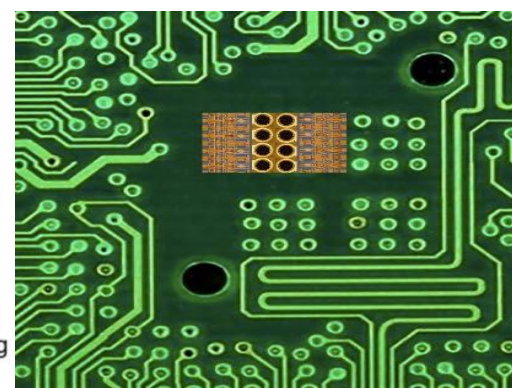
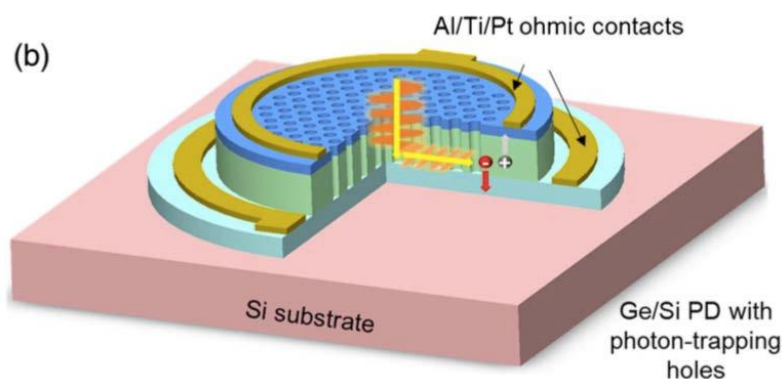
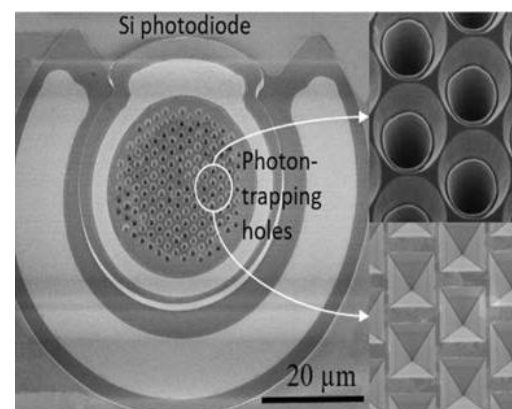
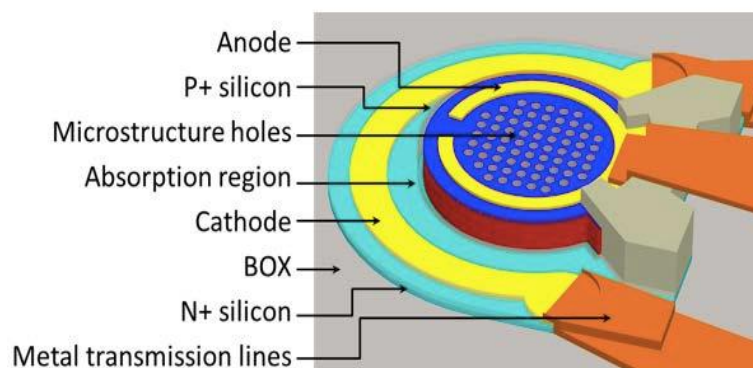
- Monolithically integrated Optochip with VCSEL array fluidic self-assembled 24 channel (480 Gb/s)
- 6 parts including interposer (Finisar) vs. 1 part (W&Wsens)

- Simplicity of packaging allows for:
 - Almost unlimited number of channels
 - Possibility to go to multi-Tb/s
 - Simplified optical alignment (lens alignment)

Innovation – microstructure holes in silicon photodetector

Photon trapping, Monolithic integration with CMOS ASICs, Direct attachment to PCB

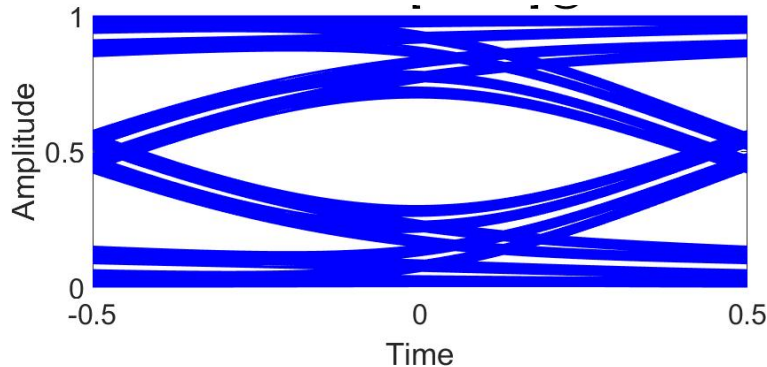
- Microstructure holes in the photo detectors allow for much higher light detection through photon trapping...
- ...resulting in over 10x reduction in layer thickness (1 μ m vs. 20 μ m used currently)...
- ...allowing for silicon photodetector (no GaAs) and integration with CMOS



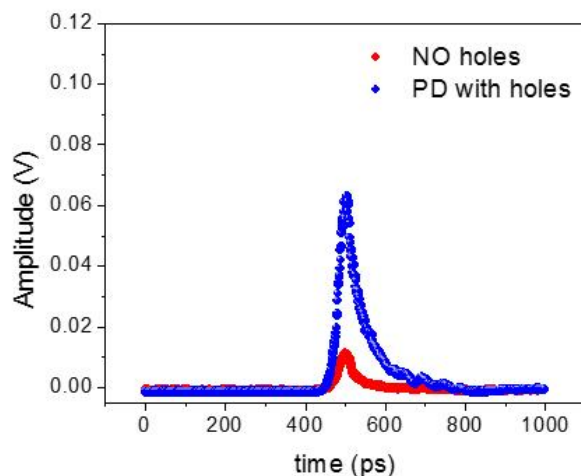
Innovation – world's first silicon-only 10-25 Gb/s photodetector with high sensitivity

- High speed and sensitivity from 800 – 1550nm wavelength
- Thin detectors allows for **world's first Si 10 – 25Gb/s+** photo detector compatible with CMOS integration

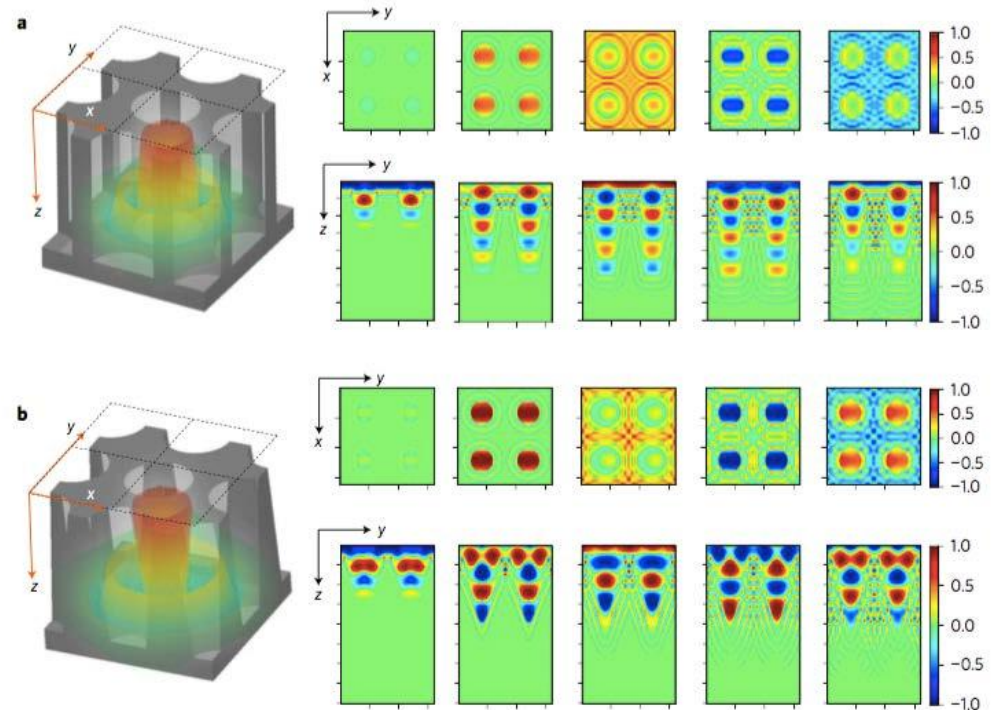
850nm Si MSM Photodetector
50 μ m diameter with holes [3V bias] @10Gb/s



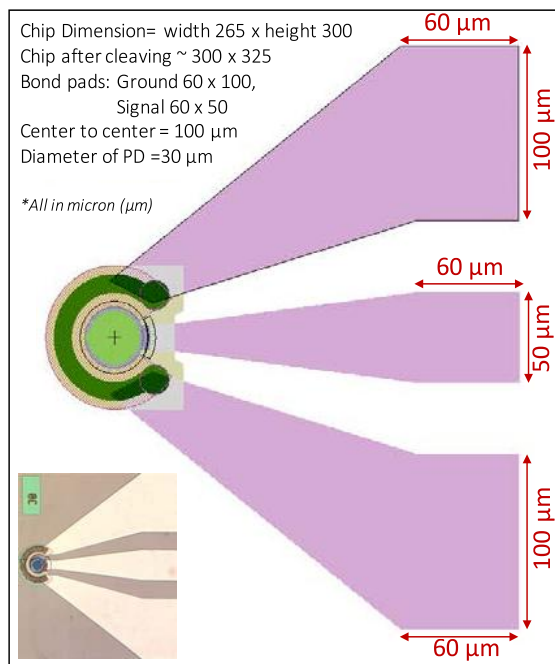
Impulse Response @ 850nm Si MSM



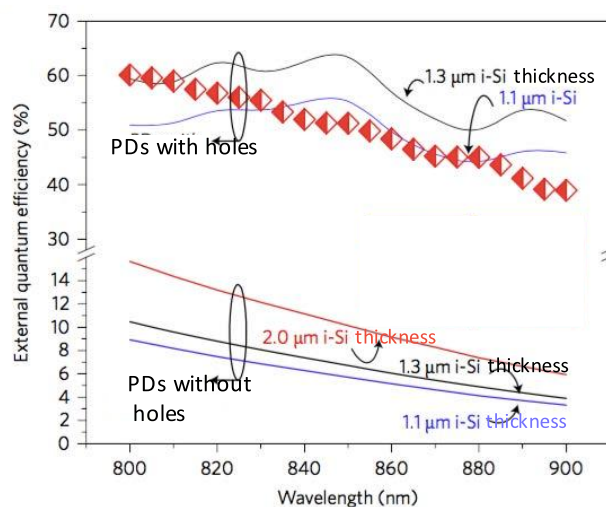
Optical field distribution in microstructure hole PD



Single chip layout and characteristics

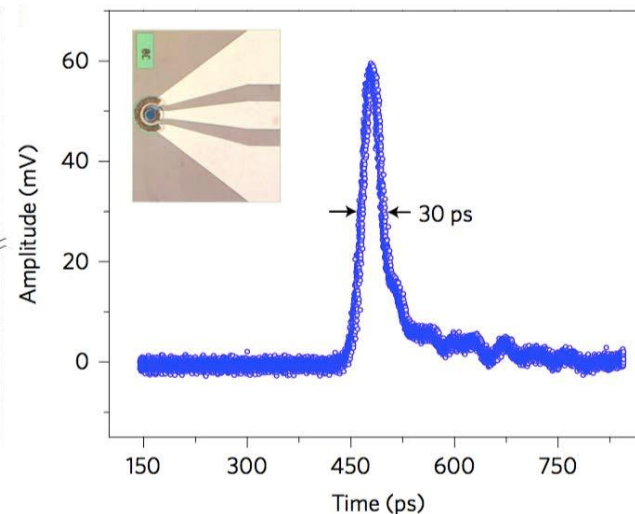


EQE vs wavelength



Si PD 850nm laser pulse

- High Speed
- High Sensitivity



Features:

- G-S-G (cathode-anode-cathode) aluminum bond pads 300 nm thickness
- Drop in replacement for GaAs PIN Photodiodes.
- Extended wavelengths to $\lambda = 980 \text{ nm}$.
- Active Optical Cable applications.
- Diameter 30 μm
 $I_{\text{dark}} = 60 \text{ pA}$ (30 μm device)
- Responsivity (A/W)
 ≈ 0.35 (@ $\lambda = 850 \text{ nm}$)
 ≈ 0.20 (@ $\lambda = 950 \text{ nm}$)
 ≈ 0.15 (@ $\lambda = 980 \text{ nm}$)
- Capacitance (pF)
 $\approx 0.084 \text{ pF}$ (at 3V bias)
- Highly linear up to 20mW input power

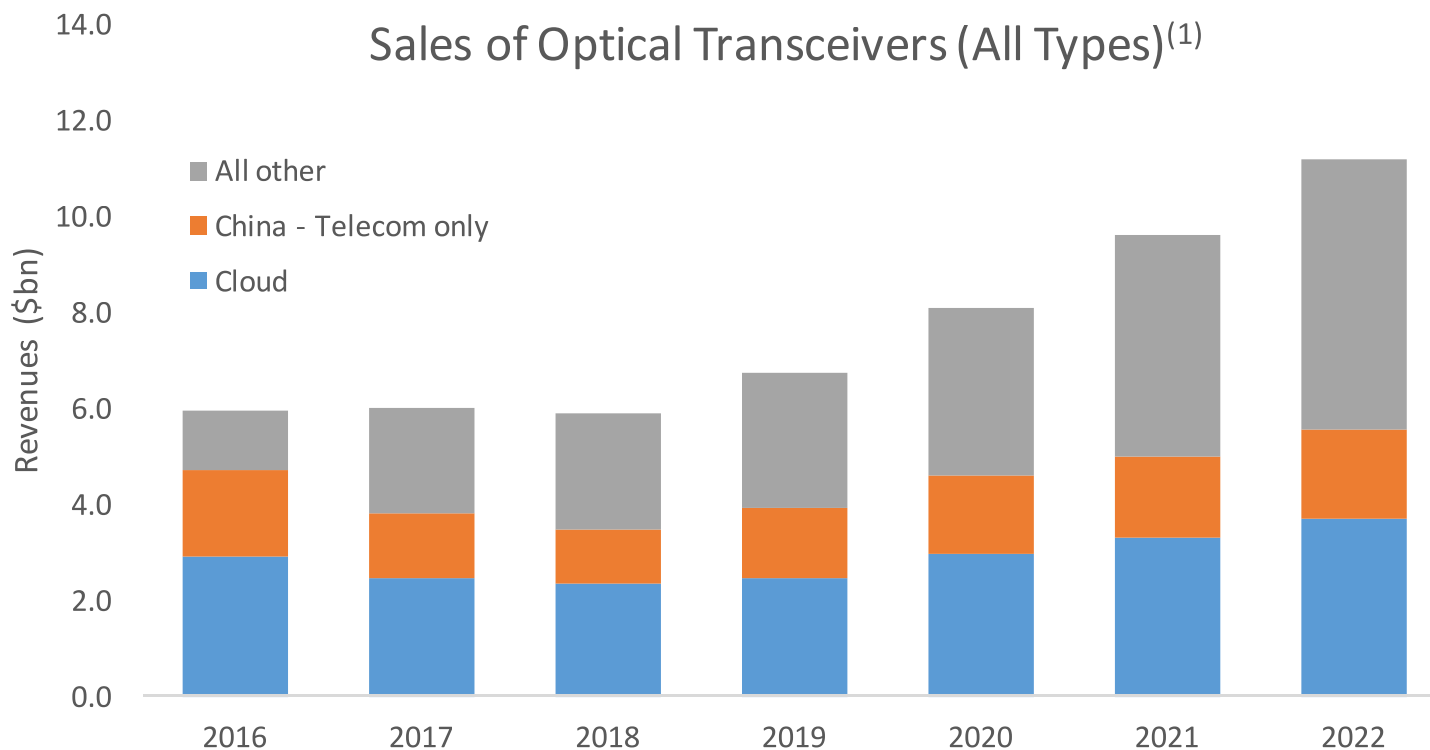
- Current best-in-class solutions for 1 μm thickness Si PD have ~5% efficiency; W&Wsens solution has ~60% efficiency
- Chip available for customer testing

Large and fast growing data center interconnect market

W&W Total Addressable Market Size for Data Center Interconnect = \$3.7bn

Growth Drivers

- Total Data Traffic CAGR [4yr] = 57%
- Monthly data traffic to reach 19.2 EB (1 Exabyte = 1 Billion Gigabytes)
- 73% of all data traffic stays within data centers
- Data centers set to increase by 60% over next 4 years



(1) Source: LightCounting April 2018.

W&W LiDAR

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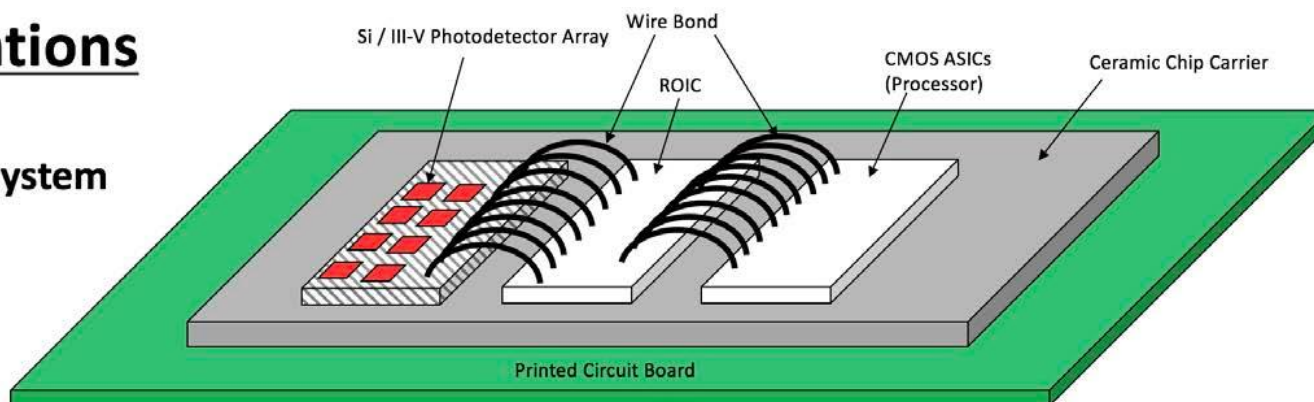
Technology differentiation of W&Wsens photodetector in LiDAR

- ✓ Complete LiDAR system on a single chip
- ✓ Integration of photo detector array with CMOS electronics
- ✓ Addresses short to long range LiDAR applications
- ✓ All Si or Ge-on-Si photodetectors
 - **Very thin** Photodetector (1μm vs 20μm used currently)
 - Allowing use of **Silicon-only and lower voltages** (30V vs 200-600V used currently)
 - **High sensitivity**, comparable to best-in-class GaAs / InP
 - **Lowest level of noise** as a result of avalanche gain in silicon
 - **Fast rise time and lower jitter** allows for high depth resolution in LiDAR detection with **~1,000x improvement (millimeter depth vs meter depth)**
- ✓ Wafer scale assembly of lasers on LiDAR chips
- ✓ 2D arrays of laser / photodetector
- ✓ Dramatic cost reduction
- ✓ Straight forward path to APD / SPAD development

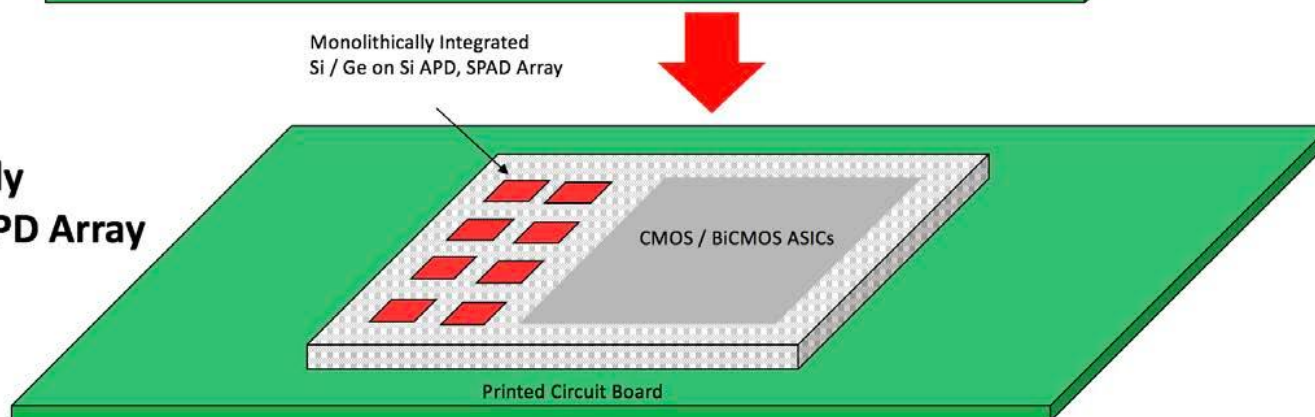
Simple CMOS monolithic integration for LiDAR

LiDAR Applications

**Existing LiDAR Subsystem
Detector Array
& ASICs Chips**



**LiDAR Subsystem
with Monolithically
Integrated W&W PD Array**



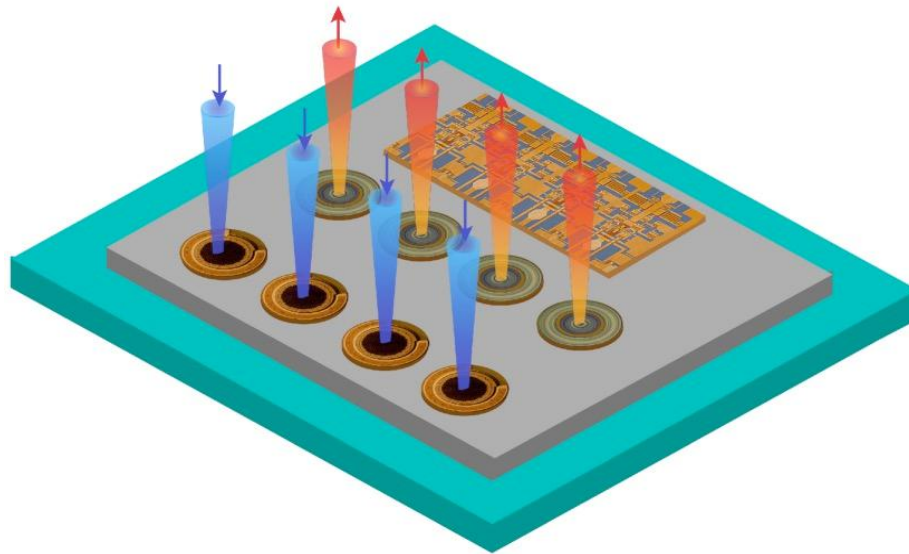
Addressable Wavelengths : 850nm, 905nm,
940nm, 1550nm with fast rise time 10s psec

Decrease Parts - Multiple to 1
Decrease Assembly Time
Increase Profit Margin

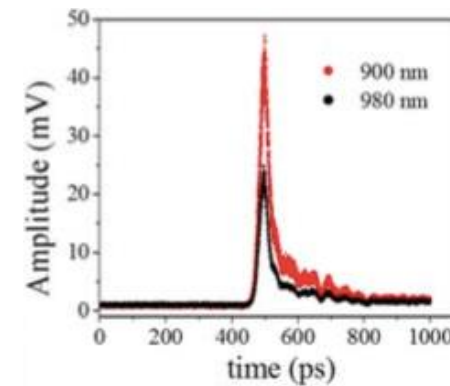
LiDAR innovation – system on a single chip

- Surface emitting laser with detector arrays & electronics on a single chip
- LiDAR chip directly attached to PCB

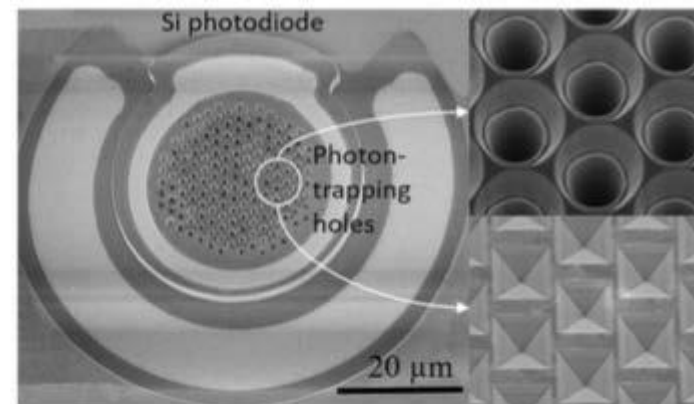
LiDAR Chip on PCB – Flash LiDAR with VCSEL array & high density PD / APD/ SPAD array



Impulse response of microstructure hole Si PD to 900nm and 980nm laser pulses

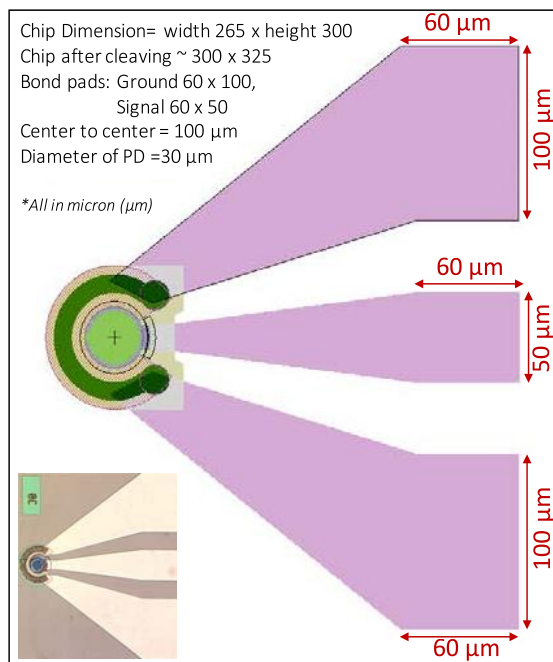


Scanning electron microscope micrograph of microstructure hole Si PD



Single chip layout and characteristics

Ultrafast and highly efficient silicon PIN photodiodes using photon trapping



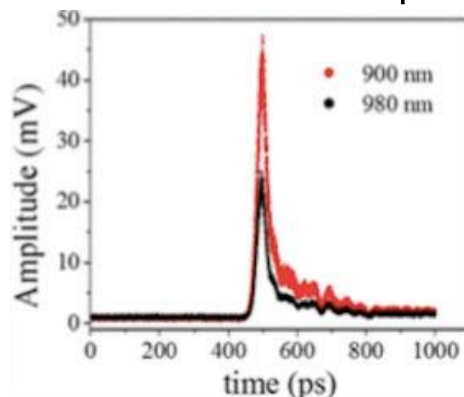
Features:

- G-S-G (cathode-anode-cathode) aluminum bond pads 300 nm thickness
- Drop in replacement for GaAs PIN Photodiodes.
- Extended wavelengths to $\lambda = 980 \text{ nm}$.
- Active Optical Cable applications.
- **Diameter** 30 μm
 $I_{\text{dark}} = 60 \text{ pA}$ (30 μm device)
- **Responsivity (A/W)**
 ≈ 0.35 (@ $\lambda = 850 \text{ nm}$)
 ≈ 0.20 (@ $\lambda = 950 \text{ nm}$)
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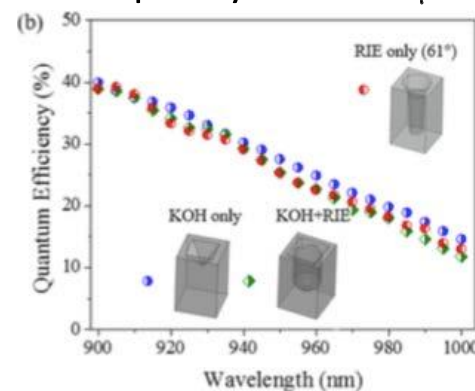
Capacitance (pF)

- $\approx 0.084 \text{ pF}$ (at 3V bias)
- Highly linear up to 20mW input power

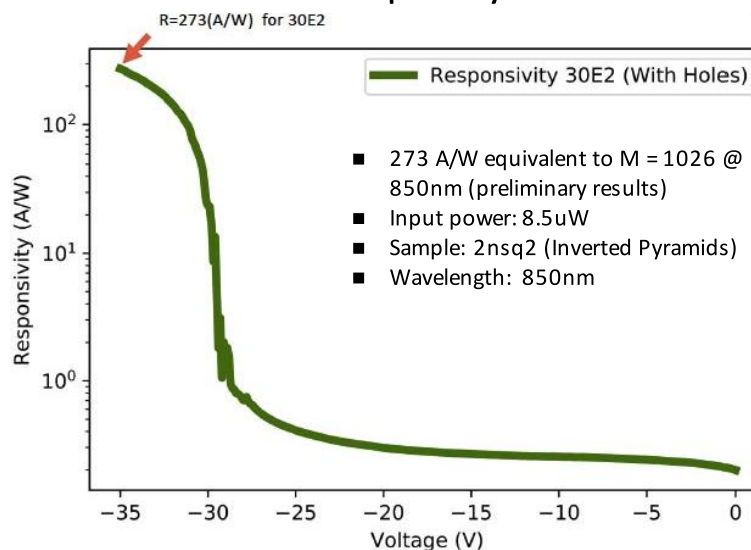
Impulse response of microstructure hole Si Pd to 900nm and 980nm laser pulses



EQE vs wavelength 900 – 1000nm for Si absorption layer thickness <2 μm



Responsivity



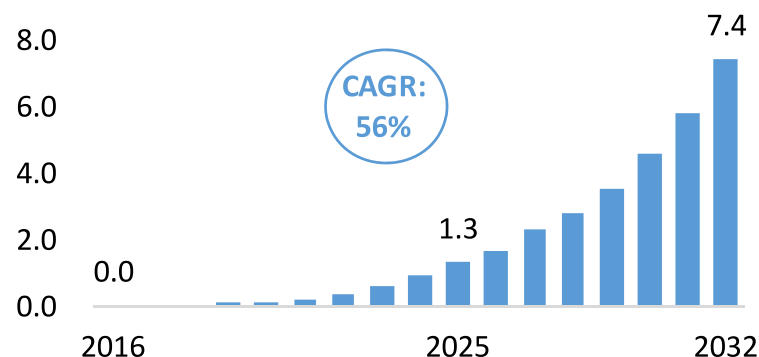
■ Chip available for customer testing

Global LiDAR market outlook

LiDAR is a key enabler for capturing real-time 3D data

	LiDAR	Short Range Radar 24GHz UWB	Long Range Radar 77 GHz	Ultrasonic	Vision	Infrared
Short Range (0-2MM)						
Nominal Range (2-30MM)						
Long Range (30-100MM)						
Narrow Vertical FOV <10deg						
Wide Vertical FOV >30deg						
Angular resolution						
Object speed measurement						
Bad weather operation						
Blockage (impurity on sensor)						
Night operation						
Sensitivity to Light						
Cost						

LiDAR Shipment Forecast⁽¹⁾ (mm units)



- LiDAR is expected to be a \$7-8bn market by 2030, with a majority of revenues coming from solid-state and flash LiDAR systems⁽¹⁾
- Between 2015 and 2025, 10 key auto OEMs are expected to spend ~\$345bn on autonomous, connectivity, and electrification R&D⁽²⁾
- IEEE estimates that roughly 75% of road-borne traffic should include self-driving cars by the year 2040⁽³⁾
- Prominent auto OEMs are asking for LiDAR modules to cost less than \$100
 - Currently, best-in-class LiDAR modules are almost 80x more expensive today

(1) Source: Yole – The Automotive LiDAR Market April 2018.

(2) Source: Frost Perspectives – July 14, 2017.

(3) Source: Technavio – Global Automotive LiDAR Sensors Market 2016-2020.

Publications & Media

- Photon-Trapping Microstructures Enable High-Speed Efficiency Silicon Photodiodes; Nature Photonics 2017
 - High Speed Surface Illuminated Si Photodiode Using Microstructure Holes for Absorption Enhancements at 900 - 1000nm Wavelength; ACS Photonics 2017
 - A New Paradigm in High-Speed and High-Efficiency Silicon Photodiodes for Communication Part 1: Enhancing Photon-Material Interactions via Low-Dimensional Structures; IEEE TED 2017
 - A New Paradigm in High-Speed and High-Efficiency Silicon Photodiodes for Communication Part 2: Device and VLSI Integration Challenges for Low-Dimensional Structures; IEEE TED 2017
 - High-Speed High-Efficiency Broadband Silicon Photodiodes for Short-Reach Optical Interconnects in Data Centers; OFC 2018
 - Surface Passivation of Silicon Photonic Devices with High Surface-to-Volume-Ratio Nanostructures; Journal of the Optical Society of America B 2018
 - Surface-illuminated photo-trapping high-speed Ge-on-Si photodiodes with improved efficiency up to 1700nm; Photonics Research OSA 2018
 - Enhanced Photon Detection Efficiency of Silicon Single Photon Avalanche Photodetectors Enabled by Photon Trapping Structures; DOI: 10.1109/PHOSST.2018.8456744 IEEE 2018
-
- Fast Silicon Photodiodes ; Nature Photonics
 - Silicon Nanostructures Bend Light to Make Faster Photodiodes; IEEE Spectrum
 - Tiny Black Holes Enable a New Type of Photodetector for High Speed Data; Phys.org
 - Nanoholes in Silicon Bolster Photodetector Speed, Efficiency; Photonics.com
 - “Black Holes” in Silicon Enable High-Speed Photodetector; Photonicsonline.com