Computational Optical Imaging - Optique Numerique

Winter 2013

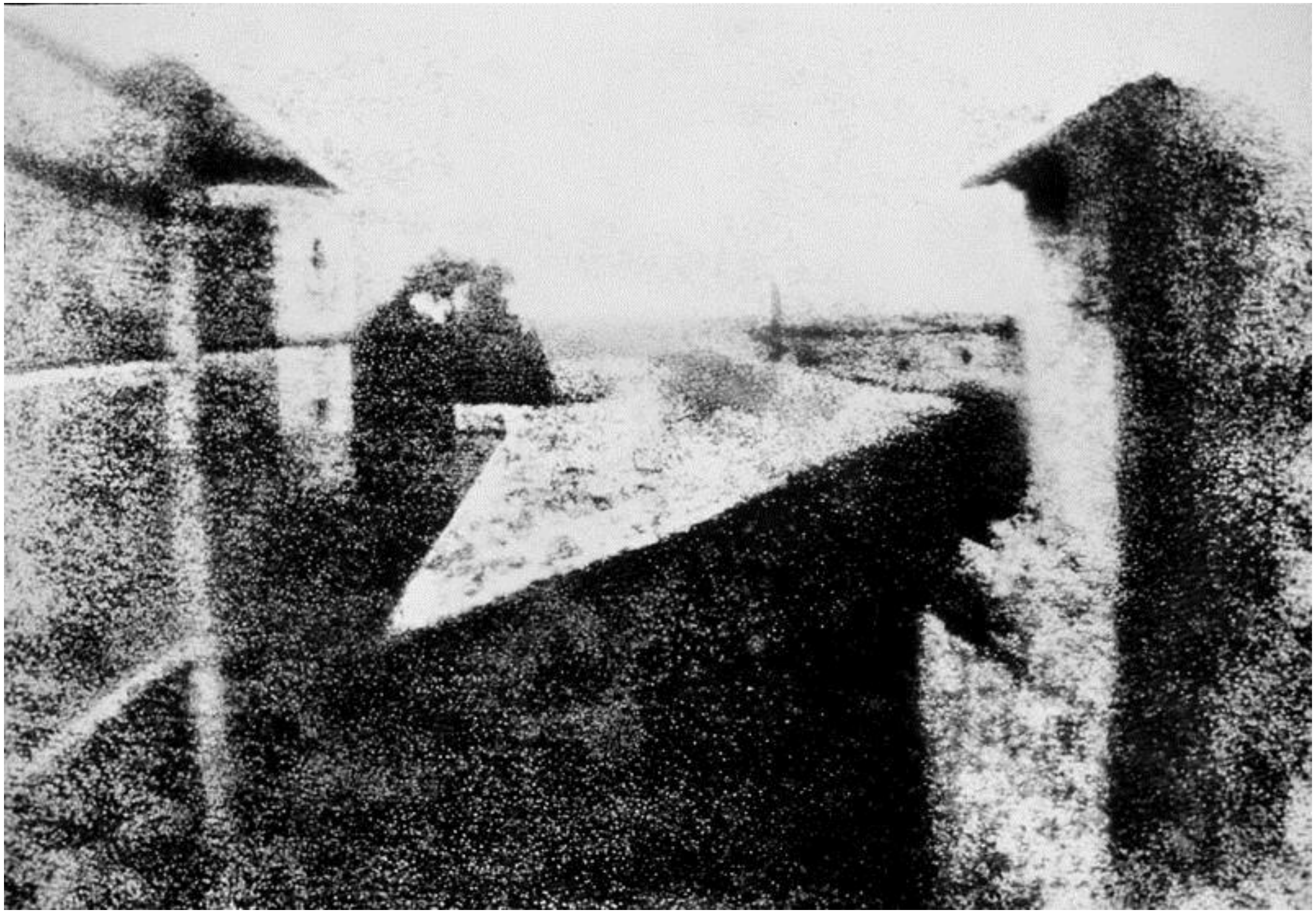
Ivo Ihrke

Joseph Nicéphore Niépce 1765 - 1833

- First photograph

1824

- Exposure time 8-12 hours



Louis Daguerre 1787-1851

Daguerrotype

- Interesting panorama 1848
  - “Cincinnati water front”
  - Restoration: Tang, X., Ardis, P.A., et. al. “Digital Analysis and Restoration of Daguerreotypes” 2010. *Proceedings of the SPIE*
  - http://1848.cincinnatilibrary.org/

Photovoltaic Effect - 1839

- Alexandre-Edmond Becquerel, 1839

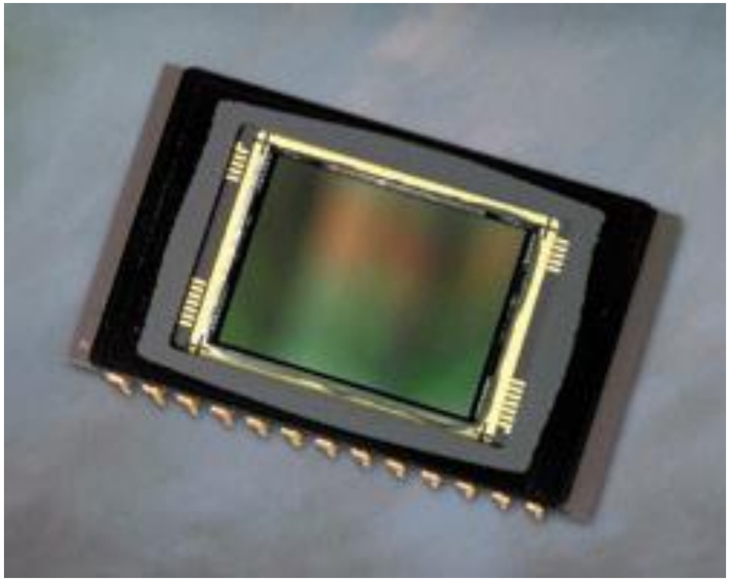
Selenium

- First semiconductor
- Photoelectric effect
  - Willoughby Smith (1873)

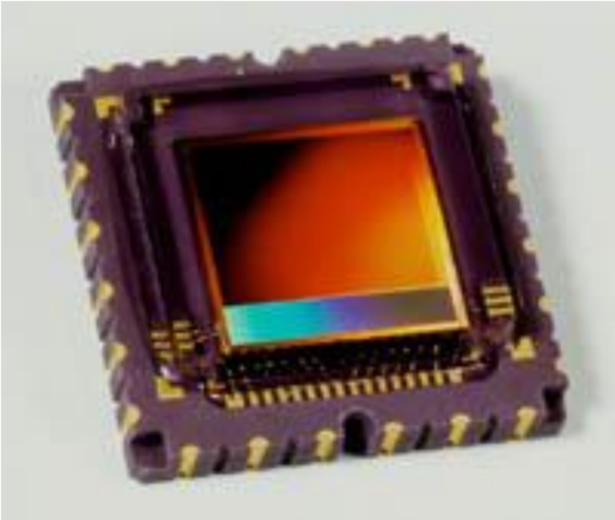
Photodiode

INSTITUT d'OPTIQUE GRADUATE SCHOOL

Image Sensors



CCD



CMOS

Image Sensors

- Photodetection
- CCD vs. CMOS
- Sensor performance characteristics
- Noise
- Color Sensors
- Exotic Sensors

Light

- Rays, waves and particles....
  - When does light behave like rays, waves, or particles?
- Today, it's a particle :)

Photons and electrons

- Light: photon
  - **m_0 = 0 (massless)**
  - **q = 0 (no electric charge)**
  - **E = hν =** hc/λ
    energy of a photon depends ONLY on the wavelength!

- Electric charge: electron
  - **$m_0 = 9.1 * 10^{-31}$ kg**
  - **$q = -1\ e = -1.6 * 10^{-19}$ C**
  - **$E = m_0c^2 + mv^2/2 - e\varphi + \ldots$**
    rest energy, kinetic energy, potential energy

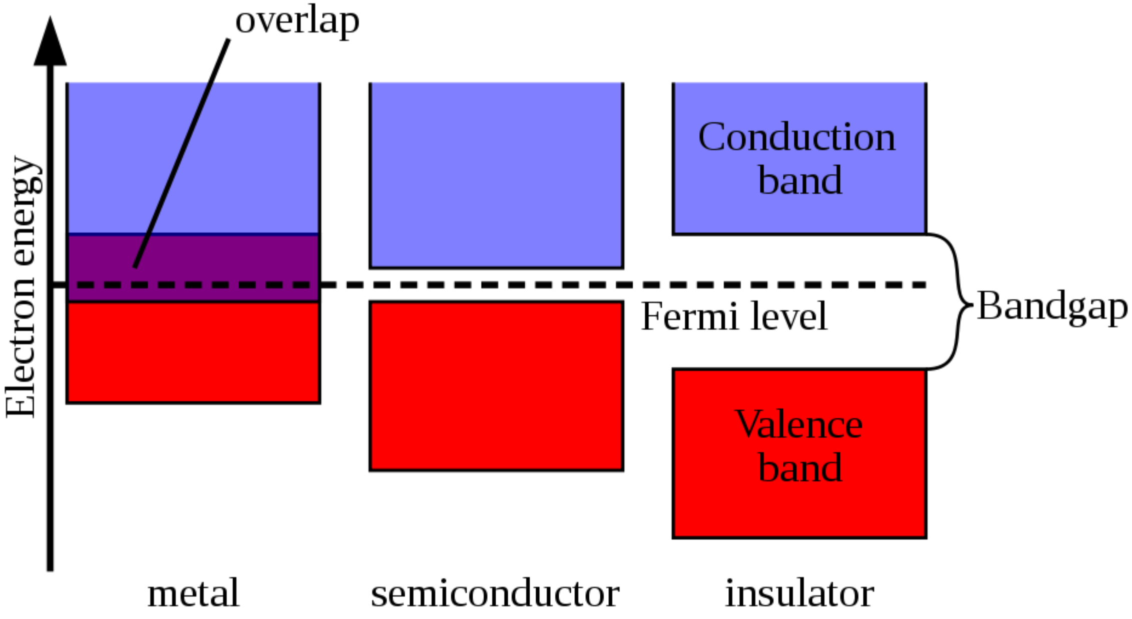
Unit of energy:

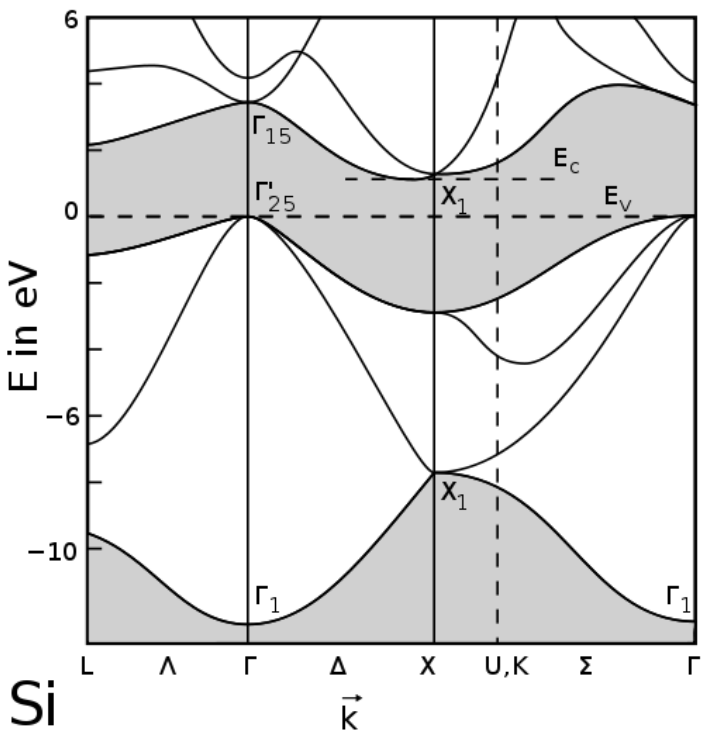
1 eV = energy required to move 1 electron by 1 V in an electrostatic potential

Amount of light

- Radiant flux [1W]: $\Phi = E\, n$
  $= h\nu\, dN/dt$
- Measurement: integrate over time Δt
- Poisson random process
- If I count 1 photon, 100 photons, what's the error (standard deviation)?
- $\sigma(N) = \sqrt{N}$

Semiconductors





Photon energy:	
400 nm (violet):	3.1 eV
700 nm (red):	1.77 eV
1100 nm (infrared):	1.12 eV

Band gap in semiconductors:	
Diamond (C):	5.47 eV
Gallium arsenide (GaAs):	1.43 eV
Silicon (Si):	1.11 eV
Germanium (Ge):	0.67 eV

Photogeneration

- Silicon
  - "Band gap" of 1.124eV between *valence band* and *conduction band*.
- Incident photon > 1.124eV (hc/ λ) may be absorbed, causing election to jump to conduction band.
- Visible light (λ=400 to 700nm)
  - λ = 400nm (violet) E = 3.1eV
  - λ = 700nm (red) E = 1.77eV
  - λ = 1100nm (infrared), E=1.12eV

Integration

- Measuring a single electron is hard! (small electric charge…)
- Fortunately, photoelectrons can be stored.
- So integrate the charge over a period of time.
  - 10’s to 1000’s of electrons.
- Two fundamental structures…

Photodetectors

- (a) photodiode, (b) photogate
- All electrons created in *depletion region* are collected, plus some from surrounding region.

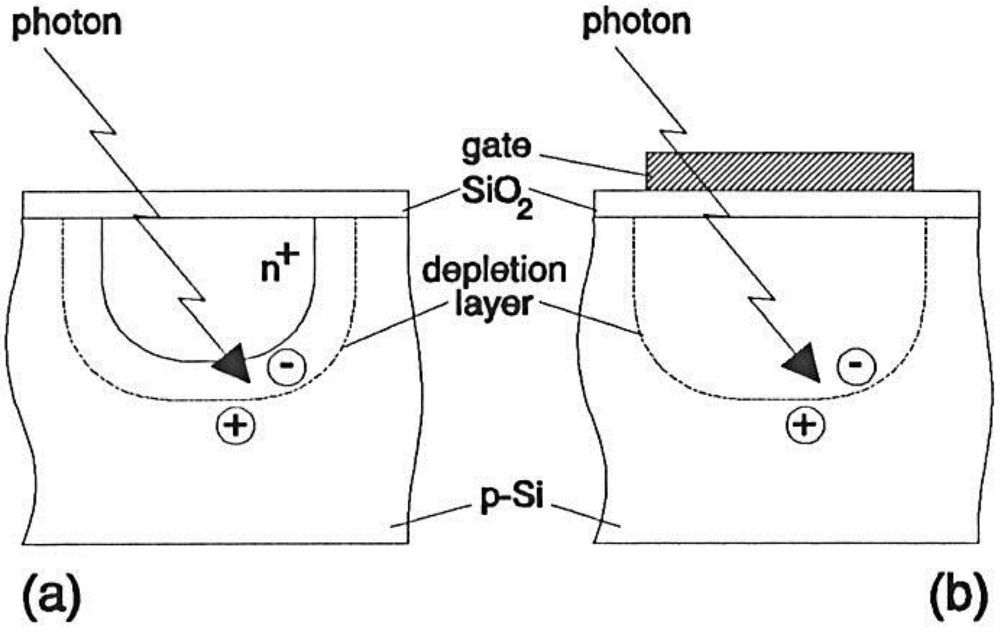
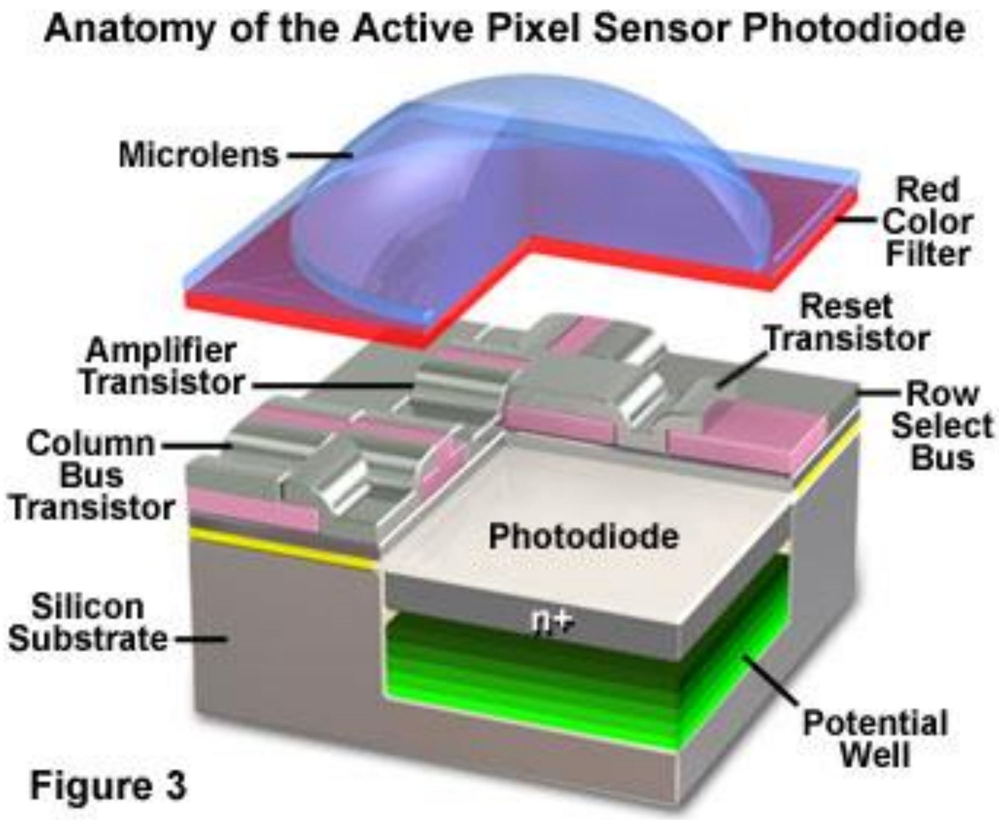


image: Theuwissen

Photodiode in CMOS sensor



Photodetector Performance Metrics

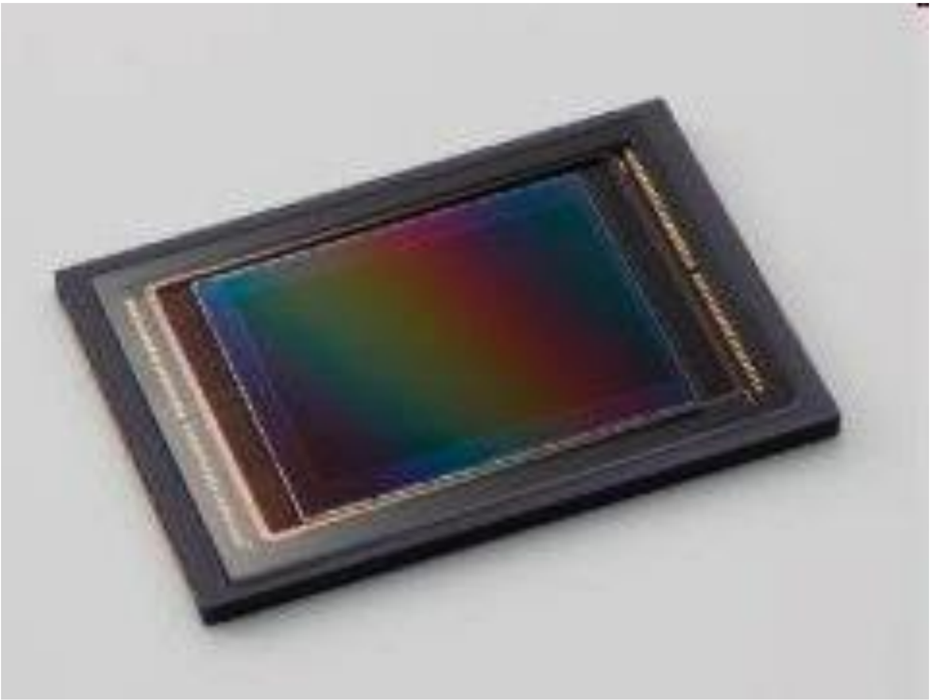
- Pixel size
- Fill factor
- Full well depth
- Spectral quantum efficiency
- Sensitivity
- (Saving noise & dynamic range for later)

Pixel Size

- Large pixels collect more light.
- Typically 3µm-10 µm
- 20 µm for astronomy
- Pixels getting tinier for cell phones, digital cameras
  - 1.4µm x 1.4µm (iPhone 5)
  - Bottleneck = optical resolution.

Currently (Aug 2010) Highest-Res Chip

- Canon 120 MPixel (13280 x 9184) - experimental
  - size 29.2 mm x 20.2mm
  - readout @ 9.5 fps



Fill Factor

- Percentage of pixel area that captures photons.
- Typically 25% to 100%
- Reduced by non-light gathering components in pixel (see CMOS sensors…)
- Can be increased using microlenses:

Lenslets

- Increase effective fill factor by focusing light
- Can double or triple fill factor

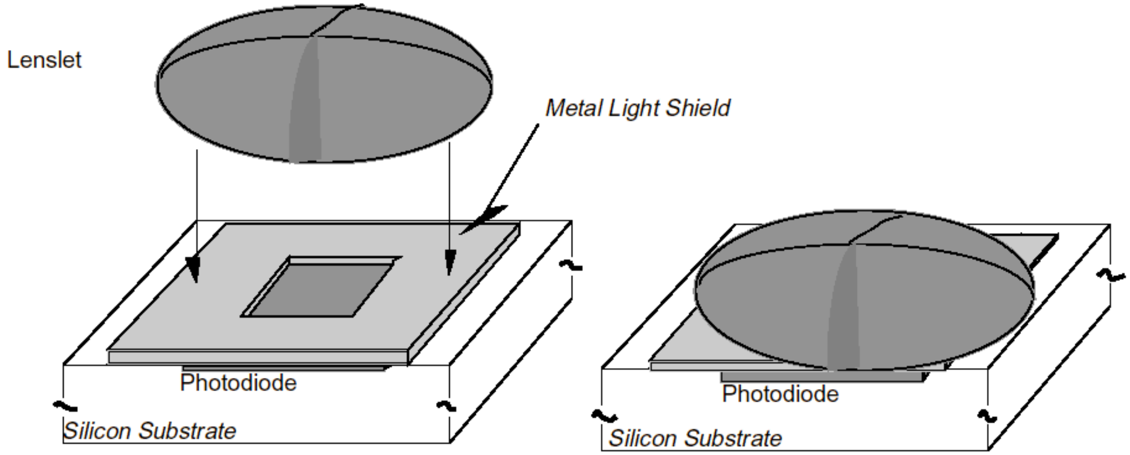


image: Kodak application note DS00-001

- Changes the cos^4 law - vignetting

Full Well Depth

- "Saturation charge" 45 to 100 ke$^-$
  - depends on the pixel size
- Limits dynamic range (more about this later)
- Once the well is filled up, it can overflow into neighbouring pixels. This is called blooming.
- (Blooming almost irrelevant for CMOS)

Blooming

http://www.ccd-sensor.de/assets/images/blooming.jpg

Extra Overflow Drain

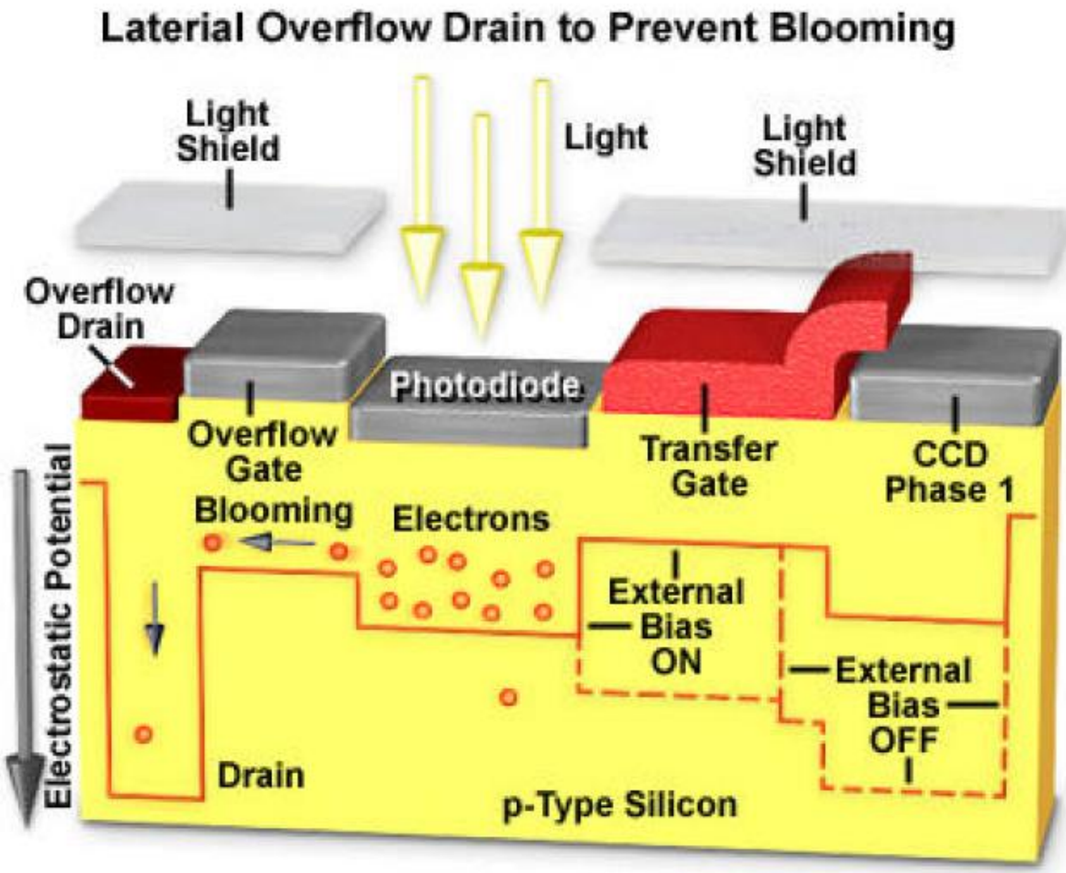


Figure 1

Absorption Coefficients

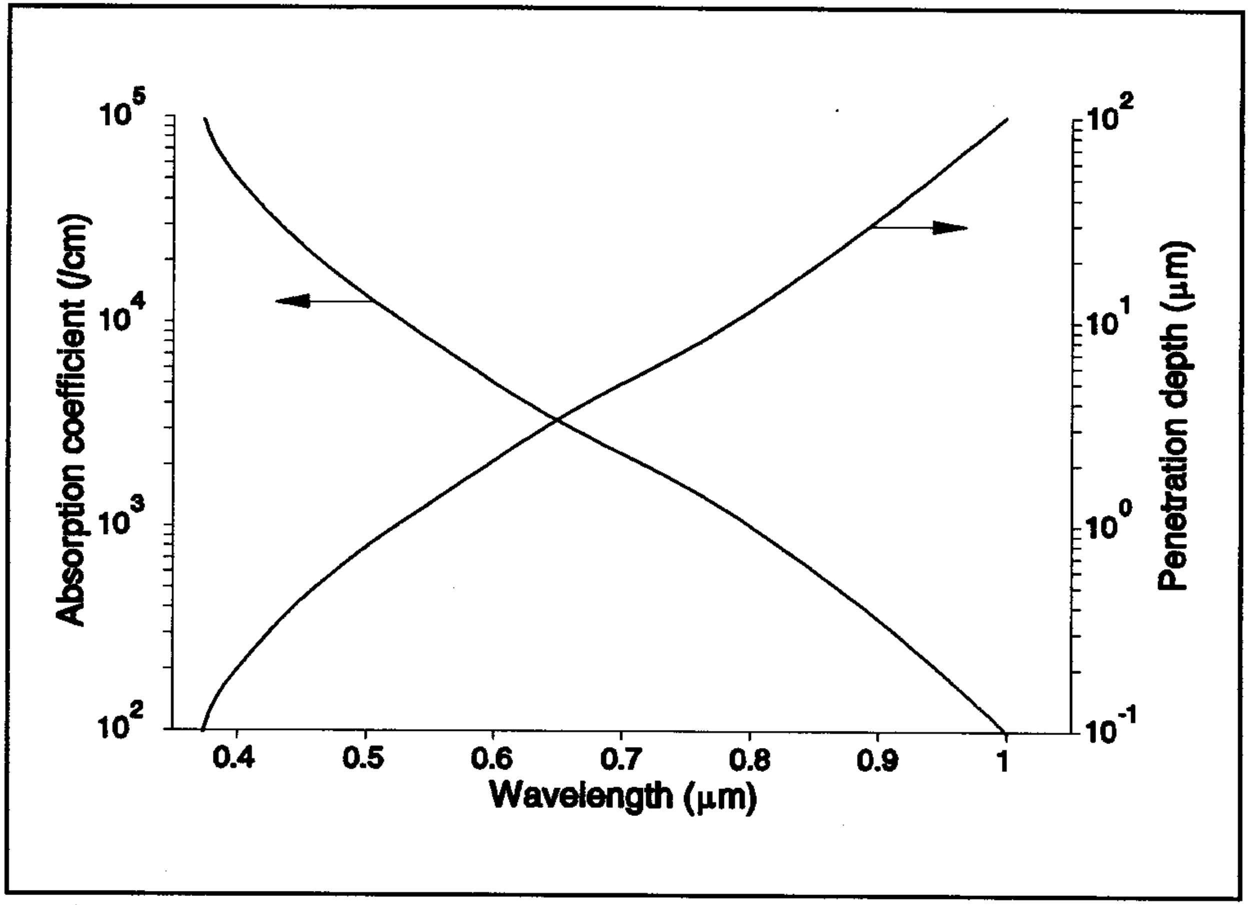


FIGURE 5.2. The absorption coefficient of silicon together with its corresponding penetration depth as a function of the wavelength of the incident light.

image: Theuwissen

Penetration Depth

Wavelength (nm)	penetration depth (μm)
400	0.19
450	1.0
500	2.3
550	3.3
600	5.0
650	7.6
700	8.5
750	16
800	23
850	46
900	62
950	150
1000	470
1050	1500
1100	7600

Spectral quantum efficiency (QE)

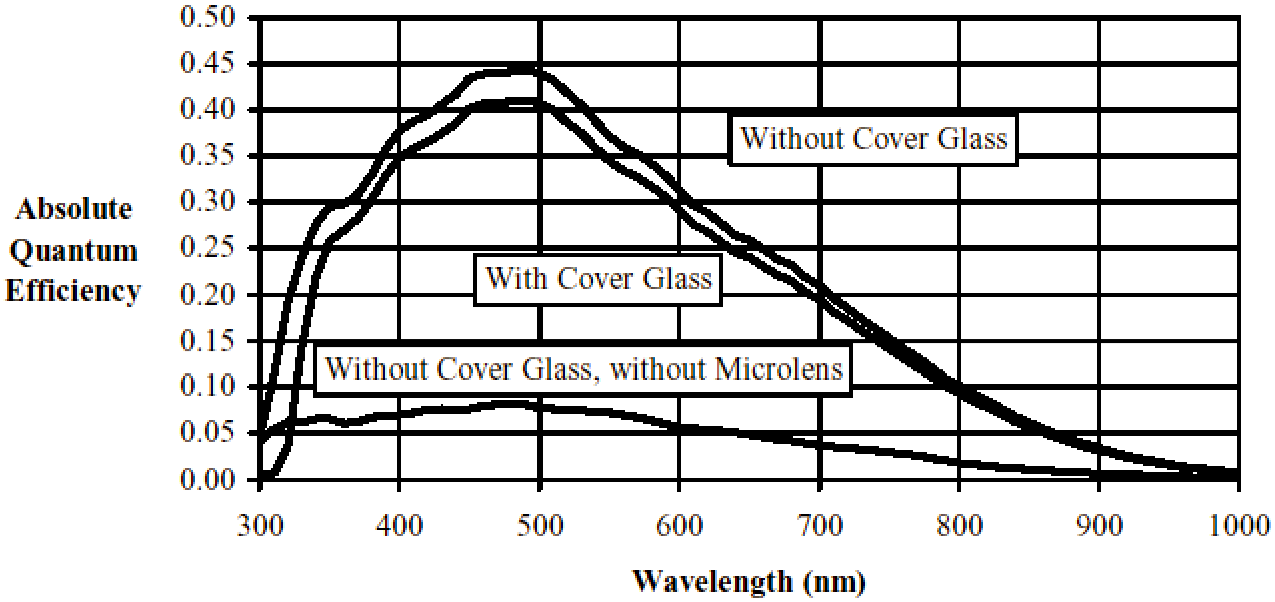


Figure 10 - Wavelength Dependence of Quantum Efficiency

source: Kodak KAI-2000m data sheet

Filtered Spectral Quantum Efficiency

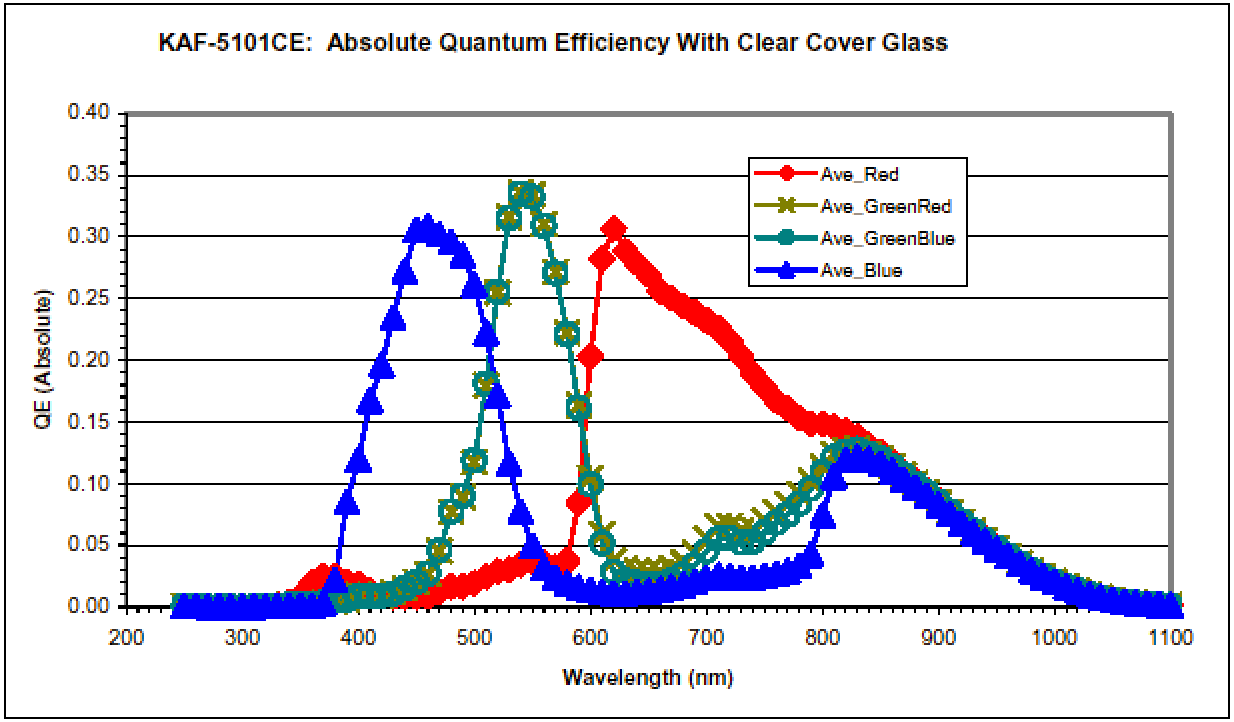


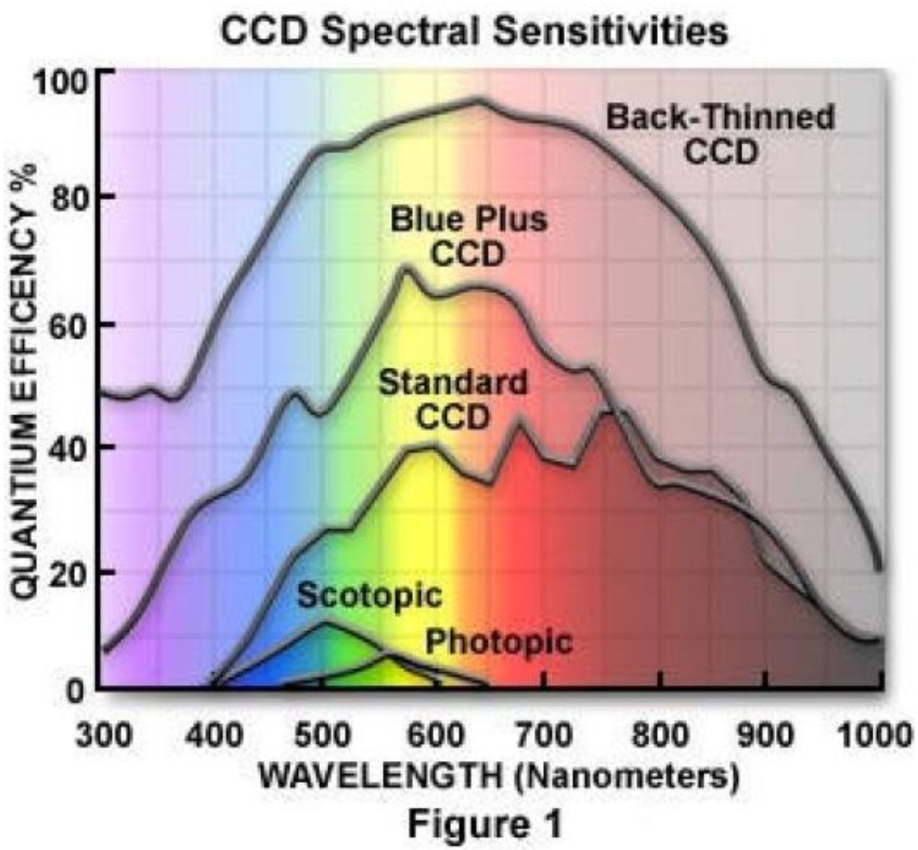
Figure 7. Typical Quantum Efficiency Curves (Clear Coverglass)

source: Kodak KAF-5101ce data sheet

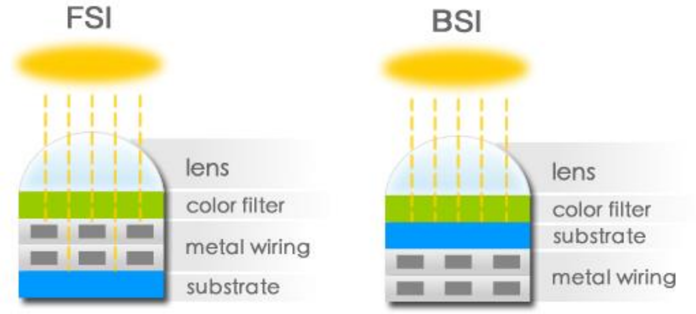
Factors for Quantum Efficiency

- Color filters
- Absorption coefficients & depletion depth
  - Blue light is absorbed quickly, red wavelengths penetrate more deeply.
  - Photogate detectors have poor blue response because the gate absorbs blue light, too.
- Fill factor

Extended Sensitivity



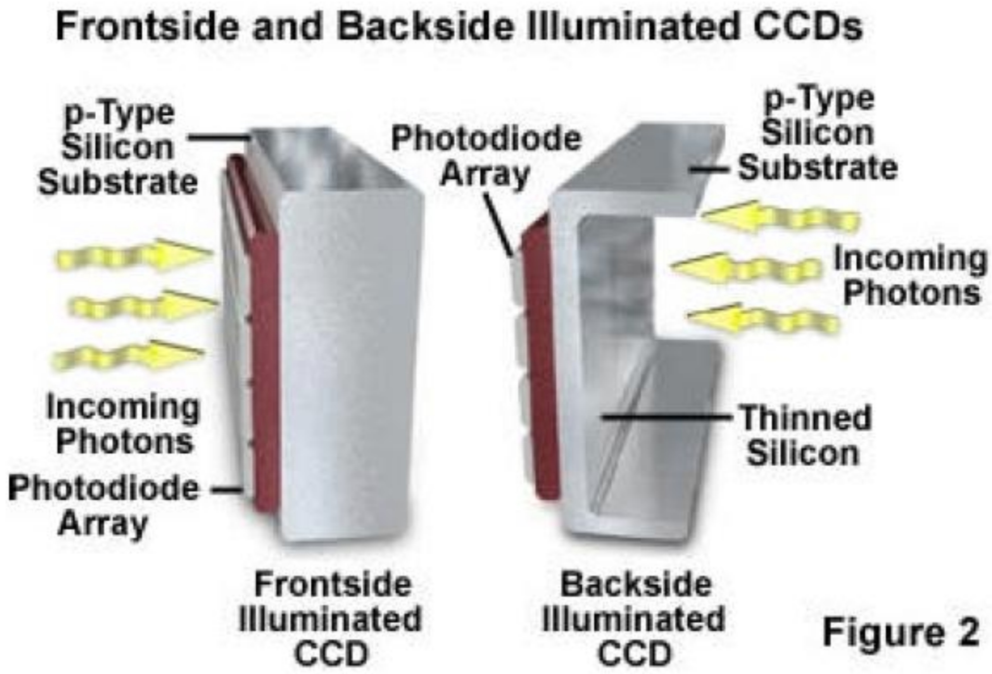
Front side illumination (FSI)
Back side illumination (BSI)



[ViseraTech]

- blue plus – applies a phosphorescent layer
- back illuminated CCDs – decrease thickness

Back Illuminated CCDs



Sensitivity

- Sensitivity = quantum efficiency * conversion gain
- Conversion gain: “how many volts per electron?”.
  - Depends on device process, topology, etc.
- Sensitivity is often expressed as Volts/lux
  - 1 Lux = (1/683)W/m^2 at λ = 555nm
  - 1 Lux (or lumens/m^2) = 4.09e11 photons/(cm^2sec)
  - Clear sky ~= 1e4 Lux
  - Room light ~= 10 Lux
  - Full moon ~= 0.1 Lux

CCD's vs CMOS Image Sensors

- Differ primarily in readout—how the accumulated charge is measured and communicated.
- CCDs transfer the collected charge, through capacitors, to *one* output amplifier
- CMOS sensors "read out" the charge or voltage using row and column decoders, like a digital memory (but with analog data).

CCD Sensor 1969

Willard S. Boyle (left) and George E. Smith (1974), Nobel Prize 2009

Charge Transfer for CCD's

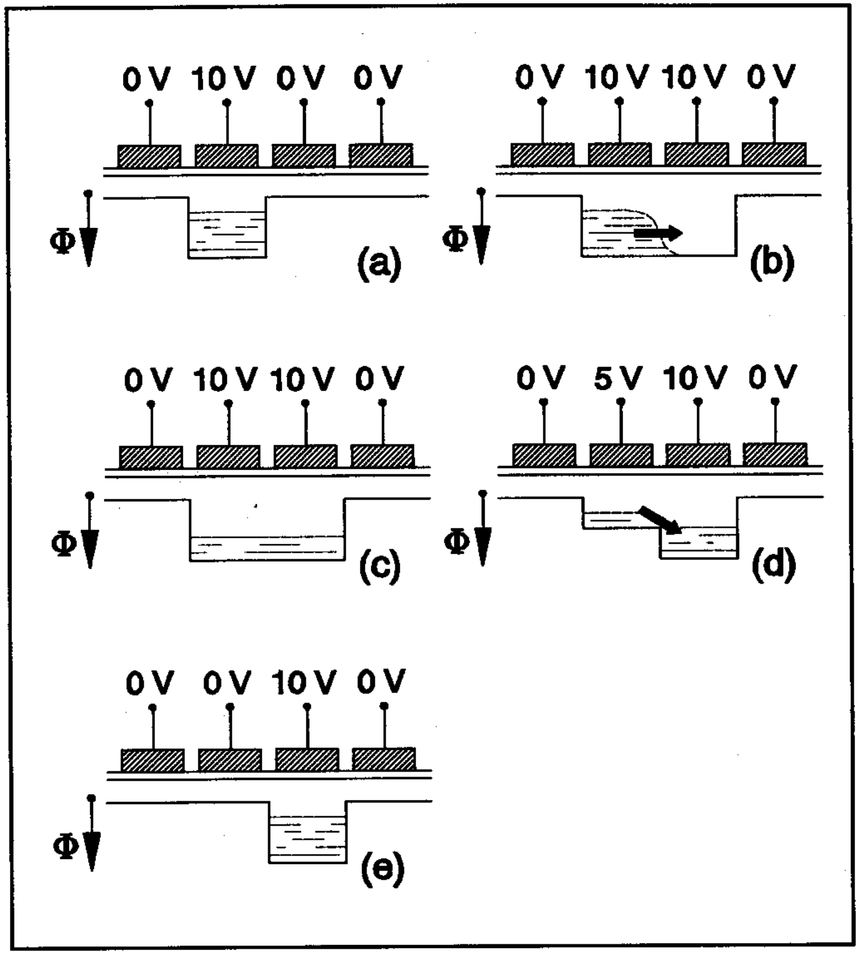
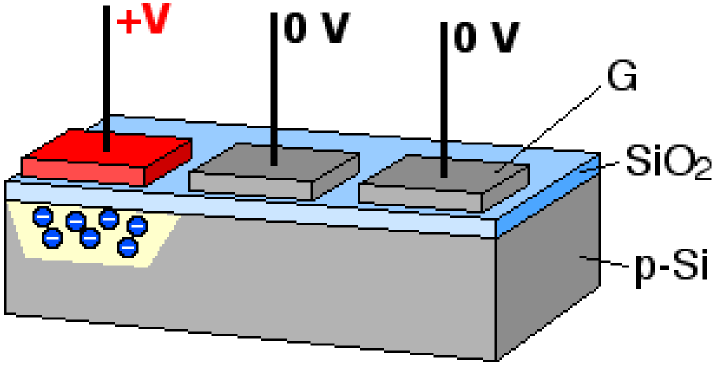


FIGURE 1.8. Illustration of the charge transport in a CCD. The charge packet of minority carriers is moved through the silicon by means of digital pulses on the CCD gates.

image: Theuwissen

Charge Transfer



Example:Three Phase CCD's

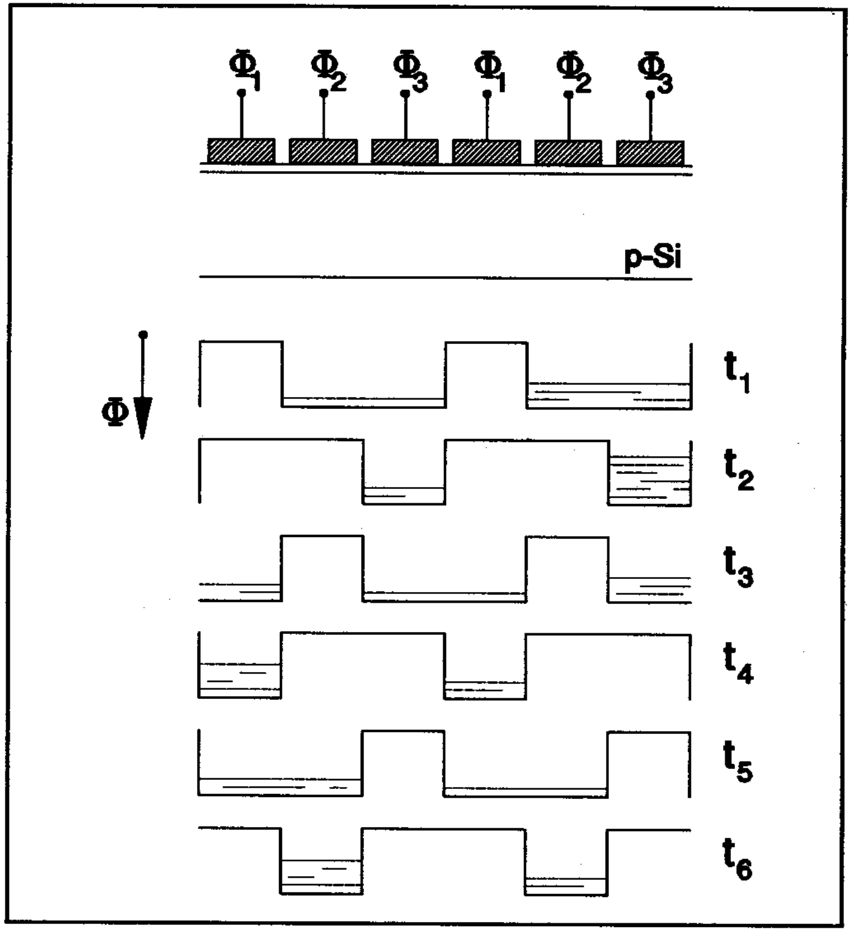
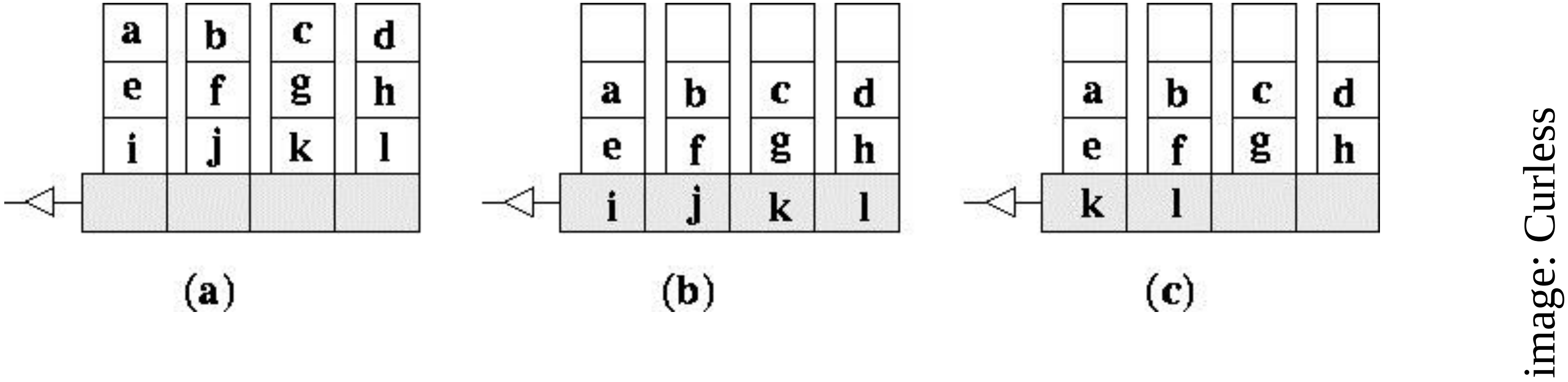


FIGURE 2.5. Cross section of a CCD transport section driven by a three-phase-clocking system.

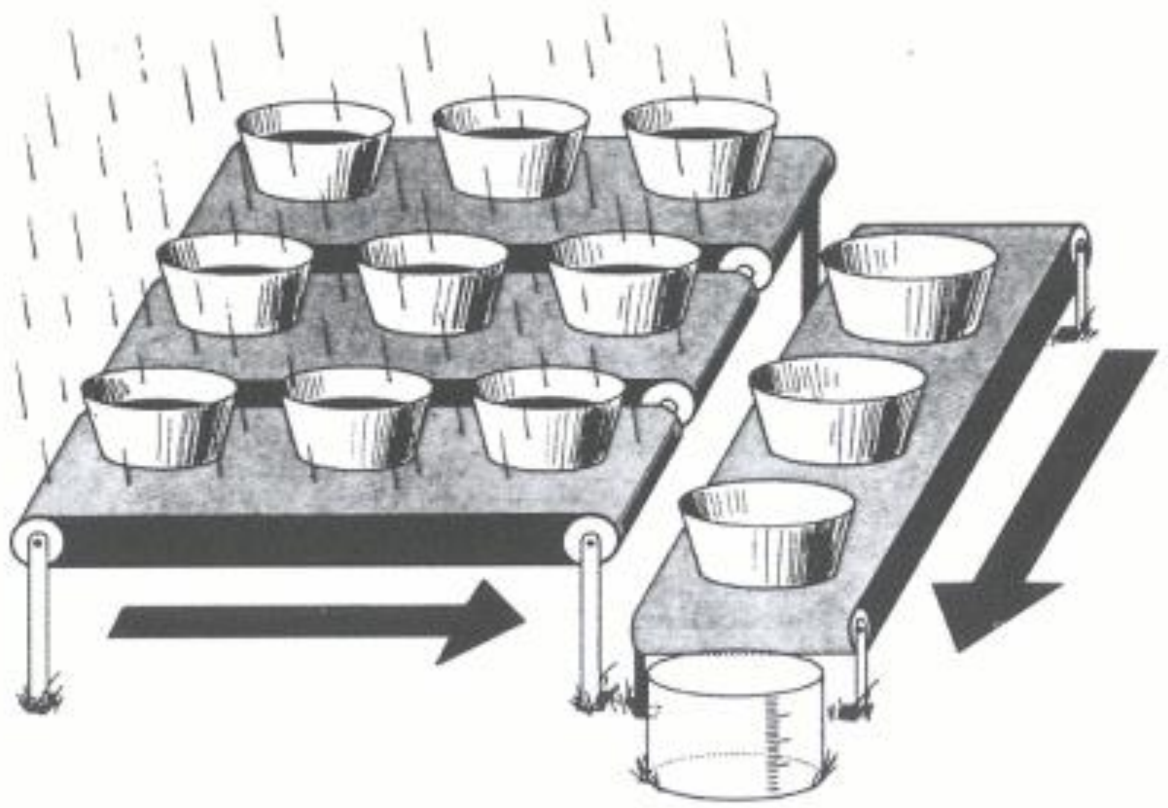
image: Theuwissen

Full Frame CCD

- Photogate detector doubles as transfer cap.
- Simplest, highest fill factor.
- Must transfer quickly (or use mechanical shutter) to avoid corruption by light while shifting charge.



CCD – Principle of Operation



Frame Transfer

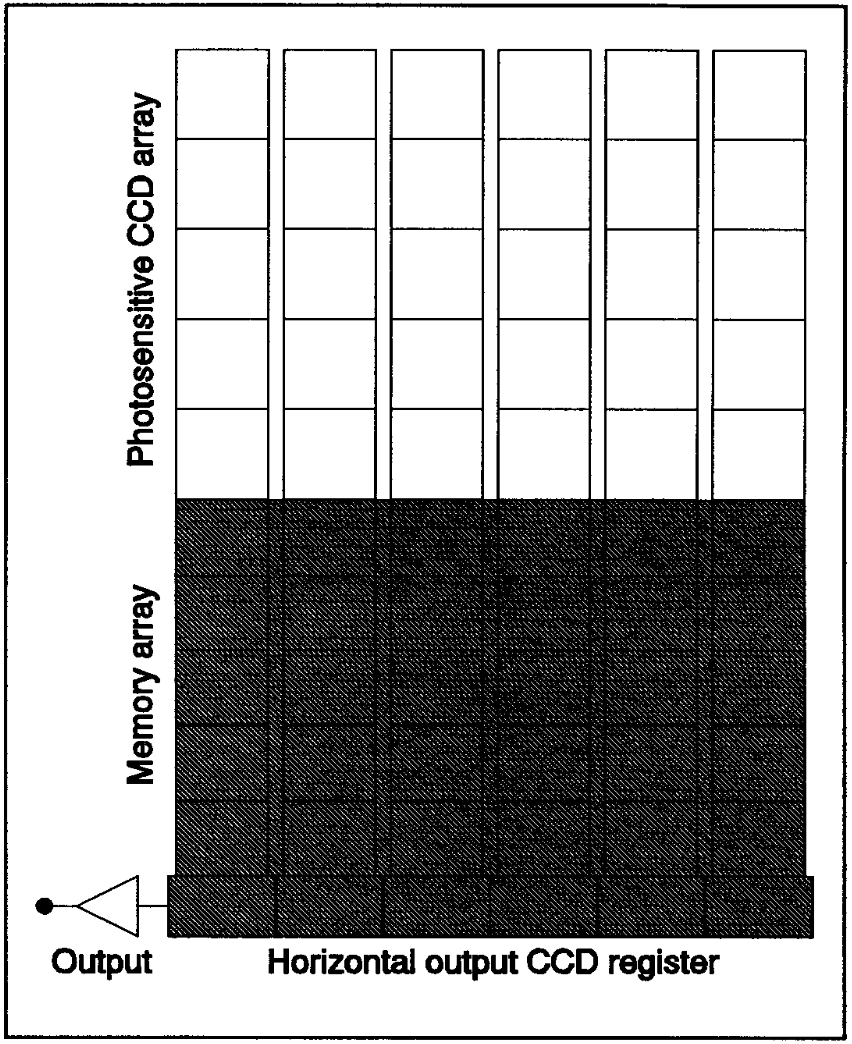


FIGURE 4.4. Device architecture of a frame-transfer image sensor.

memory area
is shielded

image: Theuwissen

Smearing

vertical streak

wikipedia

Interline CCD

- Charge simultaneously shifted to shielded gates.
- Provides electronic shutter—snapshot operation
- Uses photodiodes (better detectors)
- Most common architecture for CCDs

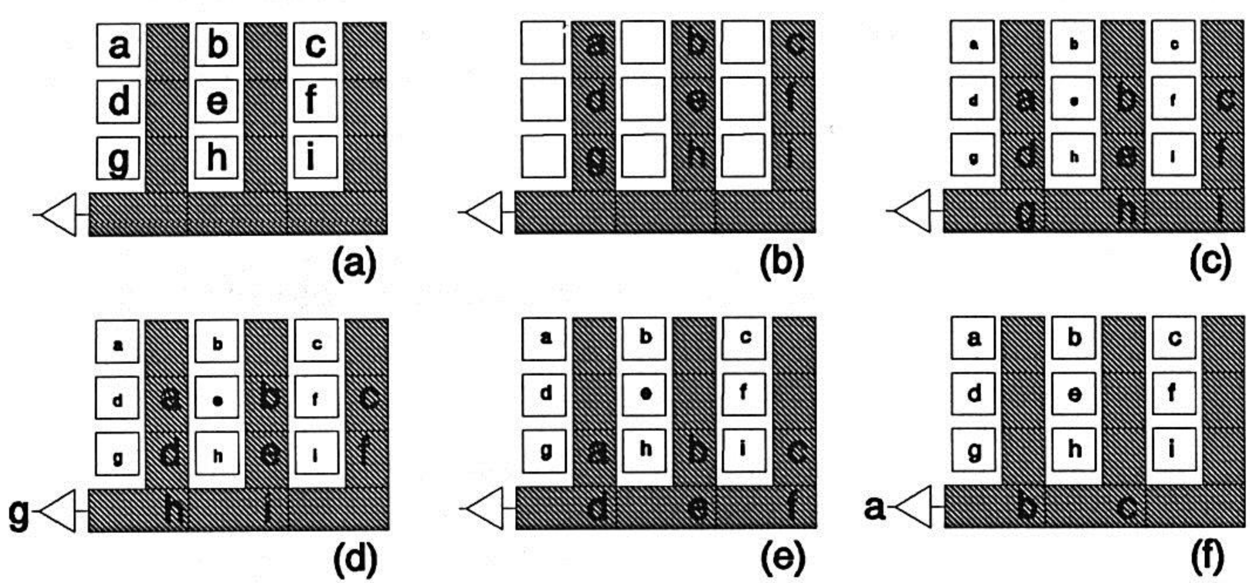


image: Theuwissen

Charge Transfer Efficiency

- CCD charge transfer efficiency, η, is the fraction of charge transferred from one capacitor to the next.
- η must be *very* close to 1, because charge is transferred up to n+m times (or more for 3-phase…)
- For a 1024 x 1024 CCD:

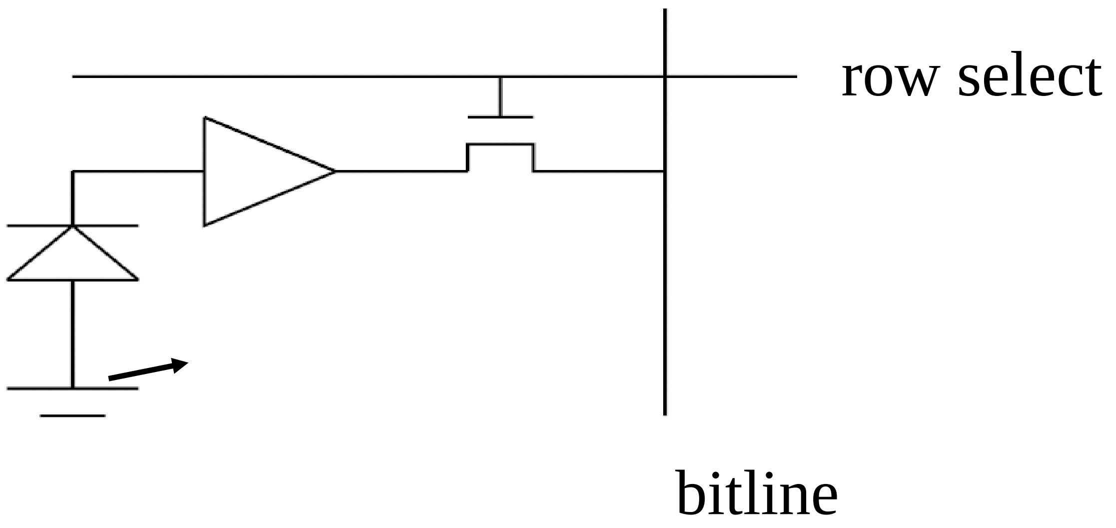
η	Fraction at output η^{2048}
0.999	0.1289
0.9999	0.8148
0.99999	0.9797

Advantages of CCD's

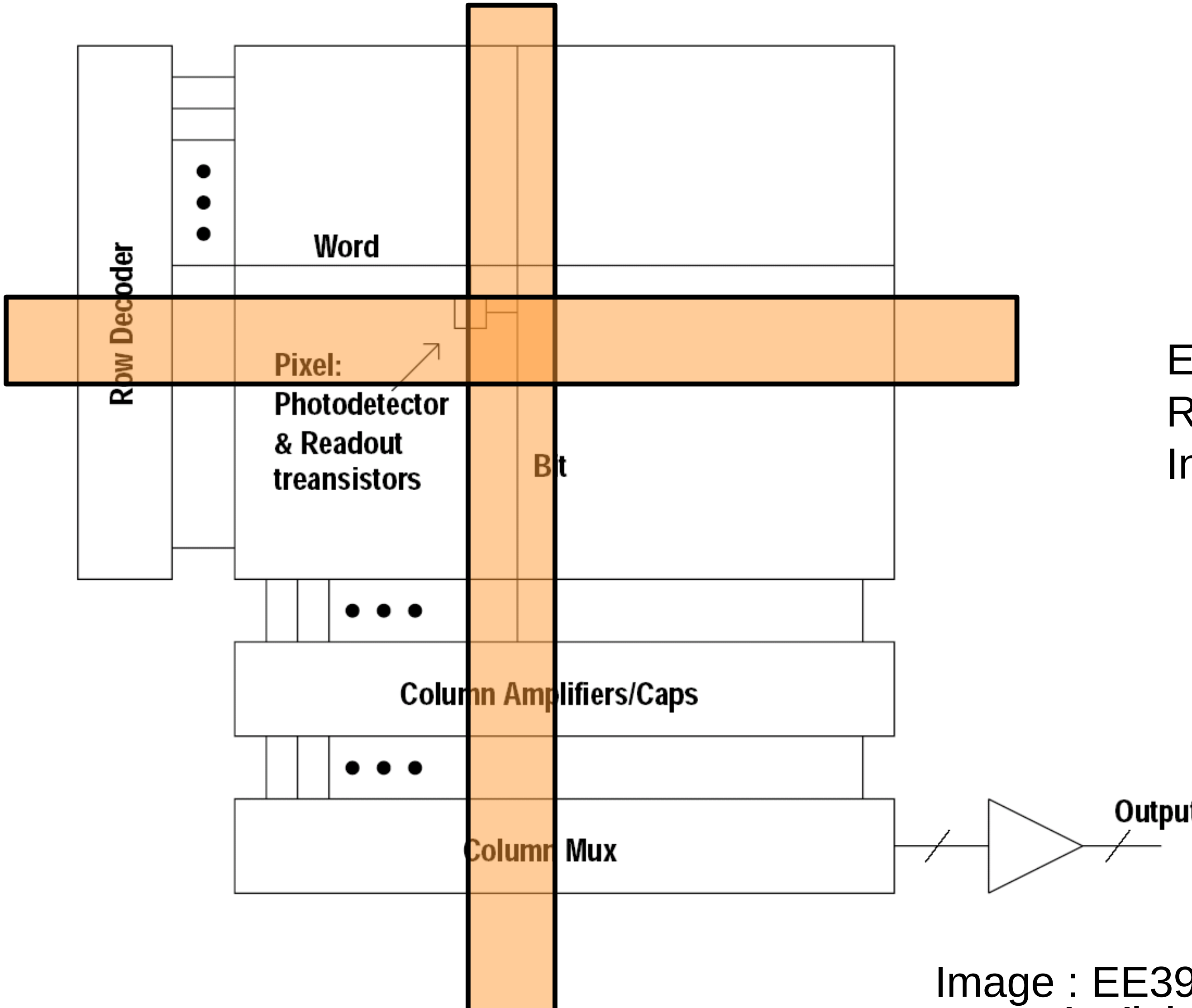
- Advantages:
  - Optimized photodetectors (high QE, low dark current)
  - Very low noise.
  - Single amplifier does not introduce random noise or fixed pattern noise.
- Disadvantages
  - No integrated digital logic
  - Not programmable (no region of interest)
  - High power (whole array switching all the time)
  - Limited frame rate due to charge transfer

CMOS Sensors (active pixel sensor)

- charge converted to a voltage at the pixel
- pixel amp, column amp, output amp.



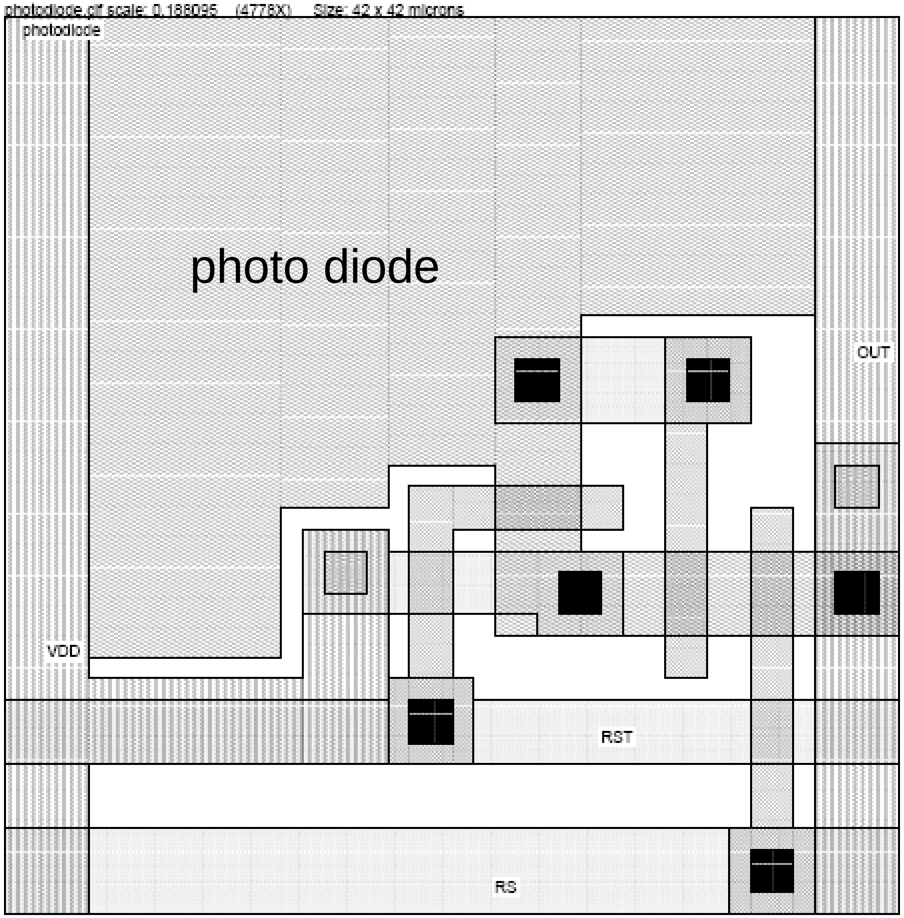
CMOS Sensors



Enables Region of Interest (ROI)

Image : EE392B, El Gamal

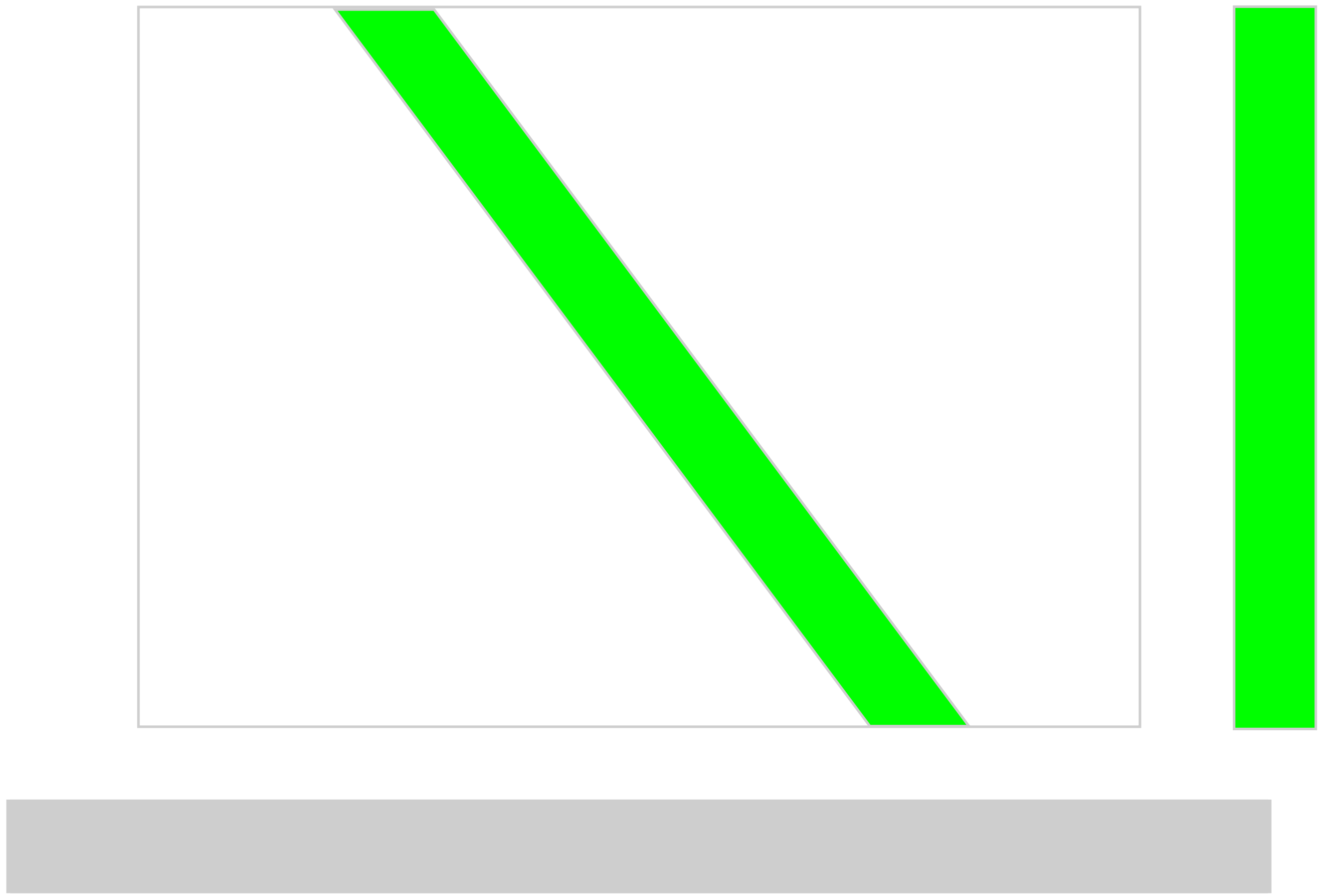
Example CMOS Pixel



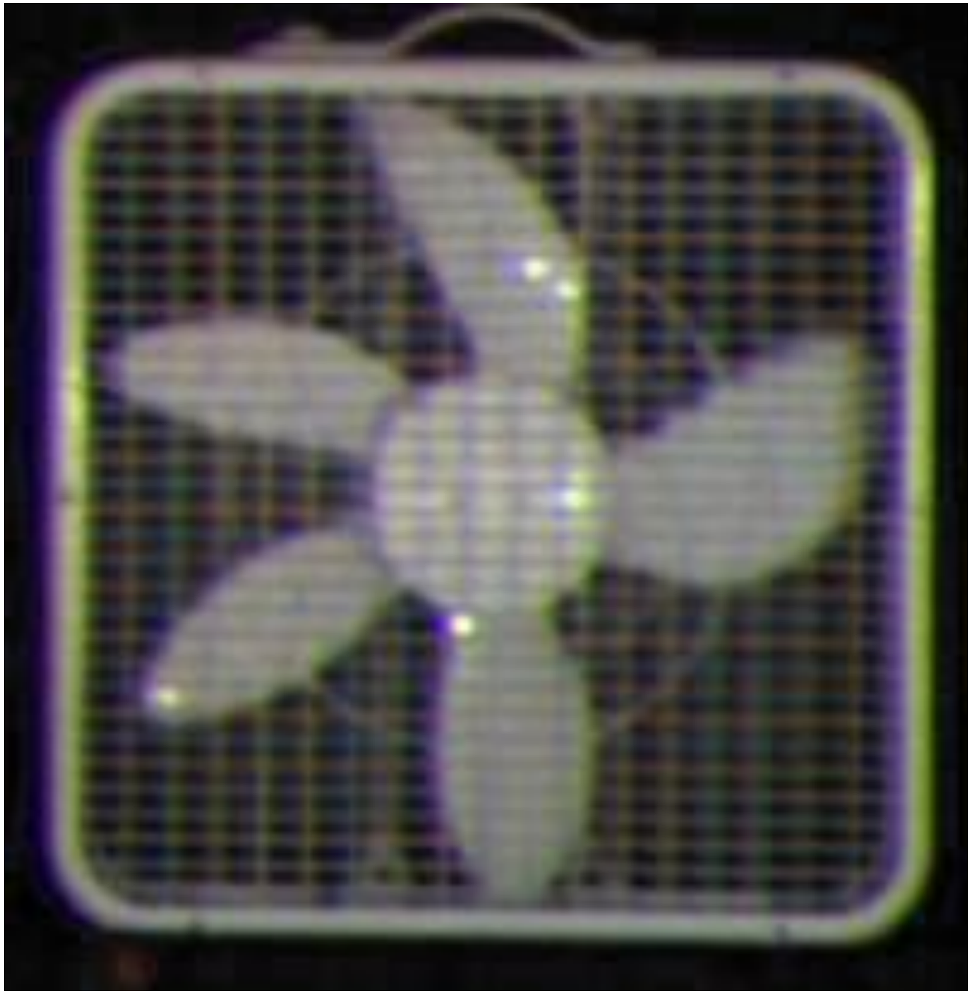
Source: Stanford EE392B notes

- Photo sensitive area is reduced by additional circuitry.

Rolling Shutter

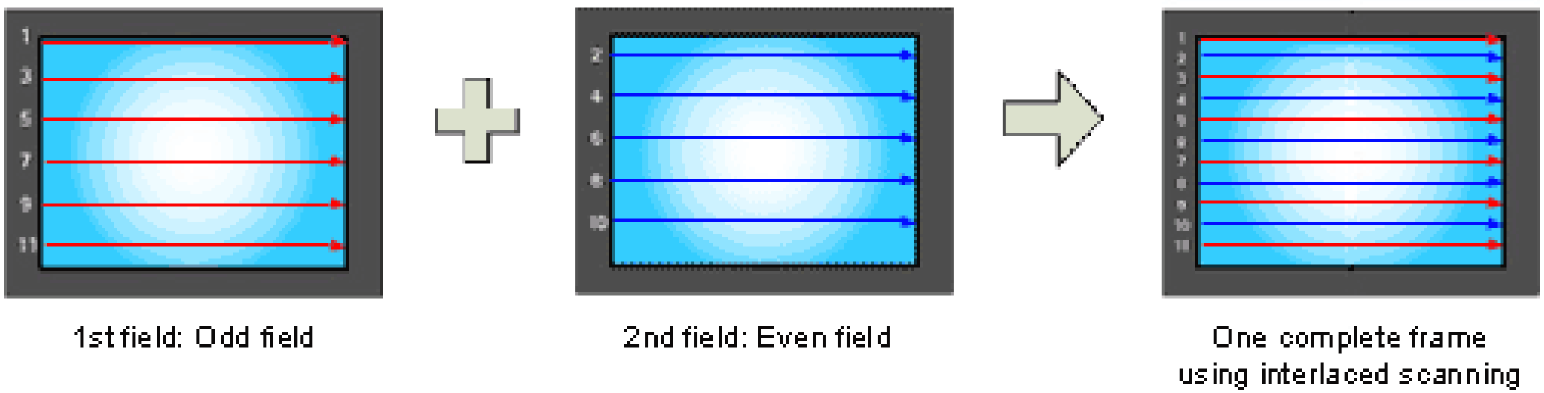


Rolling Shutter Distortion



Interlacing

- Compatibility with old TV norms

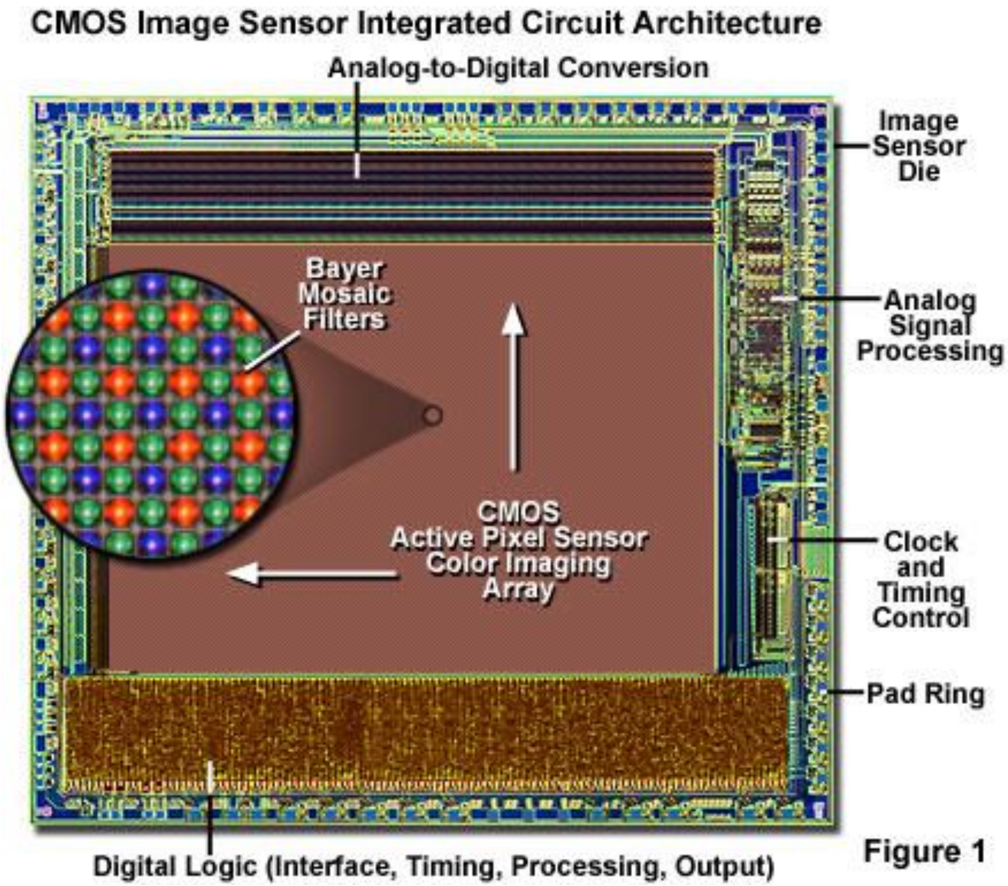


- Two half-frames (odd and even fields at twice the frame rate)
- Interlacing + rolling shutter

CMOS Sensors

- Advantages
  - Integrated digital logic
  - Fast
  - Mainstream process (cheap)
  - Lower power
- Disadvantages
  - Noise & quality
- Most high quality cameras still use CCDs.
  - this is changing though Canon 5D mark II has CMOS

CMOS with Integrated Logic



[micro.manget.fsu.edu]

CMOS vs CCD, bottom line

- CCD's transfers charge to a single output amplifier. Inherently low-noise.
- CMOS converts charge to voltage at the pixel.
  - Read out like a digital memory - windowing
  - Reset noise (can use correlated double sampling CDS)
  - Fixed pattern noise (device mismatch)