SPECIAL TOPICS IN COMPUTER ARCHITECTURE AND VLSI DESIGN:

Overview of CMOS Image Sensors

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The Start of Digital Imaging

- Invented in 1969 at AT&T Bell Labs by Willard Boyle and George E. Smith.
- Originally working on memory →"Charge 'Bubble' Devices“, can be used as a shift register and as a linear and area imaging devices
- CCDs are electronic devices, which work by converting light into electronic charge in a silicon chip (IC). This charge is digitised and stored as an image file on a computer.
- In 2009, they were awarded the Nobel Prize for Physics

The first Digital Camera from Kodak

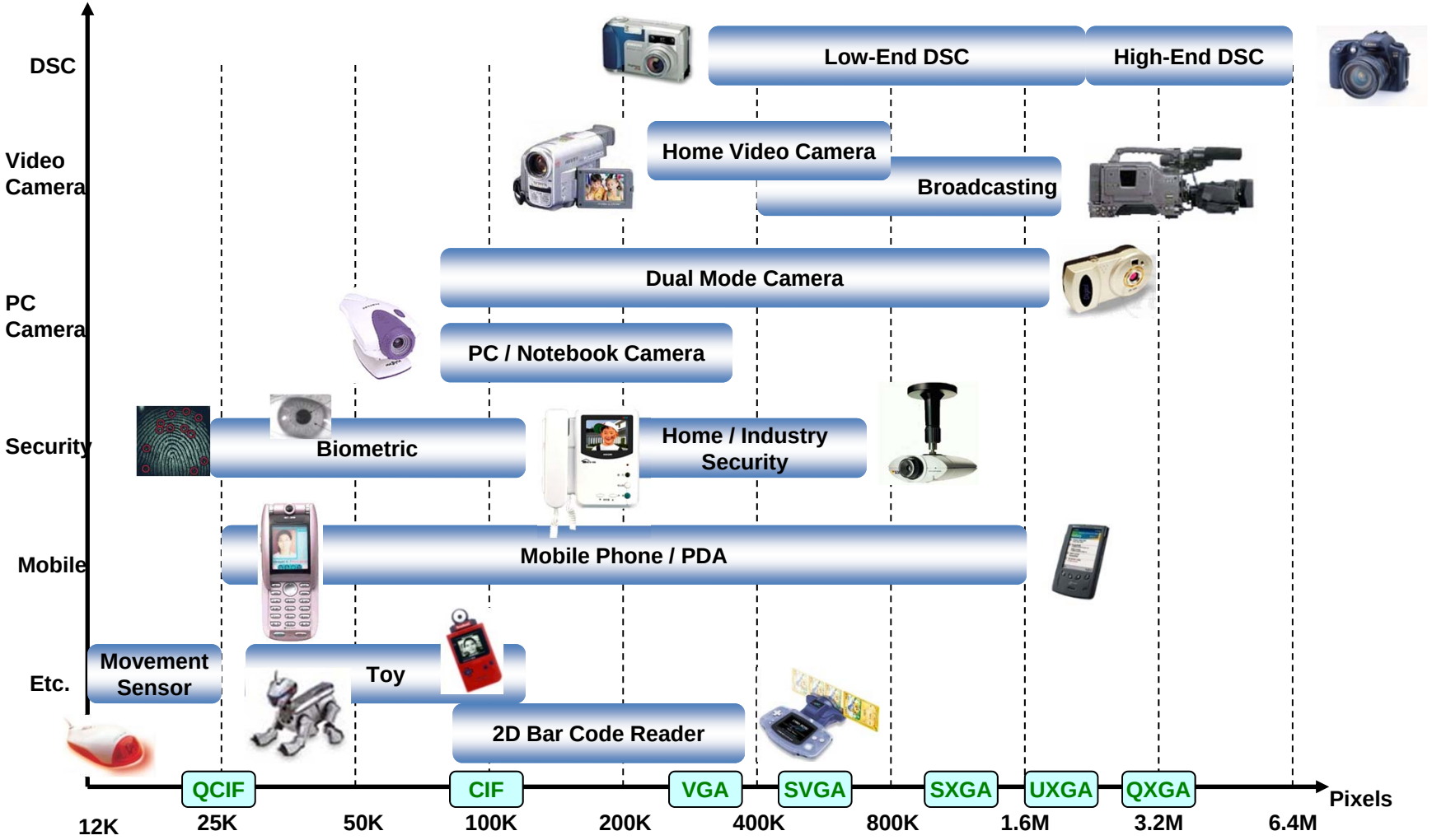
using a Fairchild 100 x 100 CCD in 1975

History

- 70s : Fairchild, 80s: Hitachi, Early 80s: Sony
- 1971 : FDA & CDS techniques are invented.
- Mid 1980s : Great success in the consumer market

- 1990: NHK/Olympus, amplified MOS Imager (AMI)
  called CMOS Image Sensor later.
- 1993: JPL, CMOS active pixel sensor
- 1998: A single chip camera
- After 2005 : CMOS image sensor becomes dominant

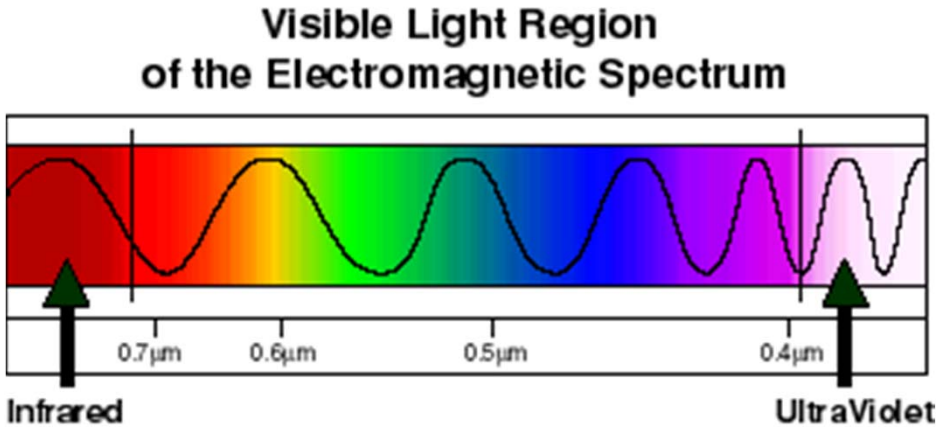
Area Image Sensor Applications



160 million pixel (Seitz)

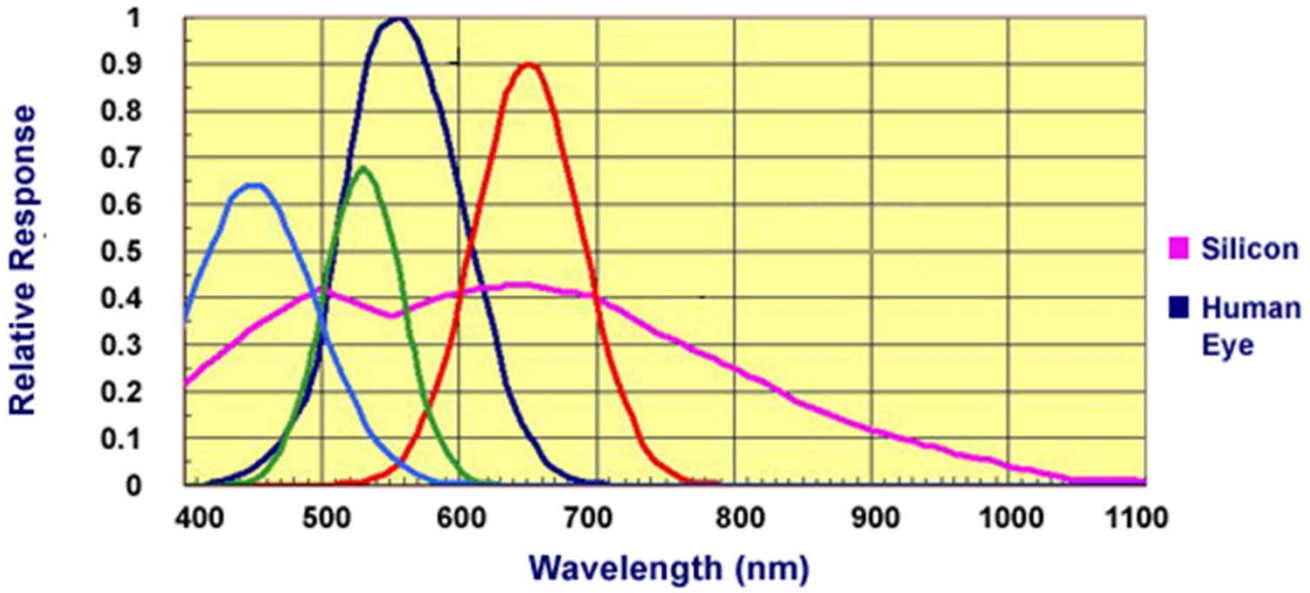
Manufacturer	Seitz Phototechnik AG
Lenses (interchangeable)	
- on Seitz lens board	- Schneider or Rodenstock large format lenses
- on adaptor plate	- Linhof Technorama, Fuji, other large format lenses
Size of 6x17 image	7,500 x 21,250 pixels (60mm x 170mm)
Total resolution	160 million pixels
File sizes	raw (16-bit): 307 MB
	uncompressed tiff (48-bit): 922 MB
Time for 6x17 panorama	~1 sec. at full speed/resolution
Exposure range	from 1/2'000 sec.
Exposure control	automatic or manual
ISO/ASA equivalent	100, 200, 400, 800, 1'600 by stage selection
Image format	up to 6x17; adjustable vertically and horizontally
File format	raw (16-bit): .dng, tiff (48-bit), jpg (24-bit), bmp
Image optimisation	Seitz custom-built image optimiser
Camera body*	
- dimensions	width: 465mm, height: 175mm, depth: 95mm
- weight	4.5 kg (camera 3.7 kg, battery 0.8k)
Image transfer	Gigabit ethernet
Power supply (camera)	12V 4.5A NiMh battery
Power charger	Universal speed charger 110-220V

Visible Light



- Photon Energy, $E_{ph}=hc/\lambda$
  - at 400nm(violet) E_{ph} = 3.1 eV
  - at 600nm(yellow) E_{ph} = 2.0 eV
  - at 700nm(red) E_{ph} = 1.77 eV
  - at 1100nm(infra red) E_{ph} = 1.12 eV
- photons in the visible range have enough energy to generate e-h pairs for silicon (E_g=1.124eV)

Photoresponsibility



Silicon Photo Sensor

- Electron-hole paier is generated when $E_{ph} > E_g$
- The generated e-h pair will be recombined in short time
- In the vicinity of P-N junction, electrons are captured in n+ region

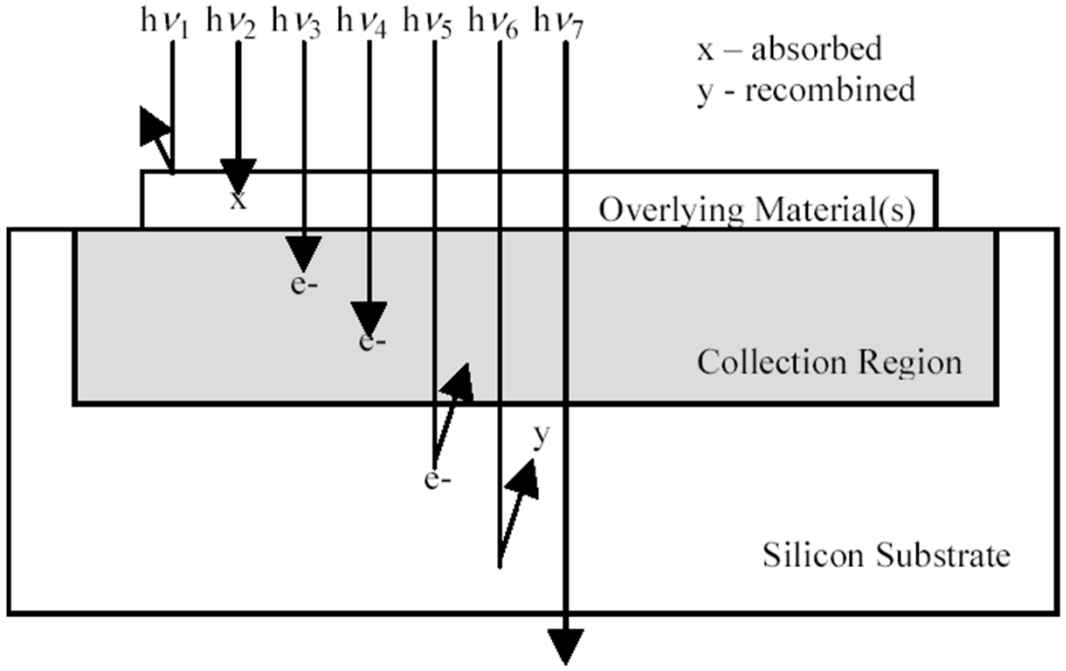
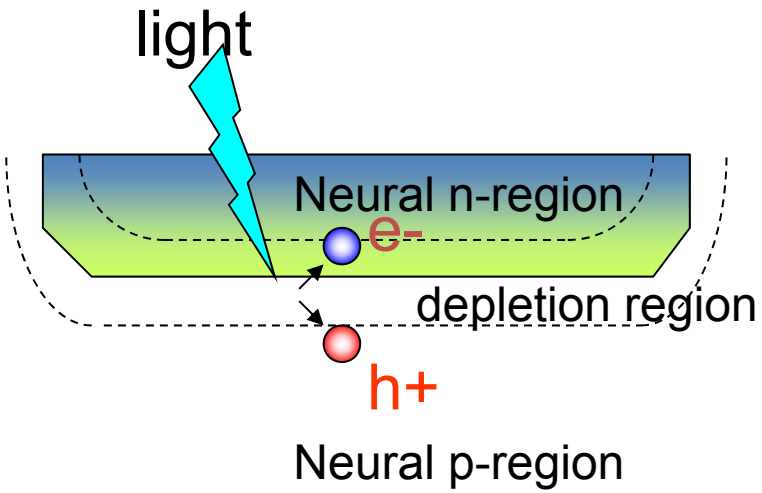
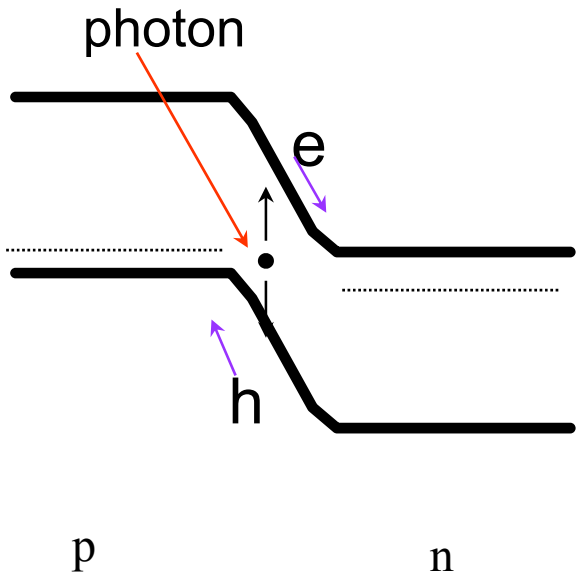


Photo sensing in PN junction





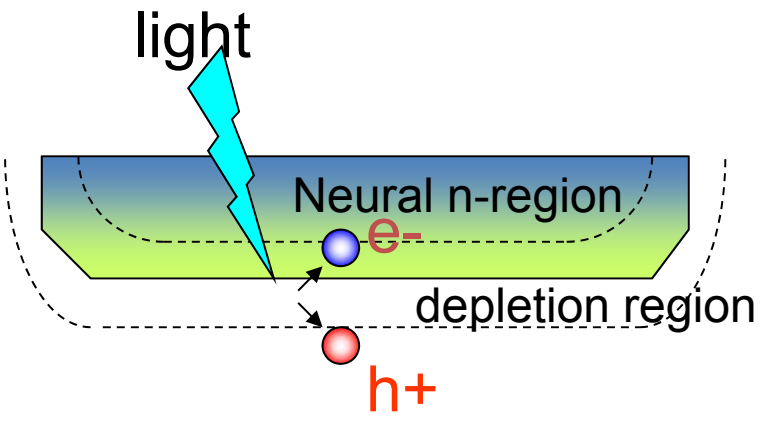
1. incident light
   = photon flux

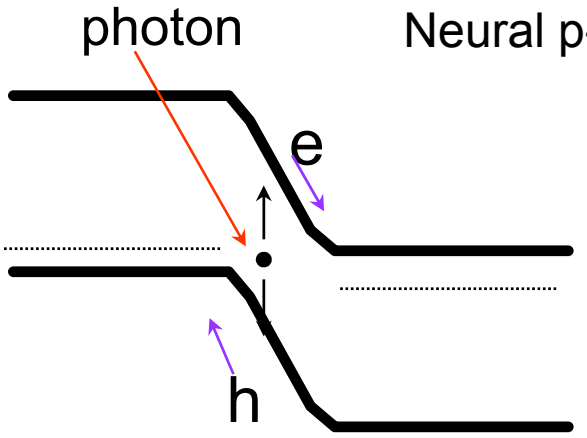
2. absorption of photons in
   silicon bulk

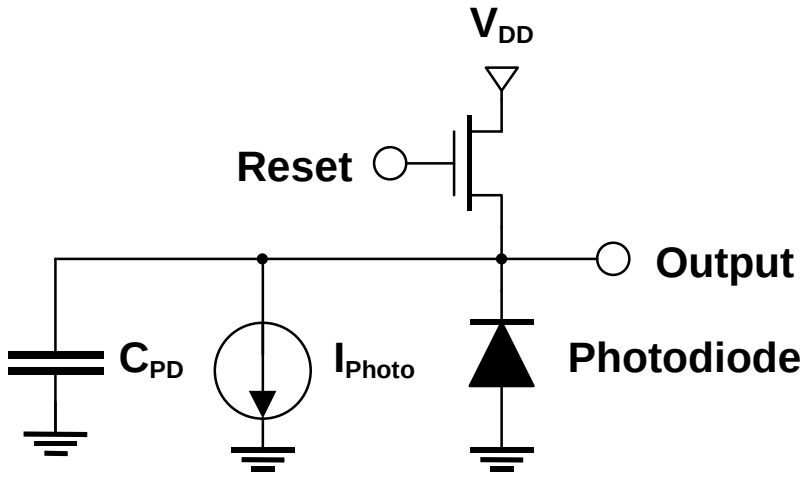
3. electron-hole pair
   generation

4. some of the generated
   carrier are separated
   before recombination by
   potential well

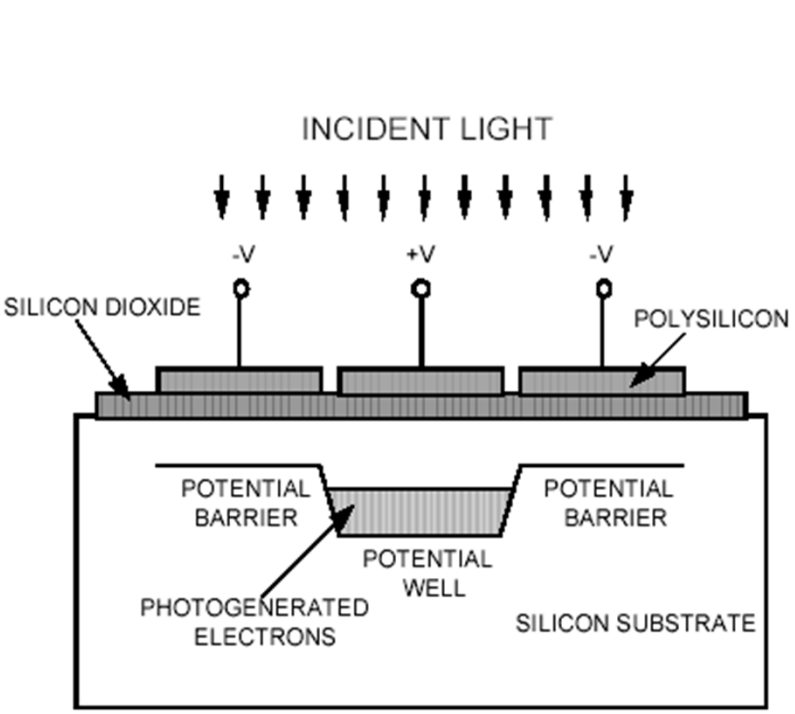
5. charge flow to photo
   current

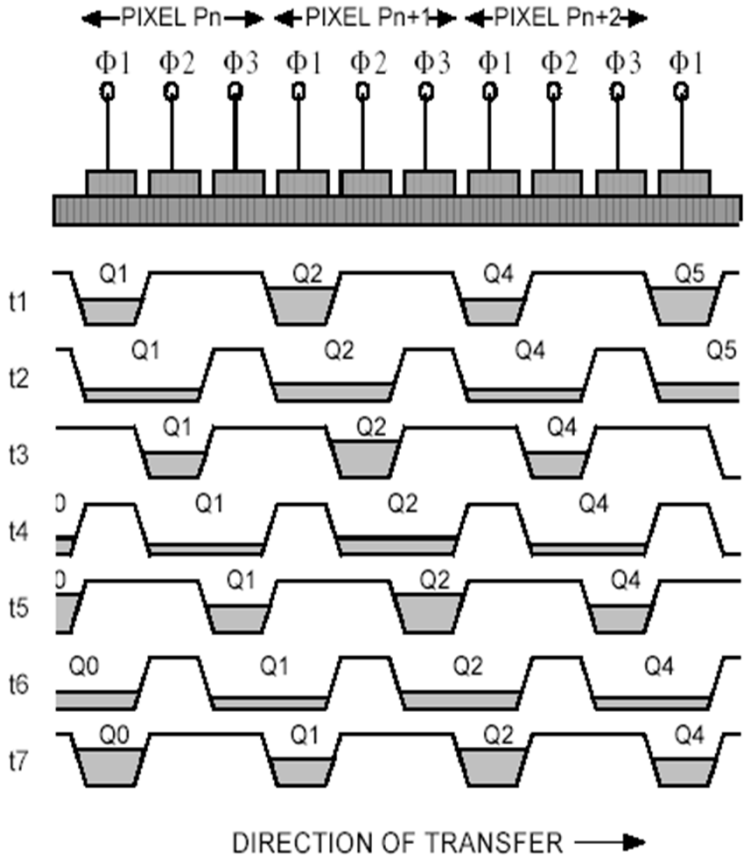




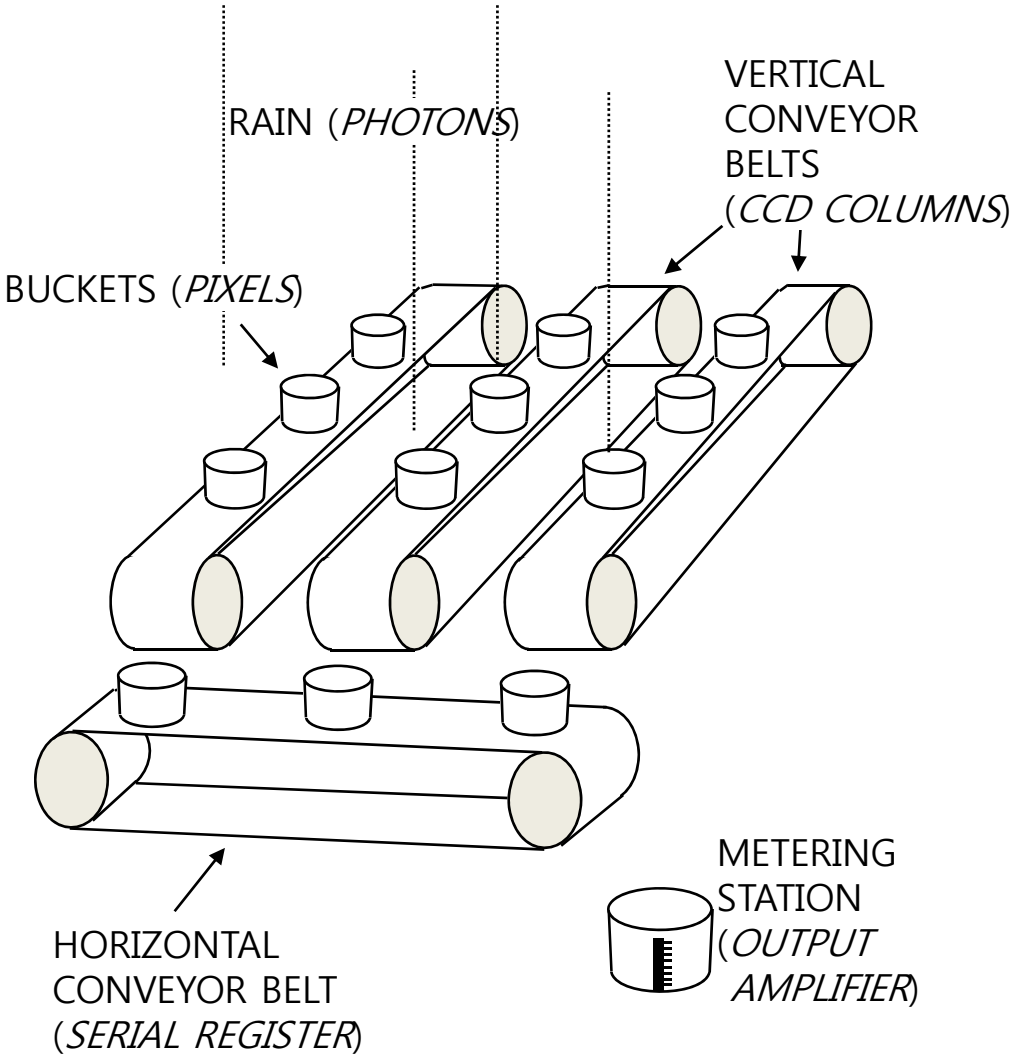


CCD Charge Transfer



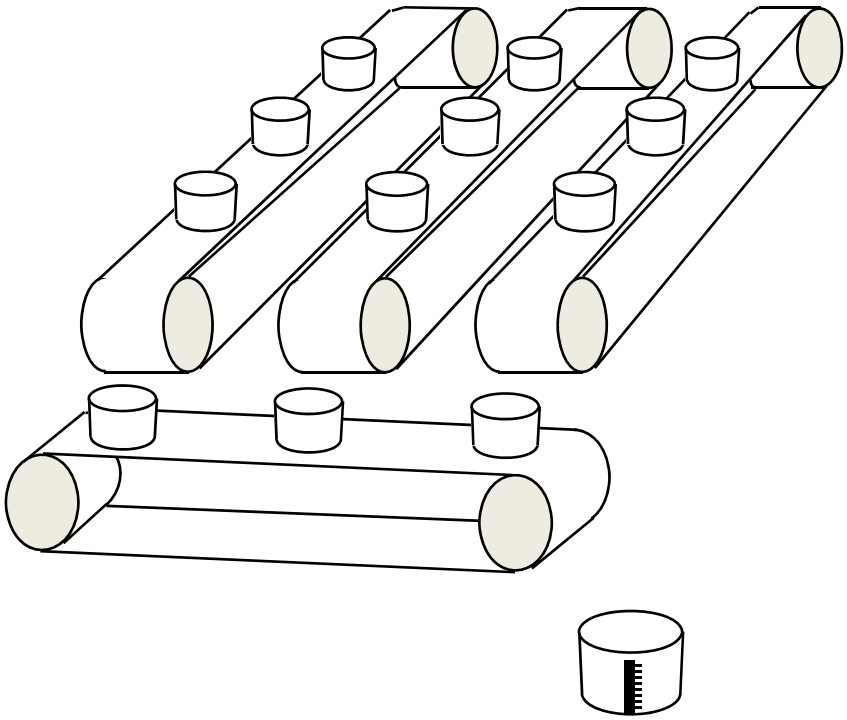


"Bucket brigade" analogy

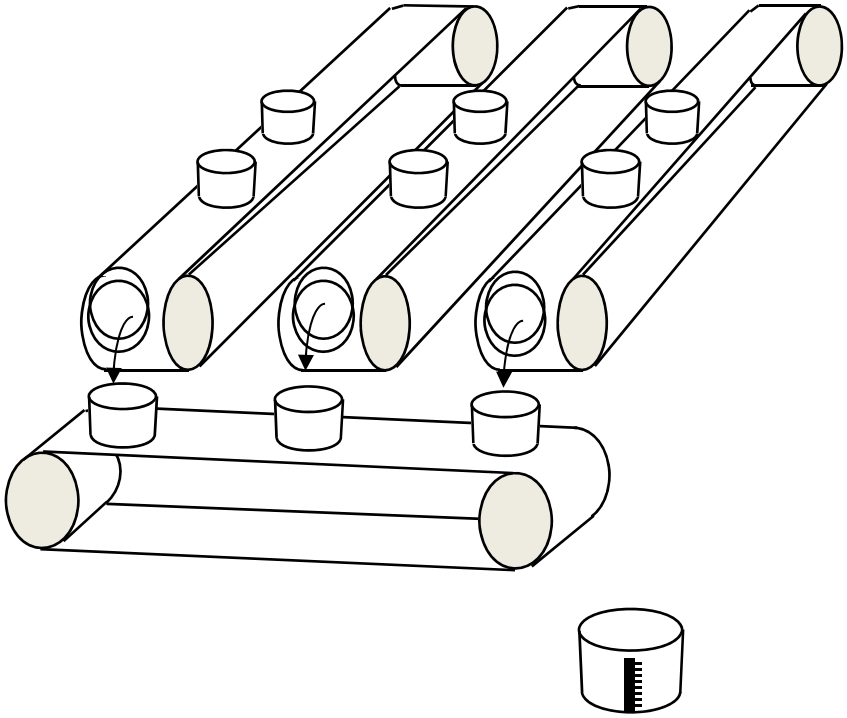


From Claudio Cumani

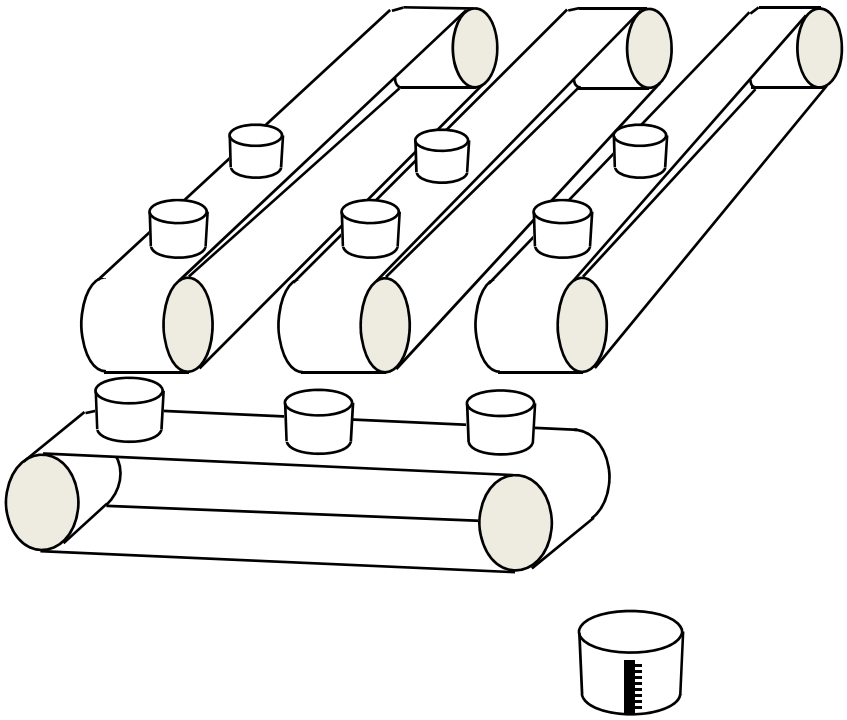
Exposure finished, buckets now contain samples of rain.



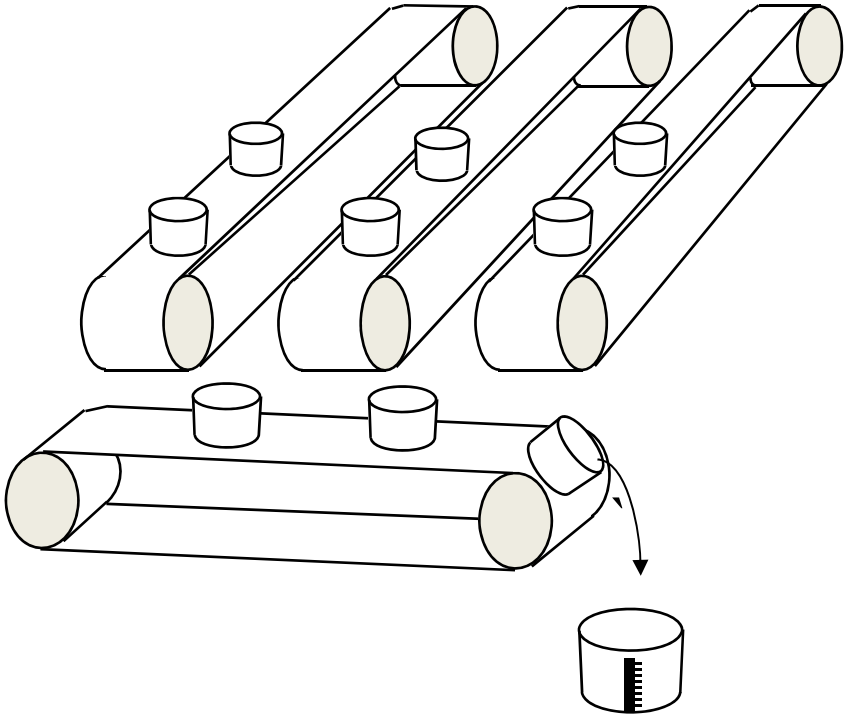
Conveyor belt starts turning and transfers buckets.
Rain collected on the vertical conveyor is tipped into buckets on the horizontal conveyor.



Vertical conveyor stops.
Horizontal conveyor starts up and tips each bucket in turn into the metering station.

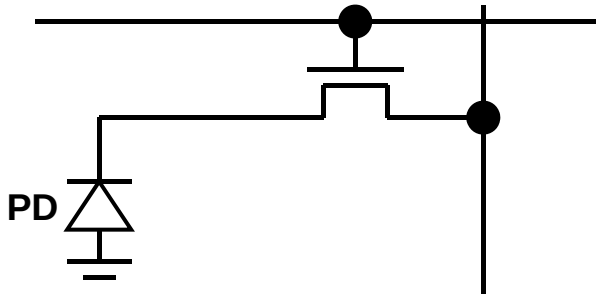


After each bucket has been measured, the metering station is emptied, ready for the next bucket load.

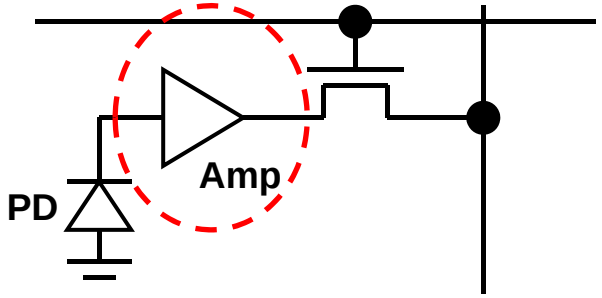


CMOS Imaging Device

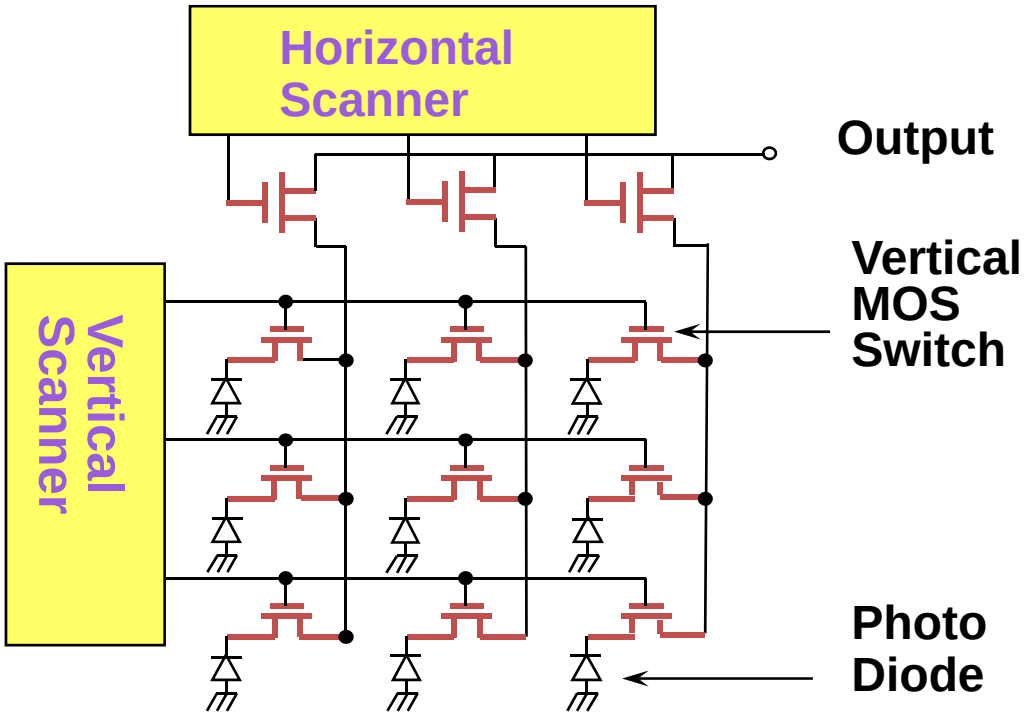
- Passive Pixel Sensor
  - 1 transistor per pixel
  - small pixel, large fill factor
  - but slow, low SNR



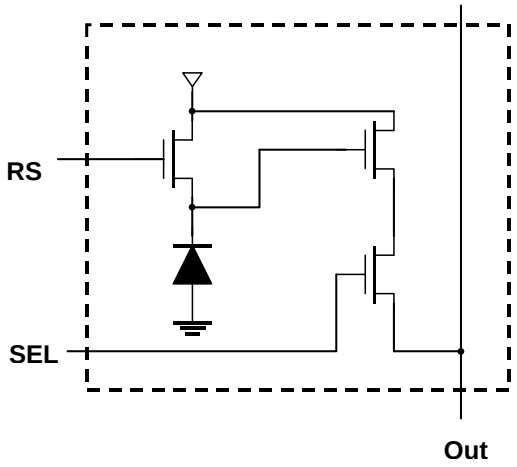
- Active Pixel Sensor
  - 3-4 transistors per pixel
  - fast, higher SNR, but
  - larger pixel, lower fill factor
  - 3 Tr structure, 4 Tr structure, photo gate structure



Passive Pixel Sensor Structure

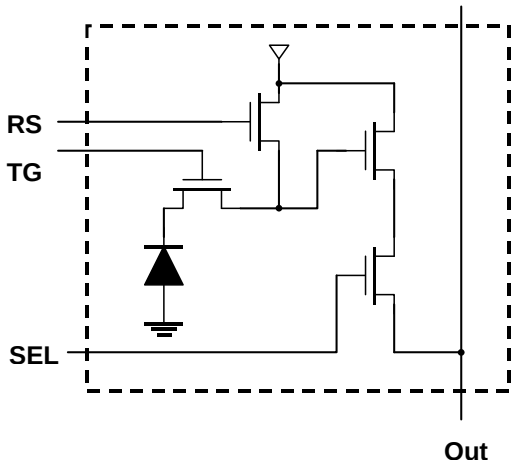


Active Pixel Sensor Structures



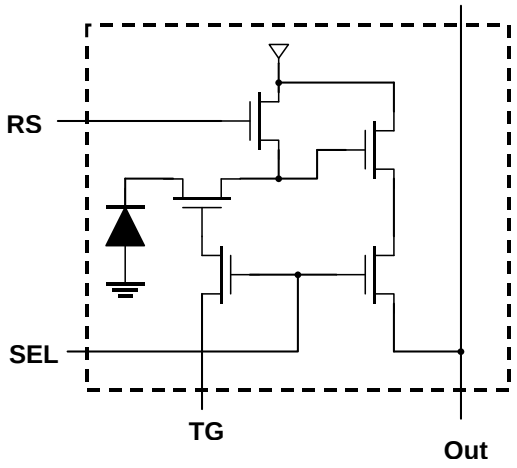
3-Tr Structure

- **simple process**
- **high fill factor**
- **pixel reset noise**
- **low S/N**



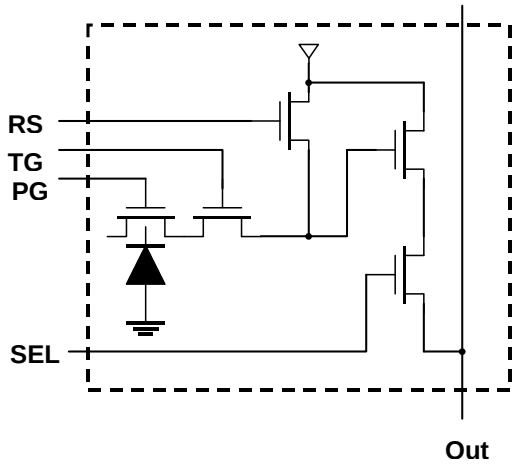
4-Tr Structure

- **process for low shallow potential photodiode**
- **low fill factor**
- **low dark level**
- **higher sensitivity**



5-Tr Structure

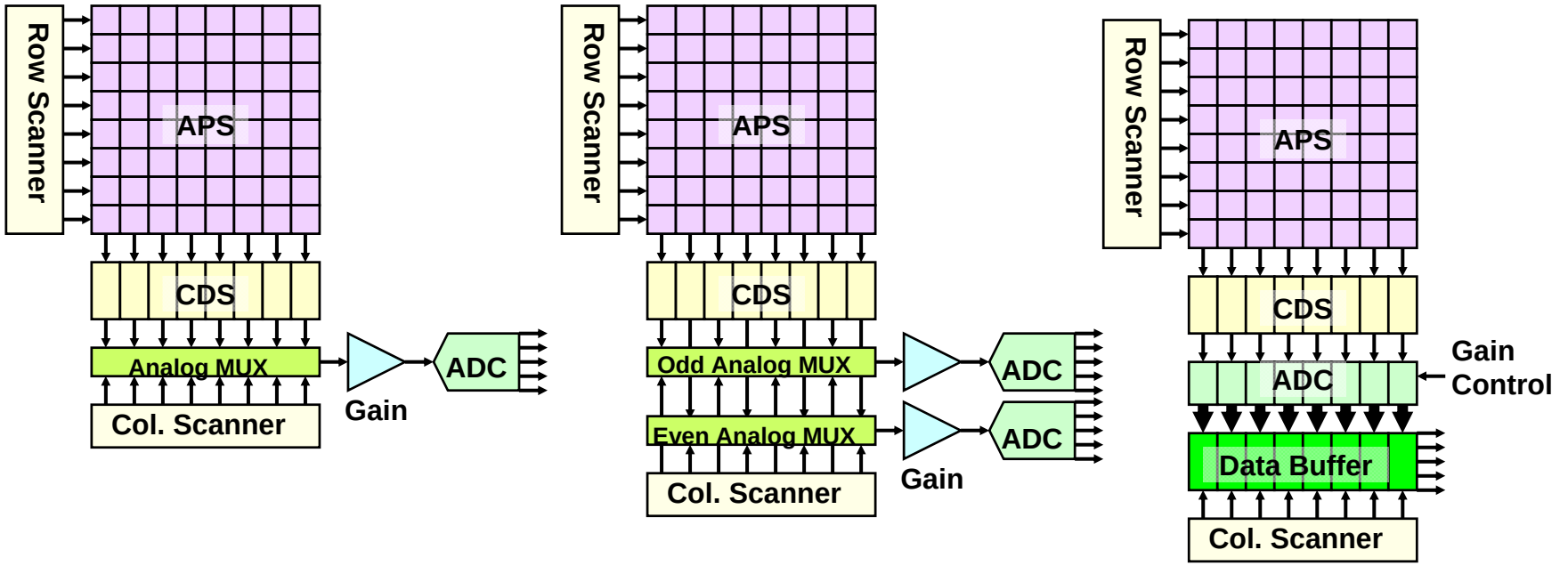
- **4-Tr + addressed readout**
- **full random access**
- **single CDS possible**
- **lowest fill factor**



Photogate Structure

- **simple process**
- **4-Tr like operation**
- **signal charge shifting by PG & TG pulse**
- **additional signal line**
- **low blue response**

Analog-Digital Converter



Single Channel ADC

- simple
- small area
- data rate limitation
- higher power consumption

Dual Channel ADC

- separated gain for each color component
- multi-port output or merged into single port

Column Parallel ADC

- simple & low speed ADC
- large area
- ADC mismatching
- lower power consumption

CCD Image Sensor vs. CMOS Image Sensor

- Optimized photodetectors
  - high QE, low dark current
- Very low noise
  - no noise introduced during shifting
- Very low fixed pattern noise (nonuniformity)
  - no FPN introduced by shifting

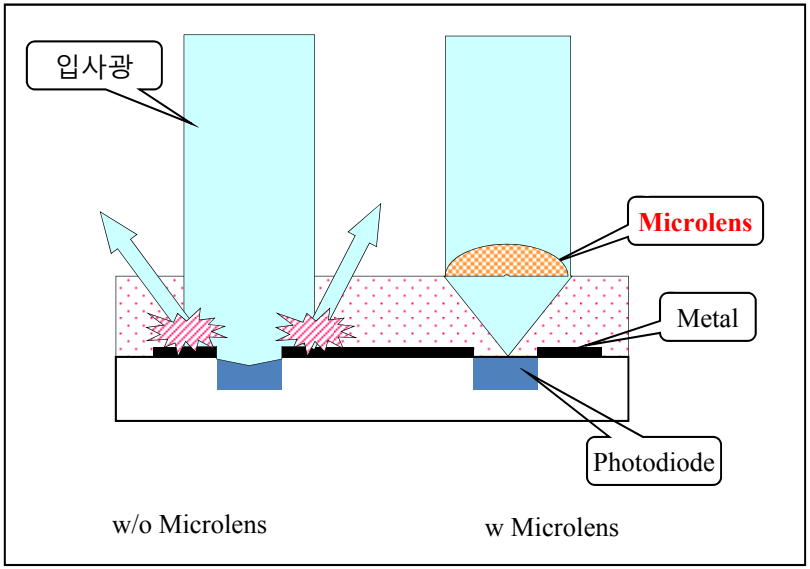
- Integration
  - analog and digital circuits, *e.g.*, for clock generation, control, or A/D conversion
- Highly Programmable
  - windowing and panning
  - fully random access of a pixel in array
- Low power consumption
  - low voltage operation
  - for CCD, entire array switching all the time (high C, high V, and high f results in high CV^2f)
- High frame rate possible
  - no limitation in signal transfer speed

Post processing (Color Filter & Microlens)

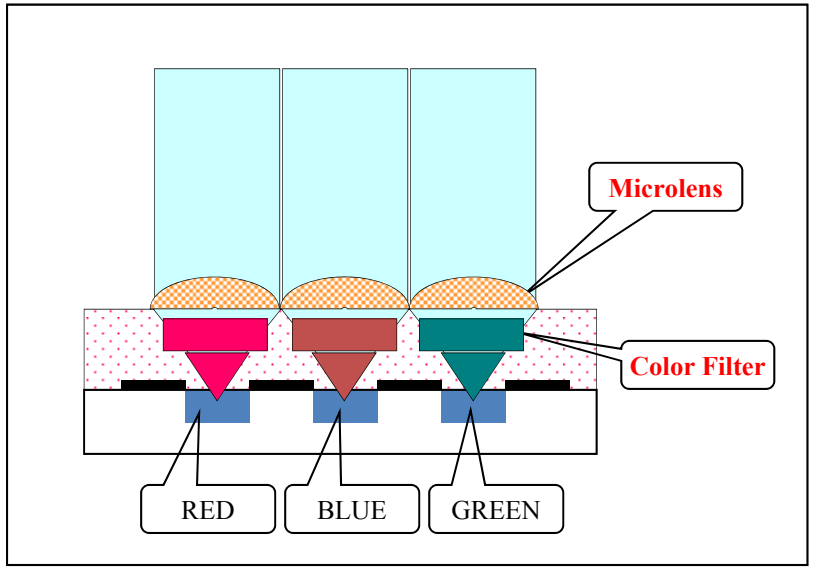
CCD,CIS's sensitivity is improved by Microlens

For color image, Color Filter Layer is implemented

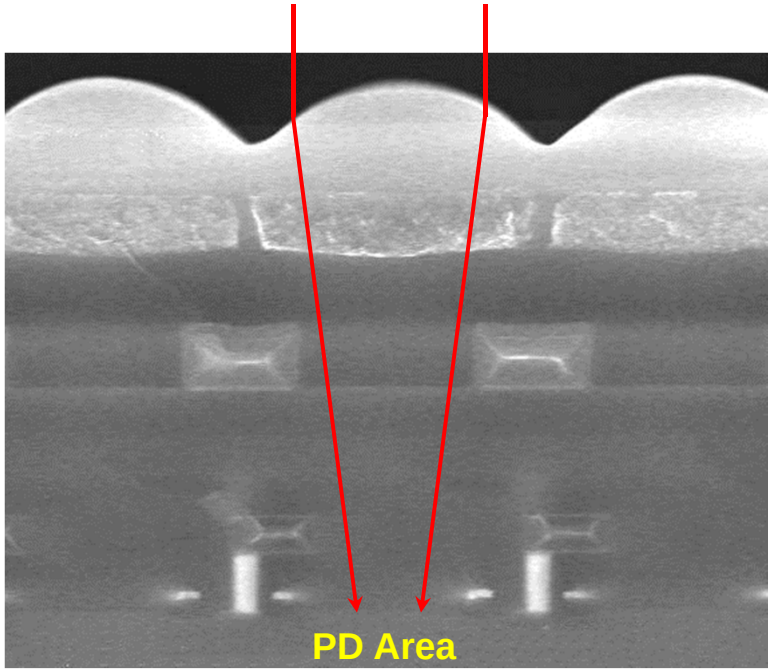
Microlens



Color Filter



Micro Lens



Micro Lens

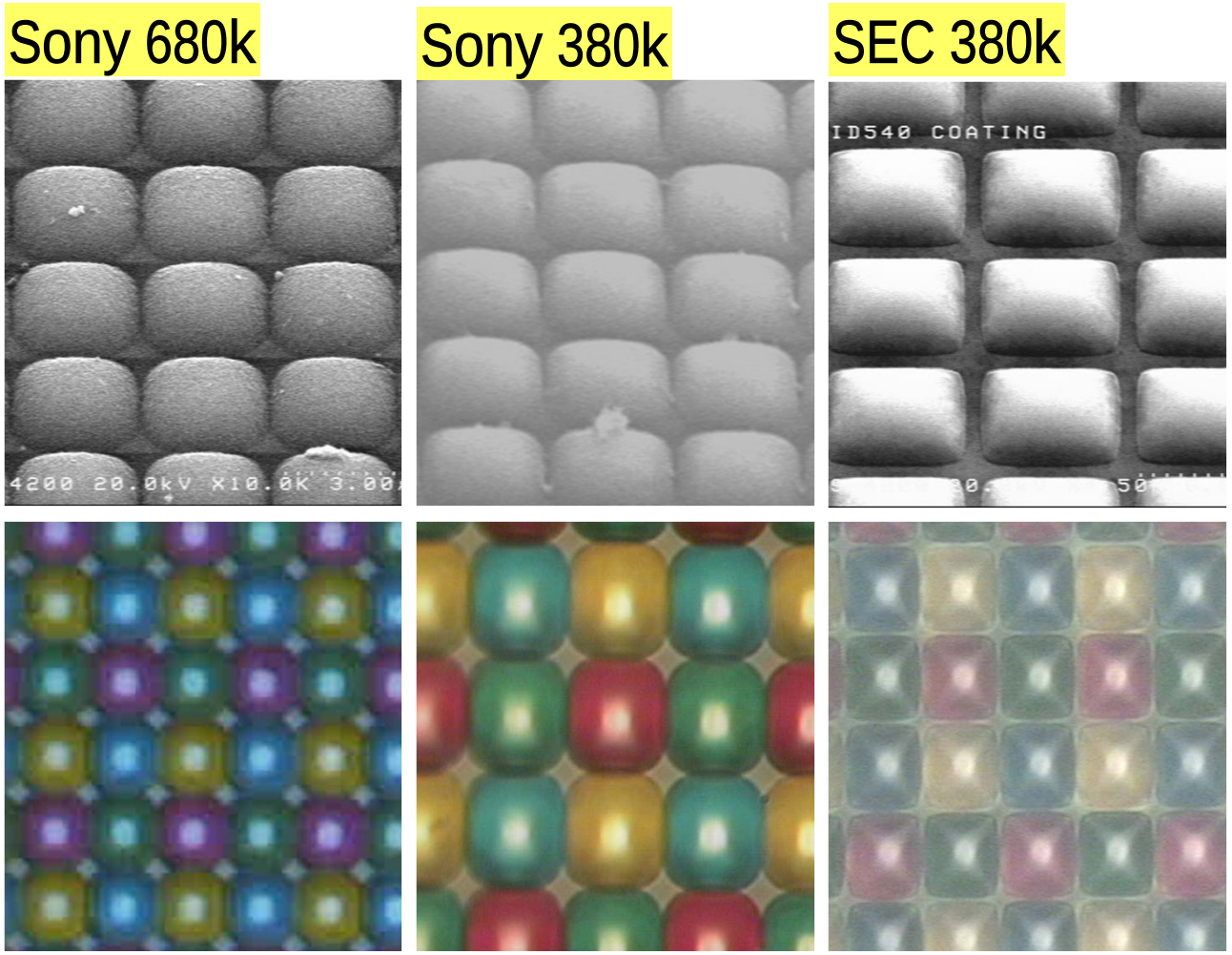
Color Filter

Shield Metal Layer

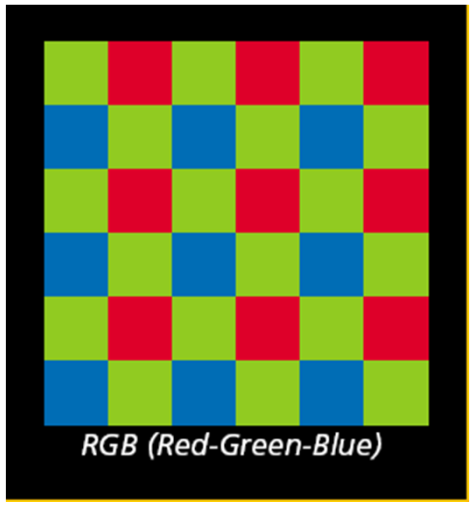
MOS Transistors

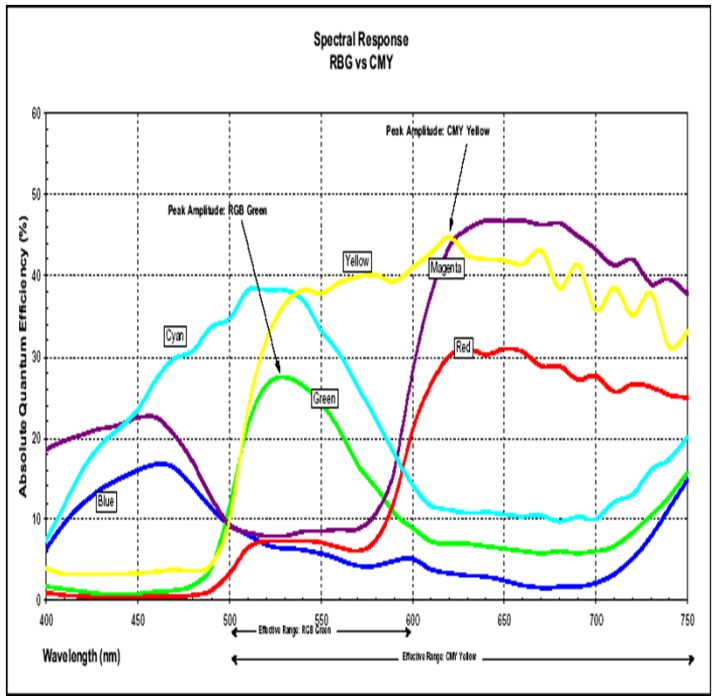
Silicon Substrate

µ-lens Comparison

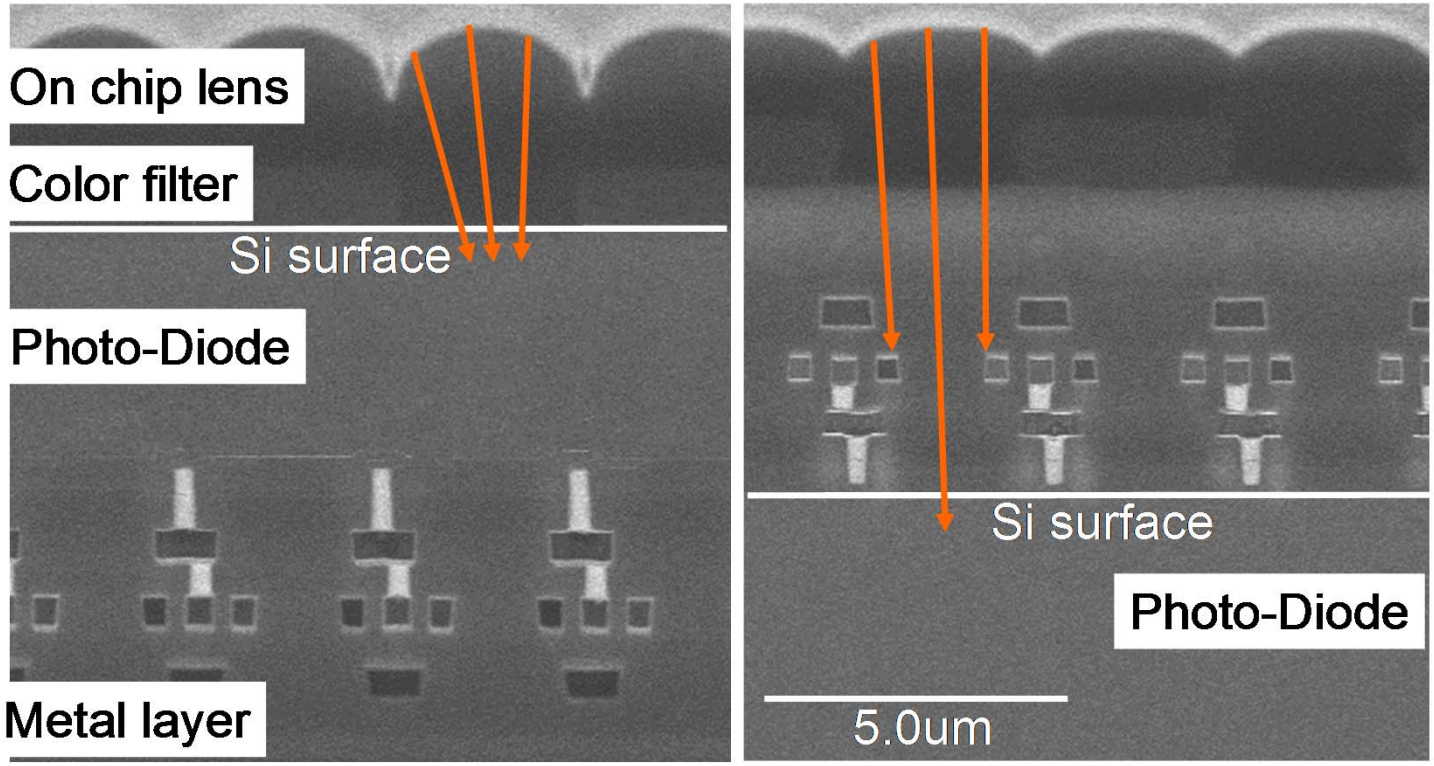


Color Filter





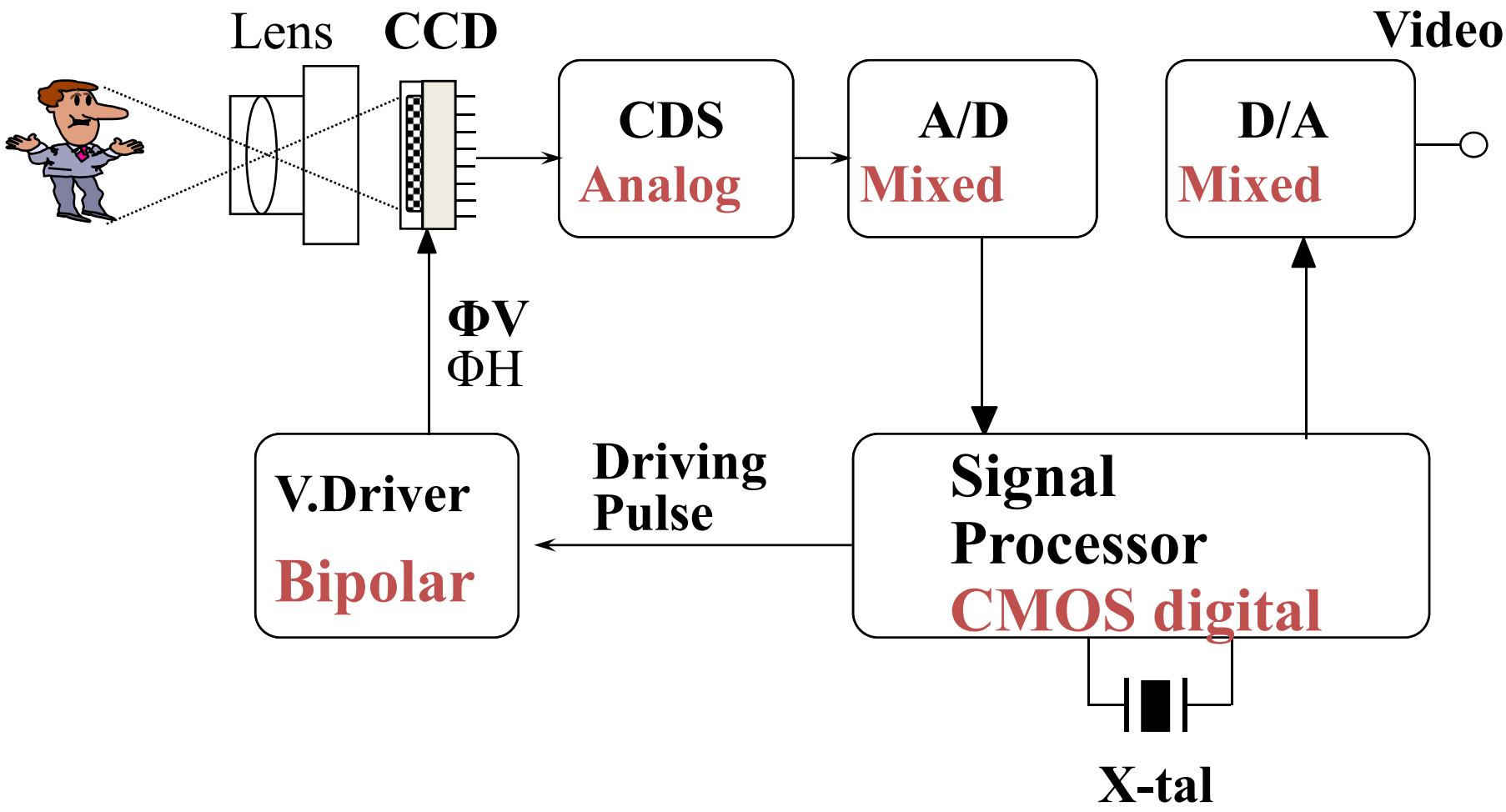
Back-illuminated CMOS image sensor



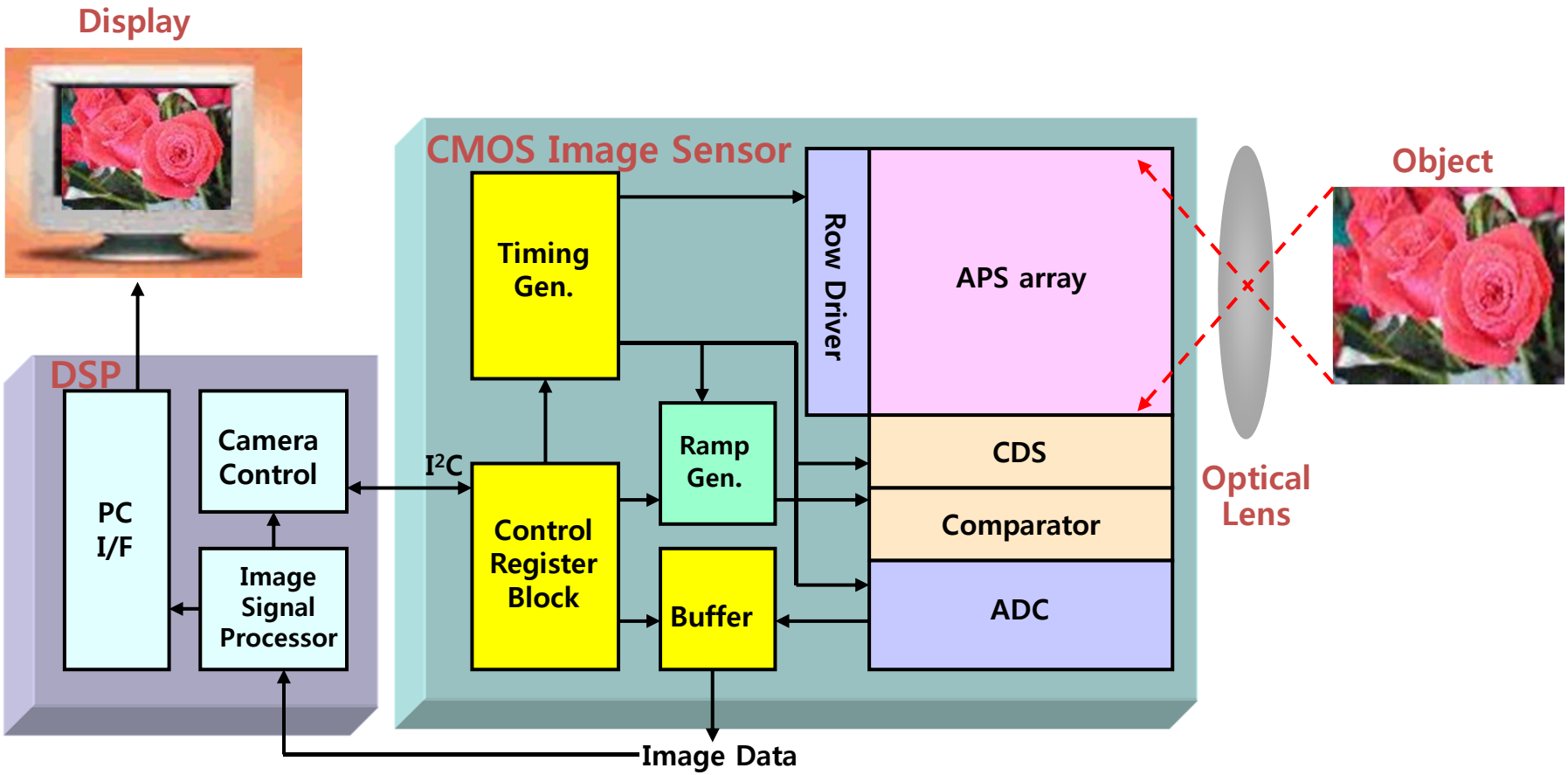
Back-illuminated **Conventional**

Cross sectional SEM photographs

CCD Camera System Configuration



CIS Camera System Block Diagram

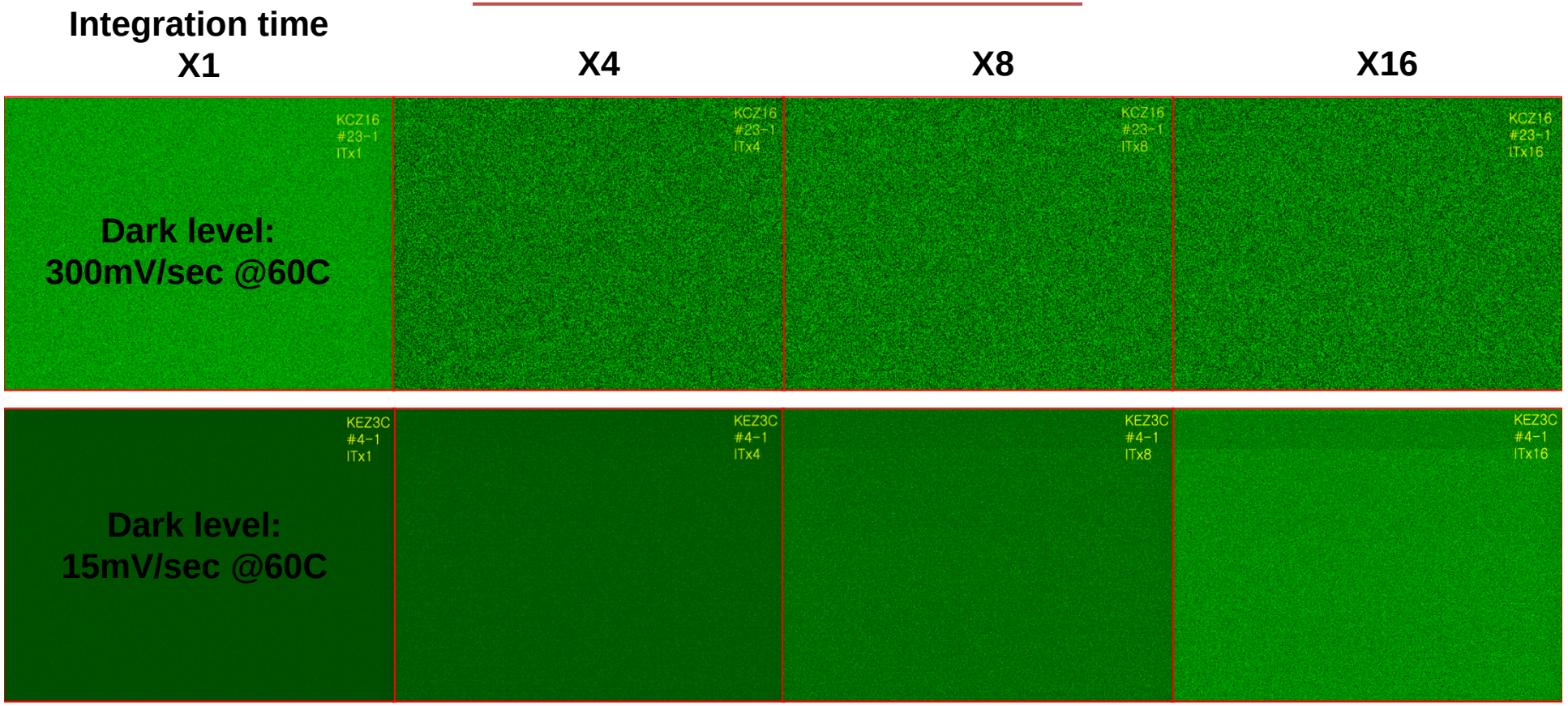


Temporal Noise (1)

- the (temporal) variation in pixel output values under uniform illumination due to device noise, e.g., thermal and shot noise, substrate noise, and supply voltage fluctuations
- it increases with signal (photo current), but its effect is most pronounced at low signal values (low illumination) - SNR increases with signal
- temporal noise under dark conditions sets a fundamental limit on the sensor dynamic range

Temporal Noise (2)

Dark level & Dark shot noise



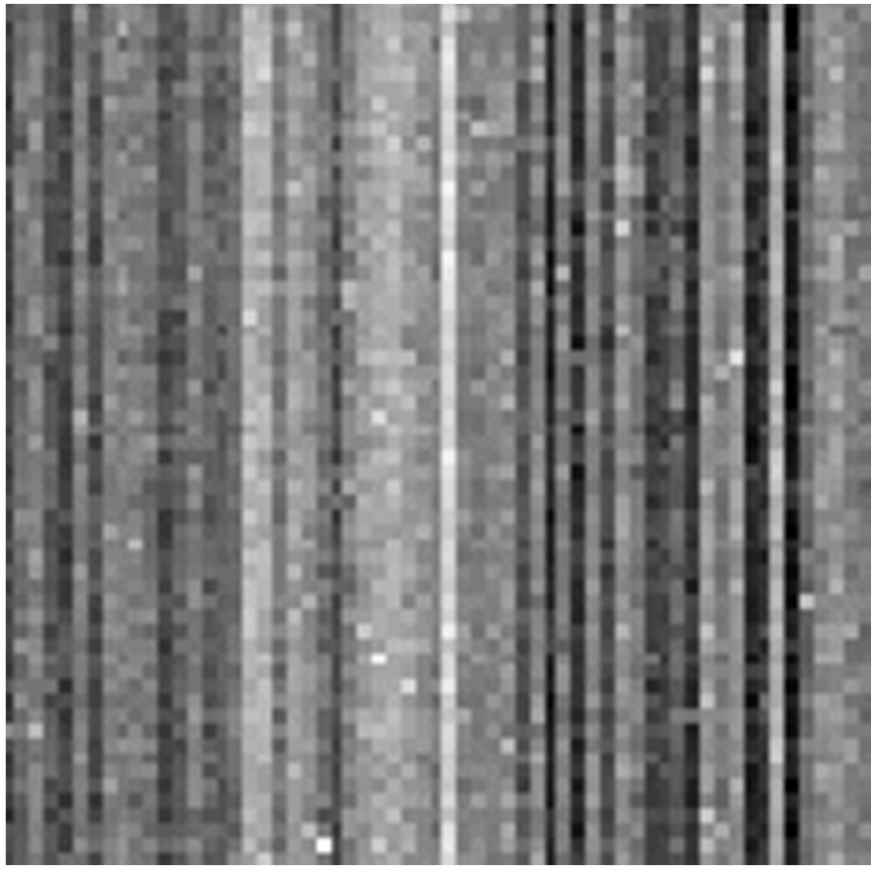
Temporal Noise (3)
10 % pixel random noise

Temporal Noise (4)
25 % pixel random noise

Fixed Pattern Noise (1)

- FPN (also called nonuniformity) is the spatial variation in pixel output values under uniform illumination due to device and interconnect parameter variations (mismatches) across the sensor
- it is fixed for a given sensor, but varies from sensor to sensor
- FPN consists of offset and gain components - increases with illumination, but causes more degradation in image quality at low illumination
- FPN for CCD image sensors appears random
- from column FPN, which appears as “stripes” in the image and can result in significant image quality degradation

Fixed Pattern Noise (2)

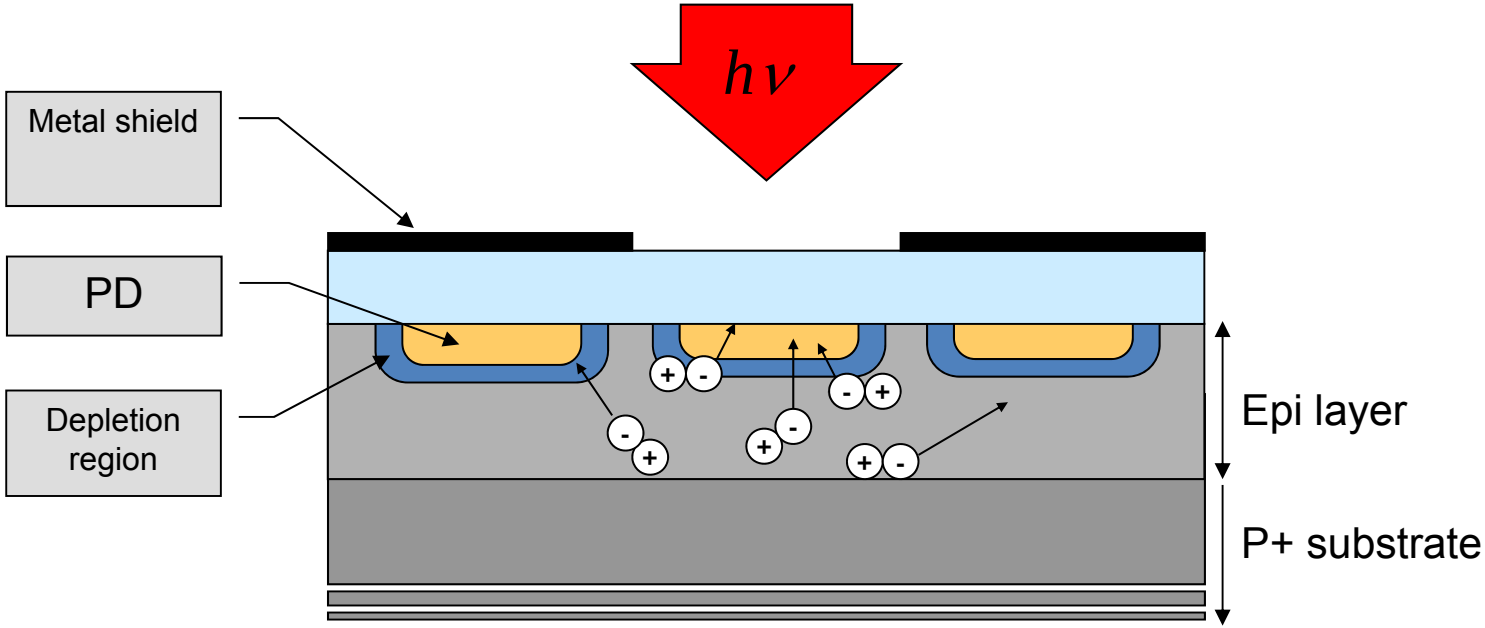


Fixed Pattern Noise (3)
0.5 % column FPN

Fixed Pattern Noise (4)
2 % column FPN

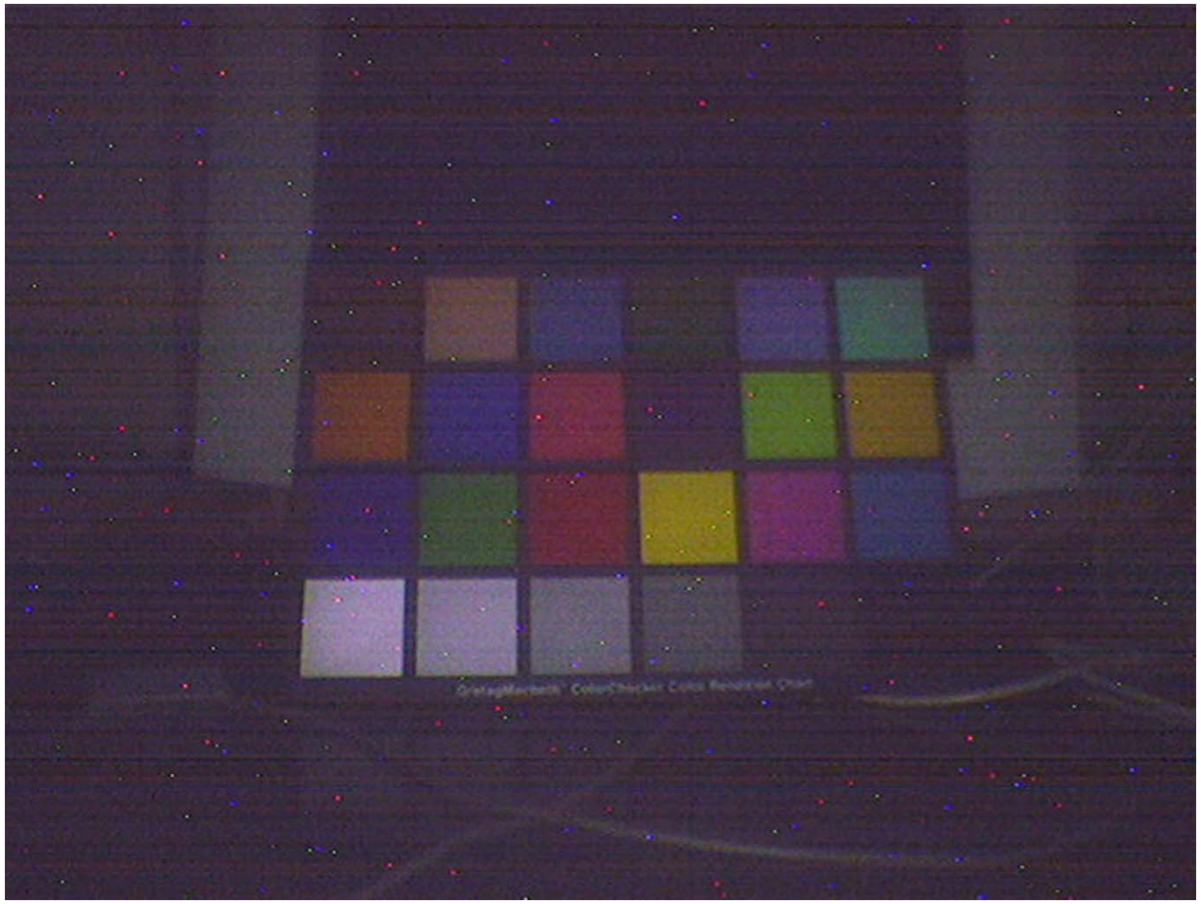
Crosstalk

- Blooming
- Smearing

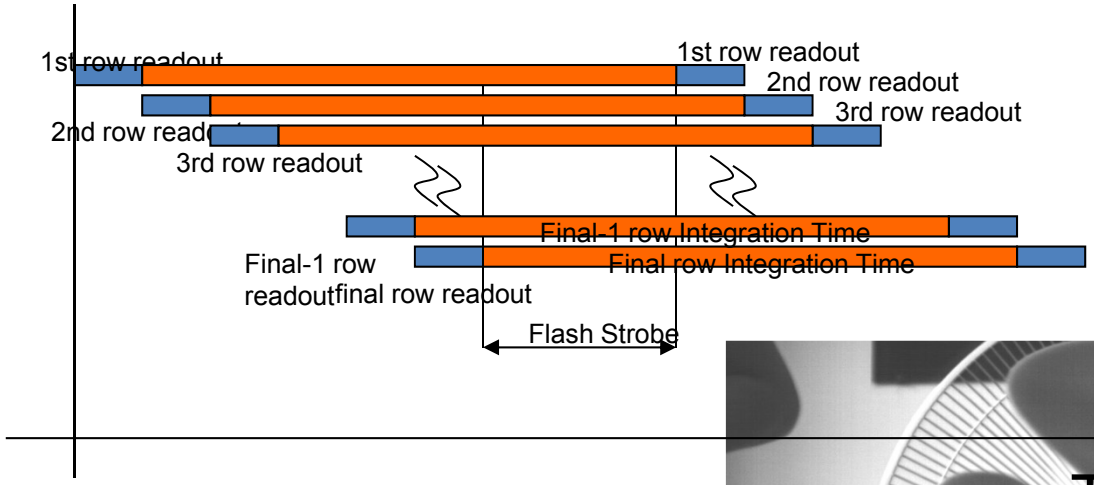


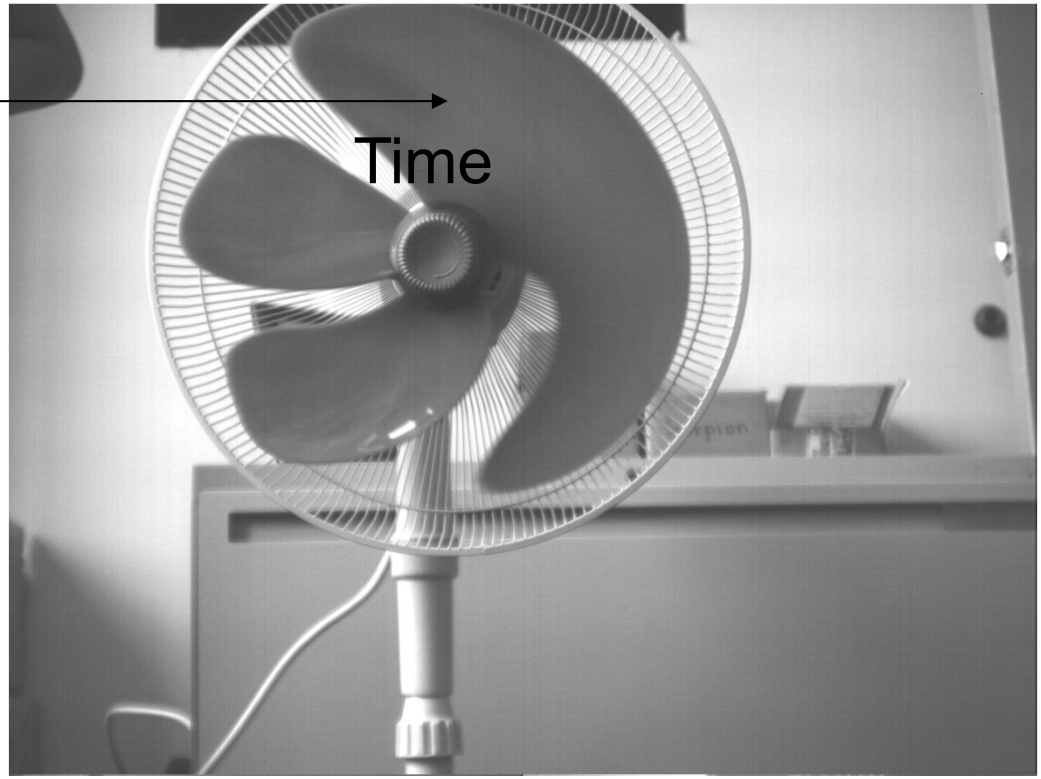
Defect

- Dark defect, White defect, Black defect, Saturation defect



Motion Distortion





CMOS Image Sensors @ Yonsei

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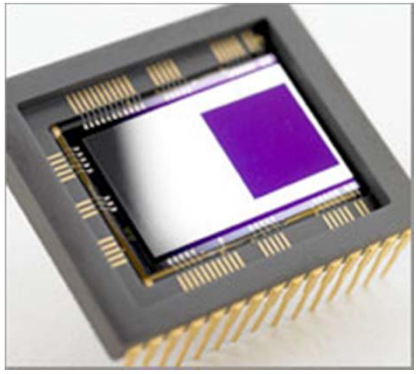
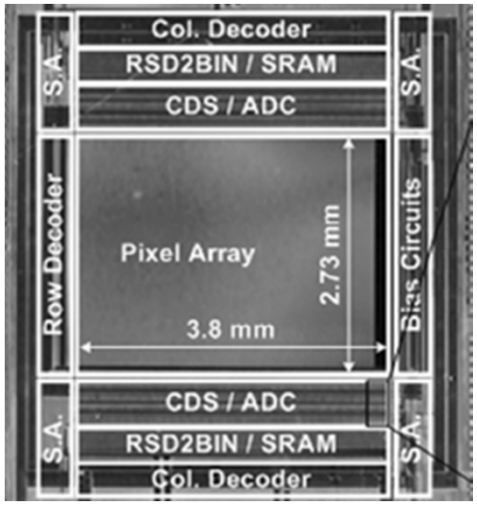
CMOS Image Sensors

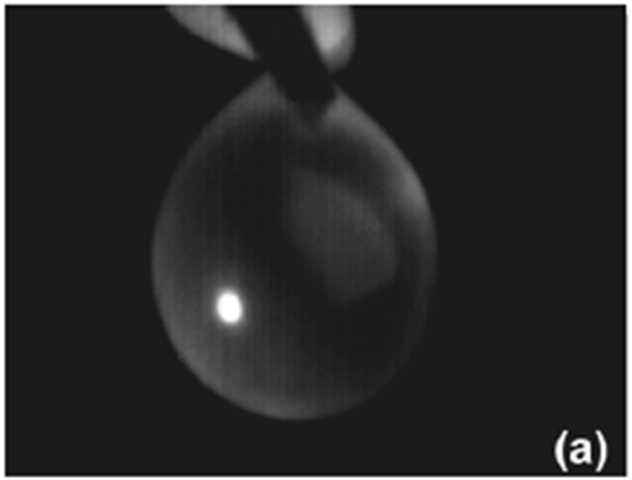


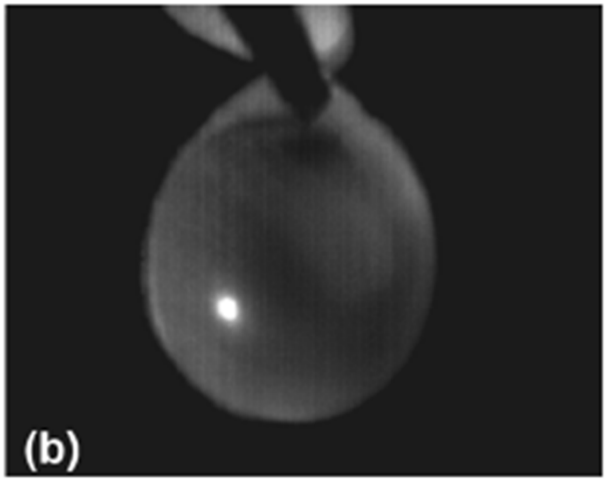
Readout Circuits, APS Pixels and Smart Sensors

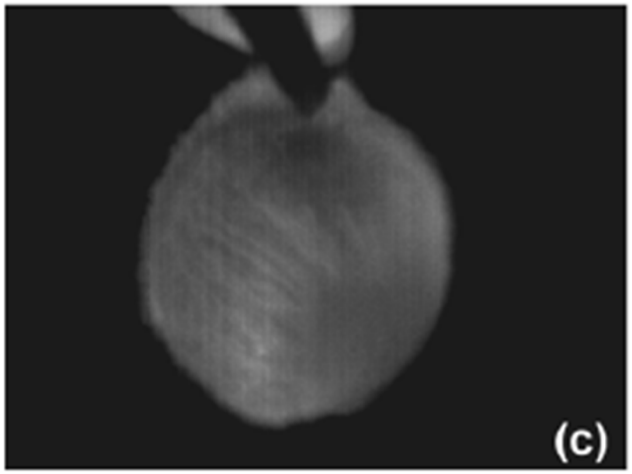
High Speed Image Sensor

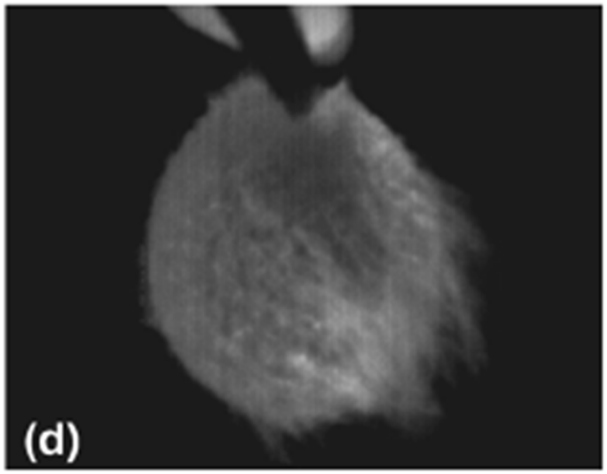
Sample Image: 1200 fps





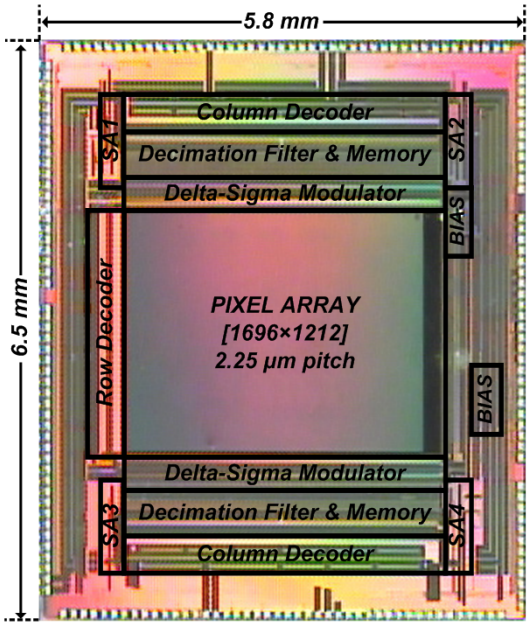






IISW'09 JSSC'11

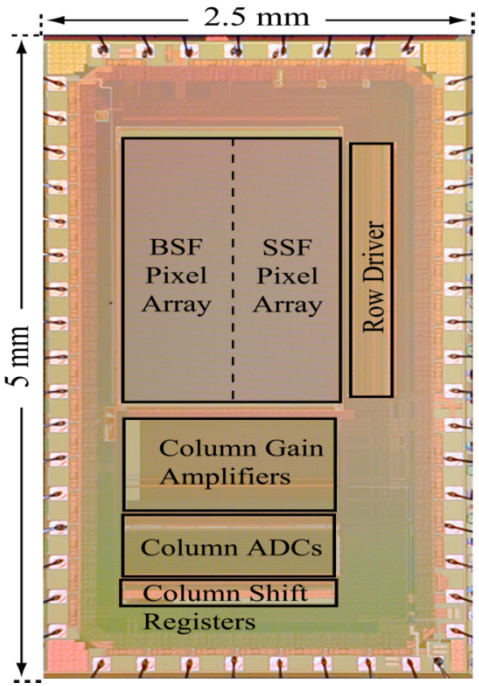
Low Noise, high speed CMOS Image Sensor



ISSCC' 10, JSSC'11

- 2Mpixel, 120fps, 1.9e-TRN, and 180mW CIS
- State-of-the-art noise and energy efficiency (3.5x)

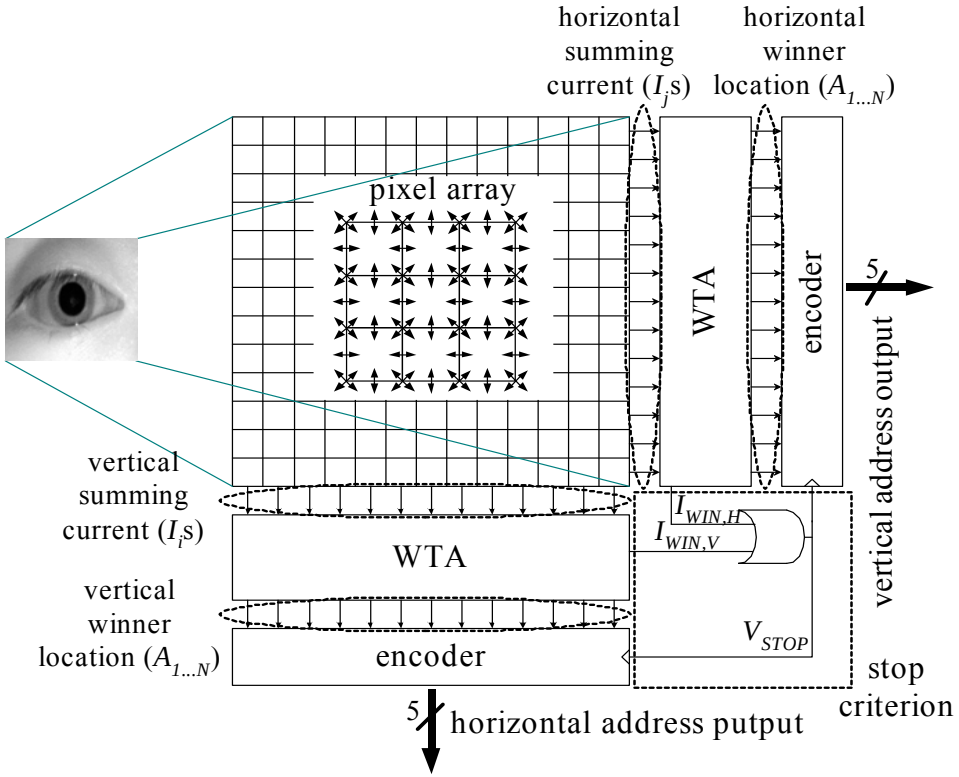
0.7e TRN CMOS Image Sensor

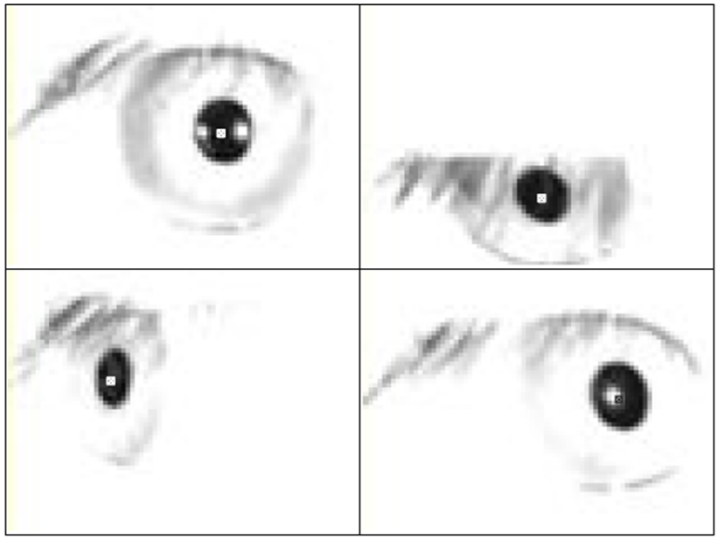


ISSCC' 12

- Sample image taken at 0.06-lux
- State-of-the-art Noise Performance (0.7e- TRN)
- The lowest noise CMOS image sensor !

High-Speed Eye Tracker

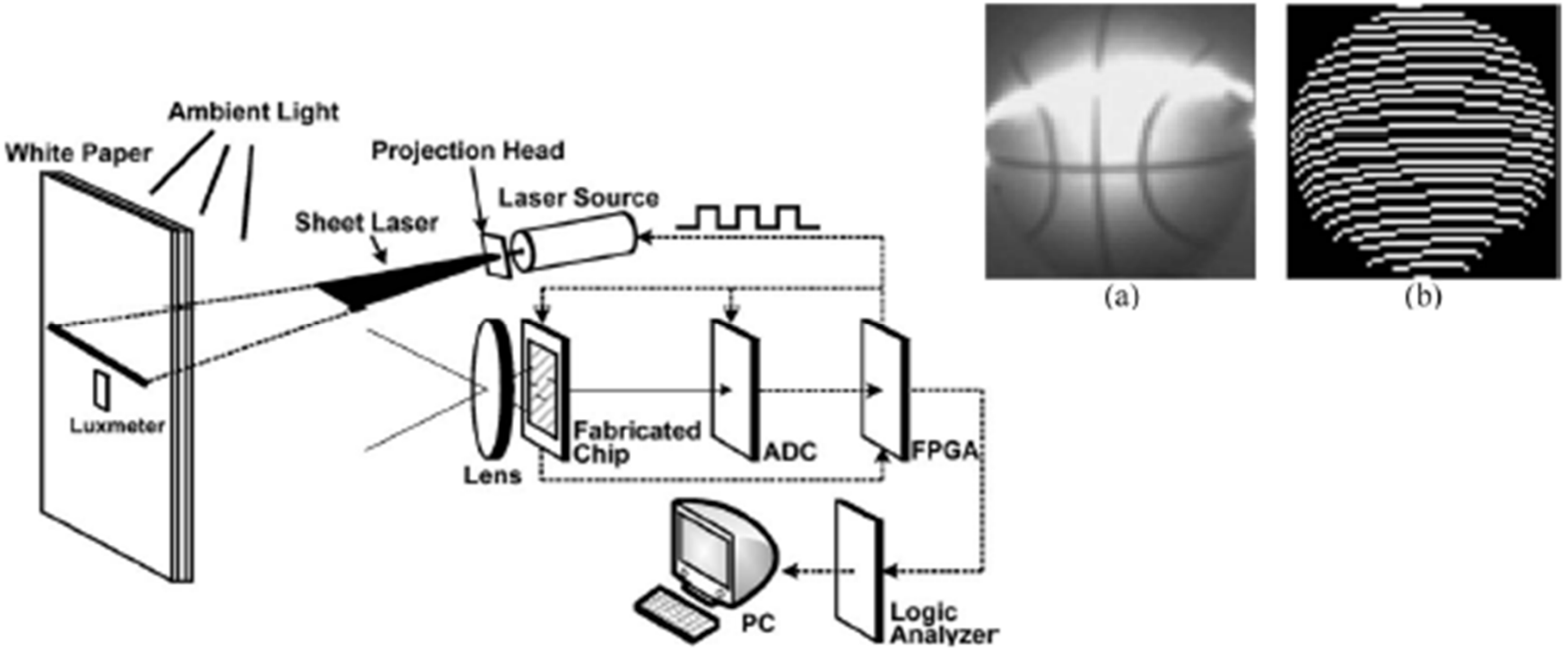




ISSCC' 08, JSSC'09

- Pixel level signal processing. → 5000 fps eye tracker.

Smart 3D Range Finer



TED' 09

- Light section based 3D imager.
- Smart pixel, Multiple sampling, -56dB worst case SBR.

Current Research

- CMOS Image Sensors
  - 3D Imaging
  - Medical Imaging

“There’s More To The Picture Than Meets The Eye”

Neil Young in HeyHey,MyMy, 1978