CMOS image sensors: Concepts

Viewpoint architectures

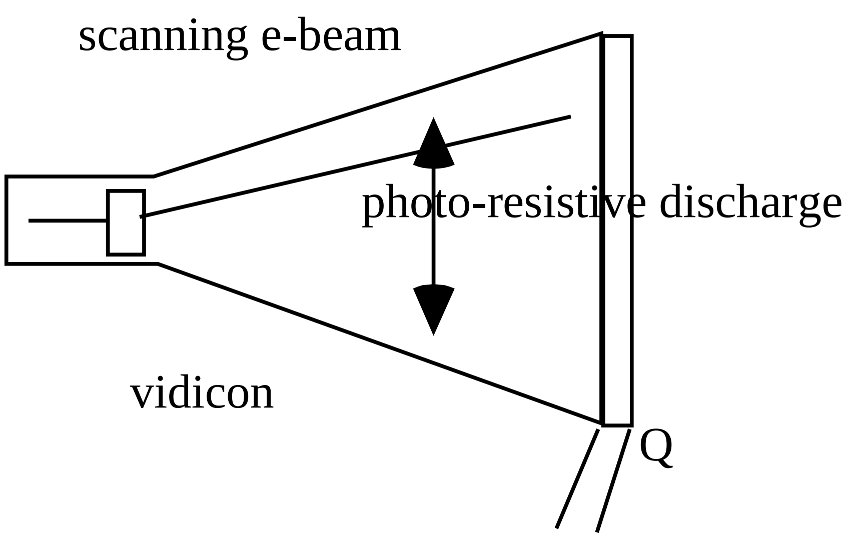
- Methods of scanning
- Methods of light detection in Silicon / CMOS
- Floor plan of a CMOS image sensor
- Basic CMOS pixels
- Special CMOS pixels
- Custom designed sensors

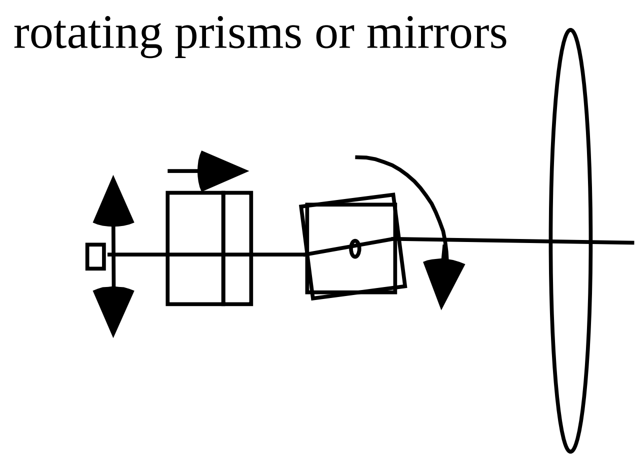
Viewpoint performance

- Silicon versus Film
- CMOS versus CCD
- Units of sensitivity
- Color sensitivity

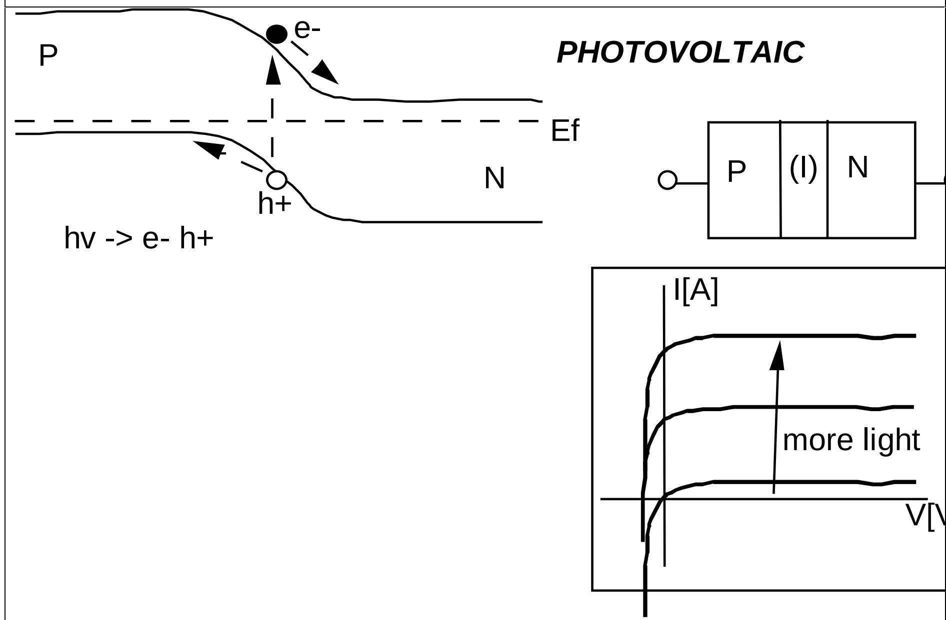
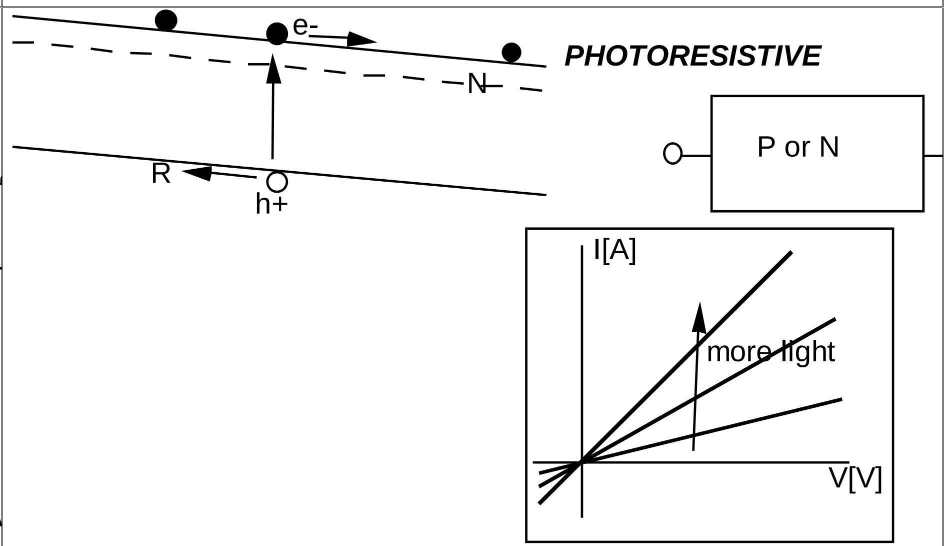
Image sensors can be classified according to the mechanism for scanning the focal plane

Non solid state	Solid state
• image tubes: scanning by an electron beam • opto-mechanical scanning • photographic emulsion: chemical memory • biological systems: parallel processing	• CCD (+ CID, CSD, Photogate): transfer • Diode array or passive pixel: switches • Active pixel CMOS: voltage mux • Field emitter arrays



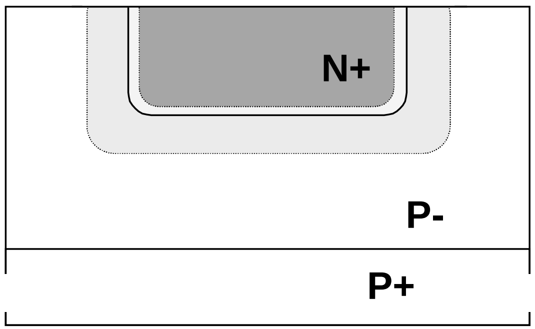
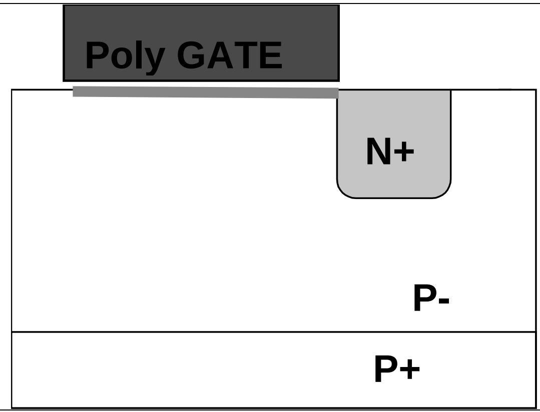
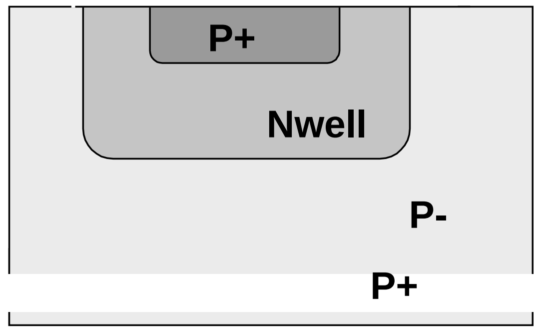


Two main circuit equivalents

Photo voltaic detector ***is a current source***	**Photo resistive detector** ***is a variable resistor***
	

I = f(light power) or I = V/R = V/f(light power)

In practice there are 3 types of light receptors available in *standard* CMOS

Photodiode	Photo gate	Photo transistor (BJT)
		
p-n junction or p-i-n junction	Inversion layer - substrate junction	Well-substrate junction + internal amplification

If one must not adhere to standard CMOS many other light receptors become available:

Light detectors in *non-standard* CMOS	**In Silicon (not even CMOS)**
• Buried diodes, pinned diodes • Photo resistors • Bolometers (temperature sensitive impedance) • Pyro-electric detectors (temperature sensitive polarisation)	• Avalanche photodiode (APD) • P-I-N diodes • Field emitter arrays • Position Sensitive Detectors (PSD) • Buried Channel CCD

Silicon is used

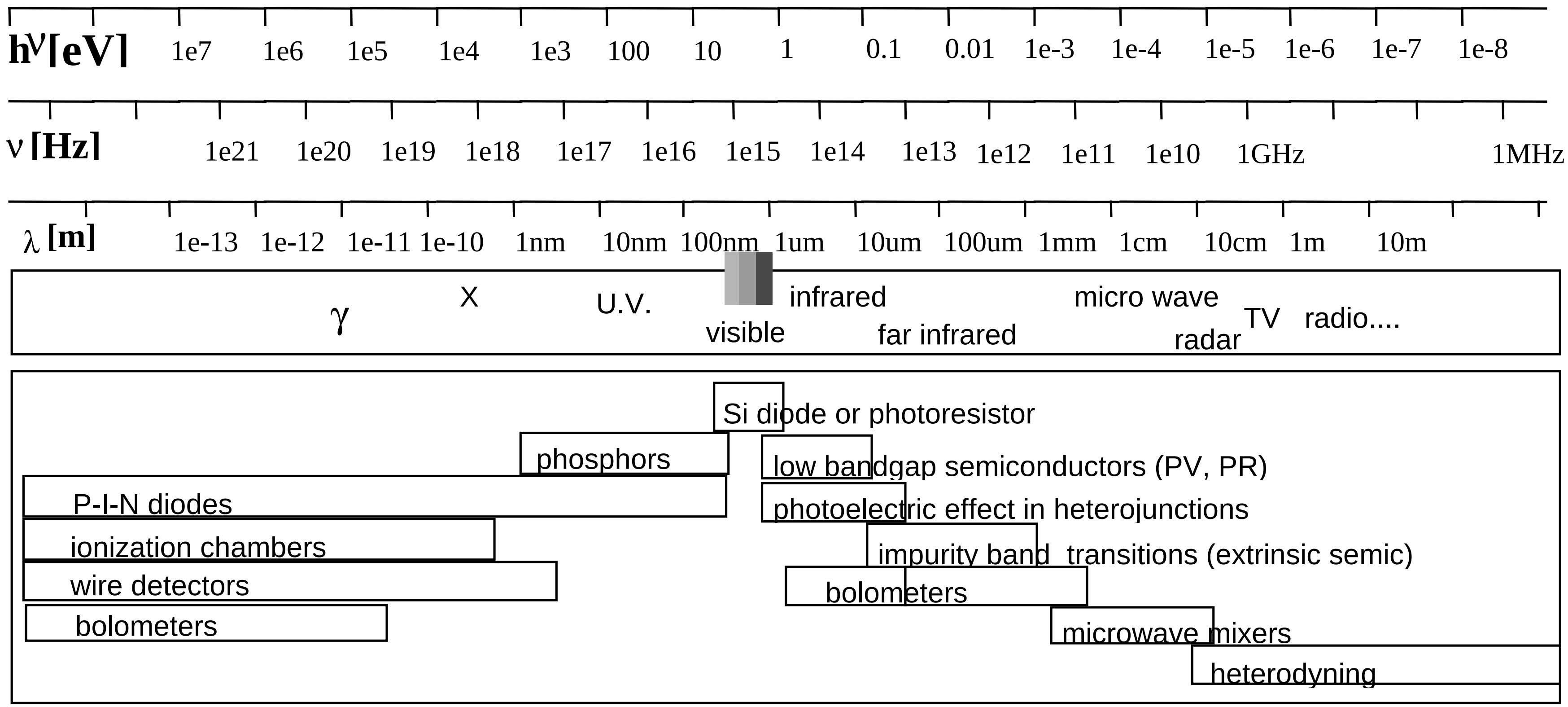
for virtually all short EM wavelengths

the visible range (400nm to 700nm)	Silicon photo diodes and photo resistors Silicon band transition: cut-off: $\lambda = 1200nm$ photon energy = $h\nu = 1.12$ eV
UV (30nm to 300nm)	• *direct* via SI-detectors with surface treatment • *indirect* via phosphorescent (scintillator) screen
X-ray (Röntgen) (< 100 nm, source=accelleration of charges)	• Silicon PIN diodes, as high energy photons have low probability for absorption. • Solid-state ionization chambers
gamma rays (source = nuclear transitions) **cosmic rays** (source = stellar nuclear transitions) ***High-Energy particles*** (electrons, nuclear fission, sub-nuclear physics experiments)	

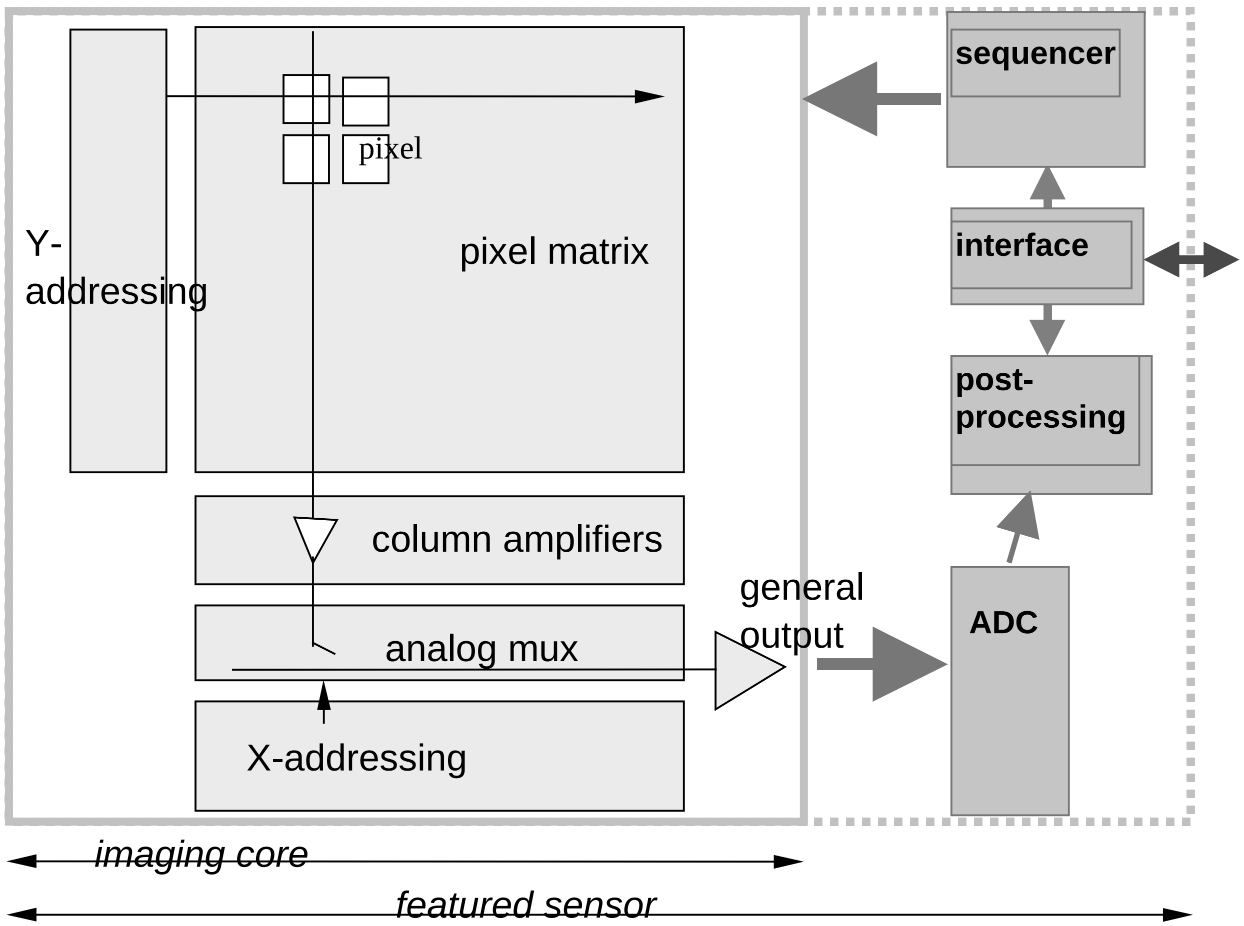
Silicon has competition from other semiconductors for longer wavelengths

Near infrared (NIR 800-2000 nm):	• 800 nm to 1100 nm: Silicon photodiode • detection by band-to-band transitions in lower bandgap semiconductors (IV, III-V, II-VI): InSb, Ge, PbTe, InGaAs, ... • photo-electric effect in silicides: Si:PtSi, Si:CoSi (Schottky-barrier diodes)
Mid-infrared (MIR 3-5um) and **Thermal infrared** (TIR 8-12um)	• direct transitions in ternary very low-bandgap semiconductors: HgCdTe, InGaAs, PbTeSn, … • photo-electric effect in heterojunctions or silicides • detection by uncooled bolometers (heat detectors)
Far infrared (14 um to 1000 um: *scientific*)	• material with bandgap <20meV conceptually impossible • impurity transitions in extrinsic semiconductors (e.g. Si::P, GaAs:Si, ...) (cryogenic) • cryogenically cooled bolometers (thermoresistive, superconductive, ...)
Microwave (300um .. 30 mm)	• non-coherent: as far infrared (cryogenic) • coherent detection: heterodyne receivers
RF, radio, TV... (sub THz)	• coherent detection only

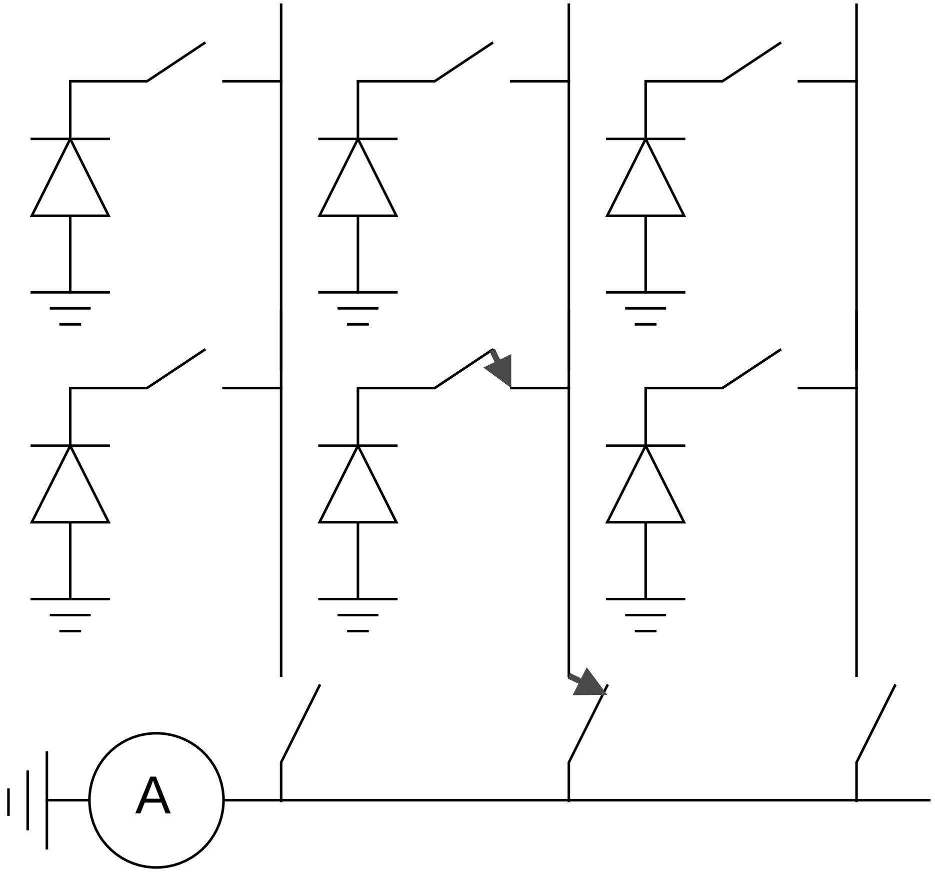
Solid-state detectors for EM-radiation



Floorplan of a typical CMOS image sensor

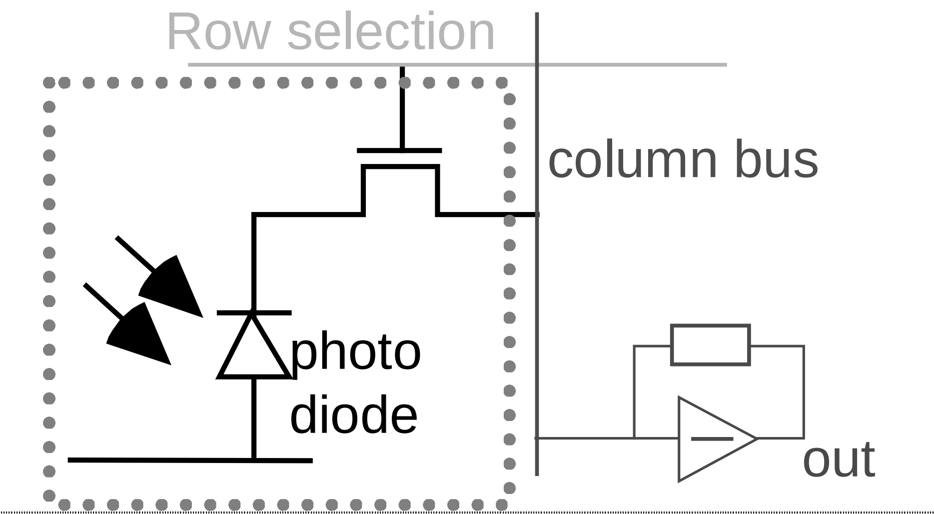


Let’s make a simple MOS image sensor

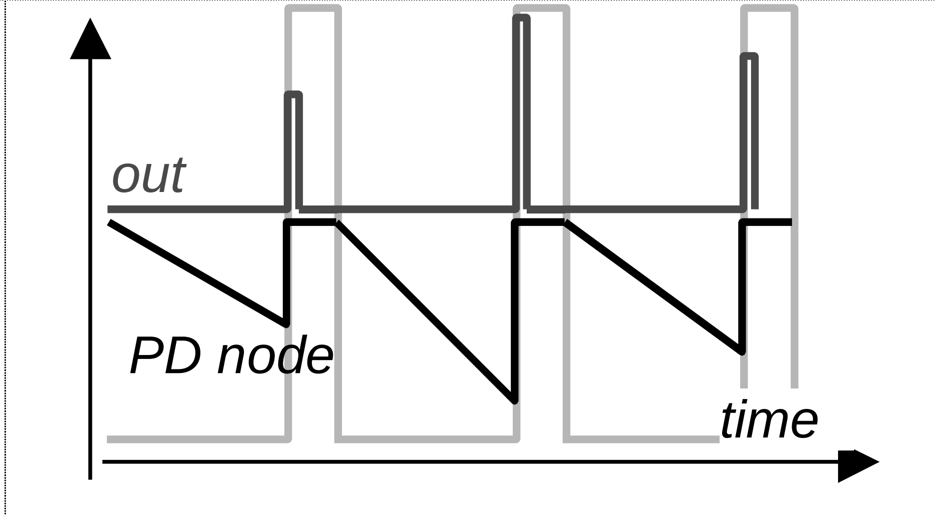


Q: what can be improved here?

The most simple pixel in CMOS: the 1-transistor passive pixel



Schematic

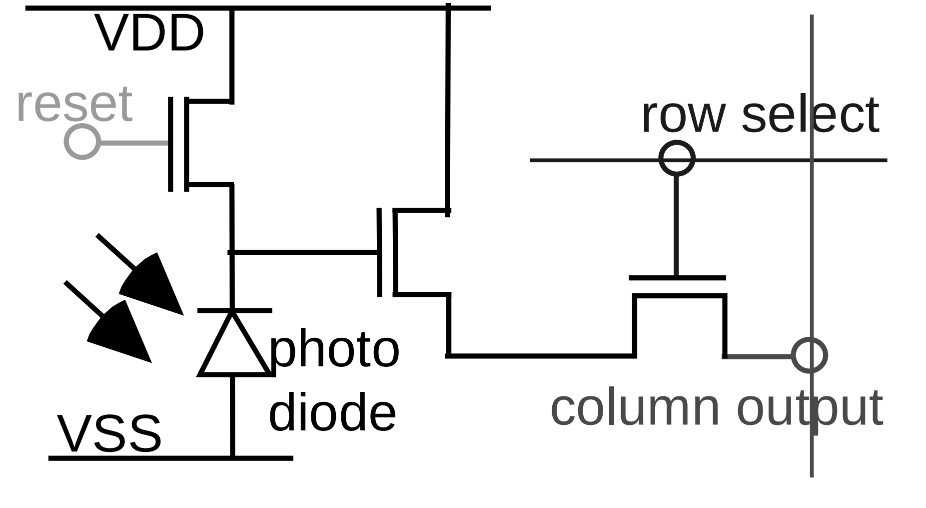


Pixel voltages versus time

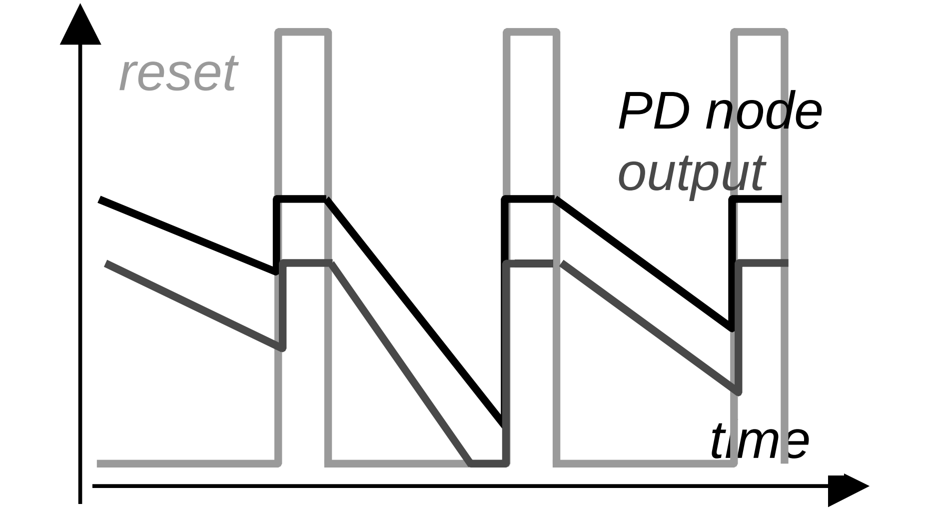
Q: advantages and drawbacks?

The most straightforward active pixel:

The 3T active pixel



Schematic



Pixel voltages versus time

Q: advantages and drawbacks?

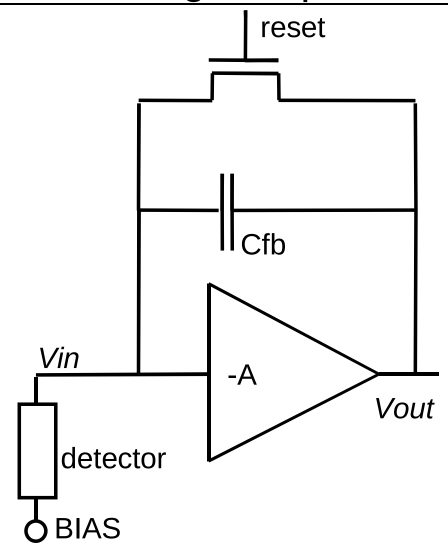
Pixels for detectors with low or defined voltage bias

Many reasons exist to deviate from the basic integrating passive or active pixels→

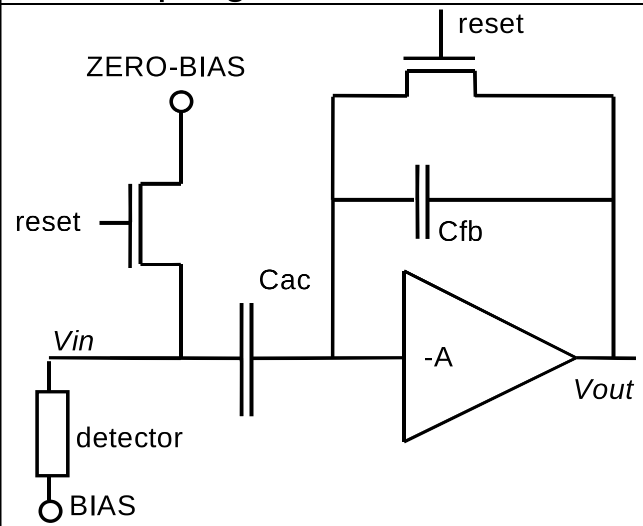
These are a few examples of more complex "pixels" that are suitable to read out a photo receptor while maintaining a constant bias voltage over the receptor ↓

- photoresistive detectors: $I = V/R$ thus $\Delta I = \Delta V/R$
- low bandgap material, with low breakdown voltage
- voltage dependent dark current: $I = Isignal + Vbias*Z$
- avalanche photo diodes require a very precise bias voltage
- detectors with V-dependent memory effects (cryogenic)
- cancellation of a large detector capacitance for response speed
- correction of the non-linear diode capacitance

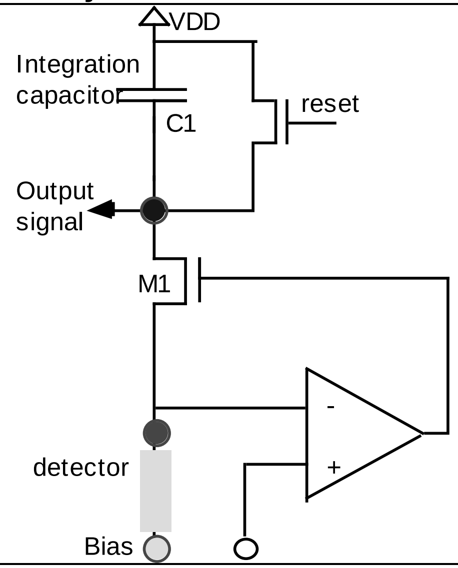
feedback charge amplifier



AC-coupling

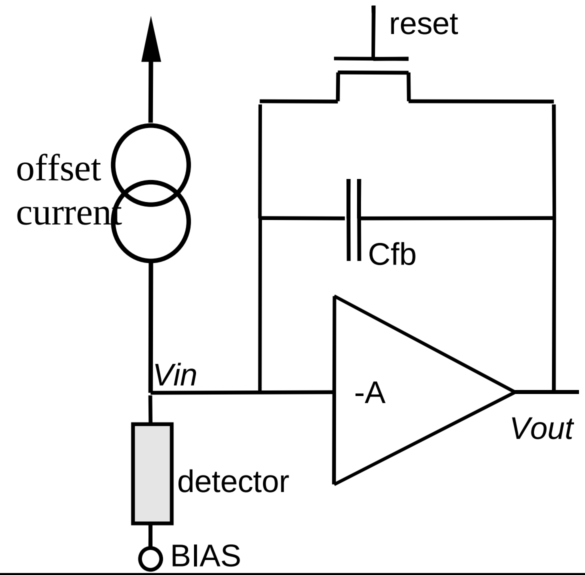
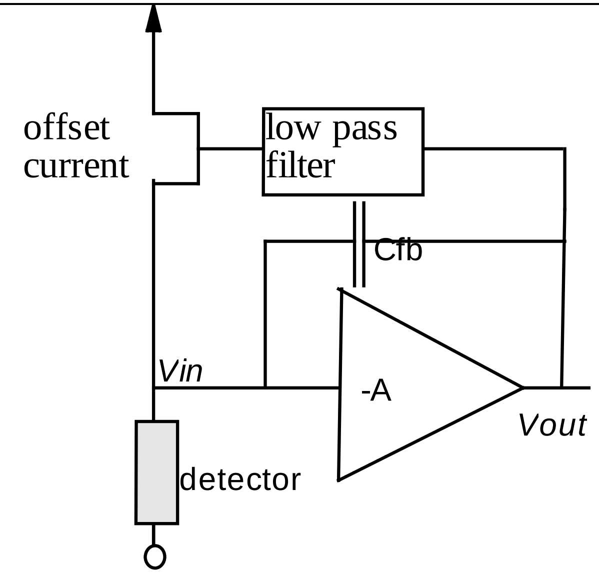
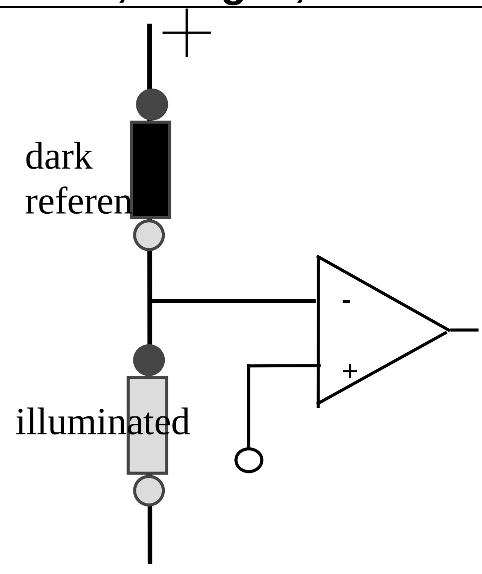


"direct-injection"



Pixels for detectors with high DC currents

The low-level photo current from visible light can be handled easily by the small storage capacitors in normal pixels. These pixels fail in the following cases:	• large dark currents • large DC background signal, as for IR-detectors, or for very intense light sources • modulated information, or beam chopping

Charge amplifier with offset current subtraction	DC / AC separation	difference with a reference detector, bridges, ...
		

Only "standard" needs are solved by "standard" components

special geometry	Application Algorithm	Wafer scale sensor (10x10 cm2) Round shape / matched to image
speed	Data reduction on-chip preprocessing parallelism	Downlink limited Filtering / pattern recognition Limited by I/O
sensitivity	spectral range low light conditions high dynamic range	IR, UV, X, … Very large diodes Logarithmic response
system price	Sensor cost Manufacturing cost Number of components	Single chip + processor
system dimensions	Size Weight	

Silicon image sensors and film are completely different systems

Similarity exists only at the beginning and the end of the process:

1. Photon detection happens by excitation of a bound electron to an unbound state
2. The end product is the same: an image

Differences

- .
- .
- .
- .
- .
- .
- .

silicon vs. film

Silicon	Film
Regular pattern of abutted *pixels* Size typical …10… um	Random placement of randomly sized overlapping *grains*. Size: 0.5 to 10 um.
High dynamic range per pixel. It's signal varies continuously. S/N >1e4 per pixel is possible	A grain is bi-stable: it becomes black or not. The *dynamic range* of patches of homogenous film is limited (about 20). The *S/N ratio* (but not the dynamic range) of patches grows with the number of grains in the patch.
Response is fundamentally linear: 1 photon = 1 electron / QE	3 to 20 photons must be absorbed by a grain to create a latent image. This creates a strong non-linear effect at low light levels.
MTF: regularity of the pixel matrix causes moiré and aliasing	MTF is limited by the smallest grain size. No aliasing.
Dark current limits the integration time	Unlimited integration time.
Key advantage: *electronic processing*	Key advantage: *homogeneity*

Film is by concept non-linear

In silicon photodiode

1 photon = 1 electron (if QE=100%)

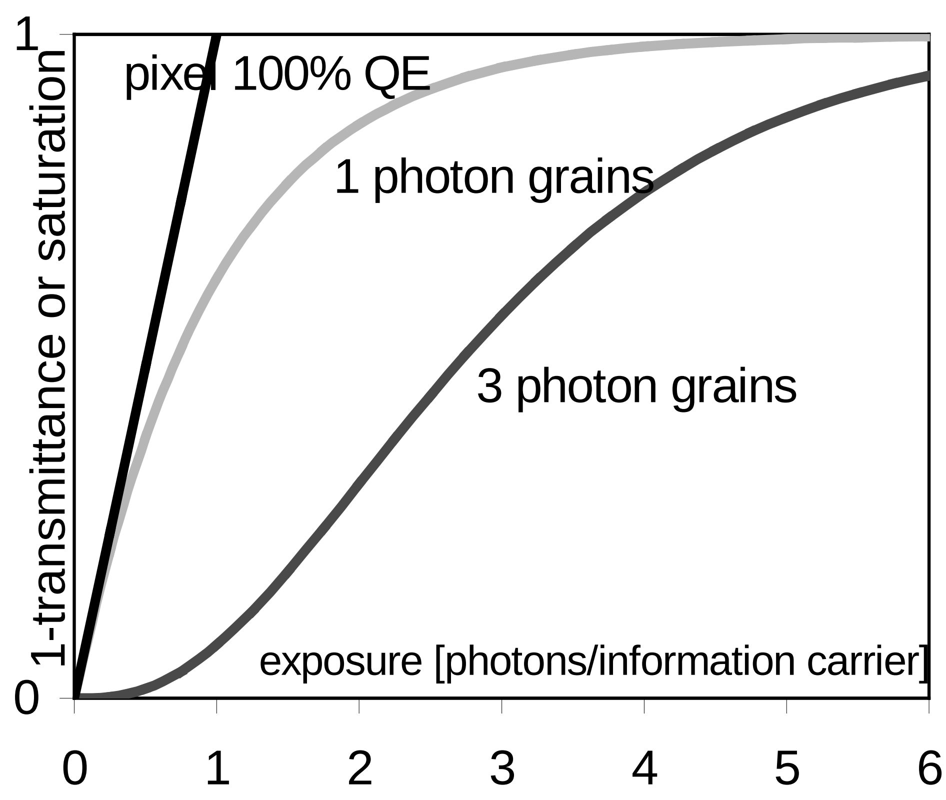
In film grains

The creation of a latent image requires (at least, ideally) 3 photon conversions.
Transmission = probability that a grain remains white = cumulative Poisson probability:

$$T = probability\_white = \sum_{p=0,1,2} \frac{\exp(-n) \times n^p}{p!}$$

n = average number of photons that hit a grain during the exposure time

ideal film: grain contrast x fill factor is 100%.



Q: is non-linearity "bad"?

The image of a thin line is not a thin line

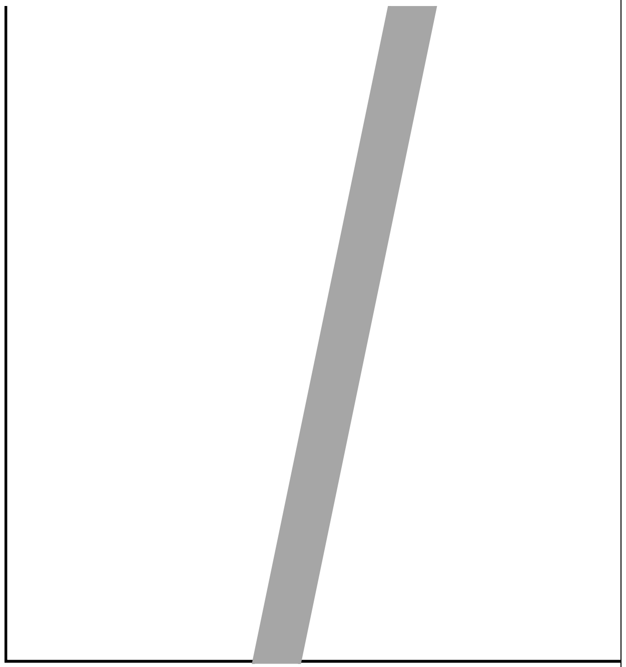
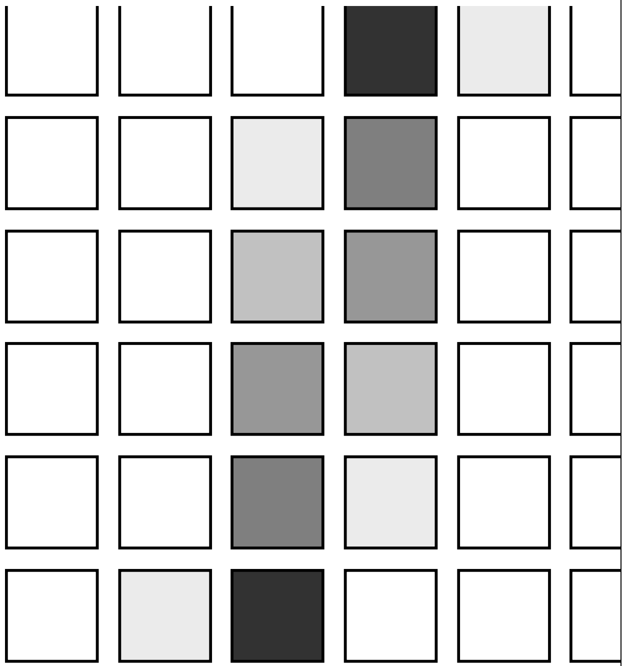
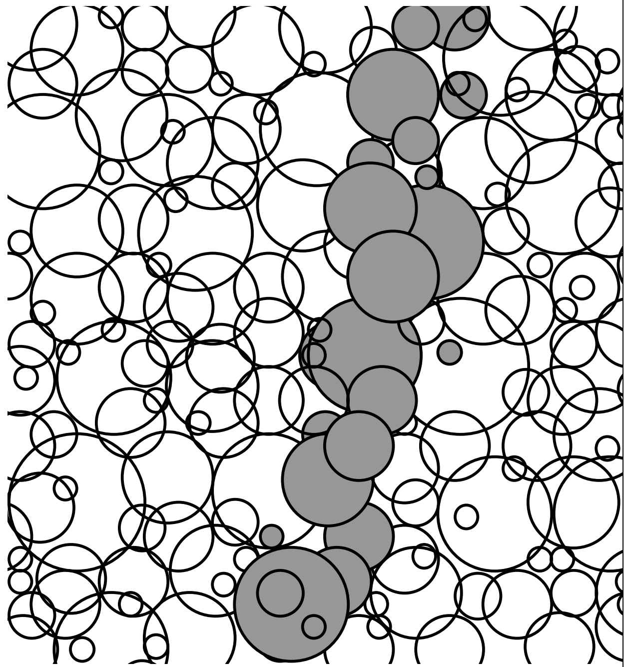


Image of a thin line



Pixel array



Film grains

Silicon vs. Film: S/N * MTF is a quality criterion

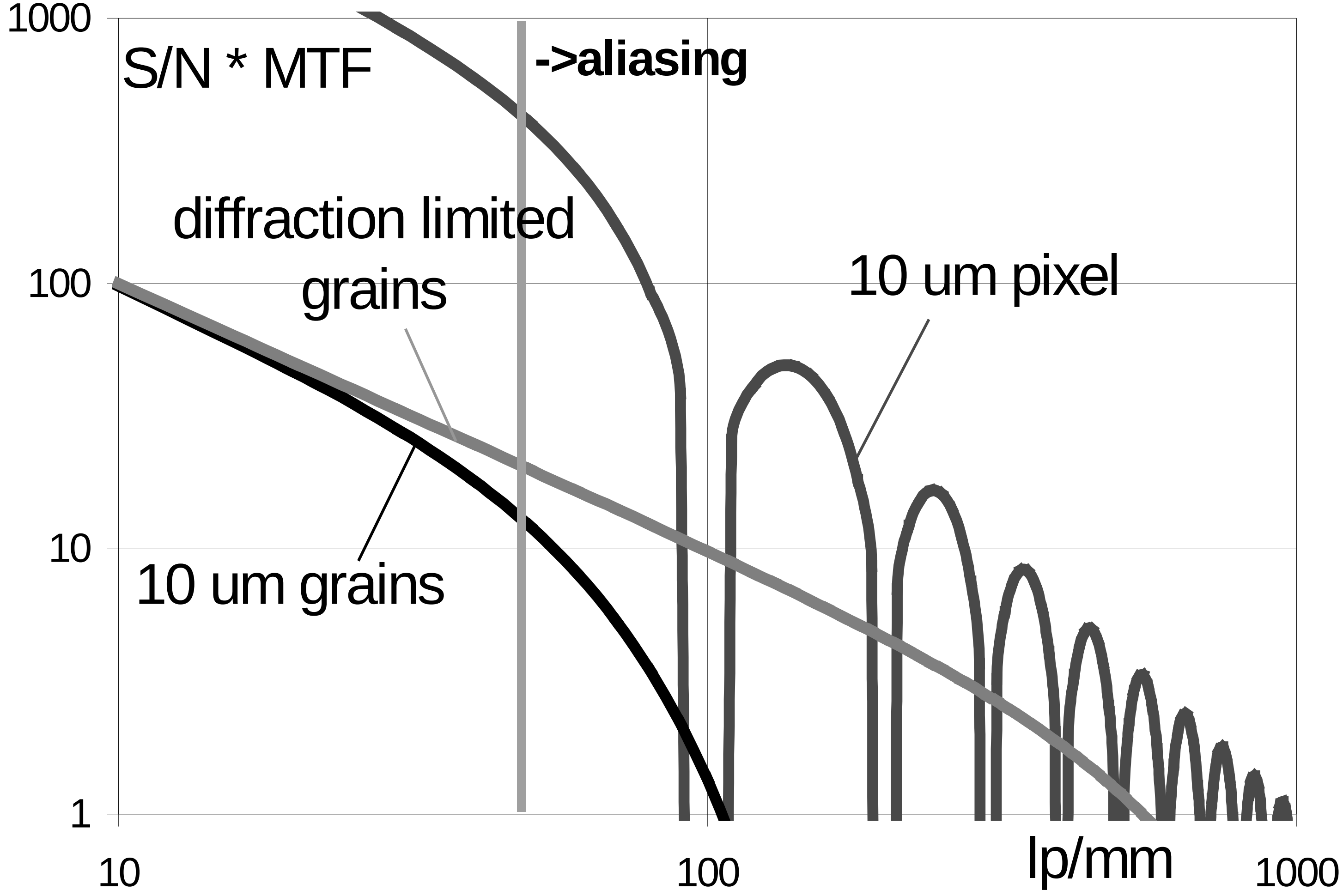
Pixel size 10 x 10 um

100000 saturation electrons per pixel

100 grains per equivalent pixel in film

- very small grains
- large, overlapping grains

Q: MTF<->S/N?



CCD technology

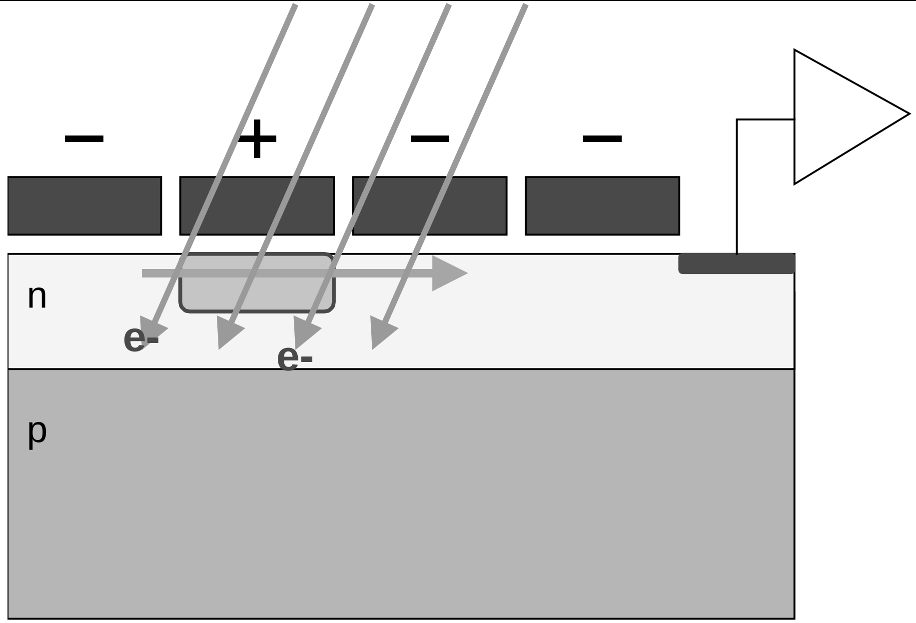
History:

- MOS diode arrays: 1967
- CCD invented in 1970 -> and became quickly the preferred image sensor technology
- MOS active pixels 1980

Technology:
Silicon MOS, but:

- Photodetection in buried diode
- buried channel charge transfer
- closely spaced electrodes

Historically optimized for optical detection



vertical cross section through the CCD register

CCD technology survives because it is really better

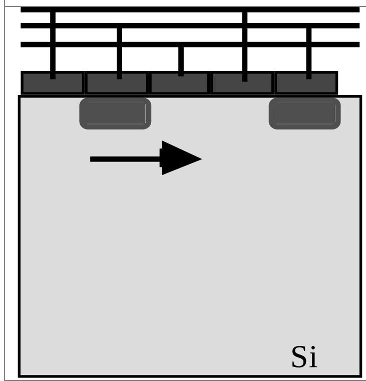
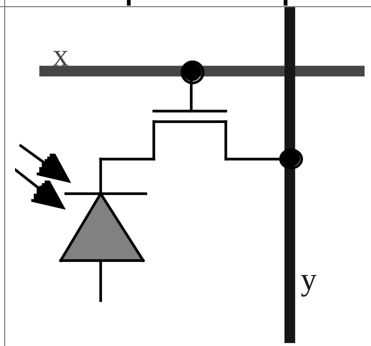
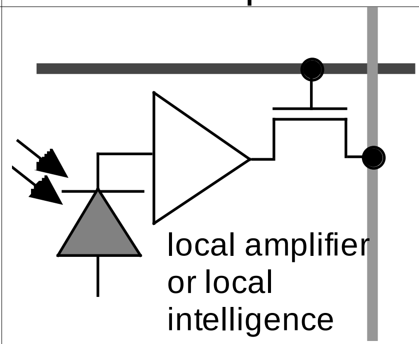
CCD	Standard CMOS	Modified CMOS
high S/N (<50 noise electrons)	lower S/N (>20 noise electrons)	= or less
FPN dark non-uniformity <1%	on chip correction of FPN	=
best PRNU (1..10% p/p)	Higher PRNU	=
very low dark current (10pA/cm2)	higher dark current (nA/cm2)	low dark current (<100pA/cm2)
technology optimized for optical detection	standard technology developed for VLSI logic	limited modifications compared to the standard technology
rare technology	mainstream technology	mainstream & extra steps
no ADC, no logic on chip, …	co-integration of logic - smart sensors	=
limited to serial scanning	random addressing	=
complicated driving and interfacing	digital interfacing	=
	single supply operation	=

not significantly different:

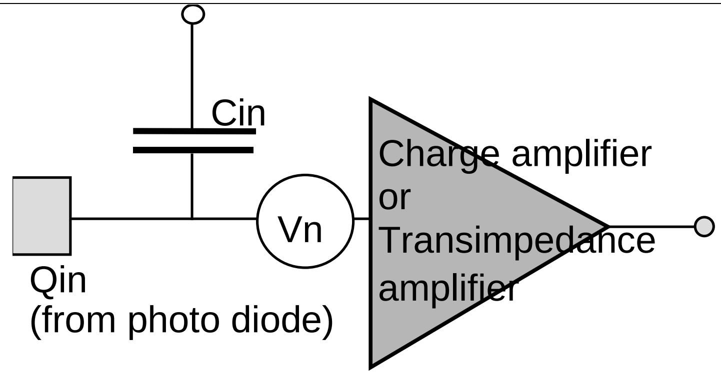
- spectral response (400...1000 nm)
- minimal pixel size (3..5 µm)
- charge storage per unit area
- chip size and number of pixels: limited by lithography
- geometrical stability

The origin of the differences in performance is in the ***photo charge*** to ***voltage conversion***

- temporal noise
- fixed pattern noise

CCD	MOS passive pixel / diode array	MOS active pixel
		
multplexing of charge packets by lossless transfer	Multiplexing by switches on photodiode node	Multiplexing of the local amplifier output
one charge sense amplifier at the end of the CCD register	One charge sense amplifier on the output bus	(charge sense) amplifier in every pixel

Charge sense amplifier is critical part



Qnoise=Vn*Cin

Just as:

$$Q_{signal}=V_{signal}*C_{transimpedance}$$

CCD	Diode array or passive pixel	CMOS active pixel (APS)
• lowest possible Cin • one single low Cin amplifier, thus optimal design and lowest possible Vn • high signal bandwidth • correlated double sampling possible • high fill-factor (FT CCD)	• high Cin (bus lines) • reasonable Vn, but optimized for unfavorable Cin • high signal bandwidth • correlated double sampling is complicated • intermediate fill-factor	• low Cin • one small amplifier per pixel, not optimized for noise: low but not lowest Vn • small signal bandwidth • correlated double sampling is complicated • low fill factor
best performance		
1 noise electron	100 noise electrons	10 noise electrons

Units of sensitivity

Sensitivity: easy to measure but hard to define?

Q: What *does* sensitivity *mean*?

1.…

2.…

3.…

4.…

Sensitivity is…

A good conversion of light power to voltage

Quantity	**unit**	**How to obtain**
Charge conversion factor (C_{eff})	fF	The ratio between photo charge at the pixels and output voltage. "Effective capacitance".
Spectral response (SR)	A/W	Ratio between photo current and incoming light power for a given wavelength
Quantum efficiency	%	Ratio between the number of generated electrons and the number of "impinging photons". $= SR * h\nu / q$
Fill factor (FF)	%	Ratio between the light sensitive pixel area and the total pixel area. (= 100% - Obscuration Factor)
Sensitivity	V.m2/W.s V/lx.s	Output [V/s] versus input [W/m2] Output [V/s] versus input in [lx]
ASA / ISO	-	Empirical procedure to obtain equivalent film speed

Sensitivity: see a faint signal in a fixed shutter time

Quantity	unit	How to obtain
Temporal noise (N)	mV RMS	RMS of consecutive samples of the output voltage for one pixel. *If not otherwise indicated, one silently assumes the noise in the dark, i.e. in the most favorable condition*
Fixed pattern noise (FPN) or spatial noise	mV p/p	Static spread of (dark) voltages of all pixels of the array
Noise charge (Q_{noise}) or Number of noise electrons (#e-)	C "electrons"	$N * C_{eff}$ $N * C_{eff} / q$
Number of noise photons (#hν)	"photons"	= #e- / QE / FF
Noise equivalent power (NEP)	W	Light power equivalent to RMS noise in one pixel in one frame $NEP = N*C_{eff}/t_{int}/SR$
Specific noise equivalent power (NEP*)	W/√Hz	NEP normalized to 1 Hz framerate NEP* = NEP / √framerate *only in case of white noise*
Specific detectivity (D*)	cm√Hz/W	NEP* normalized to pixel area A $D^* = (\sqrt{A} \times \sqrt{framerate}) / NEP$
Background limited integrated performance (BLIP). Sometimes called "shot noise limited"	-	NEP or other performance units obtained *not* using the dark noise (N), but the shot noise at the lowest signal level ("background") that will occur in reality. *In a BLIP system, the limiting noise is shot noise. It is thus "ideal"*
Sensitivity in lux	Lx	Lowest (environment) average light level for "good" sensor operation, at nominal speed,
Noise equivalent lux	Lx	As above, but the light level corresponding to the RMS noise
Saturation lux	Lx	As above, but the light level corresponding to saturation in nominal operation conditions

Sensitivity is…

The ratio of the signal and the uncertainty thereof

Quantity	**unit**	**How to obtain**
Signal to Noise ratio (S/N or SNR)	1	Output signal voltage range / output signal noise in the dark
Differential or small-signal S/N (dS/dN or dSNR)	1	Output signal saturation voltage / output signal noise at the same signal level
Noise equivalent contrast ratio (NECR)	%	Noise measured at a certain signal level / that signal. *The ability to discriminate between nearby gray levels. =1/dSNR*
Dynamic range (DR)	1	Saturation *intensity* / noise equivalent *intensity* In a linear system this is the same as S/N.
Generalized dynamic range	1	More general definition for DR: the ratio between upper and lower *intensities* for which dSNR==1.
Linear dynamic range (LDR)	1	Largest intensity for which dVolt/dIntensity is linear
Photo response non-uniformity (PRNU)	% p/p	Static spread of Ceff of the pixels the array
Background limited integrated performance (BLIP). Sometimes called "shot noise limited"	-	DR or other performance units obtained *not* using the dark noise (N), but the shot noise at the lowest signal level ("background") that will occur in reality. *In a BLIP system, the limiting noise is shot noise. It is "perfect"*
ADC bits	1	Number of (useful) bits in the digital output

Sensitivity is…

To see a faint signal in an *unlimited* shutter time

Quantity	**unit**	**How to obtain**
Dark current (Idark)	A or A/cm2	(apparent) photodiode current in the dark per pixel or normalized per unit area
Dark signal (Vdark)	V or V/s	(apparent) signal voltage [drop] in the dark, due to dark current
Autosaturation time t_{auto}	s	Longest possible integration time, where the dark signal consumes the complete output voltage range
Dark lux (*) Dark flux	Lx W/m2	Light intensity level equivalent to the dark current
ASA / ISO	-	Empirical procedure to obtain equivalent film speed
Background limited integrated performance (BLIP). Sometimes called "shot noise limited"	-	NEP or other performance units obtained *not* using the dark noise (N), but the shot noise at the lowest signal level ("background") that will occur in reality. *In a BLIP system, the limiting noise is shot noise. It is thus "perfect"*

*

1 W/m2 is ±70 lx (visible light only)
1 W/m2 is ±180 lx (over full Silicon diode band)
Lx is either given in the environment (a camera specification), or at the focal plane (a sensor specification).

RGB color sensitivity in CMOS

There are 4 ways to give 3-color sensitivity to an area image sensor

	pro	***contra***
sequential illumination with 3 light sources or filters	standard BW -sensor	Slow Static objects only Only in controlled environment
triple sensor and red-green-blue dichroic filters	optimal resolution optimal speed	Delicate construction
red-green-blue polymer color filter pattern	"normal" BW sensor with extra layers	only one color per pixel available: reconstruction? artifacts?
Vertically spectrally separate photodiodes	all color information in the same pixel	non-standard CMOS bad color separation time domain multiplexing

3 vertically stacked photodiodes per pixel	Color filter array on top of pixel array (every pixel has only one color)