Image Sensor IC Design

(EE5215)

Lecturer & TA

- EE5215 Image Sensor IC Design
- Classroom: 炯朗館 208, T5T6R6
- Instructor: 謝志成 老師
  - Office hours: Tue. 12:30~1:20pm or by reservation. @ 台達館837
  - Email : cchsieh@ee.nthu.edu.tw
  - Website: http://www.ee.nthu.edu.tw/cchsieh
- Teaching Assistant :
  - 吳宗瑋 tzungwei1118@gmail.com
  - 王伯胤 wangboyin@gmail.com
  - 王群晰 generouslywang1009@gmail.com
  - 陳奕禎 jm0987123@gmail.com

Course Description

- Course description:

  This course is organized on selected topics in the design and analysis of mixed-signal IC design for CMOS image sensor. It covers quantitative analyses, design considerations and system applications from circuit and architecture viewpoints. The mixed-signal IC design and implementation of selected key blocks in CIS including analog-font-end (AFE) and analog-to-digital converter are covered.

- Topics:
  - Introduction
  - Fundamentals of CMOS Image sensors.
  - Smart Imaging and Applications
  - Analog Front End
  - Data Converter

Syllabus

- Week 1 Introduction
- Week 2 Fundamentals of CMOS image sensors.
- Week 3 Photo-detector type
- Week 4 Sensor operation and peripherals
- Week 5 Sensor characterization
- Week 6 Smart imaging and applications
- Week 7 Advanced CIS
- Week 8 Midterm project (2026/10/27)

Syllabus

- Week 9 Analog front end
- Week 10 Background of data converter
- Week 11 Digital-to-analog converter (DAC) I
- Week 12 Digital-to-analog converter (DAC) II
- Week 13 Integrating ADC
- Week 14 Pipelined ADC
- Week 15 SAR ADC
- Week 16 Final project (2026/12/22)

Grading

- Homework (4) 40%
- Midterm Project 30%

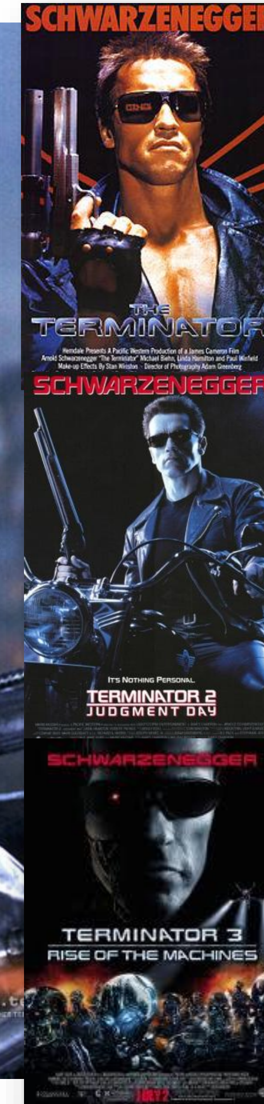
  @ week 8: 10mins / per
- Final Project 30%

  @ week 16 : 10mins / per
- In-Class performance

Background

Human Machine Interface - Vision

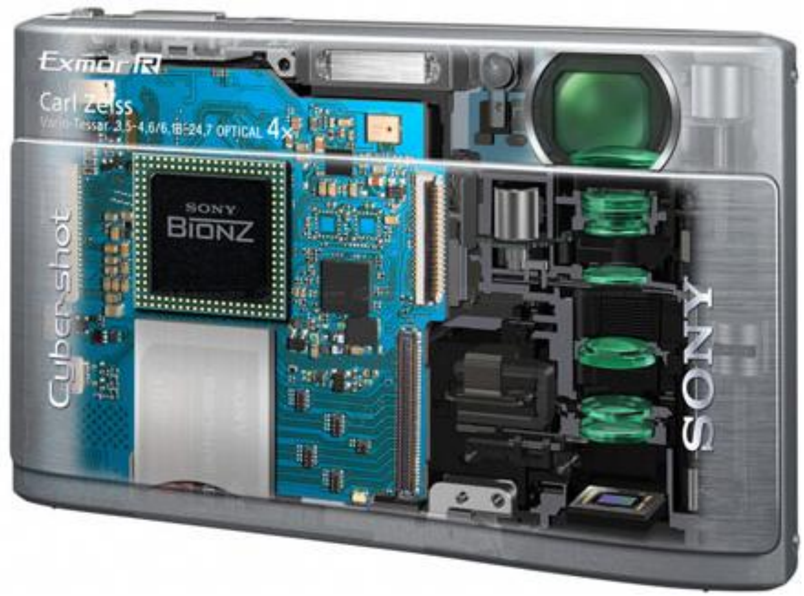
Machine Vision = Camera

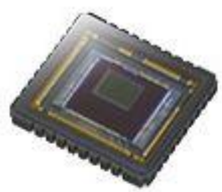


Find the Cameras in Your Life

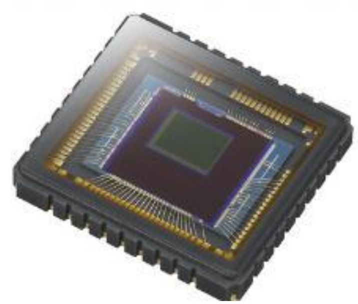
Camera : Digital Image Capture

Inside Camera / Image Sensor IC

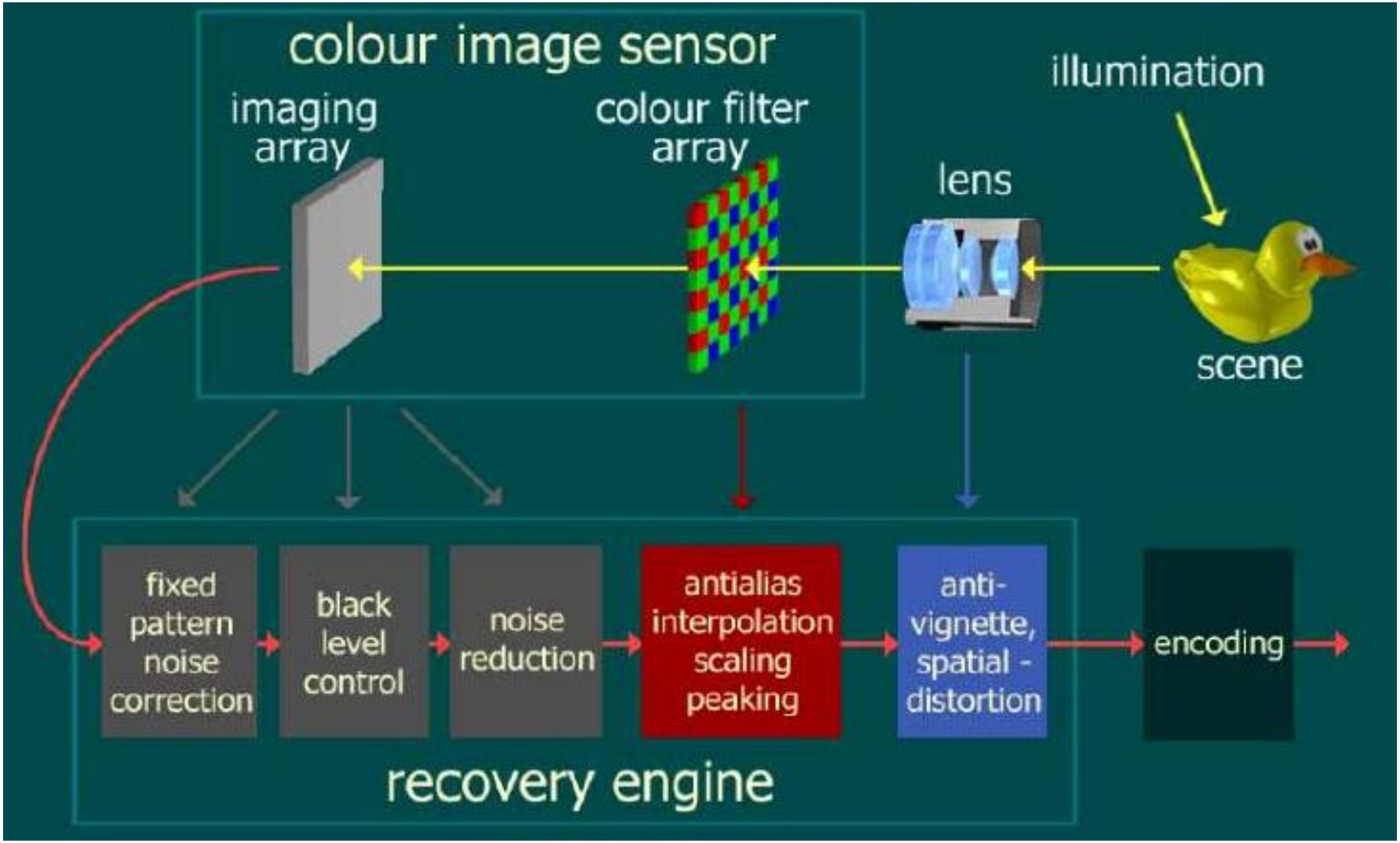




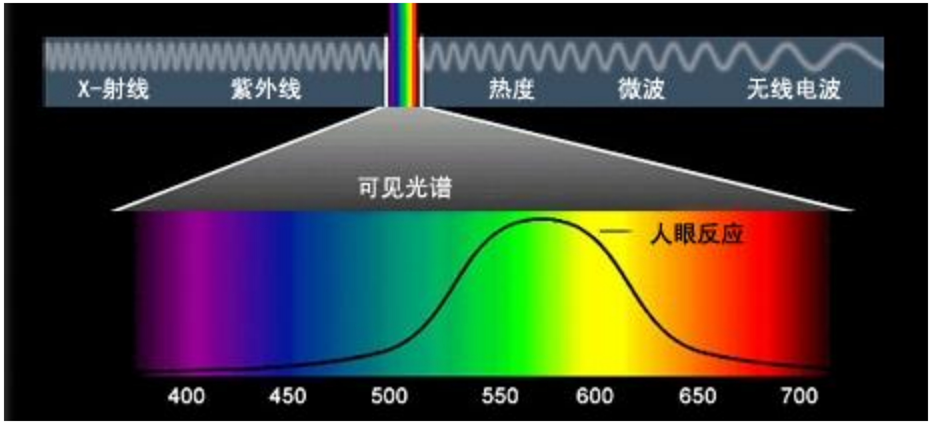
Exmor R
CMOS Sensor

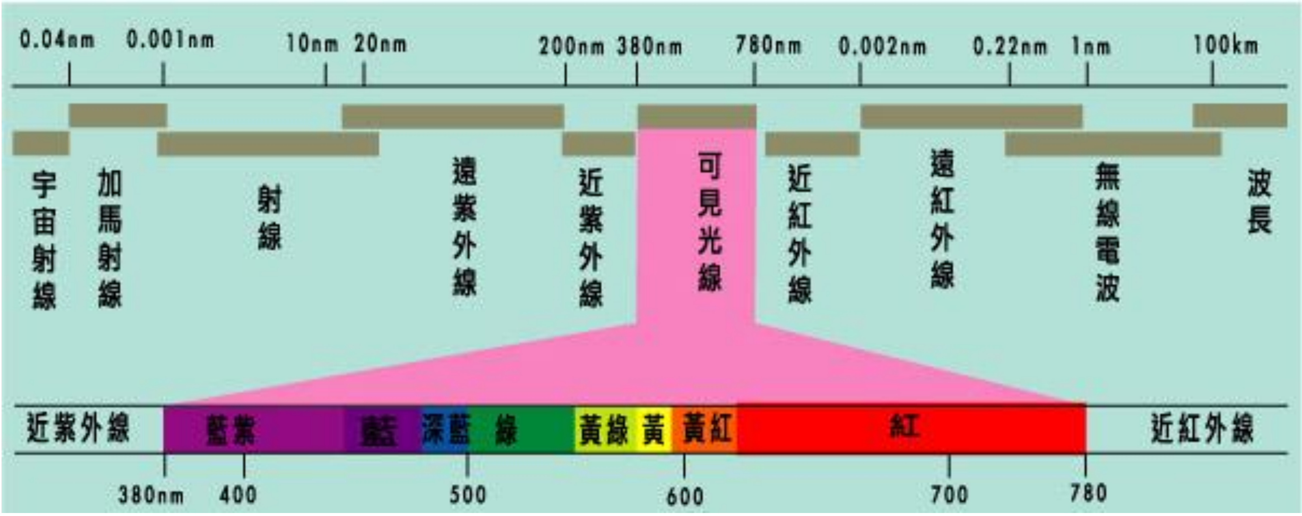


Imaging System

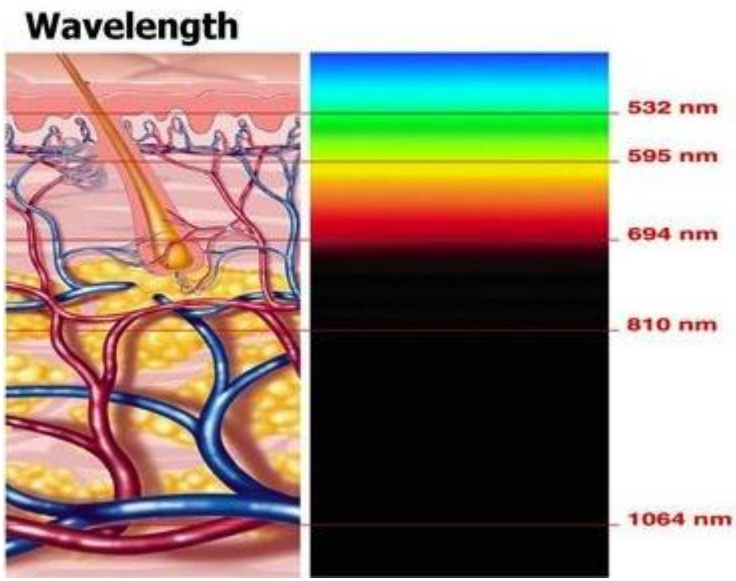


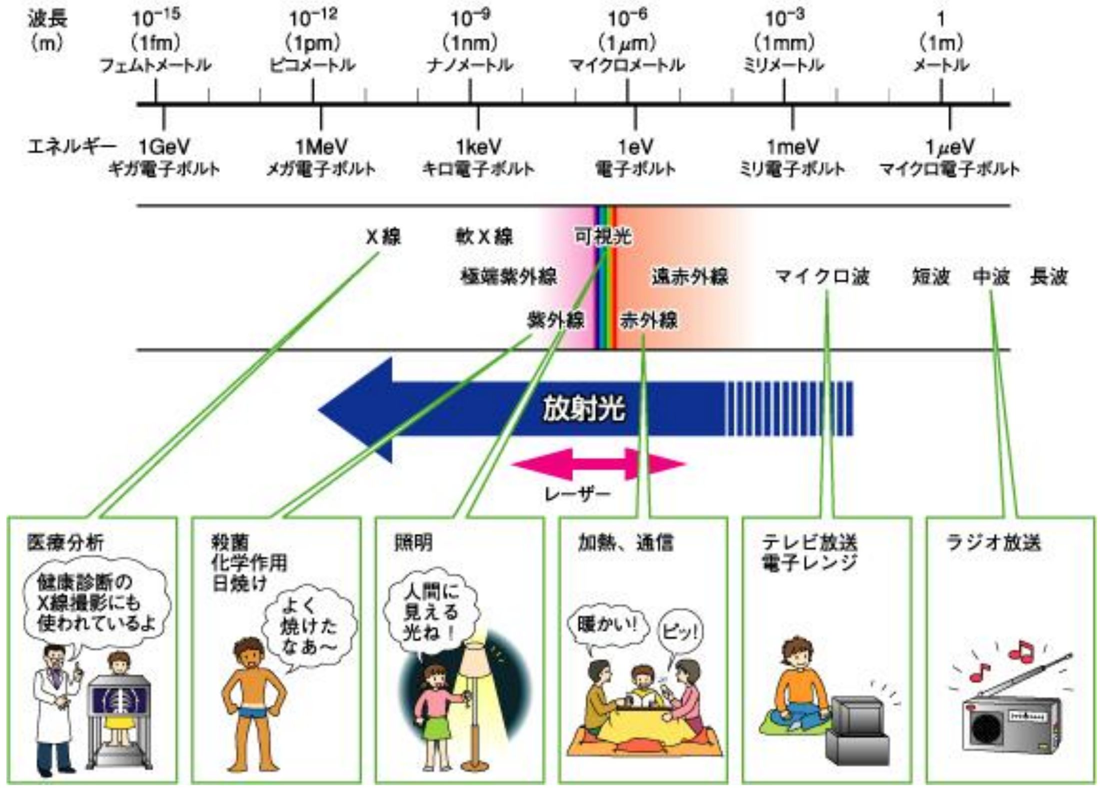
Wave Length / Color



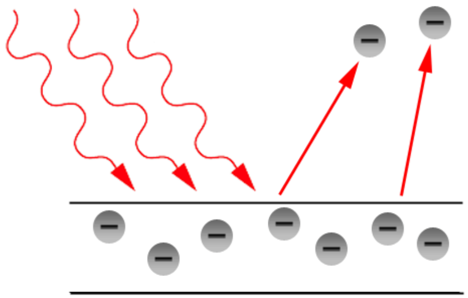


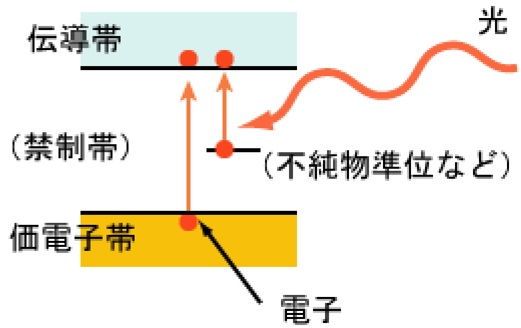
Applications with Wavelengths

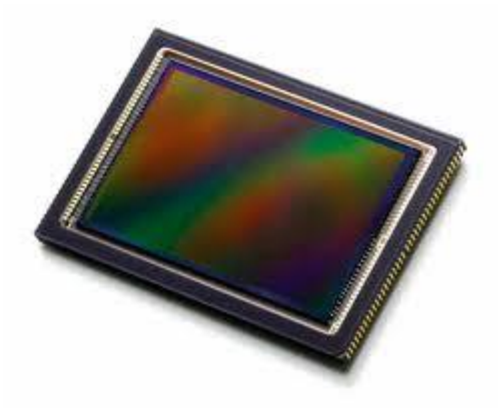


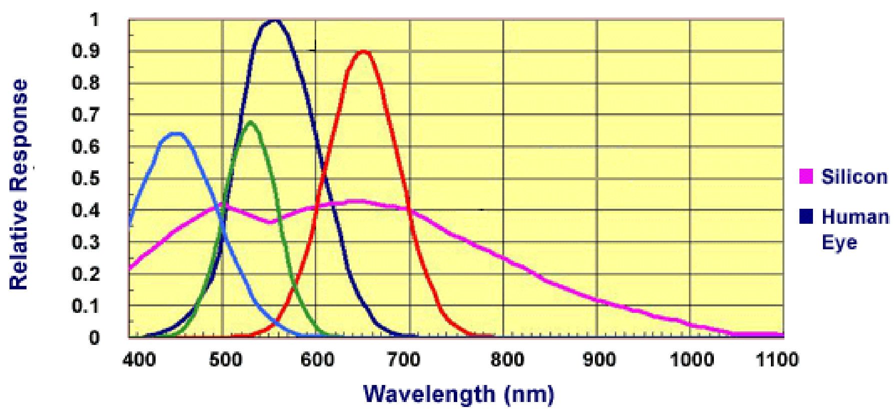


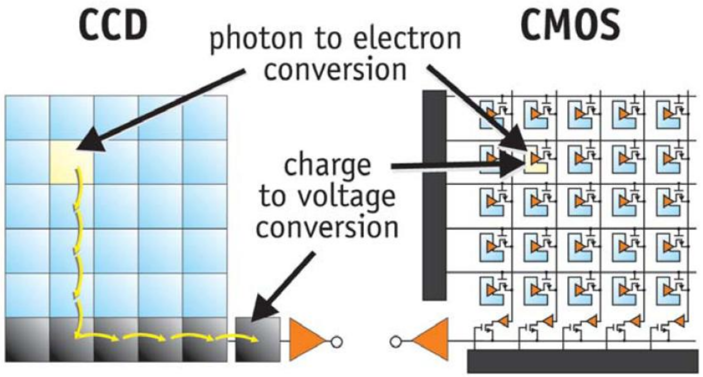
Photoelectric Effect in Silicon











CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

Inside Image Sensor IC

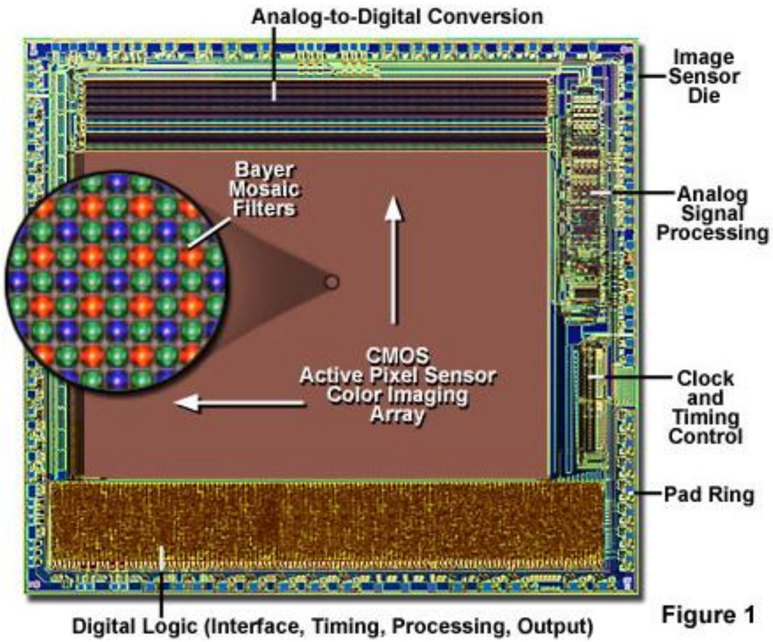


Figure 1

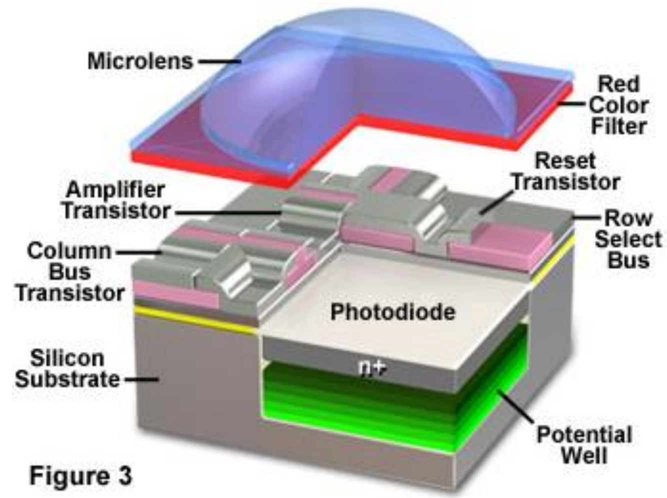
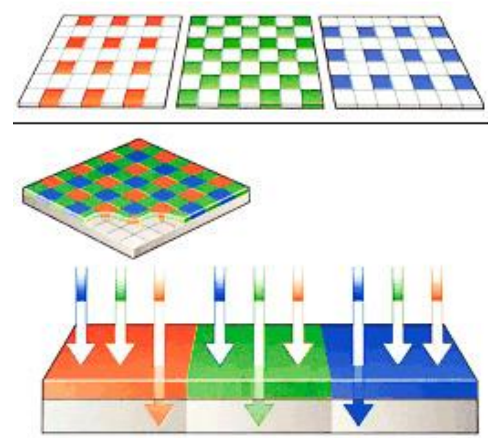
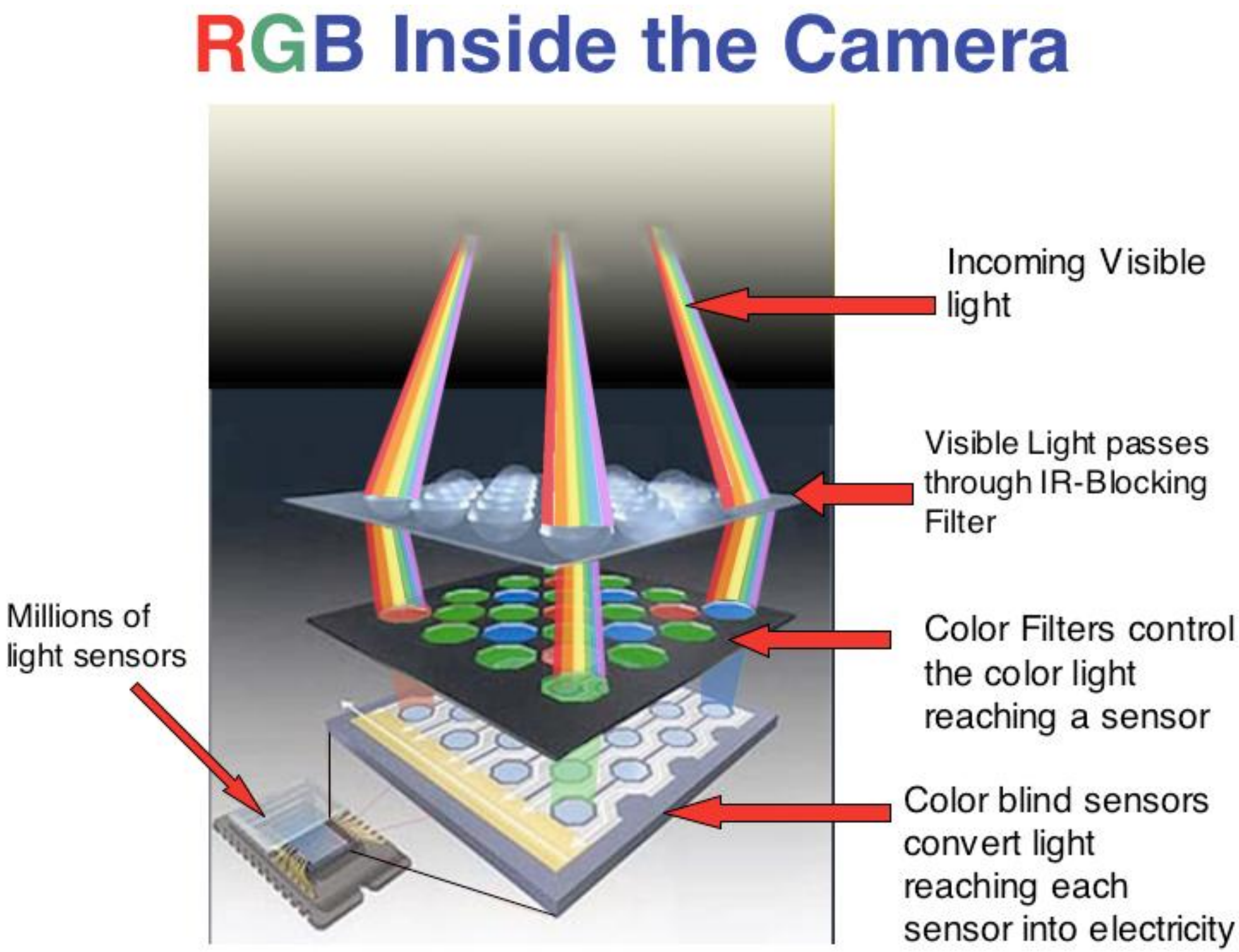


Figure 3

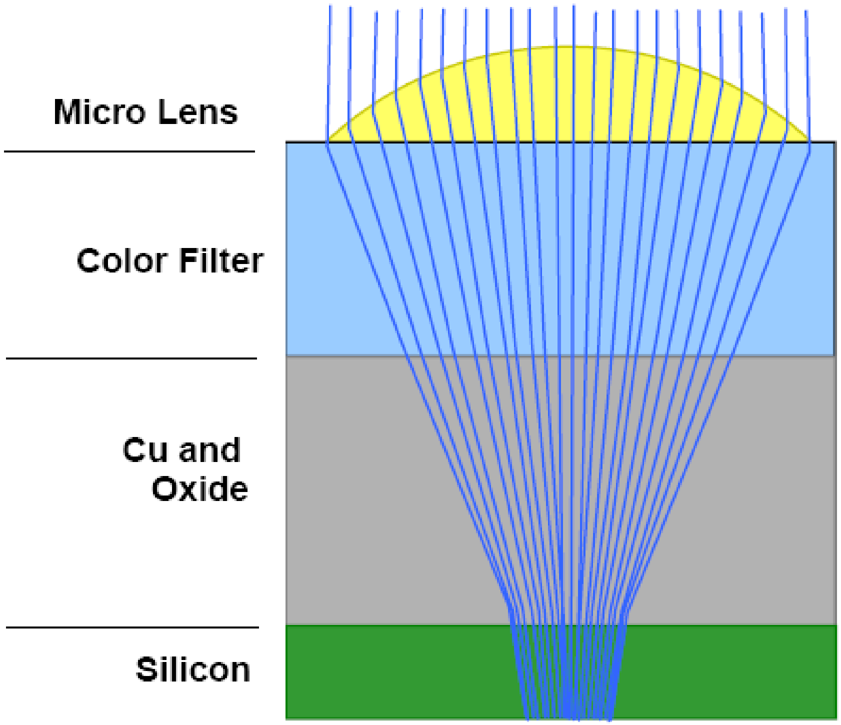
Bayer Color Filter Mosaic Array and Underlying Photodiodes



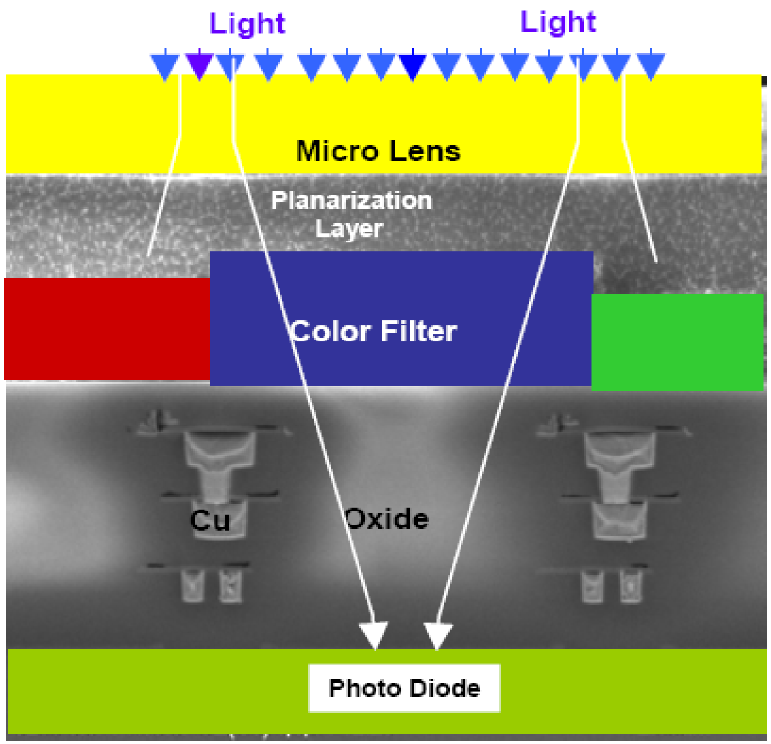
Light Path to Silicon



Color Filter & Micro Lens



Light Ray Trace Model

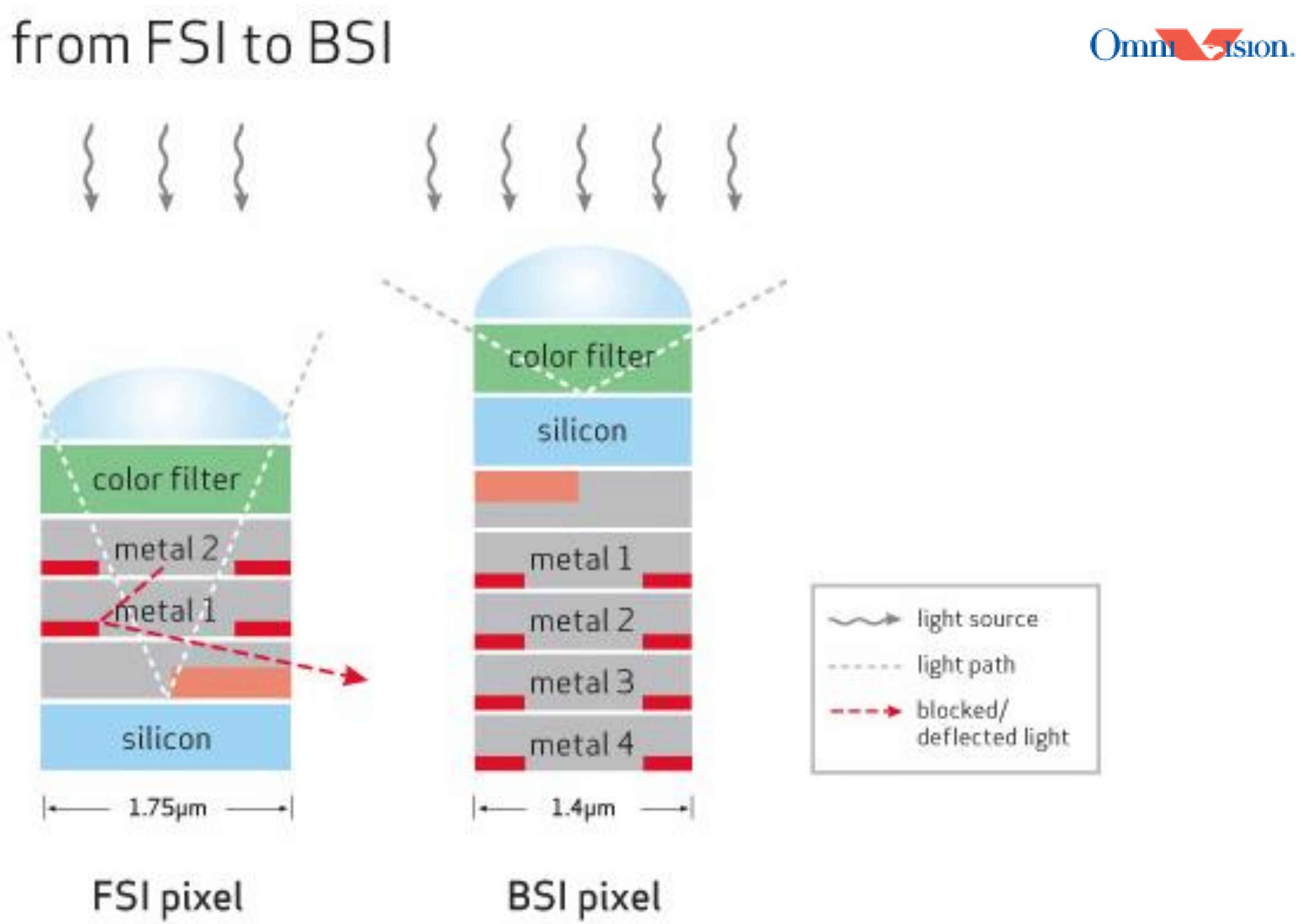


Colorized SEM Cross Section

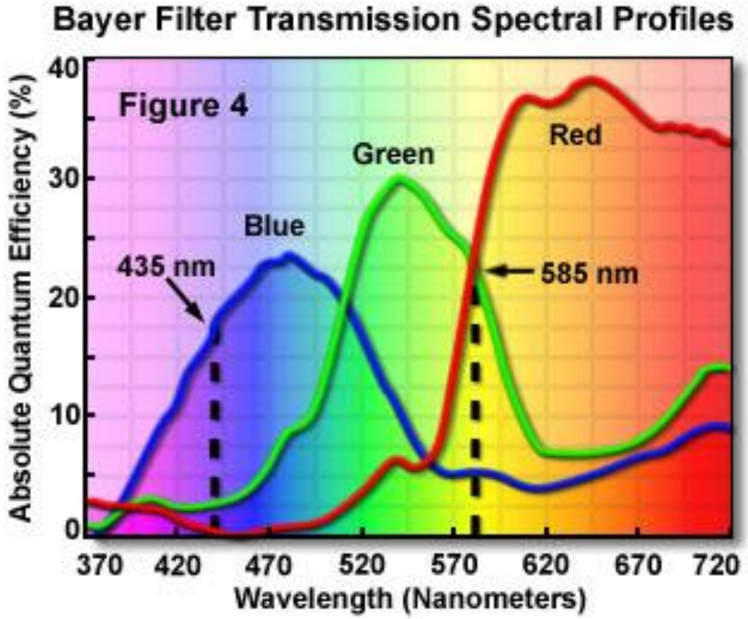
IBM's CMOS Imaging Sensor

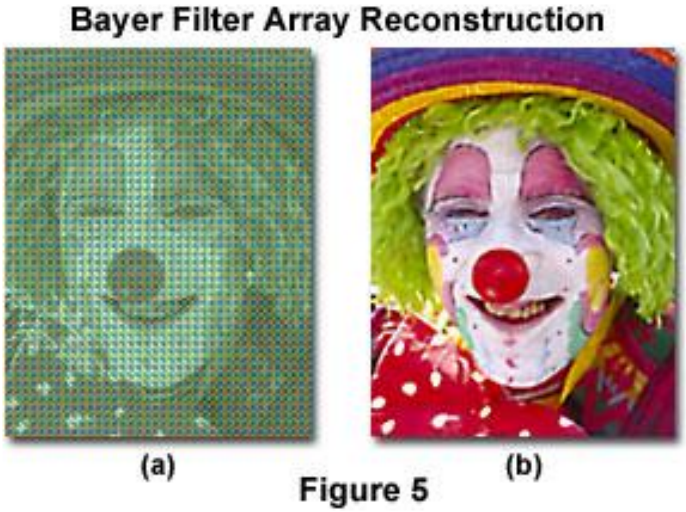
Source: IBM

Backside illumination



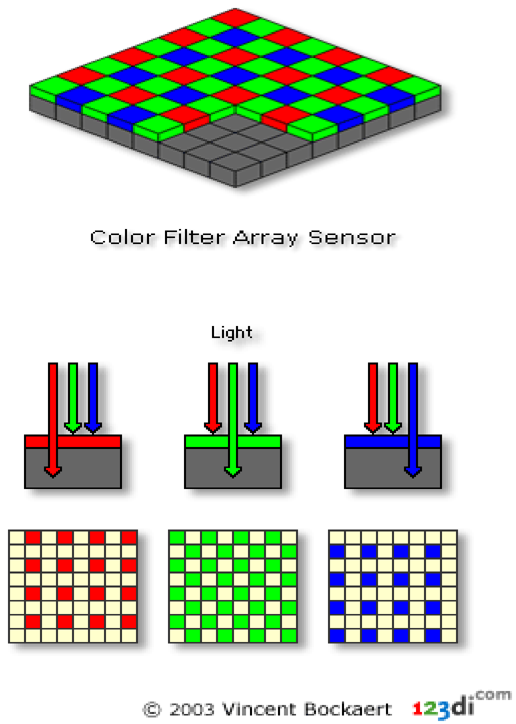
Color Filter Response

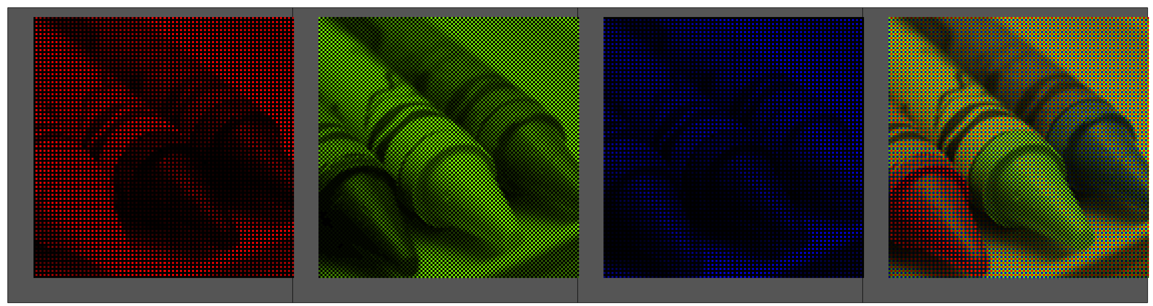




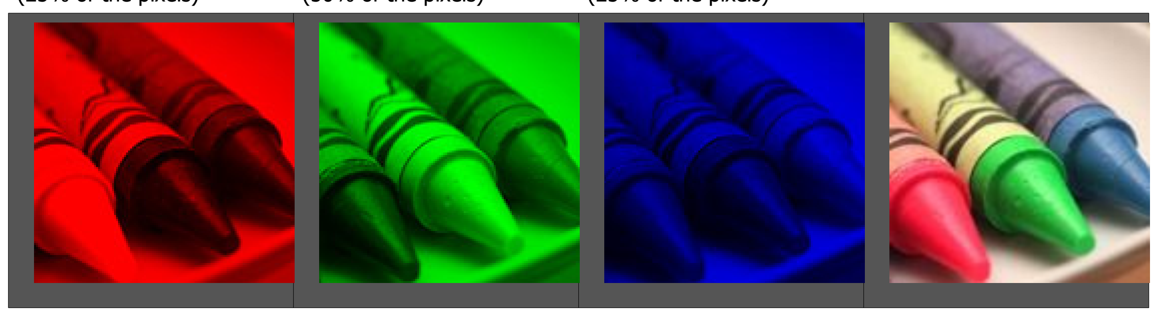
http://www.olympusmicro.com/primer/digitalimaging/cmosimagesensors.html

Color Interpolation (Bayer Pattern)



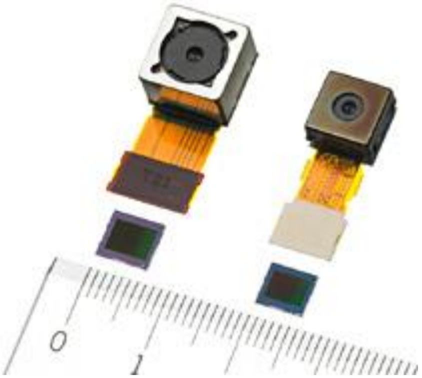


Red channel pixels (25% of the pixels) | Green channel pixels (50% of the pixels) | Blue channel pixels (25% of the pixels) | Combined image



Red, Green, and Blue channels after interpolation | Combined image

Camera in Your Phone

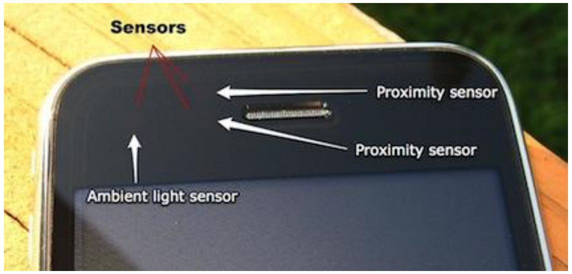


Compact & Efficient

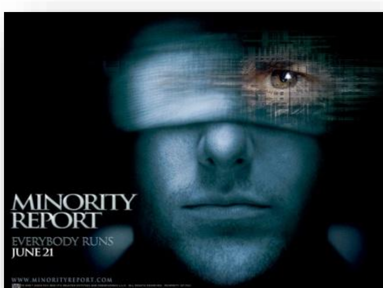
iPhone 5 Camera

iPhone 4 Camera

Ambient Light & Proximity Sensor



Gesture Recognition

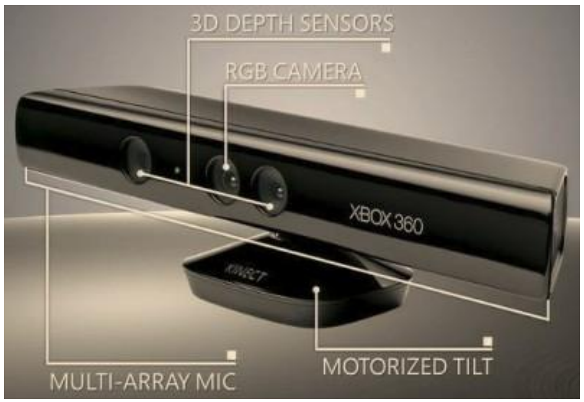


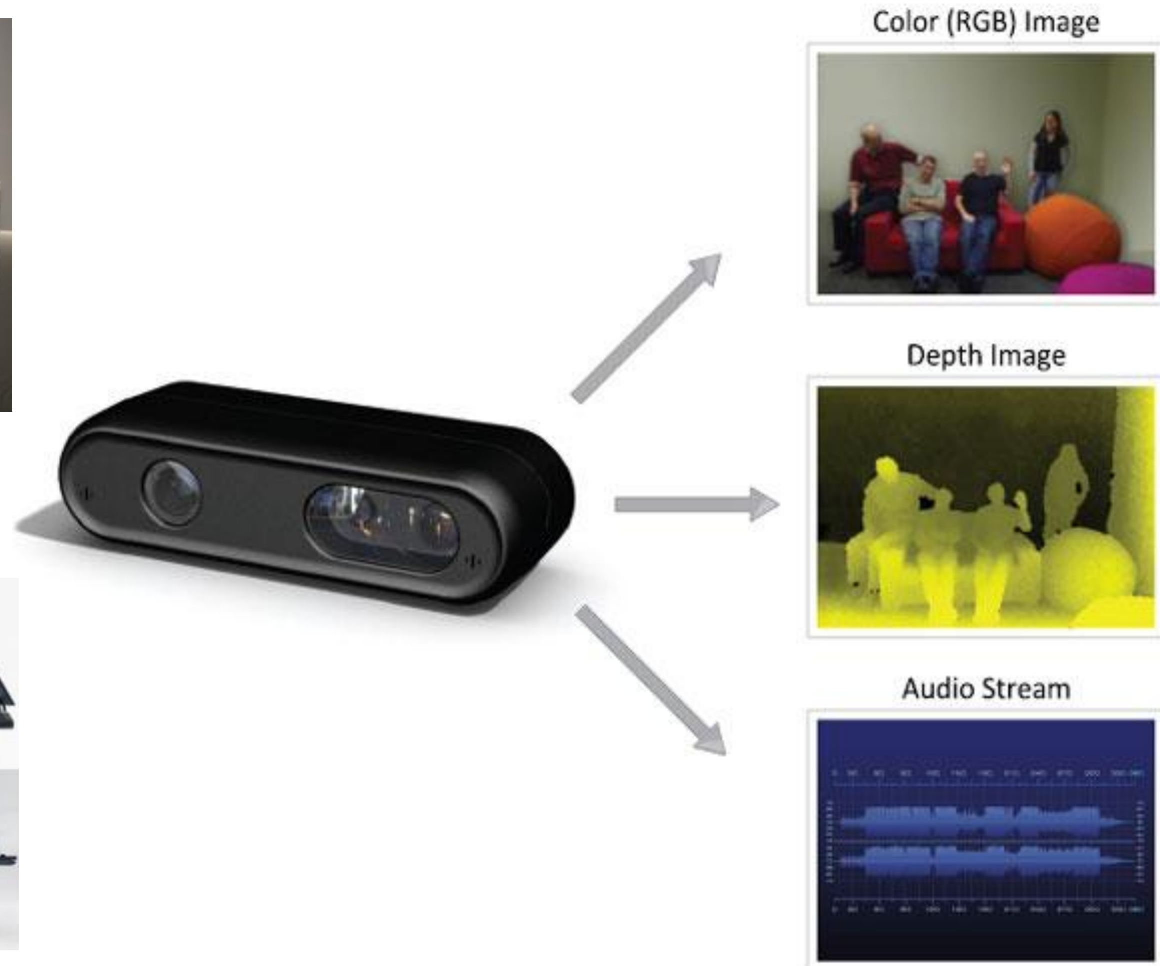
T(ether) of iPAD

Kinetic Sensing

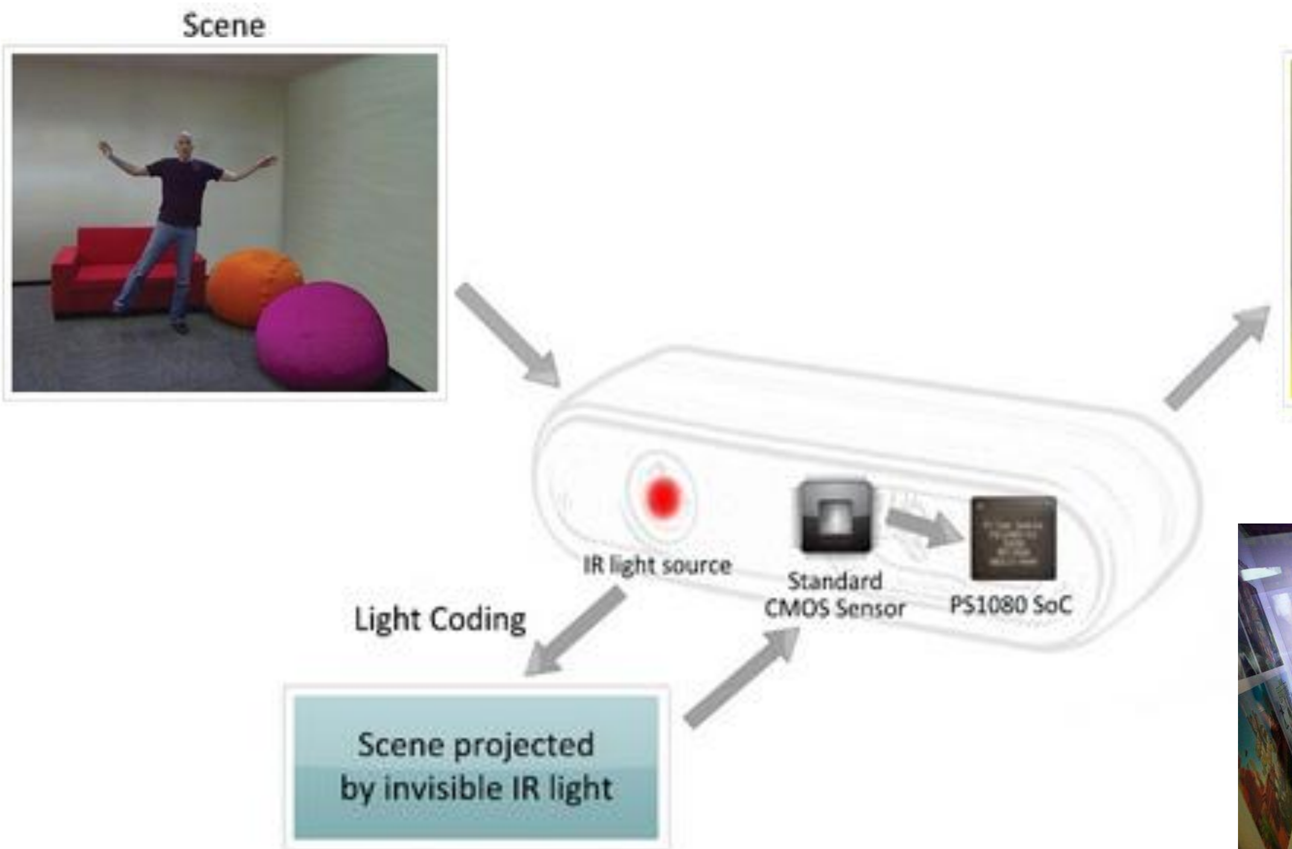
XBOX 360

Inside Kinetic Sensing

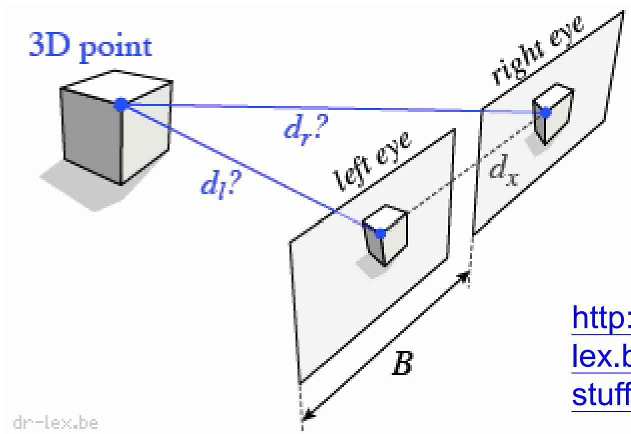




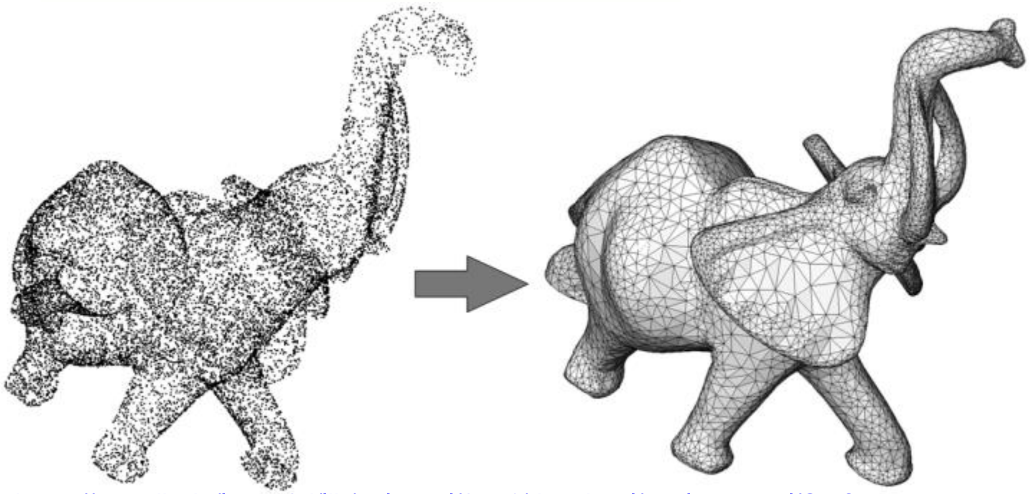
3D – Light Coding



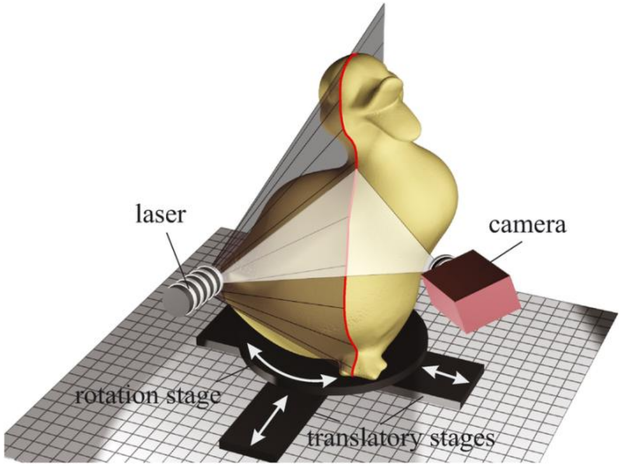
3D - Triangulation



http://www.dr-lex.be/info-stuff/3dfail.html

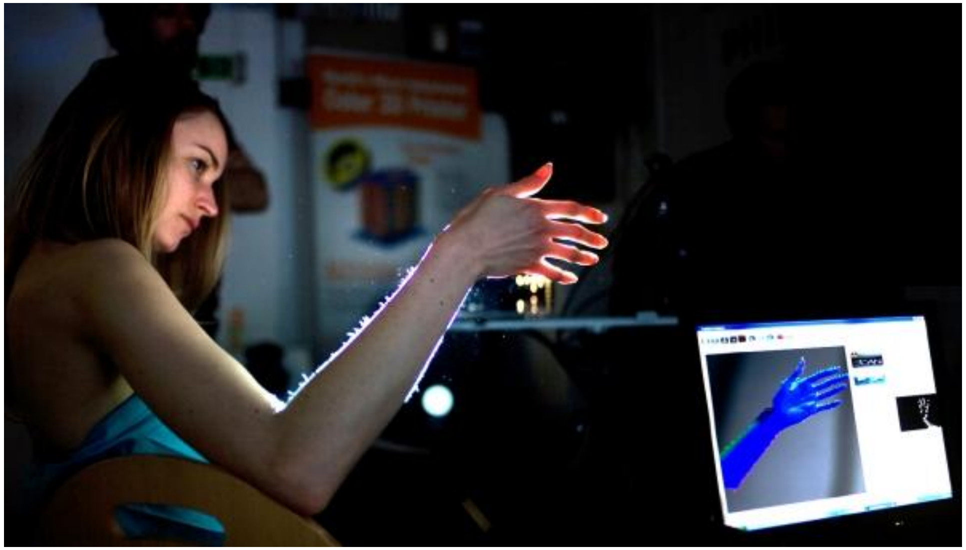


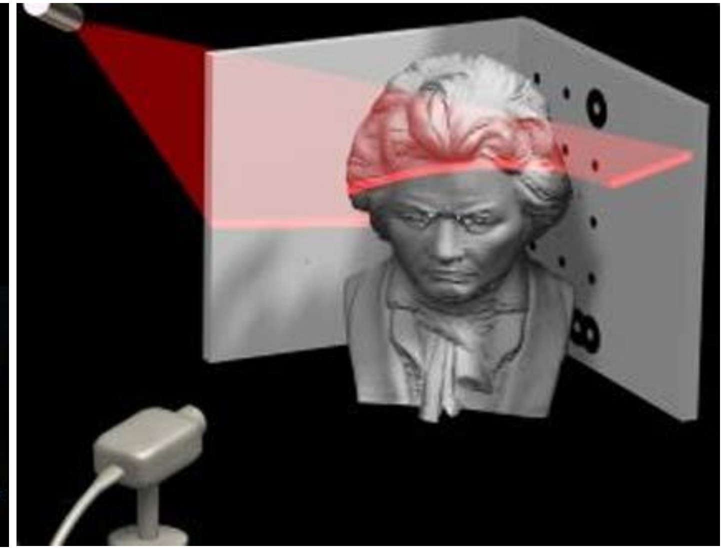
https://svn.zib.de/lenne3d/lib/qpl_cgal/3.5.1/doc_html/cgal_manual/Surface_reconstruction_points_3/Chapter_main.html

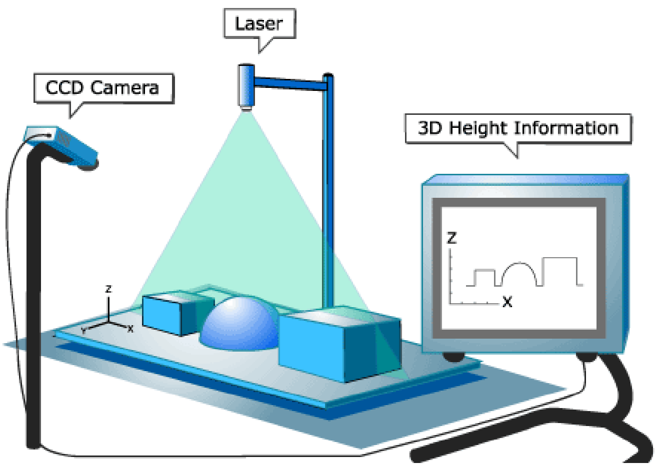


http://www.etc.cmu.edu/projects/plastico-fantastico/?author=4

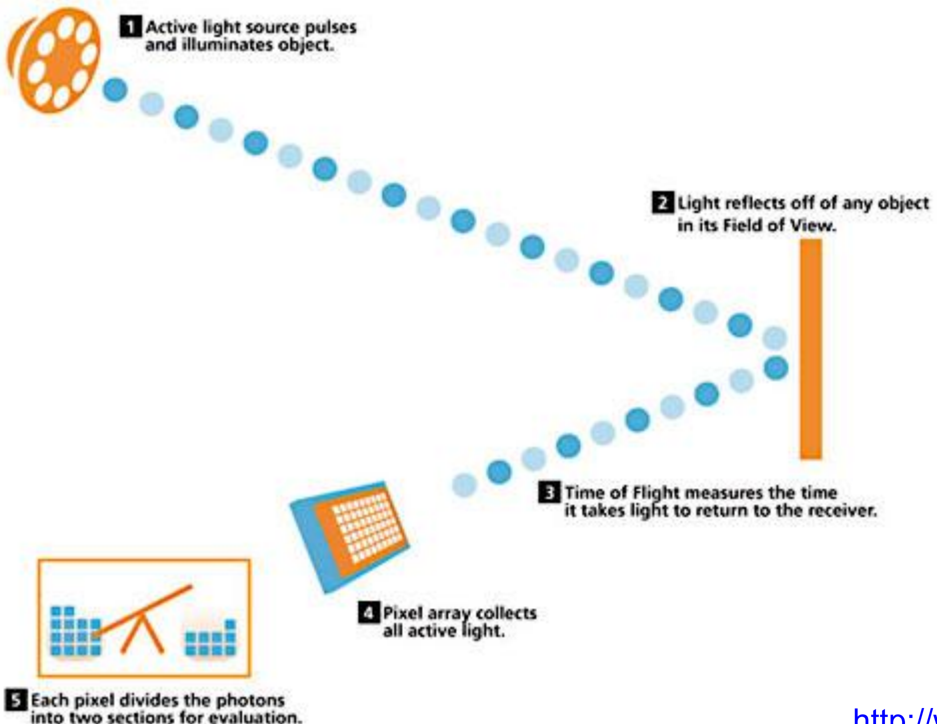
3D - Laser Scanning

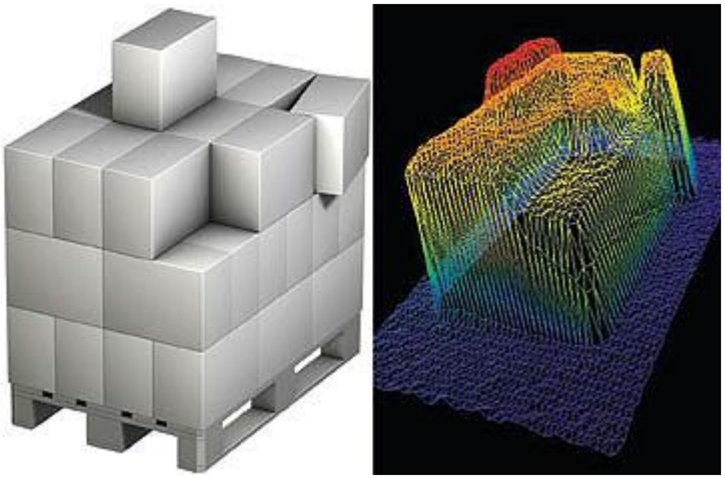






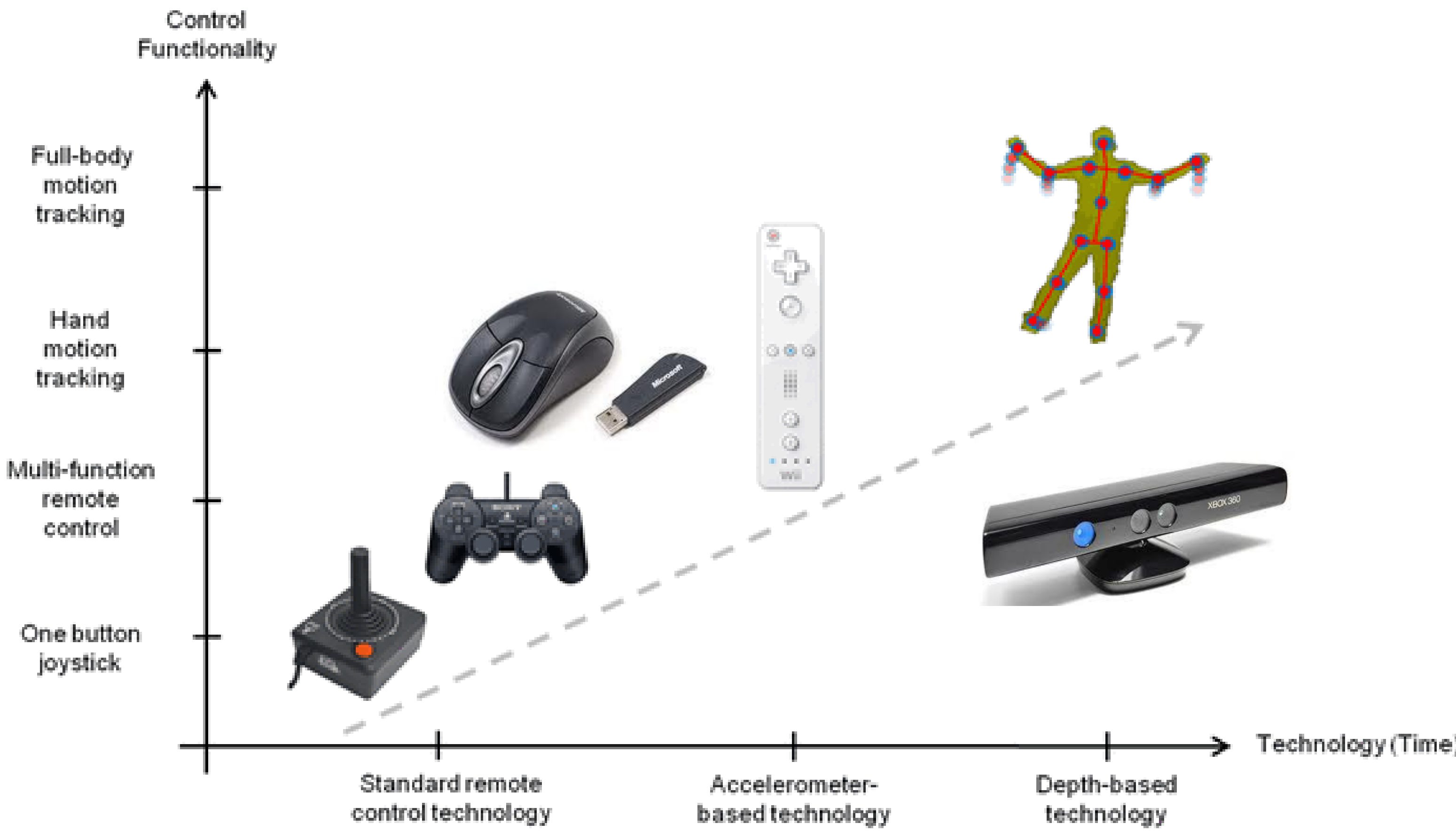
3D -Time of Flight (TOF) Sensing



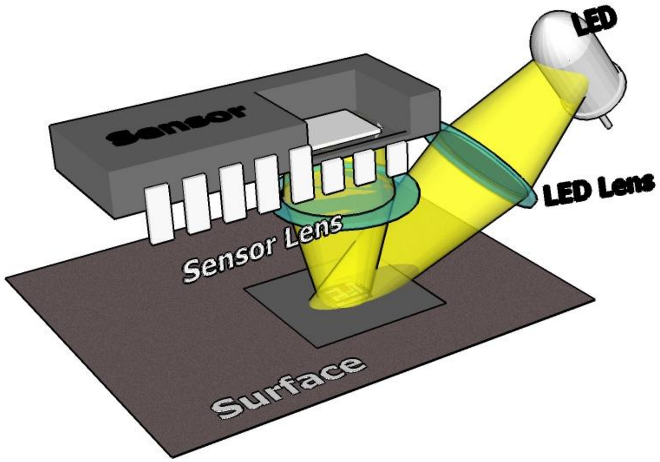


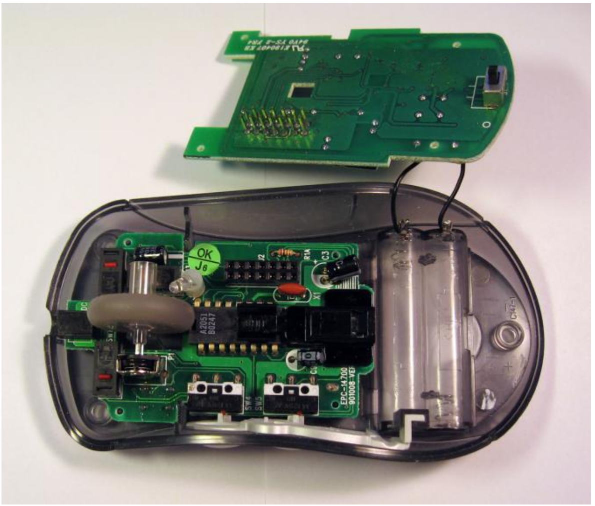
http://www.designworldonline.com/ArticleDetails.aspx?id=3722

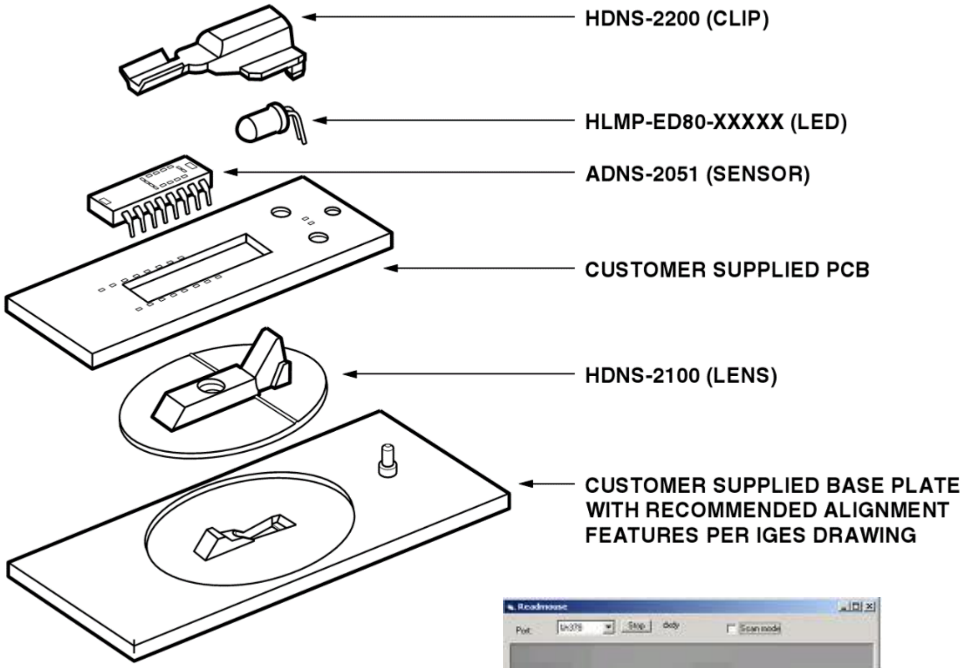
Human Interface Device

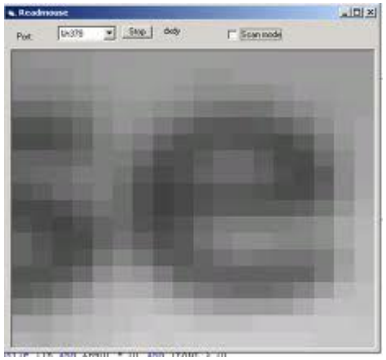


Optical Mouse

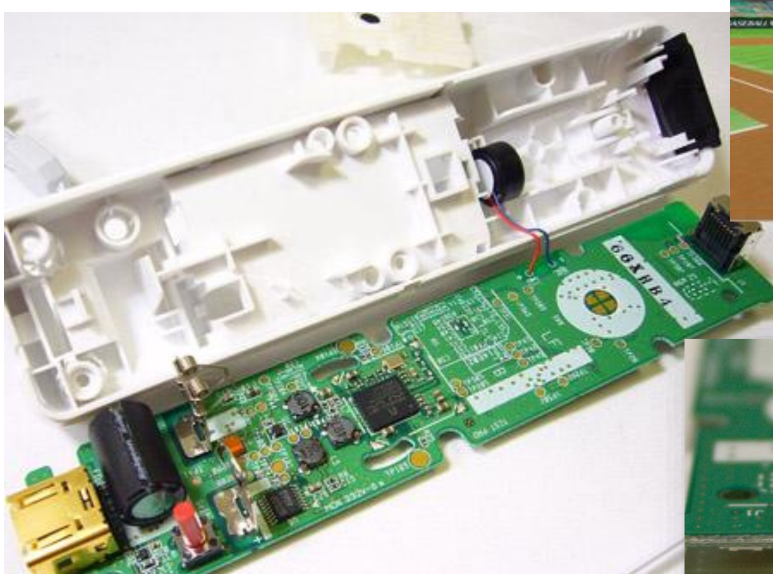


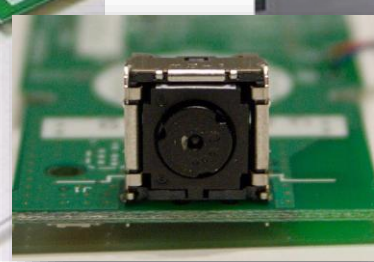




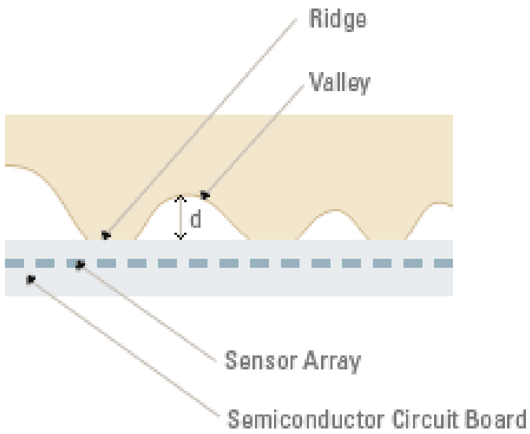


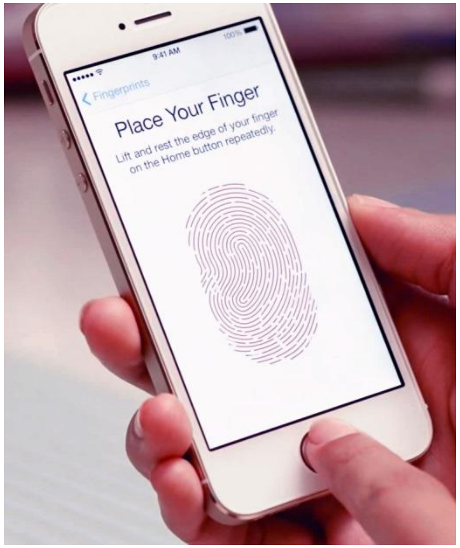
Wii Remote

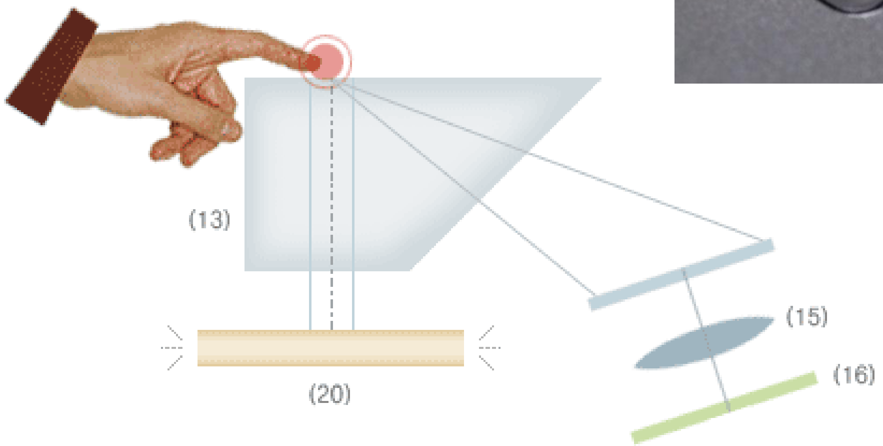




Fingerprint







Security Camera System

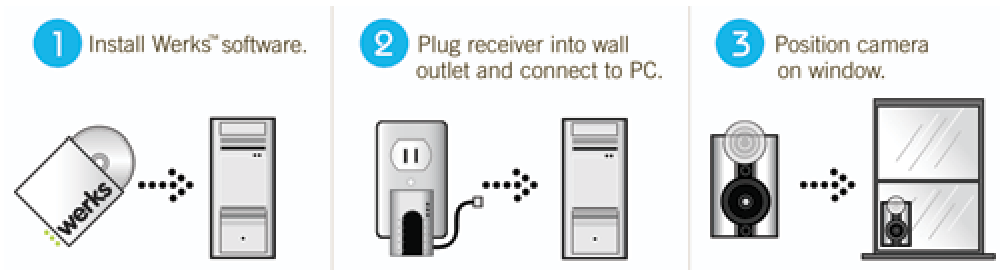
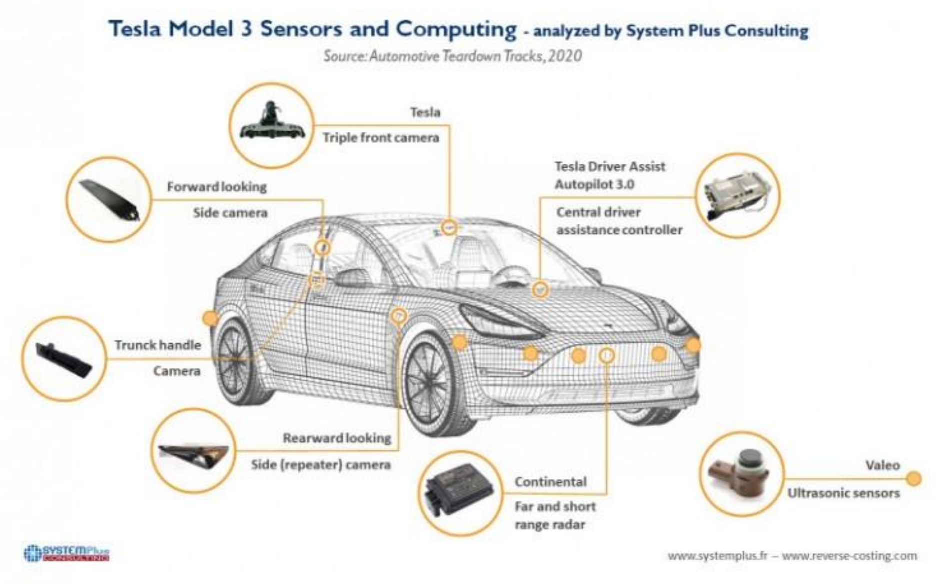
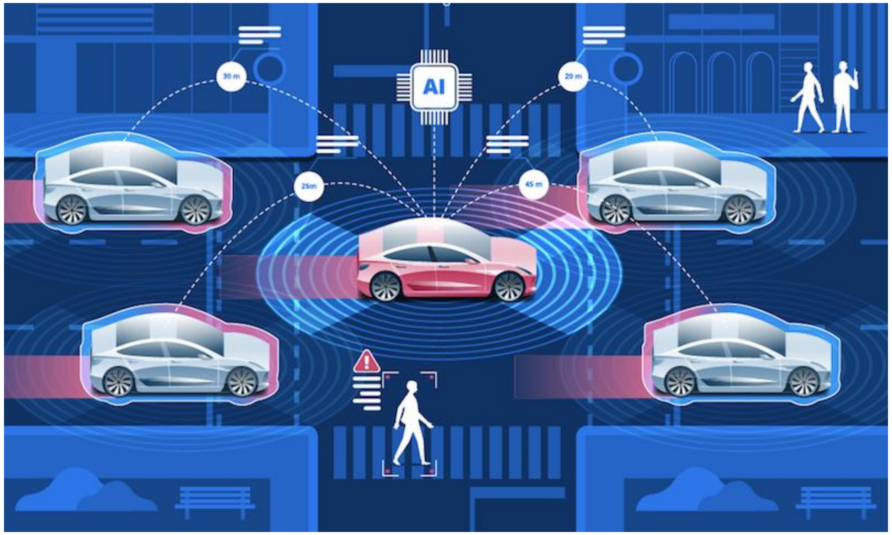


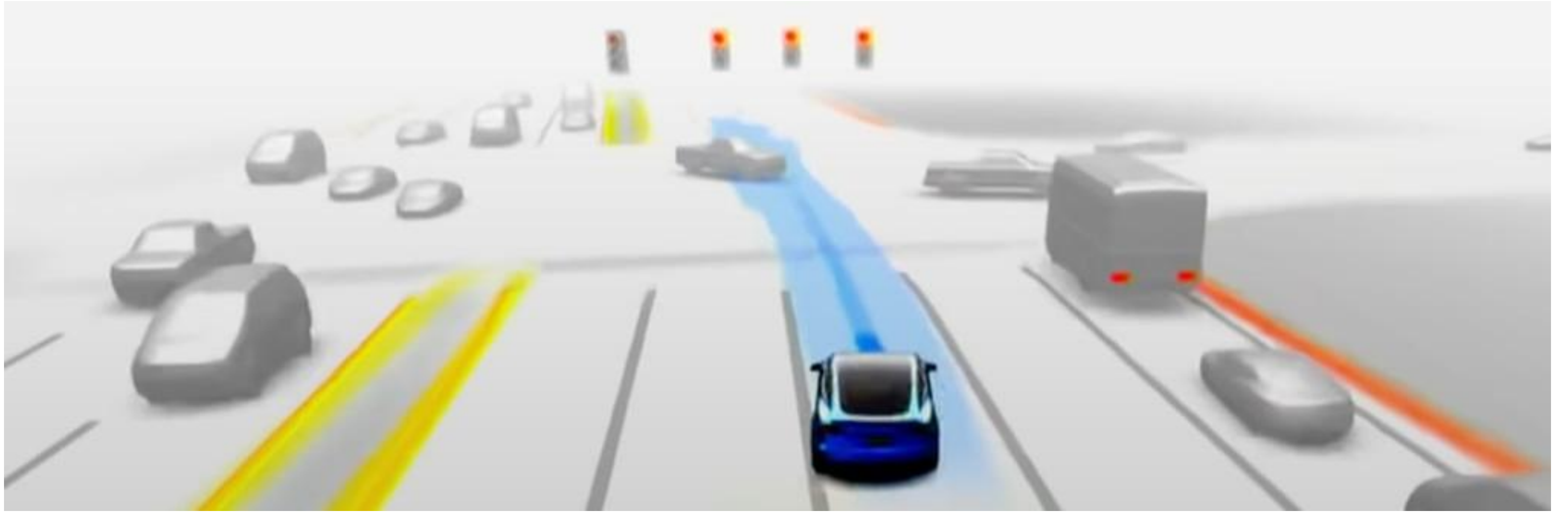
Image Sensor in Automobile

http://www.luxgen-motor.com.tw/technology/ldws.asp

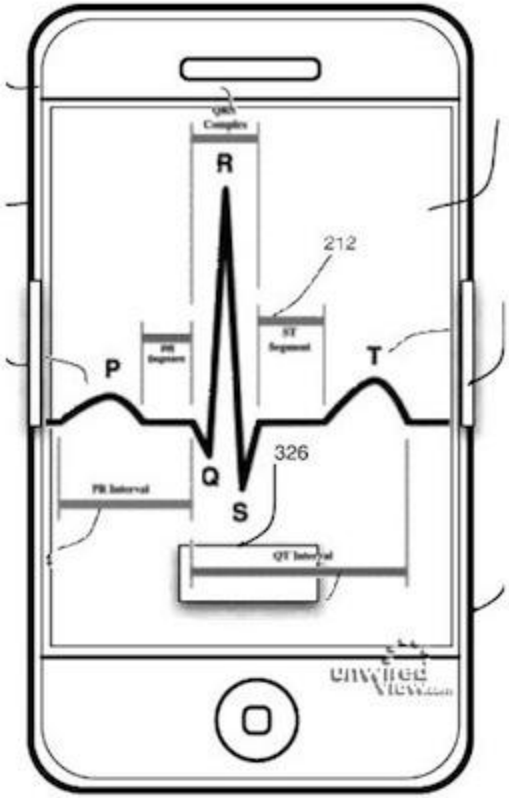
Image Sensor in ADAS



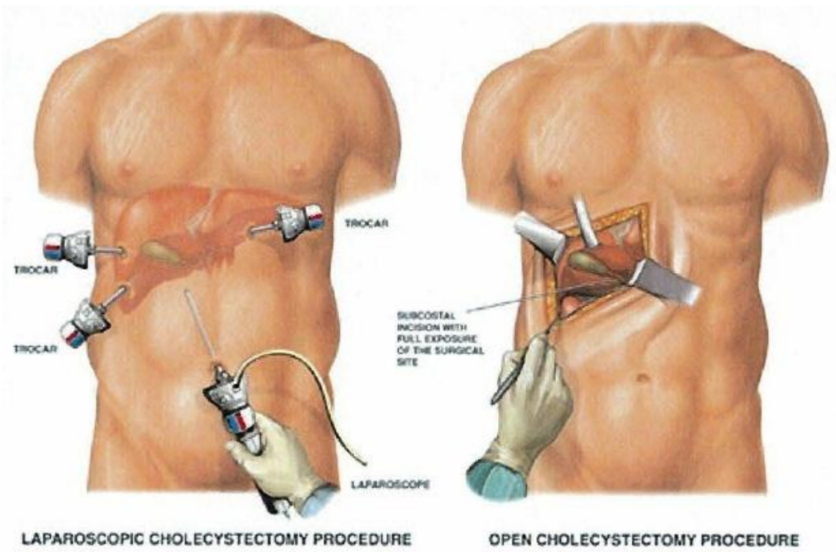


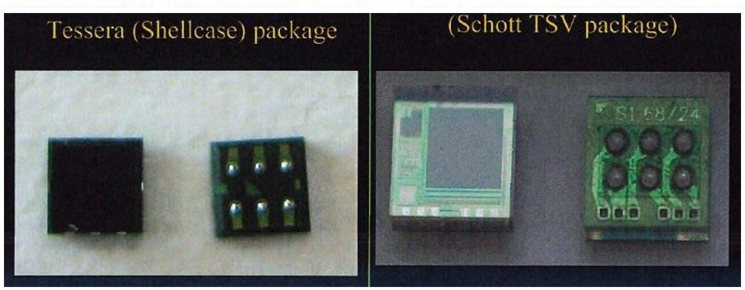


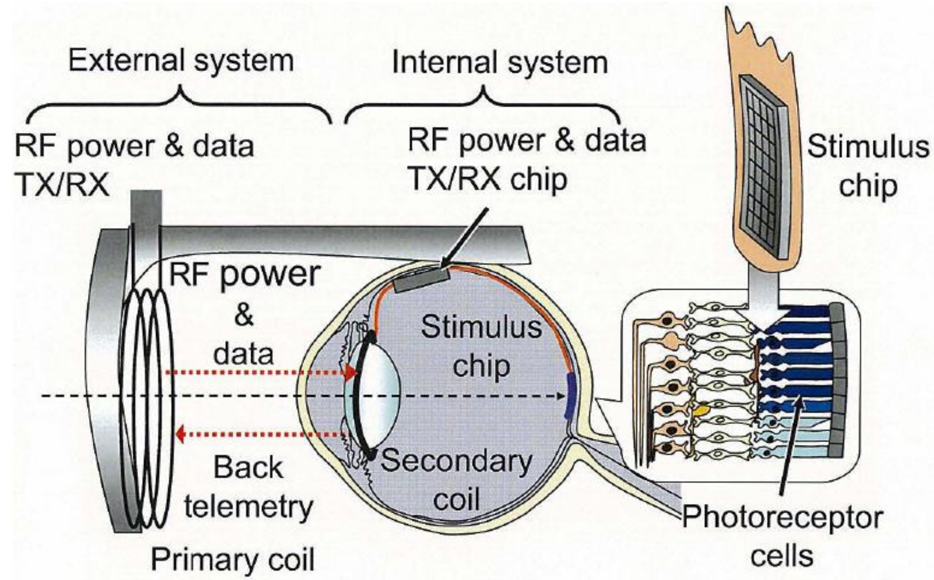
Biomedical Signal Monitoring

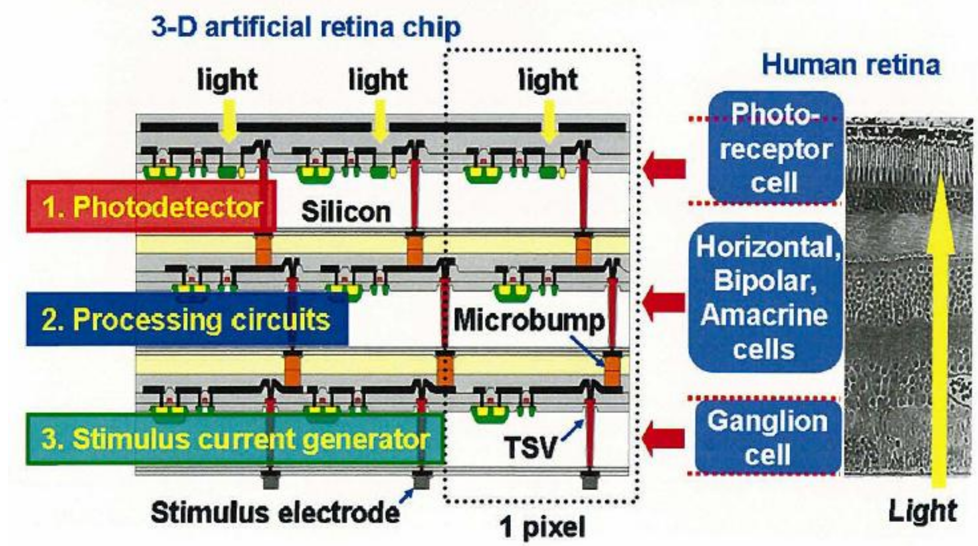


Biomedical Imaging

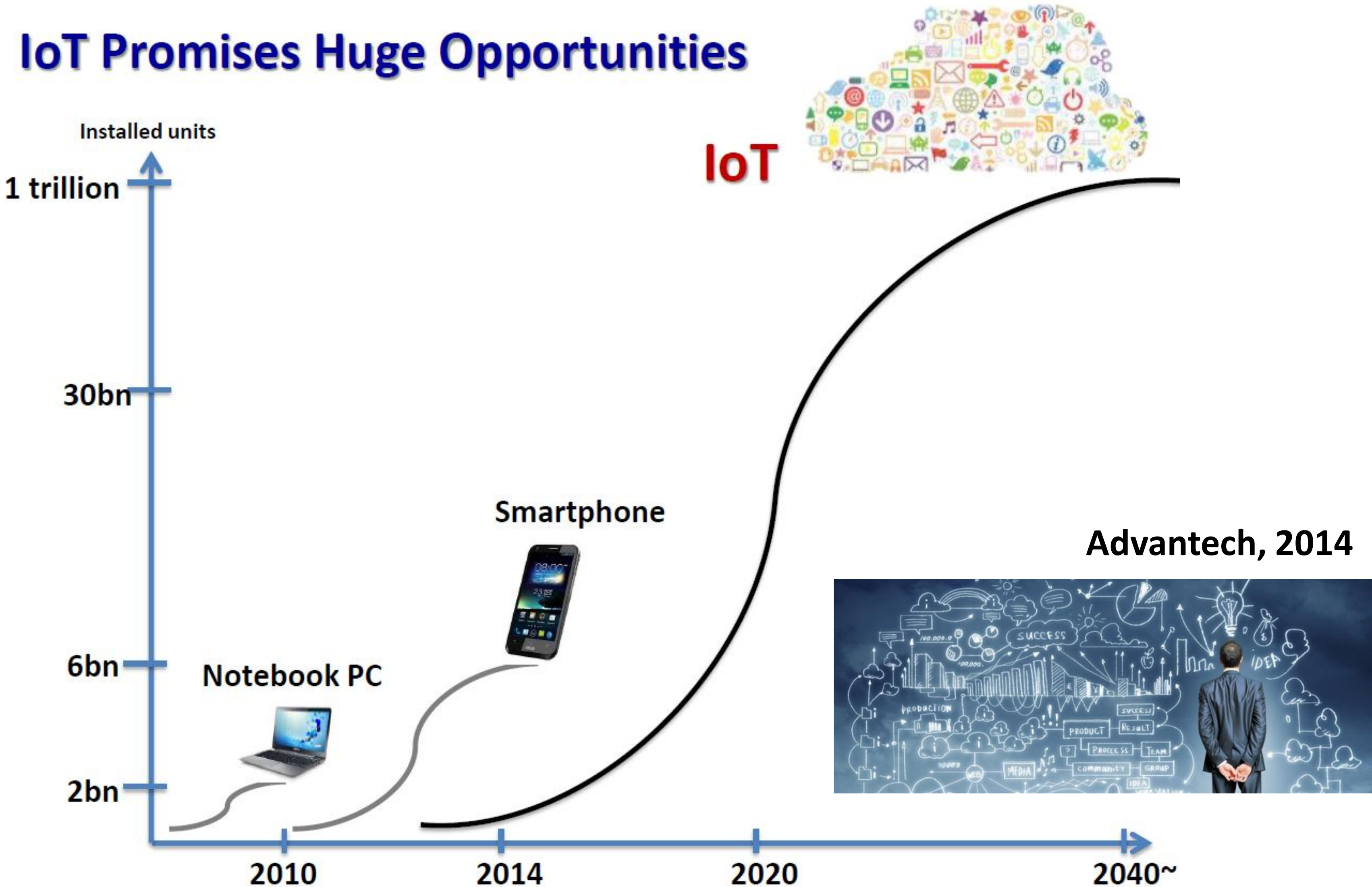








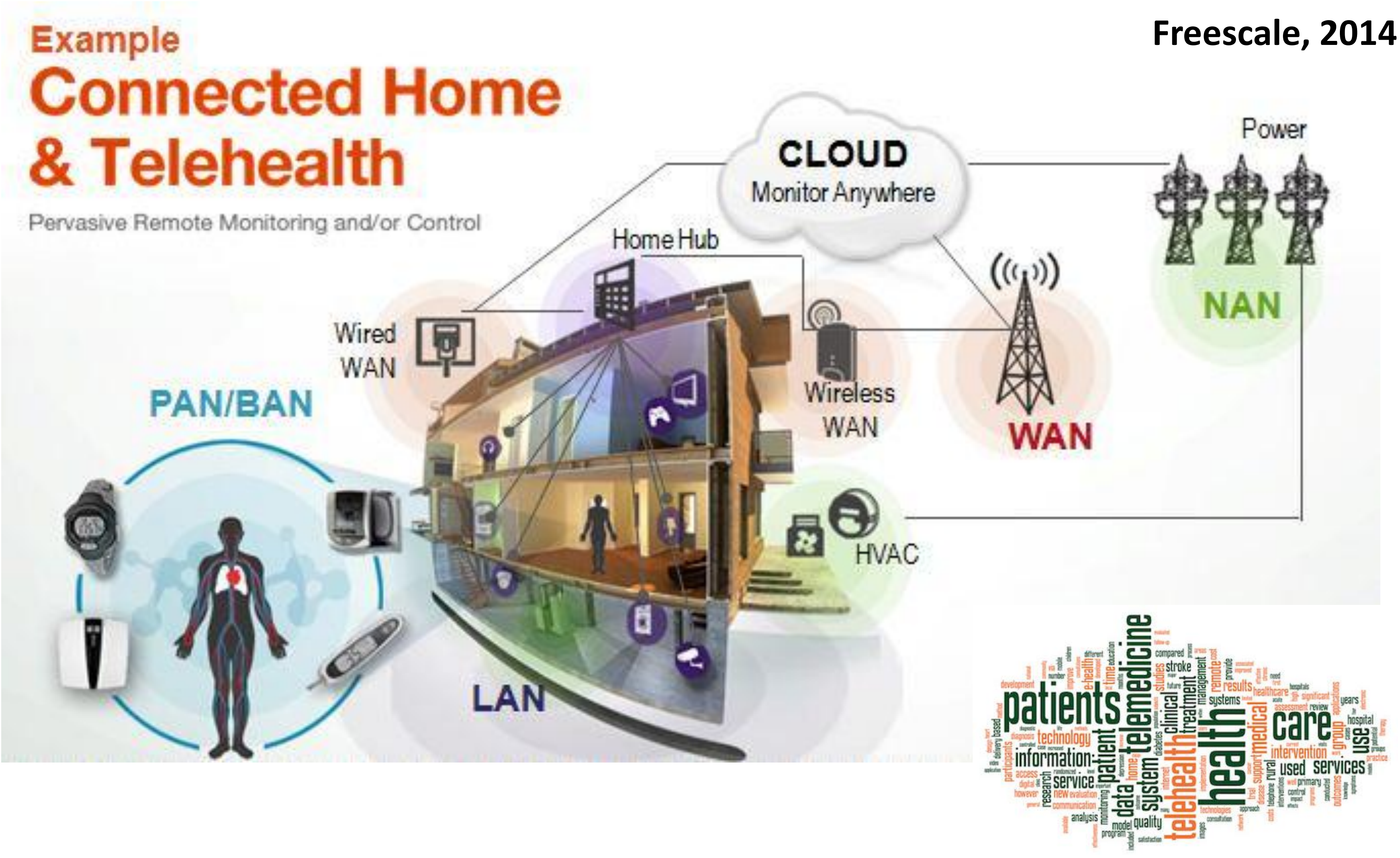
Internet of Things



Advantech, 2014

From Body to City

Freescale, 2014



Sensors of IoT

Yole, 2014

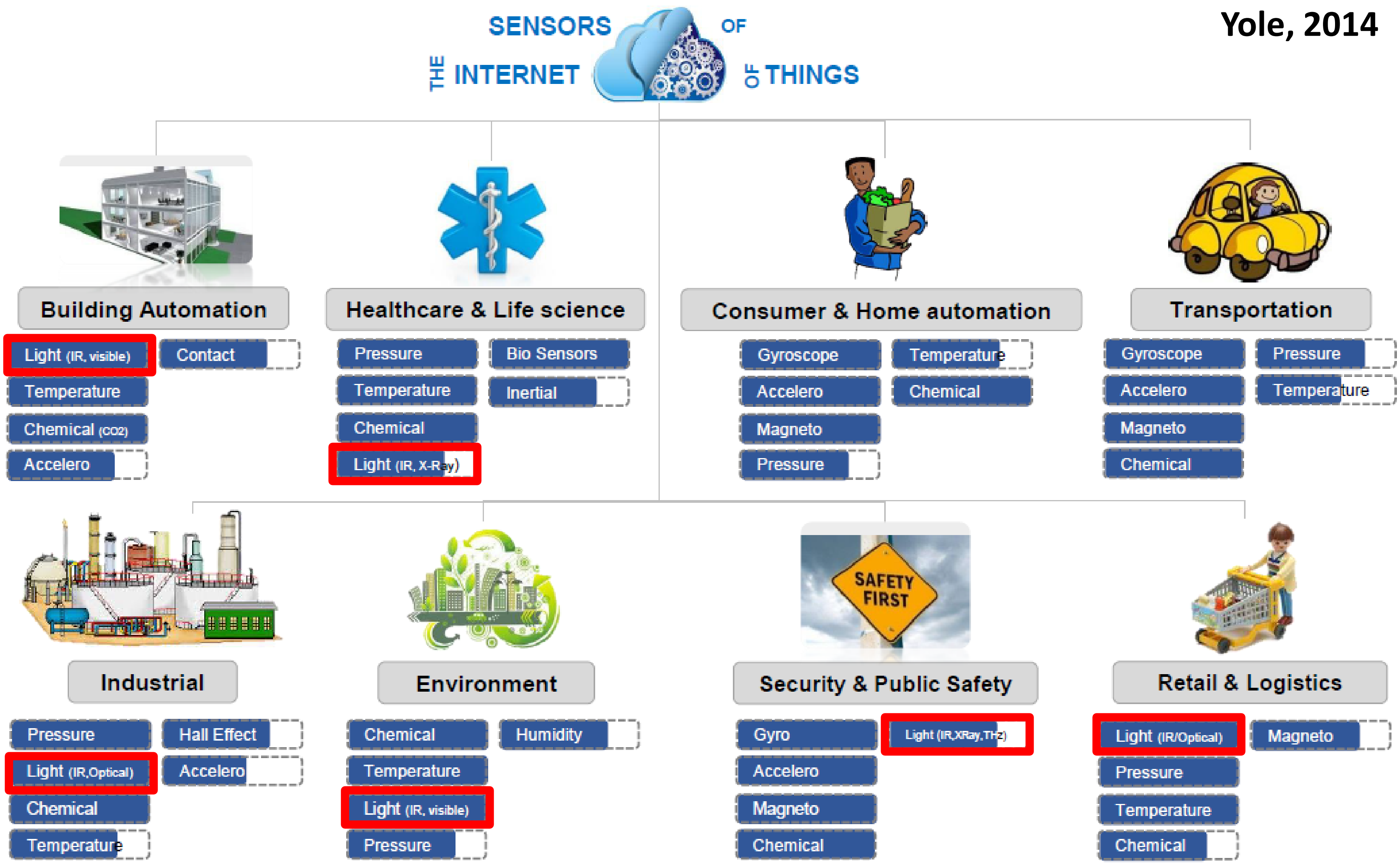
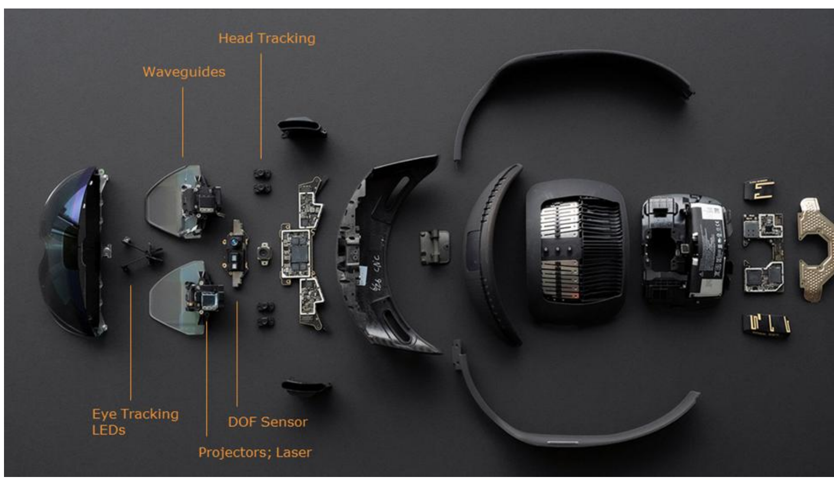


Image Sensor of IoT

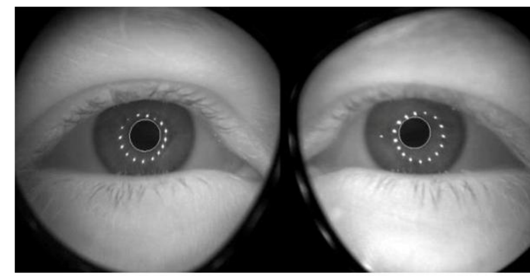
- Environmental monitoring
  - Always on (low power)
  - Imaging quality (SNR, HDR, Speed)
  - Smart functions (event identification)

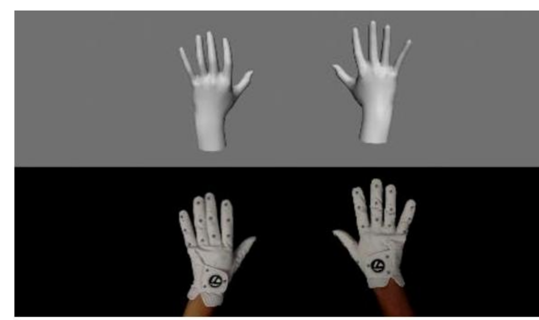
- Biomedical monitoring
  - Wearable device (tiny, low power)
  - Multispectral response (IR, UV)
  - Smart functions (bio-info identification)

Image Sensor in AR/VR/MR/XR



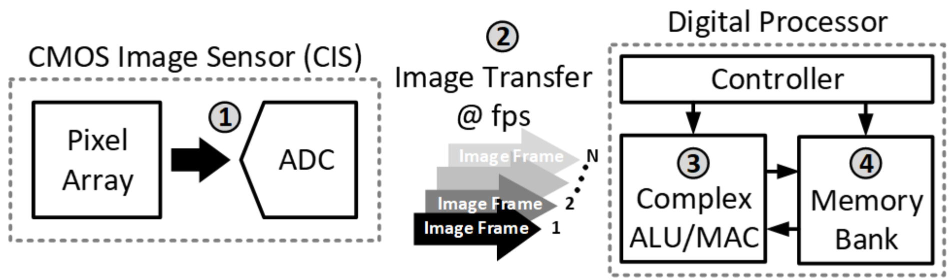

(b) Facial tracking


(c) Gaze tracking

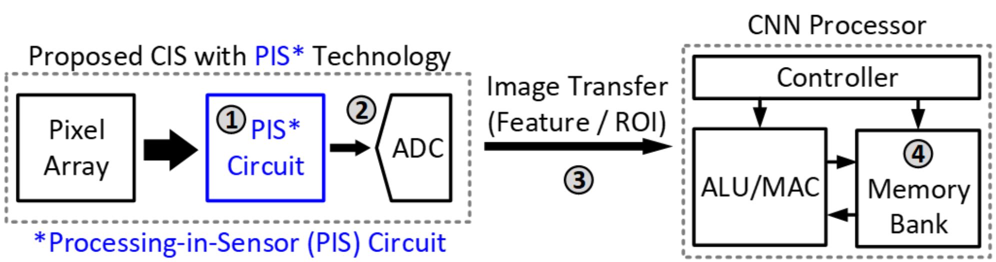

(a) Hand tracking

Intelligent Imager using PIS

Advantages of Processing-in-Sensor (PIS)



- Conventional imager
  - ① High-resolution ADC
  - ② Data transfer bottleneck
  - ③ High-complexity computation
  - ④ High-capacity memory

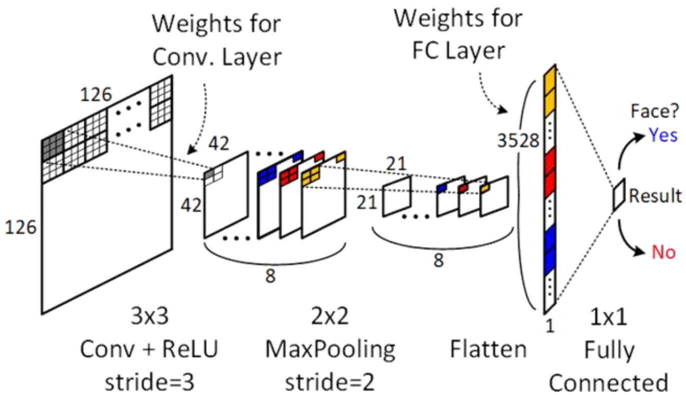


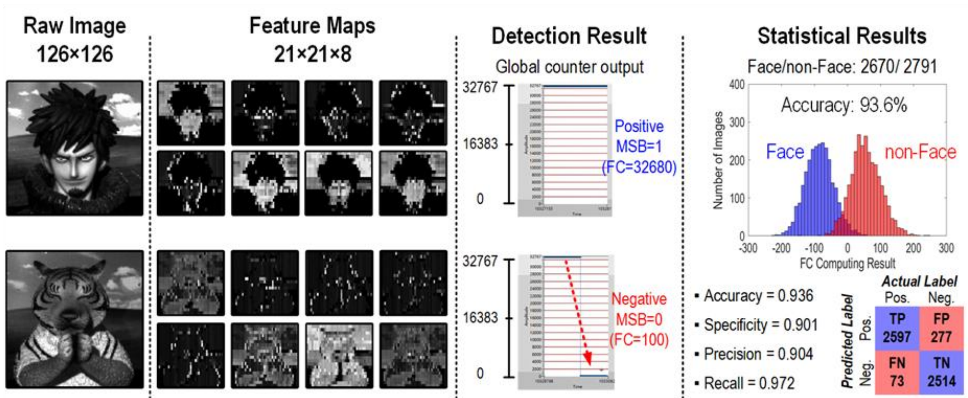
- Intelligent imager using PIS
  - ① PIS circuit for feature extraction
  - ② Relieve ADC resolution
  - ③ Transfer feature / ROI only
  - ④ Relieve memory capacity

Intelligent Imager - Spatial

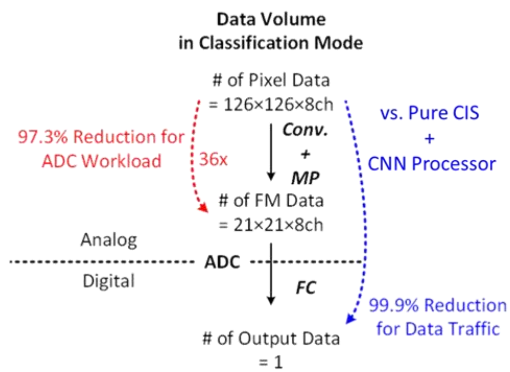
CIS + Tiny CNN

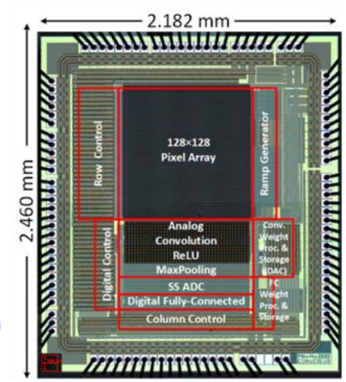
[7] T. -H. Hsu, ISSCC22 / JSSC23



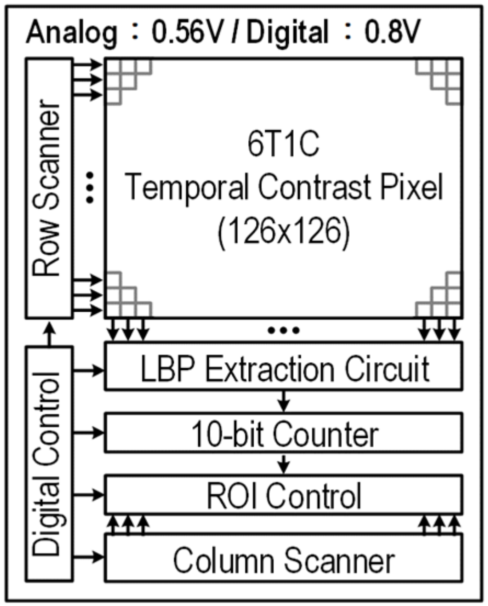


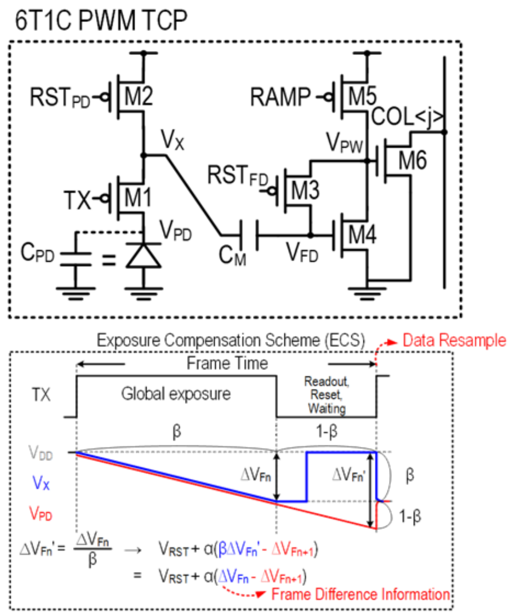
- Programmable weight feature extraction
  - In-column processing relaxed complexity
  - Customized tiny convolutional neural network to achieve face detection task

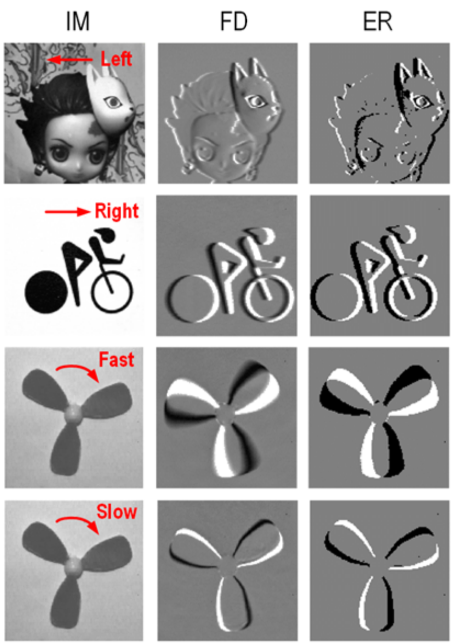




Intelligent Imager - Temporal



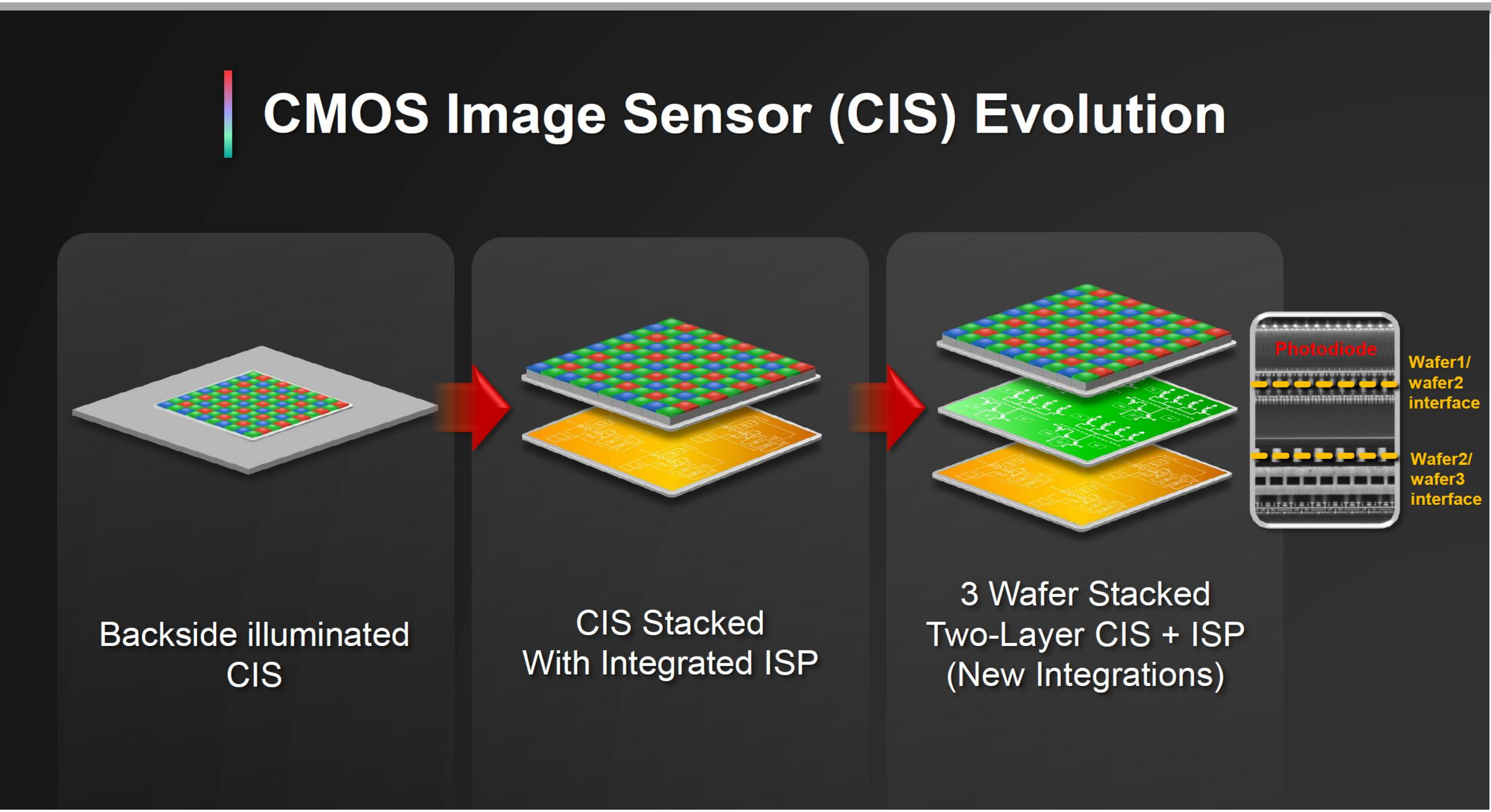




[9] M. -Y. Chiu, JSSC 2023

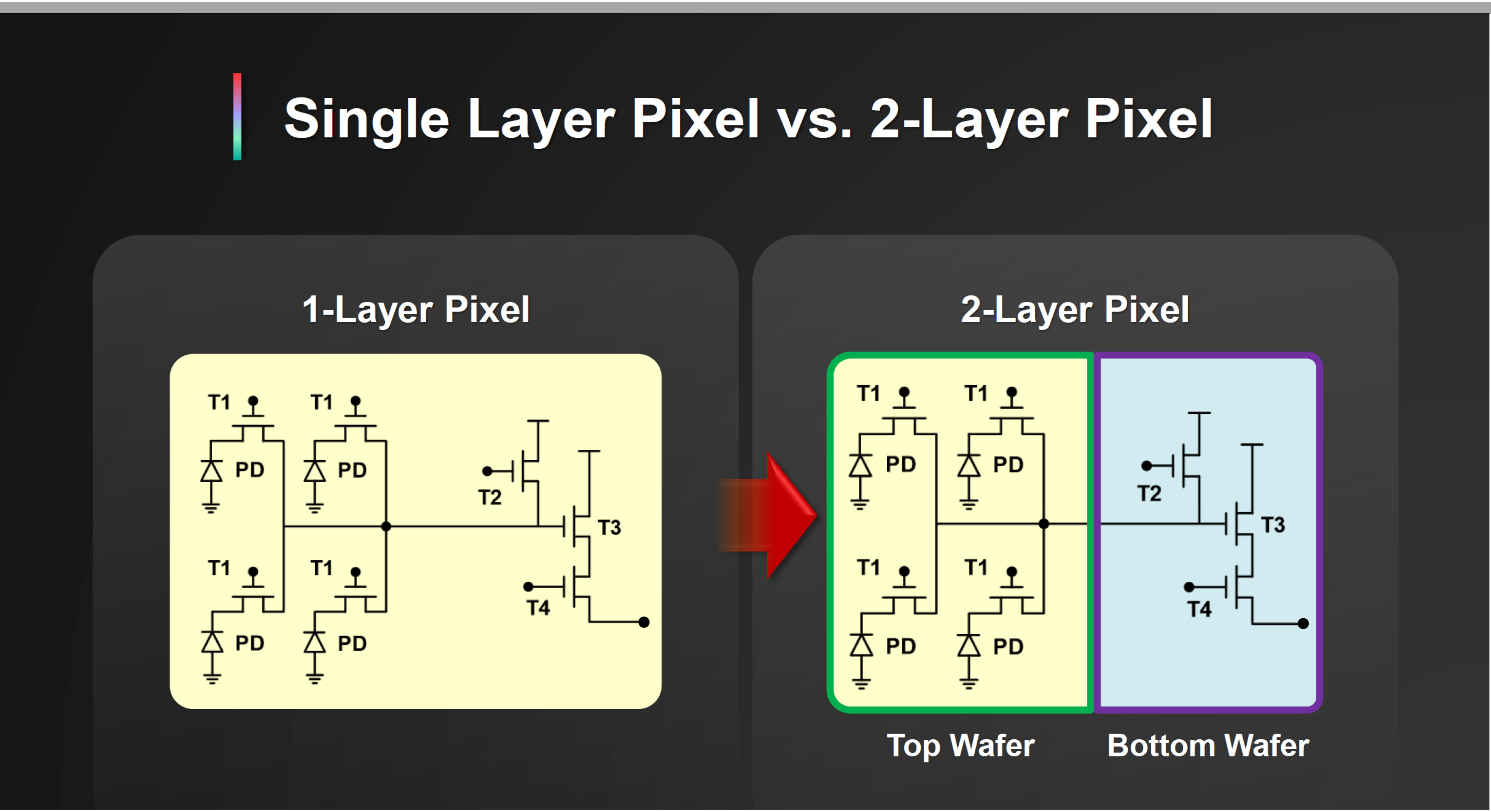
- Improved in-pixel consecutive frame differencing
  - Only 6T+1C with improved pixel pitch, fill factor, conversion gain
  - Support on-chip LBP & ROI reporting
  - Complicated pixel control, requires exposure compensation scheme (ECS)

CMOS Image Sensor Evolution



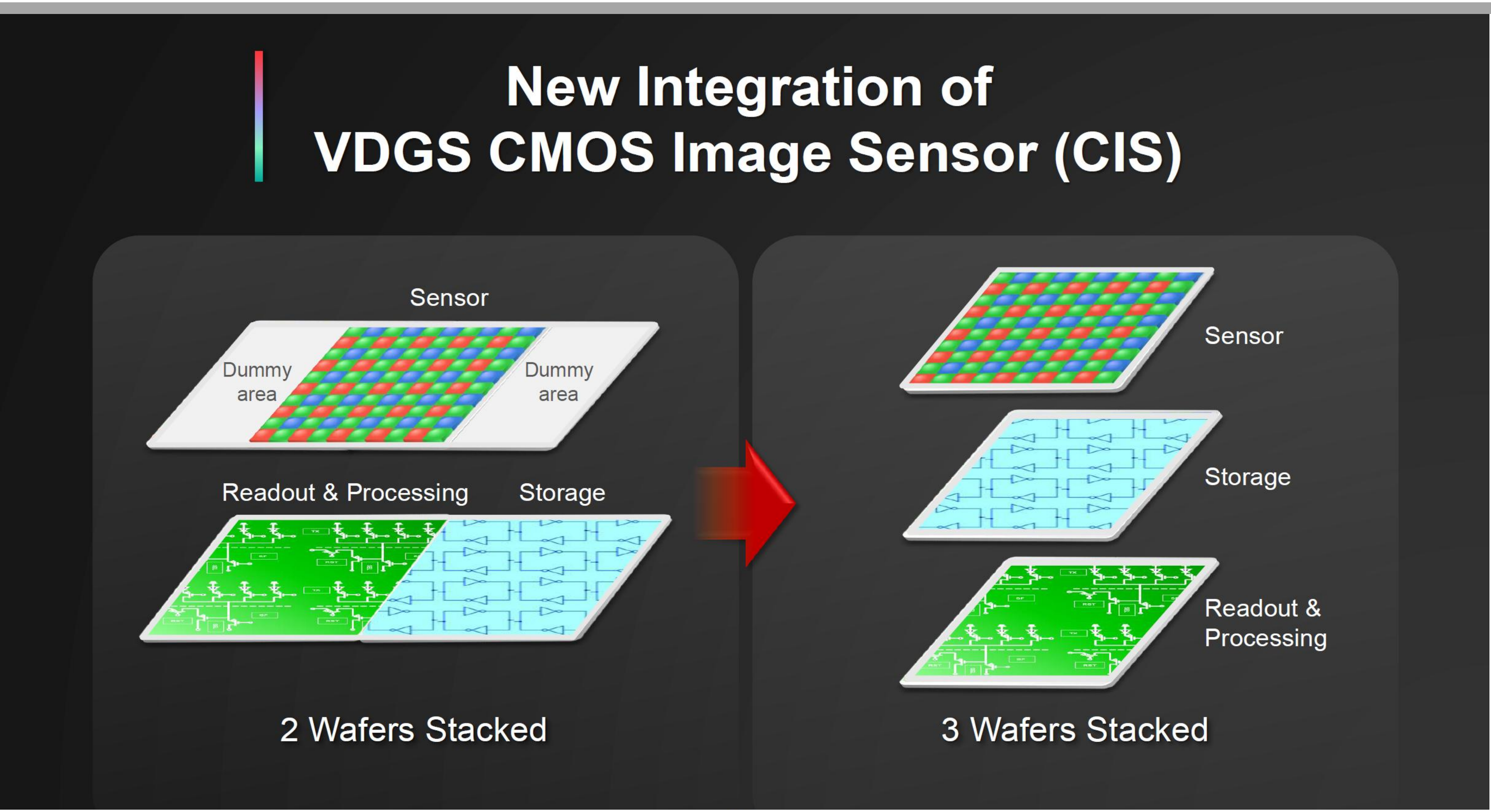
ISSCC2024 plenary talk by TSMC

Single Layer Pixel vs. 2-Layer Pixel



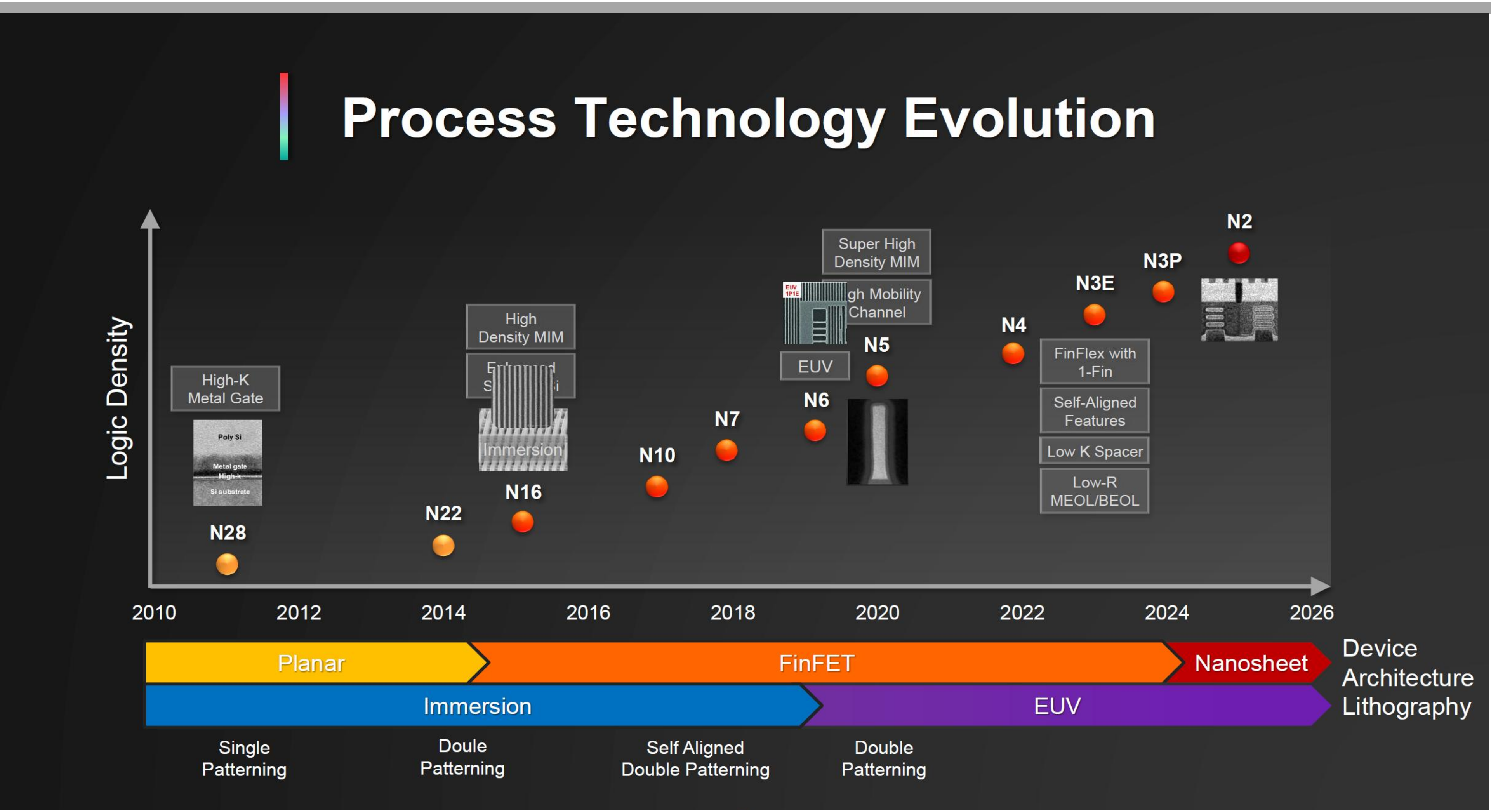
ISSCC2024 plenary talk by TSMC

New Integration of CIS



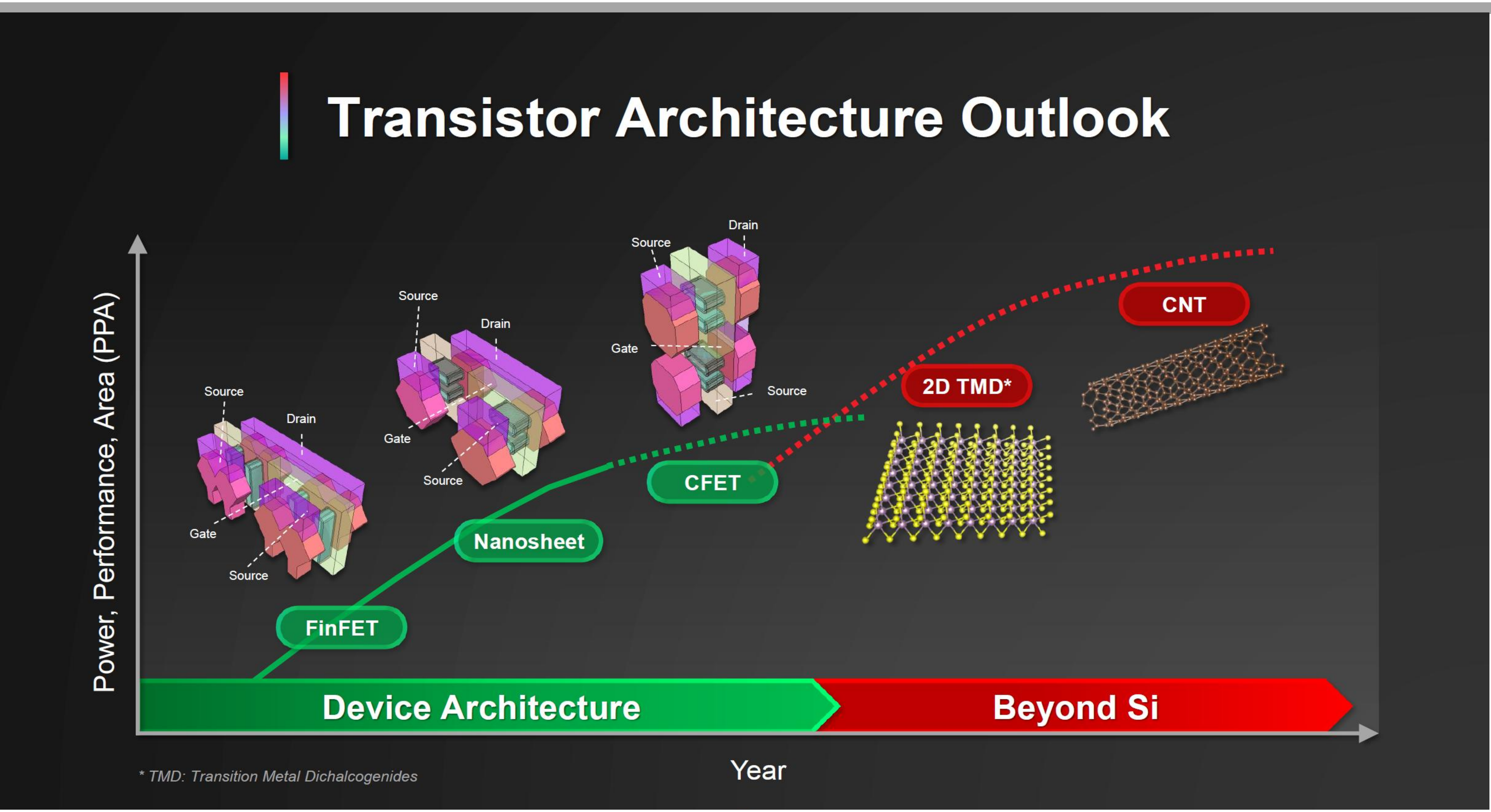
ISSCC2024 plenary talk by TSMC

Process Technology Evolution



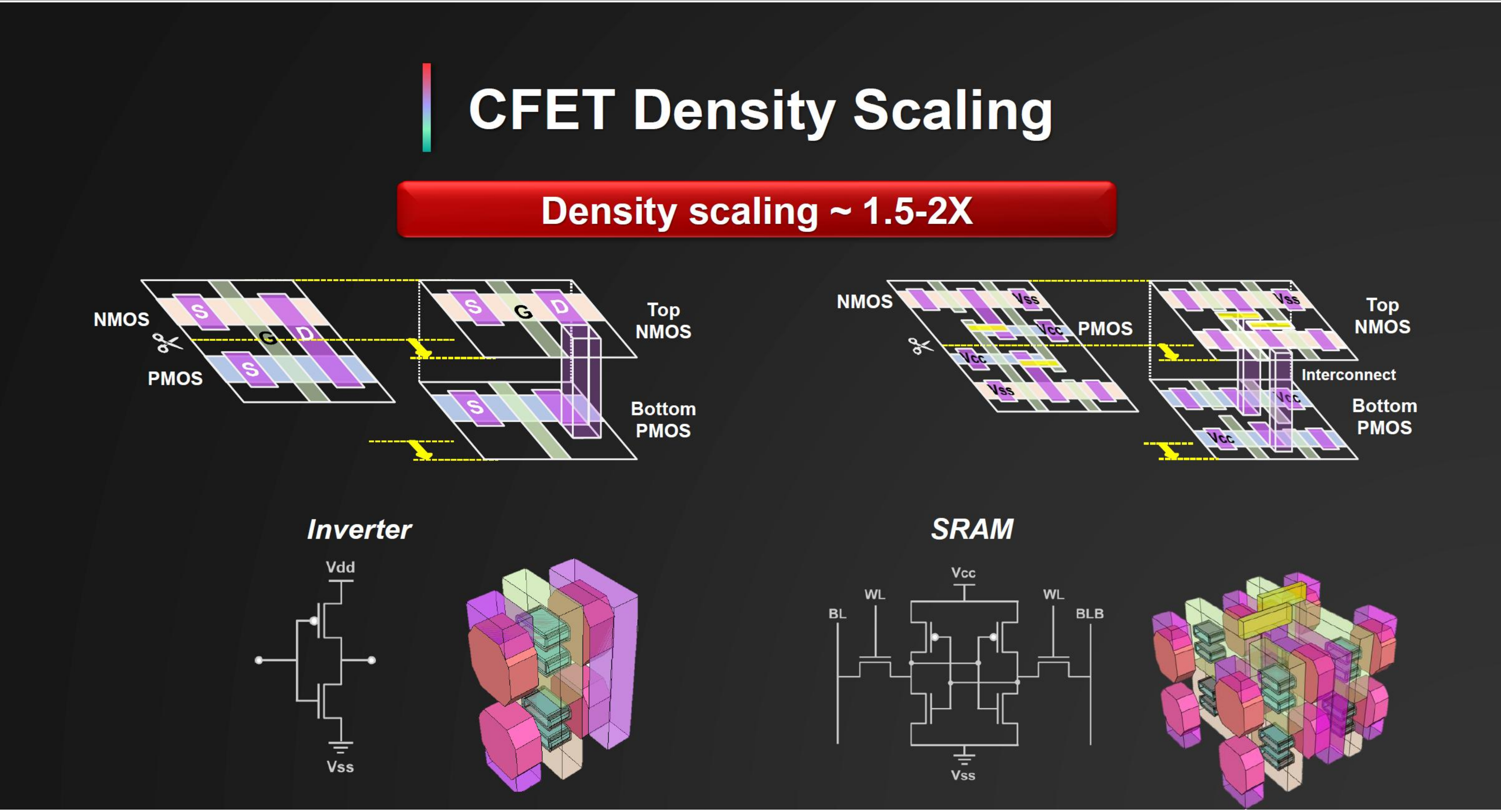
ISSCC2024 plenary talk by TSMC

Transistor Architecture Outlook



ISSCC2024 plenary talk by TSMC

CFET Density Scaling



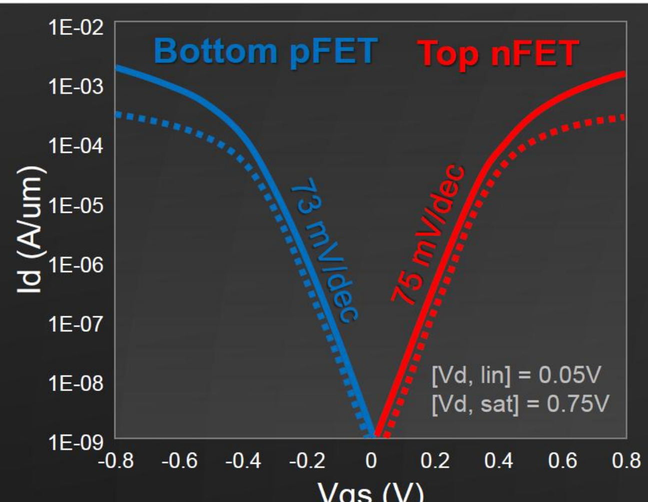
ISSCC2024 plenary talk by TSMC

CFET Silicon Demonstration

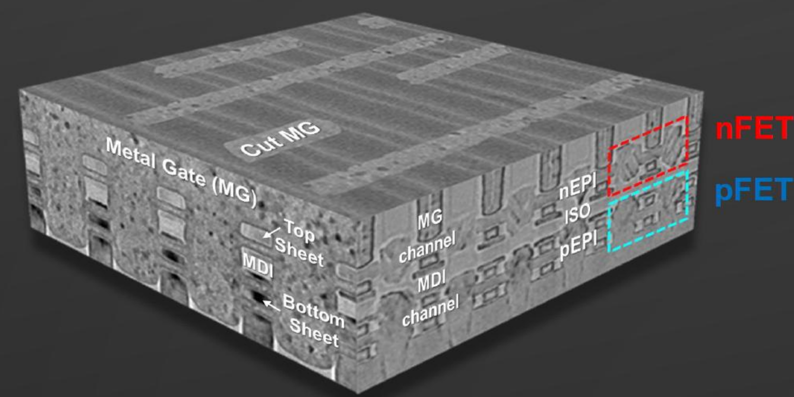
CFET Silicon Demonstration

2023 IEDM

Wednesday, Dec. 13 | 9:00 AM – 12:00 PM
11:35 AM – 12:00 PM
Program Number: 29-6
Complementary Field-Effect Transistor (CFET) Demonstration at 48nm Gate Pitch for Future Logic Technology Scaling
S. Liao, Taiwan Semiconductor Manufacturing Company (TSMC); L. Yang, Taiwan Semiconductor Manufacturing Company (TSMC)



Demonstrated the Integration of nFET and pFET



ISSCC2024 plenary talk by TSMC

CHAPTER 1

Introduction

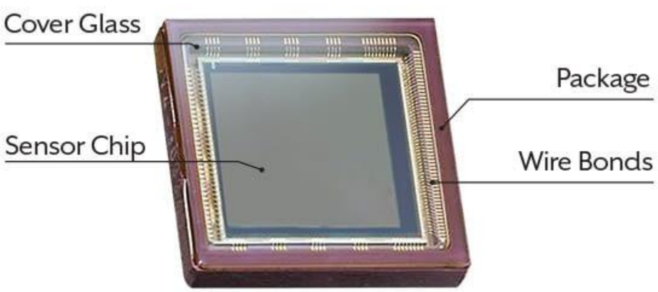
Outline

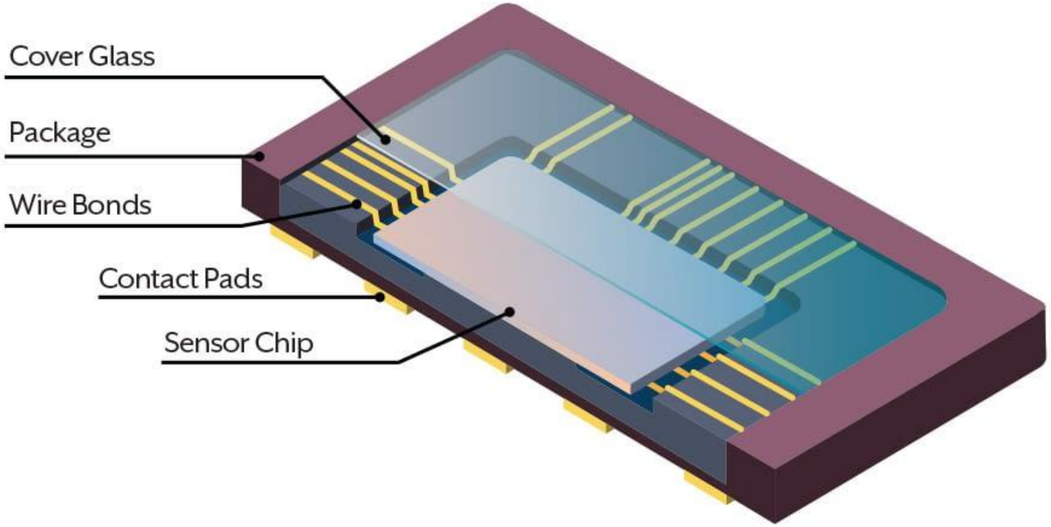
- 1.1 General overview
- 1.2 Brief history of CMOS image sensors
- 1.3 Brief history of smart CMOS image sensors

Outline

- 1.1 General overview
- 1.2 Brief history of CMOS image sensors
- 1.3 Brief history of smart CMOS image sensors

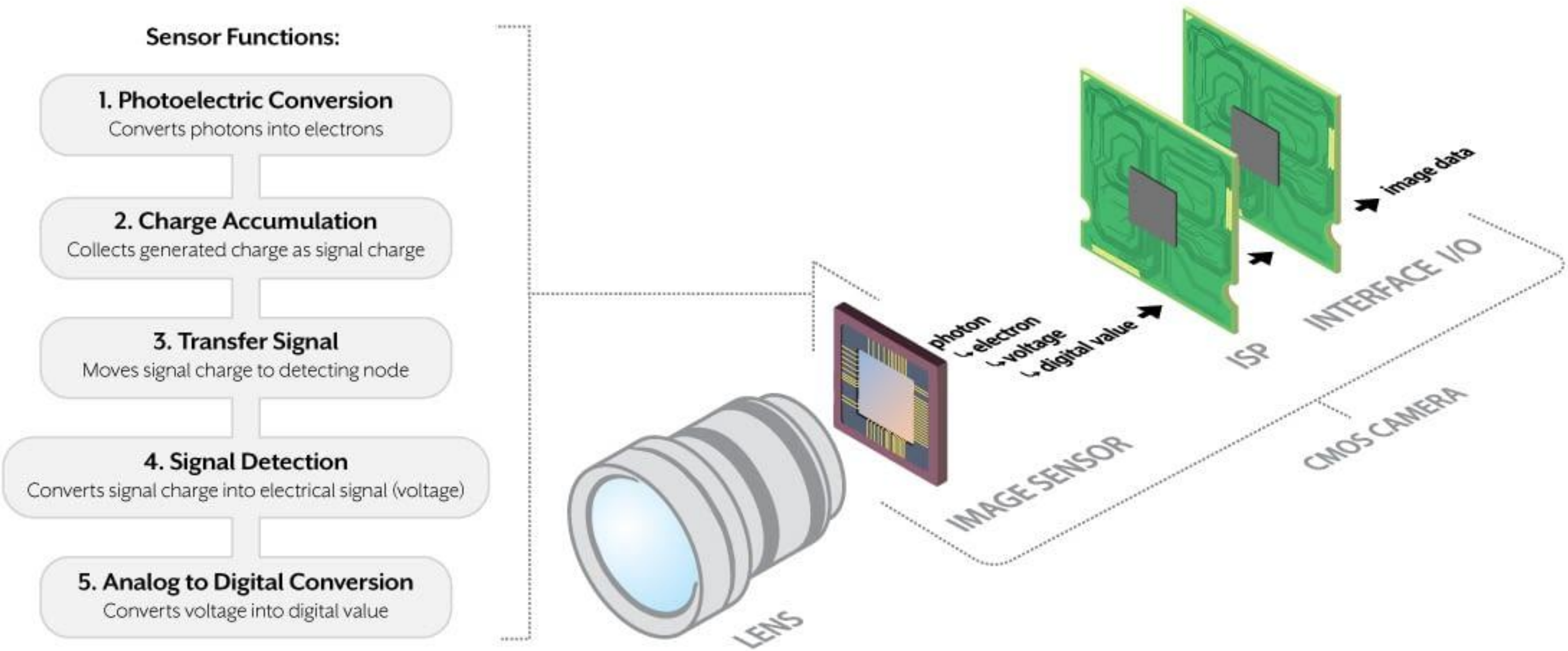
Image Sensor Components





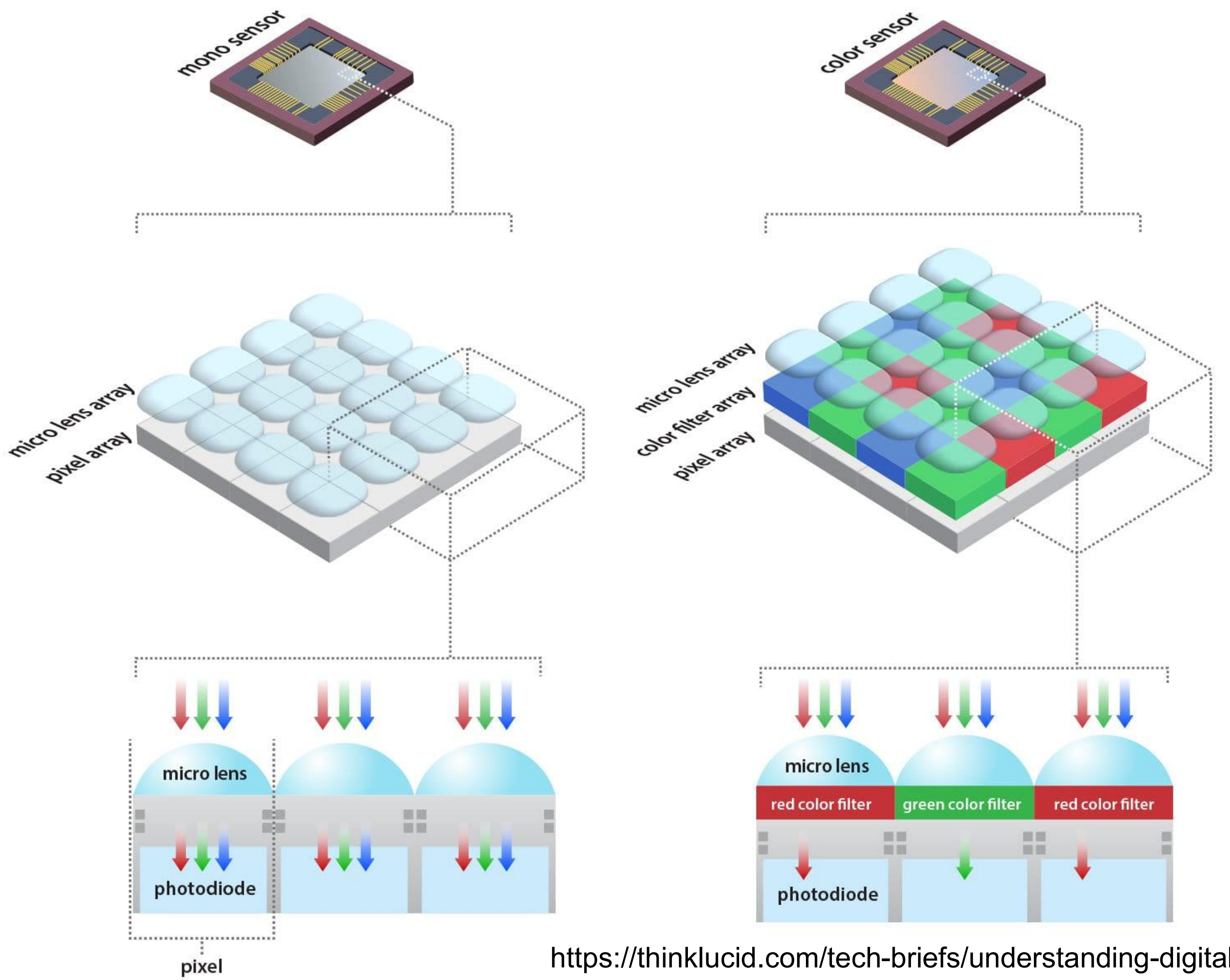
https://thinklucid.com/tech-briefs/understanding-digital-image-sensors/

Sensor Functions Inside a Camera



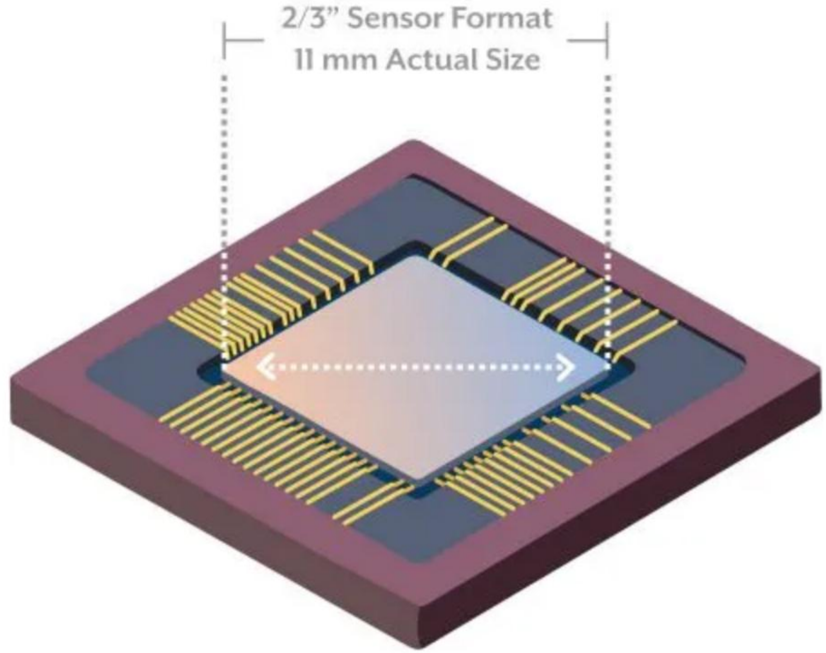
https://thinklucid.com/tech-briefs/understanding-digital-image-sensors/

Mono and Color Sensors



https://thinklucid.com/tech-briefs/understanding-digital-image-sensors/

Image Sensor Format (Size)

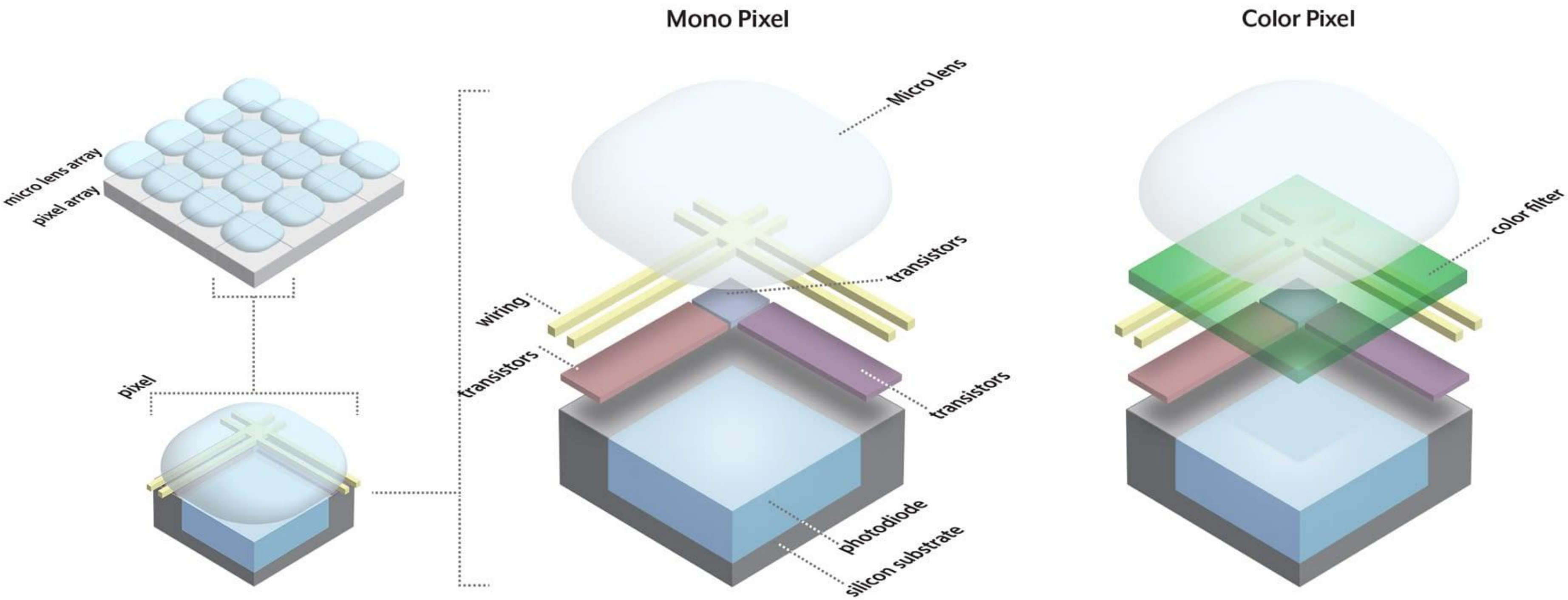


Sensor Format vs. Actual Size

Image Sensor Format (Type)	1"	2/3"	1/1.8"	1/3"
Image Sensor Diagonal (mm)	16 mm	11 mm	8.9 mm	~6 mm

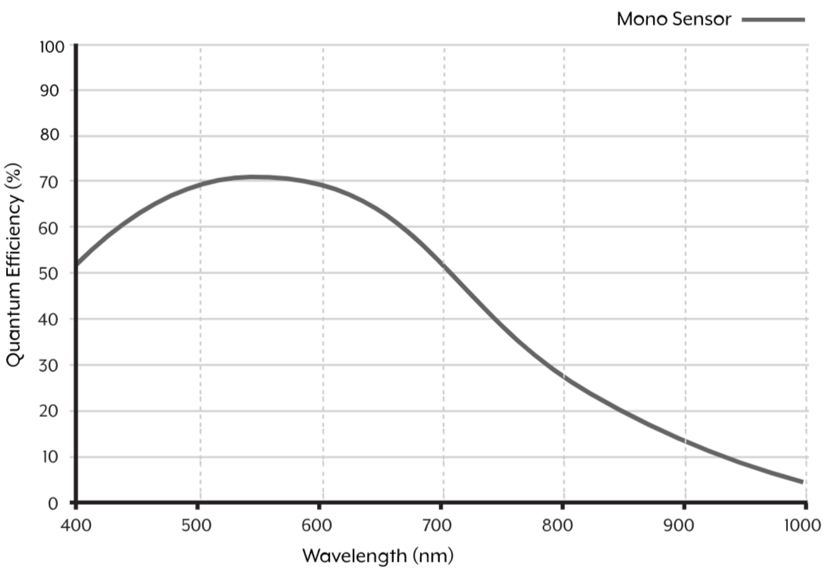
https://thinklucid.com/tech-briefs/understanding-digital-image-sensors/

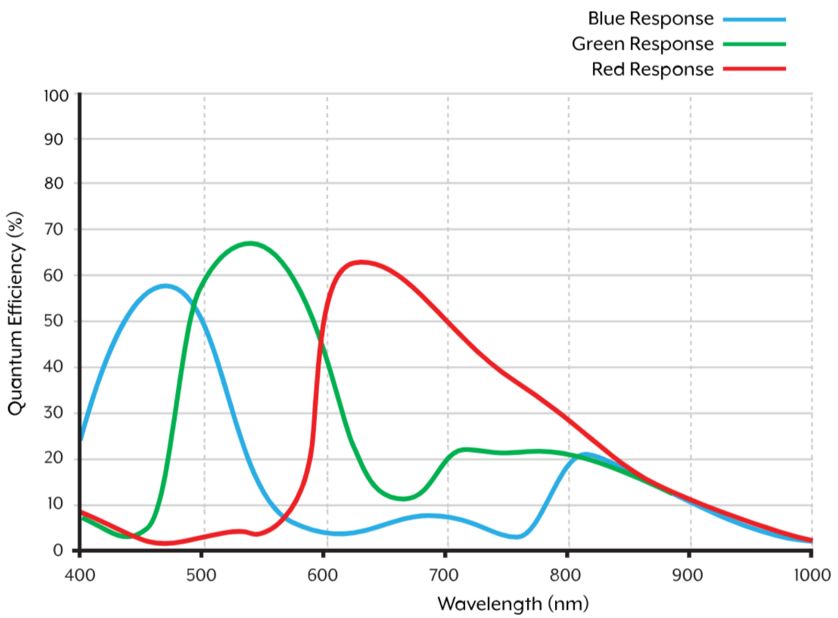
Sensor Pixel Size



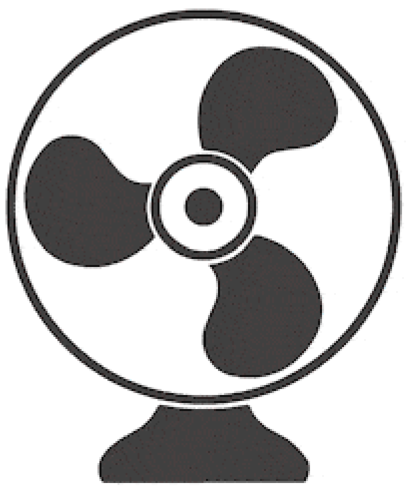
https://thinklucid.com/tech-briefs/understanding-digital-image-sensors/

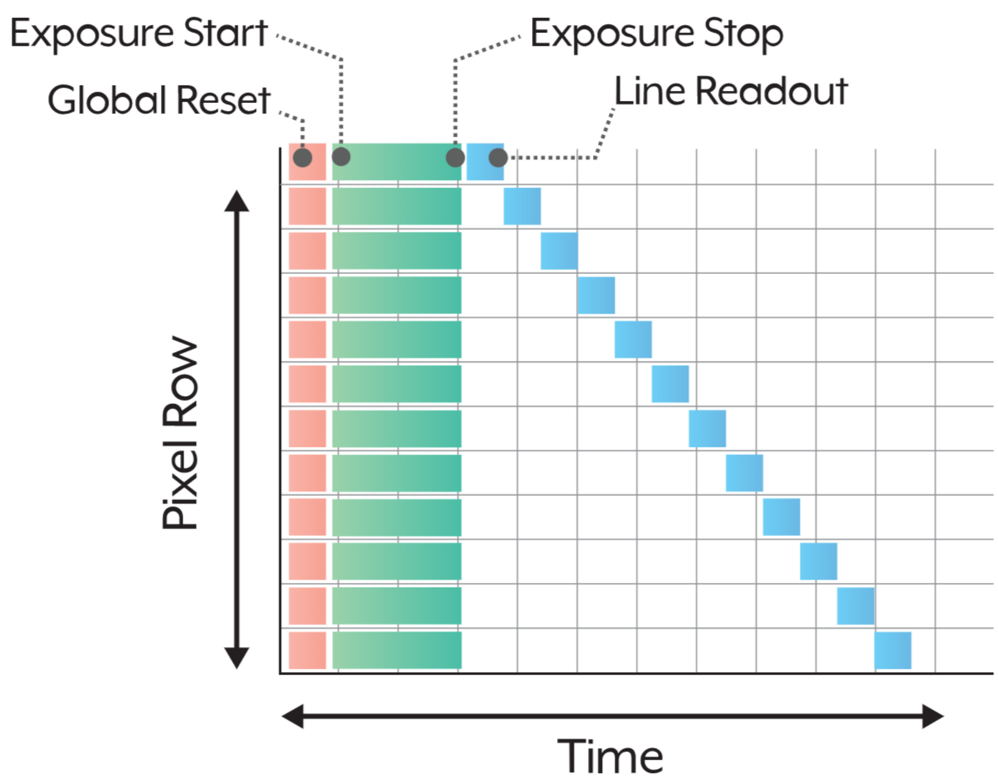
Mono & Color Spectral Response



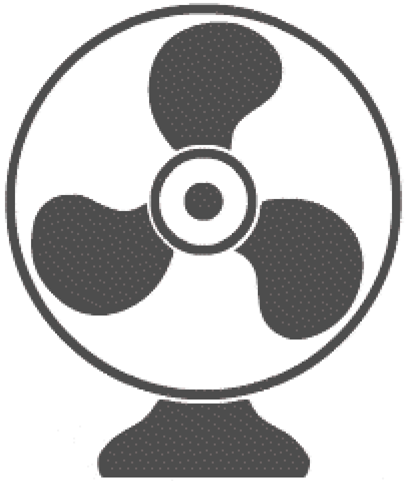


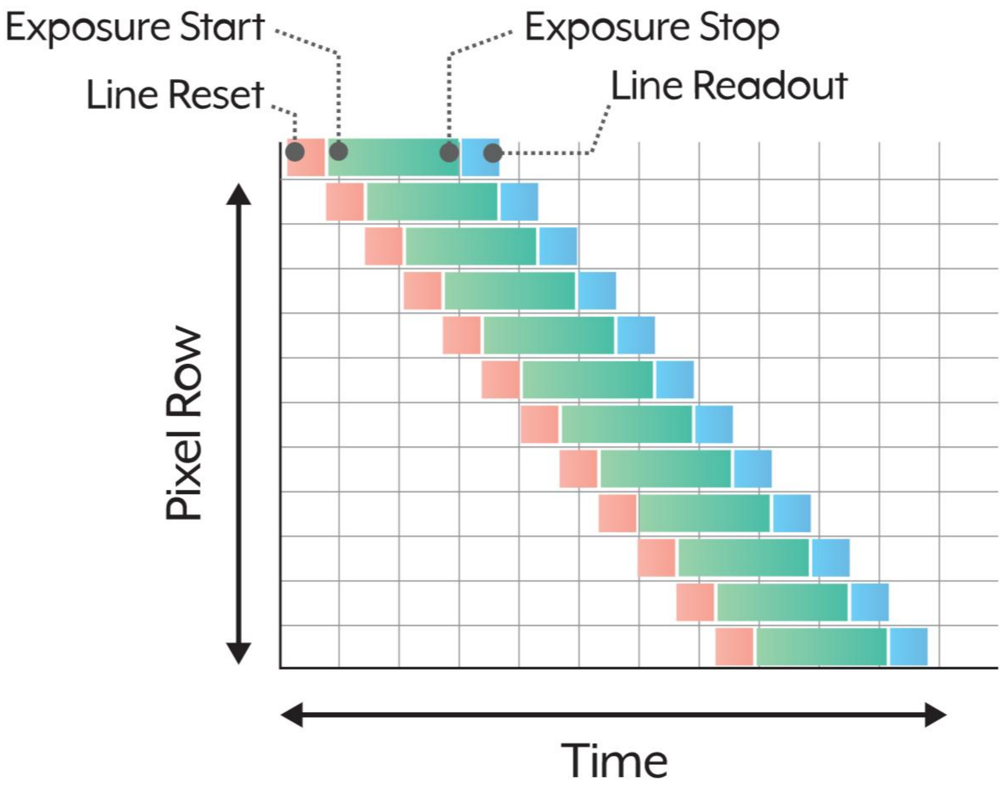
Global versus Rolling Shutter





Global versus Rolling Shutter





Imaging Sensor

- CCD
  - Have dominated the field of imaging sensors for along time
  - Based on a specially developed fabrication process
- CMOS image sensor
  - Based on standard CMOS large scale integration (LSI) fabrication processes
  - Possible to integrate functional circuits

CMOS Image Sensor

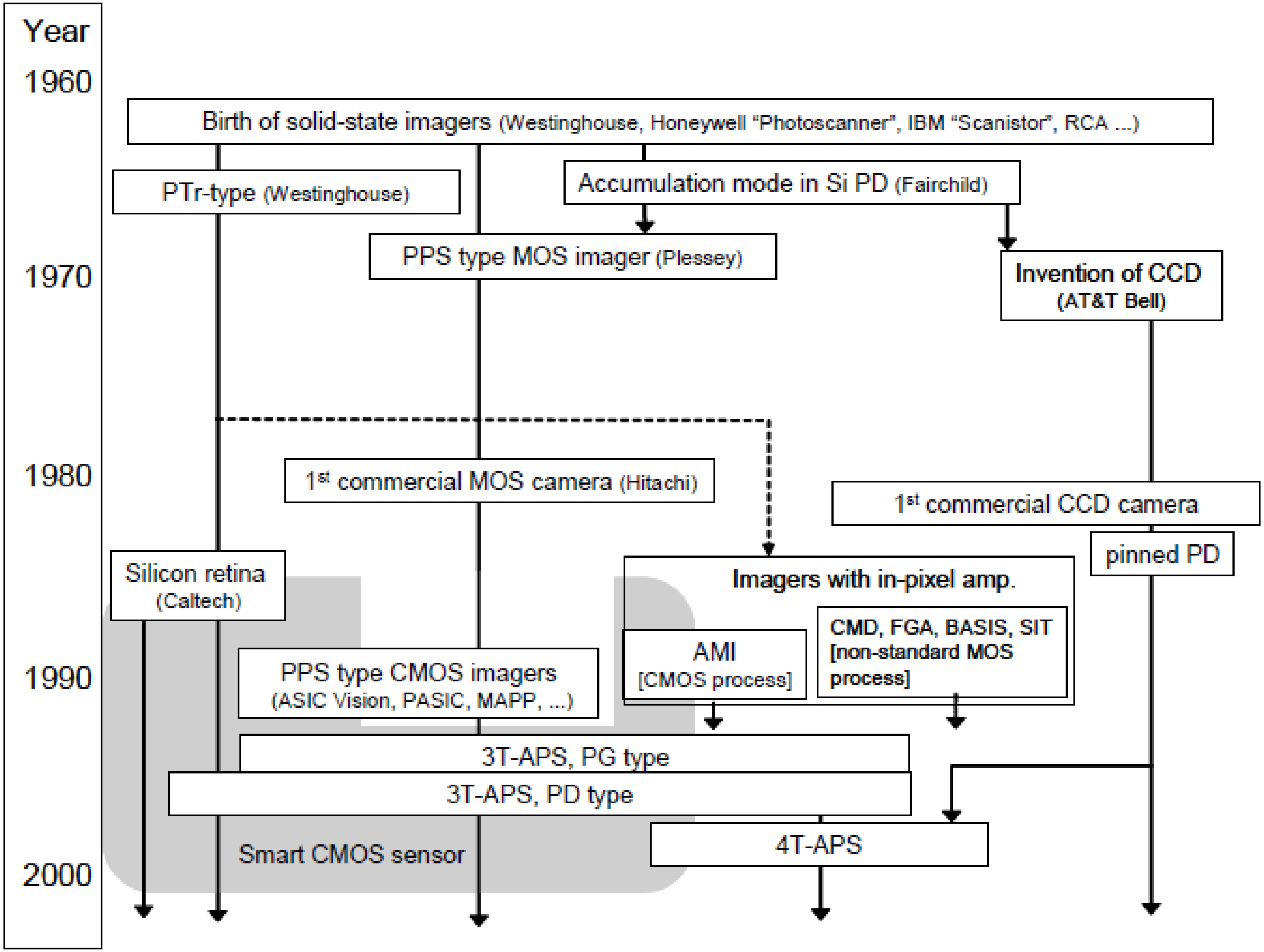
- CMOS image sensors
  - Digital still cameras (DSC)
  - Mobile phone cameras
  - Handy camcorders
  - Digital single lens reflex (DSLR) cameras
  - Automobiles, surveillance, security, robot
  - Vision, etc.

- These applications require advanced performance
  - Wide dynamic range, high speed, and high sensitivity
- While others need dedicated functions
  - Real time target tracking
  - Three-dimensional range finding
- It is difficult to perform such tasks with conventional image sensors.

Outline

- 1.1 General overview
- 1.2 Brief history of CMOS image sensors
- 1.3 Brief history of smart CMOS image sensors

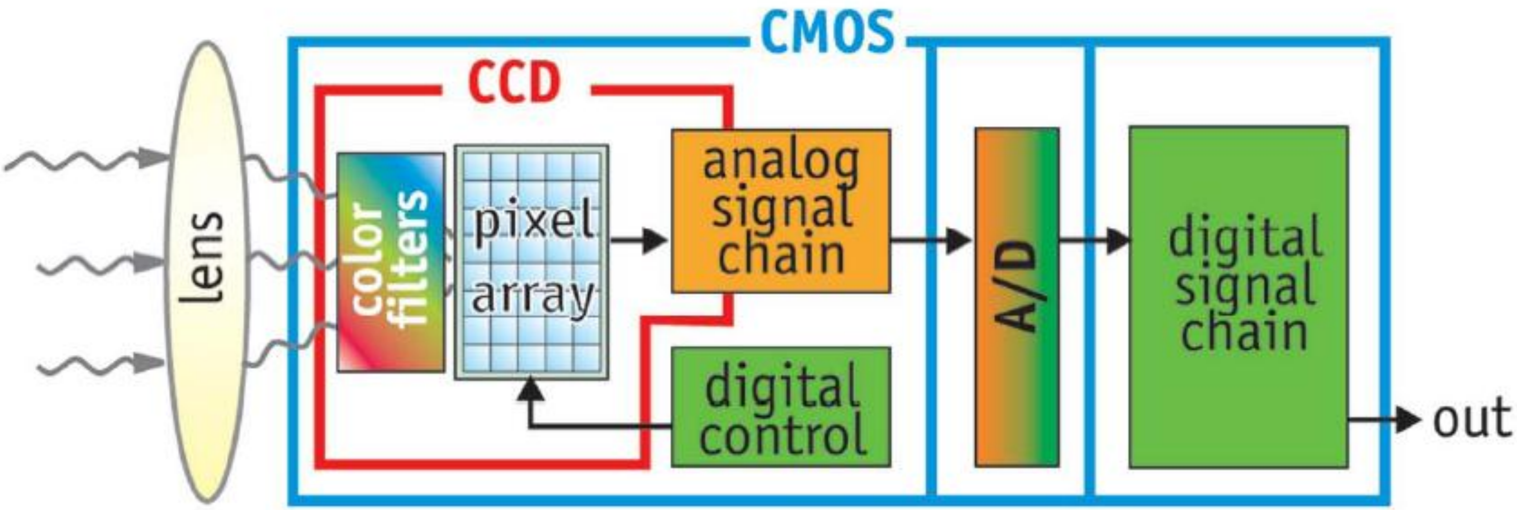
Birth of MOS imagers



Competition with CCDs

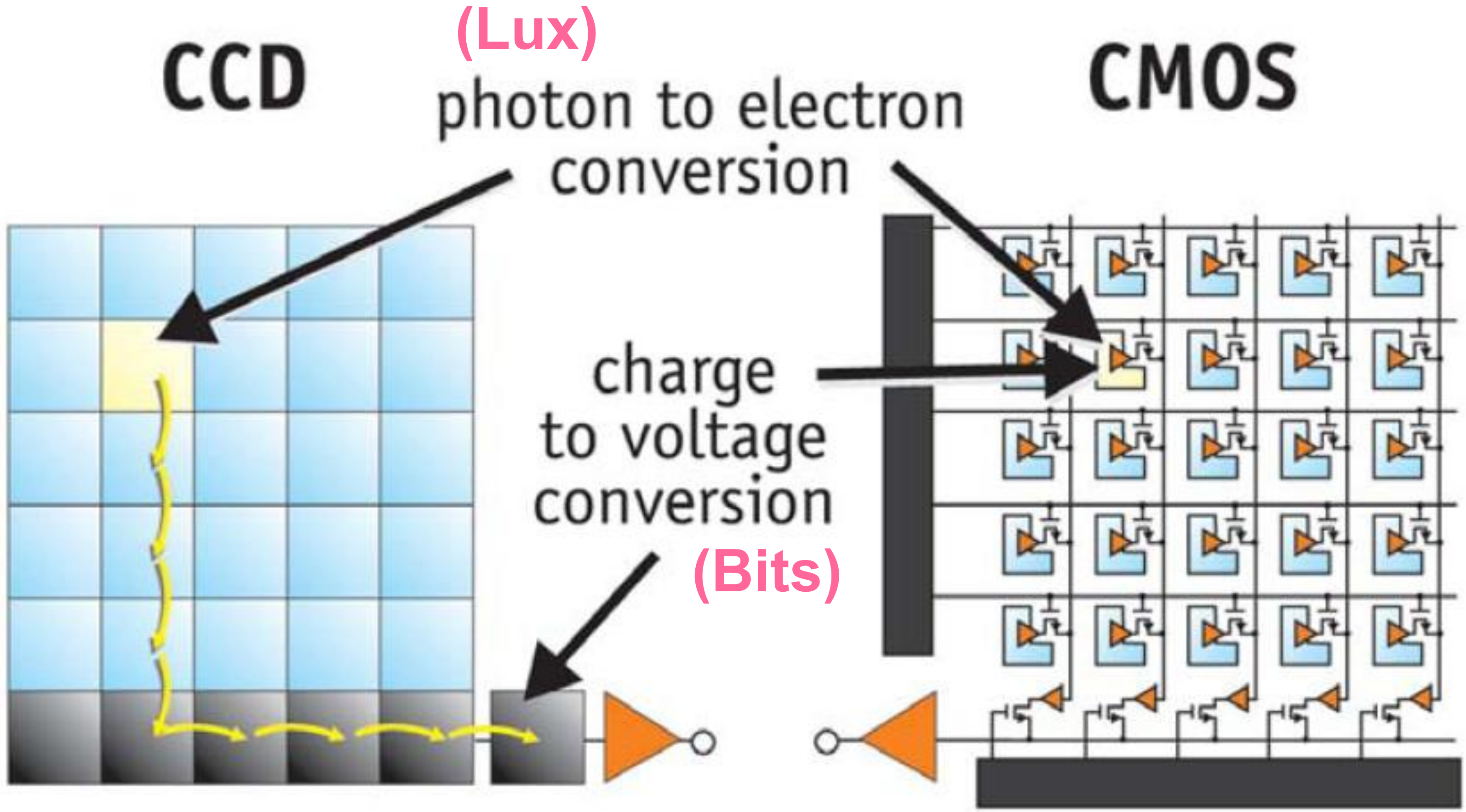
- CCD
  - Invented in 1969 by W. Boyle and G.E. Smith
  - Developed as bubble memory at first
- CCD image sensor
  - After IEEE Transaction on Electron Devices in 1968
  - Superior image quality than MOS imagers

CMOS vs CCD in System



CMOS imagers can be fabricated with more "camera" functionality on the chip. This offers advantages in size and convenience.

Chip Behavior



CCDs move photogenerated charge from pixel to pixel and convert it to voltage at an output node. CMOS imagers convert charge to voltage inside each pixel.

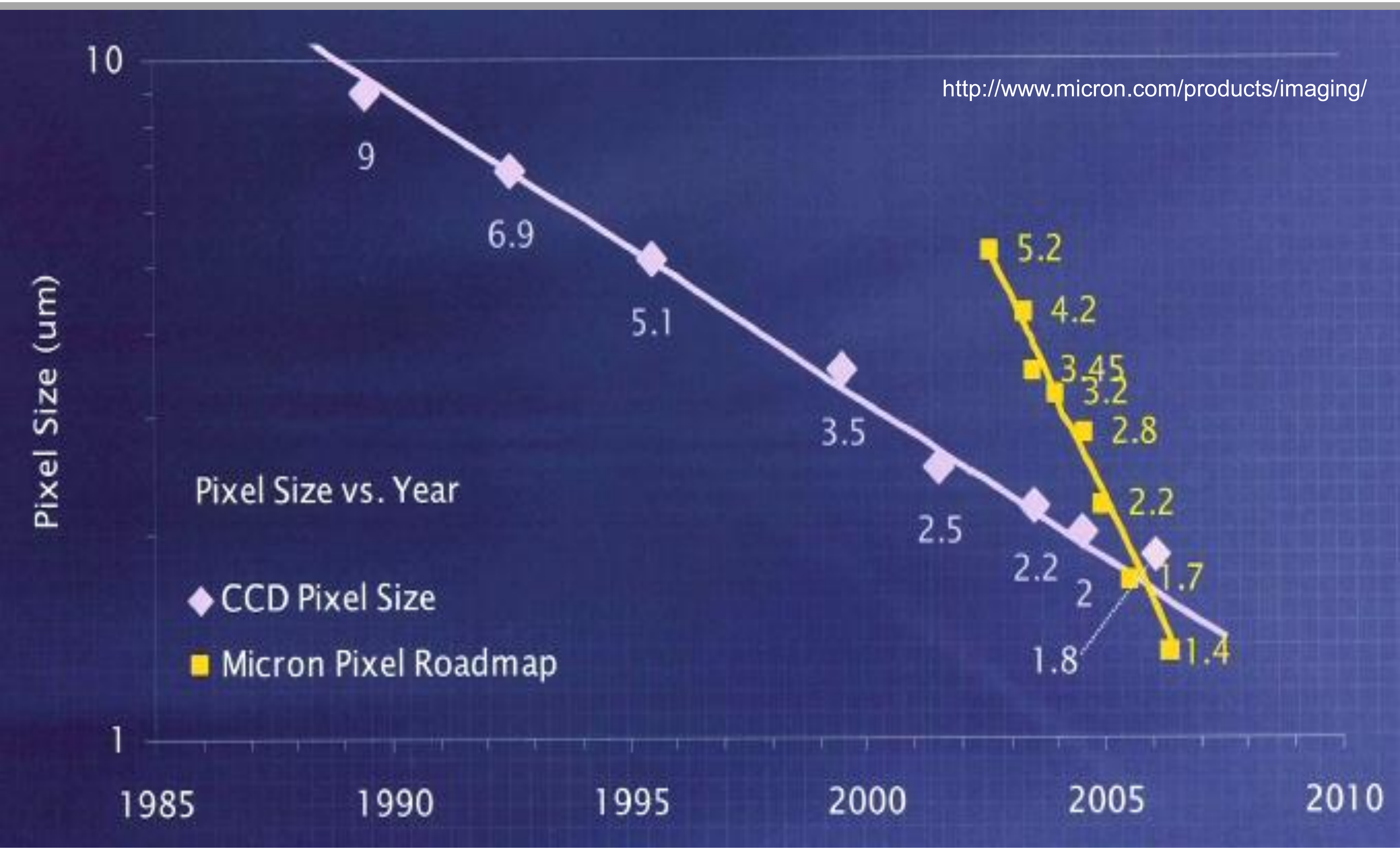
http://www.dalsa.com

CMOS vs CCD in Table

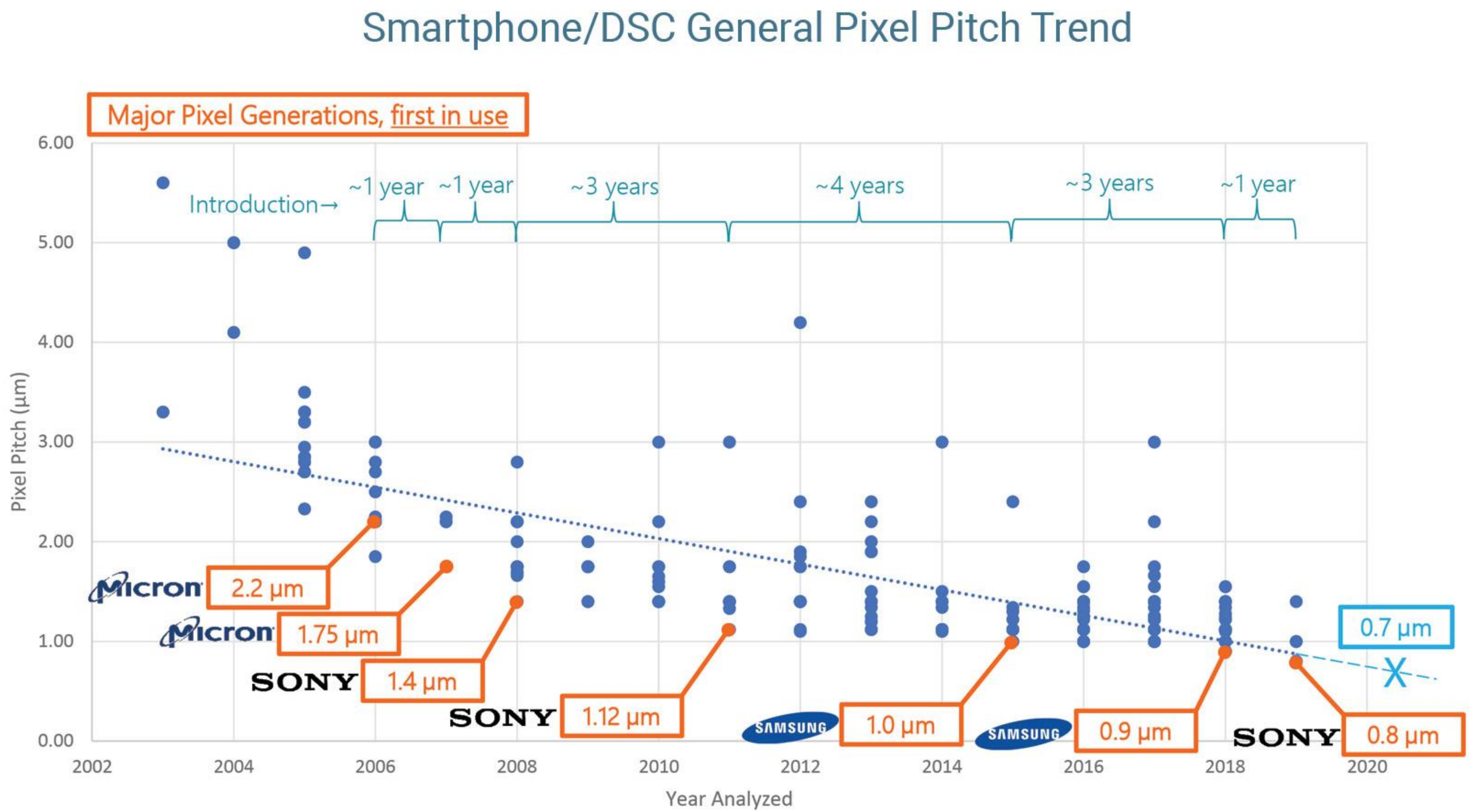
Feature	CCD	CMOS
Signal out of pixel	Electron packet	Voltage
Signal out of chip	Voltage (analog)	Bits (digital)
Signal out of camera	Bits (digital)	Bits (digital)
Fill factor	High	Moderate
Amplifier mismatch	N/A	Moderate
System Noise	Low	Moderate
System Complexity	High	Low
Sensor Complexity	Low	High
Camera components	Sensor + multiple support chips + lens	Sensor + lens possible
Relative R&D cost	Lower	Higher
Relative system cost	Depends on Application	Depends on Application
Performance	**CCD**	**CMOS**
Responsivity	Moderate	Slightly better
Dynamic Range	High	Moderate
Uniformity	High	Low to Moderate
Uniform Shuttering	Fast, common	Poor
Windowing	Limited	Extensive
Speed	Moderate to High	Higher
Biasing and Clocking	Multiple, higher voltage	Single, low-voltage

http://www.dalsa.com

CMOS vs CCD in Pitch



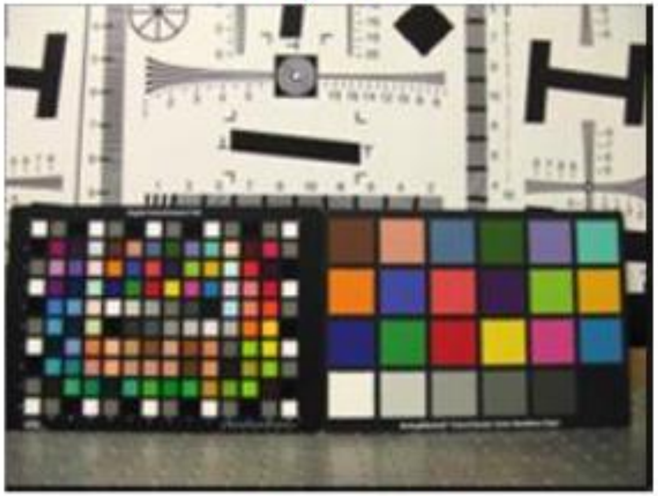
Pixel Scaling Trend



https://www.techinsights.com/blog/part-2-pixel-scaling-and-scaling-enablers#images-1

CMOS vs CCD in Image

Fuji Z1



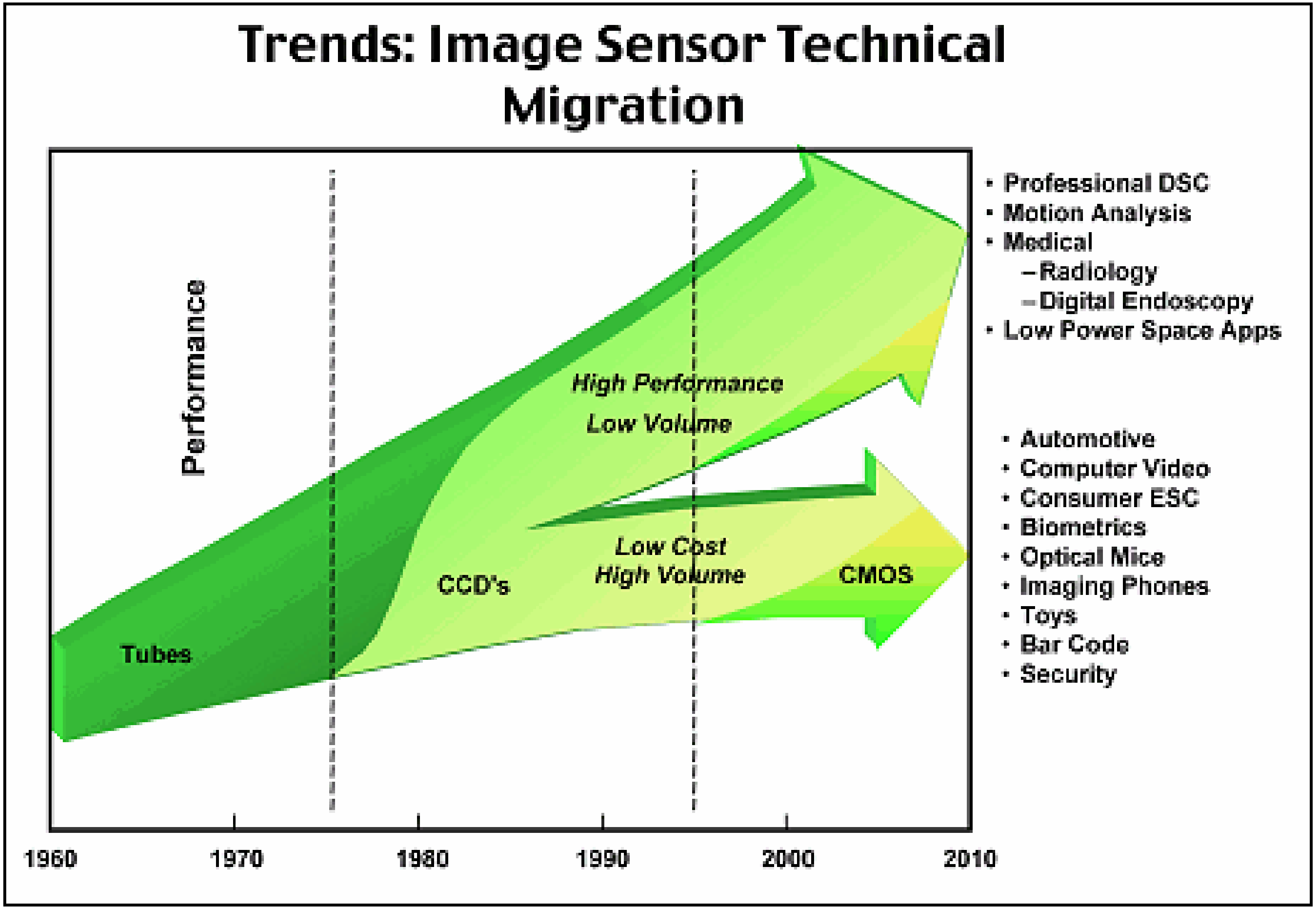
Micron 5Mp CMOS Imager

Sony T7

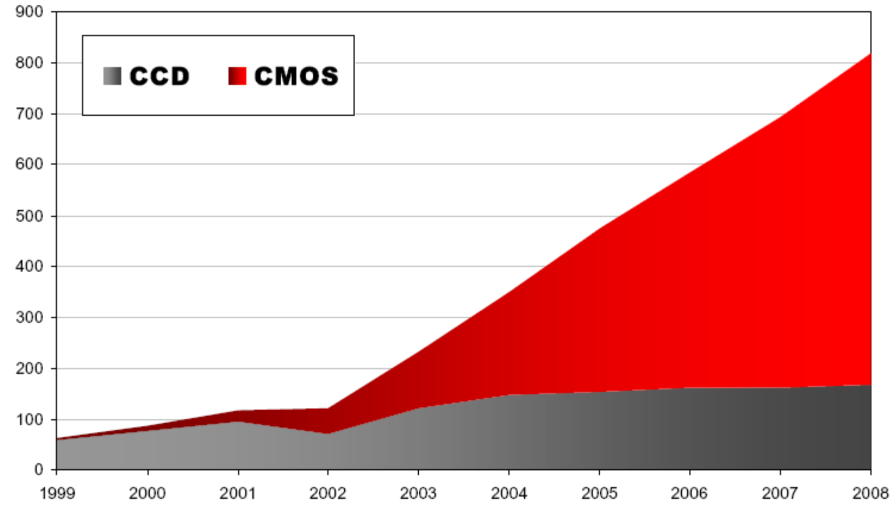
- **Comparison images taken at ISO200 with new Micron 2.2um 5MP CMOS imager and two CCD-based imagers.**
- **Aptina 9M CMOS sensor is sampling with 1.75um.**

http://www.micron.com

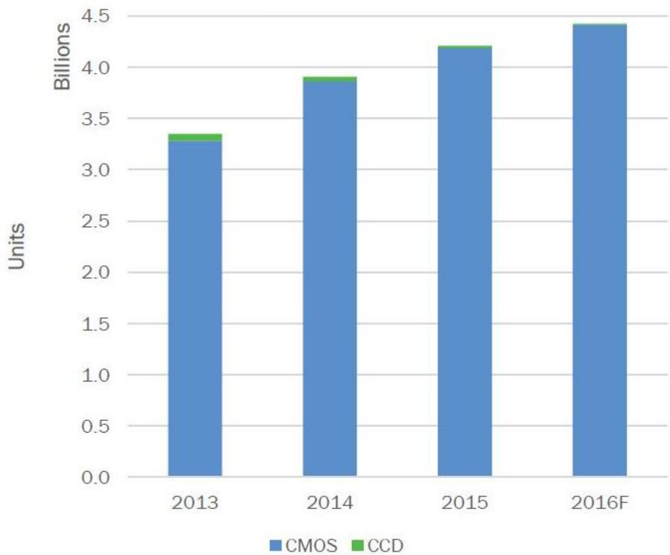
CMOS vs CCD Technical Trend

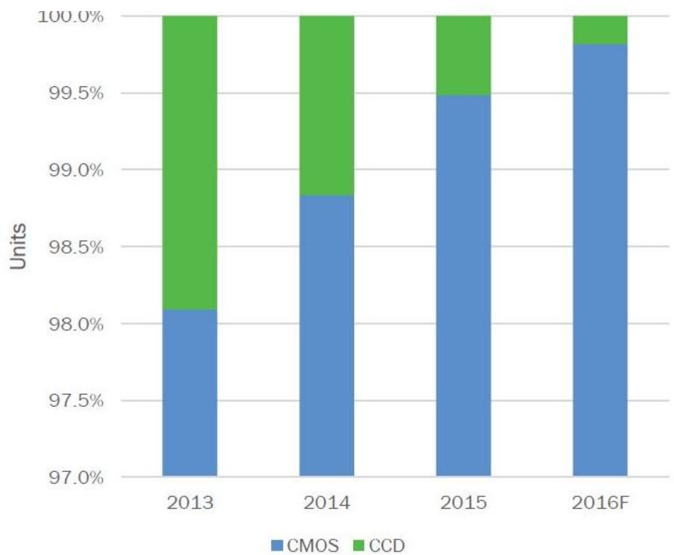


CMOS vs. CCD in Market



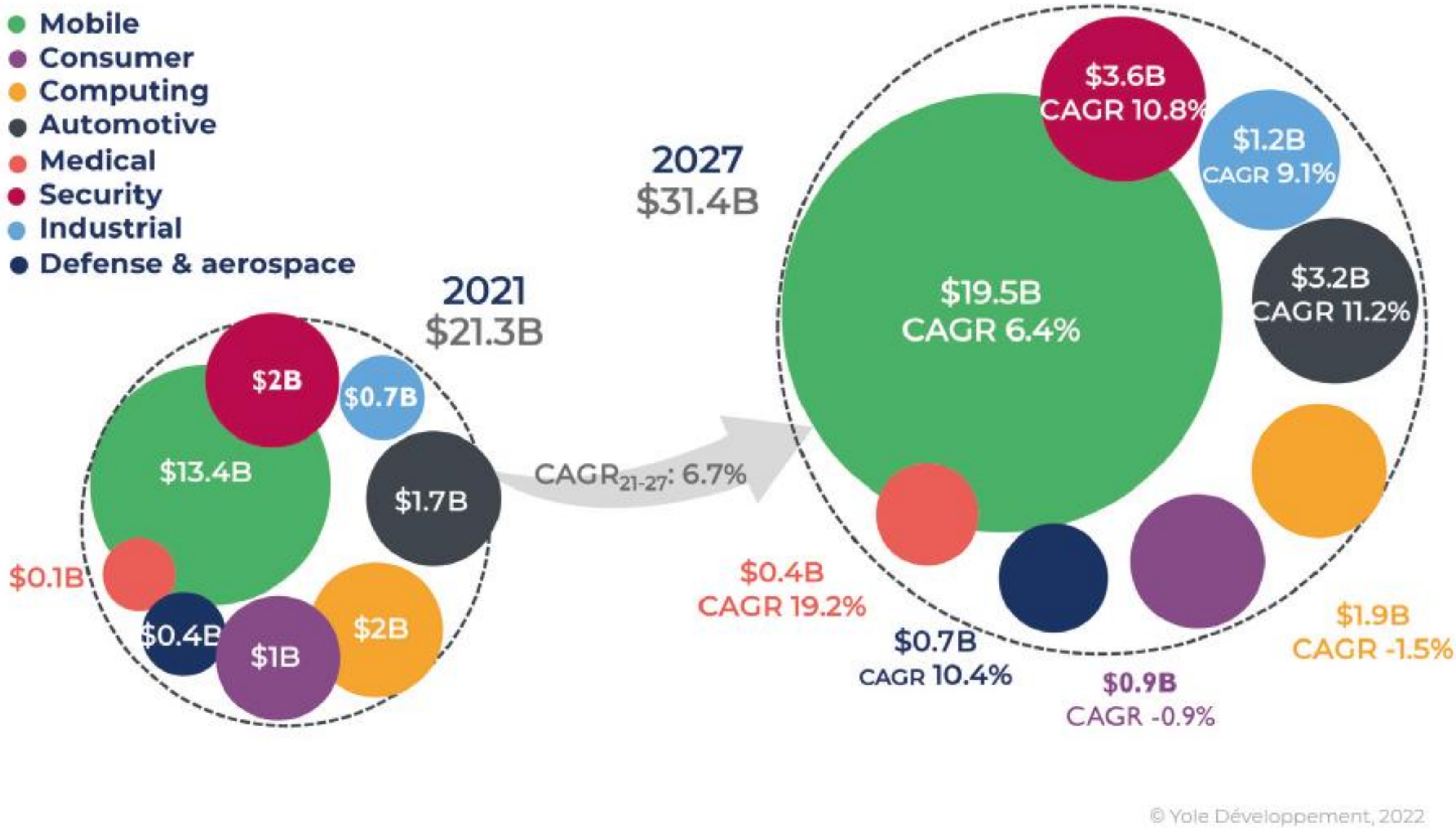
TSR April 2005





TSR

Forecast of CIS Market



Solid-State Imager

- Phototransistor (PTr) type imager was developed in the 1960s
- Several amplified type imagers were developed In the late 1980s
  - Charge modulated device (CMD)
  - Floating gate array (FGA)
  - Base-stored image sensor (BASIS)
  - Static induction transistor (SIT) type
  - Amplified MOS imager (AMI)
- AMI can be fabricated in standard CMOS technology

Present CMOS image sensors

- Photodetector

(1) Photogate (PG)

– Ease of signal charge handling

– Sensitivity is not good

(2) Photodiode (PD)

– Now widely used in CMOS image sensors

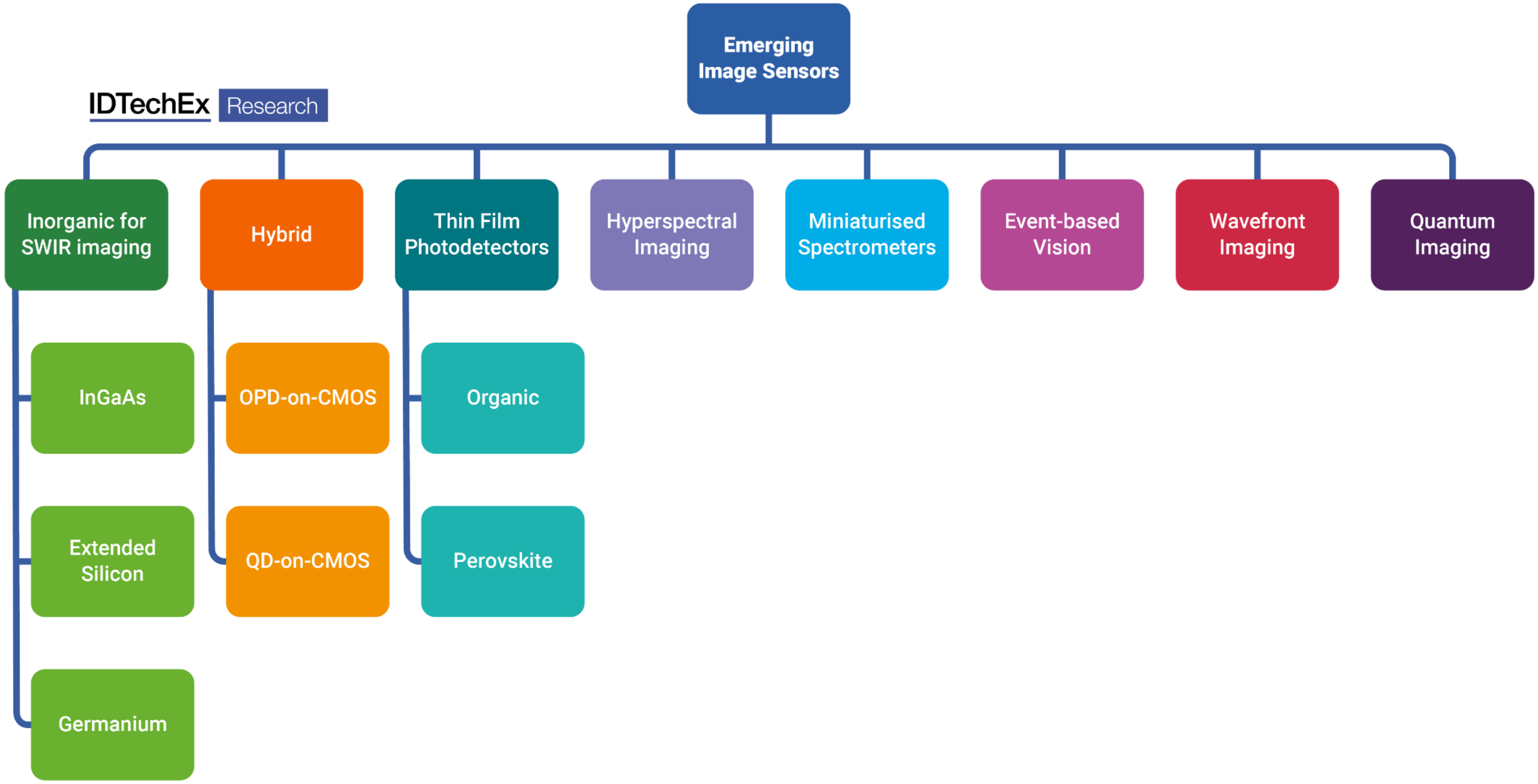
(3) Organic film

– For small pixel

(4) Bolometer

– For IR response (Thermal imaging)

Emerging Image Sensors



Active pixel sensor (APS)

- 3T-APS
  - Using PD as a photodetector
  - Image quality could not compete with CCDs
    (respect to fixed pattern noise (FPN) and random noise)

Active pixel sensor (APS)

- 4T-APS
  - PD and floating diffusion (FD) in a pixel
  - True correlated double sampling(CDS)
  - Eliminate kTC noise
  - Performance can compete with that of CCDs

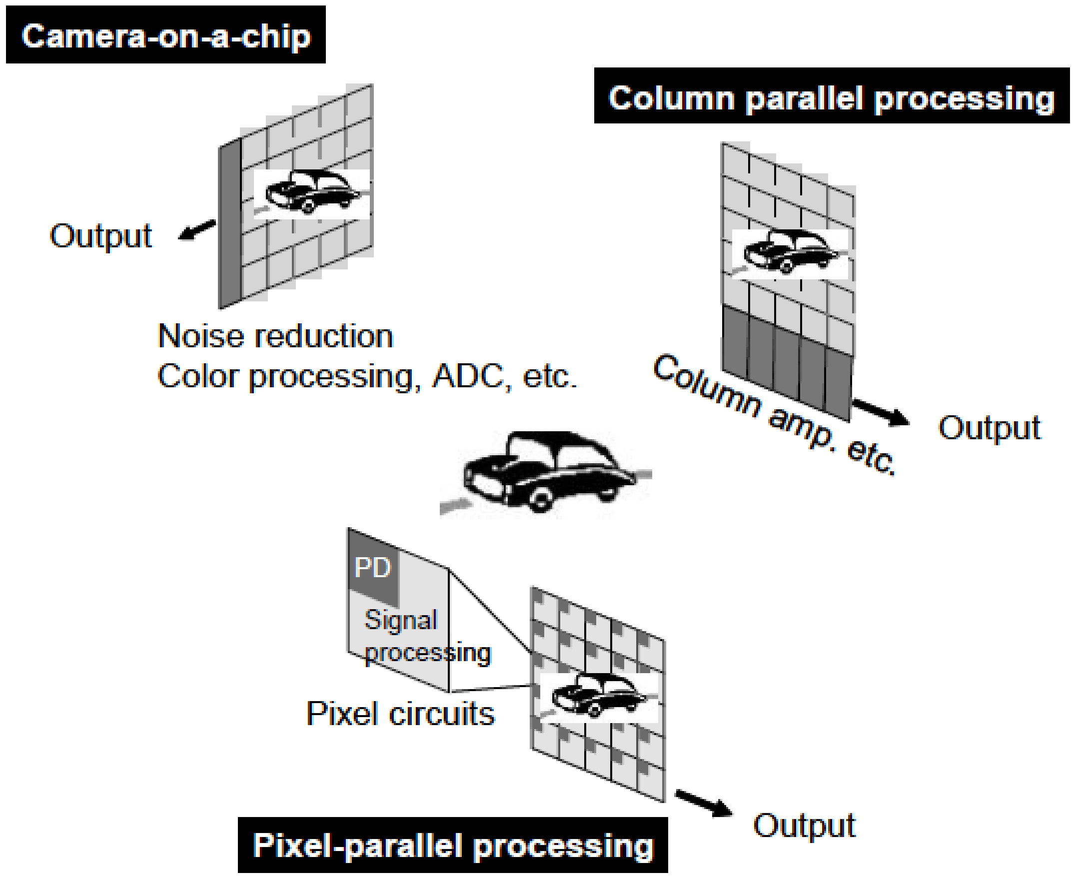
Outline

- 1.1 General overview
- 1.2 Brief history of CMOS image sensors
- 1.3 Brief introduction of smart CMOS image sensors

Smart CMOS image sensors

- Pixel-level processing
- Column level processing
- Chip-level processing (camera-on-a-chip)

Level of Parallelism



Pixel Level Processing

- Silicon retina
  - Mimic the human visual processing system
- 2-Dimensional resistive network
- Low power consumption
  - Work in the sub-threshold region

- With advancement of CMOS technology
  - Cellular neural networks (CNN)
  - Multiple instruction & multiple data (MIMD)
  - Biomorphic digital vision chips

Column Parallel Processing

- Suitable for CMOS sensor
  - Column line electrically independent
- Enhance the performance
  - Widening DR and increasing speed
- High image quality
  - With 4T sensor
- Versatile functions

Chip Level Processing

- Possible to realize highly integrated CMOS image sensors or smart CMOS image sensors for machine vision
  - ASIC vision (Image signal processing : ISP)
  - Near-sensor image processing (NSIP)
  - Matrix Array Picture Processor (MAPP)