# Scientific Imaging Sensors

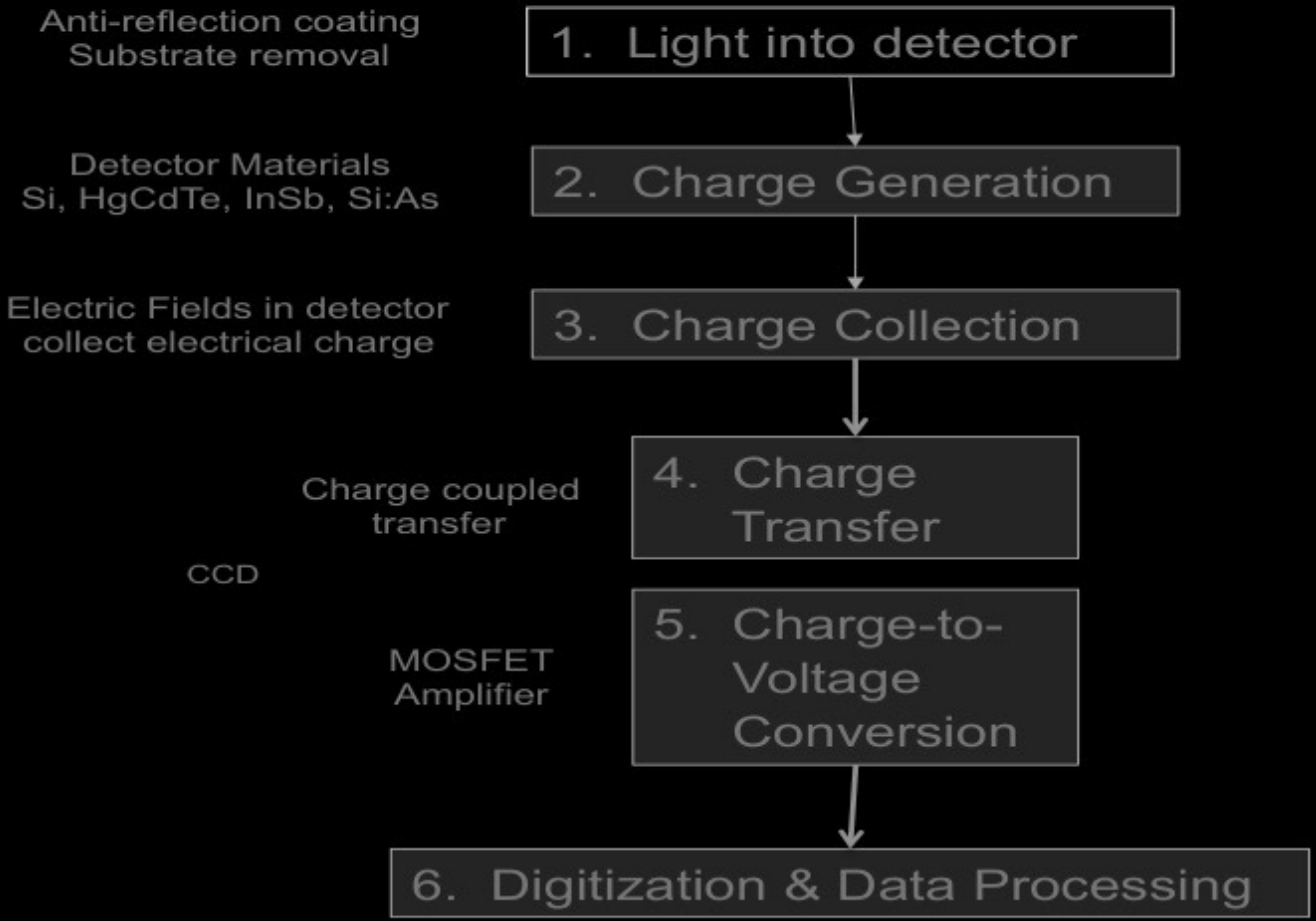
A Short Course presented by

Nicolas Haddad

Based on material provided by

Jim Beletic and Simon Tulloc

# 6 steps of optical / IR photon detection



Anti-reflection coating
Substrate removal

1. Light into detector

Detector Materials
Si, HgCdTe, InSb, Si:As

2. Charge Generation

Electric Fields in detector
collect electrical charge

3. Charge Collection

Charge coupled
transfer

4. Charge Transfer

CCD

MOSFET
Amplifier

5. Charge-to-Voltage Conversion

6. Digitization & Data Processing

# 2009 Nobel Prize in Physics awarded to the inventors of the CCD

In 1969, Willard S. Boyle and George E. Smith invented the first successful imaging technology using a digital sensor, a CCD (charge-coupled device). The two researchers came up with the idea in just an hour of brainstorming.

**Bell Labs researchers Willard Boyle (left) and George Smith (right) with the charge-coupled device.**
Photo taken in 1974. Photo credit: Alcatel-Lucent/Bell Labs.

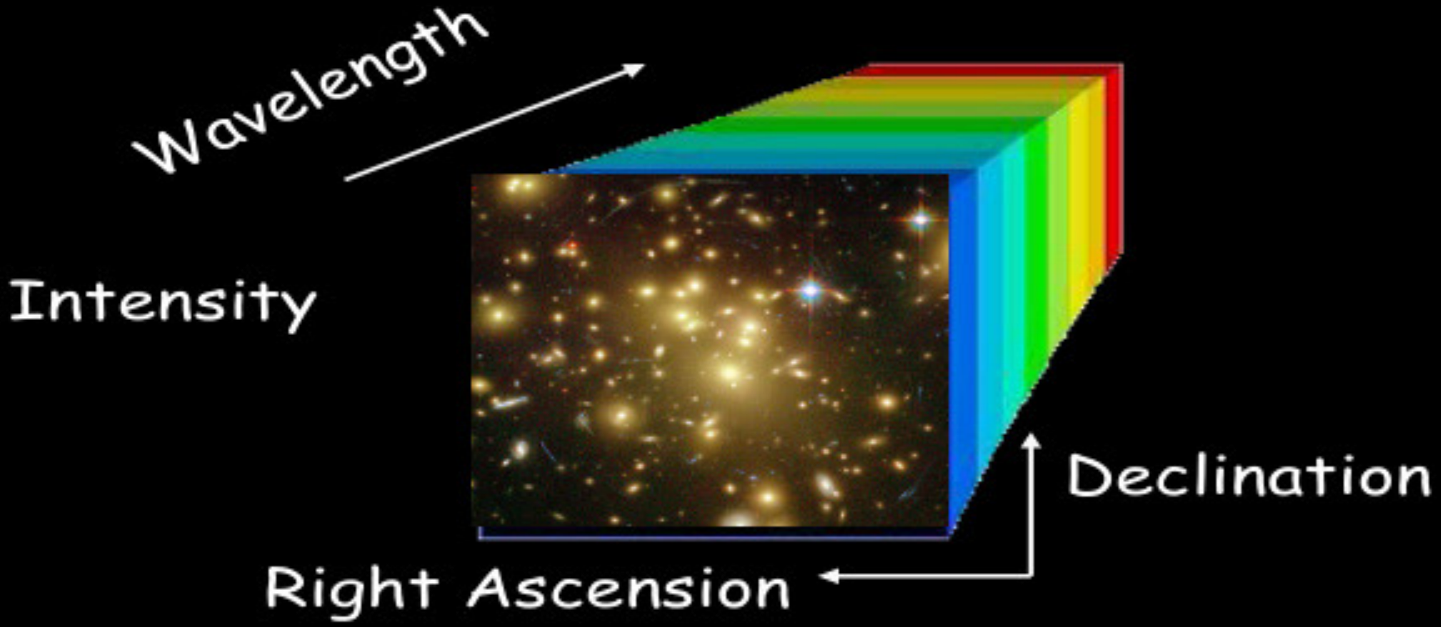
The Nobel Prize in Physics 2009

"for the invention of an imaging semiconductor circuit – the CCD sensor"

**Willard S. Boyle**

**George E. Smith**

# Instrument goal is to measure a 3-D data cube



But most detectors are 2-dimensional !

- Detectors are BLACK & WHITE
- Can not measure color
- Only measure intensity

Optics of the instrument are used to map a portion of the 3-D data cube onto the 2-D detector

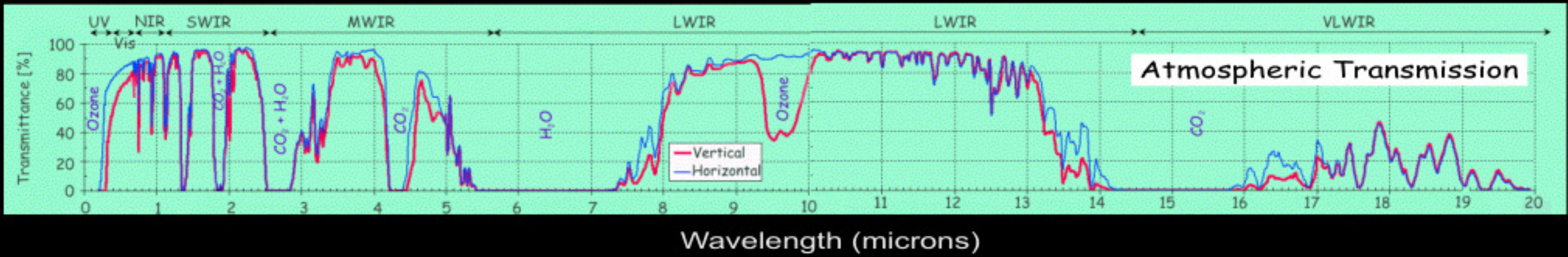
# The Ideal Detector

| | |
|---|---|
| • Detect 100% of photons | ✓ Up to 98% quantum efficiency |
| • Each photon detected as a delta function | ✓ One electron for each photon |
| • Large number of pixels | ✓~1,400 million pixels ($>10^9$) |
| • Time tag for each photon | ☒ No - framing detectors<br>✓ APDs & event driven readout |
| • Measure photon wavelength | ☒ No – defined by filter<br>✓ Foveon, 3rd Gen IR |
| • Measure photon polarization | ☒ No – defined by filter<br>Can place filter on detector |

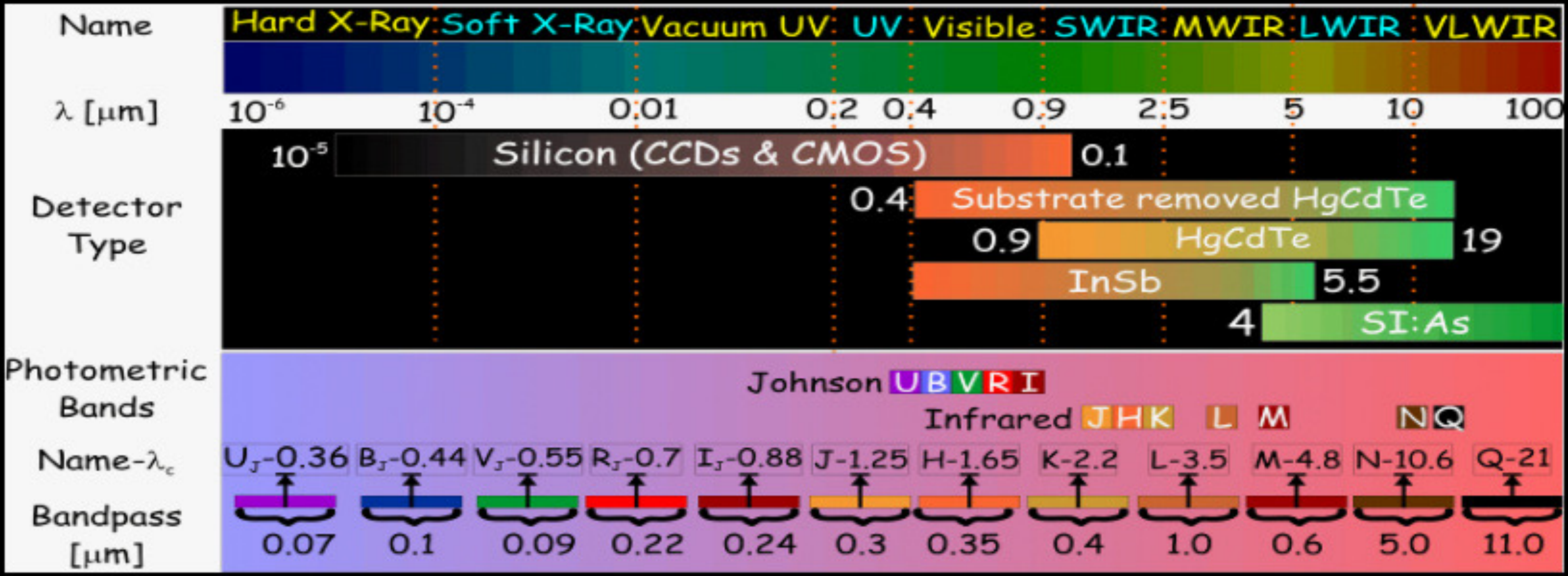
Plus READOUT NOISE and other "features"

# Spectral Bands

Defined by atmospheric transmission & detector material properties



Detector Zoology



| Name-$\lambda_c$ | Bandpass [μm] |
|---|---|
| $U_J$-0.36 | 0.07 |
| $B_J$-0.44 | 0.1 |
| $V_J$-0.55 | 0.09 |
| $R_J$-0.7 | 0.22 |
| $I_J$-0.88 | 0.24 |
| J-1.25 | 0.3 |
| H-1.65 | 0.35 |
| K-2.2 | 0.4 |
| L-3.5 | 1.0 |
| M-4.8 | 0.6 |
| N-10.6 | 5.0 |
| Q-21 | 11.0 |

# Energy of a photon

$E = h\nu$

h = Planck constant ($6.6310^{-34}$ Joule•sec)

$\nu$= frequency of light (cycles/sec) = $c/\lambda$

$\lambda_c = hc/E_g$

| Wavelength (µm) | Energy (eV) | Band |
|---|---|---|
| 0.3 | 4.13 | UV |
| 0.5 | 2.48 | Vis |
| 0.7 | 1.77 | Vis |
| 1.0 | 1.24 | NIR |
| 2.5 | 0.50 | SWIR |
| 5.0 | 0.25 | MWIR |
| 10.0 | 0.12 | LWIR |
| 20.0 | 0.06 | VLWIR |

Nota Bene:

IR Industry definitions

NOT the same for astronomers !

- Energy of photons is measured in electron-volts (eV)
- eV = energy that an electron gets when it “falls” through a 1 volt potential difference.

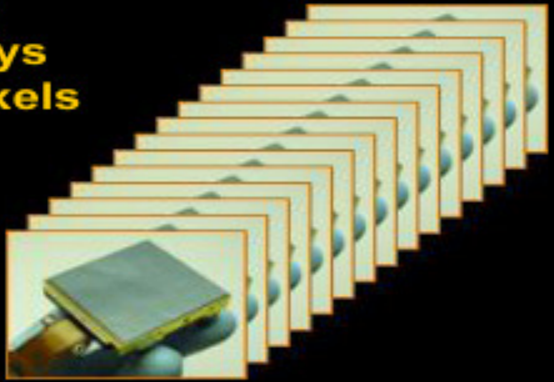
# An electron-volt (eV) is extremely small

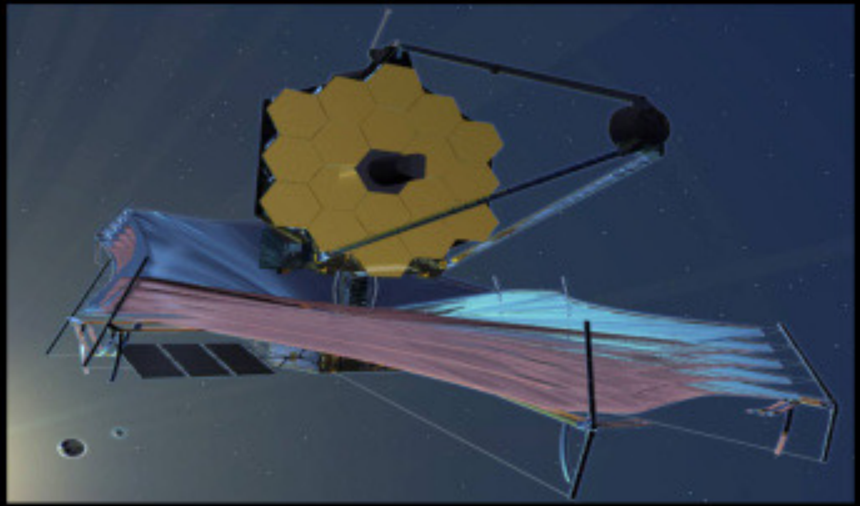
- The energy of a photon is **VERY** small
  - Energy of SWIR (2.5 μm) photon is 0.5 eV

- In 5 years, JWST will take ~1 million images
  - Total # SWIR photons detected ≈ $3.6 \times 10^{16}$
  - Total energy detected ≈ $1.8 \times 10^{16}$ eV

- Drop peanut M&M® candy (~2g) from height of 15 cm (~6 inches)
  - Potential energy ≈ $1.8 \times 10^{16}$ eV

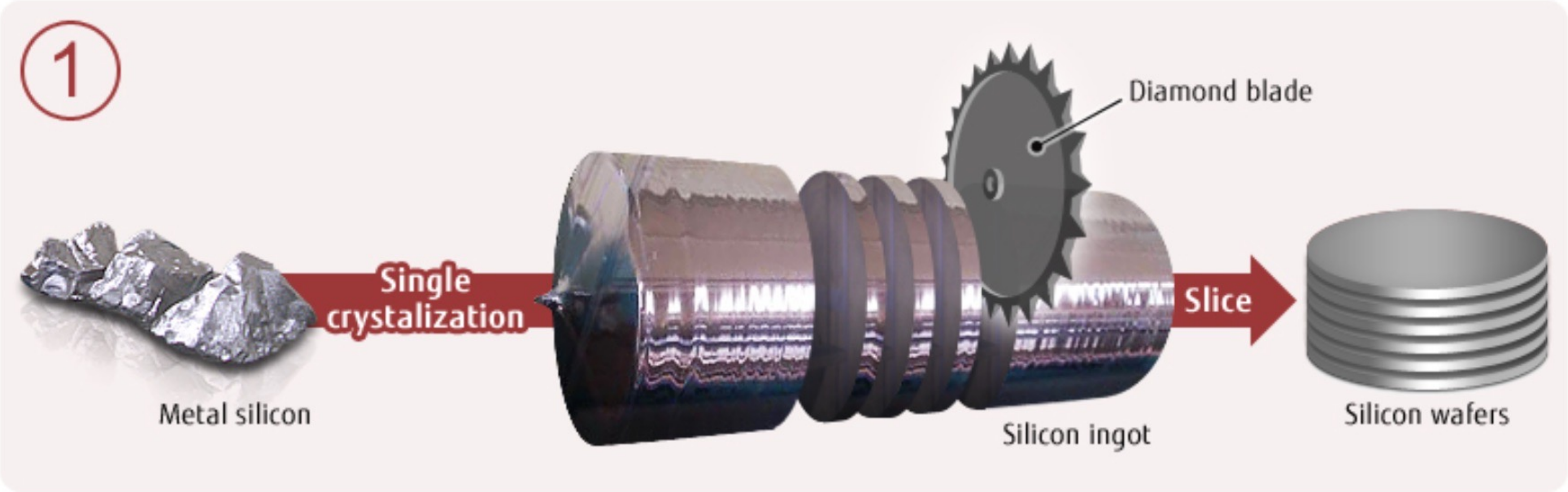
**15 H2RG**
**2K×2K arrays**
**63 million pixels**



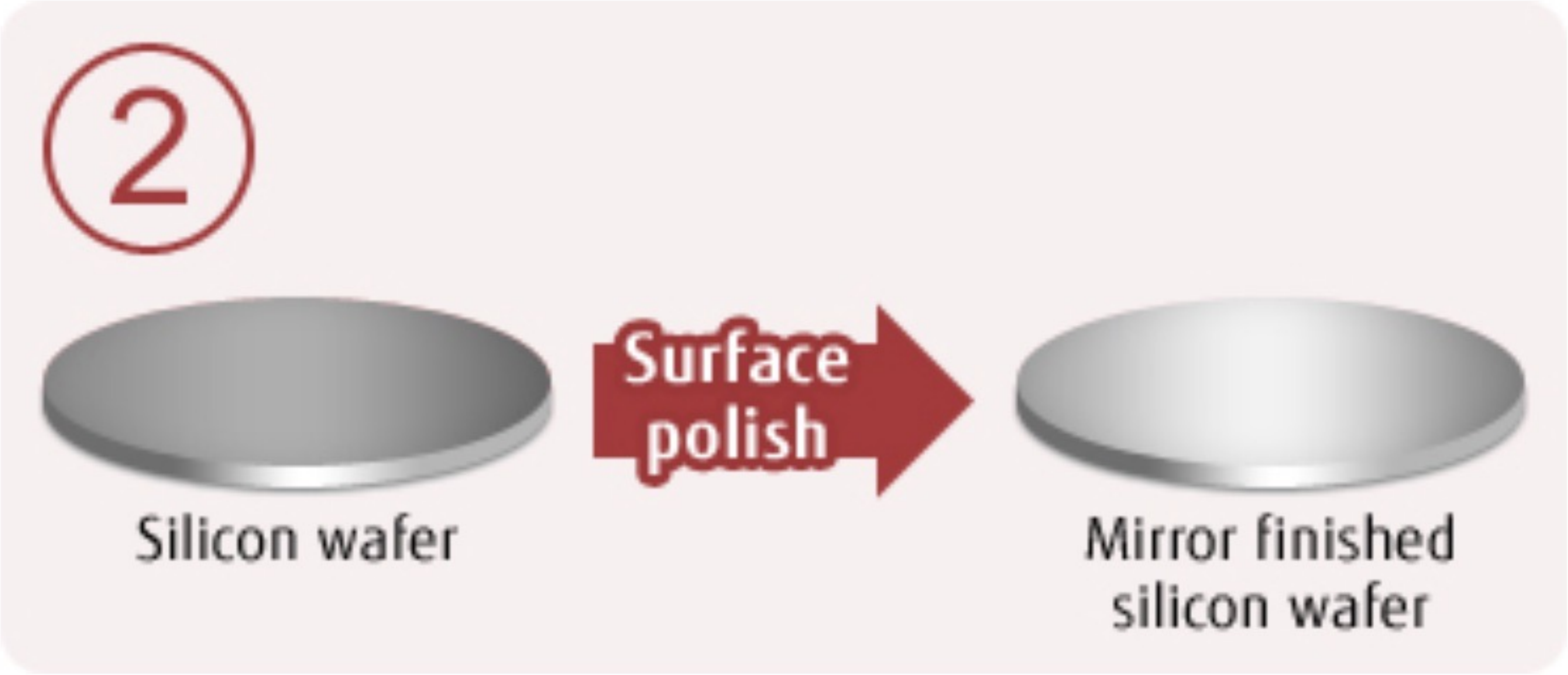


15 cm peanut M&M® drop is equal to the energy detected during 5 year operation of the James Webb Space Telescope!

## Silicon ingot is sliced to create silicon wafers

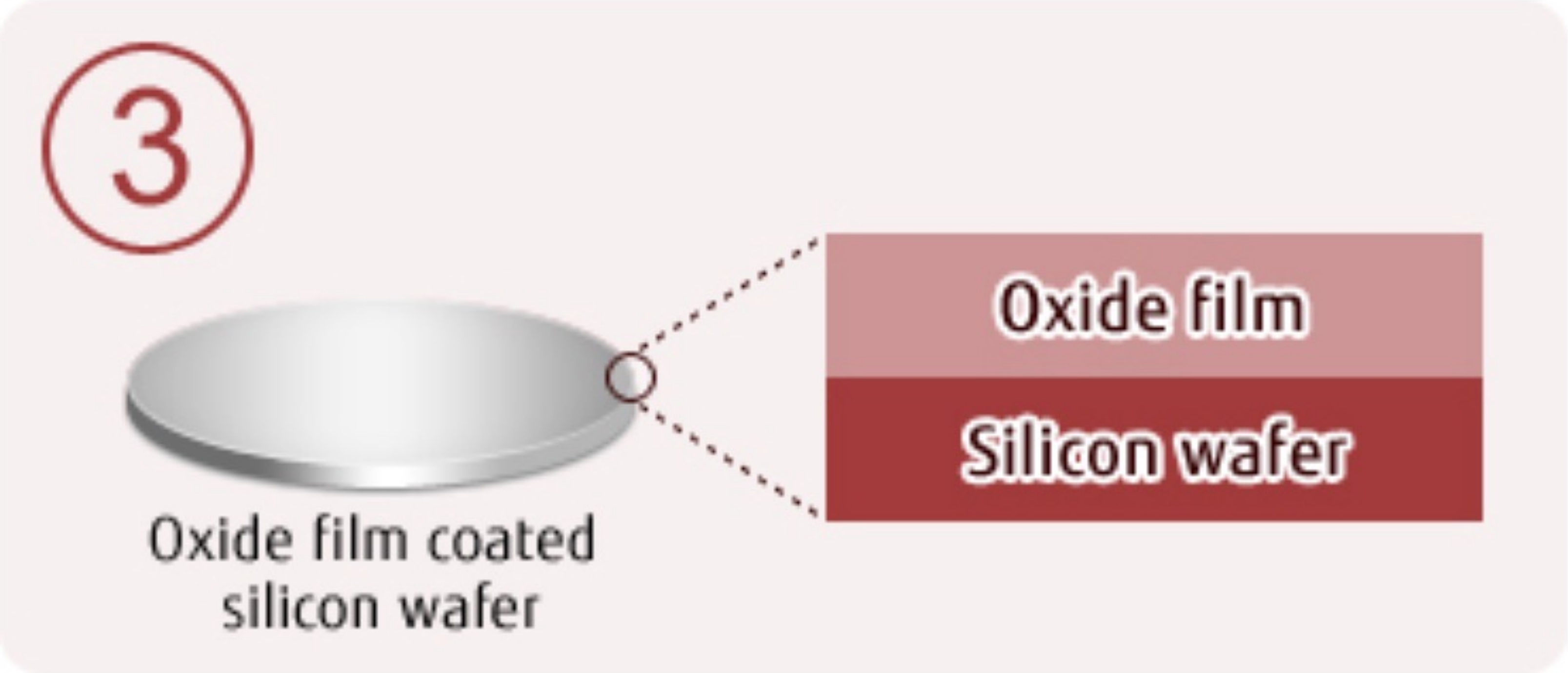


**A large silicon monocrystal or ingot (99.999999999% pure) is sliced by a diamond blade to create thin silicon wafers.**

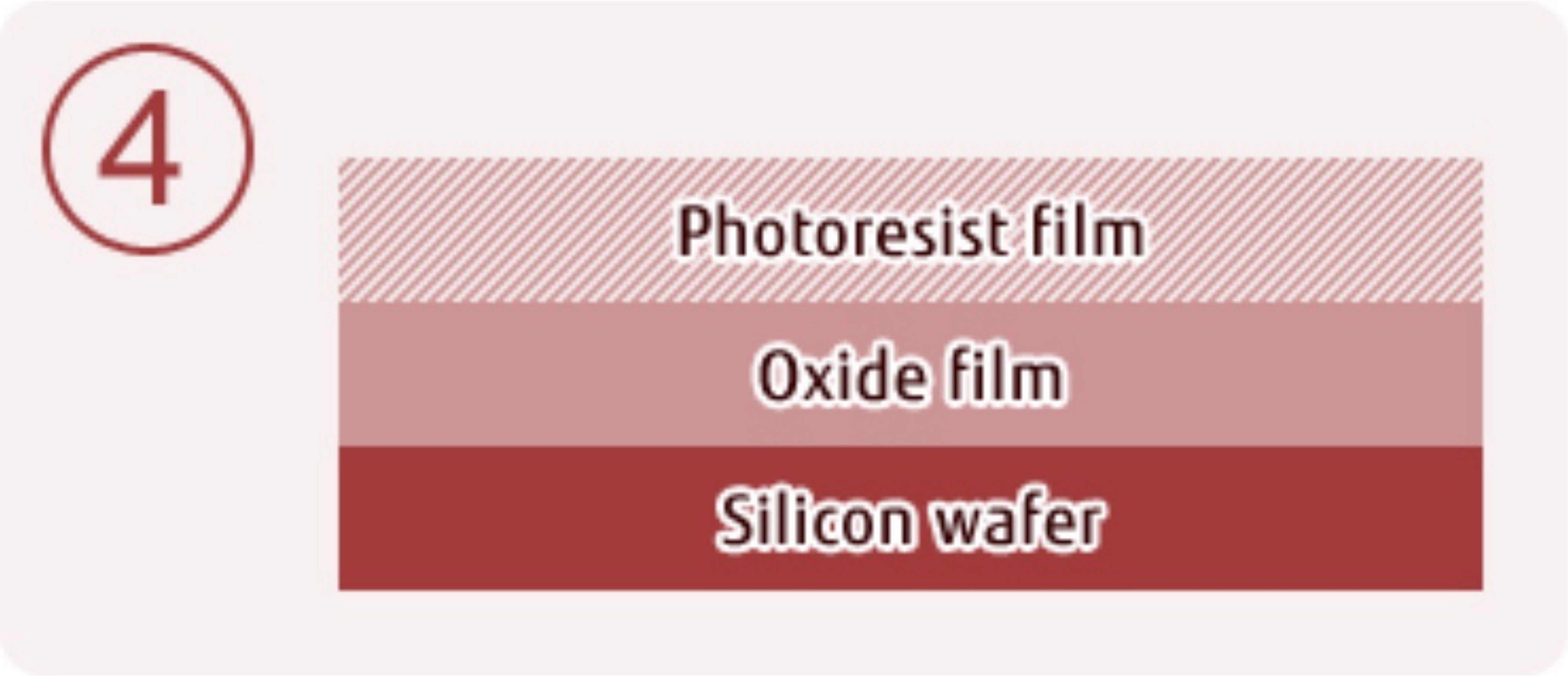


**The surface of the silicon wafer is polished to create a mirror finish.**

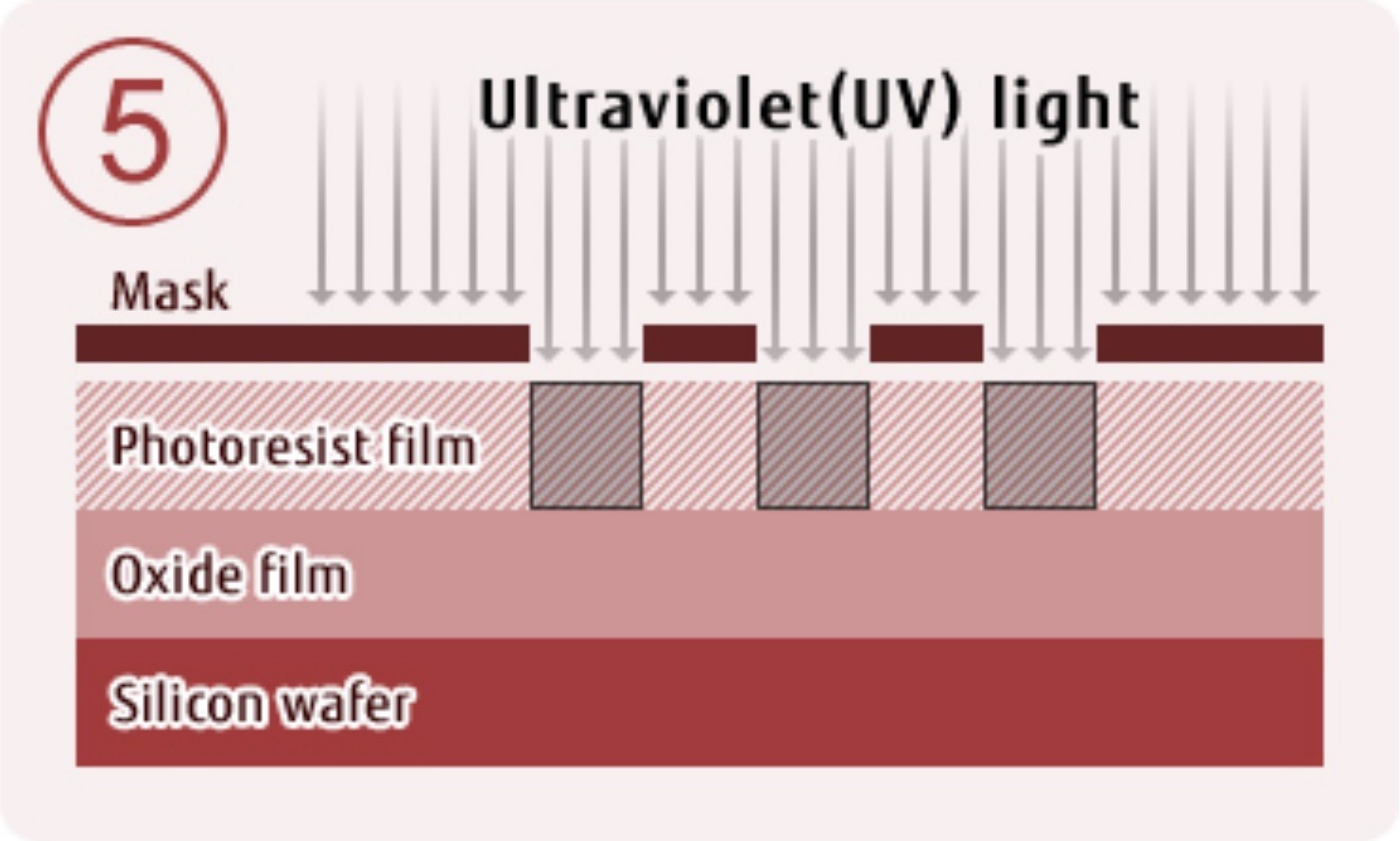
# Process the surface to make semiconductors



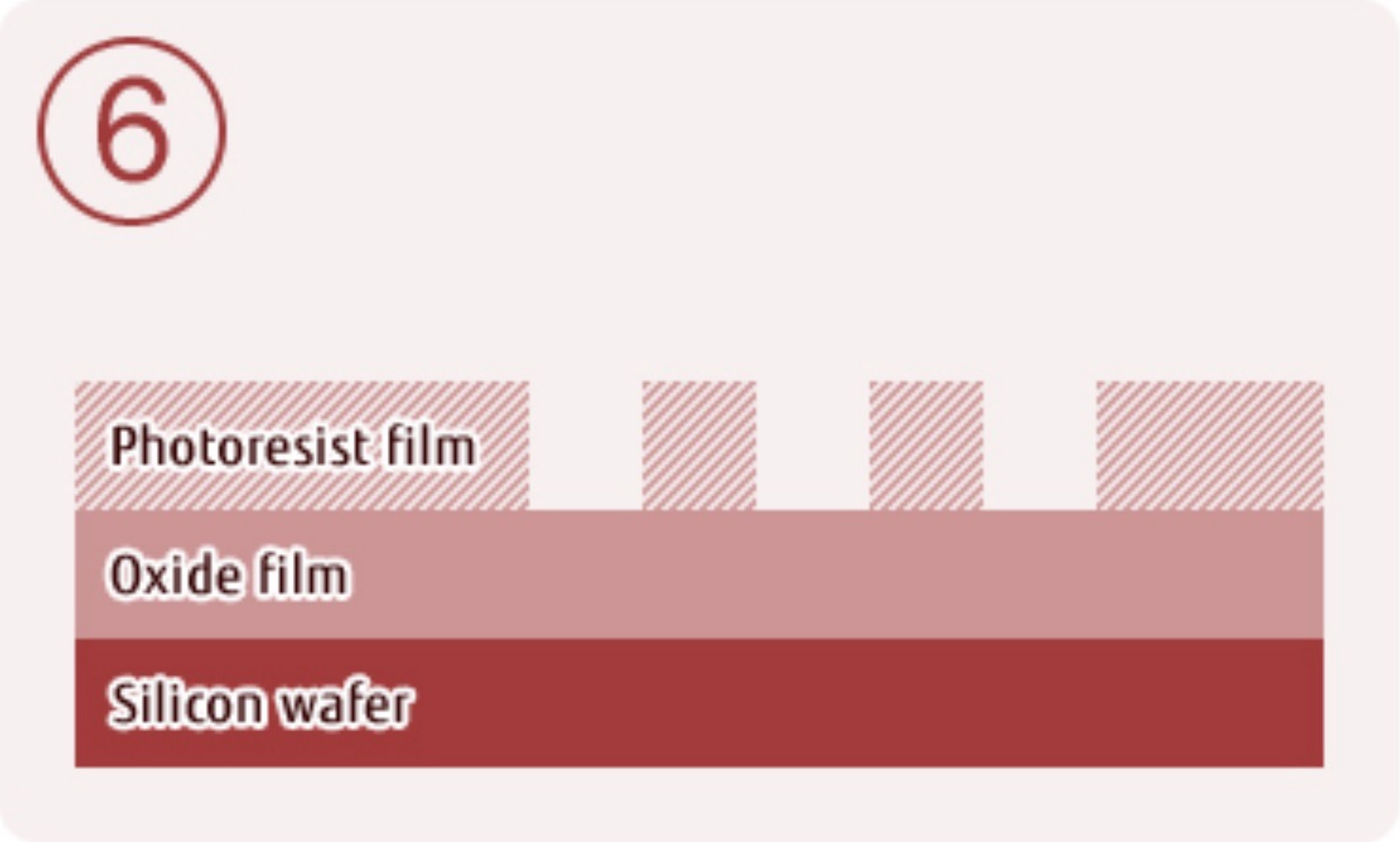
**An oxide film is grown onto the wafer.**



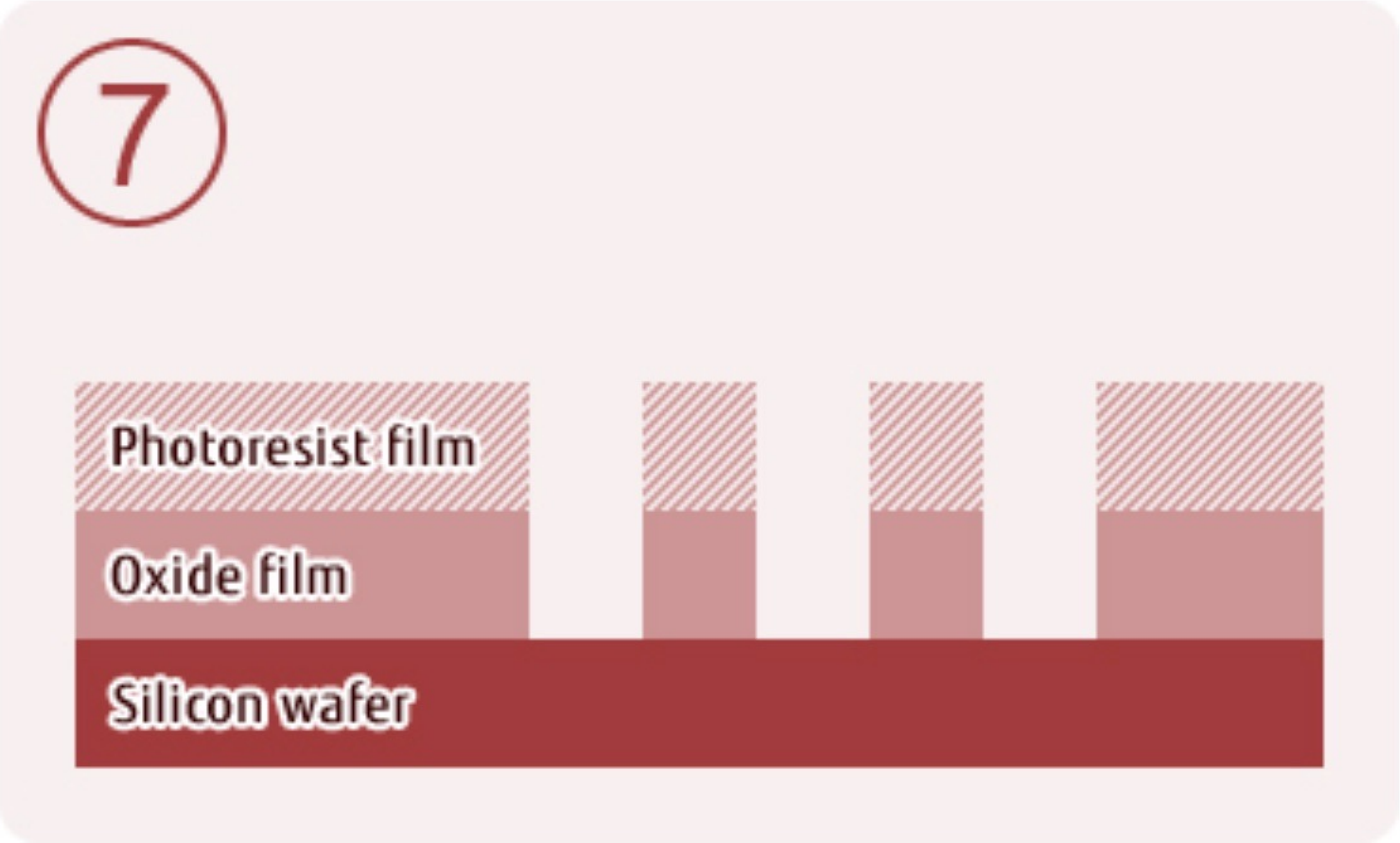
**A photoresist film is coated on the wafer surface.**



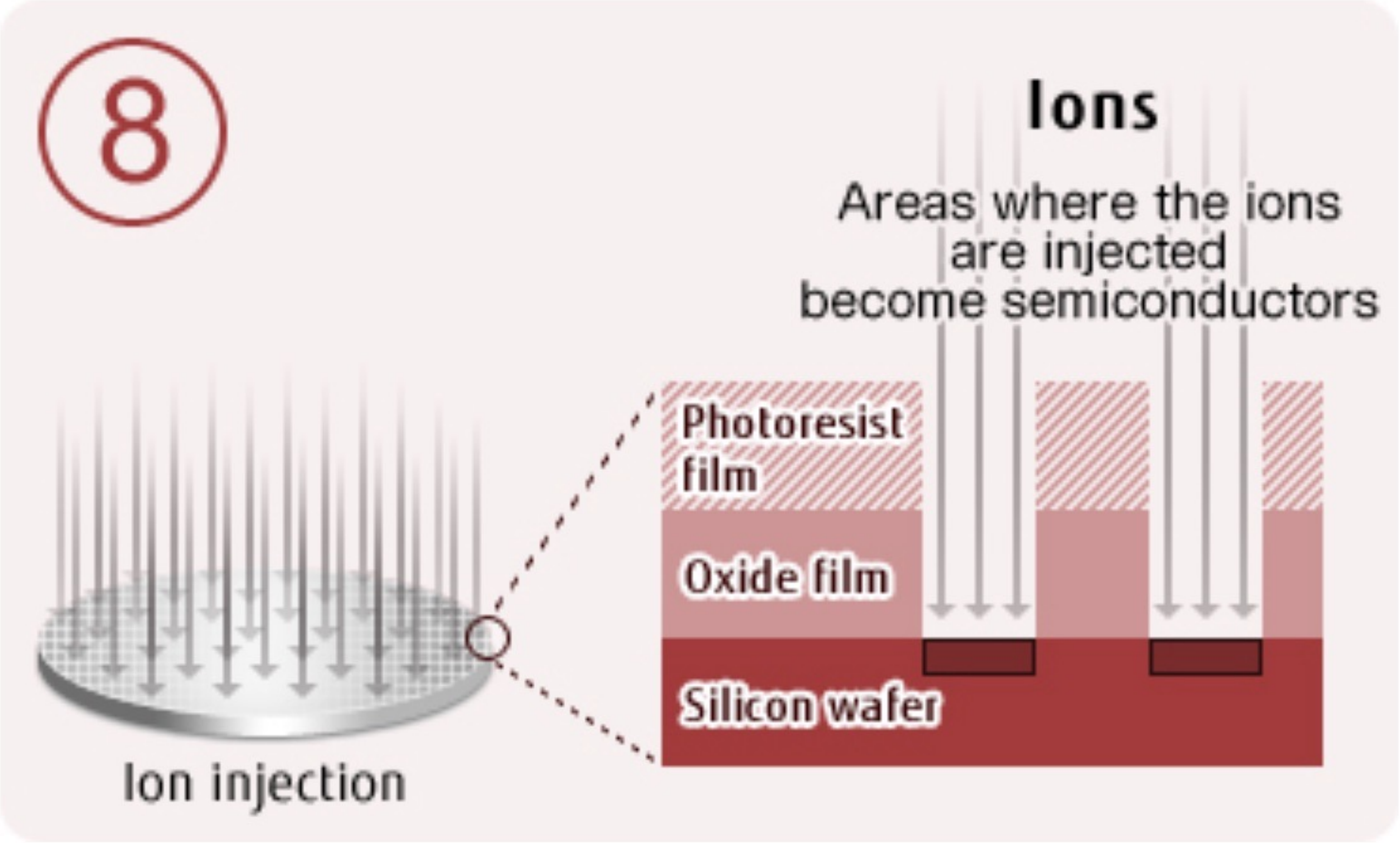
The photoresist film is exposed to ultraviolet (UV) light through the pattern on the mask.



**The photoresist region that was exposed to the UV light is removed using a developer. (The exposed area changes to a substance that is dissolved by the developer.)**

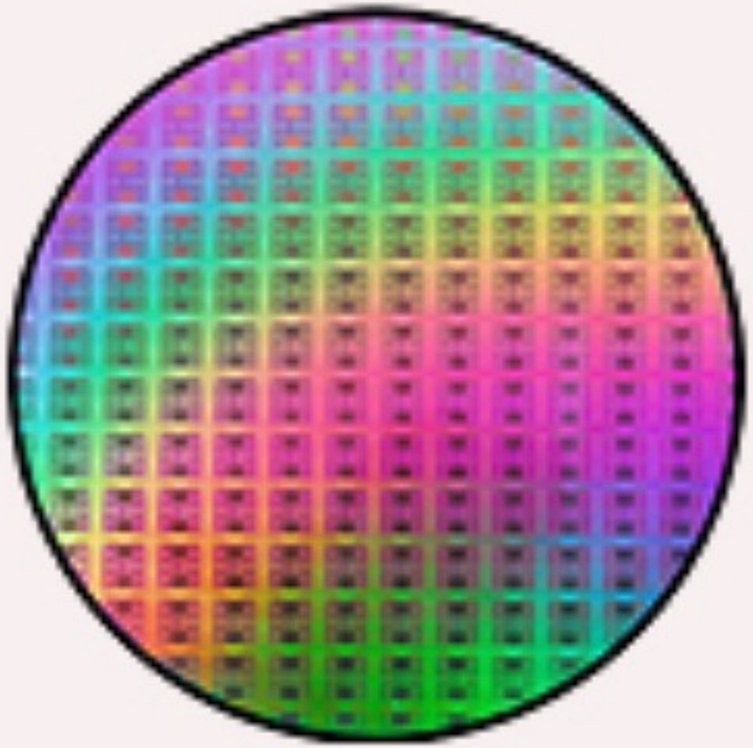


The oxide film is then removed using a caustic agent. This exposes the silicon surface.



**The required ions are then injected into the silicon surface. The character of the silicon then changes into a semiconductor, which is a state where elements with electrical characteristics can be created.**

⑨

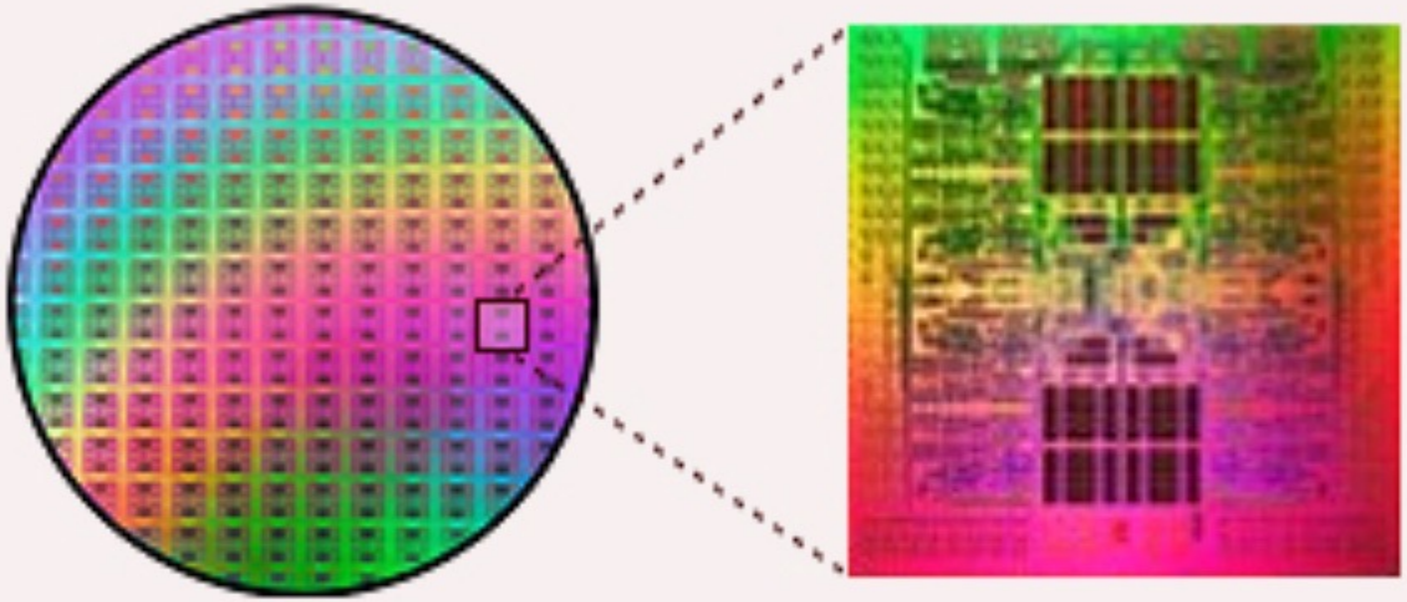


Silicon wafer (complete)

**Elements with electrical characteristics are then created by connecting wires and creating circuits. Many chips can be created on the same silicon wafer. Wafer probers are used to electrically test the chips and define good or bad chips.**

# CPU separated from the silicon wafer

⑩



**Good chips are separated from the silicon wafer.**

Note: This image has been simplified for illustration purposes. On an actual wafer, solder bumps are formed for connection to the package board.

# 6 steps of optical / IR photon detection

Anti-reflection coating
Substrate removal

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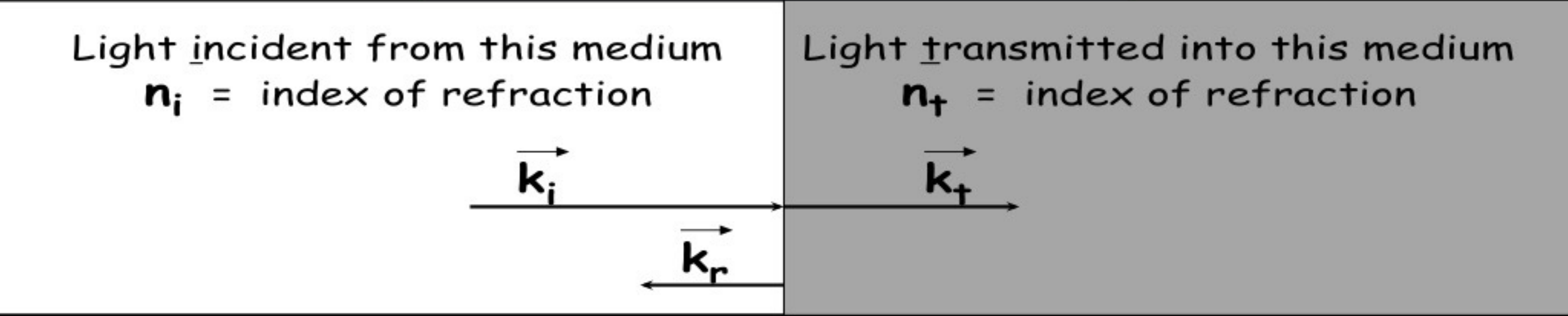
# 1st Step: Get light into the detector
## Anti-reflection coatings

Velocity of light = c / n

c = speed of light in a vacuum
n = index of refraction of medium



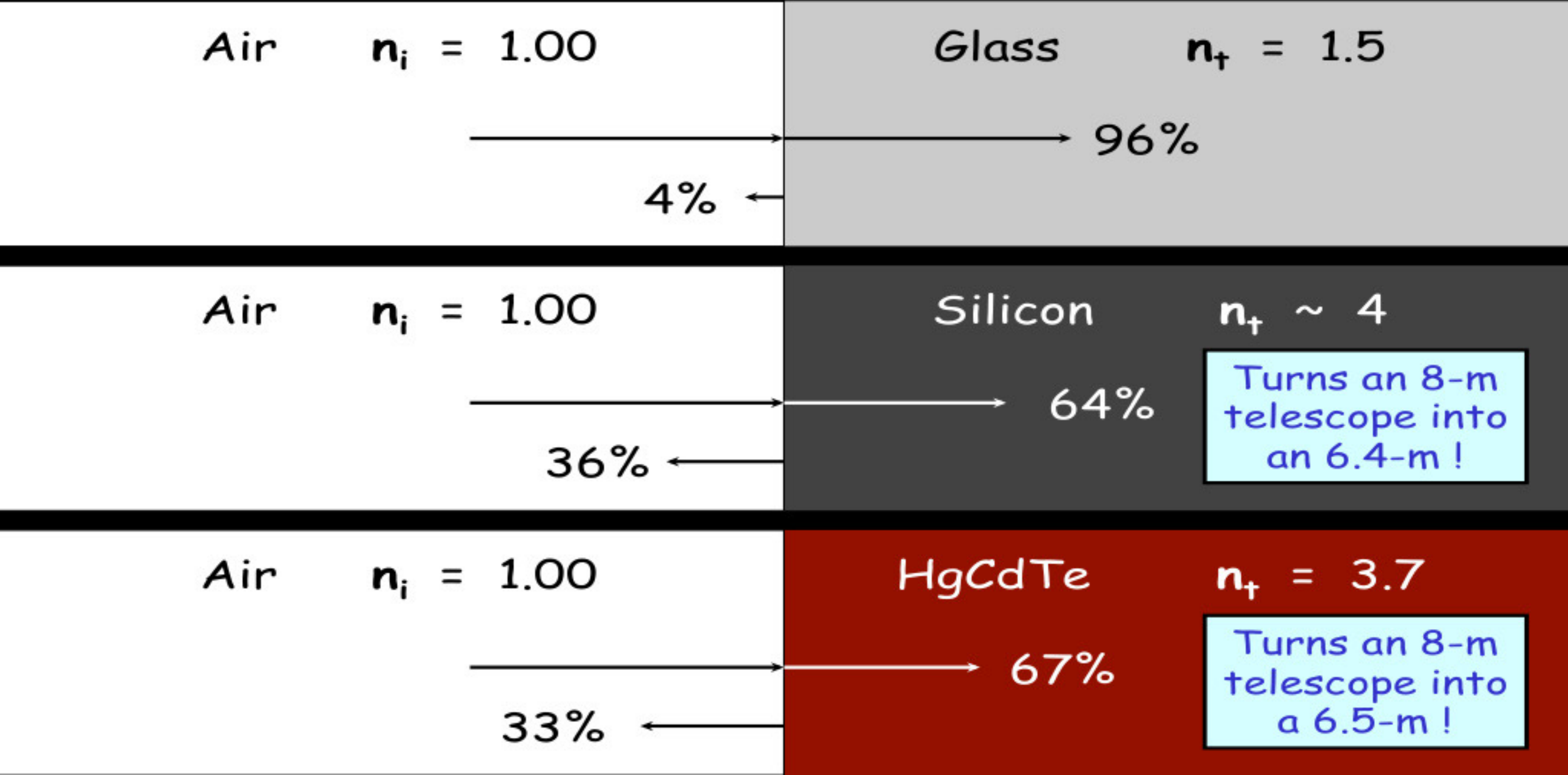
Light incident from this medium
$\mathbf{n_i}$ = index of refraction

Light transmitted into this medium
$\mathbf{n_t}$ = index of refraction

For transmission directly into interface (angle of incidence = 0°)

R = fraction of incident energy reflected
$= ((\mathbf{n_t} - \mathbf{n_i}) / (\mathbf{n_t} + \mathbf{n_i}))^2$

# Loss at a surface



Air $n_i = 1.00$

Glass $n_t = 1.5$

96%

4%

Air $n_i = 1.00$

Silicon $n_t \sim 4$

64%

36%

Turns an 8-m telescope into an 6.4-m !

Air $n_i = 1.00$

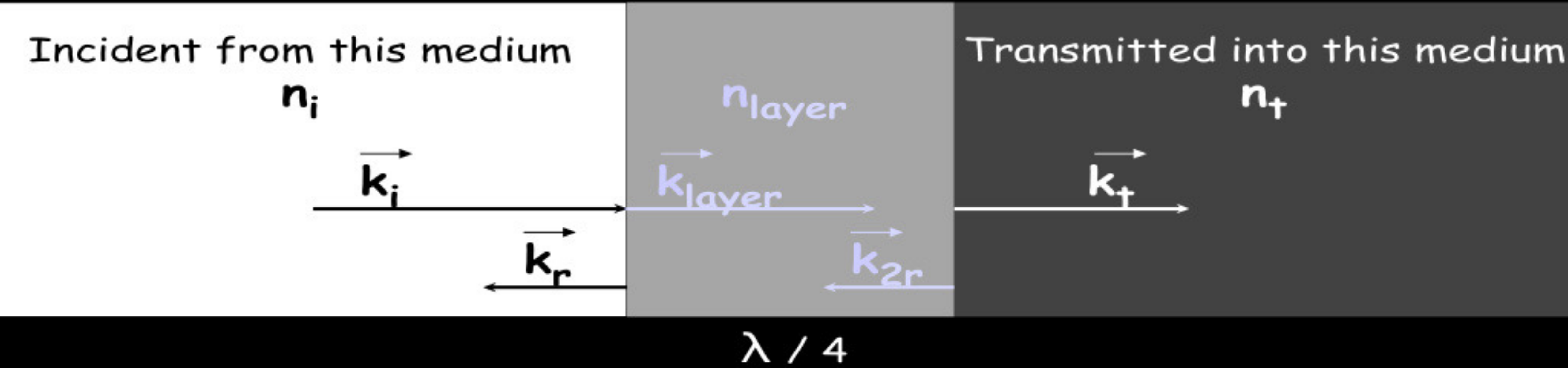
HgCdTe $n_t = 3.7$

67%

33%

Turns an 8-m telescope into a 6.5-m !

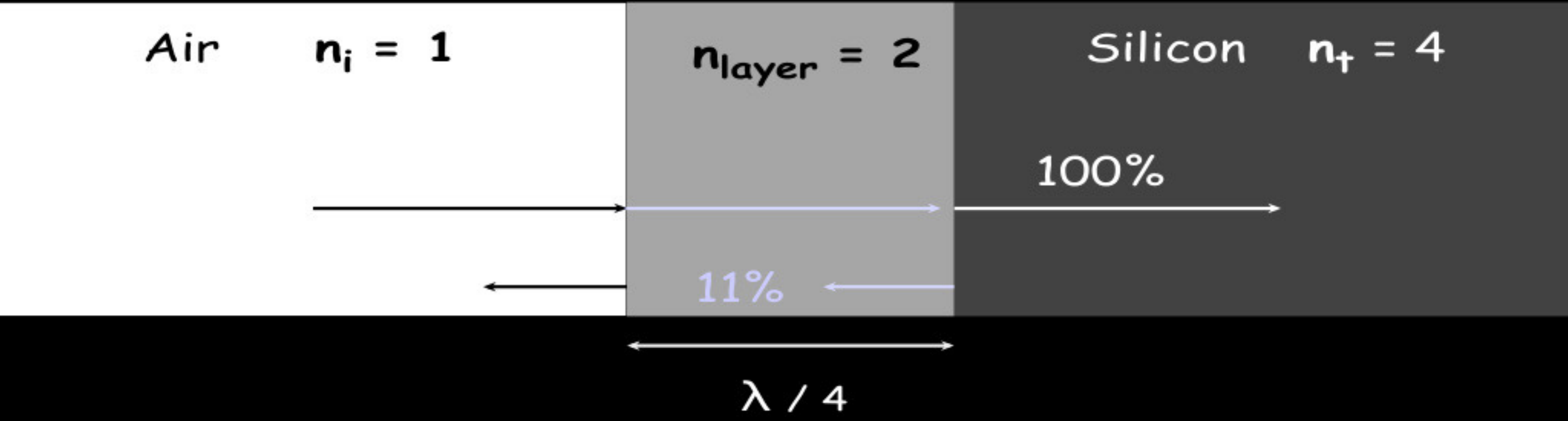
# Single layer anti-reflection coatings
## (angle of incidence = 0°)



$$R = \left[\frac{n_i n_t - n_{layer}^2}{n_i n_t + n_{layer}^2}\right]^2$$

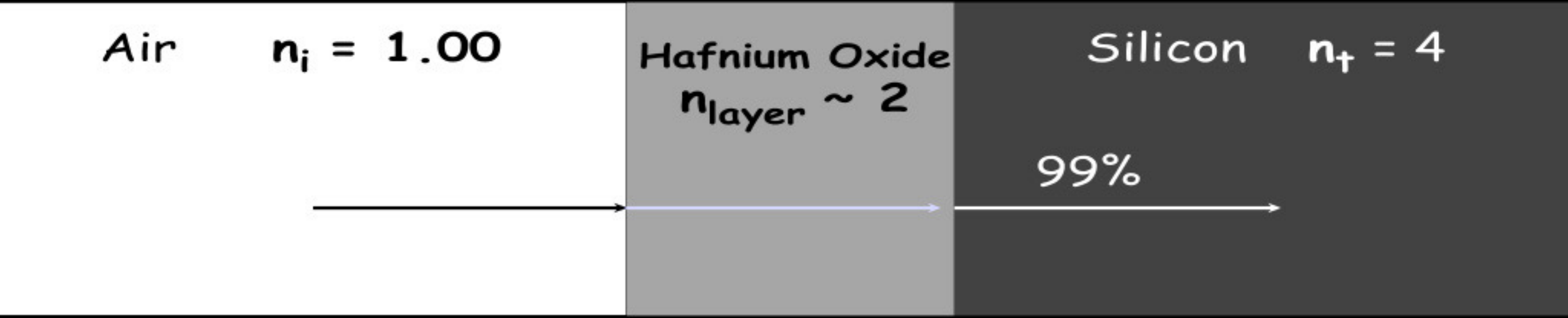
If $n_{layer}^2 = n_i n_t \Rightarrow$ 0% reflected, 100% transmitted !

# Ideal CCD anti-reflection coating



$$R = \left[ \frac{1 \cdot 4 - 2^2}{1 \cdot 4 + 2^2} \right]^2 = 0$$

# Actual CCD anti-reflection coating



Air $n_i = 1.00$

Hafnium Oxide

$n_{layer} \sim 2$

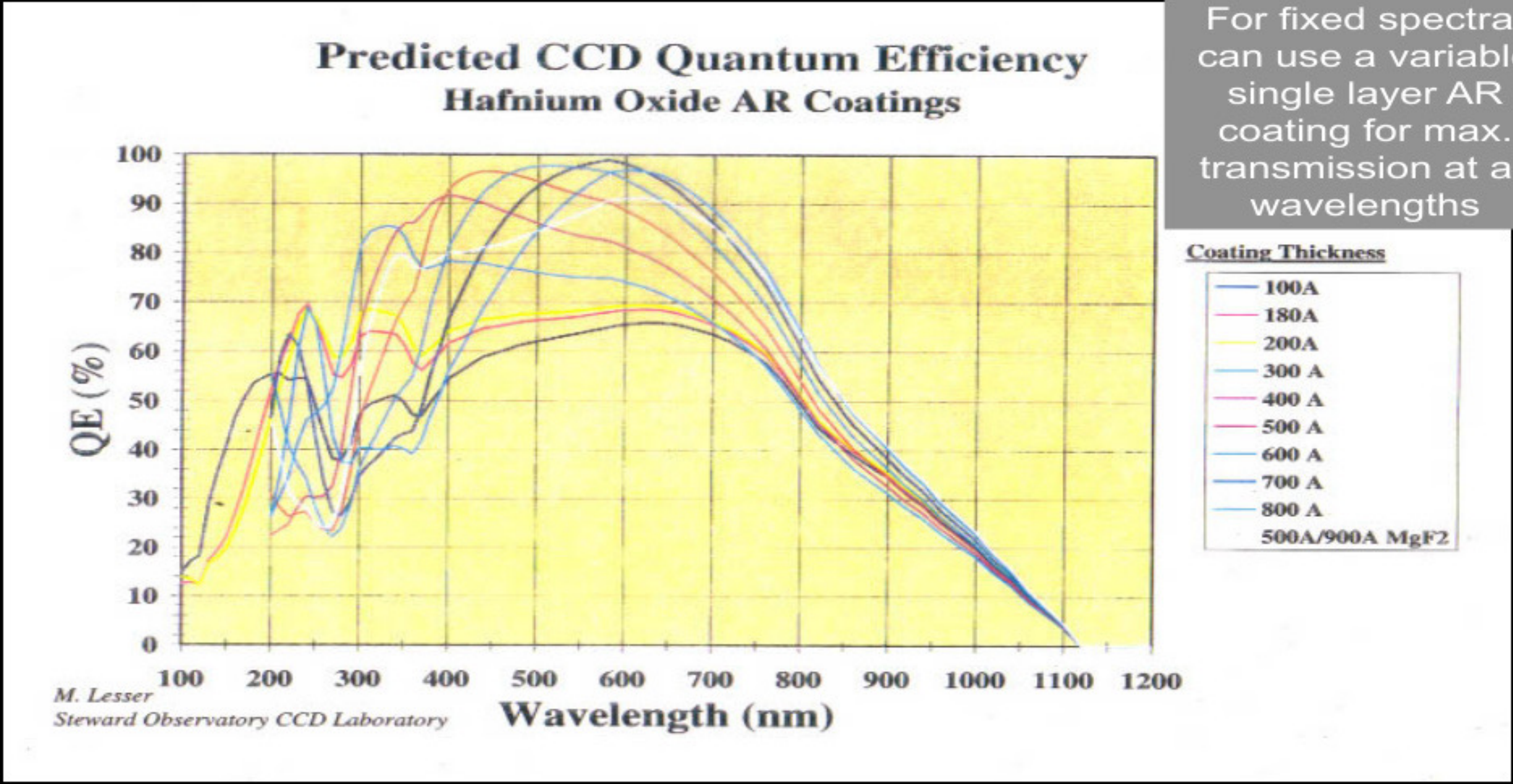
Silicon $n_t = 4$

99%

$$R = \left[ \frac{1 \cdot 4 - 2.0^2}{1 \cdot 4 + 2.0^2} \right]^2 \sim 0\ \%$$

Quarter wave $Hf0_2$ at 560 nm is 0.25(560)/2 = 70 nm

For fixed spectra, can use a variable single layer AR coating for max. transmission at all wavelengths



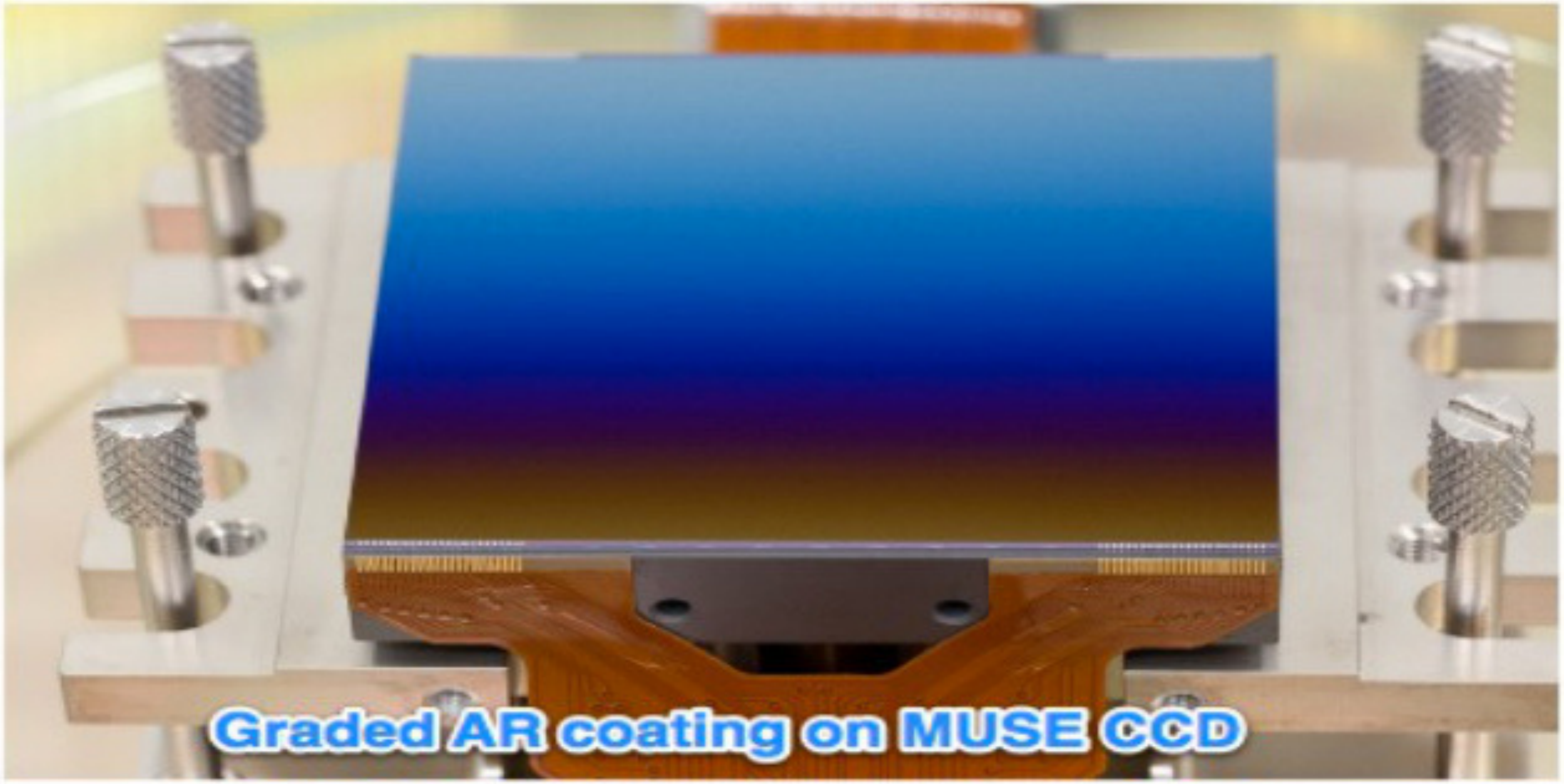
**Predicted CCD Quantum Efficiency**

**Hafnium Oxide AR Coatings**

*M. Lesser*
*Steward Observatory CCD Laboratory*

Quarter wave $HfO_2$ at 560 nm is 0.25(560)/2 = 70 nm (700 Å)

Mike Lesser, U. Arizona



Graded AR coating on MUSE CCD

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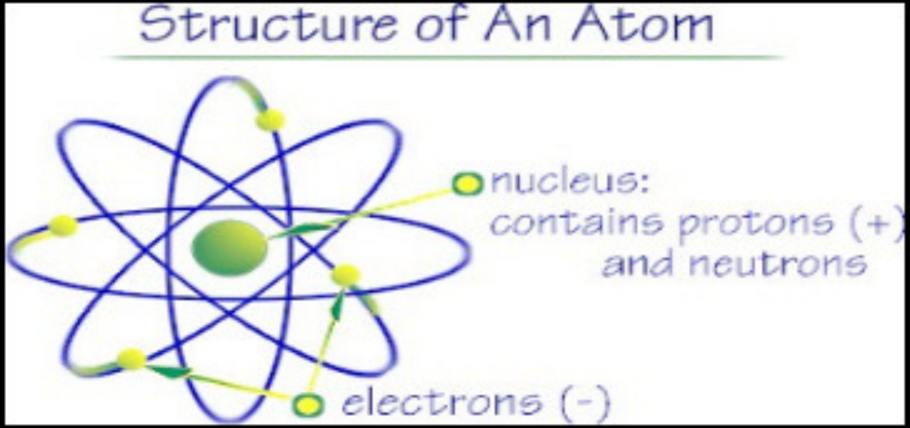
# Photoelectric effect

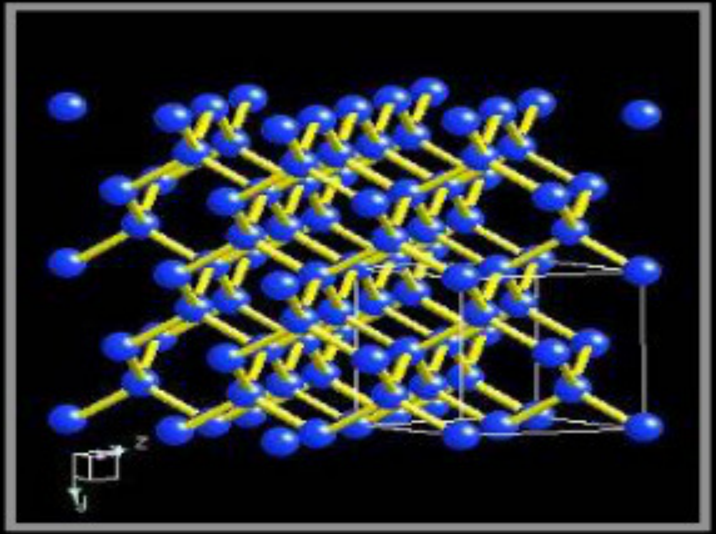
- In the early 1900s, A. Einstein worked in a phenomenon called photoelectric effect.

- He showed that a quantum of radian energy (“photon”) could eject an electron from the atom in certain materials

# Crystals are excellent detectors of light



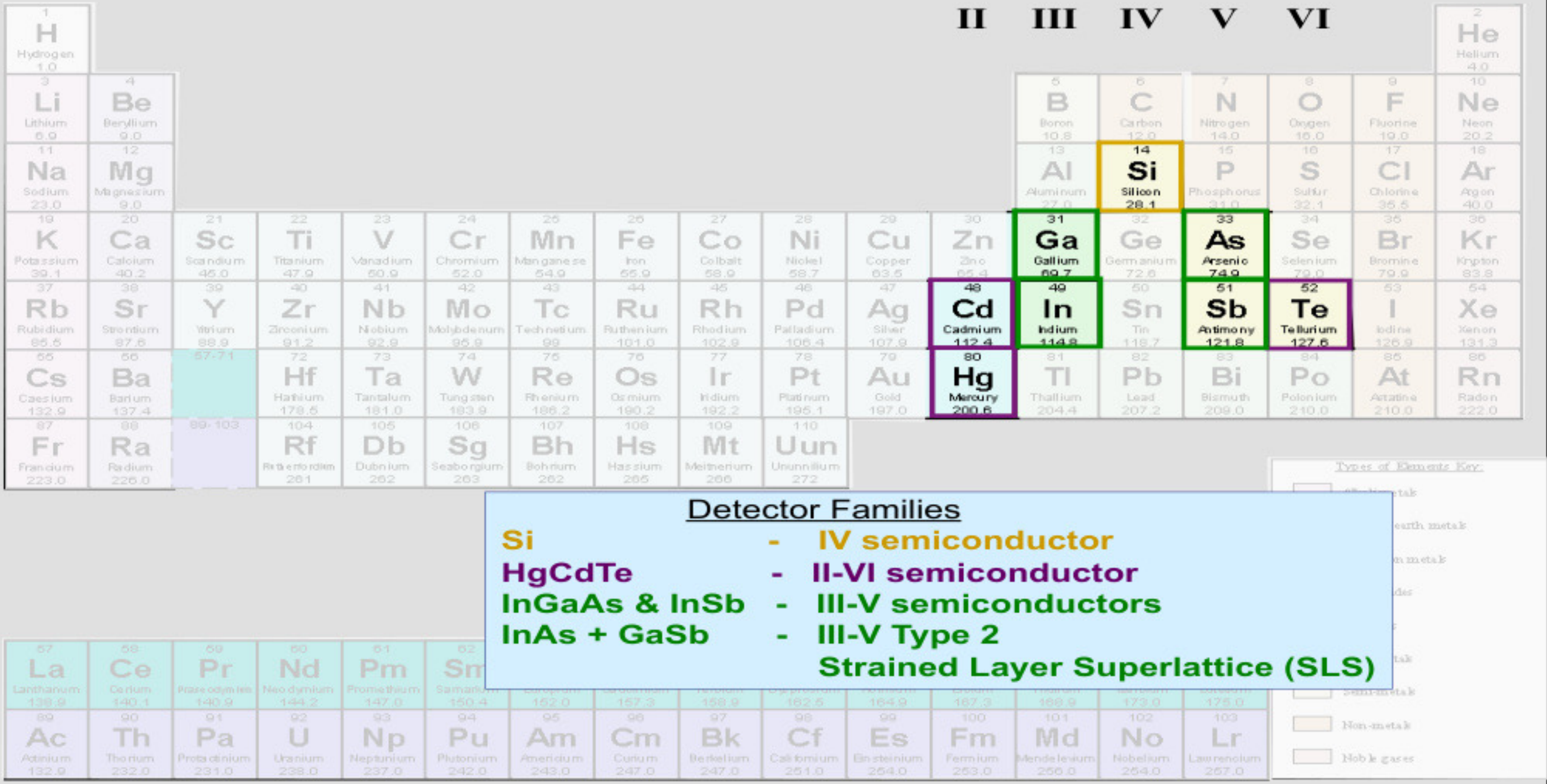
- Simple model of atom
  - Protons (+) and neutrons in the nucleus with electrons orbiting



Silicon crystal lattice

- Electrons are trapped in the crystal lattice
  - by electric field of protons
- Light energy can free an electron from the grip of the protons, allowing the electron to roam about the crystal
  - creates an “electron-hole” pair.
- The photocharge can be collected and amplified, so that light is detected
- The light energy required to free an electron depends on the material.

# Periodic Table



## Detector Families

Si - IV semiconductor

HgCdTe - II-VI semiconductor

InGaAs & InSb - III-V semiconductors

InAs + GaSb - III-V Type 2
Strained Layer Superlattice (SLS)

# Photon Detection

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

$$h\nu \;>\; \mathcal{E}_g$$

h = Planck constant ($6.6310^{-34}$ Joule•sec)
v = frequency of light (cycles/sec) = λ/c
$\mathcal{E}_g$ = energy gap of material (electron-volts)

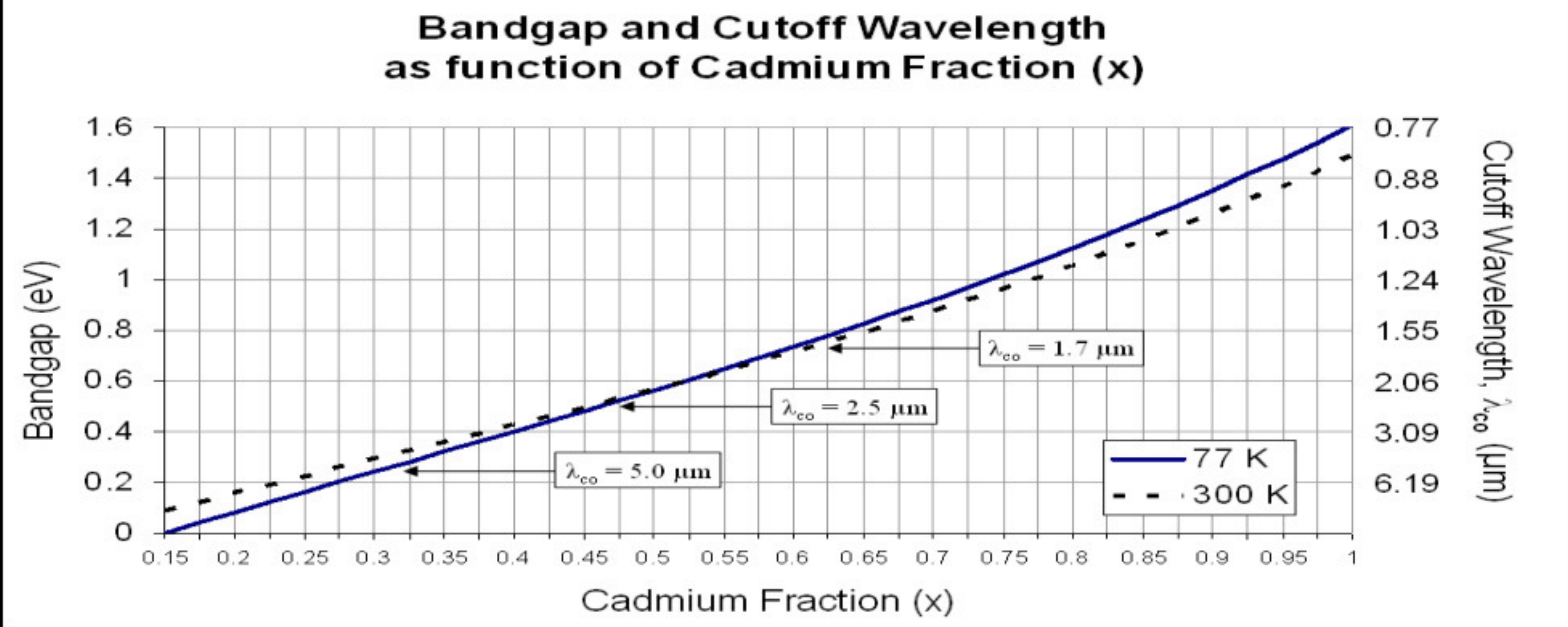
$$\lambda_c = 1.238 \,/\, \mathcal{E}_g \text{ (eV)}$$

| Material Name | Symbol | $\mathcal{E}_g$ (eV) | $\lambda_c$ (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 ($In_{0.53}Ga_{0.47}As$)

# Tunable Wavelength: Valuable property of HgCdTe

$Hg_{1-x}Cd_xTe$ Modify ratio of Mercury and Cadmium to “tune” the bandgap energy



$$E_g = -0.302 + 1.93x - 0.81x^2 + 0.832x^3 + 5.35\times10^{-4}T(1-2x)$$

G. L. Hansen, J. L. Schmidt, T. N. Casselman, J. Appl. Phys. 53(10), 1982, p. 7099

# Absorption Depth

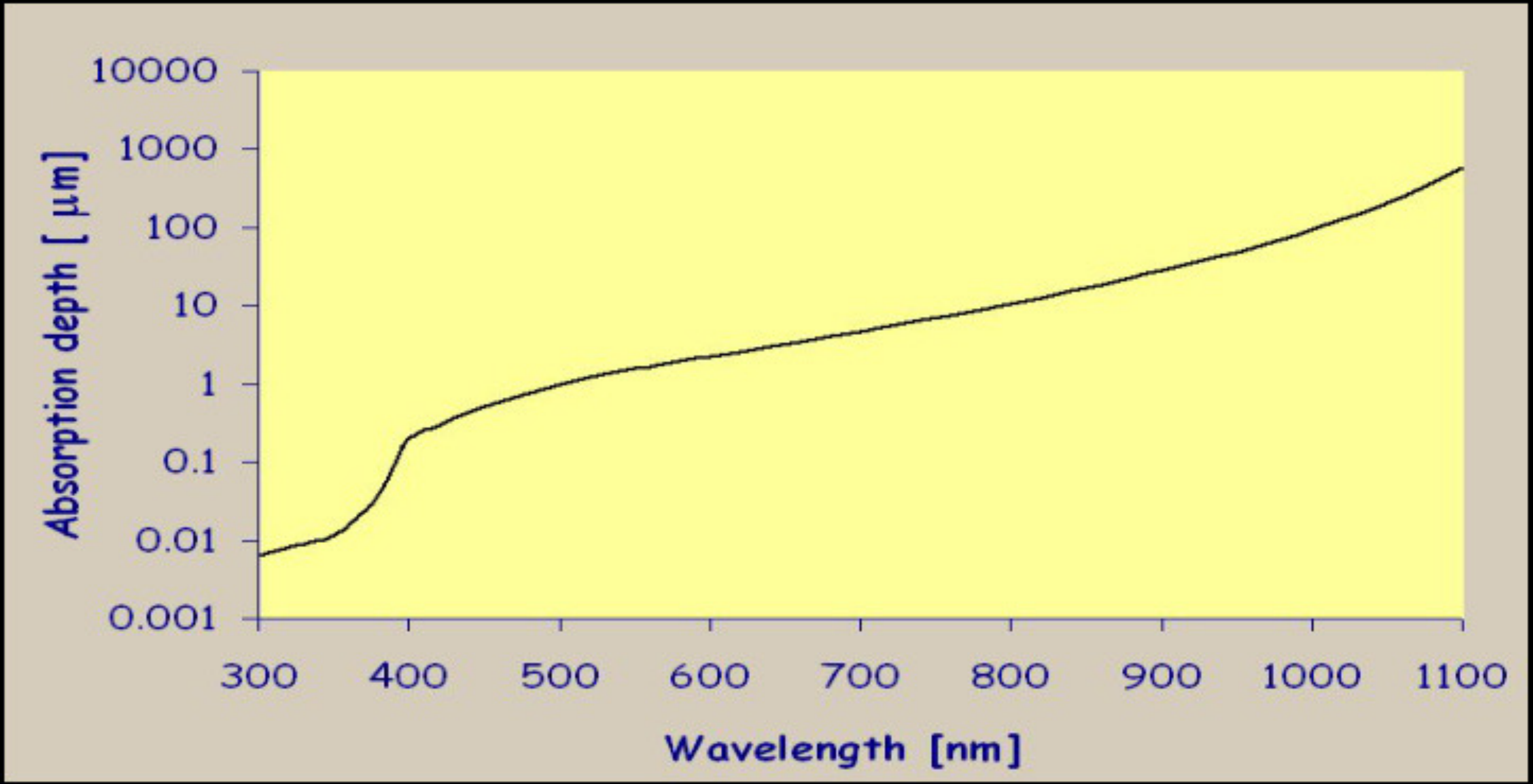
The depth of detector material that absorbs 63.2% of the radiation

(1-1/e) of the energy is absorbed

| absorption depth(s) | of light absorbed |
|---|---|
| 1 | 63.2% |
| 2 | 86.5% |
| 3 | 95.0% |
| 4 | 98.2% |

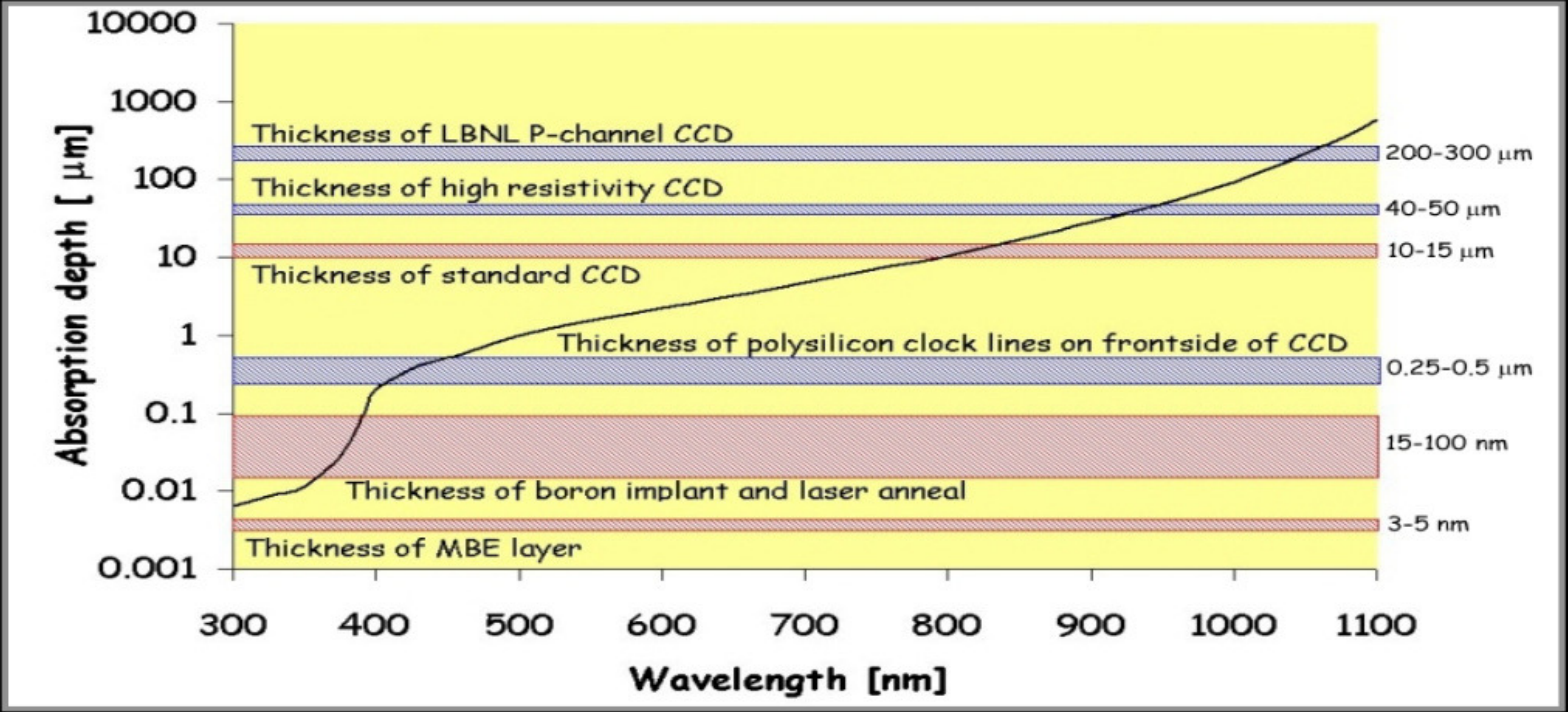
For high QE, thickness of detector material should be ≥ 3 absorption depths

# Absorption Depth of Silicon



- For high QE in the near infrared, need very thick (up to 300 microns) silicon detector layer.
- For high QE in the ultraviolet, need to be able to capture photocharge created within 10 nm of the surface where light enters the detector.
- In addition, the index of refraction of silicon varies over wavelength – a challenge for anti-reflection coatings.

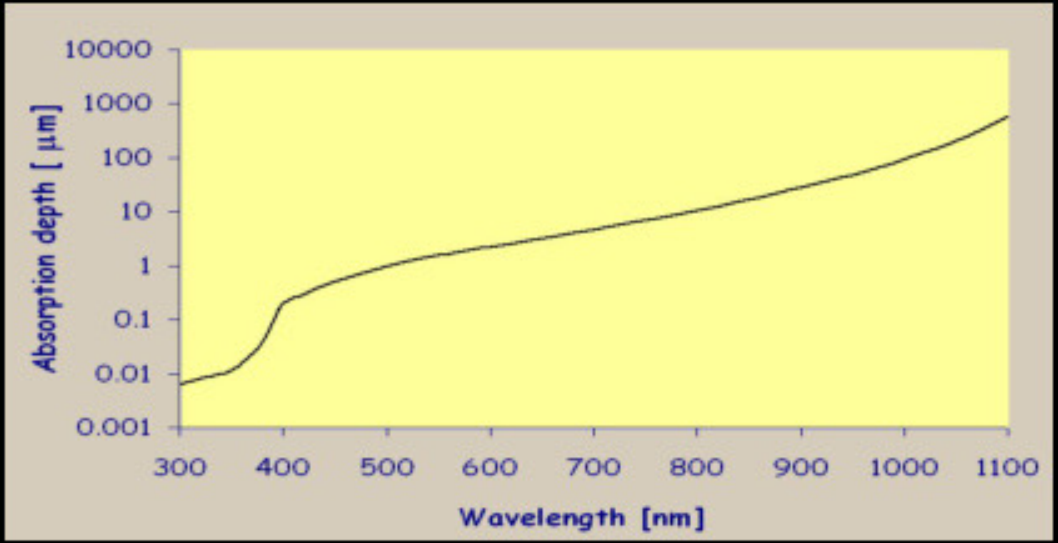
# Optical Absorption Depth in Silicon

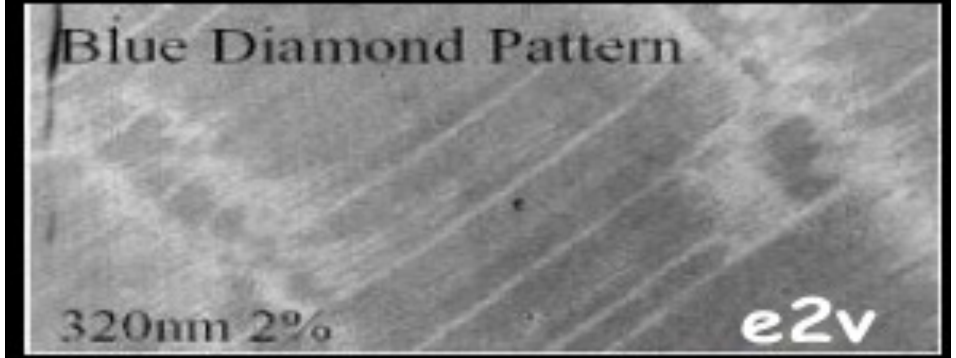


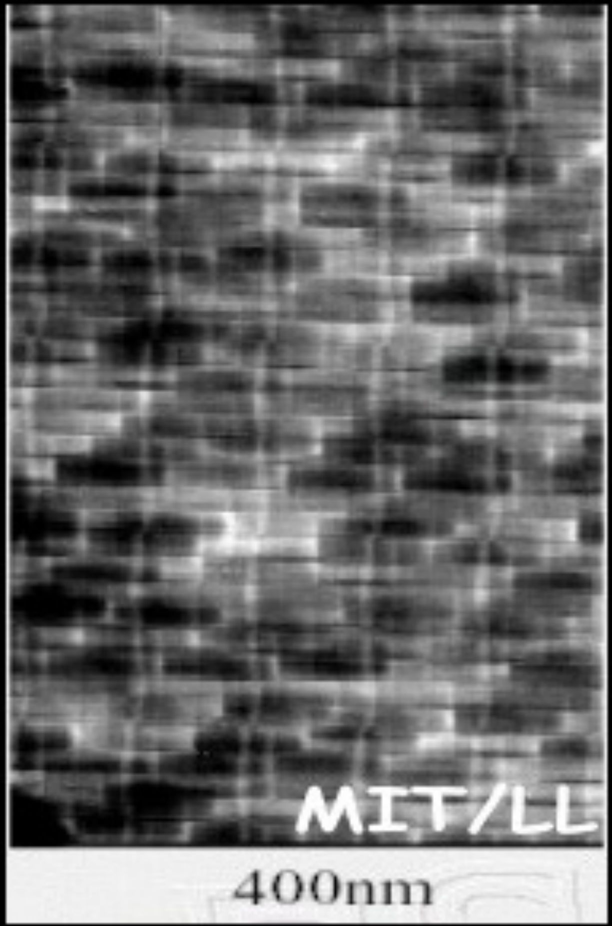
# UV / Blue CCD Quantum Efficiency

- Need very thin backside passivation layer
- Technologies
  - Boron implant and laser anneal
    - e2v, MIT/LL
  - MBE
    - JPL, MIT/LL
  - Chemisorption coating that produces positive charge
    - University of Arizona (Lesser)

      Licensed by: Fairchild
      Teledyne DALSA




Blue Diamond Pattern
320nm 2%
e2v


MIT/LL
400nm

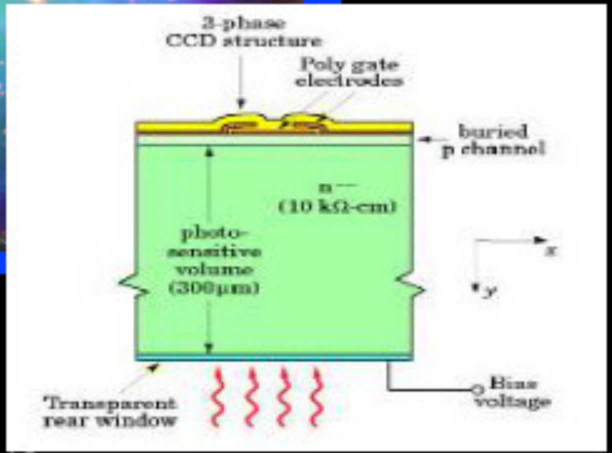
# Near-IR Imaging enabled by very thick silicon sensors

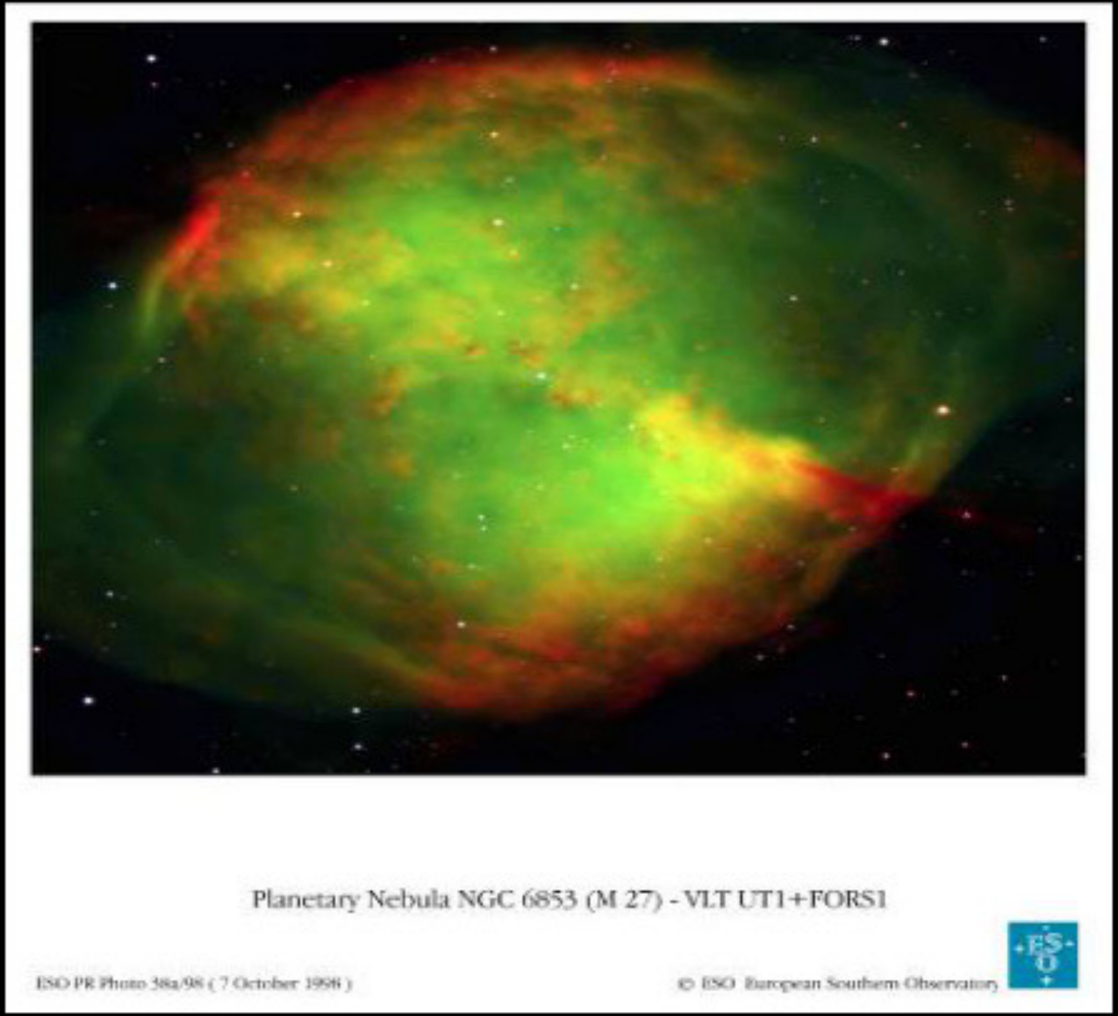
NATIONAL OPTICAL ASTRONOMY OBSERVATORY
Cerro Tololo • Kitt Peak • U.S. Gemini Program

NATIONAL SOLAR OBSERVATORY
GONG • Kitt Peak • Sacramento Peak

Newsletter 67

September 2001



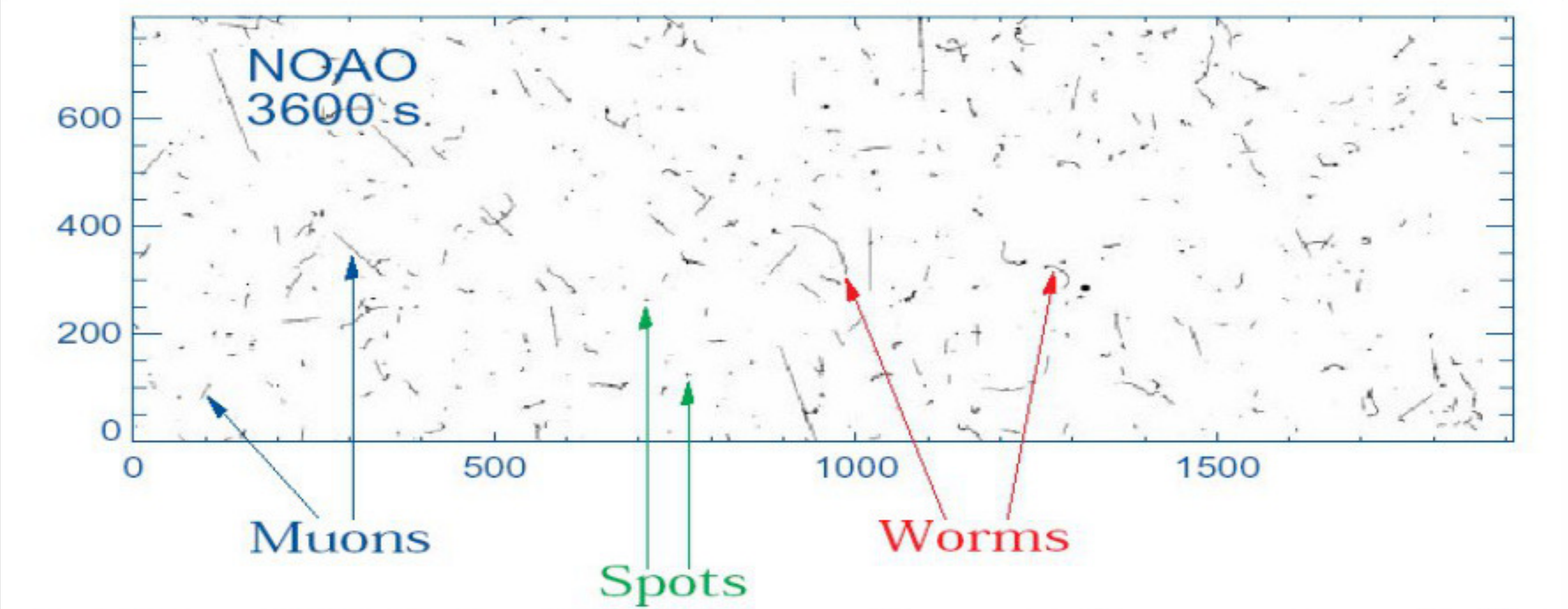


Planetary Nebula NGC 6853 (M 27) - VLT UT1+FORS1

ESO PR Photo 38a/98 ( 7 October 1998 )

© ESO European Southern Observatory

# A very thick silicon detector is also a very good sensor of cosmic rays



Our 300-$\mu$m thick depleted CCD gives us the great advantage (curse?) that we can see the events in new detail

# Quantum Yield: One photoelectron for every detected photon

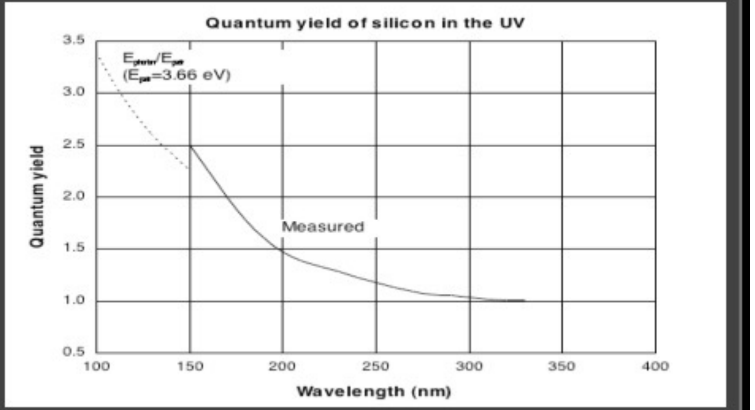
…for most wavelengths of interest to ground-based astronomy

## Silicon

For wavelengths that are 30% to 100% of the cutoff wavelength, there will a single electron-hole pair created for every detected photon.

For shorter wavelengths (higher energies), there is an increasing probability of producing multiple electron-hole pairs.

For silicon, this effect commences at ~30% of the cutoff wavelength (λ < 330 nm).



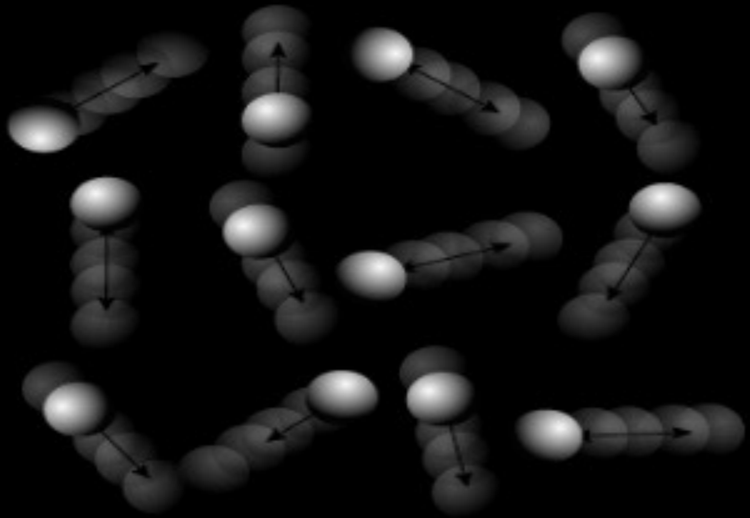
Data from Barry Burke, MIT Lincoln Laboratory

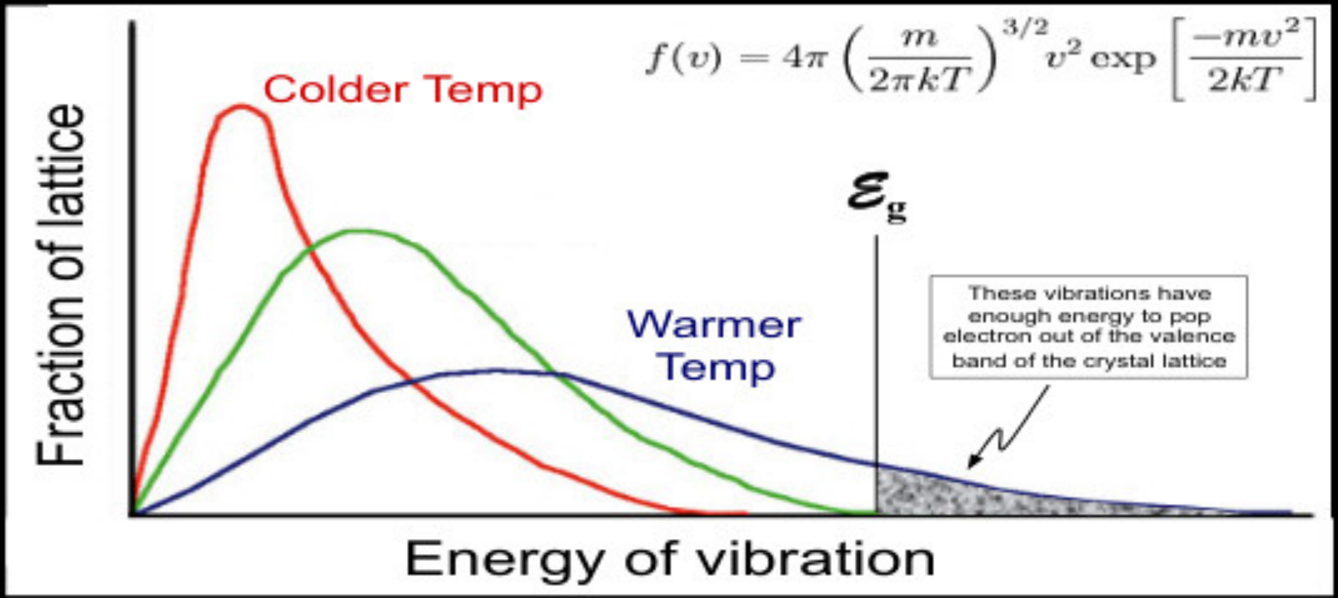
## HgCdTe

- Limited data from HgCdTe detectors shows that quantum yield is not significant at 800 nm for a 5400 nm cutoff detector (11% of cutoff wavelength).
- The quantum yield of HgCdTe is still being investigated.

# Dark Current

## Undesirable byproduct of light detecting materials

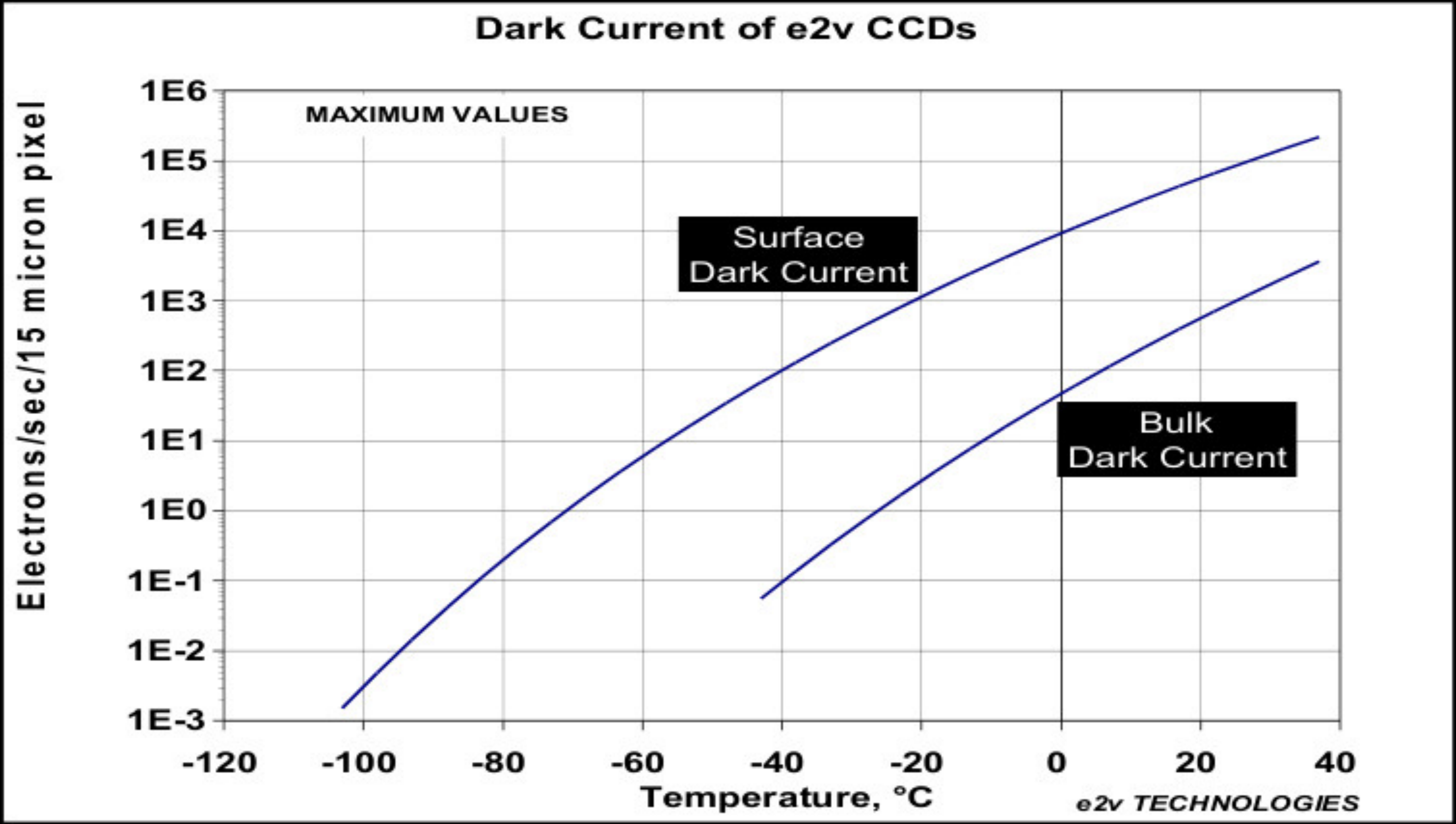




These vibrations have enough energy to pop electron out of the valence band of the crystal lattice

- The vibration of particles (includes crystal lattice phonons, electrons and holes) has energies described by the Maxwell-Boltzmann distribution. Above absolute zero, some vibration energies may be larger than the bandgap energy, and will cause electron transitions from valence to conduction band.
- Need to cool detectors to limit the flow of electrons due to temperature, i.e. the **dark current** that exists in the absence of light.
- The smaller the bandgap, the colder the required temperature to limit dark current below other noise sources (e.g. readout noise)

# Dark Current of Silicon-based Detectors



In silicon, dark current usually dominated by surface defects

e2v technologies

# 6 steps of optical / IR photon detection

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Substrate removal

1. Light into detector

Detector Materials
Si, HgCdTe, InSb, Si:As

2. Charge Generation

Electric Fields in detector
collect electrical charge

3. **Charge Collection**

Charge coupled
transfer

4. Charge Transfer

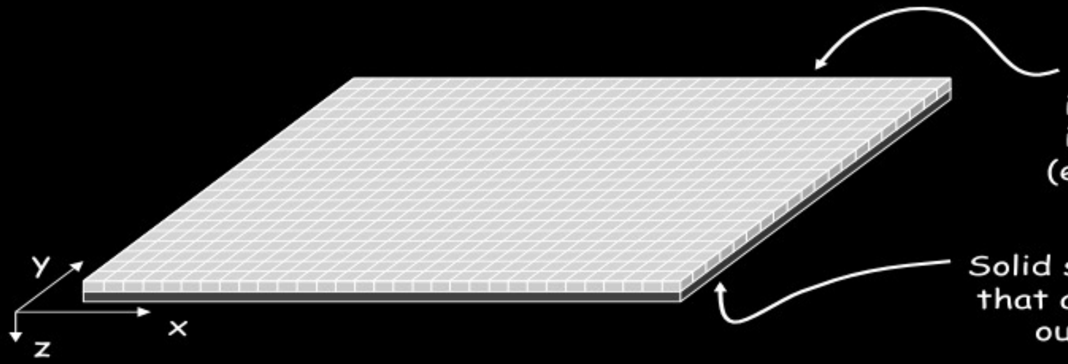
CCD

MOSFET
Amplifier

5. Charge-to-Voltage Conversion

6. Digitization & Data Processing

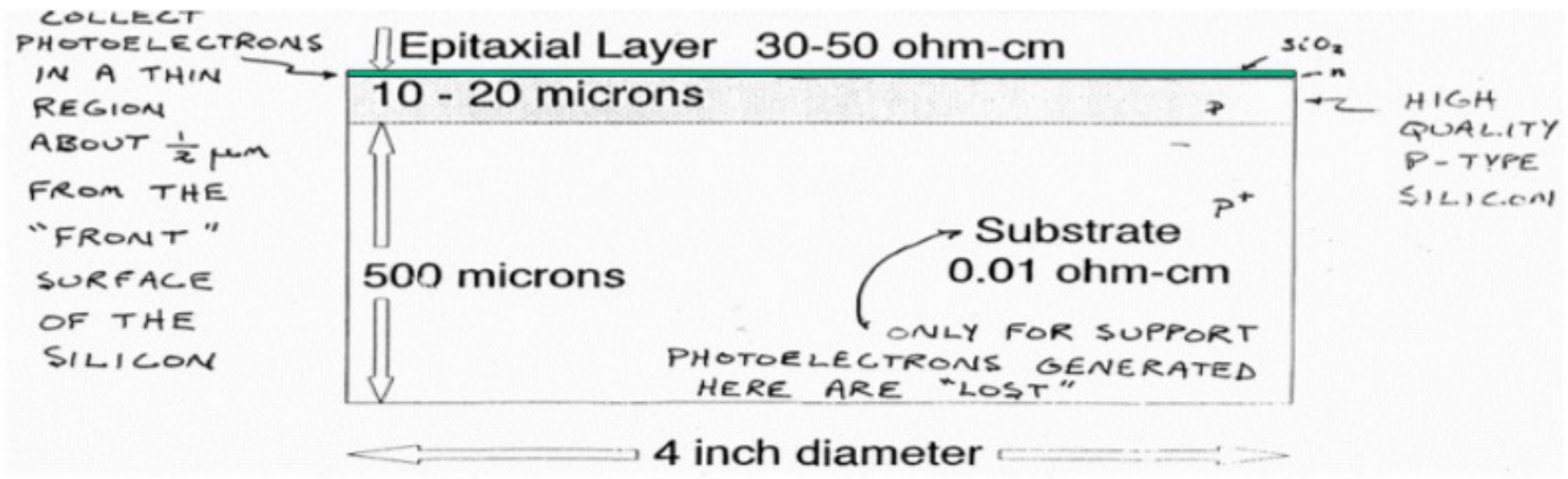
# 3. Charge Collection



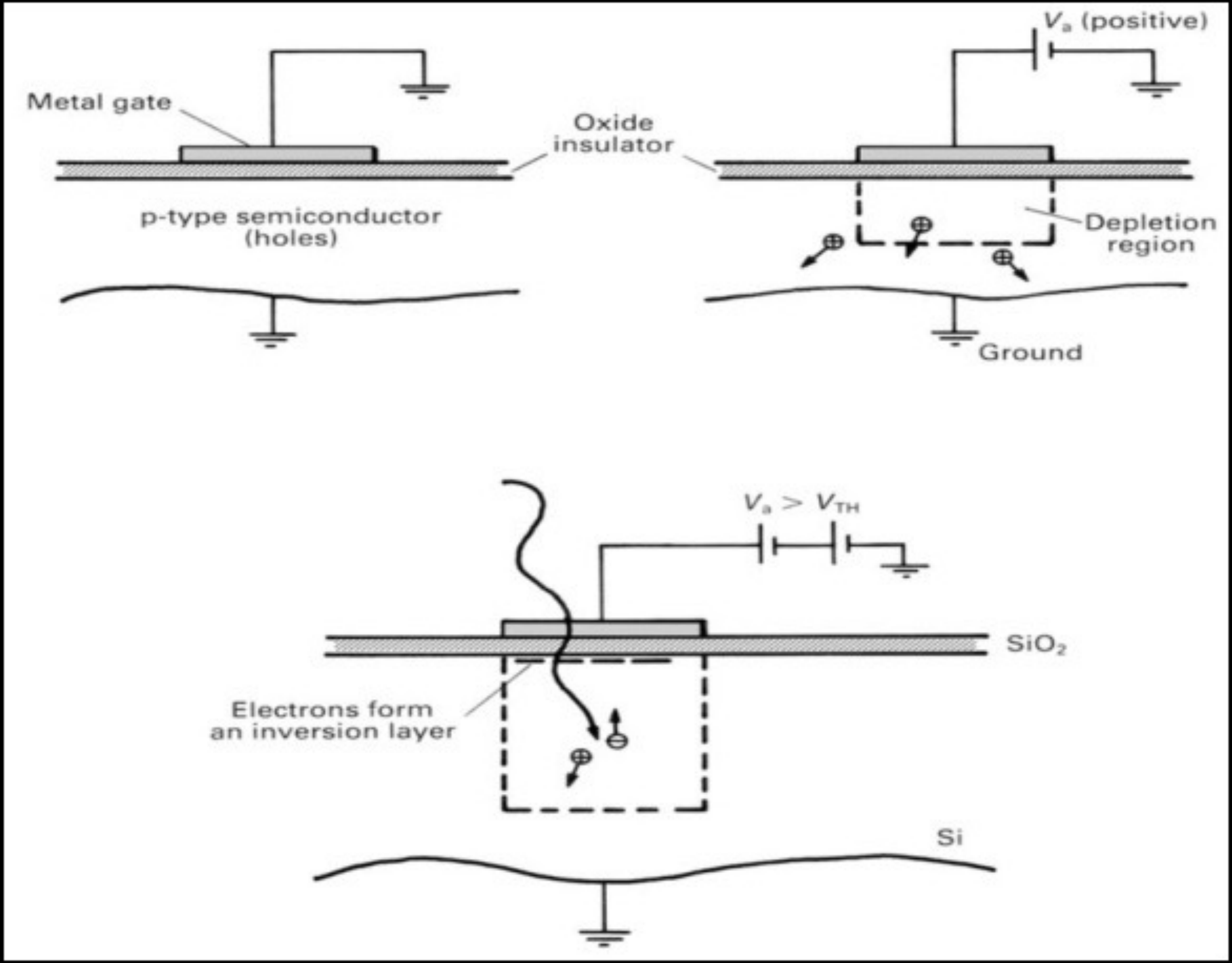
Light sensitive material
is electrically partitioned
into a 2-D array of pixels
(each pixel is a 3-D volume)

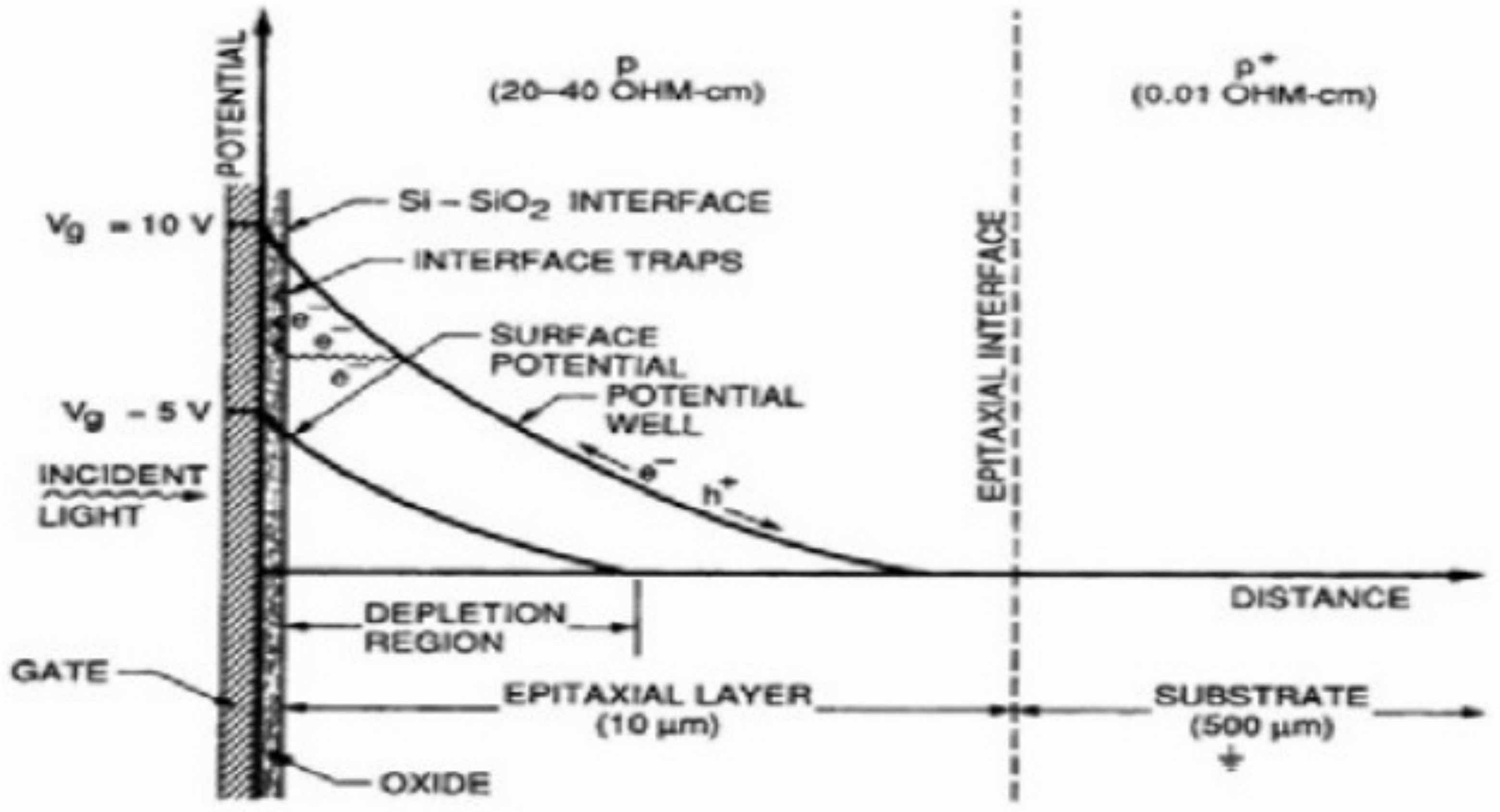
Solid state electronics
that amplify and read
out the charge

- Intensity image is generated by collecting photocharge generated in 3-D volume into 2-D array of pixels.
- Optical and IR focal plane arrays both collect charges via electric fields.
- In the z-direction, optical and IR use a p-n junction to “sweep” charge toward pixel collection nodes.

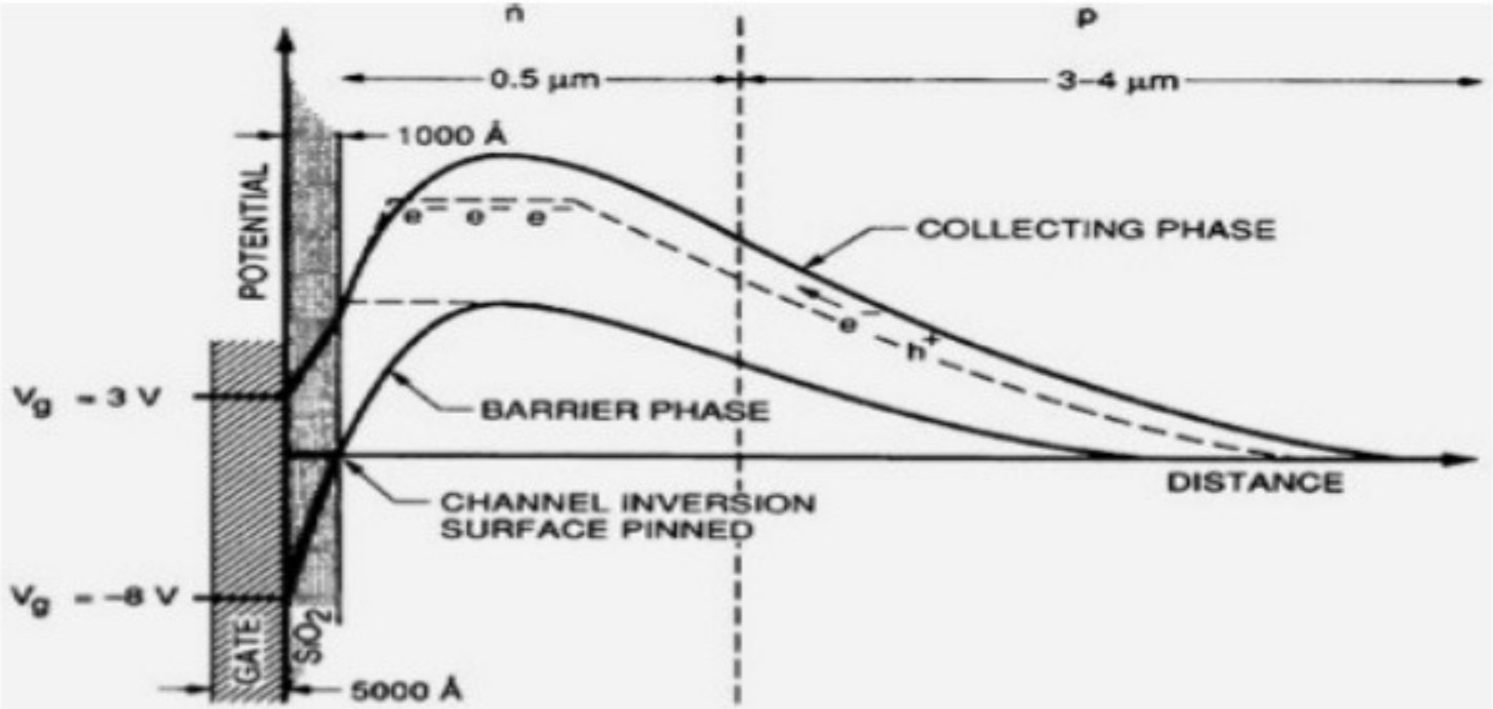

COLLECT PHOTOELECTRONS IN A THIN REGION ABOUT $\frac{1}{2}$ μm FROM THE "FRONT" SURFACE OF THE SILICON
Epitaxial Layer 30-50 ohm-cm
10 - 20 microns
SiO₂
n
p
HIGH QUALITY P-TYPE SILICON
500 microns
p+
Substrate
0.01 ohm-cm
ONLY FOR SUPPORT
PHOTOELECTRONS GENERATED HERE ARE "LOST"
4 inch diameter

# MOS CAPACITOR



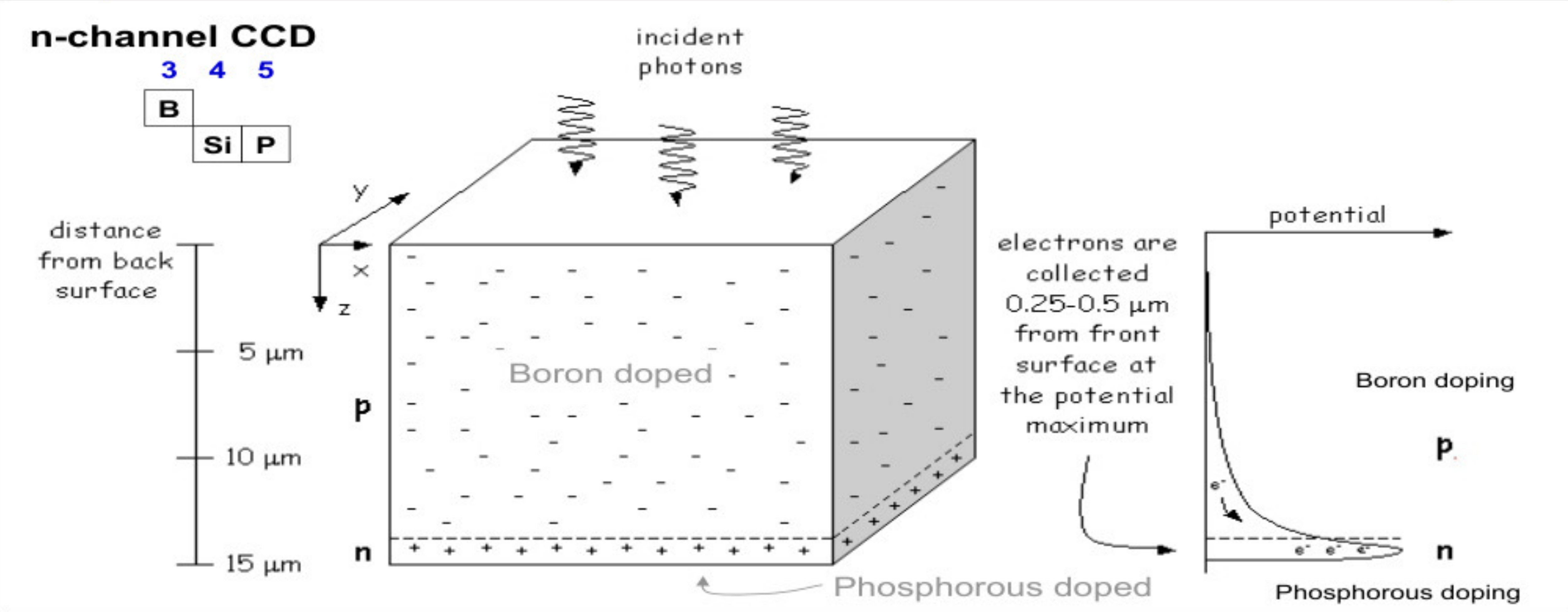


Surface channel potential well.



Buried-channel potential well.

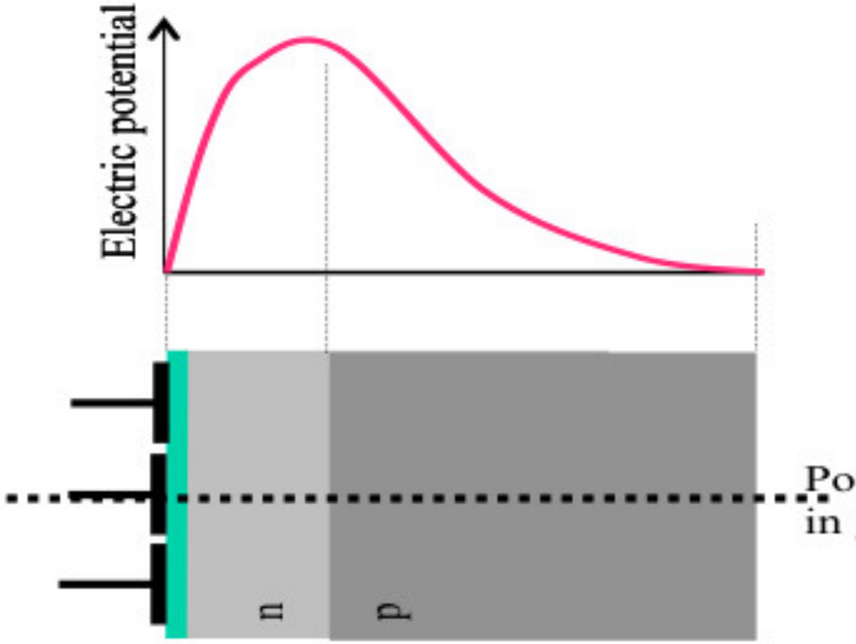
# Photovoltaic Detector Potential Well



Silicon, HgCdTe and InSb are photovoltaic detectors. All use a pn-junction to generate E-field in the z-direction of each pixel. This electric field separates the electron-hole pairs generated by a photon.

# Electric Potential on CCD

The n-type layer contains an excess of electrons that diffuse into the p-layer. The p-layer contains an excess of holes that diffuse into the n-layer. This structure is identical to that of a diode junction.
The diffusion creates a charge imbalance and induces an internal electric field. The electric potential reaches a maximum just inside the n-layer, and it is here that any photo-generated electrons will collect.
All science CCDs have this junction structure, known as a 'Buried Channel'. It has the advantage of keeping the photo-electrons confined away from the surface of the CCD where they could become trapped.
It also reduces the amount of thermally generated noise (dark current).

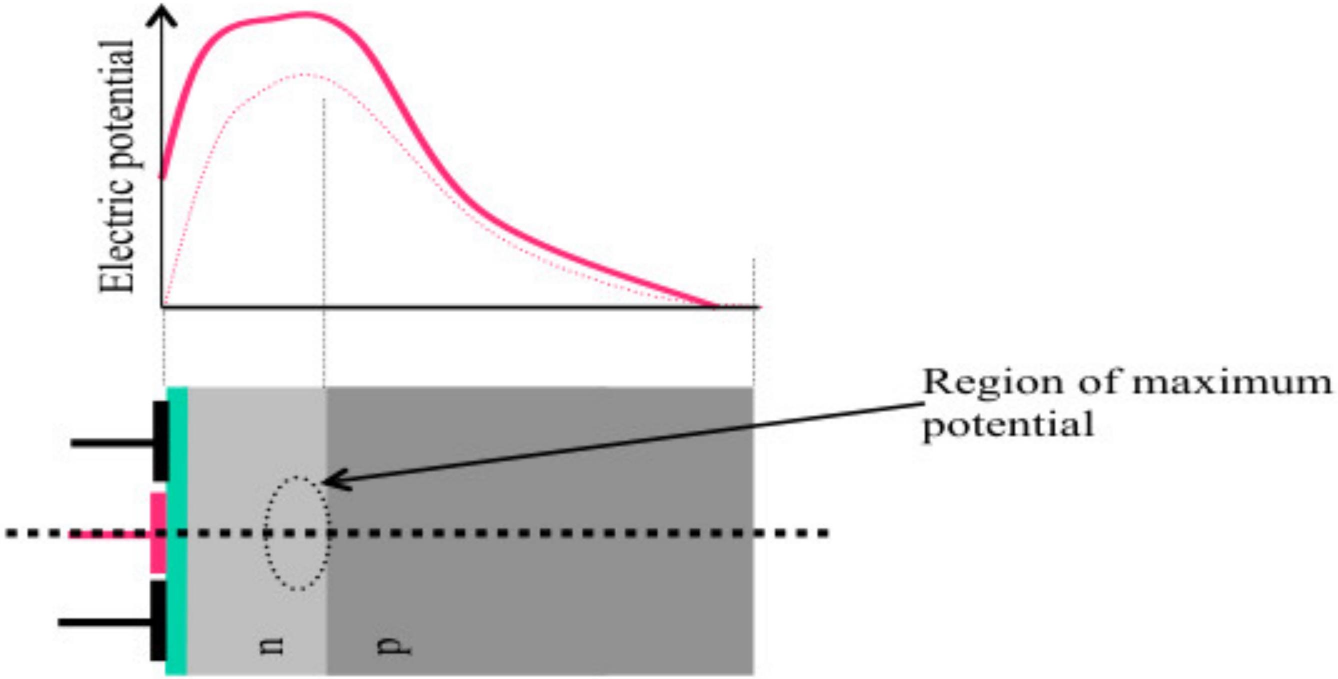


Potential along this line shown in graph above.

Cross section through the thickness of the CCD

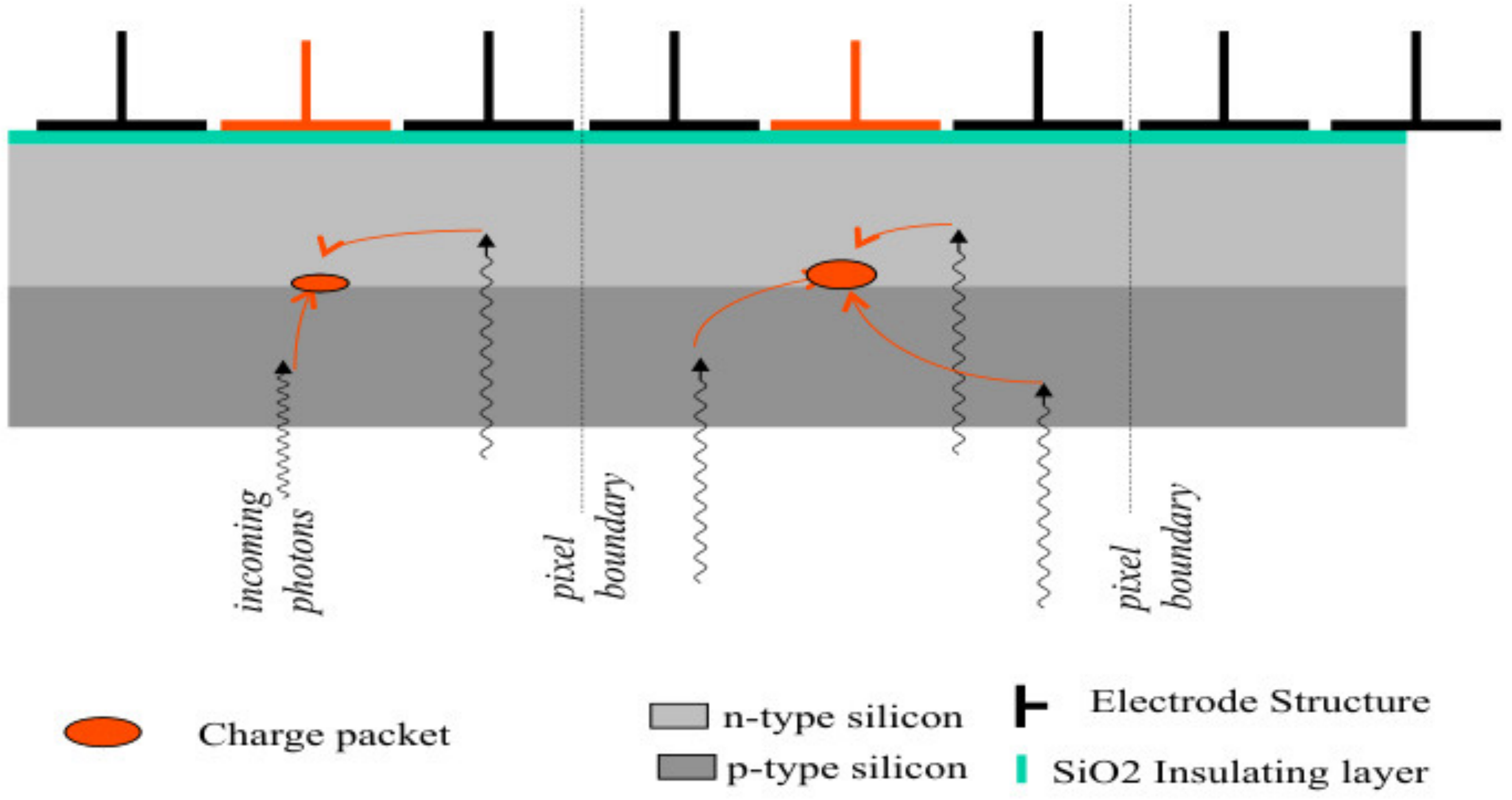
# Electric Potential on CCD

During integration of the image, one of the electrodes in each pixel is held at a positive potential. This further increases the potential in the silicon below that electrode and it is here that the photoelectrons are accumulated. The neighboring electrodes, with their lower potentials, act as potential barriers that define the vertical boundaries of the pixel. The horizontal boundaries are defined by the channel stops.



# Charge Collection in a CCD.

Photons entering the CCD create electron-hole pairs. The electrons are then attracted towards the most positive potential in the device where they create 'charge packets'. Each packet corresponds to one pixel



# 6 steps of optical / IR photon detection

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transfer

4. Charge Transfer

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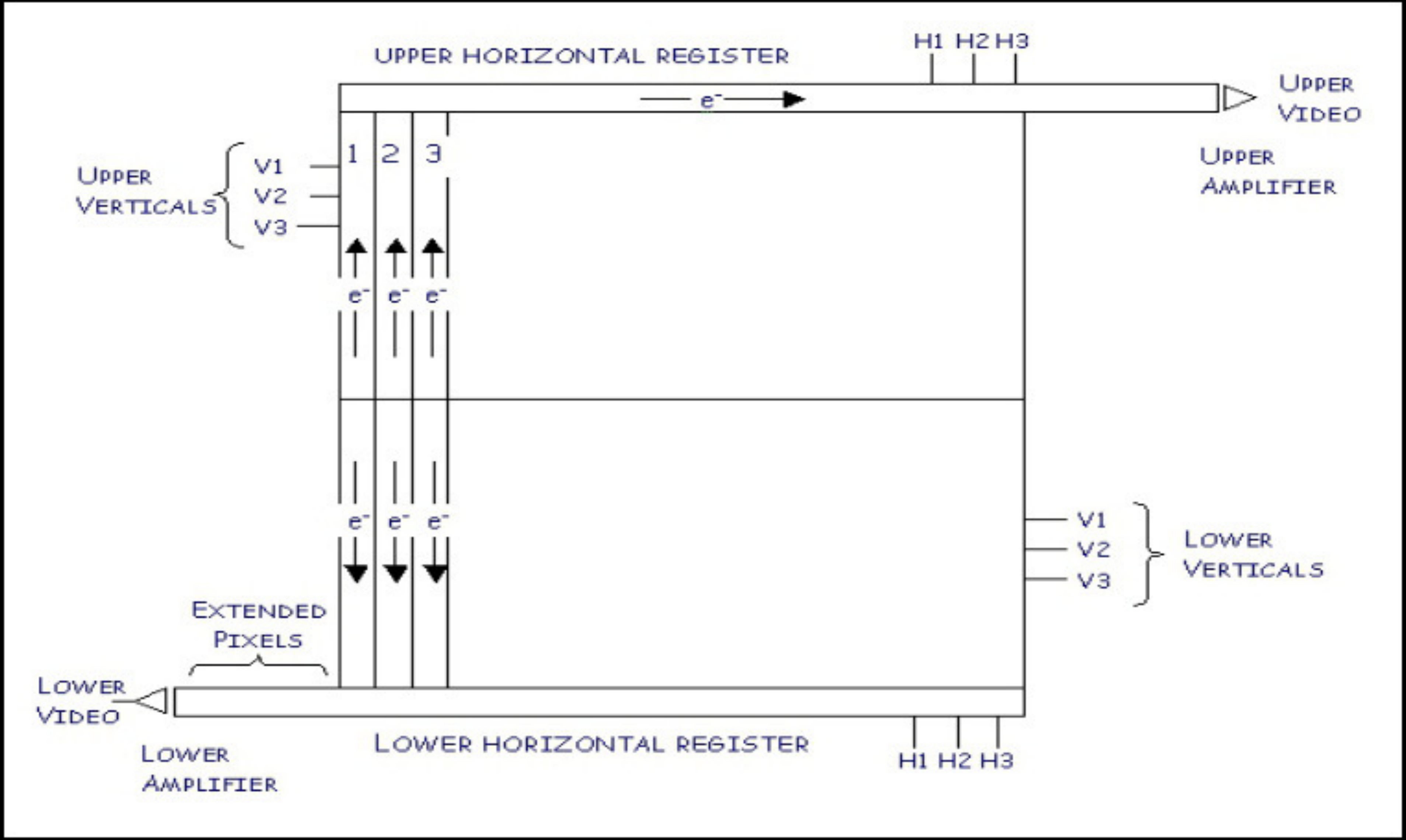
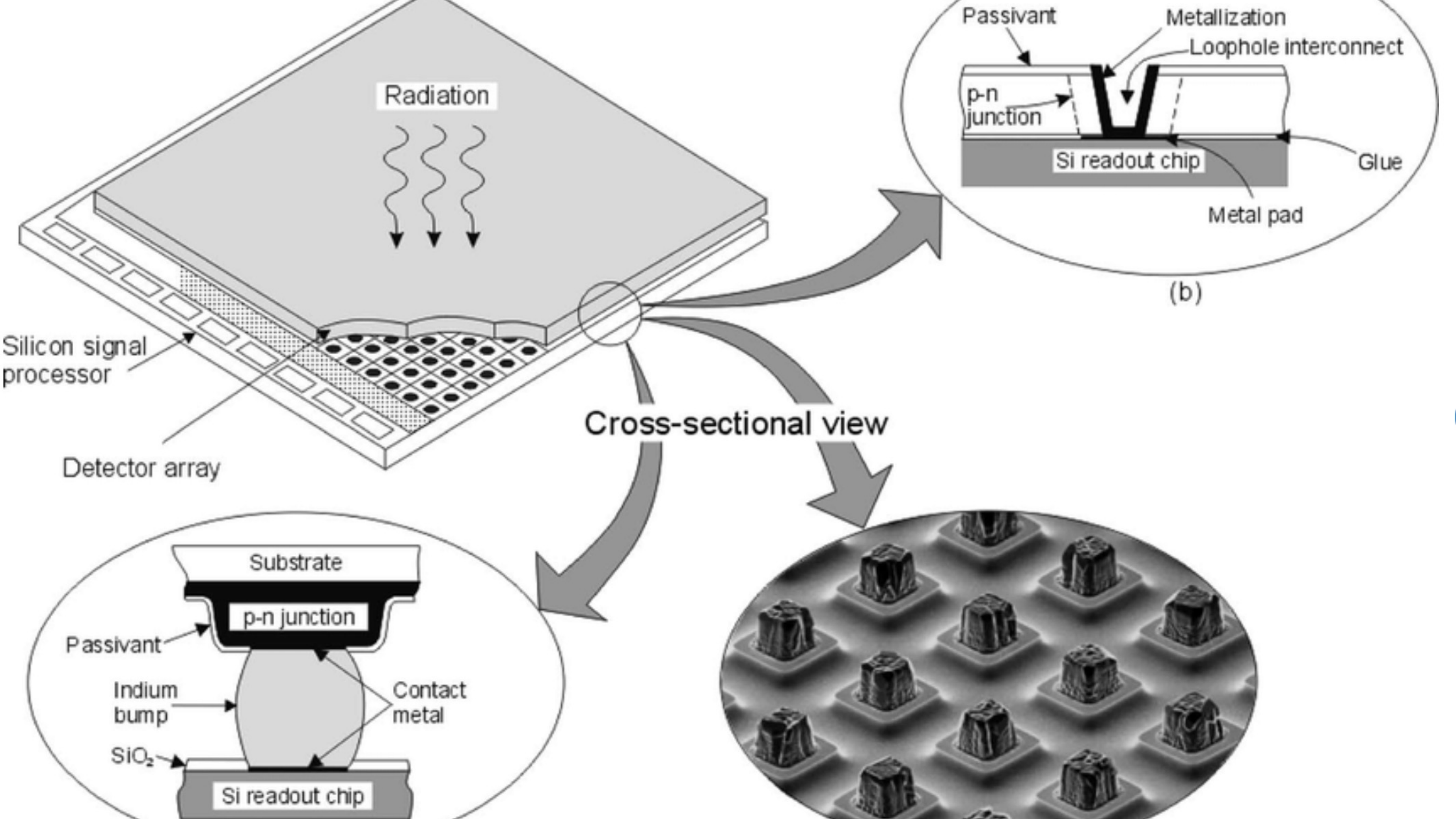
MOSFET
Amplifier

5. Charge-to-Voltage Conversion

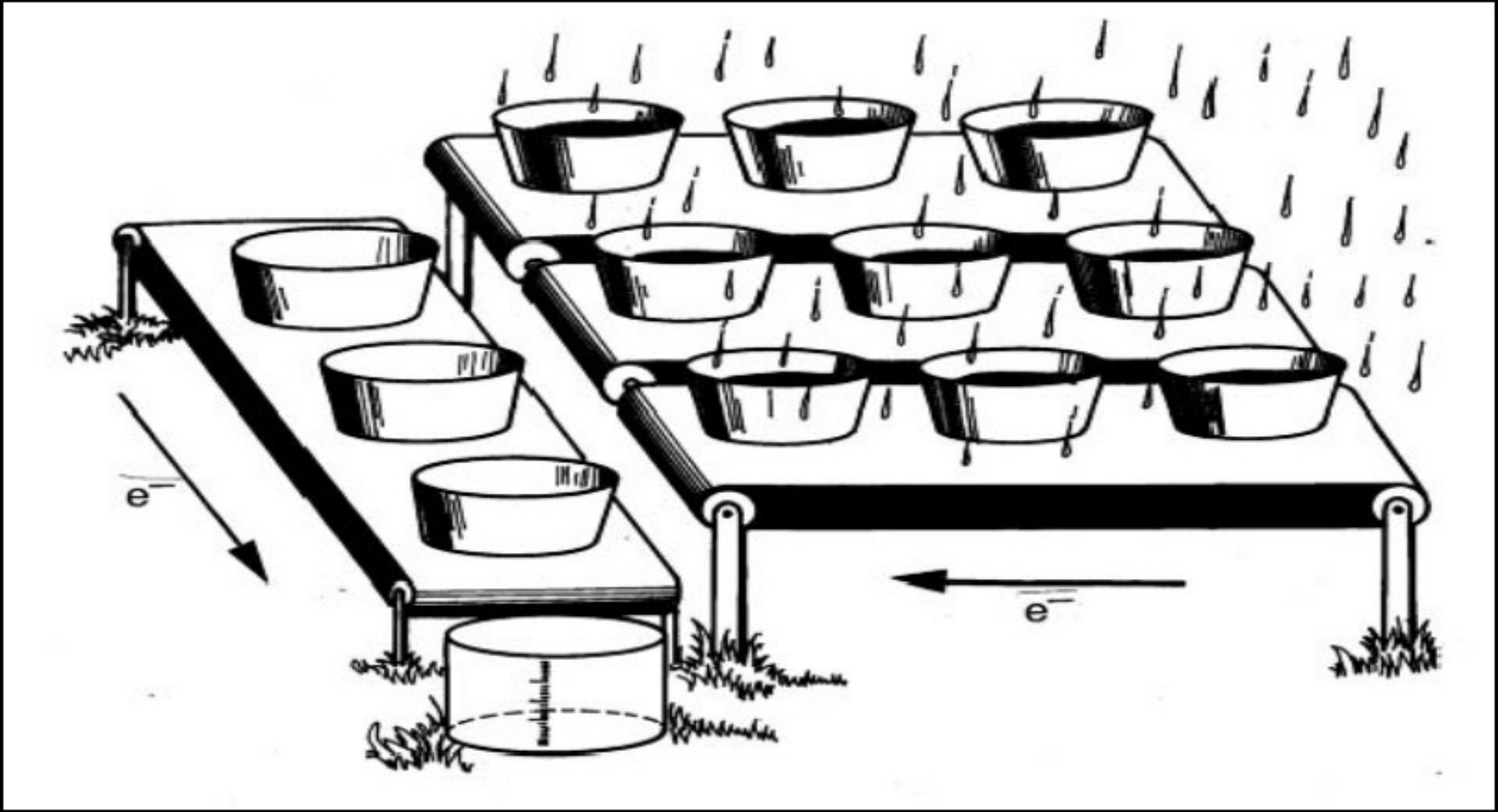
6. Digitization

# CCD Architecture




Radiation
Silicon signal processor
Detector array
Cross-sectional view
Passivant
Metallization
Loophole interconnect
p-n junction
Si readout chip
Glue
Metal pad
(b)
Substrate
p-n junction
Passivant
Indium bump
Contact metal
$SiO_2$
Si readout chip

# CCD Rain bucket analogy

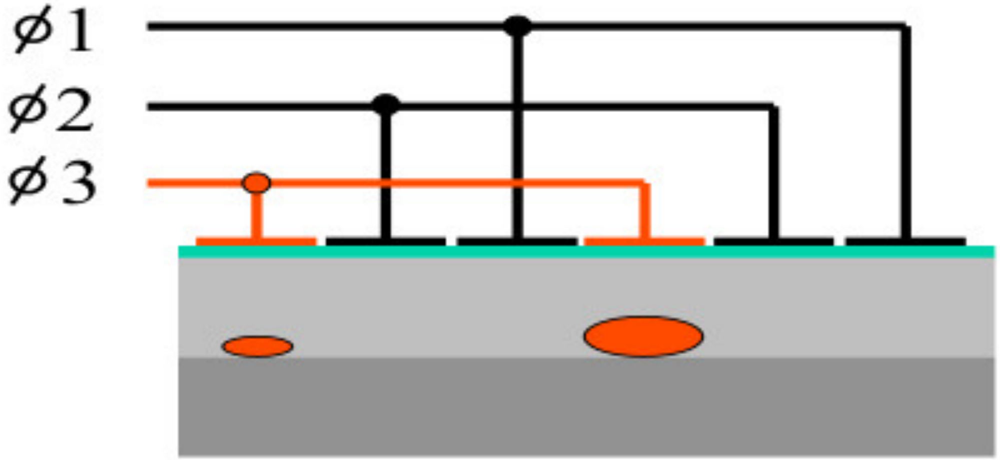


# Charge Transfer in a CCD

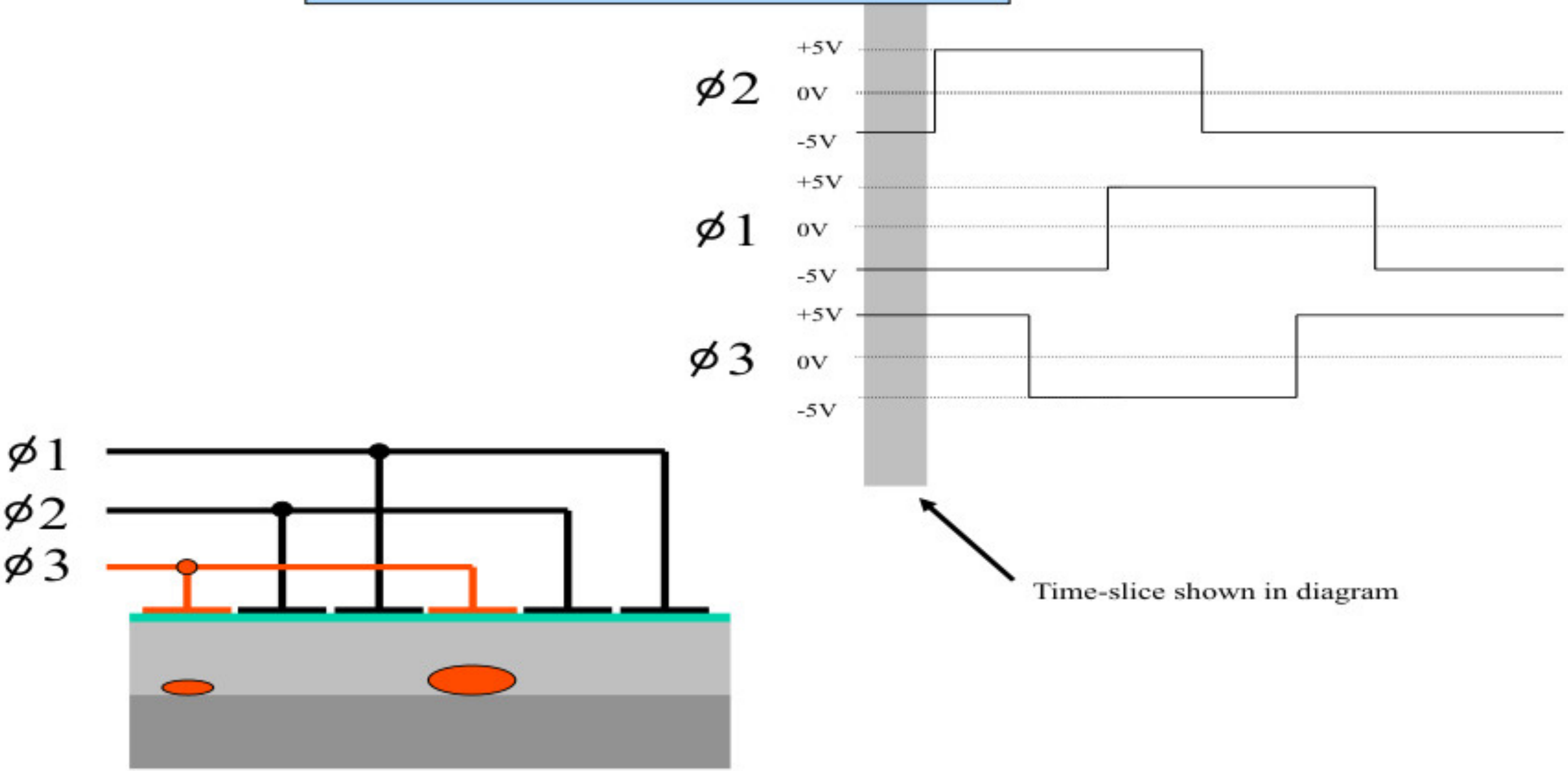
The following slides shows the charge transfer process on the CCD

Electrodes in BLACK are held at a negative potential

Electrodes in RED are held at positive potential

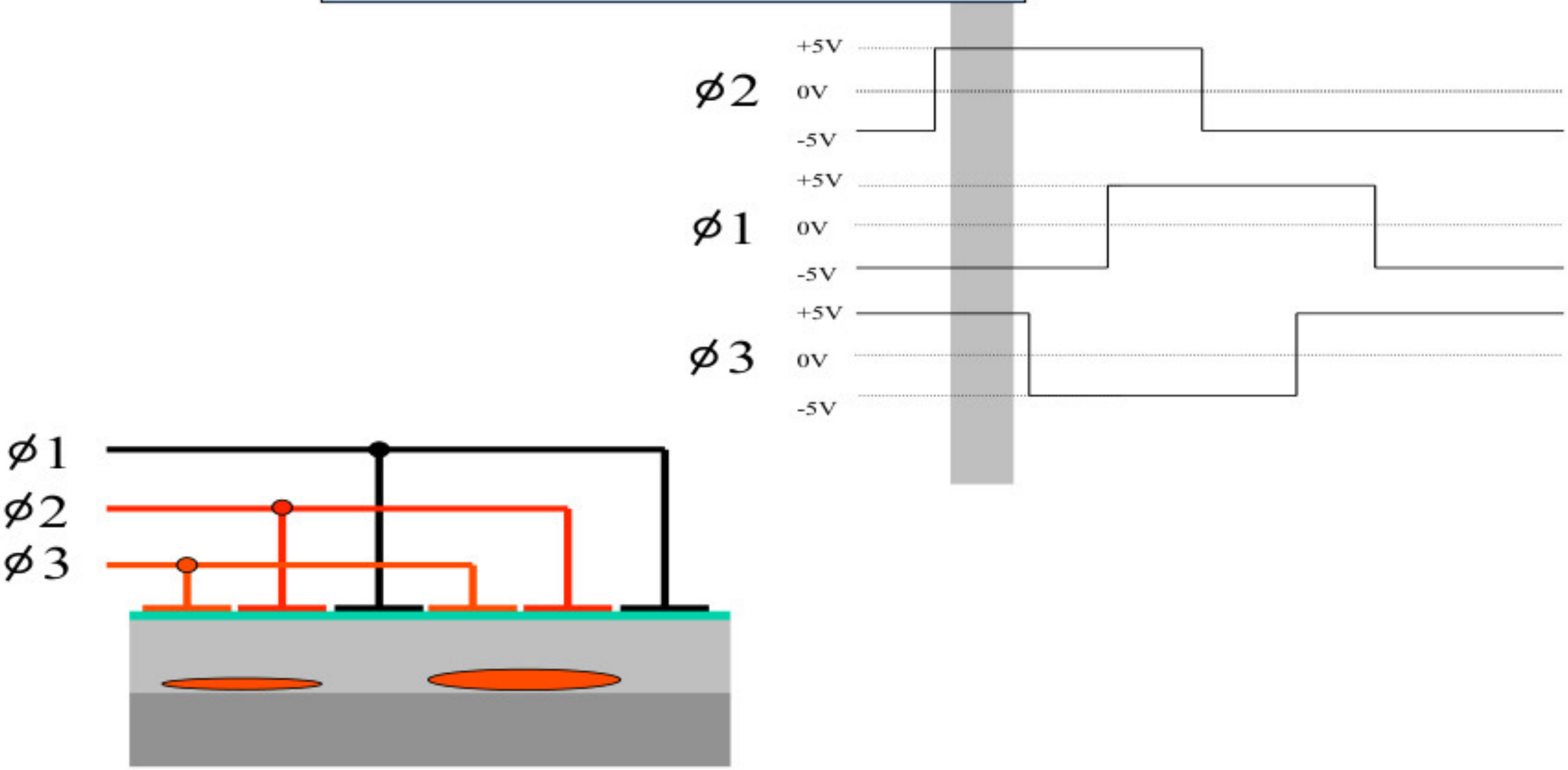


# Charge Transfer in a CCD

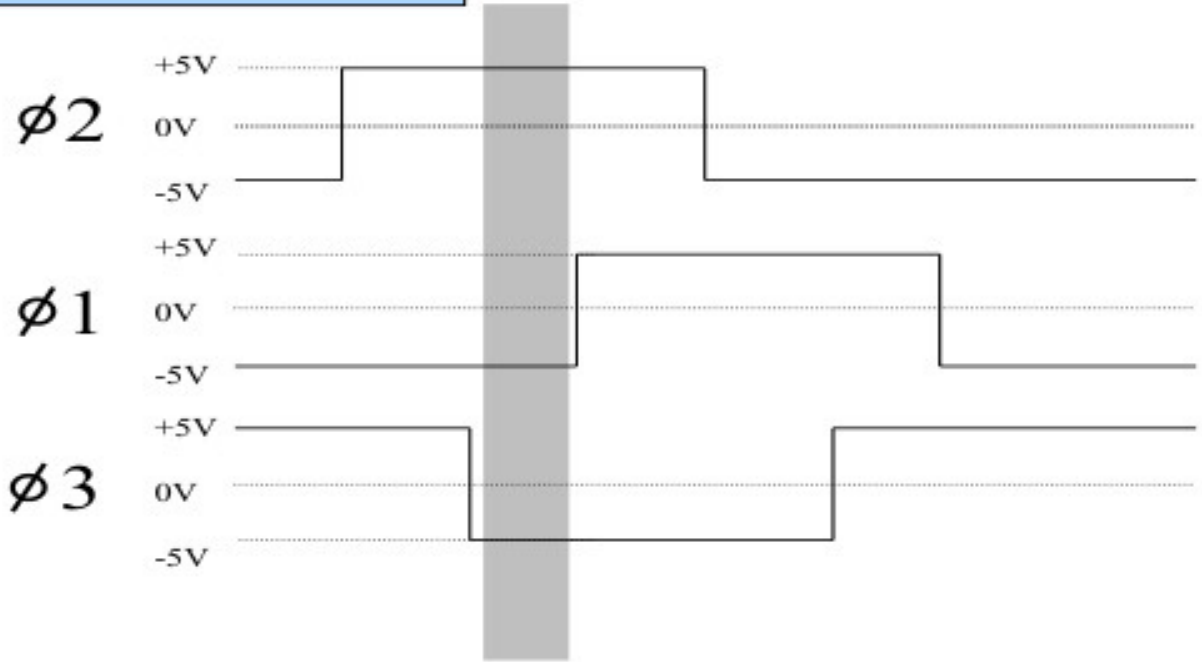


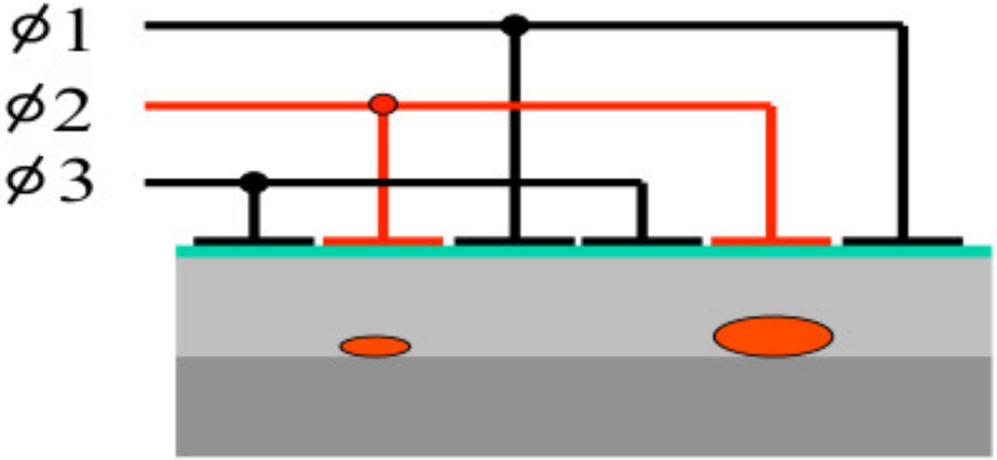
Time-slice shown in diagram

# Charge Transfer in a CCD

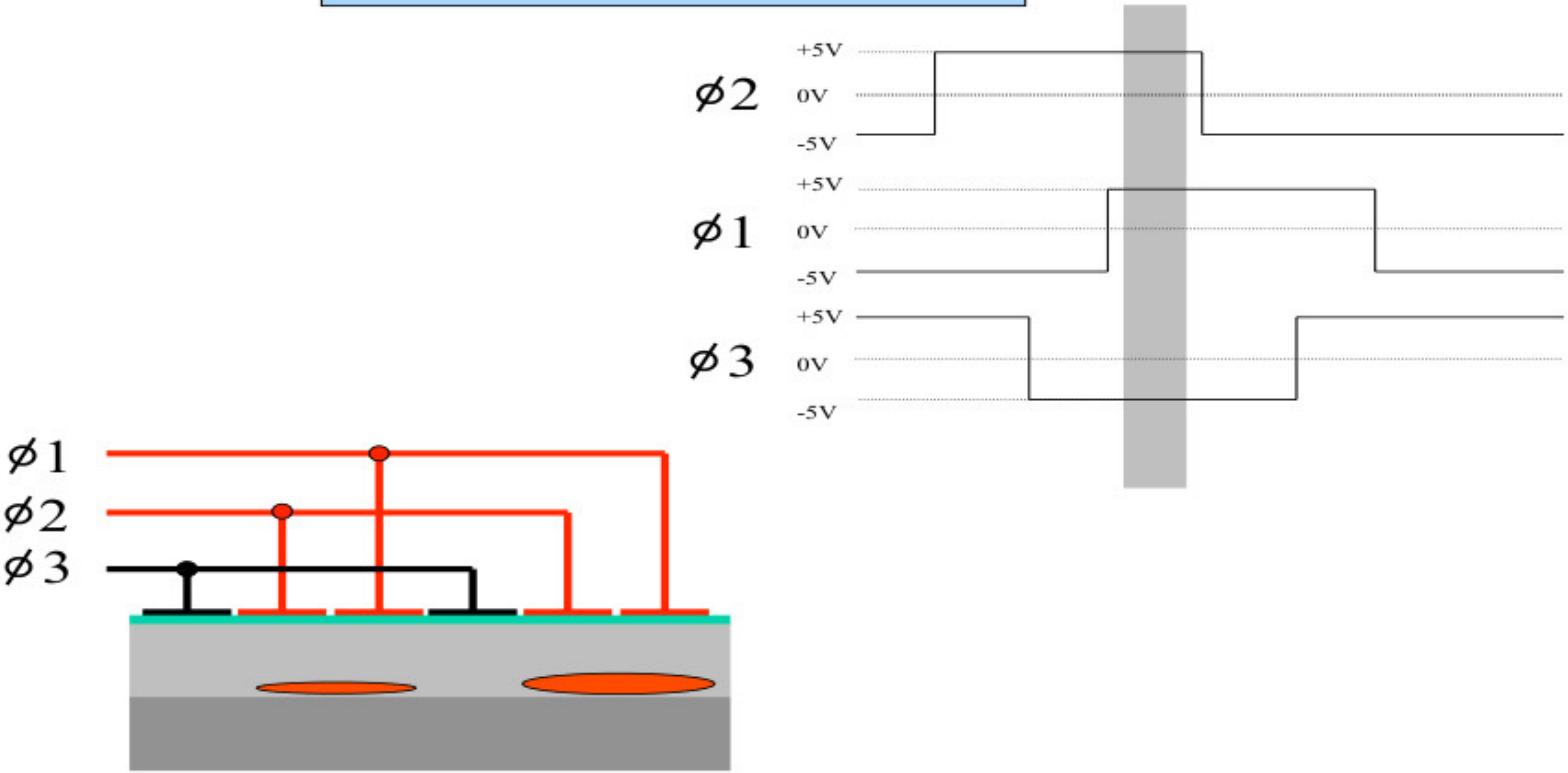


# Charge Transfer in a CCD

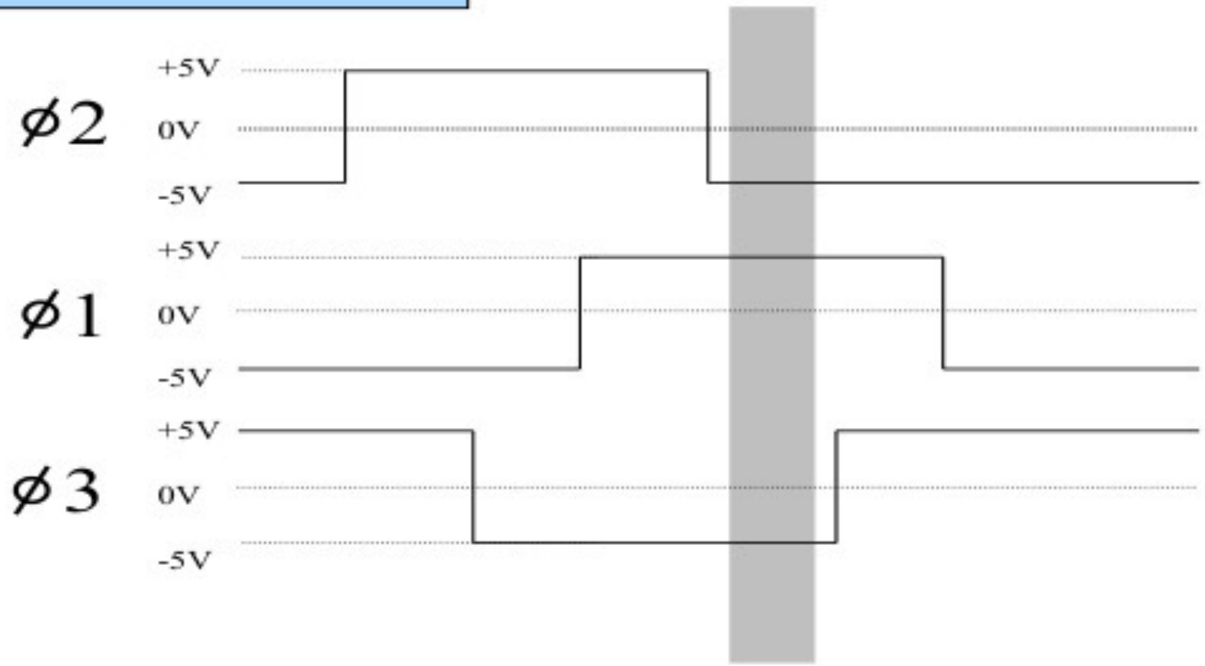


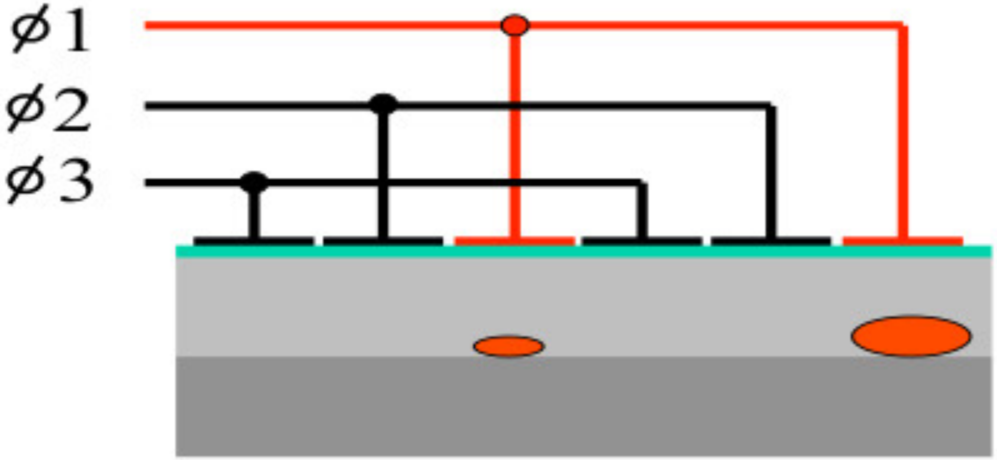


# Charge Transfer in a CCD



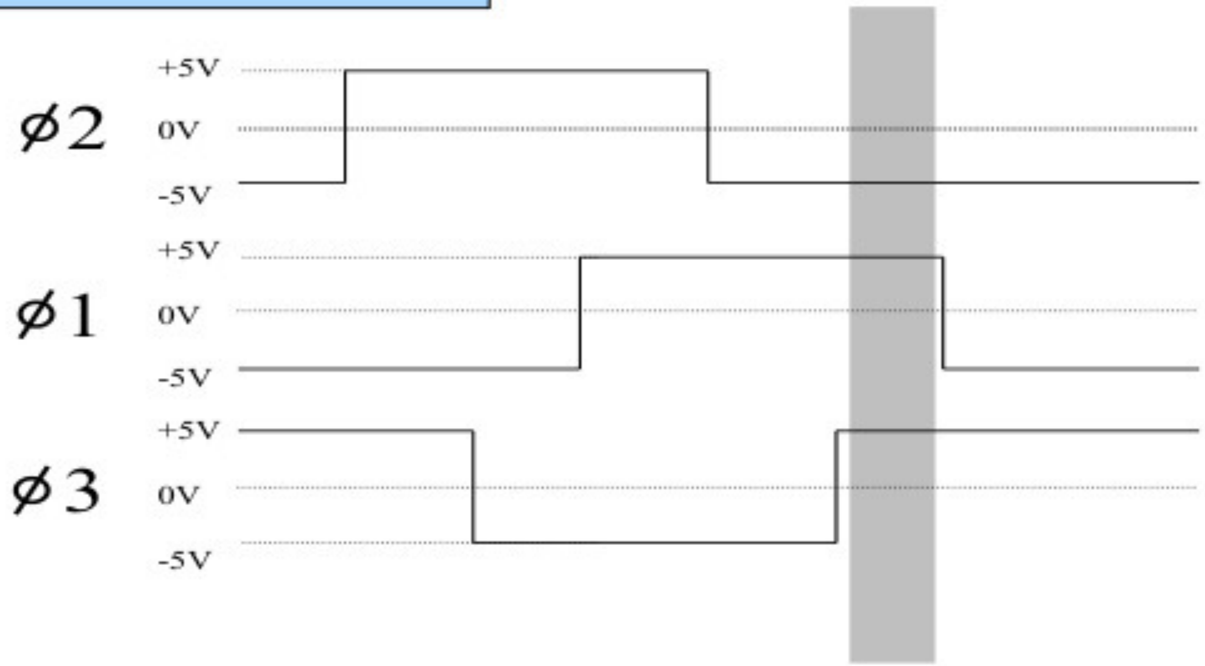
# Charge Transfer in a CCD

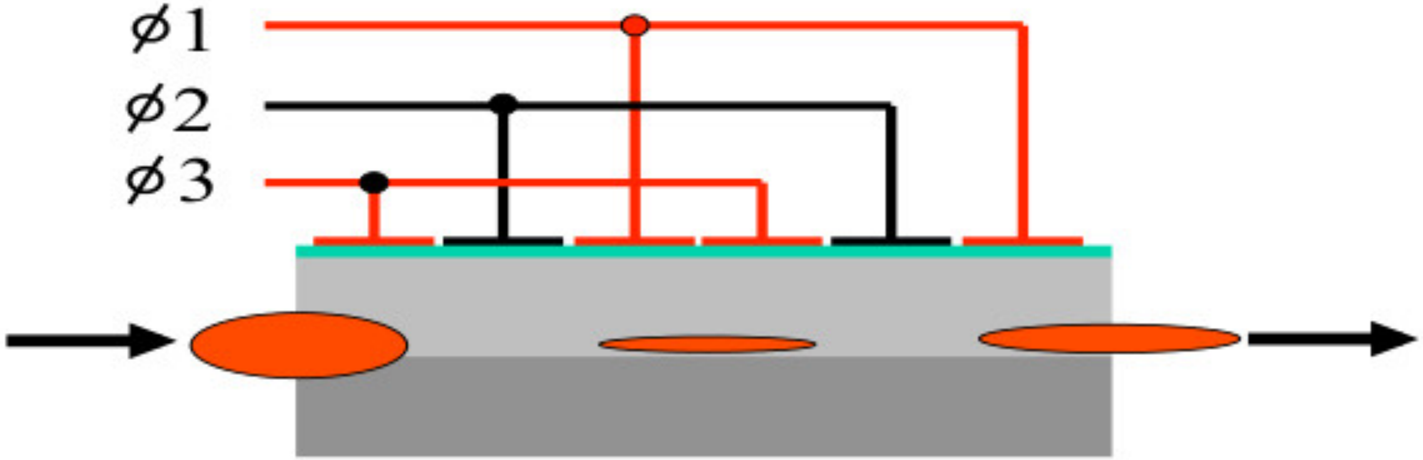




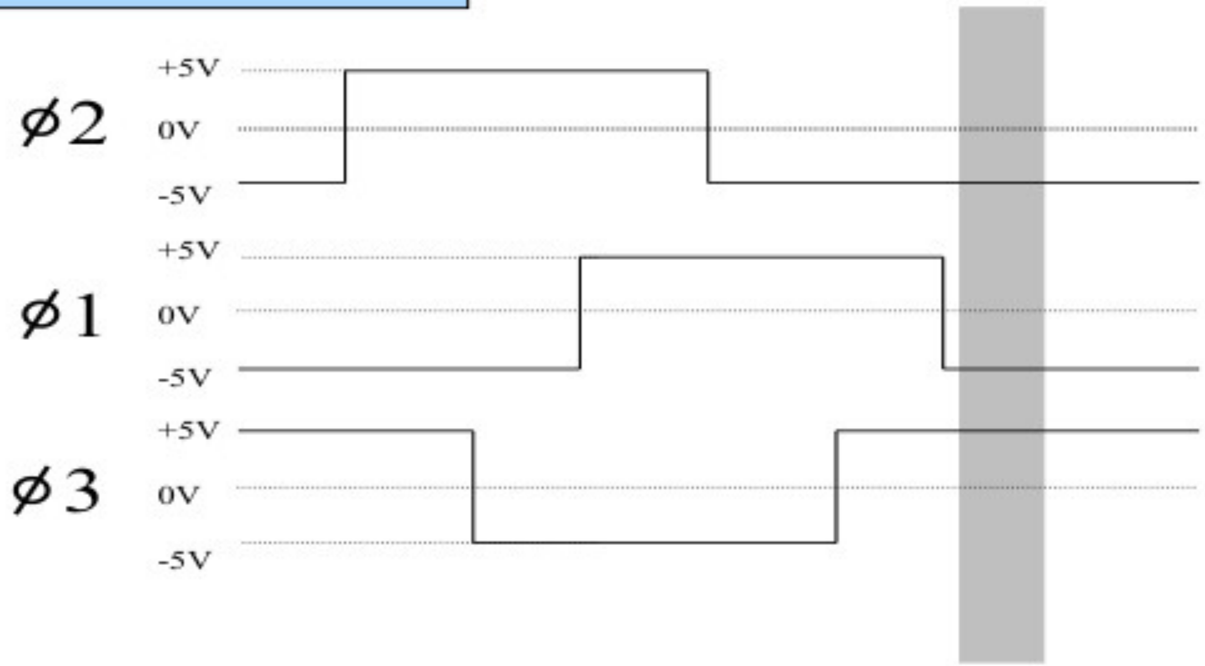
# Charge Transfer in a CCD

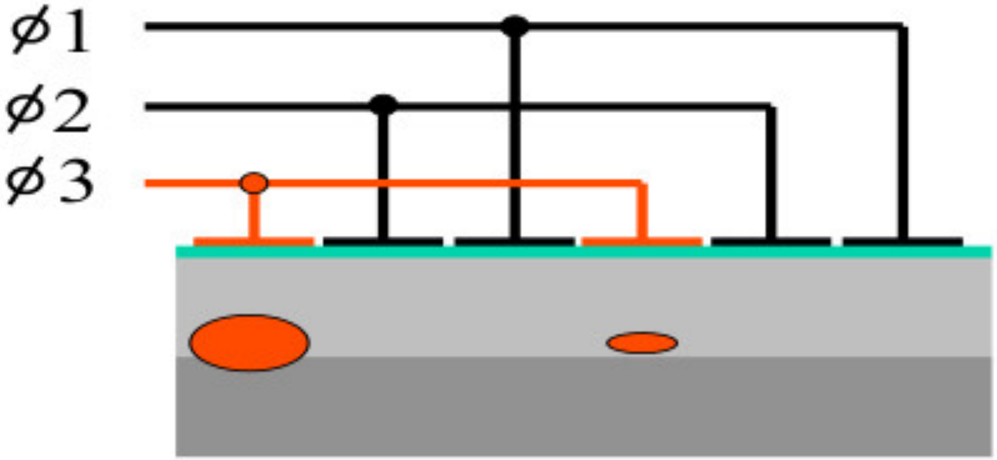
Charge packet from subsequent pixel enters from left as first pixel exits to the right.

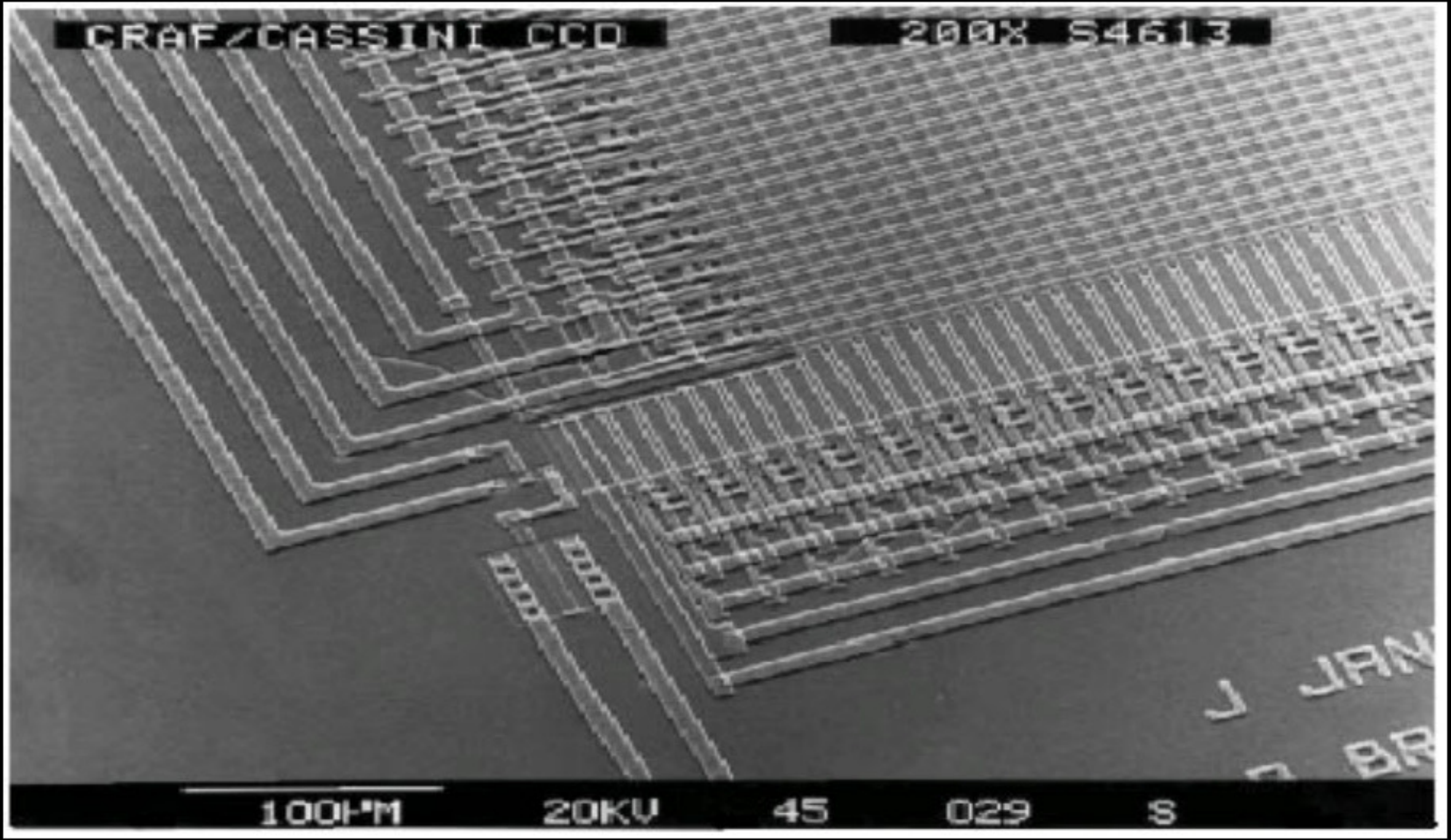


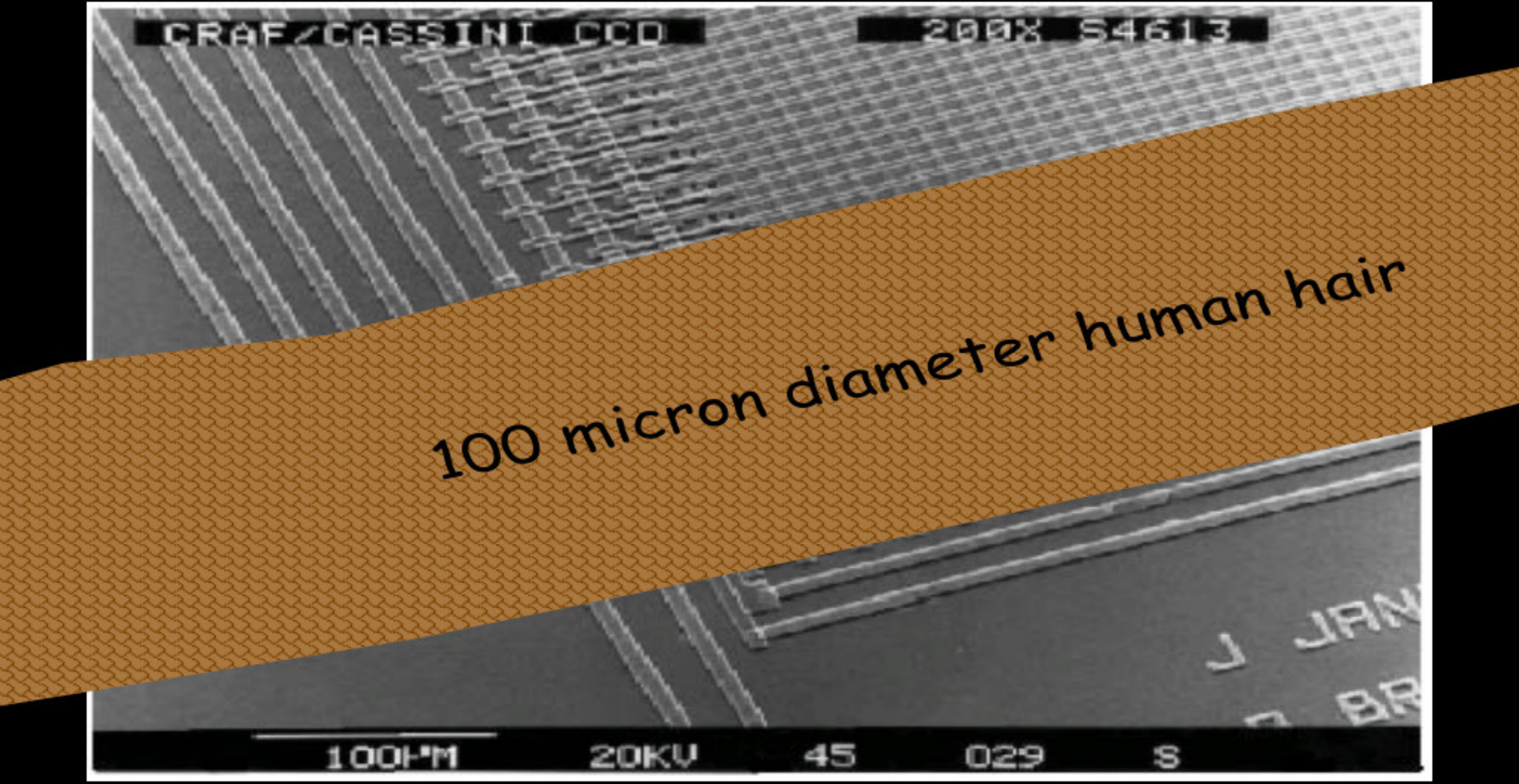


# Charge Transfer in a CCD






CRAF/CASSINI CCD
200X S4613
J JAN
BR
100µM
20KV
45
029
S



100 micron diameter human hair

# CHARGE TRANSFER EFFICIENCY

- Efficiency to move charge from one pixel to the next
- Buried channel have better CTE
- Charge is not lost but falls behind on trailing pixels
- Standard CTE=0.99999 => 5 nines
- Example for a 2k x 4k CCD:

$$0.9999^{6000} = 0.541$$

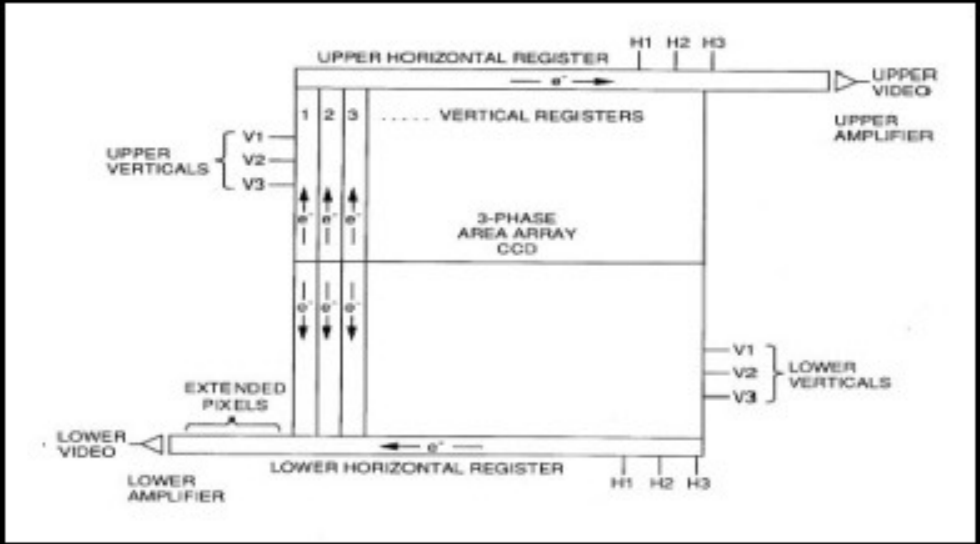
$$0.99995^{6000} = 0.735$$

$$0.99999^{6000} = 0.940$$

$$0.999999^{6000} = 0.994$$

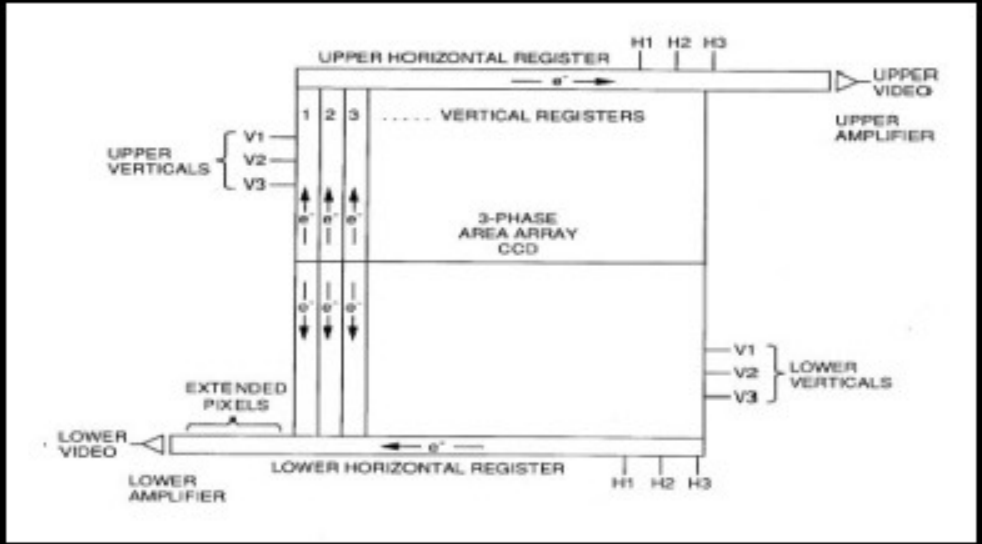
# CCD Charge transfer
## The good, the bad & the ugly

- "Bad & ugly" aspects of charge transfer
  - Takes time (limited max frame rate)
  - Can blur image if no shutter used
  - Can lose / blur charge during move (may limit astrometry accuracy)
  - Can bleed charge from saturated pixel up/down column
  - Can have a blocked column
  - Can have a hot pixel that releases charge into all passing pixels



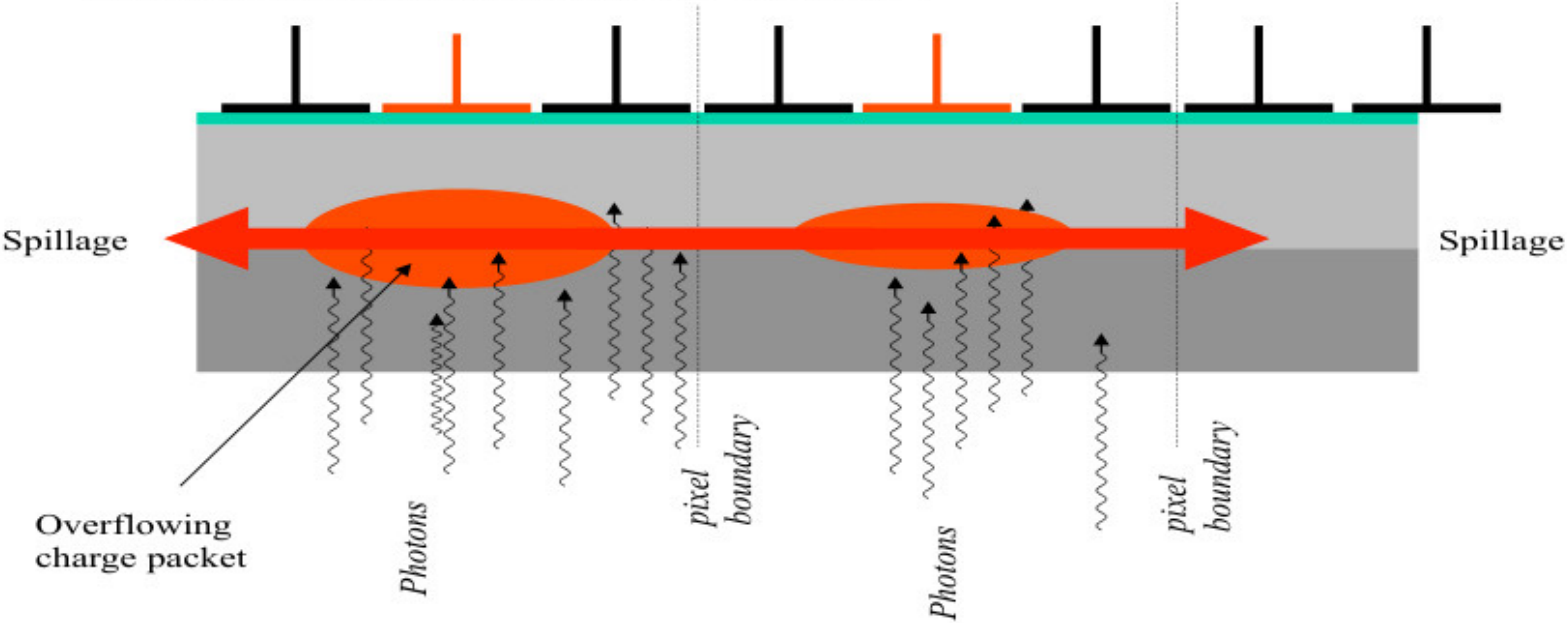
# CCD Charge transfer
## The good, the bad & the ugly

- "Good" aspects of charge transfer
  - Can bin charge "on-chip" – noiseless process
  - Can charge shift for tip/tilt correction or to eliminate systematic errors
    - "va-et-vient", "nod-and-shuffle"
  - Can build special purpose designs that integrate different areas (curvature wavefront sensing, Shack-Hartmann laser guide star wavefront sensing)
  - Can do drift scanning
  - No indium bump issues that can cause inoperable pixels
  - **Have space to build a great low noise amplifier !**



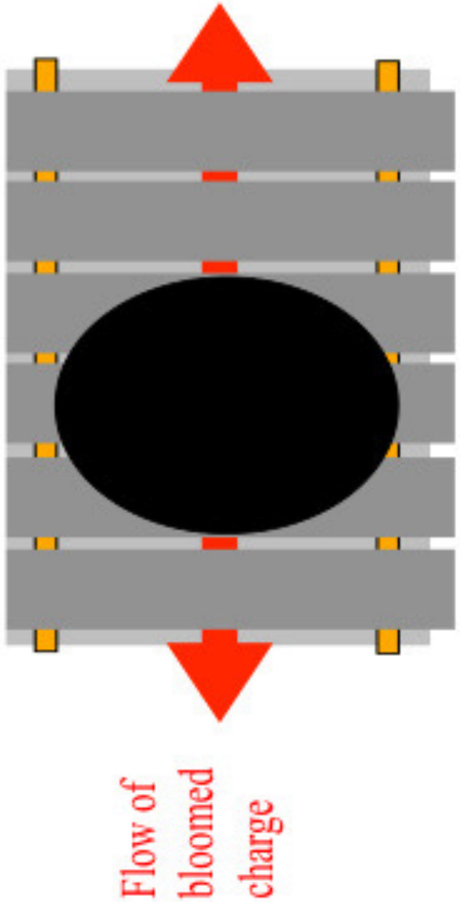
# Blooming in a CCD

The charge capacity of a CCD pixel is limited, when a pixel is full the charge starts to leak into adjacent pixels. This process is known as 'Blooming'.



# Blooming in a CCD

The diagram shows one column of a CCD with an over-exposed stellar image focused on one pixel.



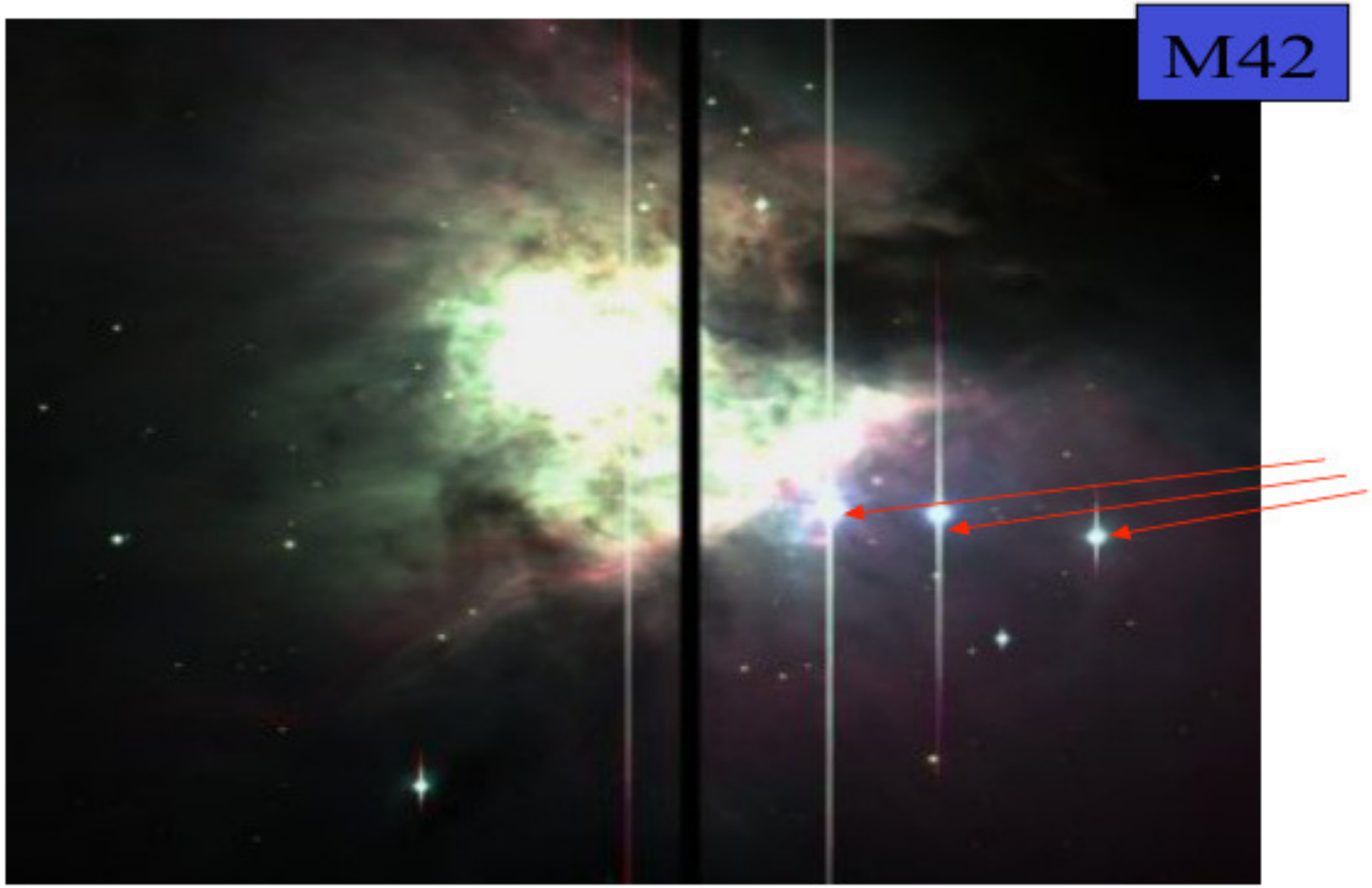
The channel stops shown in yellow prevent the charge spreading sideways. The charge confinement provided by the electrodes is less so the charge spreads vertically up and down a column.

The capacity of a CCD pixel is known as the 'Full Well'. It is dependent on the physical area of the pixel. For Tektronix CCDs, with pixels measuring 24µm x 24µm it can be as much as 300,000 electrons. Bloomed images will be seen particularly on nights of good seeing where stellar images are more compact .

In reality, blooming is not a big problem for professional astronomy. For those interested in pictorial work, however, it can be a nuisance.

# Blooming in a CCD

The image below shows an extended source with bright embedded stars. Due to the long exposure required to bring out the nebulosity, the stellar images are highly overexposed and create bloomed images.

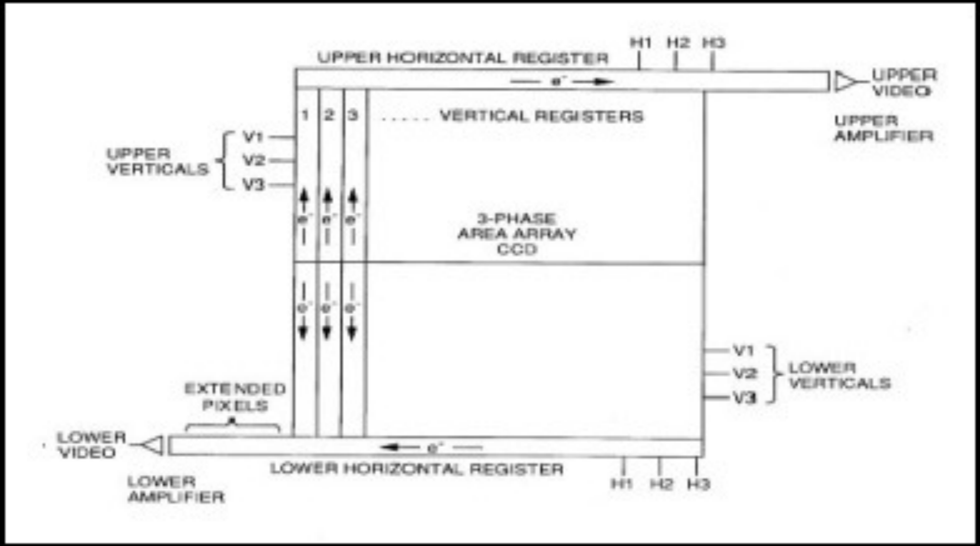


Bloomed star images

(The image is from a CCD mosaic and the black strip down the center is the space between adjacent detectors)

# CCD Charge transfer

## The good, the bad & the ugly



# Image Defects in a CCD

Unless one pays a huge amount it is generally difficult to obtain a CCD free of image defects. The first kind of defect is a '**dark column**'. Their locations are identified from flat field exposures.

Flat field exposure of an EEV42-80 CCD

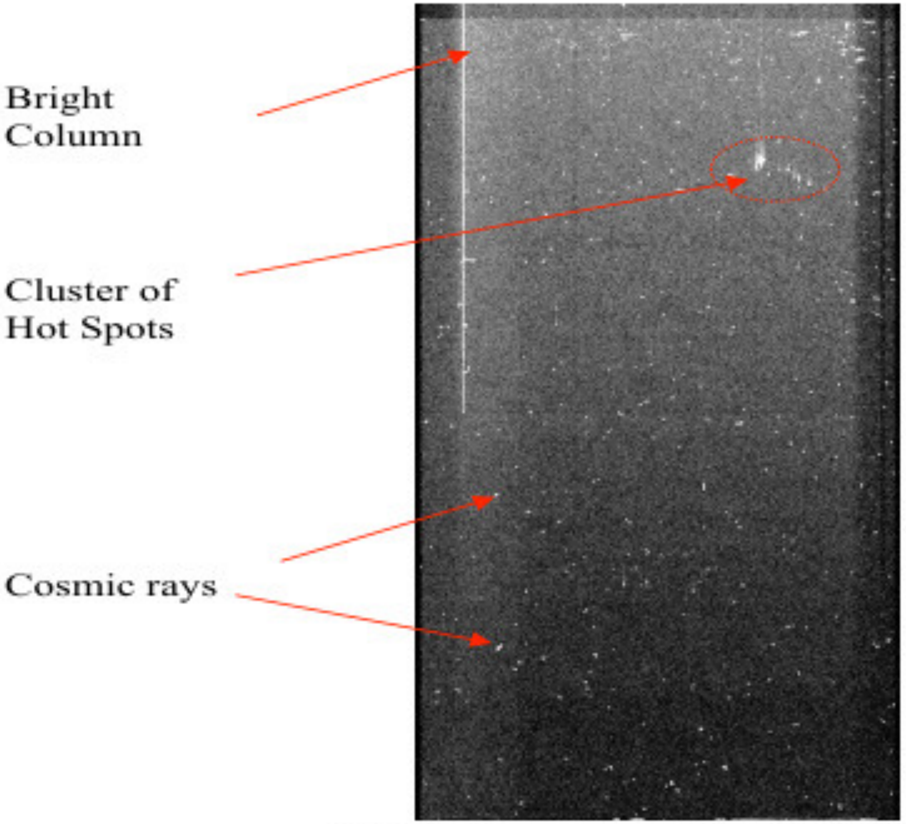
**Dark columns** are caused by 'traps' that block the vertical transfer of charge during image readout. The CCD shown at left has at least 7 dark columns, some grouped together in adjacent clusters.

Traps can be caused by crystal boundaries in the silicon of the CCD or by manufacturing defects.

Although they spoil the chip cosmetically, dark columns are not a big problem for astronomers. This chip has 2048 image columns so 7 bad columns represents a tiny loss of data.

# Image Defects in a CCD

There are three other common image defect types : Cosmic rays, Bright columns and Hot Spots.
Their locations are shown in the image below which is a lengthy exposure taken in the dark (a 'Dark Frame')



900s dark exposure of an EEV42-80 CCD

Bright columns are also caused by traps . Electrons contained in such traps can leak out during readout causing a vertical streak.

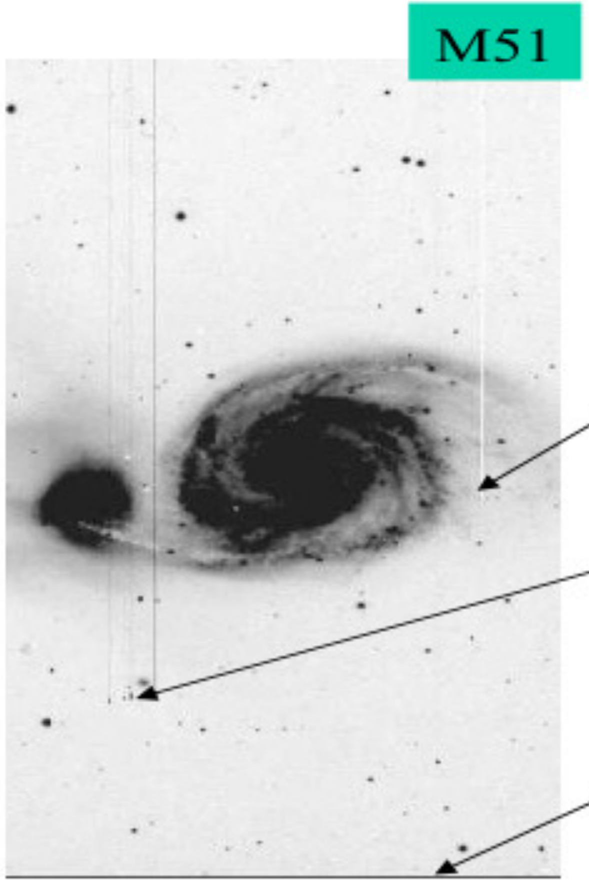
Hot Spots are pixels with higher than normal dark current. Their brightness increases linearly with exposure times

Cosmic rays are unavoidable. Charged particles from space or from radioactive traces in the material of the camera can cause ionisation in the silicon. The electrons produced are indistinguishable from photo-generated electrons. Approximately 2 cosmic rays per $cm^2$ per minute will be seen. A typical event will be spread over a few adjacent pixels and contain several thousand electrons.

Somewhat rarer are light-emitting defects which are hot spots that act as tiny LEDS and cause a halo of light on the chip.

# Image Defects in a CCD

Some defects can arise from the processing electronics. This negative image has a bright line in the first image row.



Dark column

Hot spots and bright columns

Bright first image row caused by incorrect operation of signal processing electronics.

# 6 steps of optical / IR photon detection

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transfer

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CCD

MOSFET
Amplifier

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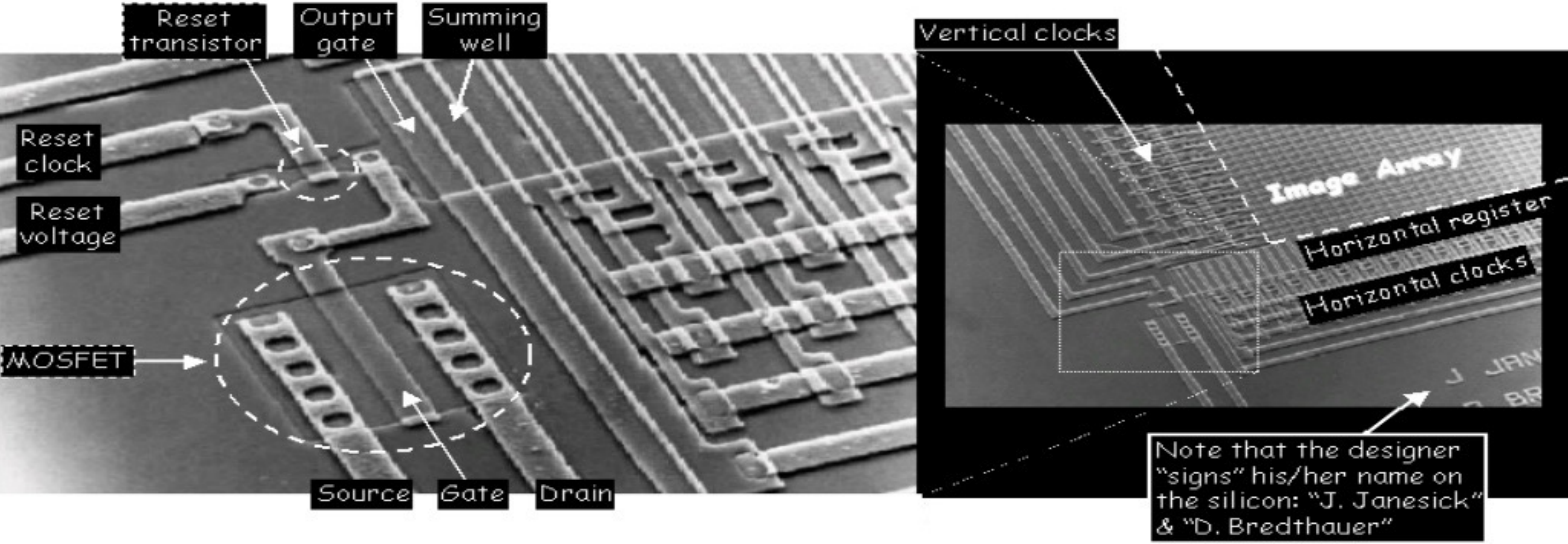
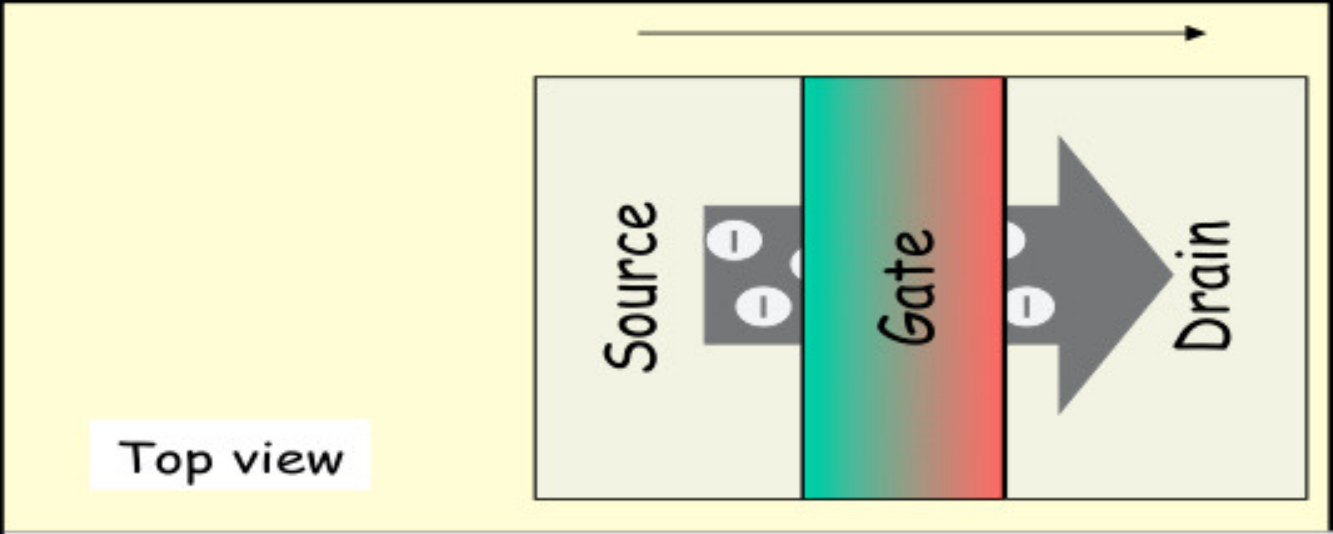


Note that the designer "signs" his/her name on the silicon: "J. Janesick" & "D. Bredthauer"

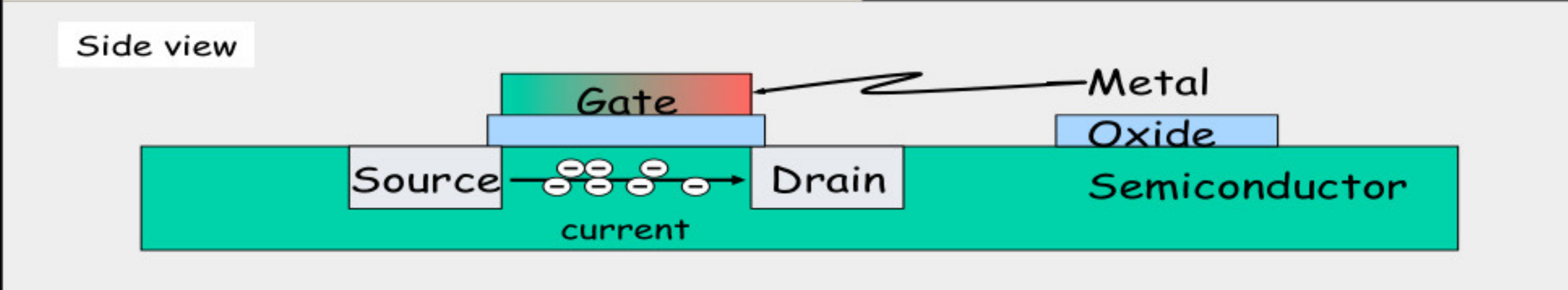
# MOSFET Principles

MOSFET = metal oxide semiconductor field effect transistor



Turn on the MOSFET and current flows from source to drain

Add charge to gate & the current flow changes since the effect of the field of the charge will reduce the current

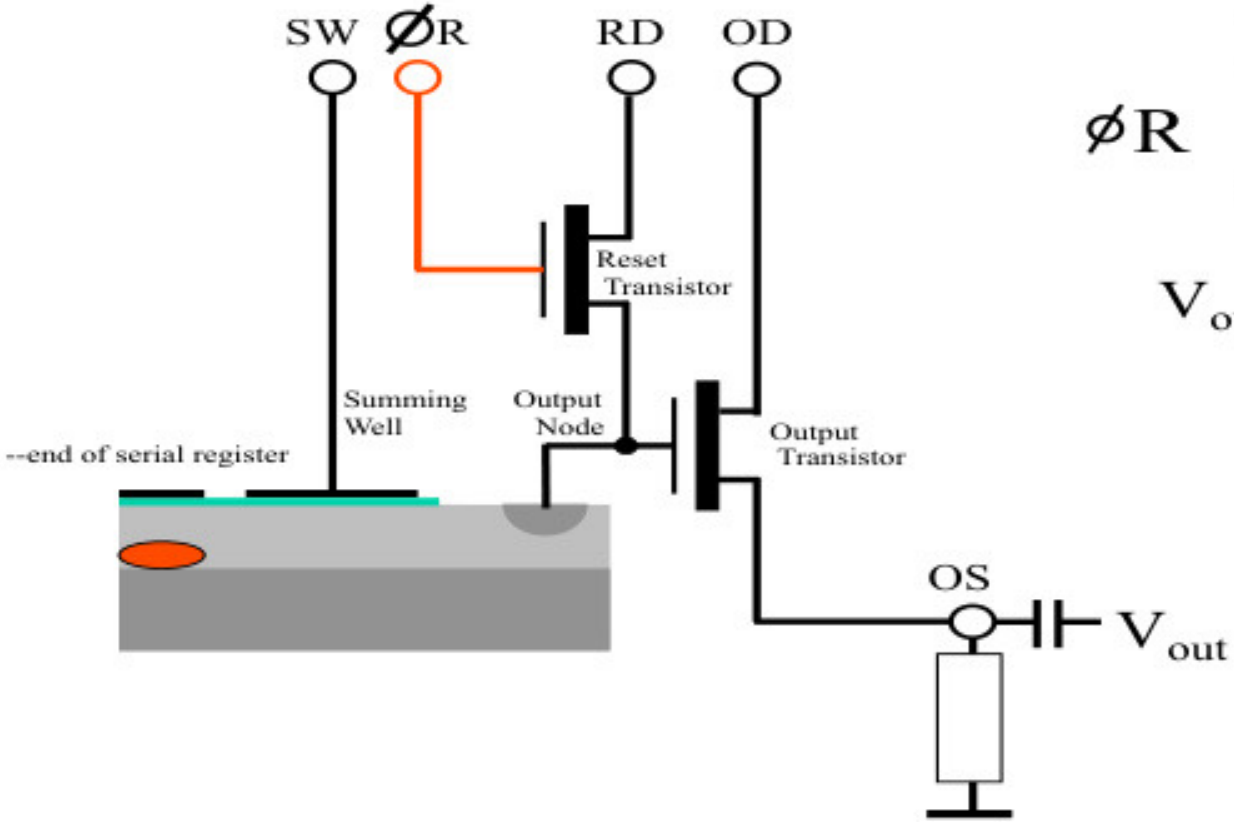


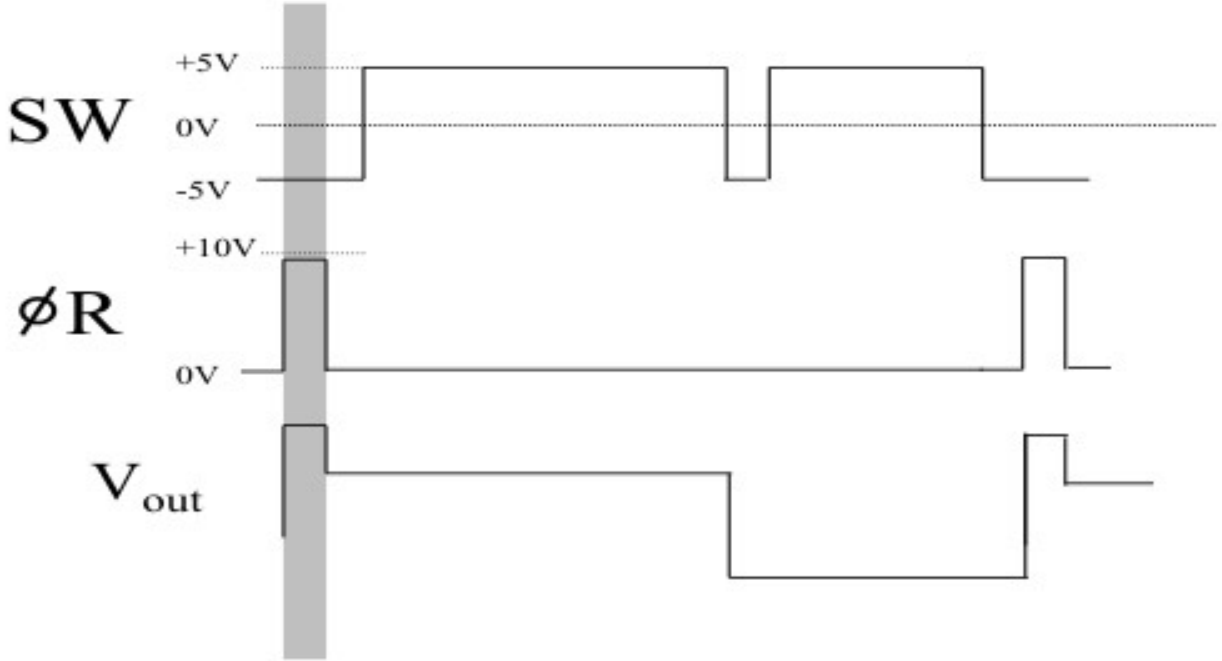
Fluctuations in current flow produce "readout noise"
Fluctuations in reset level on gate produces "reset noise"

# On-Chip Amplifier 1.

The on-chip amplifier measures each charge packet as it pops out the end of the serial register.

RD and OD are held at constant voltages



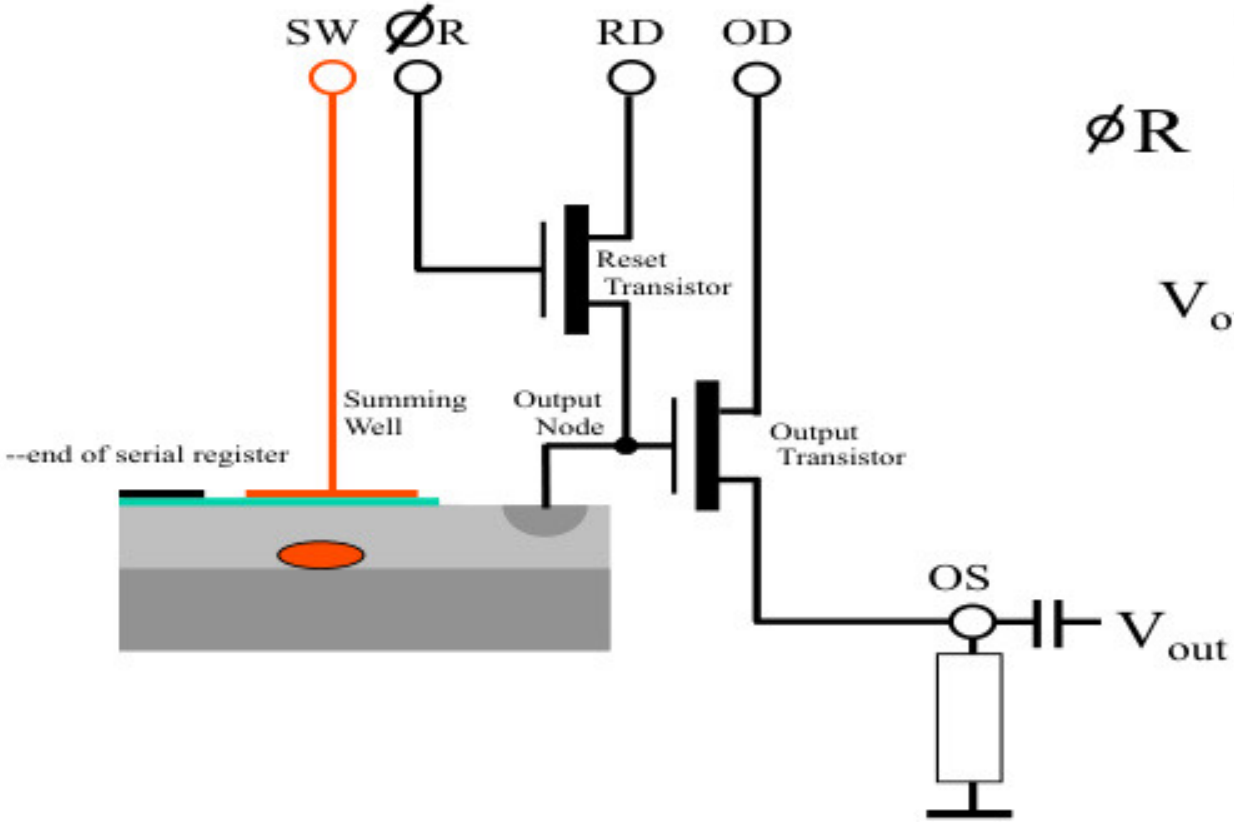


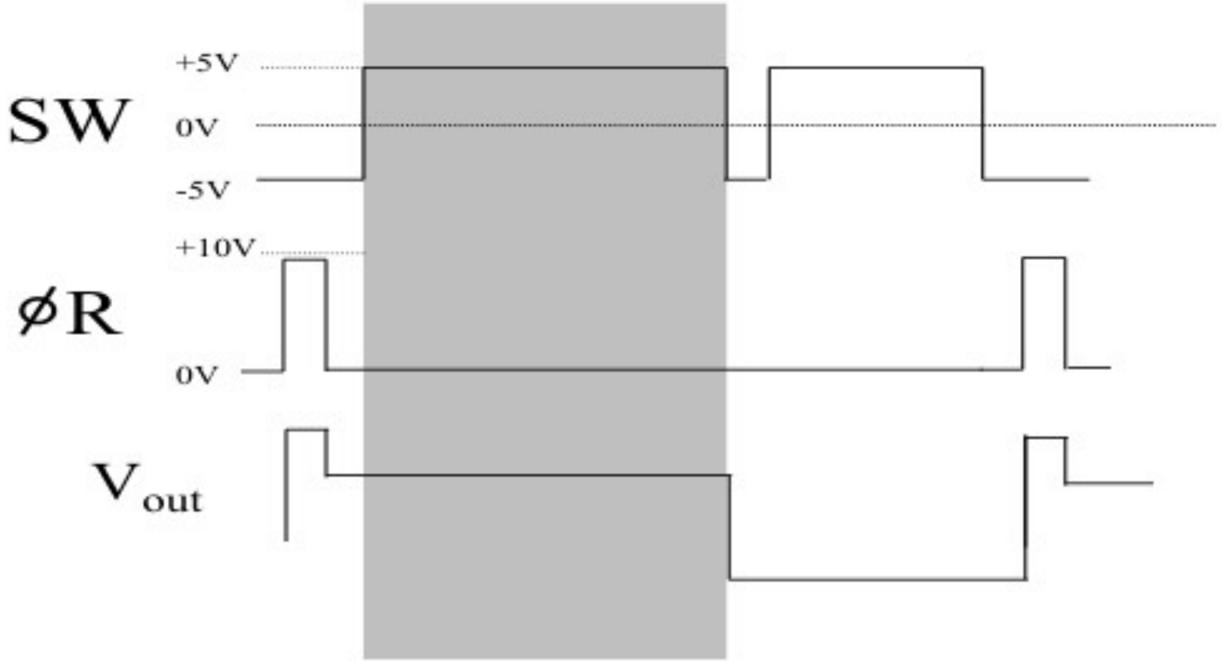
(The graphs above show the signal waveforms)

The measurement process begins with a reset of the 'reset node'. This removes the charge remaining from the previous pixel. The reset node is in fact a tiny capacitance (< 0.1pF)

# On-Chip Amplifier 2.

The charge is then transferred onto the Summing Well. $V_{out}$ is now at the 'Reference level'

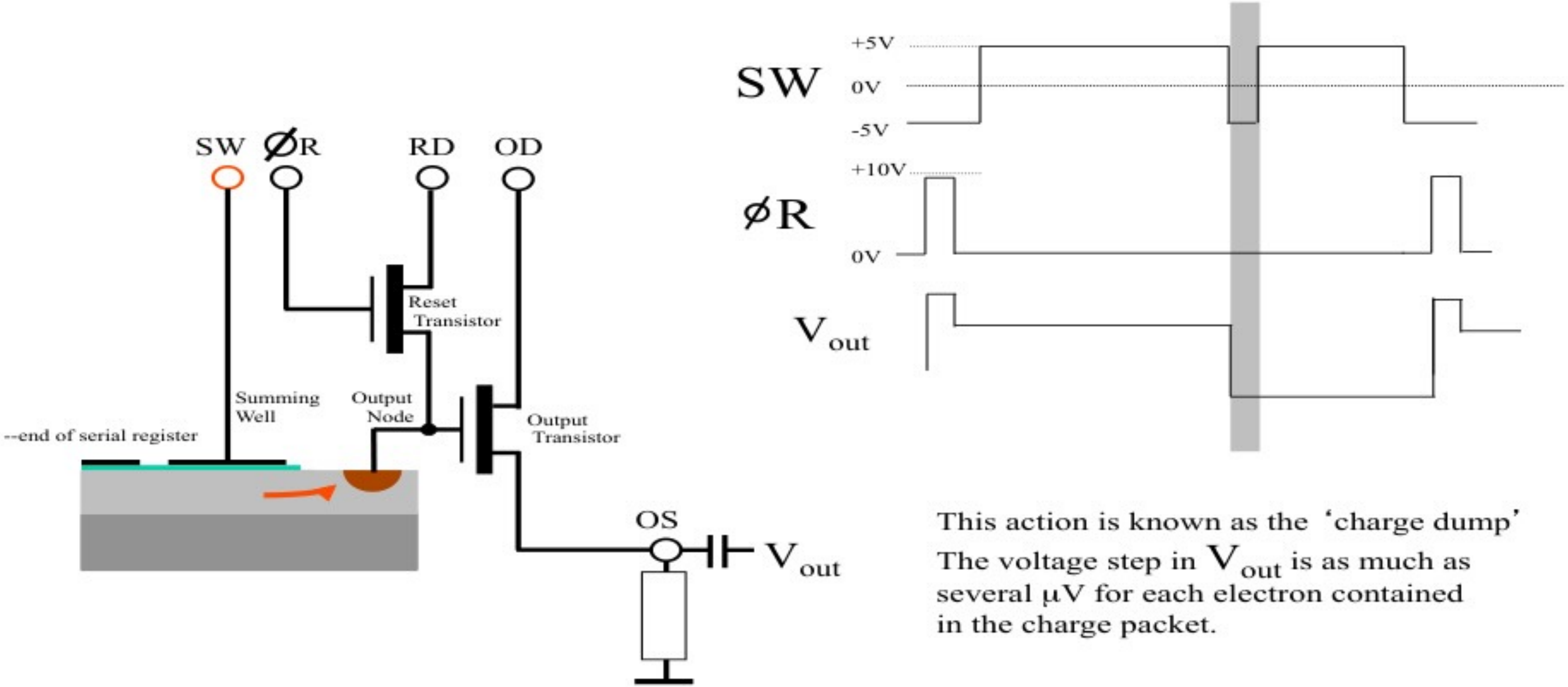




There is now a wait of up to a few tens of microseconds while external circuitry measures this 'reference' level.

# On-Chip Amplifier 3.

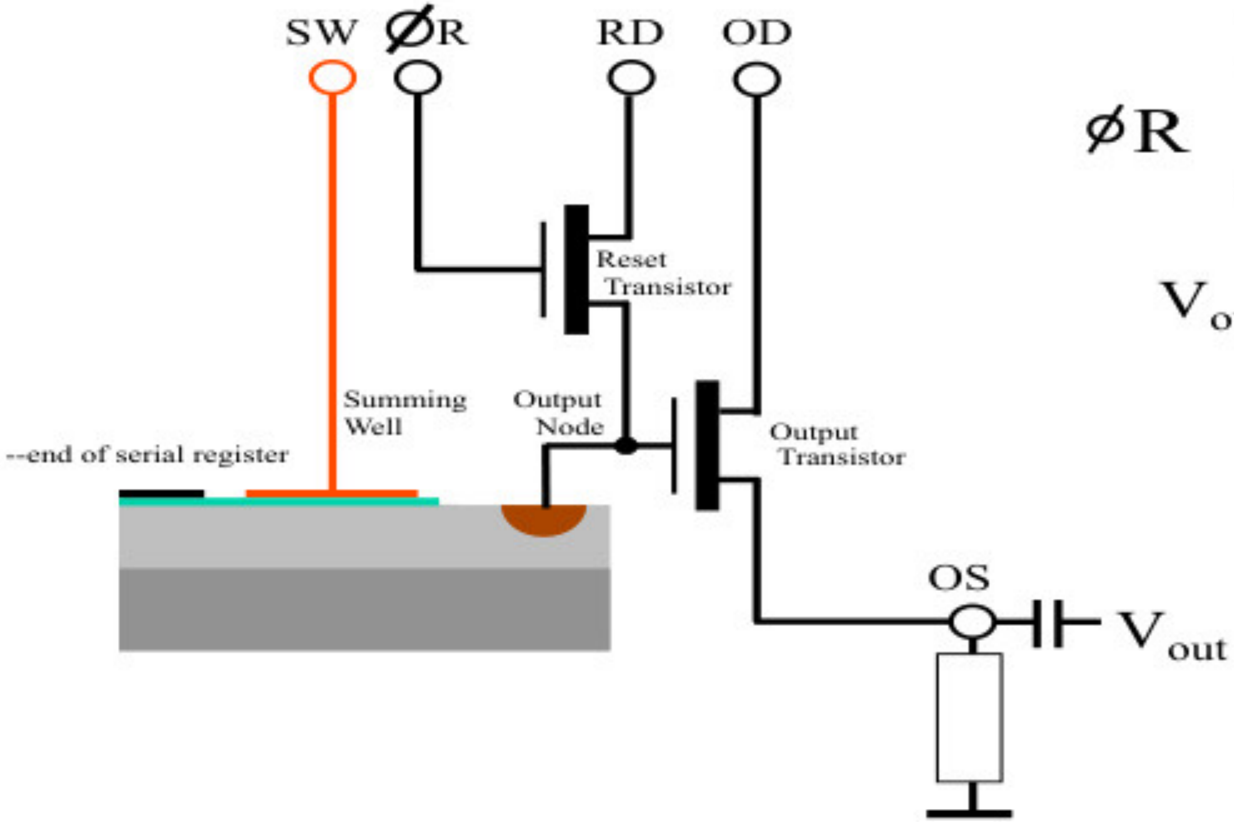
The charge is then transferred onto the output node. $V_{out}$ now steps down to the 'Signal level'

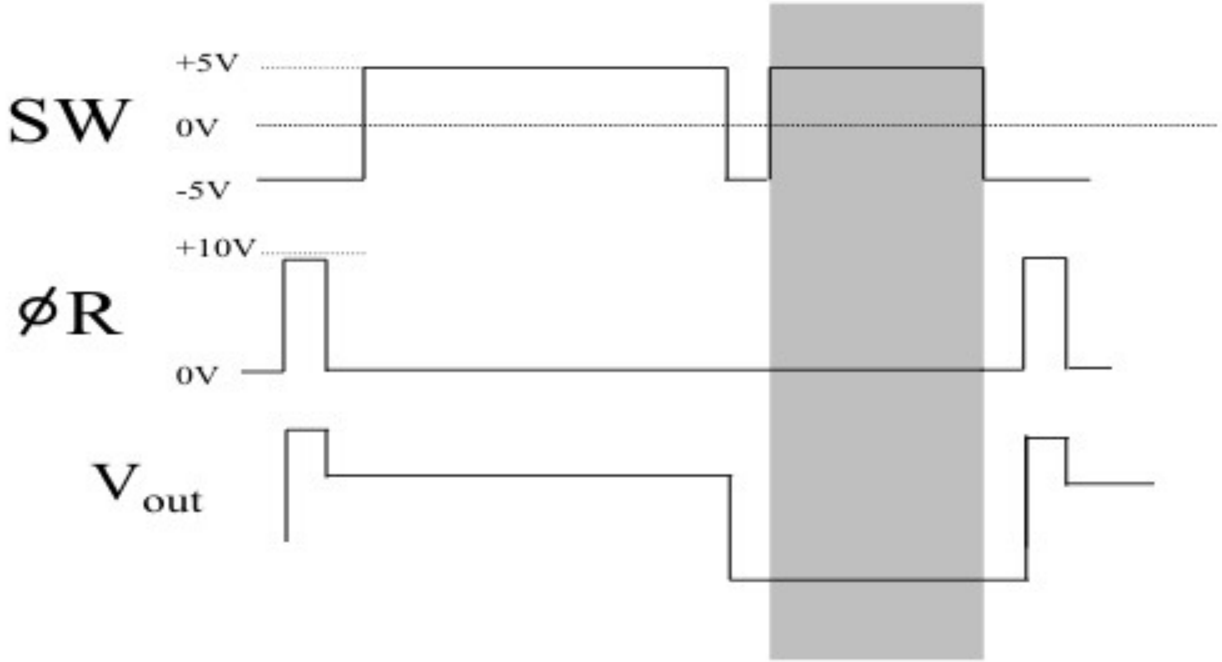


This action is known as the 'charge dump'
The voltage step in $V_{out}$ is as much as several μV for each electron contained in the charge packet.

# On-Chip Amplifier 4.

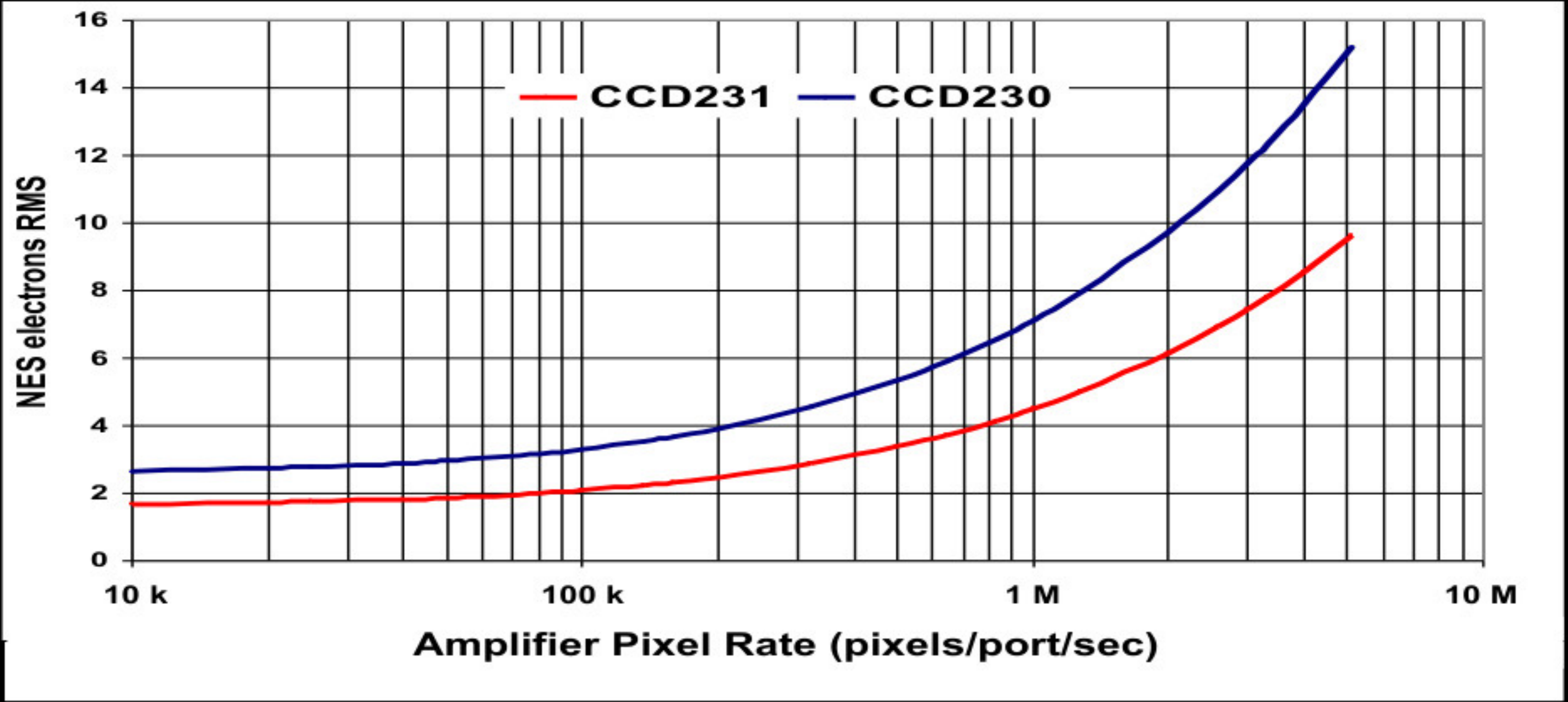
$V_{out}$ is now sampled by external circuitry for up to a few tens of microseconds.





The sample level - reference level will be proportional to the size of the input charge packet.

# Typical CCD Readout Noise (single CDS)

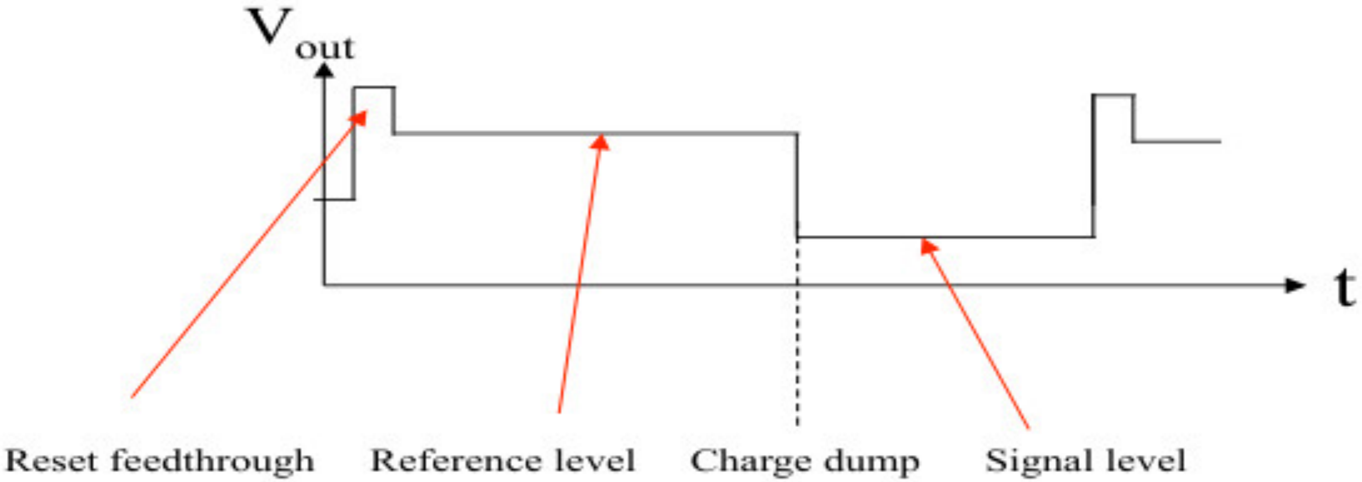


e2v technologies

# Correlated Double Sampler (CDS)

The video waveform output by a CCD is at a fairly low level : every photo-electron in a pixel charge packet will produce a few micro-volts of signal. Additionally, the waveform is complex and precise timing is required to make sure that the correct parts are amplified and measured.

The CCD video waveform , as introduced in Activity 1, is shown below for the period of one pixel measurement



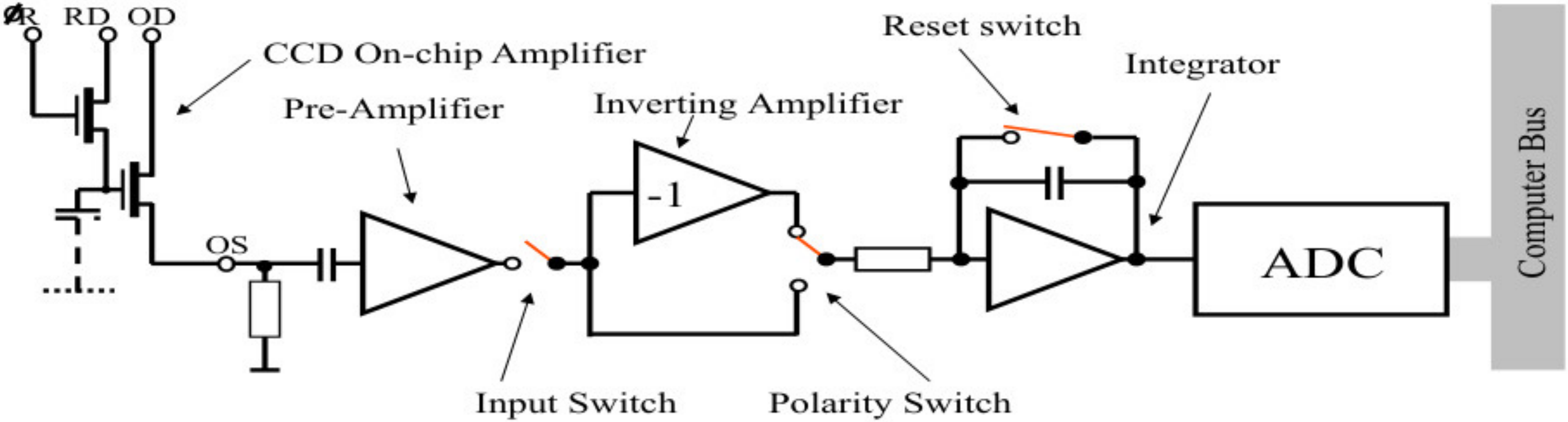
The video processor must measure , without introducing any additional noise, the Reference level and the Signal level. The first is then subtracted from the second to yield the output signal voltage proportional to the number of photo-electrons in the pixel under measurement. The best way to perform this processing is to use a ‘Correlated Double Sampler’ or CDS.

# Correlated Double Sampler (CDS)

The Correlated Double Sampler removes the reset noise (50 –e to 100 –e) and can be implemented in 2 different ways:

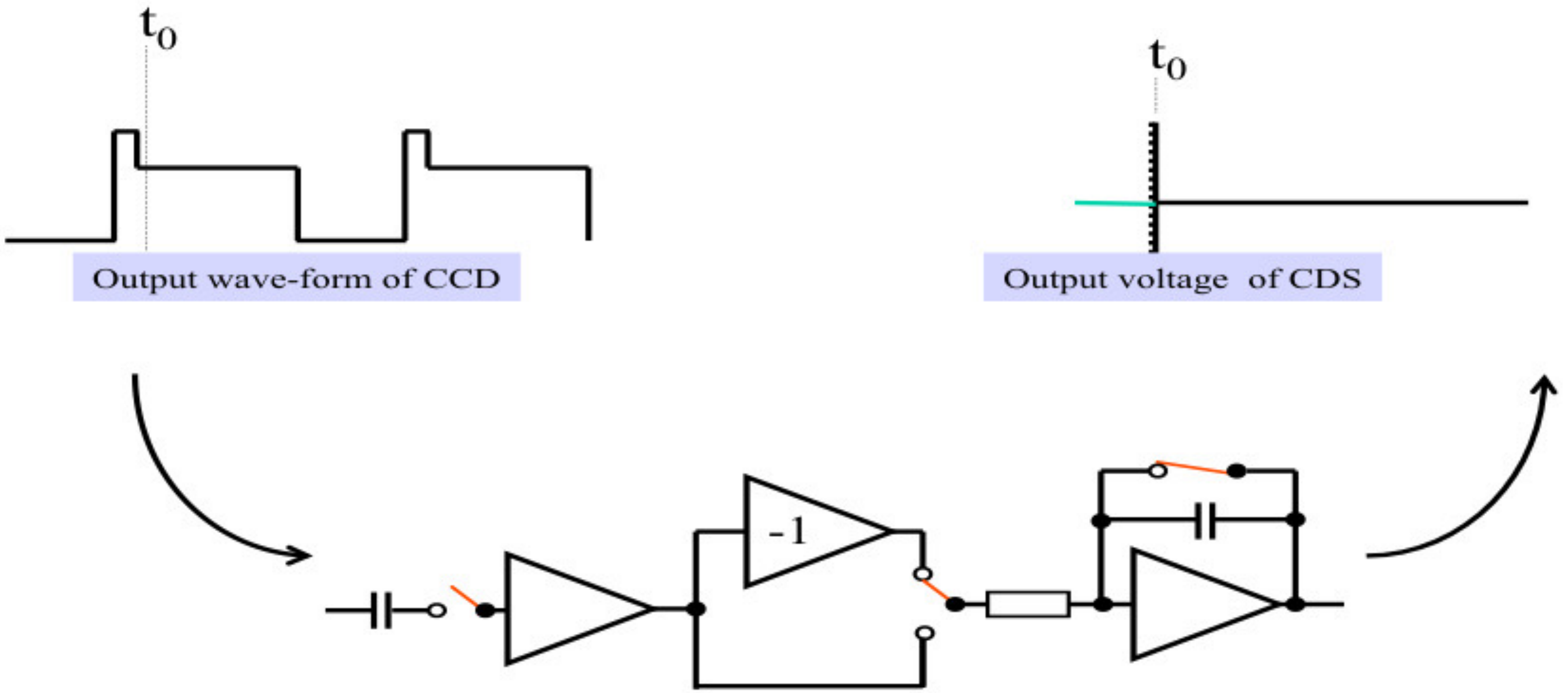
a) Digital: ADC(Signal) – ADC(Reference).

b) Analog: Dual Slope or Clamp and Sample



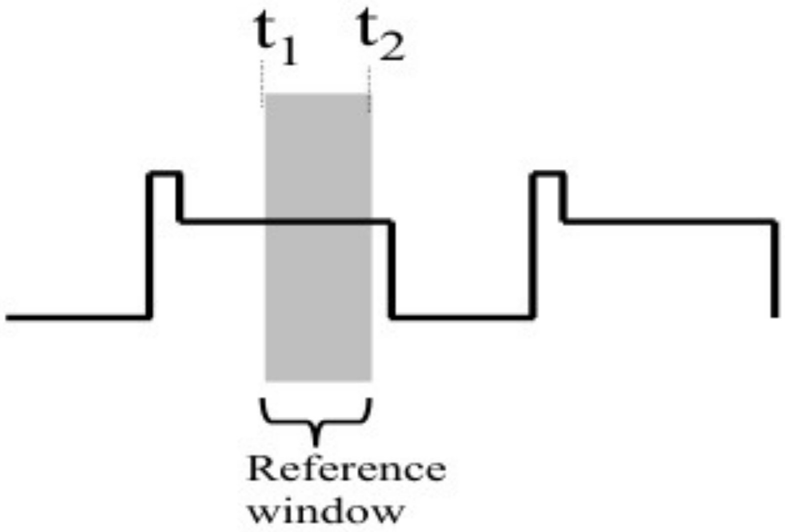
# Correlated Double Sampler (CDS)

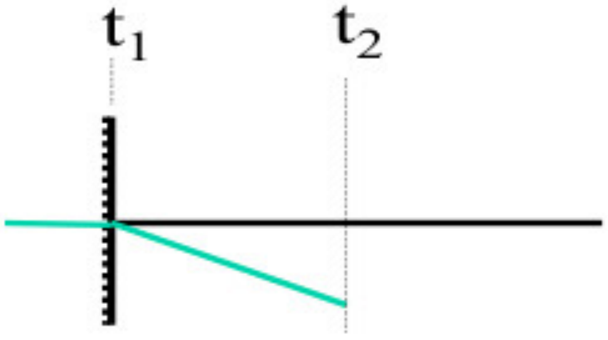
The CDS starts work once the pixel charge packet is in the CCD summing well and the CCD reset pulse has just finished. At point $t_0$ the CCD wave-form is still affected by the reset pulse and so the CDS remains disconnected from the CCD to prevent this disturbing the video processor.

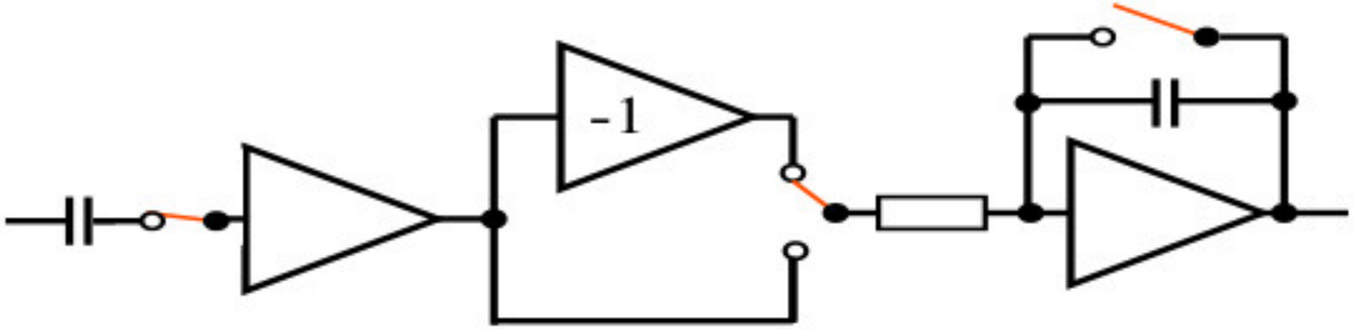


# Correlated Double Sampler (CDS)

Between $t_1$ and $t_2$ the CDS is connected and the 'Reference ' part of the waveform is sampled. Simultaneously the integrator reset switch is opened and the output starts to ramp down linearly.

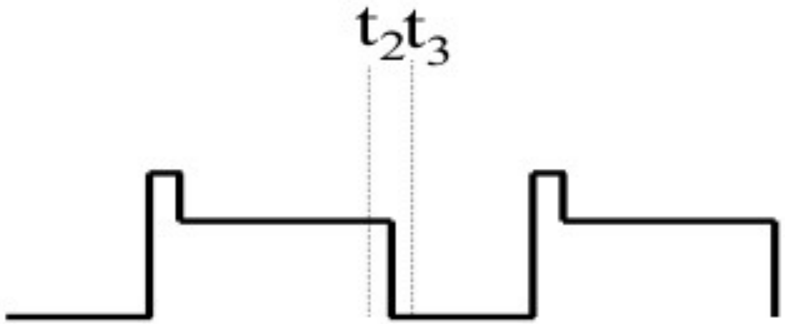


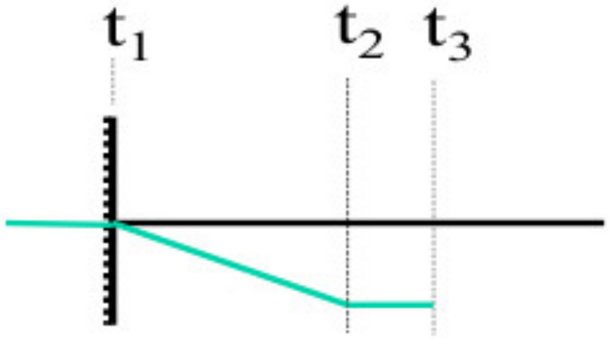


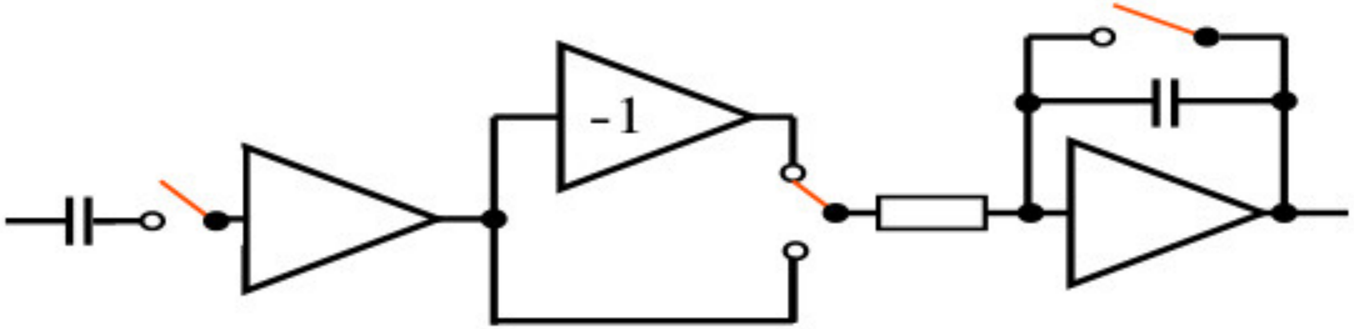


# Correlated Double Sampler (CDS)

Between $t_2$ and $t_3$ the ‘charge dump’ occurs in the CCD. The CCD output steps negatively by an amount proportional to the charge contained in the pixel. During this time the CDS is disconnected.

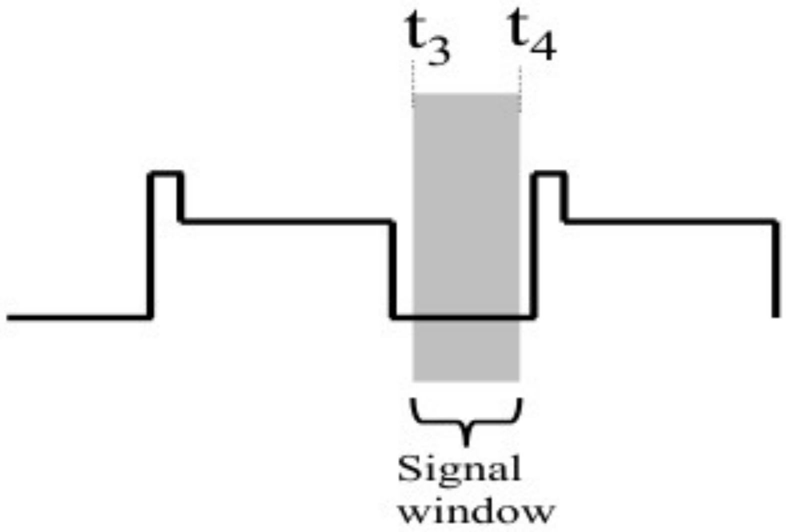


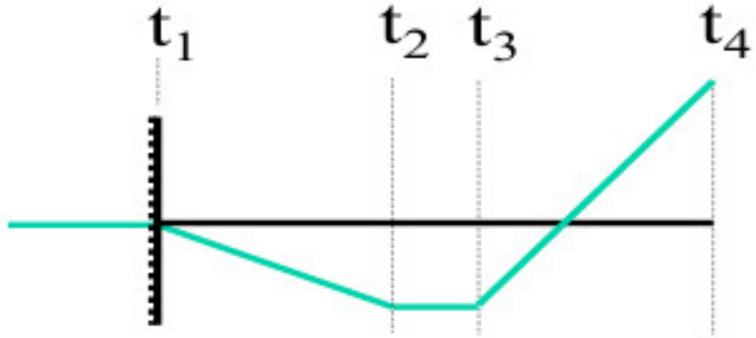


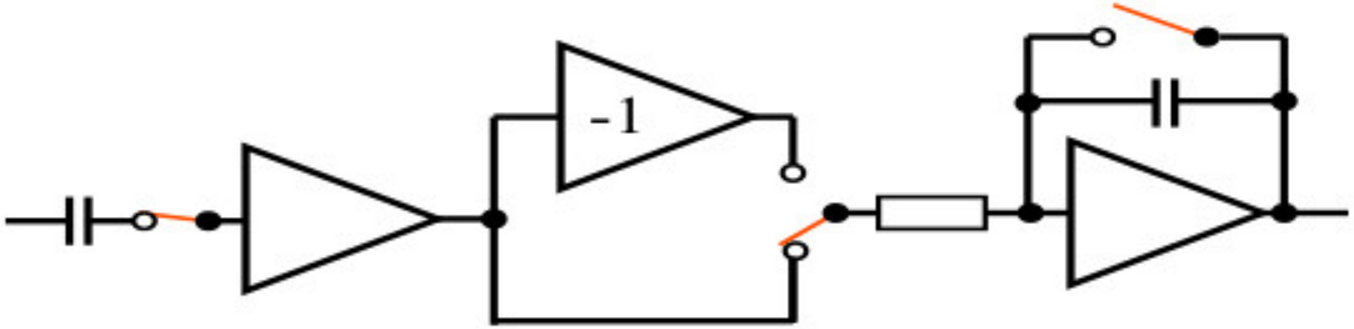


# Correlated Double Sampler (CDS)

Between $t_3$ and $t_4$ the CDS is reconnected and the ‘signal’ part of the wave-form is sampled. The input to the integrator is also ‘polarity switched’ so that the CDS output starts to ramp-*up* linearly. The width of the signal and sample windows must be the same. For Scientific CCDs this can be anything between 1 and 20 microseconds. Longer widths generally give lower noise but of course increase the read-out time.



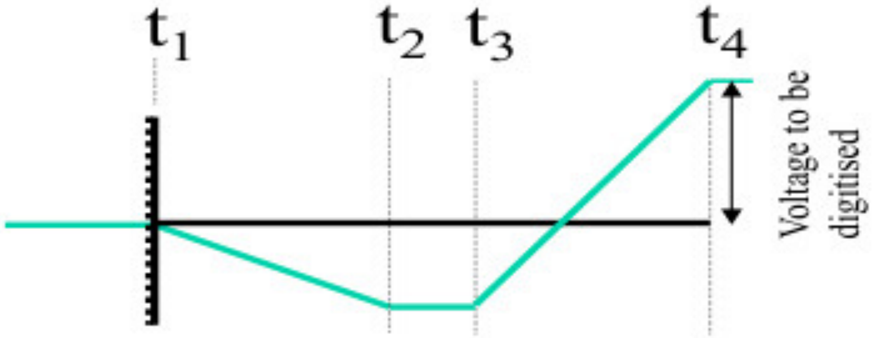


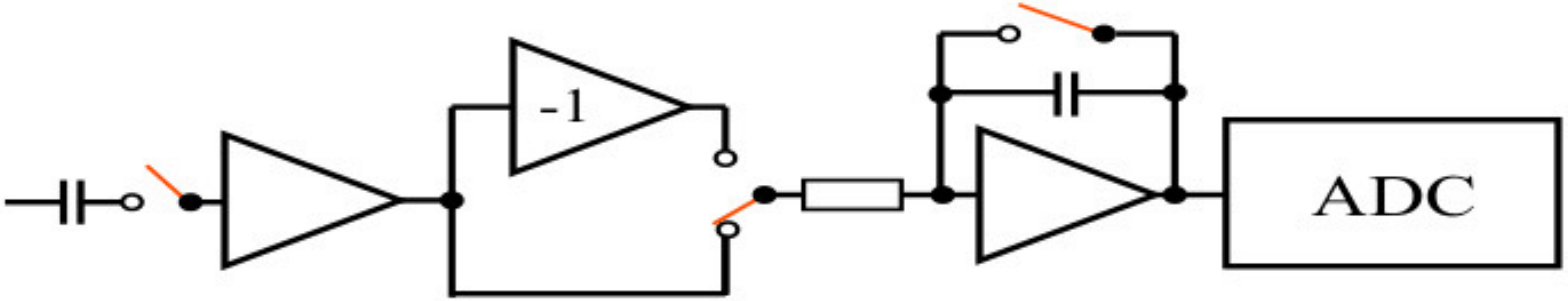


# Correlated Double Sampler (CDS)

The CDS is then once again disconnected and its output digitised by the ADC. This number , typically a 16 bit number (with a value between 0 and 65535) is then stored in the computer memory. The CDS then starts the whole process again on the next pixel. The integrator output is first zeroed by closing the reset switch. To process each pixel can take between a fraction of a microsecond for a TV rate CCD and several tens of microseconds for a low noise scientific CCD.

The type of CDS is called a 'dual slope integrator'. A simpler type of CDS known as a 'clamp and sample' only samples the waveform once for each pixel. It works well at higher pixel rates but is noisier than the dual slope integrator at lower pixel rates.





# 6 steps of optical / IR photon detection

Anti-reflection coating
Substrate removal

1. Light into detector

Detector Materials
Si, HgCdTe, InSb, Si:As

2. Charge Generation

Electric Fields in detector
collect electrical charge

3. Charge Collection

Charge coupled
transfer

CCD

4. Charge Transfer

MOSFET
Amplifier

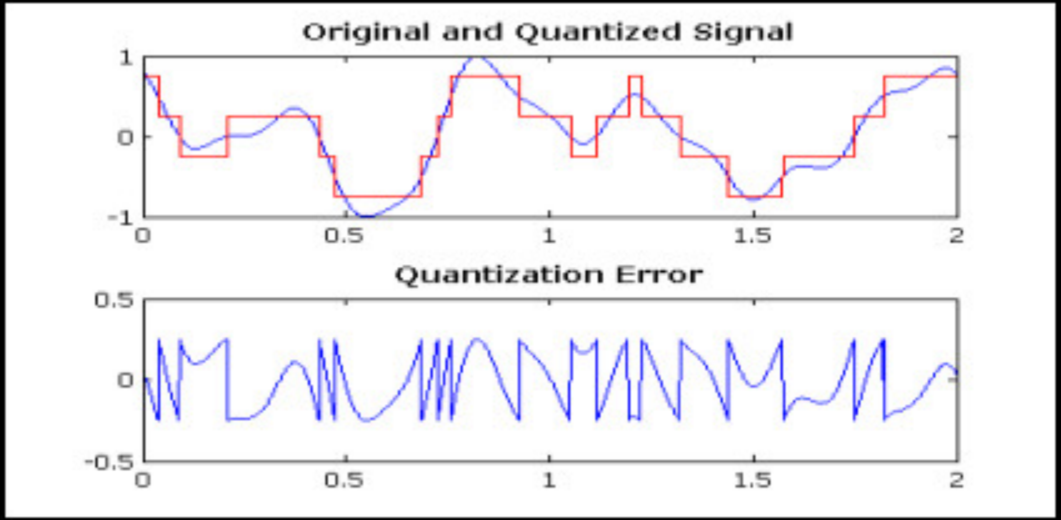
5. Charge-to-Voltage Conversion

6. DIGITIZATION

# Analog-to-digital converters

"Convert the analog signal (voltage or current) into a digital number"

- Quantization noise of an ADC is (1/√12) Least Significant Bit = 0.289 LSB
- Typically set gain of amplifier chain so that quantization noise is much less than readout noise. If readout noise is 4 electrons, set gain so that LSB equals ~2 electrons
- 16 bit ADC is most commonly used in astronomy. At ~2 electrons per ADU (analog to digital unit), or LSB, full well of a 16 bit ADC will be ~130,000 electrons; good match to the typical full well of a CCD or Short-Wave IR detector of 100,000 electrons.

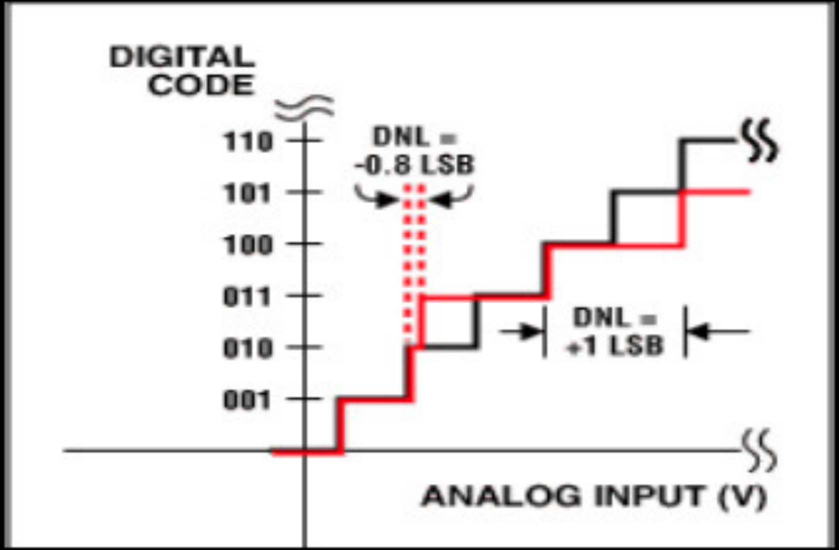


Highly exaggerated quantization noise

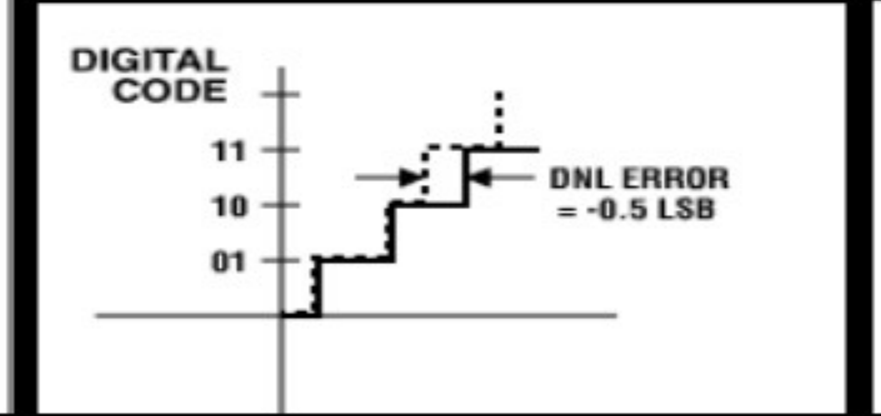
# Differential Non-Linearity (DNL)

- DNL describes the distance of an ADC code from its adjacent code.
- It is measured as a change in input voltage magnitude, and then converted to number of Least Significant Bits (LSBs).

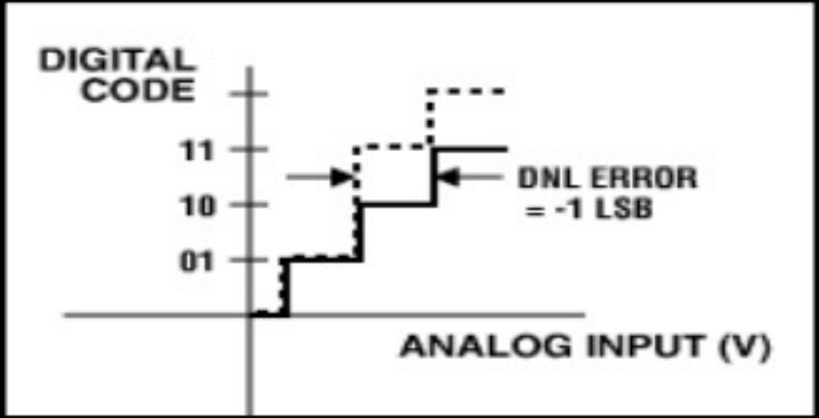
$$\boxed{DNL = (V_{D+1} - V_D) / V_{LSB\text{-}Ideal} - 1}$$



Code 100 is increased
DNL = +1



Code 10 is reduced
DNL = -0.5

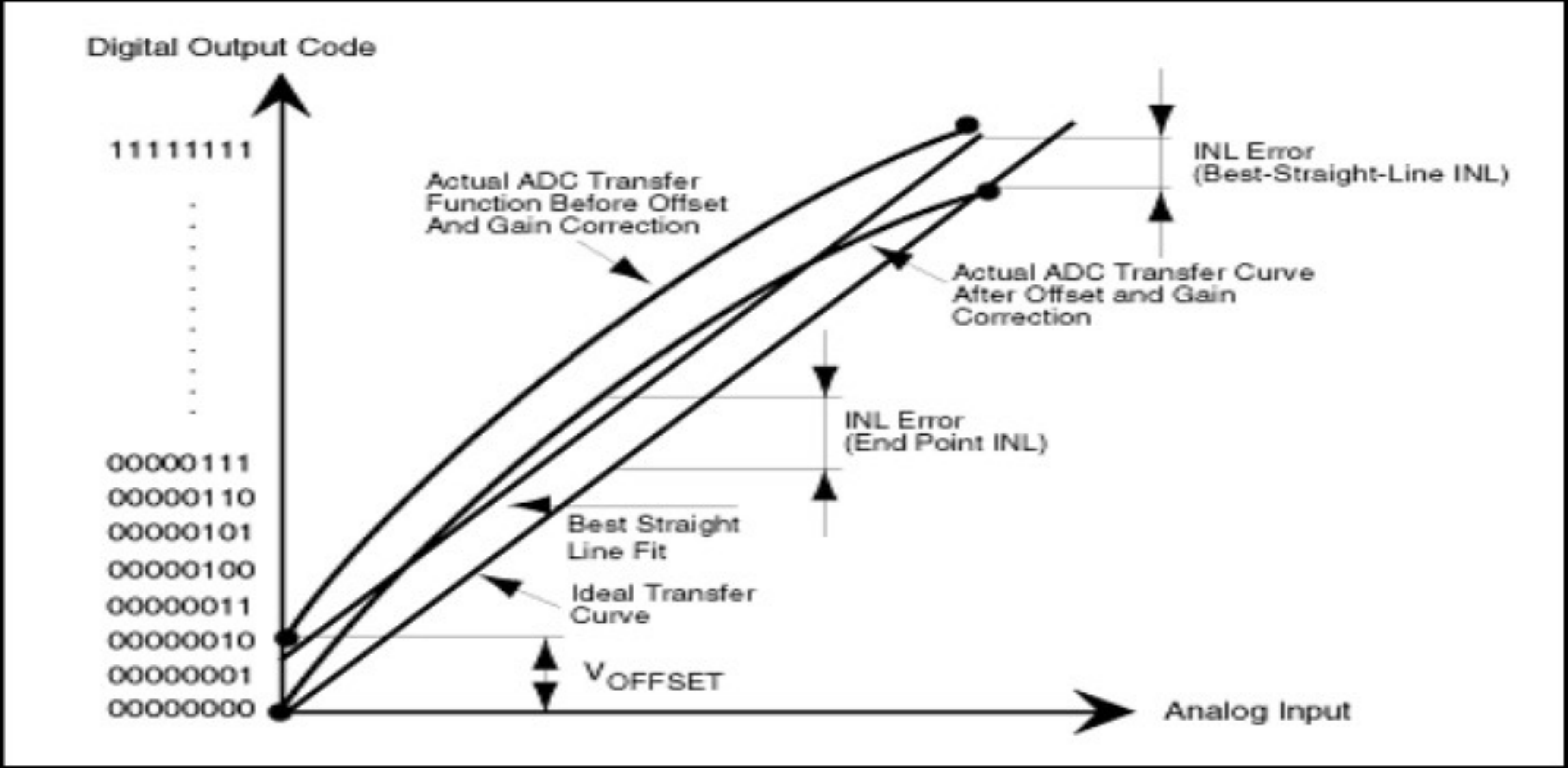


Code 10 is missing
DNL = -1

# Integral Non-Linearity (INL)

- INL describes the deviation of the ADC transfer function from a straight line
- It can be computed as the integral of the DNL, and is expressed in LSB

$$\boxed{INL = (V_D - V_{Zero}) / V_{LSB\text{-}Ideal} - D}$$



# Biases, Flat Fields and Dark Frames

These are three types of calibration exposures that must be taken with a scientific CCD camera, generally before and after each observing session. They are stored alongside the science images and combined with them during image processing. These calibration exposures allow us to compensate for certain imperfections in the CCD. As much care needs to be exercised in obtaining these images as for the actual scientific exposures. Applying low quality flat fields and bias frames to scientific data can degrade rather than improve its quality.

## Bias Frames: exposure of zero duration

- **Bias could contain some structure**
- **Median filter eliminates cosmic rays**
- **Average reduce read noise**

## Flat Field: exposure with “flat “ illumination

- **Correction for dust, and pixel to pixel QE response**

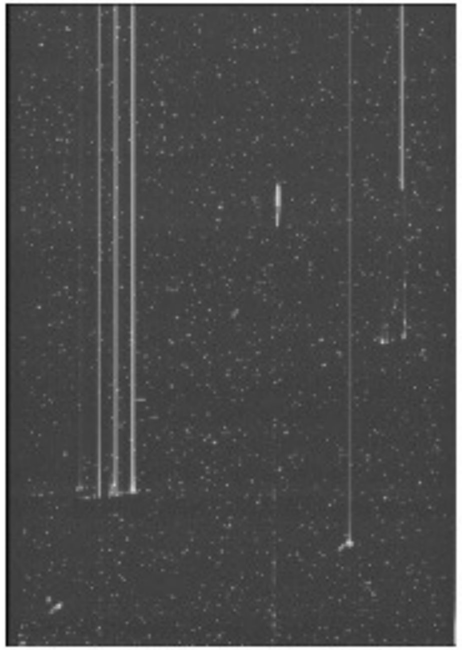
## Dark Frame: long exposure with shutter closed

- **Compensate for thermal charge generation**

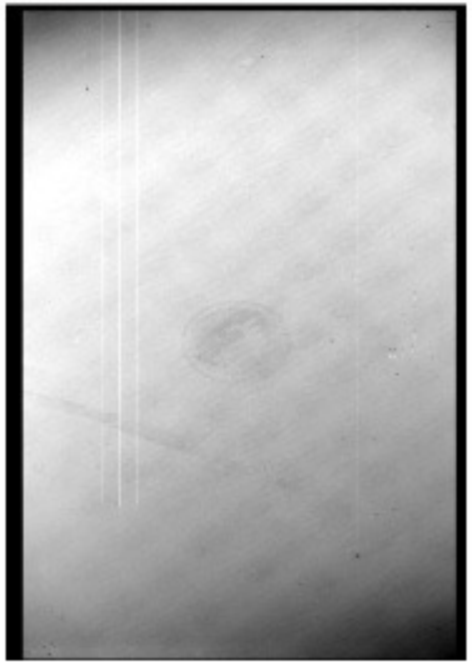
# Biases, Flat Fields and Dark Frames

A dark frame and a flat field from the same EEV42-80 CCD are shown below. The dark frame shows a number of bright defects on the chip. The flat field shows a criss-cross patterning on the chip created during manufacture and a slight loss of sensitivity in two corners of the image. Some dust spots are also visible.

Dark Frame

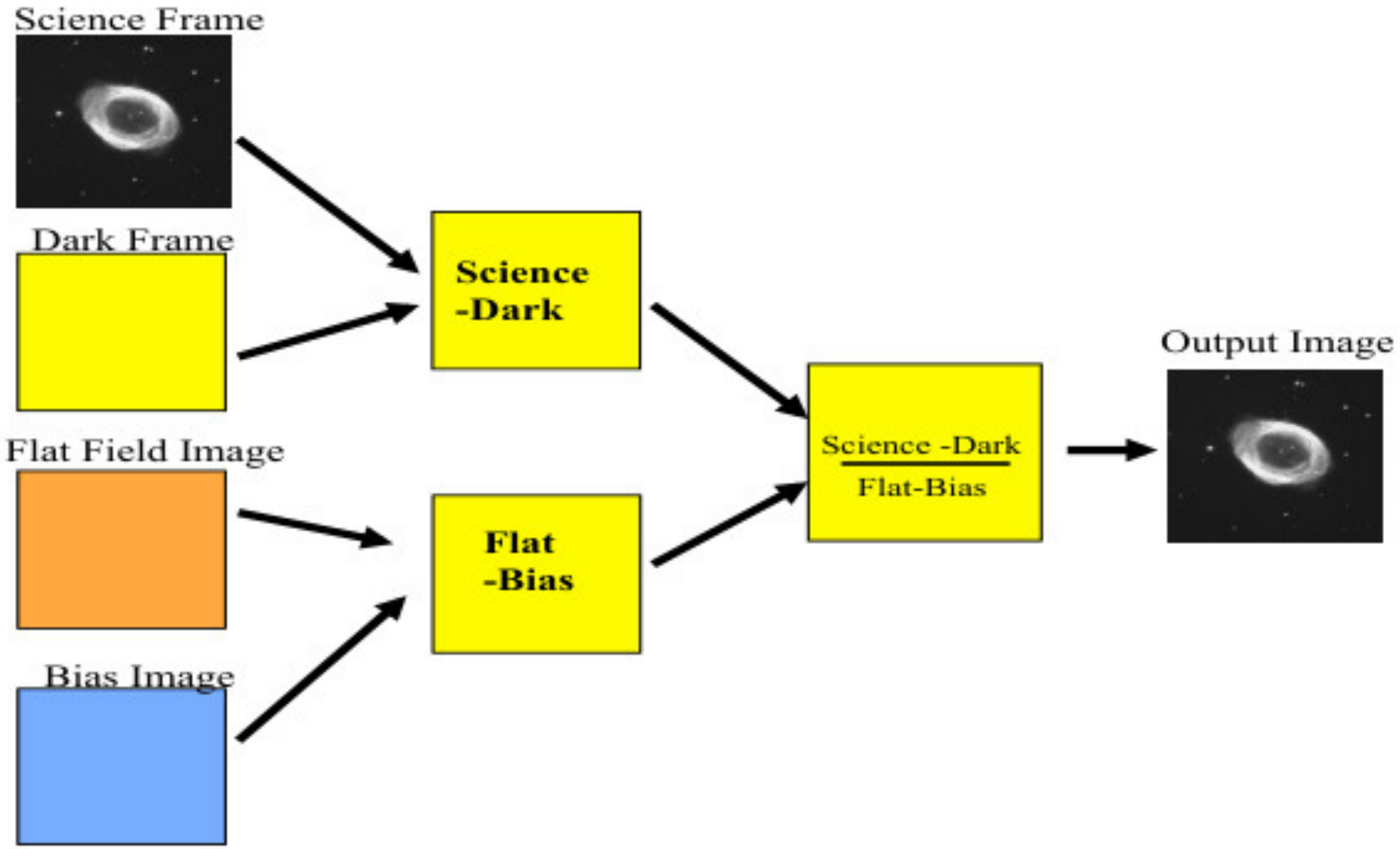


Flat Field



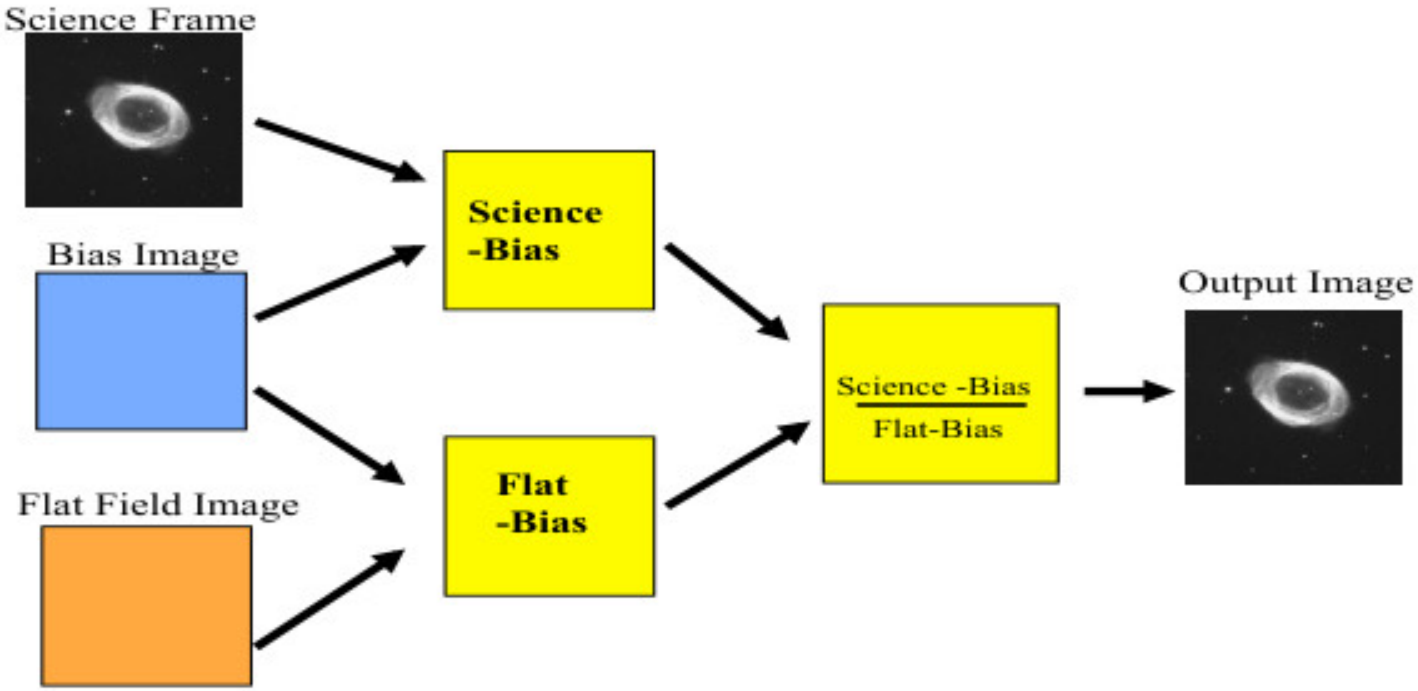
# Biases, Flat Fields and Dark Frames

If there is significant dark current present, the various calibration and science frames are combined by the following series of subtractions and divisions :



# Biases, Flat Fields and Dark Frames

In the absence of dark current, the process is slightly simpler :



# Thank you for your attention