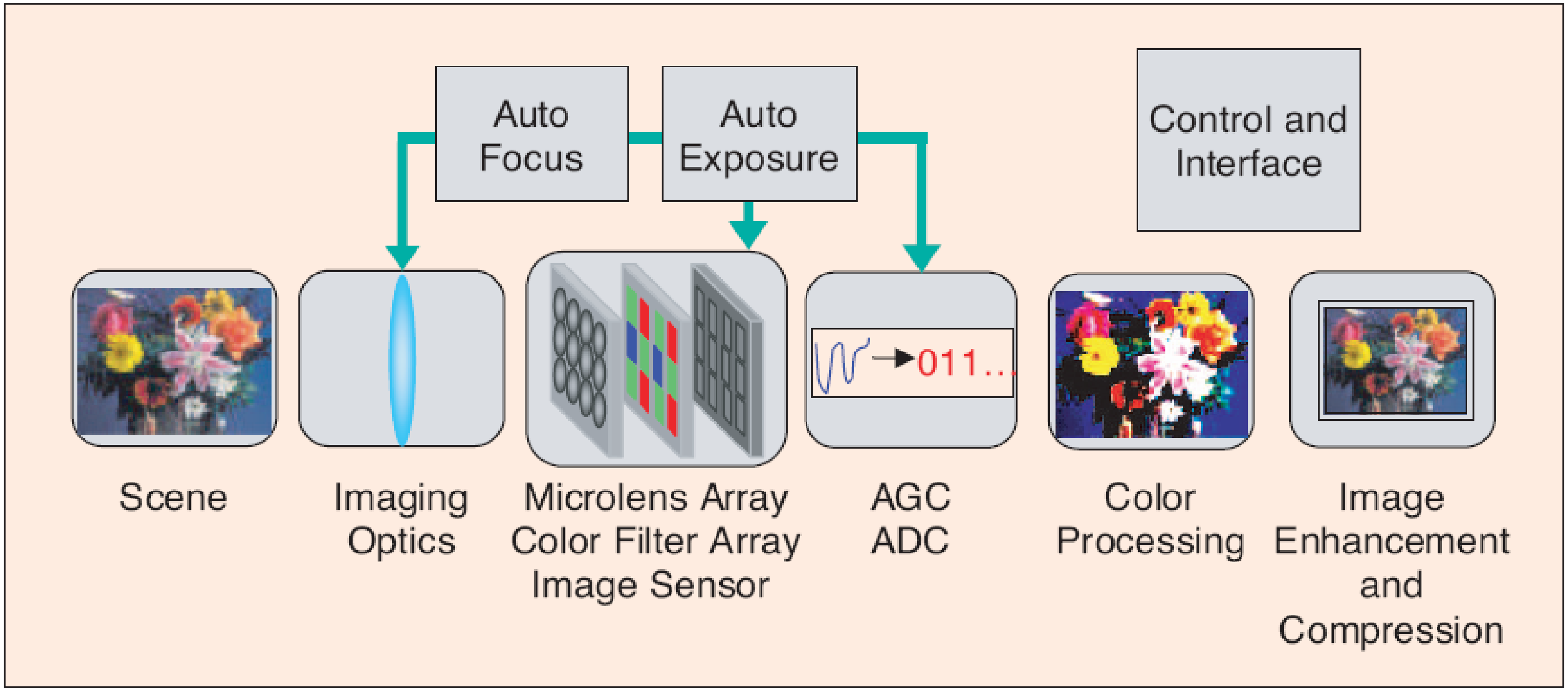
UiO : Department of Informatics
University of Oslo

INF5350/IN9350 – CMOS Image Sensor Design

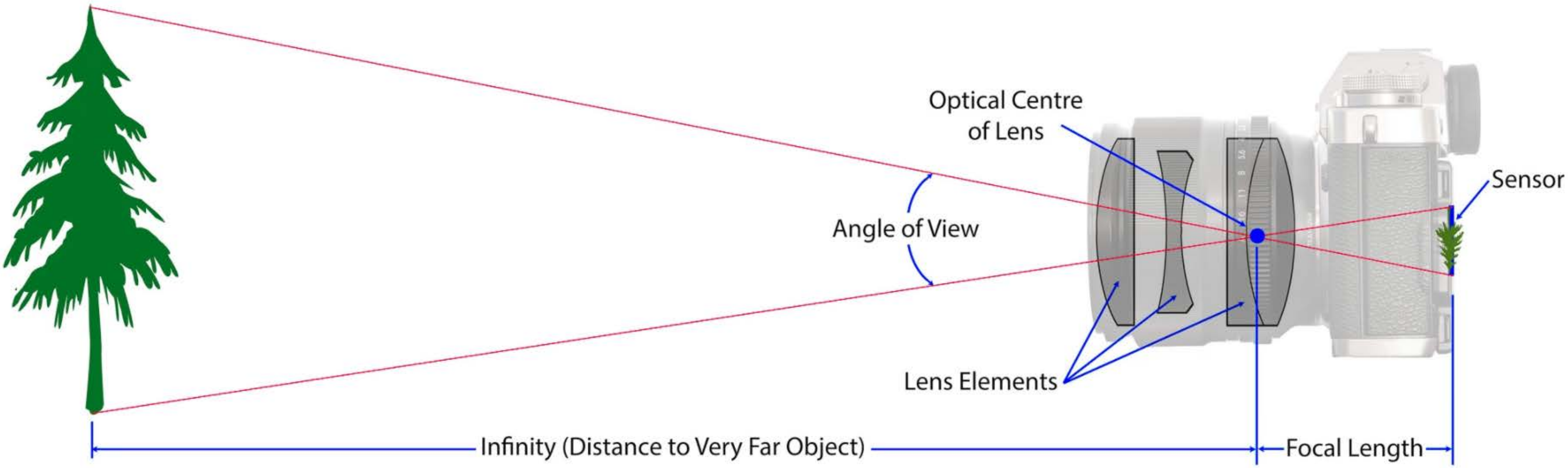
Lecture 1 – Camera systems overview

CMOS camera signal chain



Source: A.E.Gamal, et al. "CMOS Image Sensors", IEEE Circuits and Device Magazine, May. 2005

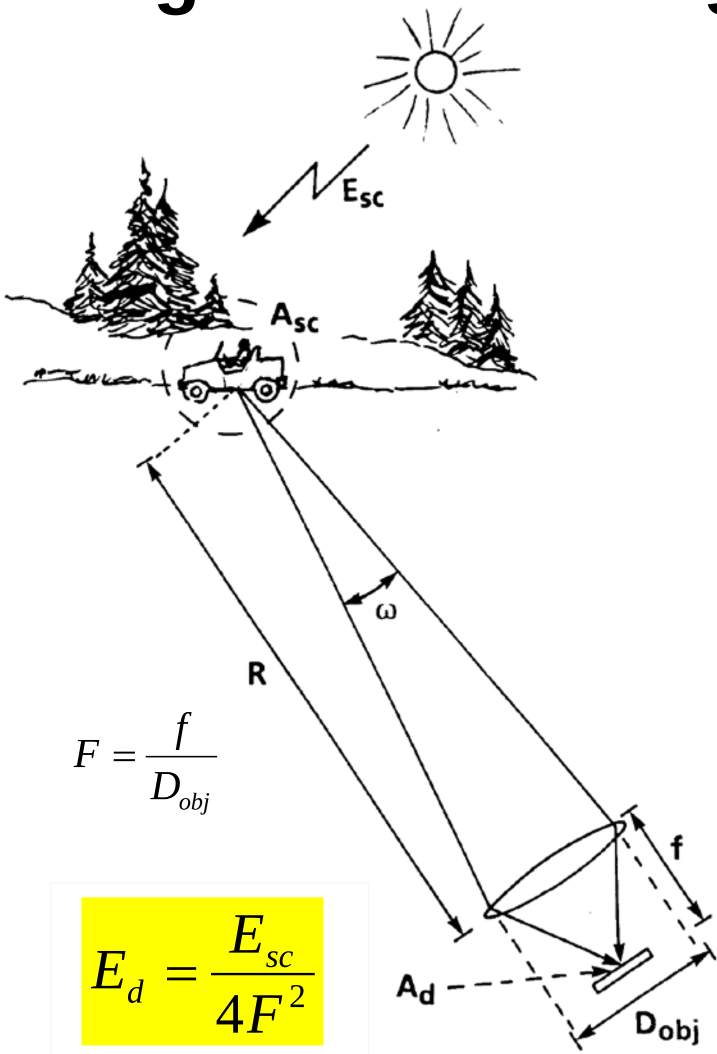
Camera focal length and field of view



Focal length = distance from 'optical centre of lens' to focal point where image sensor chip is placed

Focal length + sensor size defines the angle of view (aka field of view)

Light flux on image sensor chip



$$F = \frac{f}{D_{obj}}$$

$$E_d = \frac{E_{sc}}{4F^2}$$

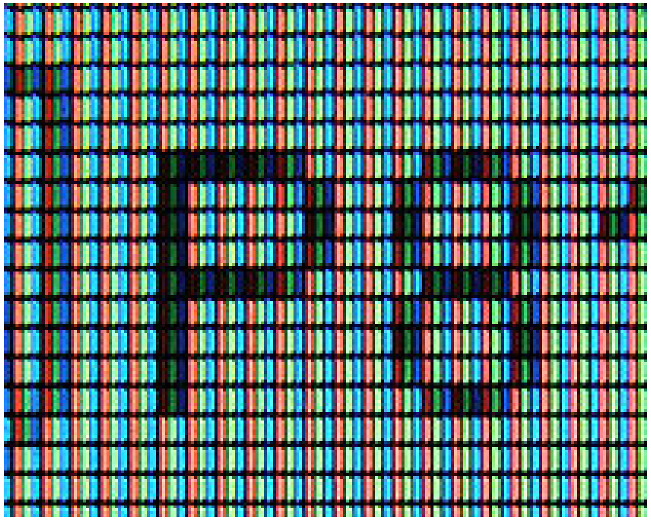
E_{sc}=scene illumination (lux or W/m^2)
ρ_{sc}=scene reflectivity (no unit)
T_{int}=camera exposure time (s)
F=lense F-nummer (=f/D_{obj})
h=Plancks constant (6.6x10^{-34} J s)
c=speed of light (3x10^8 m/s)
D_{obj}= lens aperture (m)
f = lens focal length (m)
A_d=detector area (m^2)
E_d=detector illumination (lux or W/m^2)
λ=light spectral wavelength (m)
S_d=detector photon count (no unit)

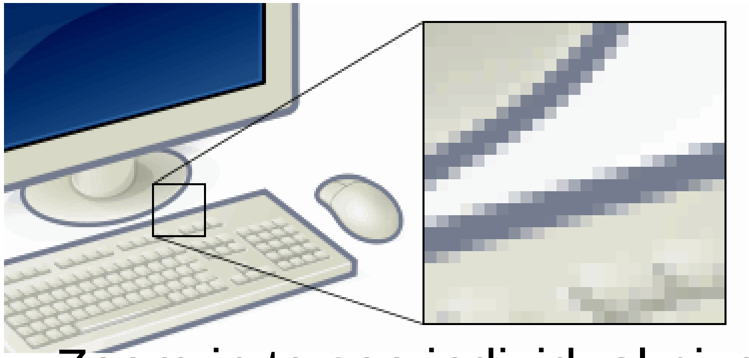
$$S_d = \frac{T_{\text{int}} A_d}{hc4F^2} E_{sc} \rho_{sc}$$

Digital picture

- Consists of 2D array of pixels each containing three numbers (R+G+B or Y+U+V) to describe the pixel color and its brightness (luminous intensity)

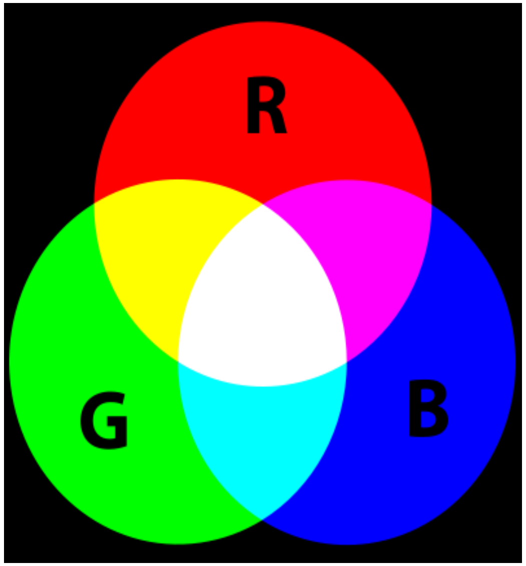
Zoom-in on LCD monitor w/RGB pixels



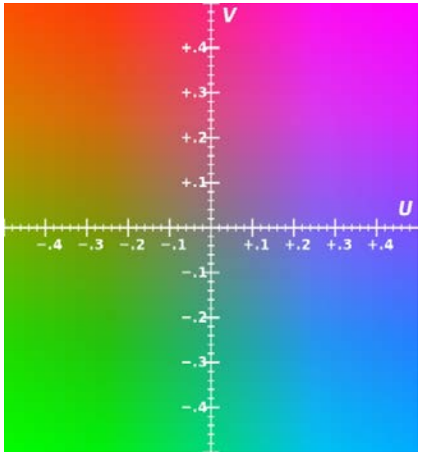


Zoom-in to see individual pixel elements

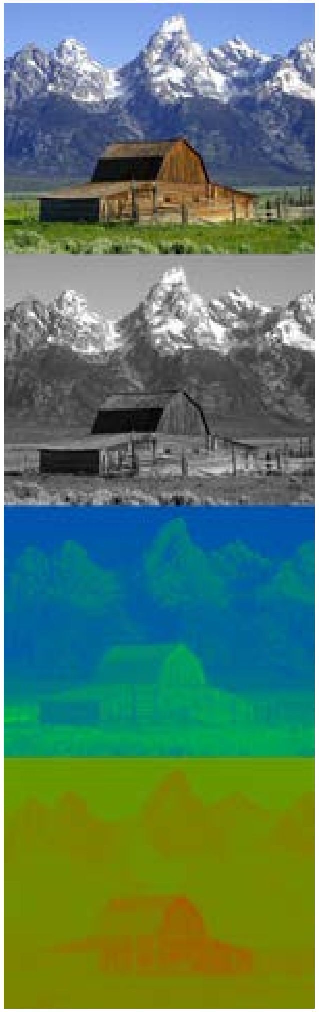
RGB vs YUV



Mixing primary colors (RGB)



U-V color plane (Y=0.5)



YUV image along with its

Y,

U, and

V components.

From RGB to YUV, and vice-versa

$$Y' = 0.299R + 0.587G + 0.114B$$

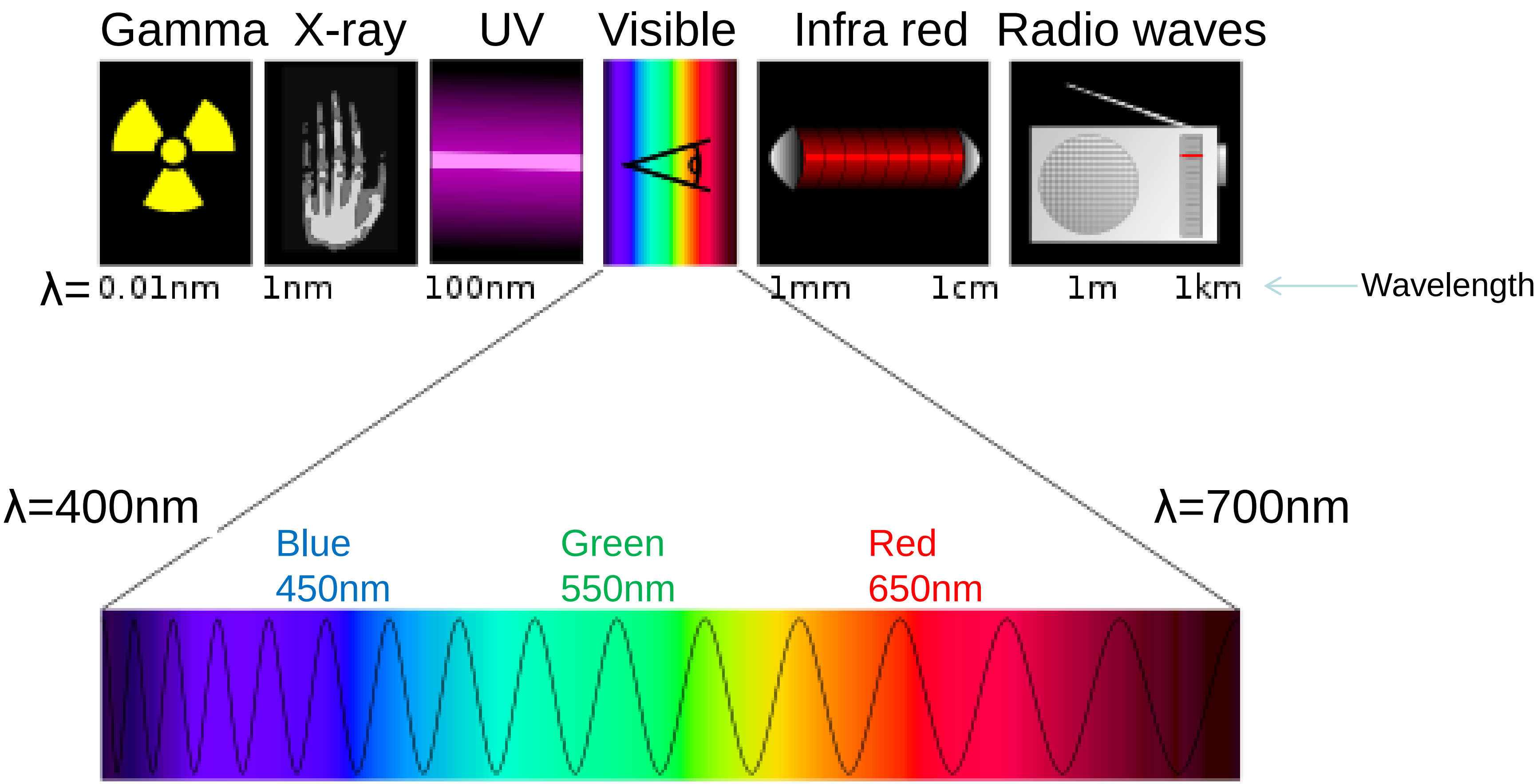
$$U = 0.492(B - Y')$$

$$V = 0.877(R - Y')$$

$$\begin{bmatrix} Y \\ U \\ V \end{bmatrix} = \begin{bmatrix} 0.2988 & 0.5869 & 0.1143 \\ -0.1689 & -0.3311 & 0.5000 \\ 0.5000 & -0.4189 & -0.0811 \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1.402 \\ 1 & -0.3441 & -0.7141 \\ 1 & 1.772 & 0.00015 \end{bmatrix} \begin{bmatrix} Y \\ U \\ V \end{bmatrix}$$

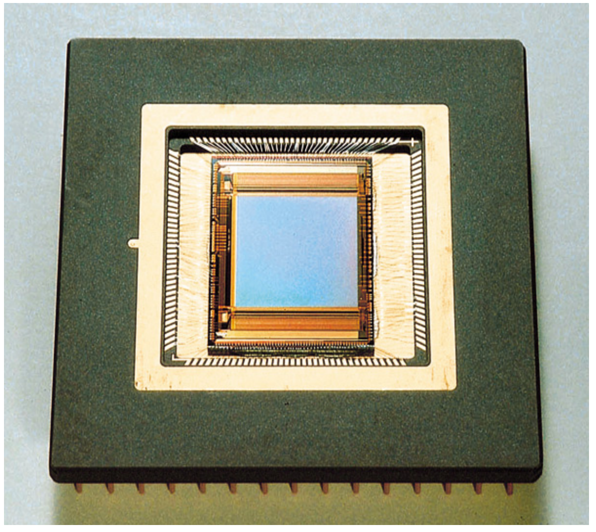
Electromagnetic Spectrum



From light in to digital pictures out

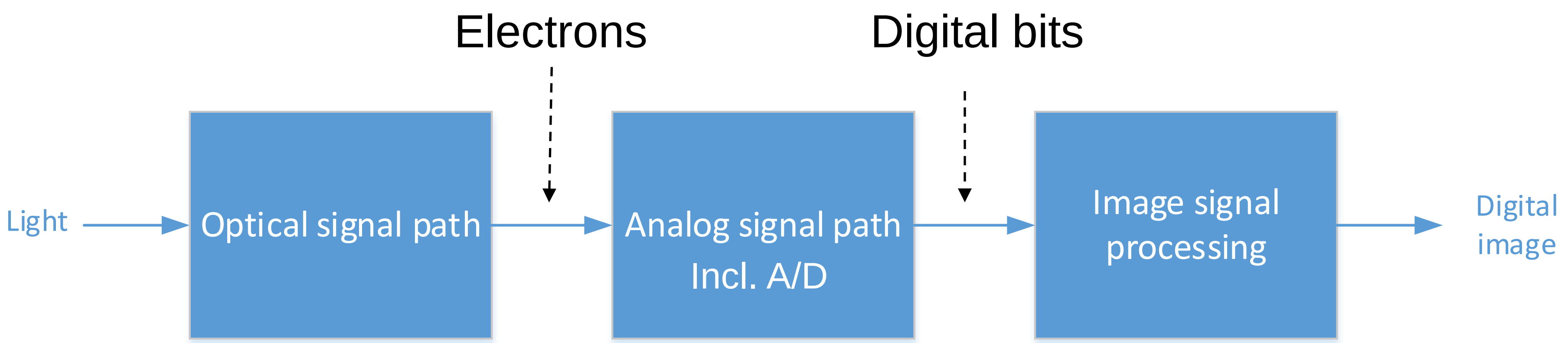
CMOS image sensor chip

Light

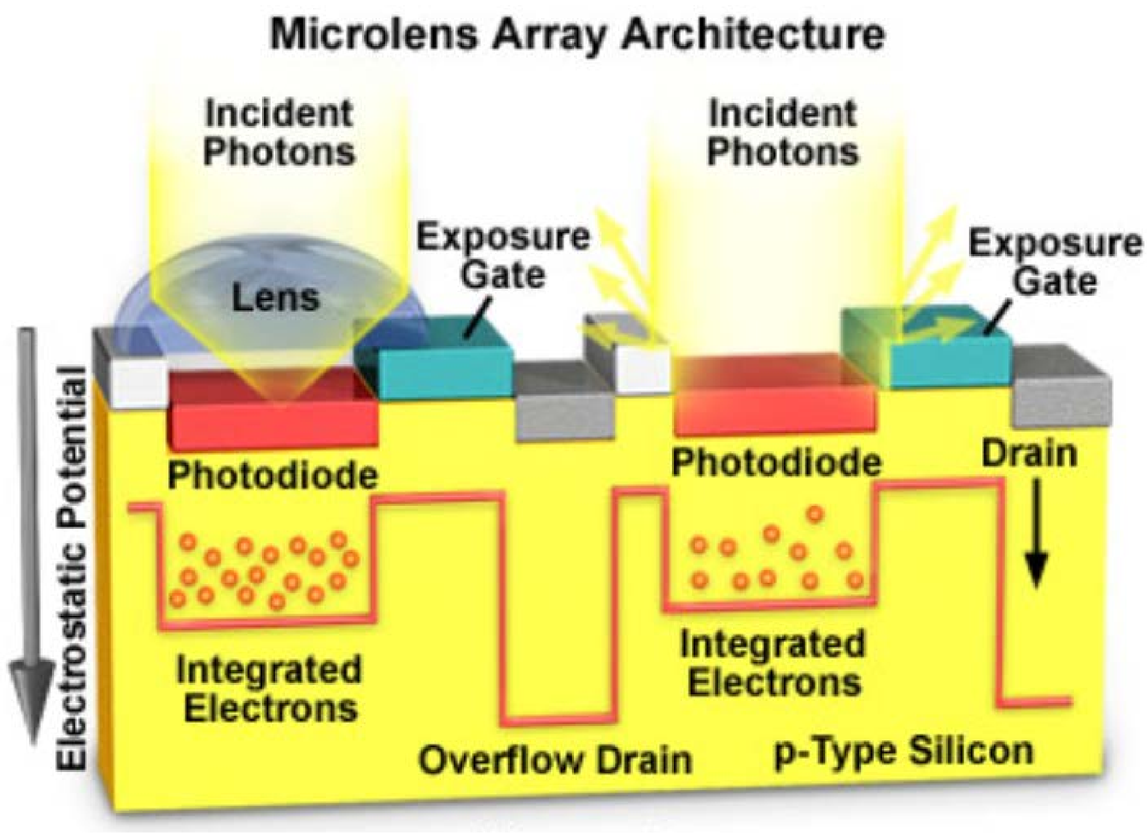


Digital pictures

CMOS image sensor signal chain

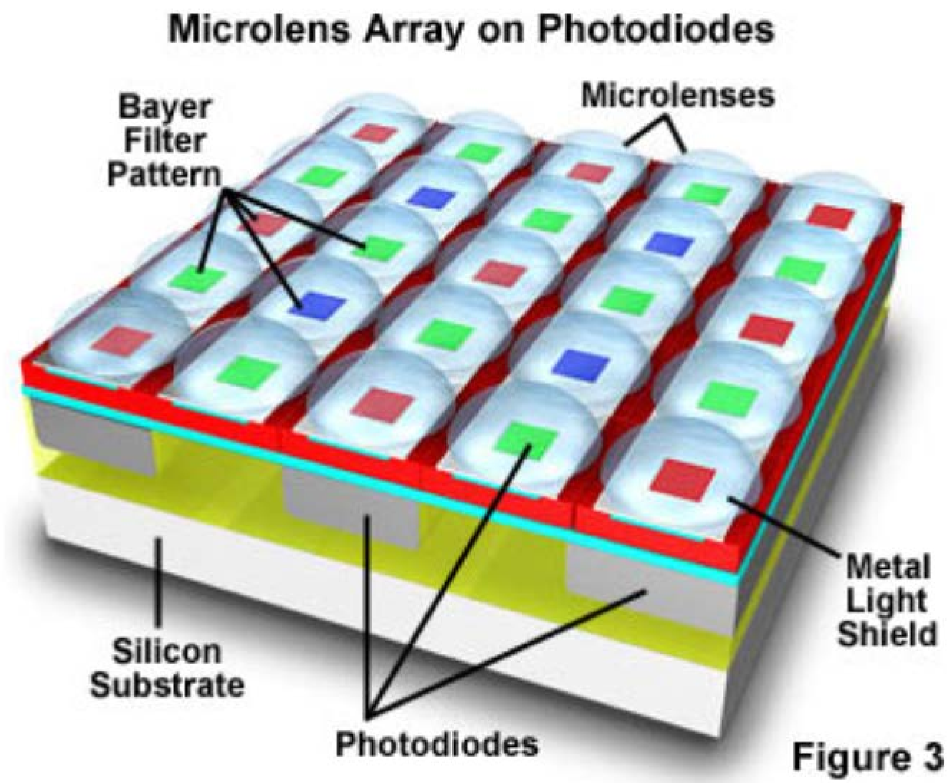


Microlenses enhance light sensitivity



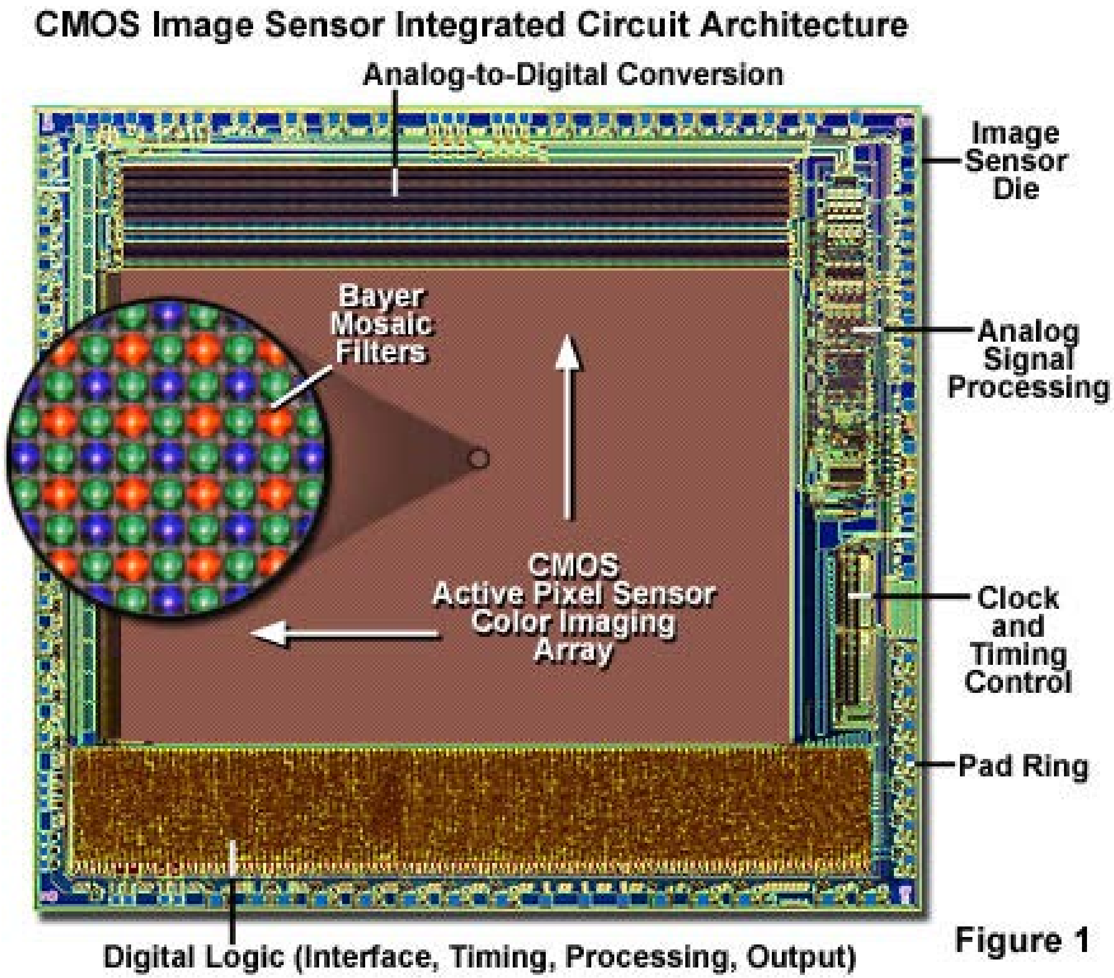
- Source: Hamamatsu

Microlenses enhance light sensitivity



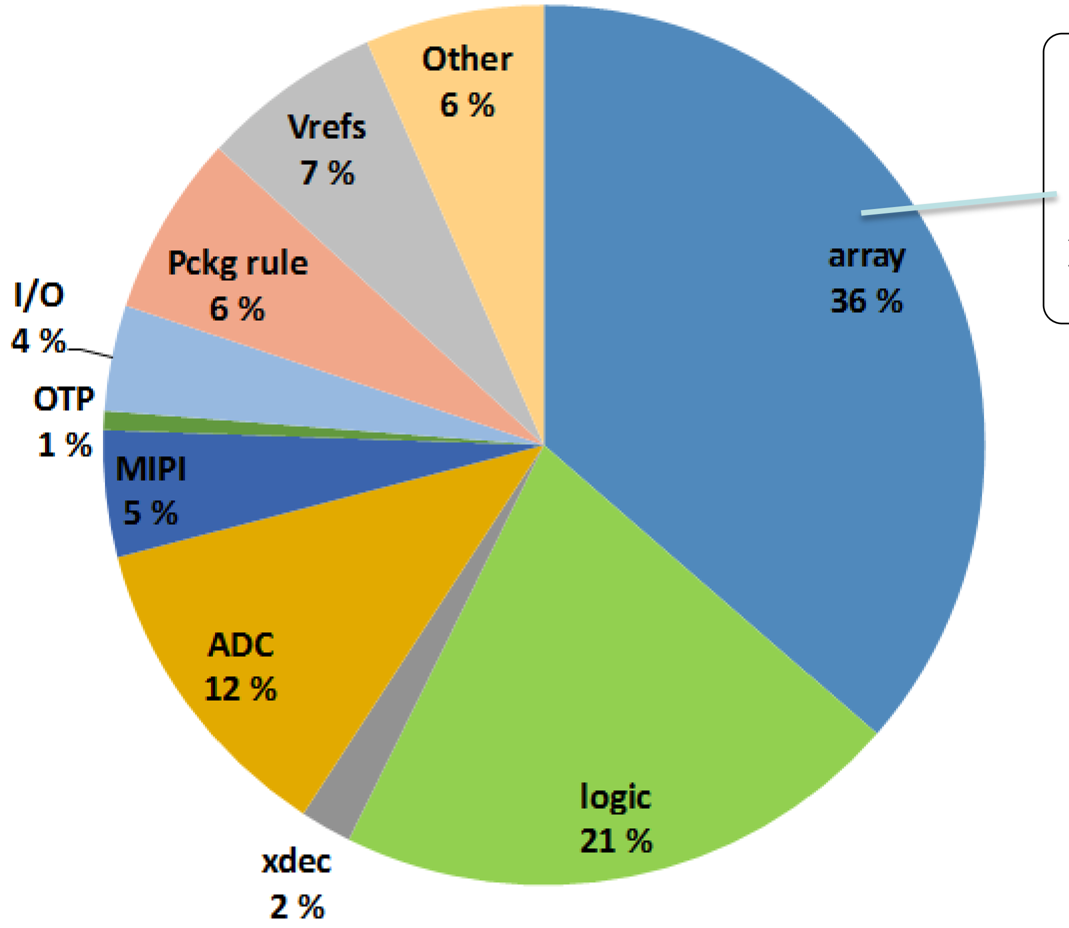
- Source: Hamamatsu

CIS chip floorplan

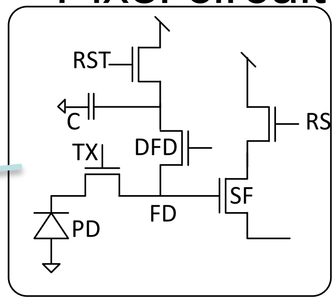


http://www.olympusmicro.com/primer/digitalimaging/cmosimagesensors.html

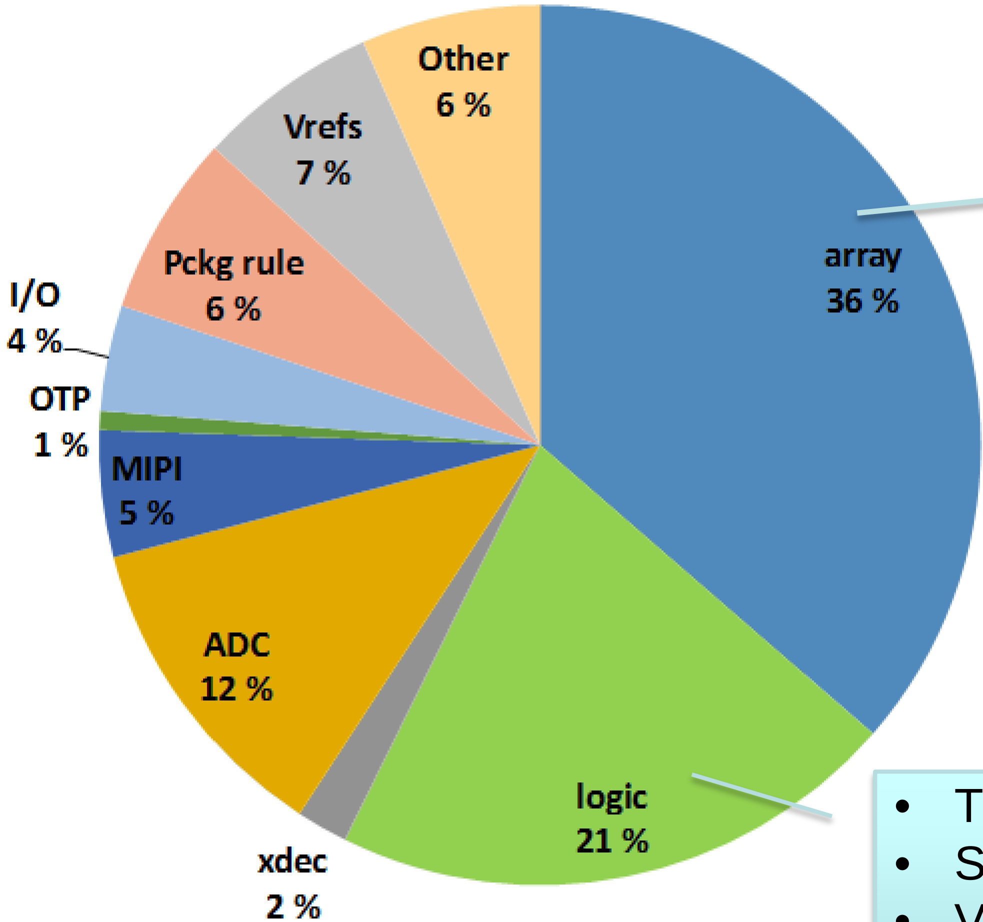
Chip area breakdown (example)



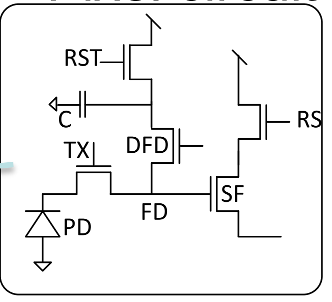
Pixel circuit



Chip area breakdown (example)



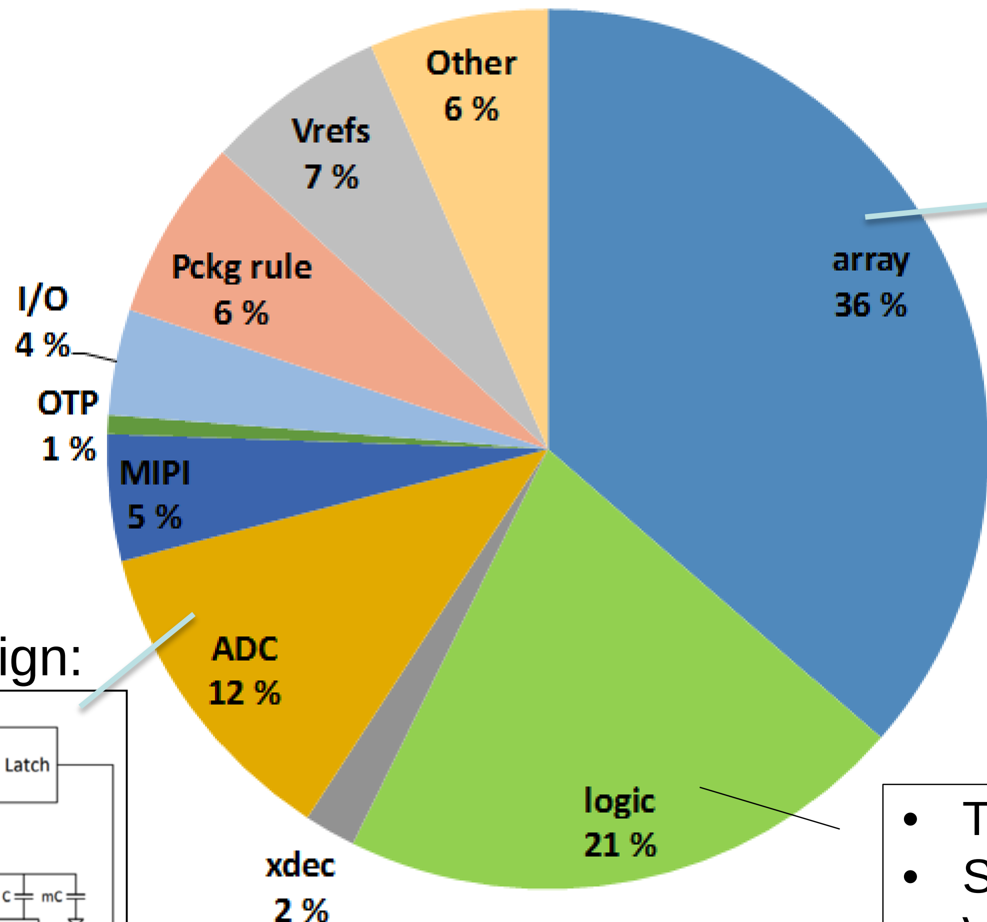
Pixel circuit



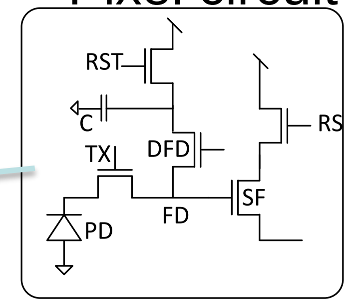
Digital design:

- Timing&Ctrl
- Signal processing
- Verilog RTL code
- FPGA emulation

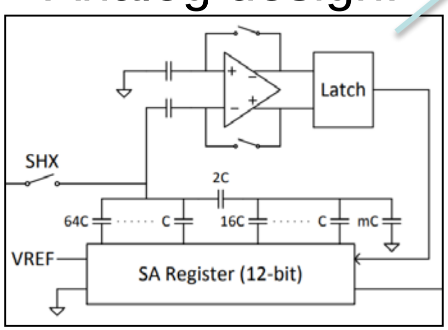
Chip area breakdown (example)



Pixel circuit



Analog design:



Digital design:

- Timing&Ctrl
- Signal processing
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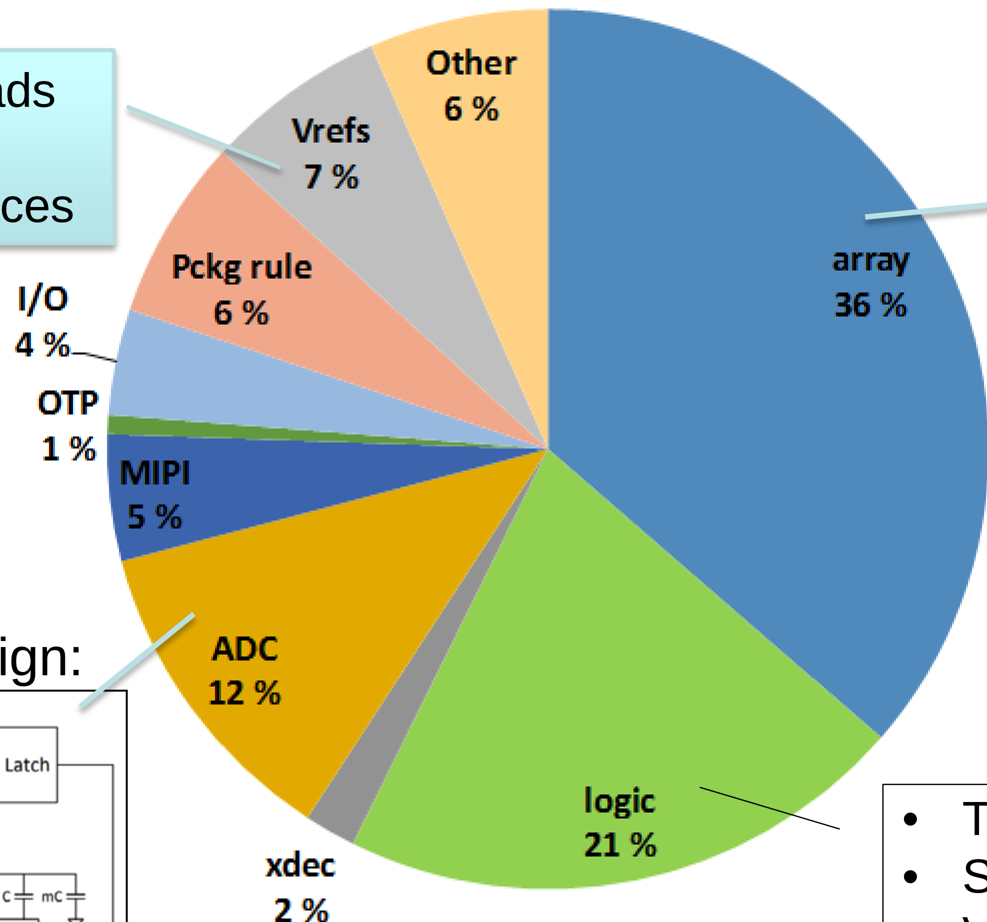
- FPGA emulation

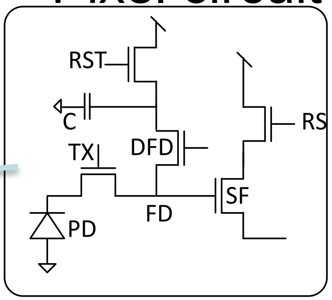
Chip area breakdown (example)

IP modules:

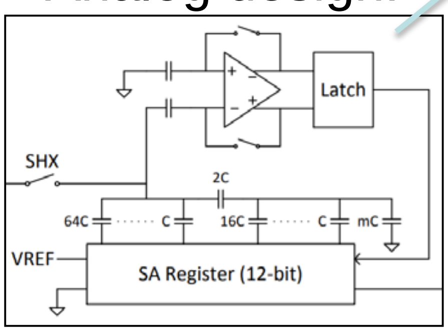
- Input/Output pads
- Serial interface
- Voltage references



Pixel circuit



Analog design:



Digital design:

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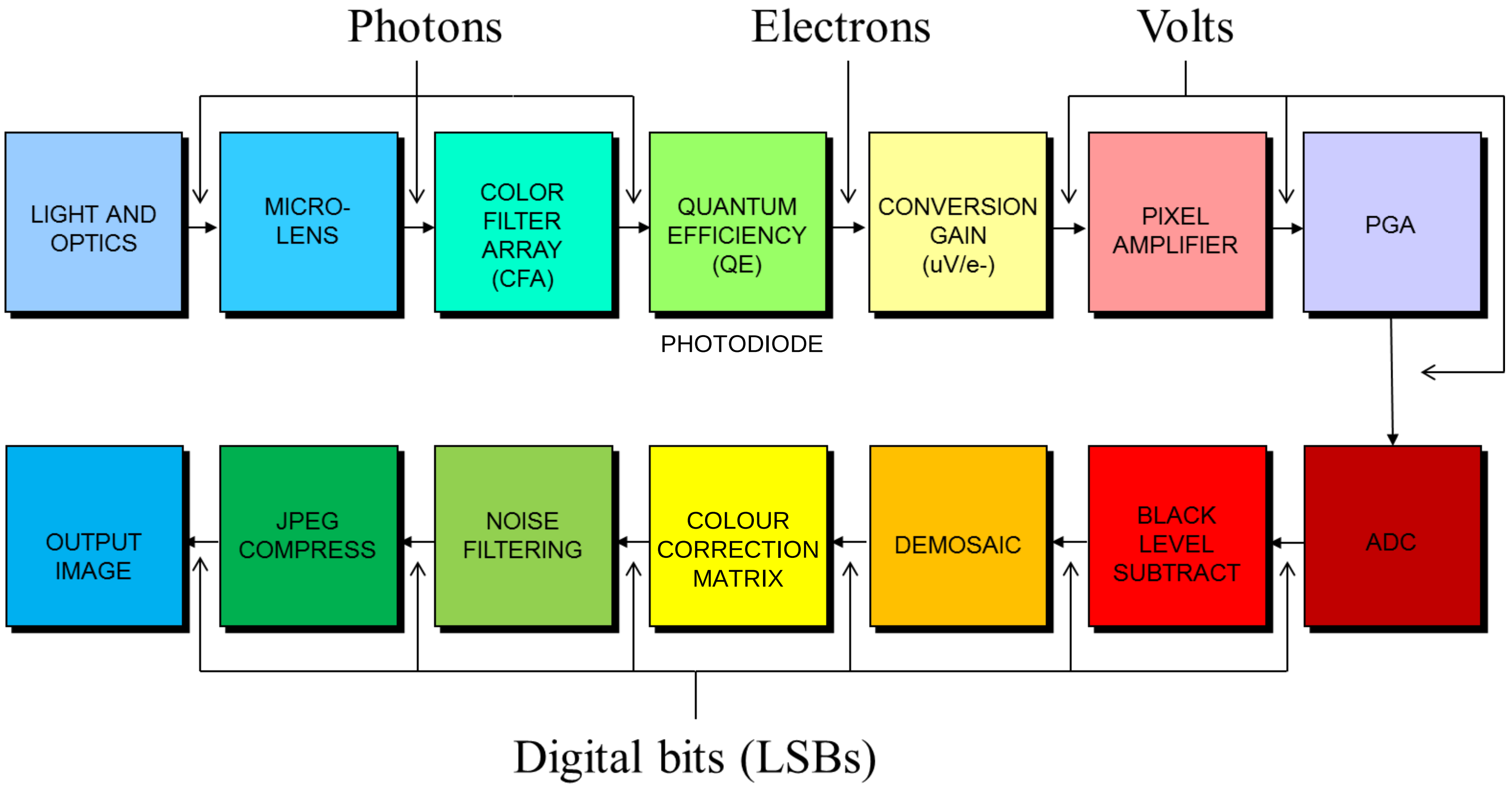
Digital camera signal chain



CIS evaluation HW and SW

- Used for design validation/debug, image capture and performance measurements

Not shown: FPGA board + USB interface to PC

Signal, Noise and Dynamic Range

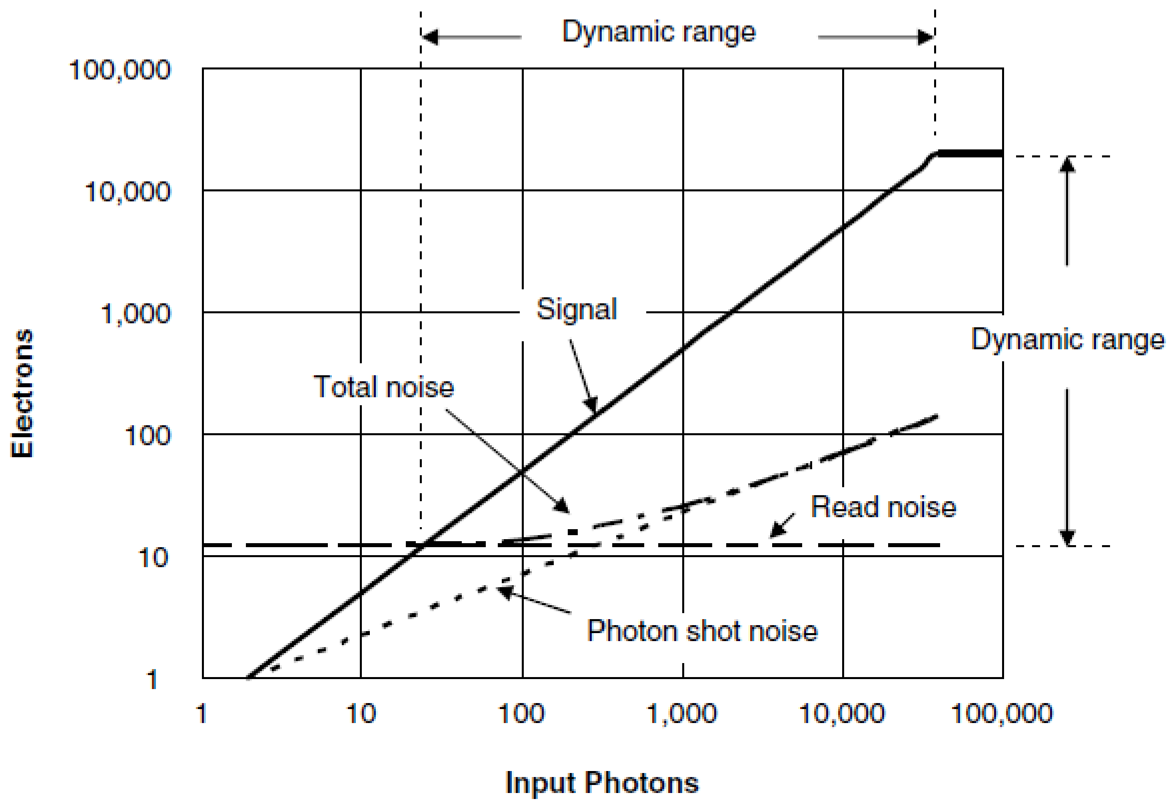
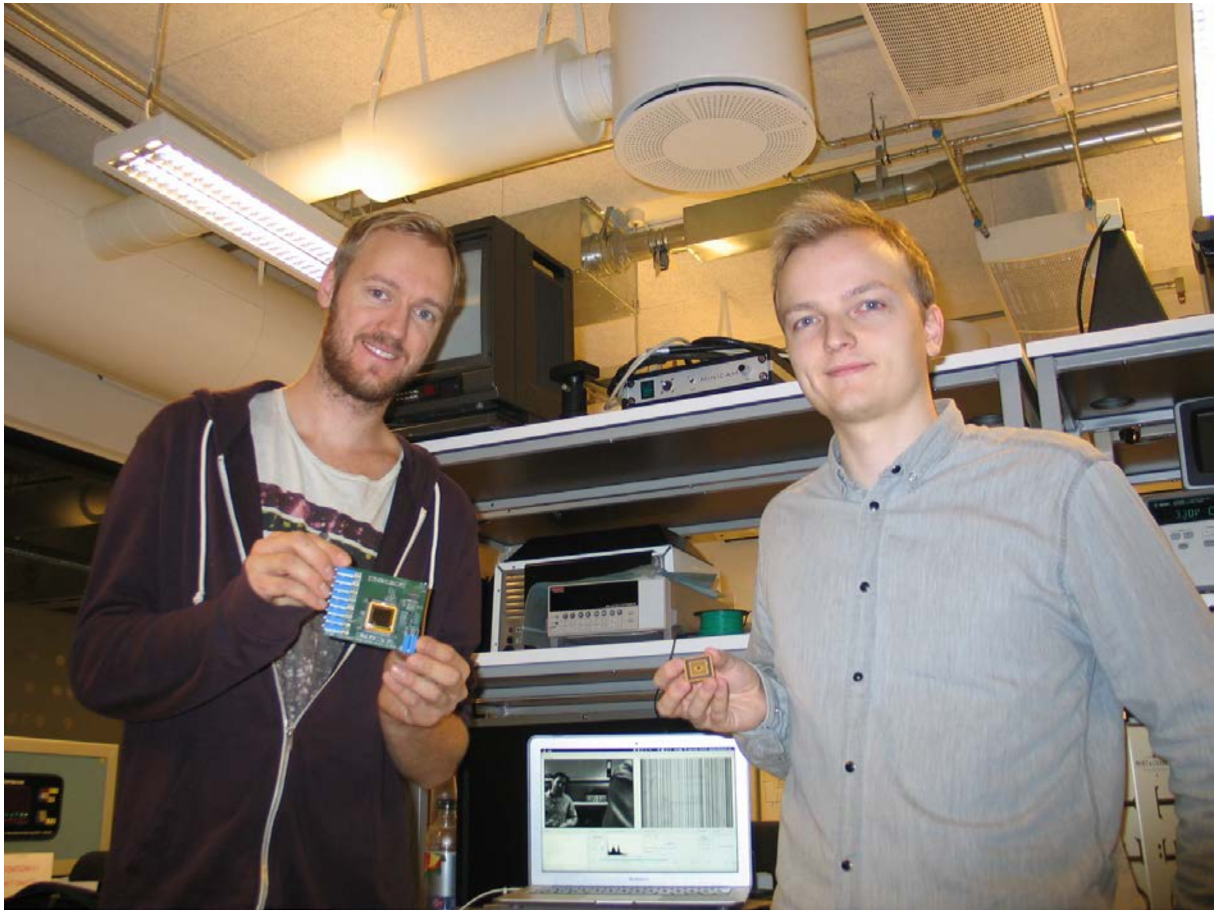


FIGURE 3.19 Example of photoconversion characteristics. A_{pix} = 25 µm²; C.G. = 40 µV/e⁻, N_{sat} = 20,000 e⁻, n_{read} = 12 e⁻.

Source: Nakamura et.al.

MSc project: CMOS camera-on-a-chip

MSc project: CIS design and characterization



APPLICATIONS AND TRENDS

CMOS image sensor applications

Automotive camera
(20bits/pixel)

Security camera
(low light, <0.1lux)

Machine vision
(high-speed, 1000Hz)

Phone camera
(small size, <5mm)

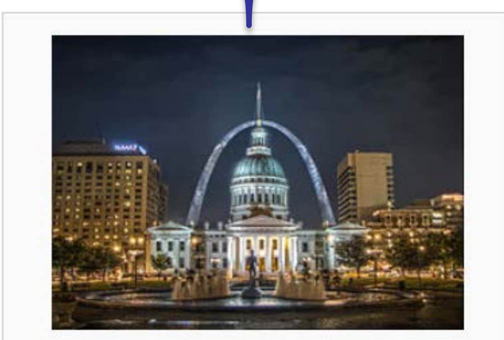
Pill camera
(low power, <10mW)

Digital still camera
(high resolution, >20Mpixels)

High Dynamic Range Imaging

- The dynamic range of the typical scene is usually greater than the dynamic range a sensor can capture in one frame

HDR techniques enable better image quality by combining multiple captures into one image



Combined HDR image

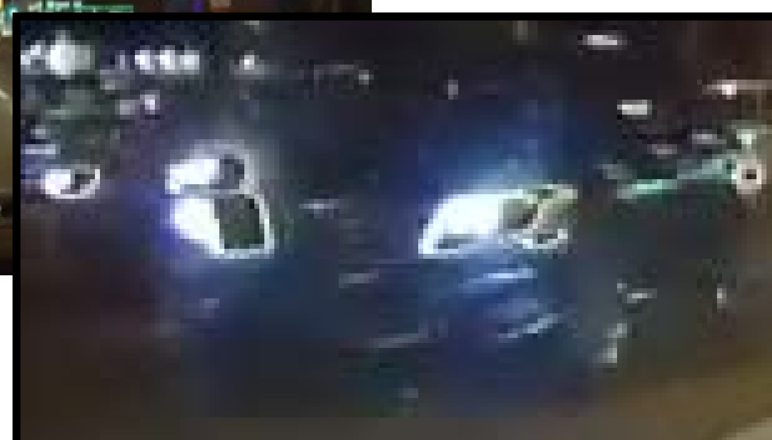
HDR images contain more scene information

Non-HDR

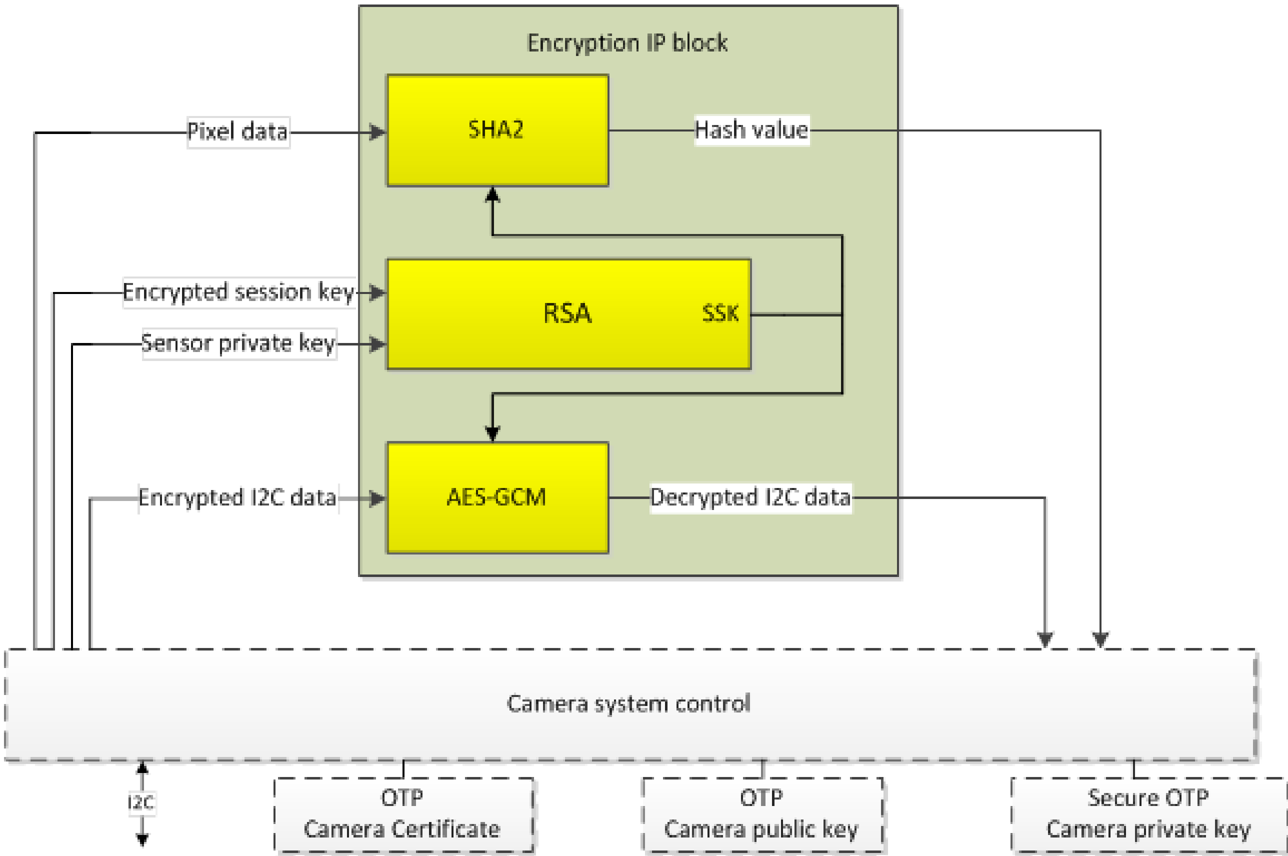
HDR

HDR Motion Artifacts

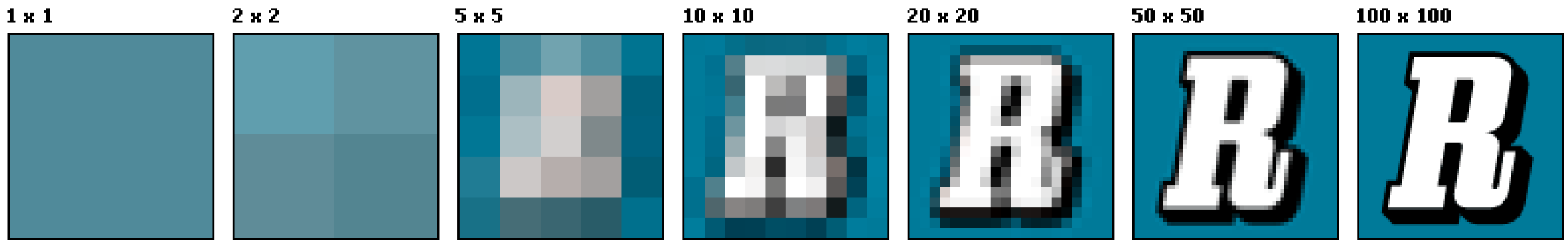
- Multi-capture HDR scheme introduces motion artifacts ("ghosting") due to motion in scene, as objects are in different position for each capture



RnD - Encryption in CMOS image sensors



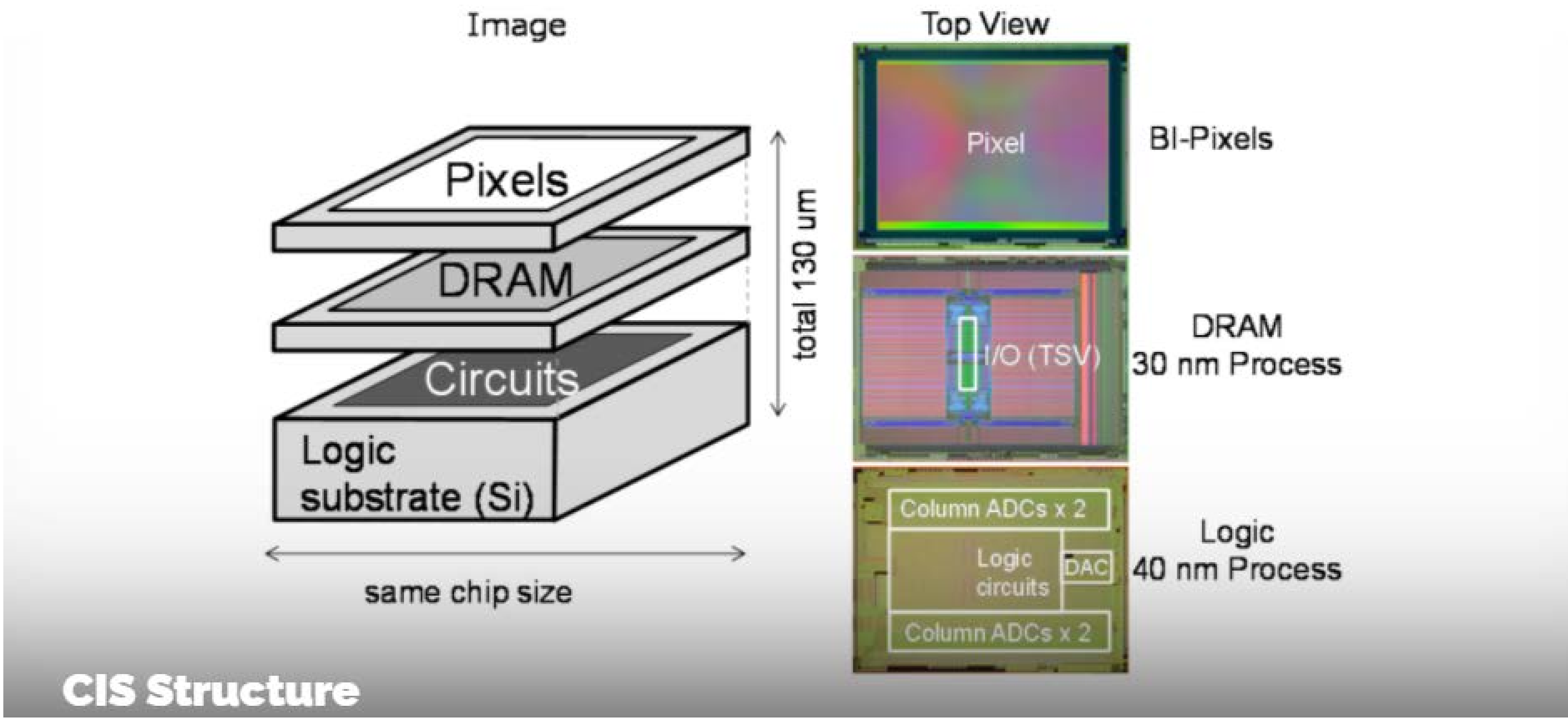
More pixels give better resolution



- Enables more detail at longer distances
- Enables digital zoom-in
- Requires faster readout, ADCs, ISPs
- Requires low-power design and innovation

Kilde: Wikipedia

Technology Trend - 3D Stacked Die



Thanks!