Imaging Sensors – Sensing Color

Computational Photography

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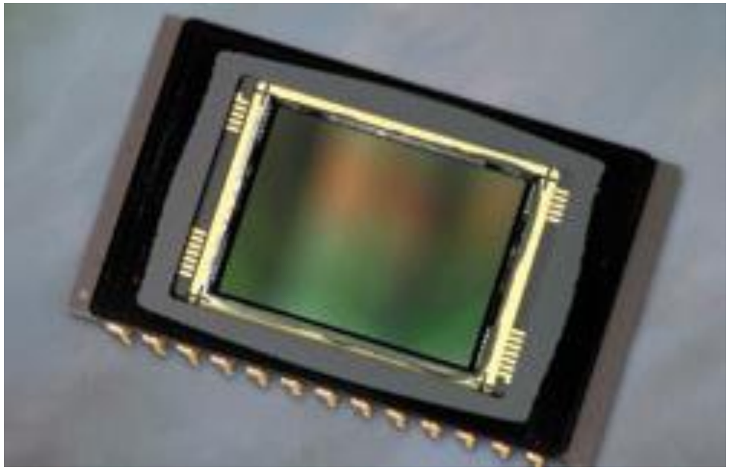
Overview

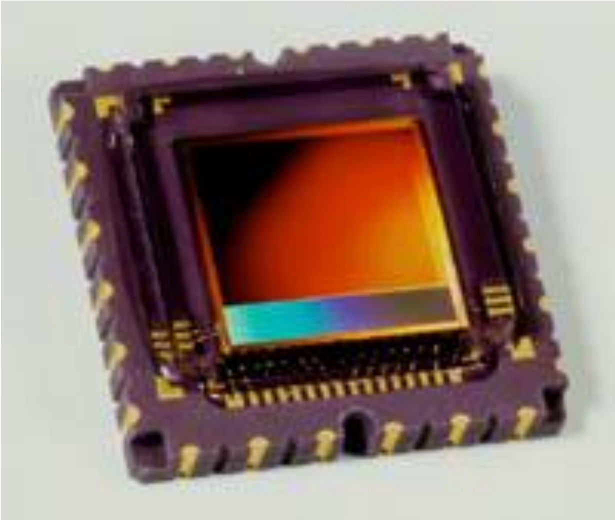
- Sensor
- Photoelectric effect
- Sensitivity
- Noise and how to get clean images
- Sensing Color
  - Methods
  - Demosaicing

- Other types of image sensors

Image Sensors



"CCD" (1969)
Nobel Prize 2009



"CMOS" (1968)

Microsoft Kinect v2 depth sensor (2013)

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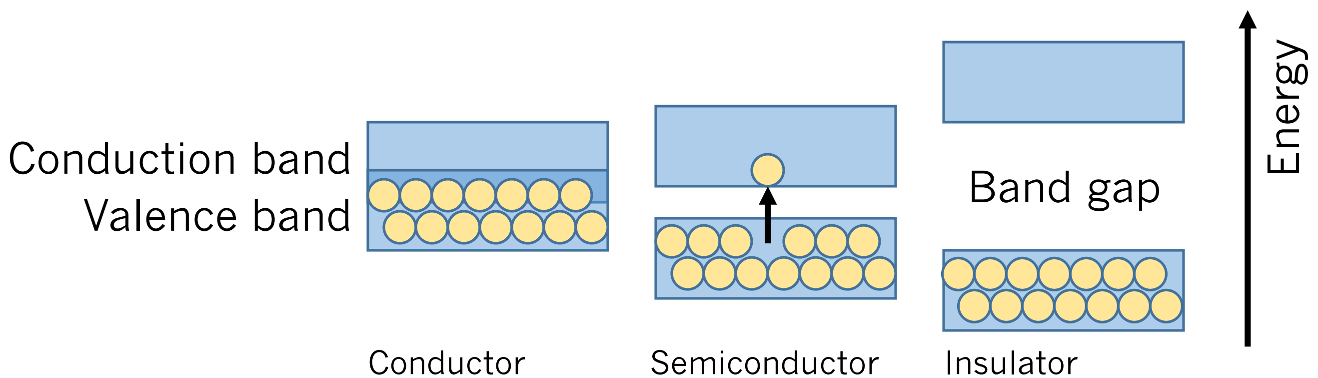
Image Sensors

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

Photogeneration

- Silicon
  - "Band gap" of 1.124eV between *valence band* and *conduction band*.
- Incident photon > 1.124eV (hc/ λ) may be absorbed, causing electron 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



Semiconductors

- Crystal lattice structure
- Energy gap between valence and conduction band is small

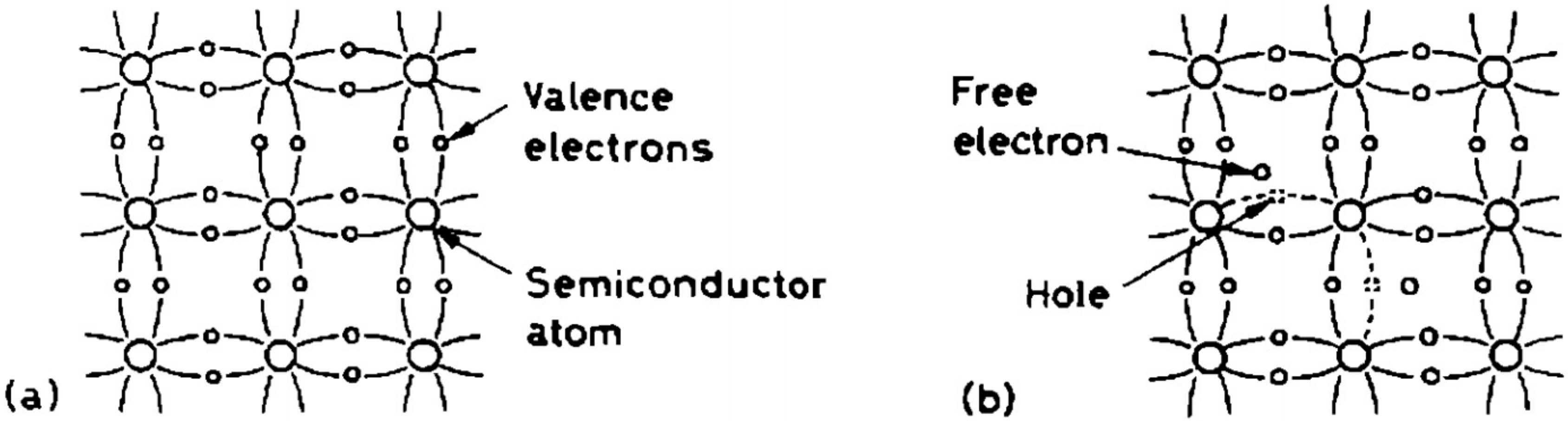
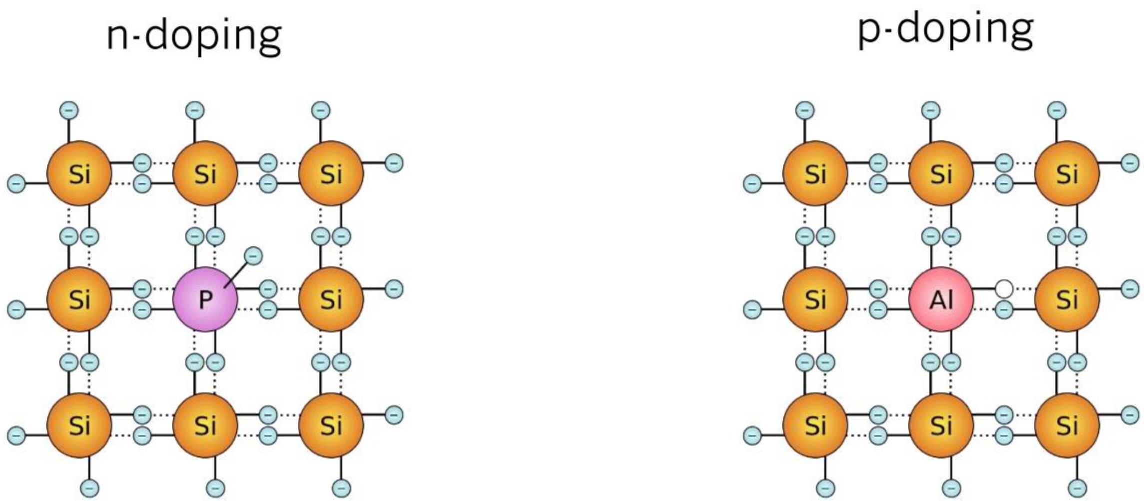


Fig. 10.2. Covalent bonding of silicon: **(a)** at 0 K, all electrons participate in bonding, **(b)** at higher temperatures some bonds are broken by thermal energy leaving a *hole* in the valence band

Doping

- Add dopant atoms into the semiconductor crystal
- => add charge carriers (electrons and “holes”)



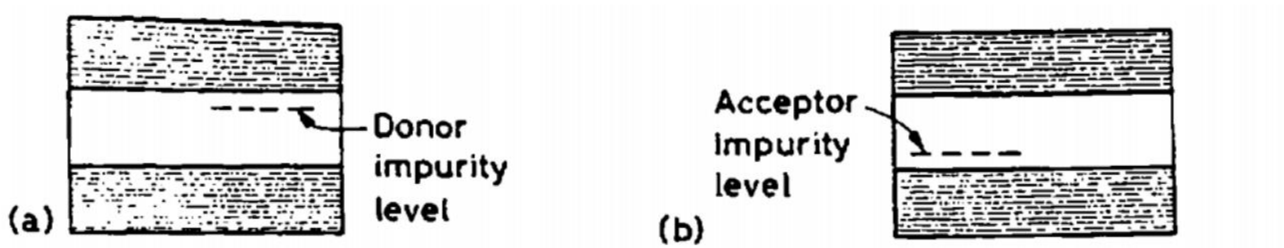
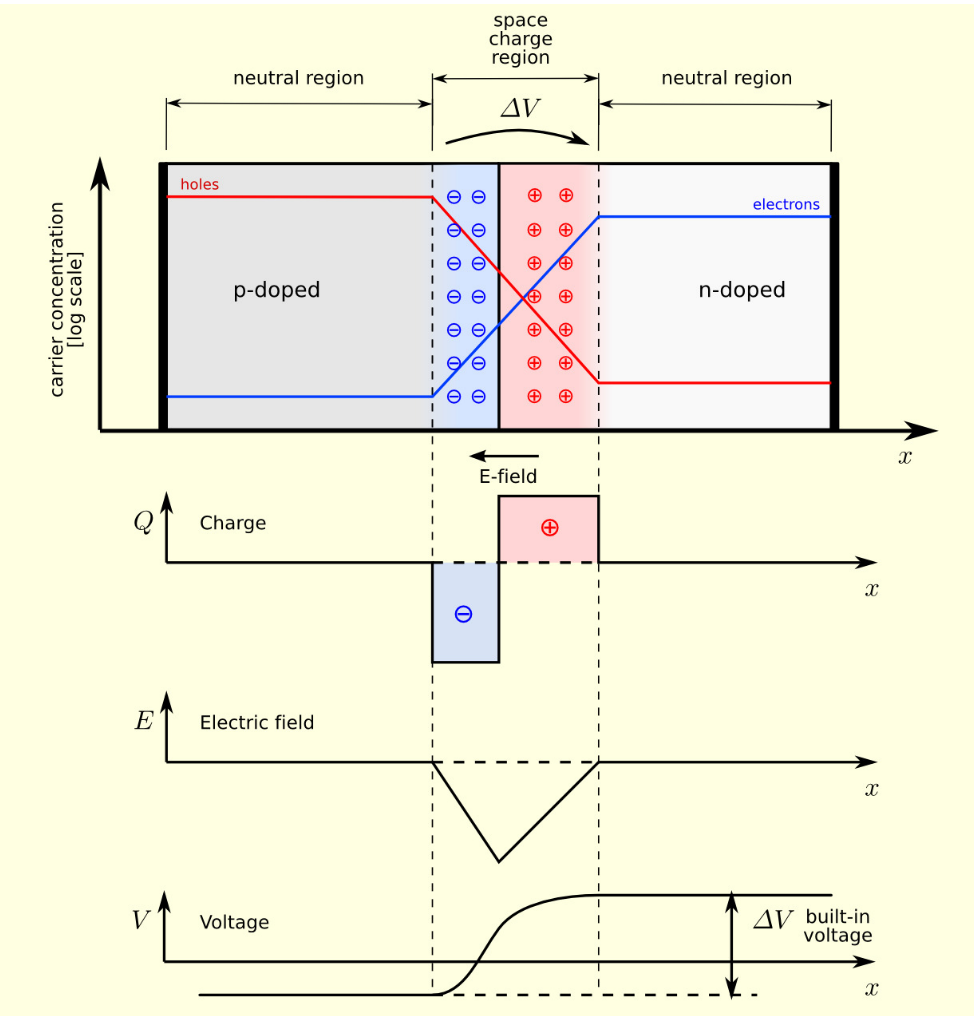


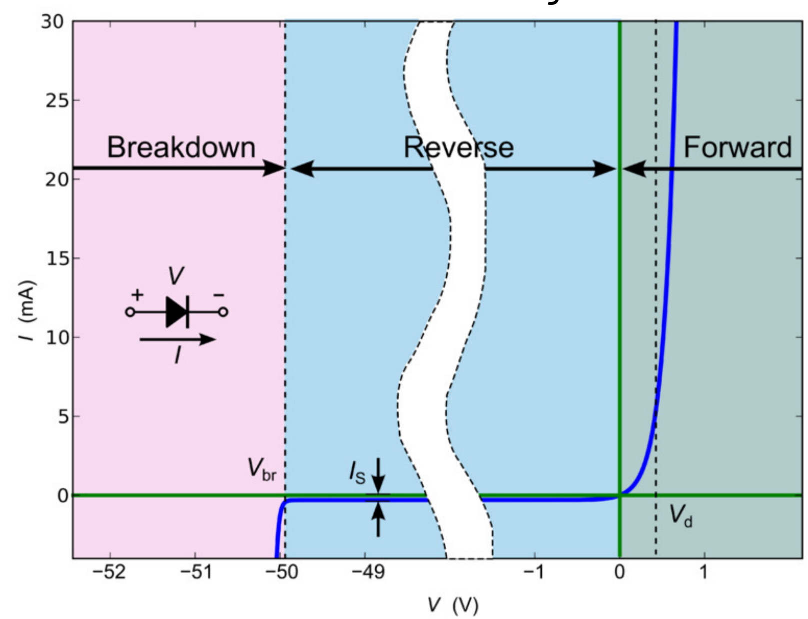
Fig. 10.4. (a) Addition of donor impurities to form n-type semiconductor materials. The impurities add *excess* electrons to the crystal and create donor impurity levels in the energy gap. (b) Addition of acceptor impurities to create p-type material. Acceptor impurities create an *excess* of holes and impurity levels close to the valence band

Semiconductor diodes

- pn-junction: p- and n-doped silicon combined



Voltage-current diagram.
"Forward bias":
positive potential on p, negative on n.
"Reverse bias": other way around



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Pixel detectors

- Photodiode
- All electrons created in *depletion region* are collected, plus some from surrounding region.

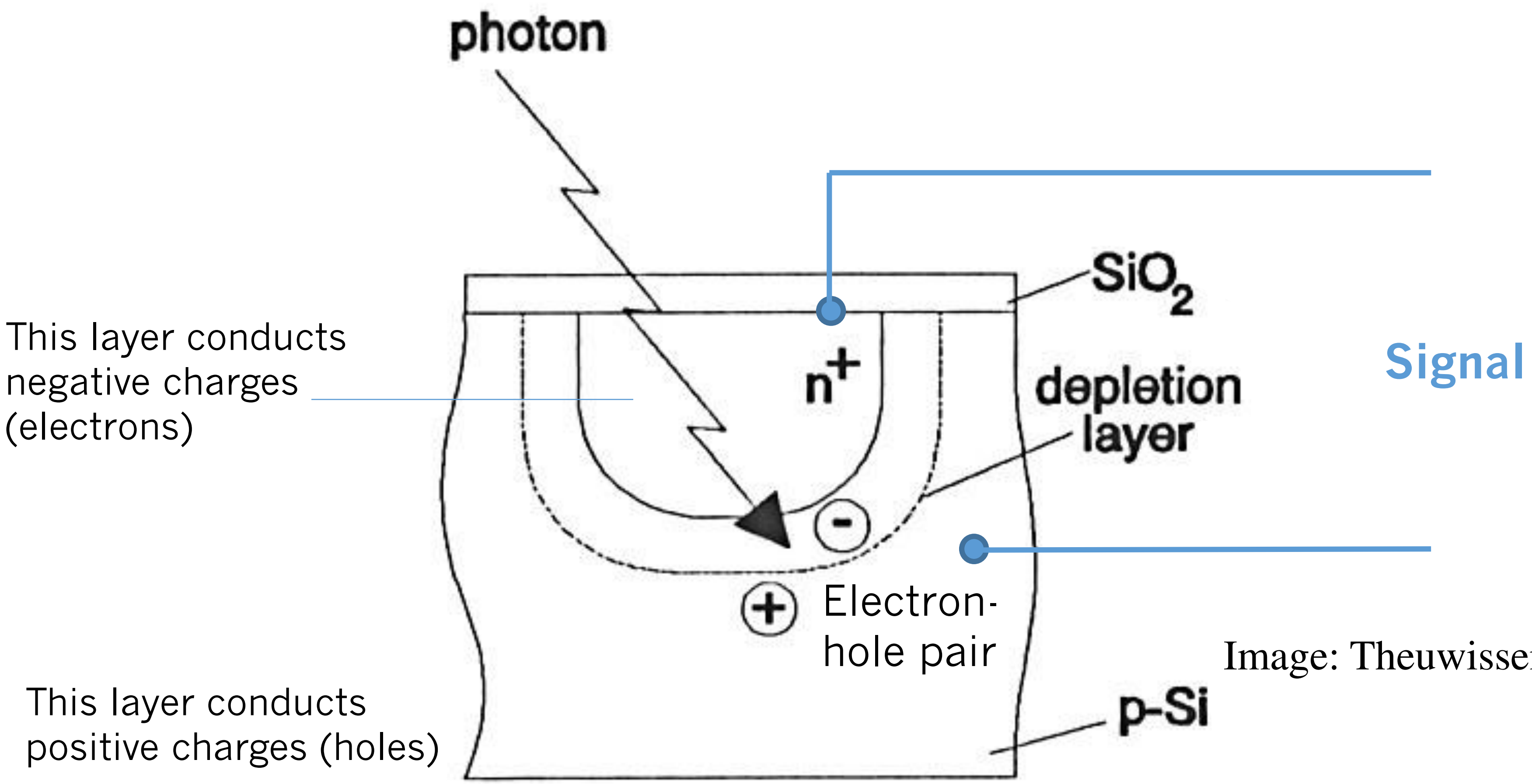
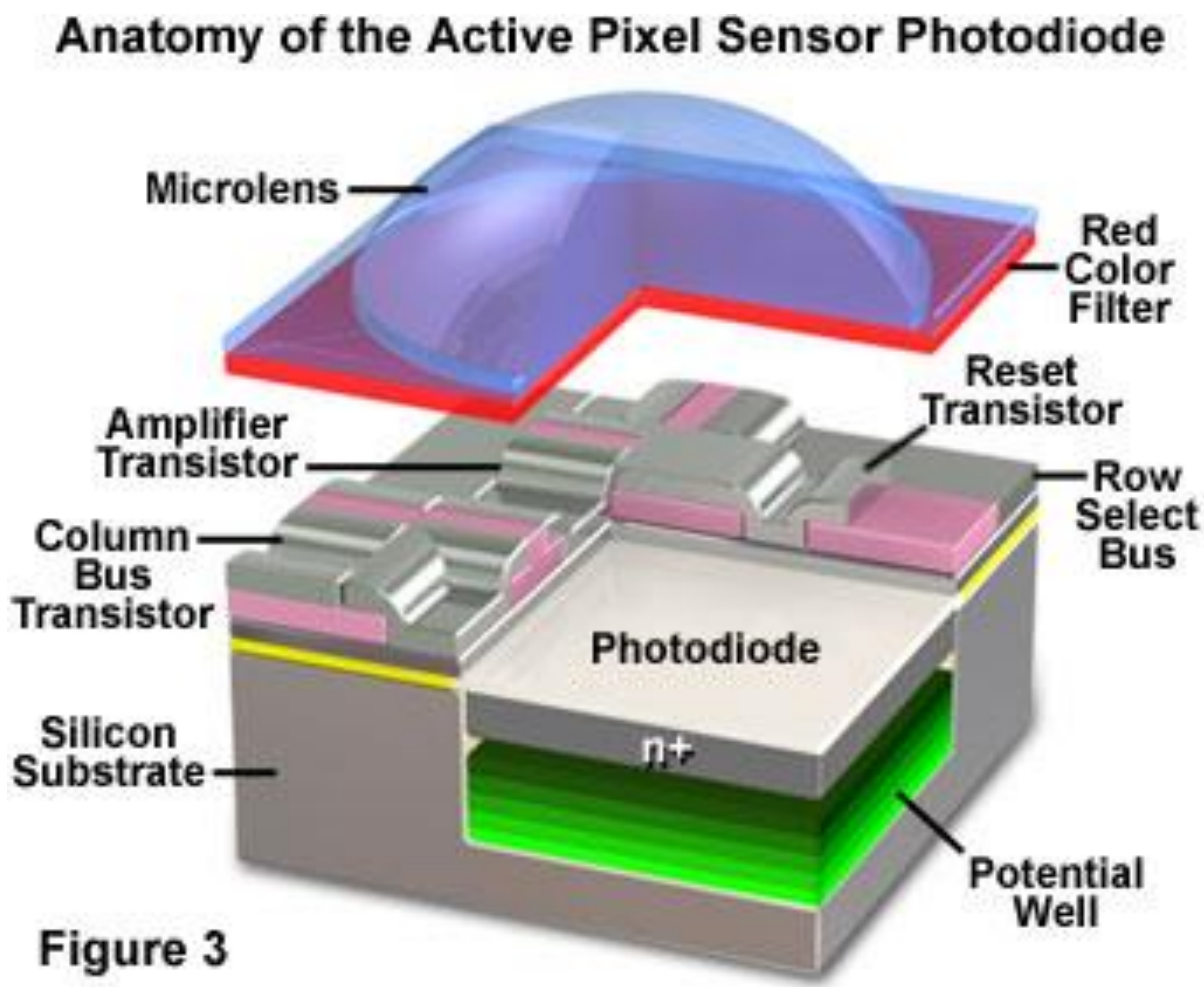


Image: Theuwissen

Integration

- Measuring a single electron is really hard!
  (very little charge: $e = 6 \cdot 10^{-19}\mathrm{C}$)
- However, electrons can be stored for a while (up to several seconds or even minutes)
- So integrate the charge over a period of time.
    - 10's to 1000's of electrons.

Photodiode in CMOS sensor



Photodetector Performance Metrics

- Pixel size
- Fill factor
- Full well depth
- Spectral quantum efficiency
- Sensitivity
- Noise
- Dynamic range

Pixel Size

- Large pixels means more light collected.
- Typically 1 µm – 10 µm
- 20 µm for astronomy, 45 µm for special pixel types
- Tinier pixels ≠ higher resolution – optics will get you eventually.

Raspberry Pi Camera
OmniVision OV5647
2592 x 1944 pixels
on 3.76 x 2.74 mm area
-> **1.4 µm x 1.4 µm**

Fill Factor

- Percent of pixel area that captures photons.
- Typically 25% to 100%
- Smaller for photogate than photodiode.
- 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

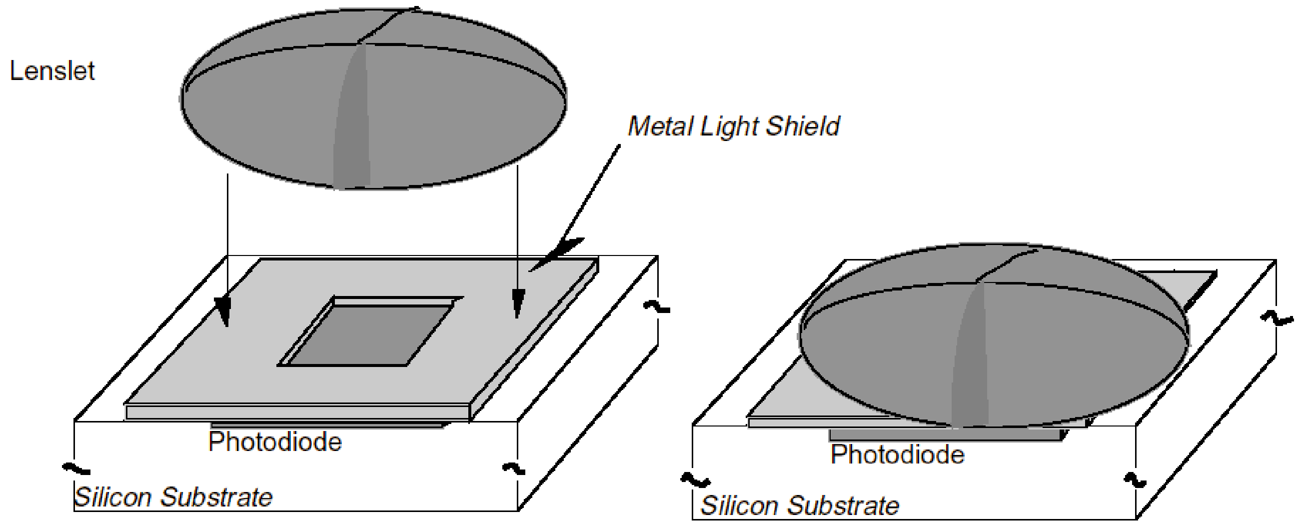


image: Kodak application note DS00-001

Absorption Coefficients

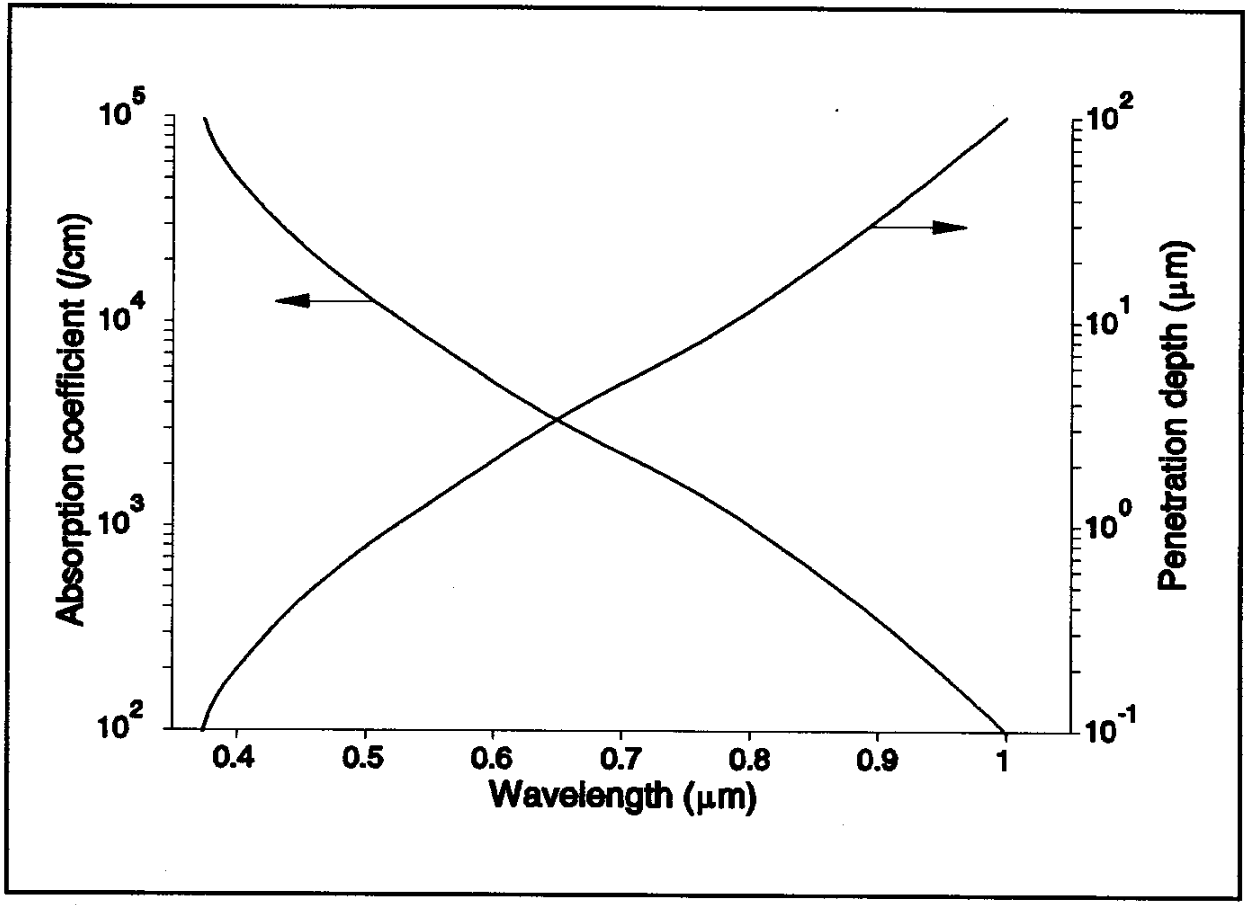


FIGURE 5.2. The absorption coefficient of silicon together with its corresponding penetration depth as a function of the wavelength of the incident light.

image: Theuwissen

Penetration Depth

Wellenlänge (Nanometer)	Durchdringungstiefe (Mikronen)
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

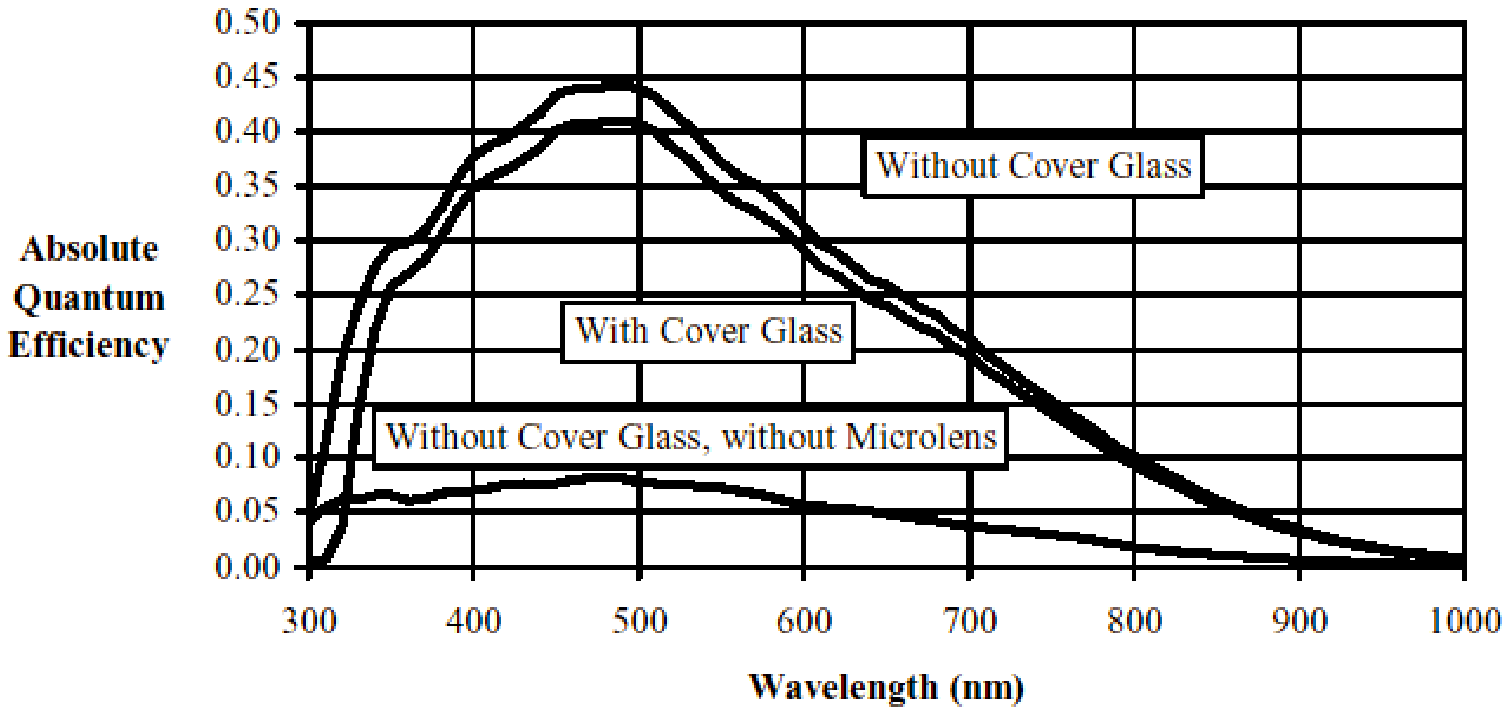


Figure 10 - Wavelength Dependence of Quantum Efficiency

source: Kodak KAI-2000m data sheet

Filtered Spectral Quantum Efficiency

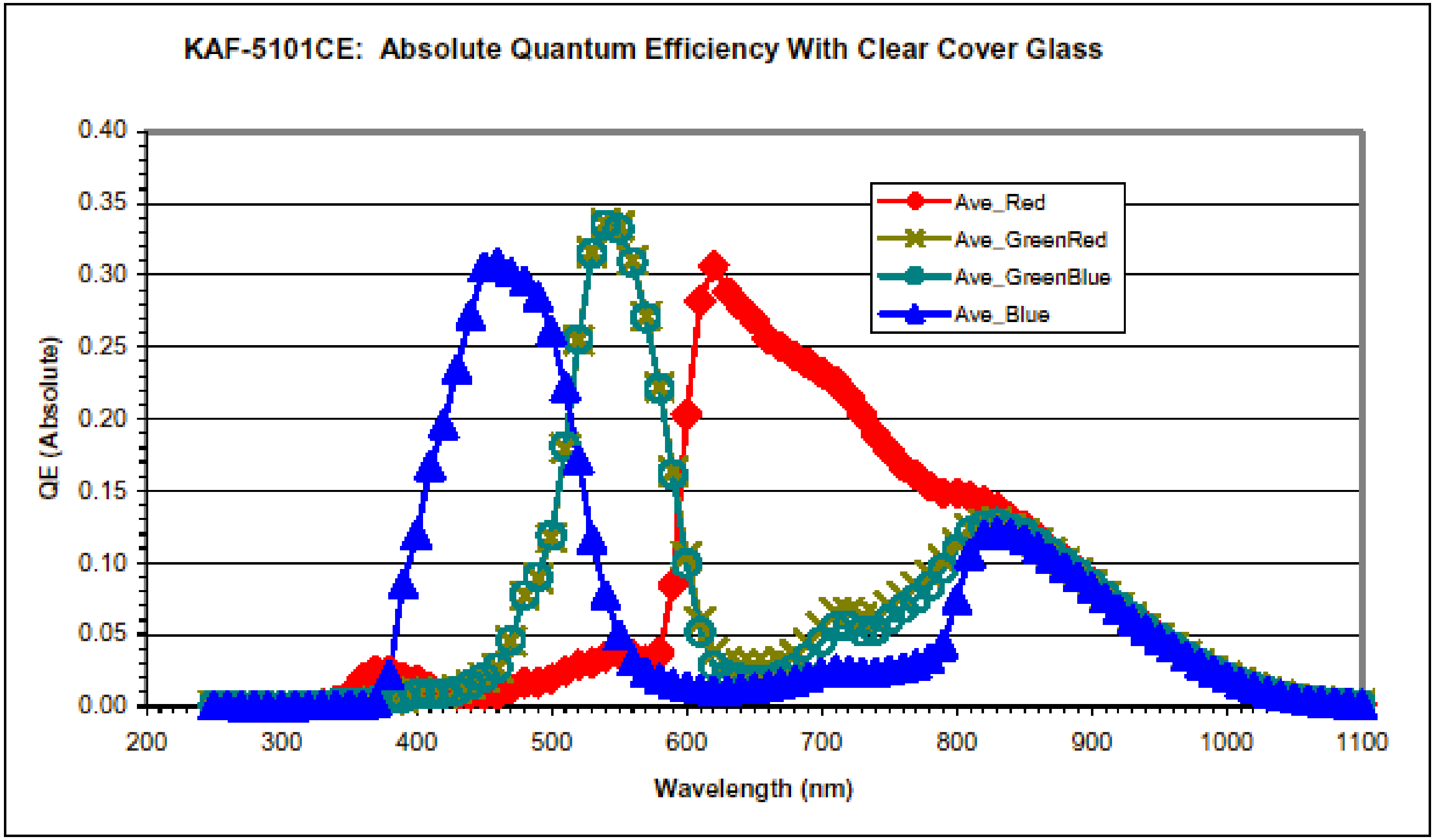


Figure 7. Typical Quantum Efficiency Curves (Clear Coverglass)

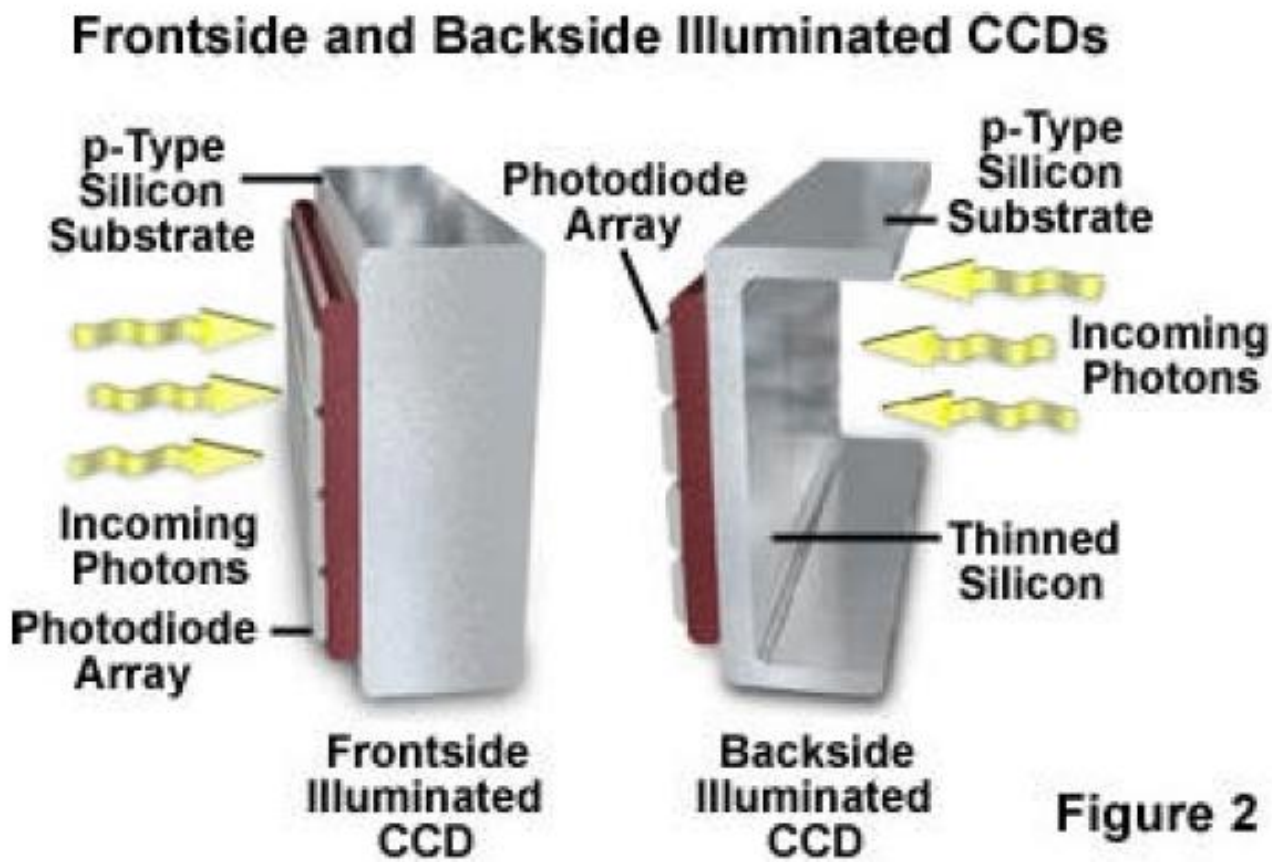
source: Kodak KAF-5101ce data sheet

Factors for Quantum Efficiency

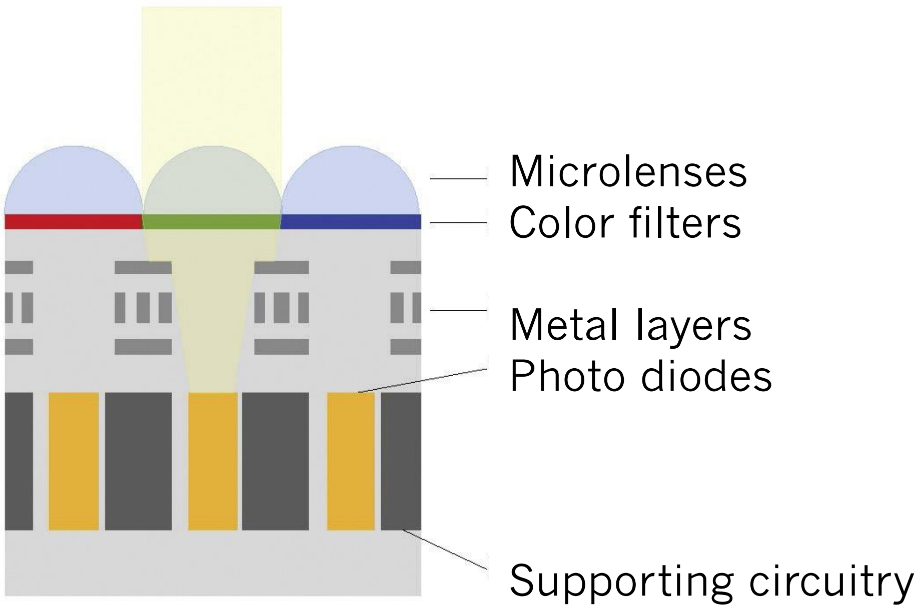
- Color filters
- Absorption coefficients and depletion depth
- Blue light is absorbed quickly, red wavelengths penetrate more deeply.
- Fill factor

Back Illuminated sensors

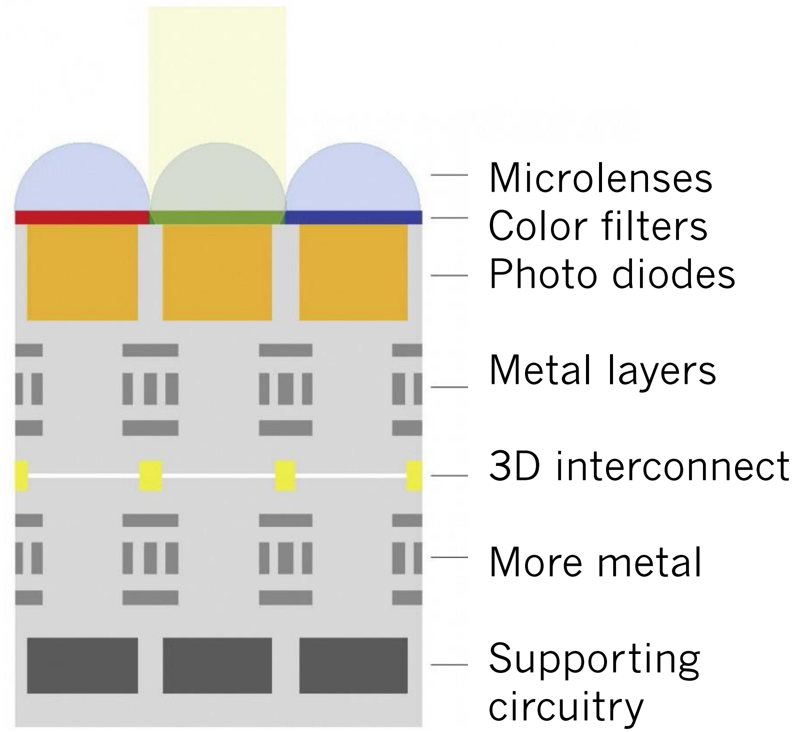
- Avoid shadowing by metal layers



Backside-illuminated CMOS sensors



CMOS FSI



CMOS BSI stacked

Source: https://www.fotomagazin.de/technik/sensortechnik-erklaert-bsi-und-stacked-cmos

Sensitivity

- Sensitivity = quantum efficiency · conversion gain
- Conversion gain: "volts per electron".
  - (arbitrarily complex topic)
  - 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^{2}sec)
  - Clear sky ~= 10E4 Lux
  - Room light ~= 10 Lux
  - Full moon ~= 0.1 Lux

Full Well Depth

- "Saturation charge" 45 to 100K e^-
  - depends on the pixel size
- Limits dynamic range (more about this later)
- Once well is filled up, charge can overflow into your neighbors. This is called **blooming**.

Blooming

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

Extra Overflow Drain

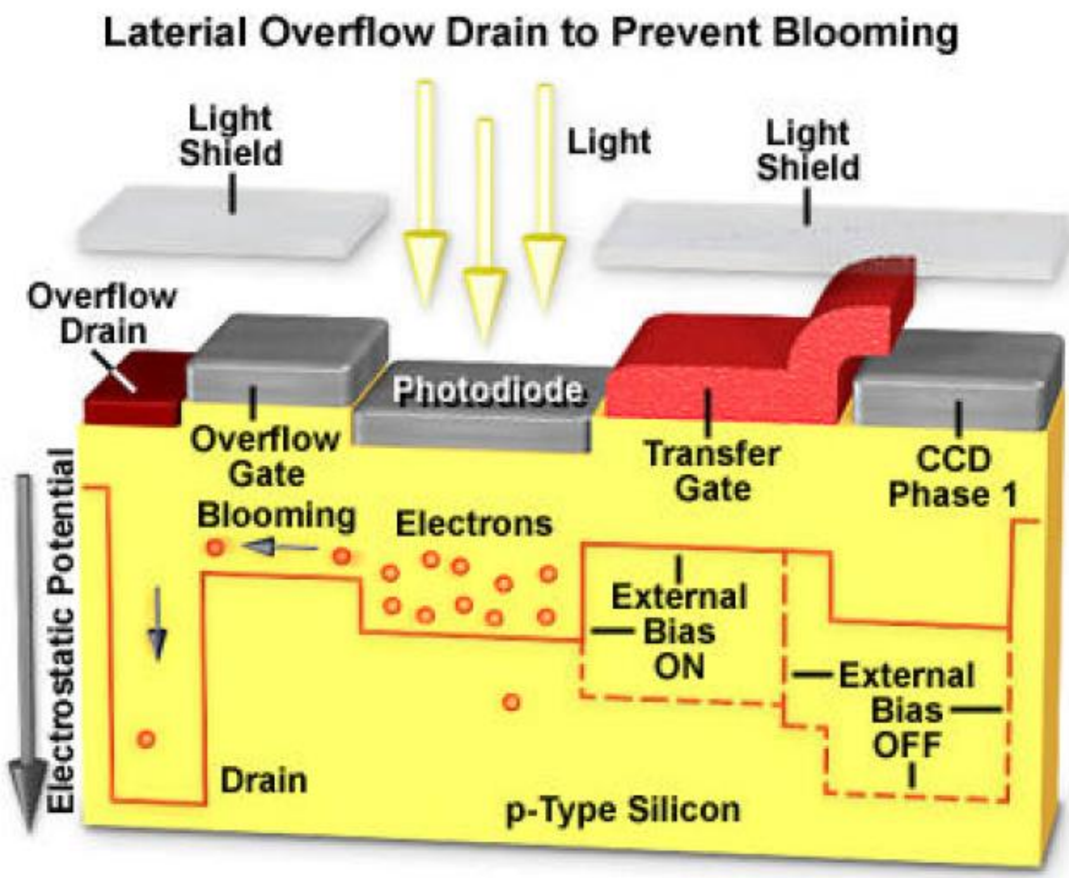


Figure 1

CCD & CMOS

CCD's vs CMOS Image Sensors

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

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)

Charge Transfer for CCD's

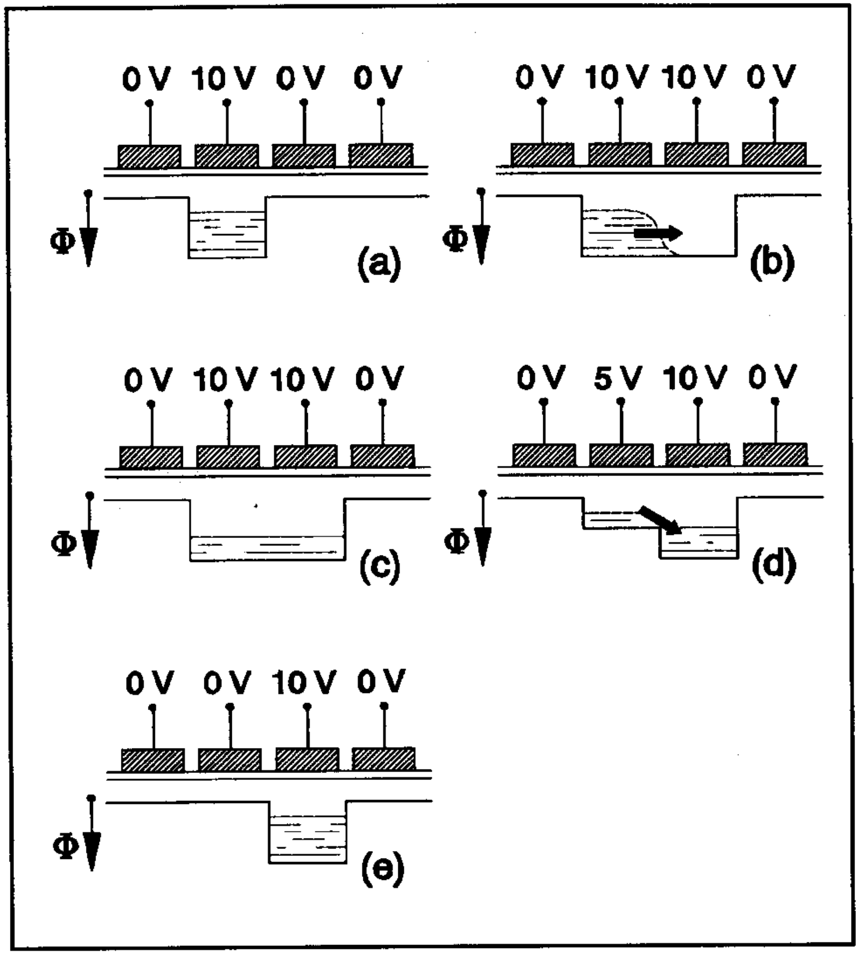


FIGURE 1.8. Illustration of the charge transport in a CCD. The charge packet of minority carriers is moved through the silicon by means of digital pulses on the CCD gates.

image: Theuwissen

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Example: Three Phase CCD's

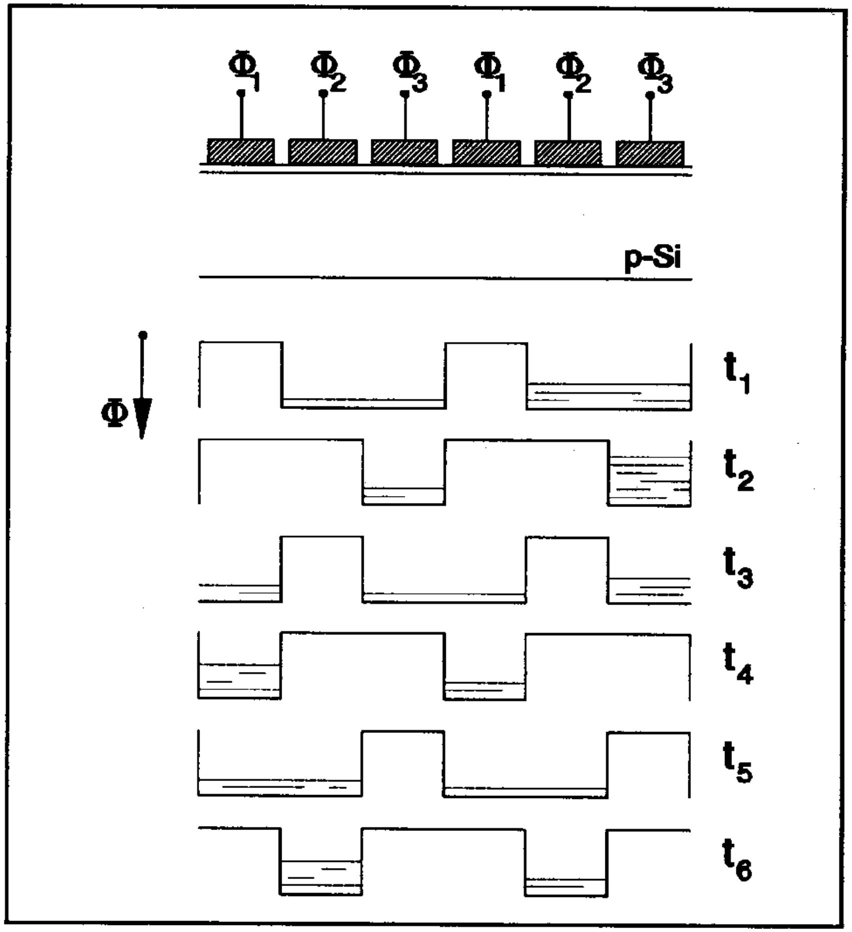
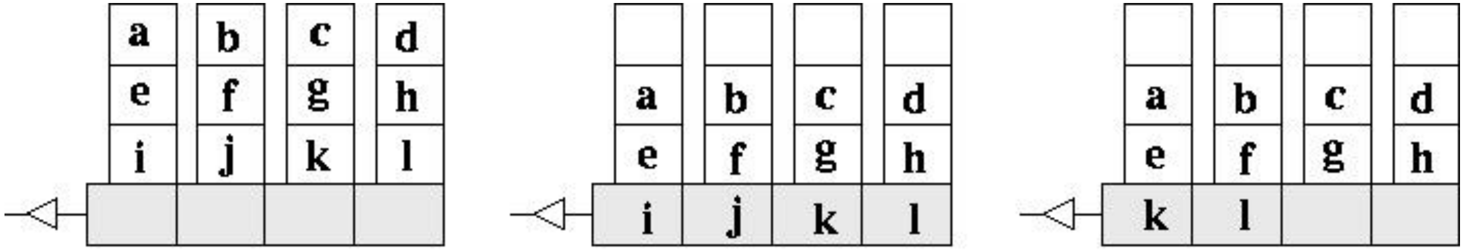


FIGURE 2.5. Cross section of a CCD transport section driven by a three-phase-clocking system.

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.



(a) (b) (c)

image: Curless

Smearing

vertical streak

wikipedia

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Frame Transfer

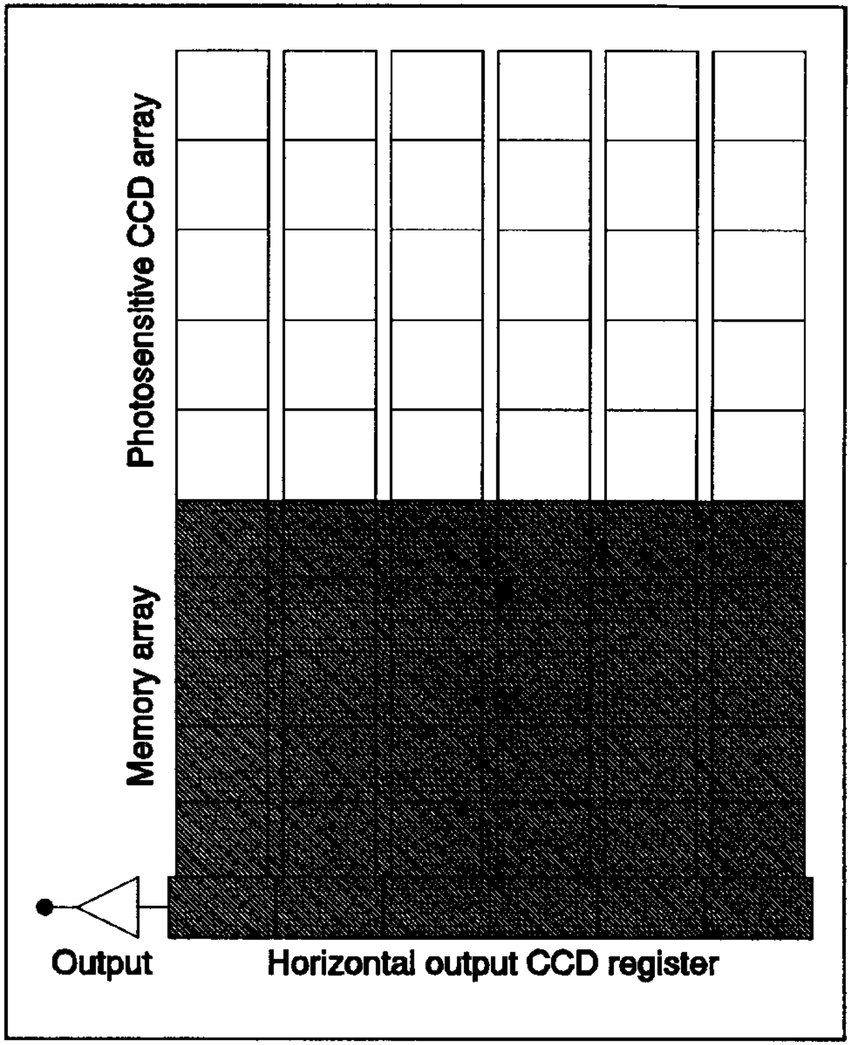


FIGURE 4.4. Device architecture of a frame-transfer image sensor.

memory area
is shielded

image: Theuwissen

Interline CCD

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

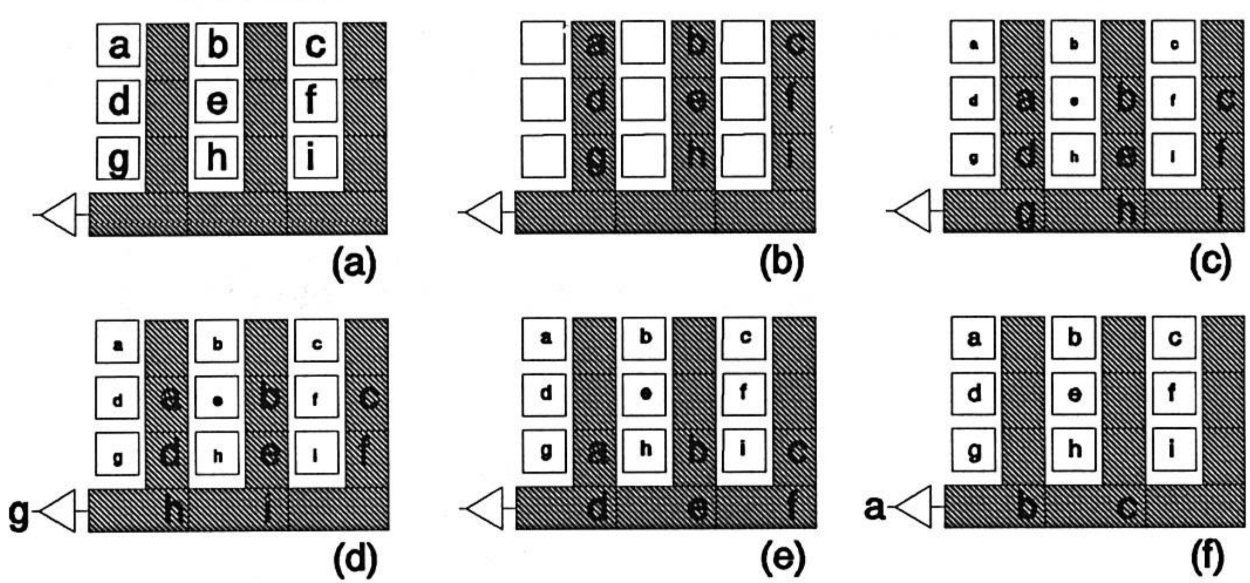


image: Theuwissen

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:

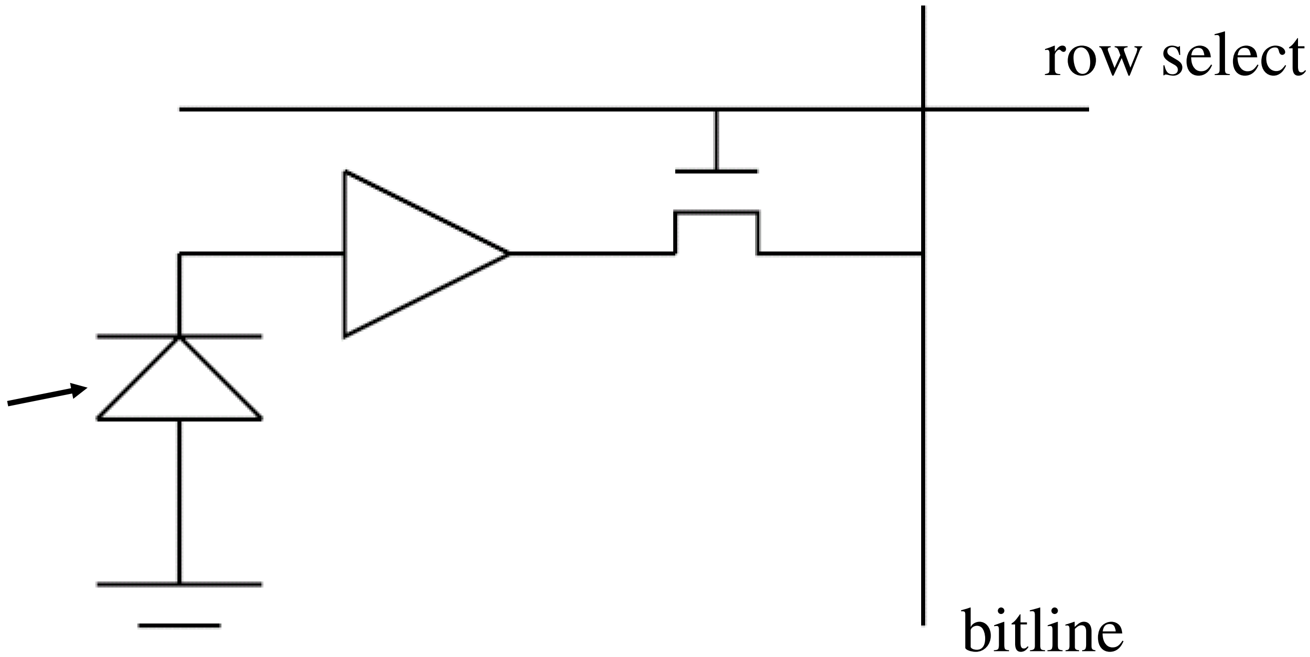
η	Fraction at output
0.999	0.1289
0.9999	0.8148
0.99999	0.9797

Advantages of CCDs

- 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 window of interest)
  - High power (whole array switching all the time)
  - Limited frame rate due to charge transfer

CMOS Sensors (active pixel sensor - APS)

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



CMOS Sensors

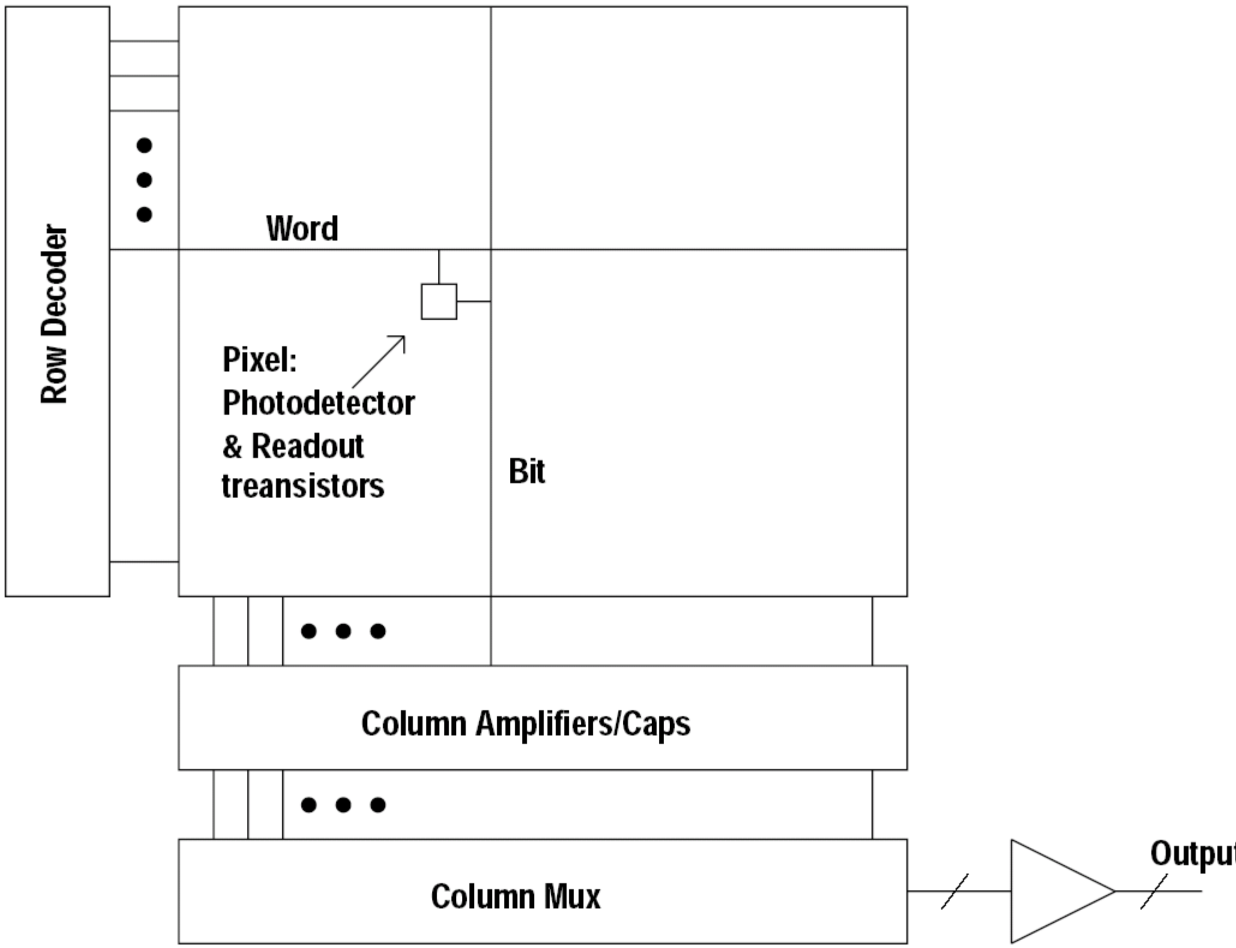
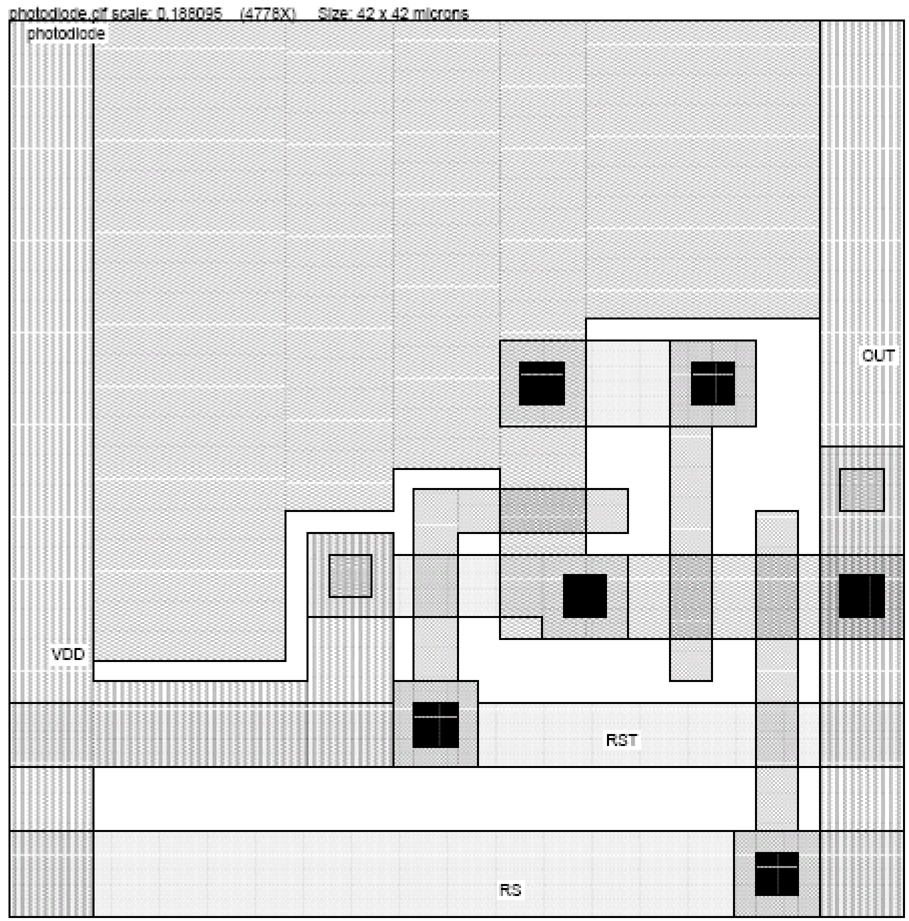


Image : Stanford EE392B, El Gamal

Example CMOS Pixel

•Photo sensitive area is reduced by additional circuitry.



Source: Stanford EE392B notes

Rolling Shutter

- Exposure + readout implemented in time-sequential manner
- Leads to image distortion

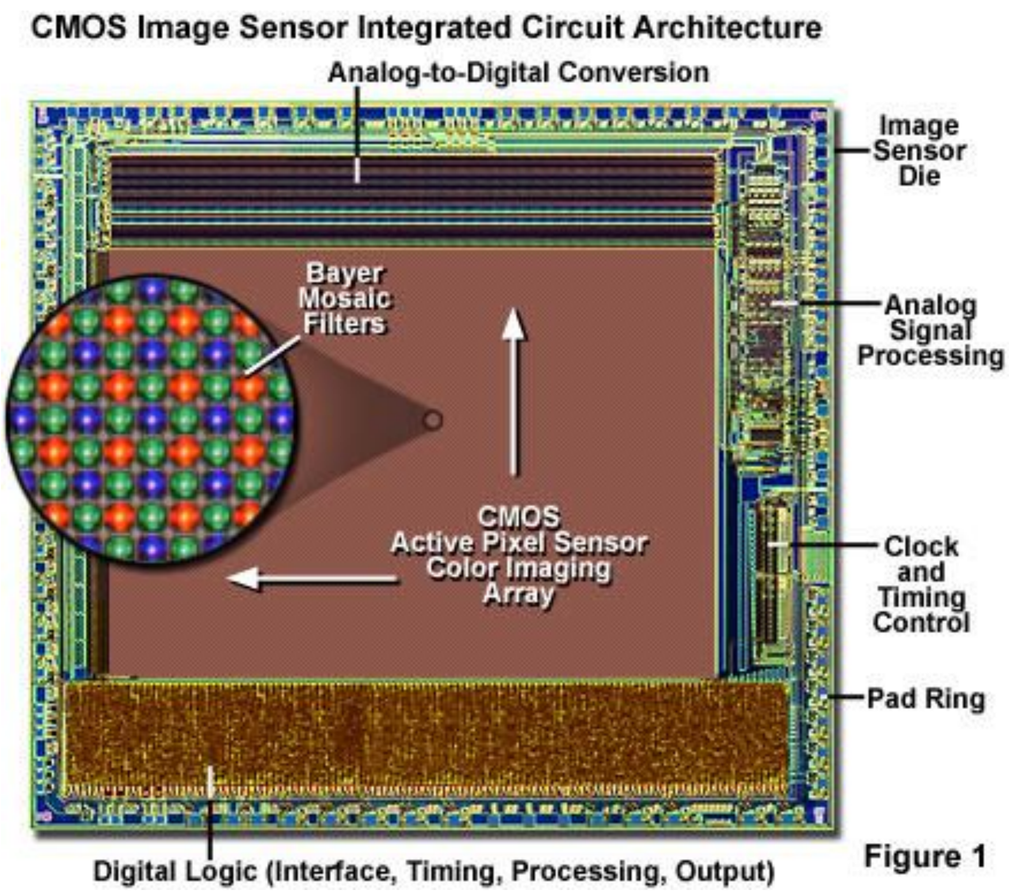
- Animation: https://upload.wikimedia.org/wikipedia/commons/4/49/Rolling_shutter_SMIL.svg

Rolling Shutter Distortion

CMOS Sensors

- Advantages
  - Integrated digital logic
  - Fast
  - Mainstream process (cheap)
  - Lower power
  - Region-of-interest operation
- Disadvantages
  - Noise & quality
- Some high quality cameras still use CCD’s.

CMOS with Integrated Logic



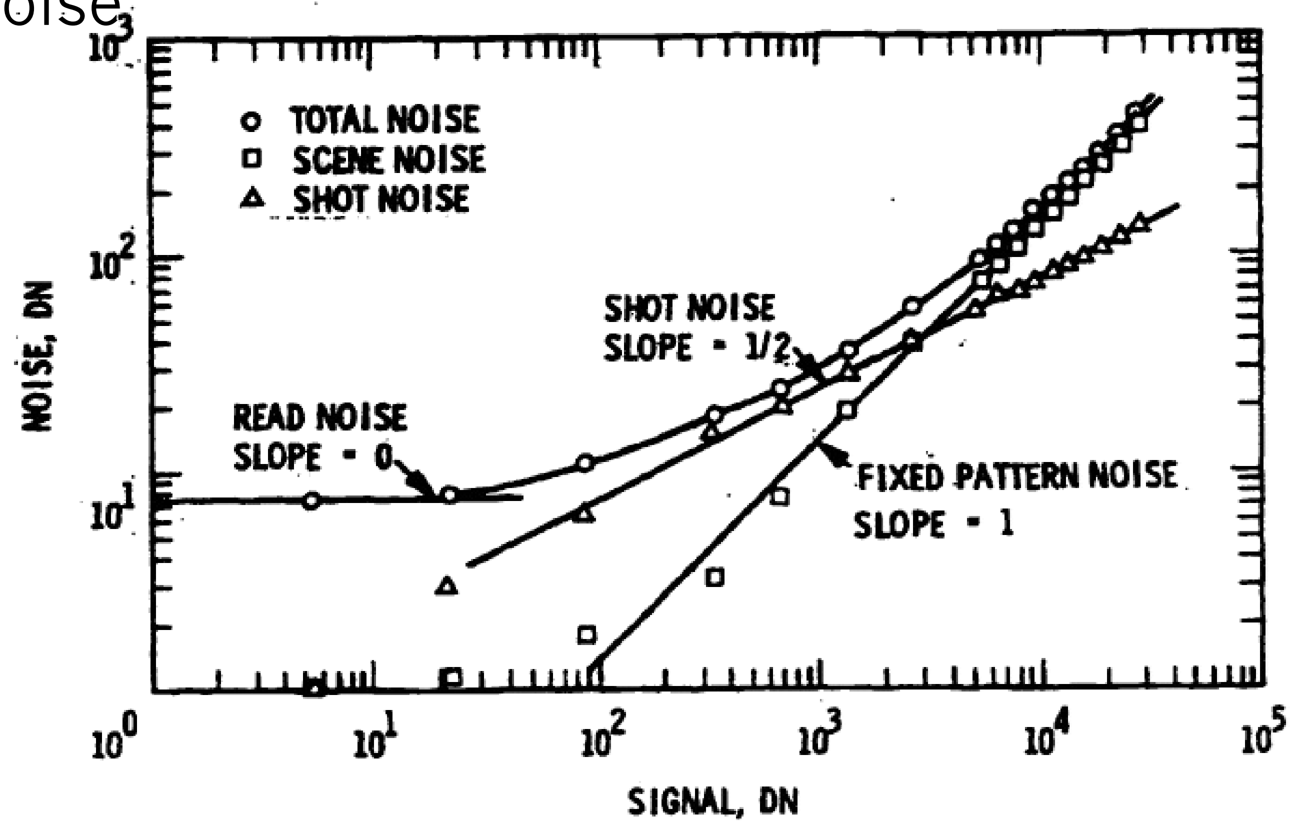
[micro.manget.fsu.edu]


Noise

Sources of noise

- Photon shot noise
- Dark current shot noise
- Fixed pattern noise
- Readout noise
- ...

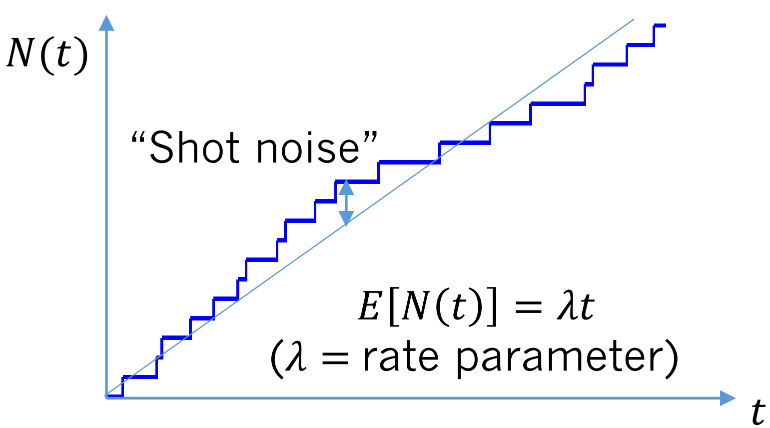
[Janesick97]



Photon shot noise

- Variance in number of photons that are counted
  - they arrive in a Poisson random process
- Standard deviation is square root of signal
  - *relative* noise decreases with signal
- Fundamental limit on photodetector precision!
- Can be reduced by averaging multiple exposures.

Example counting process



„Poisson distribution“:

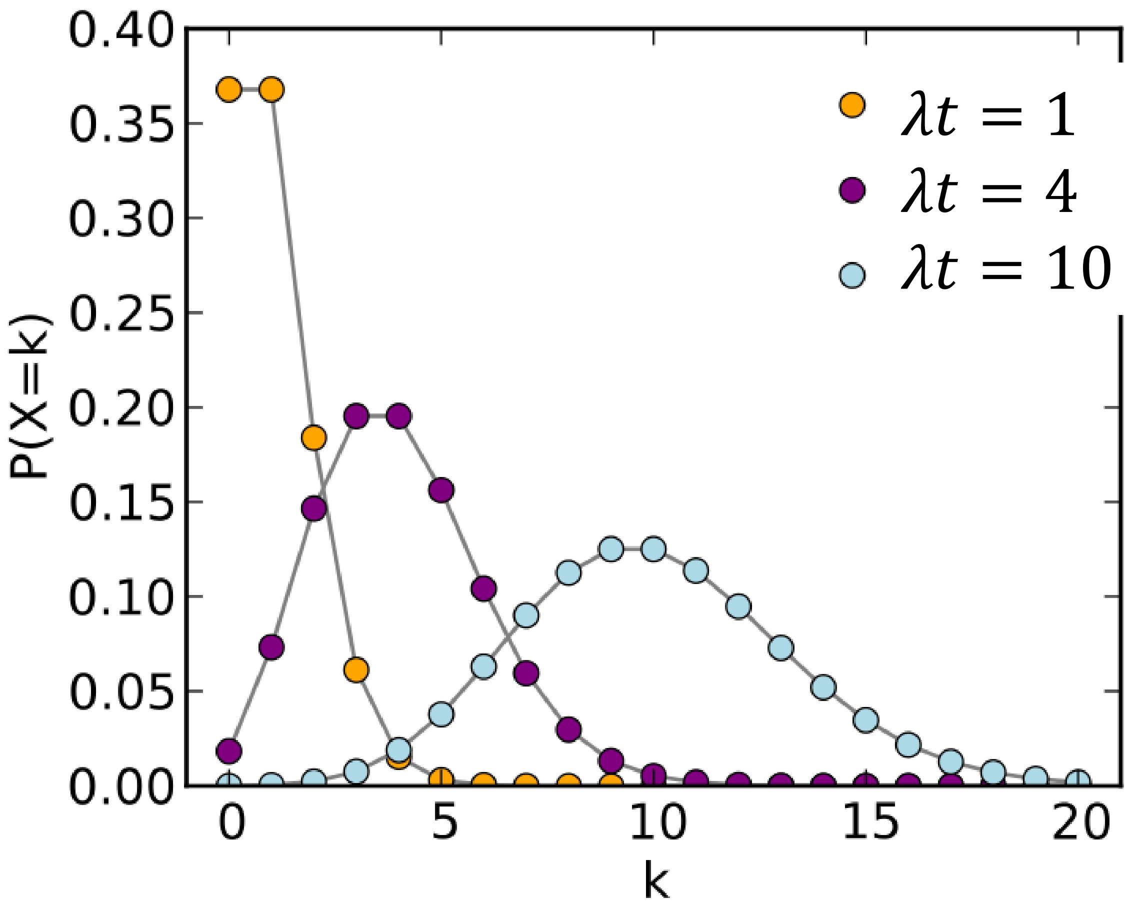
$$P[N(t) = k] = \frac{e^{-\lambda t}(\lambda t)^k}{k!}$$

$$k = 0,1,\ldots$$

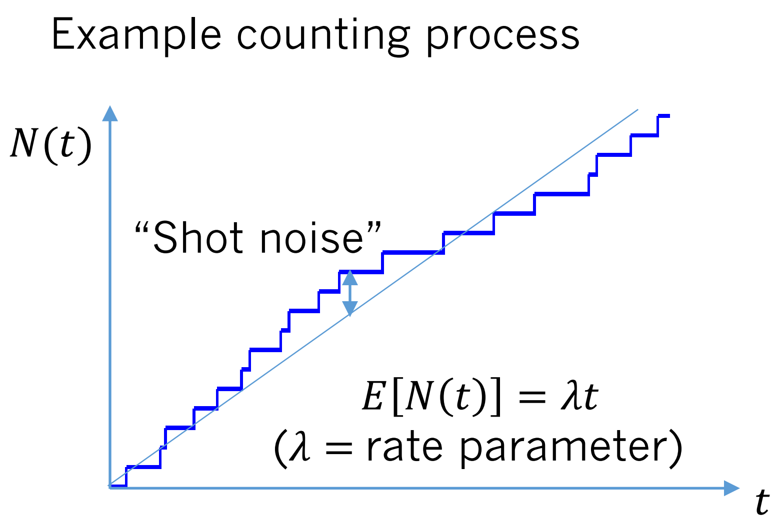
(probability of observing exactly k events in time interval $[0,t]$)

Poisson distribution

- Probability of counting k photons for different expected values λt (average number of photons detected during entire observation interval)



Shot noise cont'd



- Variance:
  $\sigma^2 = E[N^2] - (E[N])^2$
  $= \lambda t$

- Standard deviation:
  $$\sigma = \sqrt{\lambda t}$$

- Signal-to-noise ratio:
  $$SNR = \frac{\lambda t}{\sqrt{\lambda t}} = \sqrt{\lambda t}$$

=> SNR improves as counting time increases!

Shot Noise Quiz

- What happens when you...

	Shot noise σ	Signal-to-noise ratio SNR
• add $(A + B)$	$\times \sqrt{2}$	$\times \sqrt{2}$
• average $(A + B)/2$	$/\sqrt{2}$	$\times \sqrt{2}$
• subtract $(A - B)$	$\times \sqrt{2}$	**Only noise, no signal**

two images A and B taken under identical conditions?

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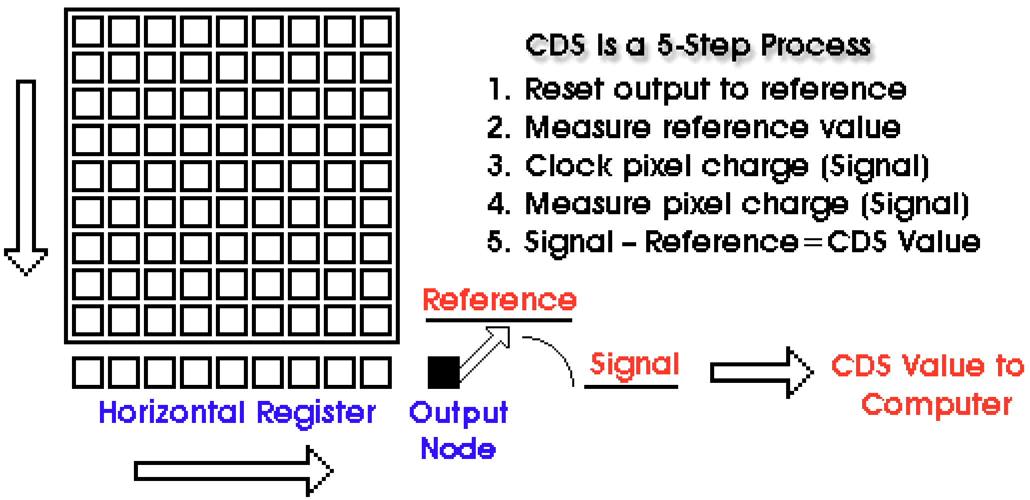
Fixed pattern noise

- Caused by variations in component values
- Big problem for CMOS sensors
  - An amp at every pixel, and one for every column
  - Gain variation (proportional to signal PRNU)
  - Bias variation (independent of signal – dark current)
  - Can be partially canceled by correlated double sampling (CDS)
- CCD's transfer all charge to a single output amplifier

Correlated Double Sampling

- reduce noise by comparing against a reference charge



Dark current

- Electrons generated by other mechanisms are collected, too.
- Highly temperature dependent
  - doubles every 5–8 °C
- May be reduced by cooling the sensor.
- Proportional to exposure time
- Limits exposure durations—eventually, the dark current fills your well capacity.

Dark Current Noise

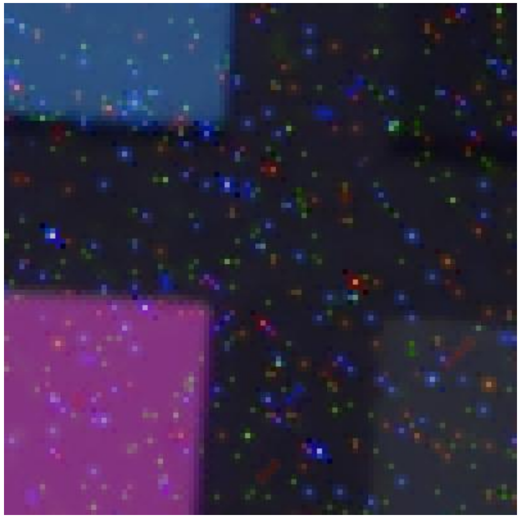
- Dark current has fixed pattern noise.
  - Dark current varies because of irregularities in the silicon.
- Dark current has shot noise, too!
  - dominates in dark areas for long exposures
- Dark current is why astronomers chill their image sensors.

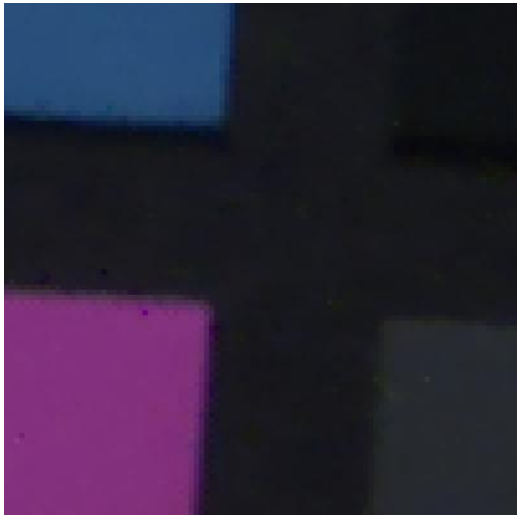
Thermal Noise

- Generated by thermally induced motion of electrons in resistive regions (resistors, transistor channels in strong inversion...)
- What does that mean?
  - Independent of the signal.
  - Zero mean, white (flat, wide bandwidth)
  - Another problem for CMOS, not CCD imagers
- Dominates at low signal levels, long exposure time
  - Can limit dynamic range

Dark Current Noise – Removal

- ideal: cooling the chip
- noise removal techniques to separate image data from noise





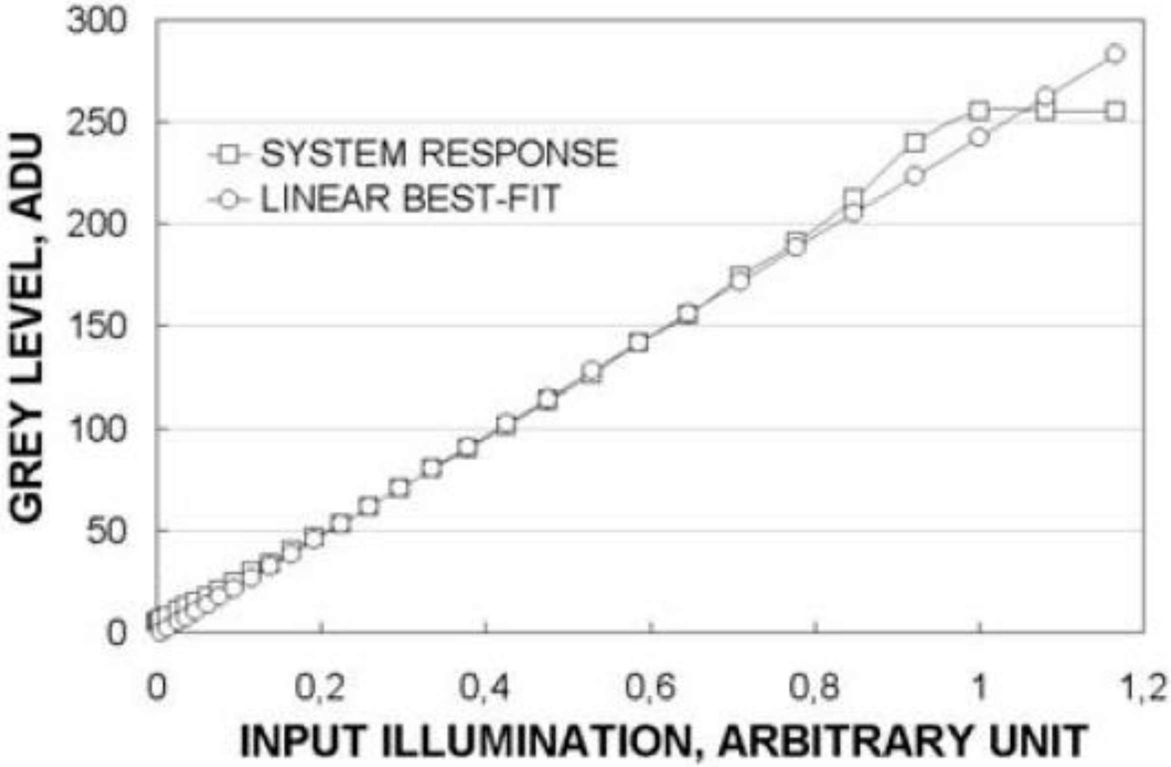
25 s exposure time

Noise, noise, noise...

- Reset (kTC) noise
  - thermal noise when "resetting" the CMOS photodetector—a big deal, actually.
  - can be corrected with CDS (correlated double sampling)
- Amplifier noise
  - thermal
  - spatially non-uniform
  - 1/f noise
  - non-linearities
- Quantization noise
  - "truncate" analog value to N bits

Non-linear Response

[Reibel2003]



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Combined Noise Model [Reibel2003]

$$\sigma^2{}_{N_{TOT}} = \sigma^2{}_{FPN} + \sigma^2{}_{R} + \sigma^2{}_{DSN} + \sigma^2{}_{PSN} + \sigma^2{}_{PSN} + \sigma^2{}_{PRNU} + C_{NL}$$

$\sigma^2{}_{FPN}$ - fixed pattern noise

$\sigma^2{}_{R}$ - reset noise

$\sigma^2{}_{DSN}$ - thermal dark current shot noise

$\sigma^2{}_{PSN}$ - photon shot noise

$\sigma^2{}_{PRNU}$ - photo response non-uniformity

C_{NL} - non-linear effects

Combined Noise Model [Reibel2003]

$$\sigma^2{}_{N_{TOT}} = \sigma^2{}_{FPN} + \sigma^2{}_{R} + \sigma^2{}_{DSN} + \sigma^2{}_{PSN} + \sigma^2{}_{PSN} + \sigma^2{}_{PRNU} + C_{NL}$$

- $\sigma^2{}_{FPN}$ - fixed pattern noise (can be calibrated)
- $\sigma^2{}_{R}$ - reset noise (CDS)
- $\sigma^2{}_{DSN}$ - thermal dark current shot noise (cooling)
- $\sigma^2{}_{PSN}$ - photon shot noise (multiple exposures)
- $\sigma^2{}_{PRNU}$ - photo response non-uniformity (per-pixel gain)
- C_{NL} - non-linear effects (can also be calibrated for)

Dynamic Range

$$\mathrm{dr} = \frac{\text{max output swing}}{\text{noise in the dark}} = \frac{\text{Saturation level – dark current}}{\text{Dark shot noise + readout noise}}$$

- “noise in the dark” is really random noise sources that we cannot correct with clever circuit tricks.
  - reset noise can be corrected with CDS.
  - non-random fixed pattern noise can be calibrated.

A Pragmatic Recipe for high-quality LDR images

Ingredients:

- Tons of light; light-efficient sensor at lowest possible temperature; calibrated response curve (if available)

1. Metering (set exposure parameters)
2. Turn off all light or put on lens cap, take **dark frame** DF.
3. Optional: Take **bright frame** BF (defocused image of flat white target), apply inv. response curve
4. Take the actual **image** I, apply inv. response curve
   - *Repeat if you need more images or video*
5. Cleaned image = $\frac{I-DF}{BF-DF}$ (reference value = 1)

Extra Spices for our Recipe

- Reduce stochastic noise by taking 100 frames of each kind, and averaging them. (At least for dark and bright frame, this is well-invested time. Also look at statistics between frames – which pixels show highest variability when there shouldn't be any?)
- Using dark and bright frames, extract a map of broken / dead / "hot" or otherwise unreliable pixels on the sensor; fill them in later by interpolating neighboring values
- Detect overexposed (saturated) pixels directly in I, as dividing by BF will destroy this information

Sensing color

Sensing color

- Eye has 3 types of color receptors (loosely)
- Therefore we need 3 different spectral sensitivities

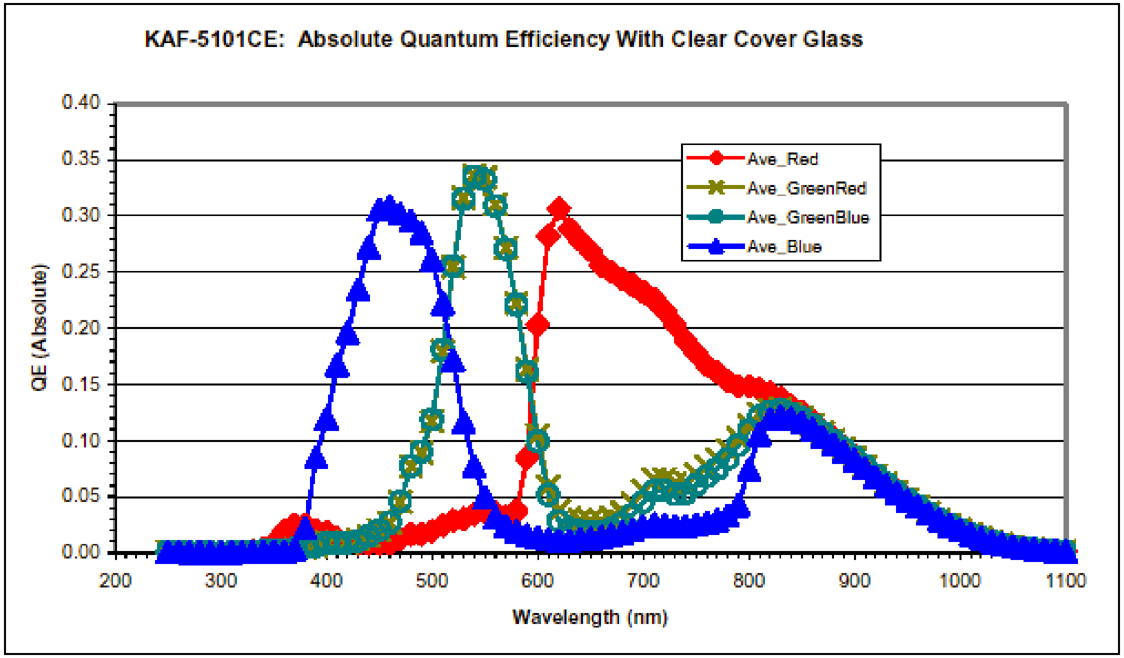

Figure 7. Typical Quantum Efficiency Curves (Clear Coverglass)

source: Kodak KAF-5101ce data sheet

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Ways to sense color

- Field-sequential color
  - simplest to implement
  - only still scenes

Proudkin-Gorskii, 1911
(Library of Congress exhibition)

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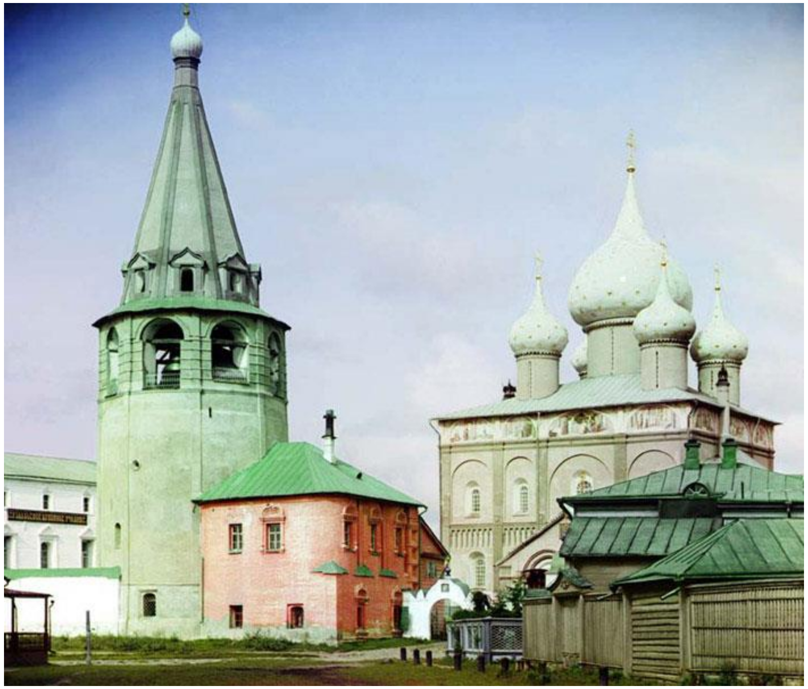
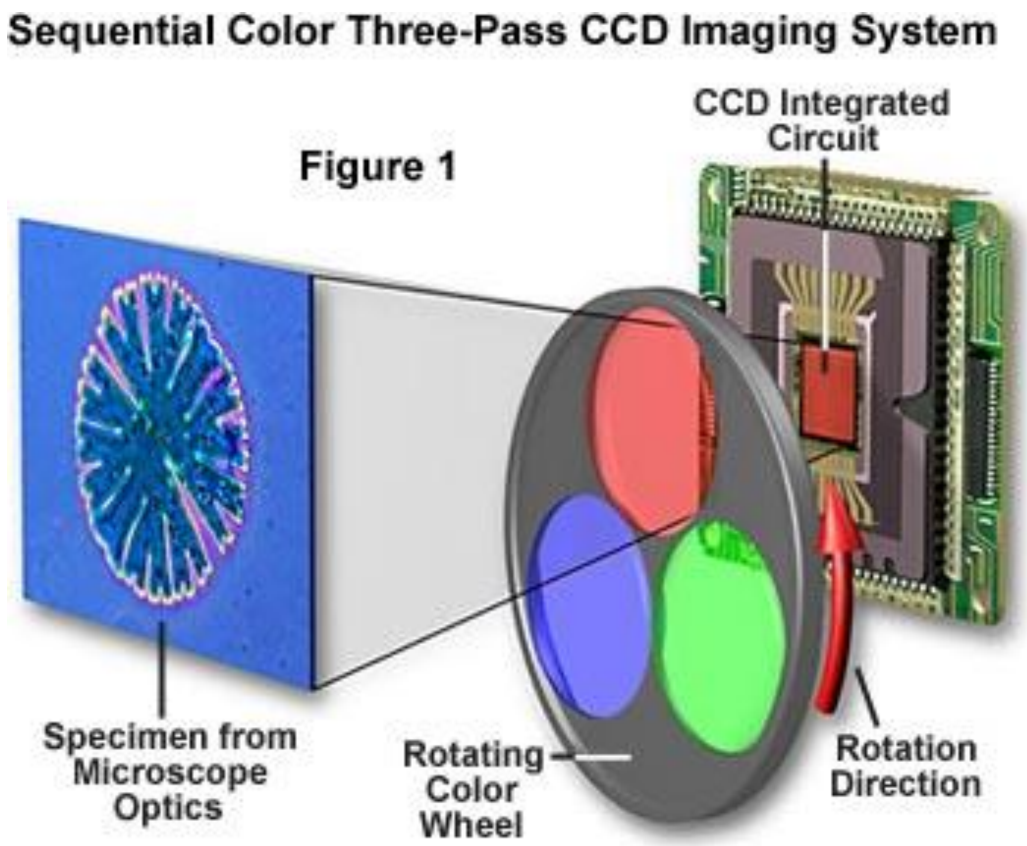
- Field-sequential color
  - simplest to implement
  - only still scenes



Proudkin-Gorskii, 1911
(Library of Congress exhibition)

Color Wheel

- one color channel is captured at one shot
- 3 times the acquisition time
- static images only



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Ways to sense color – 3-Chip Camera

- dichroic mirrors divide light into wavelength bands
- does not remove light: excellent quality but expensive
- interacts with lens design
- problem with polarization

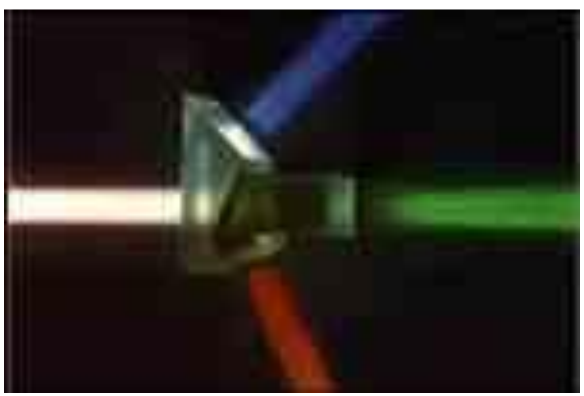
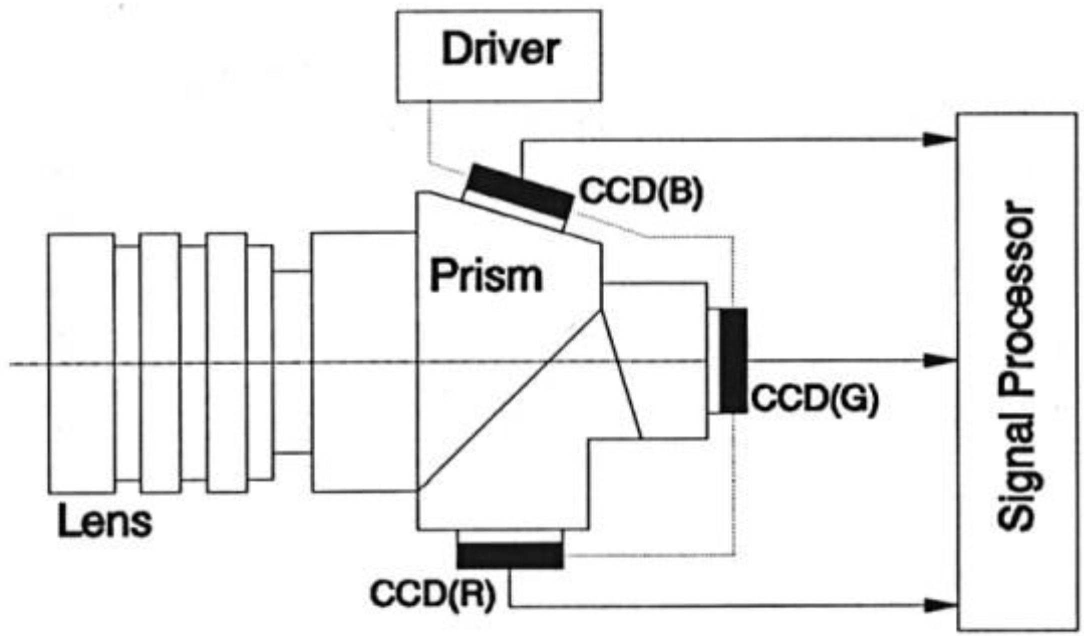
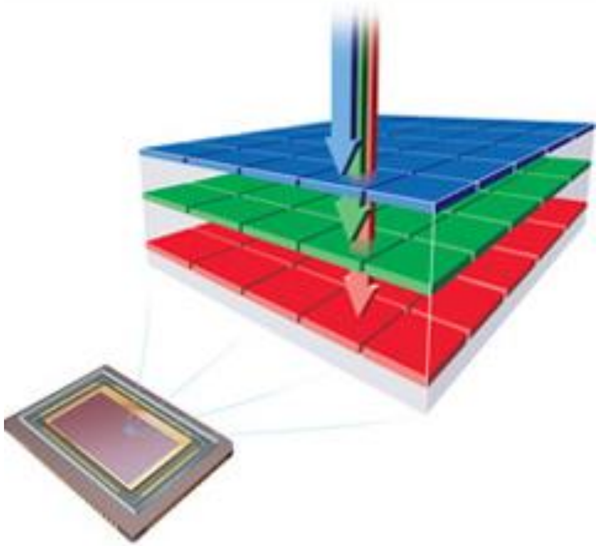


image: Theuwissen



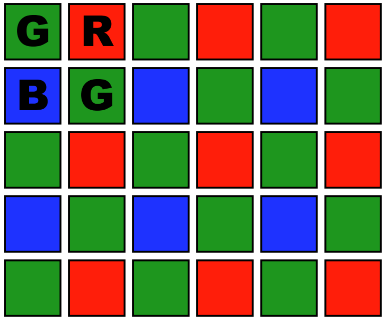
Foveon Technology

- 3 layers capture RGB at the same location
- takes advantage of silicon's wavelength selectivity
- light gets absorbed at different rates for different wavelengths and depths
- multilayer CMOS sensor gets 3 different spectral sensitivities
- Limited control over absorption curves



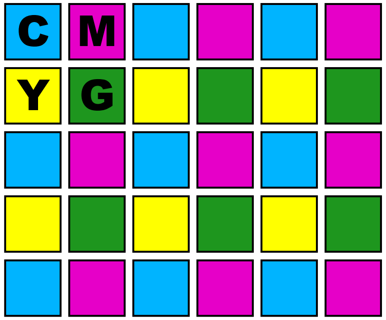
Ways to sense color

- Color filter array
  - paint each sensor with an individual filter
  - requires just one chip but loses some spatial resolution
  - “demosaicing” requires some image processing



primary

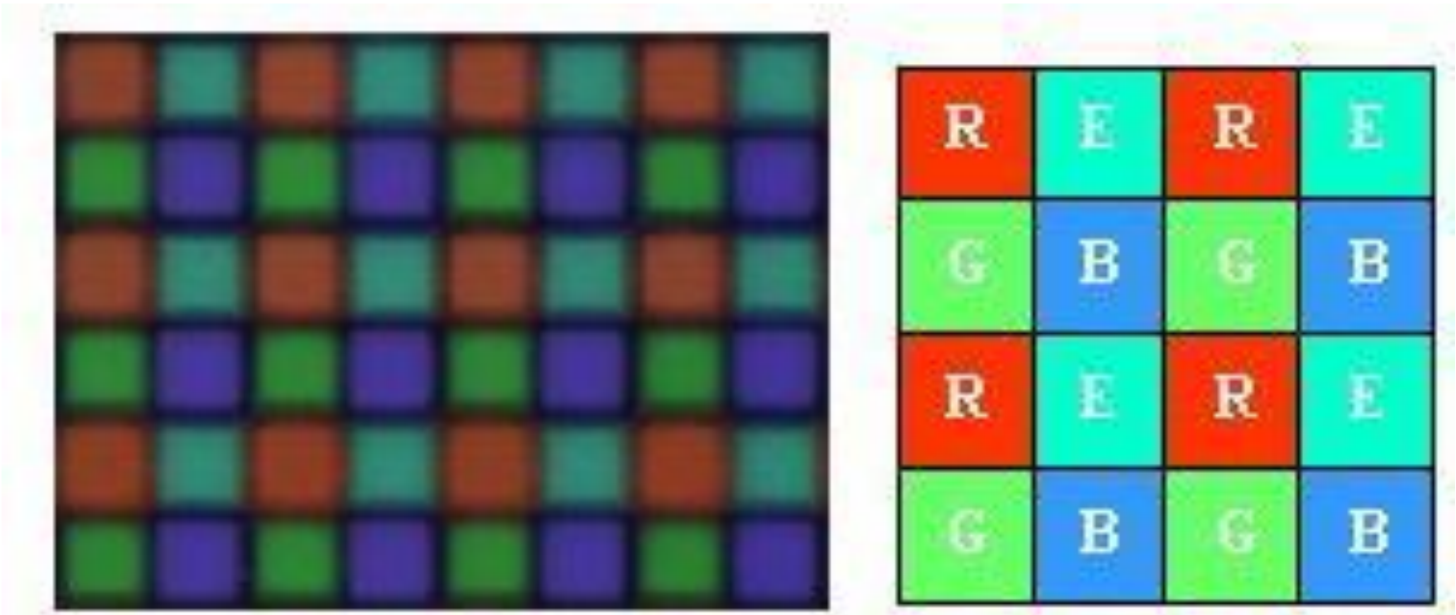
(“Bayer pattern”, pat. 1976)



secondary

SONY 4-Color Filter

- RGB+E (supposedly halves color errors)
- Cyber-Shot DSC-F828



4-color filters

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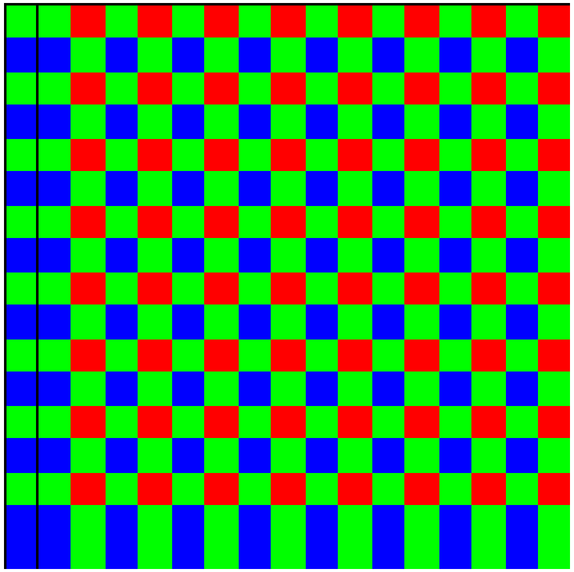
Multi-Shot

- take four images, moving the sensor by one pixel
- (use fourth image for noise reduction)



- can be used for supersampling
  (move by ½, ¼ pixel)

Demosaicing

Bilinear interpolation

Sampling theory

Edge-directed/pattern-based interpolation

Correlation-based

Demosaicing

Original image Bilinear interpolation

Ron Kimmel, http://www.cs.technion.ac.il/~ron/demosaic.html

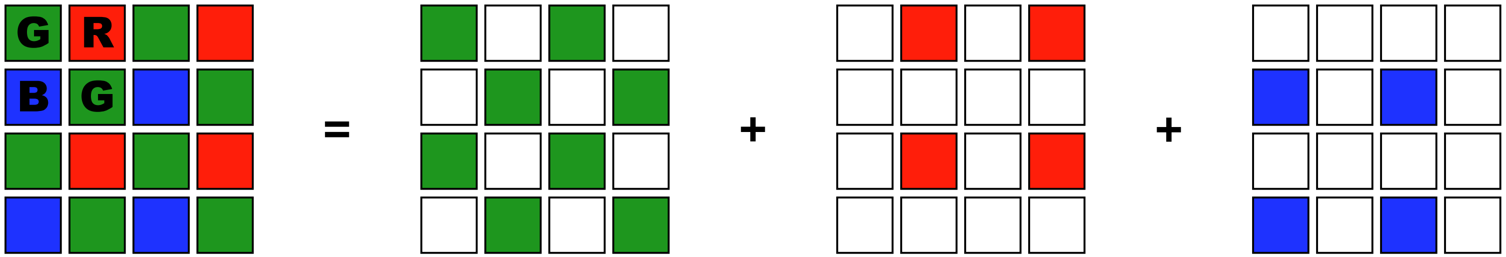
Demosaicing

Bilinear interpolation

Edge-weighted interpolation

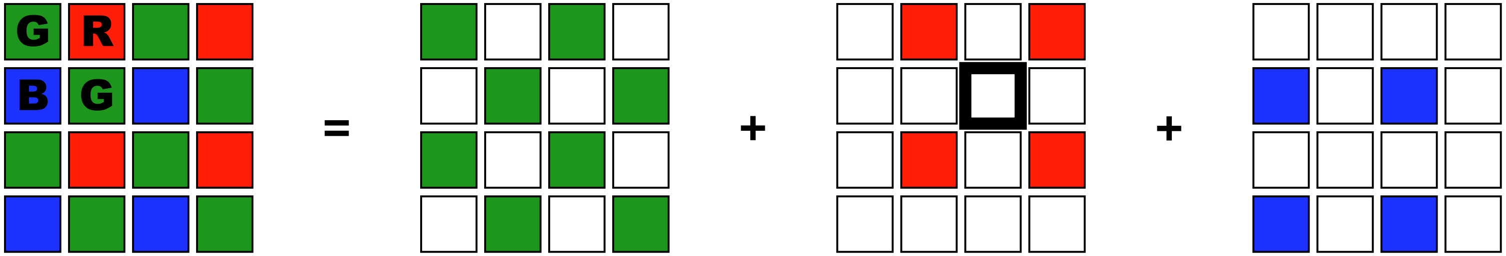
Ron Kimmel, http://www.cs.technion.ac.il/~ron/demosaic.html

Bilinear Interpolation



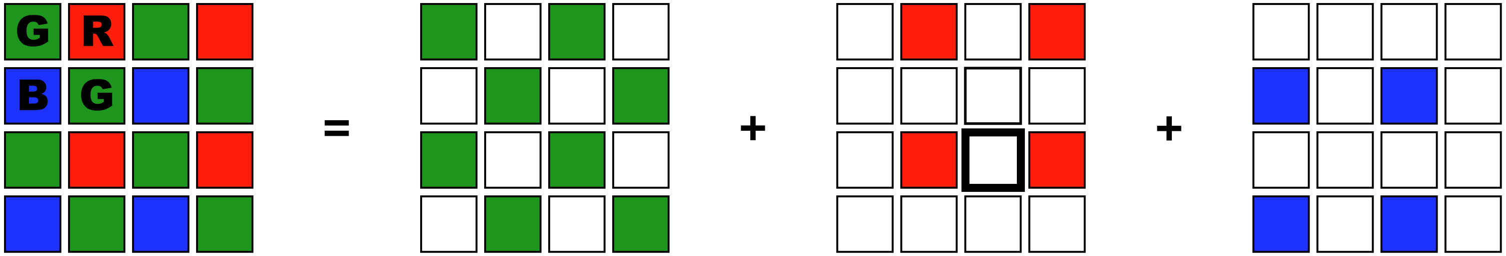
- perform interpolation for each color channel separately

Bilinear Interpolation



$$R_{23} = \frac{R_{12} + R_{14} + R_{32} + R_{34}}{4}$$

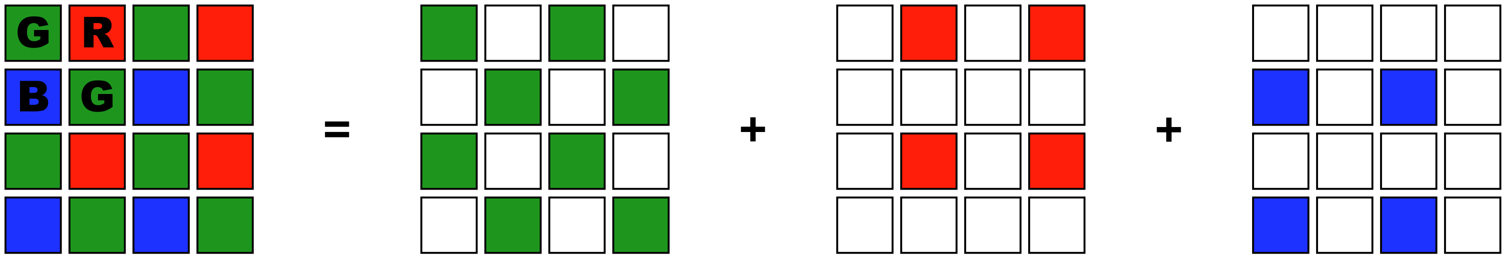
Bilinear Interpolation



$$R_{23} = \frac{R_{12} + R_{14} + R_{32} + R_{34}}{4}$$

$$R_{33} = \frac{R_{32} + R_{34}}{2}$$

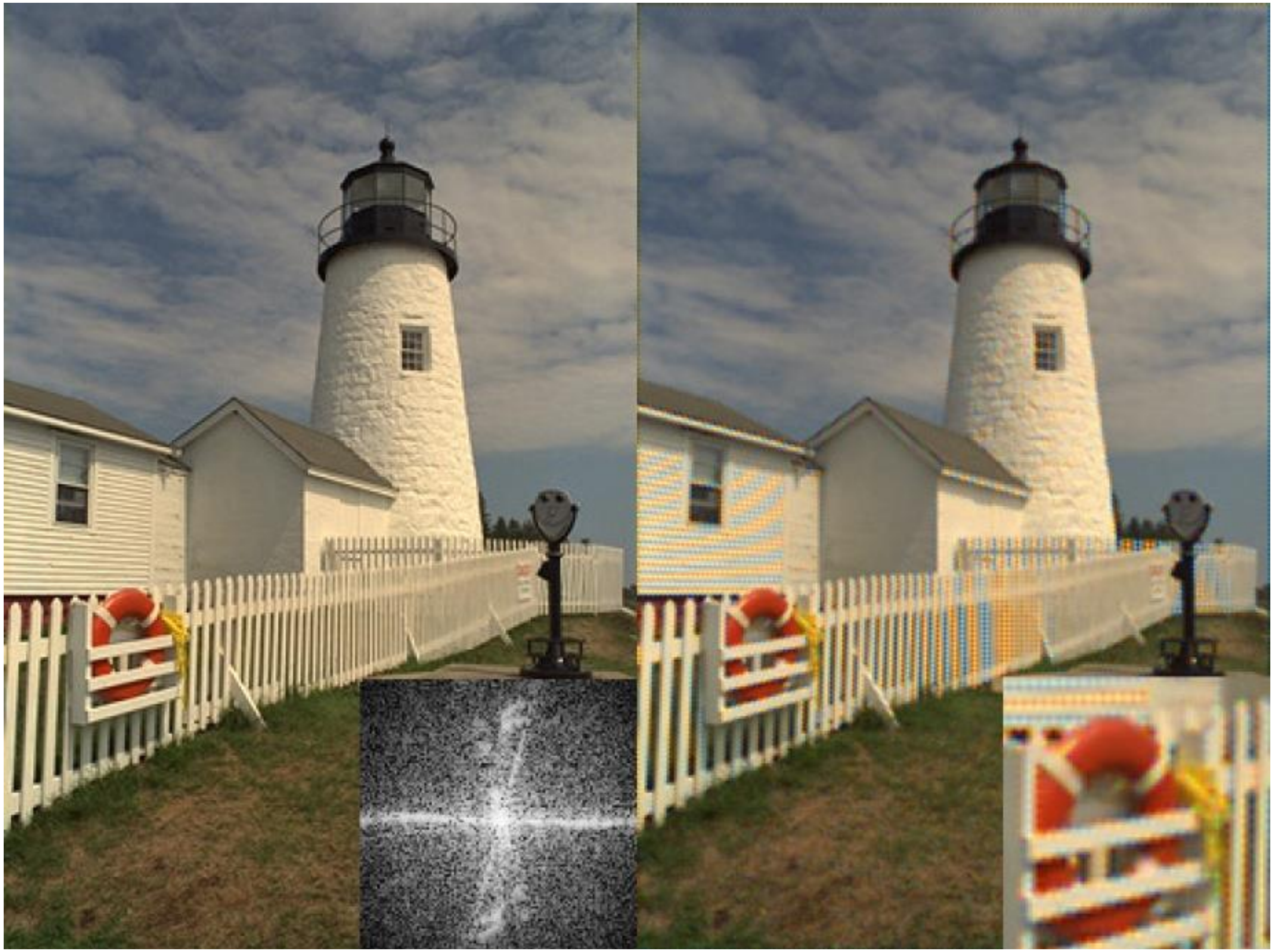
Bilinear Interpolation



- set all non-measured values to zero then convolve

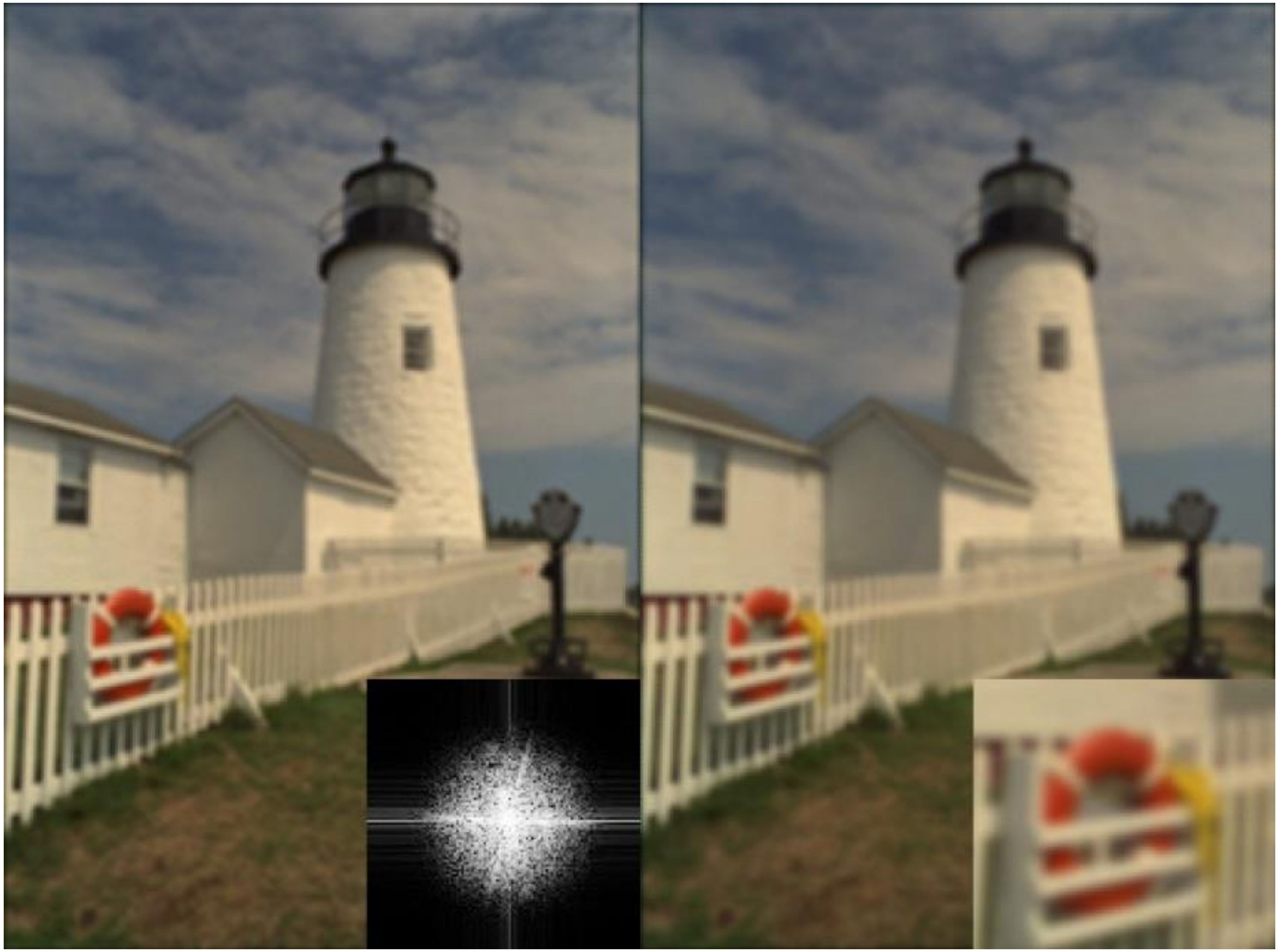
$$F_{R,B} = \begin{bmatrix} 1 & 2 & 1 \\ 2 & 4 & 2 \\ 1 & 2 & 1 \end{bmatrix} / 4 \qquad F_G = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 4 & 1 \\ 0 & 1 & 0 \end{bmatrix} / 4$$

Problem: Aliasing



[Alleysson et al. 05]

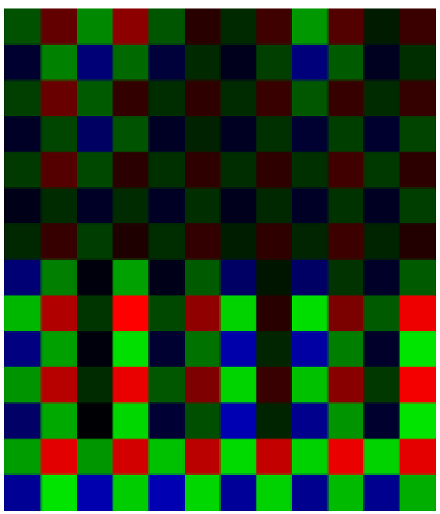
Problem: Aliasing



[Alleysson et al. 05]

Directional interpolation

- Interpolating across edges produces false colors and grid effect
- Ton of literature on “adaptive” demosaicing – first, find edge direction; then, interpolate.
- How to find the right direction?



Input data

Poor direction field

Good direction field

Constant Hue Assumption

- Assume explicit correlation between color channels:

$$I^R = \rho_R < \vec{n}, \vec{l} >$$

$$I^G = \rho_G < \vec{n}, \vec{l} >$$

$$I^B = \rho_B < \vec{n}, \vec{l} >$$

$< \vec{n}, \vec{l} >$ - incident irradiance

- even across intensity changes the ratio stays constant:

$$\frac{I^i}{I^j} = \frac{\rho_i}{\rho_j} = const.$$

- Try to find direction field that minimizes hue changes in interpolation outcome

Optimization by Smoothing along 1D-features

- Idea: $$E(x) = \sum_{y \in Nbh(x)} \min_d \left(\frac{S_p(y,d) + \Delta(y,d)}{B(x)} + \lambda\, sd(y,d) \right)$$
  - Do not guess the green channel by ad-hoc interpolation but optimize it so that the resulting image is as smooth as possible
  - Use existing technique (AAI) to interpolate missing colors.

[Ajdin et al. 2008]

Demosaicing – Take-home-points

- 2/3 of your image are just made up!
- color resolution is less than image resolution
- be careful with spiky BRDFs
- combining multiple video frames might help
- 98% of all demosaicing algorithms so far are ad-hoc
  - smoothing based on constant hue assumption afterwards
- What's in the future?
  - Integrated imaging pipelines for deblurring, HDR, demosaicing, ... [Heide et al. 2014]
  - Formulate image reconstruction as one big inverse problem, regularize with natural-image priors -> later
  - Of course, deep learning

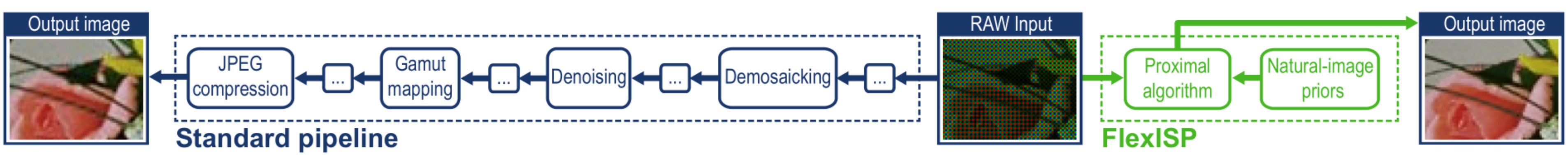


Figure 2: *The traditional camera processing pipeline consists of many cascaded modules, introducing cumulative errors. We propose to replace this pipeline with a unified and flexible camera processing system, leveraging natural-image priors and modern optimization techniques.*

White balance

Capture the spectral characteristics of the light source to assure correct color reproduction

tungsten

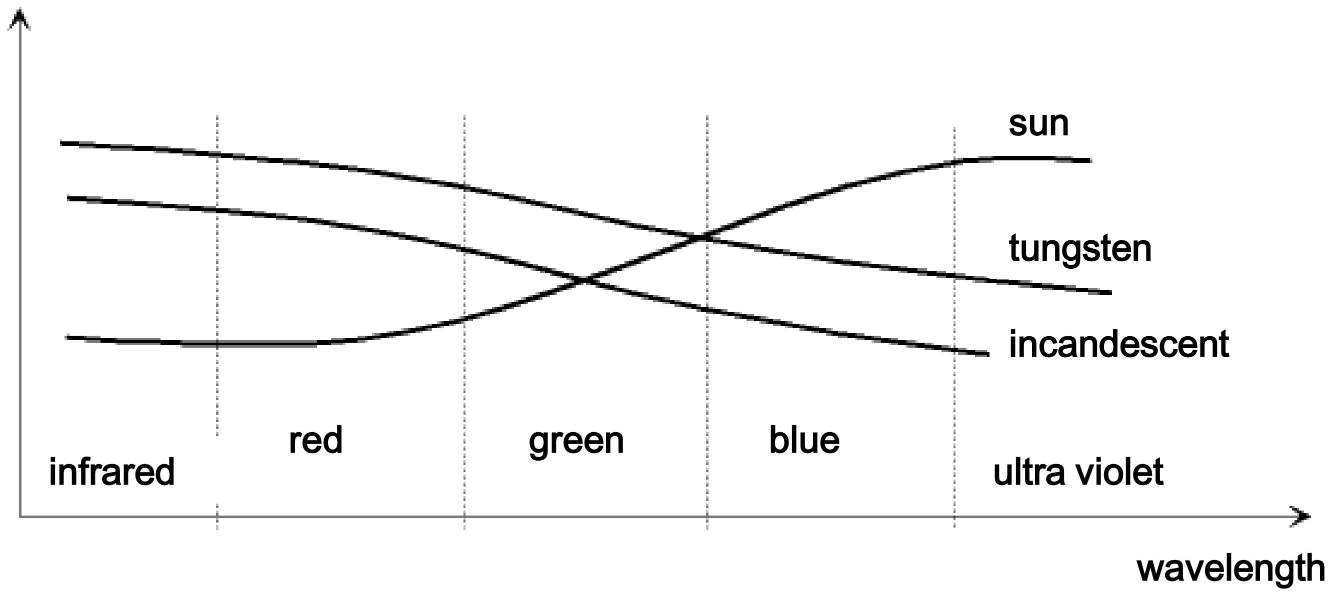
daylight

fluorescent

flash

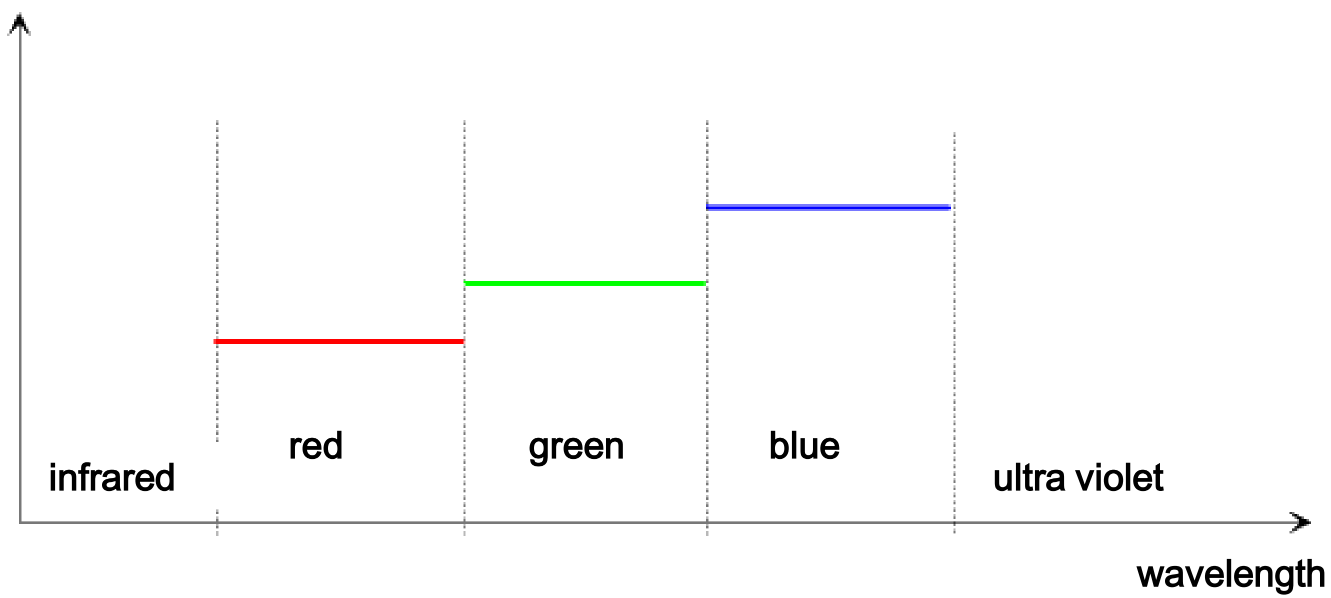
White balance

- Built-in function
- Derive scale from white point



White balance

- Built-in function
- Derive scale from white point



White balance

- Built-in function
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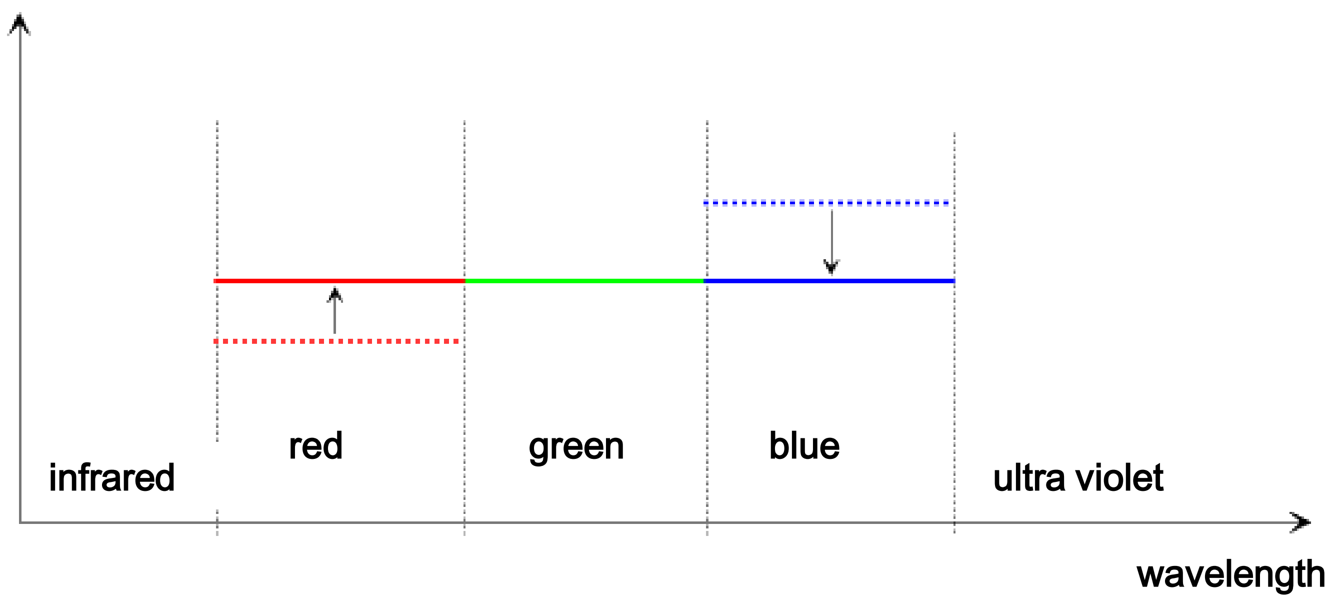

White balance matrix

- Most often expressed as a matrix
- Simple scaling (using single white point):

Restored RGB vector >>

$$\begin{pmatrix} r \\ g \\ b \end{pmatrix} = \begin{pmatrix} r_r & 0 & 0 \\ 0 & g_g & 0 \\ 0 & 0 & b_b \end{pmatrix} \cdot \begin{pmatrix} r_c \\ g_c \\ b_c \end{pmatrix}$$

<< Captured RGB vector

White balancing matrix

- Full matrix to account for cross-talk between channels:

$$\begin{pmatrix} r \\ g \\ b \end{pmatrix} = \begin{pmatrix} r_r & r_g & r_b \\ g_r & g_g & g_b \\ b_r & b_g & b_b \end{pmatrix} \cdot \begin{pmatrix} r_c \\ g_c \\ b_c \end{pmatrix}$$

Color calibration: estimating WB matrix

- Using color checker image

$$\begin{pmatrix} r \\ g \\ b \end{pmatrix} = \begin{pmatrix} r_r & r_g & r_b \\ g_r & g_g & g_b \\ b_r & b_g & b_b \end{pmatrix} \cdot \begin{pmatrix} r_c \\ g_c \\ b_c \end{pmatrix}$$

- Color checker provides known RGB color per patch

$$\begin{pmatrix} r & g & b \end{pmatrix}_0^T = WB \cdot \begin{pmatrix} r_c & g_c & b_c \end{pmatrix}_0^T$$

$$\begin{pmatrix} r & g & b \end{pmatrix}_1^T = WB \cdot \begin{pmatrix} r_c & g_c & b_c \end{pmatrix}_1^T$$

$$\begin{pmatrix} r & g & b \end{pmatrix}_2^T = WB \cdot \begin{pmatrix} r_c & g_c & b_c \end{pmatrix}_2^T$$

$$\begin{pmatrix} r & g & b \end{pmatrix}_3^T = WB \cdot \begin{pmatrix} r_c & g_c & b_c \end{pmatrix}_3^T$$

...

$$\underbrace{\begin{pmatrix} \vec{o}_0 \\ \vec{o}_1 \\ \vdots \\ \vec{o}_{N-1} \end{pmatrix}}_{\text{Nx3}} = \underbrace{\begin{pmatrix} \vec{c}_0 \\ \vec{c}_1 \\ \vdots \\ \vec{c}_{N-1} \end{pmatrix}}_{\text{Nx3}} \bullet \underbrace{WB^T}_{\text{3x3}}$$

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Linear Least Squares

- N sets of linear equations
- determine optimal WB-matrix squared error:

$$E = \sum_{N} \left\| o_i - WB \cdot c_i \right\|_2$$

- solve for WB

$$O = C \cdot WB^T$$

- using normal equation:

$$y = Ax$$

$$A^T y = A^T A x$$

$$x = (A^T A)^{-1} A^T y$$

Linear Least Squares

- N sets of linear equations
- determine optimal WB-matrix squared error:

$$E = \sum_N \left\| o_i - WB \cdot c_i \right\|_2$$

- solve for WB

$$O = C \cdot WB^T$$

- using normal equation:

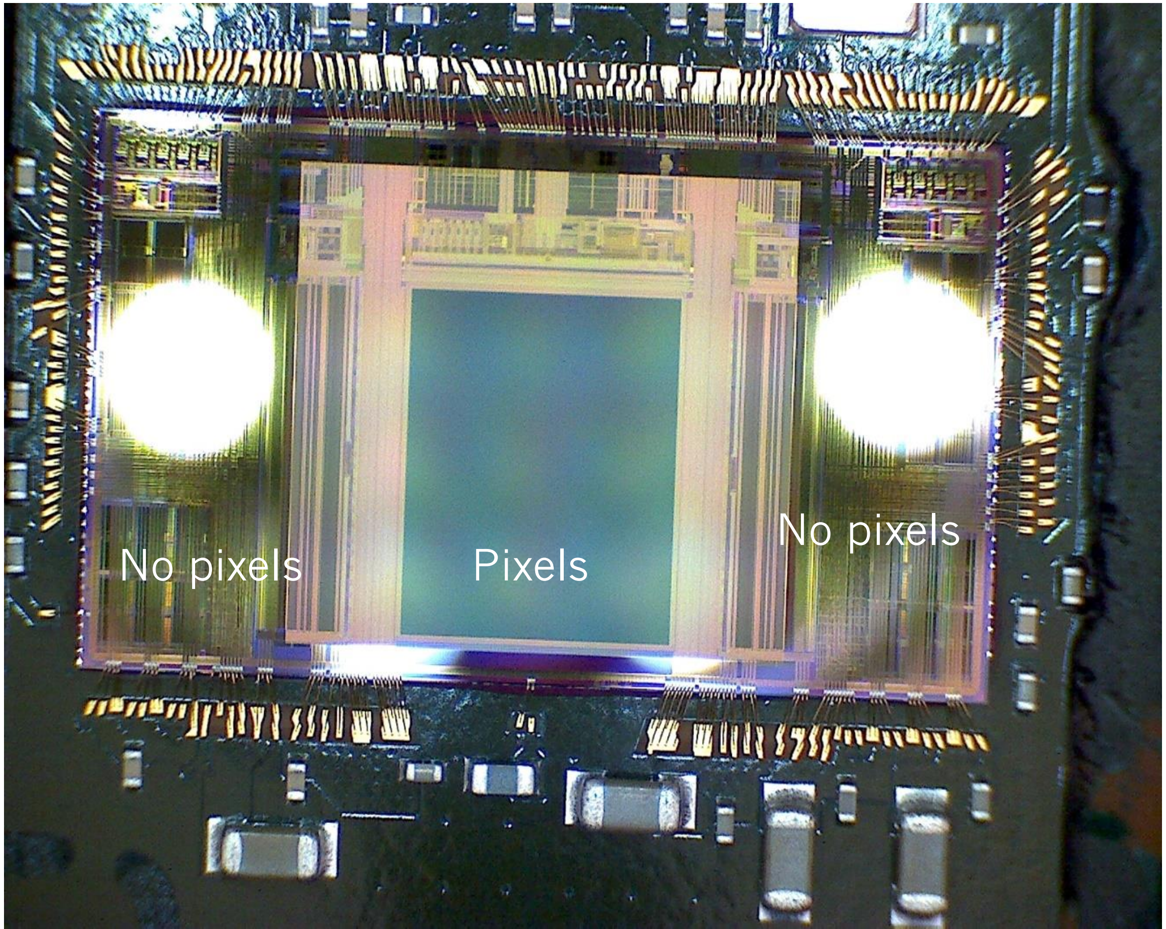
$$y = Ax \qquad\qquad O = C \cdot WB^T$$

$$A^T y = A^T A x \qquad\qquad C^T O = C^T C WB^T$$

$$x = (A^T A)^{-1} A^T y \qquad\qquad WB^T = (C^T C)^{-1} C^T O$$

“Exotic” sensors

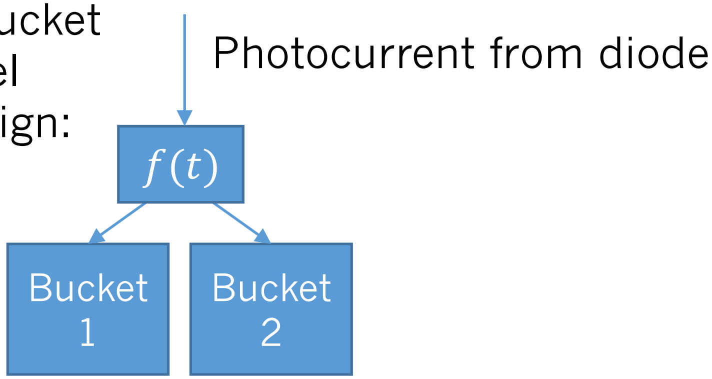
- Photonic mixer devices / quadrature sensors
- Single-photon detectors



Microsoft
Kinect v2 sensor

Photonic mixer device

2-bucket pixel design:



Observed pixel value:

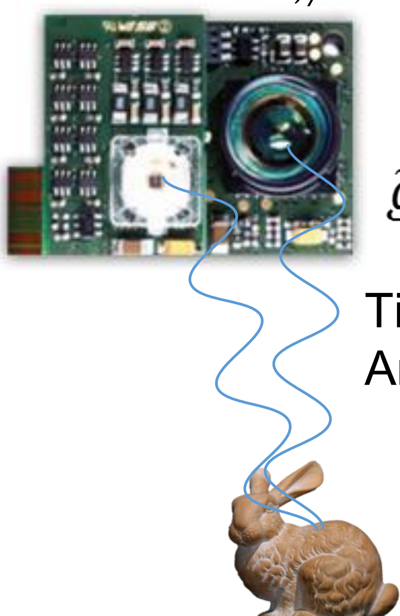
$$H_{\omega,\phi} = \int_0^T \tilde{g}_\omega(t) f_{\omega,\phi}(t)\,dt$$

$$= \alpha \int_0^T g_\omega(t-\tau) f_{\omega,\phi}(t)\,dt$$

$g_\omega(t) = \sin(\omega t)$
$f_{\omega,\phi}(t) = \sin(\omega t + \phi)$

$$= \alpha \frac{T}{2} \cos(\phi - \omega\tau)$$

Illumination $g_\omega(t)$ Reference $f_{\omega,\phi}(t)$



$$\tilde{g}_\omega(t) = \alpha g_\omega(t-\tau)$$

Time of flight τ
Amplitude α

Quadrature time-of-flight imaging:
Take sin, cos measurements; solve for τ, α for each pixel

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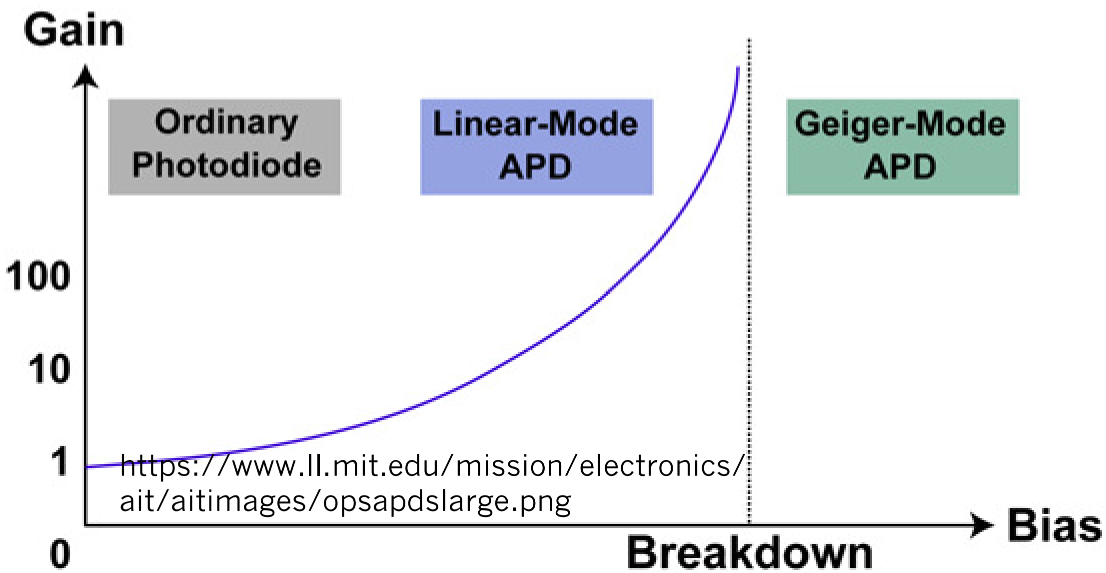
Single-Photon Avalanche Diodes

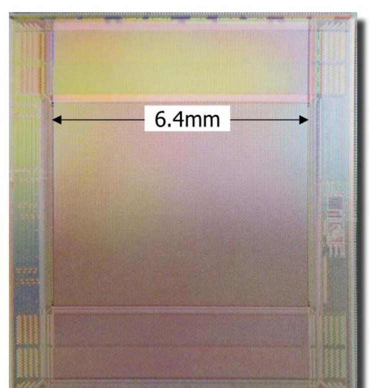


https://www.ll.mit.edu/mission/electronics/ait/aitimages/opsapdslarge.png

- Geiger counter for photons
- With 55ps stopwatch!!!! (time-to-digital converter)

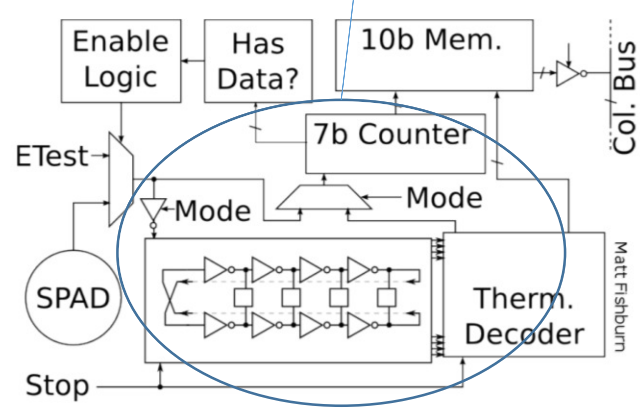
FP6 FET Open: MEGAFRAME
2006-2010

- 160x128 single-photon pixels
  - 55ps resolution
  - 140ps IRF
  - 50Hz DCR
  - 250kfps
  - Standard CMOS
- Demonstrated in
  - FLIM, FRET, FCS



Veerappan *et al.*, to appear, International Solid-state Circuits Conference 2011

Pixel Architecture



Summary

- Digital images created by sensor

- CMOS or CCD
  - Which one should you buy for your still camera?

- Sensing Color
  - How would you capture a multispectral image (many wavelengths)?

Overview

- This lecture
  - Sensors
  - Sensitivity
  - Colors

- Next lecture
  - Optics
  - Lenses and image formation
  - Diffraction

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