Lecture 04:
Solid State Detectors:
CCD, CMOS and IRFPA

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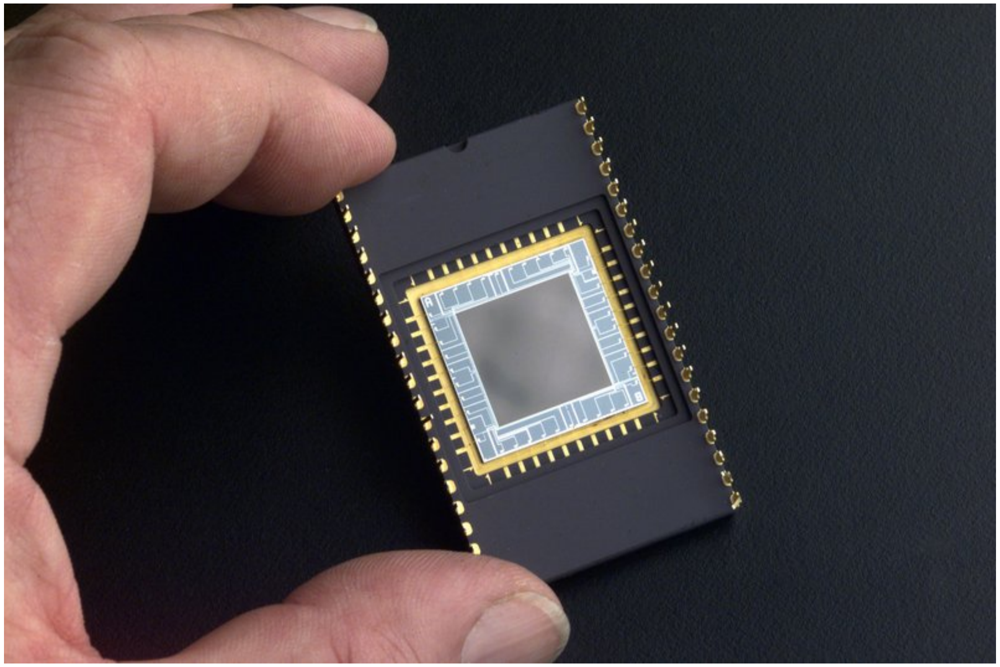
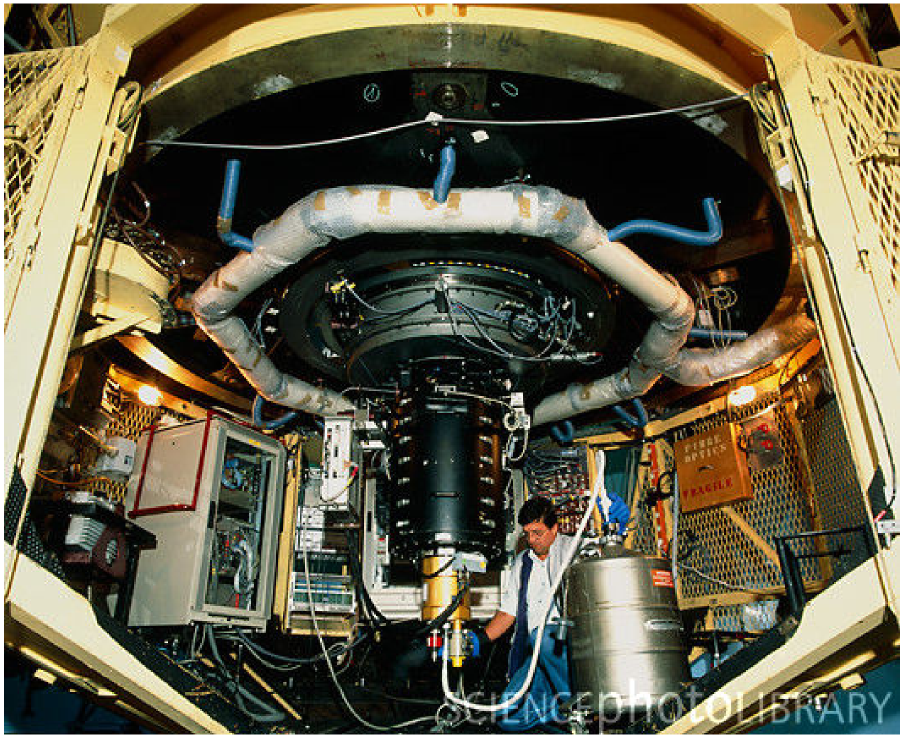
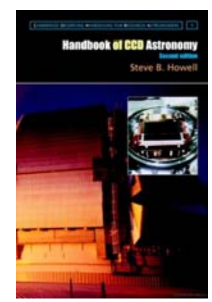


Outline



- What is Solid State Detector?
- Basic Operating Principle
- Performance of Solid State Detectors
- CCD, CMOS and IRFPA
- Observation with Solid State Detectors

Textbook: Handbook of CCD Astronomy, Steve B. Howell



1. Introduction

- ***History***
- ***What are Solid State Detectors?***
  - ***CCD – Charge Coupling Device***
  - ***CMOS – Complementary Metal Oxide Semiconductor***
  - ***IRFPA – Infrared Focal Plane Array***
- ***Why Use Solid State Detectors for Astronomical Imaging ?***
  - ***Naked eyes***
  - ***Films***

History

- *First CCD was designed in AT&T Bell Lab in 1969*
- *Willard S. Boyle and George E. Smith, Murray Hill, NJ*
- *Awarded with the Nobel Prize in Physics for 2009*
- *First astronomical image with a CCD camera came out in 1975*

What is Solid State Detector ?

- *A Solid State Device is a photosensitive device that converts light signals into digital signals*
  - *An incoming photon kicks an electron in the conduction band*
  - *The read-out system gives a digital signal*
- *Typically, the three main types in astronomical imaging are CCD, CMOS and IRFPA*
  - *CCD: Charge-Coupled Device*
  - *CMOS: Complementary Metal-Oxide Semiconductor*
  - *IRFPA: Infrared Focal Plane Array*

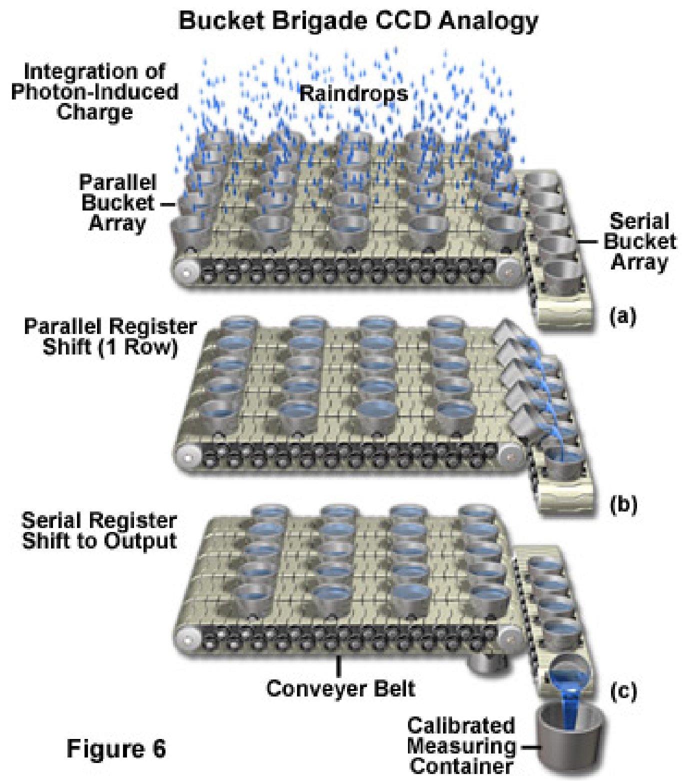
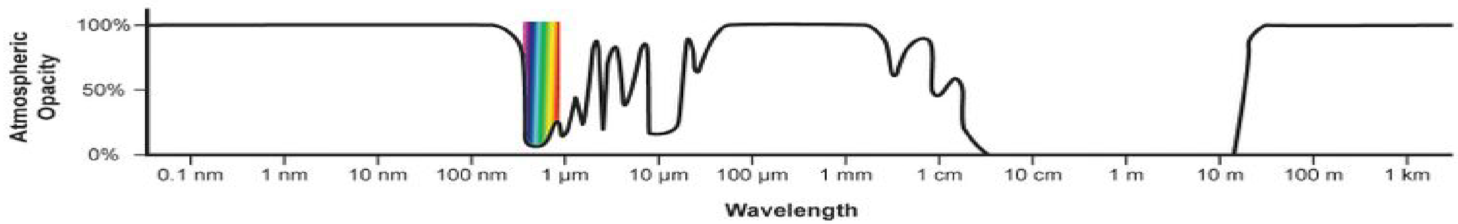


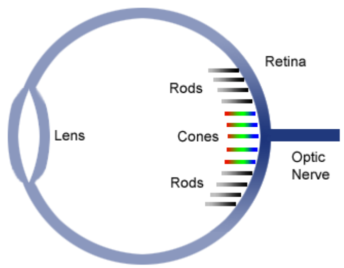
Figure 6

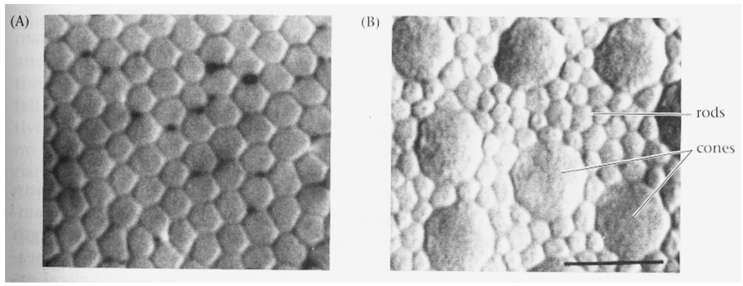
Why not Naked Eyes ?

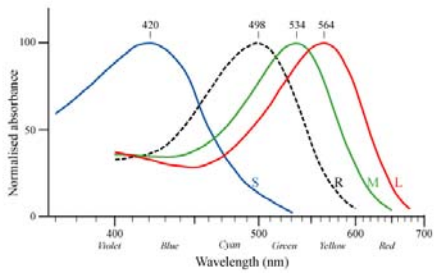
- ***Visible to human eyes: 380 ~ 780 nm***

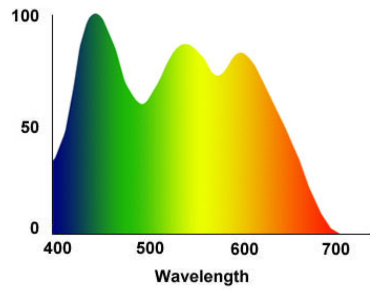


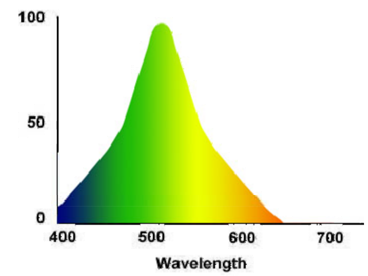
- ***Human eyes: good optical system***
  - *6 M cones*
  - *200 M rods*
  - *Logarithmic sensor*
  - *Daylight (Photopic) vision*
  - *Nighttime (Scotopic) vision*



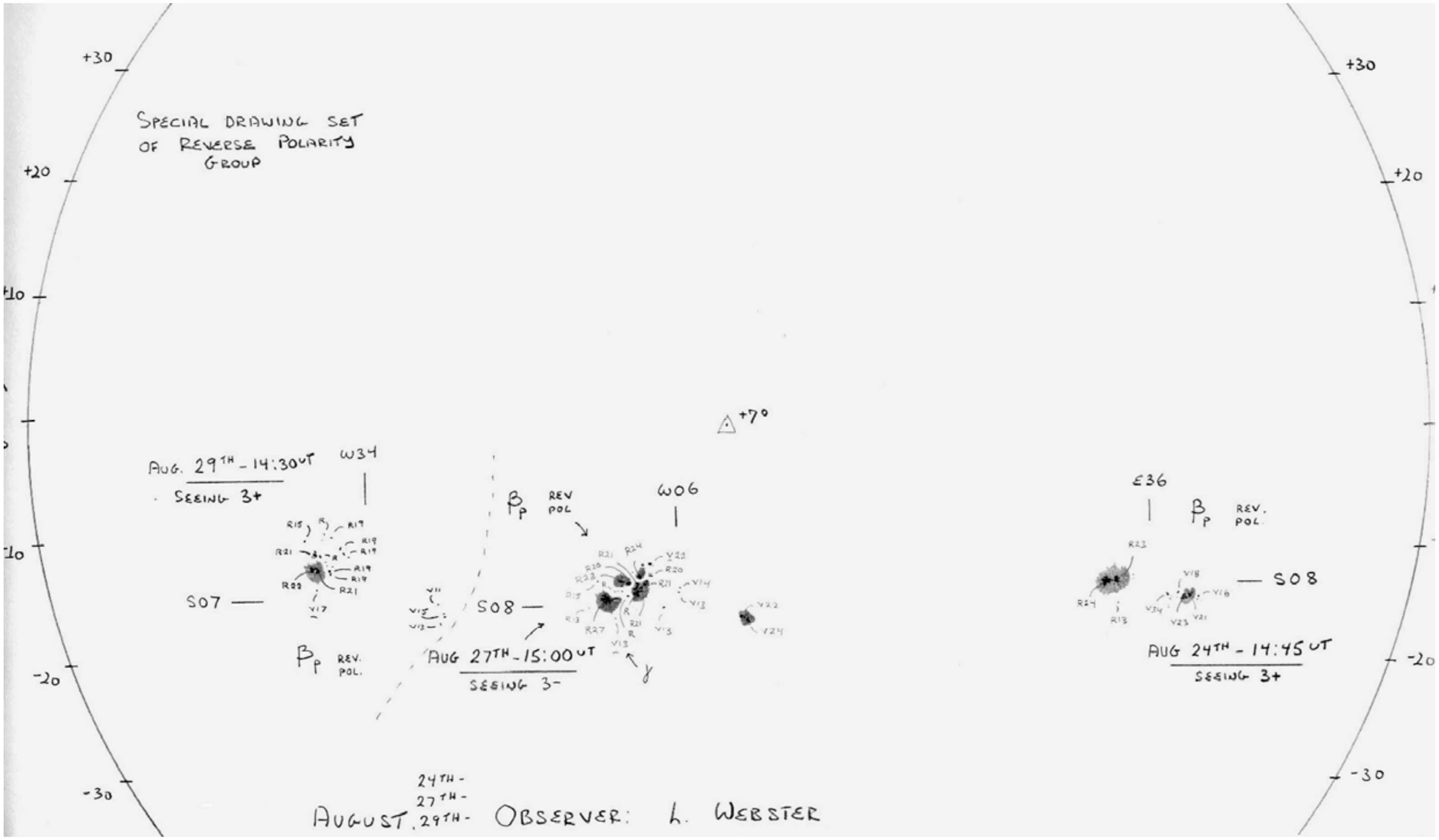






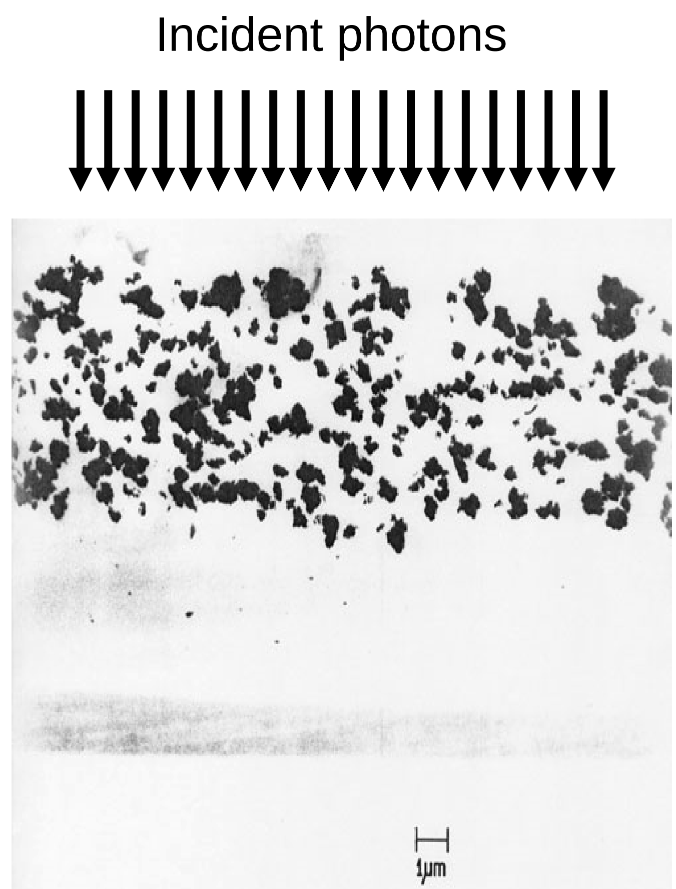


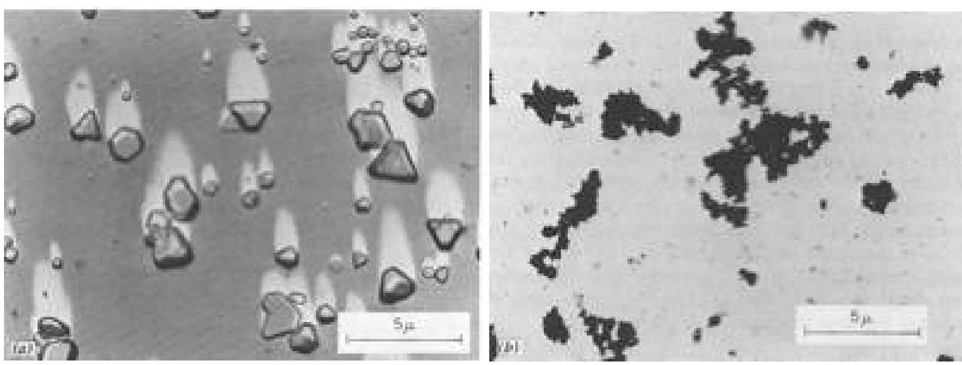
Naked Eye Solar Observation



Why not Films ?

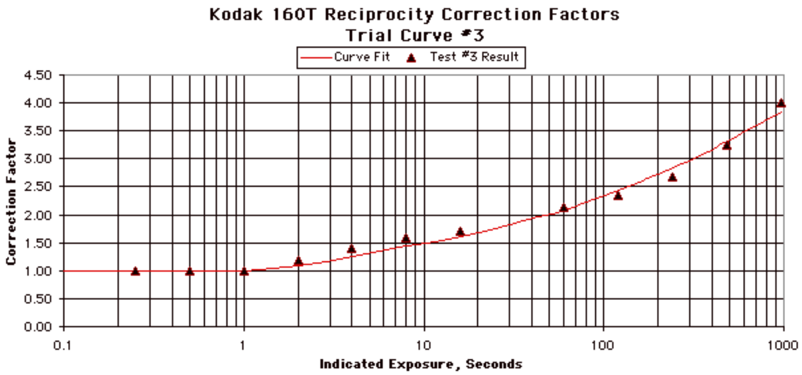
- *Film: silver emulsion on film*
- *Allow objective measurements and light integration*
- *Broader spectral coverage and acceptable QE*

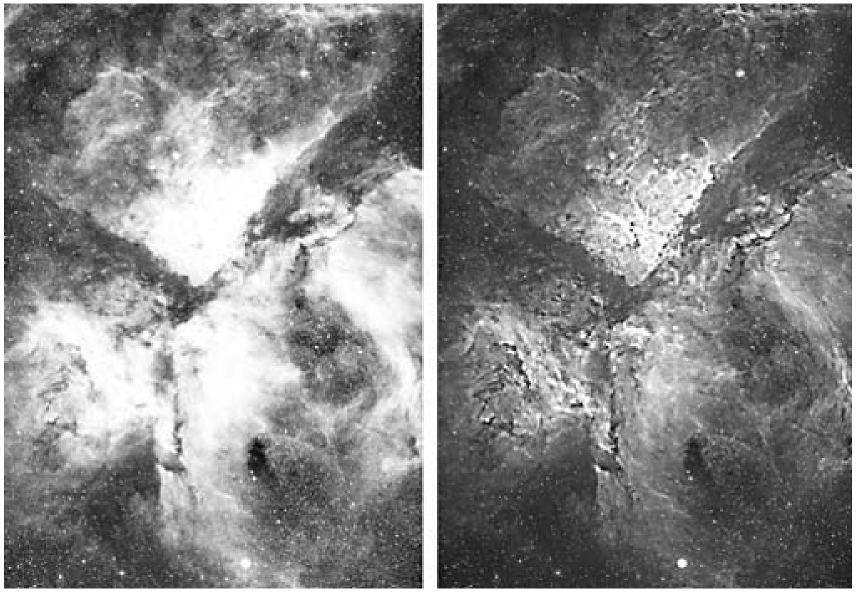




Why not Films ?

- Reciprocity failure
- Very long exposure (low QE)
- Nonlinearity
- Low dynamic range
- Resolution
- Not allow post-processing





Pros and Cons

Films

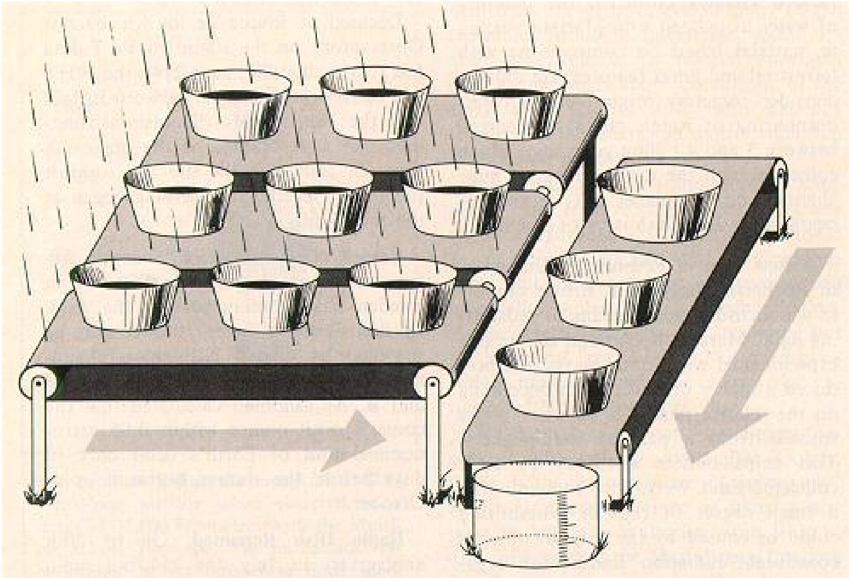
- *reciprocity failure beyond a few second exposure*
- *minimal light intensity required to detect a target at all*
- *low quantum efficiency (5 ~ 20% at optimal wavelengths)*
- *response to light is non-linear*
- *small dynamic range (6-bit)*
- *picture elements (grain) are randomly distributed*
- *needs to be processed in a chemical darkroom*
- *good MTF*

Solid State Devices

- *no loss of sensitivity to light during exposure*
- *no minimal light intensity required to detect a target*
- *high efficiency of light detection (up to 50 ~ 90%, though device- and wavelength-dependent)*
- *signal is proportional to light intensity*
- *large dynamic range (typically 16-bit)*
- *picture elements (pixels) are regularly spaced*
- *ready for digital processing*

2. Basic Operating Principle

- ***Step 0 - Light into Detector***
- ***Step 1 - Charge Generation***
- ***Step 2 - Charge Collection***
- ***Step 3 - Charges Transfer***
- ***Step 4 - Charge-to-Voltage Conversion***
- ***Step 5 - Digitization***



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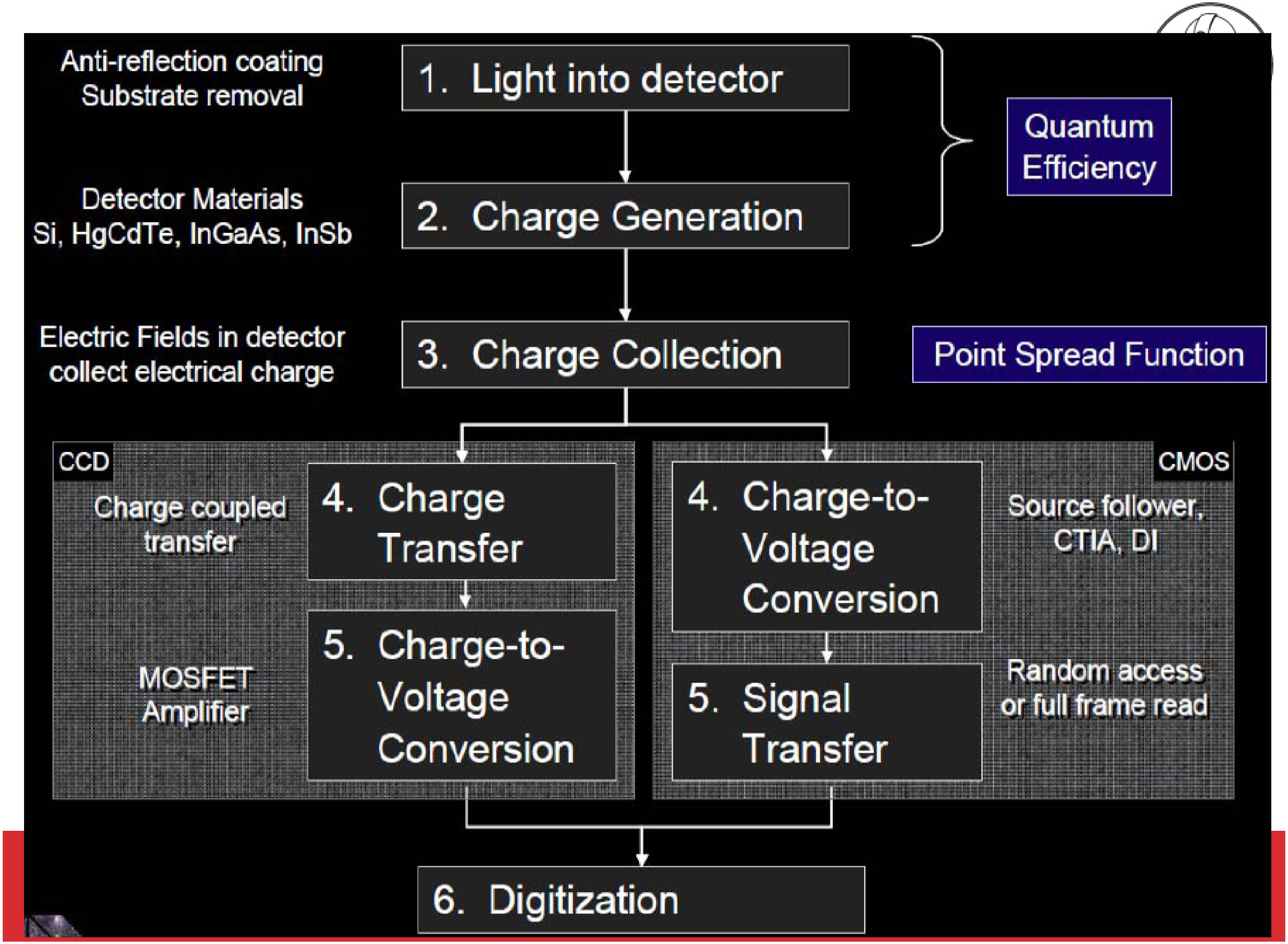
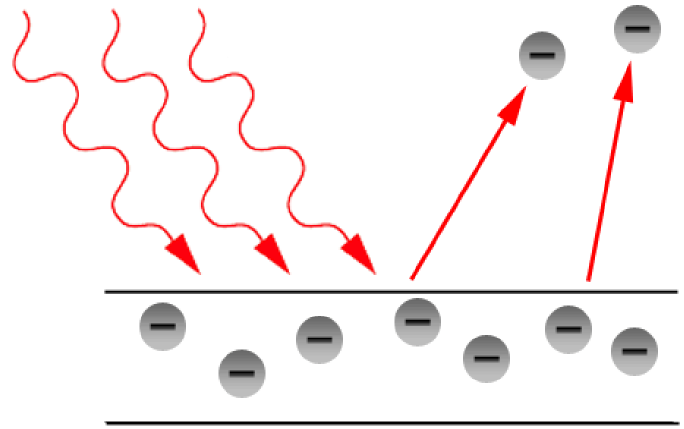
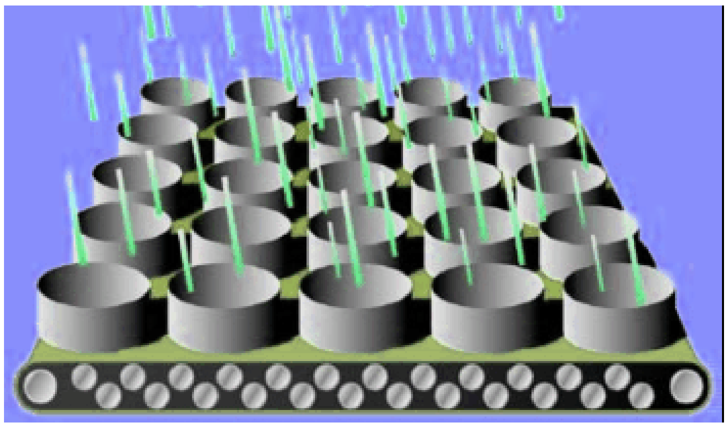


Anti-reflection coating
Substrate removal
1. Light into detector
Detector Materials
Si, HgCdTe, InGaAs, InSb
2. Charge Generation
Quantum Efficiency
Electric Fields in detector collect electrical charge
3. Charge Collection
Point Spread Function
CCD
Charge coupled transfer
4. Charge Transfer
MOSFET Amplifier
5. Charge-to-Voltage Conversion
CMOS
Source follower, CTIA, DI
4. Charge-to-Voltage Conversion
Random access or full frame read
5. Signal Transfer
6. Digitization

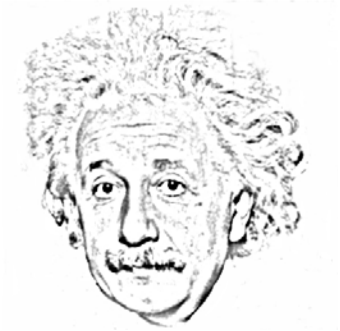
2.1 Charge Generation

- *Photoelectric Effect*
- *Photoelectric Material*
- *Conductors*
- *Insulators*
- *Semiconductors*
- *Band Gap Energy*
- *CCD, CMOS and IRFPA Photoelectric Materials*





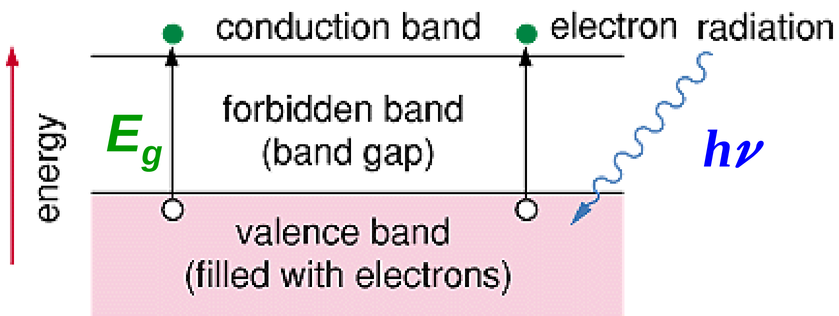
Photoelectric Effect



- *For an electron to be excited from valence band to conduction band*

$$h\nu \geq E_g$$

  - ***h*** *= 6.63 ×10^{-34} Joule ·s (Planck constant)*
  - ***ν = c / λ*** *(Frequency of light)*
  - *E_g: electron-volts (Energy gap of material)*



- *Long wavelength cut-off*

$$\lambda \leq \frac{1.238}{E_g(eV)} = \lambda_{cut-off}(\mu m)$$

- *Silicon: E_g = 1.12 eV, $\lambda_{cut-off}$ = ?*

Periodic Table

Periodic Table of the Elements

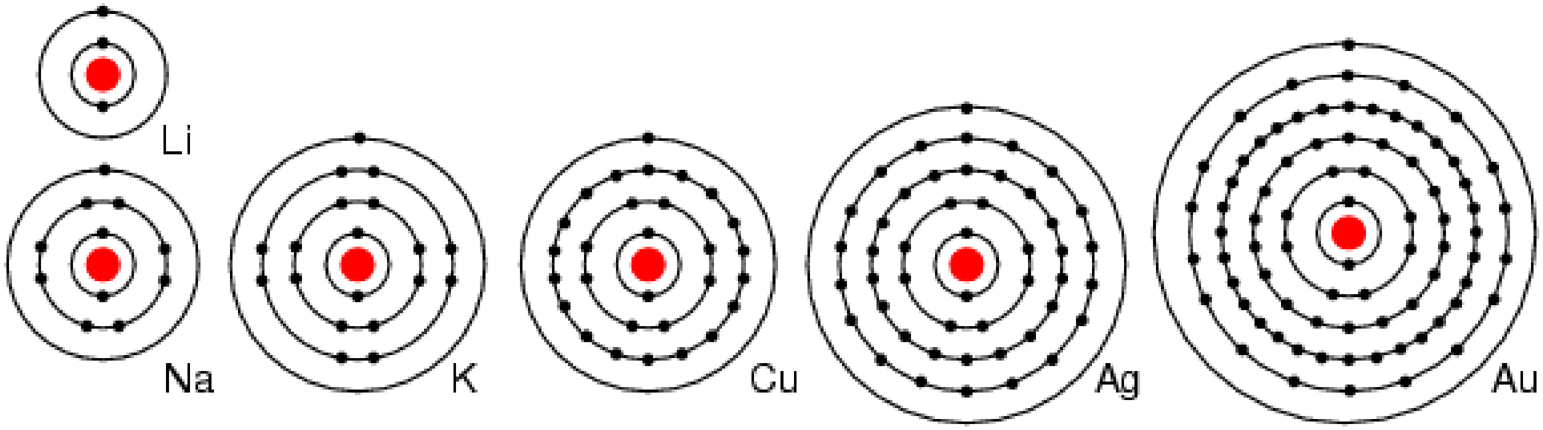
	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	O
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110 110	111 111	112 112	113 113					

* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

- ***Material properties depend on outer electron shell***

Conductors

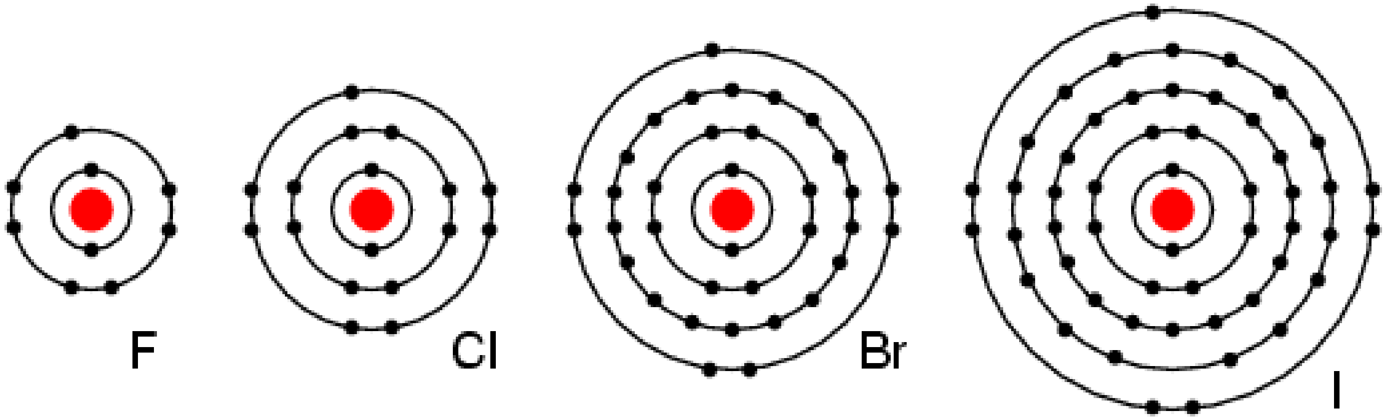
- *Li, Na, K, Cu, Ag, and Au have a single valence electron.*
- *These elements all have similar chemical properties. These atoms readily give away one electron to react with other elements.*
- *The ability to easily give away an electron makes these elements excellent conductors.*



- *Periodic table group IA elements: Li, Na, and K, and group IB elements: Cu, Ag, and Au have one electron in the outer, or valence, shell, which is readily donated.*

Insulators

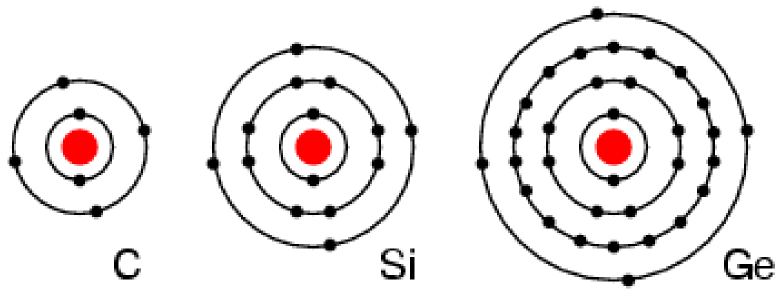
- *Group VIIA elements: Fl, Cl, Br, and I all have 7 electrons in the outer shell.*
- *These elements readily accept an electron to fill up the outer shell with a full 8 electrons.*
- *These elements which do not give up electrons are insulators.*



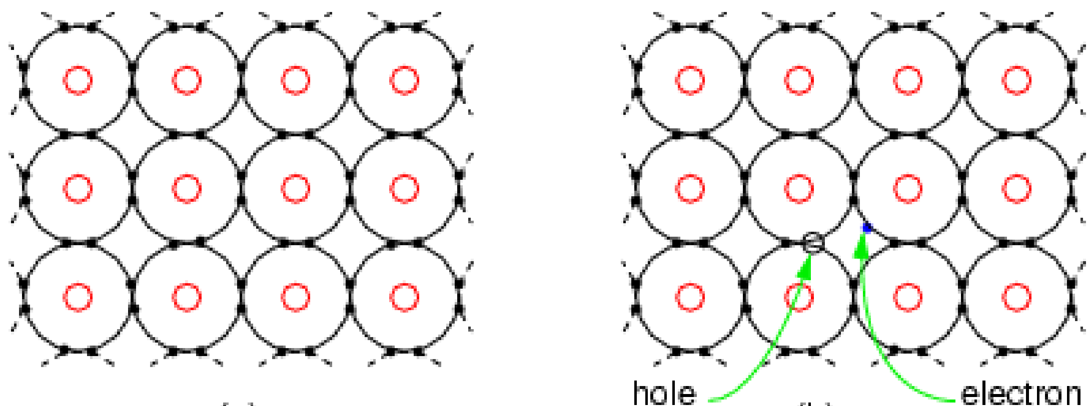
- *Periodic table group VIIA elements: F, Cl, Br, and I with 7 valence electrons readily accept an electron in reactions with other elements.*

Semiconductors

- *Group IVA elements: C, Si, Ge, having 4 electrons in the valence shell, form compounds by sharing electrons with other elements without forming ions.*
- *A semiconductor becomes a conductor if the electrons are excited to high enough energies, otherwise it is an insulator.*



(a)

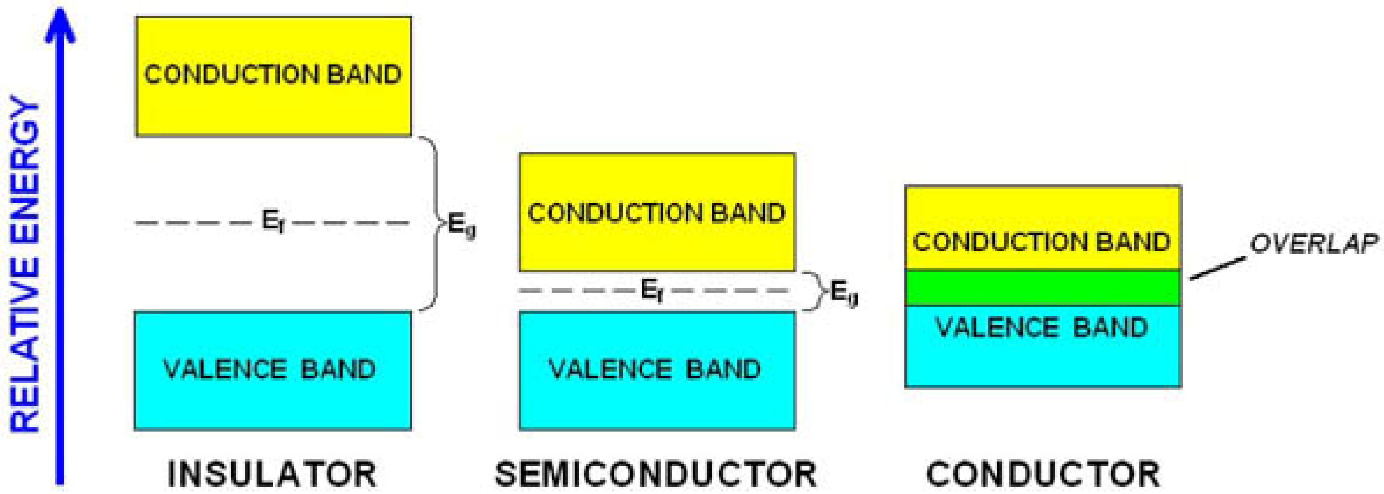


(a) (b)

- *Allows for photo-sensitive circuits (photon absorption adds energy to electron). Minimum energy to elevate an electron into conduction is the "band gap energy".*

Band Gap Energy

- *Minimum energy to elevate an electron into conduction is the "band gap energy".*
- *semiconductors have a narrow gap between the valence and conduction bands.*



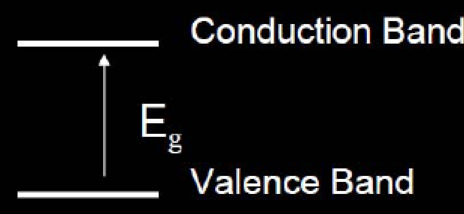
- *Semiconductors allow for photo-sensitive circuits (photon absorption adds energy to electron).*

Detector Family

For an electron to be excited from the valence band to the conduction band

$$h\nu > E_g$$

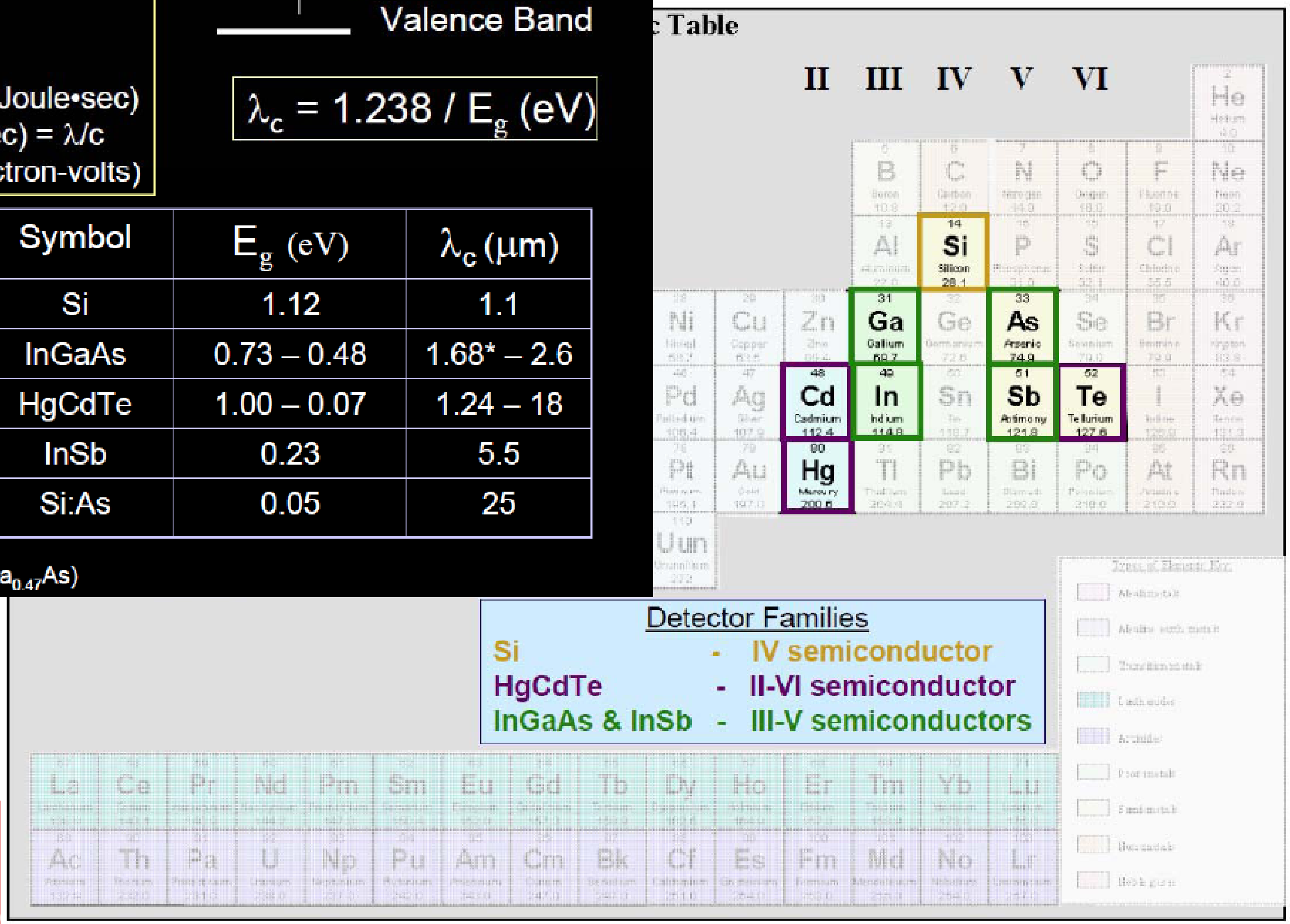
h = Planck constant (6.6310-[34] Joule•sec)
ν = frequency of light (cycles/sec) = λ/c
E_g = energy gap of material (electron-volts)



$$\lambda_c = 1.238 / E_g \text{ (eV)}$$

Material Name	Symbol	E_g (eV)	λ_c (µm)
Silicon	Si	1.12	1.1
Indium-Gallium-Arsenide	InGaAs	0.73 – 0.48	1.68* – 2.6
Mer-Cad-Tel	HgCdTe	1.00 – 0.07	1.24 – 18
Indium Antimonide	InSb	0.23	5.5
Arsenic doped Silicon	Si:As	0.05	25

*Lattice matched InGaAs ($In_{0.53}Ga_{0.47}As$)



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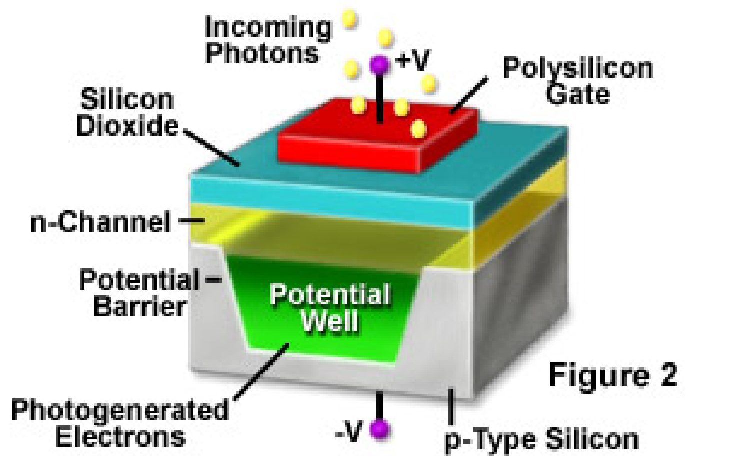
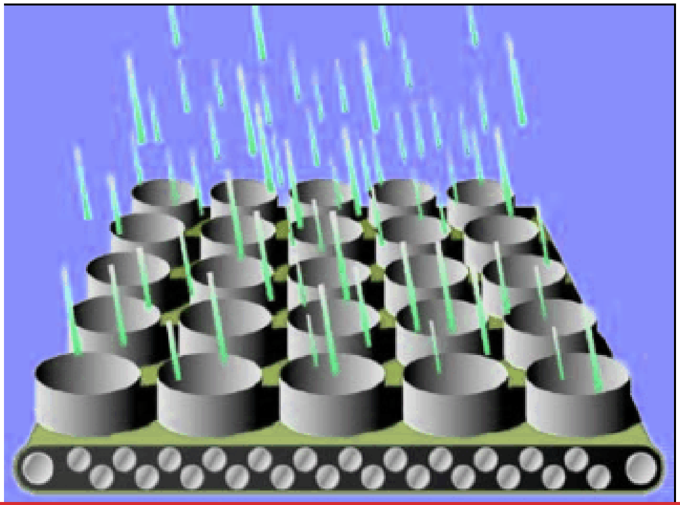
2.2 Charge Collection

- *Capacitor*
- *MOS Capacitor*
- *Potential Well*
- *Surface Channel**
- *Buried Channel**

Metal Oxide Semiconductor (MOS) Capacitor





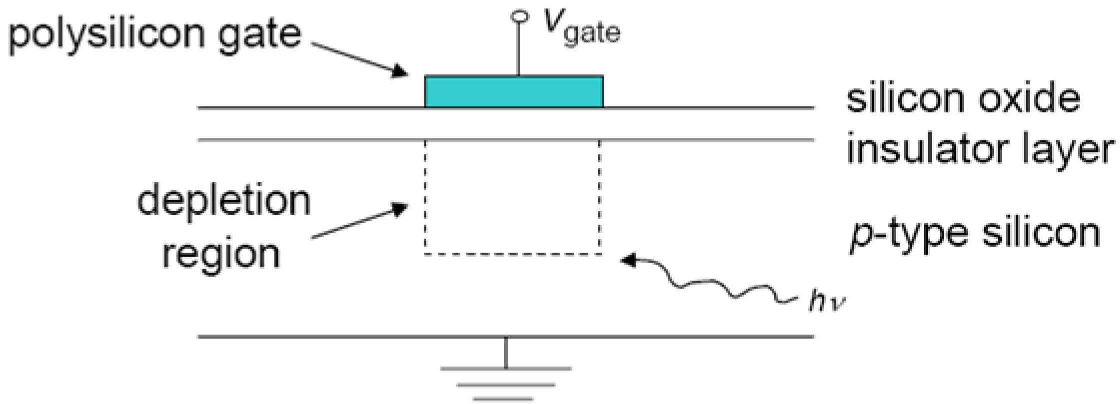
Capacitor

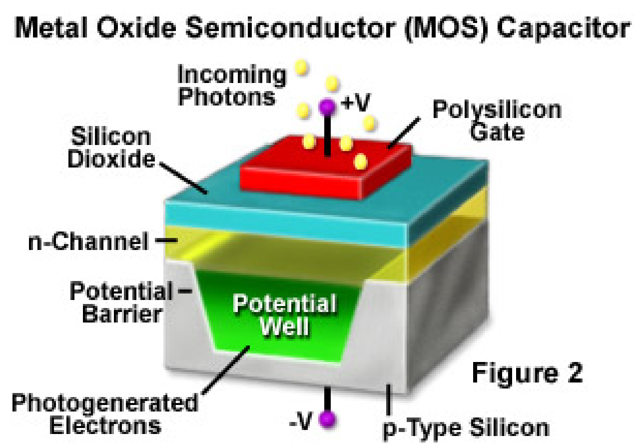
- *The capacitance of two parallel plates is 4.5pF. Calculate the charge on one plate when a voltage of 8.0 V is applied to the plates ?*

- *Each pixel releases electrons (by the photoelectric effect) when light is incident on it.*
- *We may think of each pixel like a small capacitor.*
- *The electrons released in each pixel constitute a certain amount of charge Q, and so a potential difference V develops at the ends of the pixel.*
- *The number of electrons released, and the voltage created across the pixel is proportional to the intensity of light.*

MOS Capacitor

- *A Metal-Oxide-Semiconductor (MOS) capacitor has a potential difference between two metal plates separated by an insulator.*





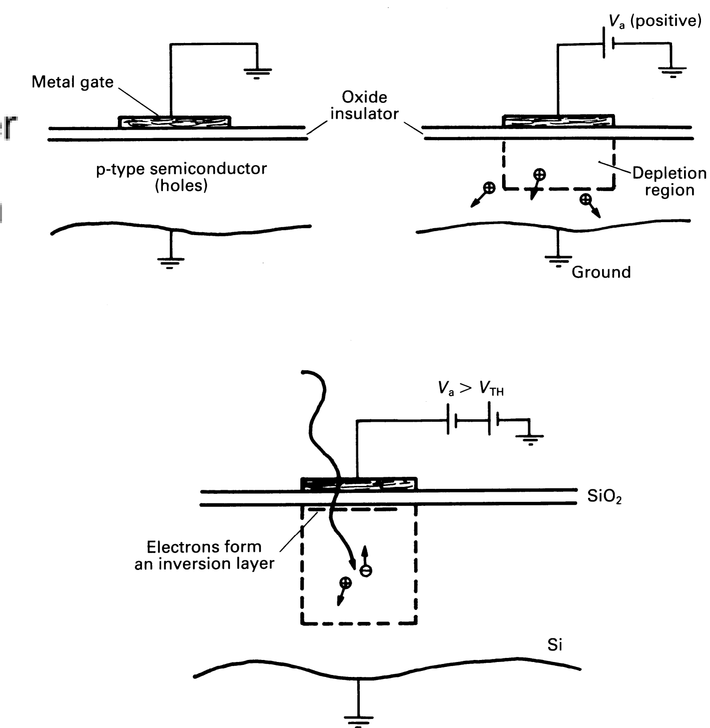


Fig. 6.7. A single metal-oxide-semiconductor (MOS) storage well, the basic element in a CCD.

Potential Well

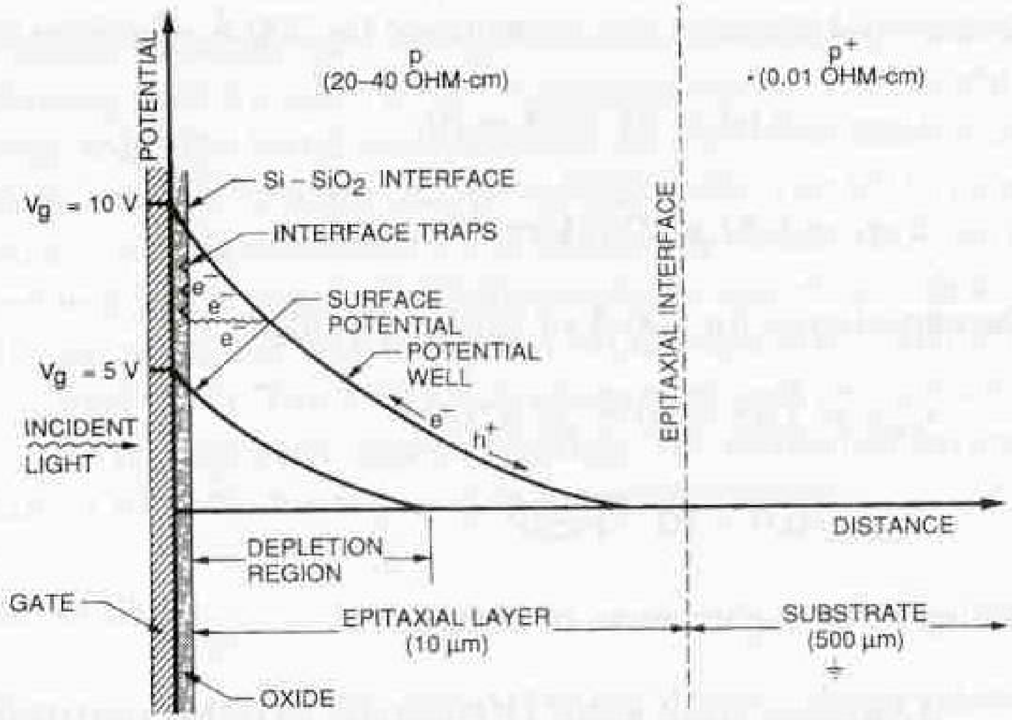


Figure 1.18 Surface channel potential well.

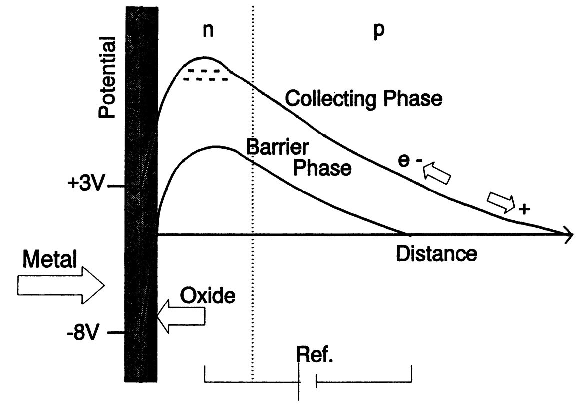


Fig. 6.12. (b) The collection layer lies well below the surface at the overlap between the gate depletion and the depletion of the pn junction. Courtesy Jim Janesick.

Metal Oxide Semiconductor (MOS) Capacitor

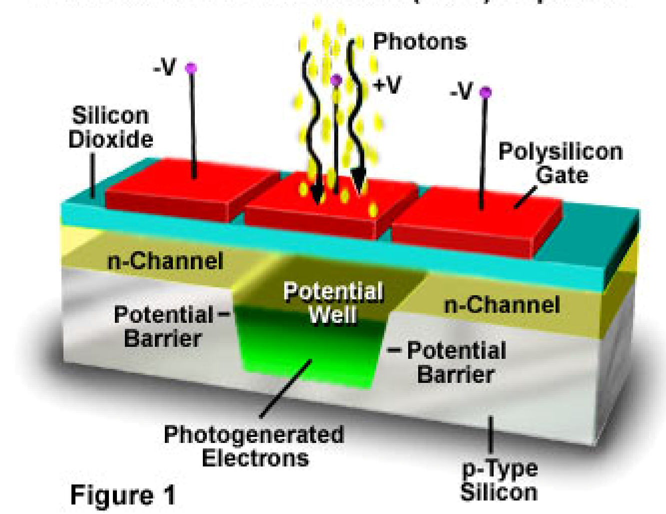
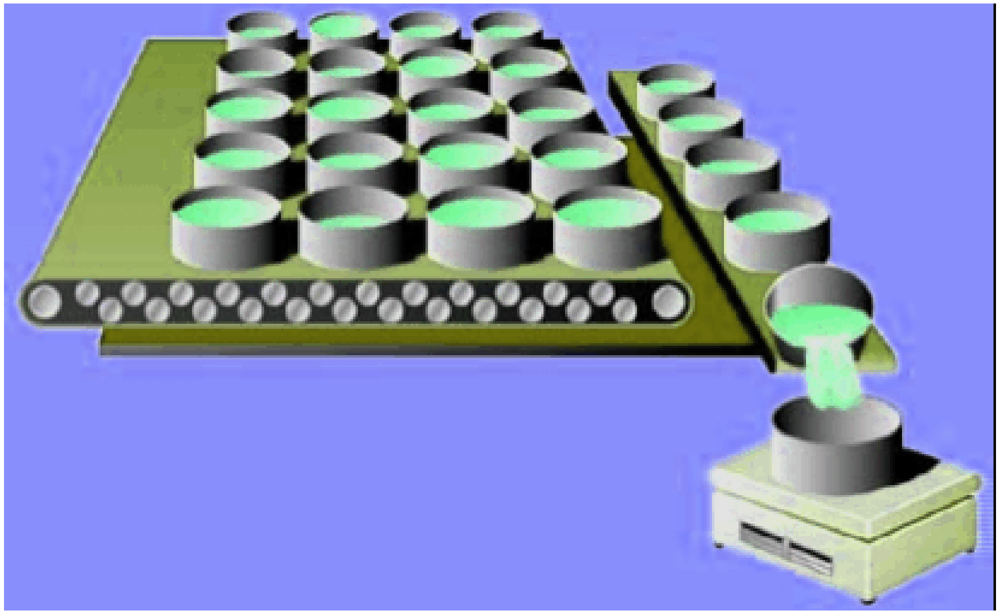
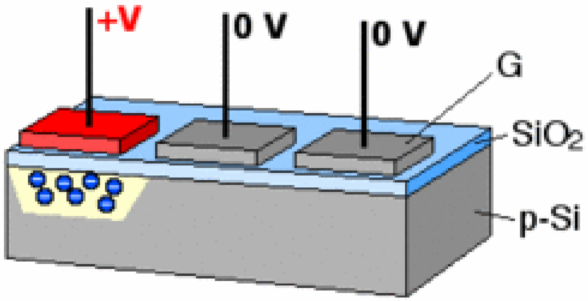


Figure 1

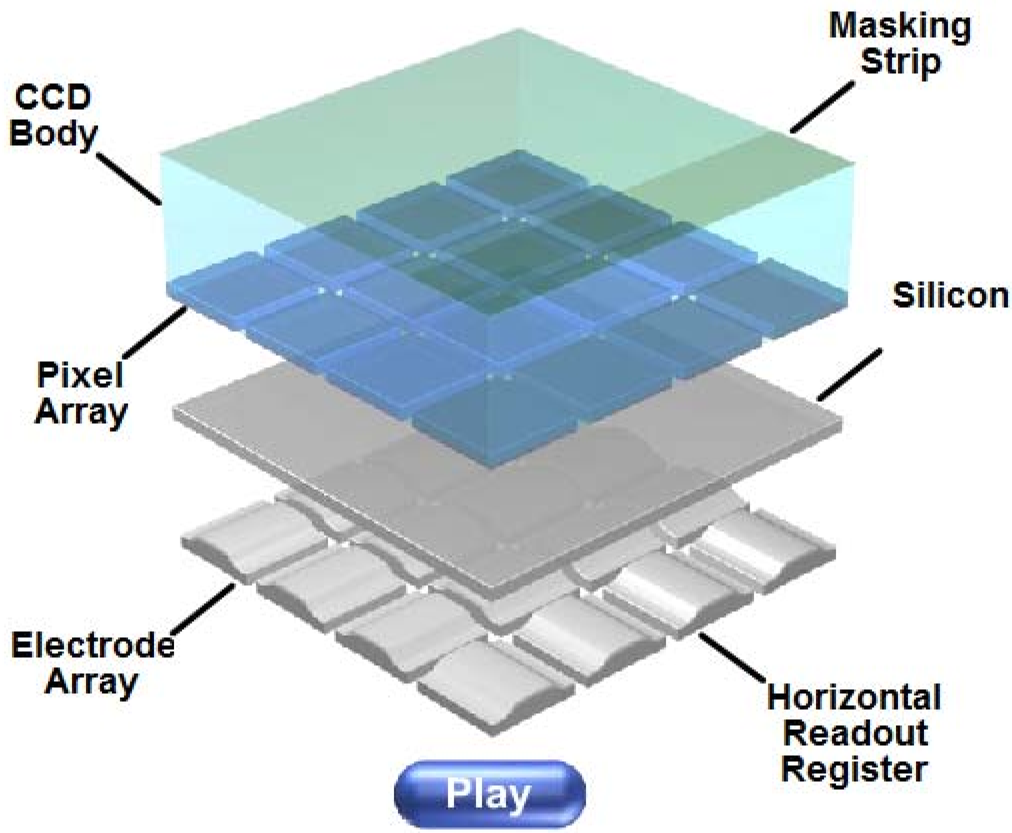
2.3 Charge Transfer

- CCD Readout Architecture
- Pixel and Register
- CCD Phase Clocking
- Parallel Register
- Serial Register

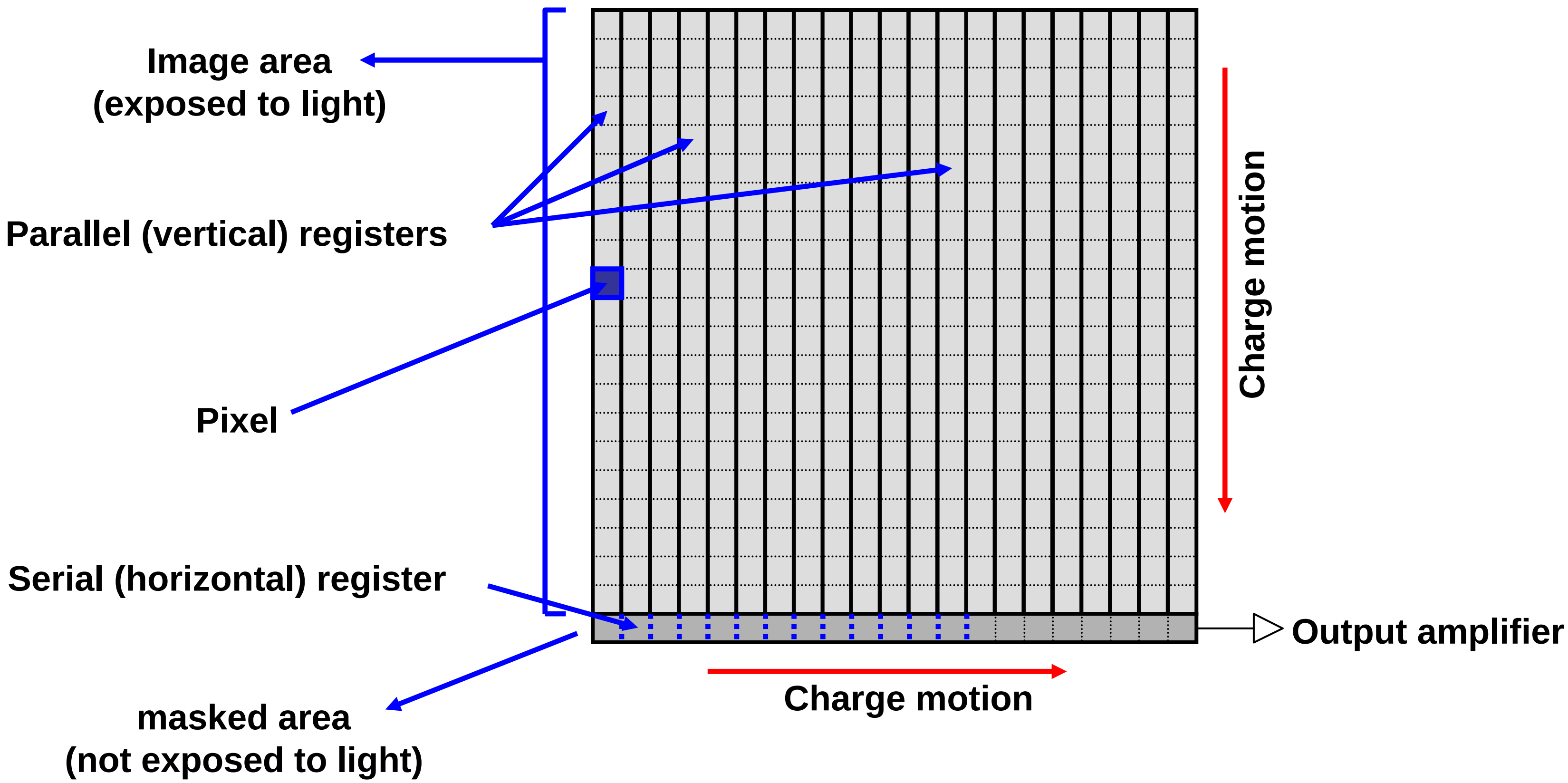




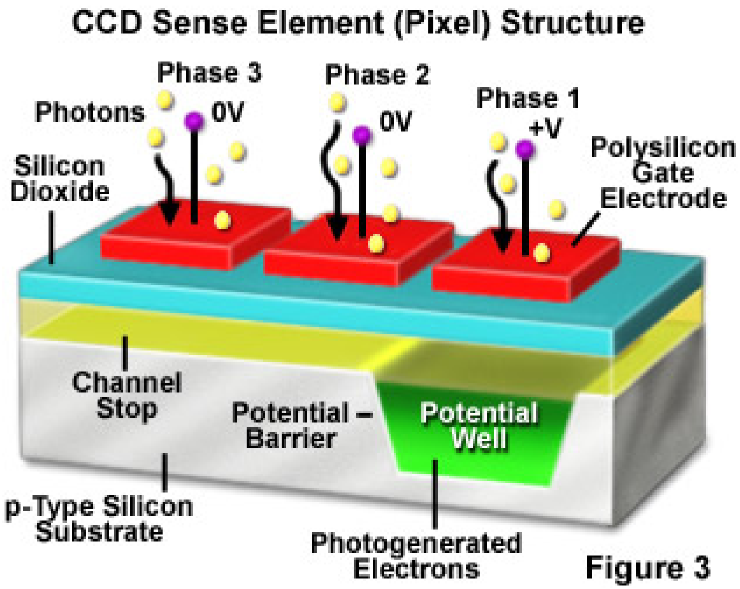
CCD Image Readout Animation

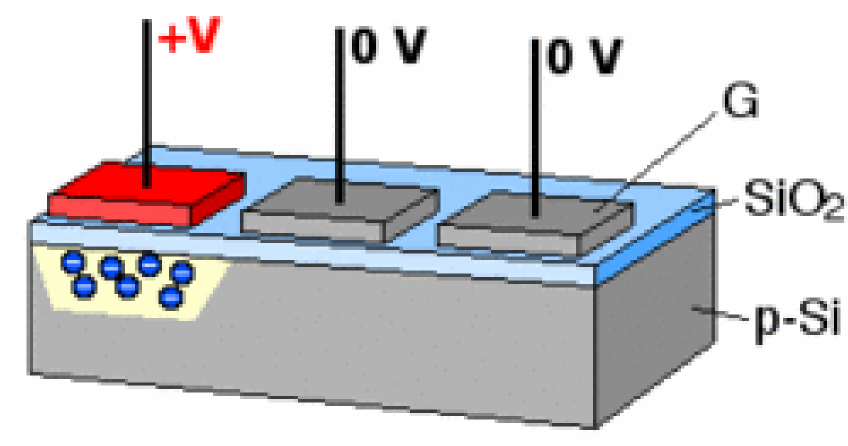

Masking Strip
CCD Body
Silicon
Pixel Array
Electrode Array
Horizontal Readout Register
Play

CCD Readout Architecture Term



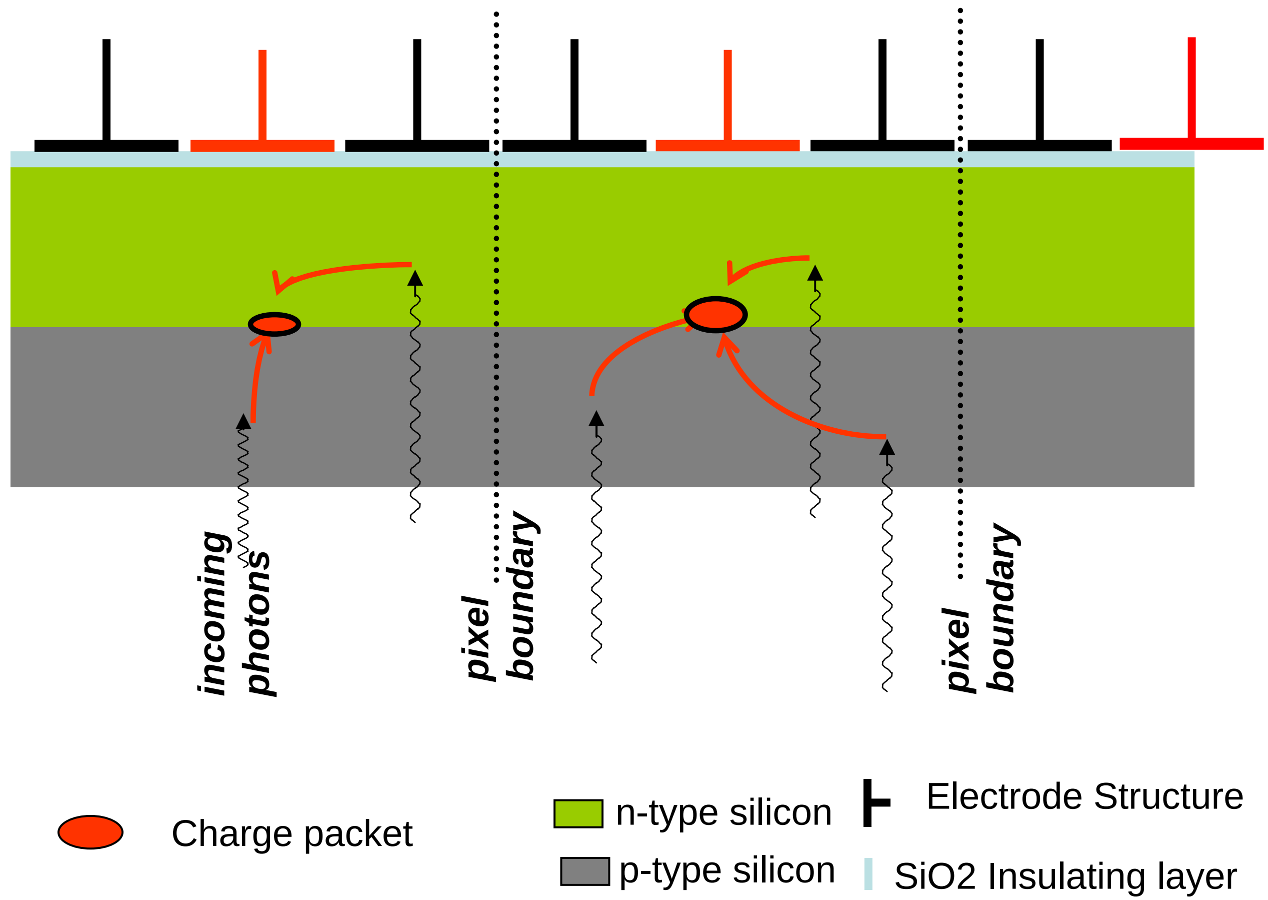
CCD Pixel and Register



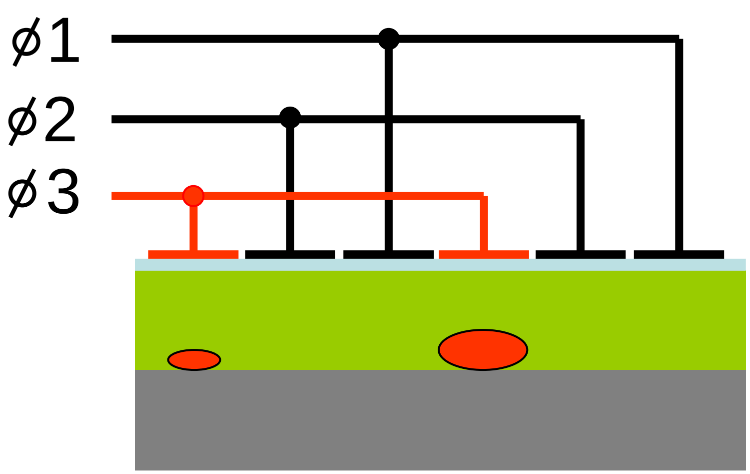


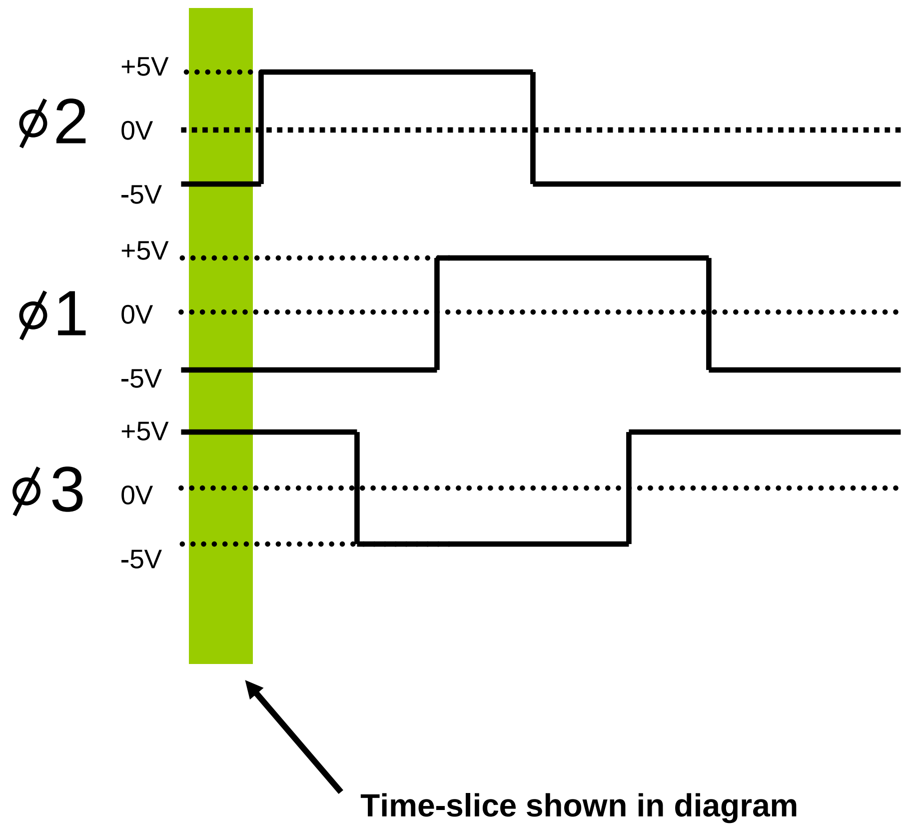
- ***MOS capacitors are the basic building blocks of the CCD***
- ***Each pixel consists of several MOS capacitors***
- ***MOS capacitors follow phase clock to transfer charges***

CCD Phased Clocking

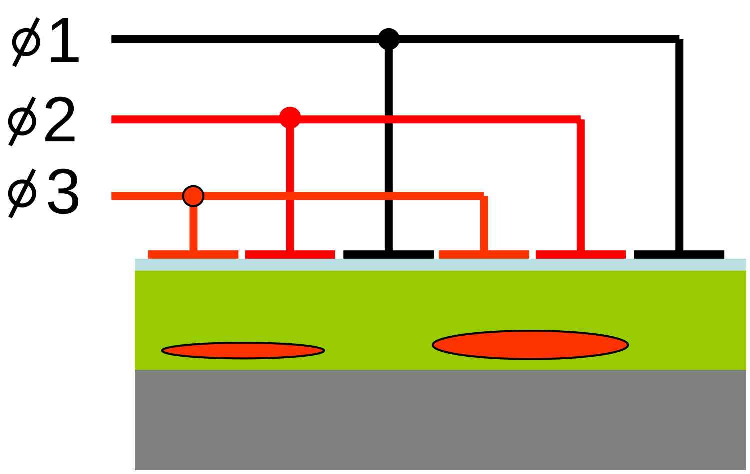


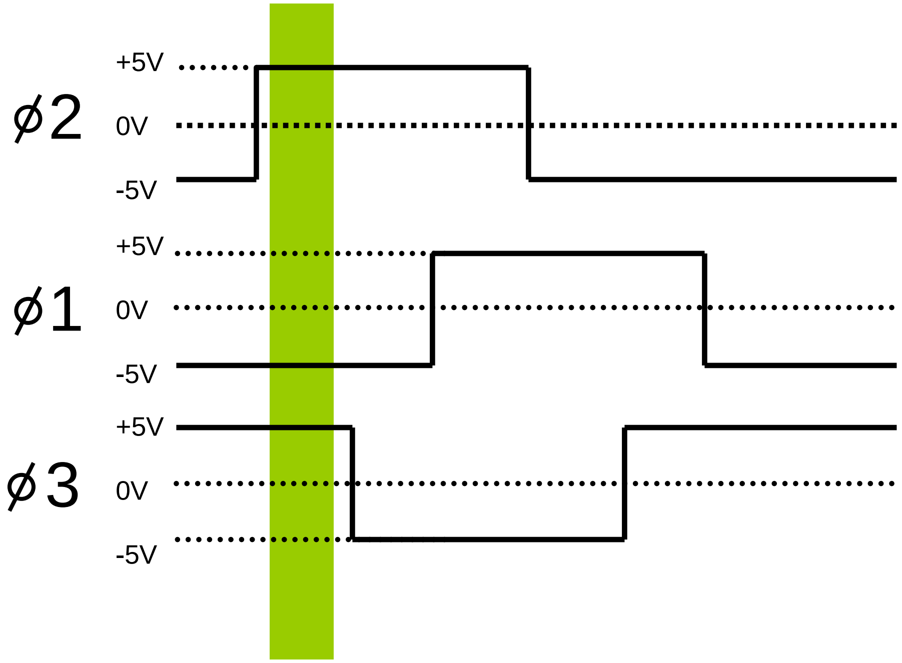
CCD Phased Clocking: Step 1



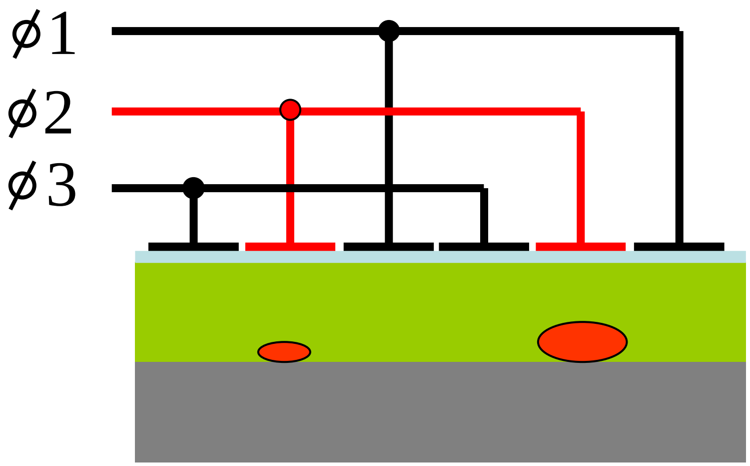


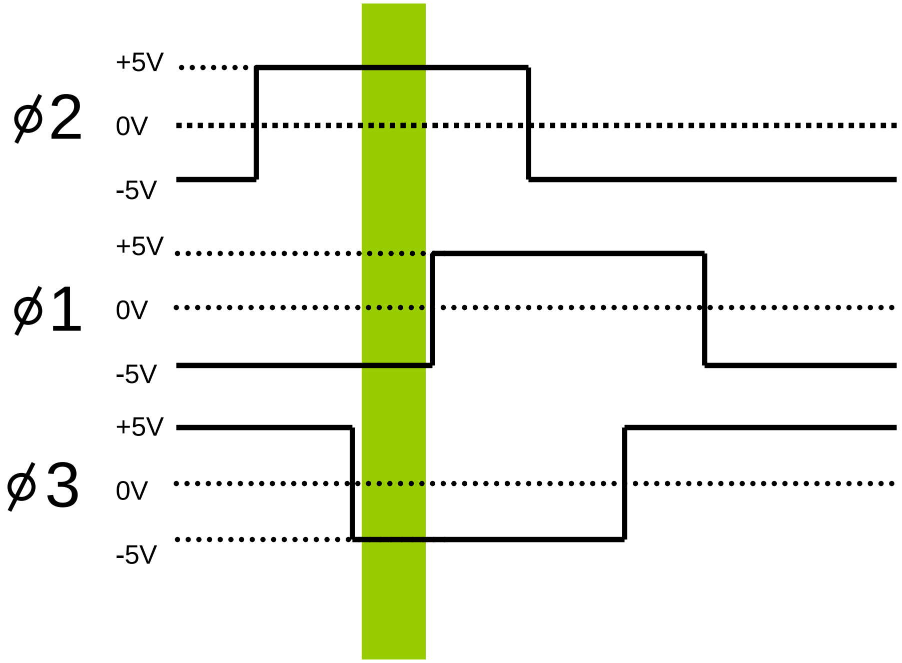
CCD Phased Clocking: Step 2



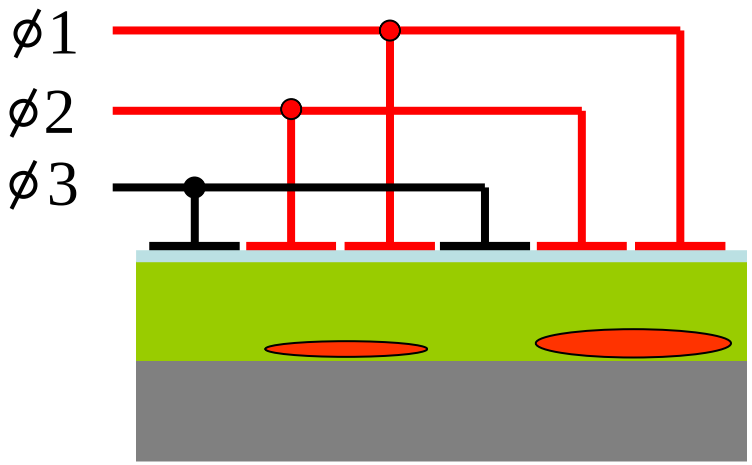


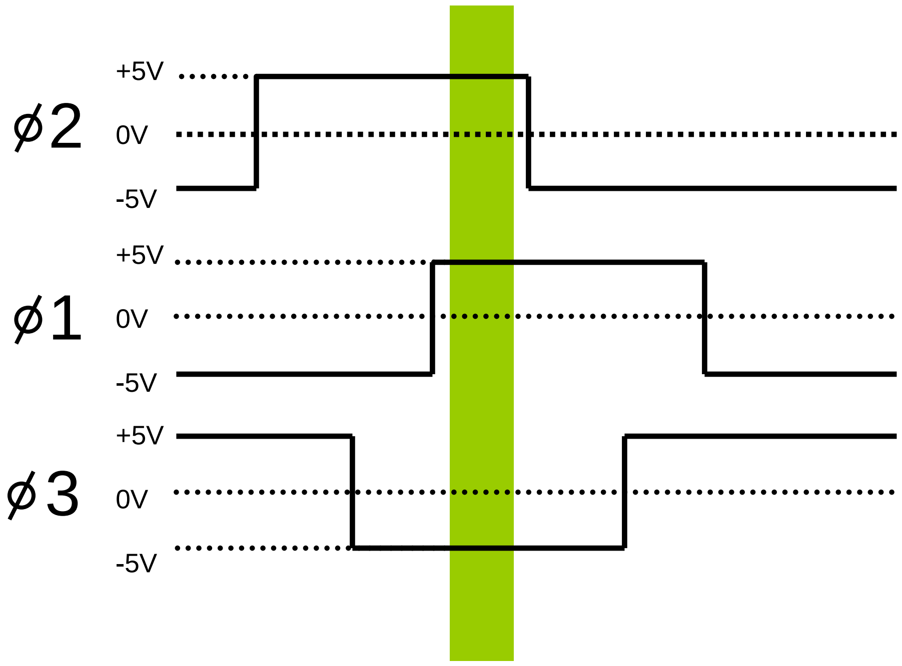
CCD Phased Clocking: Step 3



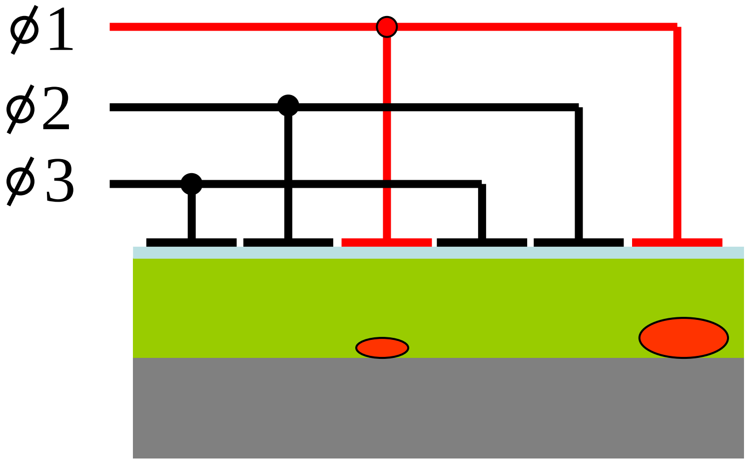


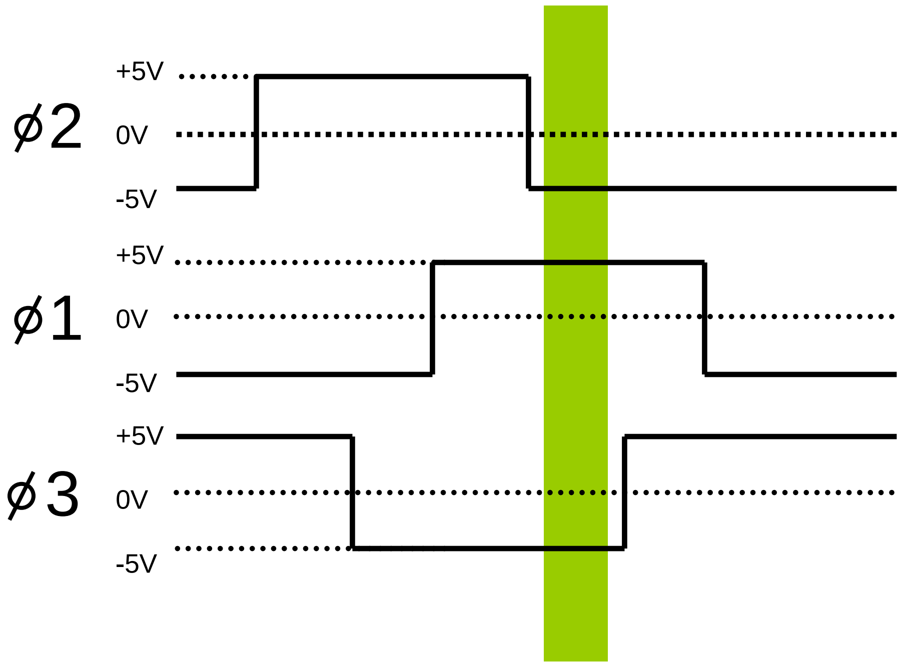
CCD Phased Clocking: Step 4



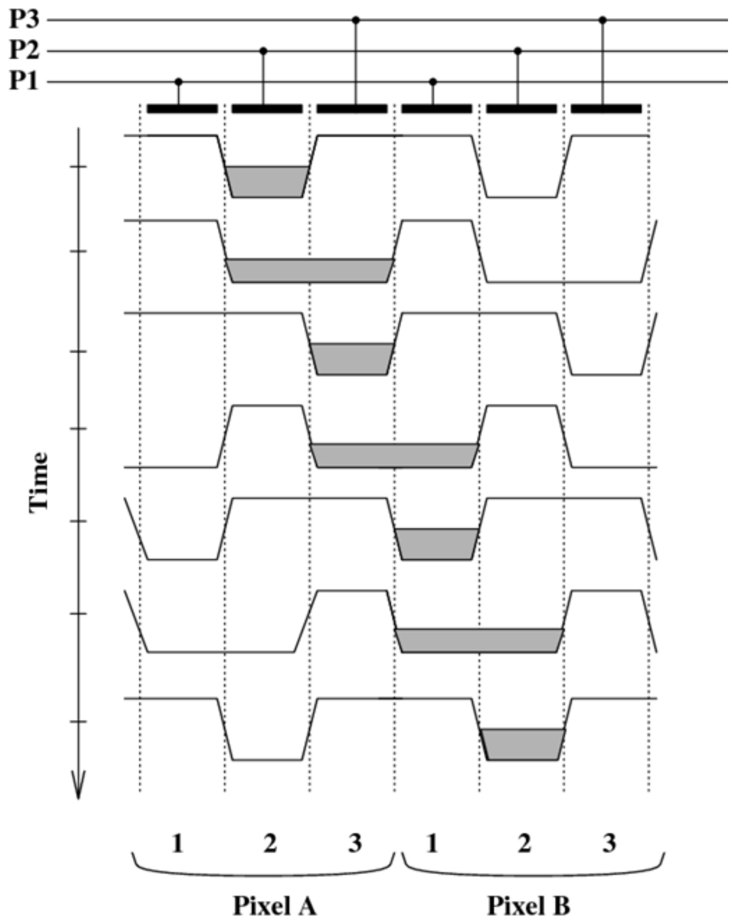


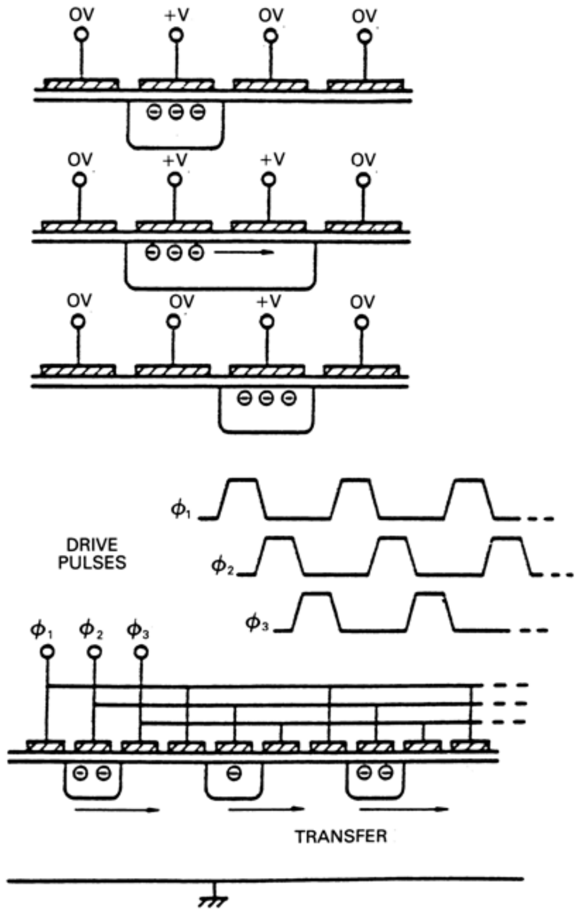
CCD Phased Clocking: Step 5



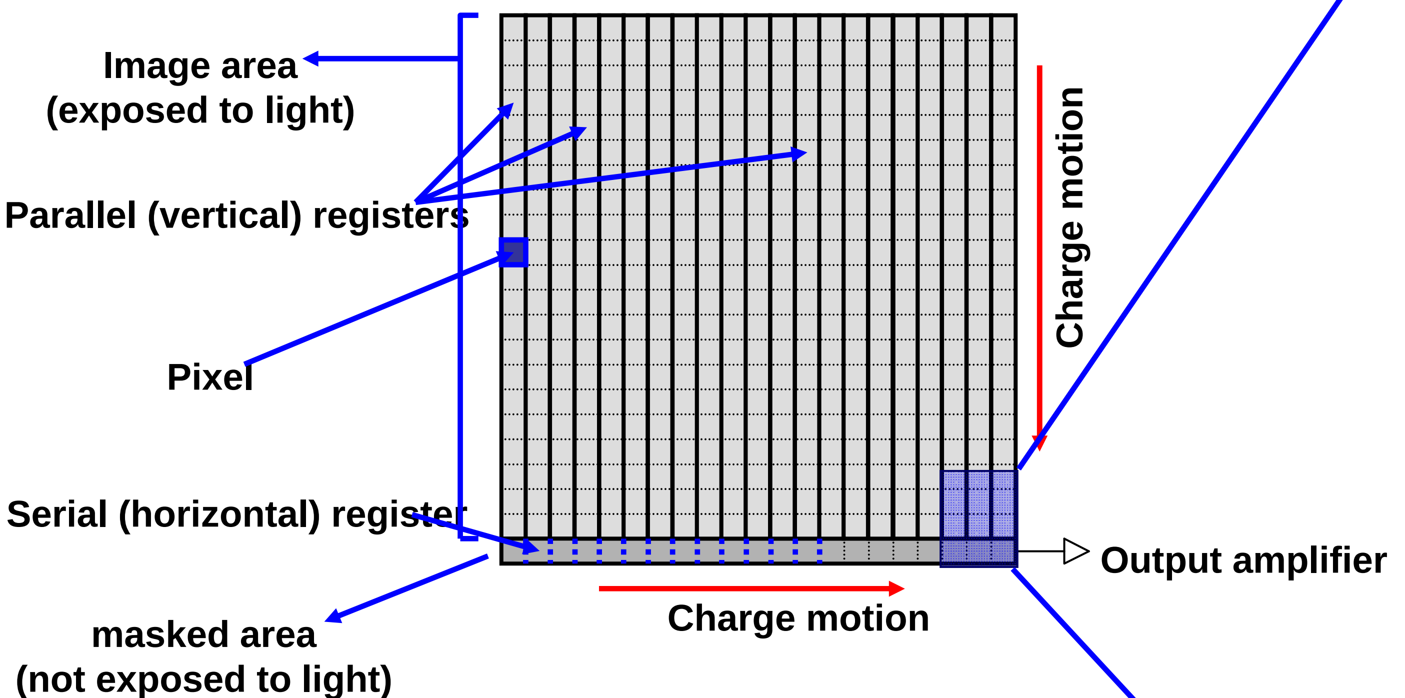


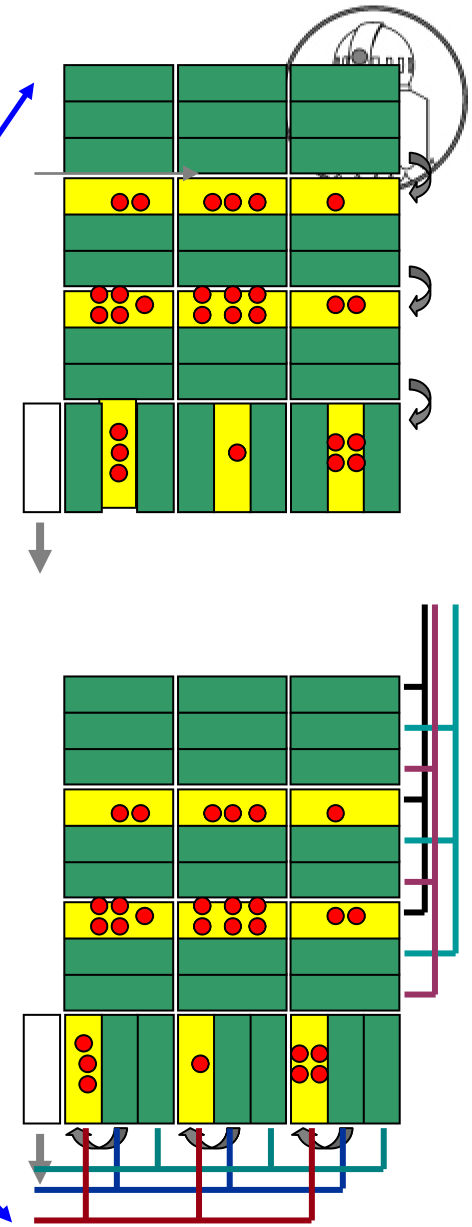
CCD Phased Clocking: Summary





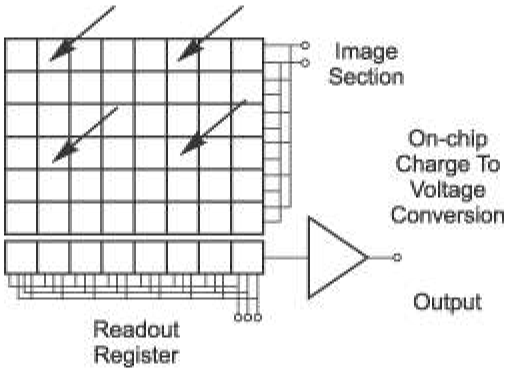
Parallel and Serial Registers

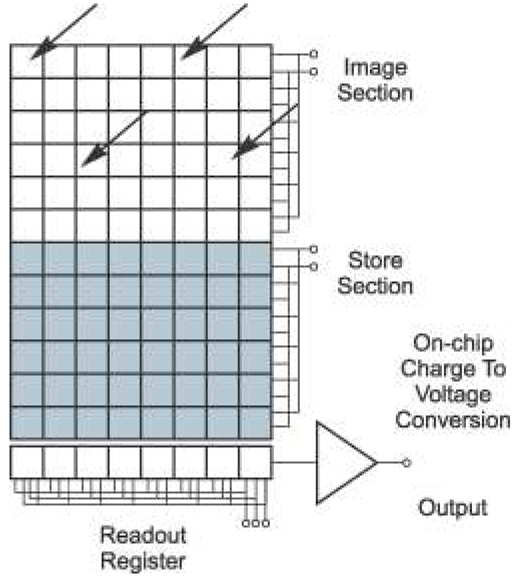


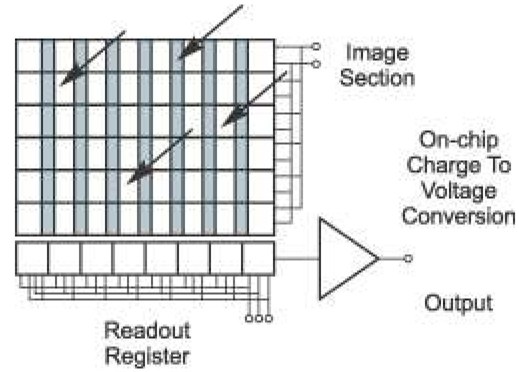


- *Parallel registers transfer charges vertically*
- *Serial registers transfer charges horizontally*
- *They operate at different frequencies*
- *For 3 by 3 CCD, $f_{vertical}$ = 10 Hz, f_{serial} = ?*

Other Types of Architecture

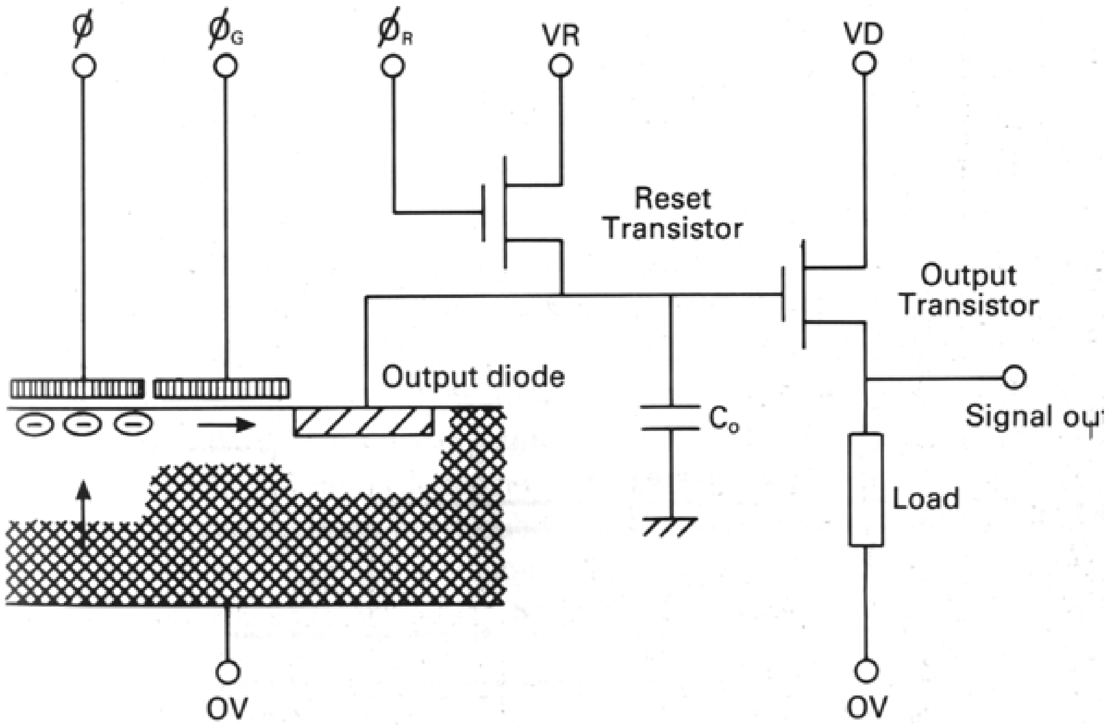






- *Full frame and frame transfer devices tend to be used for scientific applications.*
- *Interline transfer devices are used in consumer camcorders and TV systems.*
- *Frame transfer imager consists of two almost identical arrays, one devoted to image pixels and one for storage.*
- *Interline transfer array consists of photodiodes separated by vertical transfer registers that are covered by an opaque metal shield.*

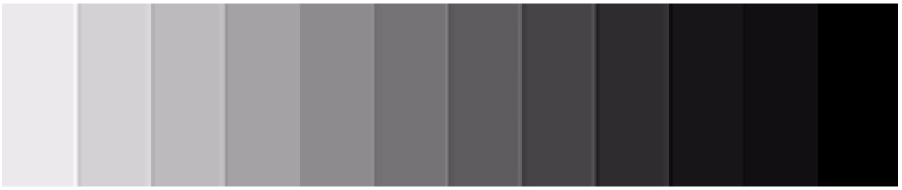
2.4 Charge-to-Voltage Conversion



- *Each pixel's collected charge is sensed and amplified by an output amplifier*
- *They are designed to have low noise and built into the silicon circuitry*
- *Typical values are in the range of 0.5 to 4 microvolts per electron*

2.5 Digitization (A/D Conversion)

- *Output voltage from a given pixel is converted to a digital number (ADUs – analog-to-digital units)*
- *A/D (ADC, analog-to-digital converter) performs the conversion of output voltage signal to a digital number*
- *Digitization circuits are complicated and not included in a CCD chip, "off-chip" circuit.*
- *Digital output values can only be integer numbers with digital bits:*
  - *8 bits: $2^8 = 256$*
  - *10 bits: $2^{10} = 1024$*
  - *14 bits: $2^{14} = 16383$*
  - *16 bits: $2^{16} = 65535$*



- *Ultimate readout speed depends on how fast the process of pixel examination and A/D conversion can take place*
  - *At a readout rate of 50 μs/pixel (~ 20 kHz), how long does it take over to read out a 2048 by 2048 CCD ?*

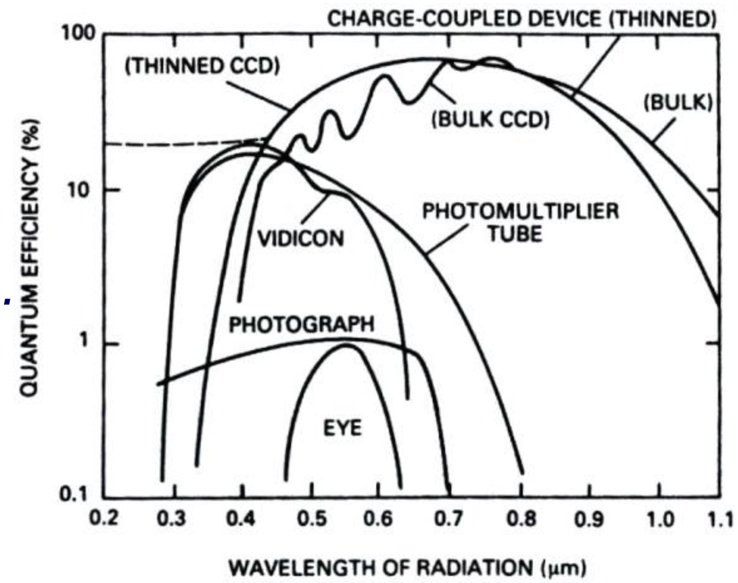
3. Performance of CCD

- ***Charge Generation***
  - *QE – Quantum Efficiency*
  - *Dark Current*
- ***Charge Collection***
  - *Pixel Size*
  - *On-Chip Pixel Binning*
  - *Full Well Capacity*
- ***Charge Transfer***
  - *CTE – Charge Transfer Efficiency*
  - *Defects*
- ***Charge Detection***
  - *Readout Noise*
  - *Linearity*
  - *Gain and Dynamic Range*

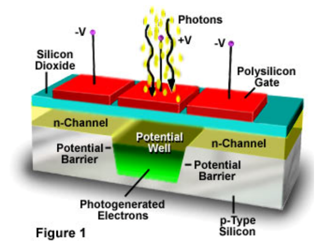
3.1 Quantum Efficiency

- *QE: the percentage of photons hitting the photoreactive surface that will produce an electron-hole pair .*
- *QE is an accurate measurement of device's electrical sensitivity to light.*
- *QE is a function of wavelength.*
- *QE is often measured over a range of different wavelengths*
- *Film typically has a QE of less than 10%.*
- *CCDs have a QE of well over 90% at some wavelength.*
- *QE depends on many factors, such as the gate structure, surface reflection, illuminating way …*

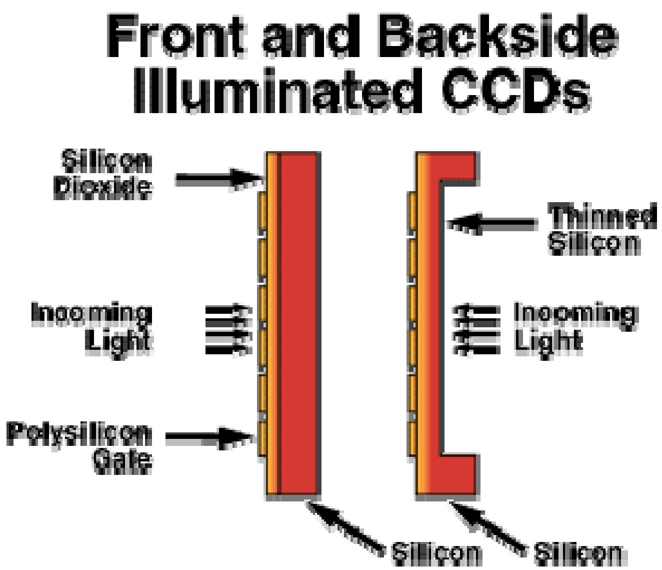
$$QE = \frac{electrons/\sec}{photons/\sec}$$

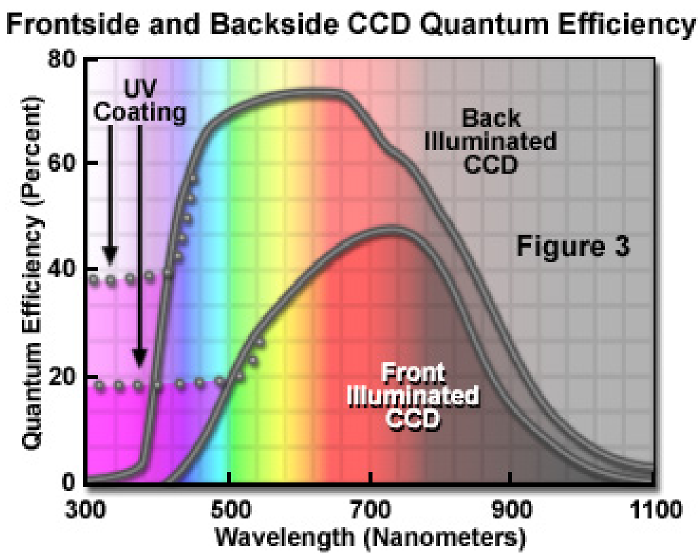


Front or Back Side Illumination



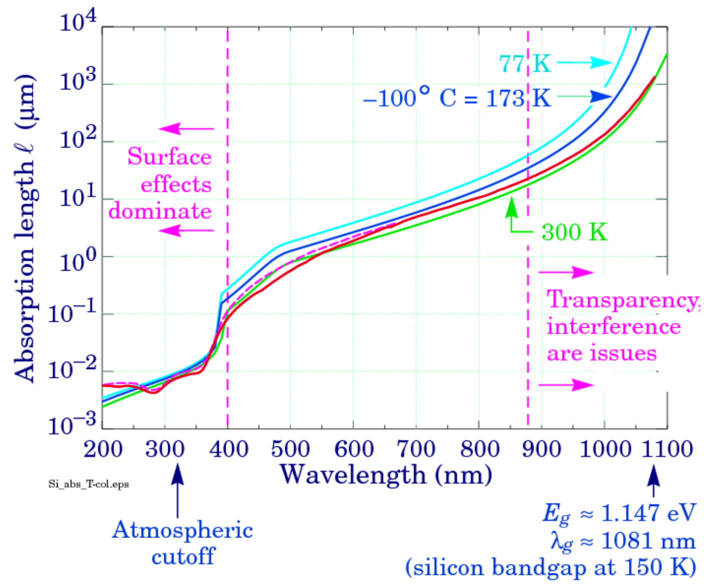
- *Front side illumination: CCDs are illuminated through the electrodes. Electrodes are semi-transparent, but some losses occur.*
- *Back side illumination: CCDs are illuminated from the back side.*
- *Front-side illuminated device: relatively low QE, filling factor < 1.*
- *Back-side illuminated device (or thinned devices): high QE* and *physically thinned to about 15 microns, filling factor close to 1.*

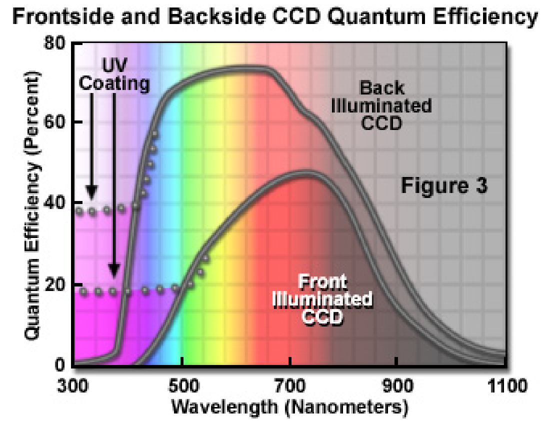




Photon Absorption Length in Si

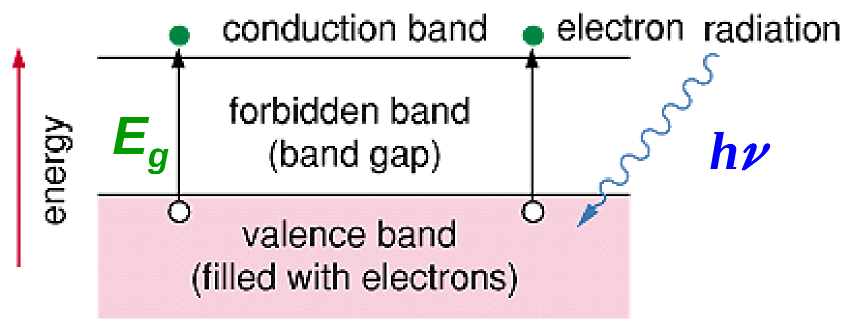
- Si is responsible for the response of the detector to various wavelength of light.
- For light outside the range of 350 to over 850 nm, CCDs become transparent:
  - at short wavelengths, > 70% of photons are reflected.
  - at long wavelengths, light photons pass right through the silicon.
- For light inside the range of 350 to over 850 nm, photons get absorbed.
- Back-side device thickness ~15 microns.
- Front-side device thickness ~300 microns, QEs are more red sensitive and lower in the blue.

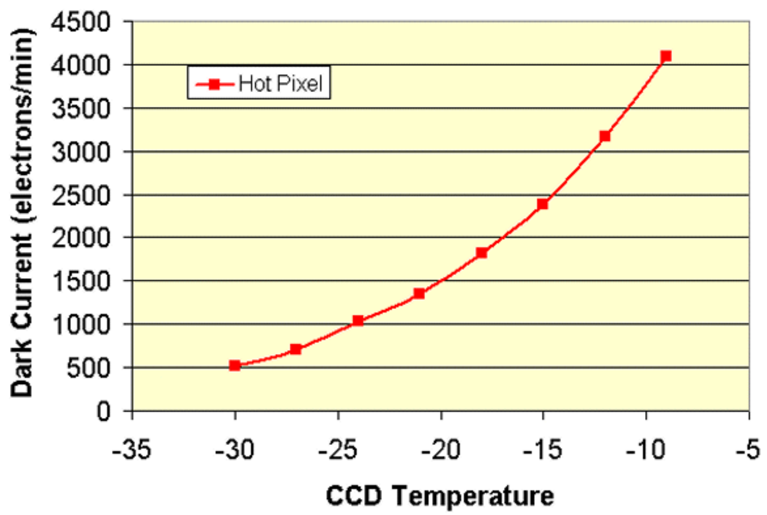




3.1 Dark Current

- When thermal agitation is high enough, electrons get free from the valence band.
- They become collected within the potential well of a pixel.
- These dark current electrons become part of the signal, indistinguishable from object photons.
- Dark current is a strong function of the temperature of the device.
- At room temperature, dark current of a typical CCD is 25,000 e-/pixel/sec.
- Darks are more serious in IRFPAs than that in Si CCD/CMOS camera



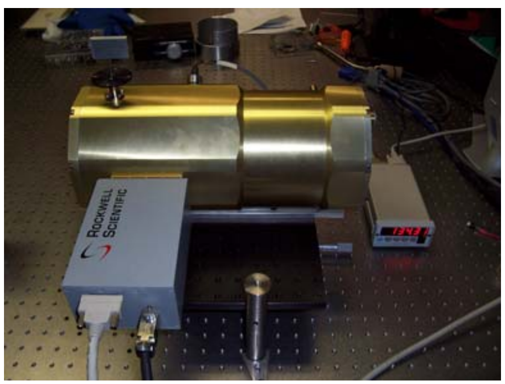


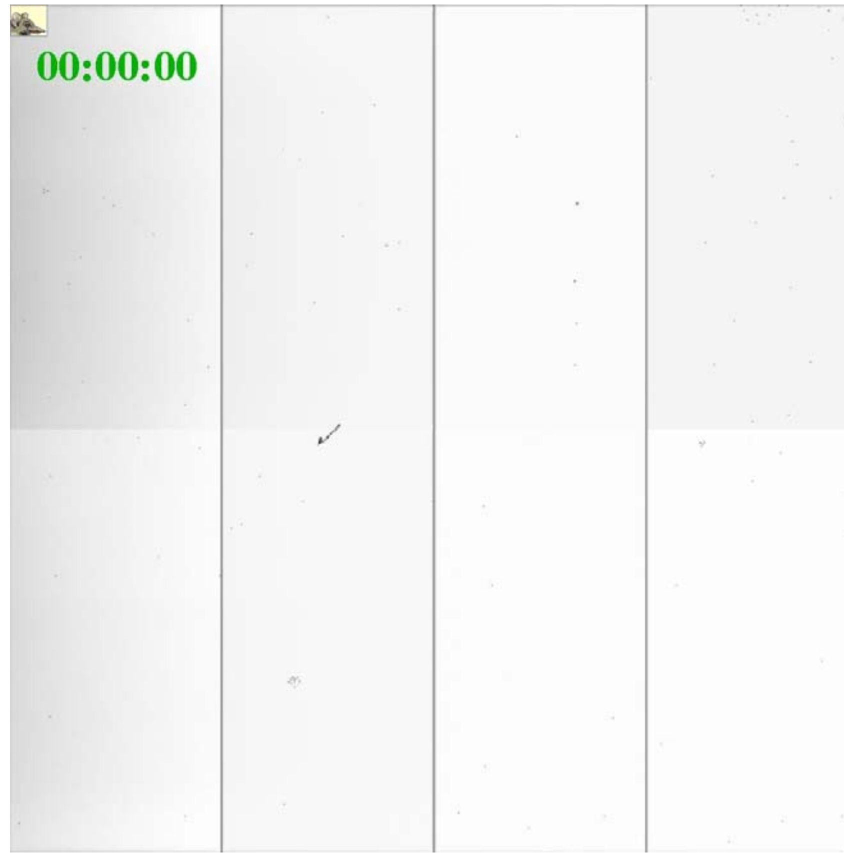
Minimize Dark Current

- *Dark noise has a Poisson distribution*

$$N_D = \sqrt{dark\ current}$$

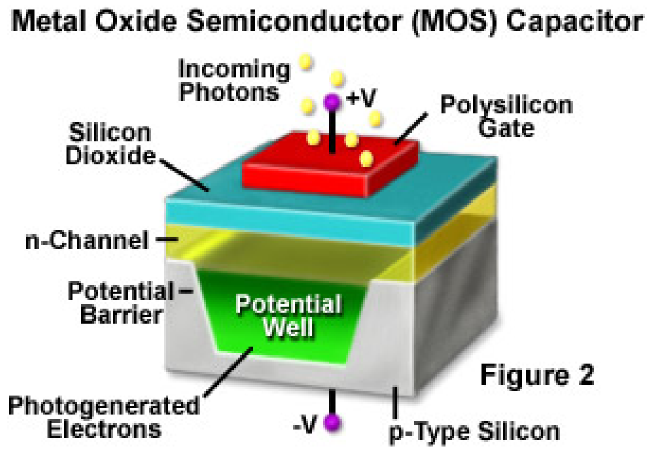
- *LN2 (Liquid Nitrogen) cooling*
  - *Dewar in vacuum and LN2 in dewar*
  - *Cool CCD chip to -100℃*
  - *Cool IRFPA to 77 Kelvin*
- *Thermoelectric cooling*
  - *Cool CCD to -20 to -50 ℃*





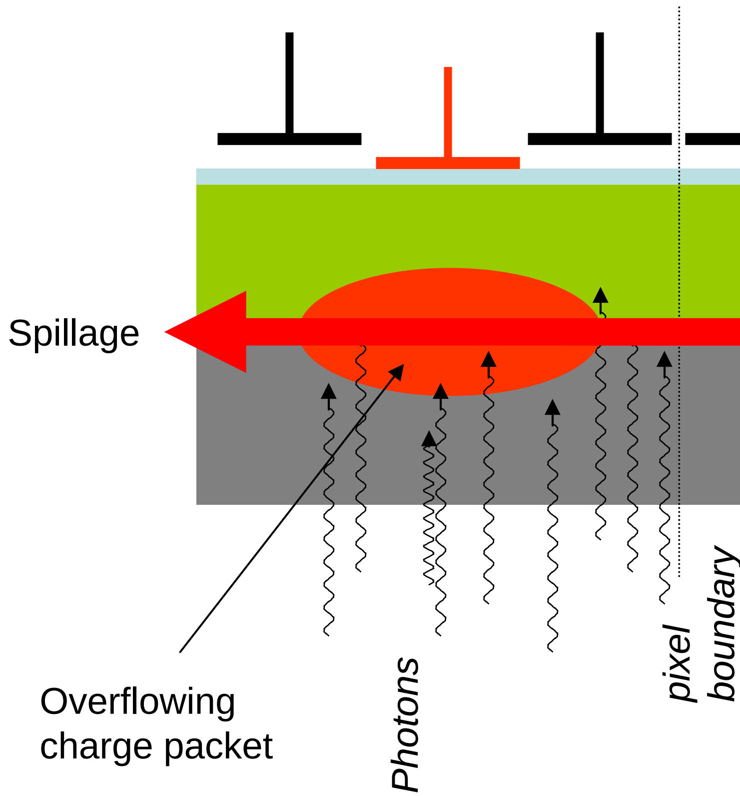
3.2 Full Well Capacity

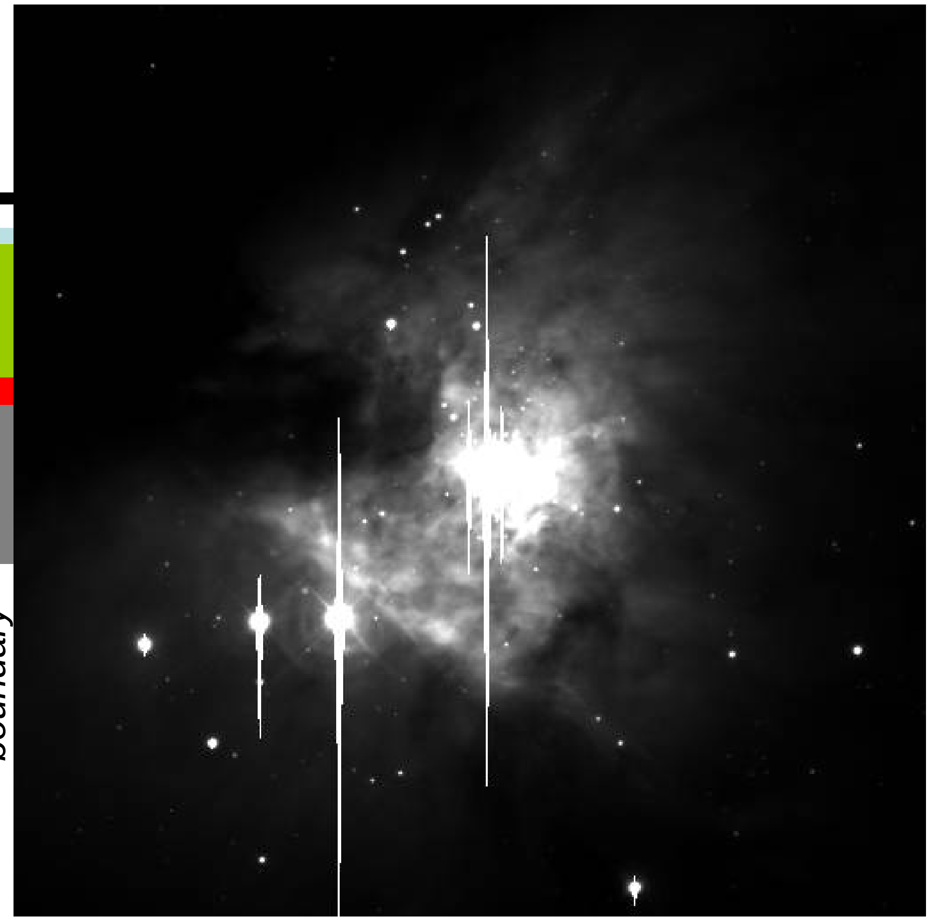
- *Well capacity is defined as the maximum charge that can be held in a pixel*
- *The physically larger the pixel (both in area and in thickness) the more charge that it can collect and store.*
- *"Saturation" is the term that describes when a pixel has accumulated the maximum amount of charge that it can hold*
- *Full well capacity in a CCD is typically ~100,000 e-/pixel*
- *A rough rule of thumb is that well capacity is about 10,000 e-/μm^2.*
- *What will happen when the full well capacity of a pixel is exceeded?*



Blooming

- *Bright objects can lead to the collection of too many charges in one pixel, causing pixel to overflow …*





Anti-blooming CCDs

- *Blooming occur when the full well capacity of a pixel is exceeded.*
- *Blooming causes a bright streak leading away from bright pixel, generally in two opposite directions.*
- *"Saturation" effects are irritating and sometimes render measurement useless.*
- *Anti-blooming gates allow saturated pixels to be "drained" off.*
- *Anti-blooming gates occupy 30% of active pixel area, causing QE reduction.*

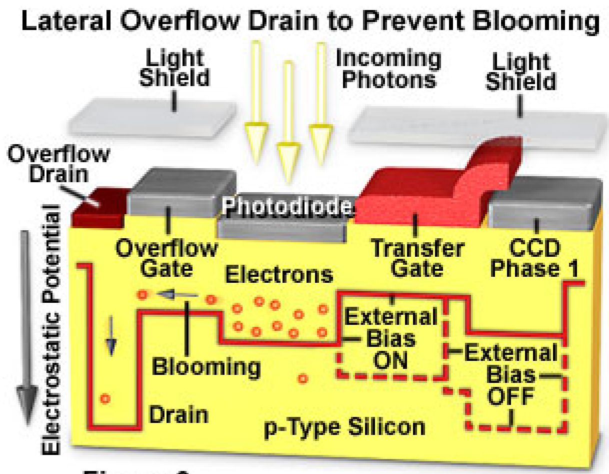


Figure 3

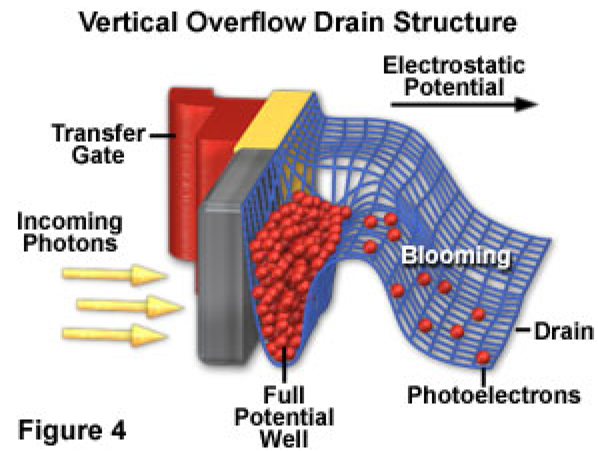
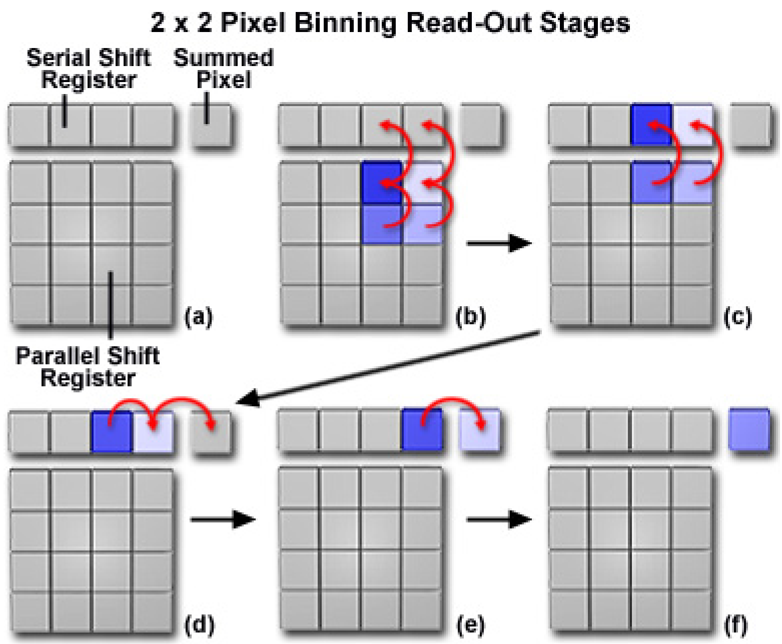


Figure 4

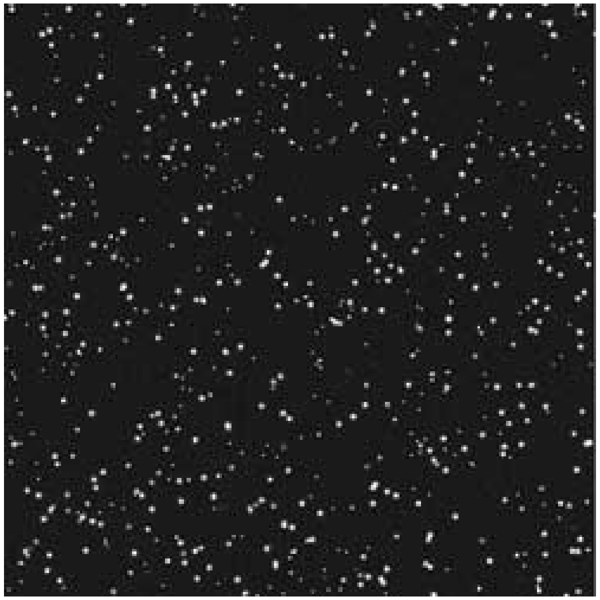
3.2 Pixel Binning

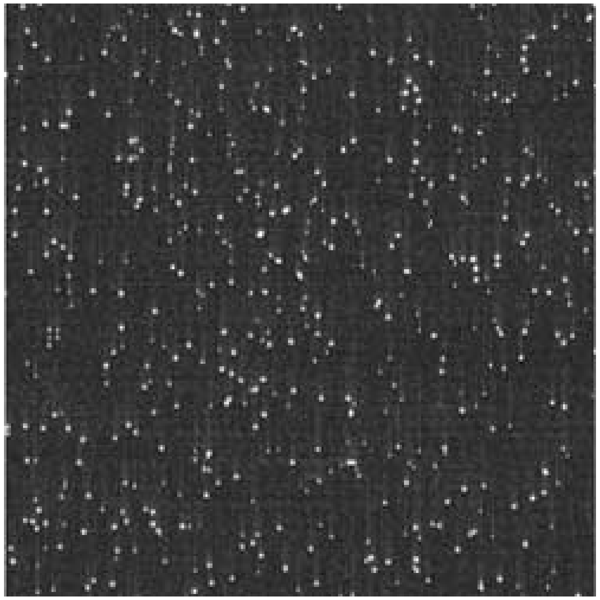
- *Pixel binning is a clocking scheme used to combine the charge collected by several adjacent CCD pixels .*
- *Binning process is performed on-chip, which assumes that accumulated charge is brought together and summed prior to amplification of analog signal and A/D conversion.*
- *Pixel binning reduces noise and image size, improves the signal-to-noise ratio and frame rate.*
- *Pixel can be binned in both directions.*
- *Serial register pixels can hold 5-10 times the charge of a single pixel.*
- *Pixel binning decrease image resolution.*



3.3 Charge Transfer Efficiency

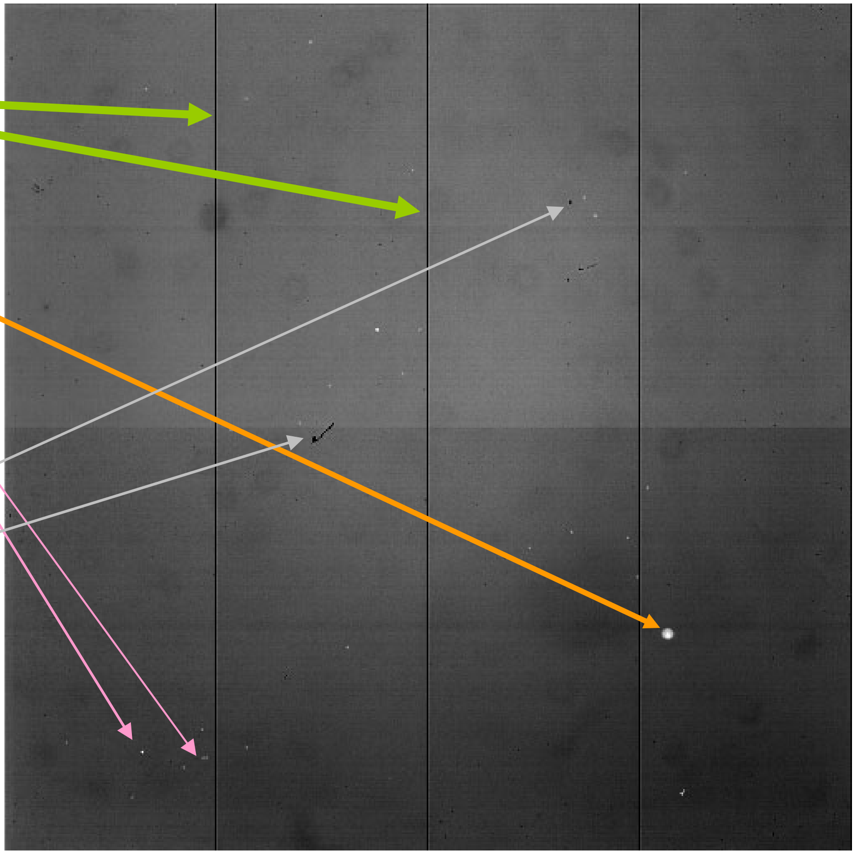
- *When the well are nearly empty, charge can be trapped by impurities in the silicon. So faint image can have tails in the vertical direction.*
- *Modern CCDs can have a CTE per transfer of 99.999995% (five 9s), so after 2000 transfers only 0.1% of the charge is lost.*





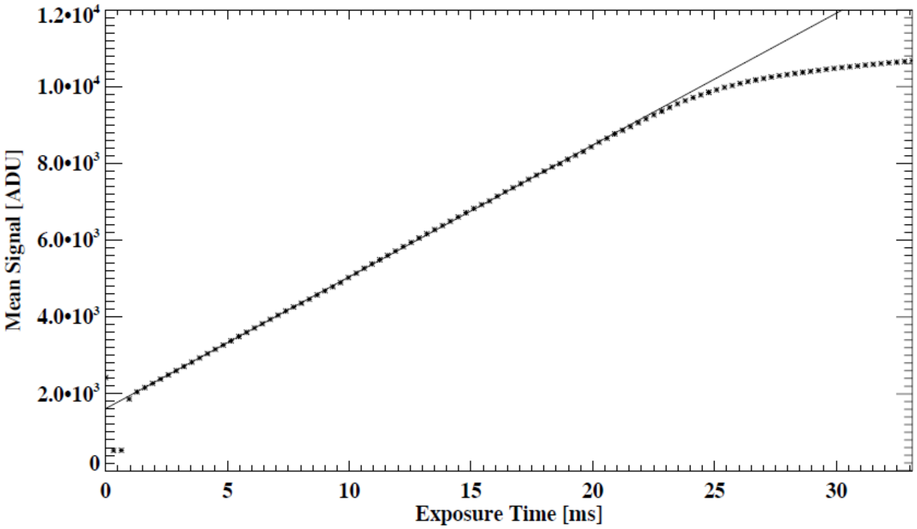
3.3 Defects

- *Dark/bright columns are caused by traps of electrons during image readout.*
- *Stuck pixel: a pixel that always reads high on all exposures.*
- *Hot pixel: a pixel that reads high on longer exposures.*
- *Dead pixel: a pixel that reads zero (black) on all exposures.*
- *Defects can't be corrected by flat fielding.*
- *Defects can be removed by calibration.*



3.4 Linearity

- *Linearity is a measure of how consistently the CCD/CMOS responds to light over its well depth.*
  - *Low light level: readout noise*
  - *Linear range*
  - *High light level: non-linear flattening when the charge in the well > 80%*
  - *Extremely high light level: saturation*
- *If uncertain of the linear range of a CCD/CMOS, it is best to measure it*
- *Method of obtaining a linearity curve:*
  - *Use stable light source or stars*
  - *Obtain consecutively increasing exposures*
  - *Plot output ADU vs. exposure time*



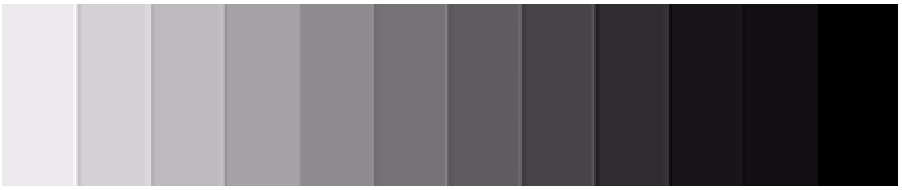
$$nonlinearity(\%) = \frac{Max(+)Deviation + Max(-)Deviation}{MaximumSignal}$$

3.4 Gain

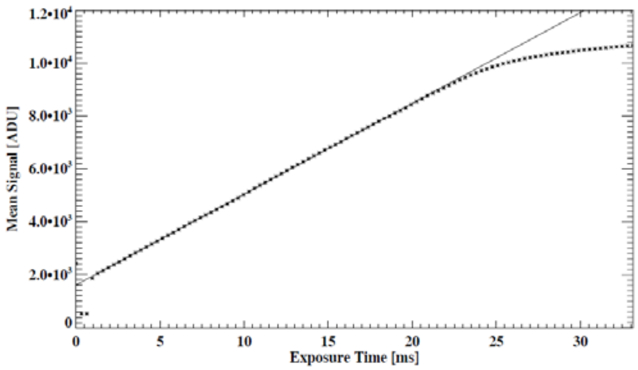
- *Output voltage (electrons) from a given pixel is converted to a digital number (ADUs – analog-to-digital units)*
- *Gain: amount of charge collected in each pixel will be assigned to produce 1 ADU*
  - *Gain = 10 e-/ADU: for 1509 e- coming, how many ADUs ?*
- *Gain value: given in terms of the number of electrons needed to produce one ADU (e-/ADU)*
- *Gain is set by the electronics that read out the CCD chip.*
- *Gain value is an average conversion ratio, based on changing large numbers of electrons into large numbers of ADUs.*
- *What does a gain of 1.8e-/ADU stand for?*

Saturation and Gain

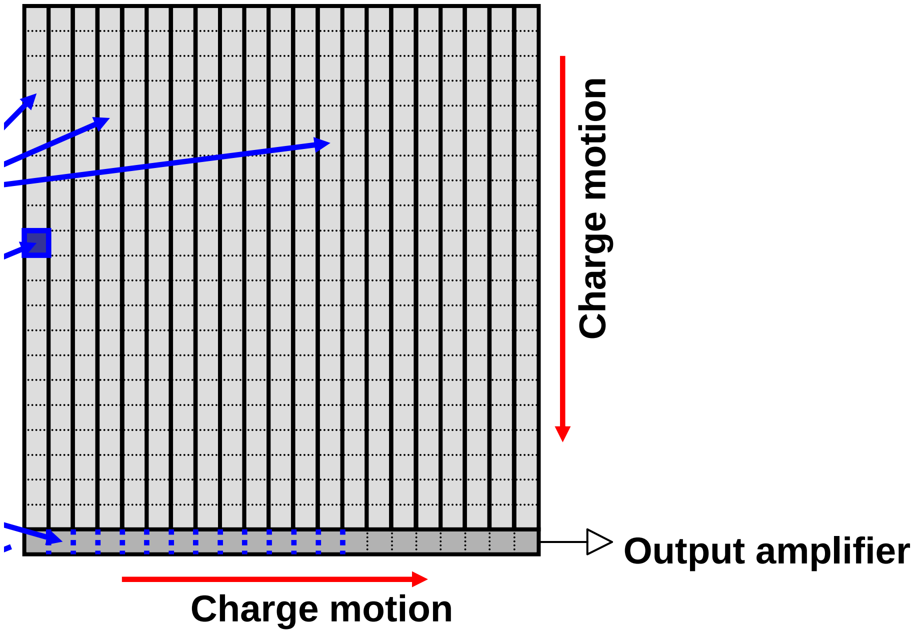
- Full well saturation: full well of a given pixel is full of electrons.
- The largest output number that a CCD can produce is set by the number of bits in the A/D converter:
  - 8 bits: $2^8 = 256$
  - 10 bits: $2^{10} = 1024$
  - 14 bits: $2^{14} = 16383$
  - 16 bits: $2^{16} = 65535$

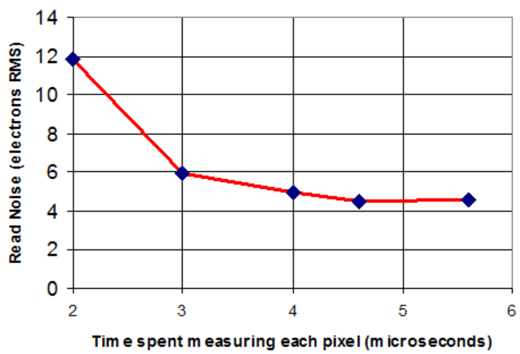


- A/D saturation: output number reach its maximum set by A/D converter.
- A/D saturation can occur prior to full well saturation, and vice verse, depending on gain.
  - A CCD camera: 14-bit A/D converter and full well capacity of 25000 e-
  - If gain = 2 e-/ADU, light curve?
  - If gain = 1 e-/ADU, light curver?



3.4 Readout Noise





- *Readout noise is mainly due to Johnson noise in on-chip amplifier and A/D circuit.*
- *Readout noise: in terms of the number of electrons.*
- *This noise can be reduced by reducing the bandwidth, but this requires that readout is slower.*
- *Readout noise is added into every pixel every time the array is read out.*
- *Pixel binning can reduce image noise*
  - *2 by 2 binning*

$$N = N_{RN}$$

  - *2 by 2 co-addition*

$$N = \sqrt{N_1^2 + N_2^2 + N_3^2 + N_4^2}$$

Dynamic Range

- *Dynamic Range defined as the ratio between the brightest and faintest detectable signal.*

$$DR = \frac{V_{\max}}{V_{noise}} = \frac{N_{fullwell}}{N_{RN}}$$

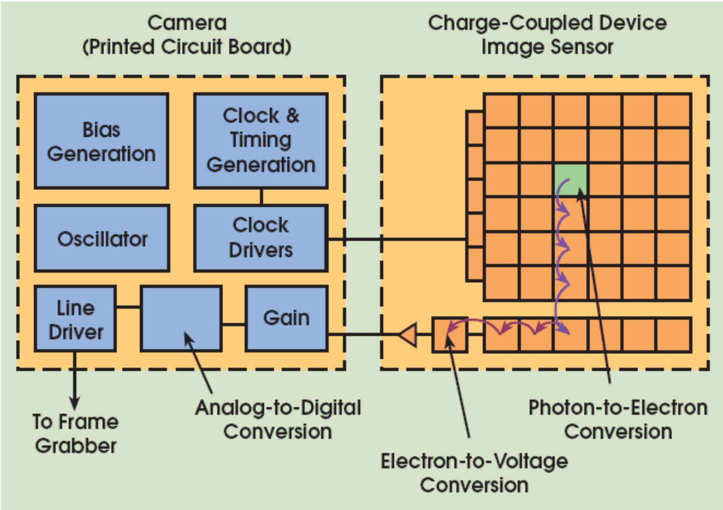
- *Dynamic range is simplified as the ratio of full well and readout noise*
- *Dynamic range has no unit, but often expressed in decibels,*

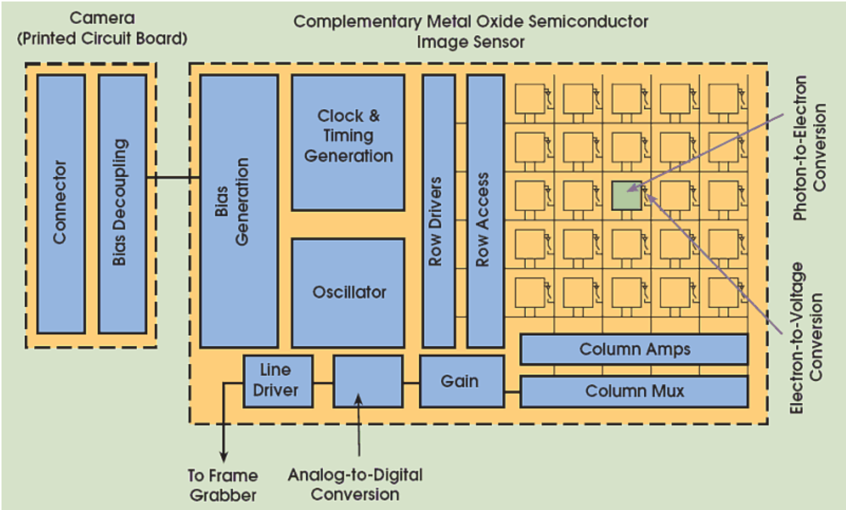
$$DR = 20\log\left(\frac{N_{fullwell}}{N_{RN}}\right) dB$$

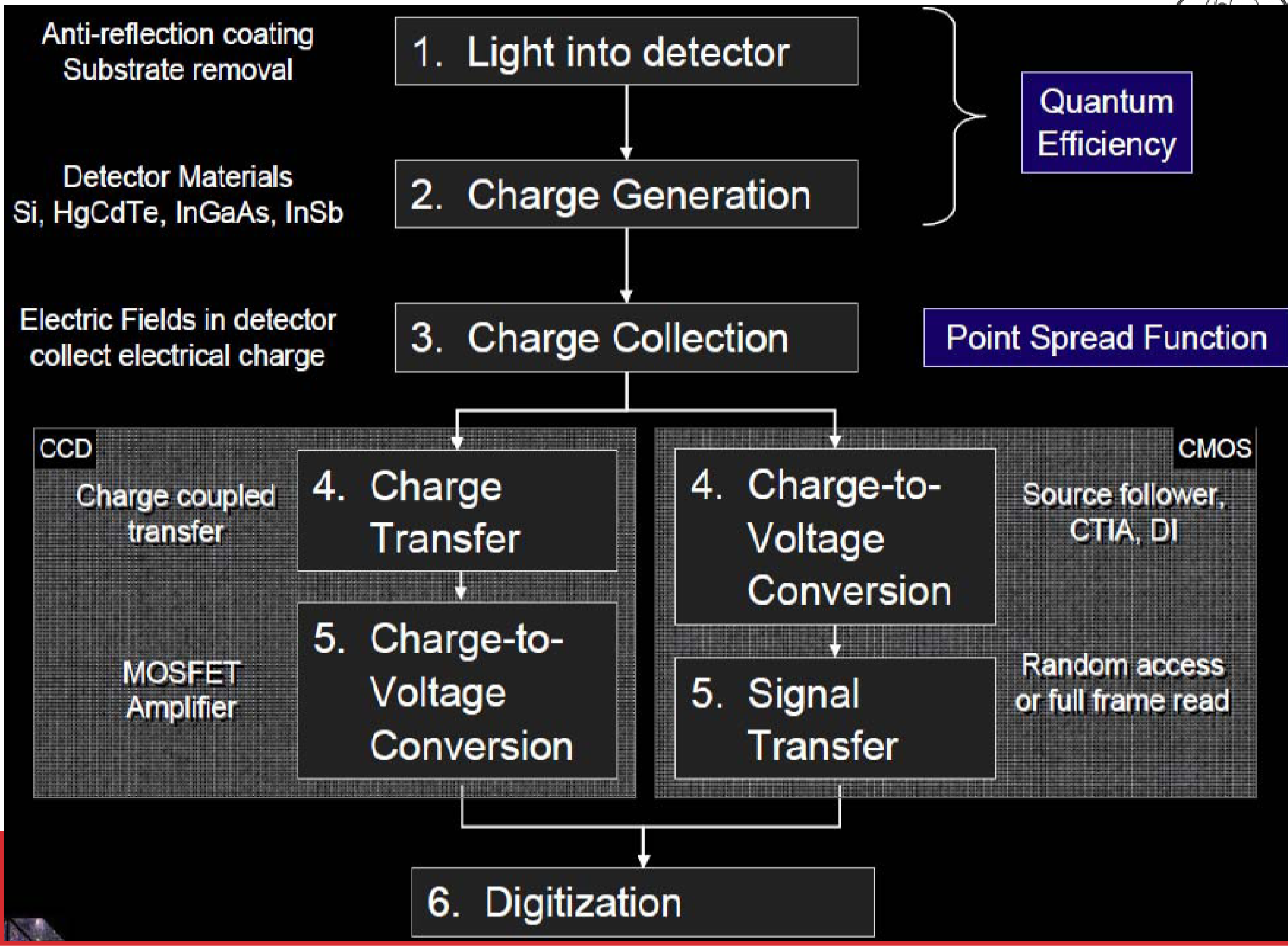
- *A CCD array has a full well of 150,000 e-. The advertised dynamic range is 80dB. Could you estimate its readout noise?*

4.1 CMOS vs CCD

- *CMOS: Complementary Metal Oxide Semiconductor*
- *CCD: Charge Coupling Device*
- *Both are pixelated MOS and have the same process in charge generation and charge collection*
- *However, charge transfer and charge detection are different*
- *CCD: all pixels share one charge-to-voltage converter*
- *CMOS: every pixel has its own charge-to-voltage converter*







Anti-reflection coating
Substrate removal
1. Light into detector
Detector Materials
Si, HgCdTe, InGaAs, InSb
2. Charge Generation
Quantum Efficiency
Electric Fields in detector collect electrical charge
3. Charge Collection
Point Spread Function
CCD
Charge coupled transfer
4. Charge Transfer
MOSFET Amplifier
5. Charge-to-Voltage Conversion
CMOS
4. Charge-to-Voltage Conversion
Source follower, CTIA, DI
5. Signal Transfer
Random access or full frame read
6. Digitization

Pros and Cons

CCD

- *offer high-quality, low-noise images*
- *greater sensitivity and fidelity*
- *100 times more power*
- *acceptable speed*
- *complicated anti-blooming technique*
- *require specialized assembly lines*
- *equal reliability*
- *older and more developed technology*

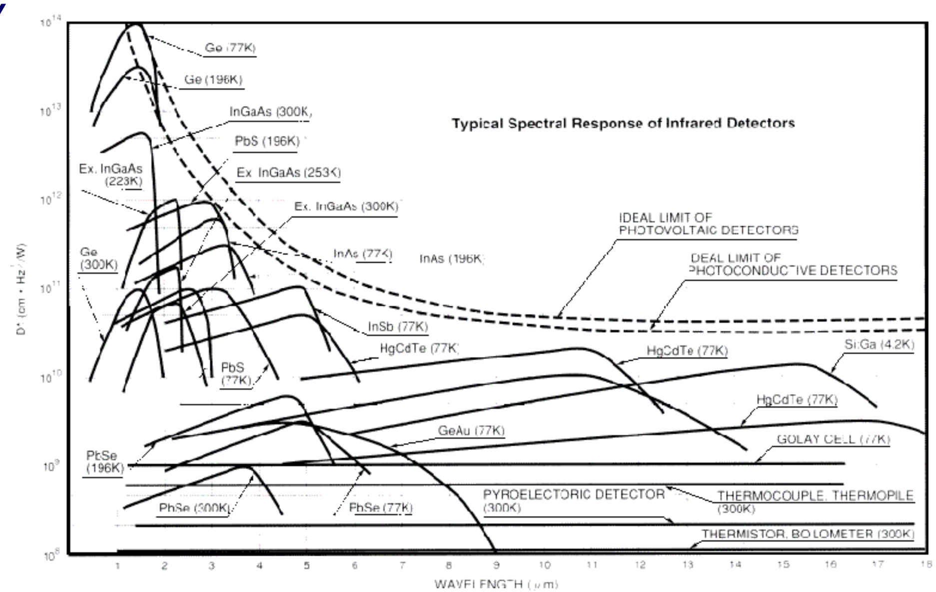
CMOS

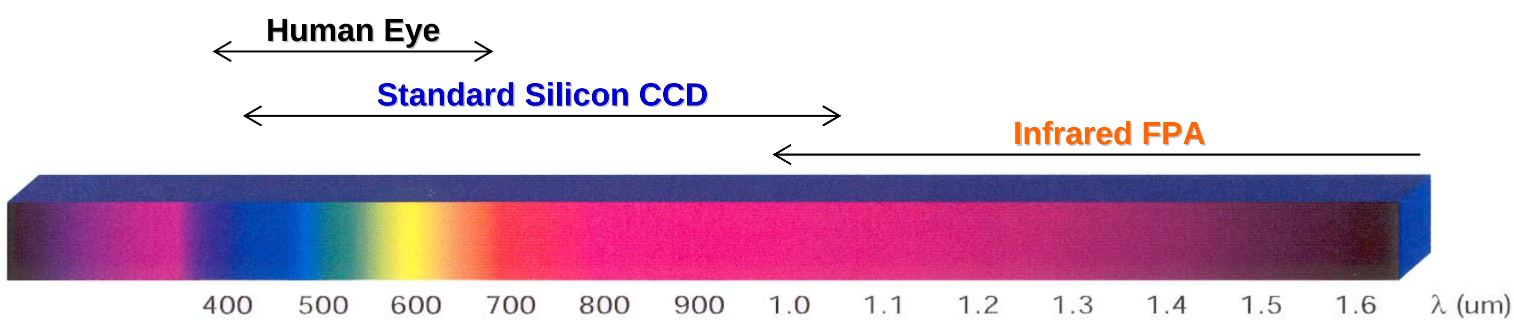
- *more susceptible to noise*
- *light sensitivity is lower*
- *consume little power*
- *much fast*
- *natural blooming immunity*
- *easy to manufacture*
- *highly integrated*
- *less expensive*

- *CMOS imagers offer superior integration, power dissipation and system size at the expense of image quality (particularly in low light) and flexibility. They are the technology of choice for high-volume, space-constrained applications where image quality requirements are low.*
- *CCDs offer superior image quality and flexibility at the expense of system size. They remain the most suitable technology for high-end imaging applications.*

4.2 IRFPA

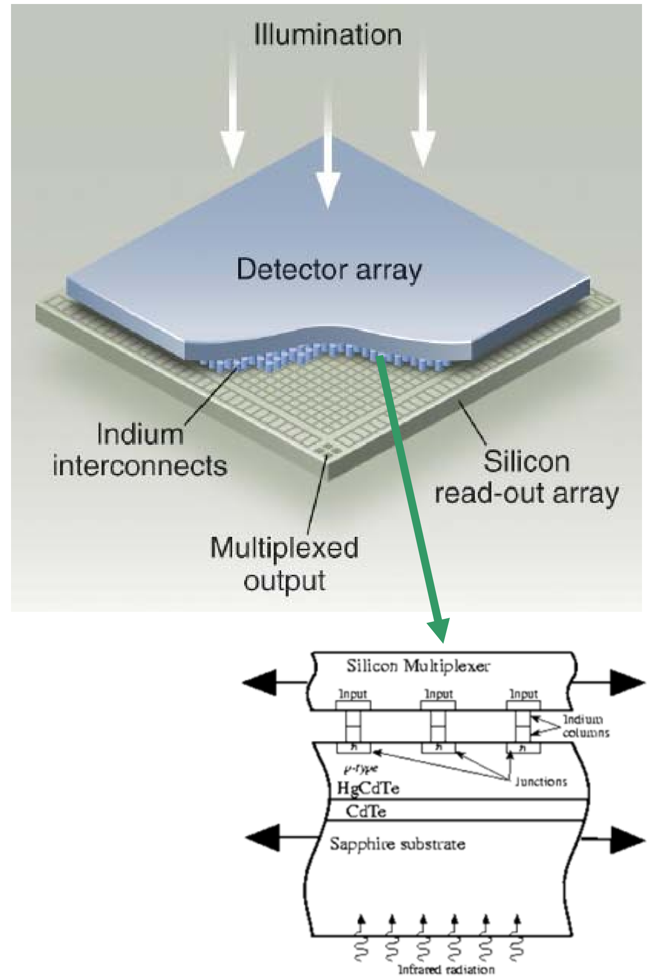
- *IRFPA: InfraRed Focal Plane Array*
- *Silicon CCD/CMOS detectors are unable to sensor photons in the infrared*
- *Which material for NIR ?*
  - *HgCdTe*
  - *InSb*
  - *PtSi*
  - *InGaAs*
  - *……*





Hybrid IRFPA

- *IRFPAs mostly deploy hybrid structure*
  - *Photosensitive substrate*
  - *Silicon read-out circuit*
- *Sapphire Substrate*
  - *Array of n-p-photodiodes made from HgCdTe (epitaxially grown on transparent carrier (AlsO3/CdTe, CdZnTe/CdTe))*
  - *Boron implants to define pixel structure*
  - *Read-out Circuit (ROIC)*
  - *Si based integrated circuit (CMOS array) with individually addressable pixels*
- *Flip-chip Technique*
  - *Substrate and ROIC are electrically connected pixel by pixel*
  - *Indium bumps*



5. Observation with Solid State Detectors

$$image(x,y) = \frac{raw(x,y) - dark(x,y)}{flat(x,y)}$$

- ***CCD, CMOS, IRFPA Imaging***
- ***Dark Fielding***
- ***Flat Fielding***
- ***Image Reduction***