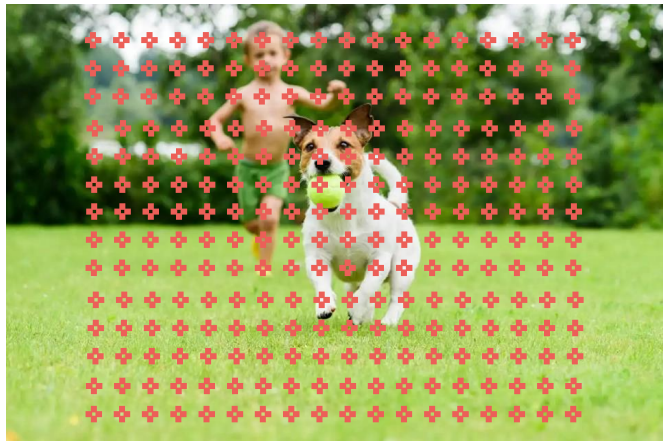
Physical and Cost Comparison of Smartphone Laser Autofocus Solutions

presented by P.L. Bonanno

HONOR MEIZU SAMSUNG



SONY

YOLE GROUP
Activities

We provide industrial companies, financial investors and R&D organizations, with market research and marketing analysis, technology, supply chain and cost analysis, as well as performance evaluation, to help our customers in their decision-making about their future business and manufacturing strategy in the semiconductor, photonic and electronic sectors.

3 CORE ACTIVITIES BASED ON DEEP SYNERGIES

Market & Technology

- Market, technology, and strategy consulting
- M&A, Due Diligence and evaluation of companies

Teardown Reverse engineering and costing

- Technology, process & cost analysis
- Teardown and reverse engineering
- Comparative analysis

Performance analysis

- Test of electric and electro-optical performance of devices
- Comparison of performances and related technical choice

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LASER AUTOFOCUS REVERSE COSTING

Presentation Outline

1. Smartphone 3D Imaging and Laser Autofocus

2. 3 systems
   - iPhone 15 Pro LiDAR module by Sony
   - VL53L5 by STMicroelectronics
   - TMF8821 by ams AG

3. Reverse Costing Methodology

4. Approximative Model

5. Results & Discussion

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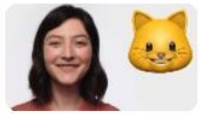
SMARTPHONE 3D IMAGING AND LASER AUTOFOCUS

Smartphone 3D Imaging use cases

Use-cases and opportunities for the front 3D camera

- Easy unlocking

- Morphing Augmented reality



Tik Tok

- Payment Face recognition

支付宝 ALIPAY

Pay

- Gaming Avatar

faceshift

- Enhanced video call

- Holographic displays

Use-cases and opportunities for the rear 3D camera

- Better photography

- Augmented reality

QLONE

CANVAS

- Gaming

- Commercial

- 3D printing

- Others?

SMARTPHONE 3D IMAGING AND LASER AUTOFOCUS

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Interesting, but out of scope

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- Others?

SMARTPHONE 3D IMAGING AND LASER AUTOFOCUS

Smartphone 3D Imaging use cases

Photography (space-resolved laser autofocus)

selective focus & bokeh

Continuous mode autofocus

Smartphone 3D Imaging use cases

Mixed Reality Gaming

SMARTPHONE 3D IMAGING AND LASER AUTOFOCUS

Smartphone 3D Imaging use cases

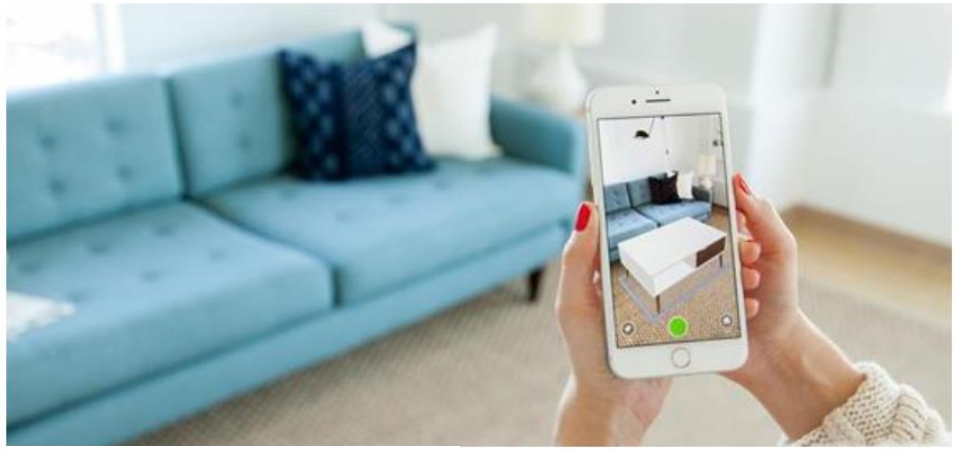
Commercial / Shopping

Virtual mall

Fitting clothes

AR Advertisement

Reality curation

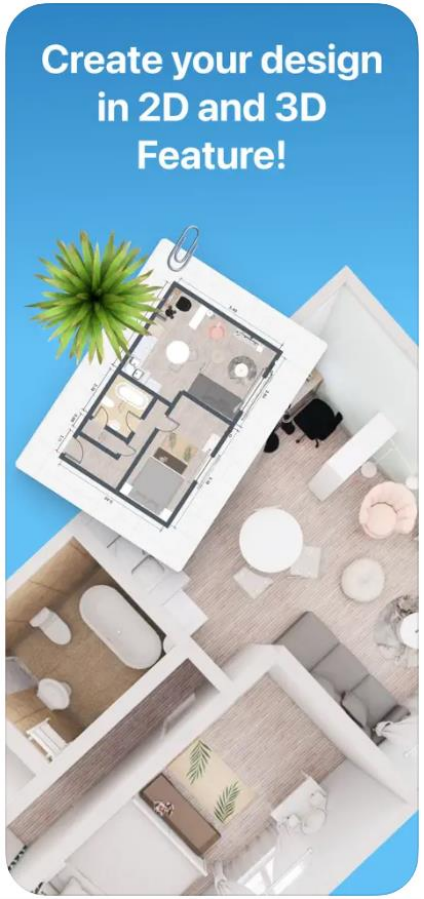


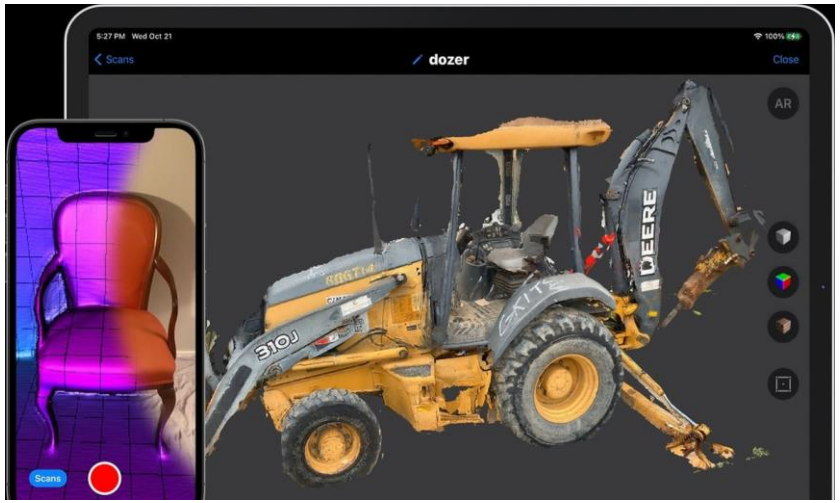
Interior decorating

SMARTPHONE 3D IMAGING AND LASER AUTOFOCUS

Smartphone 3D Imaging use cases

and more...

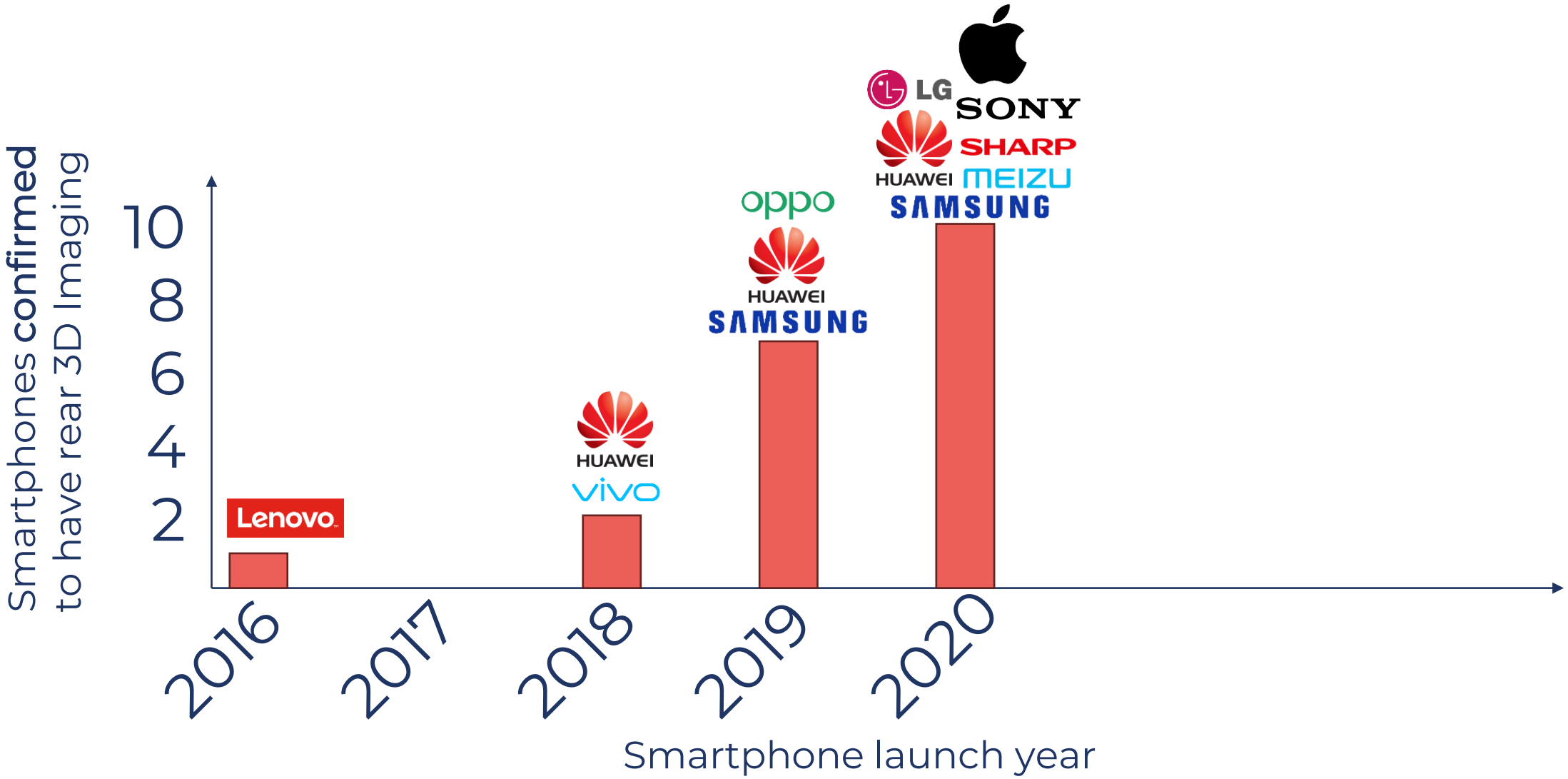




SMARTPHONE 3D IMAGING AND LASER AUTOFOCUS

Incidence of Rear-facing 3D Imaging

Logos: smartphone OEMs



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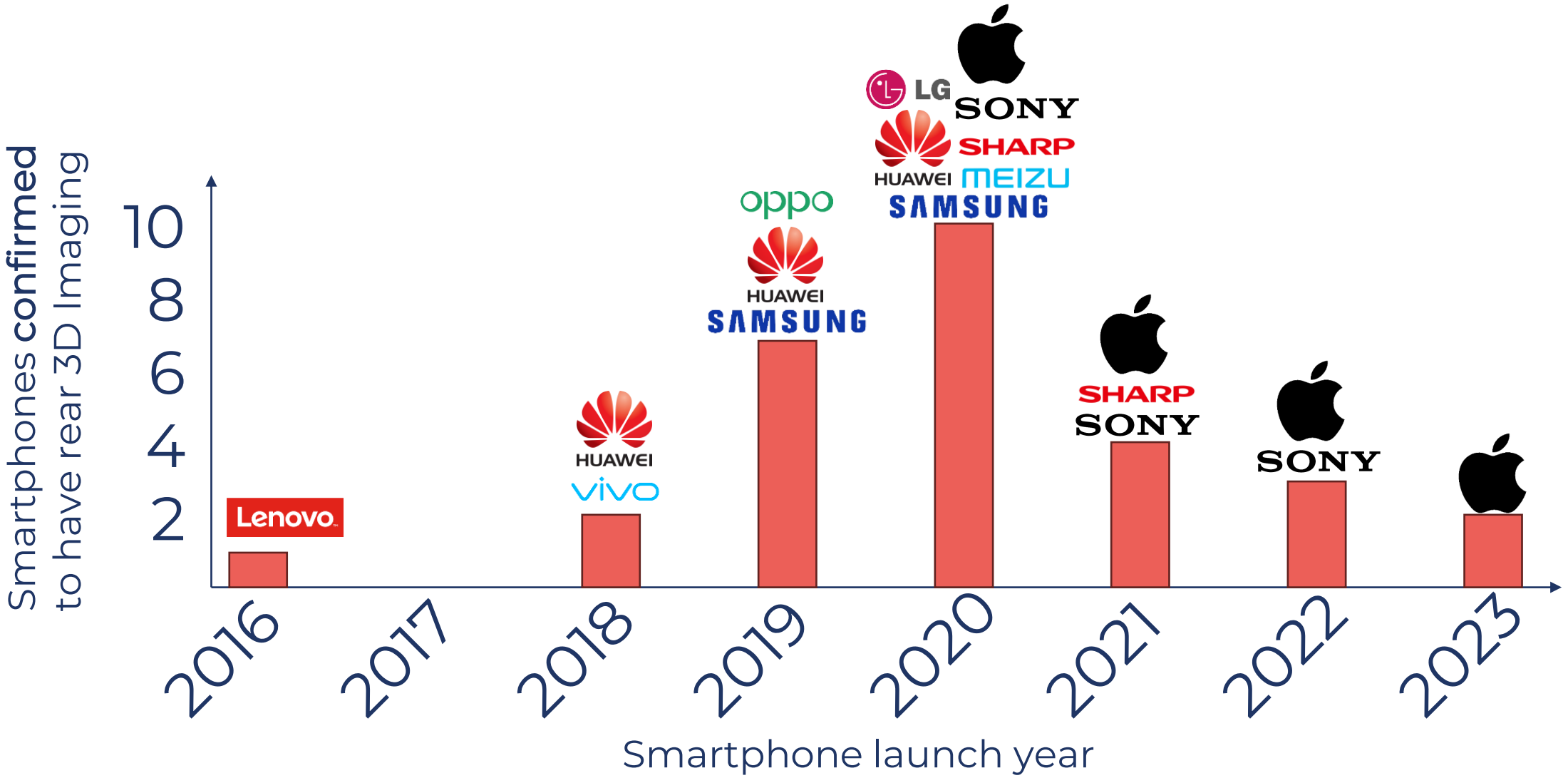

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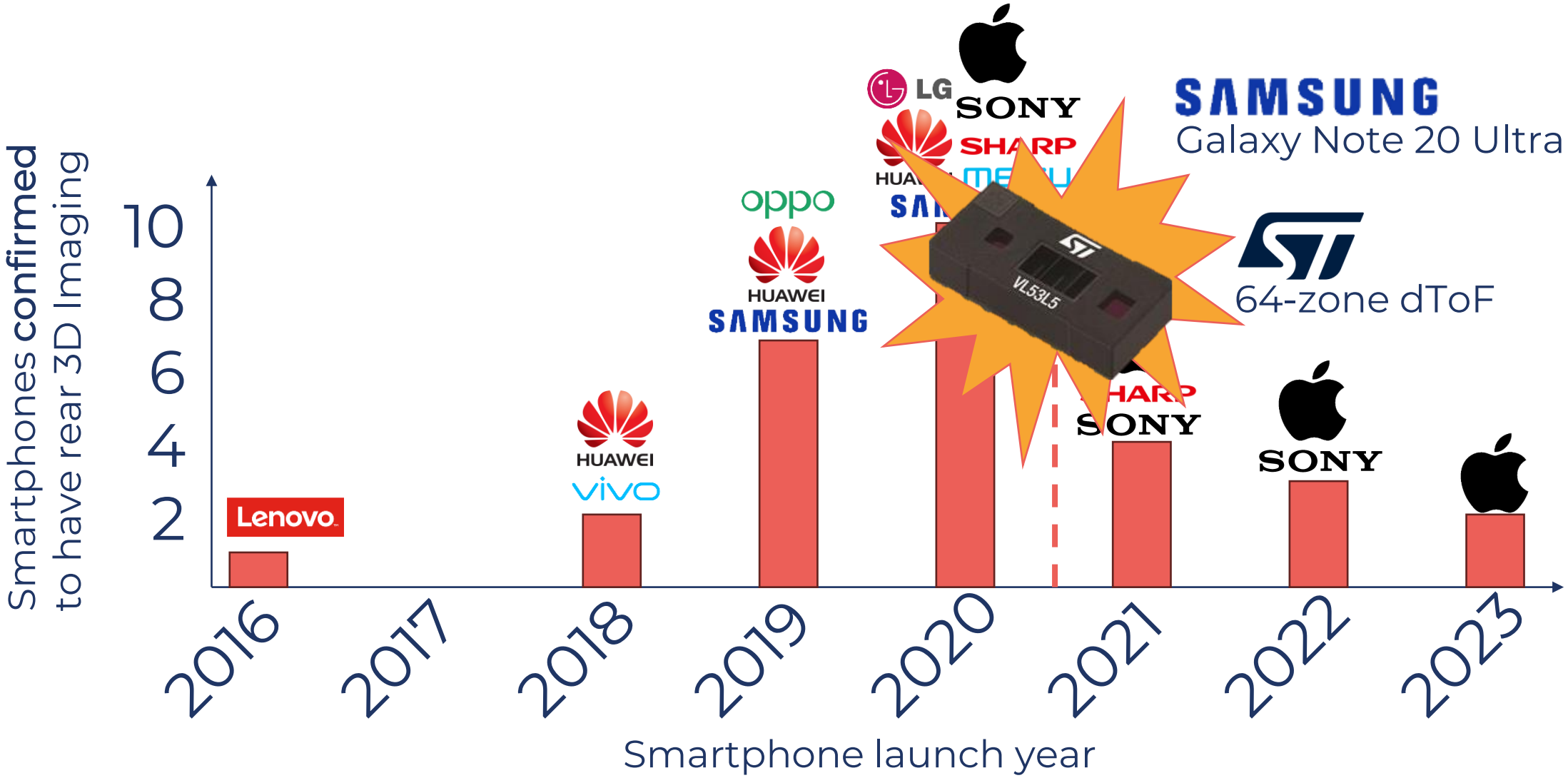

SMARTPHONE 3D IMAGING AND LASER AUTOFOCUS

Multizone dToF use cases

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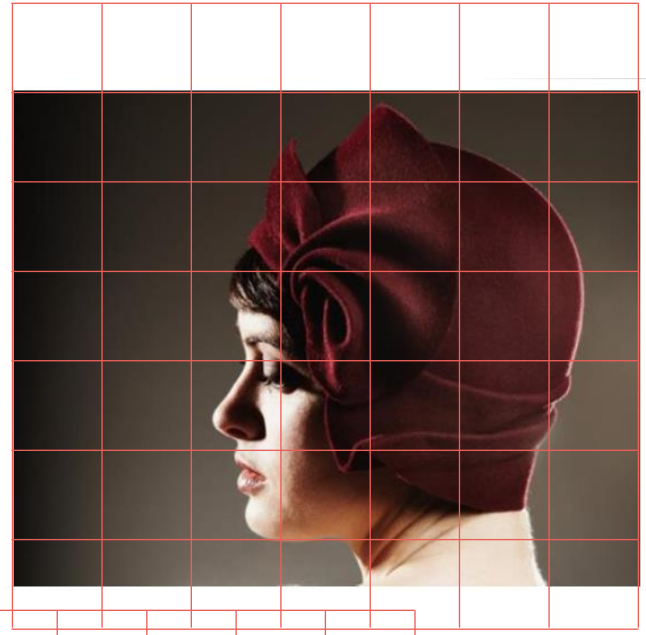
- Others?

SMARTPHONE 3D IMAGING AND LASER AUTOFOCUS

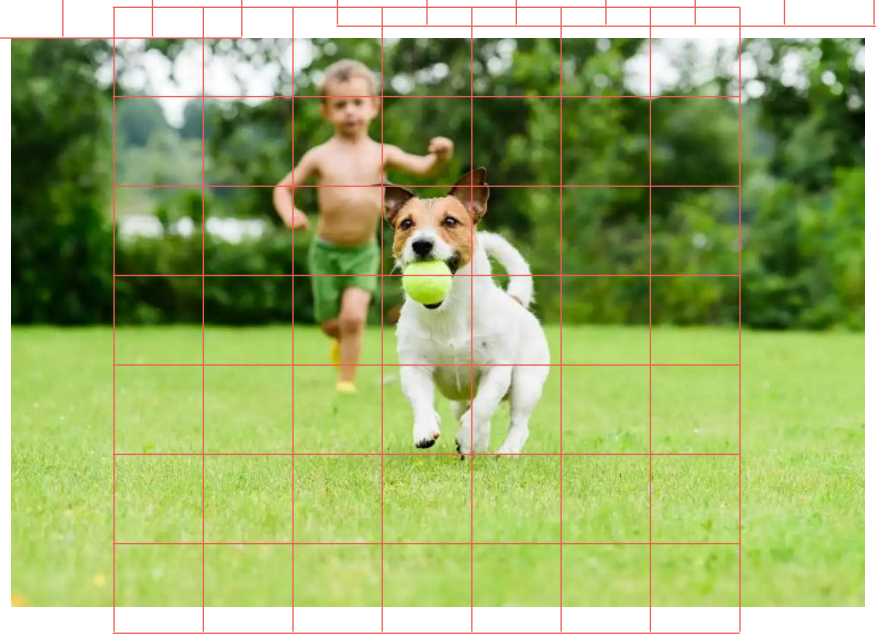
Multi-zone Laser Autofocus

Photography (space-resolved laser autofocus)

"Multi-zone" Laser Autofocus



selective focus & bokeh



Continuous mode autofocus

SMARTPHONE 3D IMAGING AND LASER AUTOFOCUS

Ultra-premium Smartphone Autofocusing Strategies

Passive Autofocus

Uses special pixels in the CIS

- Very Inexpensive
- Needs bright, high contrast scene

used by all smartphones

Active Autofocus

“Multi-zone” ToF

- Moderate cost
- Low resolution

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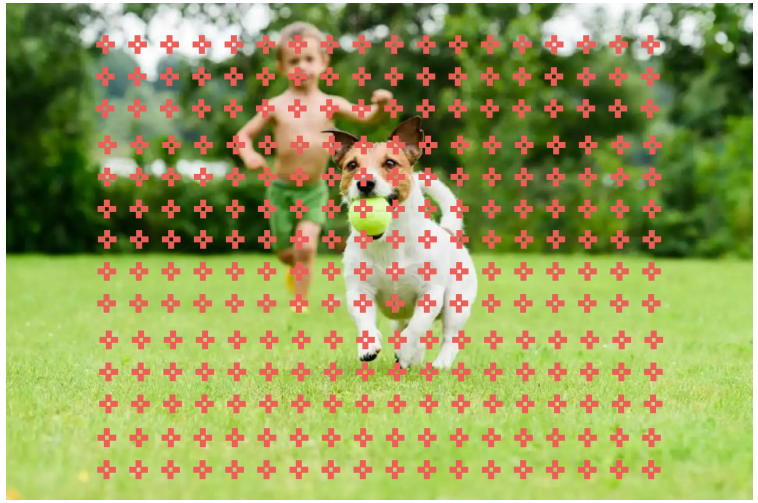
3D Imaging



- High cost
- High resolution

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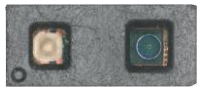
LASER AUTOFOCUS REVERSE COSTING
Presentation Outline



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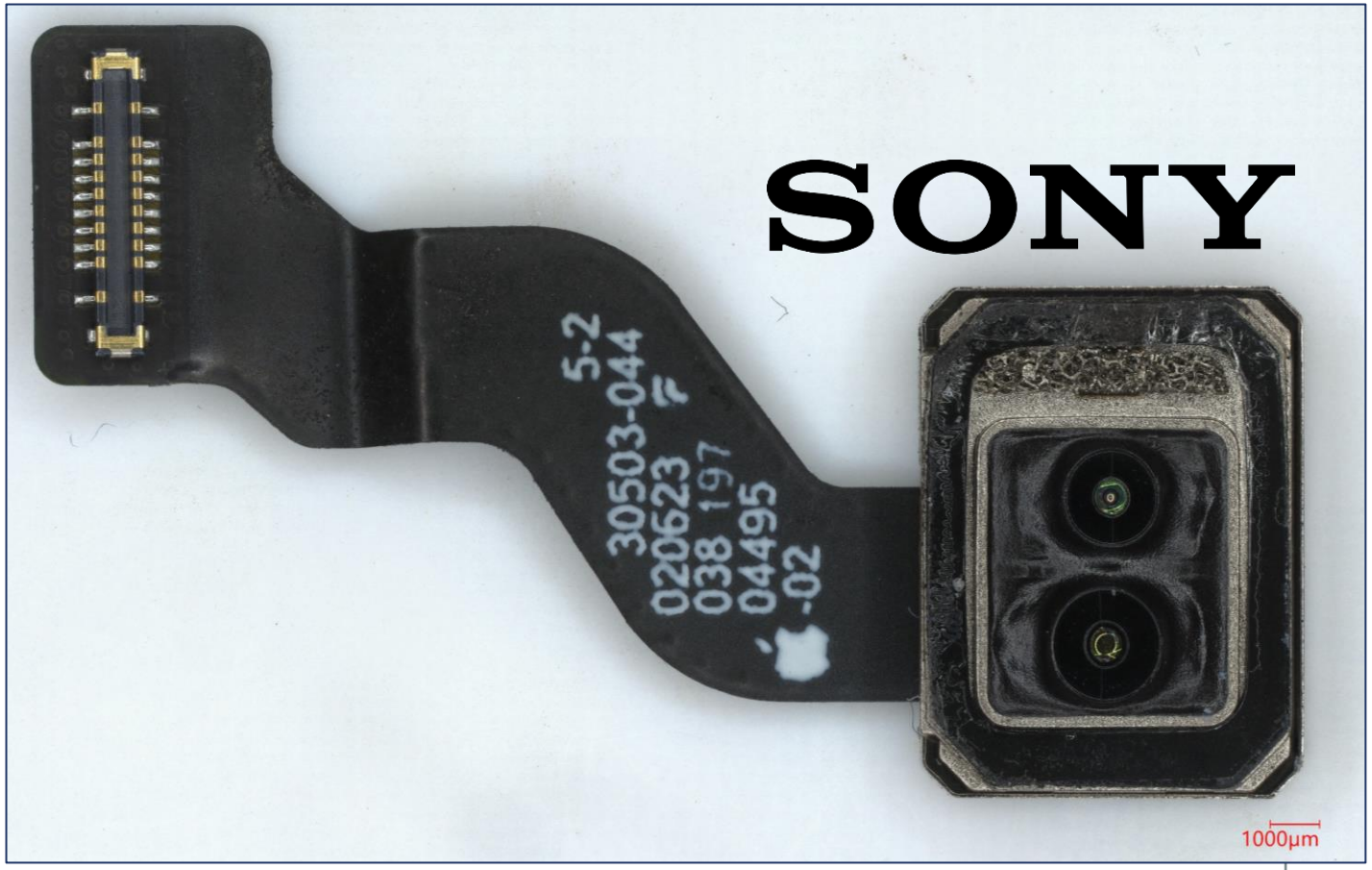


IPHONE 15 PRO LIDAR MODULE

iPhone 15 Pro Max Teardown

iPhone 15 Pro Max Rear View ©2024 Yole SystemPlus

iPhone 15 Pro Max Rear Camera
©2024 Yole SystemPlus

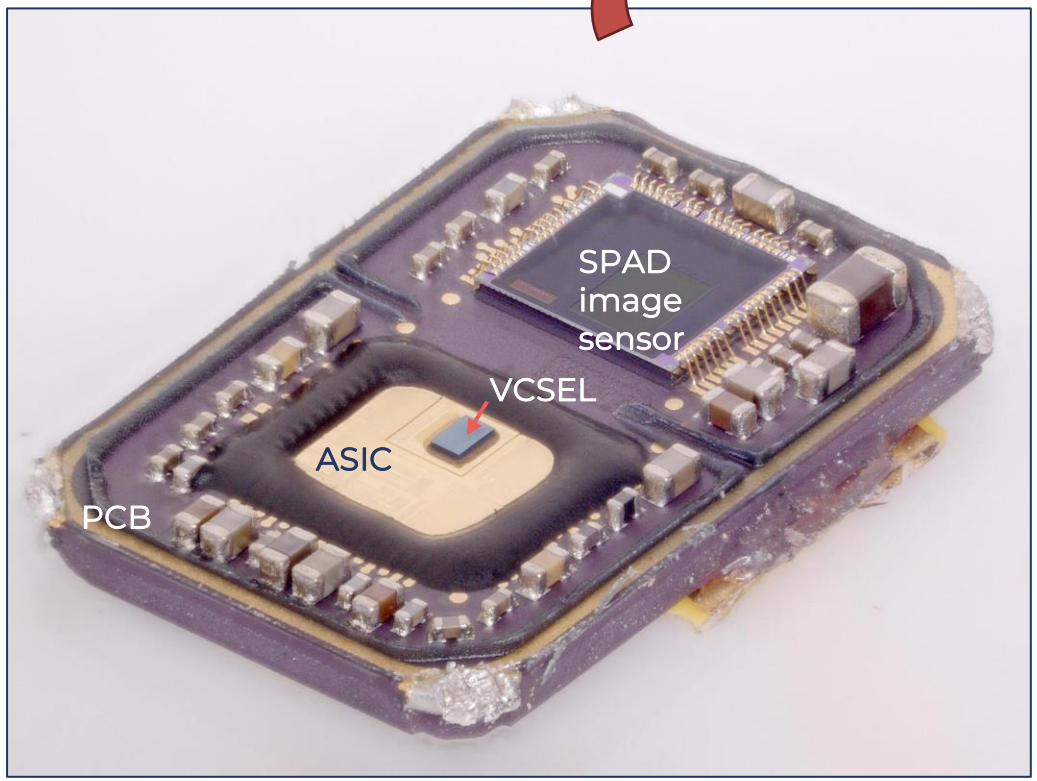
LiDAR Module
©2024 Yole SystemPlus

The LiDAR module is part of the rear camera.

IPHONE 15 PRO LIDAR MODULE

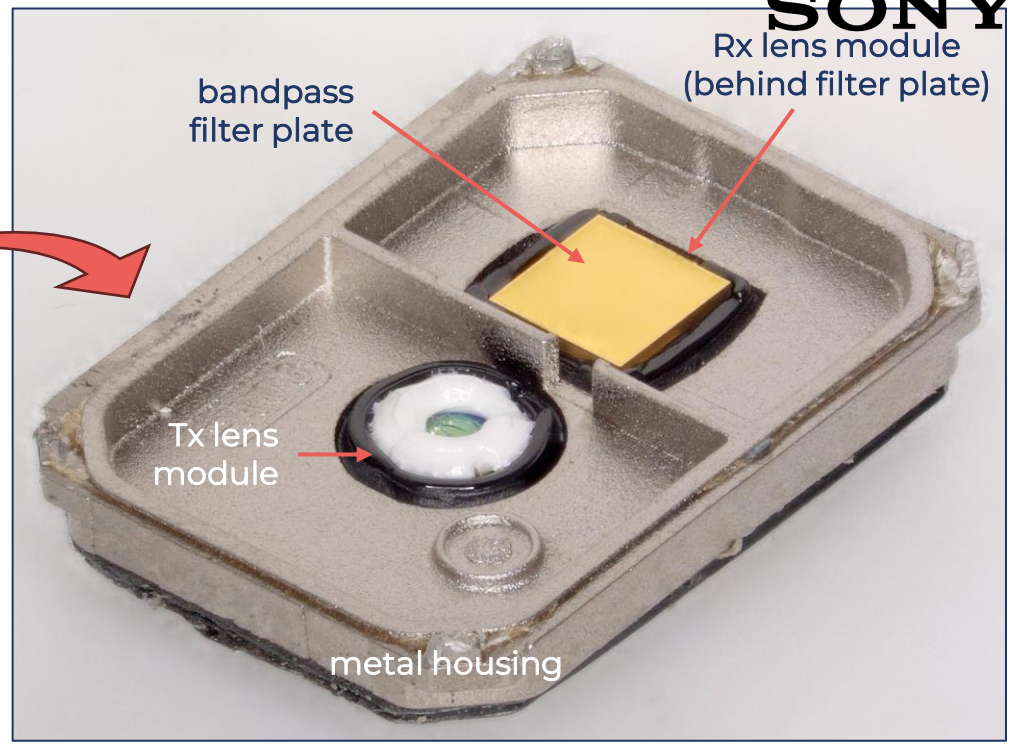
Module Teardown

separate optics assembly from substrate



LiDAR Module /with optics removed - Perspective View

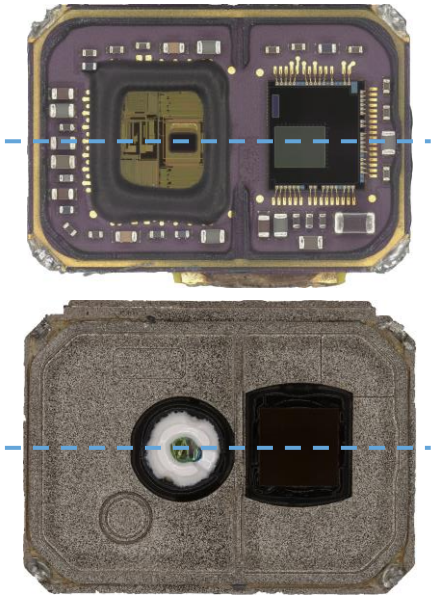
SONY



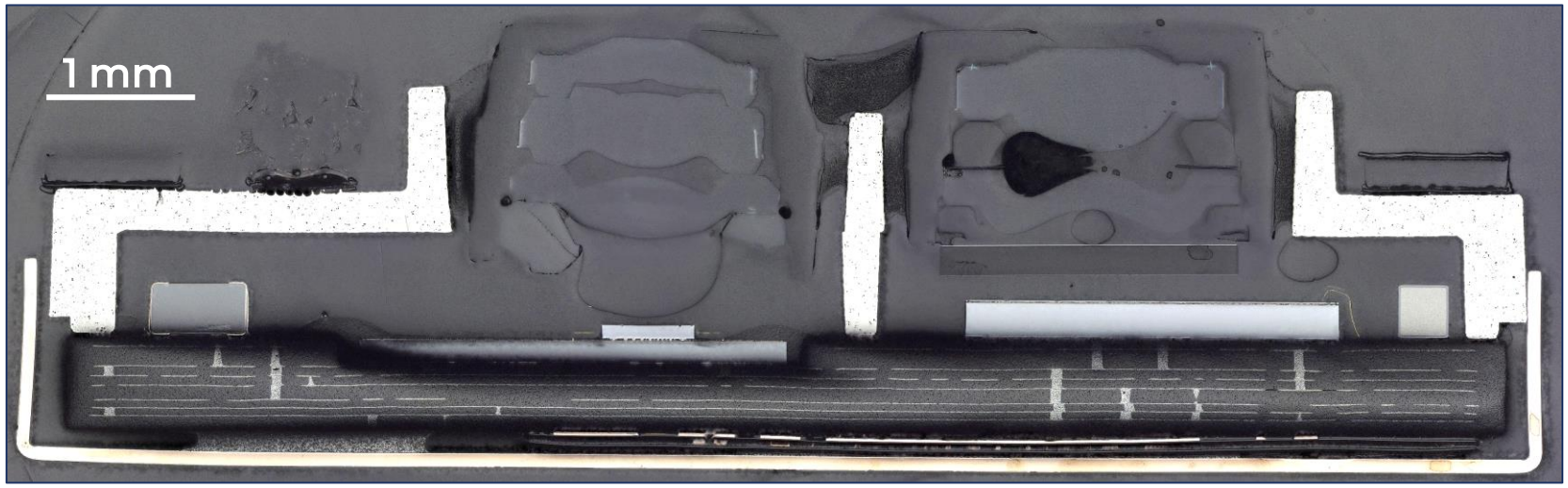
LiDAR Module Optics Assembly - Perspective View

IPHONE 15 PRO LIDAR MODULE

Cross Section

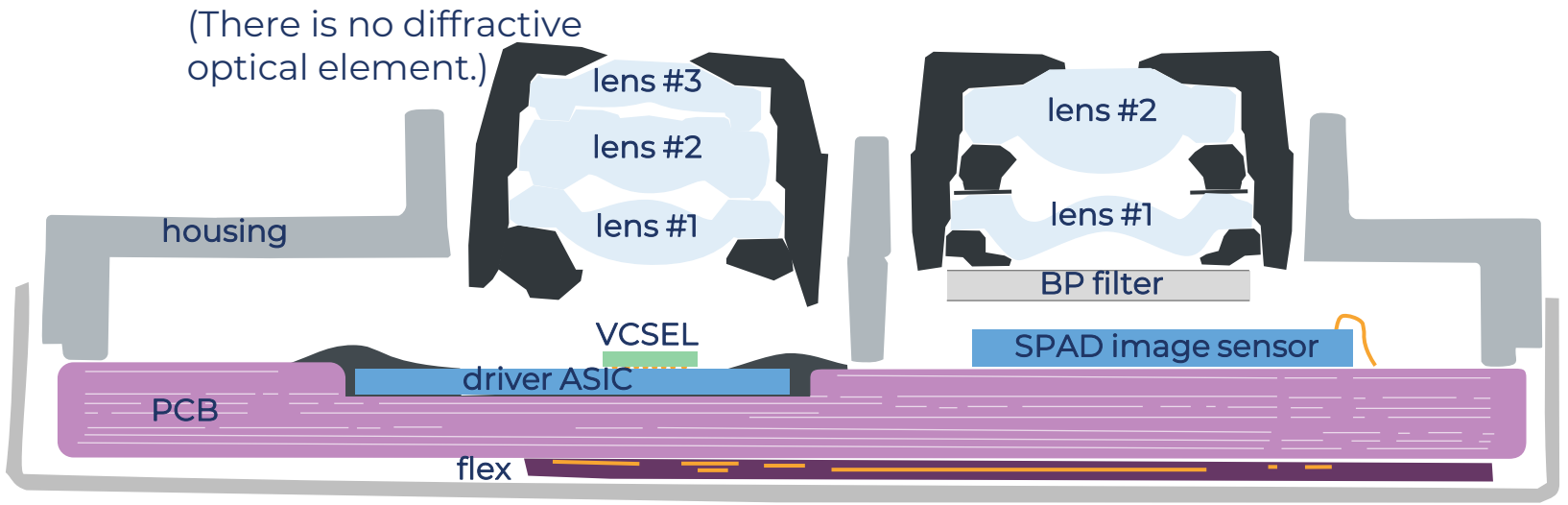


Opened LiDAR Module w/ cross-sectional plane indicated - Optical Views ©2024 Yole SystemPlus



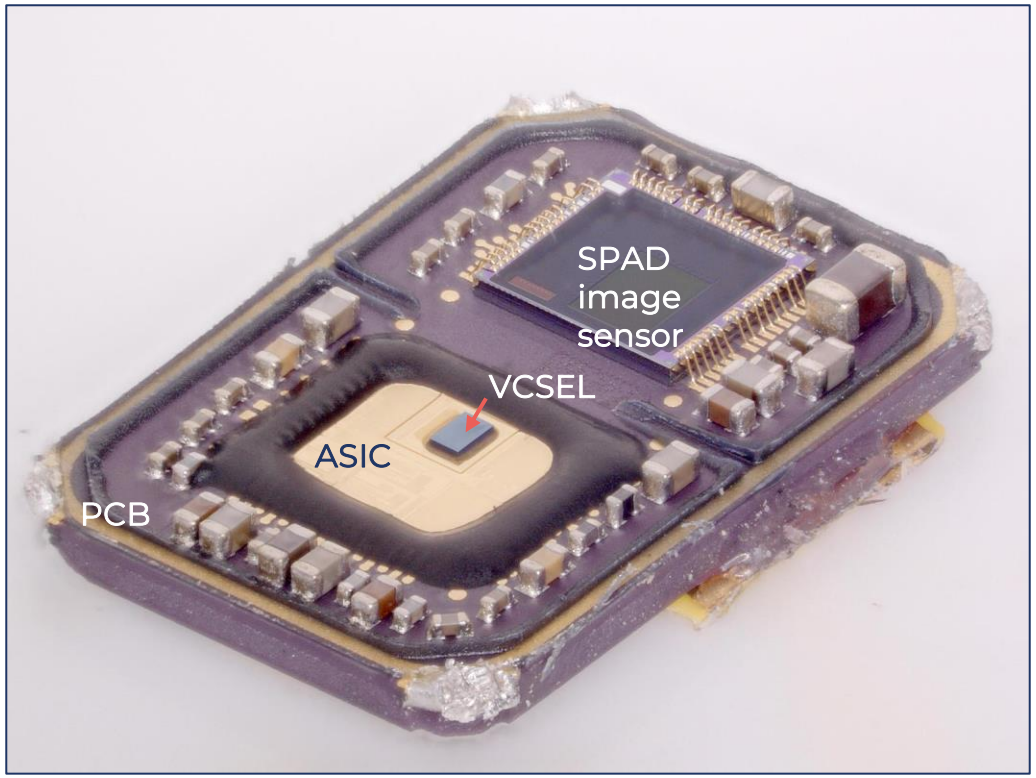
LiDAR Module Cross Section - Optical View ©2024 Yole SystemPlus

The 3 active dies, the driver ASIC, SPAD image sensor and VCSEL, are all supplied by Sony.

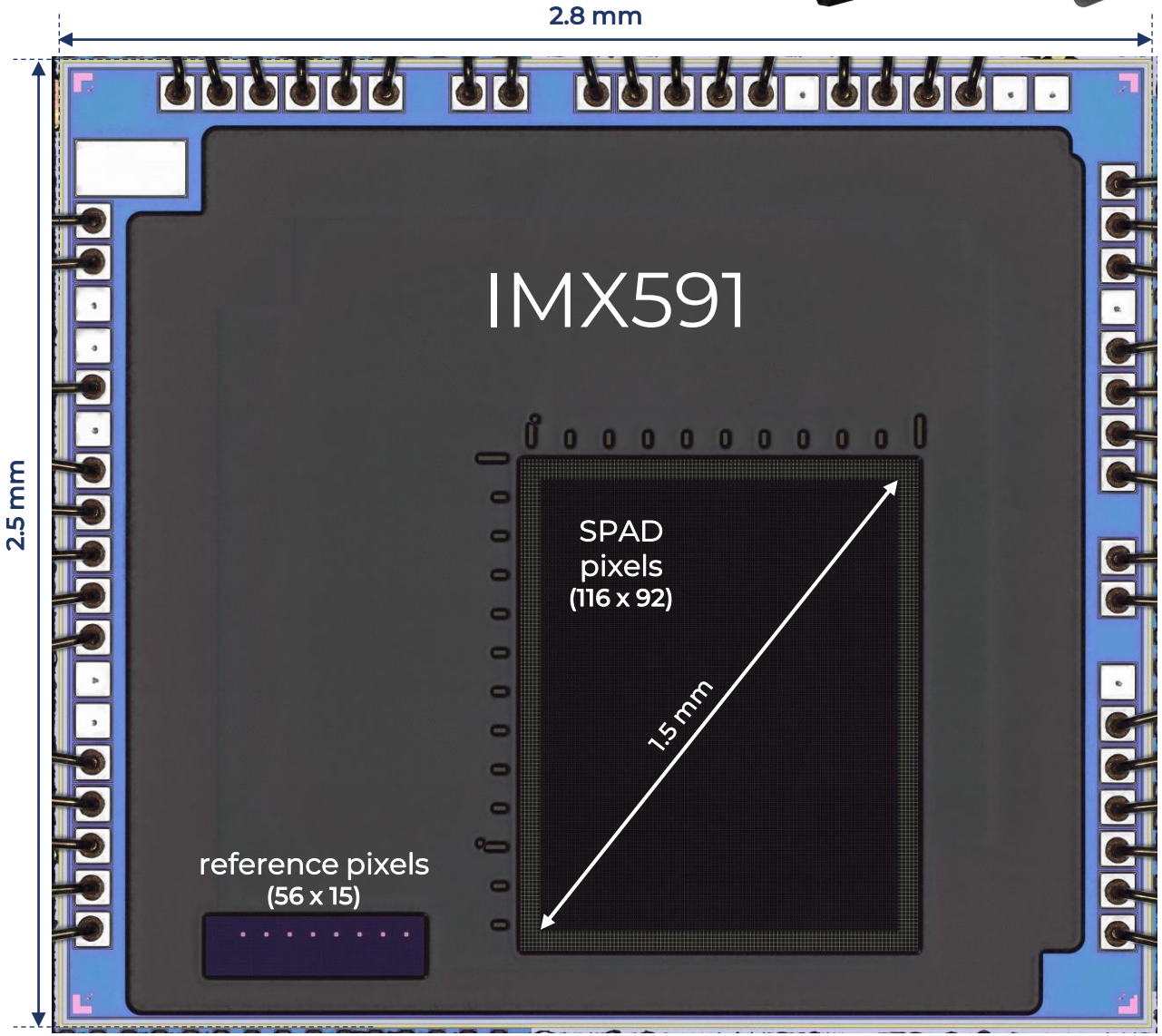


LiDAR Module in Profile - Schematic View ©2024 Yole SystemPlus

IPHONE 15 PRO LIDAR MODULE
SPAD CIS Overview



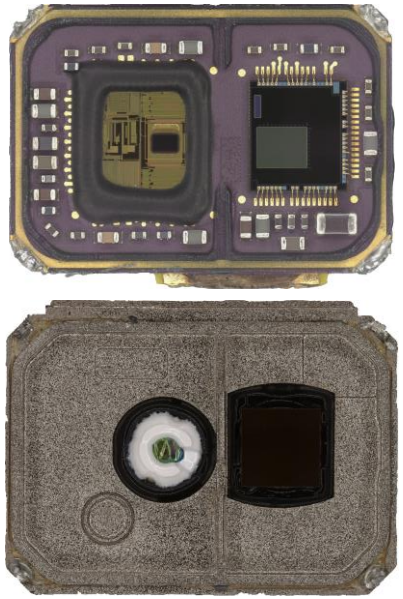
LiDAR Module /with optics removed - Perspective View



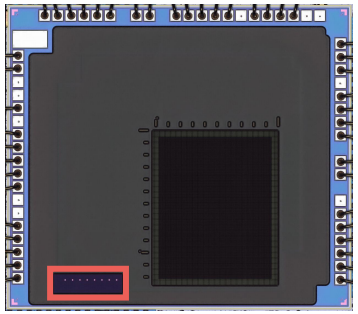
SPAD image Sensor Die Overview - Optical View

0.01 Mp SPAD CIS
10 µm SPAD pixel

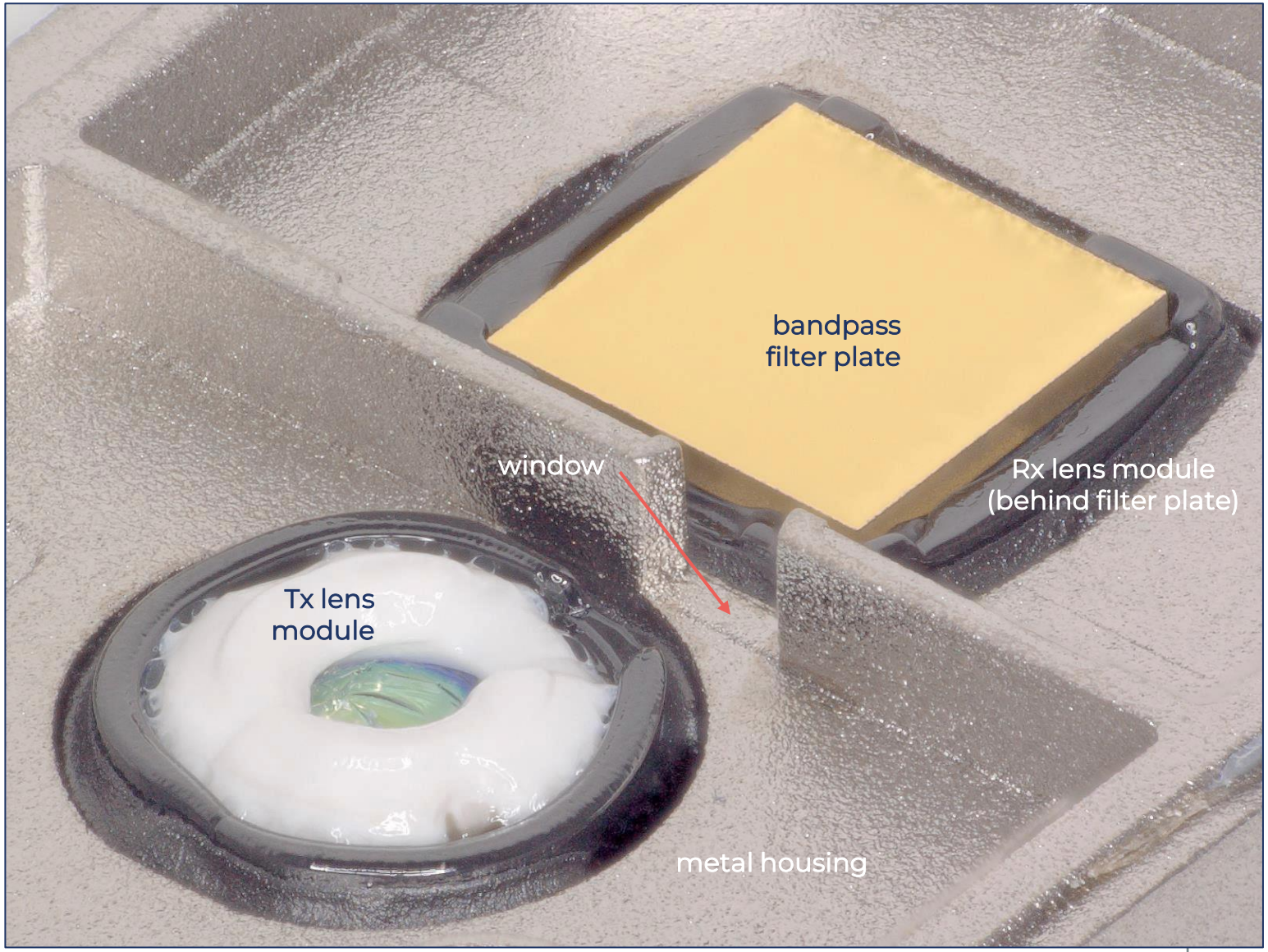
IPHONE 15 PRO LIDAR MODULE
Window



Opened LiDAR Module - Optical Views



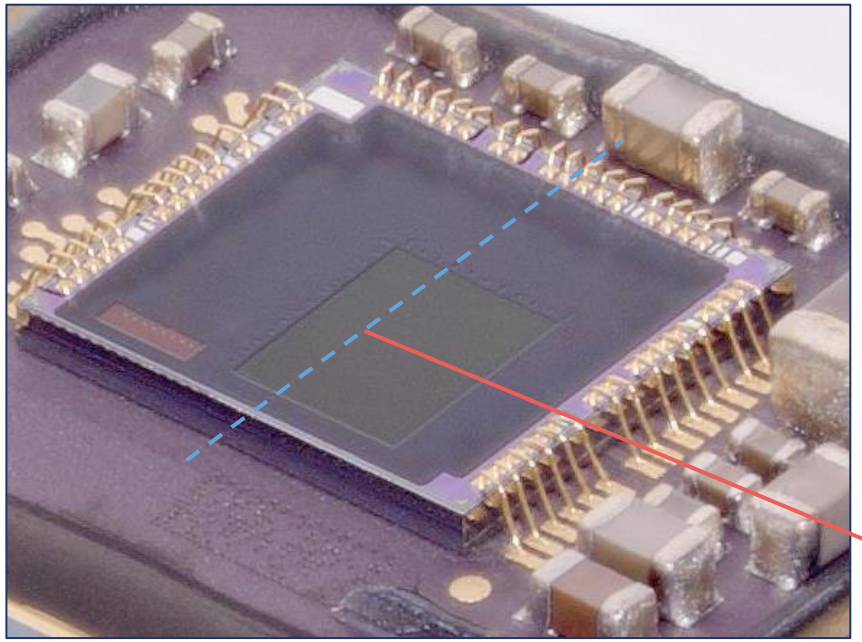
A window in the light-blocking wall transmits a small portion of the emission to give a t=0 signal for dToF. We hypothesize that all histogramming is handled by the CIS.



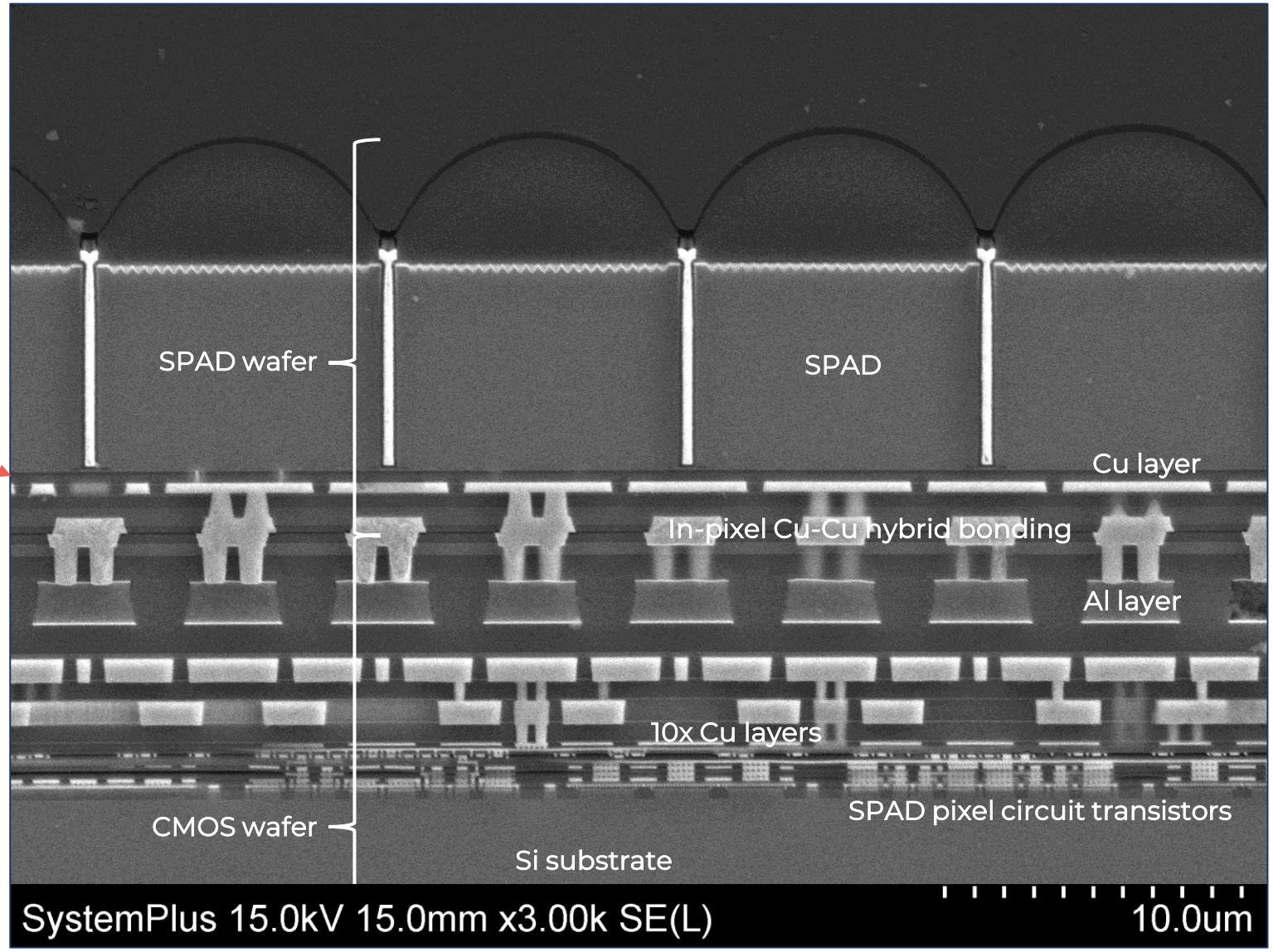
Window in the Light-Blocking Wall - Optical View

IPHONE 15 PRO LIDAR MODULE

SPAD CIS Overview



Opened LiDAR Module w/ cross-sectional plane indicated - Optical View ©2024 Yole SystemPlus

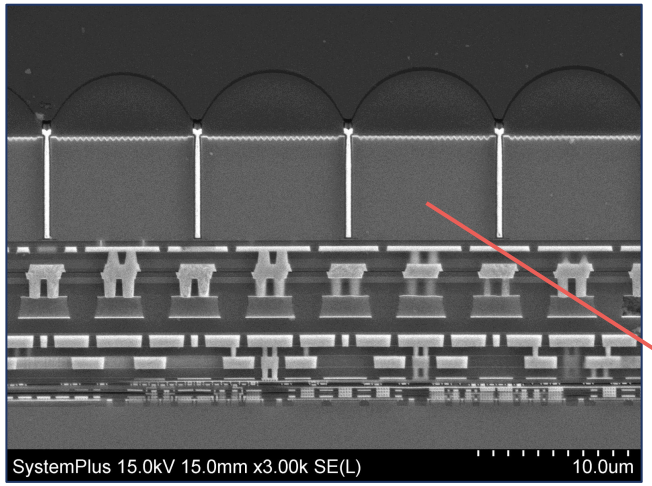


Cross Section through the SPAD Pixel Array - SEM View ©2024 Yole SystemPlus

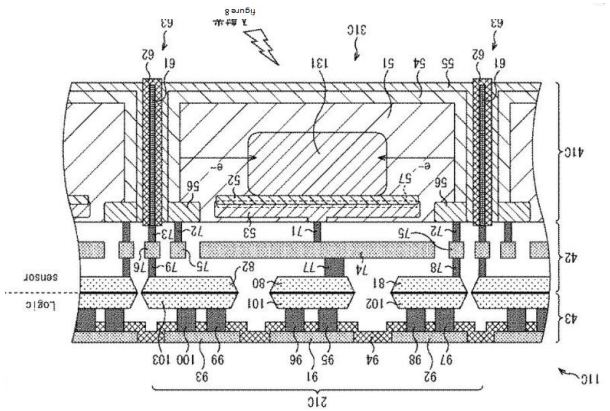
3D integrated BSI

IPHONE 15 PRO LIDAR MODULE

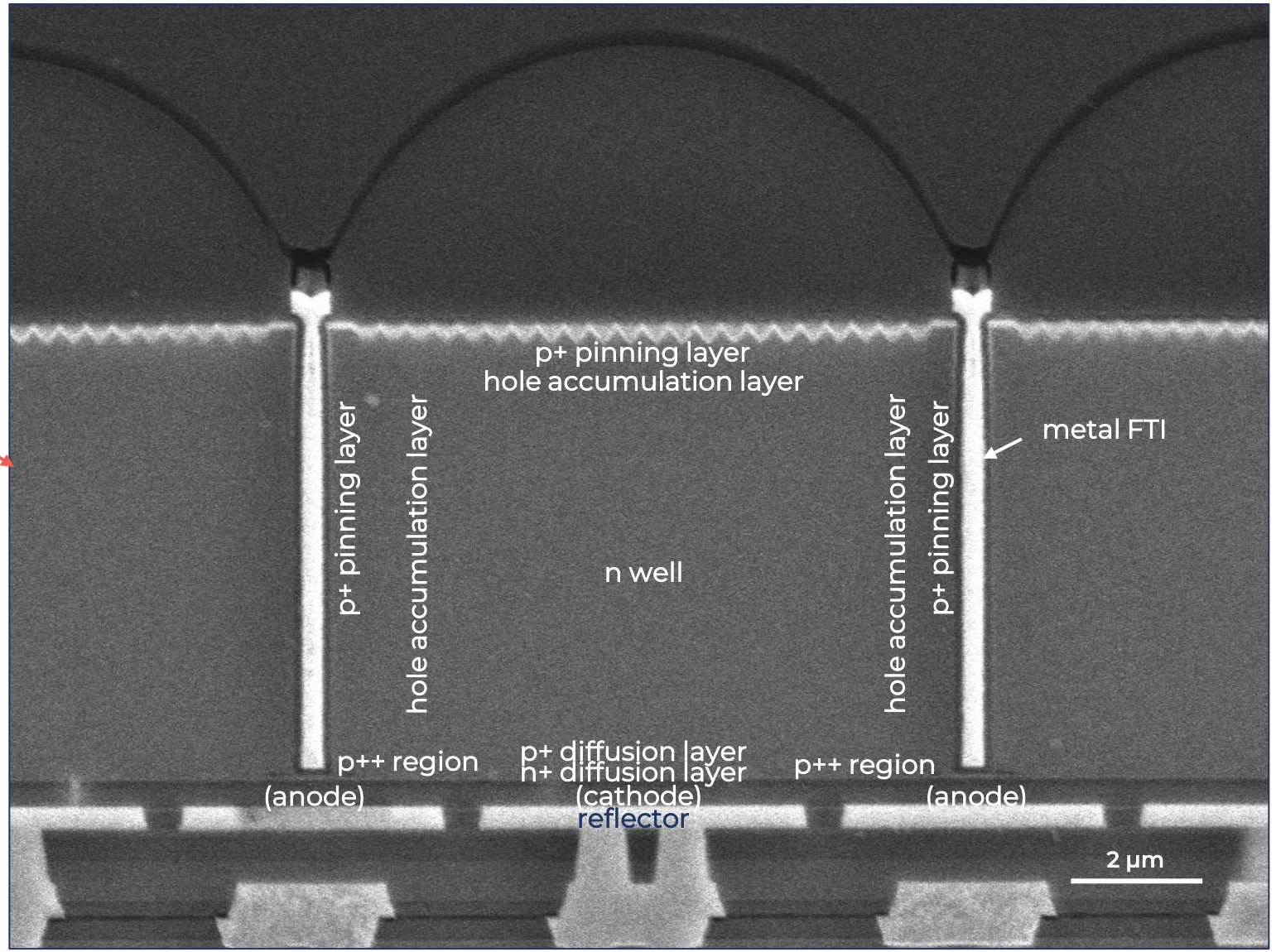
SPAD CIS Overview



Cross Section through the SPAD Pixel Array - SEM View ©2024 Yole SystemPlus



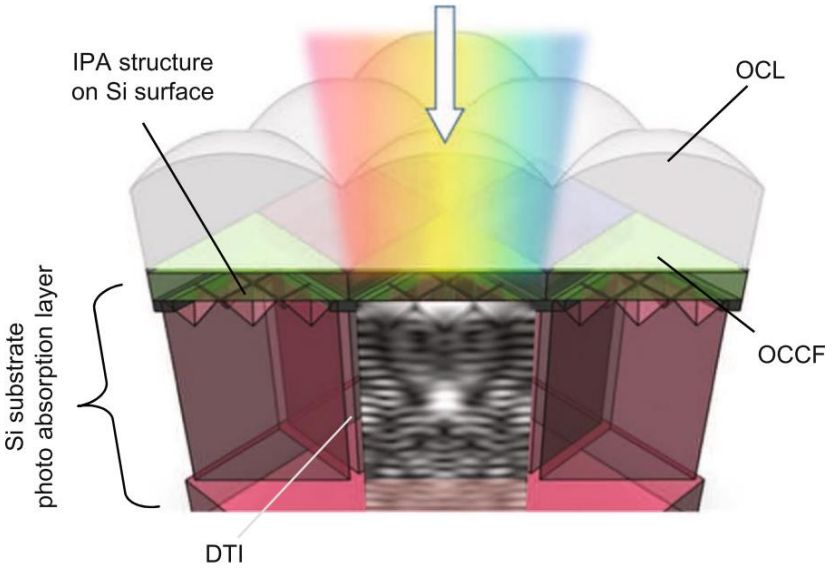
[1] Sony semiconductor patent Publication number JP,2018-088488A



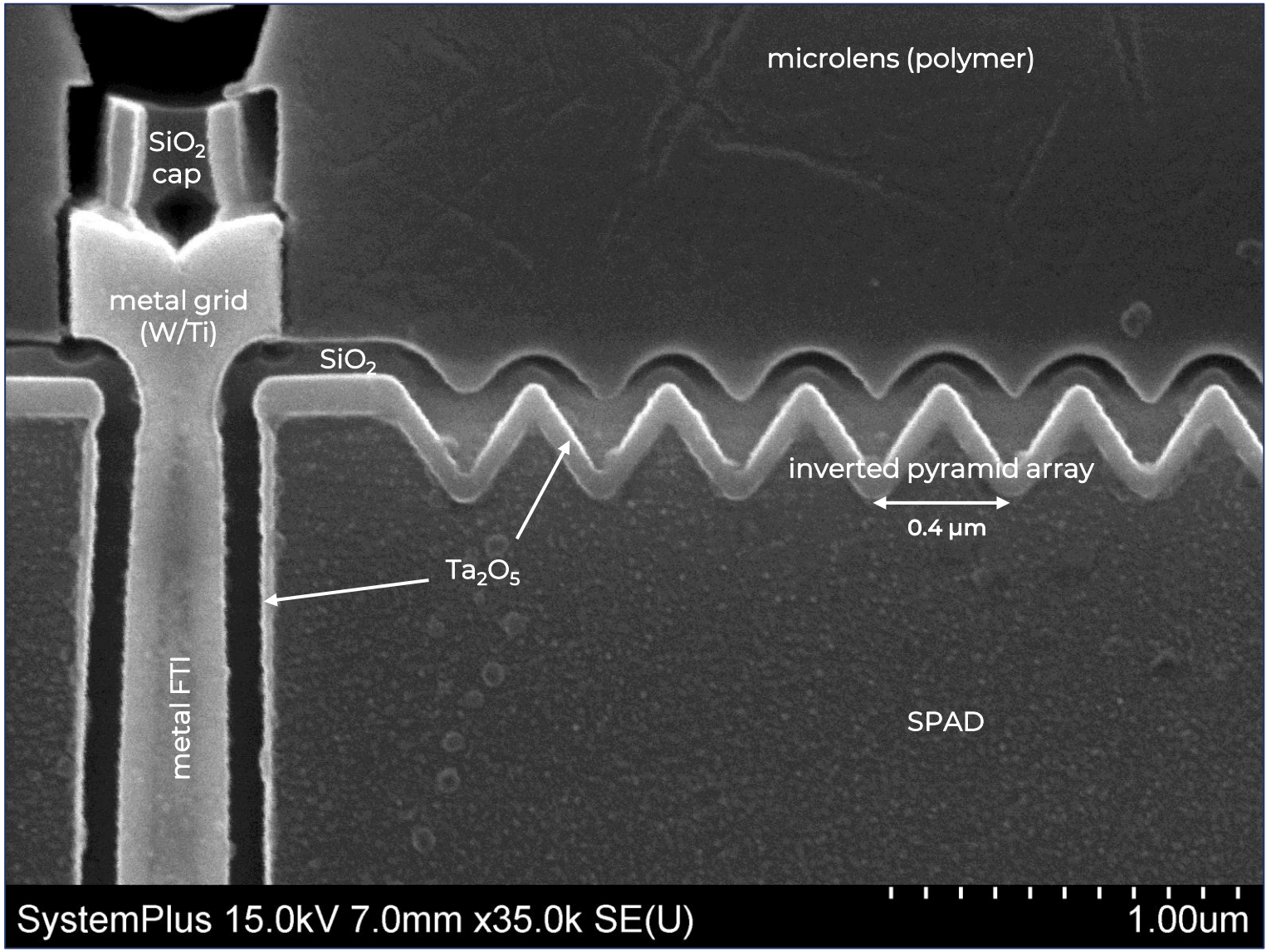
Cross Sectionsof BSI SPAD with 3D Integration - SEM View ©2024 Yole SystemPlus

IPHONE 15 PRO LIDAR MODULE

SPAD CIS Overview



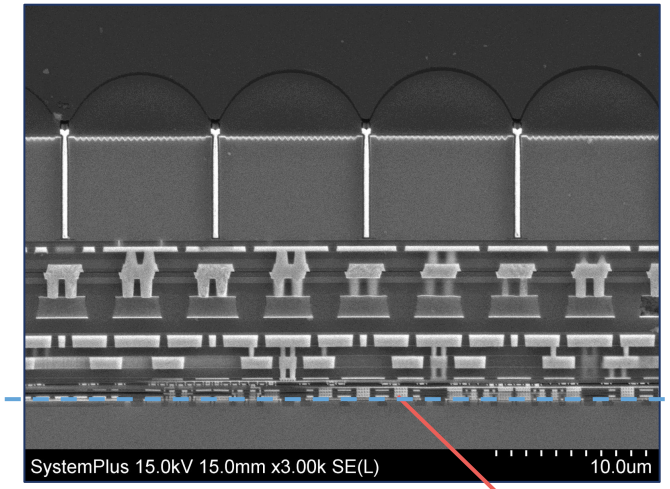
Yokogawa, S., Oshiyama, I., Ikeda, H. *et al.* IR sensitivity enhancement of CMOS Image Sensor with diffractive light trapping pixels. *Sci Rep* **7**, 3832 (2017). https://doi.org/10.1038/s41598-017-04200-y



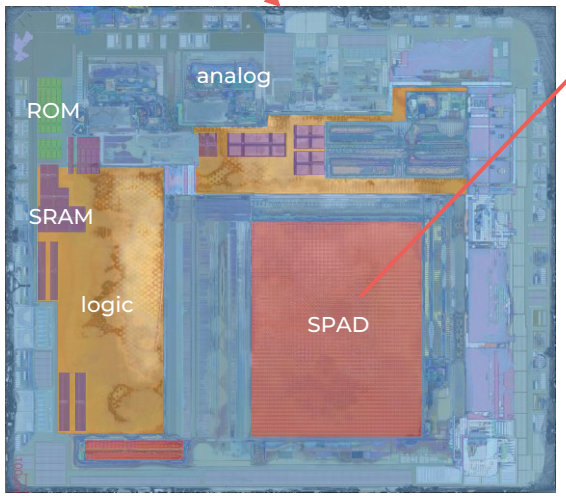
Cross Section through of Inverted Pyramid Array and Metal Grid - SEM View

IPHONE 15 PRO LIDAR MODULE

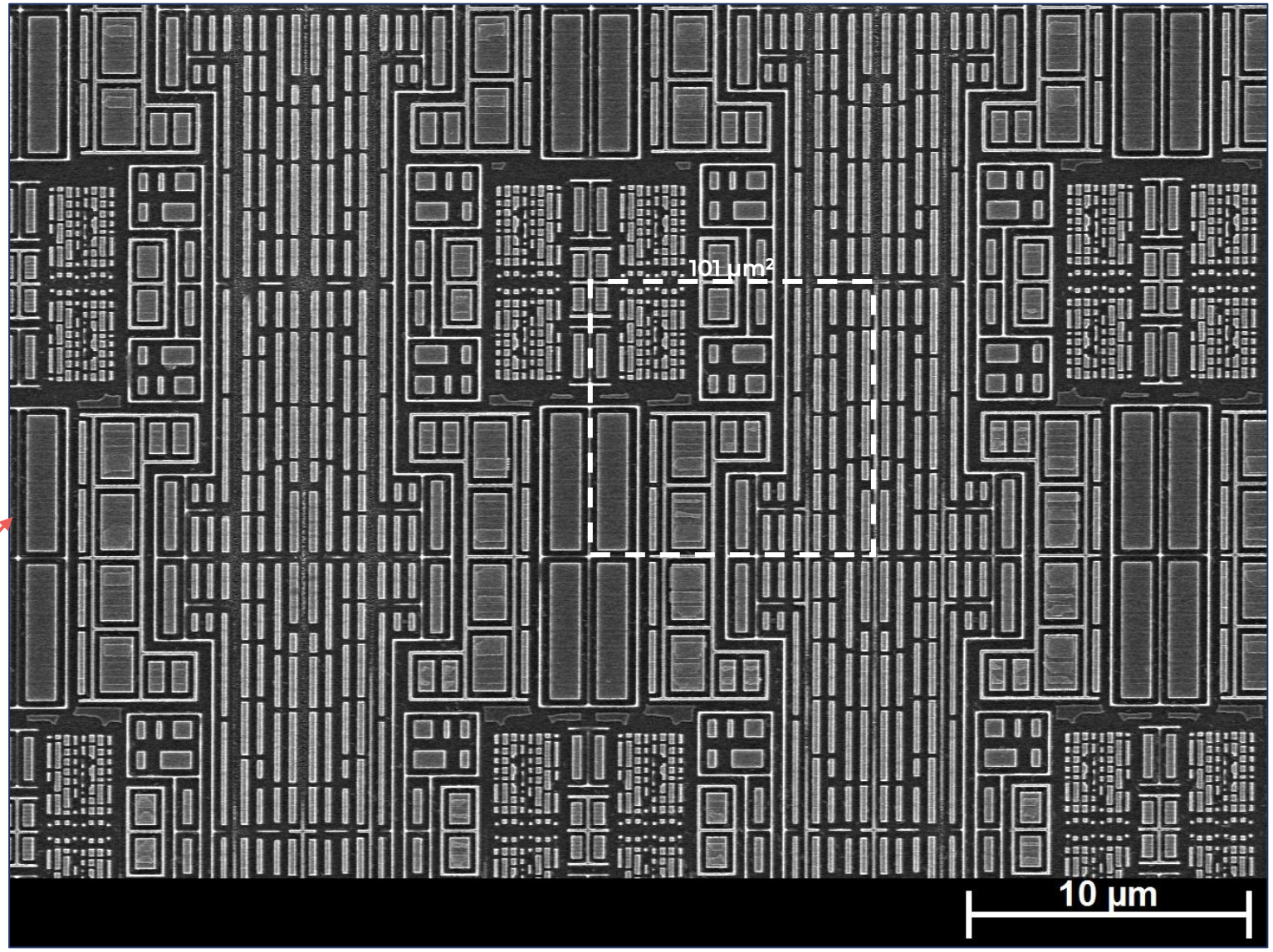
SPAD CIS Overview



Cross Section through the SPAD Pixel Array - SEM View

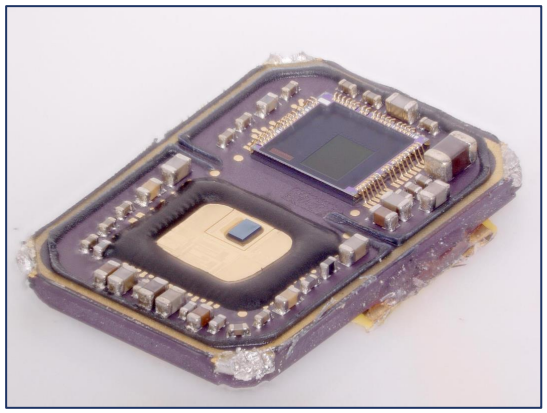


Die Overview w/ Main Blocks



SPAD circuit transistors in the SPAD Block - SEM View

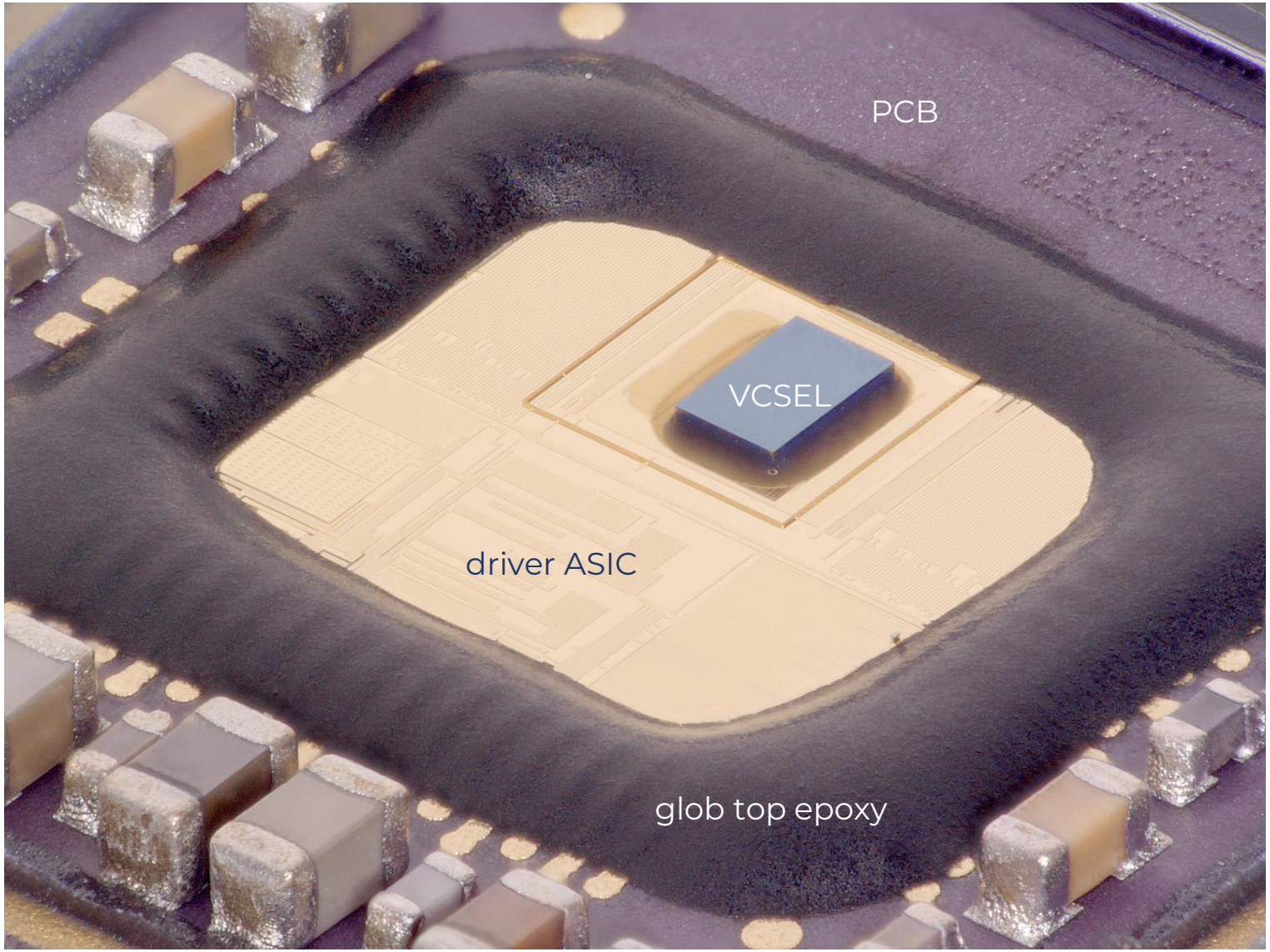
IPHONE 15 PRO LIDAR
VCSEL+Driver Overview



LiDAR Module /with optics removed - Perspective View ©2024 Yole SystemPlus

The VCSEL is flip-chip bumped directly onto the driver ASIC.

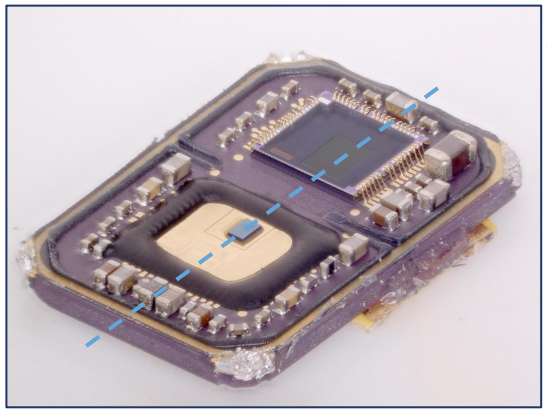
Wirebonds are covered by glob top epoxy.



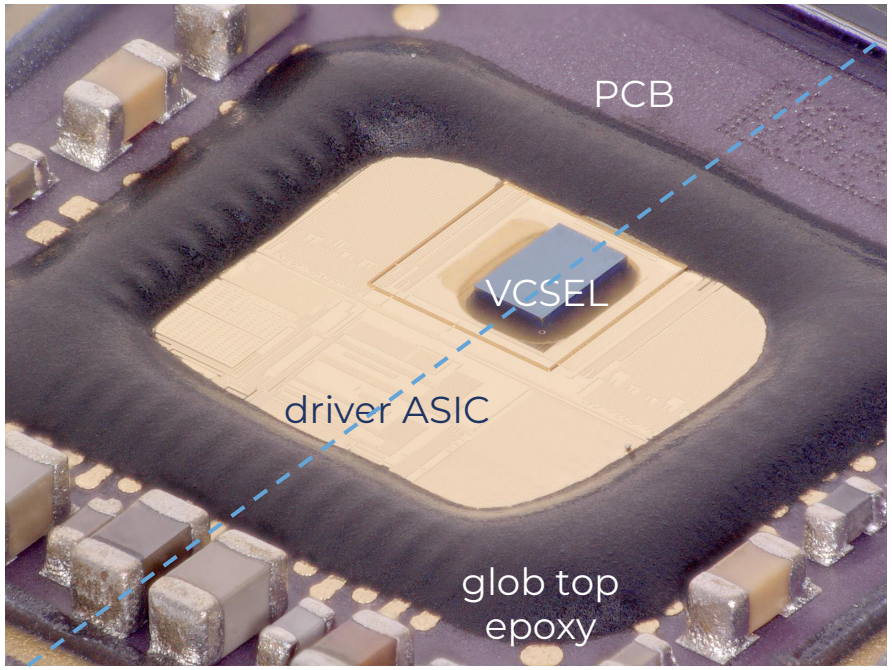
Driver ASIC Overview - Perspective View ©2024 Yole SystemPlus

REVERSE COSTING METHODOLOGY

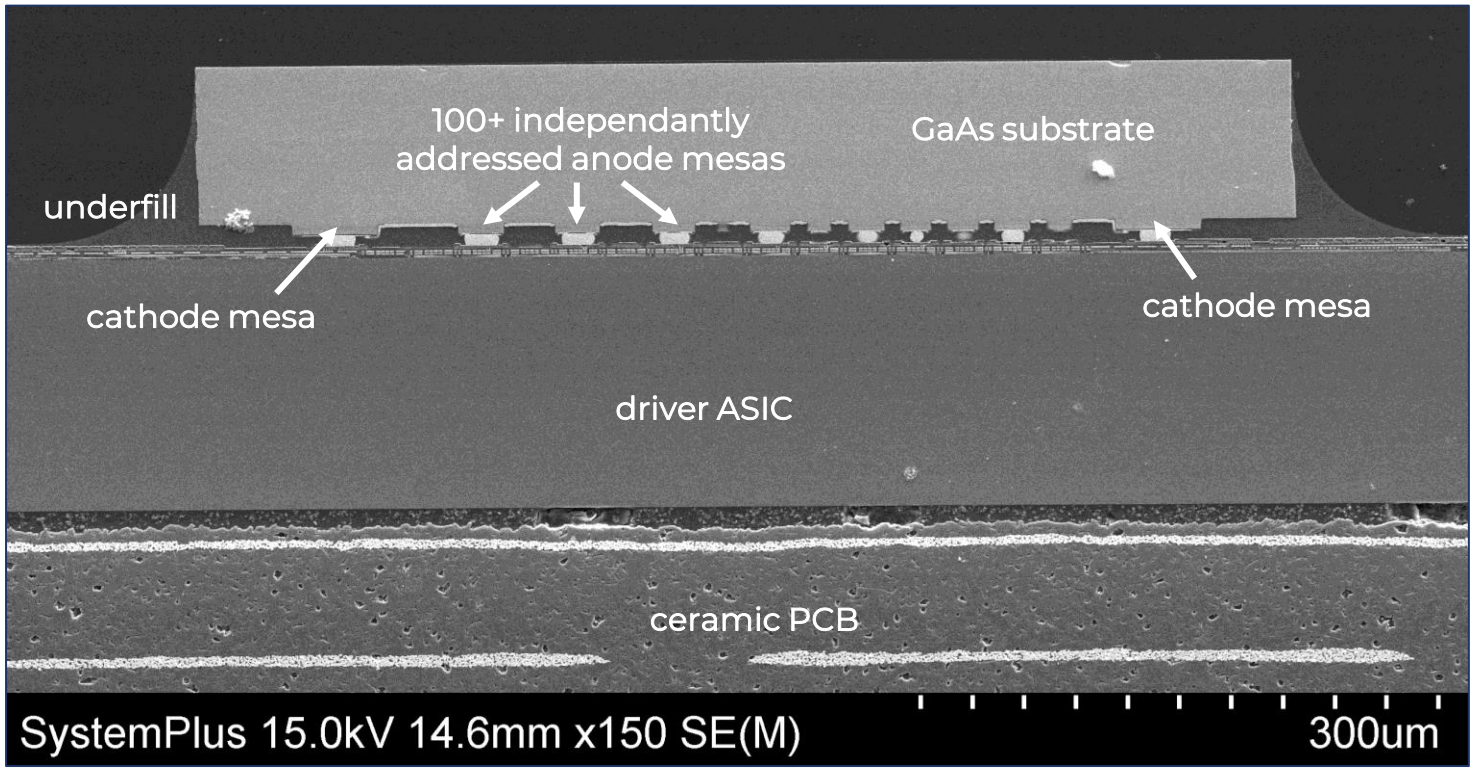
VCSEL+Driver Overview



LiDAR Module /with optics removed - Perspective View ©2024 Yole SystemPlus



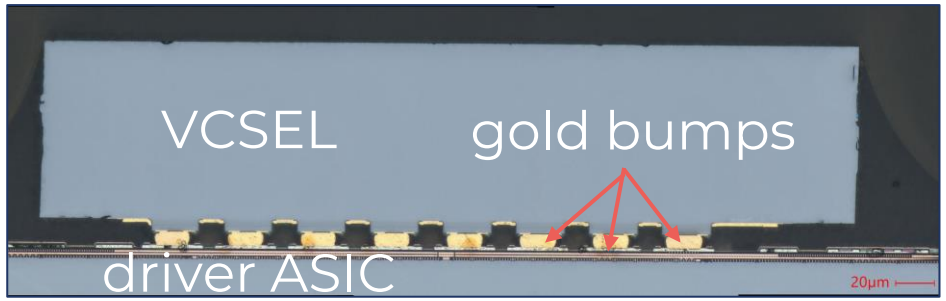
Driver ASIC Overview - Perspective View ©2024 Yole SystemPlus



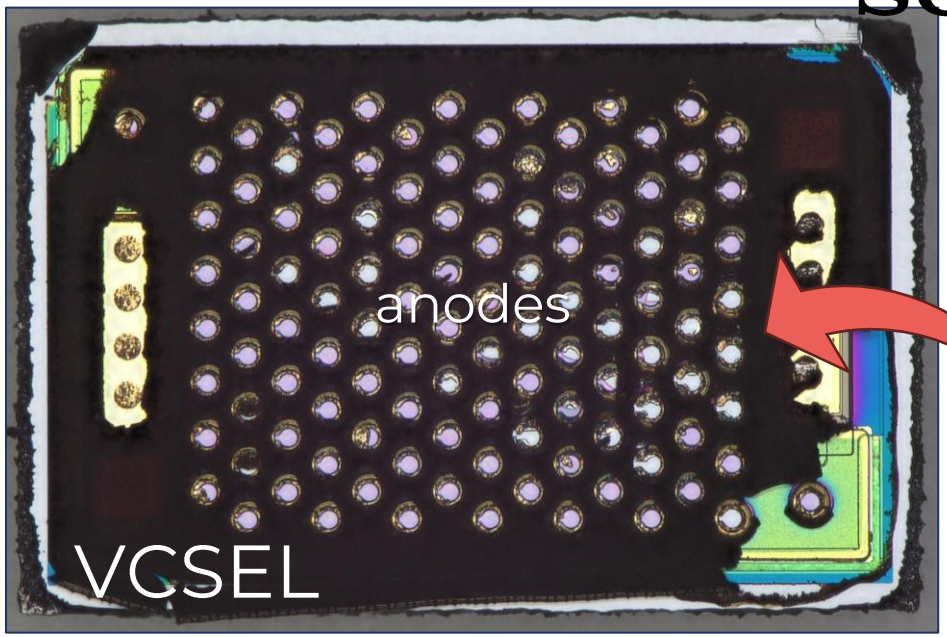
VCSEL Cross Section - Optical Overview ©2024 Yole SystemPlus

REVERSE COSTING METHODOLOGY

VCSEL+Driver Overview



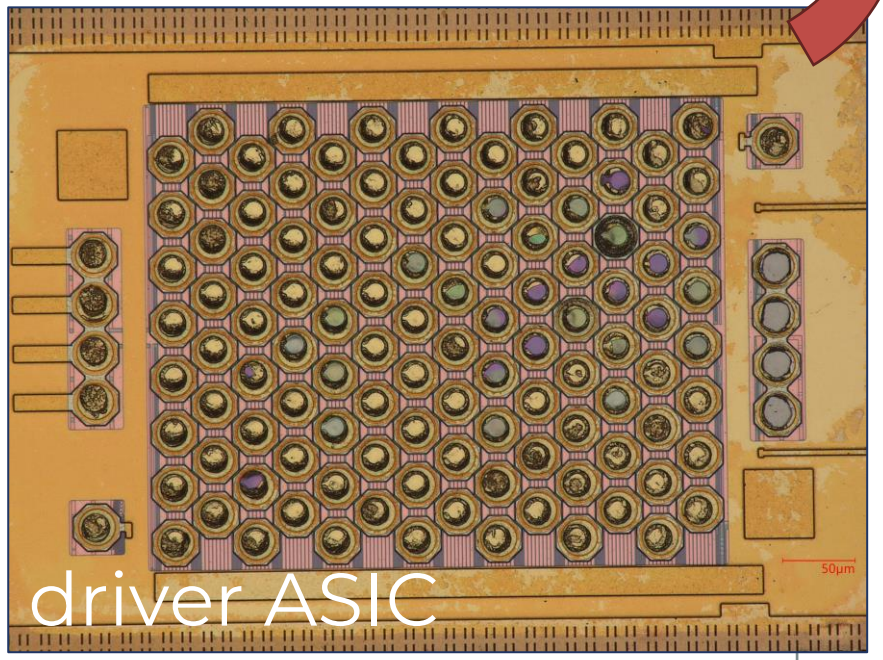
Cross-Section of VCSEL showing gold-bump connections to the driver ASIC - Optical View ©2024 Yole SystemPlus



Bottom View of VCSEL with underfill partially removed - Optical View ©2024 Yole SystemPlus

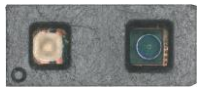
The VCSEL is gold bumped to the driver ASIC such that **every anode is independently addressed**. The cathode is shared. There are a total of 122 bumps.

This is a cost-saving strategy as it removes the need for the diffractive optic.



Top View of Driver ASIC where it connects to the VCSEL - Optical View ©2024 Yole SystemPlus

LASER AUTOFOCUS REVERSE COSTING
Presentation Outline



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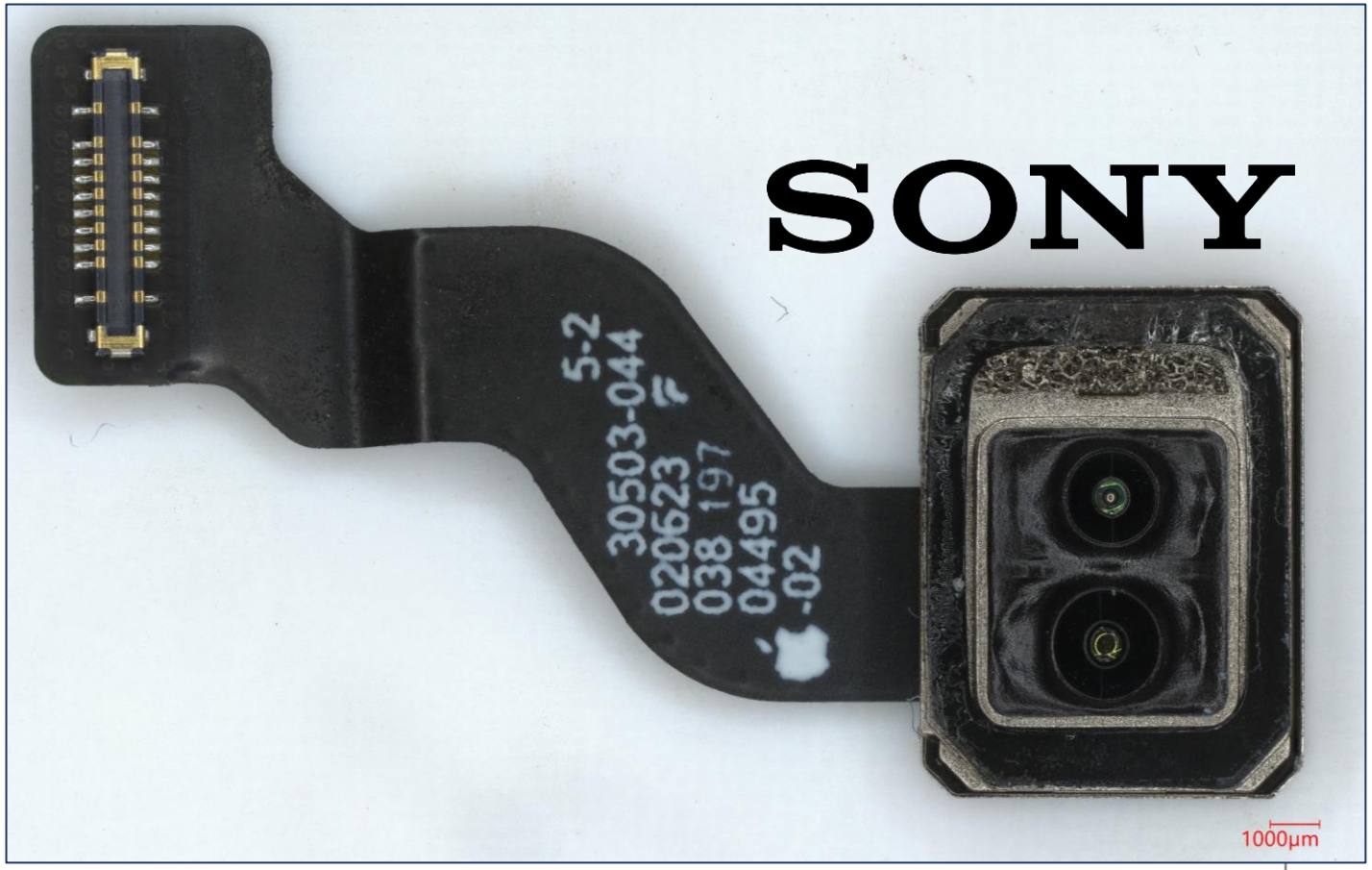
4. Simplified Model

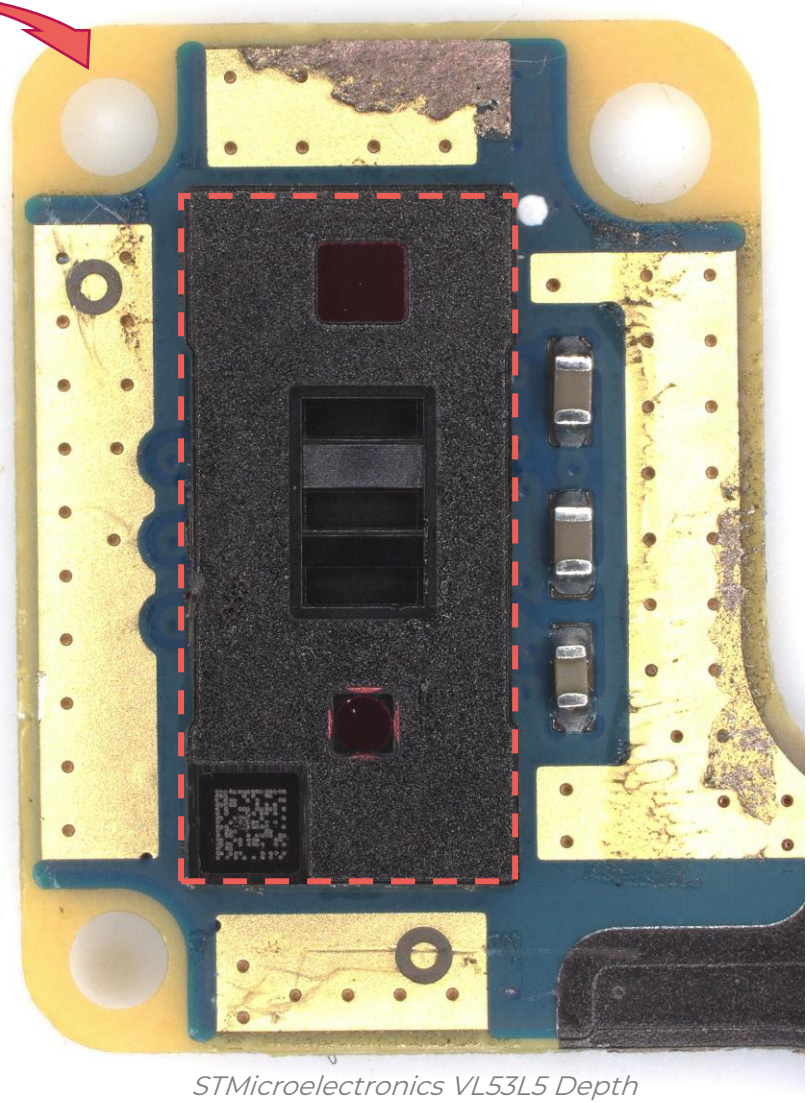
5. Results & Discussion



VL53L5
Galaxy S22 Ultra Teardown

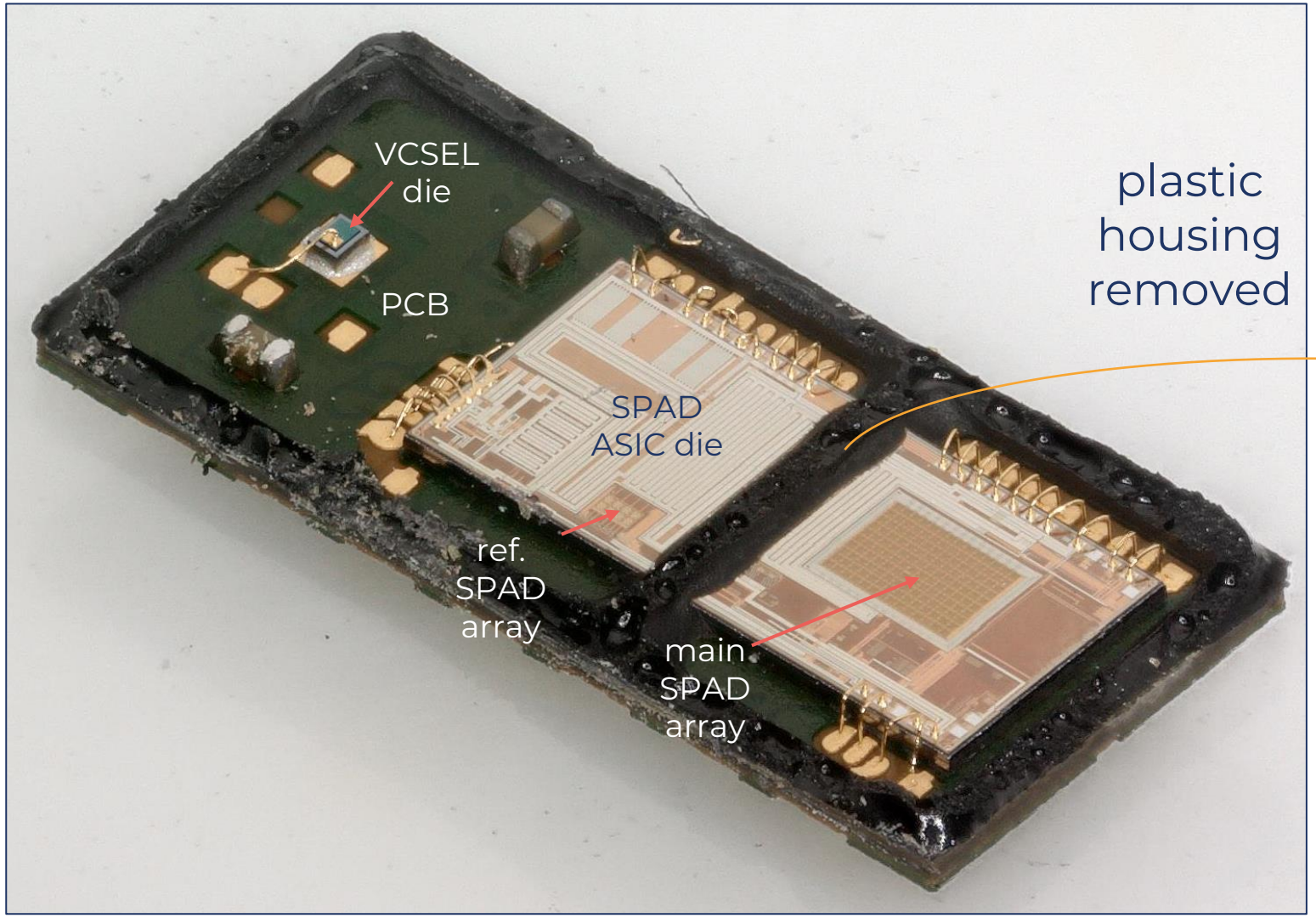
We've also found the VL53L5 in the
- Galaxy S21 Ultra,
- Galaxy Note20 Ultra,
- Xiaomi 12S Ultra,
- Xiaomi Mi 11 Ultra, and Meizu 20 INF

Samsung Galaxy S22 Ultra - Back and Opened Views



STMicroelectronics VL53L5 Depth Ranger Module on Smartphone PCB

VL53L5
Module Teardown



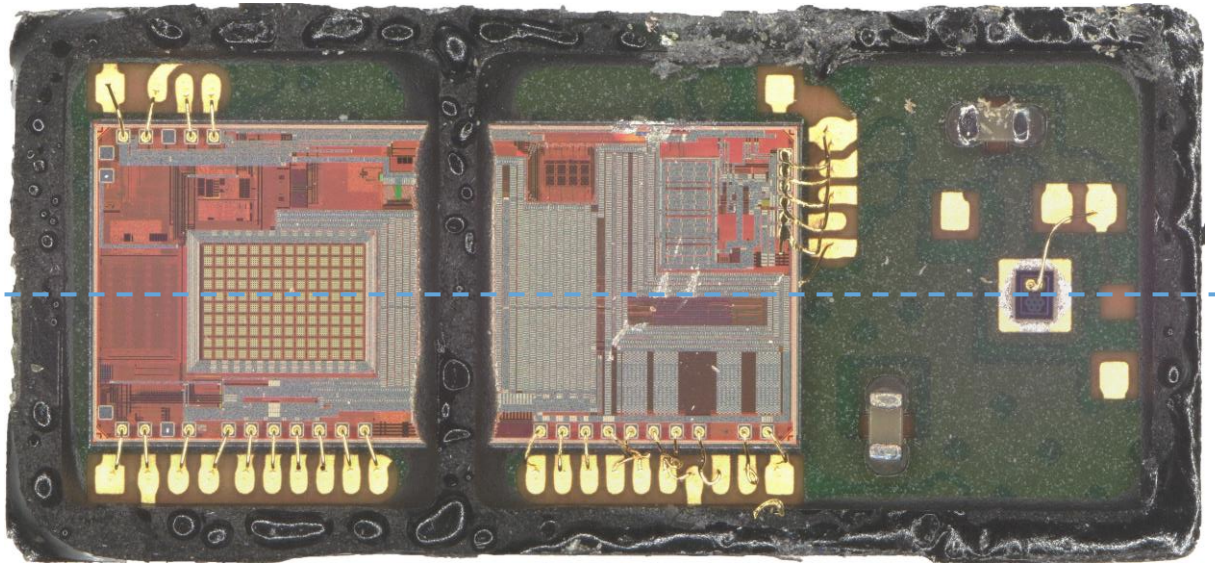
VL53L5 Module with Plastic Housing Removed - Tilted View

(not to scale)

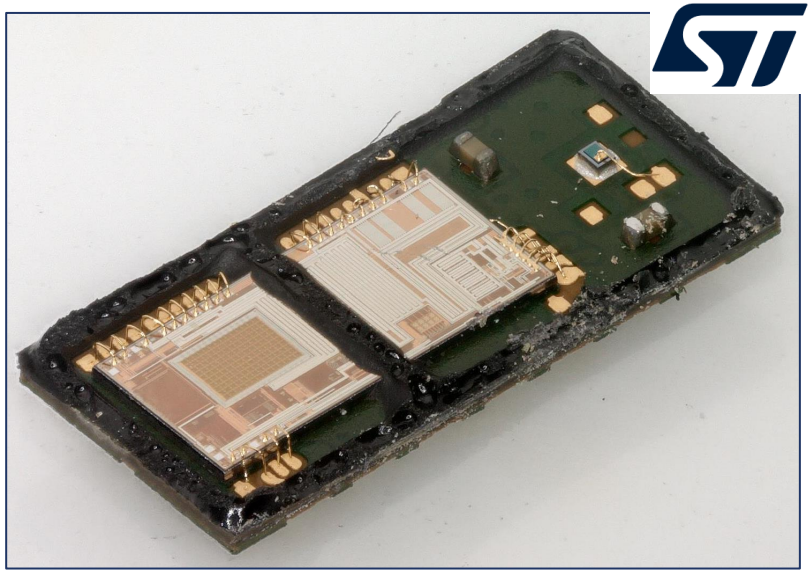
Plastic Housing w/ Diffuser and Fresnel Lens - Bottom View

The diffuser and Fresnel-like lens are glued into the plastic housing.

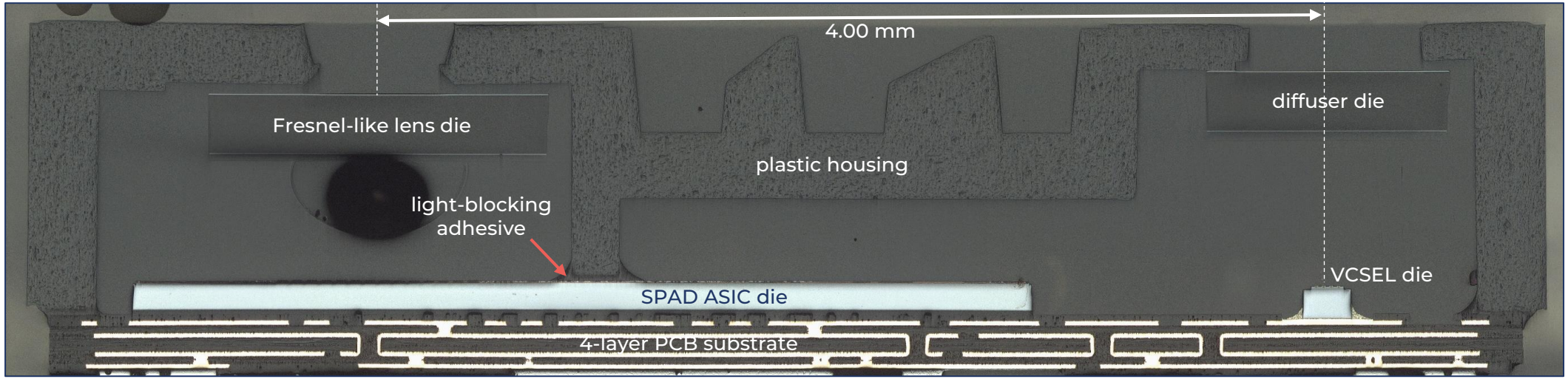
VL53L5
Cross Section



Top View of Opened Module showing the Cross-Sectional Plane



Tilted Top View of Opened Module (image mirrored left-right)

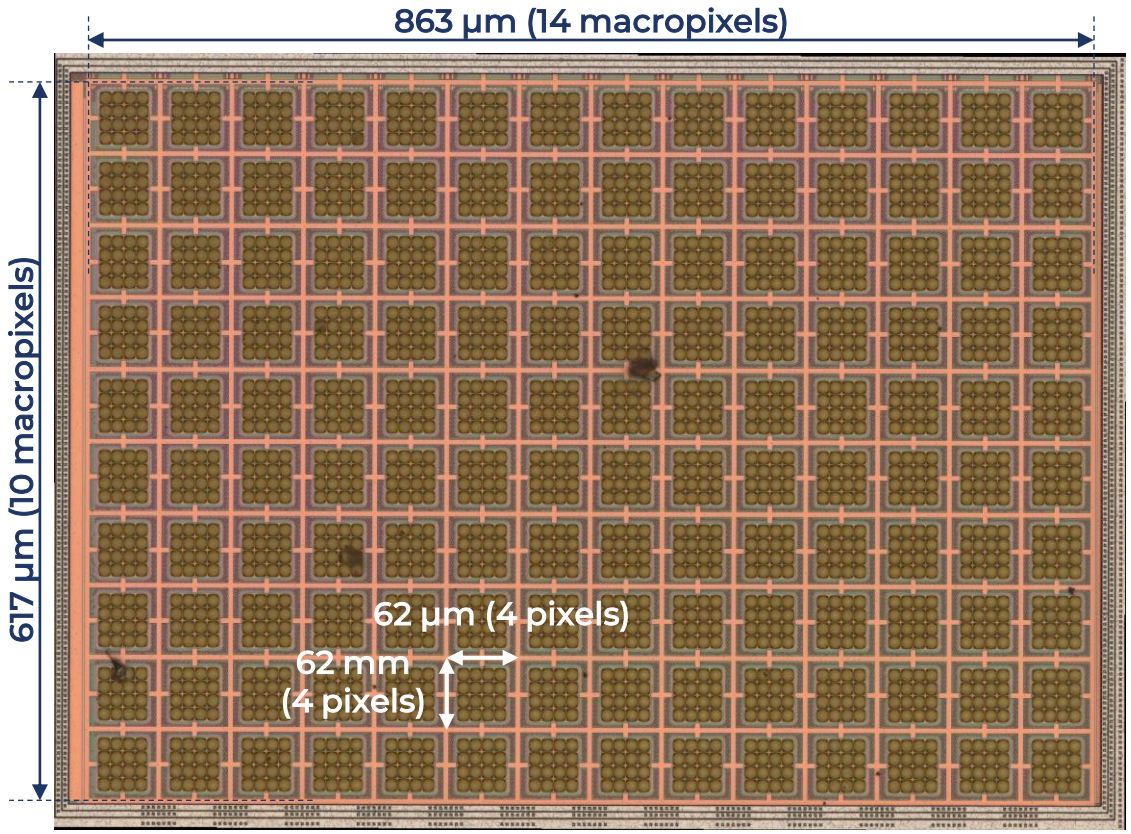


Module Cross Section - Optical View

VL53L5
Optics & VCSEL

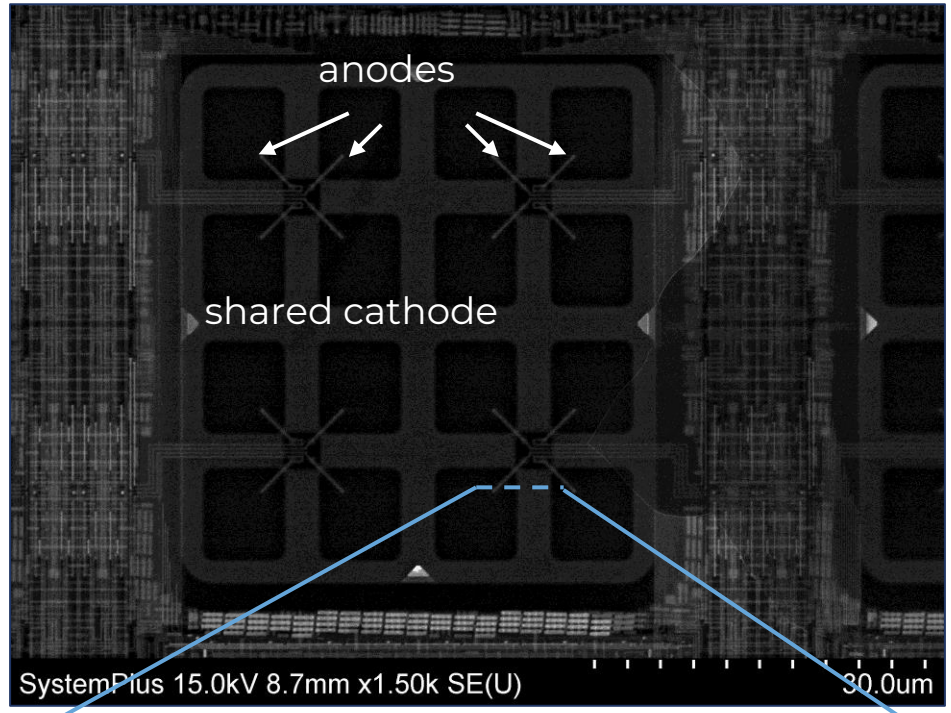
- Diffractive optics are embossed polymer on glass
- Microlenses on SPAD pixels

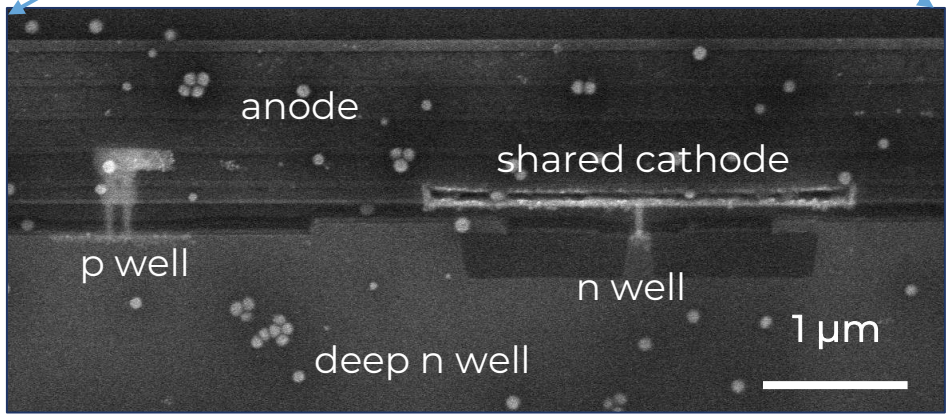
VL53L5
SPAD Array



SPAD ASIC Die Overview - Optical View ©2024 Yole SystemPlus

SPAD Overview – SEM View ©2024 Yole SystemPlus

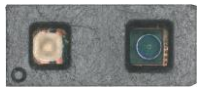




SPAD Section – SEM View ©2024 Yole SystemPlus

3. S. Pellegrini et al., "Industrialised SPAD in 40 nm technology," IEEE International Electron Devices Meeting (IEDM) 2017, doi: 10.1109/IEDM.2017.8268404.
4. S. Pellegrini. “Industrialized SPADs in deep-submicron CMOS technology.” ISSW 2018.
5. Bruce Rae and Pascal Mellot, “A SPAD-based, Direct Time of Flight, 64 Zone, 15fps, Parallel Ranging Device Based on 40nm CMOS SPAD Technology.” ISSW 2018.

LASER AUTOFOCUS REVERSE COSTING
Presentation Outline



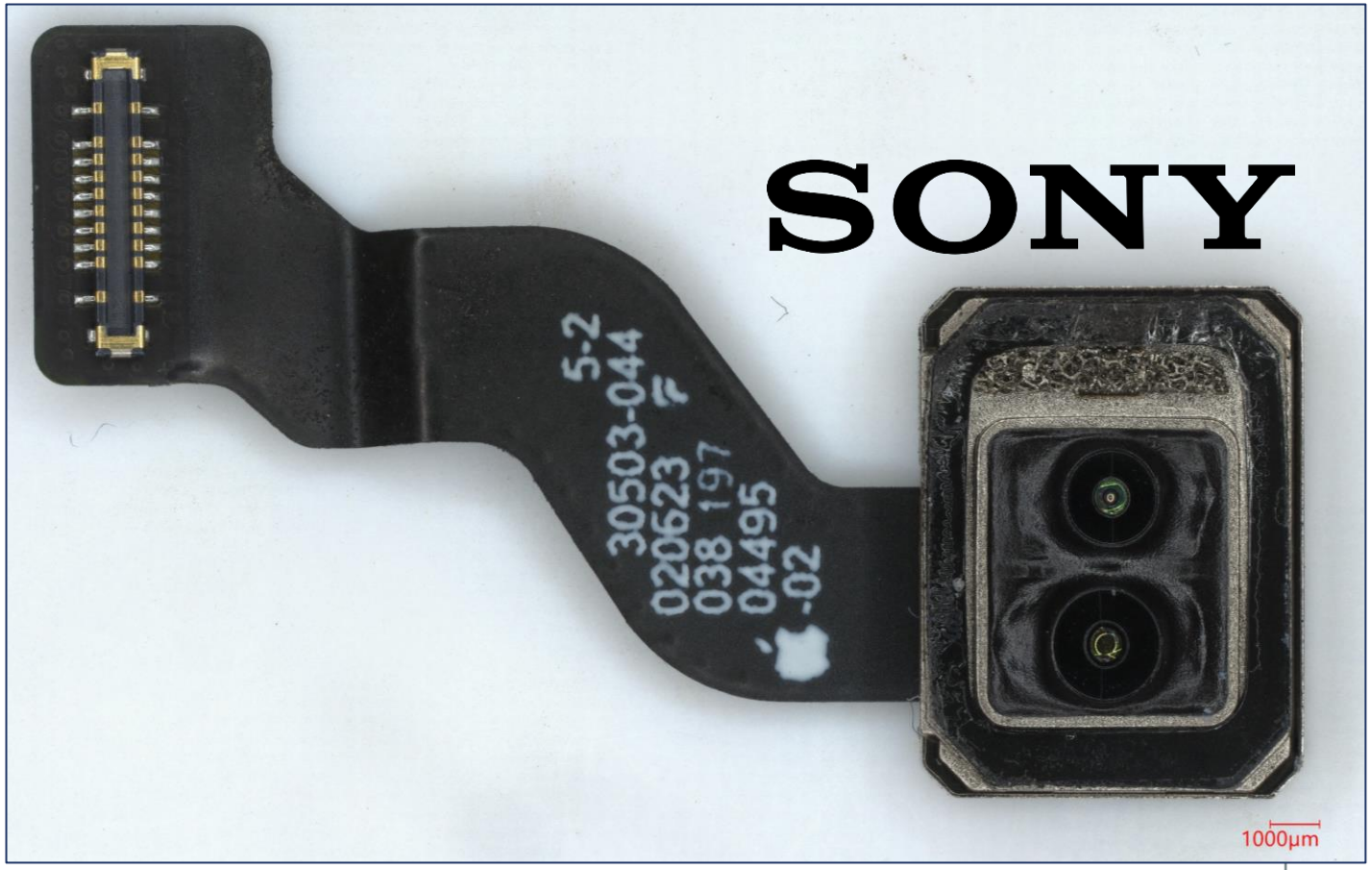
1. Smartphone 3D Imaging and Laser Autofocus

2. 3 systems
   - iPhone 15 Pro LiDAR module by Sony
   - VL53L5 by STMicroelectronics
   - TMF8821 by ams AG

3. Reverse Costing Methodology

4. Approximative Model

5. Results & Discussion



TMF8821
Magic3 Pro Teardown

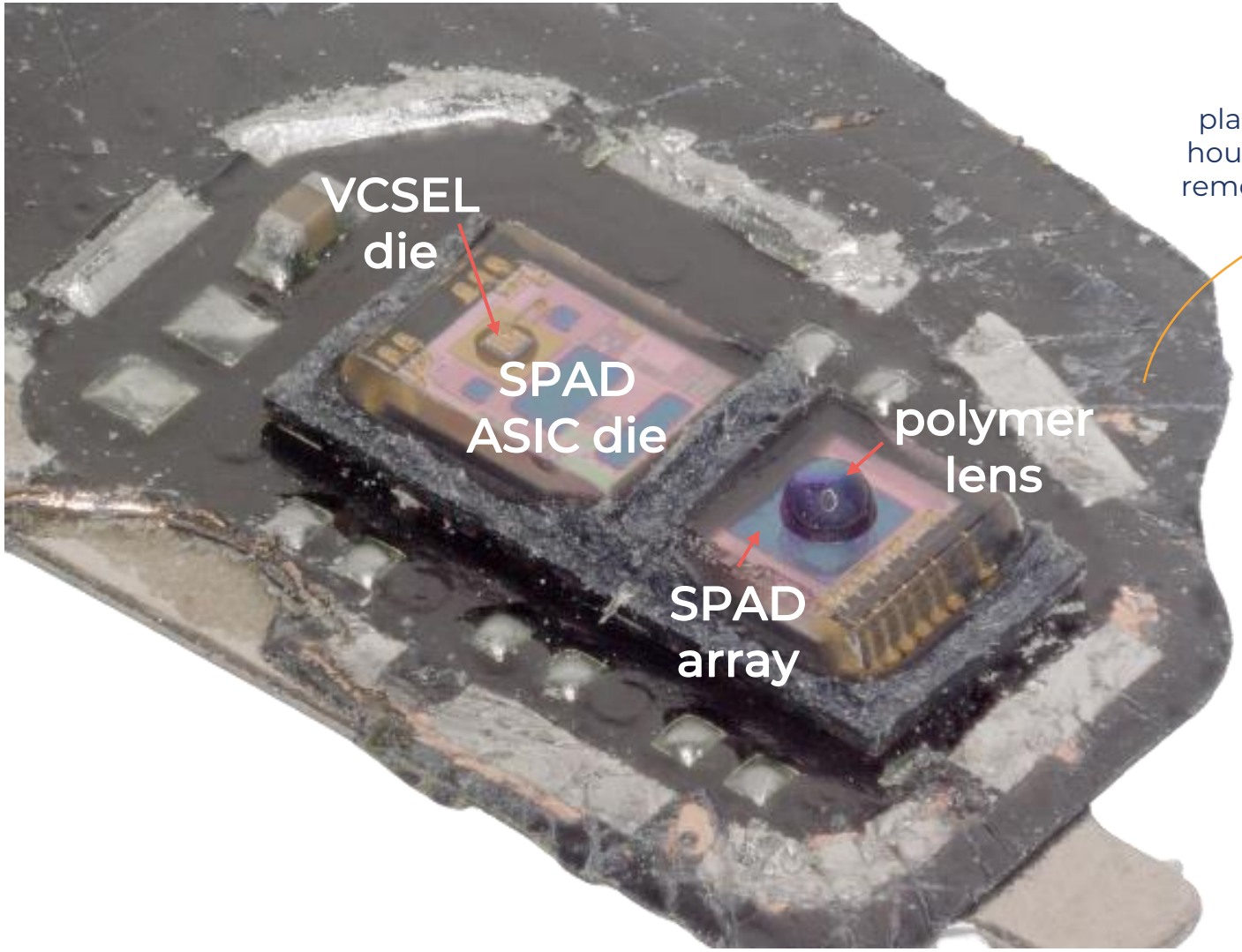
We've also found the TMF8821 in the
- Honor Magic 5 Pro
- Honor Magic V2

Honor Magic3 Pro - Back and Opened Views
©2024 Yole SystemPlus

ams TMF8821 Depth Ranger Module on Smartphone PCB
©2024 Yole SystemPlus

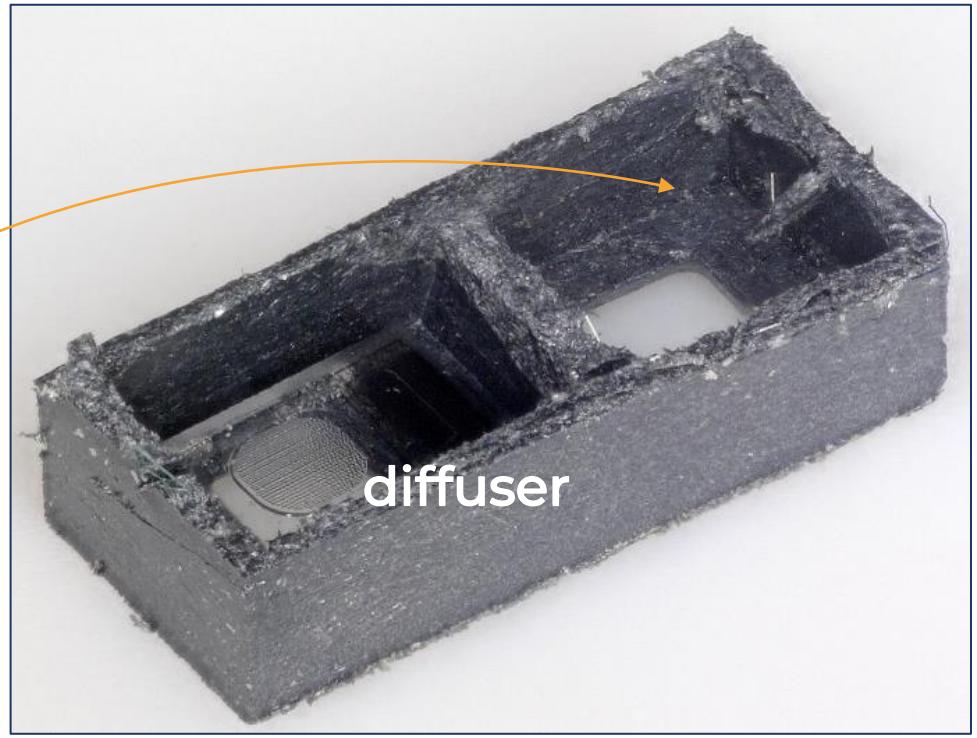
ams TMF8821 Depth Ranger Module on Smartphone PCB with Metal Cap Separated
©2024 Yole SystemPlus

TMF8821
Module Teardown



ams TMF8821 Module with Plastic Housing Removed - Tilted View

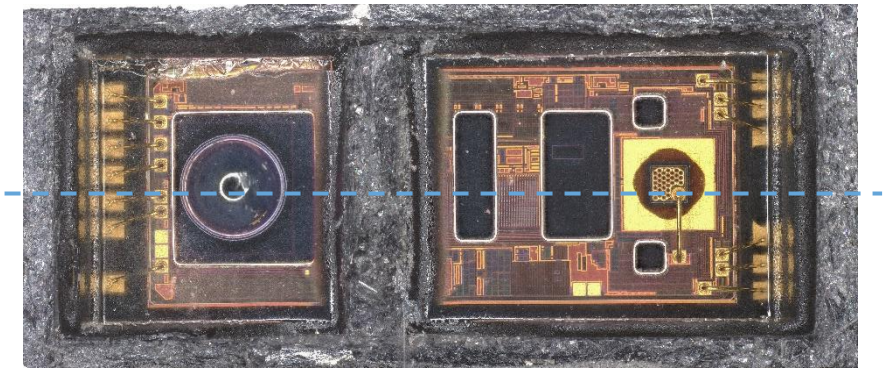
plastic
housing
removed

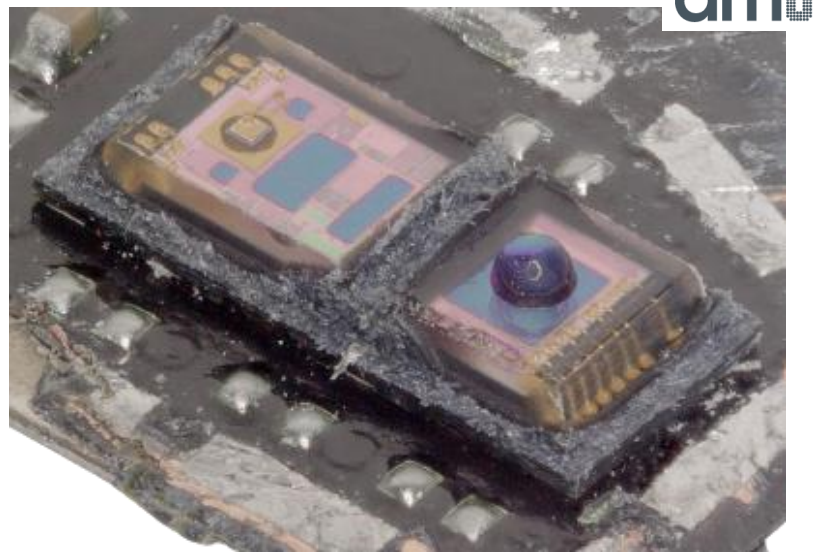


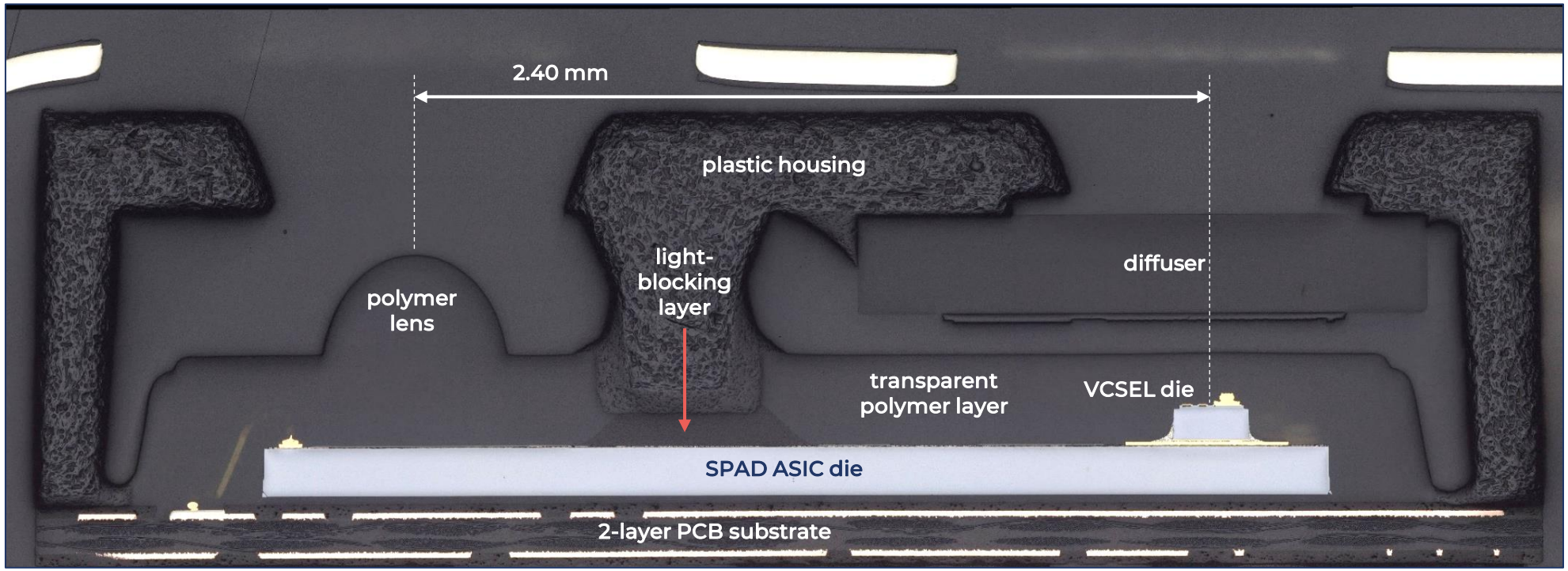
Plastic Housing w/ Diffuser - Tilted View

TMF8821
Cross Section

Top View of Opened Module showing the Cross-Sectional Plane



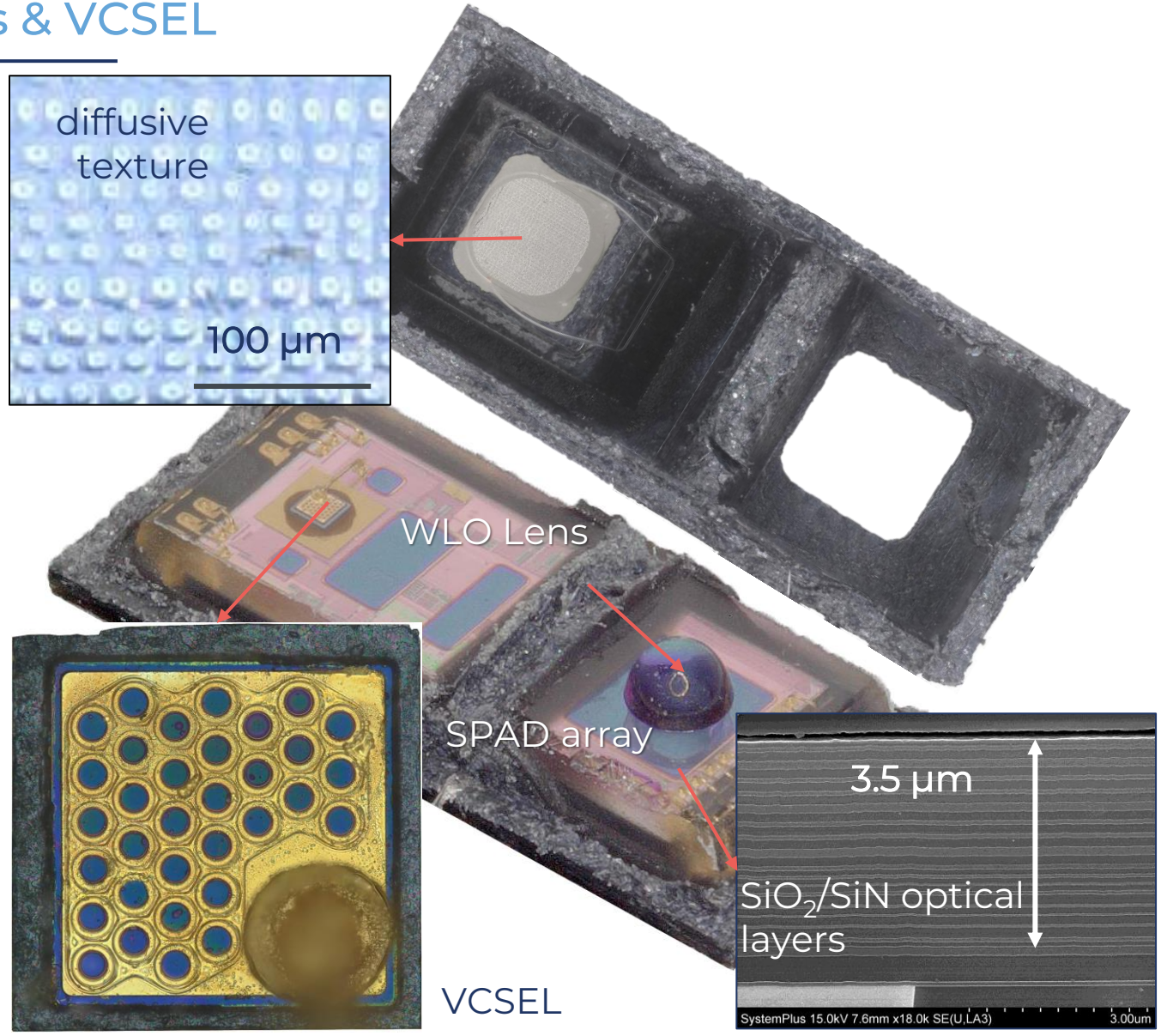




Module Cross Section - Optical View

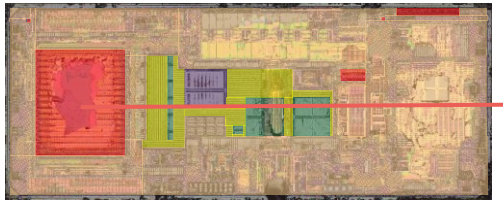
TMF8821

Optics & VCSEL

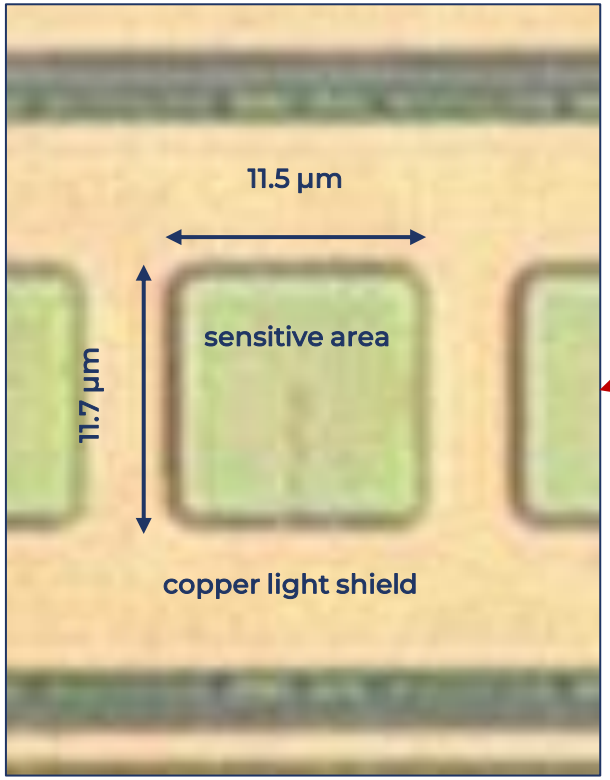


- Tx optic is embossed polymer on glass
- Rx optics are on-chip
- powerful VCSEL

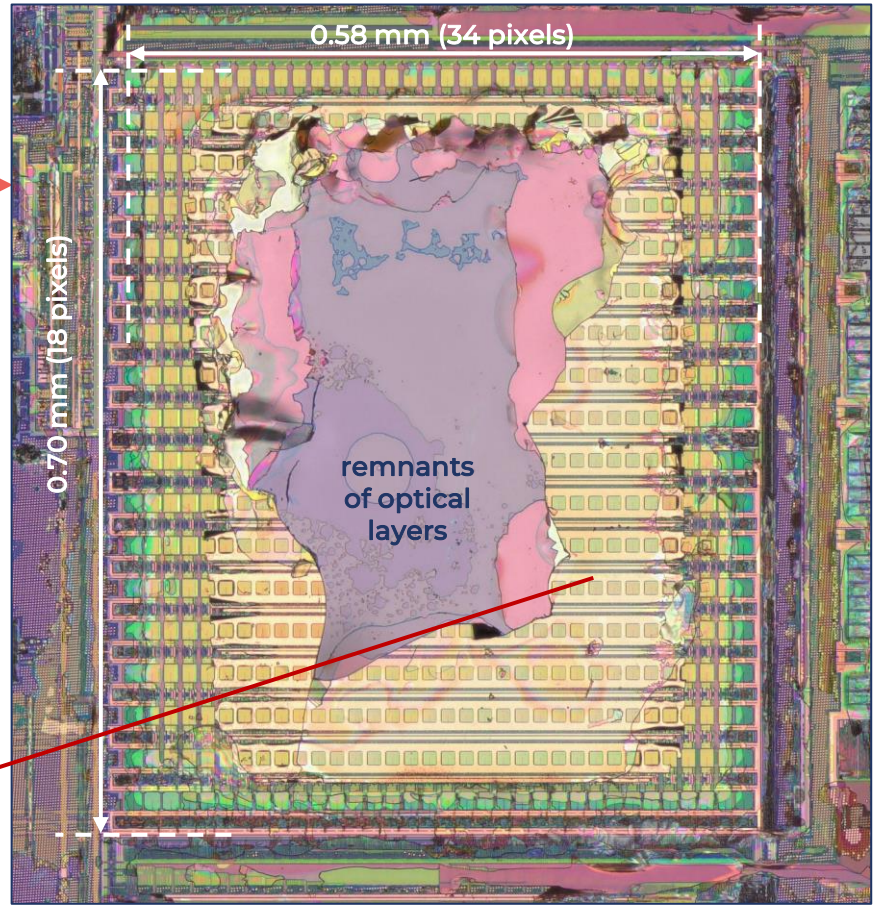
TMF8821
SPAD Array



SPAD ASIC Die with Main Blocks Identified ©2024 Yole SystemPlus



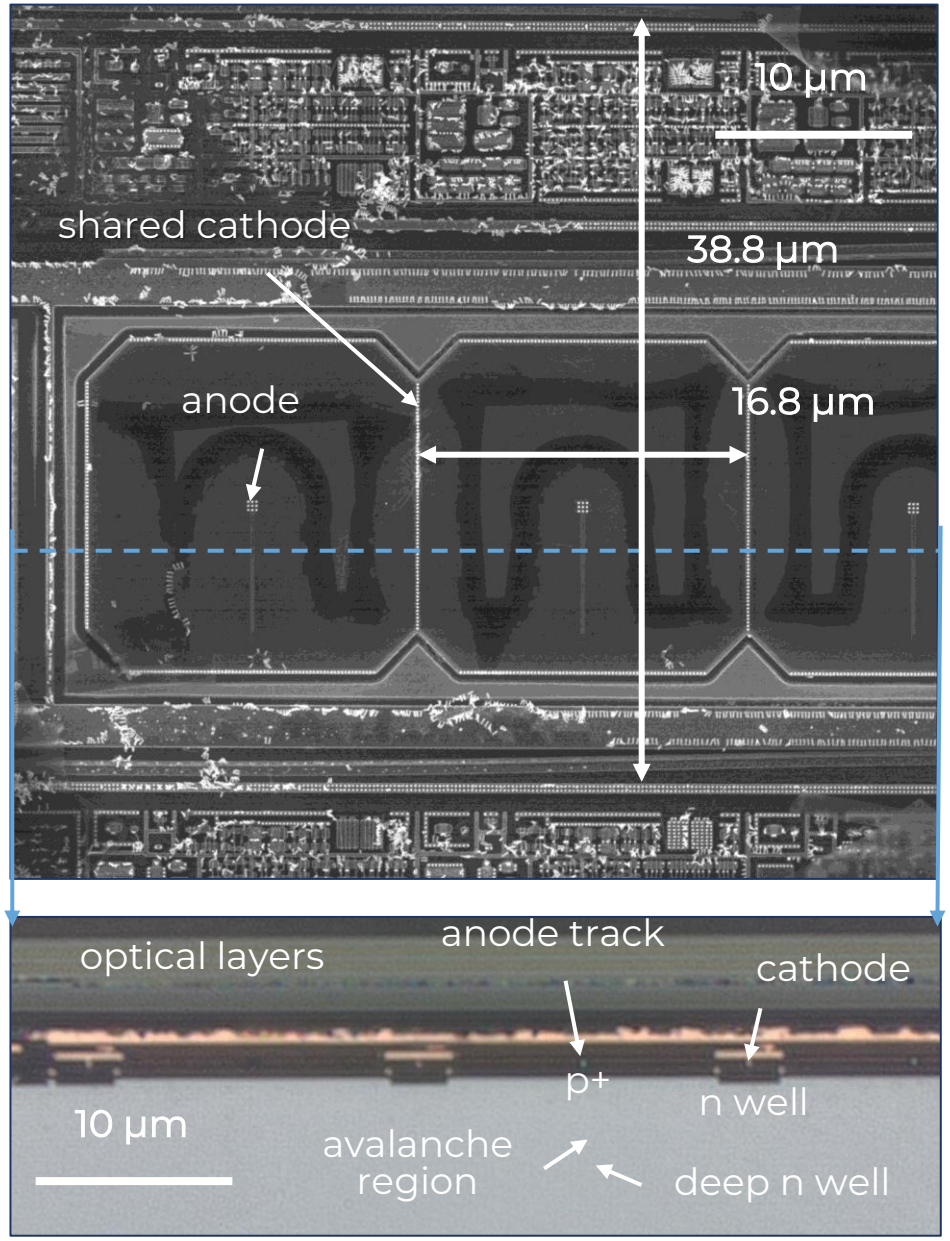
SPAD Pixel Active Area - Optical View ©2024 Yole SystemPlus



Main SPAD Array with Optical Filters and Metal Layers Partially Removed - Optical View ©2024 Yole SystemPlus

[5] R. Kappel. "Multizone, Multiobject D-TOF System in 55nm." ISSW2018.

SPAD Overview – SEM View ©2024 Yole SystemPlus



SPAD Section – Optical View ©2024 Yole SystemPlus

LASER AUTOFOCUS REVERSE COSTING
Presentation Outline

1. Smartphone 3D Imaging and Laser Autofocus

2. 3 systems
   - iPhone 15 Pro LiDAR module by Sony
   - VL53L5 by STMicroelectronics
   - TMF8821 by ams AG

3. **Reverse Costing Methodology**

4. Approximative Model

5. Results & Discussion

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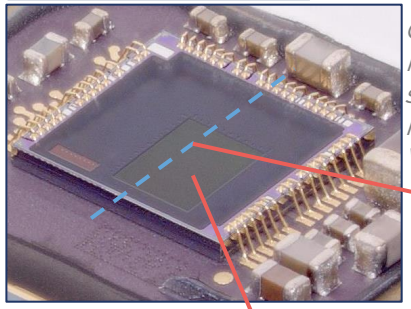
« Reverse Costing Methodology »

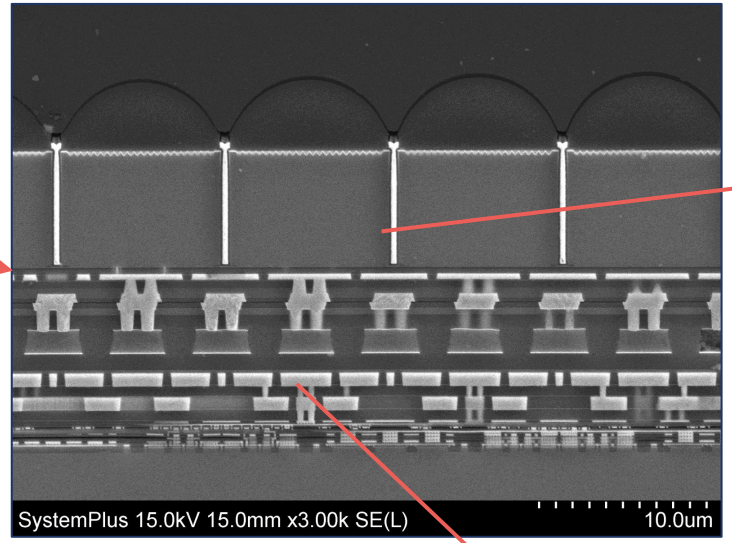
1. Detailed Physical Analysis
2. Reverse Engineer Manufacturing Process
3. Supply Chain & Financial Analysis
4. Simulate Manufacturing Process to Calculate Cost

REVERSE COSTING METHODOLOGY

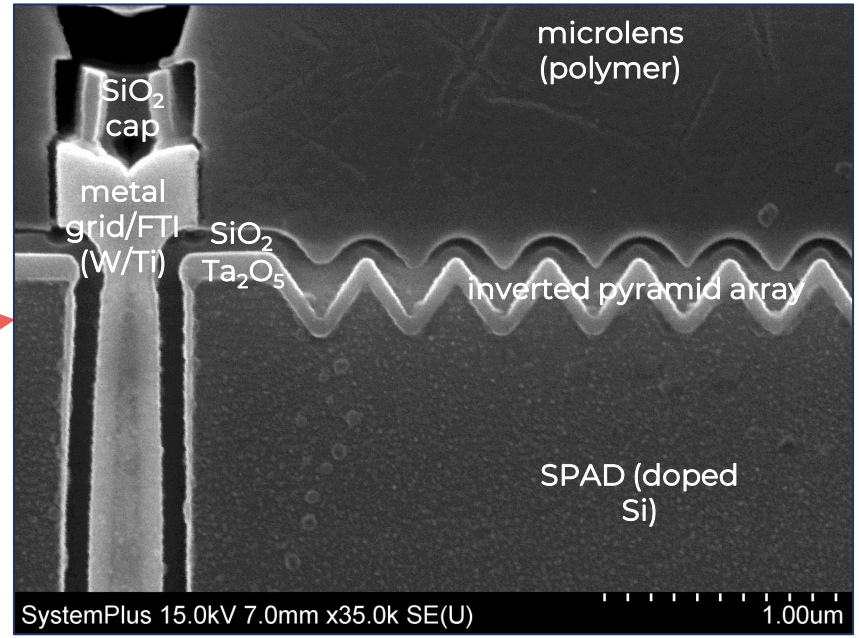
Detailed Physical Analysis

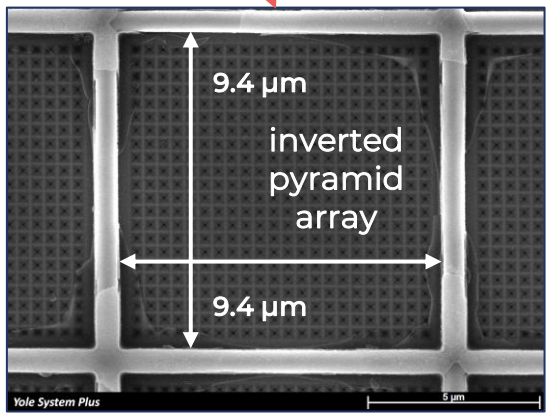


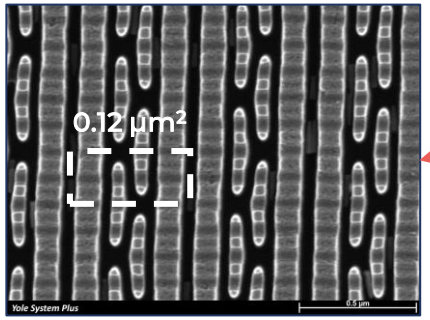
Opened LiDAR Module w/ cross-sectional plane indicated - Optical View ©2024 Yole SystemPlus

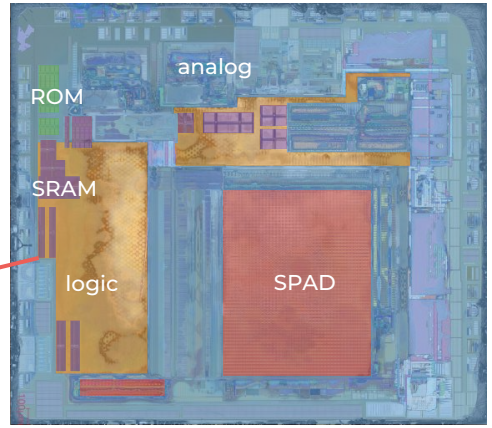


Cross Section through the SPAD Pixel Array - SEM View ©2024 Yole SystemPlus

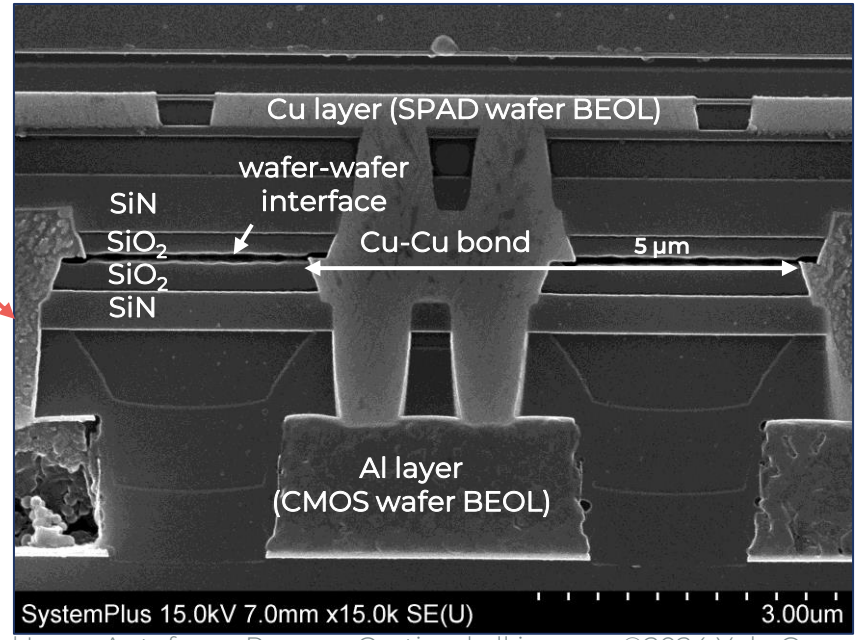








CMOS Die Overview w/ Main Blocks ©2024 Yole SystemPlus



REVERSE COSTING METHODOLOGY

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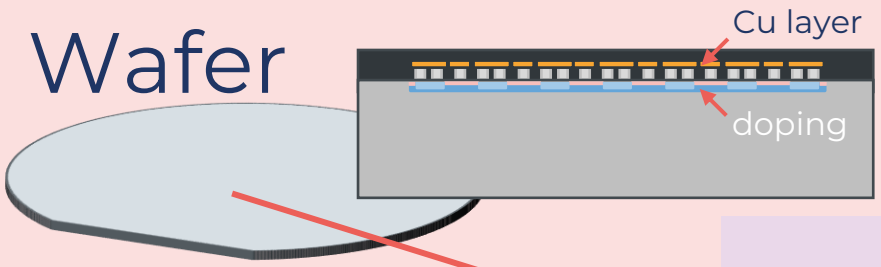
« Reverse Costing Methodology »

1. Detailed Physical Analysis
2. **Reverse Engineer Manufacturing Process**
3. Supply Chain & Financial Analysis
4. Simulate Manufacturing Process to Calculate Cost

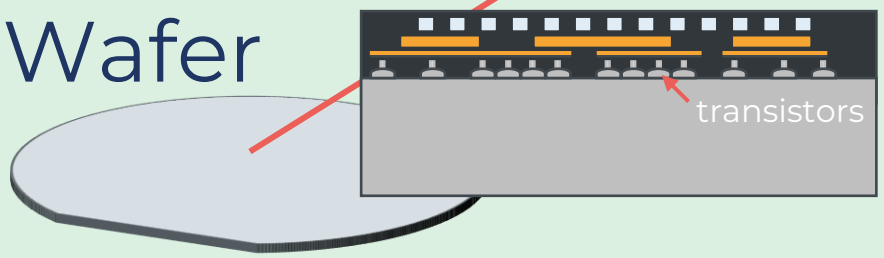
REVERSE COSTING METHODOLOGY

Reverse Engineer the Manufacturing Process

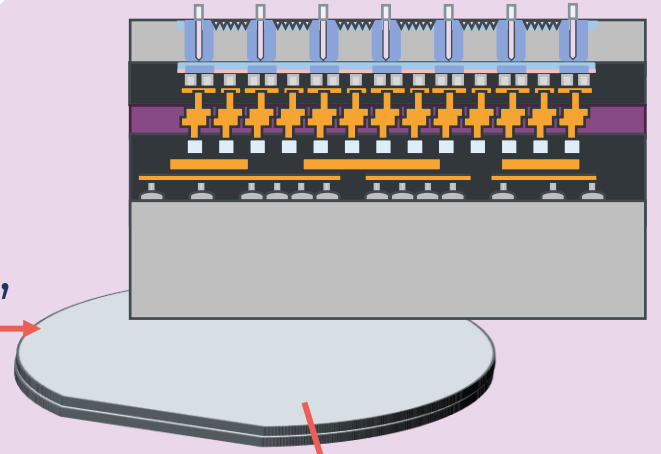
SPAD Wafer



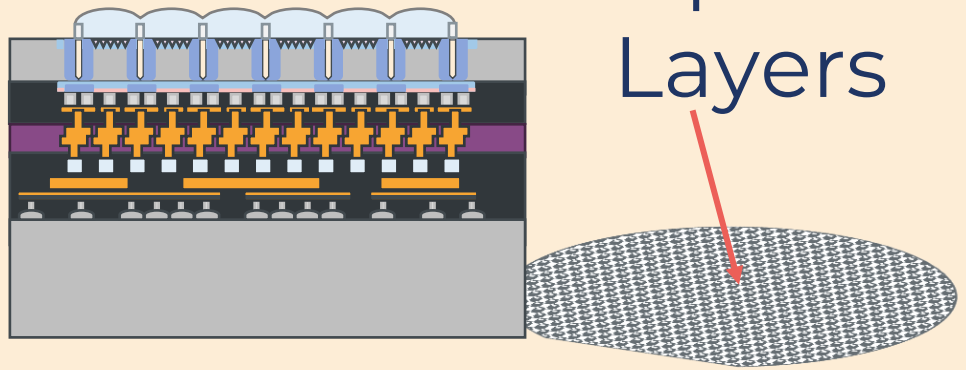
CMOS Wafer

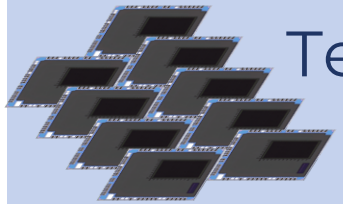


Stacking, Isolation, Doping, NIR-enhancement



Optical Layers





Testing, Dicing, Backgrinding

REVERSE COSTING METHODOLOGY

Reverse Engineer the Manufacturing Process

1. **Prep SPAD & CMOS Wafers**
   - Oxide + Nitride Deposition
   - Via Lithography
   - Metalization (Cu/Ta/TaN)
   - Planarization
   - Plasma Activation
2. **Bonding**
   - Bonding
   - Annealing
3. **Finish Pixels**
   - Thinning
   - Implantation & Annealing
   - Isolation Trench
   - NIR Enhancement + ARC
4. **Guard Ring & Pads**
   - Grid (Oxide/W/Ti)
   - Pads

REVERSE COSTING METHODOLOGY

Outline

1. Smartphone 3D Imaging and Laser Autofocus
2. 3 systems
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   - TMF8821 by ams AG
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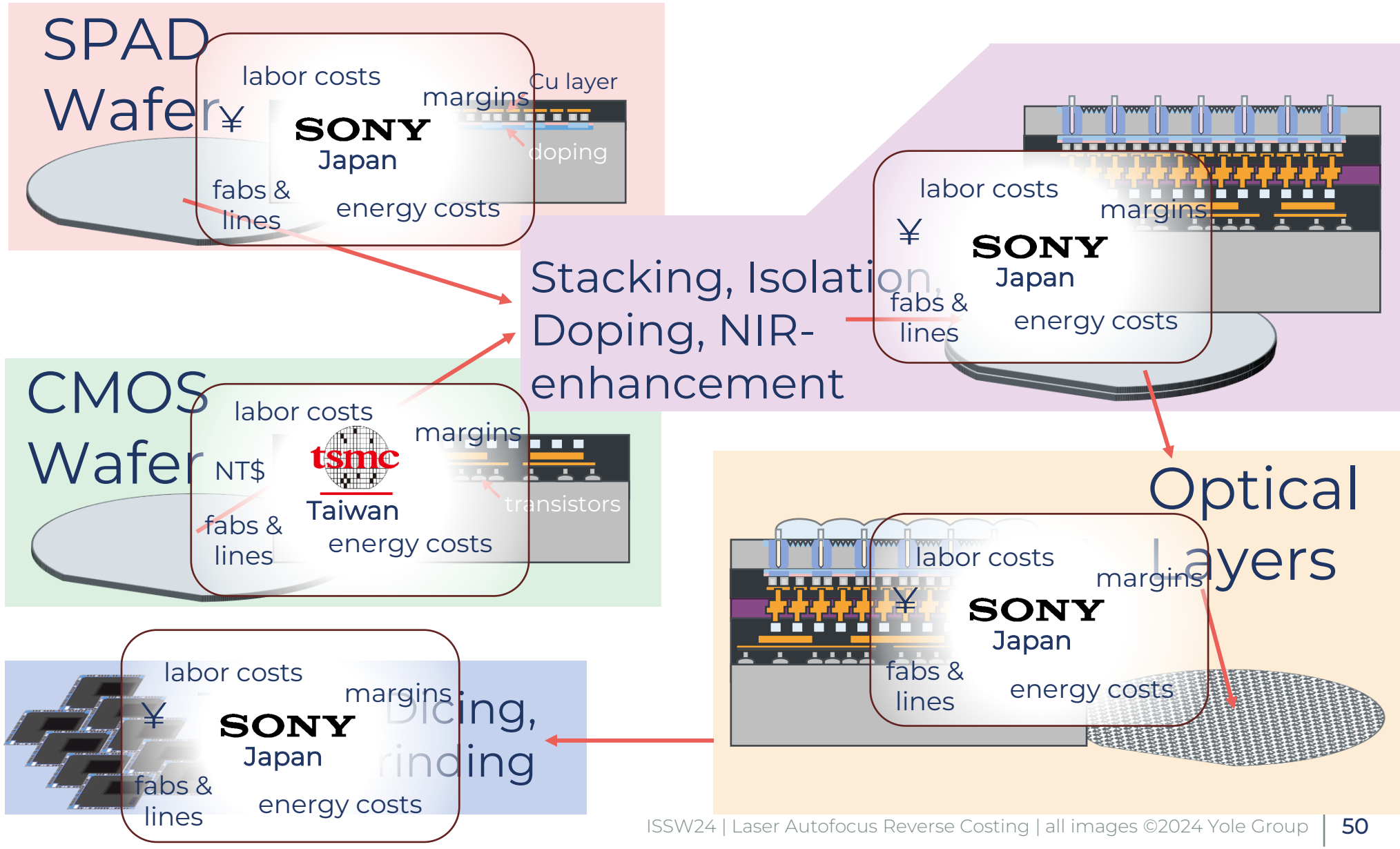
4. Approximative Model
5. Results & Discussion

« Reverse Costing Methodology »

1. Detailed Physical Analysis
2. Reverse Engineer Manufacturing Process
3. **Supply Chain & Financial Analysis**
4. Simulate Manufacturing Process to Calculate Cost

REVERSE COSTING METHODOLOGY

Supply Chain and Financial Analysis



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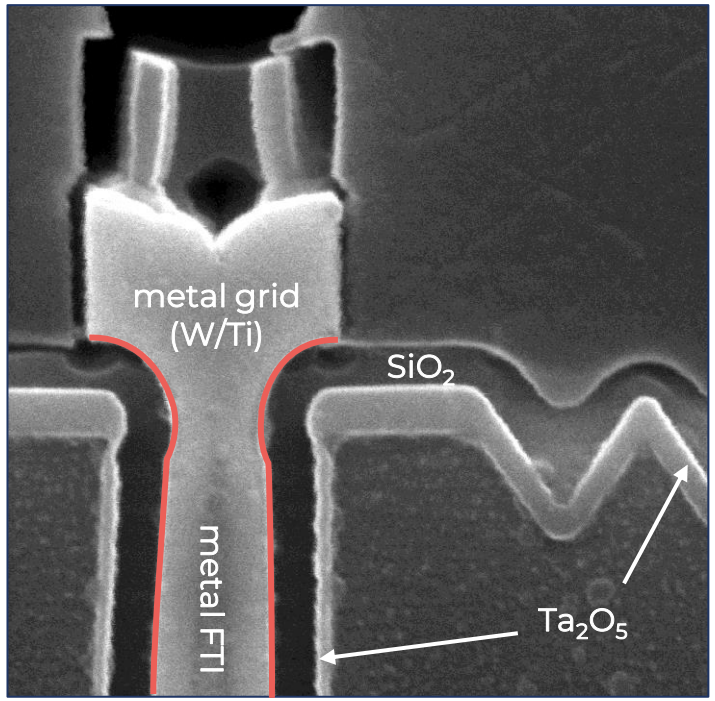
4. **Simulate Manufacturing Process to Calculate Cost**

REVERSE COSTING METHODOLOGY

Cost Modeling Overview



Cross Section through of Inverted Pyramid Array and Metal Grid - SEM View ©2024 Yole SystemPlus

4. Guard Ring & Pads

- Grid (Oxide/W/Ti)
- Pads

Operation name	Step Cost (USD/Wafer)
Tungsten grid - Lithography 8	$18.05
Tungsten grid - Oxide Etching (Dry)	$0.95
Tungsten grid - Resist Strip	$2.26
Tungsten grid - Ti Deposition	$2.95
Tungsten grid - W Deposition	$5.11
Tungsten grid - Lithography 9	$18.05
Tungsten grid - W Etching	$1.08
Tungsten grid - Resist Strip	$2.26
Oxide Cap - Lithography 10	$18.05
Oxide Cap - HDP Oxide	$14.33
Oxide Cap - Resist Strip	$2.26
Pad Trench - Lithography 11	$18.05
Pad Trench - Silicon Etching (Dry)	$2.04
Pad Trench - Resist Strip	$2.26
Pad Trench - Lithography 12	$18.05
Pad Trench - Silicon Etching (Dry)	$1.32
Pad Trench - IMD Etching	$3.66
Pad Trench - Resist Strip	$2.26

REVERSE COSTING METHODOLOGY

Cost Modeling Overview

Tungsten grid - Ti Deposition $2.95

Operation (PVD of Ti)

- Wafer spends a certain amount of **time** in the **PVD sputtering equipment**.
- The equipment occupies costly **cleanroom space.**
- The machine is managed by an **operator**.
- The process consumes a certain amount of **Ti target.**

Cost Components to calculate:

- Equipment depreciation
- Equipment maintenance
- Cleanroom depreciation
- Cleanroom maintenance
- Labor cost
- Consumable cost
- Energy cost
- Overhead

$2.95

REVERSE COSTING METHODOLOGY

Cost Modeling Overview

Cost Model Parameters (non-exhaustive)

- Equipment details
  - Purchase cost & date
  - Depreciation scheme
  - Maintenance costs
  - Footprint & power
  - Operator time
  - Batch size & loading time
  - Uptime
- Cleanroom details
  - ISO class & constr. date
  - Depreciation scheme
  - Maintenance costs
  - Total area, % load
  - Hours per year
- Country details
  - Salary
  - Energy cost
  - Shift and supervisor structure
  - ~~Govt. incentives~~
- Consumables costs
- Process
  - Growth rate
  - Consumable consumption
  - Throughput

model

Calculated Cost Components

- Equipment depreciation
- Equipment maintenance
- Cleanroom depreciation
- Cleanroom maintenance
- Labor cost
- Consumable cost
- Energy cost
- Overhead

4. Guard Ring & Pads

- Grid (Oxide/W/Ti)
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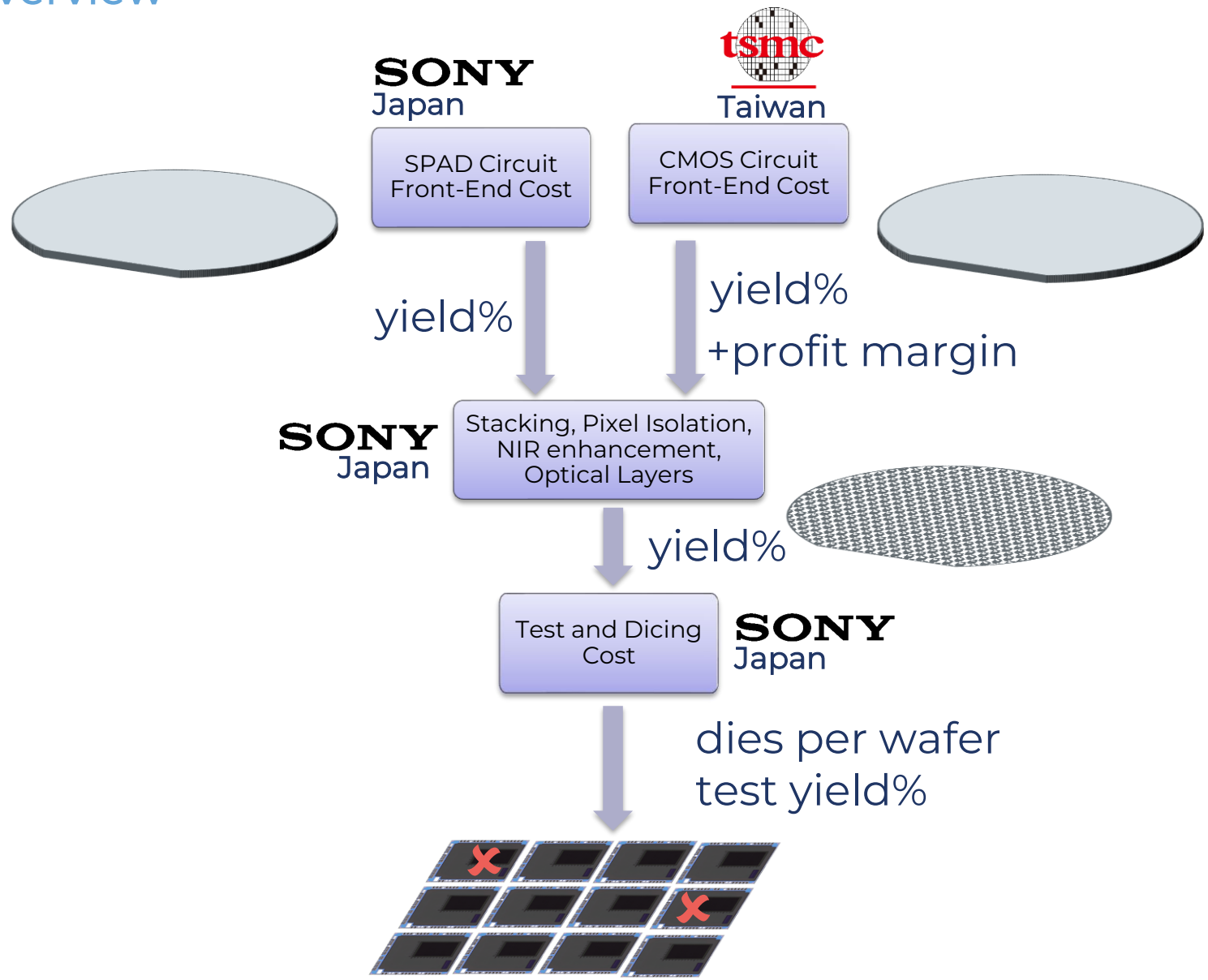
Tungsten grid - Lithography 9	$18.05
Tungsten grid - W Etching	$1.08
Tungsten grid - Resist Strip	$2.26
Oxide Cap - Lithography 10	$18.05
Oxide Cap - HDP Oxide	$14.33
Oxide Cap - Resist Strip	$2.26
Pad Trench - Lithography 11	$18.05
Pad Trench - Silicon Etching (Dry)	$2.04
Pad Trench - Resist Strip	$2.26
Pad Trench - Lithography 12	$18.05
Pad Trench - Silicon Etching (Dry)	$1.32
Pad Trench - IMD Etching	$3.66
Pad Trench - Resist Strip	$2.26

REVERSE COSTING METHODOLOGY

Die Cost Model Overview



LASER AUTOFOCUS REVERSE COSTING
Presentation Outline

1. Smartphone 3D Imaging and Laser Autofocus

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   - TMF8821 by ams AG

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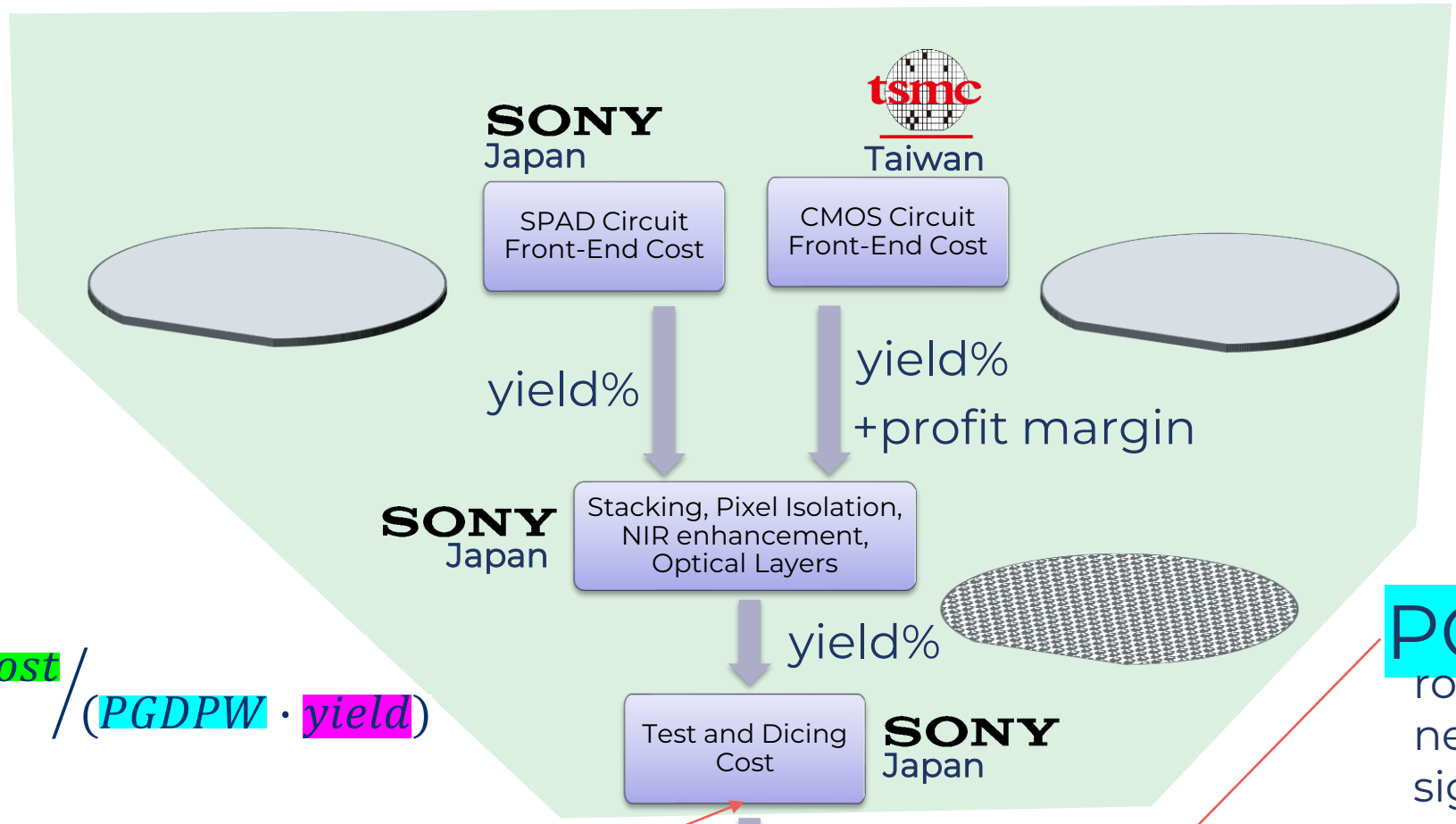
5. Results & Discussion

APPROXIMATIVE COSTING MODEL

Die Cost Model



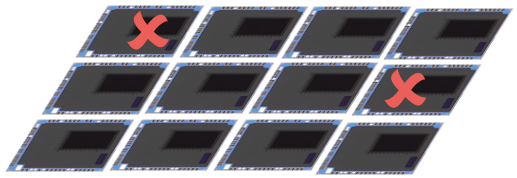
$$diecost = wafer\ cost \Big/ (PGDPW \cdot yield)$$

wafer cost
rounded to nearest most significant figure

PGDPW
rounded to nearest most significant figure

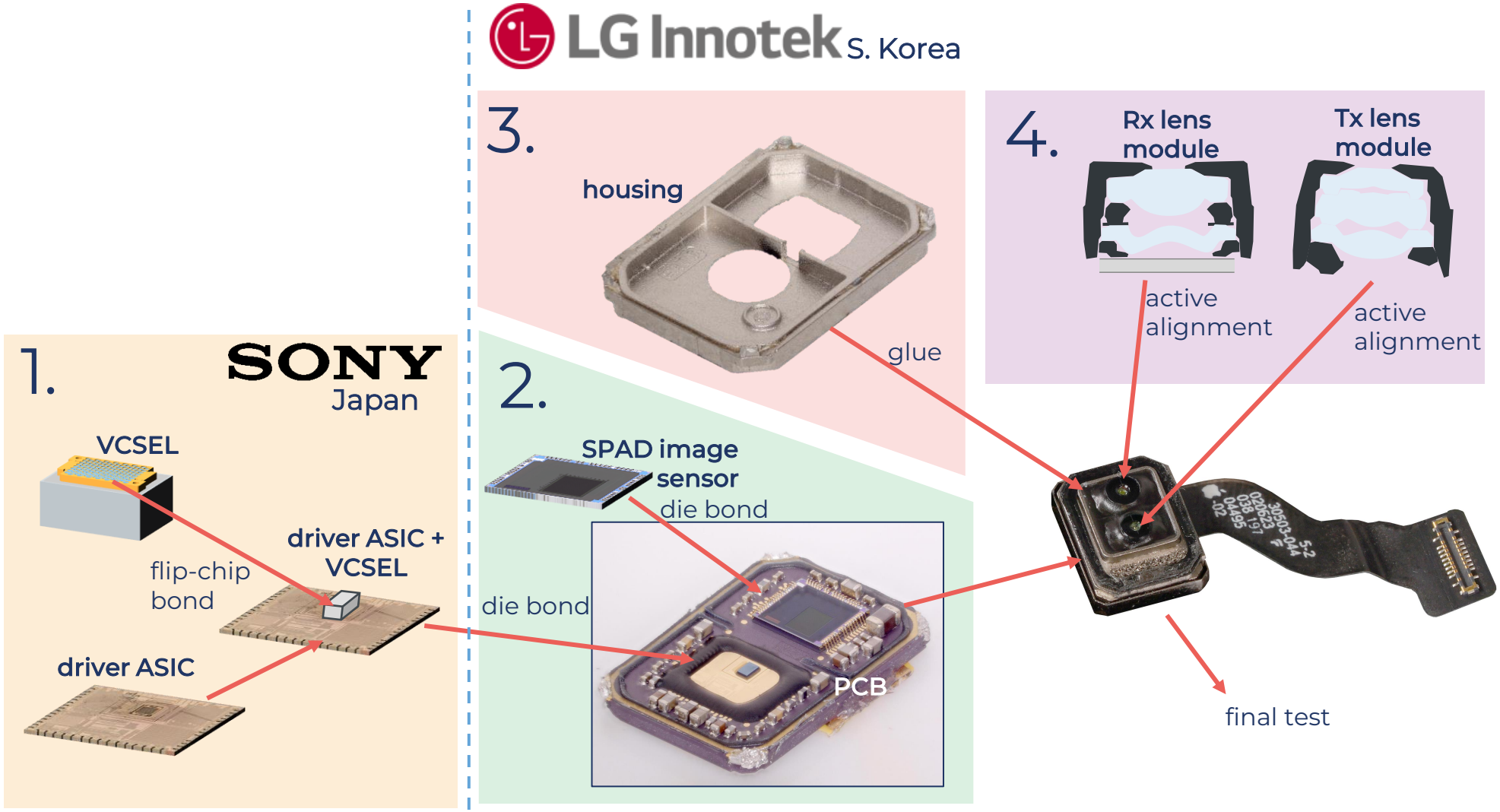
dies per wafer
test yield%

yield
rounded to nearest most significant figure



APPROXIMATIVE COSTING MODEL

Module Cost Model

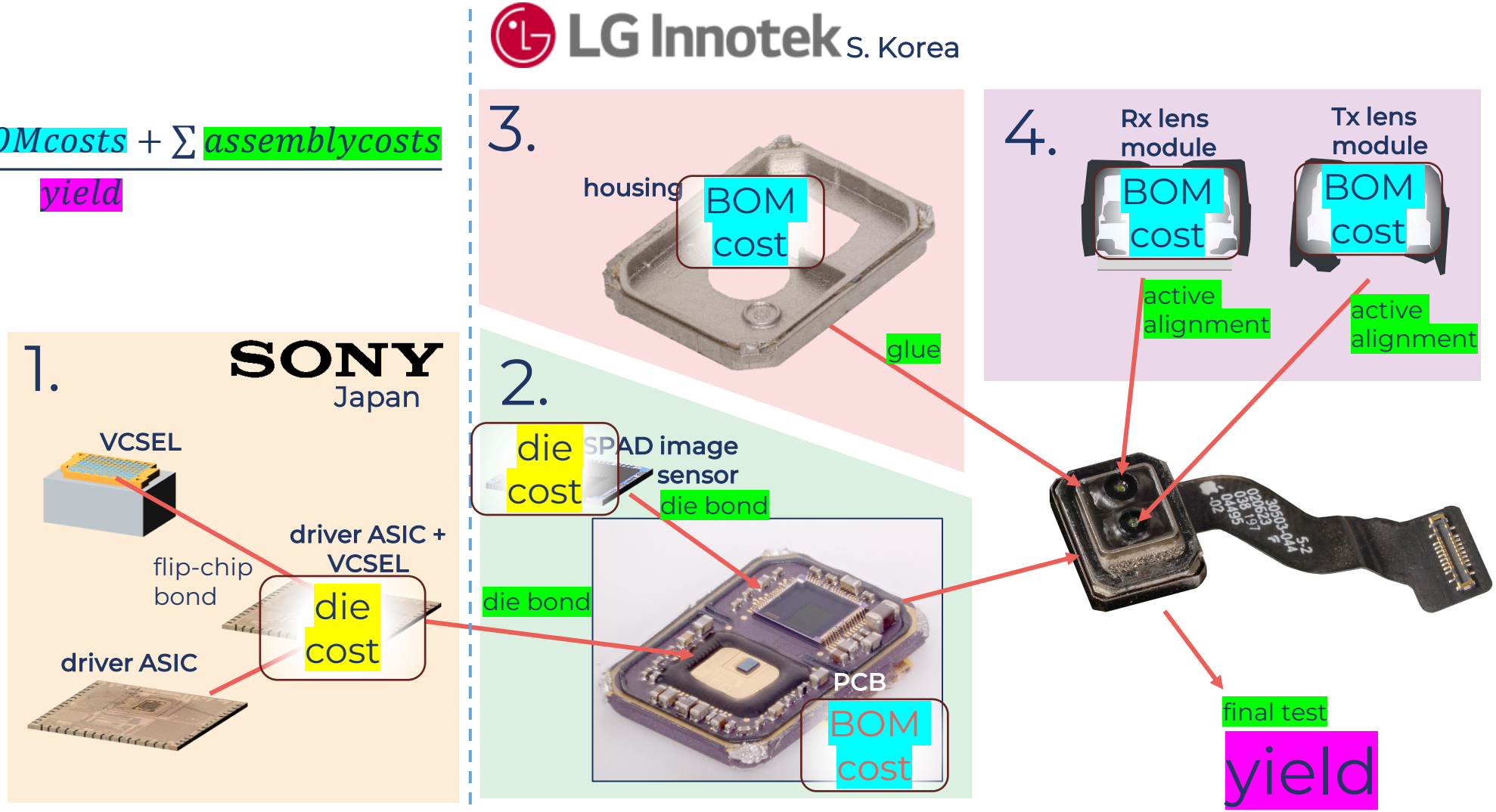


APPROXIMATIVE COSTING MODEL

Module Cost Model

$$cost = \frac{\sum diecosts + \sum BOMcosts + \sum assemblycosts}{yield}$$

All components rounded to nearest most significant figure



LASER AUTOFOCUS REVERSE COSTING

Presentation Outline

1. Smartphone 3D Imaging and Laser Autofocus

2. 3 systems
   - iPhone 15 Pro LiDAR module by Sony
   - VL53L5 by STMicroelectronics
   - TMF8821 by ams AG

3. Reverse Costing Methodology

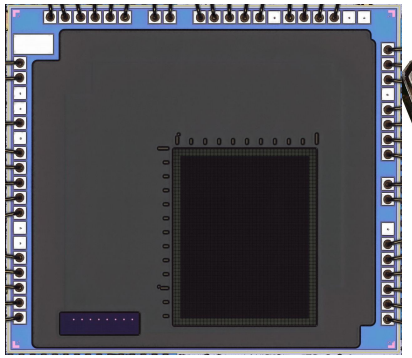
4. Approximative Model

5. **Results & Discussion**

RESULTS & DISCUSSION

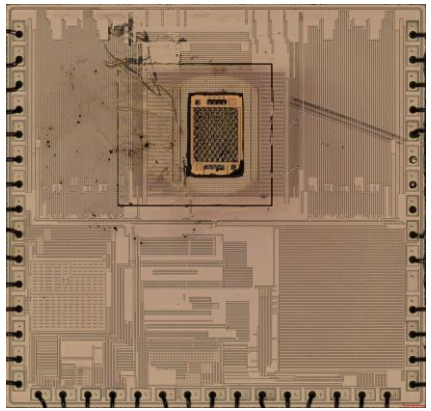
Die Costs

$$diecost = wafercost / (PGDPW \cdot yield)$$

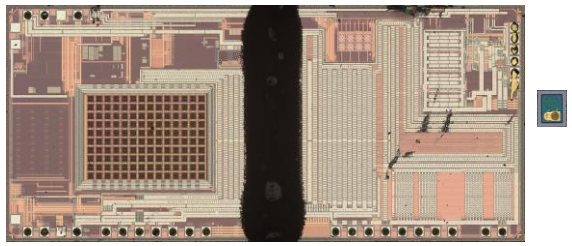


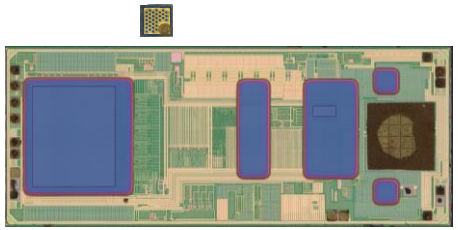
SONY

Die	wafercost	PGDPW	yield	diecost
SPAD CIS	$5,000	9,000	80%	$0.69
VCSEL+Driver	$6,000	7,000	70%	$1.22



Die	wafercost	PGDPW	yield	diecost
SPAD ASIC	$2,000	10,000	90%	$0.22
VCSEL	$2,000	200,000	90%	$0.01



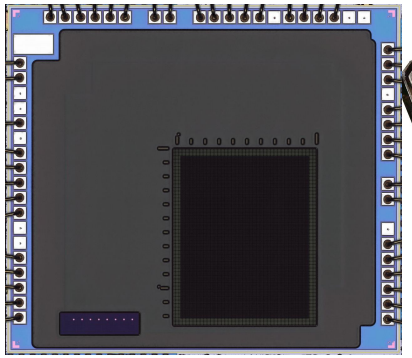


Die	wafercost	PGDPW	yield	diecost
SPAD ASIC	$3,000	10,000	90%	$0.33
VCSEL	$3,000	200,000	90%	$0.02

RESULTS & DISCUSSION

Die Costs

$$diecost = wafercost / (PGDPW \cdot yield)$$



SONY

Die	wafercost	PGDPW	yield	diecost
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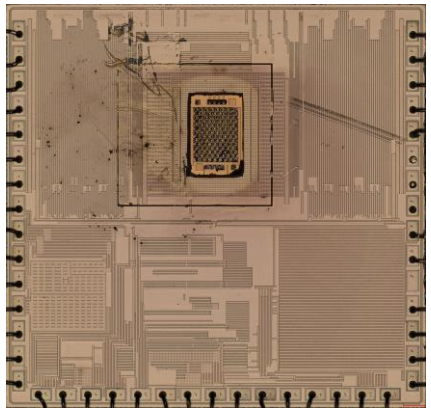
VCSEL+Driver	$6,000	7,000	70%	$1.22

3D-integrated SPAD is costly



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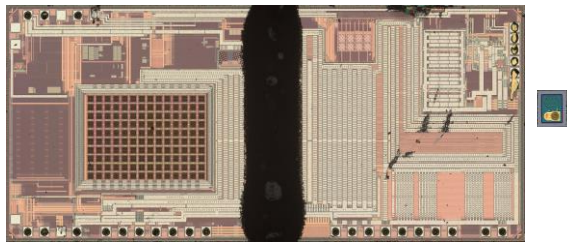

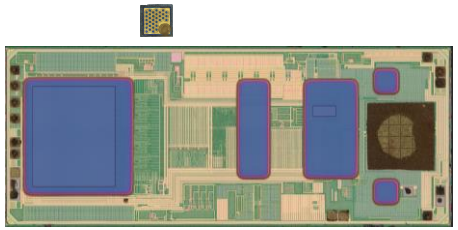

Die	wafercost	PGDPW	yield	diecost
SPAD ASIC	$3,000	10,000	90%	$0.33
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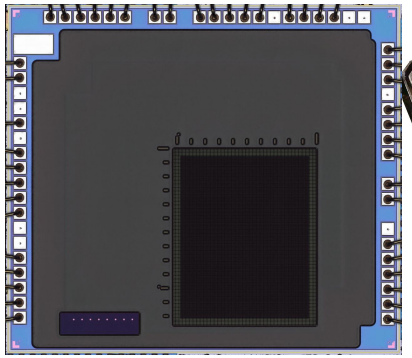
RESULTS & DISCUSSION

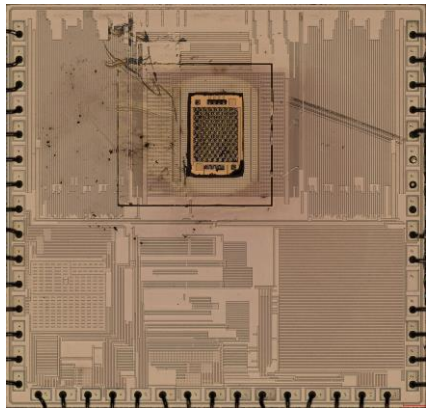
Module Costs

$$cost = \frac{\sum diecosts + \sum BOMcosts + assemblycosts}{yield}$$

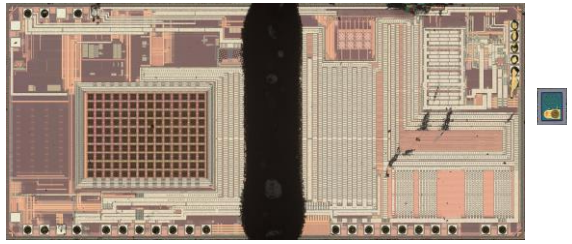


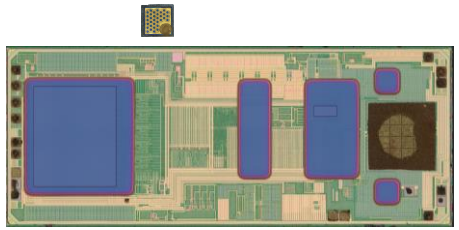
SONY

∑diecosts	∑BOMcosts	assembly	Yield	cost
$1.91	$3	$1	90%	$6.60



∑diecosts	∑BOMcosts	assembly	Yield	cost
$0.23	$0.1	$0.2	90%	$0.60

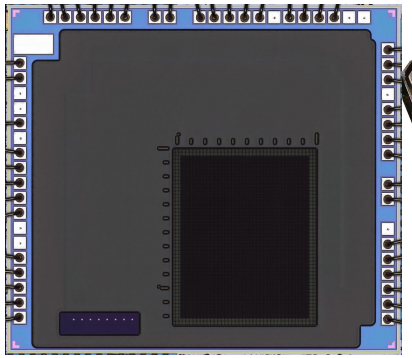




∑diecosts	∑BOMcosts	assembly	Yield	cost
$0.35	$0.02	$0.1	90%	$0.50

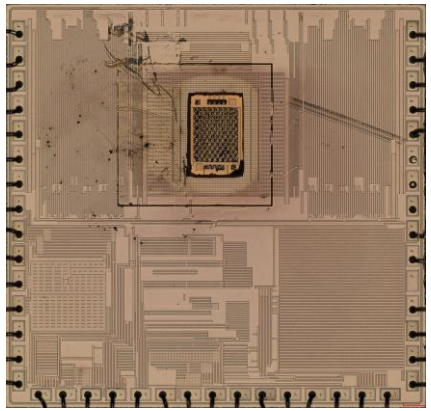
RESULTS & DISCUSSION
Module Costs

$$cost = \frac{\sum diecosts + \sum BOMcosts + assemblycosts}{yield}$$

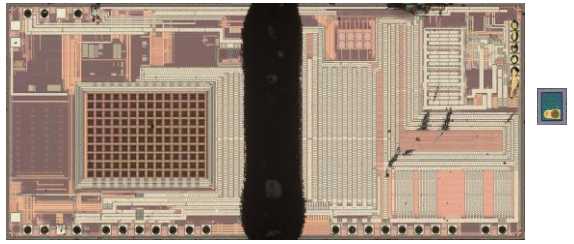


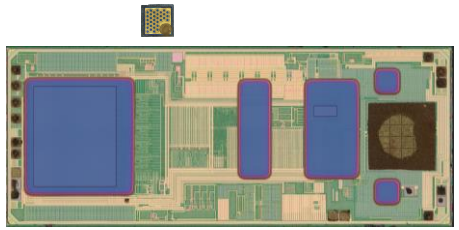
SONY

∑diecosts	∑BOMcosts	assembly	Yield	cost
$1.91	$3	$1	90%	$6.60



∑diecosts	∑BOMcosts	assembly	Yield	cost
$0.23	$0.1	$0.2	90%	$0.60





ams

∑diecosts	∑BOMcosts	assembly	Yield	cost
$0.35	$0.02	$0.1	90%	$0.50

Optics and active alignment in the LiDAR are costly.

STMicro module also has active alignment of Rx optic.

RESULTS & DISCUSSION

Key Findings

TABLE 1. KEY FINDINGS OF PHYSICAL & COSTING ANALYSIS			
	iPhone LiDAR	VL53L5	TMF8821
estimated cost	$6.60	$0.60	$0.50
SPAD ASIC Cost	-	$0.22	$0.33
VCSEL (alone)	-	$0.01	$0.02
Total Die Cost	$1.91	$0.23	$0.35
Total BOM costs	$3	$0.1	$0.02
Assembly costs	$1	$0.2	$0.1
module vol. (LxWxH=V)	10.3x7.6x3.0 = 235 mm^3	6.4x3.0x1.5 = 29 mm^3	4.6x2.0x1.4 = 13 mm^3
VCSEL cavities	112 (indep.)	5	33
VCSEL total cavity area[a]	12,650 μm^2	1,150 μm^2	5,400 μm^2
transmission optic	refractive lens module	diffractive optic	multi-lens diffusor
emission shape	8x14 dot pattern	square	diffuse
baseline	3.0 mm	4.0 mm	2.4 mm
reception optics	refractive lenses, bandpass filter plate, on-chip µlenses, NIR enhanced	Fresnel-like flat lens, on-chip µlenses	WLO refractive lens, on-chip interferometric layers
SPAD process	90nm on 28nm CMOS with in-pixel DBI [1]	40nm CMOS [3-5]	55nm high-voltage CMOS & DMOS [6]
pixel pitch	10.1x10.1 μm^2	54x54 $\mu m^{2,b}$	38.8x16.8 μm^2
detecting area per pixel	68 μm^2 (µlens area)	1100 μm^2 (µlens area)[b]	132 μm^2
SPAD array resolution	10,672 (116 x 92)	140 (14 x 10)[b]	612 (34 x 18)
total detecting area	0.73 mm^2	0.15 mm^2	0.08 mm^2

a. Cavity estimated by aperture in the anode

b. Per 4x4 macro-pixel

RESULTS & DISCUSSION

Key Findings – LiDAR vs multi-zone ranging

TABLE 1. KEY FINDINGS OF PHYSICAL & COSTING ANALYSIS

	iPhone LiDAR	VL53L5	TMF8821
estimated cost	$6.60	$0.60	$0.50
SPAD ASIC Cost	-	$0.22	$0.33
VCSEL (alone)	-	$0.01	$0.02
Total Die Cost	**$1.91**	**$0.23**	**$0.35**
Total BOM costs	**$3**	**$0.1**	**$0.02**
Assembly costs	**$1**	**$0.2**	**$0.1**
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RESULTS & DISCUSSION

Key Findings – LiDAR vs multi-zone ranging

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total detecting area	**0.73 mm²**	**0.15 mm²**

lens modules

x10

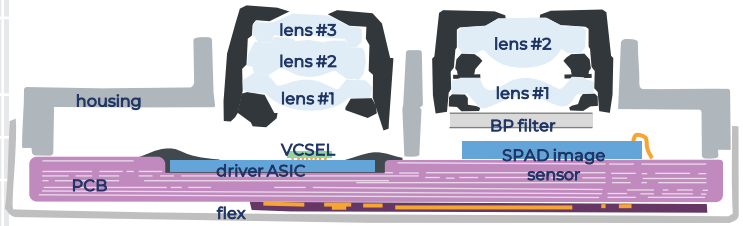
x5

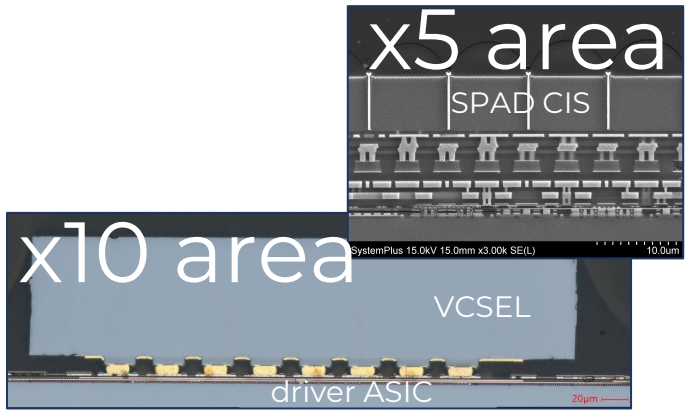
a. Cavity estimated by aperture in the anode

b. Per 4x4 macro-pixel

LiDAR 10x more costly

- Large SPAD CIS with costly 3D-integration
- Large back-emitting VCSEL flip-chip bonded directly to driver
- Complex optics for both Rx and Tx

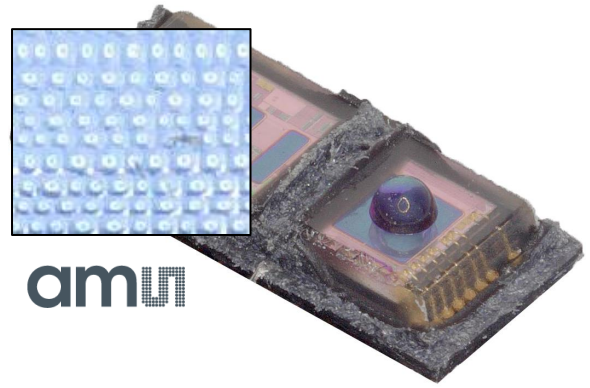


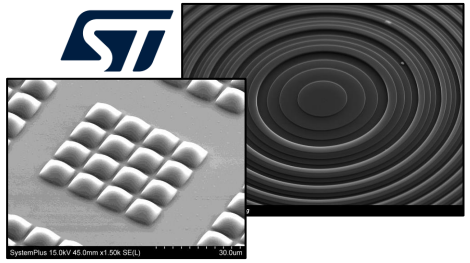


RESULTS & DISCUSSION

VL53L5 vs TMF8821 – WLO vs optical dies

- WLO Rx inexpensive compared to sophisticated diffractive element
  - Downside: no µlens
- No active alignment in ams AG module





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Total BOM costs	**$0.1**	**$0.02**
Assembly costs	**$0.2**	**$0.1**
module vol. (LxWxH=V)	6.4x3.0x1.5 = 29 mm³	4.6x2.0x1.4 = 13 mm³
VCSEL cavities	5	33
VCSEL total cavity area[a]	1,150 µm²	5,400 µm²
transmission optic	diffractive optic	multi-lens diffusor
emission shape	square	diffuse
baseline	4.0 mm	2.4 mm
reception optics	Fresnel-like flat lens, **on-chip µlenses**	**WLO refractive lens**, on-chip interferometric layers
SPAD process	40nm CMOS [3-5]	55nm high-voltage CMOS & DMOS [6]
pixel pitch	54x54 µm²,[b]	38.8x16.8 µm²
detecting area per pixel	1100 µm² (µlens area)[b]	132 µm²
SPAD array resolution	140 (14 x 10)[b]	612 (34 x 18)
total detecting area	**0.15 mm²**	**0.08 mm²**

diffractive optical dies

HEPTAGON™

WLO inexpensive

µlenses

no µlenses

RESULTS & DISCUSSION

VL53L5 vs TMF8821 – TSMC

ams AG must compensate for smaller detecting area

- Foundry partner makes SPAD ASIC costly for ams AG

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detecting area per pixel	1100 μm^2 (µlens area)[b]	132 μm^2
SPAD array resolution	140 (14 x 10)[b]	/2 612 (34 x 18)
total detecting area	0.15 mm^2	small 0.08 mm^2

detecting area

a. Cavity estimated by aperture in the anode

b. Per 4x4 macro-pixel

RESULTS & DISCUSSION

VL53L5 vs TMF8821 – VCSEL solution

ams AG must compensate for smaller detecting area

- Foundry partner makes SPAD ASIC costly for ams AG
- Powerful VCSEL
  - downside: power hungry

	FINDINGS OF PHYSICAL & COSTING ANALYSIS	
	VL53L5	TMF8821
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x5 powerful VCSEL

/2 small detecting area

a. Cavity estimated by aperture in the anode

b. Per 4x4 macro-pixel

LASER AUTOFOCUS REVERSE COSTING
Conclusions

3D Imaging (LiDAR) is 10x the cost and 10x the module volume

- Large SPAD CIS with costly 3D-integration
- Large and innovative back-emitting VCSEL flip-chip bonded directly to driver
- Complex optics for both Rx and Tx

STMicroelectronics module has highly engineered optics, including microlenses

ams AG module designed to optimize costs

- Heptagon WLO very inexpensive
  - Downside: doesn't allow µlenses
  - Downside: Tx pattern less engineered
- Challenge: Small sensitive area (no µlens, TSMC partner)
  - Solution: compensate with large VCSEL (power hungry)

Fin.