CS 250
VLSI Design
Lecture 12 – CMOS Imagers

2012-10-2

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www-inst.eecs.berkeley.edu/~cs250/

CMOS imagers sensors are everywhere

2011

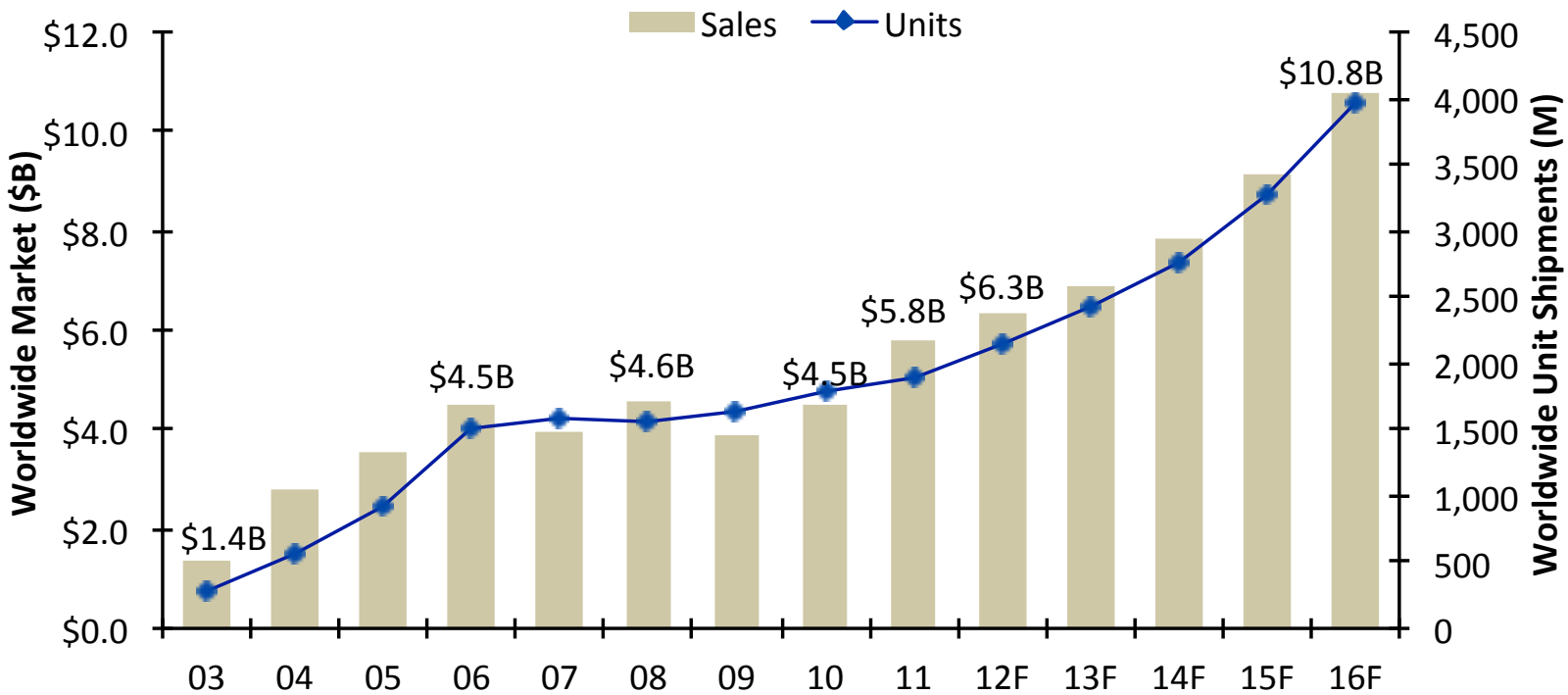
2.1B units

5.8B US $

2016 (F)

4B units

10.8B US $



Humans on earth: 6.9B

Year (F == forcast)

	2007	2008	2009	2010	2011	2012	2013	2014	2015
CCD sensors	235	215	195	185	180	175	165	149	138
CMOS sensors	971	1 194	1 338	1 501	1 704	1 939	2 235	2 520	2 893

Source: www.icinsights.com

iPhone 5
4.5 x 3.4 mm sensor.

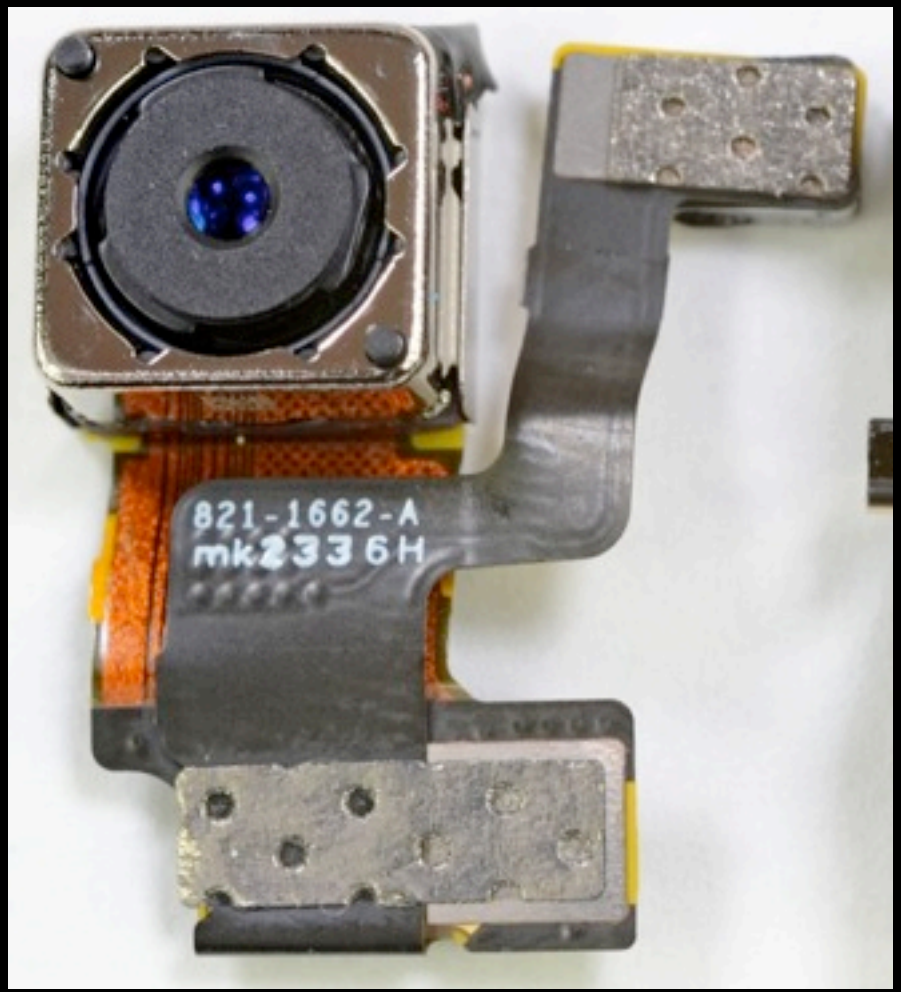
Canon 5D Mark III
36 x 24 mm sensor.

Six generations of iPhone camera

Cameras: 9% of the $199 Bill of Materials (BOM).

	Apple iPhone 5 (Pricing as of Sept, 2012)			
Components / Hardware Elements	iPhone 5 Hardware Comments	16GB3	32GB4	64GB5
Camera(s)	8MP + 1.2MP	$18.00	$18.00	$18.00

Source: IHS iSuppli Research, September 2012



Sony rear camera module

Omnivision camera

2006: One year before iPhone


Source: www.brighthand.com

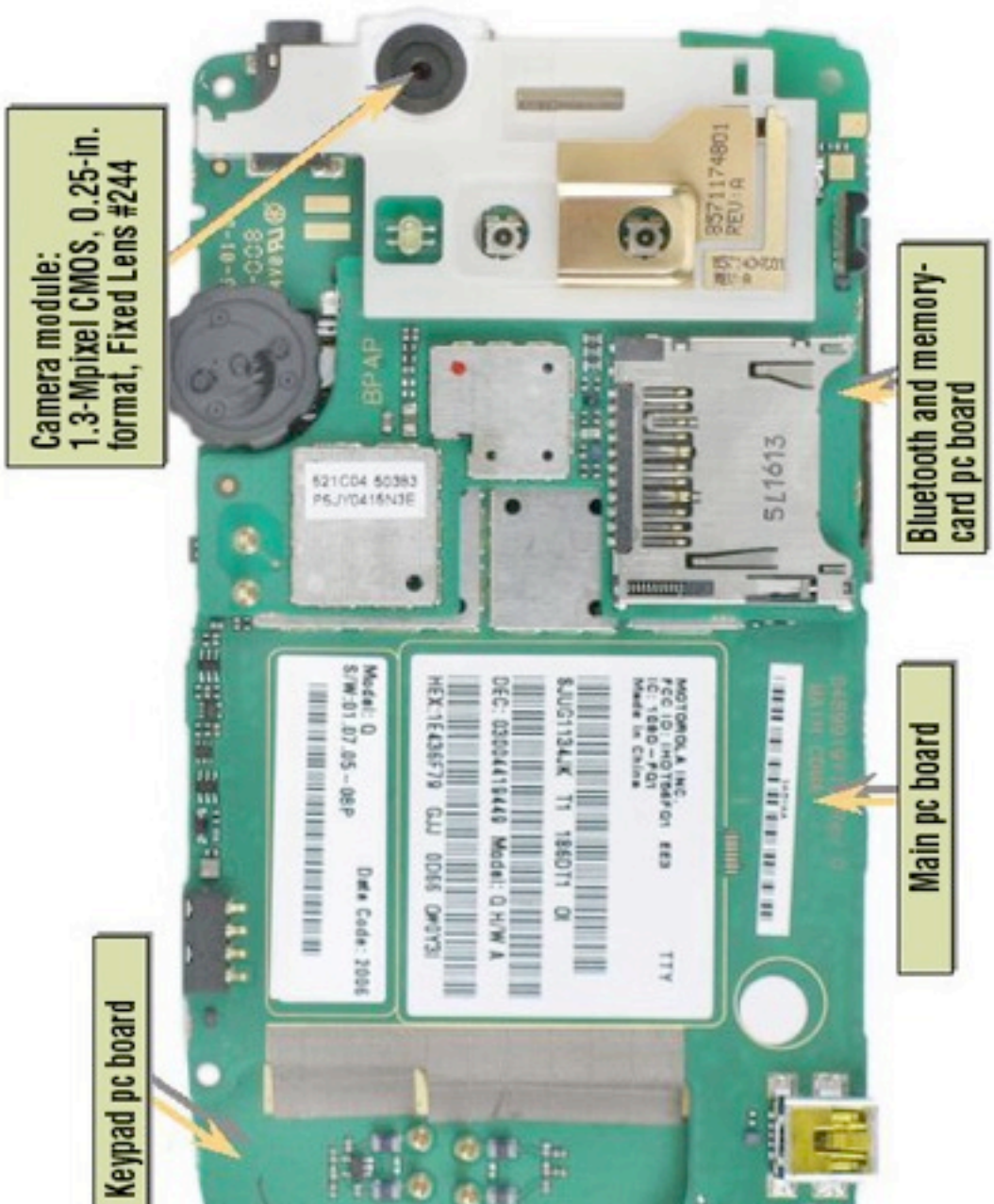

0.45 inches
50% thicker than iPhone 5
Motorola Q
Smart
Phone
Moto predicted 3M
shipped Q4 2006.
Source: www.elecdesign.com

CMOS Camera Sensor | Micron | MT9M111

Source: iSuppli Corp. July 2006

Camera module cost: $7

↓↓↓ **4.4% of $158 BOM.** ↓↓↓



Typical camera module for the Micron MT9M111

Fixed-focus lens.
No "optical" zoom.

0.27 inches deep.

0.37 inch x 0.37 inch square

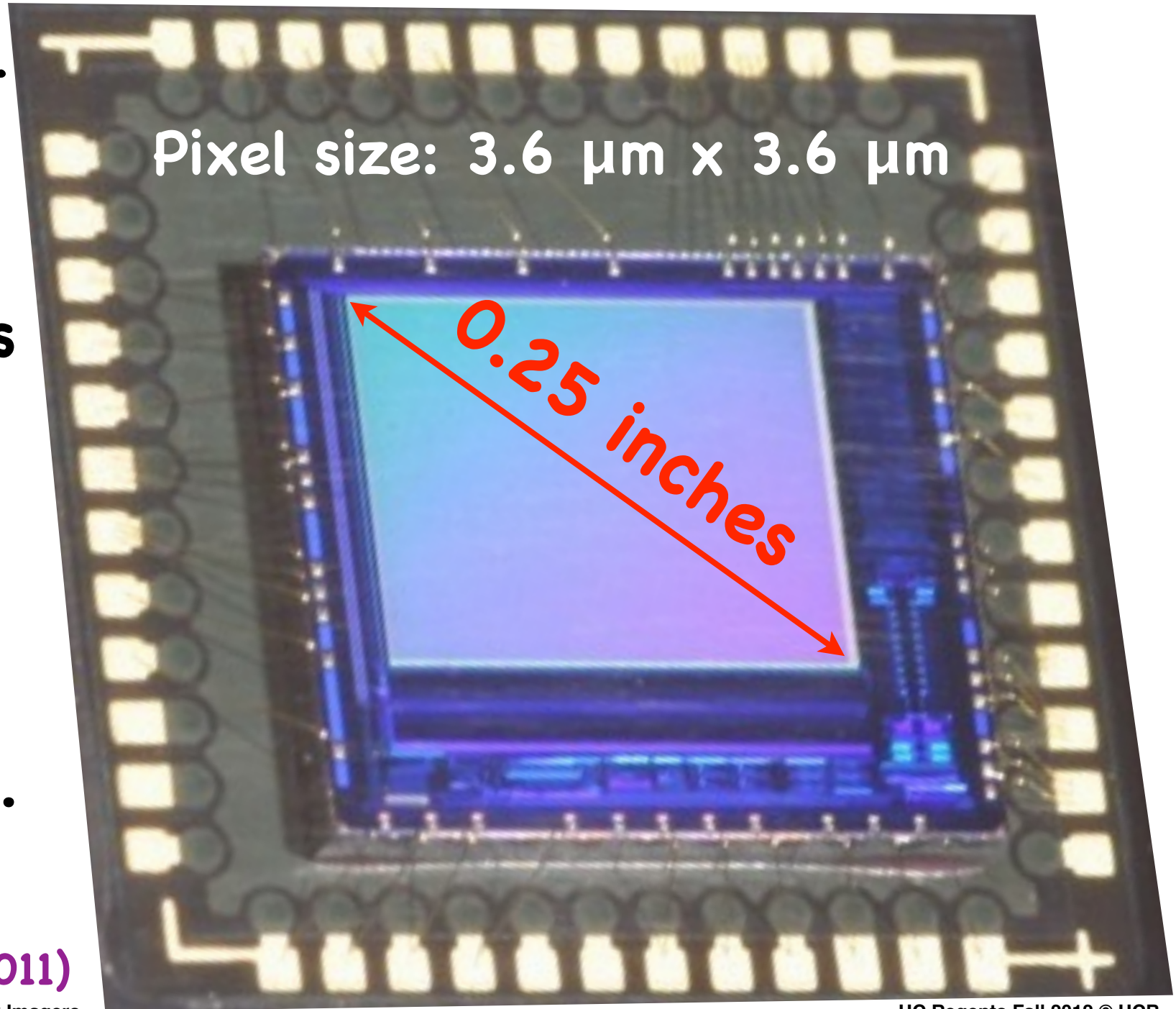
Source: www.asia-optical.com.tw

Micron MT9M111* – 1.3 MPixel CMOS Imager

1280 x 1024 pixels.

Each pixel is R, G, or B. So, 2/3 of RGB image data is interpolated.

* Photo a close relative (MT9M011)



Camera interface to the outside world

Simple Power Hookup

Serial port to control the camera.

8-bit D_{out} Port
54 MHz Clk

1280 x 1024
@ 15 fps

640 x 512
@ 30 fps

YCrCb 4:2:2

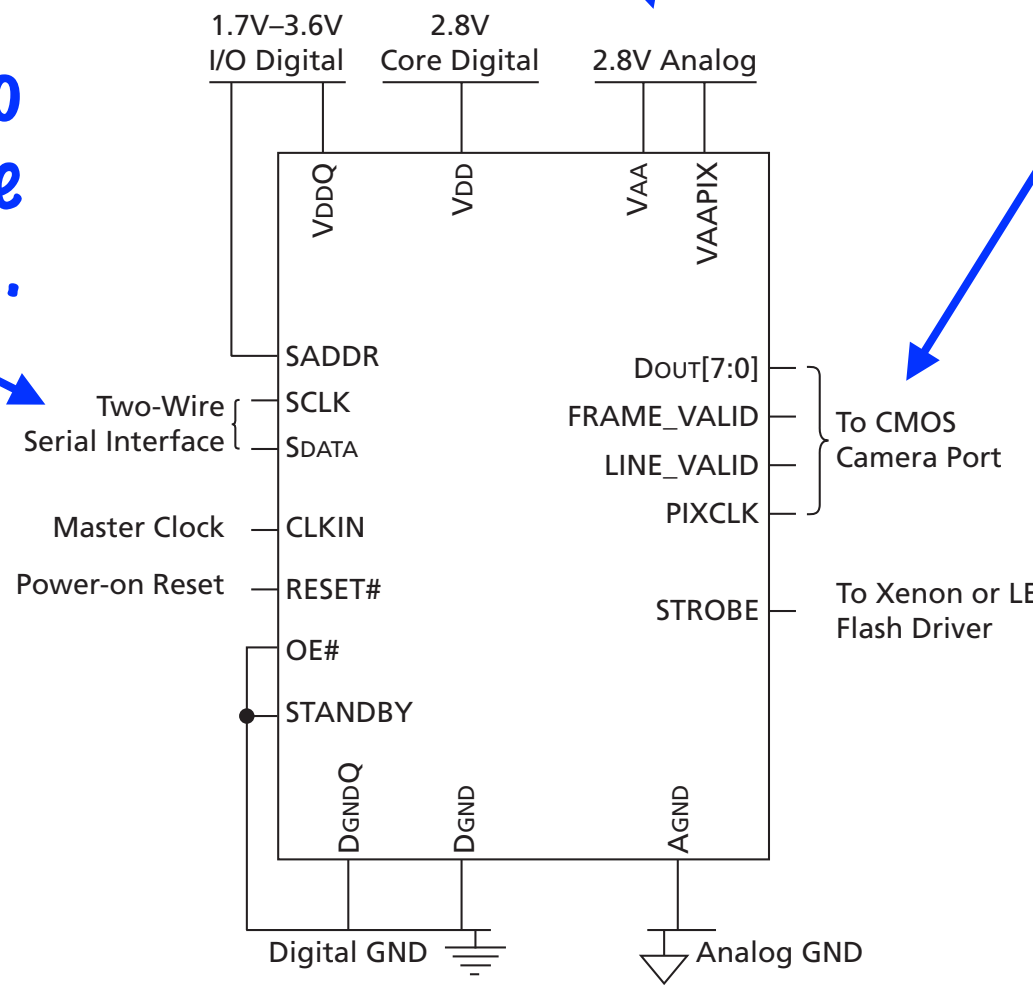
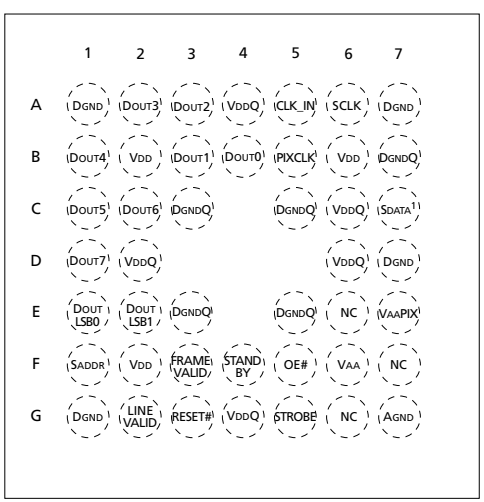
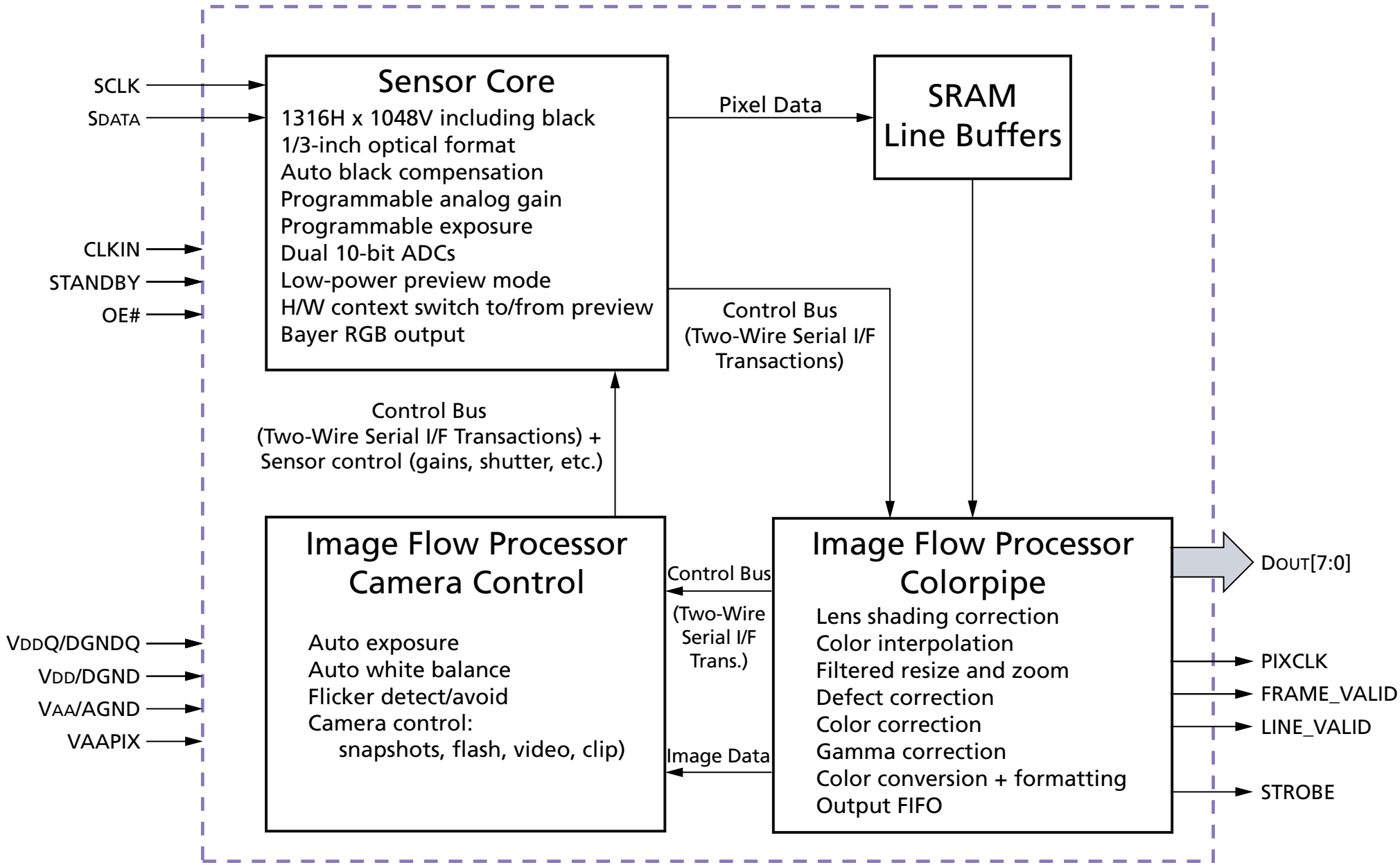


Figure 4: 44-Ball iCSP Assignment



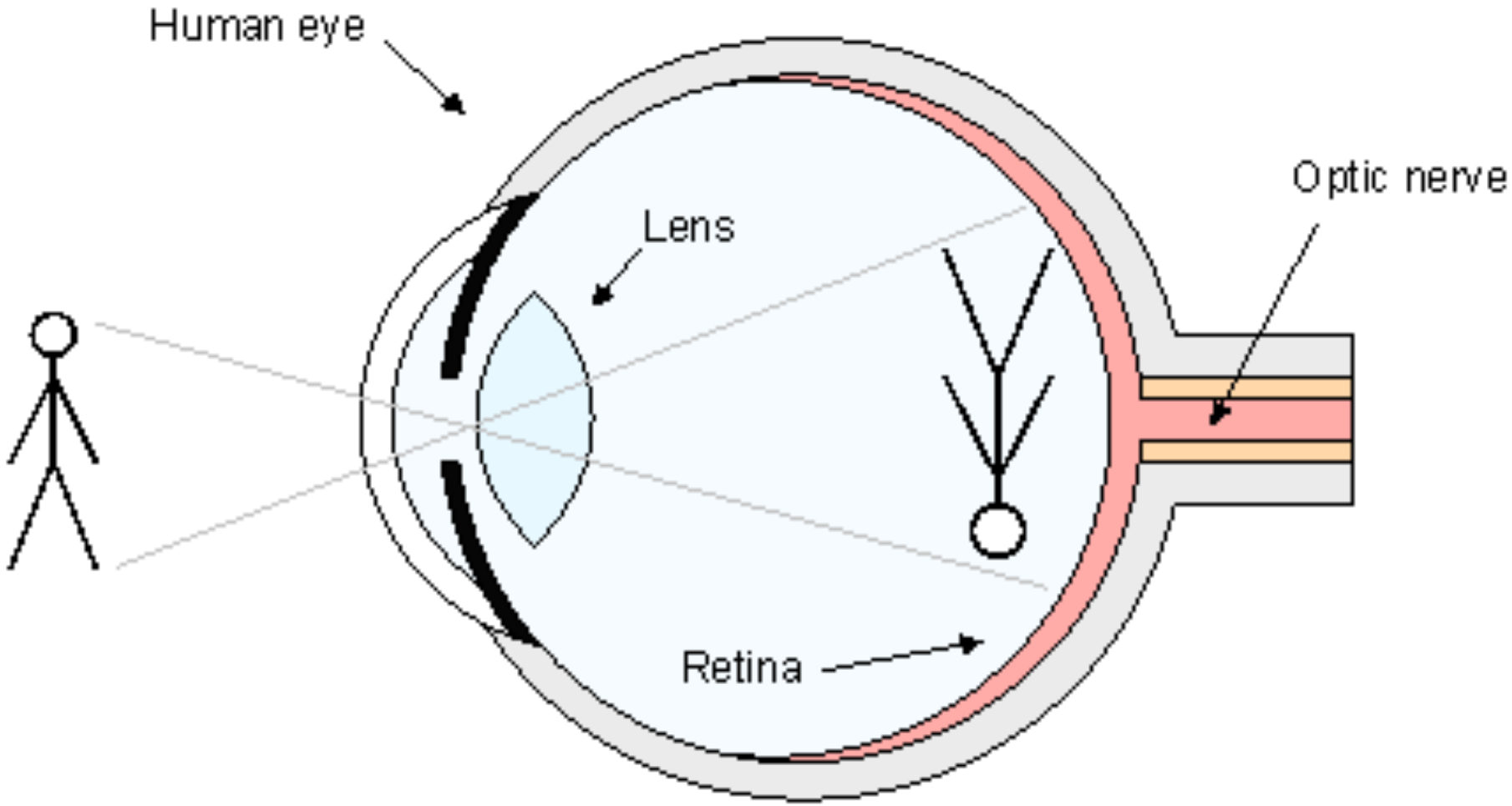
Top View
(Ball Down)

Functional Block Diagram



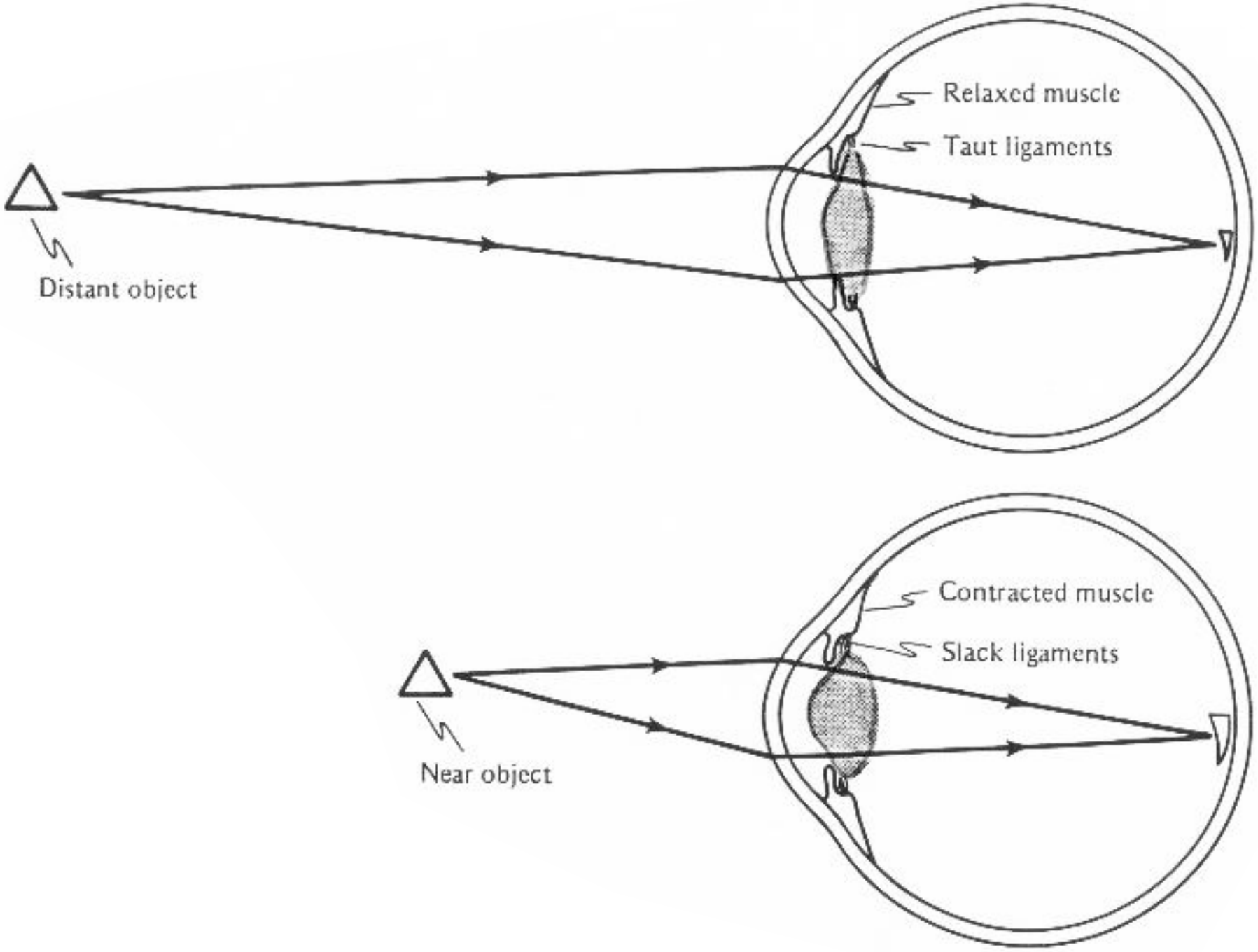
Focusing the Camera

Focus: The Basics

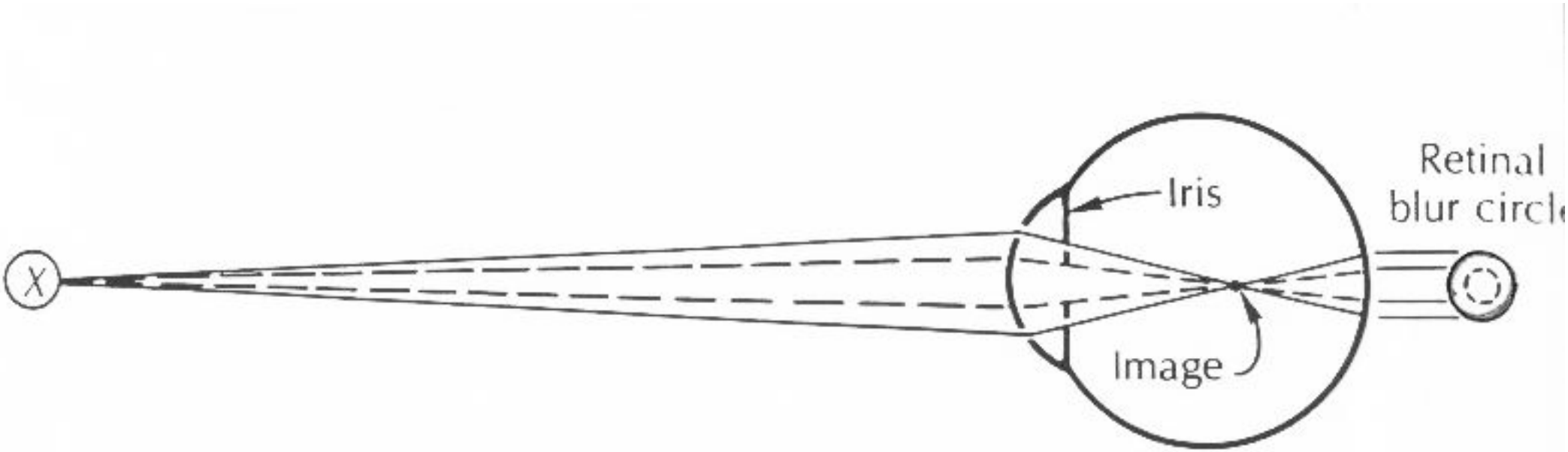


Images are inverted on their way to the retina at the back of the eye

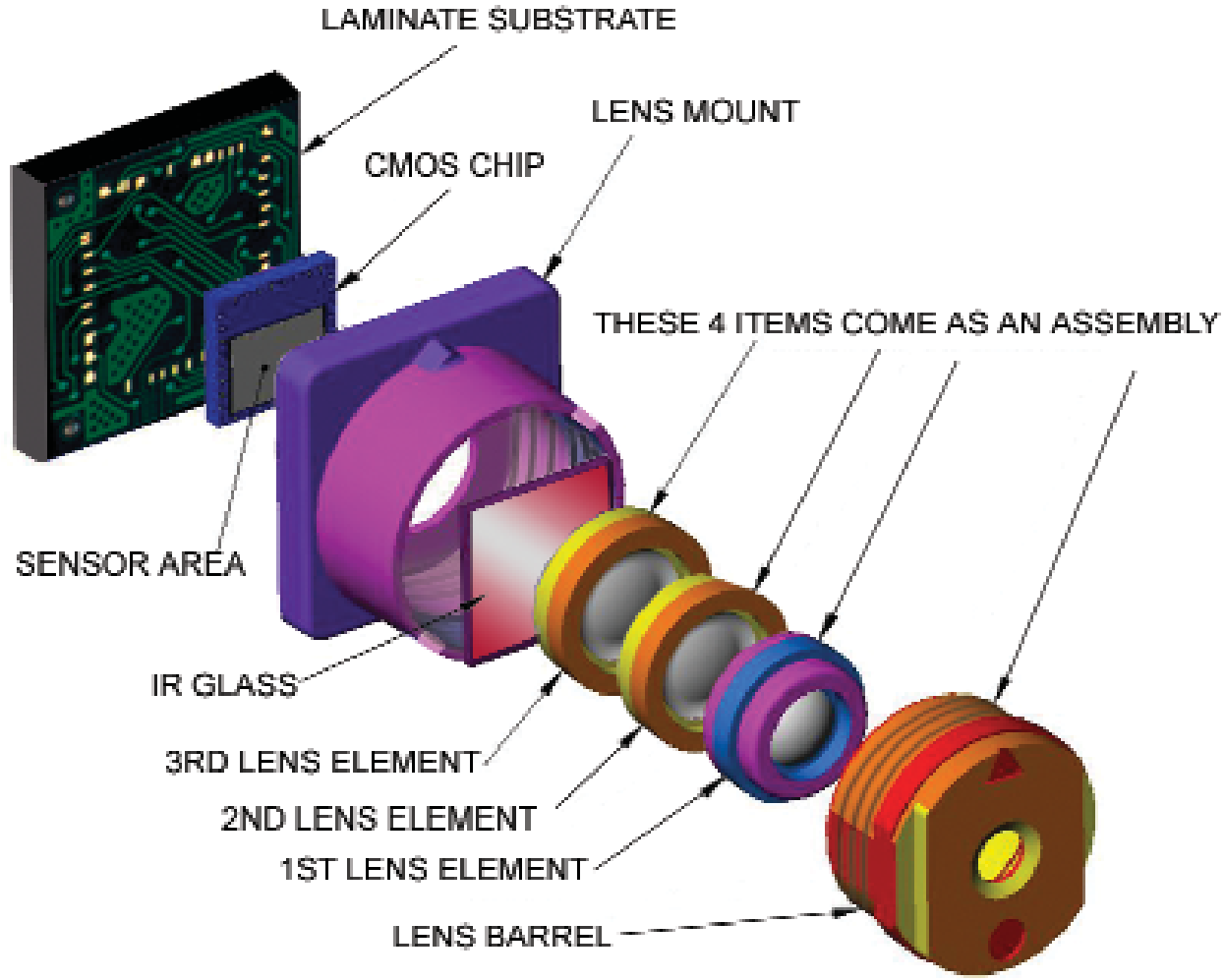
Variable focus



Out of focus



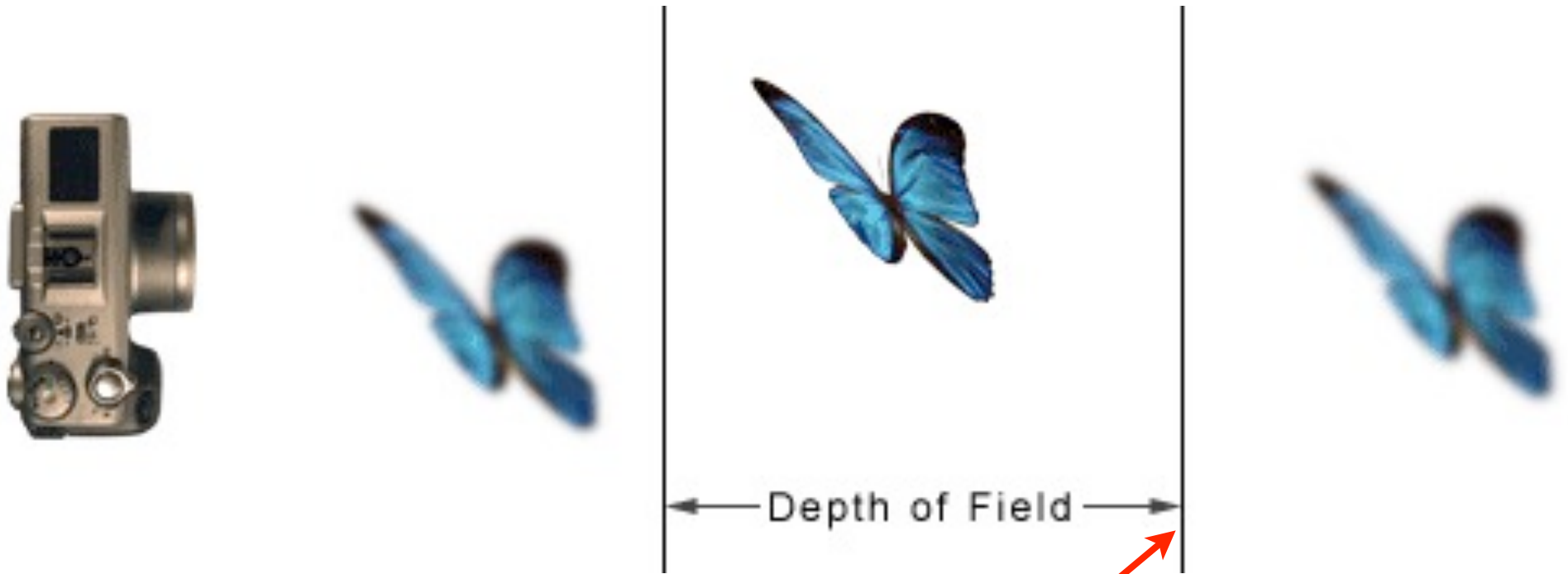
Fixed focus camera module.



Camera Module Exploded View

Fixed-focus: What do we give up?

Camera is only in focus for objects within the depth of field: other objects are blurry.

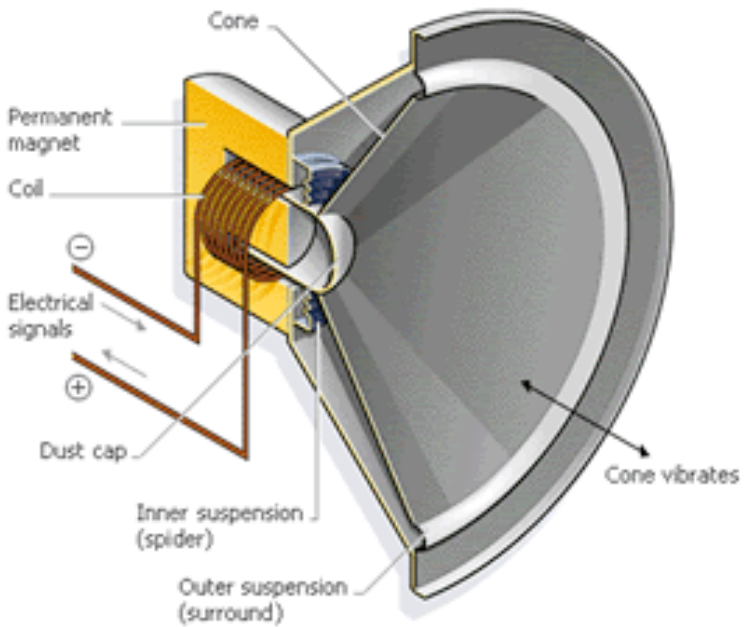


However, we can set the "far" boundary to "infinity". Fixed-focus cameras do.


Best we can do with
a fixed-focus camera.

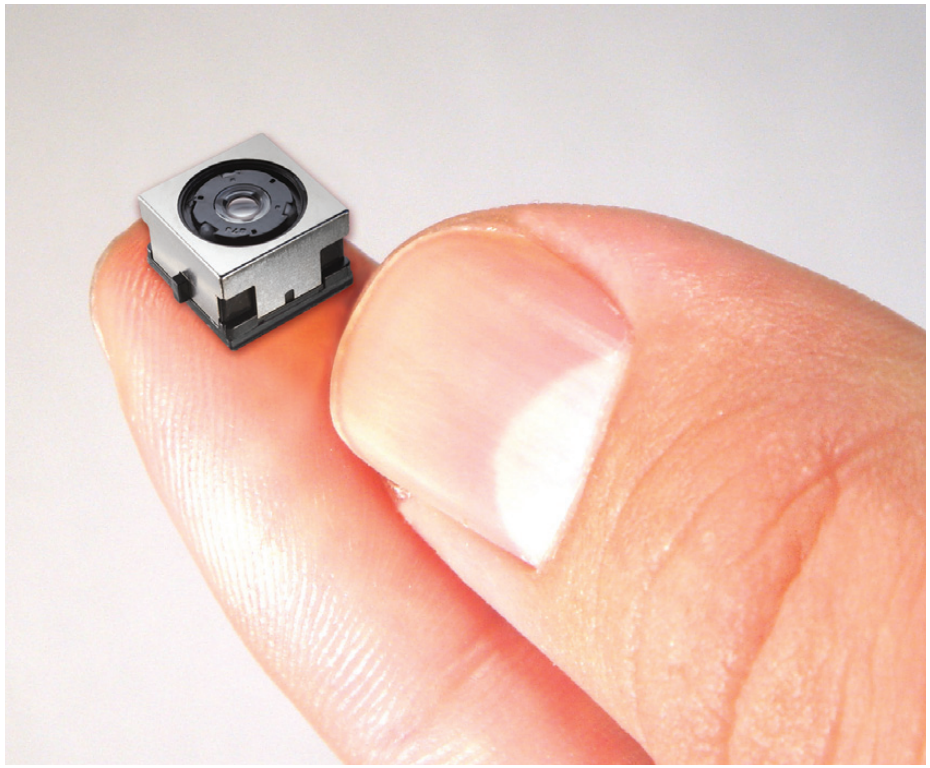
Auto-Focus Module in iPhone 5

"Voice Coil" solenoid → moves lens element.



Works like a loudspeaker …

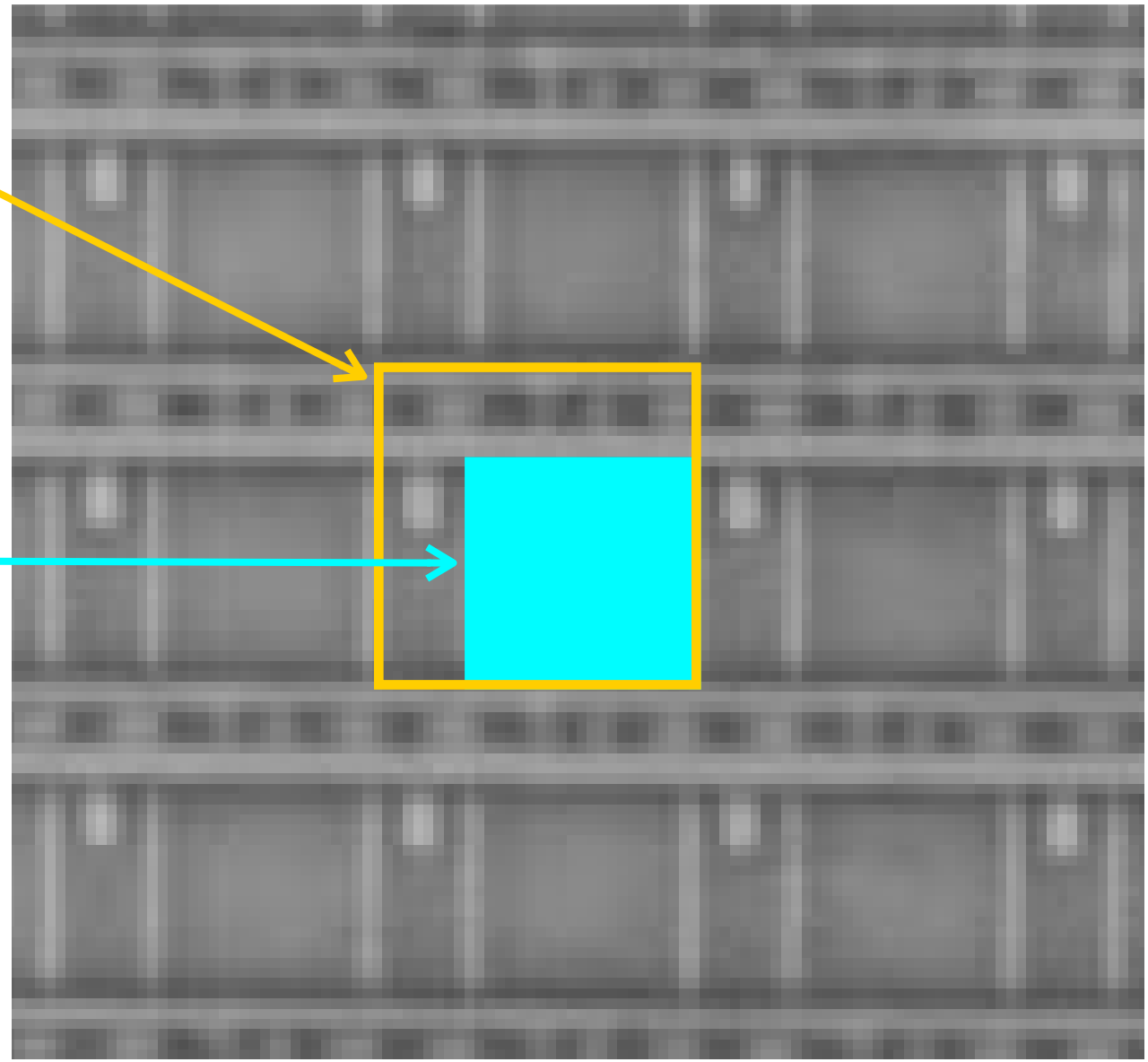
Coming soon: MEMS auto-focus



MEMS Autofocus Module

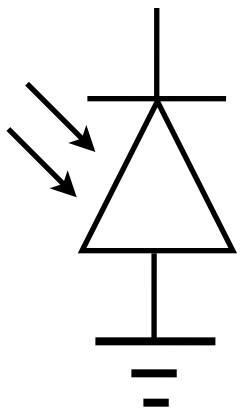
Silicon Photosensitivity

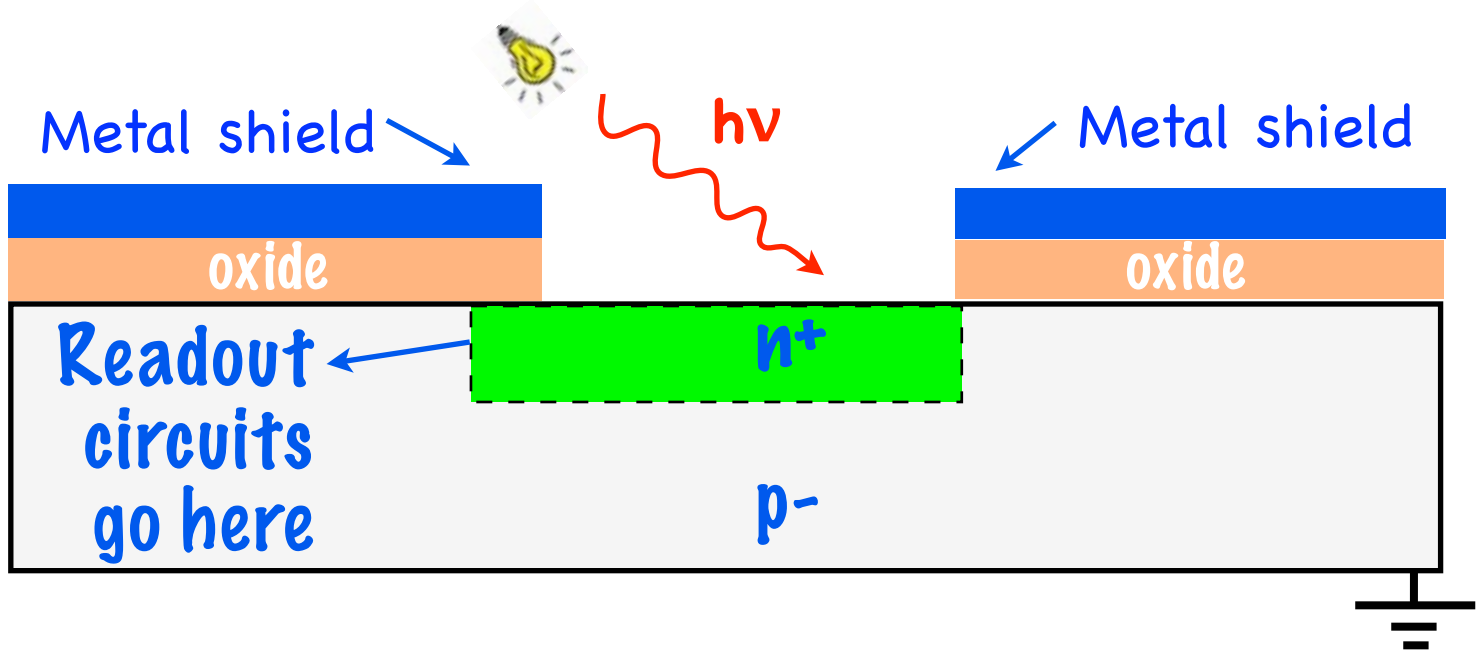
Zooming in on the array ...



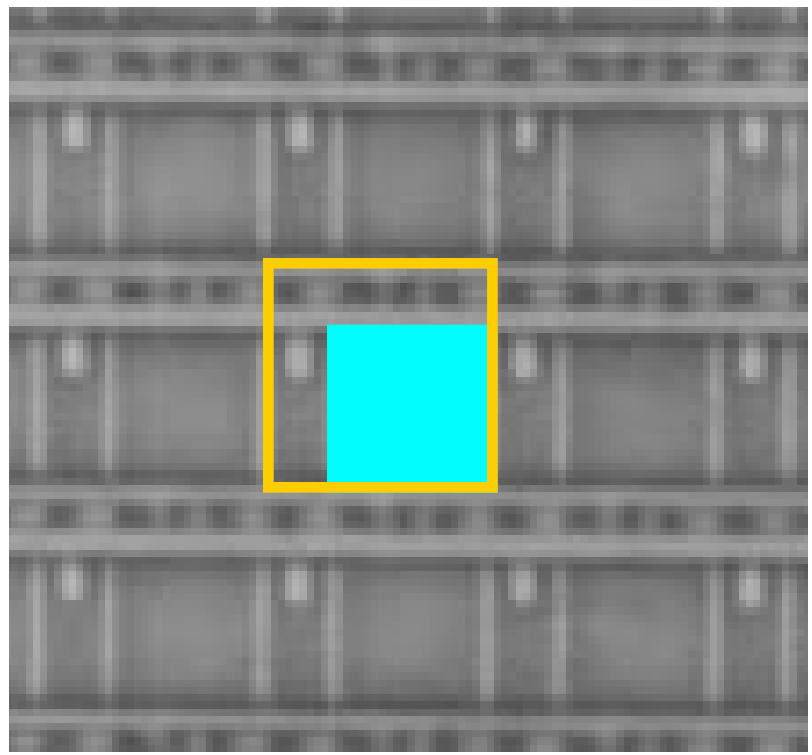
Each sensor is a photodiode

Side view:

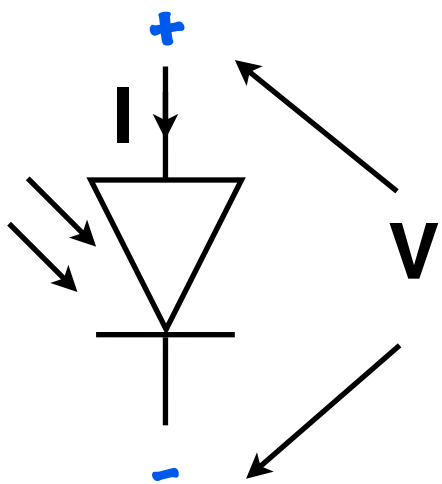


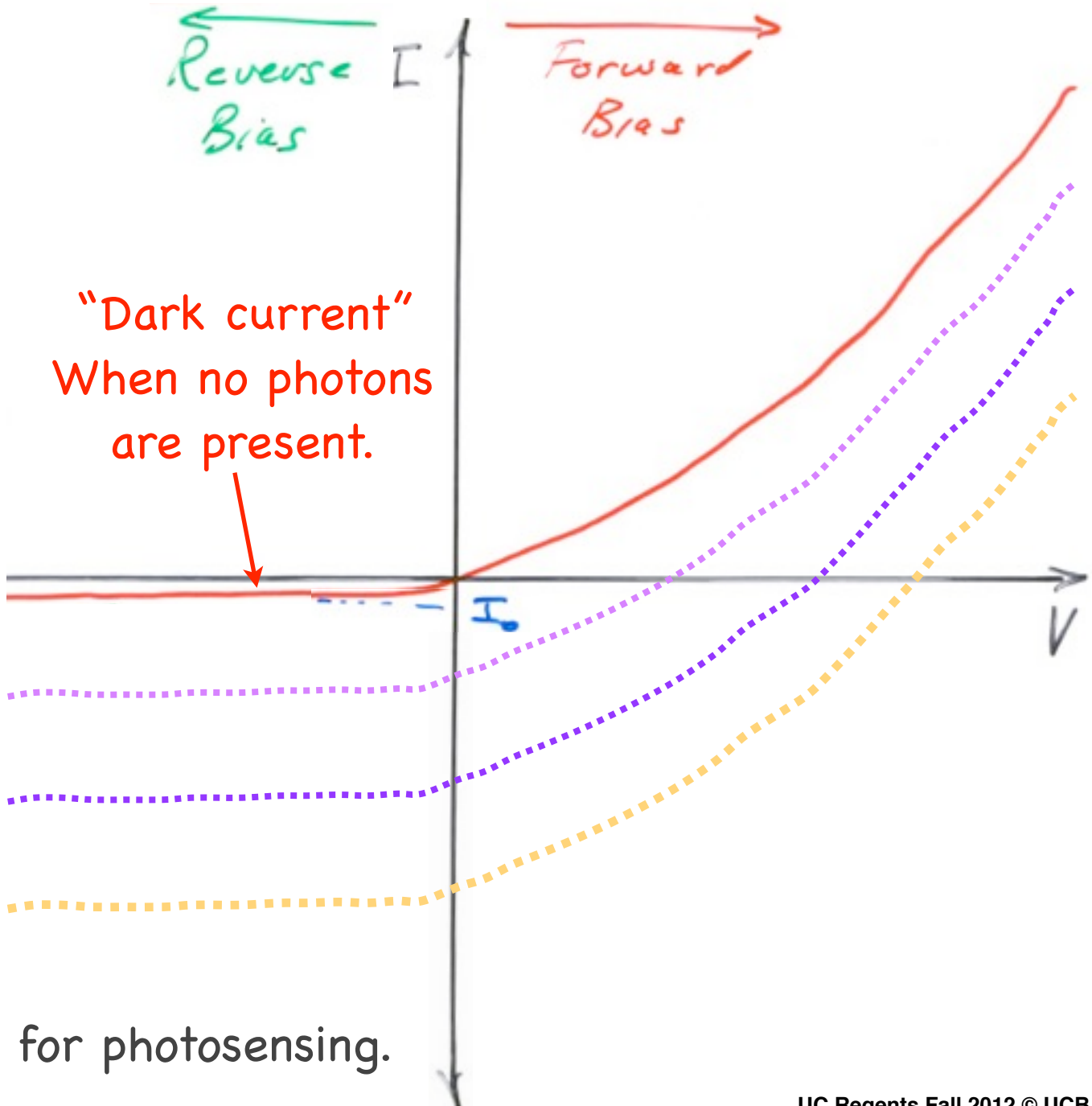


Top view:



Photodiode: Like a normal diode ...



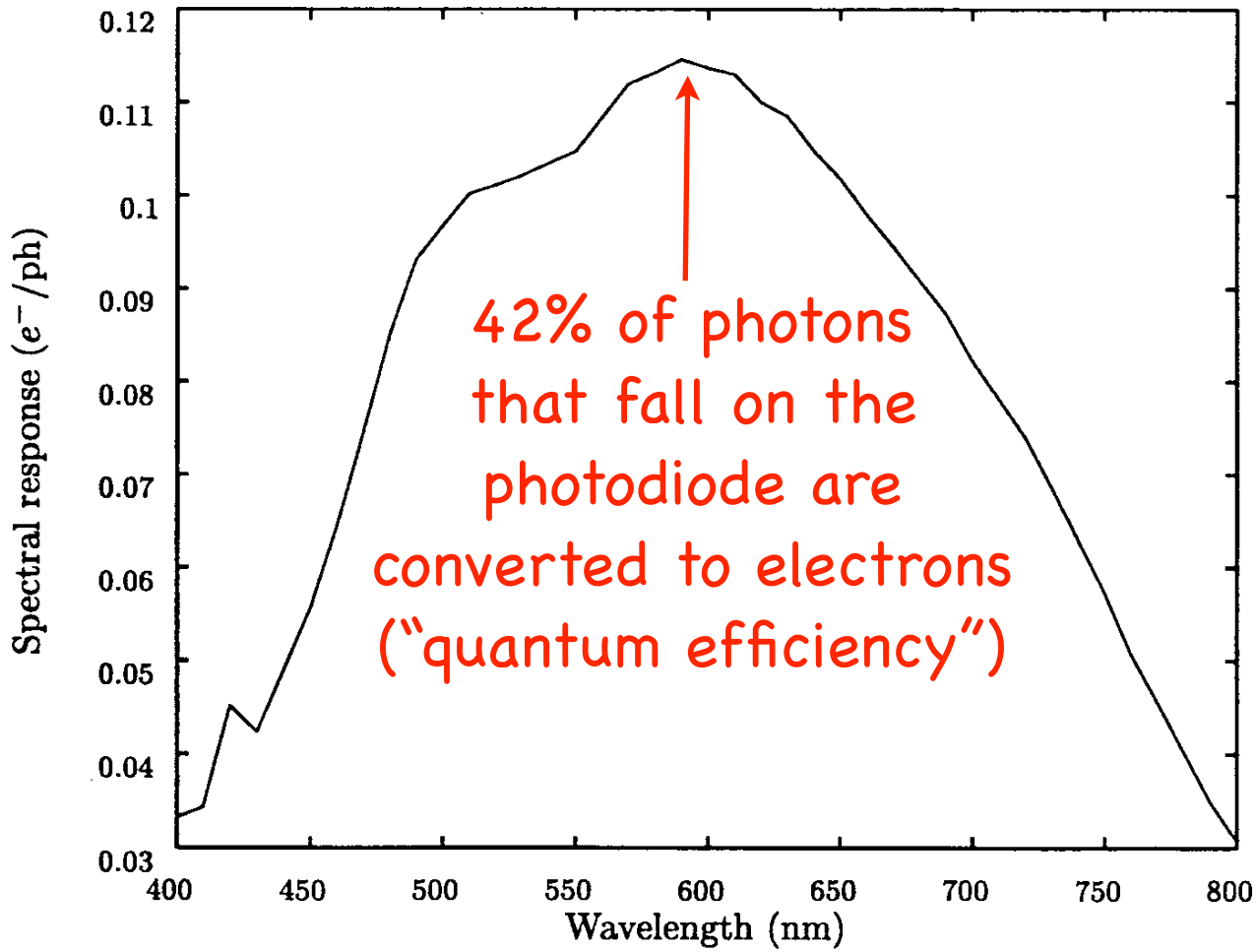


Quadrant for photosensing.

Photodiodes see a gray world ...

Data shown is for a standard 0.35μ CMOS logic process.

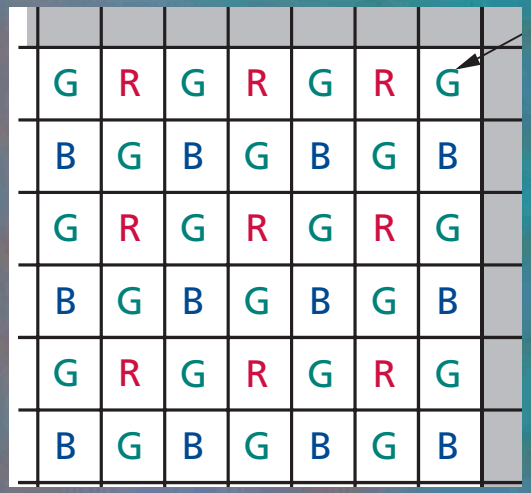
Quantum efficiency can be improved by modifying the process.



Source: "A 640 512 CMOS Image Sensor with Ultrawide Dynamic Range Floating-Point Pixel-Level ADC", David X. D. Yang, Abbas El Gamal, Boyd Fowler, and Hui Tian, JSSC, Dec 1999.

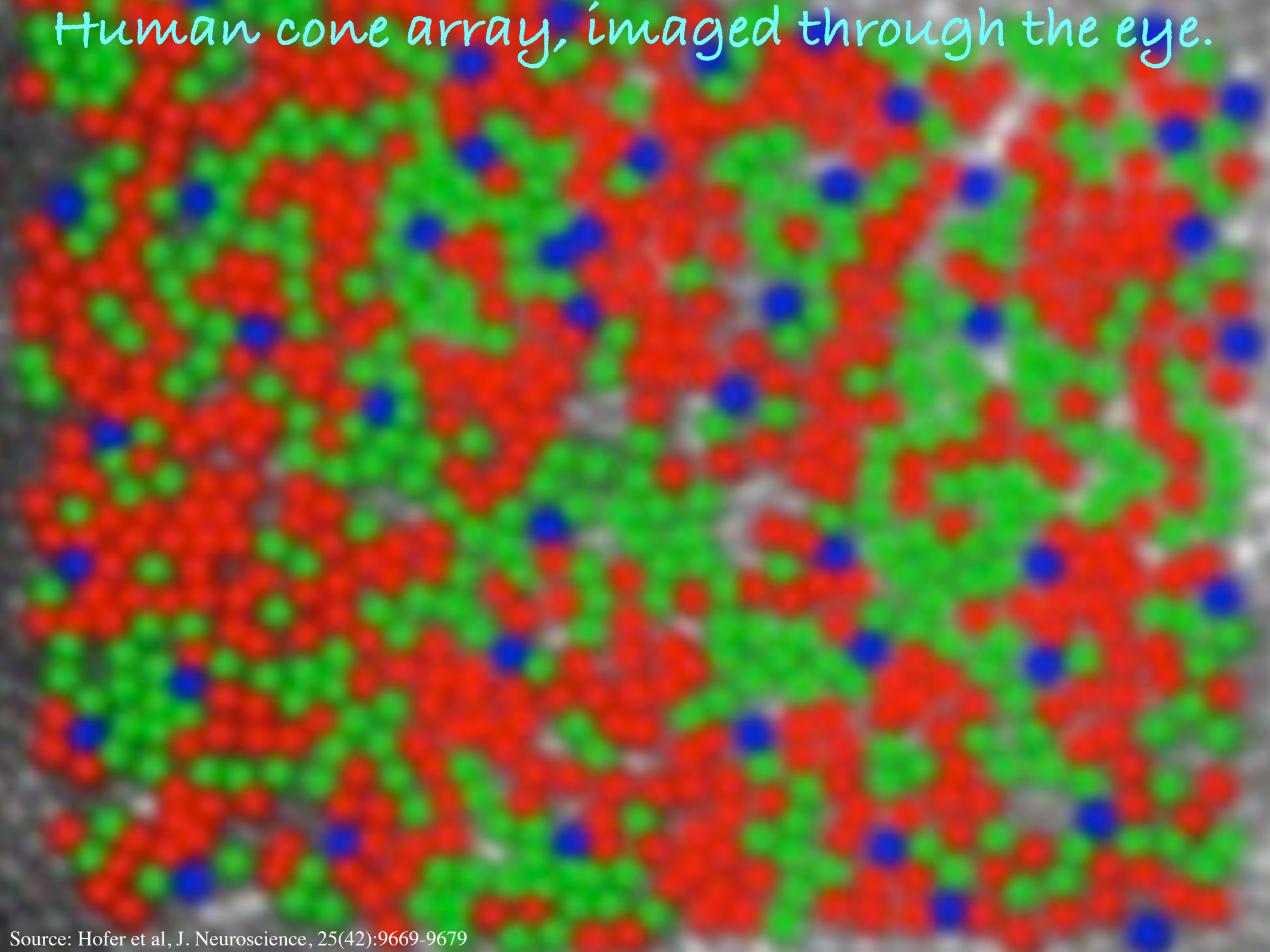
Color

Color filters deposited on pixel array



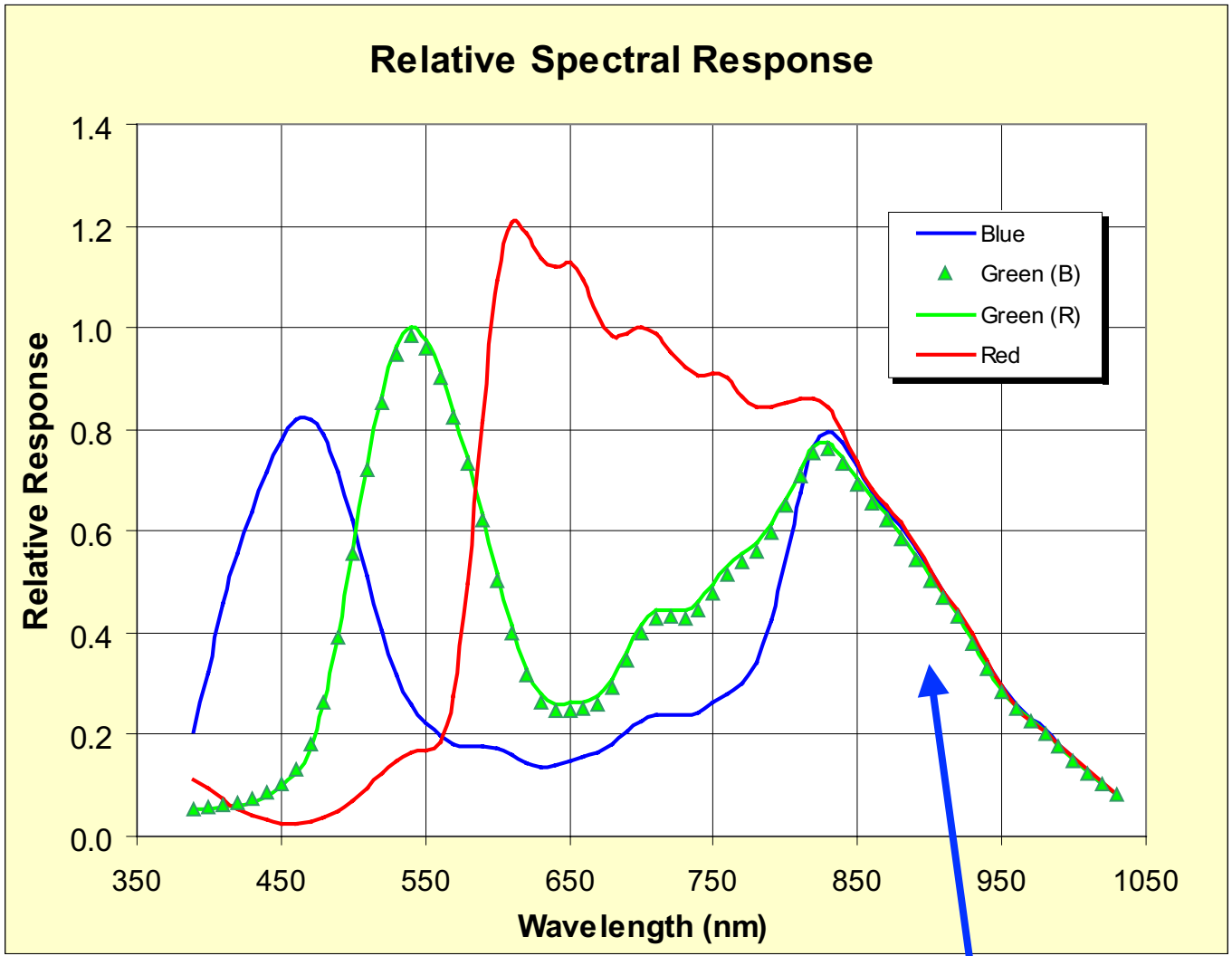
"RGB Bayer" Why?

Source: Eric Fossum, IEEE Micro, and Micron Data Sheets



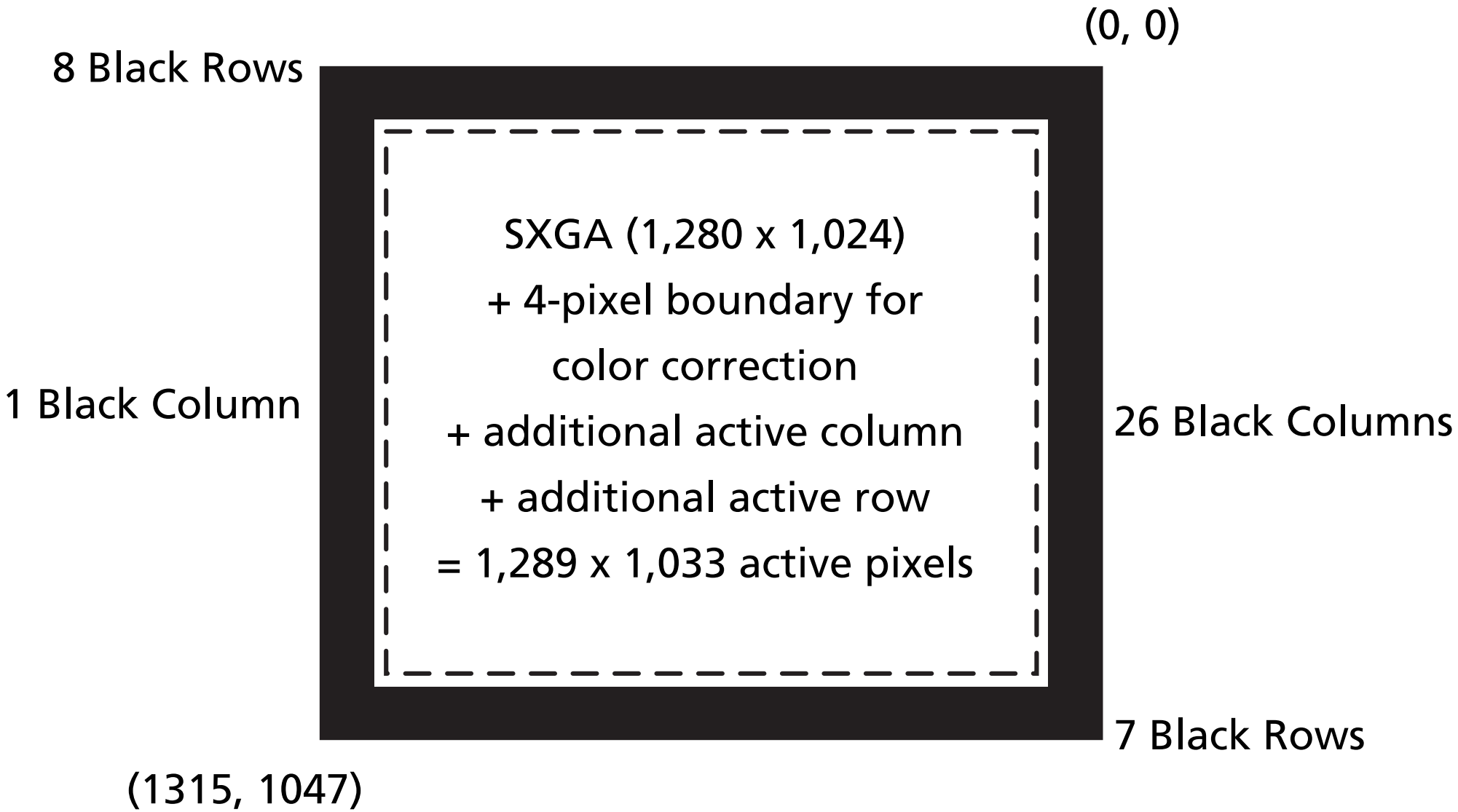
Source: Hofer et al, J. Neuroscience, 25(42):9669-9679

Micron MT9M111 spectral response ...



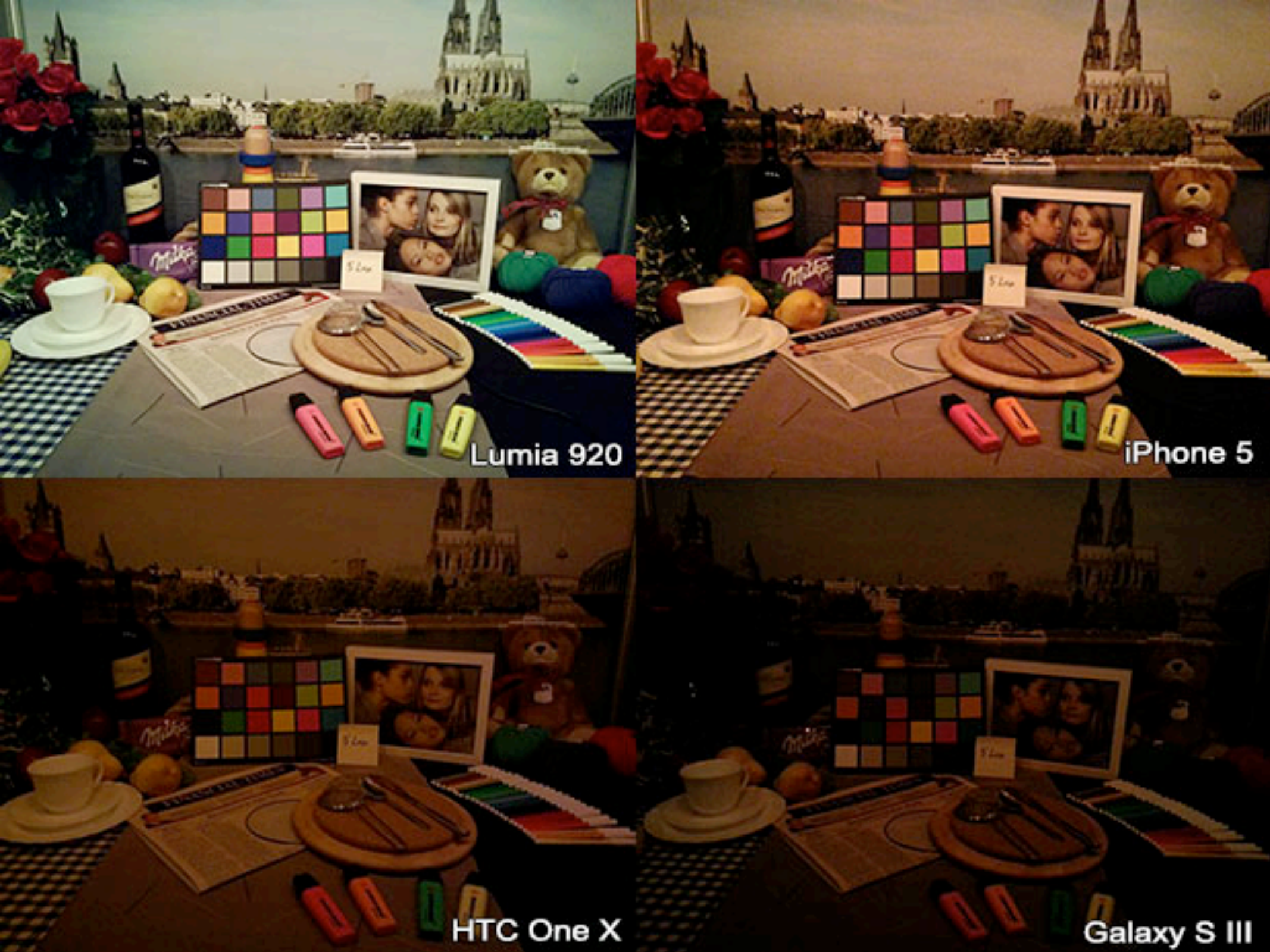
Note IR response. This is why camera module needs an IR filter.

Array border cells aid calibration ...



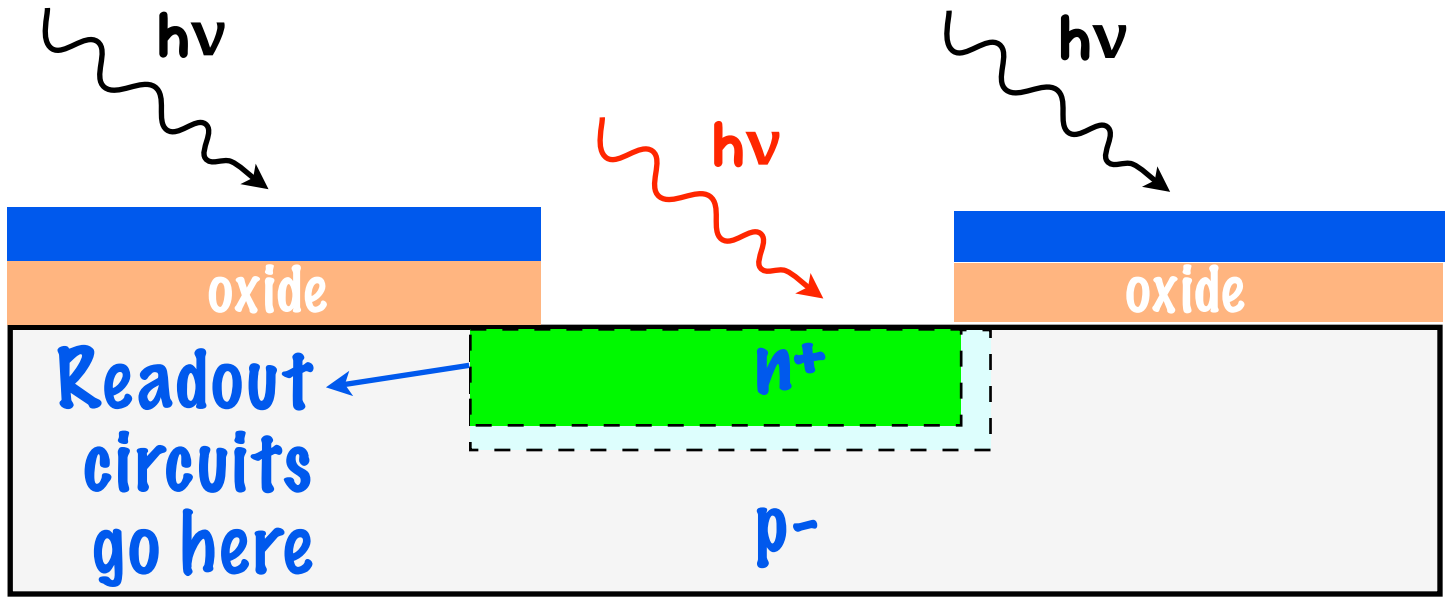
Black pixels have photodiodes covered by metal.

Microlenses

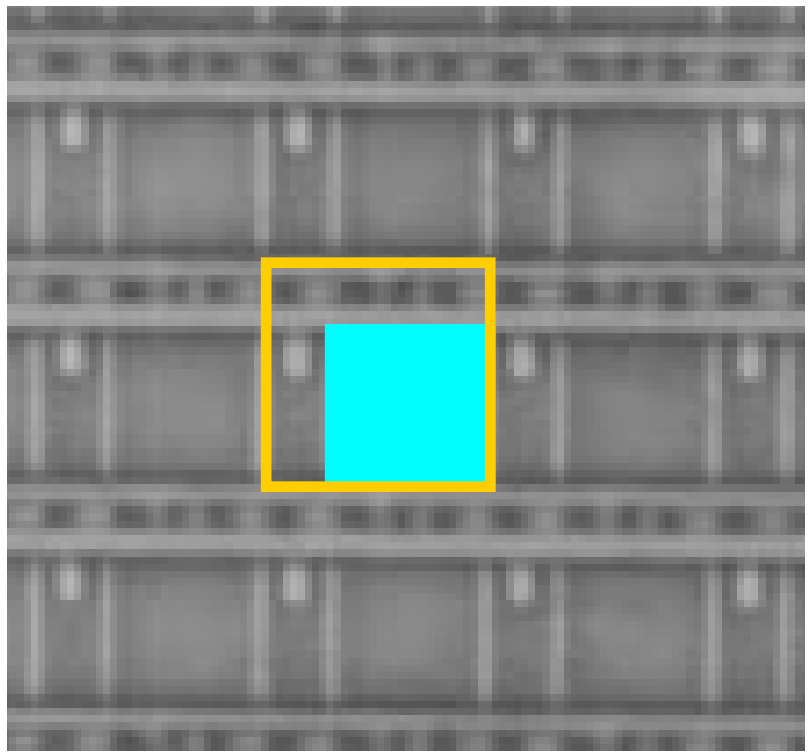

Lumia 920
iPhone 5
HTC One X
Galaxy S III

Recall: Side view of a photodiode ...

Photons that reflect off metal shielding are lost.

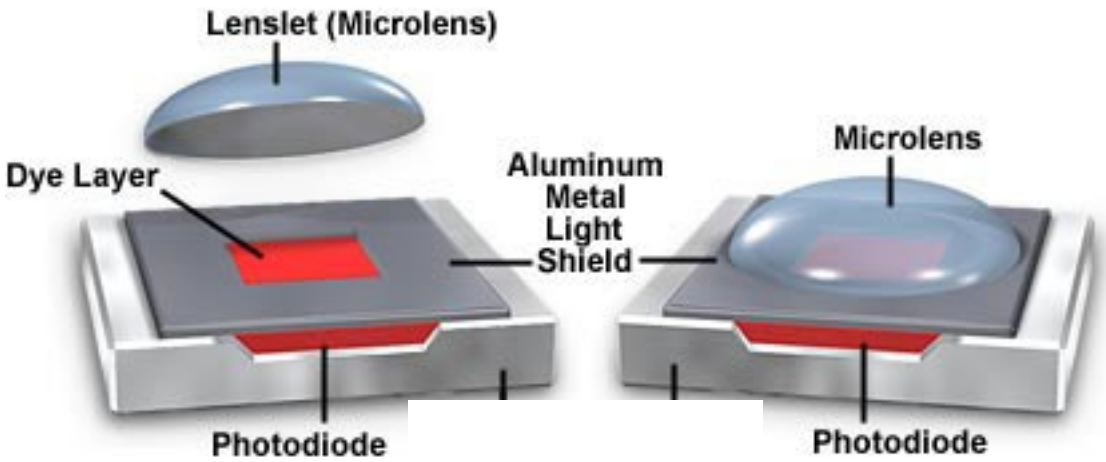


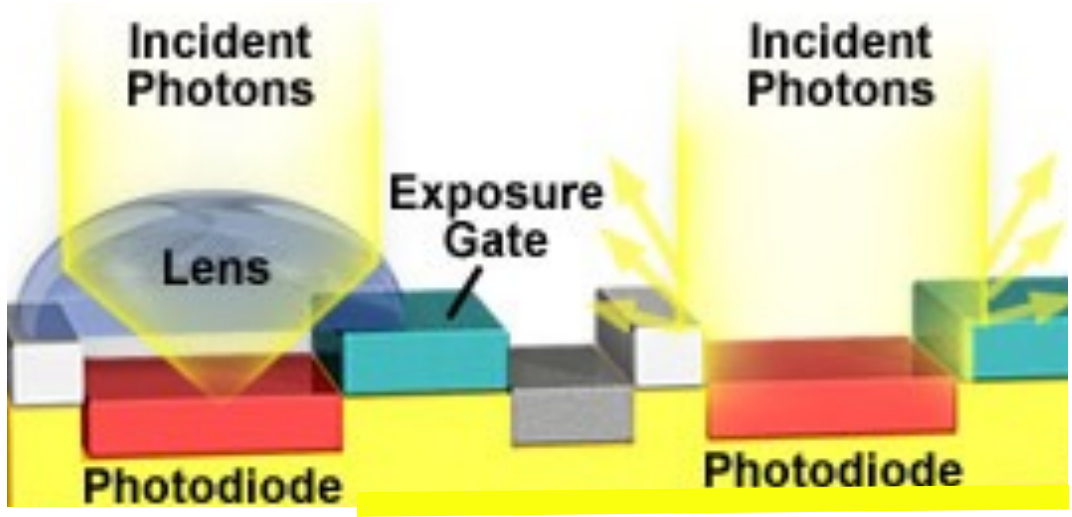
If there was a way to sense the photons that bounce off the metal, low-light photos would look better.

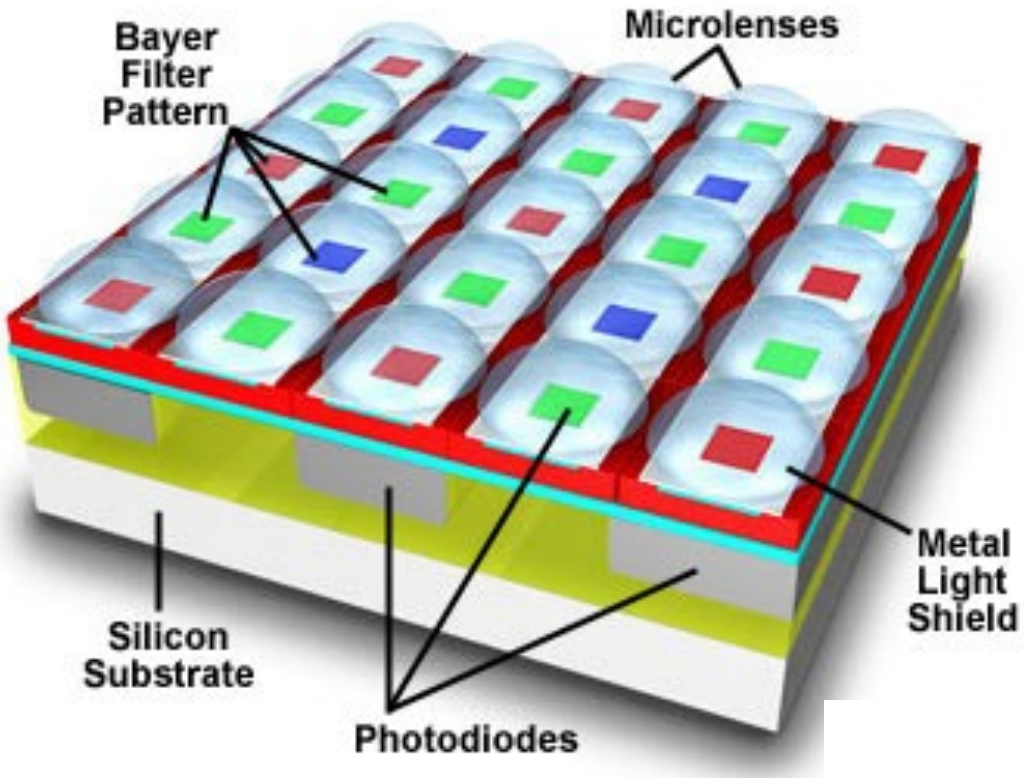


"Compound eyes" of an insect – "microlenses"

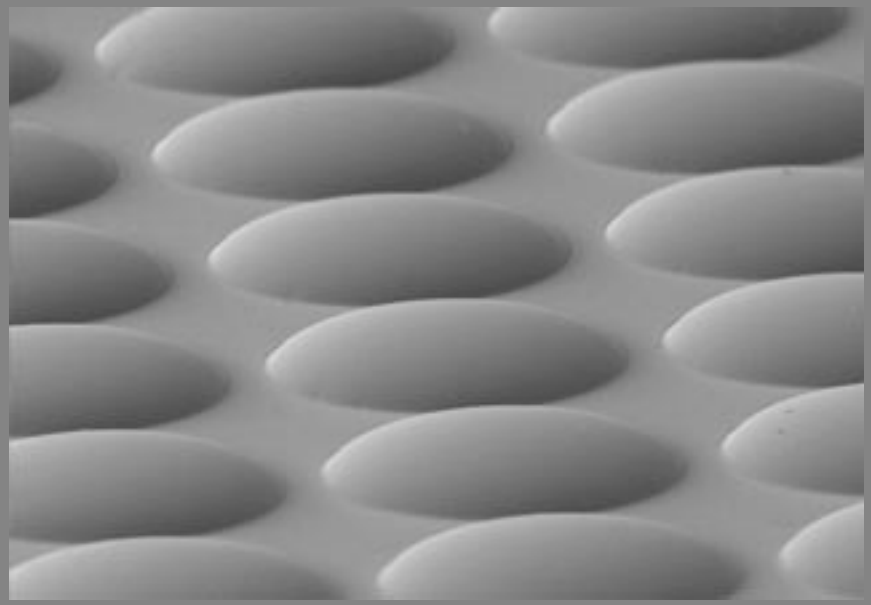
Source: www.bioschool.co.uk, BBC

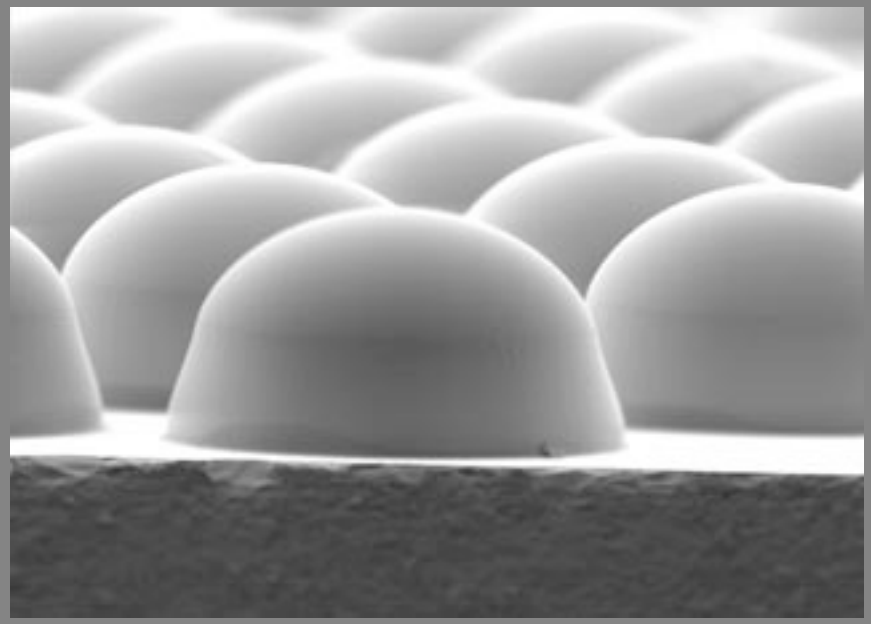


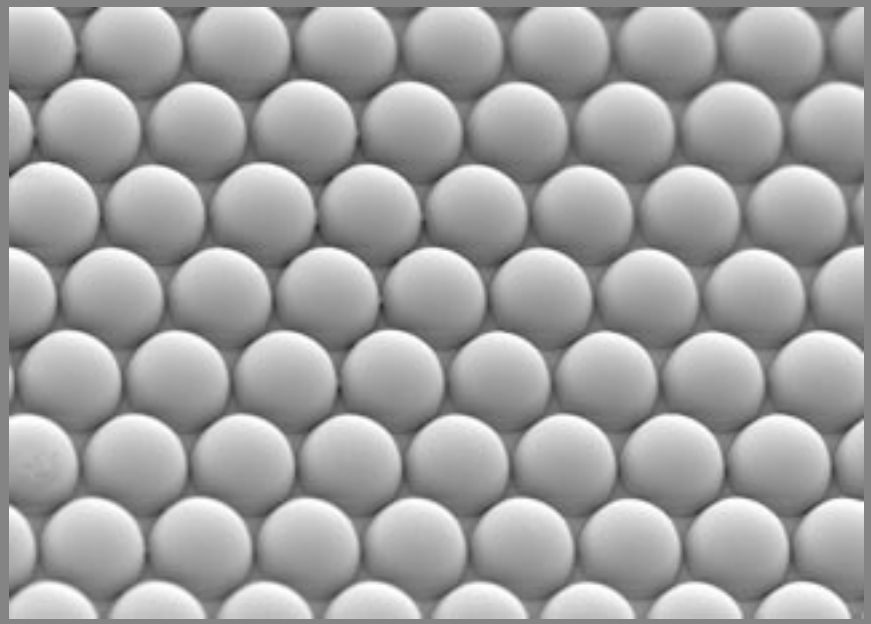


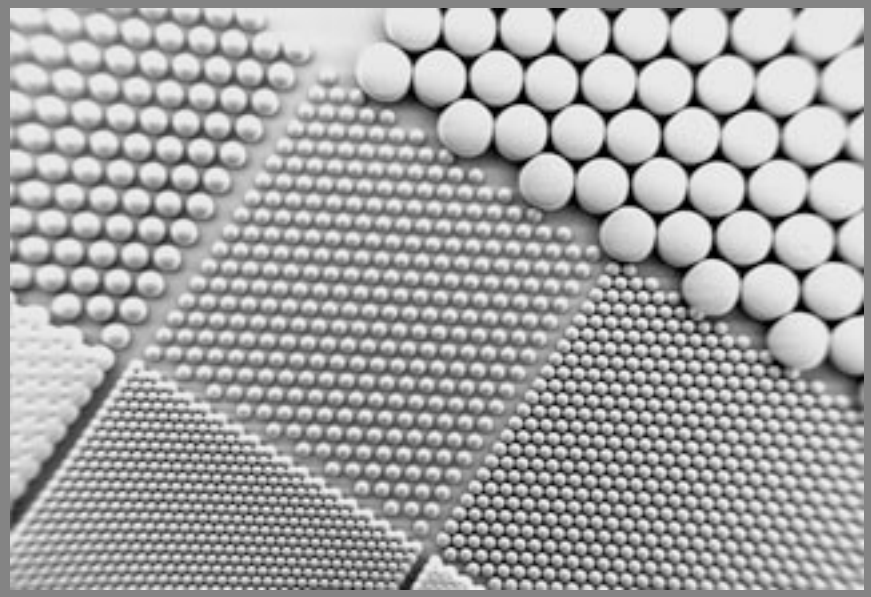


Source: http://micro.magnet.fsu.edu/





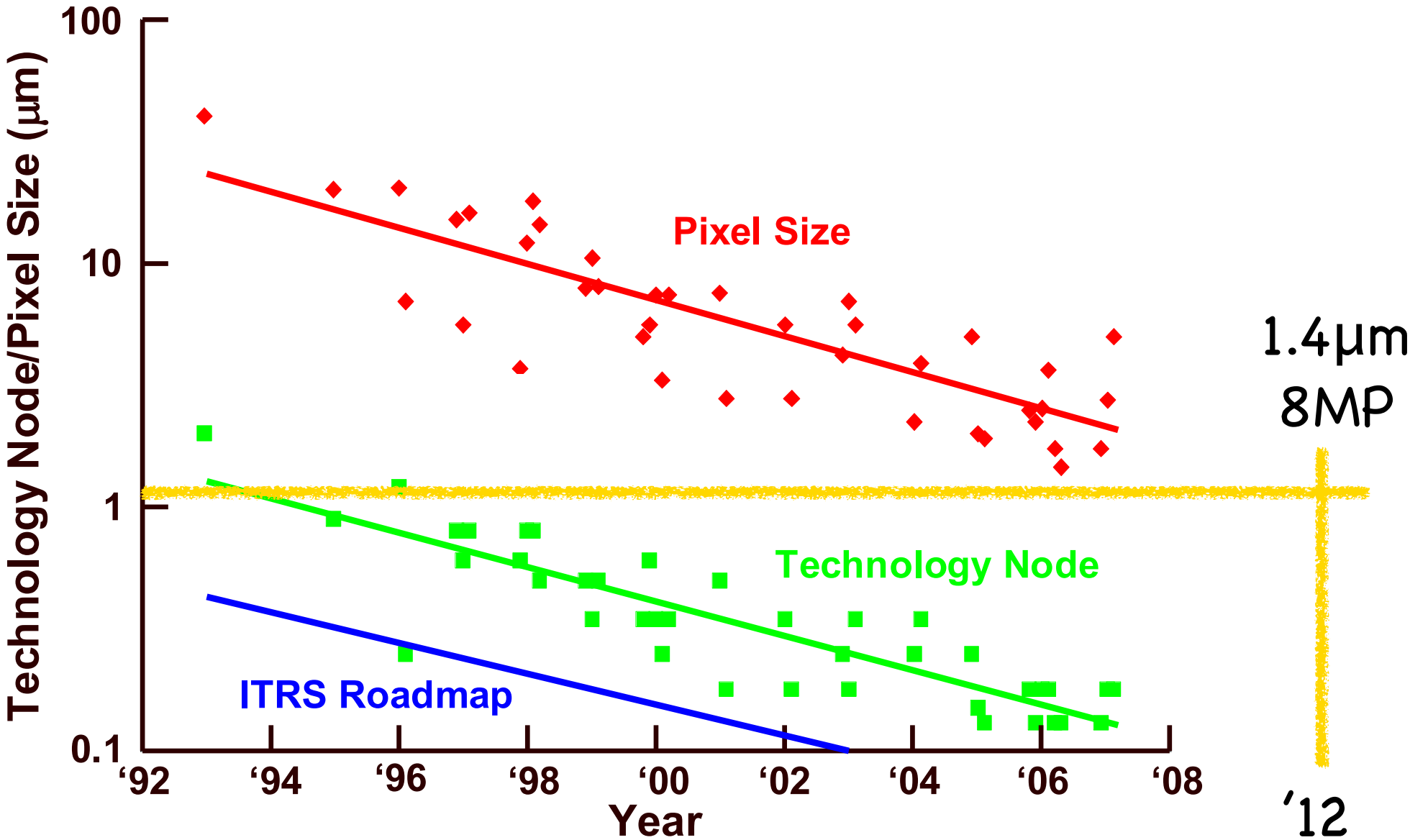




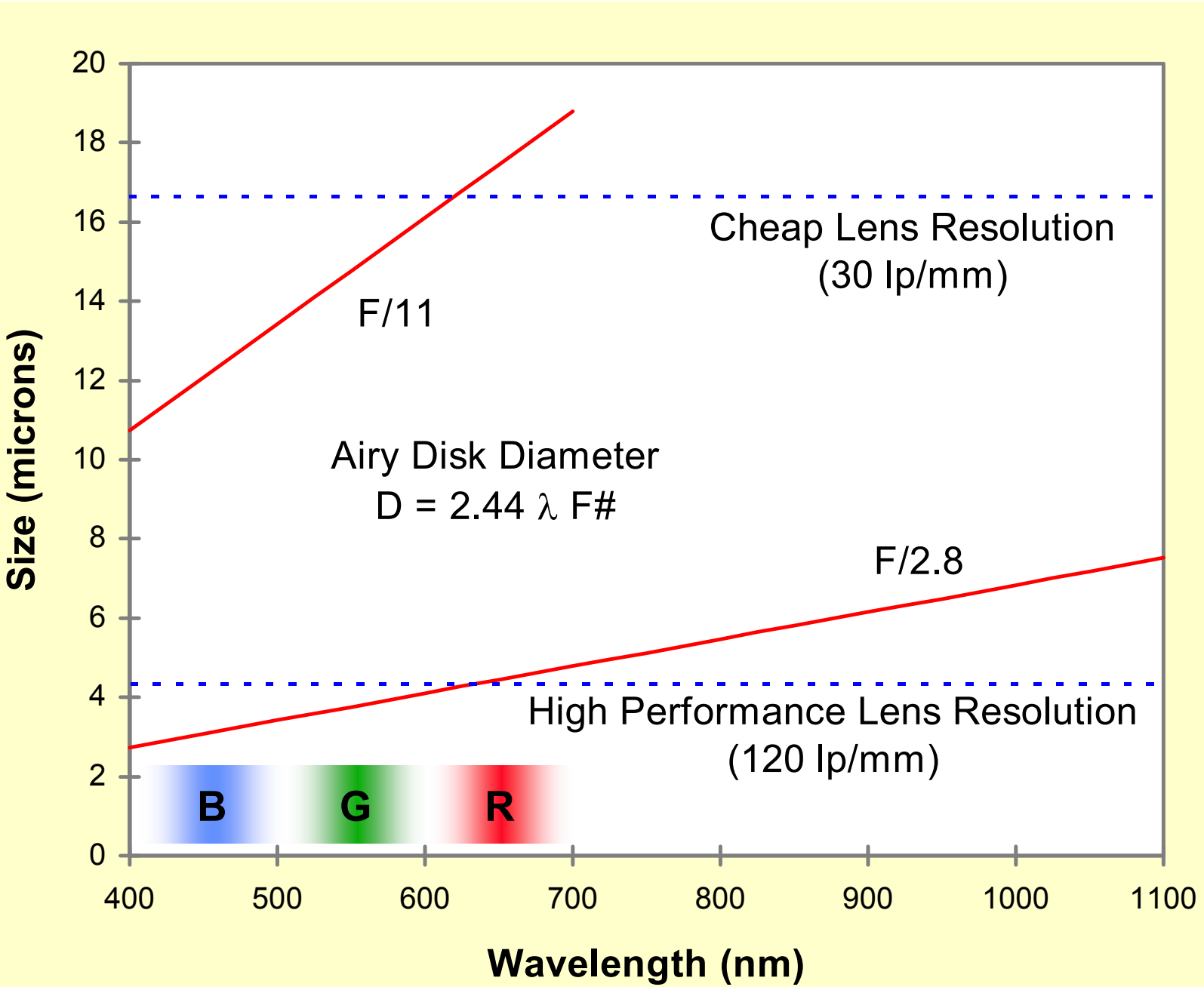
Source: Fraunhofer ISIT

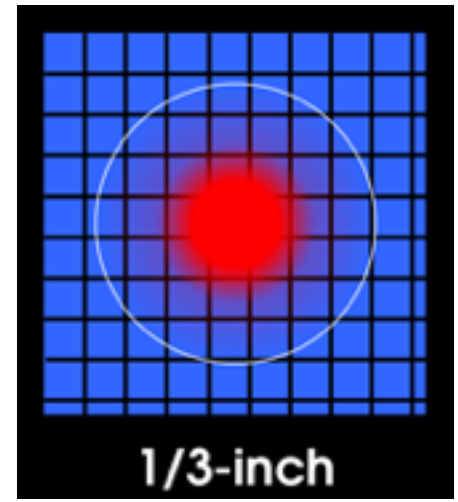
Pixel Scaling

The MegaPixel race ...



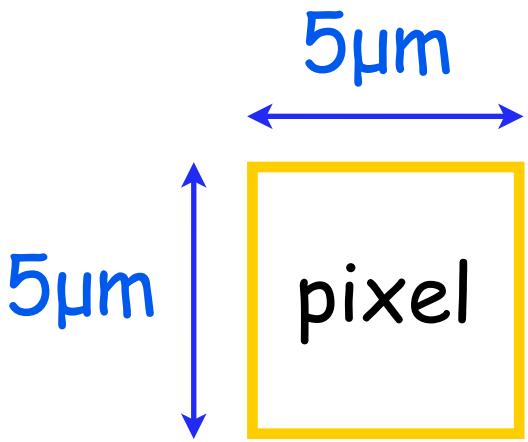
Resolution limit of lens technology ...

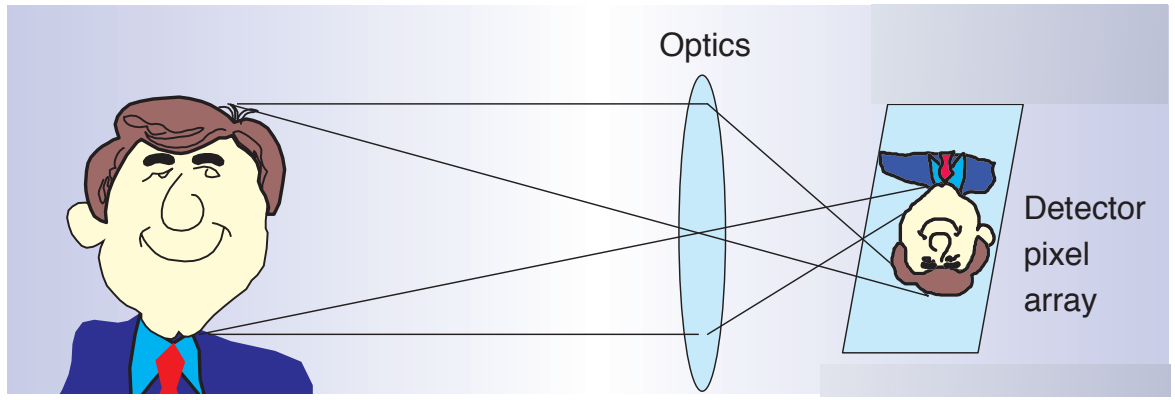




"Airy Disk"

Why more pixels are not always better



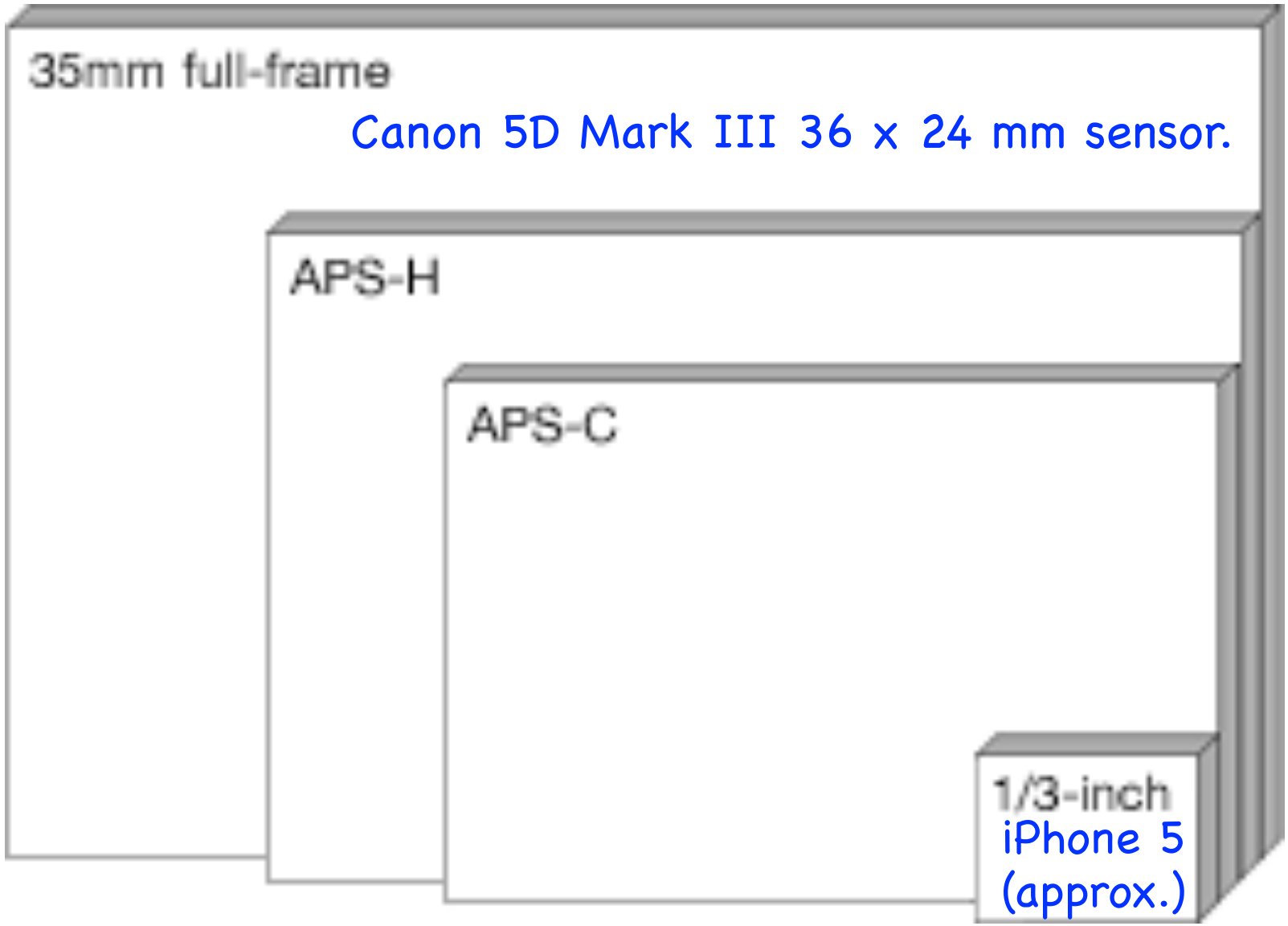


5µm pixels match the optical resolving power of practical camera optical systems (1997, Fossum). 2012 figure may be smaller.

Shrinking pixels beyond limit does not add resolution.

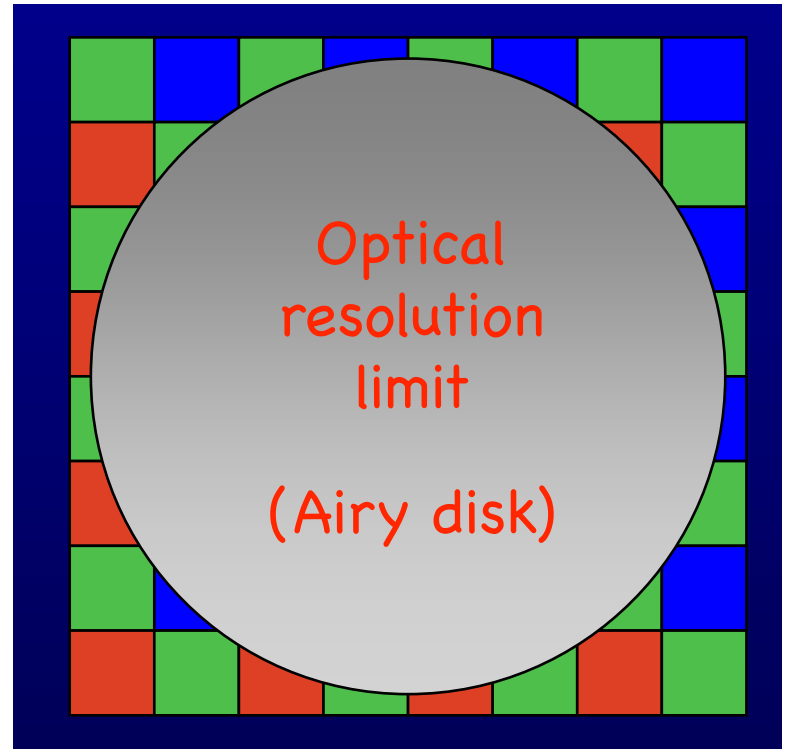
Larger die sizes are the path to higher resolution.

Sensor size: Pro camera vs iPhone 5



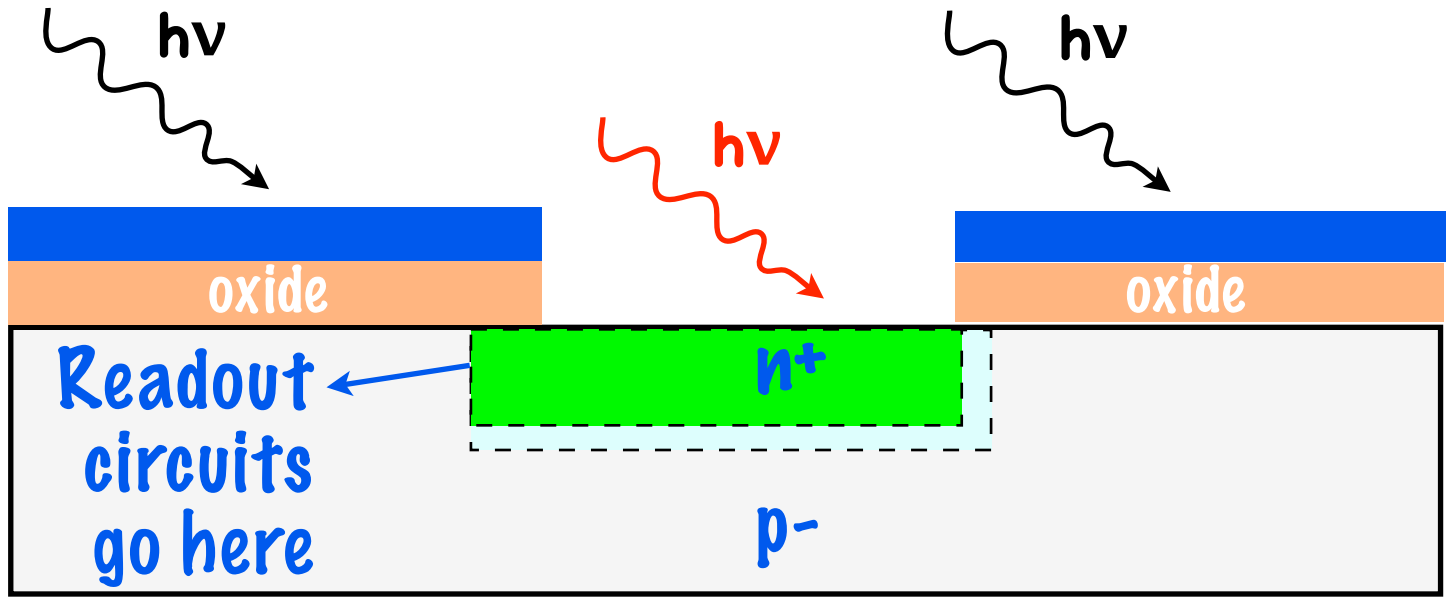
Megapixels: Benefits other than resolution

Small pixels supersample color space. Color interpolation improves.



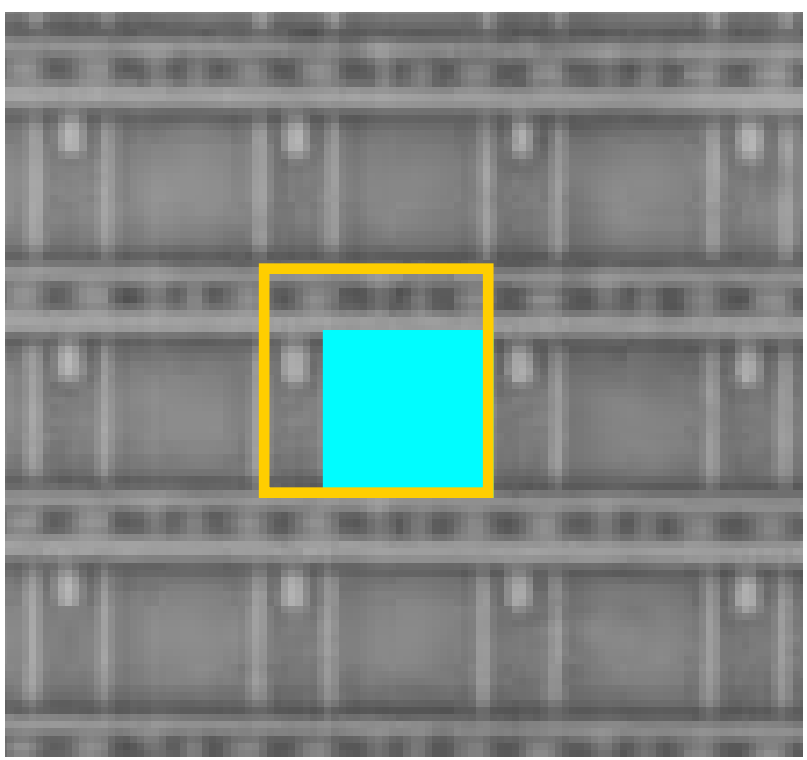
Process scaling helps imager arrays in another way ...

Recall: Photodiode design ...



Fill factor = $\frac{\text{Photodiode area}}{\text{Pixel area}}$

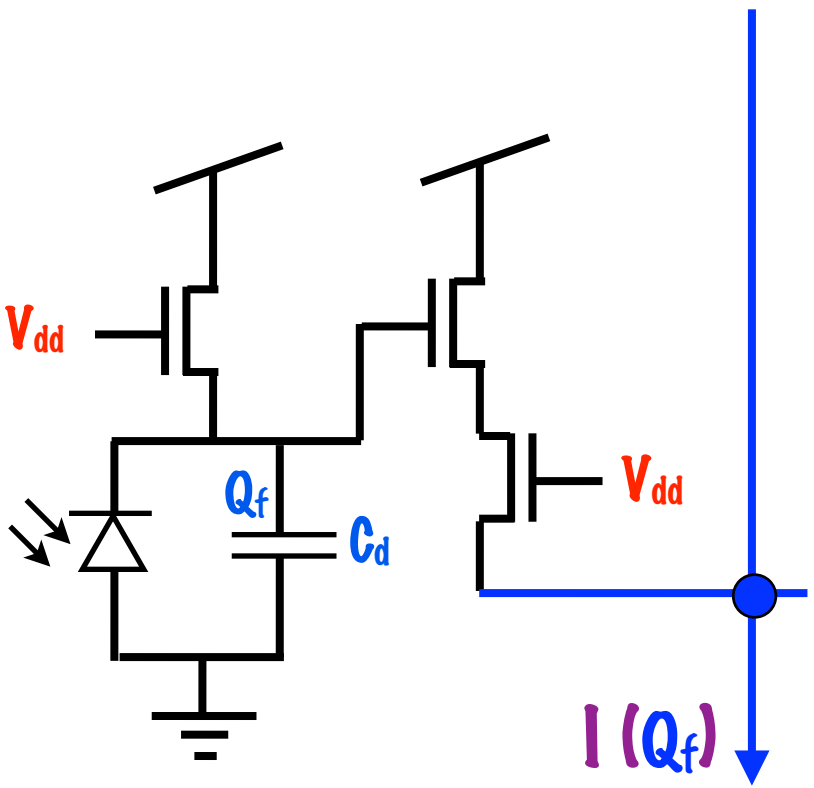
As process shrinks, readout circuits shrink and diode grows. So, fill factor increases and fewer photons lost.



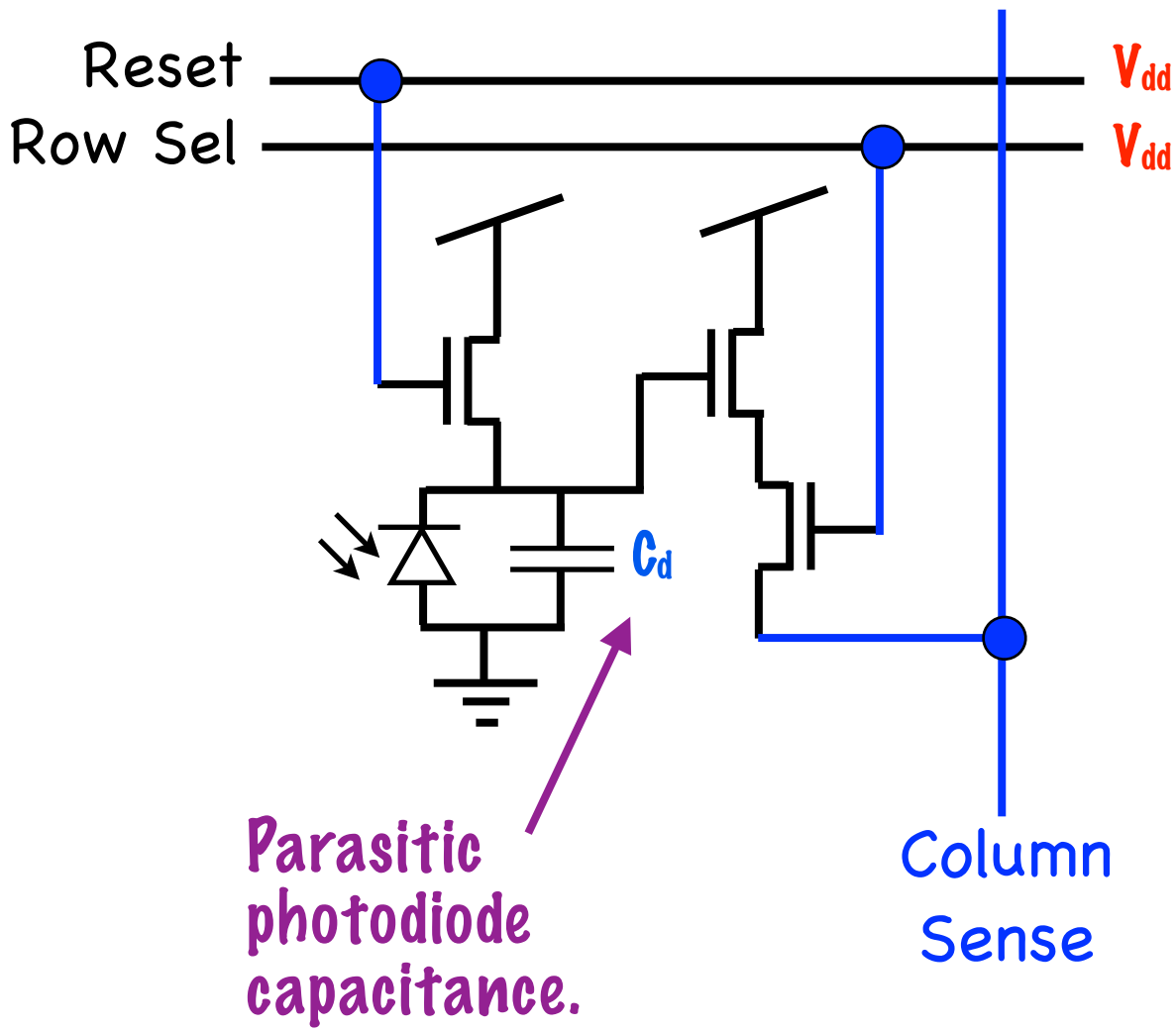
Readout Circuits

Three-Transistor Active Pixel Cell

Step 1: Fill C_d, and sense column current.

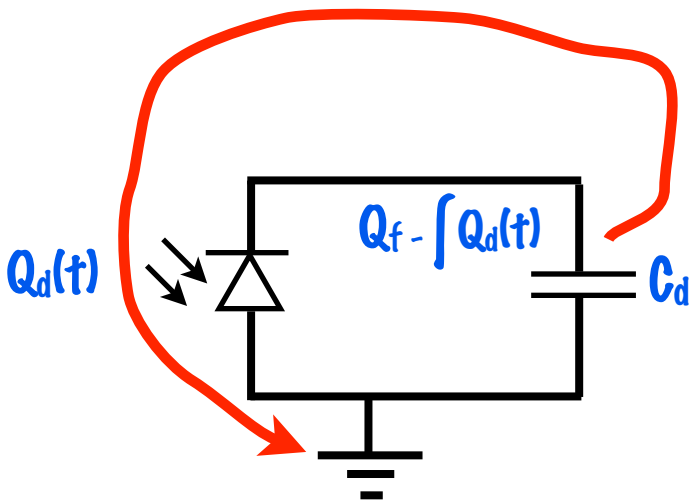


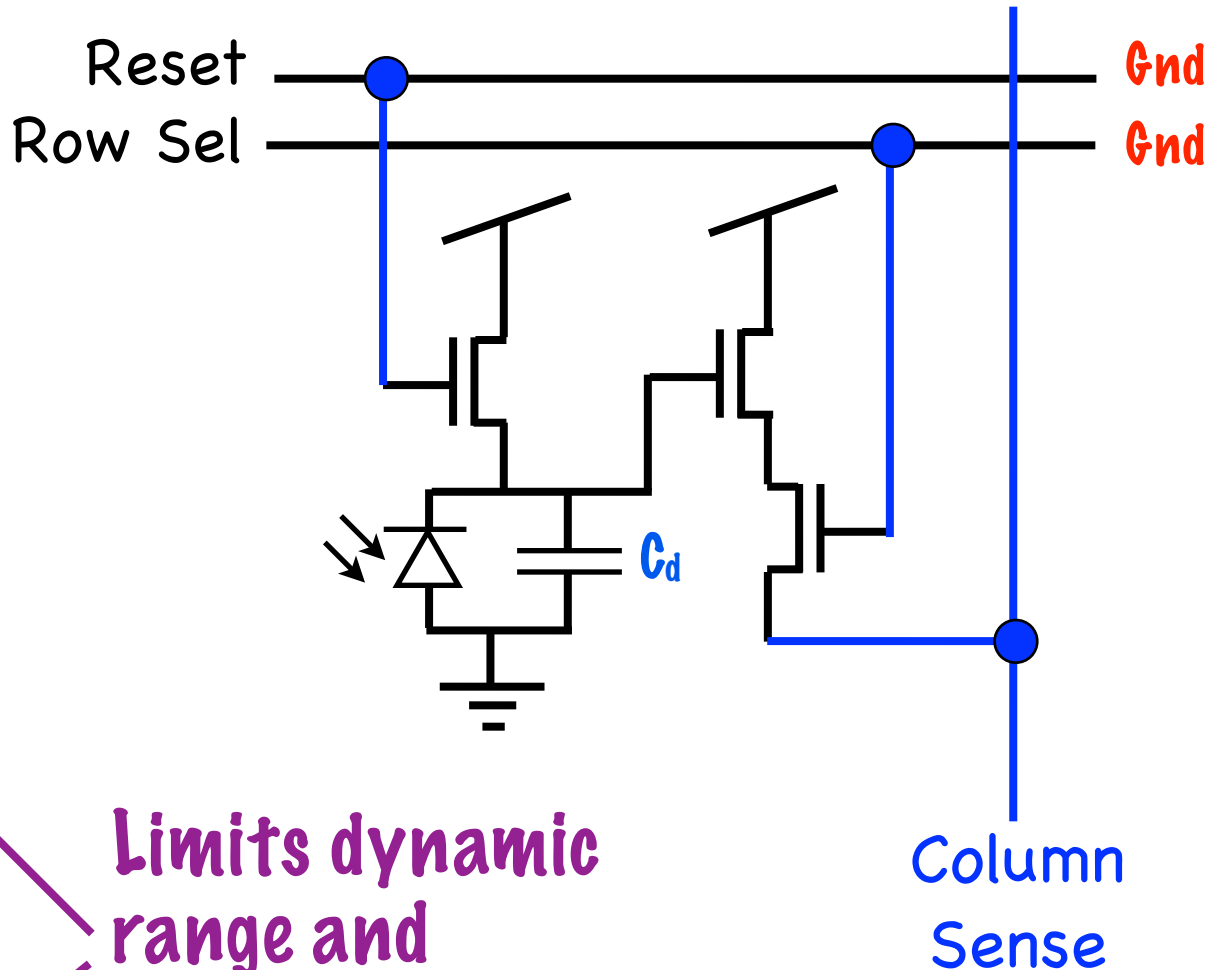
Edge circuitry samples current $I(Q_f)$ for later use.



Opening the electronic shutter ...

Step 2: "Electronic shutter" opens, photodiode empties C_d.





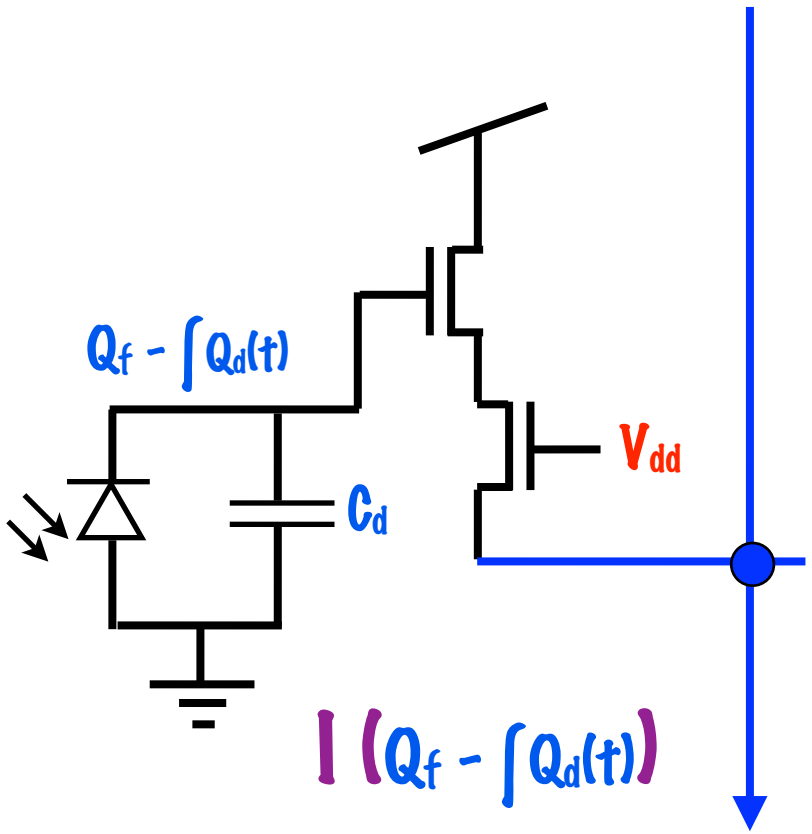
Too much $\int Q_d(t)$, and we empty bucket before shutter closes.

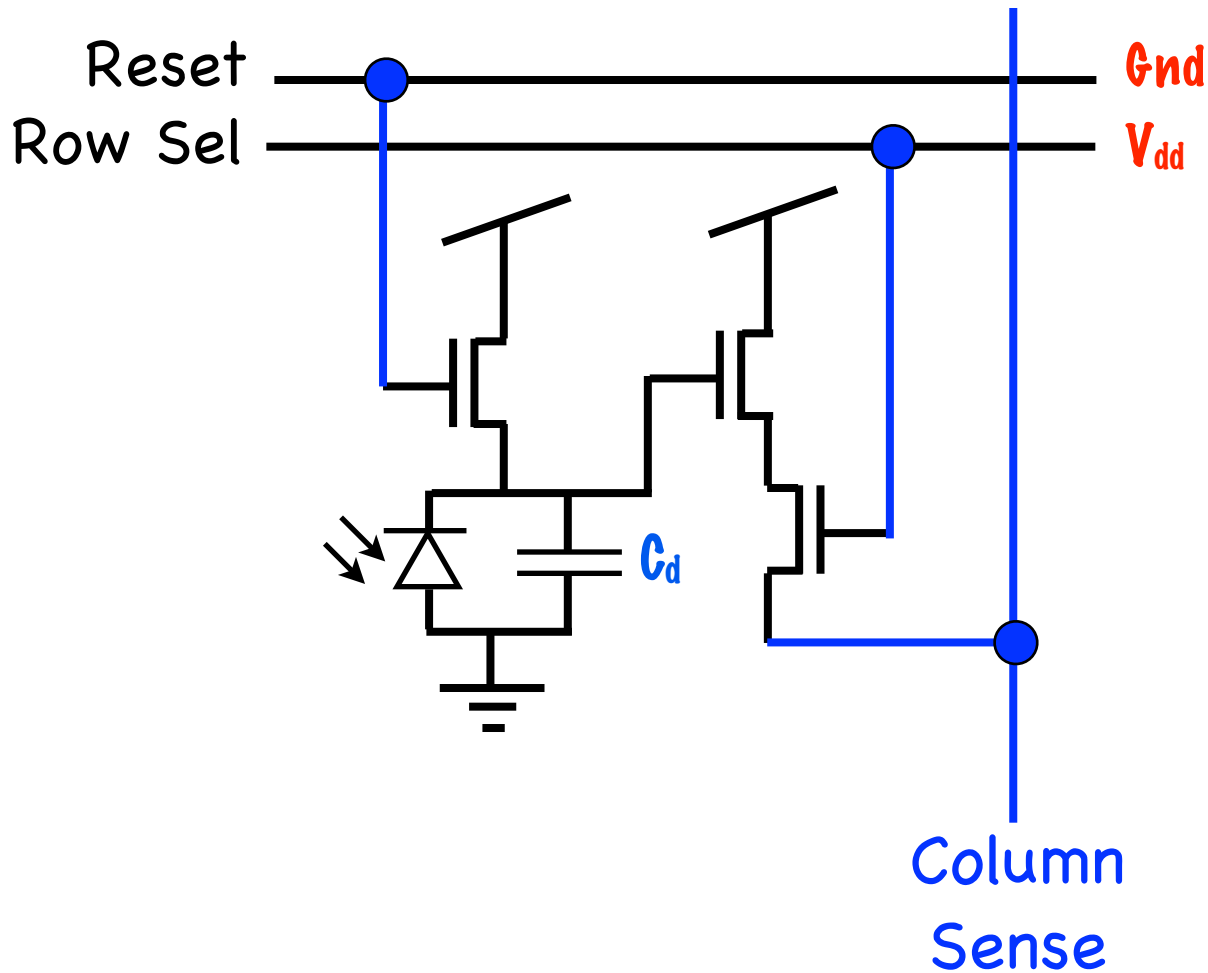
Not enough $\int Q_d(t)$, and we capture temporal noise.

Limits dynamic range and signal-to-noise.

Close shutter, read pixel value ...

Step 3: Sense how empty C_d has become.





Use $I(Q_f)$ from start of the cycle to reduce kTC (reset) noise.

"Correlated double sampling"

Temporal noise affects Qf value.

Readout: Column-parallel ADCs ...

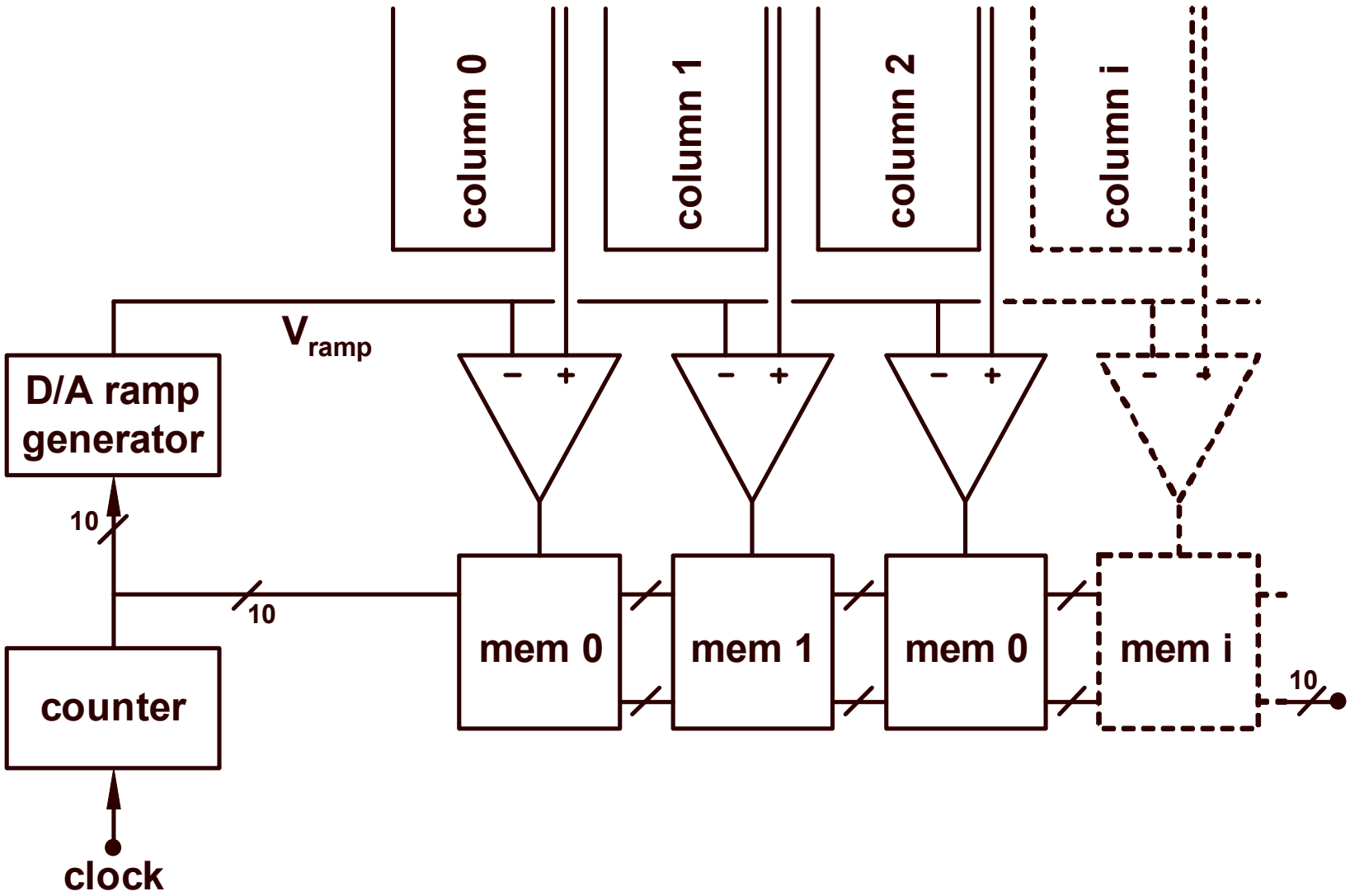
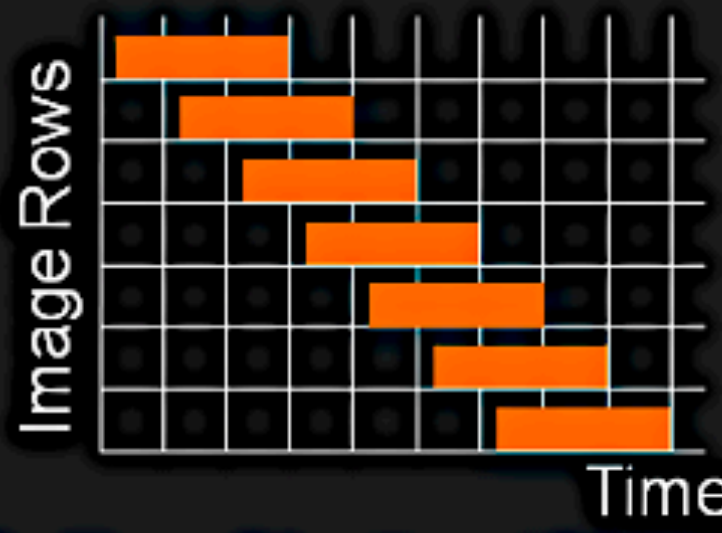


Figure 7. Basic architecture of a column-parallel, single-slope analog-to-digital converter.

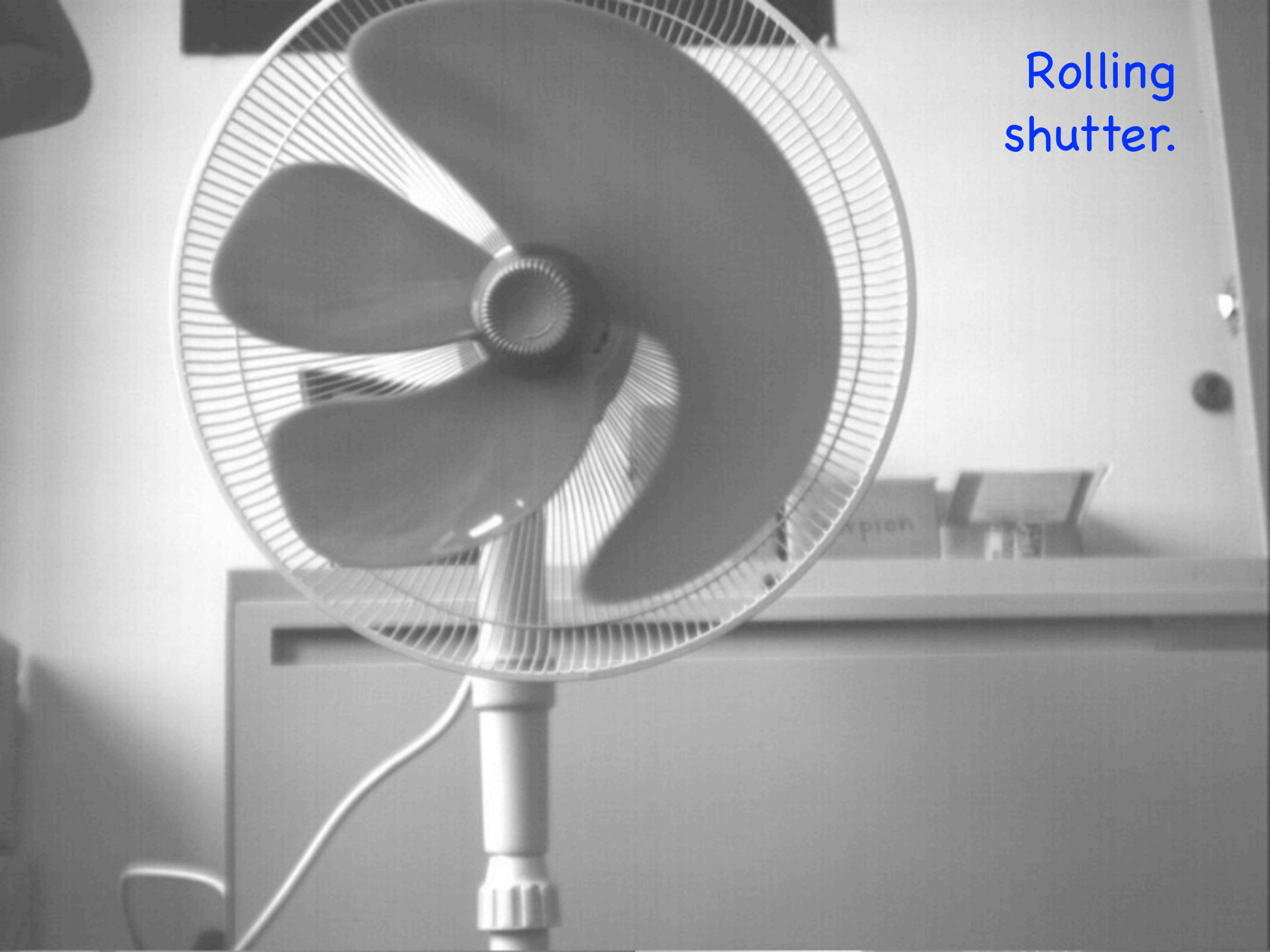
Camera Shutter: Space-Time Sampling



Rolling Shutter (CMOS)

Global Shutter (CCD)


Global
shutter.
Fan in
motion.

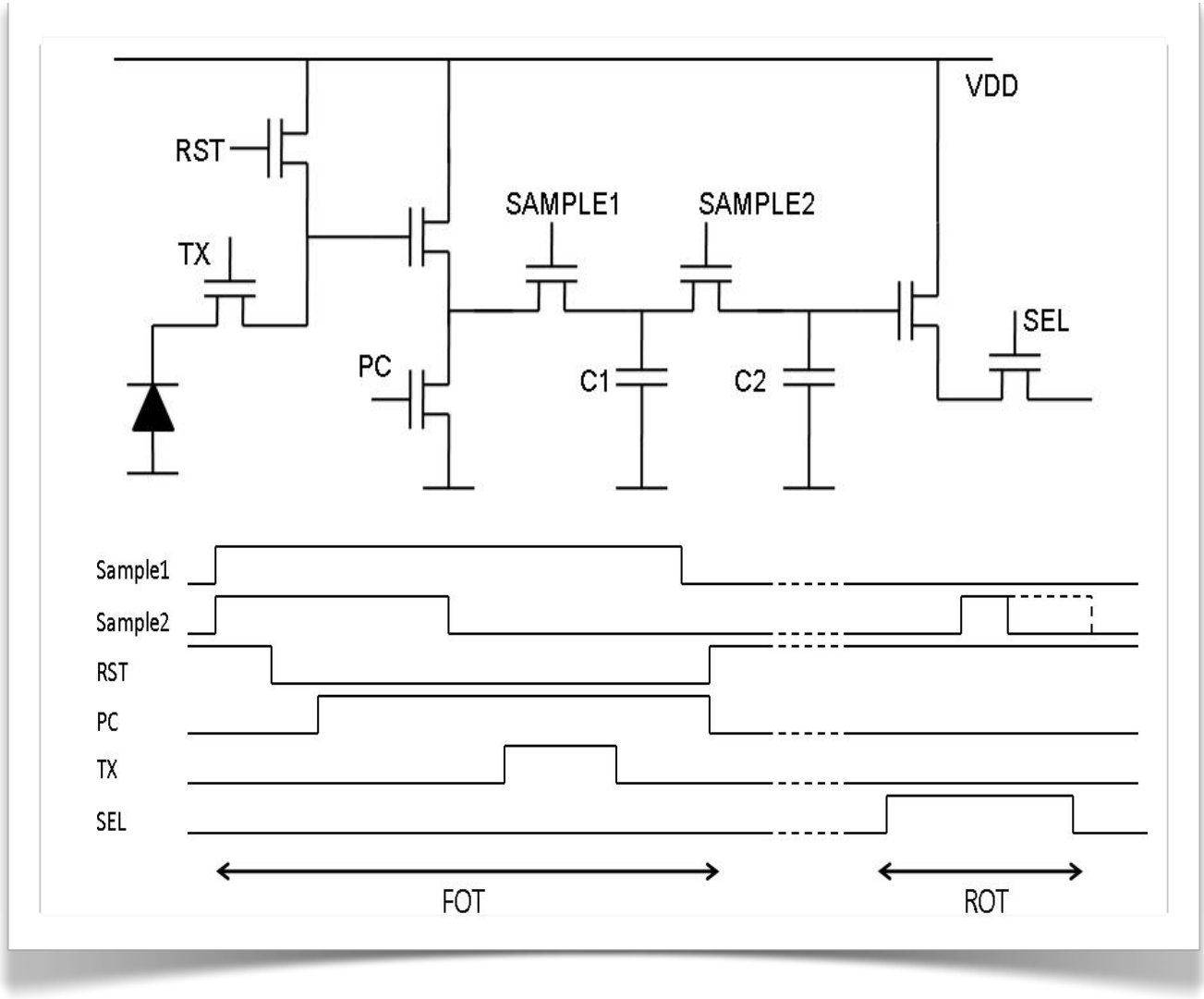

Rolling
shutter.

Solution: Add "analog memory" ...

Does not come for free.

Reduces fill factor, adds edge circuit complexity.

Mechanical shutters are more popular.

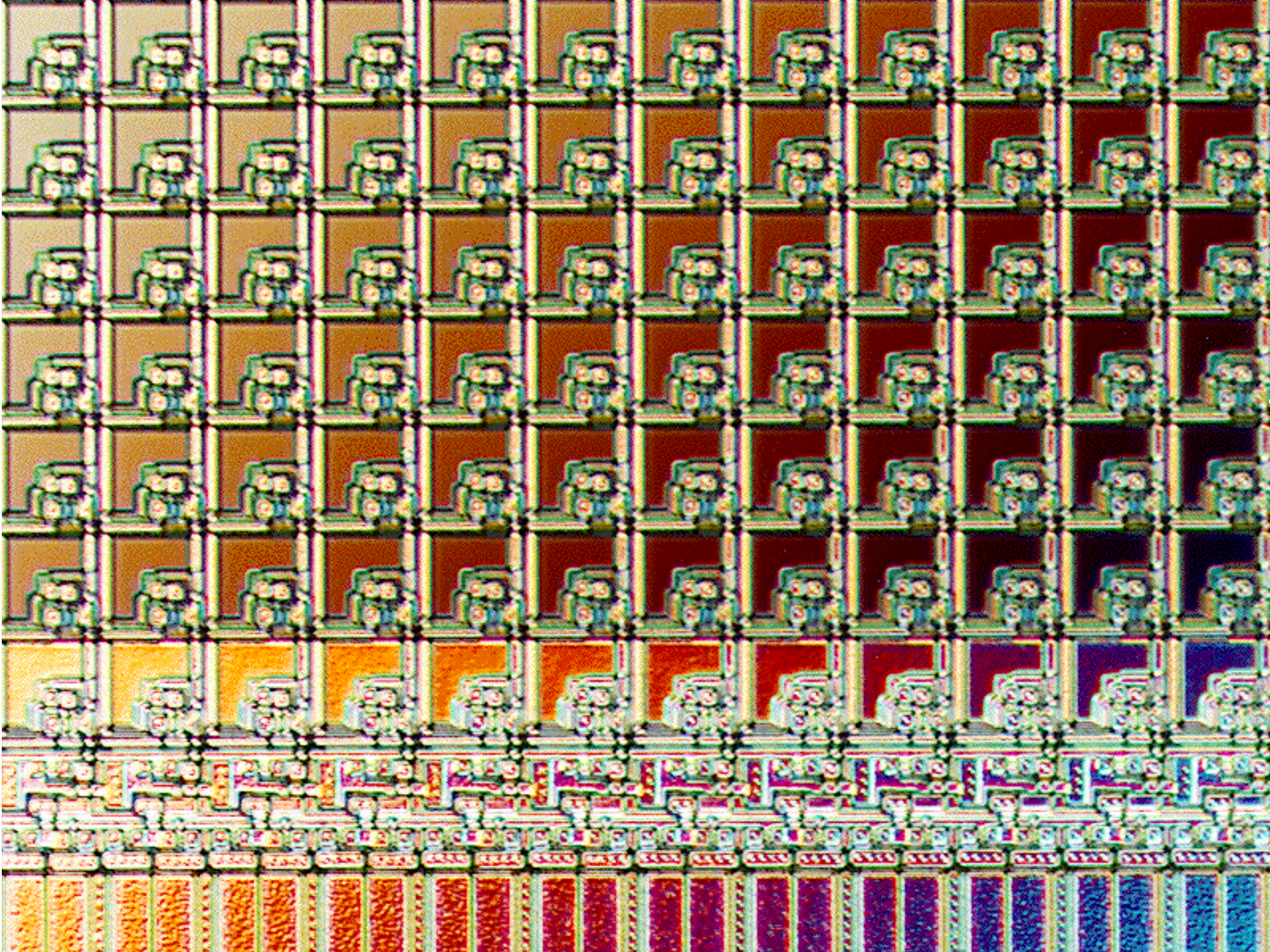


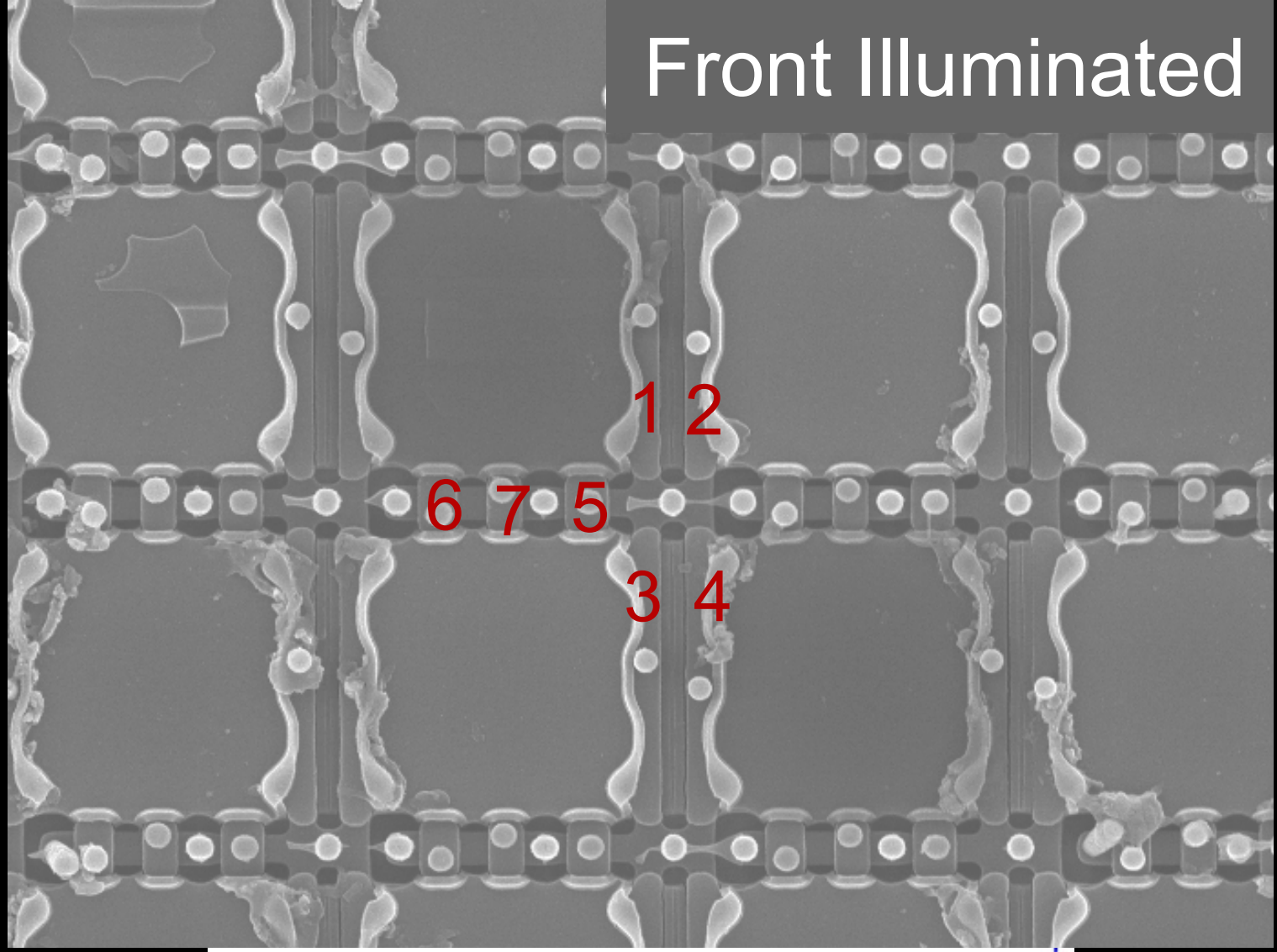
Backside illuminated global shutter CMOS image sensors

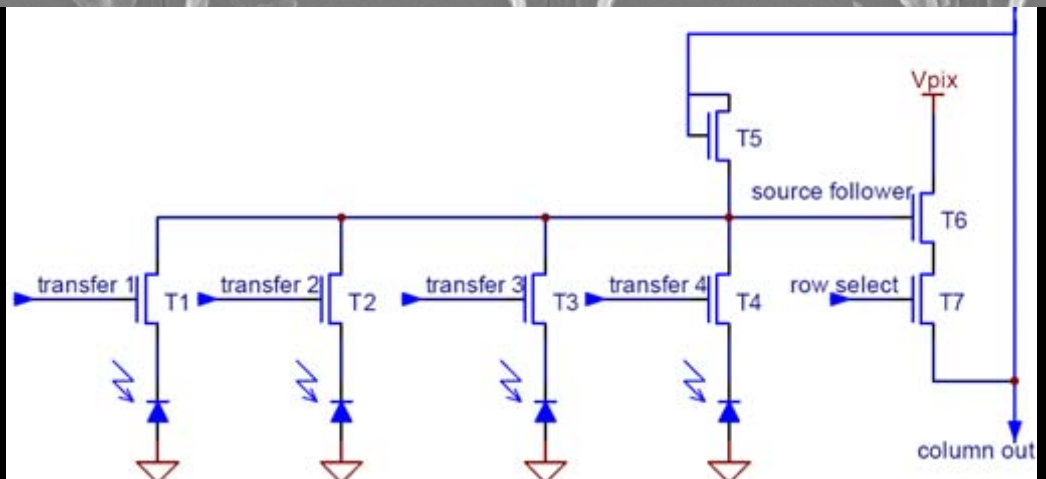
Guy Meynants, Jan Bogaerts, Xinyang Wang, Guido Vanhorebeek
CMOSIS nv, Coveliersstraat 15, 2600 Antwerp, Belgium

Break

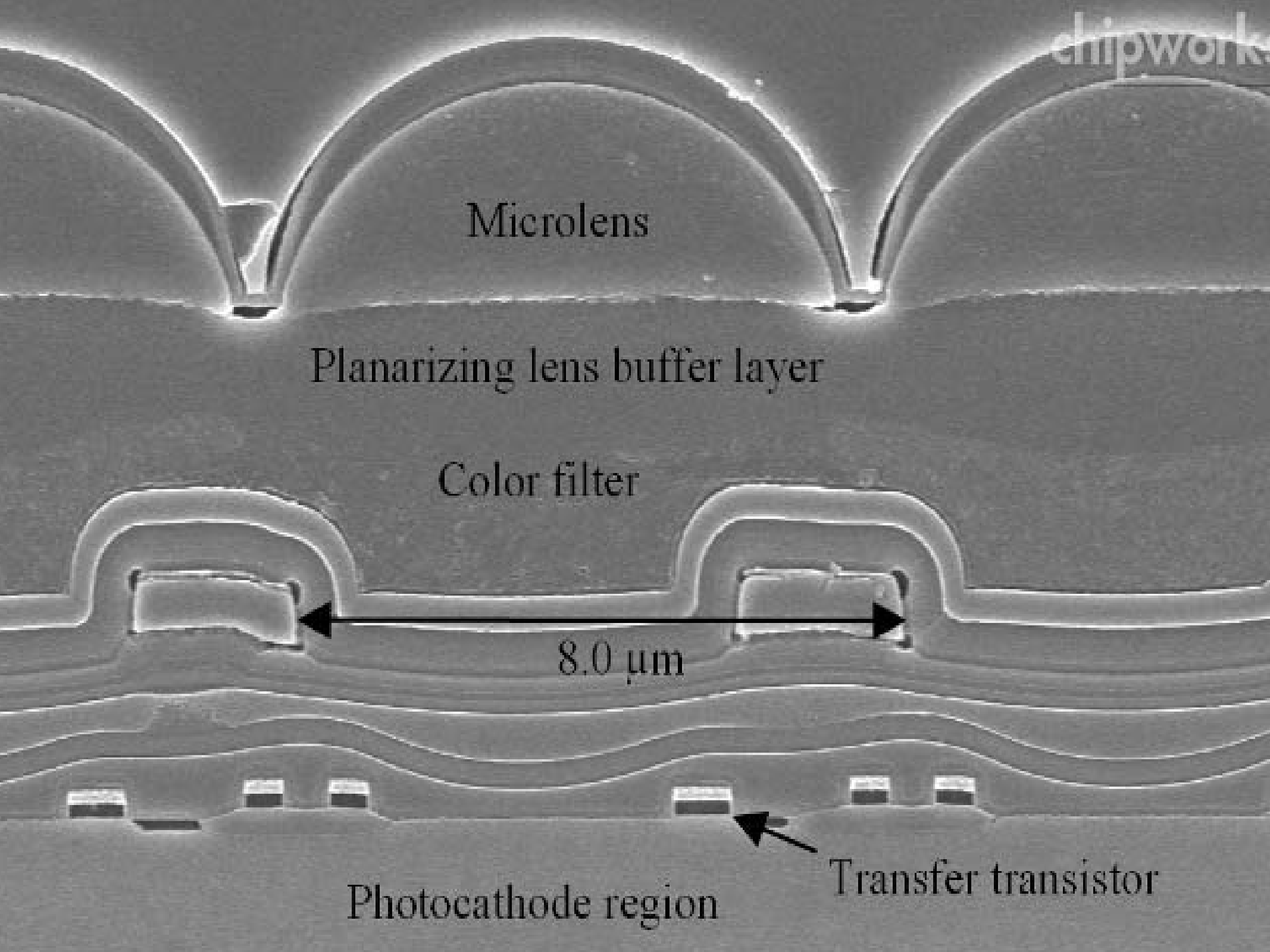
Fabrication Technology

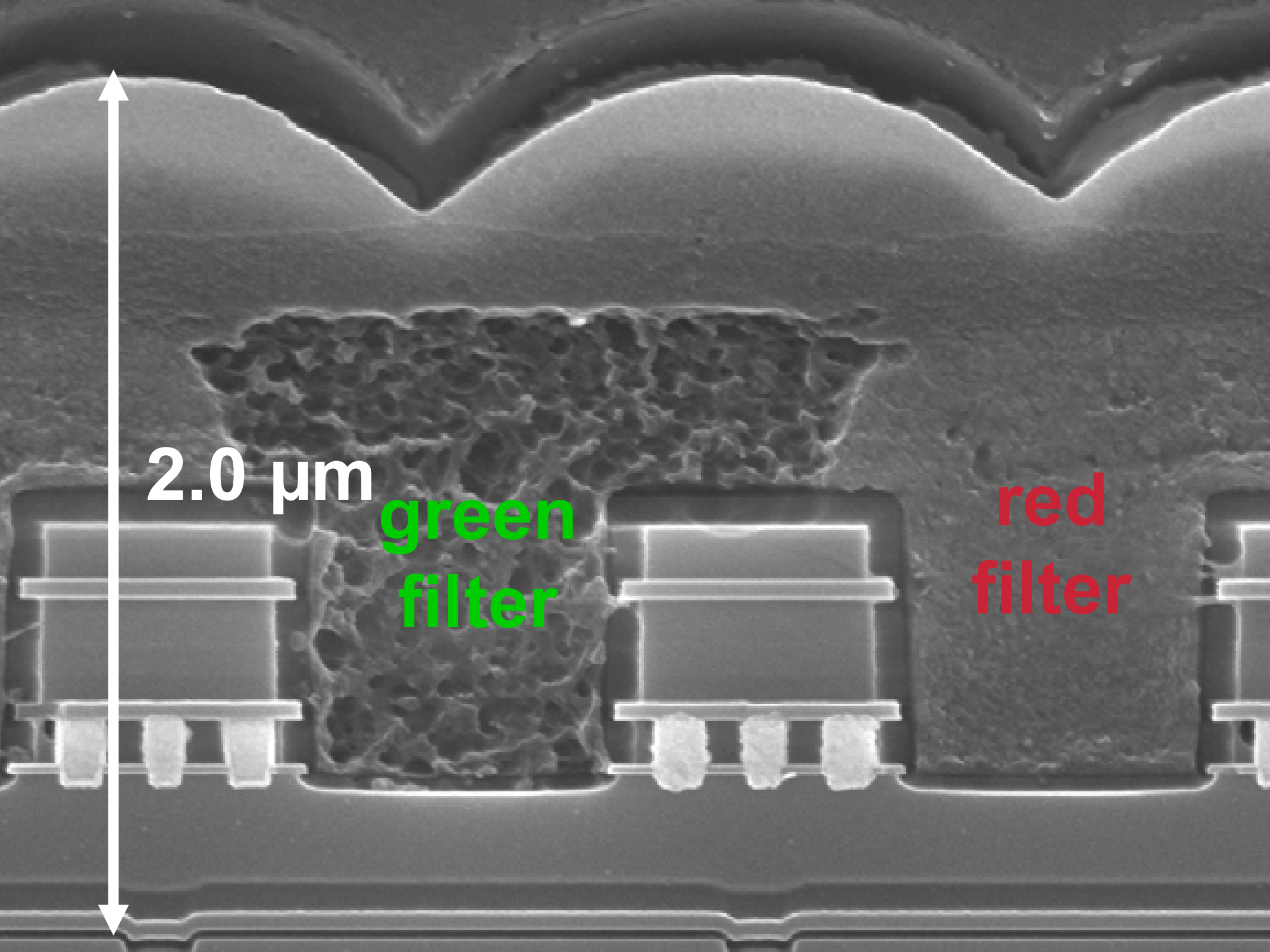


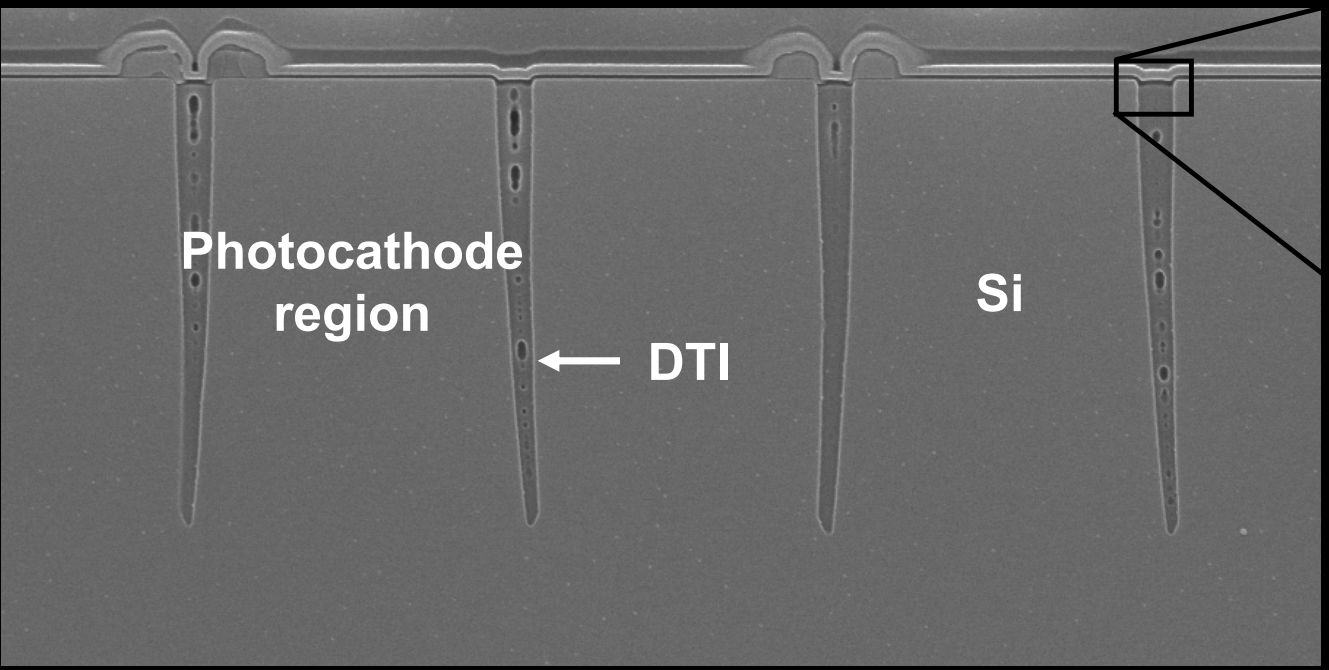


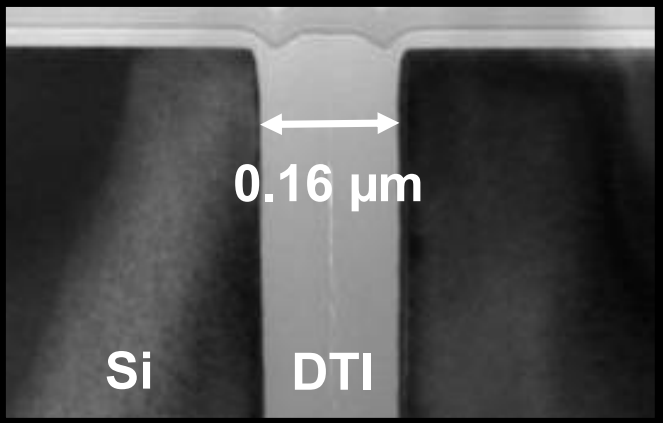


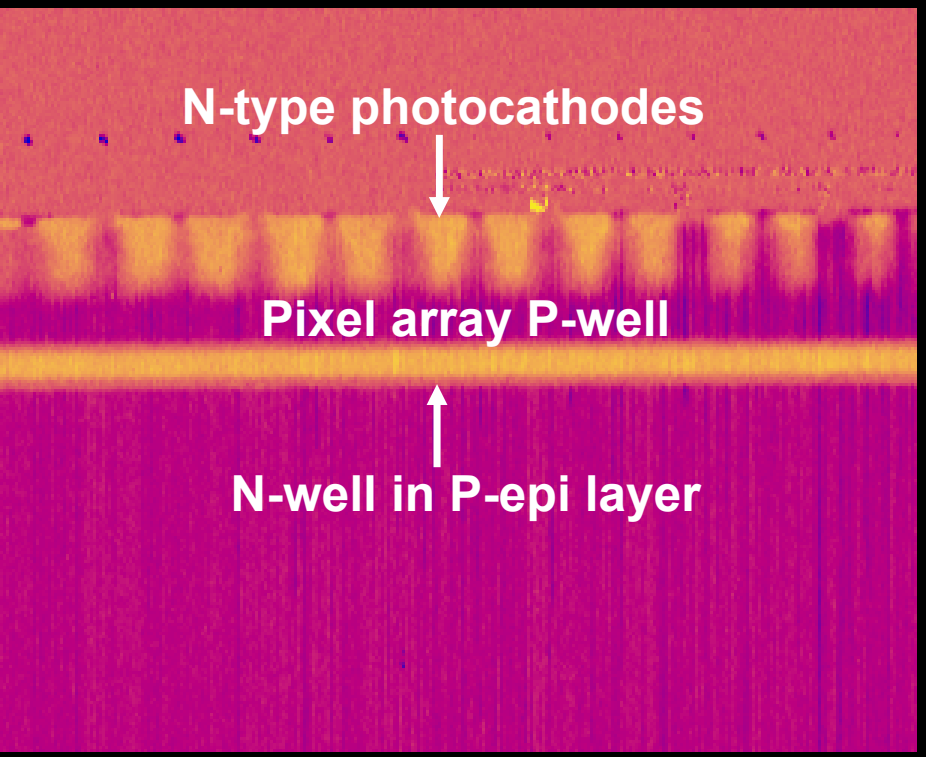
1.75 effective transistors per pixel.

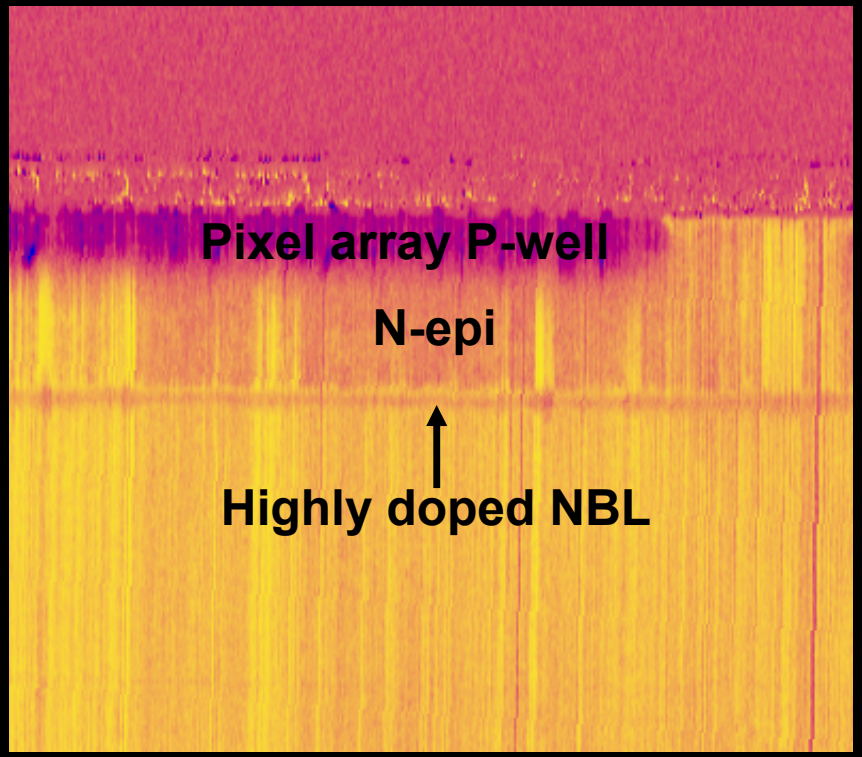

chipworks
Microlens
Planarizing lens buffer layer
Color filter
8.0 µm
Transfer transistor
Photocathode region

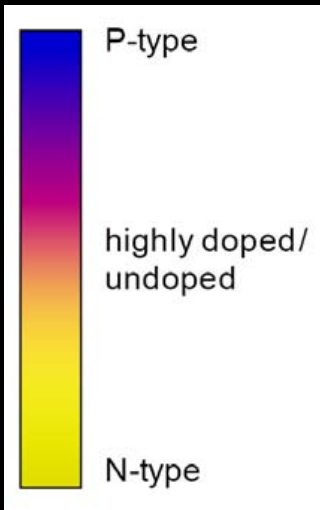

2.0 µm
green
filter
red
filter

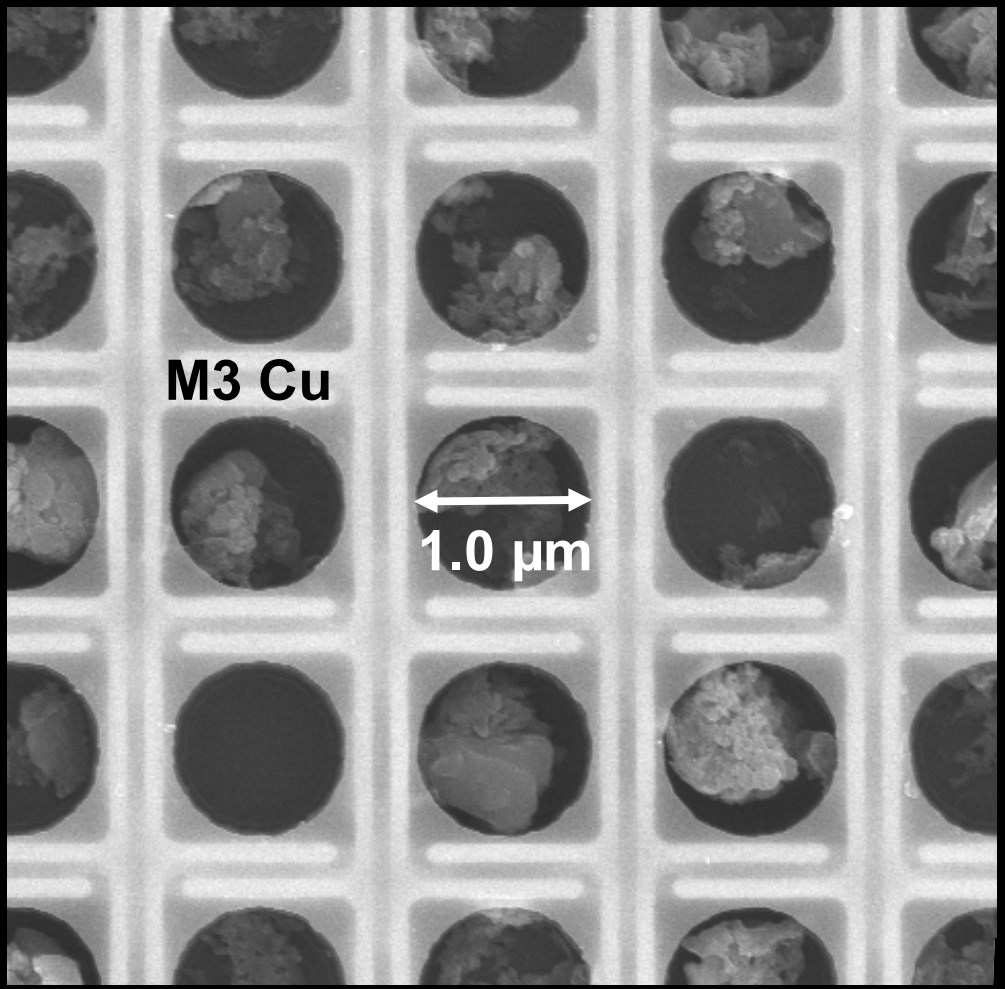

Photocathode
region
DTI
Si

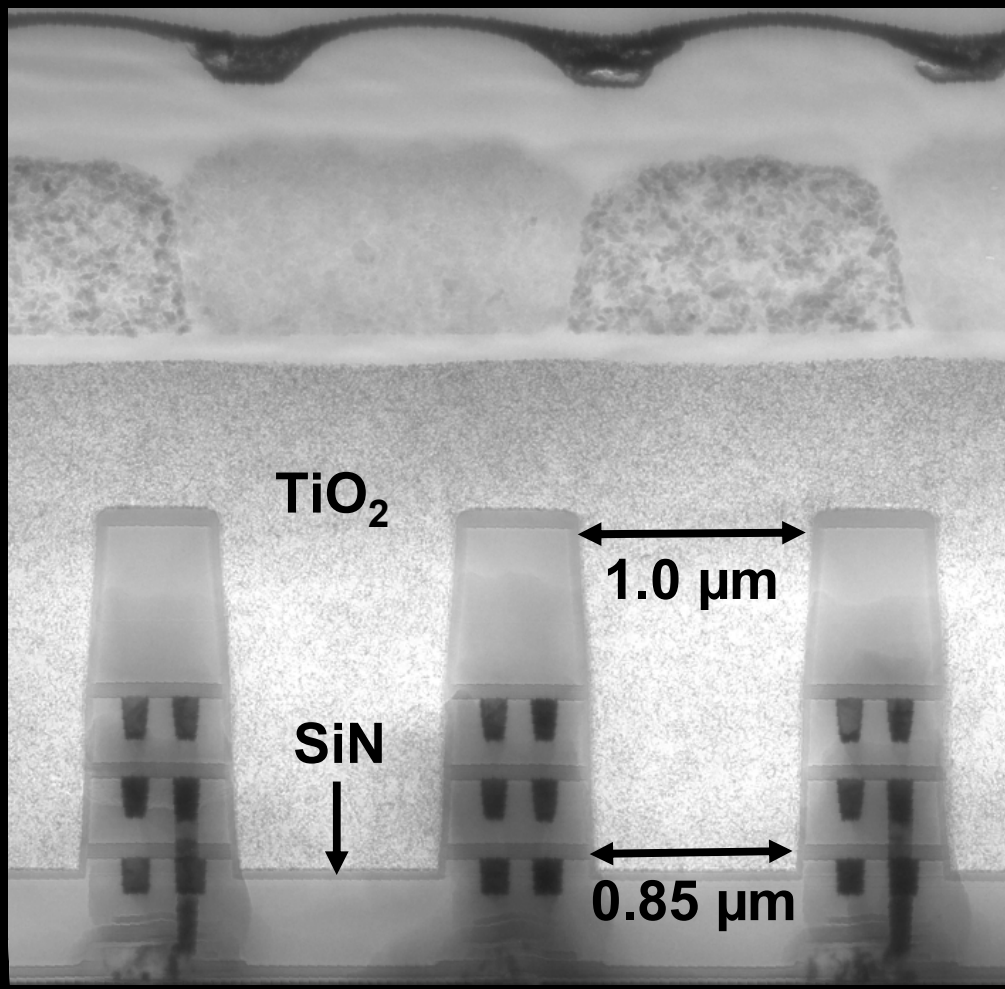

0.16 µm
Si
DTI

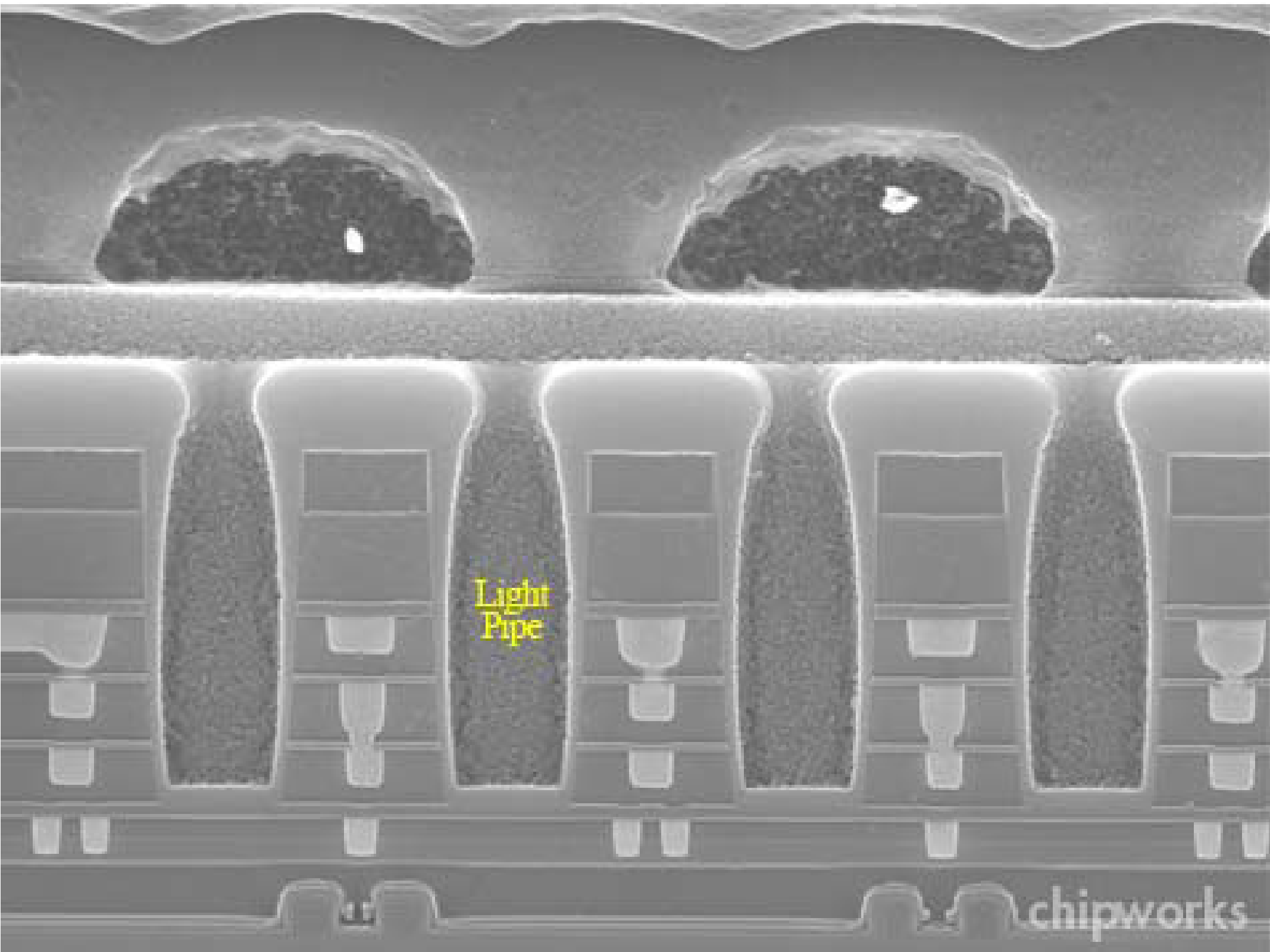

N-type photocathodes
Pixel array P-well
N-well in P-epi layer


Pixel array P-well
N-epi
Highly doped NBL

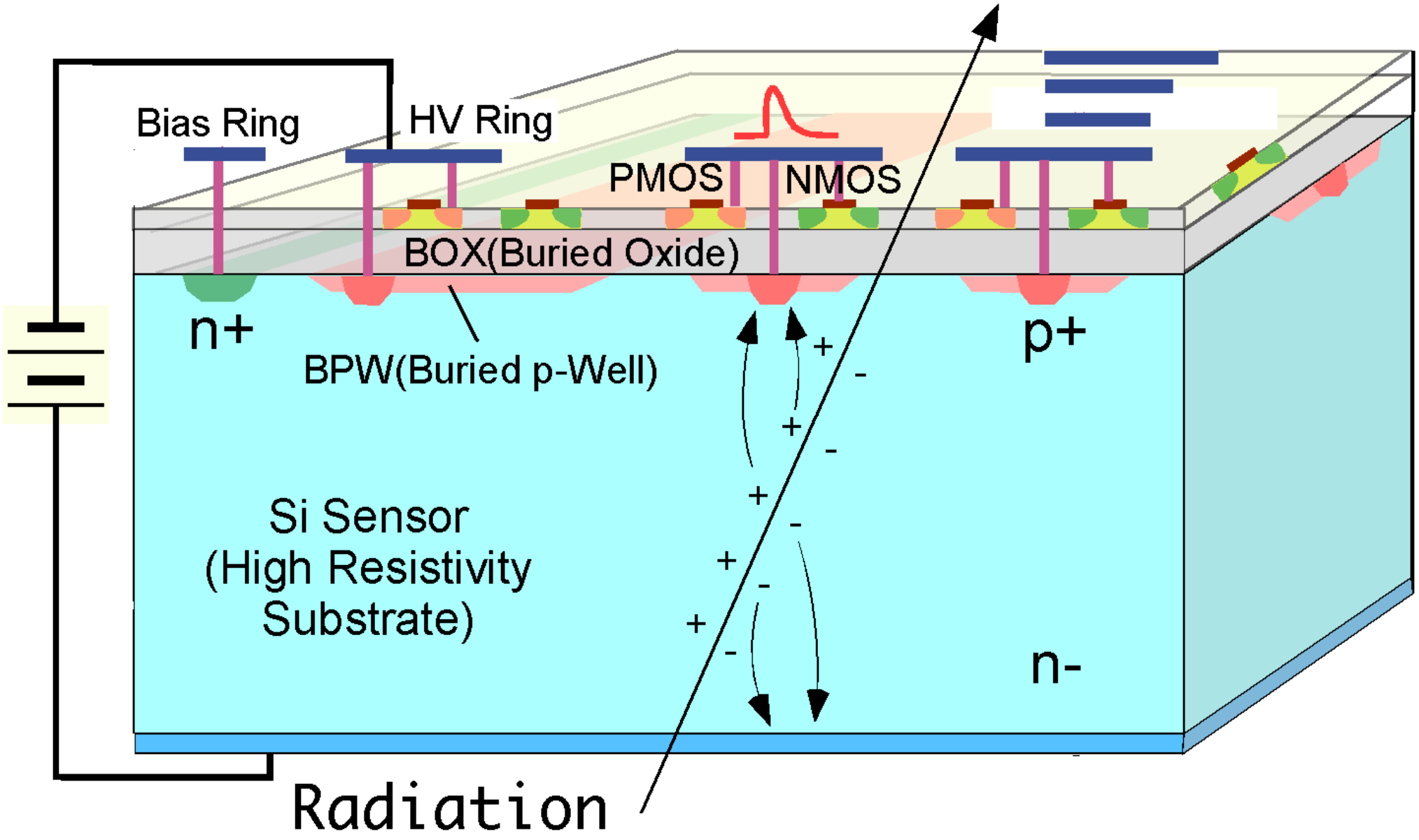

P-type
highly doped/
undoped
N-type

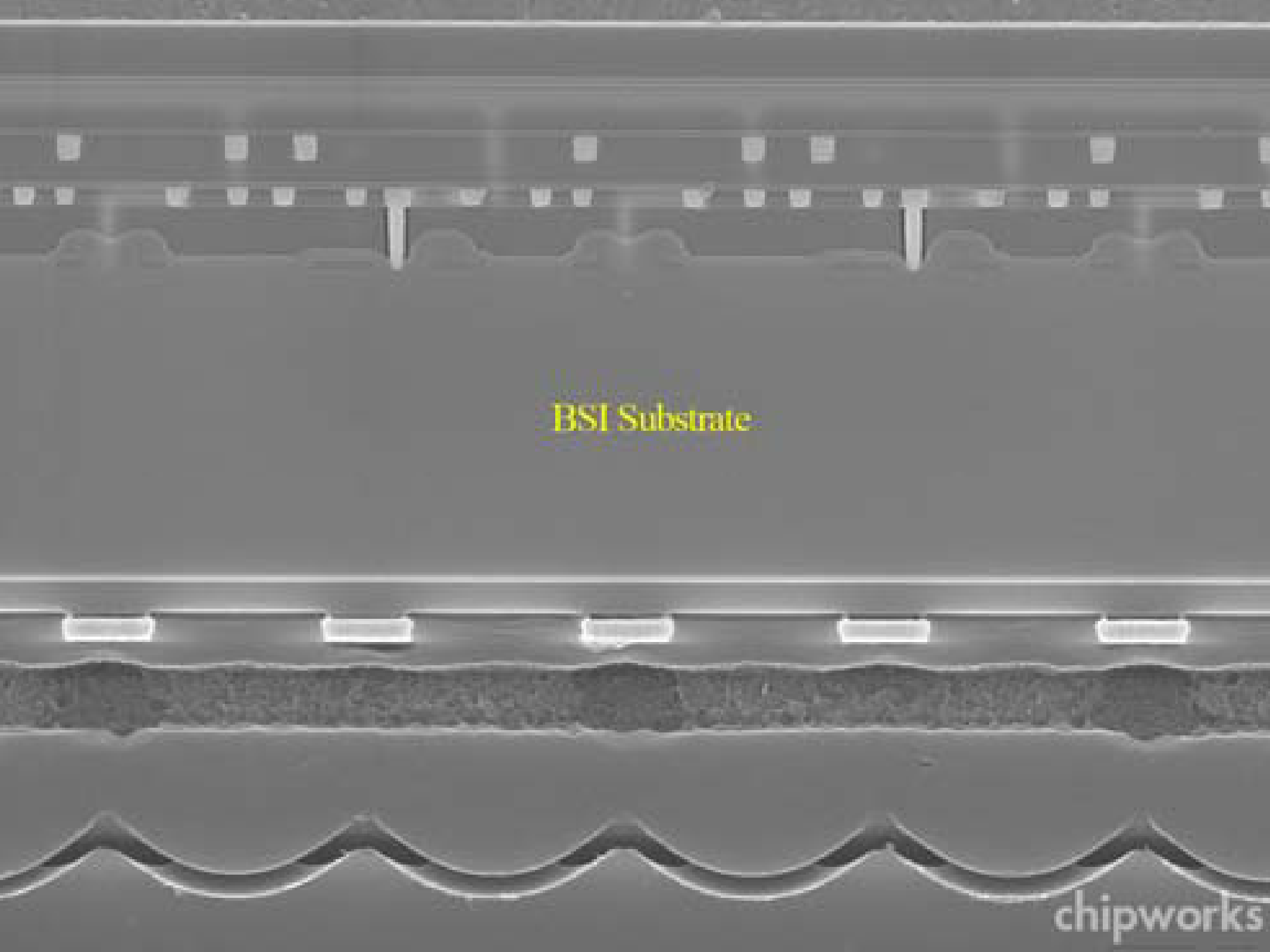

M3 Cu
1.0 µm

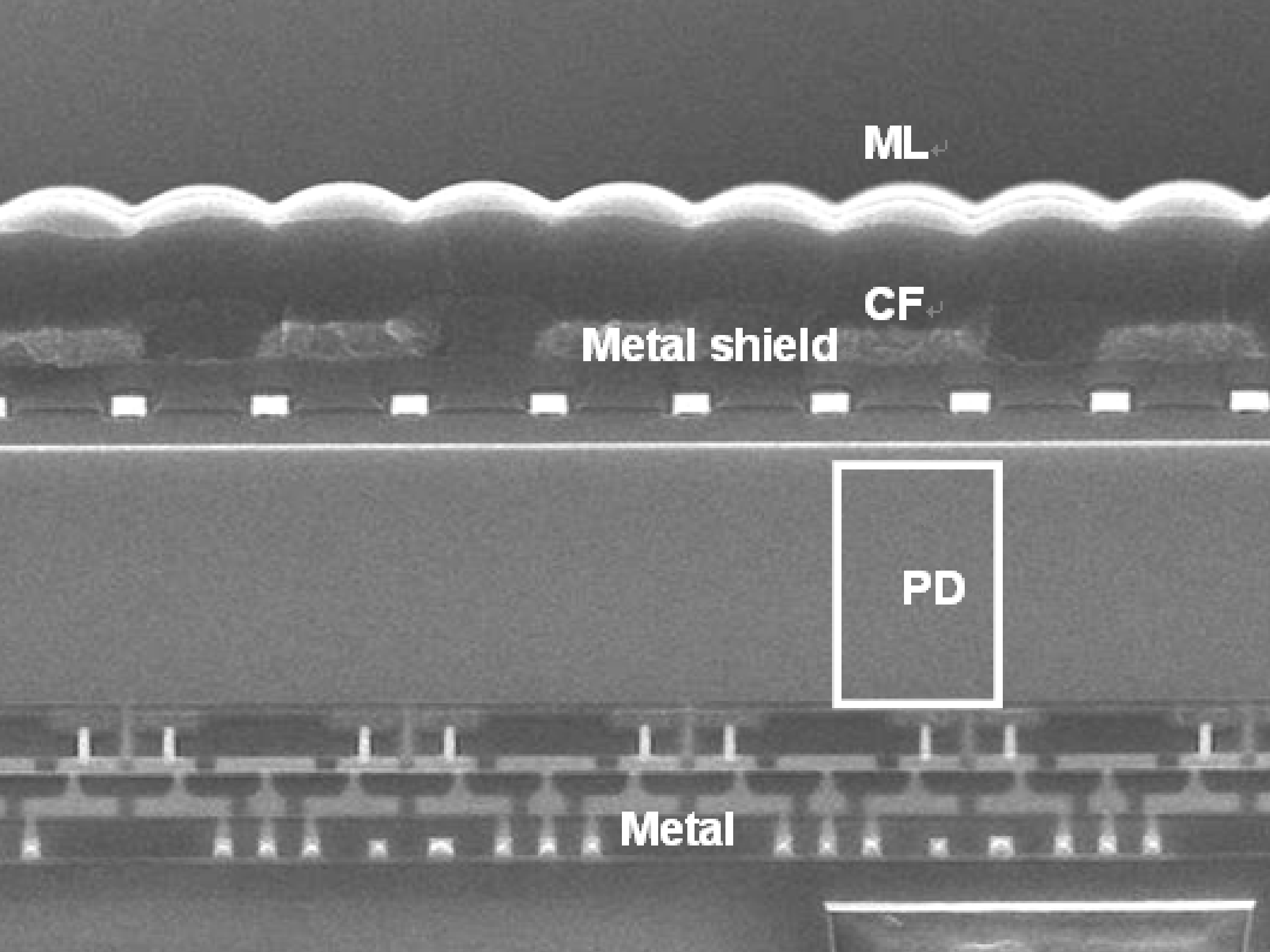

TiO2
1.0 µm
SiN
0.85 µm

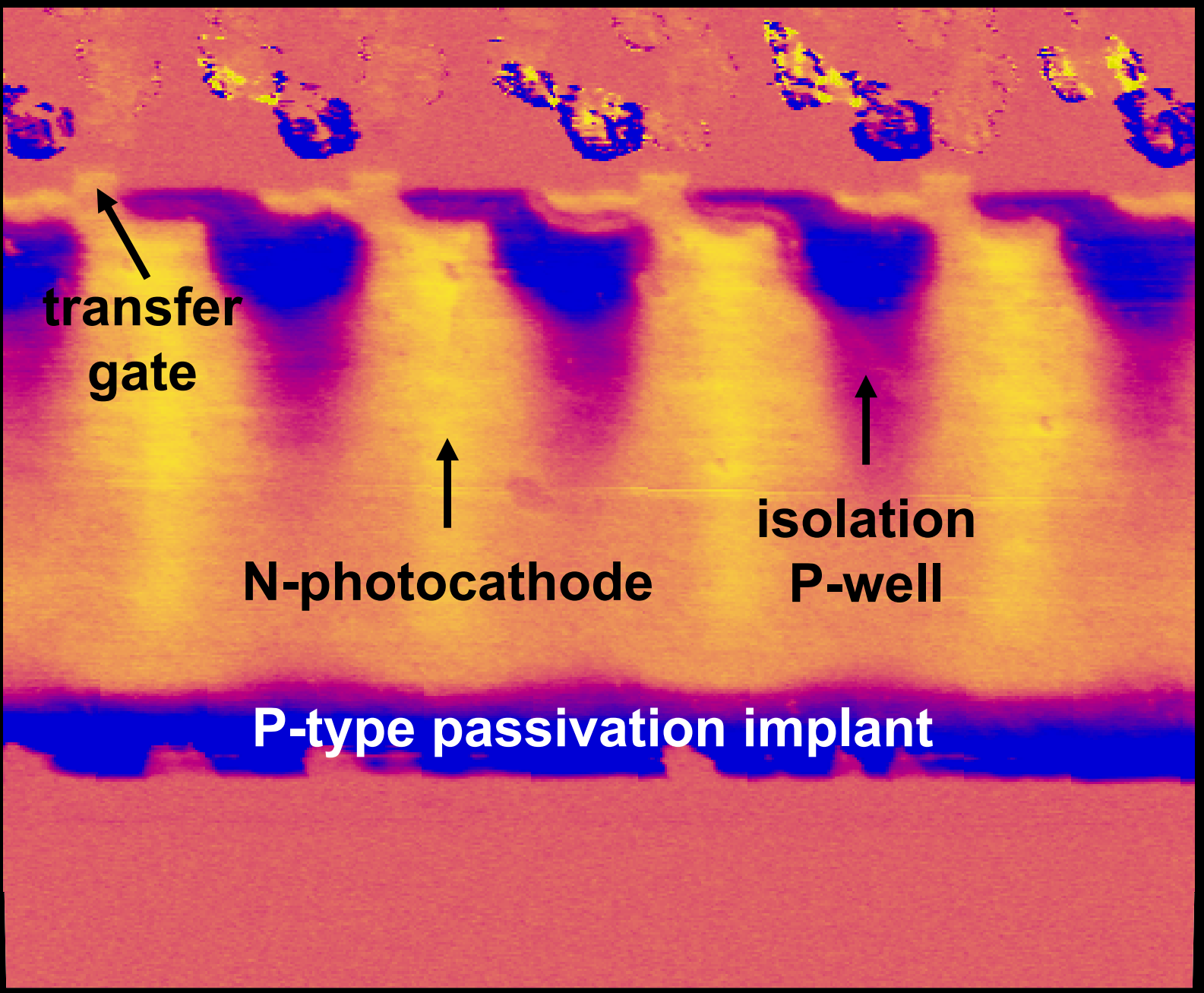

Light
Pipe
chipworks

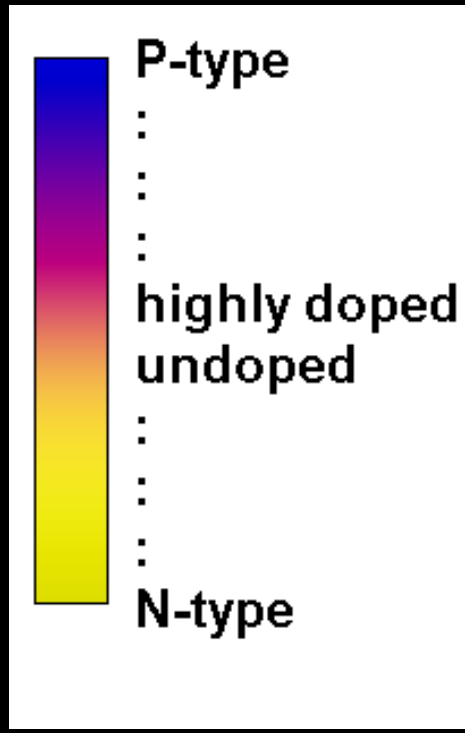
Back-Side Illumination

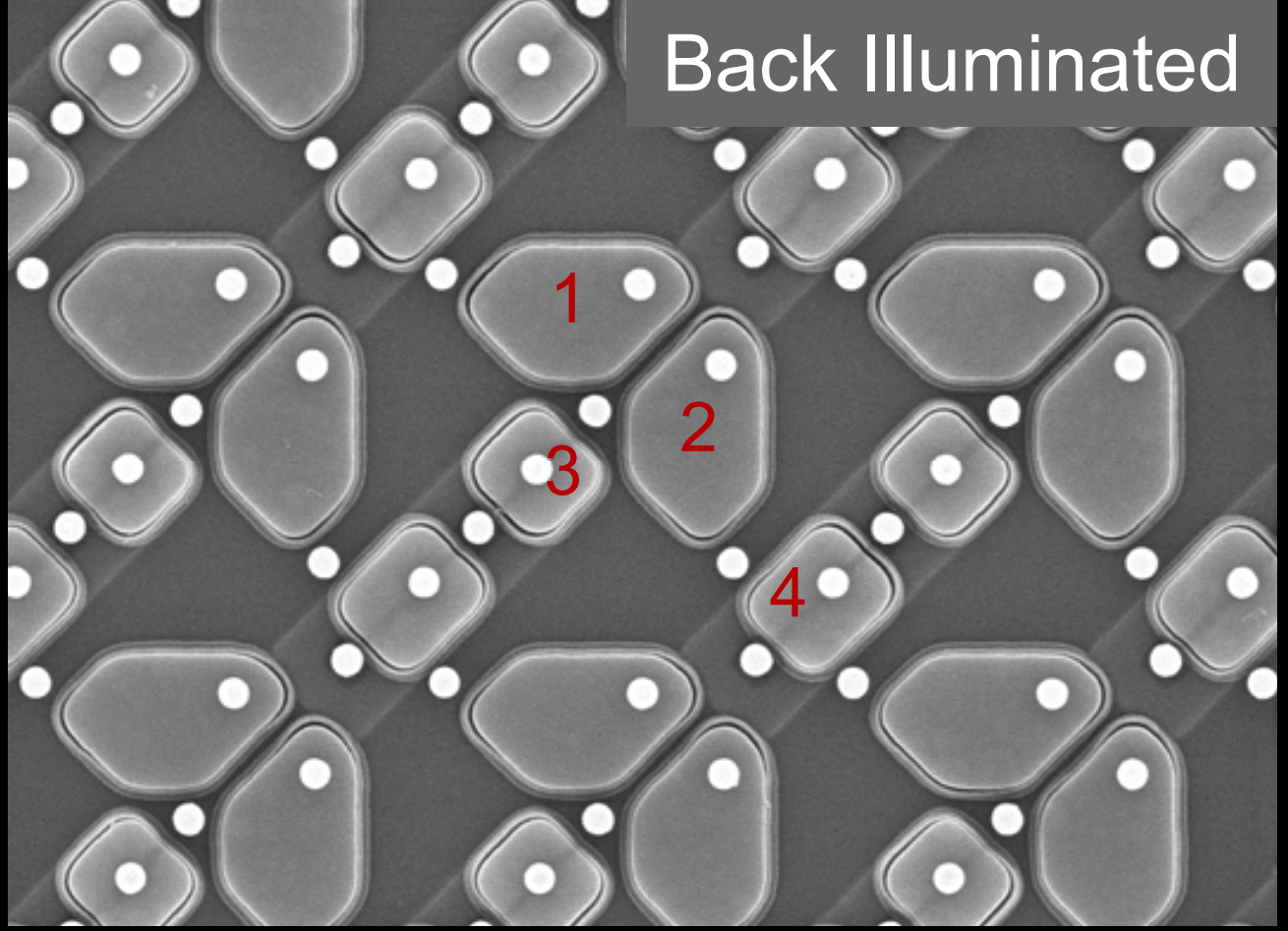

Bias Ring
HV Ring
PMOS
NMOS
BOX(Buried Oxide)
n+
BPW(Buried p-Well)
p+
Si Sensor
(High Resistivity
Substrate)
n-
Radiation

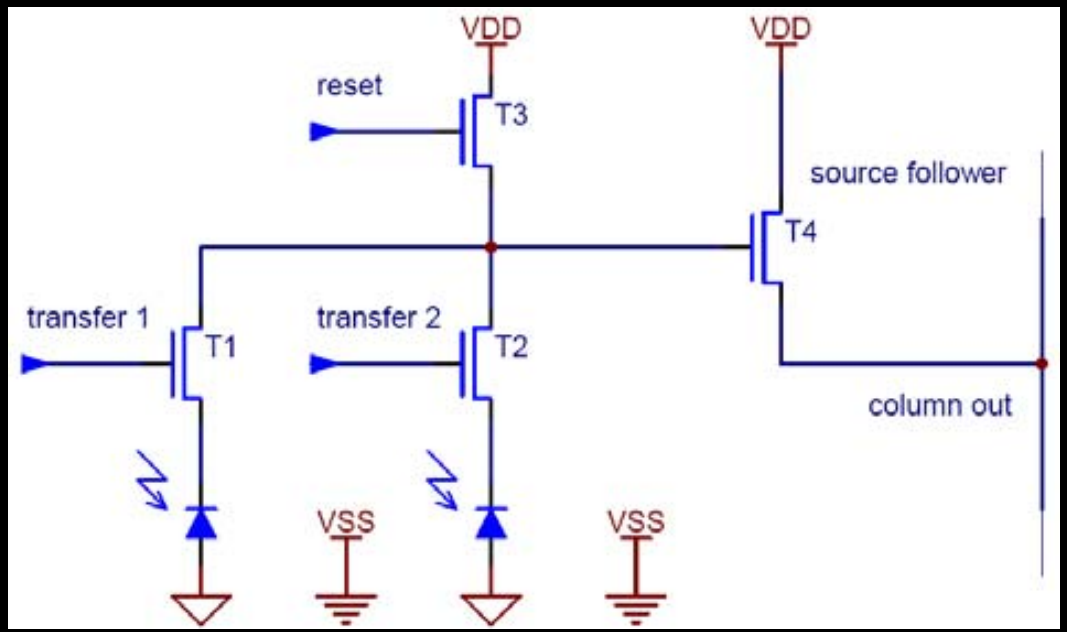

BSI Substrate
chipworks


ML
CF
Metal shield
PD
Metal

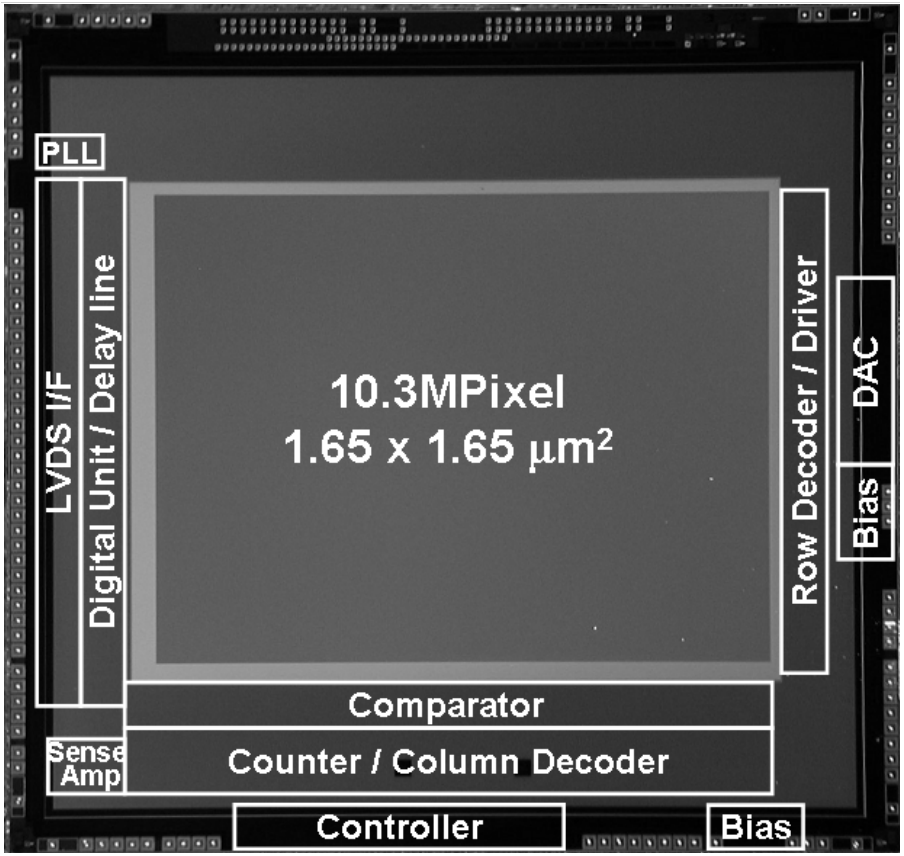

transfer
gate
N-photocathode
isolation
P-well
P-type passivation implant

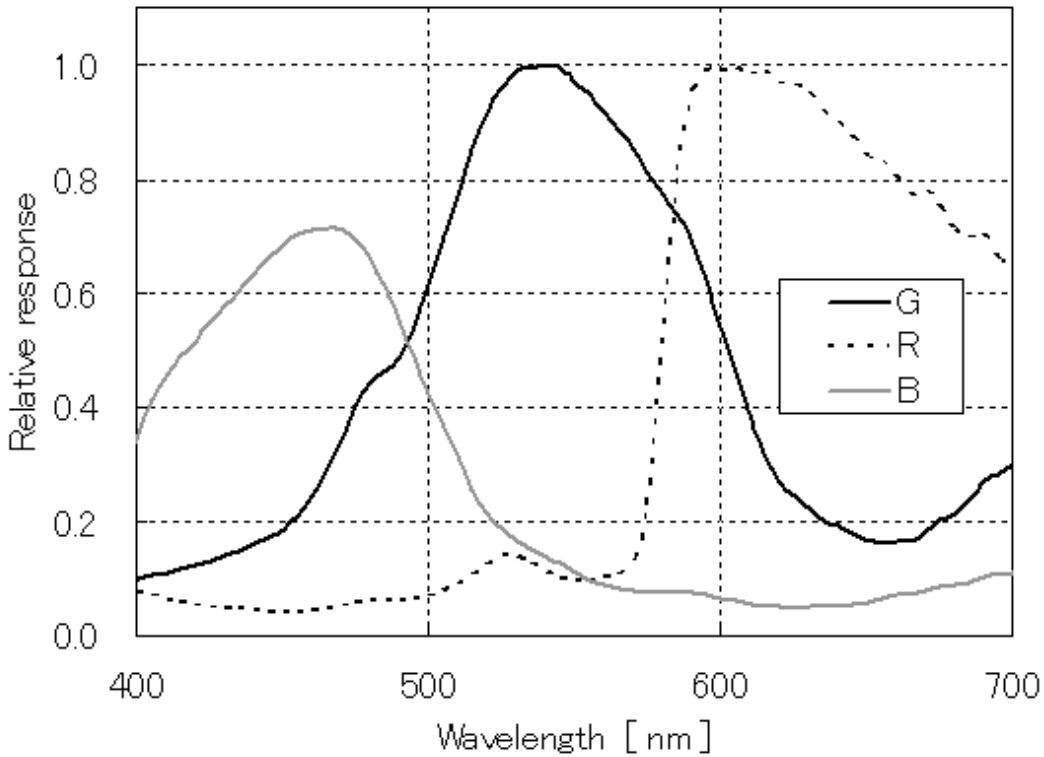

P-type
highly doped
undoped
N-type

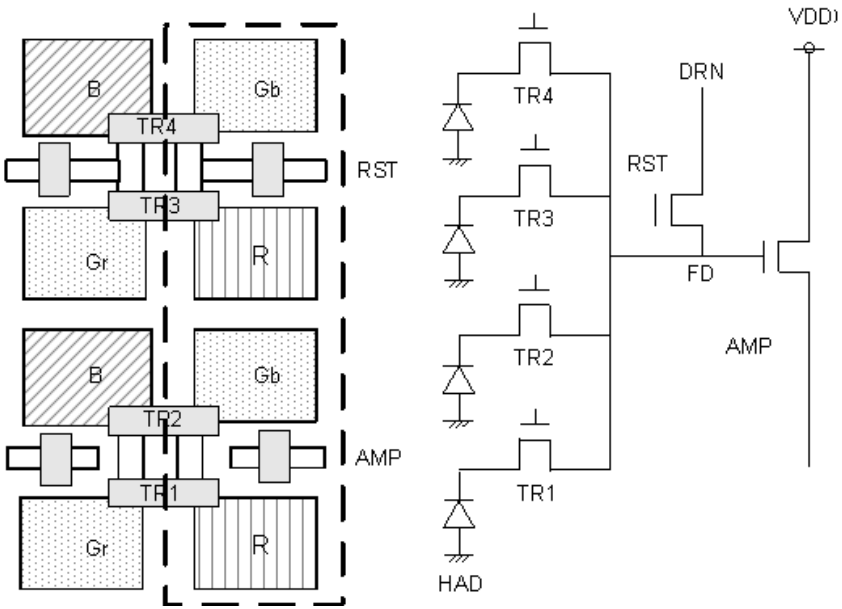


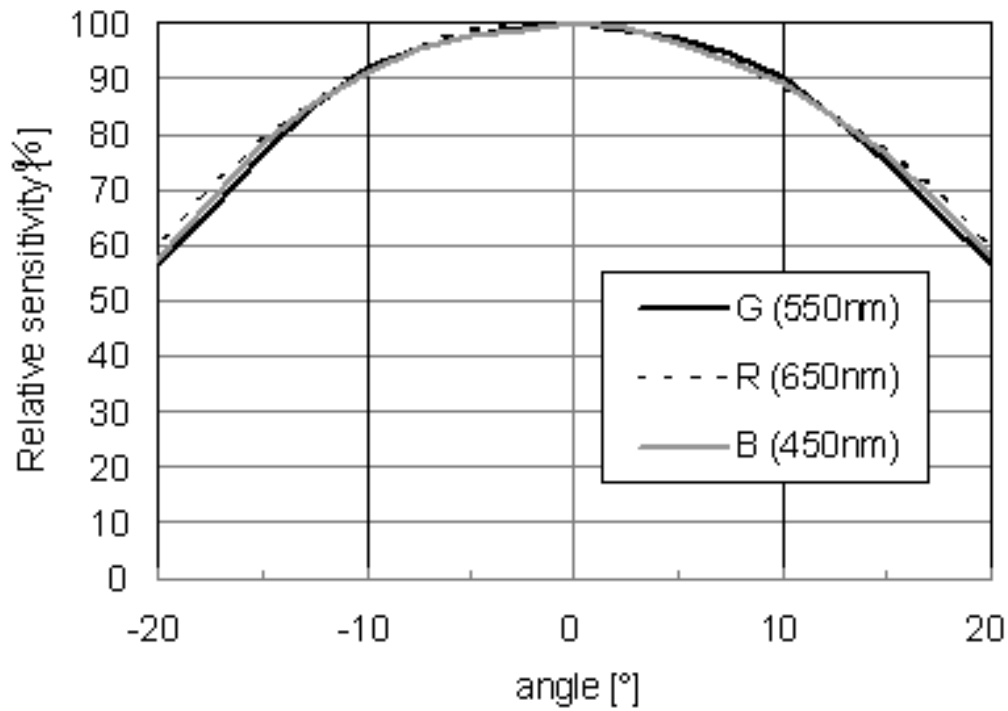


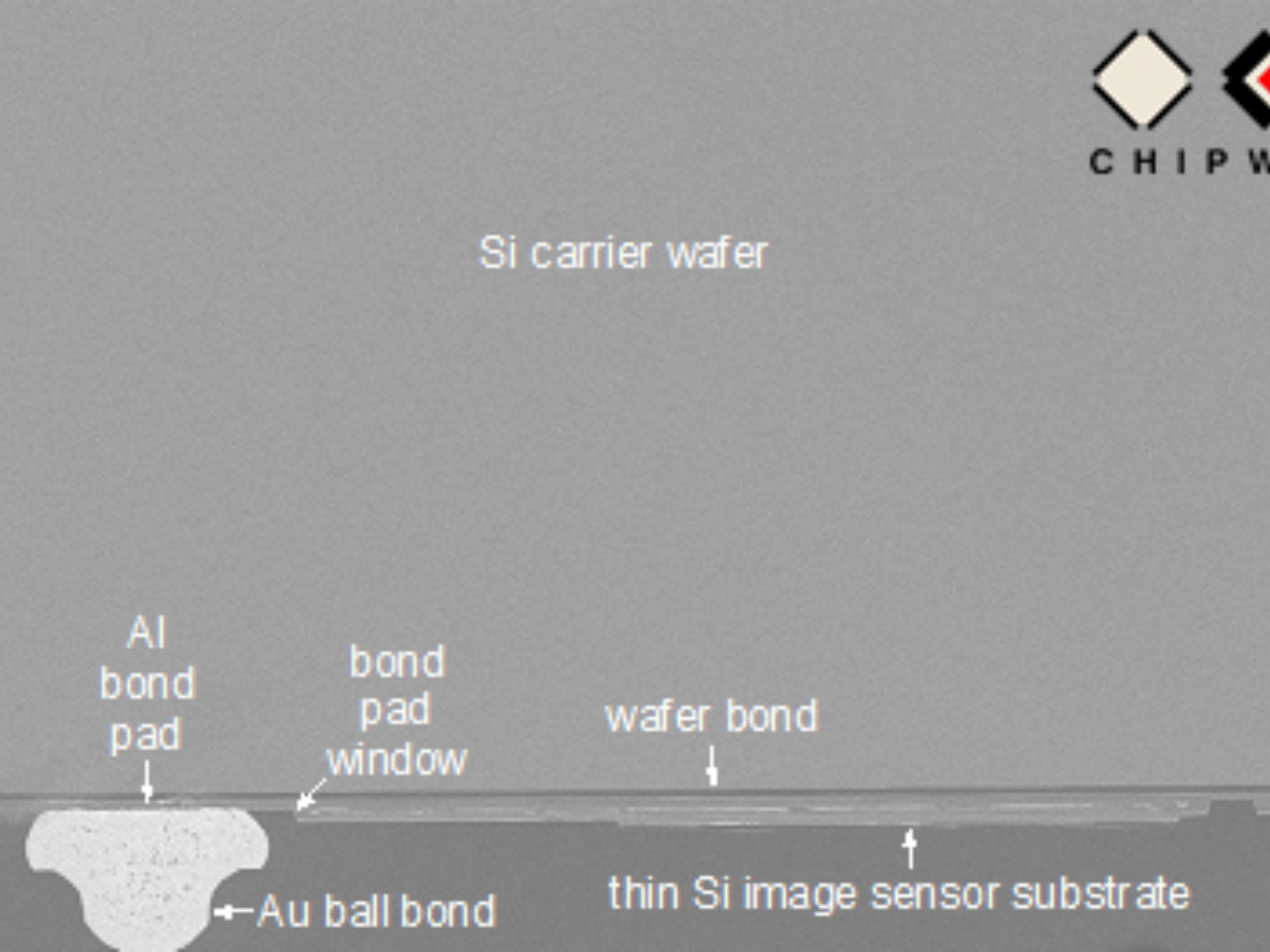
2.0 effective transistors per pixel.

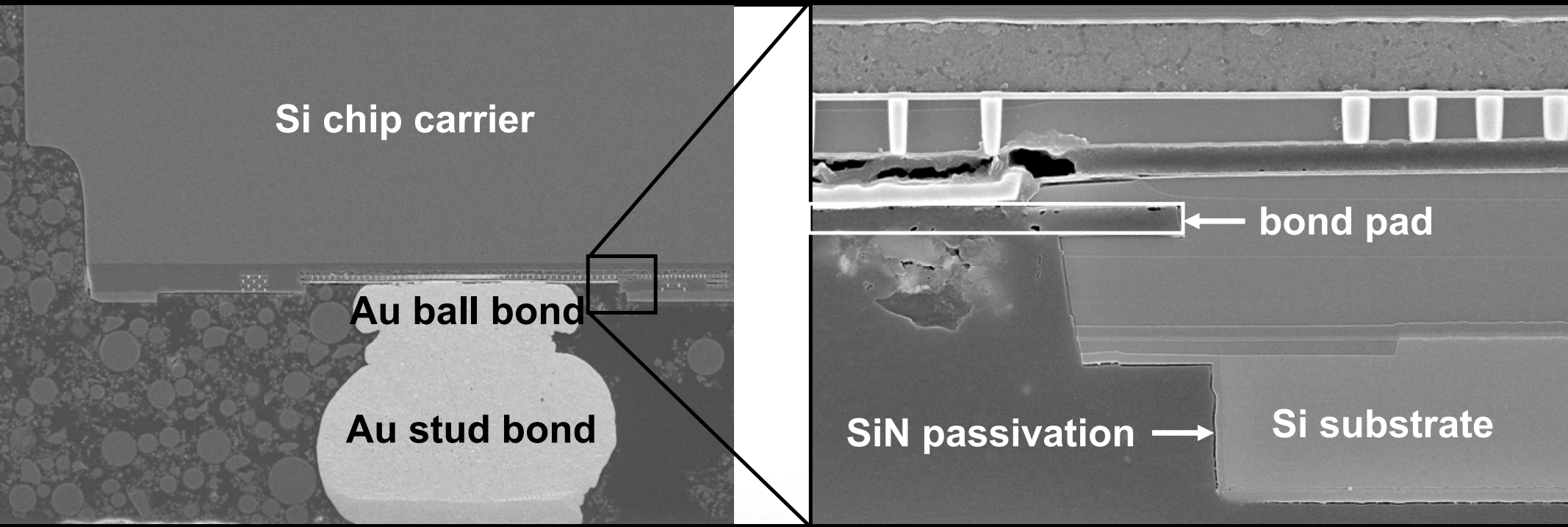

PLL
LVDS I/F
Digital Unit / Delay line
10.3MPixel
1.65 x 1.65 μm²
Row Decoder / Driver
DAC
Bias
Comparator
Sense Amp
Counter / Column Decoder
Controller
Bias


Relative response
1.0
0.8
0.6
0.4
0.2
0.0
400
500
600
700
Wavelength [nm]
G
R
B


B
Gb
TR4
RST
TR3
Gr
R
B
Gb
TR2
AMP
TR1
Gr
R
TR4
TR3
TR2
TR1
HAD
RST
DRN
VDD
FD
AMP

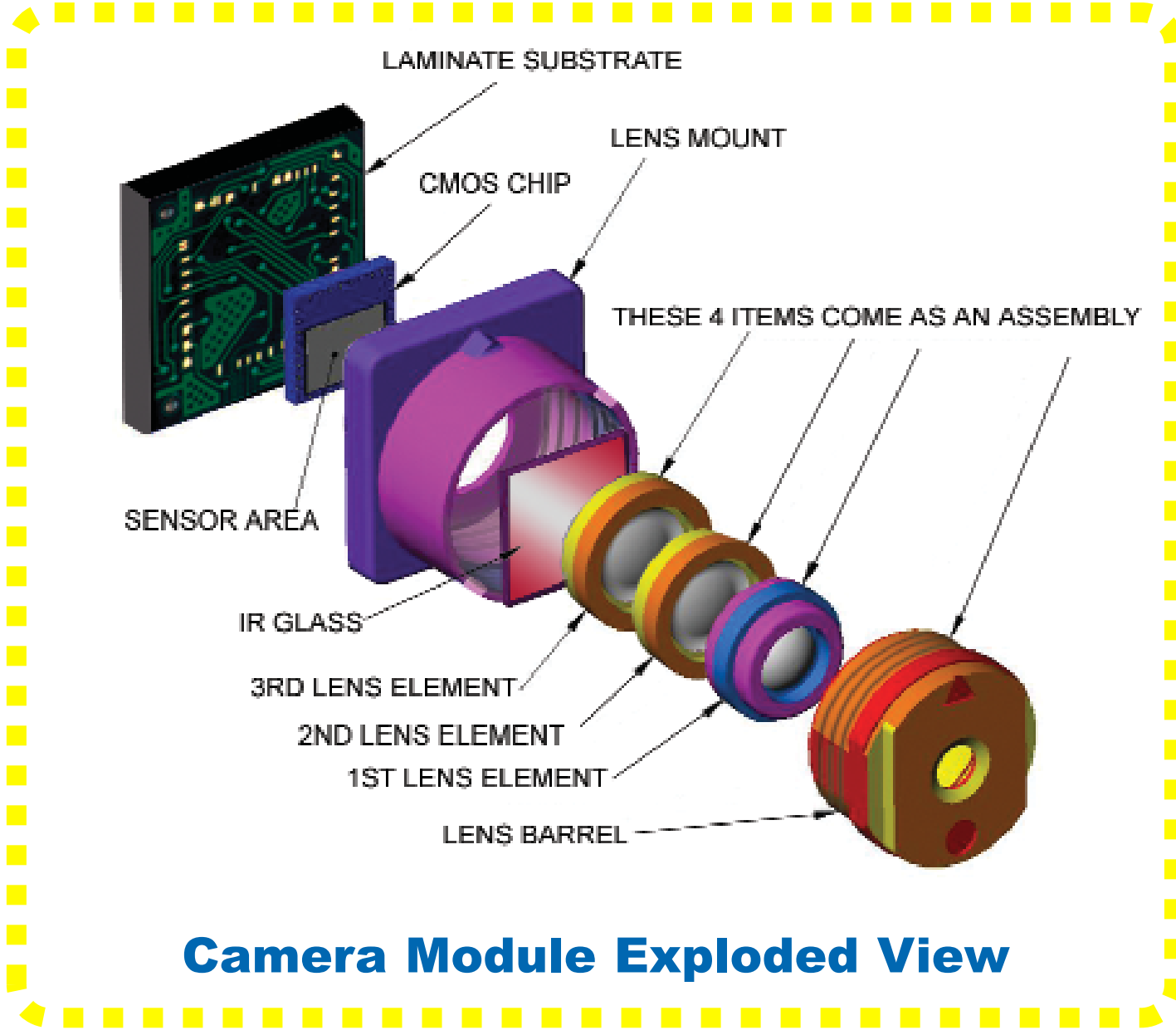

Relative sensitivity [%]
100
90
80
70
60
50
40
30
20
10
0
-20
-10
0
10
20
angle [°]
G (550nm)
R (650nm)
B (450nm)


Si carrier wafer
Al
bond
pad
bond
pad
window
wafer bond
Au ball bond
thin Si image sensor substrate

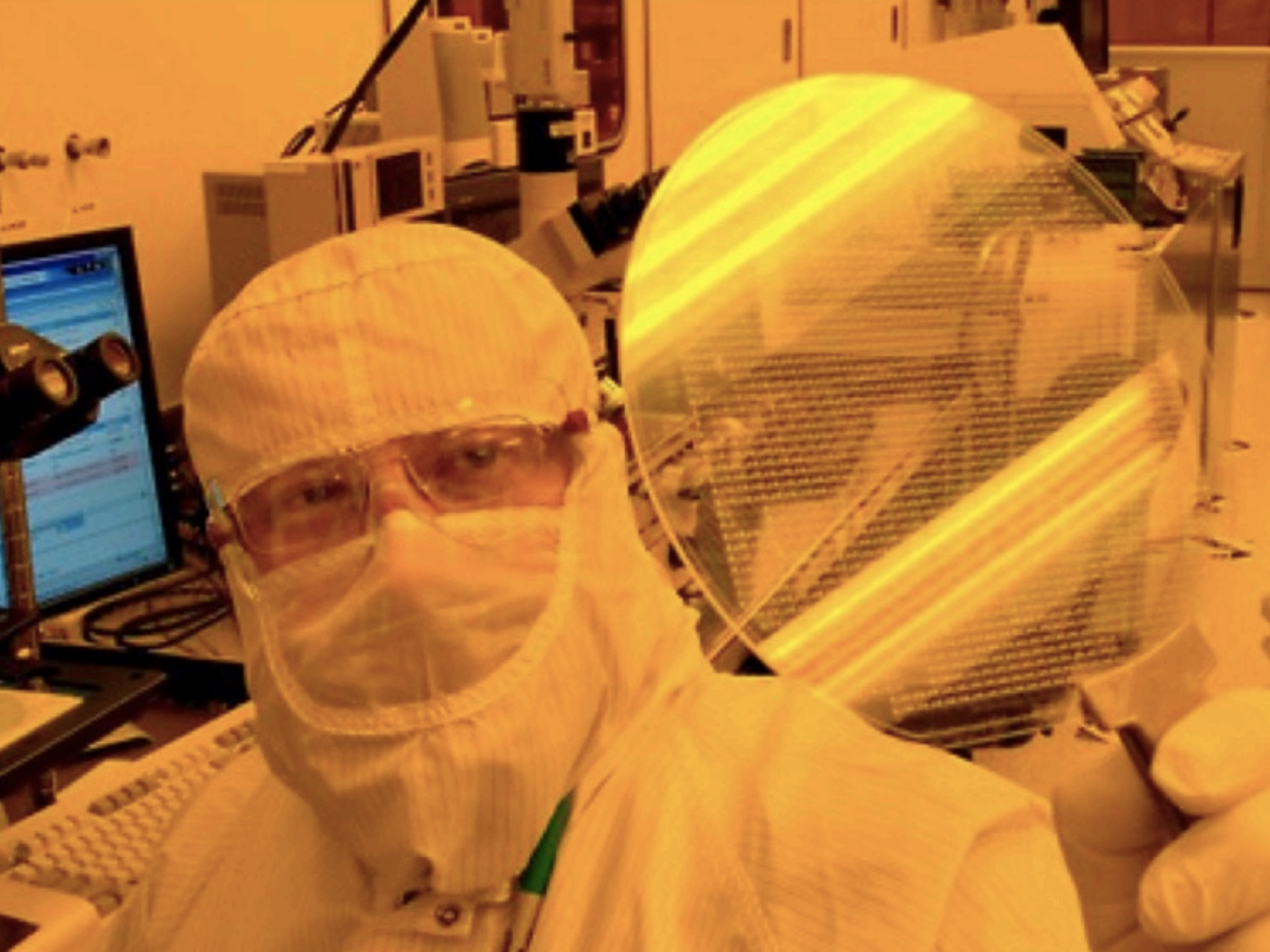

Si chip carrier
Au ball bond
Au stud bond
bond pad
SiN passivation
Si substrate

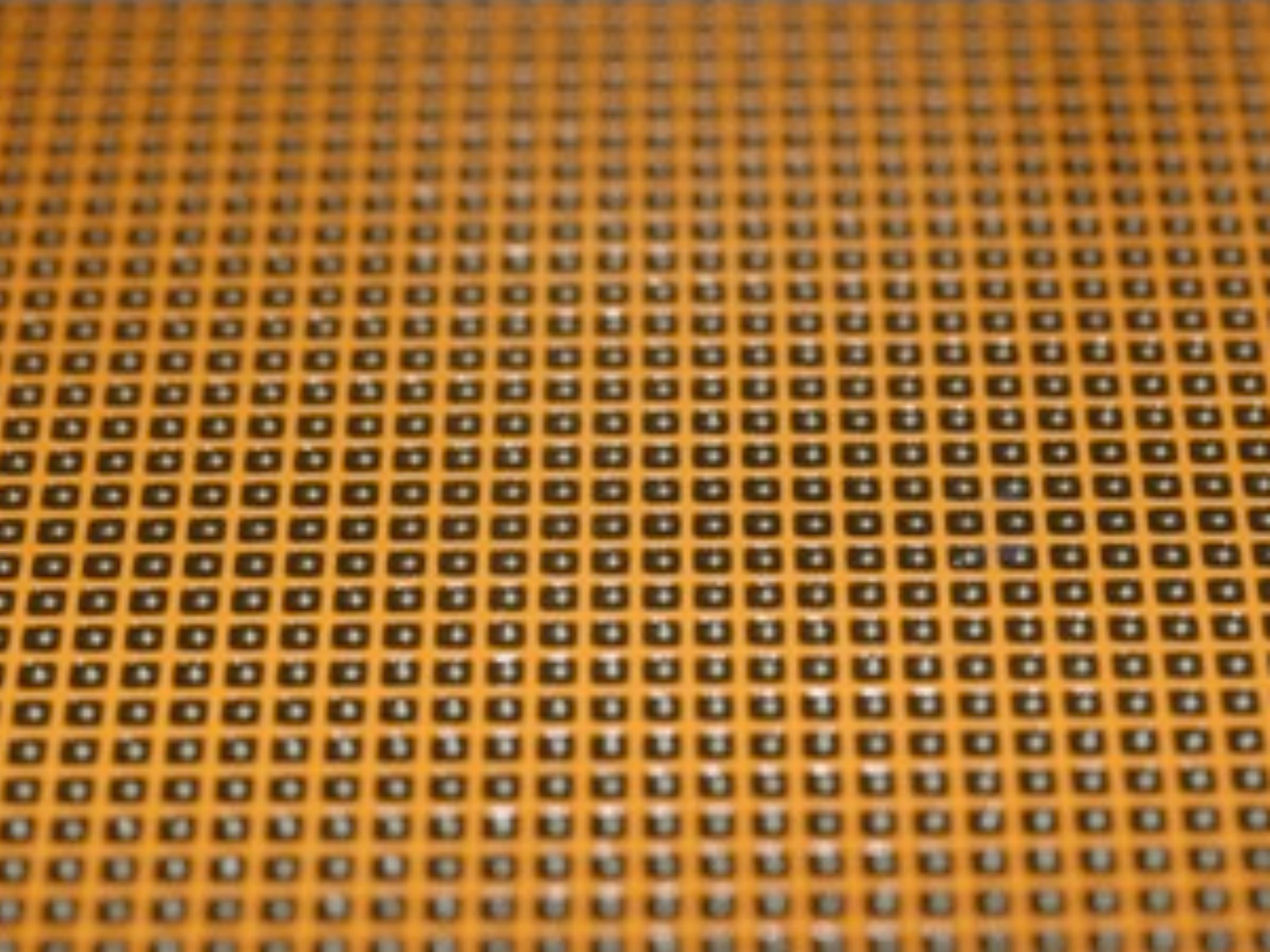
Wafer-Scale Packaging

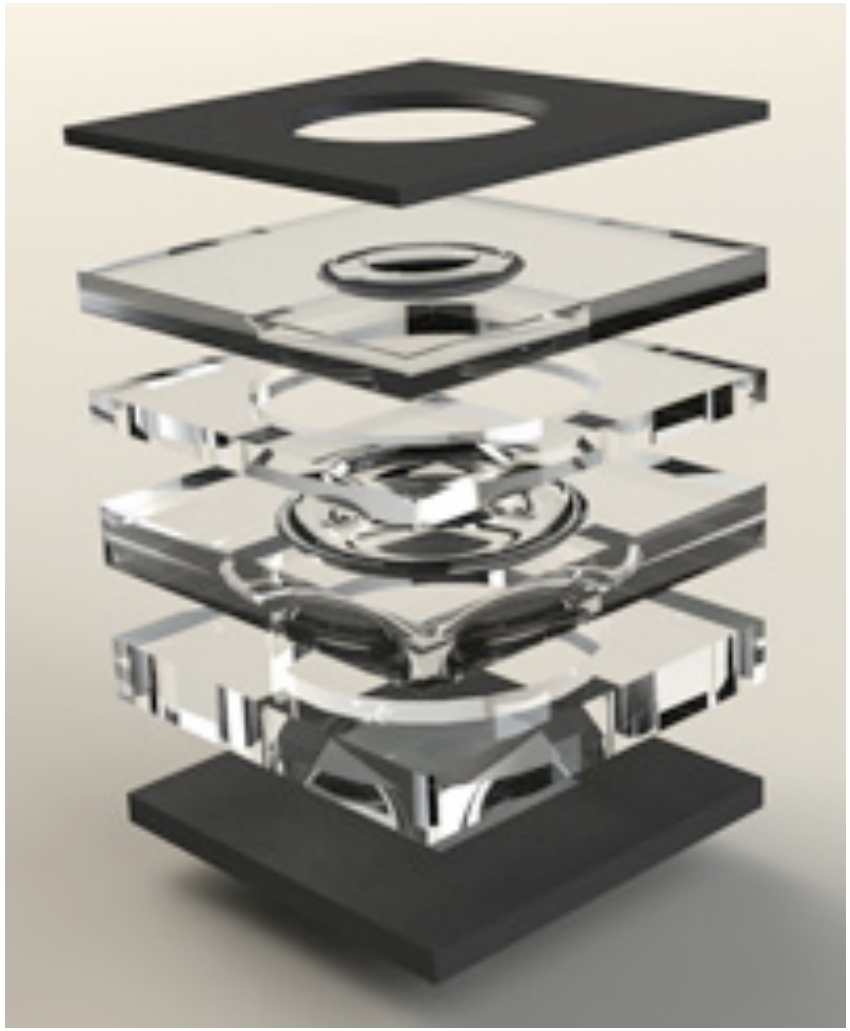
Fixed focus camera module.

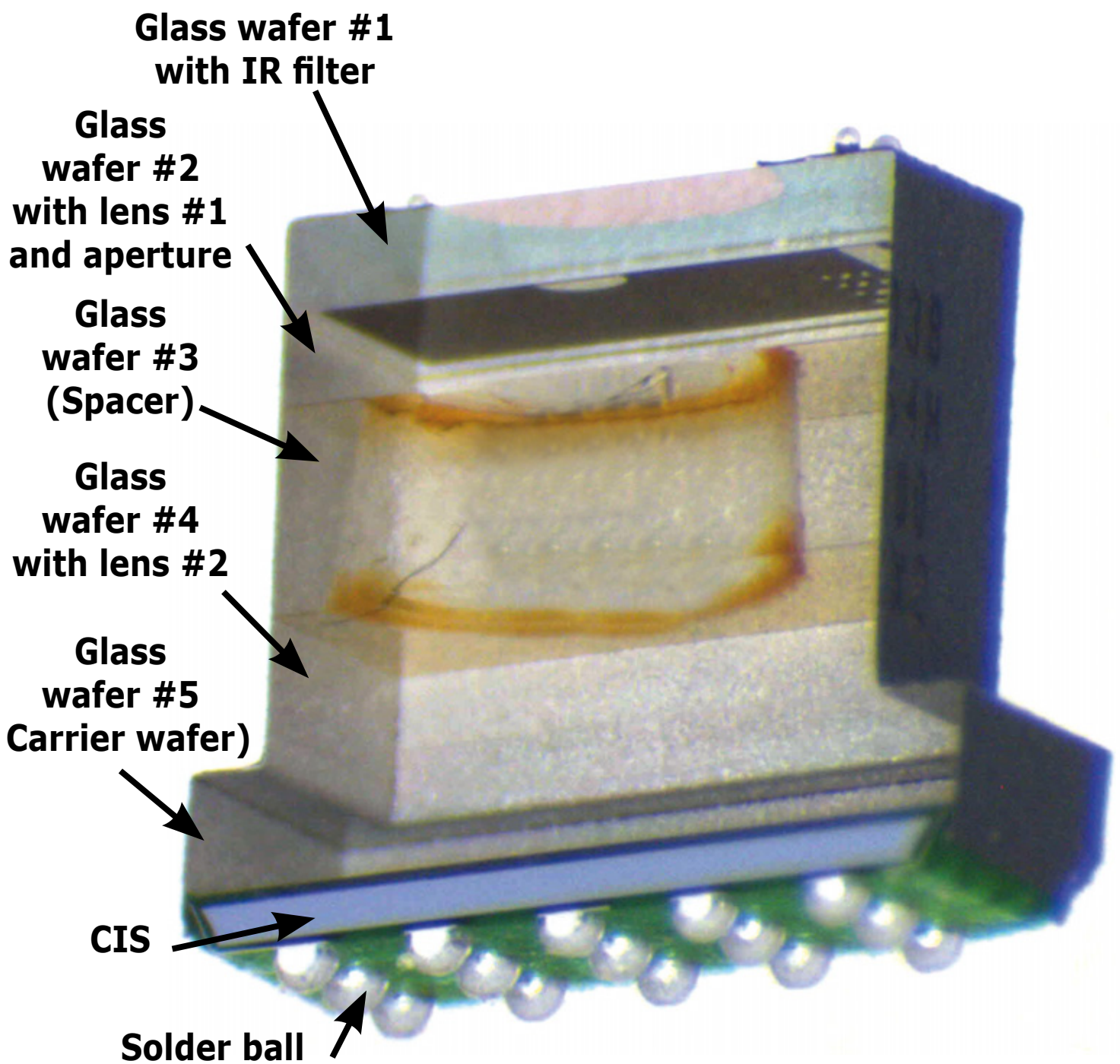


Camera Module Exploded View

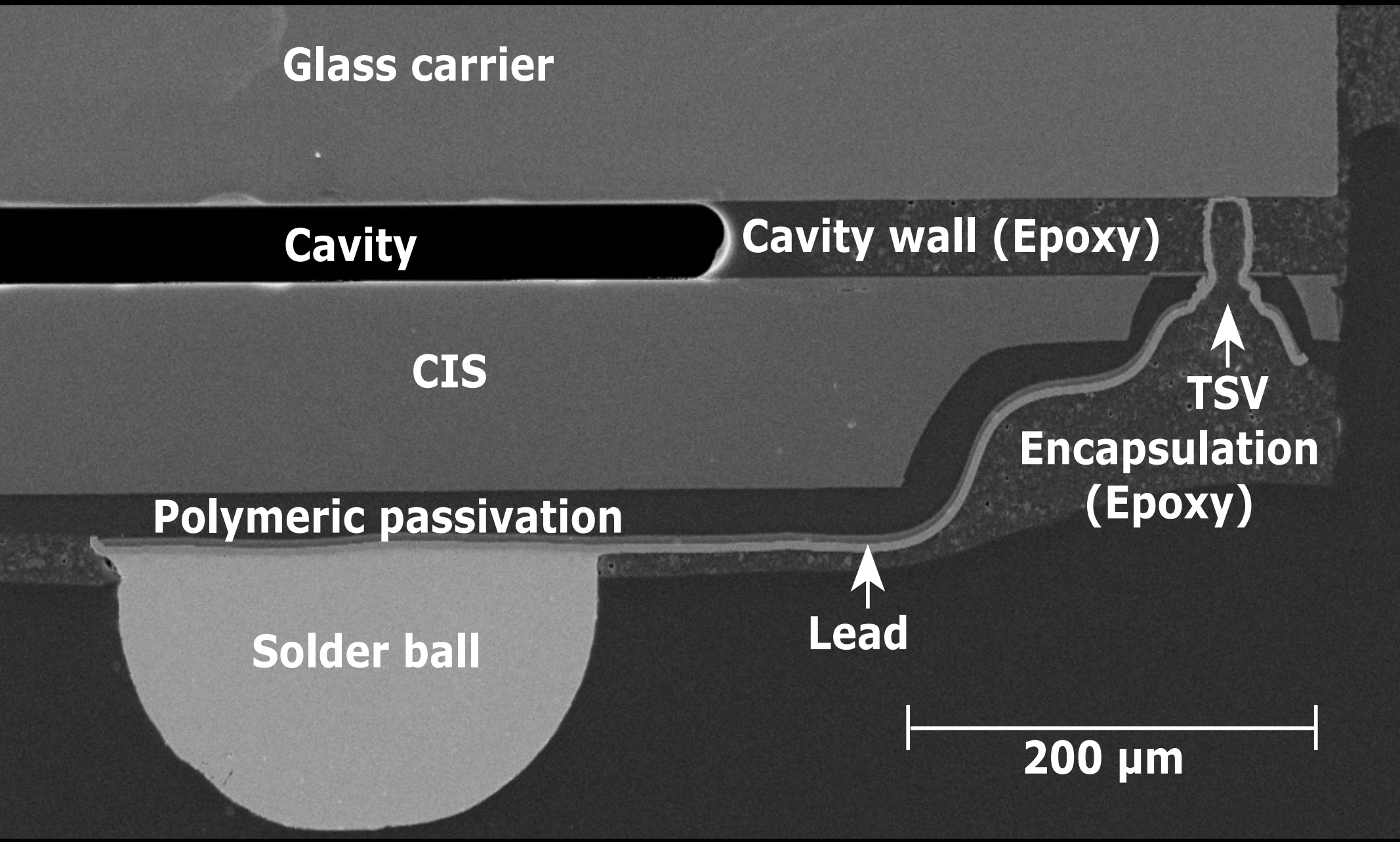


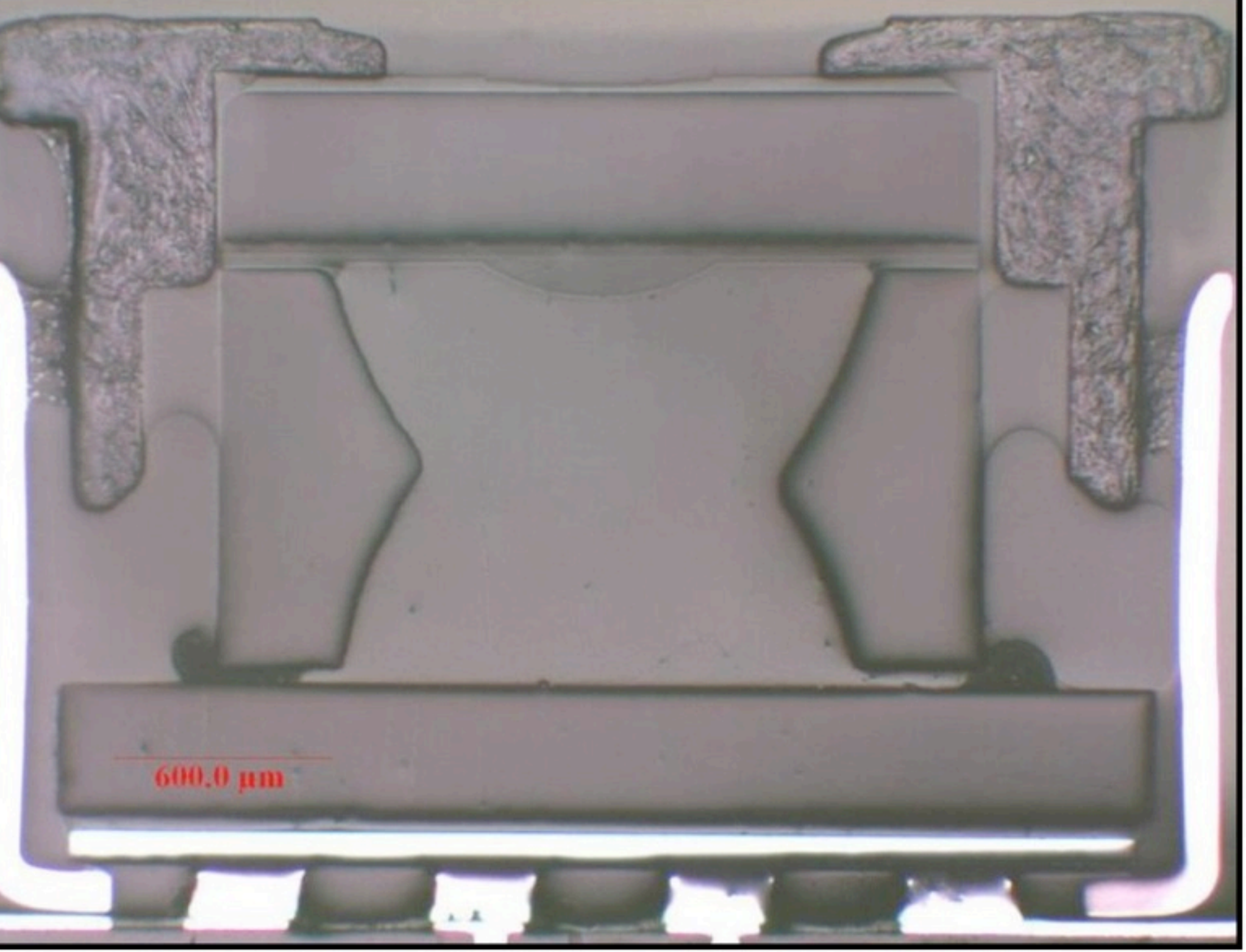


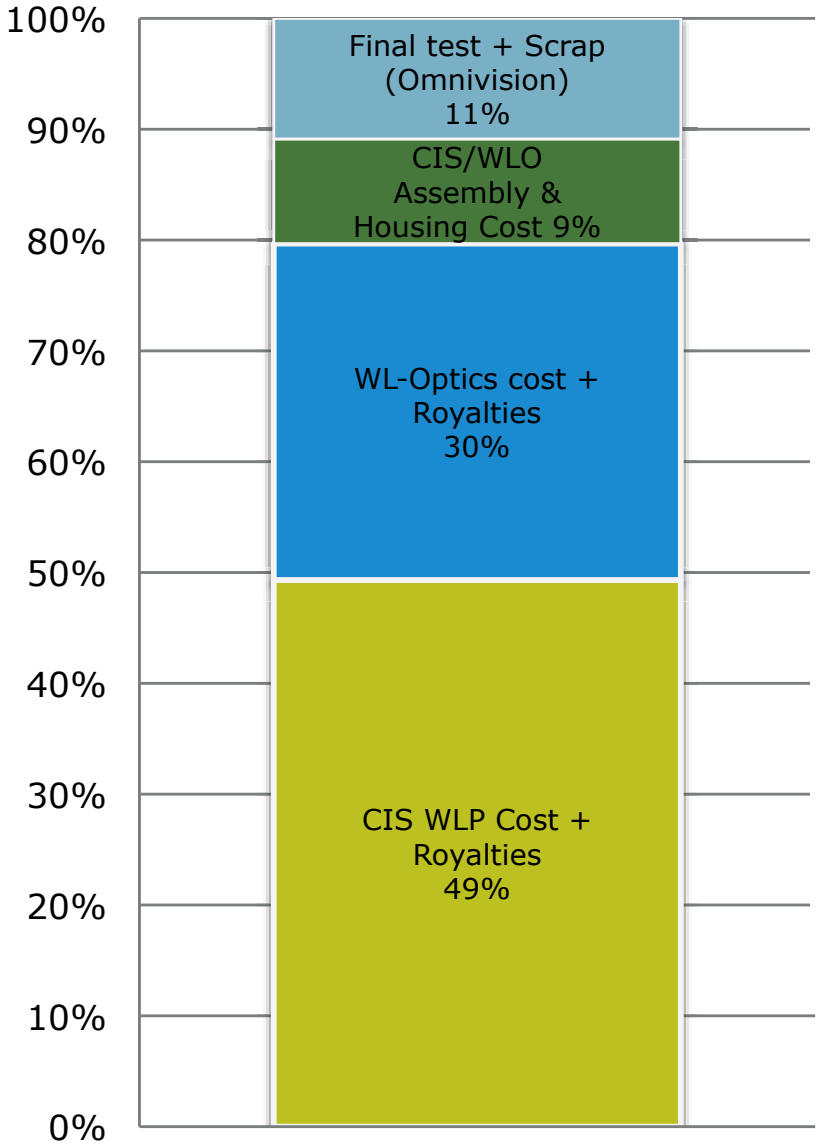


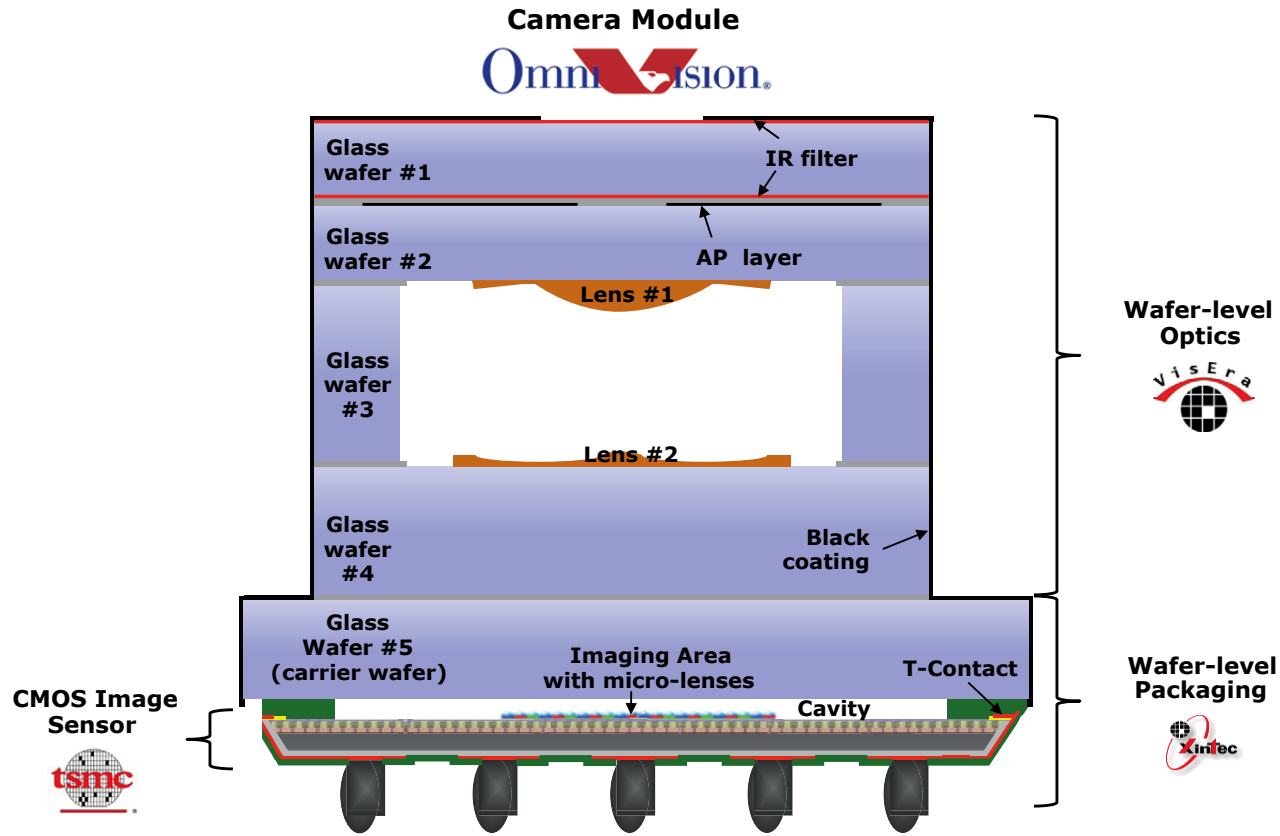


OmniVision OVM7692 cross-section
(Courtesy of System Plus Consulting)


Glass carrier
Cavity
Cavity wall (Epoxy)
CIS
TSV
Encapsulation
(Epoxy)
Polymeric passivation
Lead
Solder ball
200 µm

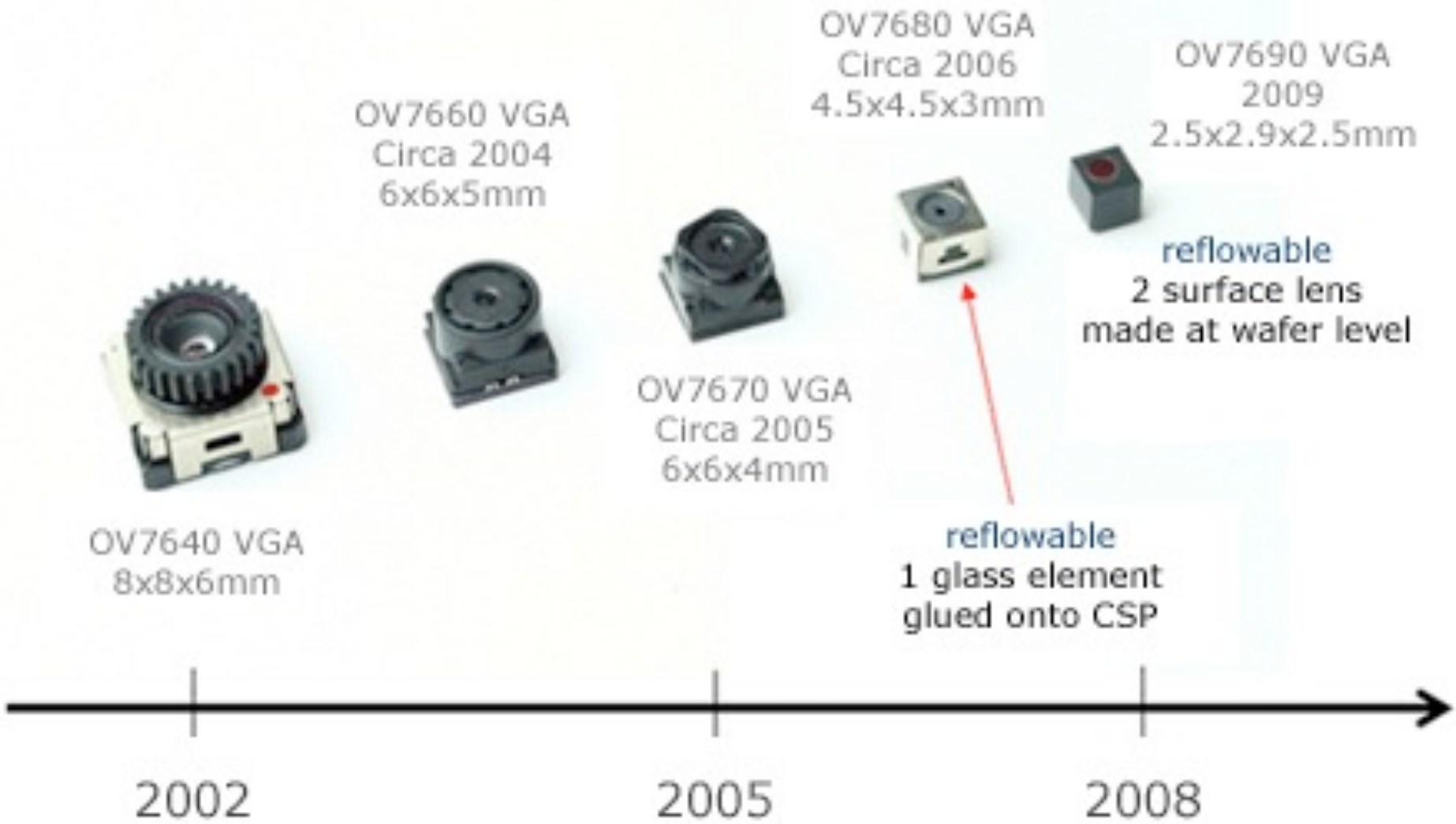

600.0 µm


100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Final test + Scrap (Omnivision) 11%
CIS/WLO Assembly & Housing Cost 9%
WL-Optics cost + Royalties 30%
CIS WLP Cost + Royalties 49%


Camera Module
OmniVision
Glass wafer #1
IR filter
Glass wafer #2
AP layer
Lens #1
Glass wafer #3
Lens #2
Glass wafer #4
Black coating
Glass Wafer #5 (carrier wafer)
Imaging Area with micro-lenses
T-Contact
Cavity
CMOS Image Sensor
tsmc
Wafer-level Optics
VisEra
Wafer-level Packaging
Xintec

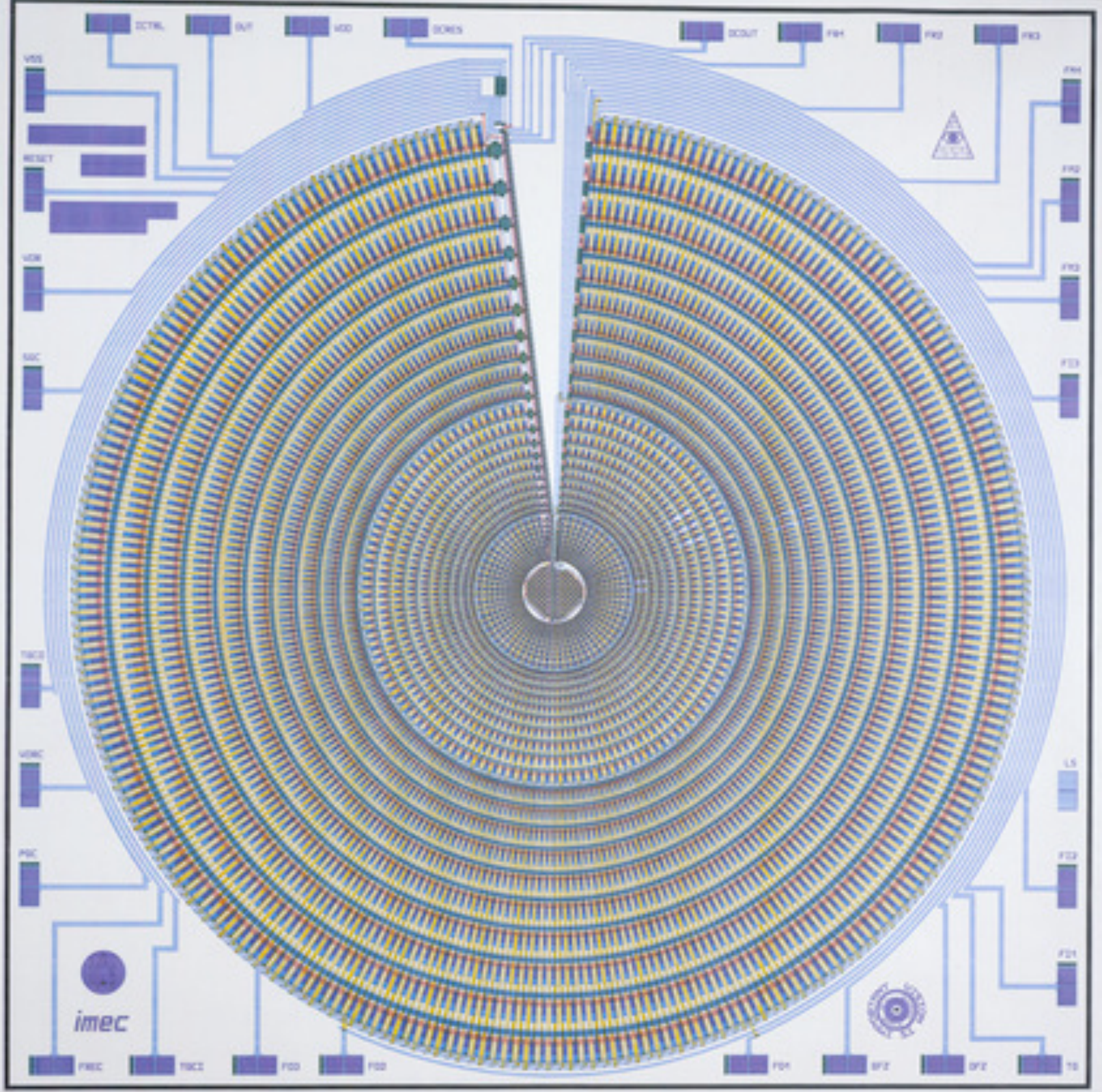

UNITED
LIBERTY

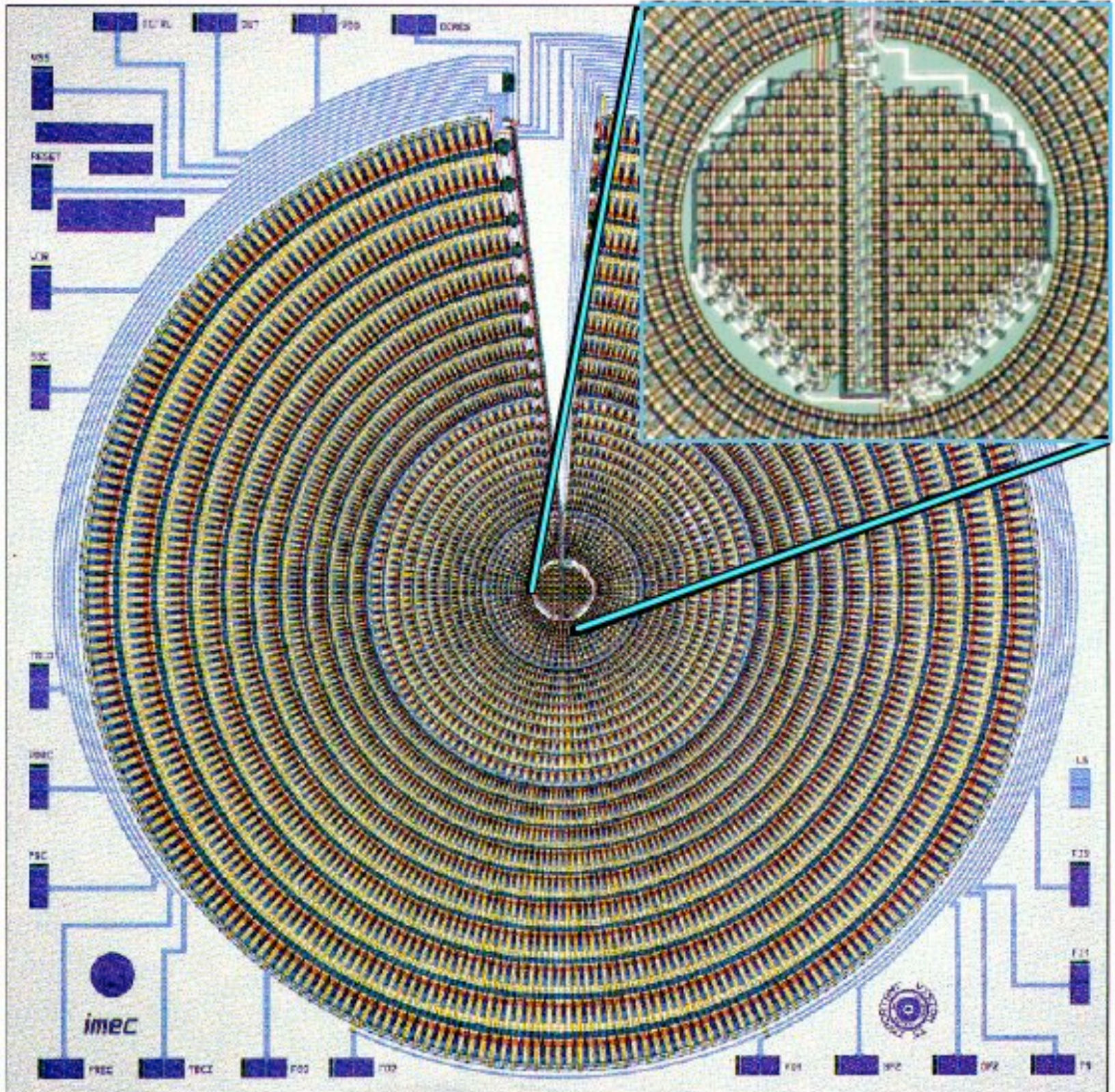
evolution of the mobile phone camera



Camera Modules ...

- Design shown is “dominant paradigm”.
- Evolves with every product generation.
- Some research projects and start-ups focus on the evolution.
- Others shoot for “revolutionary jump”


imec


imec