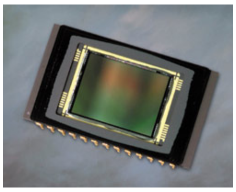
Imaging Sensors

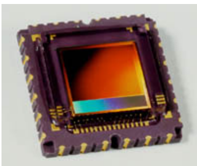
Organization

- lectures
- discussion of research papers
- student projects
  - (1-2 student(s) per group)
  - list of possible ideas
  - presentation of ideas
  - project proposal (2 pages)
  - implementation
  - presentation of results
  - report (like a conference paper 6-8 pages)

Image Sensors



CCD



CMOS

Image Sensors

Photodetection

CCD's vs CMOS

Sensor performance characteristics

Noise

Color Sensors

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 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 one electron is really hard!

(Doesn't have much energy…)

Fortunately, the electrons hang around for a while.

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.

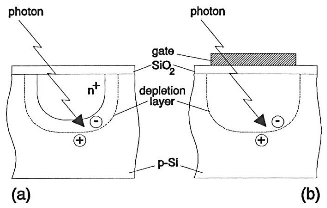


image: Theuwissen

Photodetector Performance Metrics

Pixel size

Fill factor

Full well depth

Spectral quantum efficiency

Sensitivity

(Saving noise & dynamic range for later)

Pixel Size

Large pixels means more light collected.

Typically 3μm-10 μm

20 μm for astronomy

Pixels getting tiny for cell phones, digital cameras

- 2μm x 2μm is probably the smallest CMOS pixel today (Matsushita, ISSCC 2005)
- Optics will get you eventually.

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

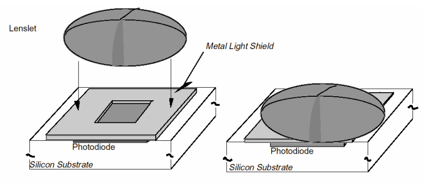


image: Kodak application note DS00-001

Full Well Depth

"Saturation charge" 45 to 100 ke^-

- depends on the pixel size

Limits dynamic range (more about this later)

Once you fill up your well, can overflow into your neighbors. This is called blooming.

Blooming almost irrelevant for CMOS

Blooming

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

Extra Overflow Drain

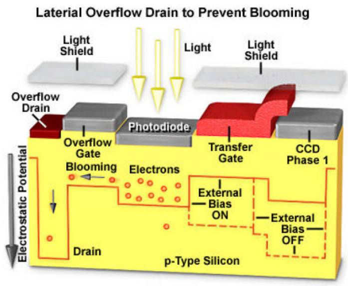


Figure 1

Absorption Coefficients

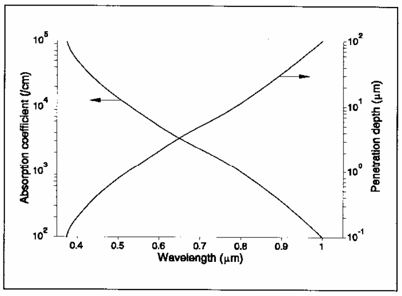


FIGURE 5.2. The absorption coefficient of silicon together with its corresponding penetration depth as a function of the wavelength of the incident light.

image: Theuwissen

Penetration Depth

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

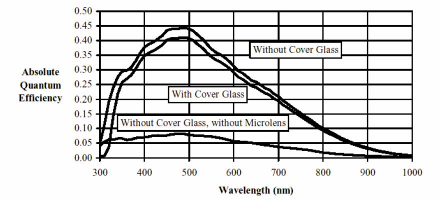


Figure 10 - Wavelength Dependence of Quantum Efficiency

source: Kodak KAI-2000m data sheet

Filtered Spectral Quantum Efficiency

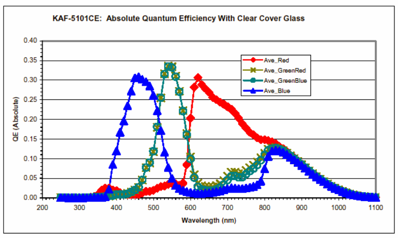


Figure 7. Typical Quantum Efficiency Curves (Clear Coverglass)

source: Kodak KAF-5101ce data sheet

Factors for Quantum Efficiency

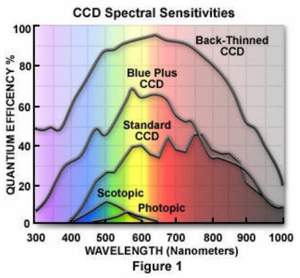
Color filters

Absorption coefficients & 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.

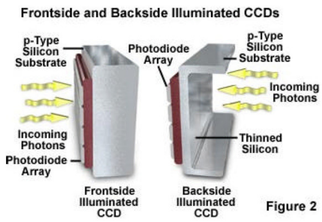
Fill factor

Extended Sensitivity



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

Back Illuminated CCDs



Sensitivity

Sensitivity = quantum efficiency * conversion gain

Conversion gain is basically volts per electron.

- You don't want to know about this…
- 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 ~= 10E4 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.

CCD's 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).

Charge Transfer for CCD's

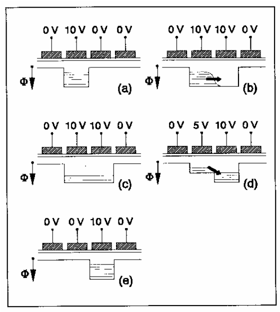


FIGURE 1.8. Illustration of the charge transport in a CCD. The charge packet of minority carriers is moved through the silicon by means of digital pulses on the CCD gates.

image: Theuwissen

Example:Three Phase CCD’s

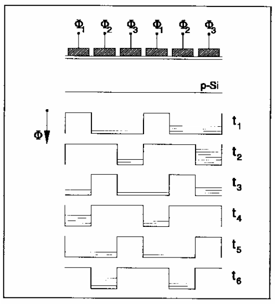


FIGURE 2.5. Cross section of a CCD transport section driven by a three-phase-clocking system.

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.

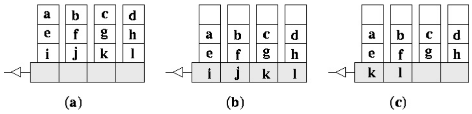


image: Curless

Frame Transfer

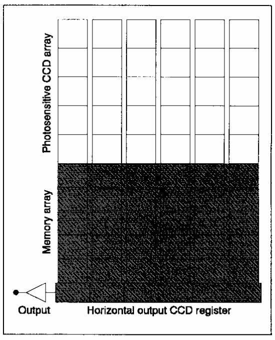


FIGURE 4.4. Device architecture of a frame-transfer image sensor.

image: Theuwissen

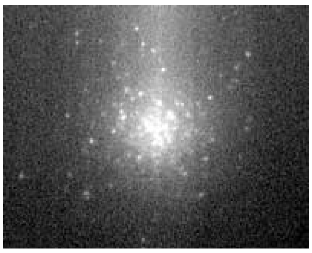
memory area is shielded

Smearing

vertical streak

wikipedia

Smearing



http://www.astrosurf.com/maugis/topo_ccd/smearing.jpg

Interline CCD

Charge simultaneously shifted to shielded gates.

Provides electronic shutter—snapshot operation

Uses photodiodes (better detectors)

Most common architecture for CCDs

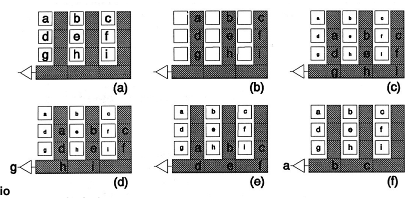


image: Theuwissen

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 CCD's

Advantages:

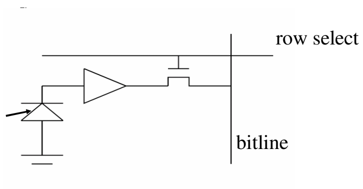
- Optimized photodetectors (high QE, low dark current)
- Very low noise.
- Single amplifyer does not introduce random noise or fixed pattern noise.

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

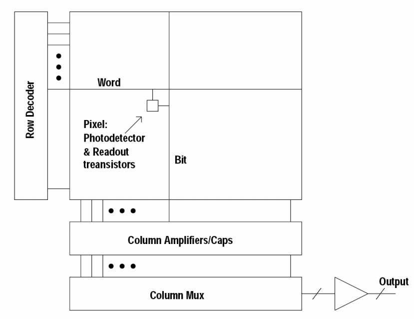


Image : EE392B, El Gamal

Example CMOS Pixel

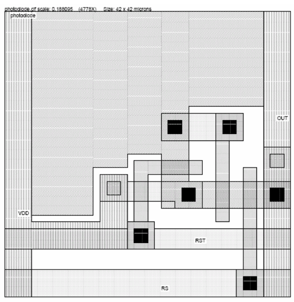
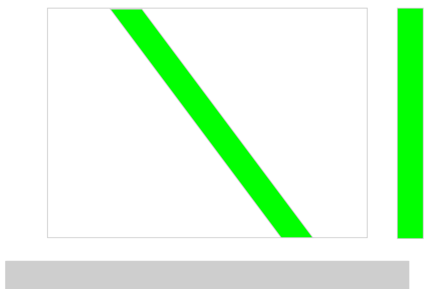


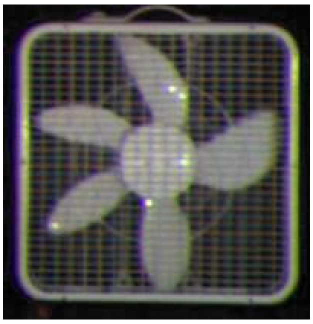
Photo sensitive area is reduced by additional circuitry.

Source: Stanford EE392B notes

Rolling Shutter



Rolling Shutter Distortion



CMOS Sensors

Advantages

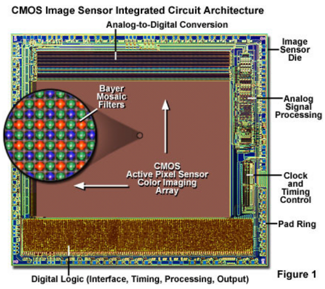
- Integrated digital logic
- Fast
- Mainstream process (cheap)
- Lower power

Disadvantages

- Noise & quality

Most high quality cameras still CCD's.

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)

Sources of noise

Photon shot noise

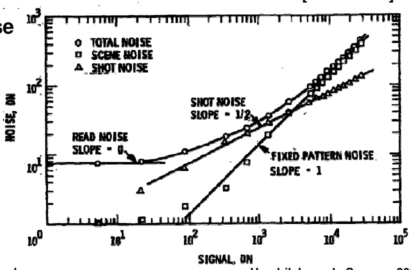
Dark current shot noise

Fixed pattern noise

Readout noise

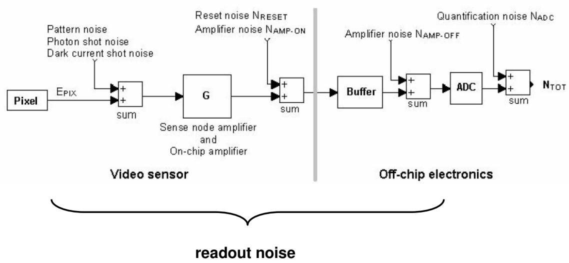
…

[Janesick97]



Noise Sources

[Reibel2003]



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.

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

Dark current

Things besides photons can knock electrons loose in the silicon. These are collected, too.

Highly temperature dependent

- doubles every 5-8 degrees 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

Mean dark current may be subtracted

- but subtracting frames increases shot noise
- subtract the average dark current

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…)

Whatever. What does it mean?

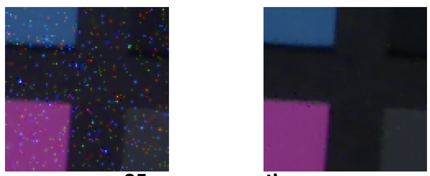
- Independent of the signal.
- Zero mean, white (flat, wide bandwidth)
- Another problem for CMOS, not CCD imagers

Dominates at low signal levels

- 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

Amplifier noise

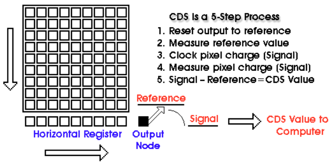
- thermal
- spatially non-uniform
- 1/f noise
- non-linearities

Quantization noise

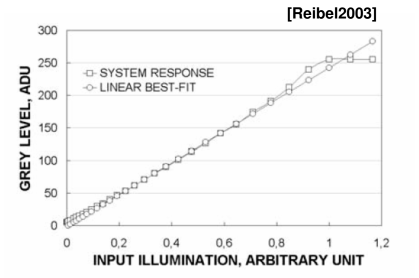
- "truncate" analog value to N bits

Correlated Double Sampling

- reduce noise by comparing against a reference charge



Non-linear Response



Combined Noise Model [Reibel2003]

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

σ^2_{FPN} - fixed pattern noise

σ^2_{R} - readout noise

σ^2_{DSN} - thermal dark current shot noise

σ^2_{PSN} - photon shot noise

σ^2_{PRNU}- photo response non-uniformity

C_{NL} - non-linear effects

Combined Noise Model [Reibel2003]

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σ^2_{FPN} - fixed pattern noise (can be calibrated)

σ^2_{R} - readout noise (CDS)

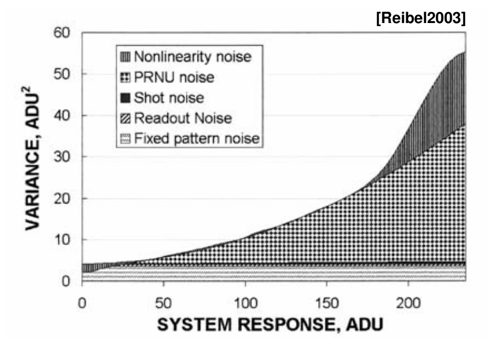
σ^2_{DSN} - thermal dark current shot noise (cooling)

σ^2_{PSN} - photon shot noise (multiple exposures)

σ^2_{PRNU}- photo response non-uniformity (per-pixel gain)

C_{NL} - non-linear effects (can also be calibrated for)

Noise Distribution



Sensing color

Eye has 3 types of color receptors (loosely)

Therefore we need 3 different spectral sensitivities

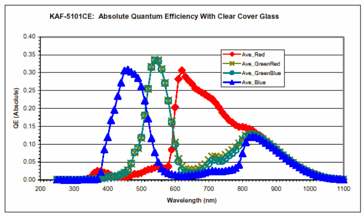


Figure 7. Typical Quantum Efficiency Curves (Clear Coverglass)

source: Kodak KAF-5101ce data sheet

Ways to sense color

Field-sequential color

- simplest to implement
- only still scenes

Proudkin-Gorskii, 1911
(Library of Congress exhibition)

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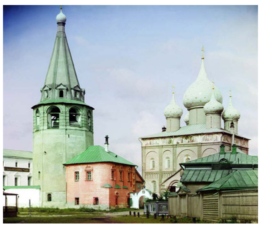


Proudkin-Gorskii, 1911
(Library of Congress exhibition)

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

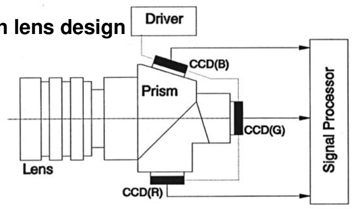
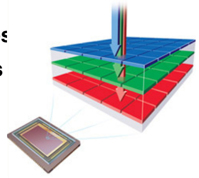


image: Theuwissen

Foveon Technology

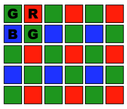
- 3 layers capture RGB at the same location
- takes advantage of silicon's wavelength selectivity
- light decays at different rates for different wavelengths
- multilayer CMOS sensor gets 3 different spectral sensitivities
- don't get to choose the curves



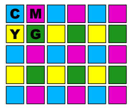
Ways to sense color

Color filter array

- paint each sensor with an individual filter
- requires just one chip but loses some spatial resolution
- "demosaicing" requires tricky image processing



primary

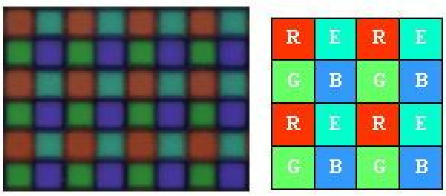


secondary

SONY 4-Color Filter

RGB+E (supposedly halves color errors)

Cyber-Shot DSC-F828



4-color filters

Demosaicing

Original image

Bilinear interpolation

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

Demosaicing

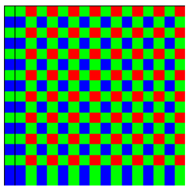
Bilinear interpolation

Edge-weighted interpolation

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

Multi-Shot

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



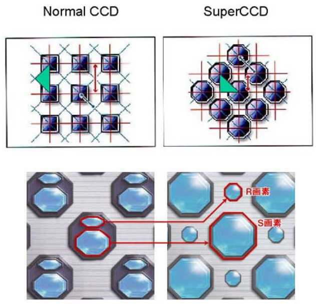
- can be used for supersampling (move by ½, ¼ pixel)

Exotic Sensors

- Super CCD
- HDRC - logarithmic
- HDR – floating point
- PMD

Super CCD

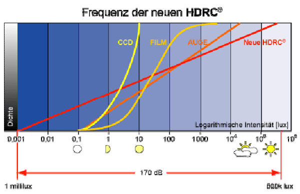
- hexagonal grid
- elements with different sensitivity
- extended DR
- better in low light

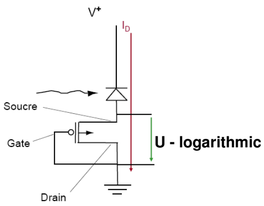


http://www.henner.info/super_ccd.htm

HDRC

- CMOS – pixel amplifier output is logarirthmic



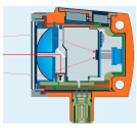


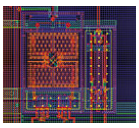
Other HDR approaches

- Determine for each pixel when enough photons haven been collected.
- Logarithmic timings yields floating point representation (mantissa + exponent).

PMD

- measured distance in each pixel
- exploit interference
  - emit light (modulated) at each pixel
  - compare reflected light to reference light
- computation in a “smart” pixel





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Reibel et al., *CCD or CMOS camera noise characterization*, Eur. Phys. J. AP 21, 2003