[Invited] Journey of pixel optics scaling into deep sub-micron and migration to meta-optics era

In-Sung Joe
Semiconductor R&D Center, Samsung Electronics
1 Samsungjeonja-ro, Hwaseong-si, Gyeonggi-do, 18448 Korea, Republic of
E-mail: insung.joe@samsung.com

Abstract This paper reviews pixel optics trend of current CMOS image sensors. In order to pack more pixels into compact form factor of high-resolution mobile cameras, pixel scaling continues into deep sub-micron size. Evolution of pixel optics technology to compensate inherent performance drop from pixel scaling is explained, and the introduction of meta-optics technology to overcome the performance limit of conventional optics is discussed.

Keywords: CMOS image sensor, color filter isolation grid, micro-lens, nano photonics, meta-surface, meta-materials, meta-optics, nano-prism, meta-prism

1. Mobile camera and market trend

CMOS image sensor (CIS) market is recovering slowly after pandemic thanks to the number of cameras per mobile phone keeps increasing. In addition, there is a distinct trend of more high resolution cameras are adopted, such as recent 200MP [1], to provide superior image quality. In order to pack more pixels into compact form factor of slim mobile phones, pixel scaling is inevitable, and deep sub-micron pixel, for example 0.5 µm is presented recently [2]. This trend would continue as the demand for thin camera modules increases due to foldable phones are gaining popularity in the market.

2. Journey of pixel optics scaling

Fundamentally, the sensitivity of each pixel drops as the pixel area decreases. Pixel optic architecture has been evolved to increase the signal (received photons) and reduce the noise (optical crosstalk) so that signal-to-noise ratio (SNR) remains comparable even with the pixel scaling: from front-side illumination (FSI), light guide [3], back-side illumination (BSI) [4], backside deep-trench isolation (DTI) [5] to full-depth DTI [6]. Although the architectural evolution, one-micron pixel was not enough for the main camera until the merged color filter technology, such as tetra-pixel (2x2) could provide both full-resolution image with re-mosaic image signal processing (ISP) technique when bright, and brighter image at dark conditions [7]. This technology continues to extend toward Tetra^2-pixel (4x4) [8] enabling deep sub-micron pixel scaling such as 0.5 µm [2].

A major challenge to maintain reasonable sensitivity at sub-micron pixel is from the diffraction limit of the micro-lens. Because the beam spot size does not scale as pixel scales, conventional metal color-filter isolation grid interacts more with incoming light, for example, 32% at 0.7 µm pixel case, which results in optical loss [9]. Metal-free, low-refractive index dielectric-based grid technology solved this problem [9], and extends to air-gap grid technology [10, 11].

3. Migration to meta-optics

There is a clear wall of maximum sensitivity at given pixel size with the conventional optic structure, which relies on micro-lens and color filters. More than half of incoming light is absorbed at the color filter in case of a green pixel. In order to overcome this sensitivity wall, recent attempts to adopt meta-optics technology show promising results [12-14]. Proposed nano-prism functions as a color router and larger-than-pixel lens to scavenge more light from nearby color pixels for improved sensitivity (+25%) [13]. Still in early stage of application to sensors, meta-optics showed potentials to provide other interesting opportunities such as extreme pixel scaling (0.22 µm pixel pitch) [15], and improved color accuracy at 0.22 µm pixel pitch [16].

References

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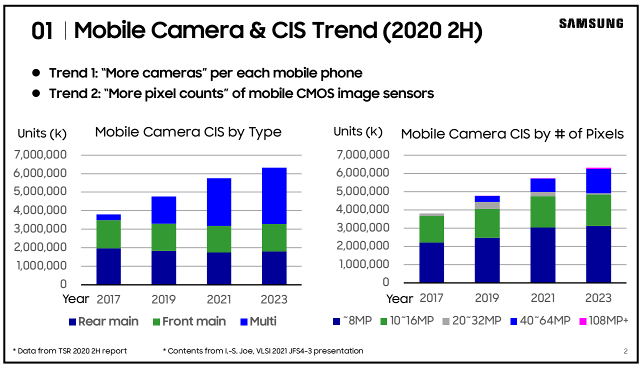
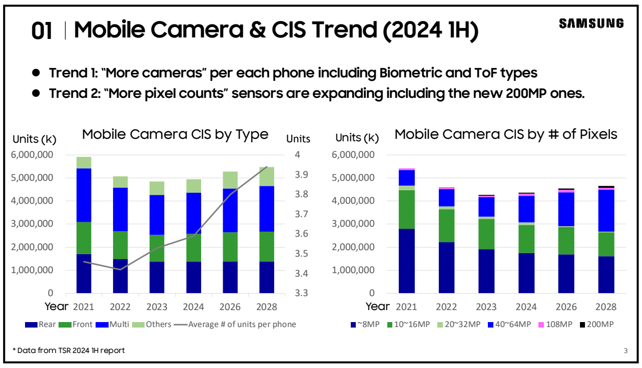
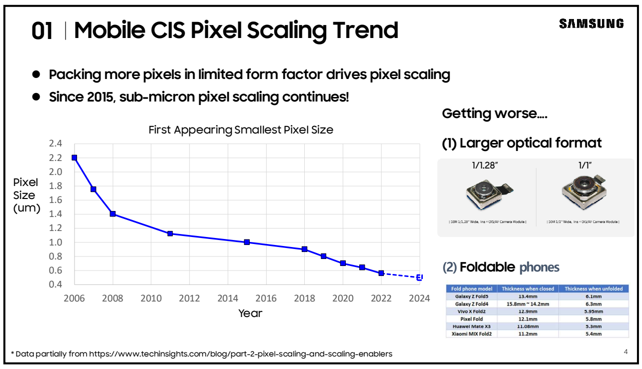
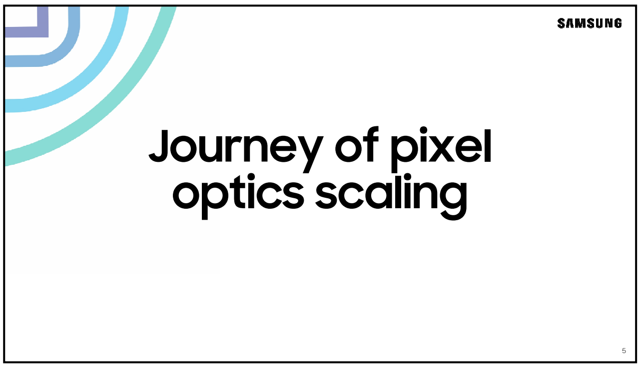
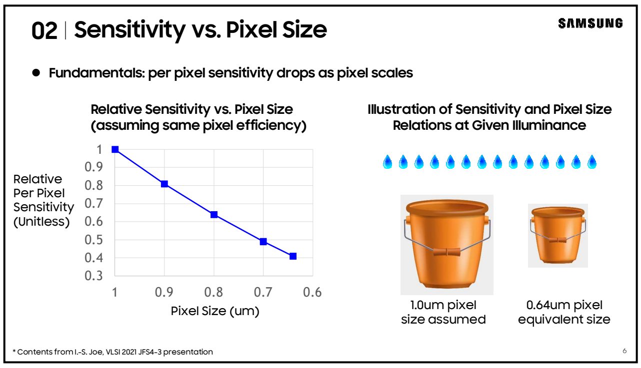
Mobile camera & market trend
1

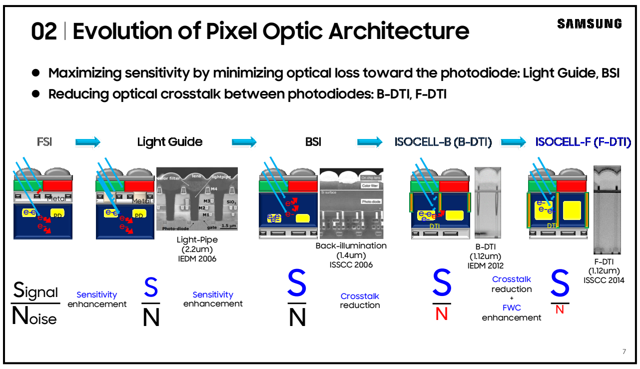

01 | Mobile Camera & CIS Trend (2020 2H)
SAMSUNG
Trend 1: "More cameras" per each mobile phone
Trend 2: "More pixel counts" of mobile CMOS image sensors
Mobile Camera CIS by Type
Units (k)
7,000,000
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
Year 2017 2019 2021 2023
Rear main
Front main
Multi
Mobile Camera CIS by # of Pixels
~8MP
10~16MP
20~32MP
40~64MP
108MP+
* Data from TSR 2020 2H report
* Contents from I.-S. Joe, VLSI 2021 JFS4-3 presentation
2

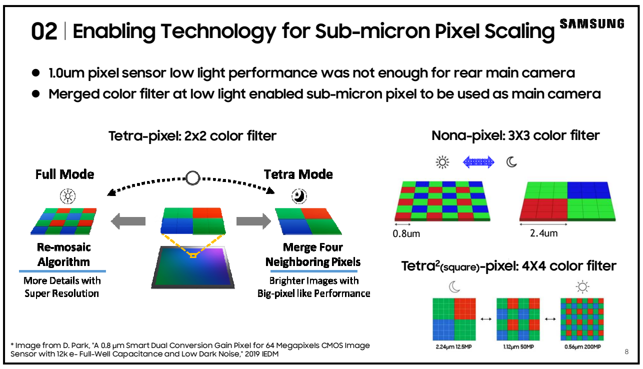

01 | Mobile Camera & CIS Trend (2024 1H)
SAMSUNG
Trend 1: "More cameras" per each phone including Biometric and ToF types
Trend 2: "More pixel counts" sensors are expanding including the new 200MP ones.
Mobile Camera CIS by Type
Units (k)
Units
6,000,000
5,000,000
4,000,000
3,000,000
2,000,000
1,000,000
0
4
3.9
3.8
3.7
3.6
3.5
3.4
3.3
Year 2021 2022 2023 2024 2026 2028
Rear
Front
Multi
Others
Average # of units per phone
Mobile Camera CIS by # of Pixels
~8MP
10~16MP
20~32MP
40~64MP
108MP
200MP
* Data from TSR 2024 1H report
3


01 | Mobile CIS Pixel Scaling Trend
SAMSUNG
Packing more pixels in limited form factor drives pixel scaling
Since 2015, sub-micron pixel scaling continues!
First Appearing Smallest Pixel Size
Pixel Size (um)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
2006 2008 2010 2012 2014 2016 2018 2020 2022 2024
Year
Getting worse….
(1) Larger optical format
1/1.28"
1/1"
(2) Foldable phones
* Data partially from https://www.techinsights.com/blog/part-2-pixel-scaling-and-scaling-enablers
4


SAMSUNG
Journey of pixel optics scaling
5


02 | Sensitivity vs. Pixel Size
SAMSUNG
Fundamentals: per pixel sensitivity drops as pixel scales
Relative Sensitivity vs. Pixel Size (assuming same pixel efficiency)
Relative Per Pixel Sensitivity (Unitless)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
1 0.9 0.8 0.7 0.6
Pixel Size (um)
Illustration of Sensitivity and Pixel Size Relations at Given Illuminance
1.0um pixel size assumed
0.64um pixel equivalent size
* Contents from I.-S. Joe, VLSI 2021 JFS4-3 presentation
6


02 | Evolution of Pixel Optic Architecture
SAMSUNG
Maximizing sensitivity by minimizing optical loss toward the photodiode: Light Guide, BSI
Reducing optical crosstalk between photodiodes: B-DTI, F-DTI
FSI
Light Guide
BSI
ISOCELL-B (B-DTI)
ISOCELL-F (F-DTI)
Light-Pipe (2.2um) IEDM 2006
Back-illumination (1.4um) ISSCC 2006
B-DTI (1.12um) IEDM 2012
F-DTI (1.12um) ISSCC 2014
Signal
Noise
Sensitivity enhancement
S
N
Sensitivity enhancement
S
N
Crosstalk reduction
S
N
Crosstalk reduction + FWC enhancement
S
N
7


02 | Enabling Technology for Sub-micron Pixel Scaling
SAMSUNG
1.0um pixel sensor low light performance was not enough for rear main camera
Merged color filter at low light enabled sub-micron pixel to be used as main camera
Tetra-pixel: 2x2 color filter
Full Mode
Tetra Mode
Re-mosaic Algorithm
More Details with Super Resolution
Merge Four Neighboring Pixels
Brighter Images with Big-pixel like Performance
Nona-pixel: 3X3 color filter
0.8um
2.4um
Tetra²(square)-pixel: 4X4 color filter
* Image from D. Park, "A 0.8 µm Smart Dual Conversion Gain Pixel for 64 Megapixels CMOS Image Sensor with 12k e- Full-Well Capacitance and Low Dark Noise," 2019 IEDM
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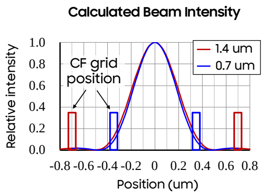
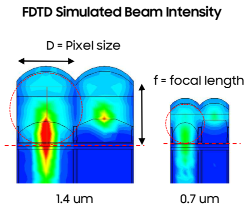
02 | Sub-micron Scaling Challenge: Micro-lens Focus Spot Size

SAMSUNG

- Color-filter grid (conventionally Tungsten) introduced to suppress crosstalk between nearby pixels, but light-to-grid interaction increases as pixel scales into sub-micron





* Contents from I.-S. Joe, VLSI 2021 JFS4-3 presentation

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02 | Color-Filter Grid for Sub-micron Optic Scaling

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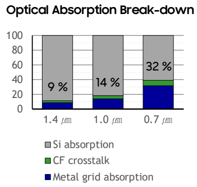
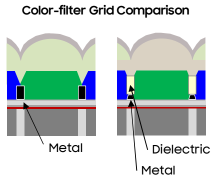
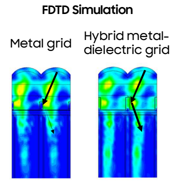
- Optical loss from absorption increases as more light interacts with conventional metal color-filter grids (32% at 0.7um pixel)
- Hybrid metal-and-dielectric grid structure introduced at 0.8um pixel generation







* Contents from I.-S. Joe, VLSI 2021 JFS4-3 presentation

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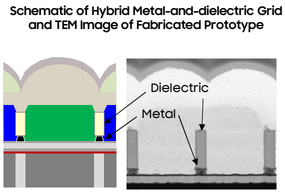
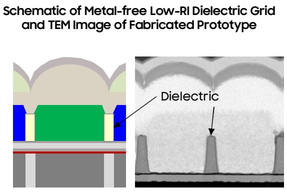
02 | Metal-free Low-RI Grid for 0.64um Pixel

SAMSUNG

- New metal-free, low-refractive-index dielectric material based grid structure designed and implemented with 0.64um pixel prototype





* Contents from I.-S. Joe, VLSI 2021 JFS4-3 presentation

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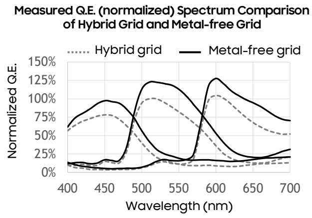
02 | Metal-free Low-RI Grid Measurement Results

SAMSUNG

- Prototype sensor with new metal-free low-RI dielectric grid compared with previous hybrid grid type → 29% improved sensitivity



Performance Comparison of Hybrid Grid and Metal-free Grid Prototype Sensors (0.64um)

	Hybrid grid	Metal-free grid
Normalized QE (Green)	100 %	123 %
Sensitivity (Green)	1,190 e-/lux.s	1,530 e-/lux.s (+29%)
Y-SNR	29.5 dB	30.7 dB
Crosstalk	18.4%	18.5%

* Contents from I.-S. Joe, VLSI 2021 JFS4-3 presentation

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02 | What's Next? Air-gap Grid!

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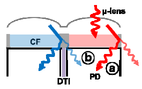
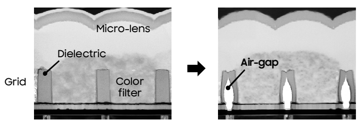
- Next stage for low RI color filter grid is introducing air (n=1.0) into grid structure
- Successful demonstration of air-gap grid is done at 0.56um pixel prototype (ISSCC 2022)

✓ Problem: Pixel shrink → poor sensitivity & crosstalk
Solution: Lower RI grid → TIR▲ → ⓐ sensitivity▲ & ⓑ crosstalk▼

✓ Air-gap (RI▼) → better optical performance





Crosstalk	1.2%▼
Q.E	7 %▲
Sensitivity	5.5%▲
YSNR	0.3 dB▲

RI: Refractive index
TIR: Total internal reflection
Q.E: Quantum efficiency

* Contents from S. Park, ISSCC 2022 5.8 presentation

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02 | Air-gap Grid Example

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- Another air-gap grid technology is presented at IEDM 2022: two types for 0.7um and 0.64um pixel sensors

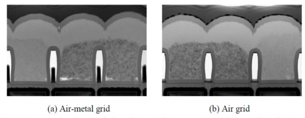

Fig. 6. Cross-sectional transmission electron microscopy (TEM) images of (a) the air-metal grid and (b) air grid.

✓ Air-metal grid for 0.7um pixel
✓ Air grid for 0.64um pixel

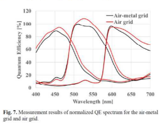

Fig. 7. Measurement results of normalized QE spectrum for the air-metal grid and air grid.

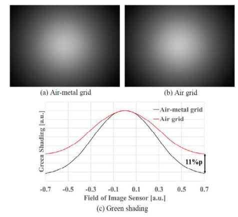

Fig. 8. Measurement results of (a, b) white image and (c) green shading for the air-metal grid and air grid.

* Images from H. Bak, "Advanced Color Filter Isolation Technology for Sub-Micron Pixel of CMOS Image Sensor," IEDM 2022

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02 | Evolution of Pixel Optic Structures: DTI

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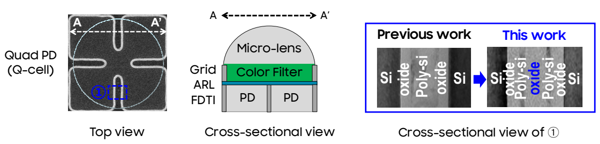
- Poly-Si used to suppress dark noise at DTI to photodiode interface by negatively bias it
- Optical loss from poly-Si gets larger as pixel scales, and introduction of quad PD (Q-cell) type
- New DTI structure made of "oxide / poly-Si / oxide / poly-Si / oxide" demonstrated improved sensitivity at 0.5um Q-cell type pixel



* Images from D. Kim, ISSCC 2024 6.10 presentation

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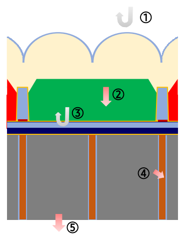
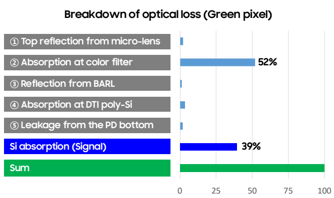
02 | Conventional Pixel Optics Performance Break-down

SAMSUNG

- Recent conventional pixel optics technology reached near-saturated sensitivity
- New approach to fight color filter optical loss would be the next breakthrough





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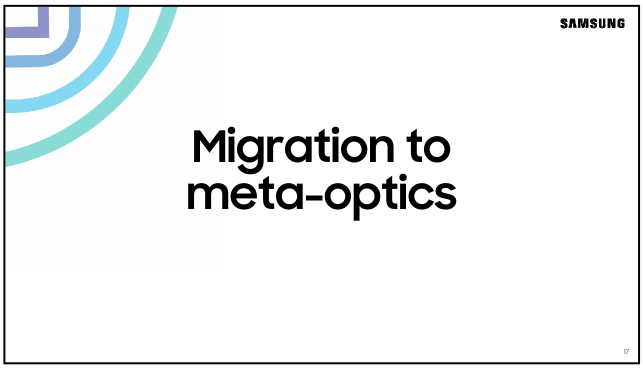
SAMSUNG
Migration to
meta-optics
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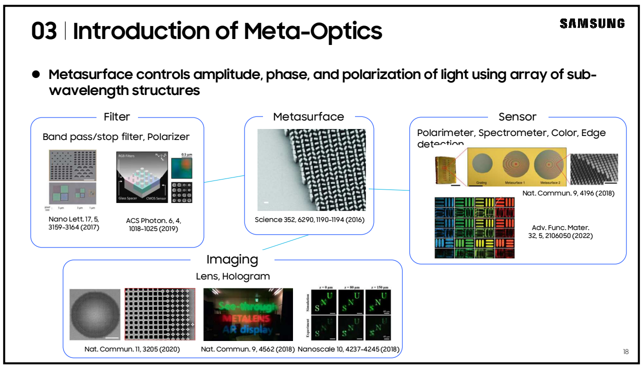
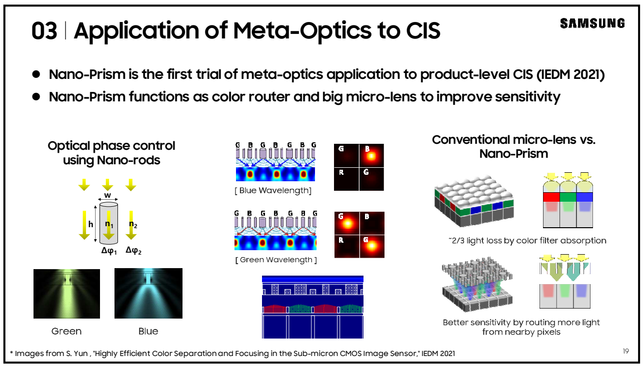

03 | Introduction of Meta-Optics
SAMSUNG
Metasurface controls amplitude, phase, and polarization of light using array of sub-wavelength structures
Filter
Band pass/stop filter, Polarizer
Nano Lett. 17, 5, 3159-3164 (2017)
ACS Photon. 6, 4, 1018-1025 (2019)
Metasurface
Science 352, 6290, 1190-1194 (2016)
Sensor
Polarimeter, Spectrometer, Color, Edge detection
Nat. Commun. 9, 4196 (2018)
Adv. Func. Mater. 32, 5, 2106050 (2022)
Imaging
Lens, Hologram
Nat. Commun. 11, 3205 (2020)
Nat. Commun. 9, 4562 (2018)
Nanoscale 10, 4237-4245 (2018)
18


03 | Application of Meta-Optics to CIS
SAMSUNG
Nano-Prism is the first trial of meta-optics application to product-level CIS (IEDM 2021)
Nano-Prism functions as color router and big micro-lens to improve sensitivity
Optical phase control using Nano-rods
Green
Blue
[Blue Wavelength]
[Green Wavelength]
Conventional micro-lens vs. Nano-Prism
*2/3 light loss by color filter absorption
Better sensitivity by routing more light from nearby pixels
* Images from S. Yun , "Highly Efficient Color Separation and Focusing in the Sub-micron CMOS Image Sensor," IEDM 2021
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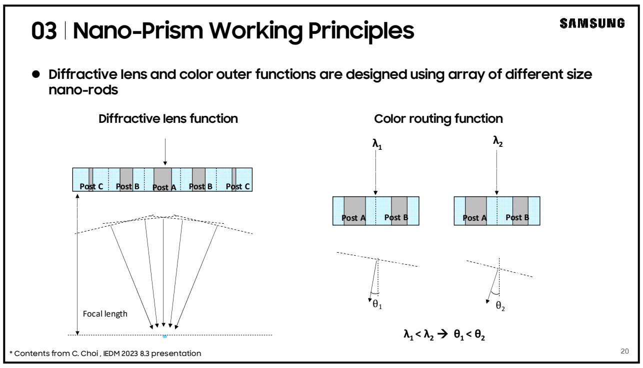
03 | Nano-Prism Working Principles
SAMSUNG
Diffractive lens and color outer functions are designed using array of different size nano-rods
Diffractive lens function
Post C
Post B
Post A
Post B
Post C
Focal length
Color routing function
Post A
Post B
Post A
Post B
λ1 < λ2 → θ1 < θ2
* Contents from C. Choi , IEDM 2023 8.3 presentation
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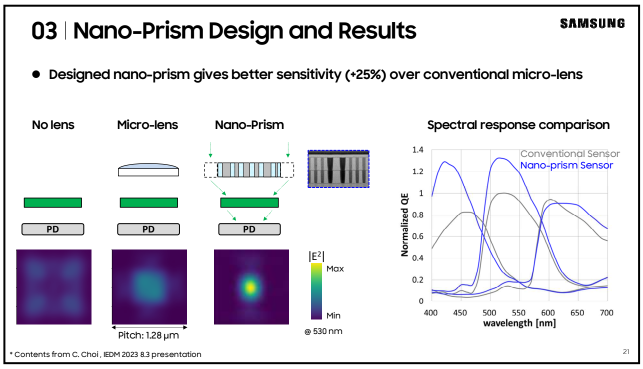
03 | Nano-Prism Design and Results
SAMSUNG
Designed nano-prism gives better sensitivity (+25%) over conventional micro-lens
No lens
Micro-lens
Nano-Prism
PD
PD
PD
Pitch: 1.28 μm
|E²|
Max
Min
@ 530 nm
Spectral response comparison
Conventional Sensor
Nano-prism Sensor
Normalized QE
wavelength [nm]
* Contents from C. Choi , IEDM 2023 8.3 presentation
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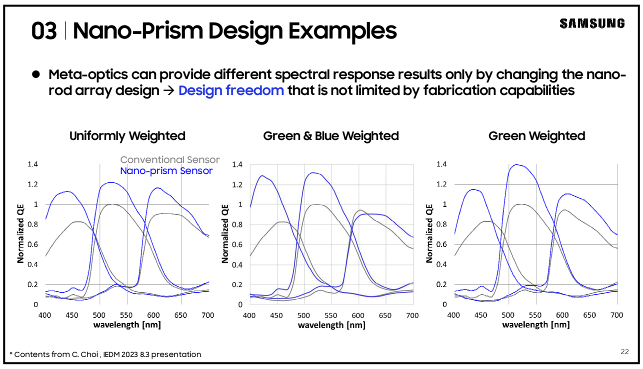
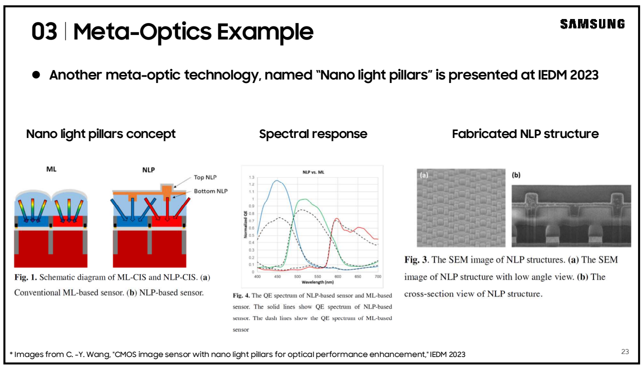

03 | Nano-Prism Design Examples
SAMSUNG
Meta-optics can provide different spectral response results only by changing the nano-rod array design → Design freedom that is not limited by fabrication capabilities
Uniformly Weighted
Green & Blue Weighted
Green Weighted
Conventional Sensor
Nano-prism Sensor
Normalized QE
wavelength [nm]
* Contents from C. Choi , IEDM 2023 8.3 presentation
22


03 | Meta-Optics Example
SAMSUNG
Another meta-optic technology, named "Nano light pillars" is presented at IEDM 2023
Nano light pillars concept
Spectral response
Fabricated NLP structure
Fig. 1. Schematic diagram of ML-CIS and NLP-CIS. (a) Conventional ML-based sensor. (b) NLP-based sensor.
Fig. 4. The QE spectrum of NLP-based sensor and ML-based sensor. The solid lines show QE spectrum of NLP-based sensor. The dash lines show the QE spectrum of ML-based sensor
Fig. 3. The SEM image of NLP structures. (a) The SEM image of NLP structure with low angle view. (b) The cross-section view of NLP structure.
* Images from C. -Y. Wang, "CMOS image sensor with nano light pillars for optical performance enhancement," IEDM 2023
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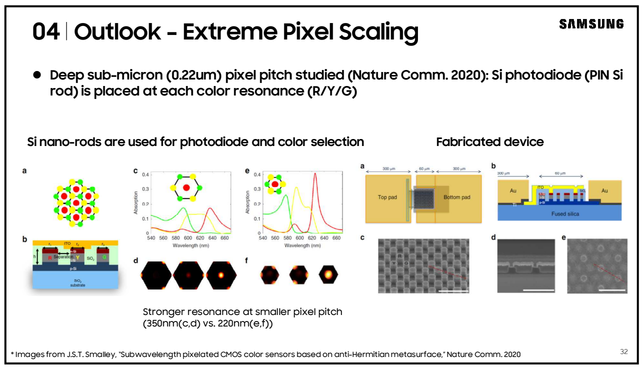
04 | Outlook - Extreme Pixel Scaling
SAMSUNG
Deep sub-micron (0.22um) pixel pitch studied (Nature Comm. 2020): Si photodiode (PIN Si rod) is placed at each color resonance (R/Y/G)
Si nano-rods are used for photodiode and color selection
Fabricated device
Stronger resonance at smaller pixel pitch (350nm(c,d) vs. 220nm(e,f))
* Images from J.S.T. Smalley, "Subwavelength pixelated CMOS color sensors based on anti-Hermitian metasurface," Nature Comm. 2020
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