Charge-coupled devices for precision astrophysics

Andean Cosmology School,
Universidad de Los Andes, Bogotá
Week 4, lecture 3
25-6-2015

Jet Propulsion Laboratory
California Institute of Technology

Andrés Alejandro Plazas Malagón
andres.a.plazas.malagon@jpl.nasa.gov
Caltech Postdoctoral Scholar
Astrophysics and Space Sciences Section
NASA JPL-Caltech

Overview of this week

- First lecture: Weak Gravitational Lensing (WL): history, basics, applications, systematics
- Second Lecture: The challenge of measuring shapes for WL, current and planned WL experiments
- **Third Lecture:** Charge-Coupled Devices: basics, characterization, data reduction
- Fourth Lecture: Instrumental signatures on astrophysical observables: photometry, astrometry, shapes.

Outline of the lecture

- Fundamentals of CCDs
- Scientific uses of CCDs: astronomy
- CCDs imperfections and characterization
- Thick, fully depleted, back illuminated CCDs: DES, LSST, etc.
- Tomorrow: cosmological impact (e.g, on shapes for WL) due to instrumental systematic errors

Astronomical Observations

- What do we want to collect?

    A: Photons from celestial objects!

    But: They are very far away (~ 1/ r^2), they are few, the atmosphere is on the way, etc

- Process:

    a) Observations

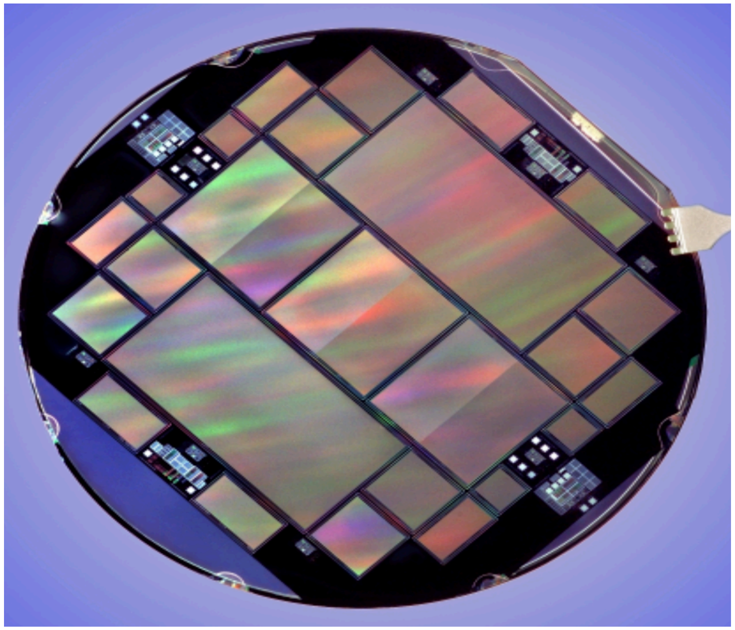
    b) Reduction of raw data

    c) Analysis

- Telescopes: act as light buckets to collect more photons. They focus the light from distant sources

-Detectors: their job is to acquire those precious photons with high efficiency.

Charged-coupled devices are widely used in astronomy.



Invention of CCDs

- Invented by W. Boyle and G. Smith from bell laboratories in 1969

- They were trying to find an **Electronic Analogue to Bubble Memory --> a bit = packet of charges (e-) or holes (h+)**

- Idea conceived in a discussion lasting "no more than an hour". Their basic design is still used today.

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

Invention of CCDs

- In 1973, JPL initiates Scientific Grade large array CCD program: Jim Janesick, Tom Elliott
- In 1974: Fairchild 100x100 on an 8-inch telescope produces first astronomical CCD image

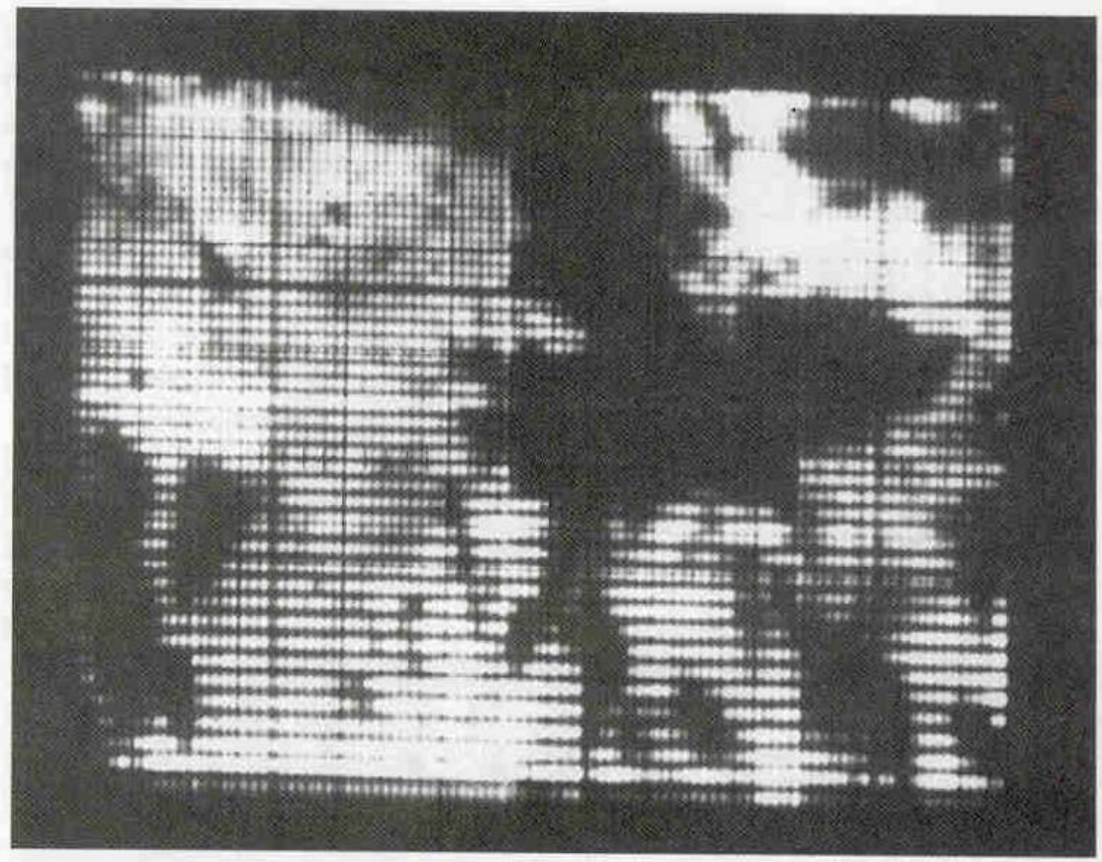
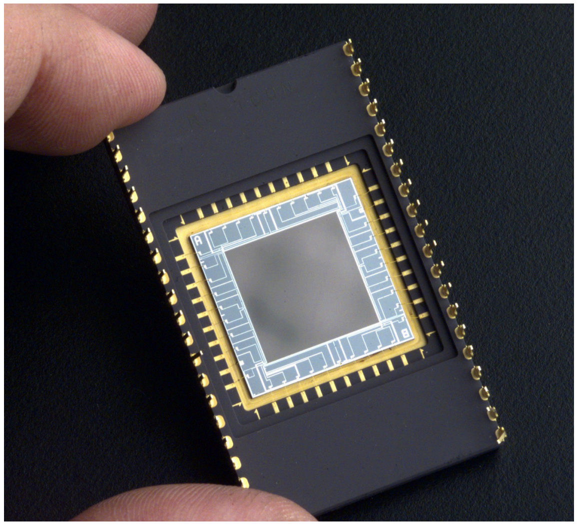


Figure 1.2(b) A CCD image of moon craters using the Fairchild 100 (V) × 100(H) CCD.

What is a CCD?

- CCD is essentially an array of light sensitive elements.
- Arranged in a grid of "picture elements" or pixels.
- A typical modern CCD may have 2048 × 2048 pixels (DES: 2k by 4K, LSST: 4k by 4k)
- The pixels are typically 15 to 25 microns in size (DES: 15 microns, LSST: 10 microns)
- A photon hitting a pixel knocks loose an electron, and hence deposits a charge on the pixel.
- The charge on each pixel is thus a measure of the number of photons which struck it.



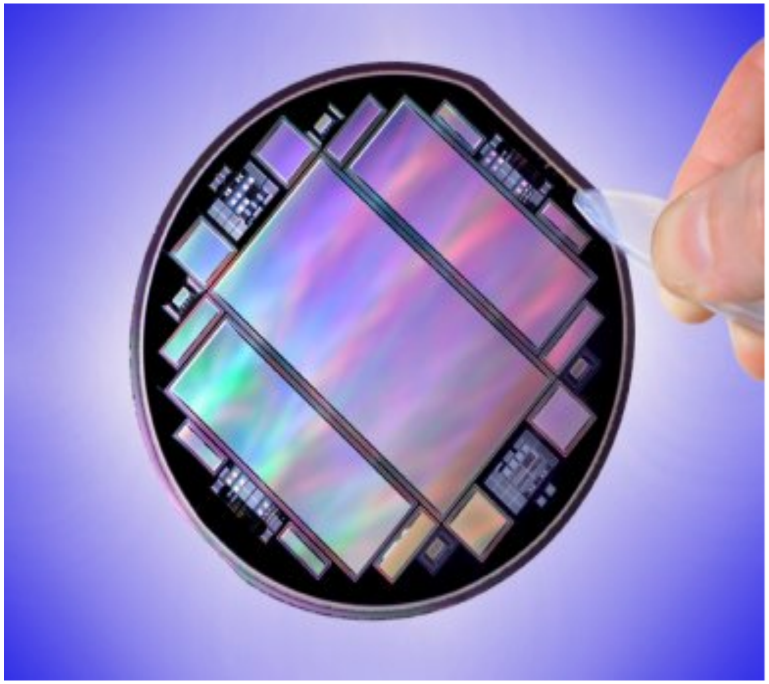
They are linear and have high efficiency

What is a CCD?

- CCDs are dynamic devices that move charge along a predetermined paths under control of clock pulses to change voltages.

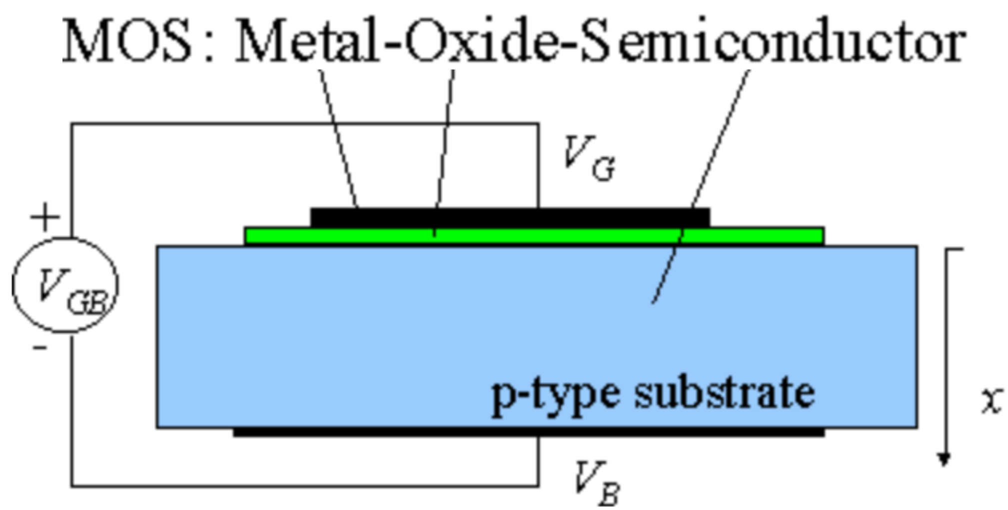
-Convert light into a pattern of electronic charge in a silicon chip, by means of the photoelectric effect

-This pattern of charge is converted into a video waveform, digitized and stored as an image file on a computer.



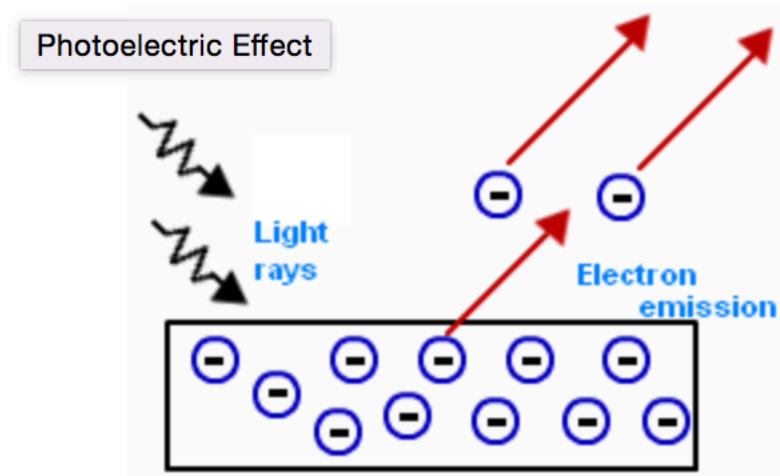
What is a CCD?

- A CCD has the structure of a MOS (metal-oxide semiconductor)
- MOS: metal, an insulator (usually an oxide of the substrate), and a semiconductor substrate
- The gate behaves like a capacitor that **stores charge near the oxide.**



Charge generation through the photoelectric effect

Process through which a material emits electrons (leaving a hole behind) when light shines upon them.



frequency of radiation, sometimes written as f giving expression $E = hf$.

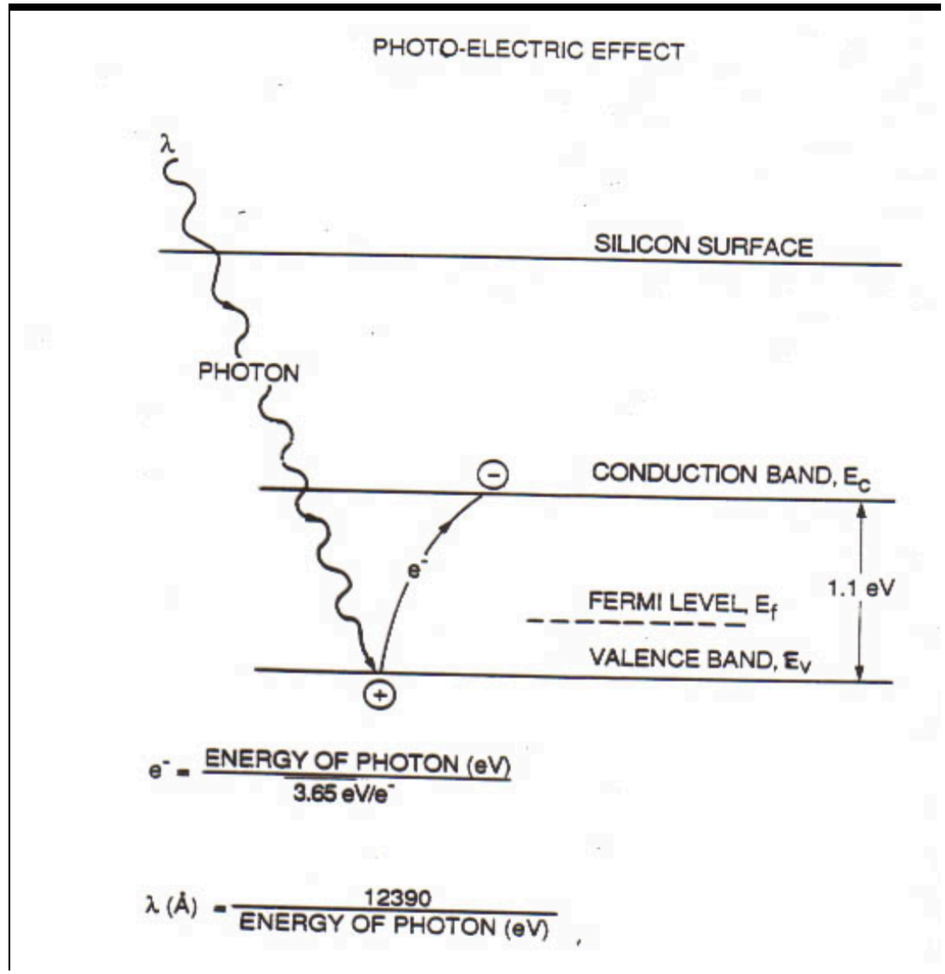
$$E = h\nu$$

Quantum energy of a photon.

h = Planck's constant = 6.626×10^{-34} Joule·sec = 4.136×10^{-15} eV·s

CCD Fundamentals: semiconductors

- Conductors: allows flow of electrons in the presence of an E field
- Insulators: prevents flow of electrons in the presence of an E field.
- Semiconductors: if the electrons are excited to high enough energies, it becomes a conductor.
  - switch: on/off
  - photo absorption adds energy to electrons



Band gap: minimum energy to move the charge from the valence to the conduction band.

A hole is left behind. Like a bubble in water.

CCD Fundamentals: semiconductors

- Silicon is the most commonly used semiconductor material

-Outer shells have four valence electrons

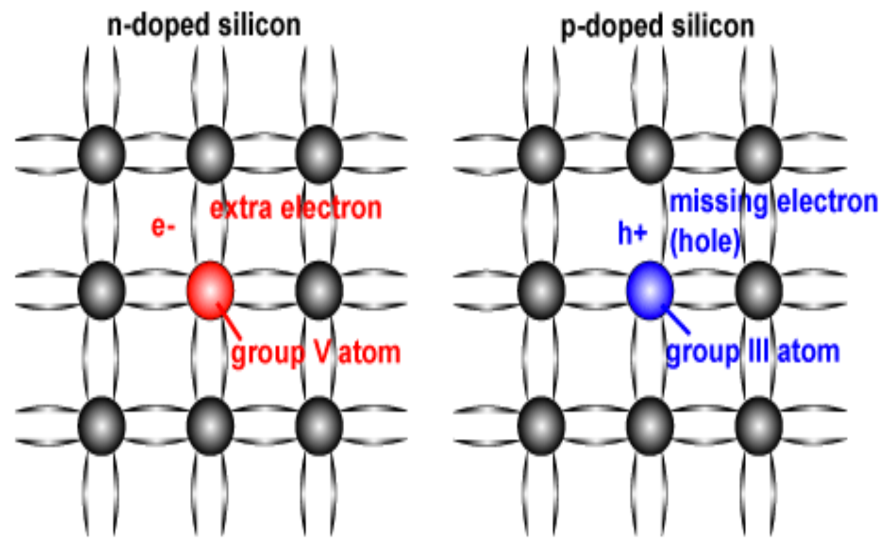
- An outer shell electron can leave the shell if it absorbs enough energy

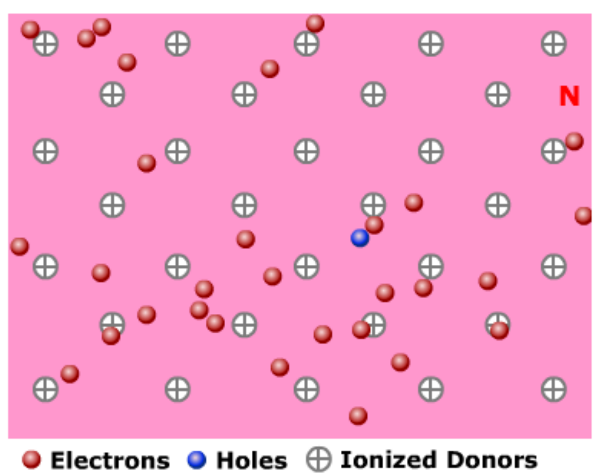
IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
							2 He 4.003
		5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
		13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)

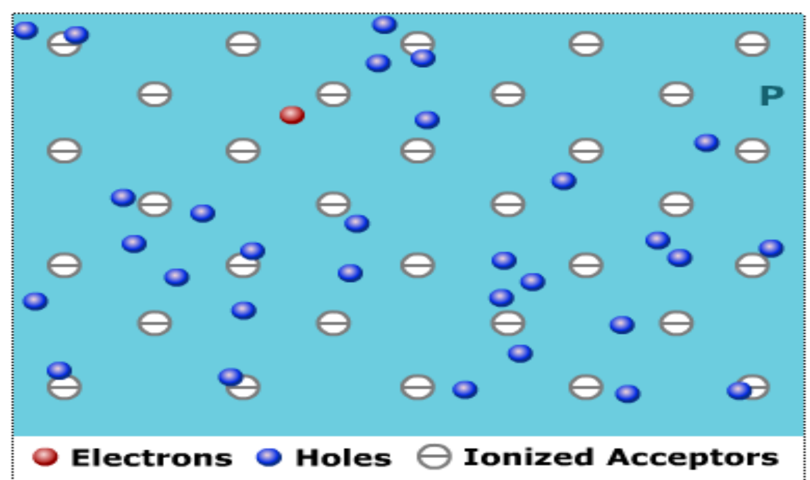
CCD Fundamentals: semiconductors

- **Doping:** The addition of a small percentage of foreign atoms in the regular crystal lattice of silicon or produces dramatic changes in their electrical properties, producing n-type and p-type **semiconductors**

  It's a technique used to vary number of electrons and holes in a semiconductor
- **N-type:** dope silicon with an atom with one more valence electron (As). Increase number of electrons (majority carriers)
- **P-type:** dope silicon with an atom with one more valence electron (B). Increase number of holes (majority carriers)

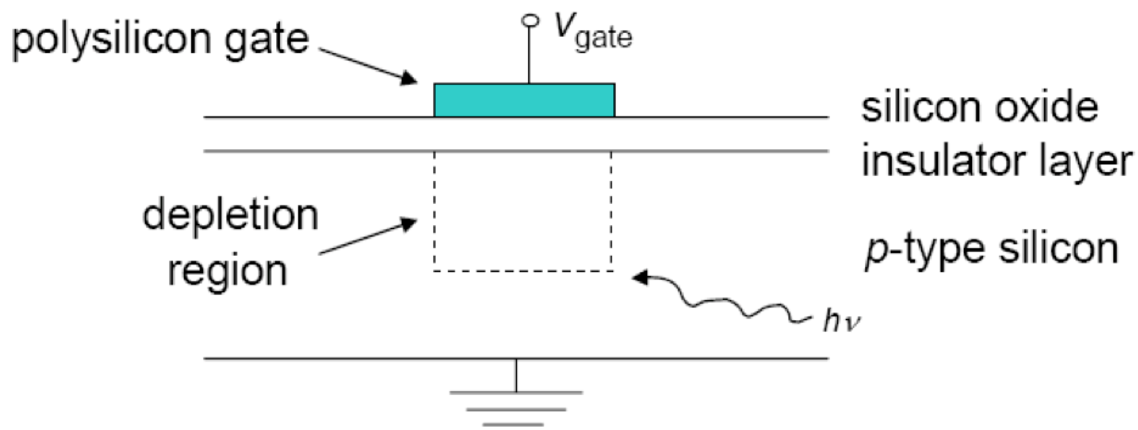






Surface channel CCDs

Applying the adequate voltage to the gate, a region free of majority carriers is created: **the depletion region**



-Electrons in the **depletion region** move to the oxide surface, where the charge is stored.

The **depletion region** is like an empty bucket waiting to be filled!

Surface channel CCDs

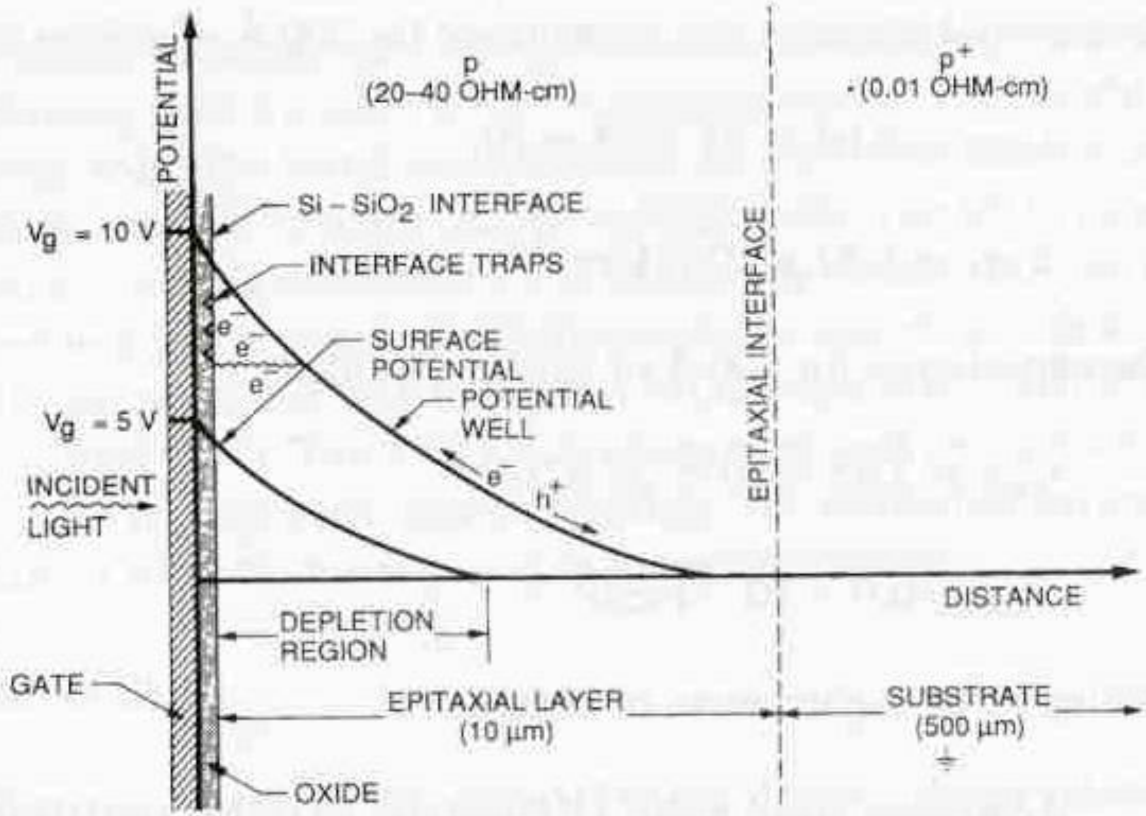


Figure 1.18 Surface channel potential well.

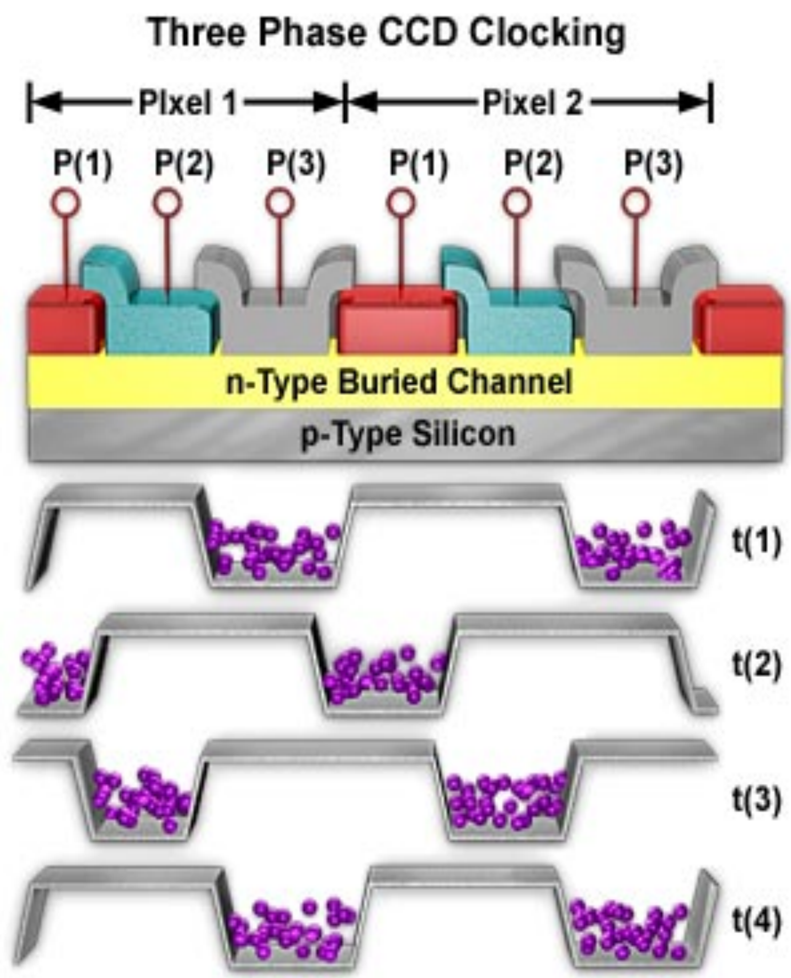
CCD: improvements

Throughout the years, some design changes have been made to improve the **CCD efficiency:**

- **Buried Channel:** no charge trapping at the surface
- **Back Side illumination**: no photons absorbed by the front gate
- **Thinning:** more efficiency in the blue (but still low in the red. See next bullet.)

Buried Channel CCDs

- Surface channel CCDs shift charge along a thin layer in the semiconductor that is just **below the oxide insulator**.
- This layer has crystal irregularities which can trap charge, causing loss of charge and image smear.
- If there is a layer of n-doped silicon above the p-doped layer, and a voltage bias is applied between the layers, the storage region will be deep within the depletion region.
- This is called **a buried-channel CCD,** and it suffers much less from charge trapping.



Buried Channel CCDs

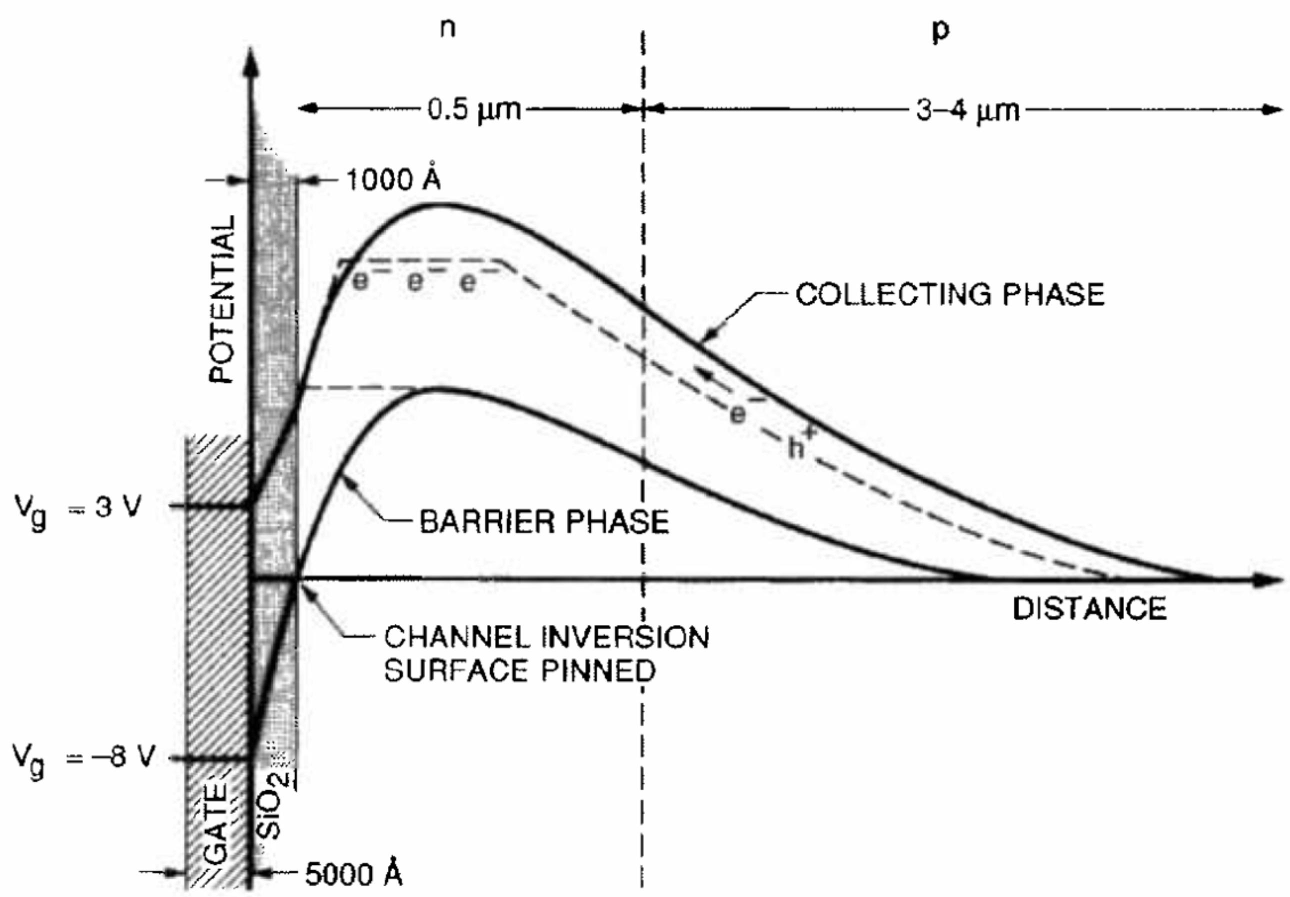
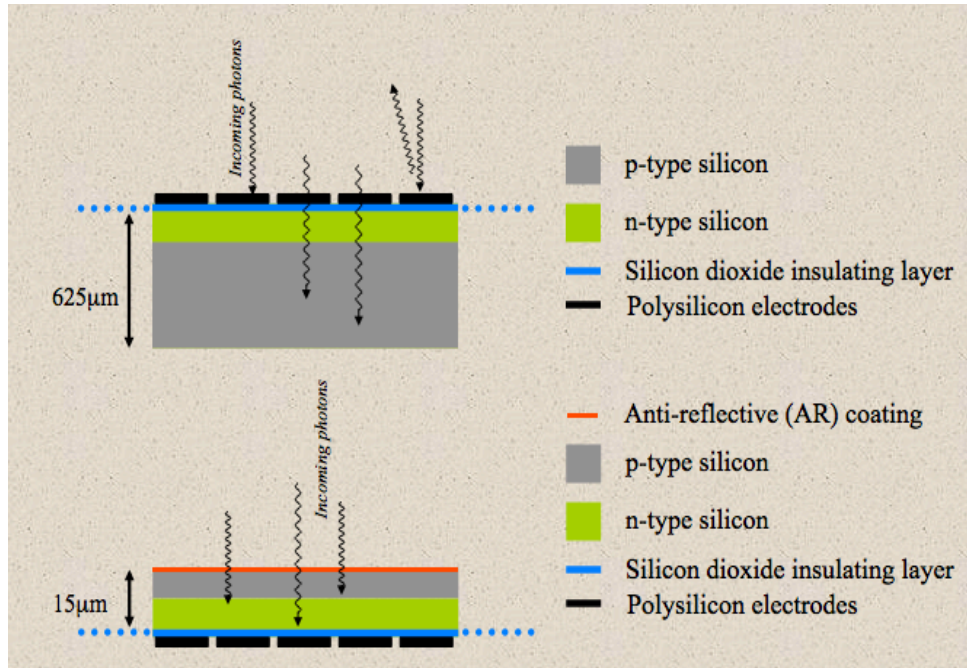


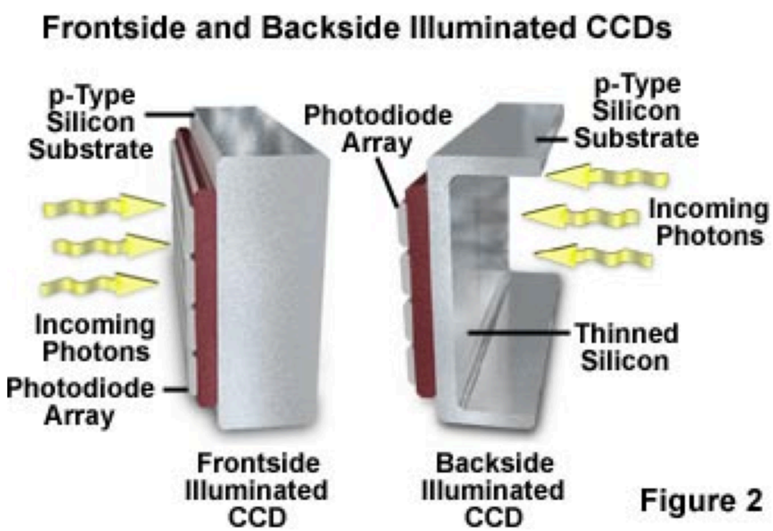
Figure 1.19 Buried-channel potential well.

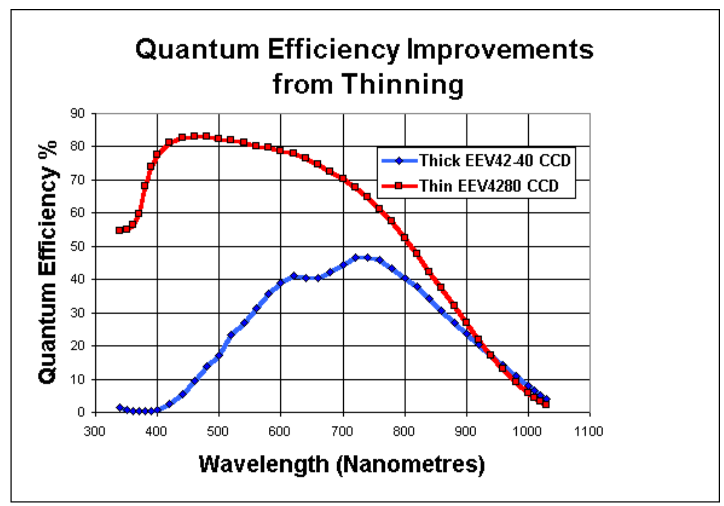
CCD improvements: thinning and back illumination

- Front-illuminated CCDs: gates absorb photons
- Solution: illuminate the CCD from the back.

But…the silicon substrate is thick. Photogenerated charge will do a random walk, and recombine before making it to the depletion region.
Solution: thin the CCD! (to the cost of lower efficiency in the red)

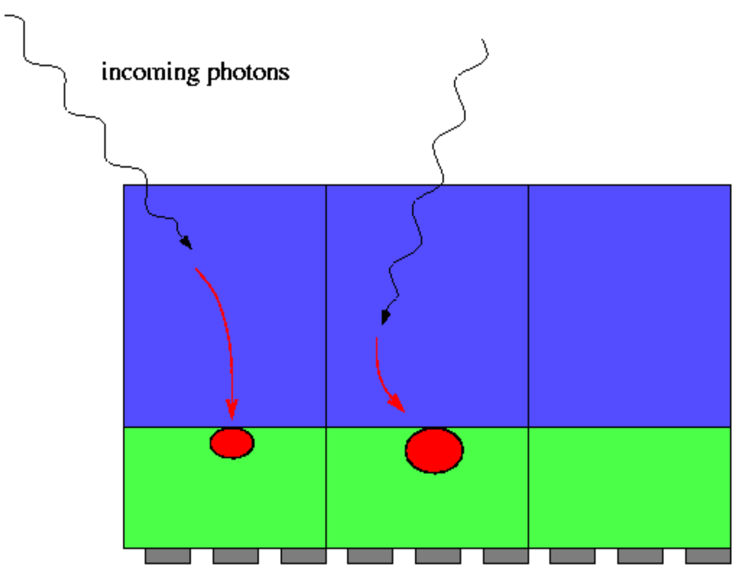


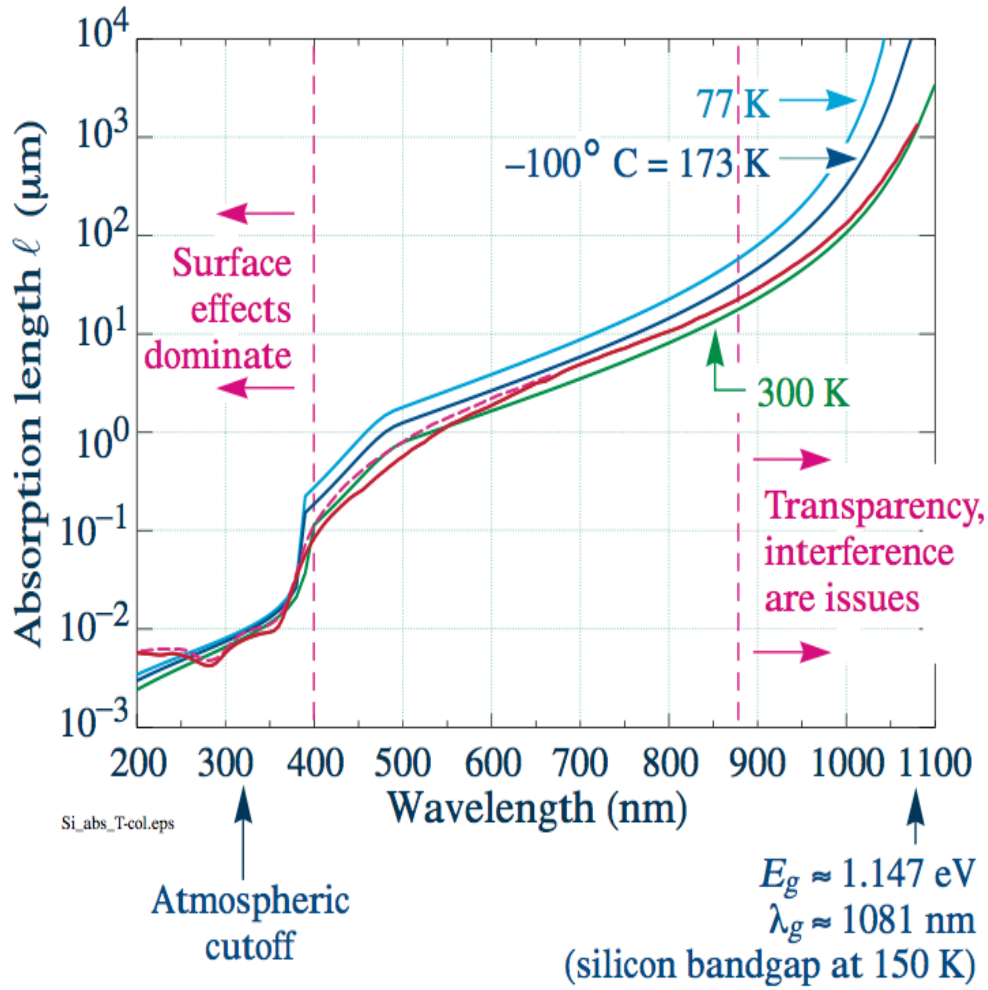




CCD: light absorption

- The light that makes it into the detector is absorbed witl a certain probability.
- Photo-generated charge is stored by a potential in the depletion region

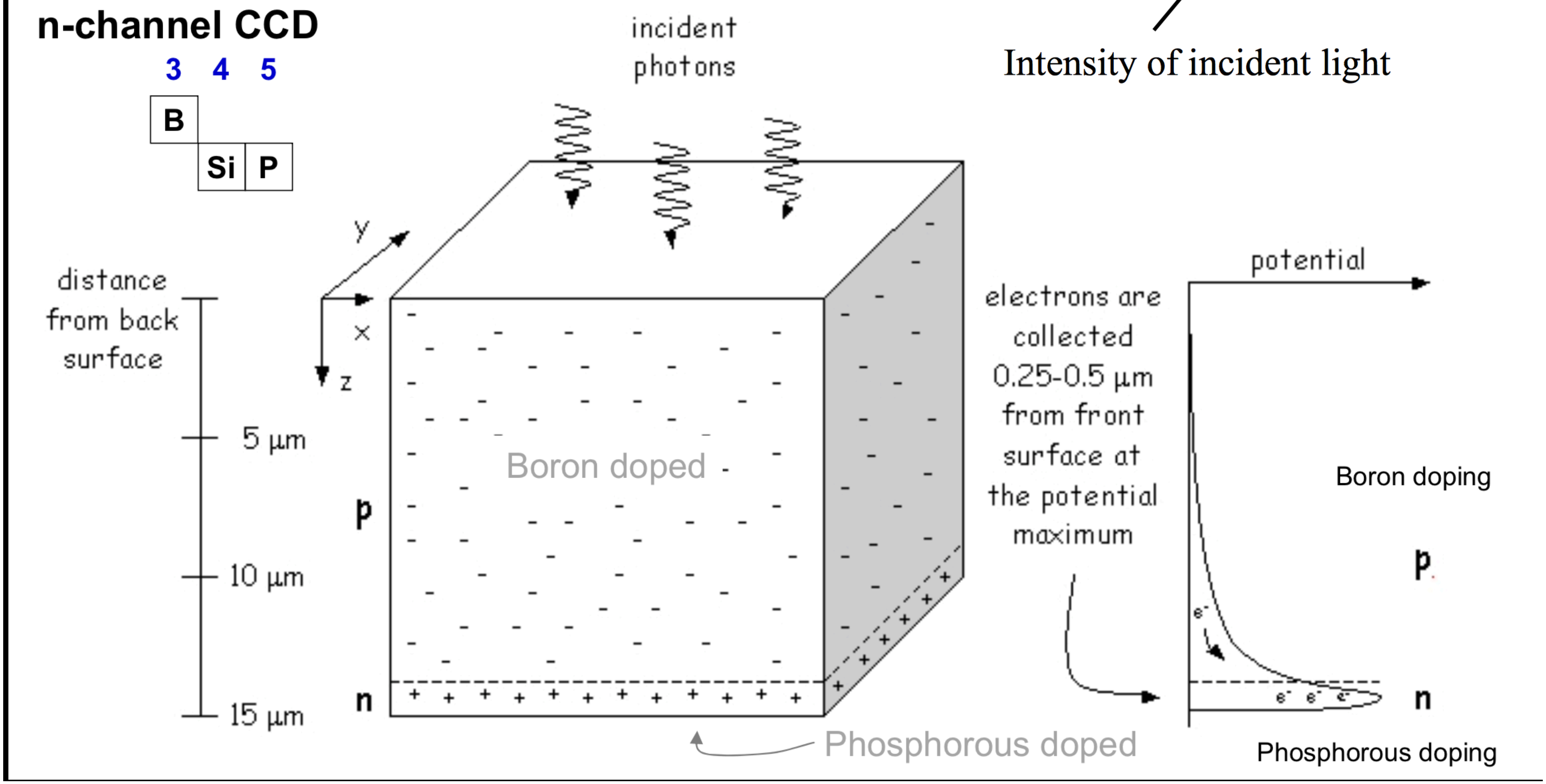




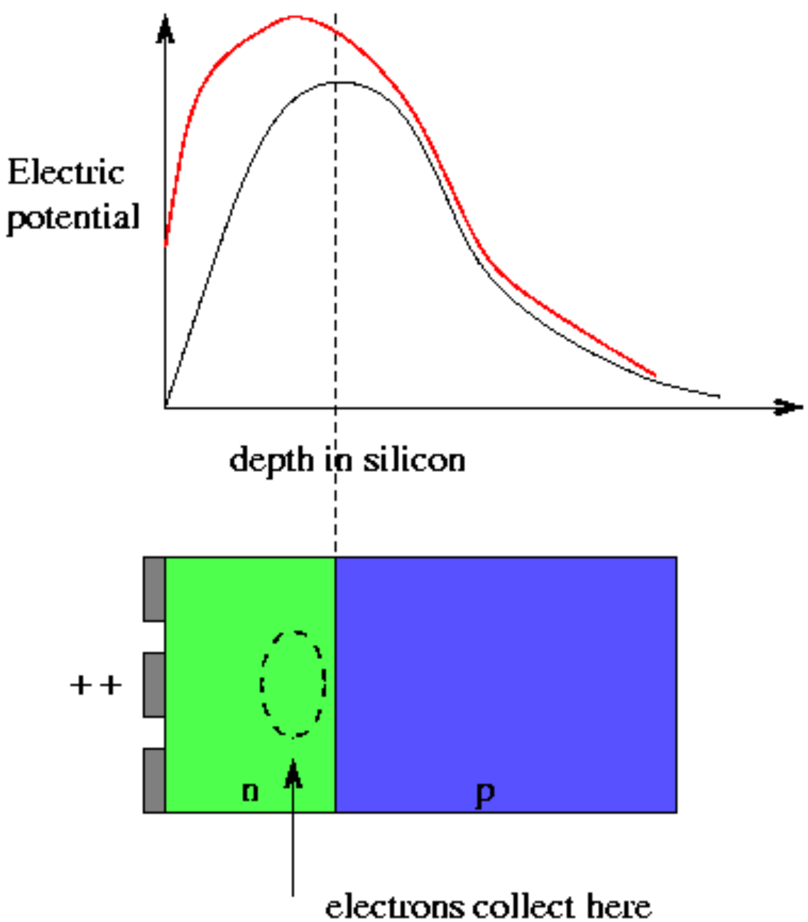
CCD: light absorption

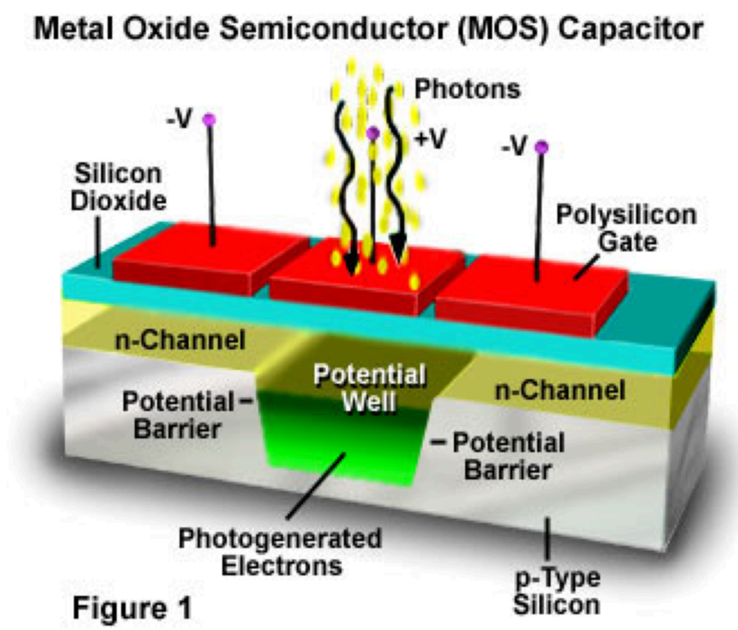
$$I(x) = I_o \exp[-\alpha x]$$

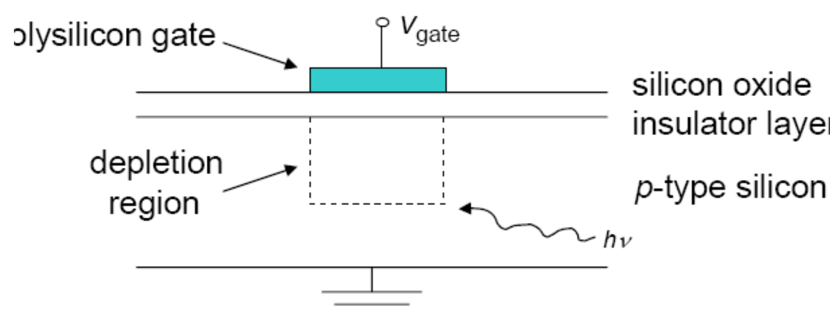
Intensity of incident light



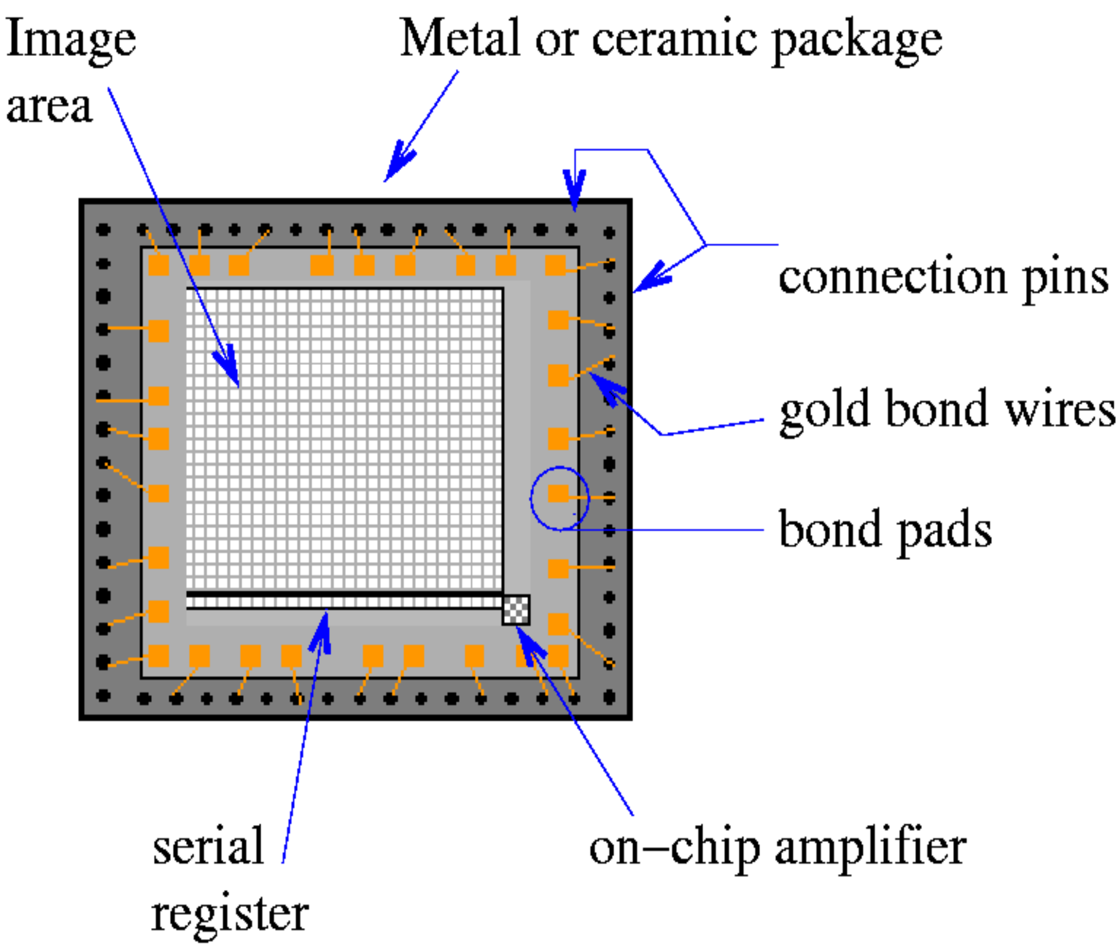
CCD structure



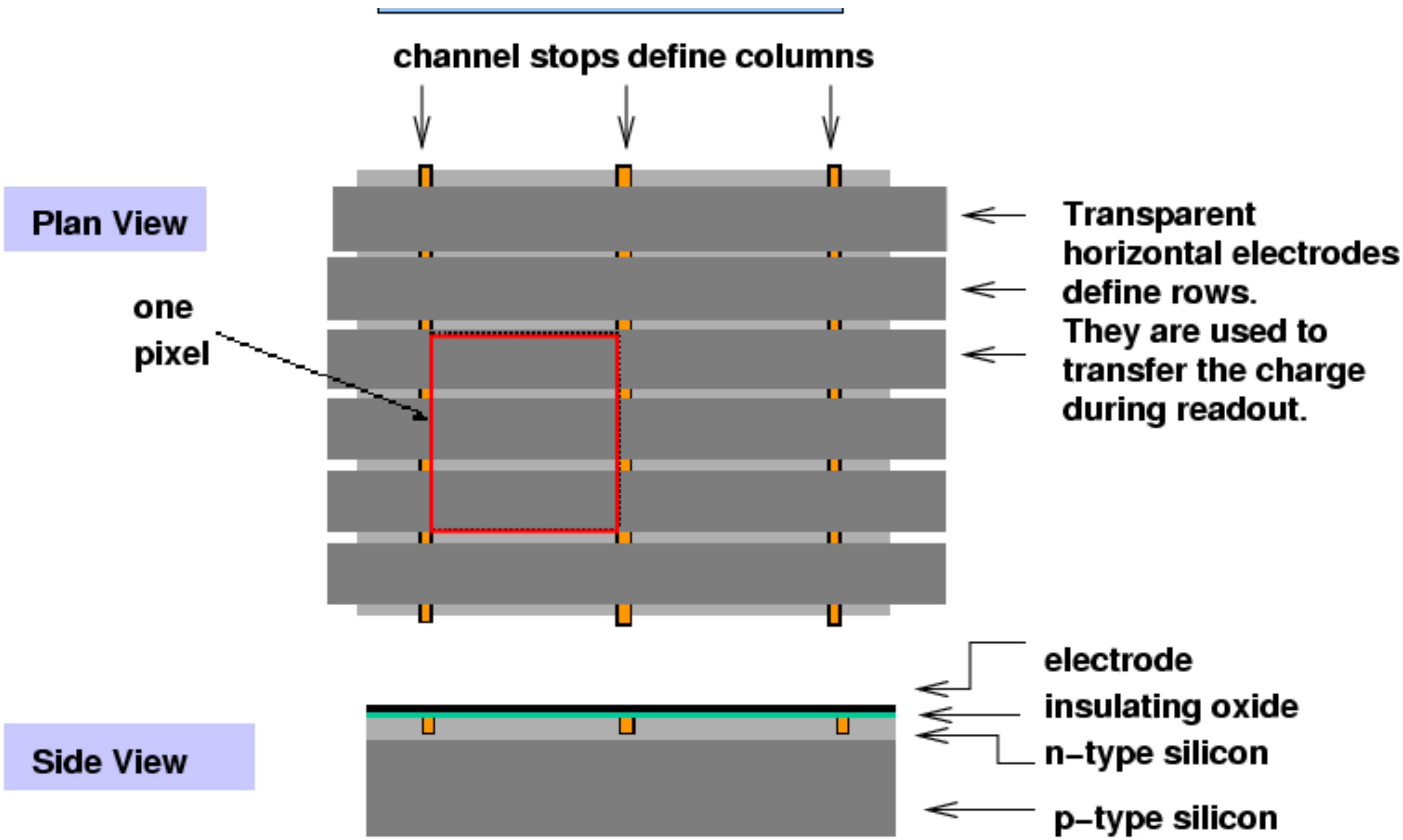




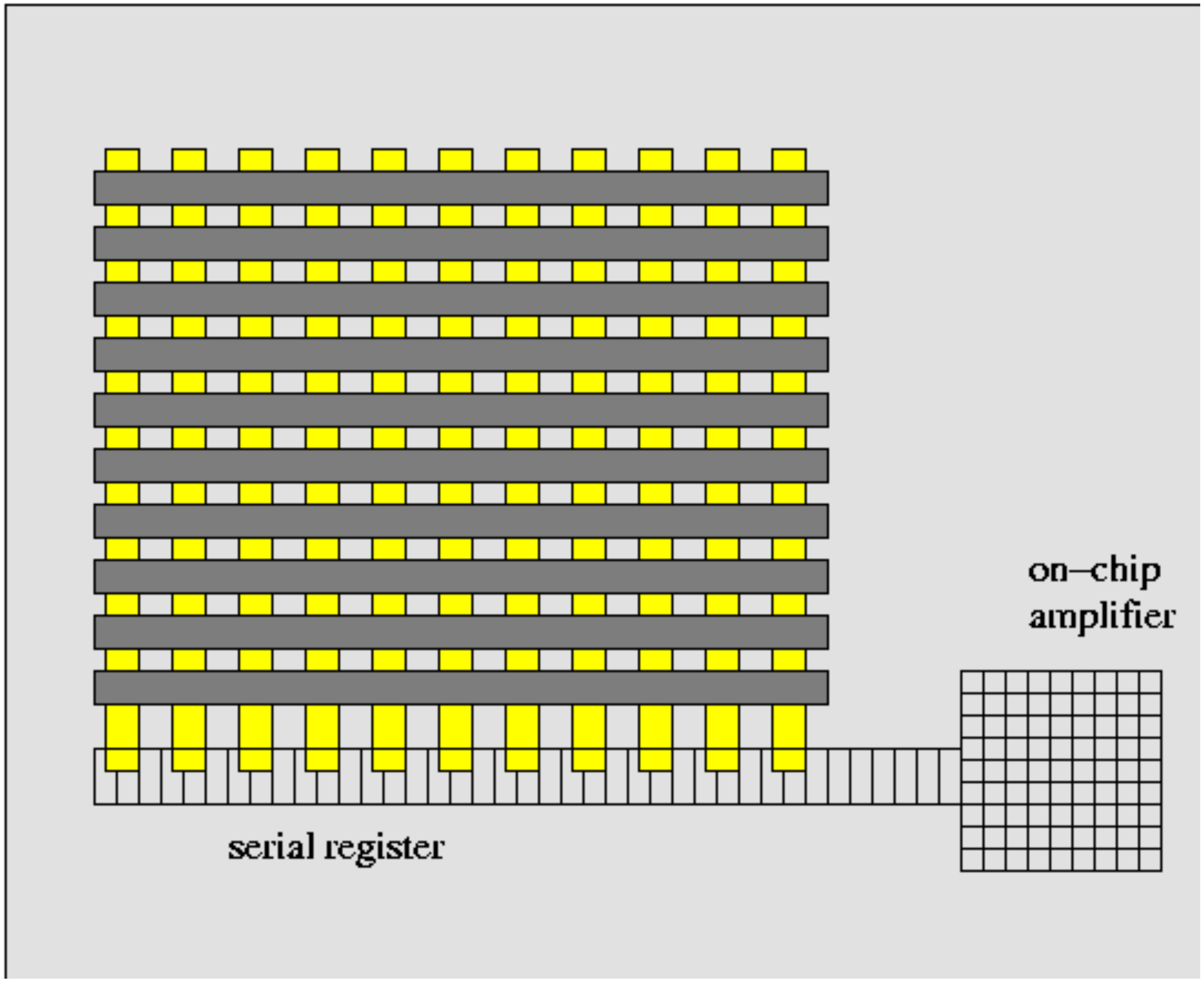
CCD Structure



CCD Structure



CCD Structure



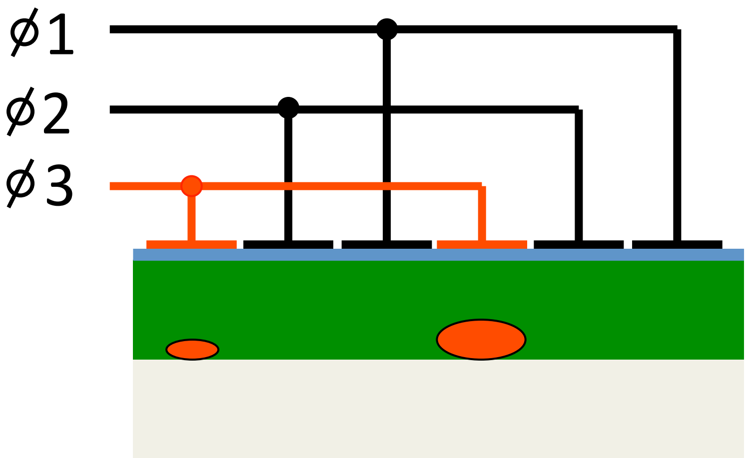
Charge transfer and readout

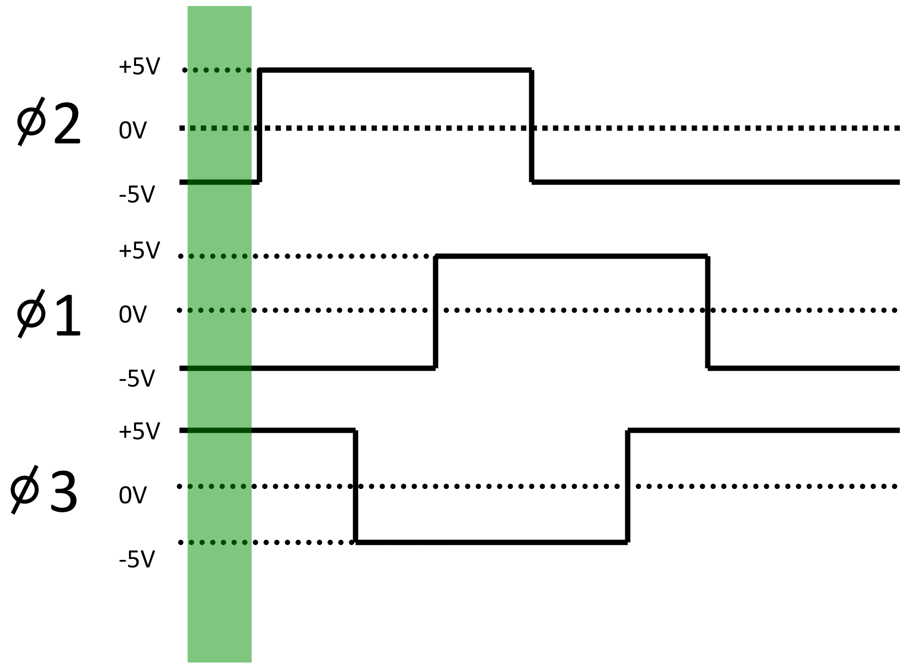
- After the integration time has elapsed, the charges are read out
- Charge is transferred linearly from one pixel to other: the charge "coupled" (hence the name CCD)
- Voltages in gates are changed accordingly, by means of specific "clocking"

CCD: Charge transfer

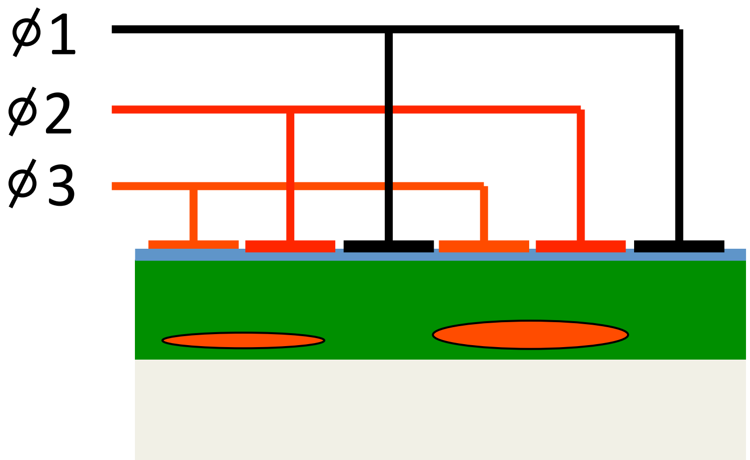
- “Bucket brigade” analogy

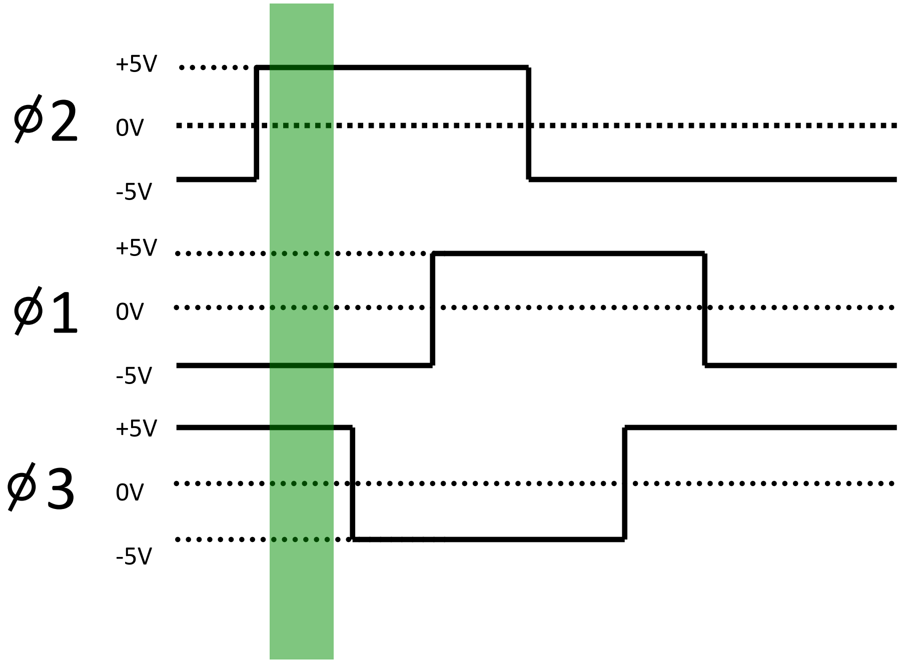
CCD clocking: three phases



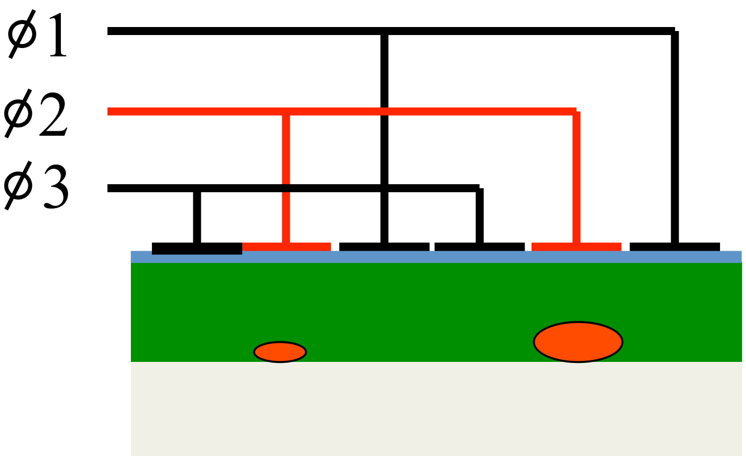


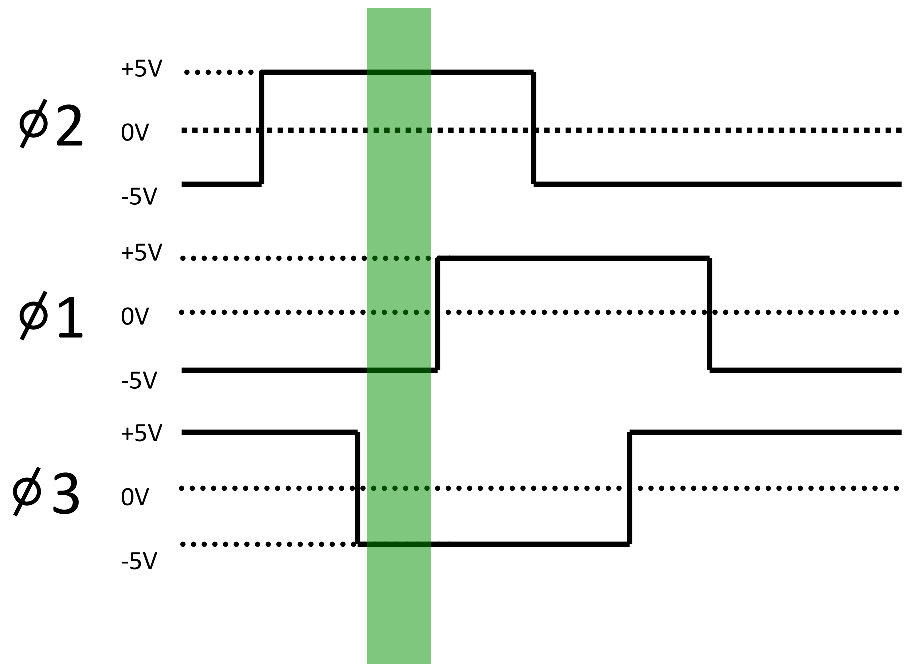
CCD clocking: three phases



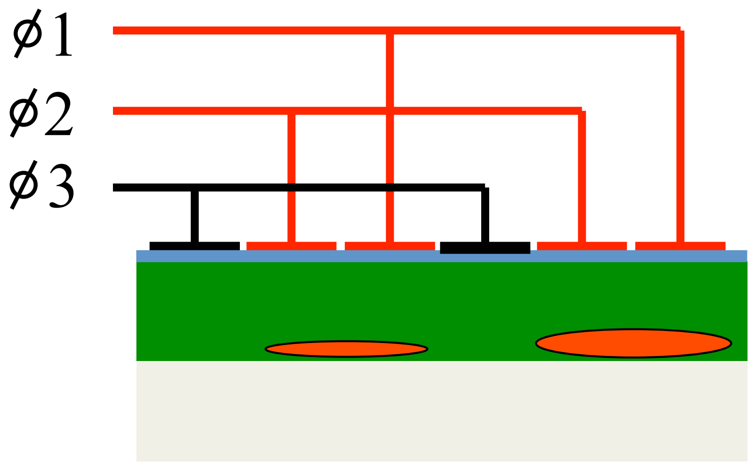


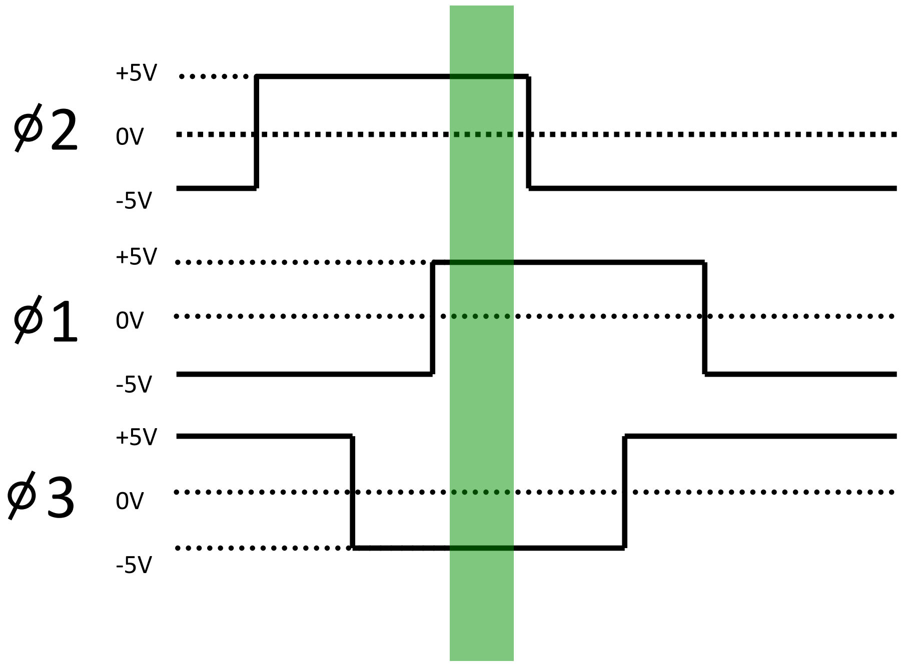
CCD clocking: three phases



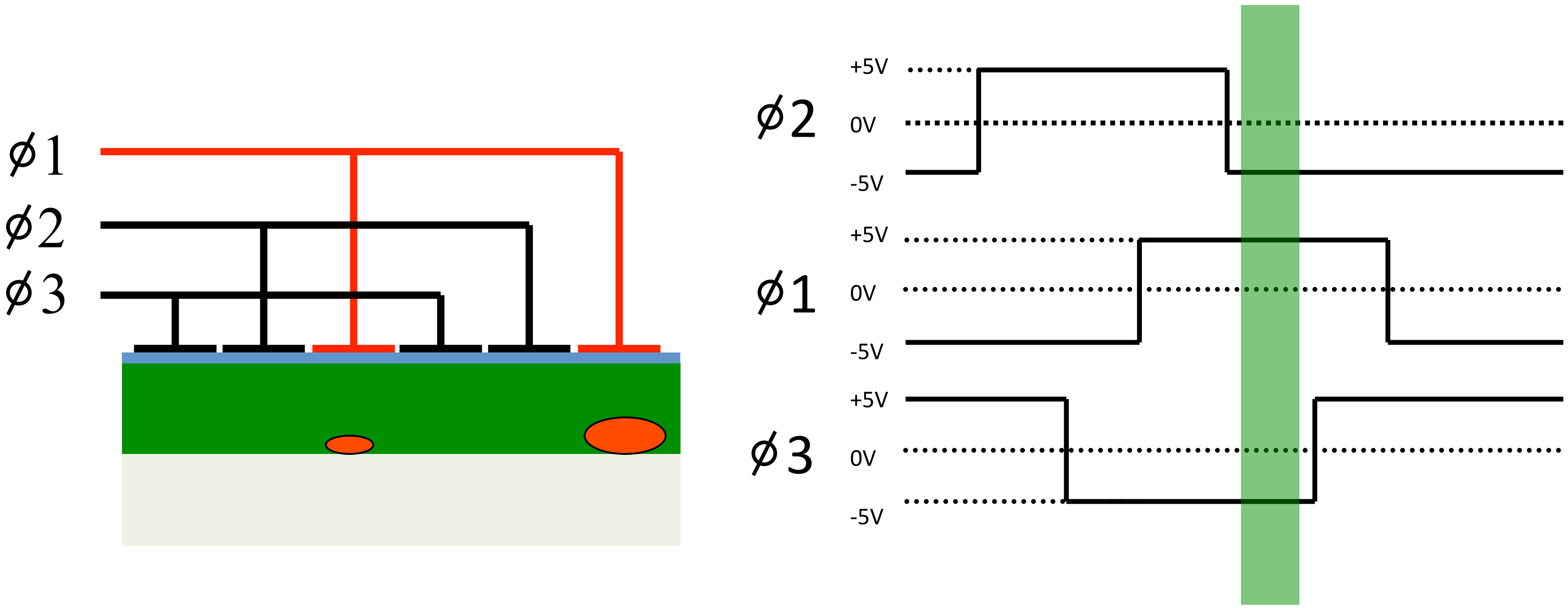


CCD clocking: three phases

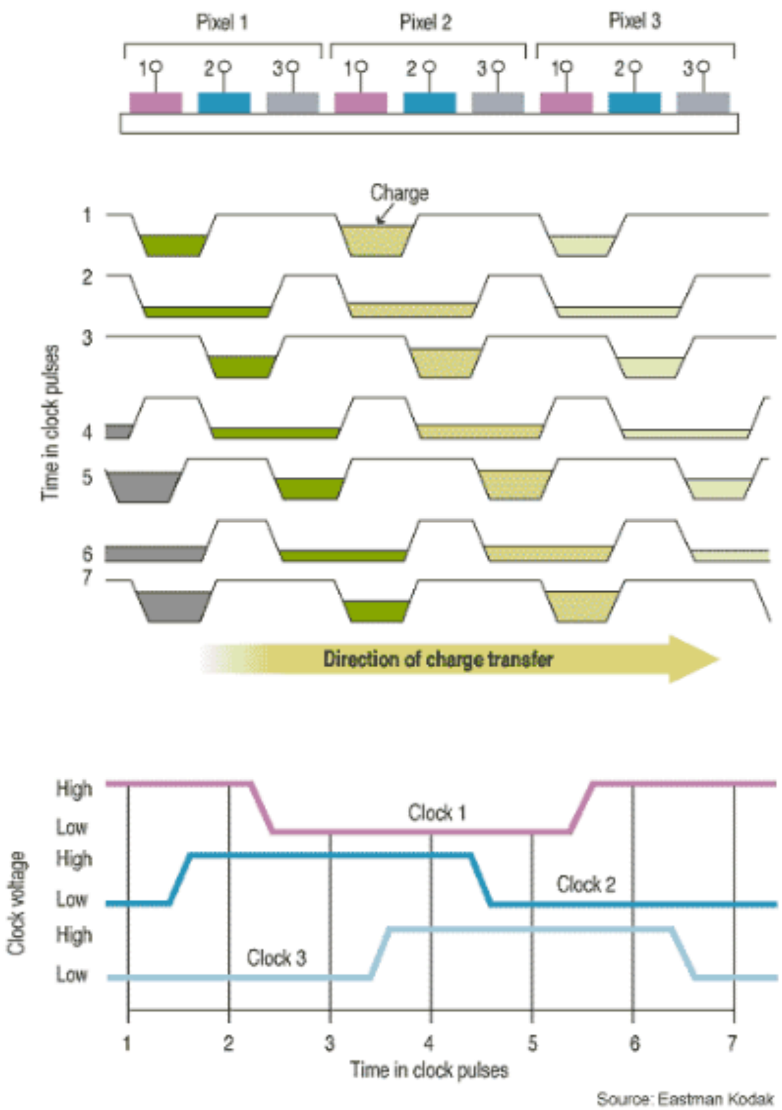


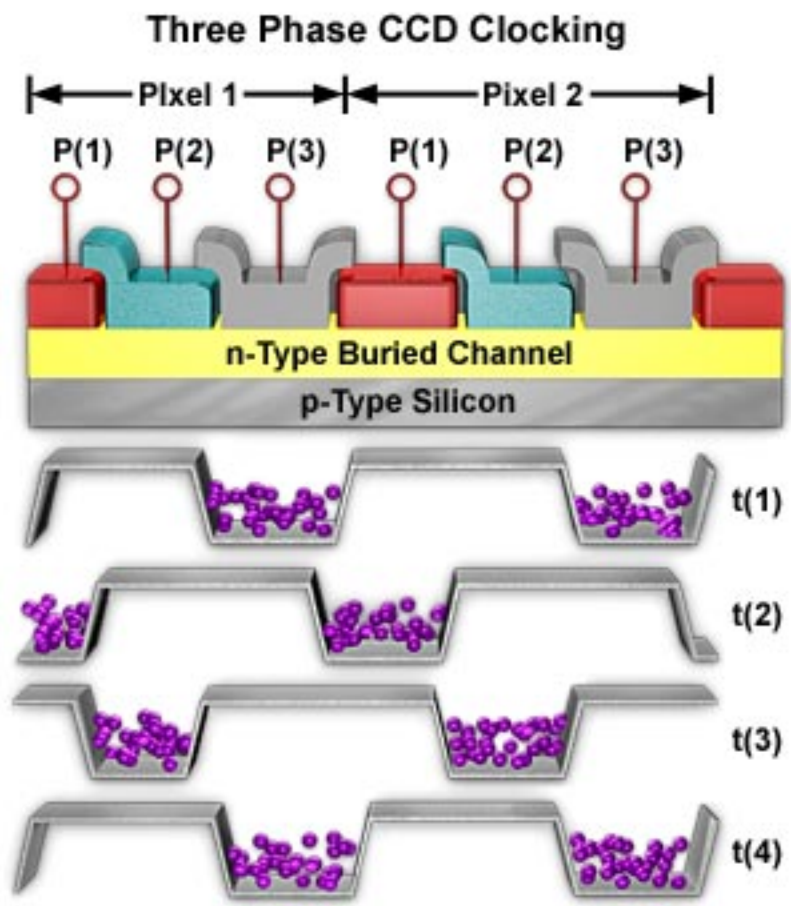


CCD clocking: three phases

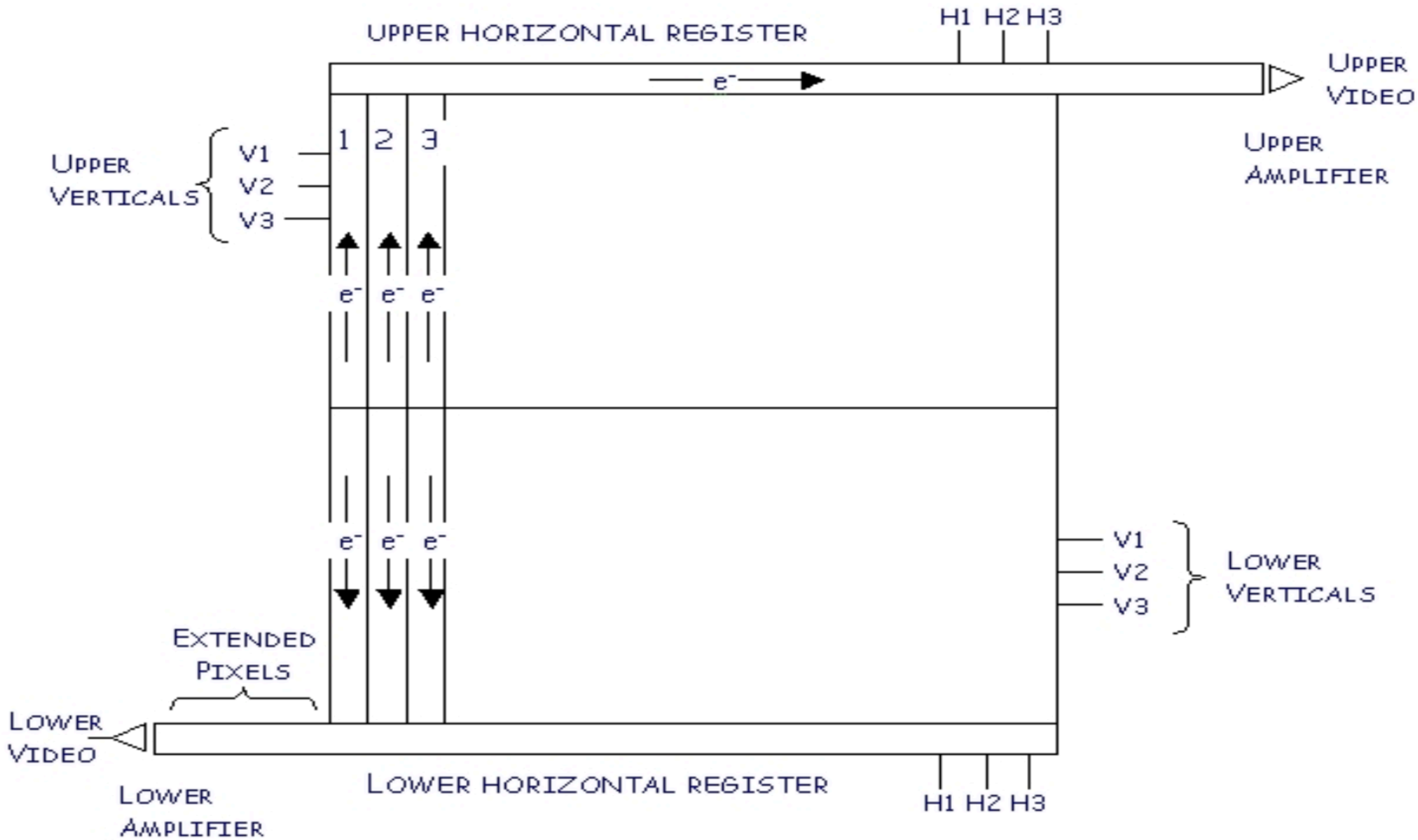


CCD clocking: three phases

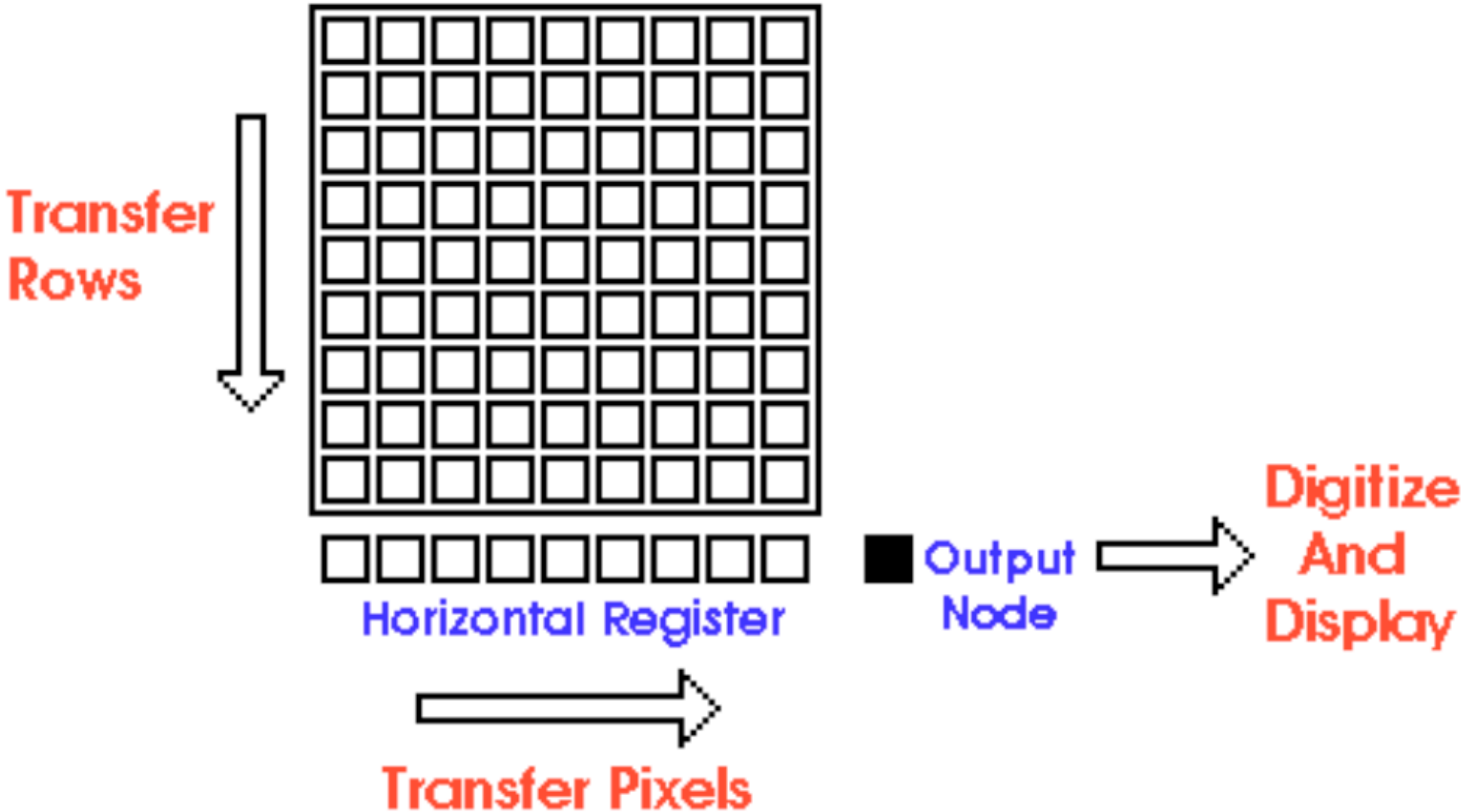




Charge Transfer



CCD Layout



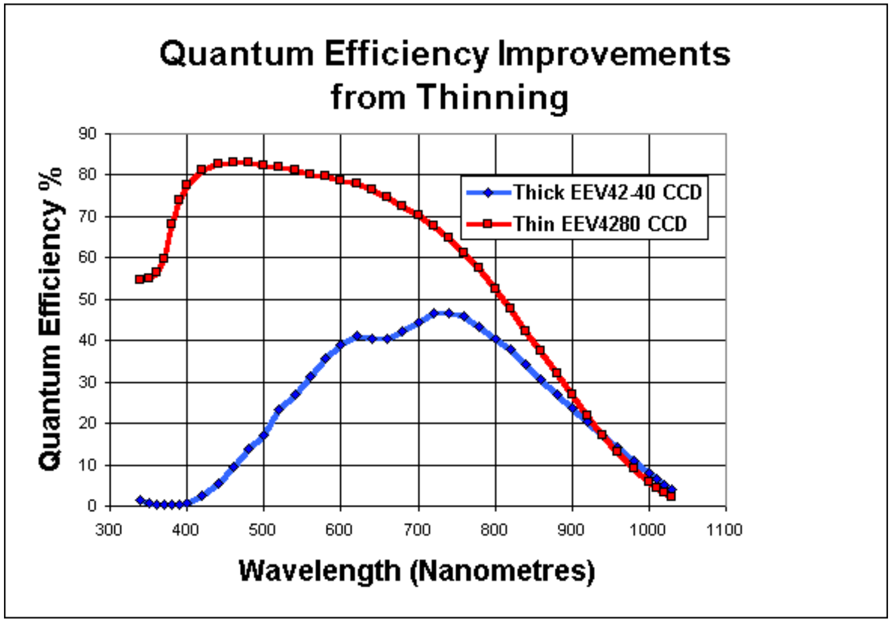
Transfer
Rows
Horizontal Register
Output
Node
Digitize
And
Display
Transfer Pixels

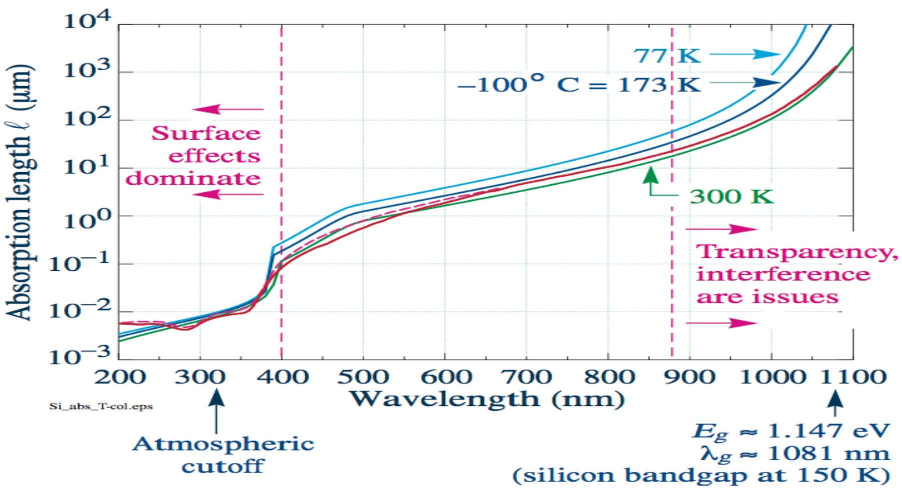
CCD performance, features, and characterization

Quantum Efficiency

- QE = average number of detected photons/pixel/second average number of incident photons/pixel/second
- Ideal case: QE=1

- QE ranges from 40% to 80% for CCDs, compared to 2% to 4% for photographic emulsion.





Readout noise

- Read Noise
  - The level of noise present in a "no exposure" readout of the electronics
  - Use a zero second "Bias" or "Zero" exposure to measure
  - 3-10 electrons per pixel per read are typical today

Read Noise acts as a shot noise, that is it enters the noise budget as R^2

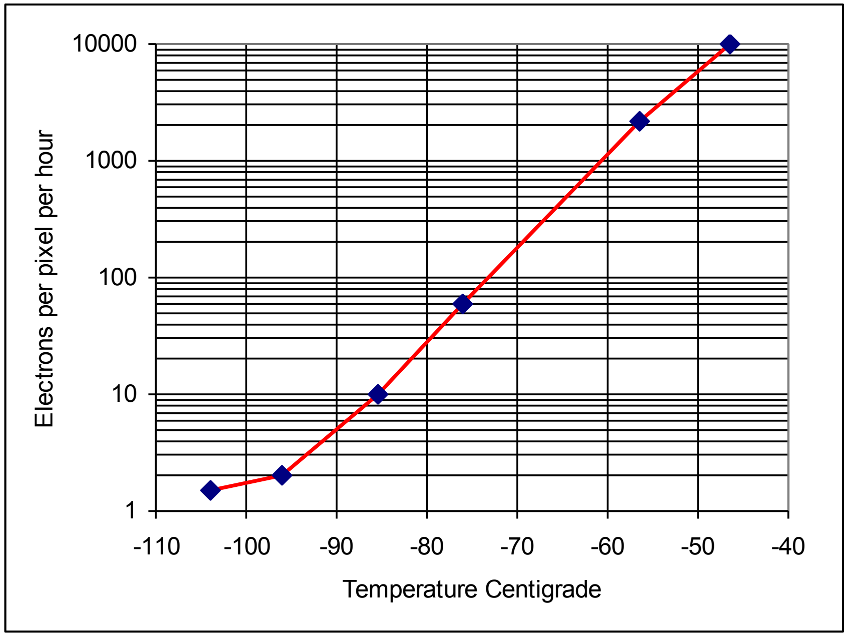
Dark Current

$$n_{dark} \sim t_{INT} T^2 e^{-E_\Delta / kT}$$

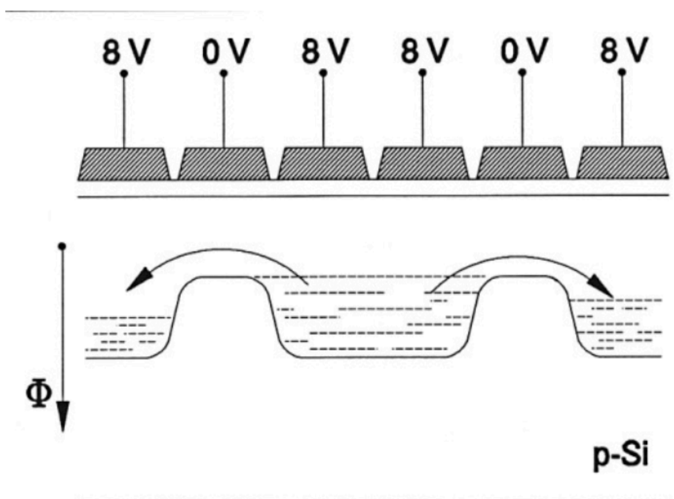
where:

- T = temperature
- K = Boltzmann's constant
- E_Δ = energy constant that depends on materials

Thermal excitation can send valence charges into the conduction band: CCDs need to be cooled down to avoid this! 173K for DECam CCDs

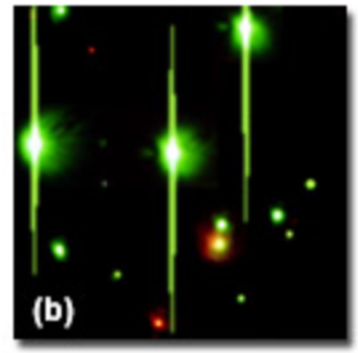


Blooming



Blooming

Over-exposure causes charges to leak into neighboring cells.



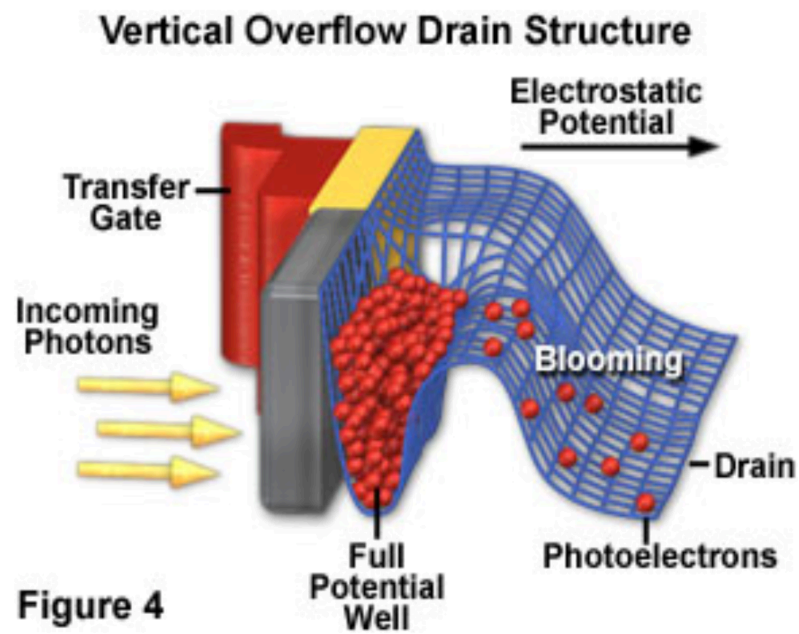
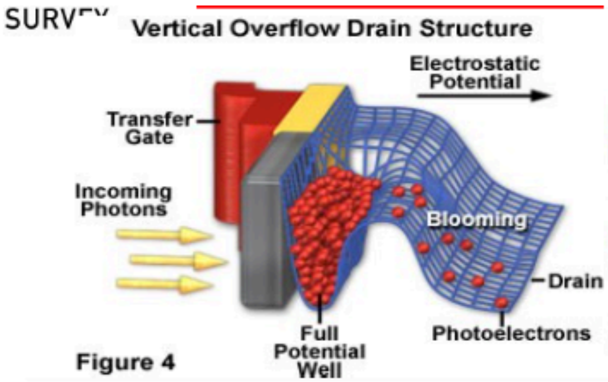
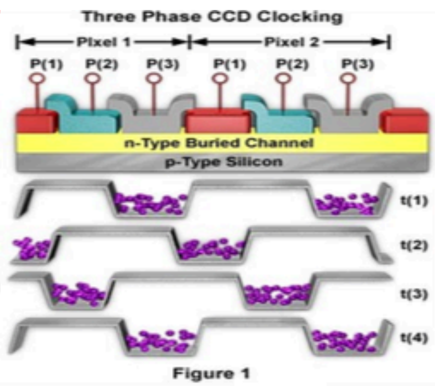
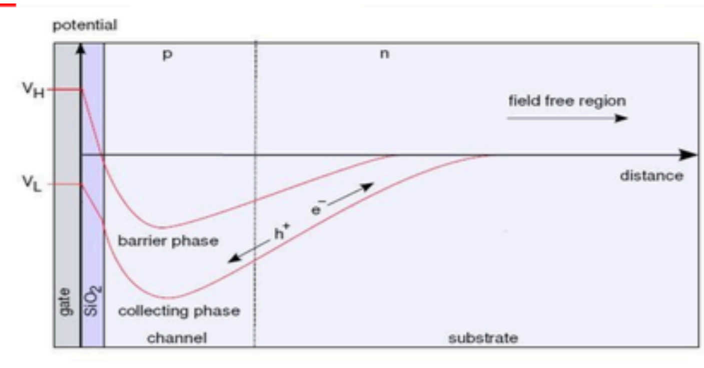


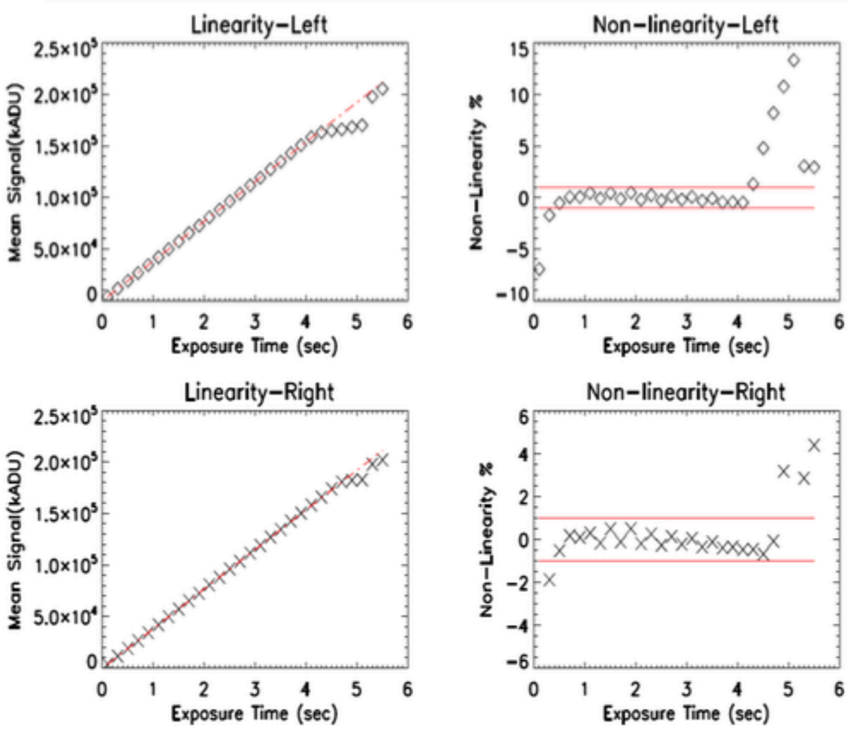
Figure 4

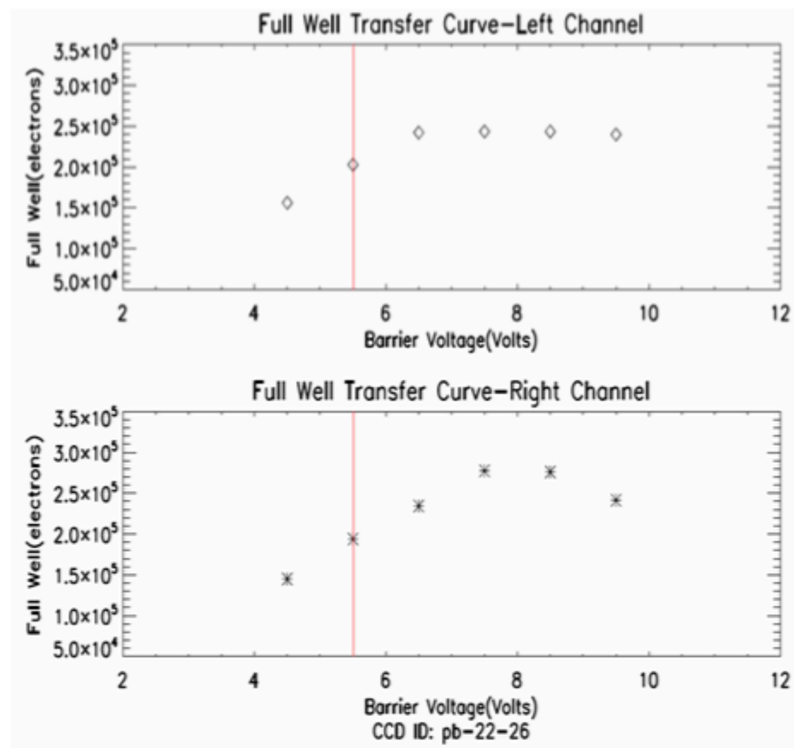
Full well capacity-(non)linearity





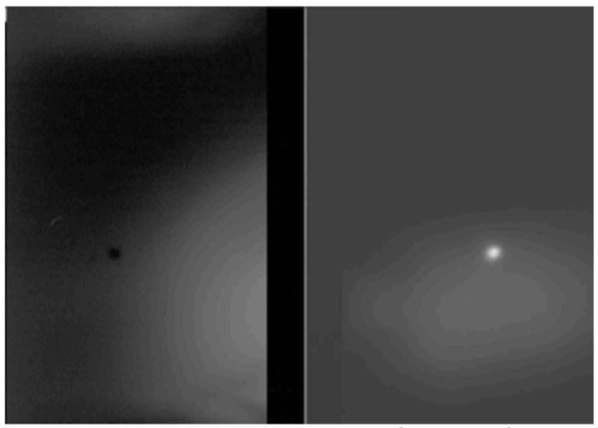


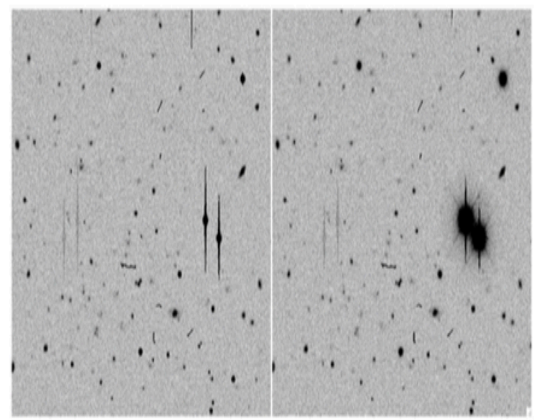


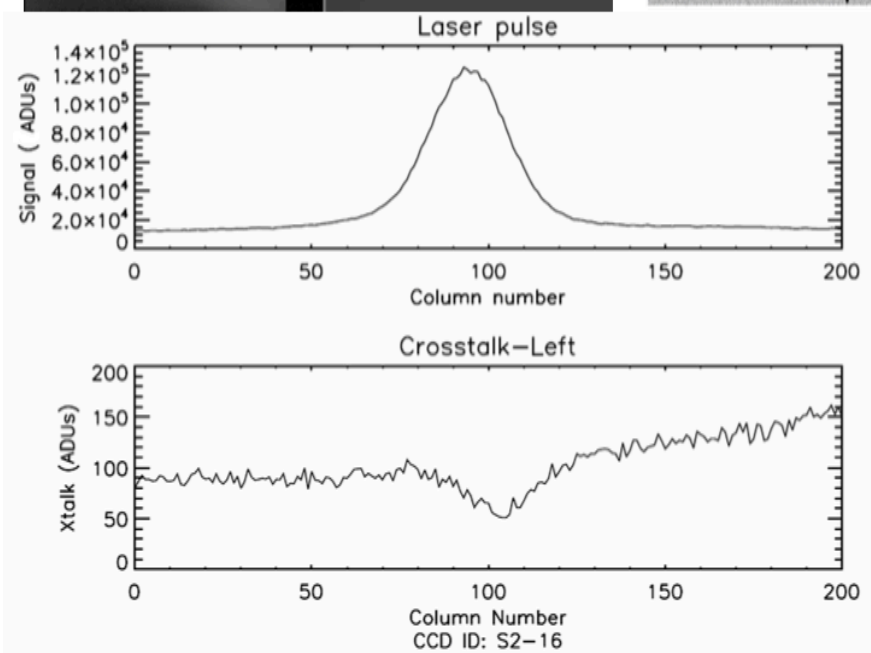


Crosstalk

Energy (capacitive) coupling between output amplifiers (also cables, etc). Creates a ghost image in other CCD channels.



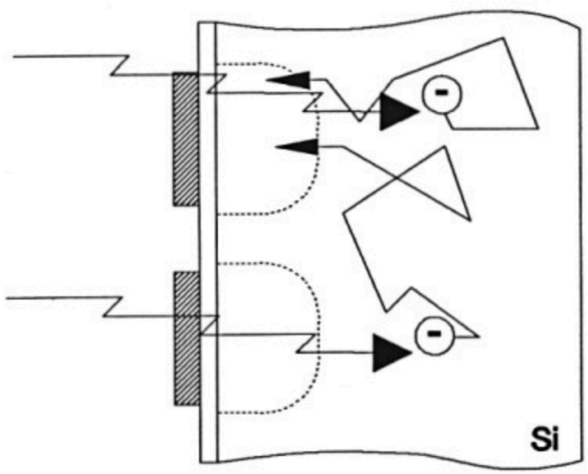




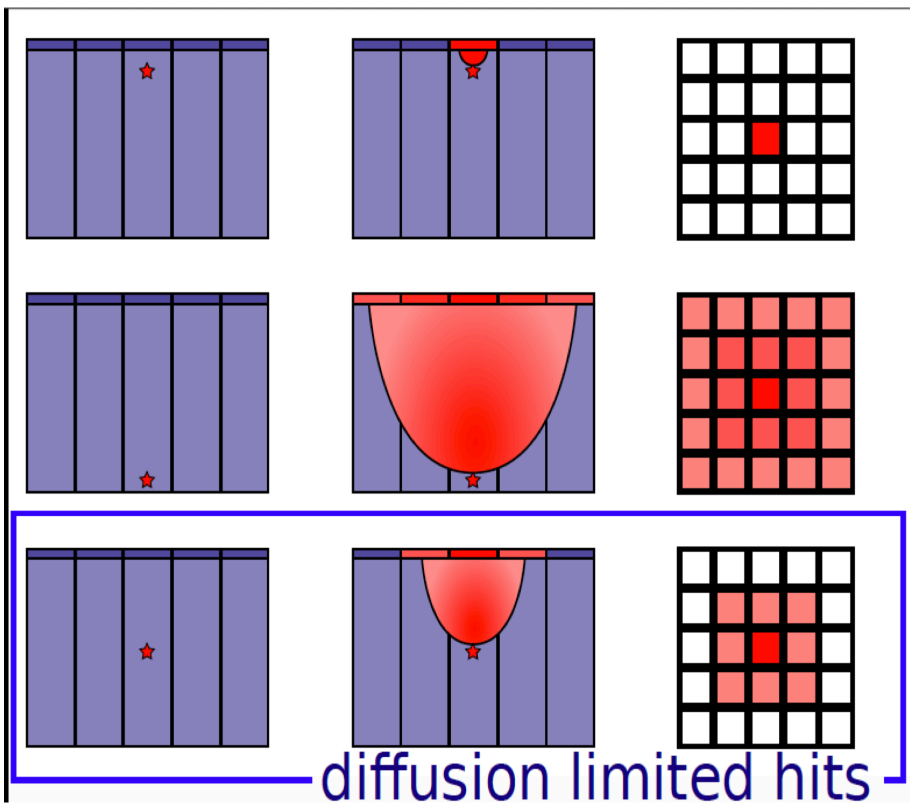
Xtalk ~ 2*10^-4

DES Requirement:
XT < 10^-3

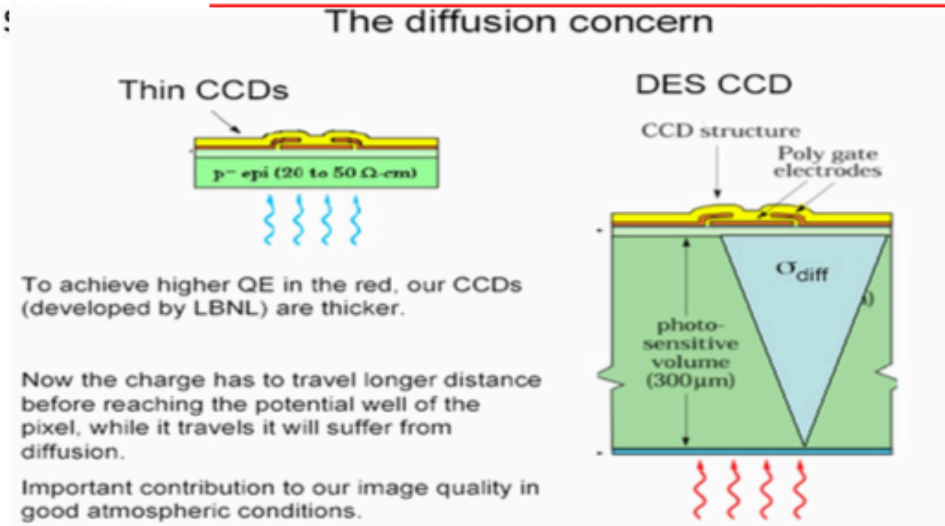
Diffusion

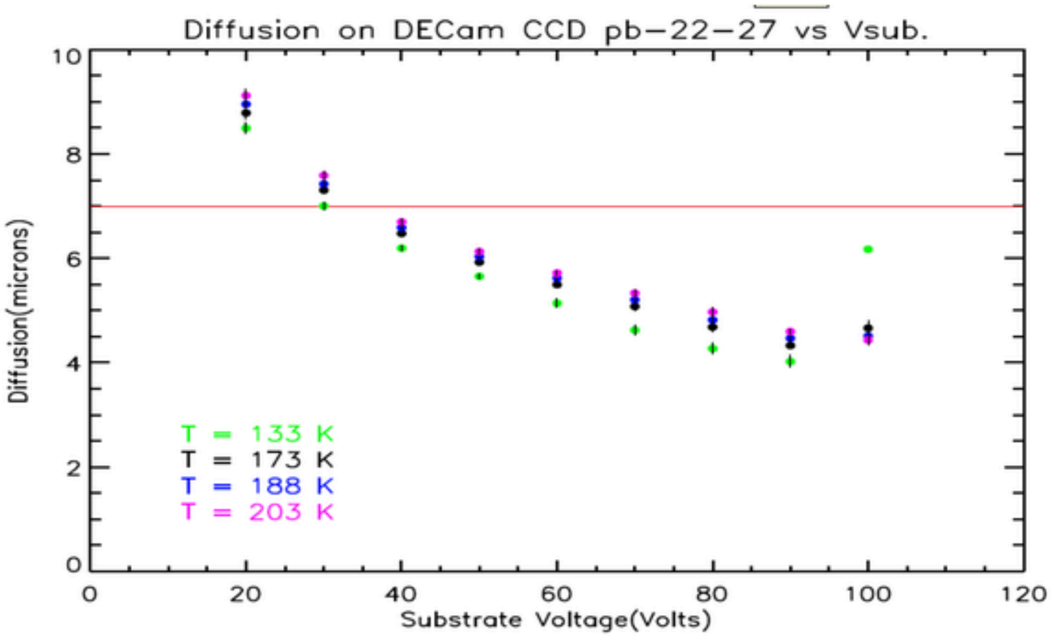


Electrons generated outside the depletion region may wander into neighboring cells.

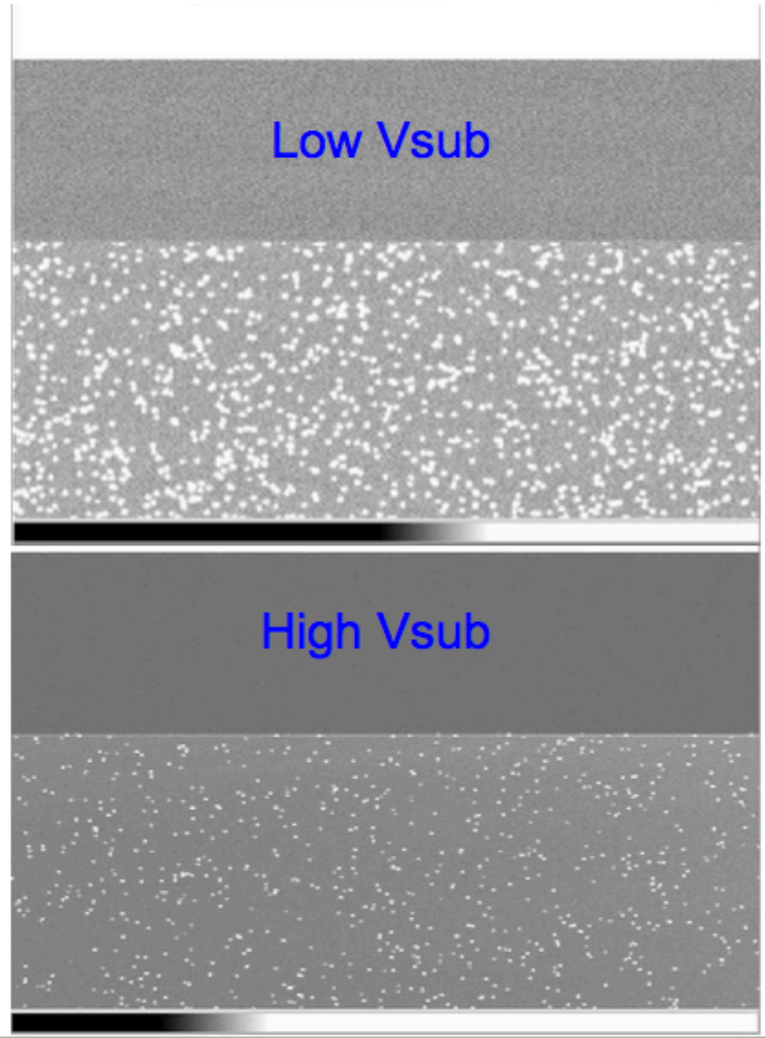


Diffusion





Use X-Rays (Fe55)



Charge Transfer Inefficiency

- CTI: When electrons (holes) are delayed during their transfer to the amplifier. Bad in space.

Massey et al 09

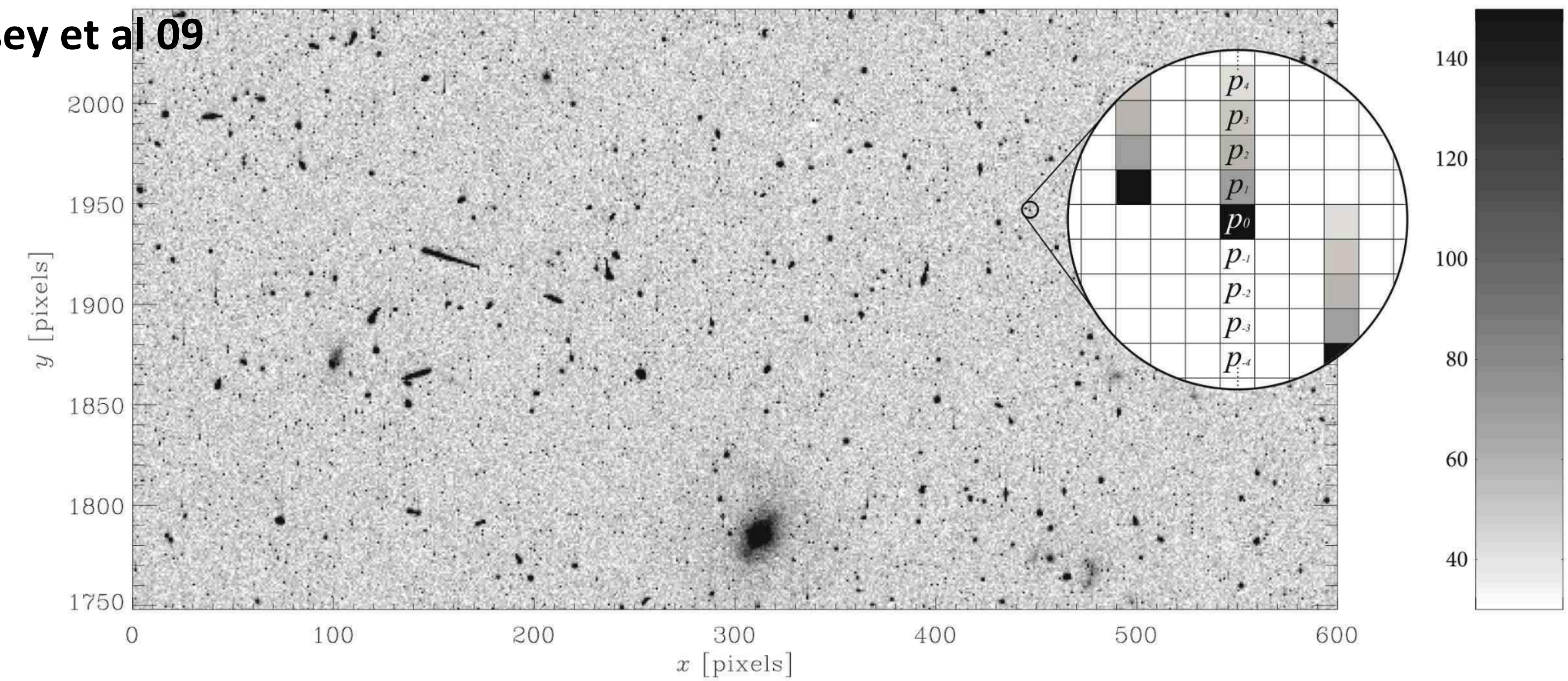


Figure 1. A typical, raw HST ACS/WFC image, in units of electrons. This 30″×15″ (600 × 300 pixels) region is at the far side of the CCD to the readout register, which lies towards the bottom of the page. It was obtained on 15 May 2005, 1171 days after the launch of ACS. Upon close inspection, as illustrated in the zoomed inset, the CTI trailing behind (above) objects is manifest.

Charge Transfer Inefficiency

Massey et al 09

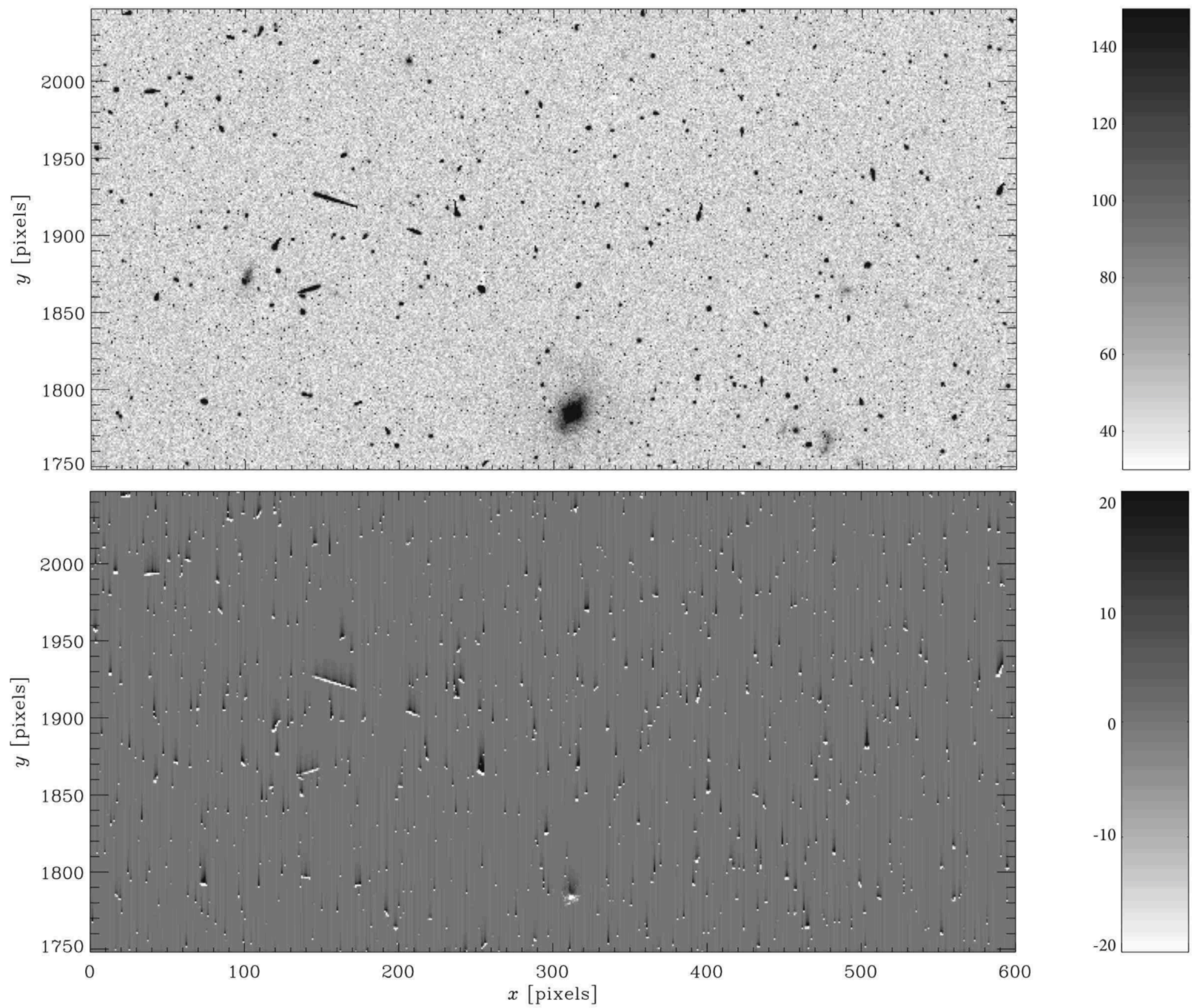
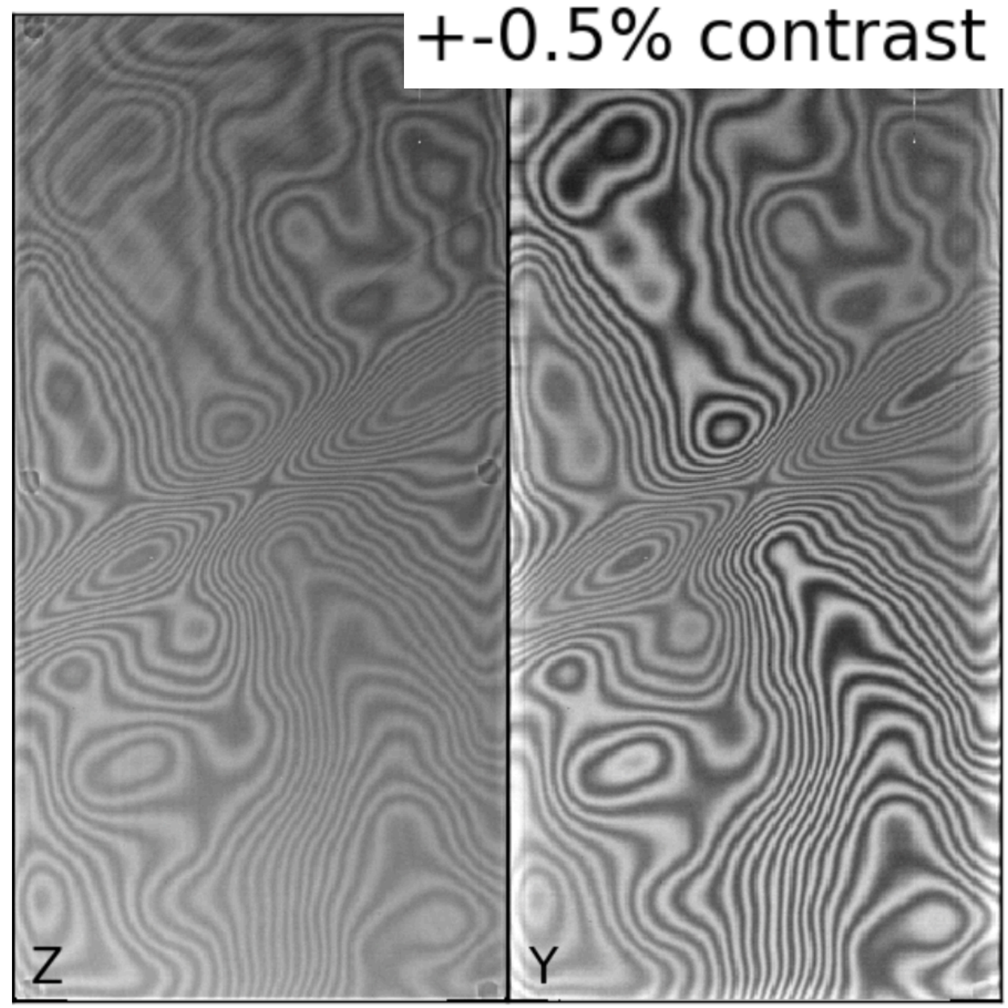


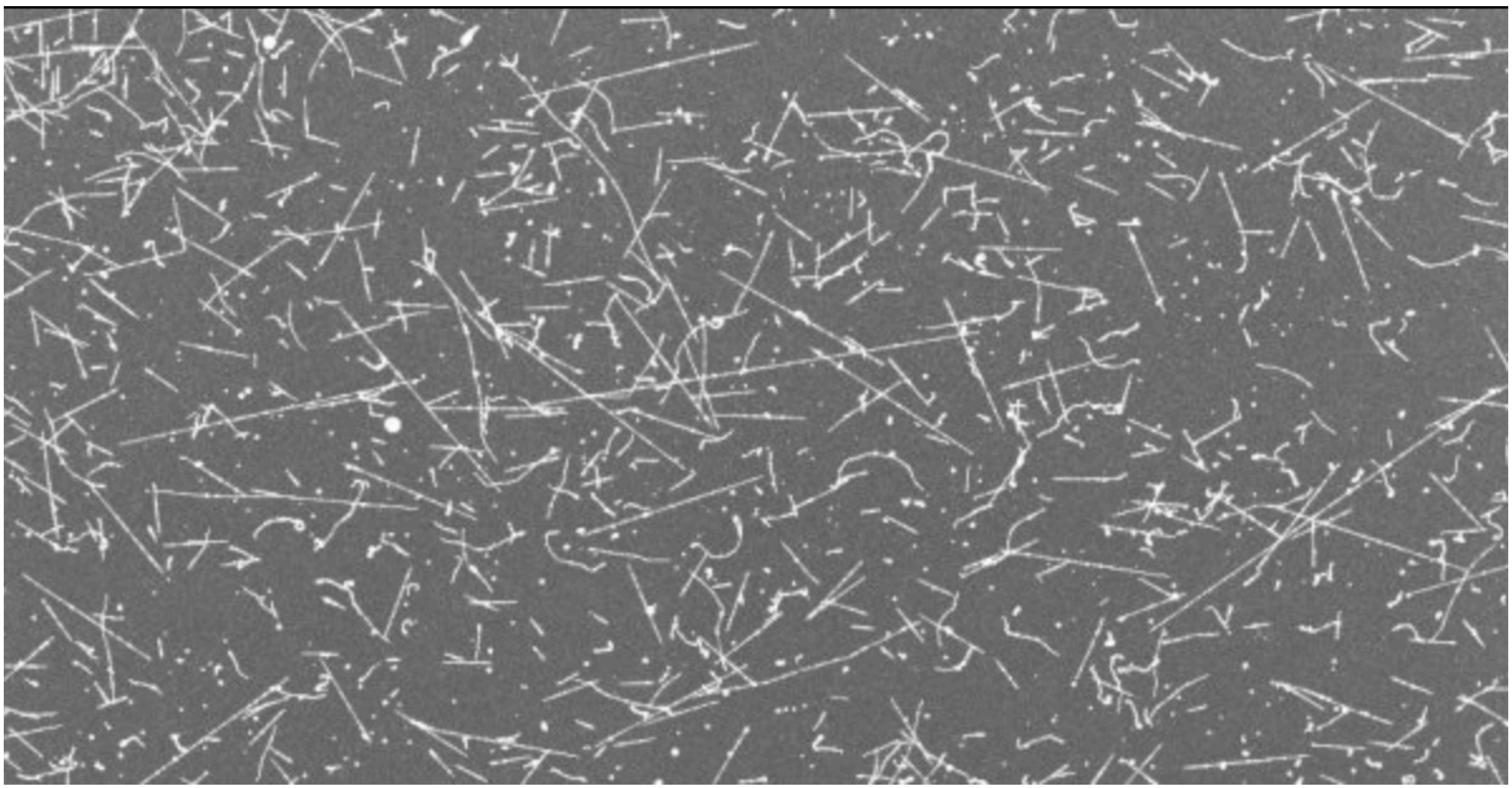
Figure 6. *Top*: The HST ACS/WFC image from figure 1, after CTI correction, in units of electrons. *Bottom*: Difference image.

Fringing

Interference between the incident light and the light internally reflected at the interfaces between the thin layers of the CCD chip



Cosmic rays



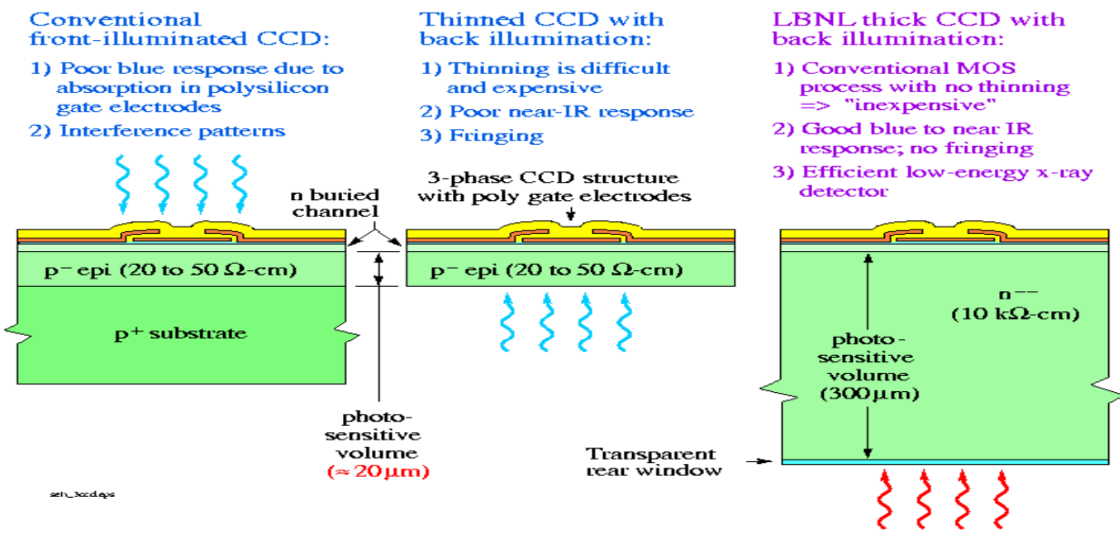
CCD constraints from science goals

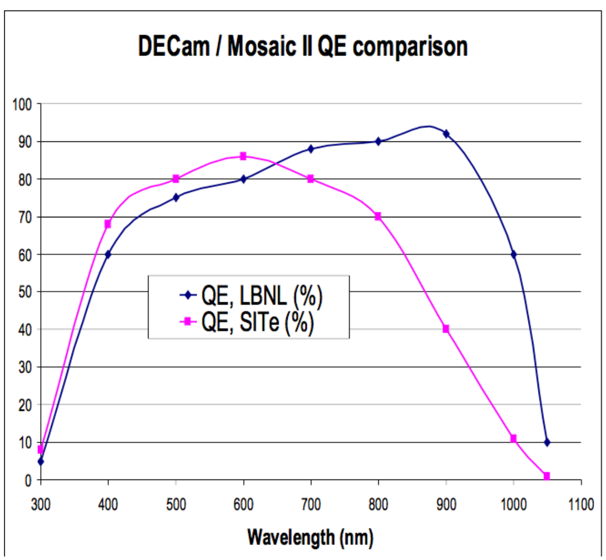
The Science Requirements...	...flow to Technical Requirements
5000 deg² of the So. Galactic Cap in 525 nights (5 yrs)	A large camera, on the Blanco 4m 3 deg² camera with ≥ 2.2 deg FOV Data Management system 300GB/night, automated processing Publicly available data archive after 1 yr
photometric-redshifts to z=1.3 with dz < 0.02.	Filters, CCDs, Read noise SDSS g,r,i,z filters; 400 - 1100nm QE > 50% in the z band (825-1100nm) Read noise <10 e-
A small and stable point spread function (PSF) < 0.9" FWHM median	Optical Corrector with excellent images Pixel size <0.3" /pixel < 0.4" FWHM in the i and z bands

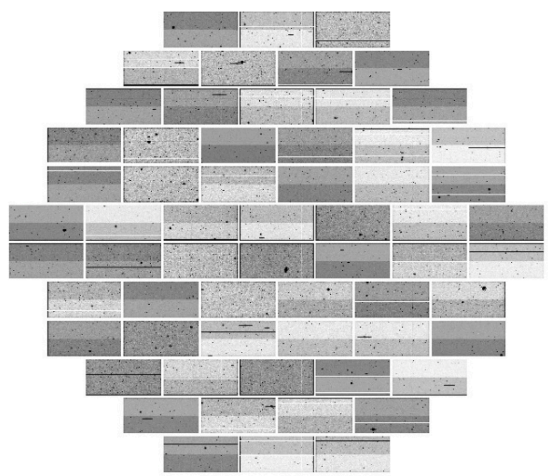
Requirements for DES

	LBNL CCD performance	DECam requirements/ Reference Design
Pixel array	2048 × 4096 pixels	2048 × 4096 pixels
Pixel size	15 μm × 15 μm	15 μm × 15 μm (nominal)
<QE (400-700 nm)>	~70%	>60%
<QE (700-900 nm)>	~90%	>80%
<QE (900-1000 nm)>	~60%	>50% at 1000 nm
Full well capacity	170,000 e^-	>130,000 e^-
Dark current	2 e^-/hr/pixel at –150°C	<~25 e^-/hr/pixel
Persistence	Erase mechanism	Erase mechanism
Read noise	7 e^- @ 250 kpixel/s	< 10 e^-
Charge Transfer Inefficiency	$< 10^{-6}$	$<10^{-5}$
Charge diffusion	8 μm	< 10 μm
Linearity	Better than 1%	1%

For DECam: testing at Fermilab





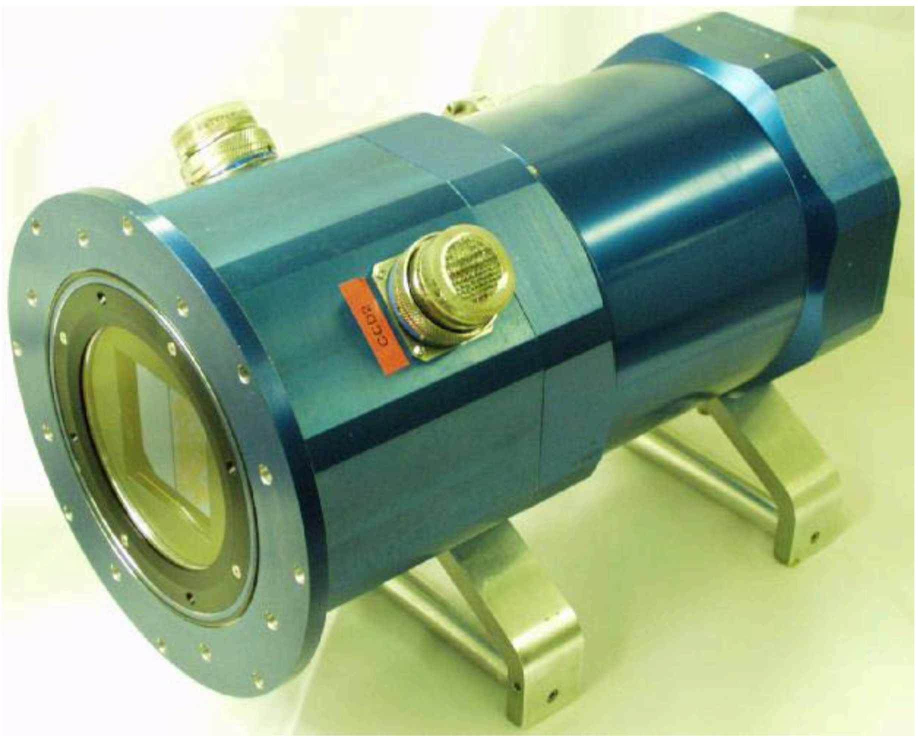


CCD testing: dewars

Kubik 2011

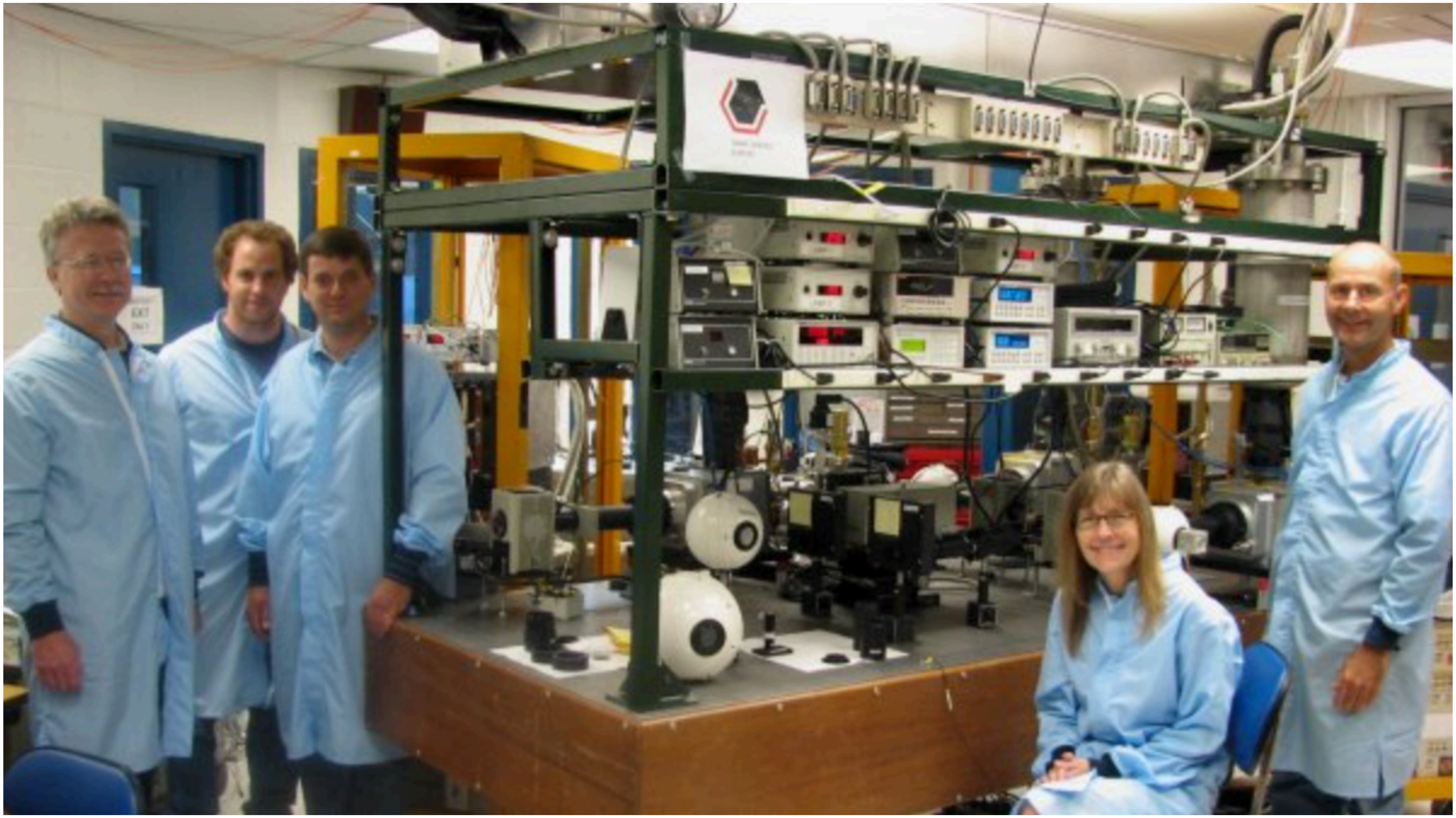
Fig. 6 . (a) View of CCD through fused silica dewar window b) Optical path: QTH lamp, filter wheel, monochrometer (not shown), shutter, integrating sphere with calibrated photodiode mounted on top port, light baffle/collimator, and test dewar.

CCD testing: dewars



- CCDs are kept cold in dewars; “thermos bottles” filled with liquid nitrogen (LN2)
- CCDs are operated at temperatures near -85 to -100C
- Temperature control to +/-0.1 C is desired

For DECam: testing at Fermilab



CCDs: S/N

Signal-to-Noise is a quantitative measurement of data quality. Observers desire high signal and low noise. S/N values are quoted as a number such as S/N = 100 or S/N = 3.

For a zero noise observation of an astronomical object, the S/N = SQRT(N) where N is the total signal received (i.e., total photons from source). [Poisson Statistics]

In reality,

$$S/N = \frac{R_* \times t}{[(R_* \times t) + (R_{sky} \times t \times n_{\mathrm{pix}}) + (RN^2 + (\frac{\mathcal{G}}{2})^2 \times n_{\mathrm{pix}}) + (D \times n_{\mathrm{pix}} \times t)]^{1/2}}$$

CCD: uses

- CCDs are used in astronomy for three major applications:
  - Imaging
  - Photometry
  - Spectroscopy
- Used in optical and outside optical bands (e.g., x-ray, UV, EUV)

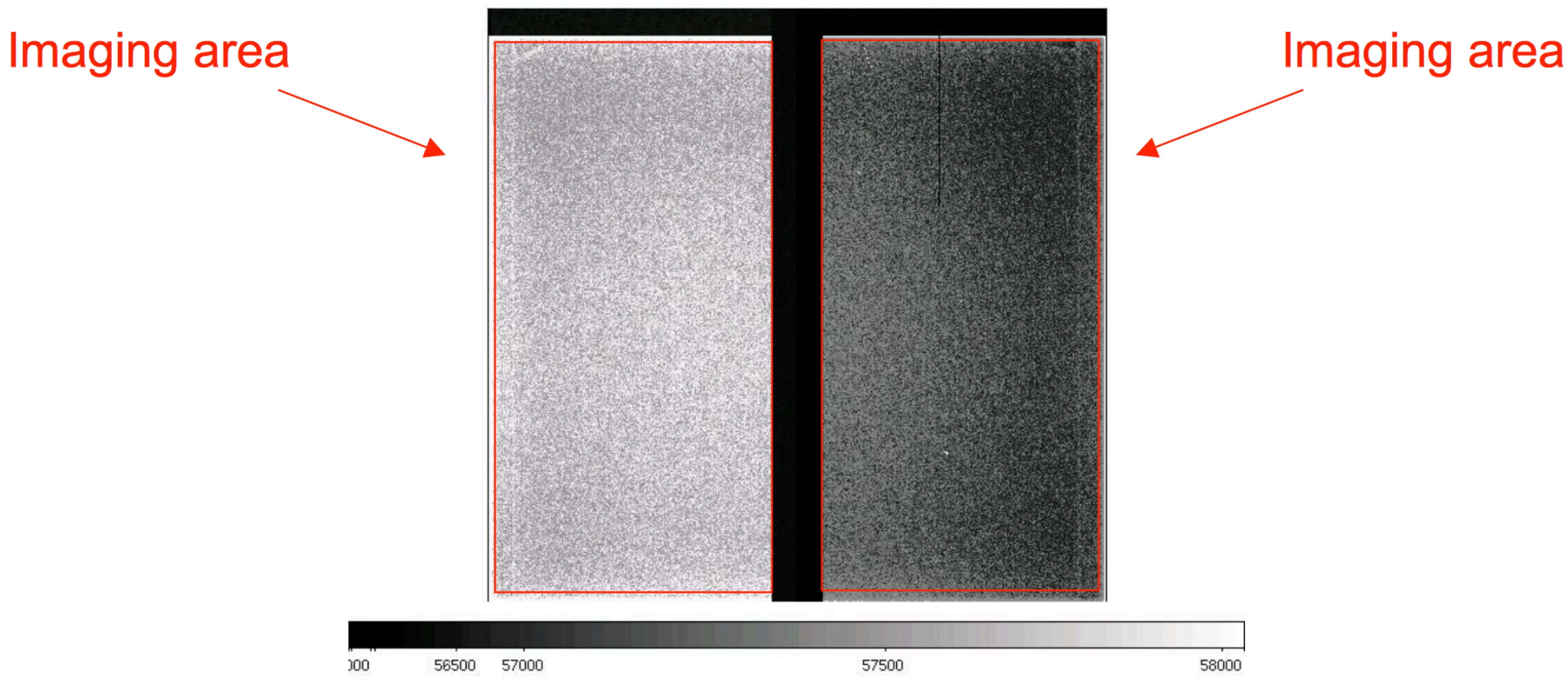
CCD data reduction

- A raw image from a CCD cannot be analyzed directly; several steps must be taken to pre-process the data prior to analysis

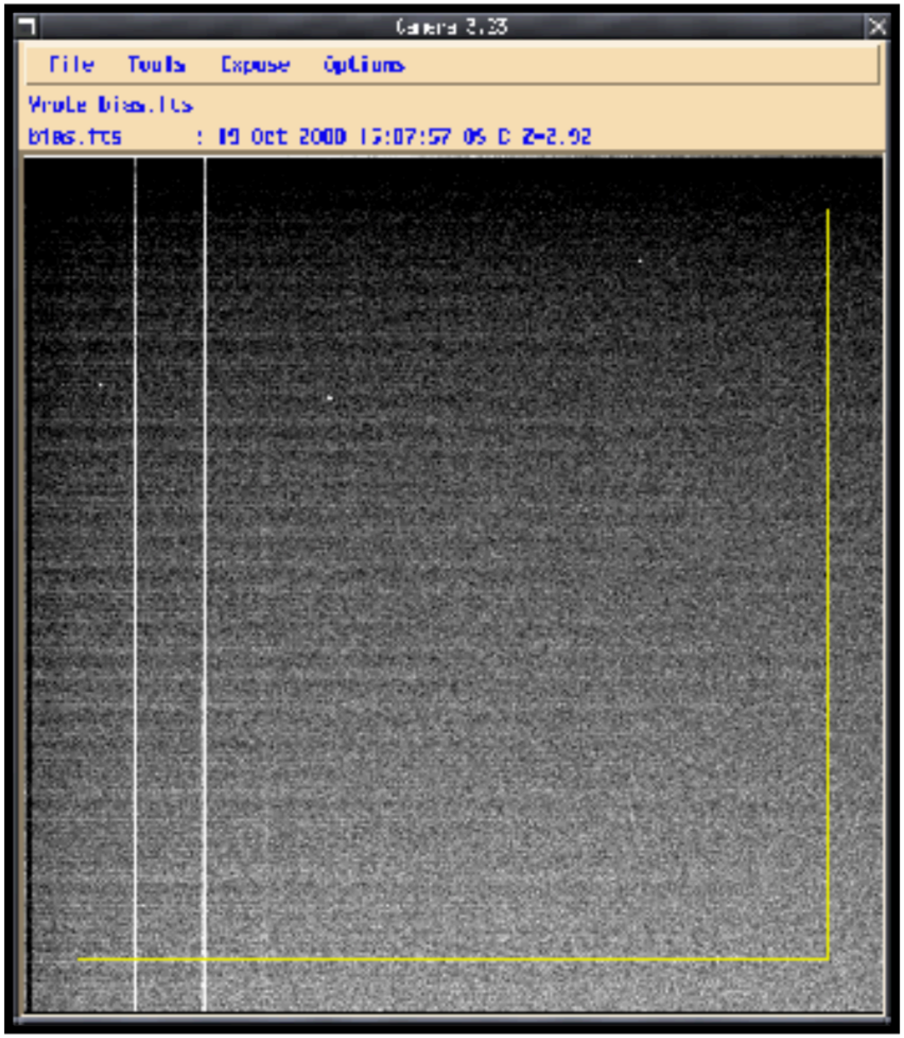
  - Overscan Correction and trimming
  - Bias frame
  - Dark frame
  - Flat field

Overscan

- Extra pixels generated by the CCD electronics when the CCD is read out.
- Not associated to physical pixels
- Mean value gives a measure of the average signal introduced by reading the CCD
- We usually subtract the mean value of a box in the overscan region, and then trim it.



CCD data reduction



- BIAS - calibration
  - A bias (or zero) is a zero second exposure used to measure the "no signal" noise level of the detector.
  - Note the two bad columns in this CCD and cosmic rays

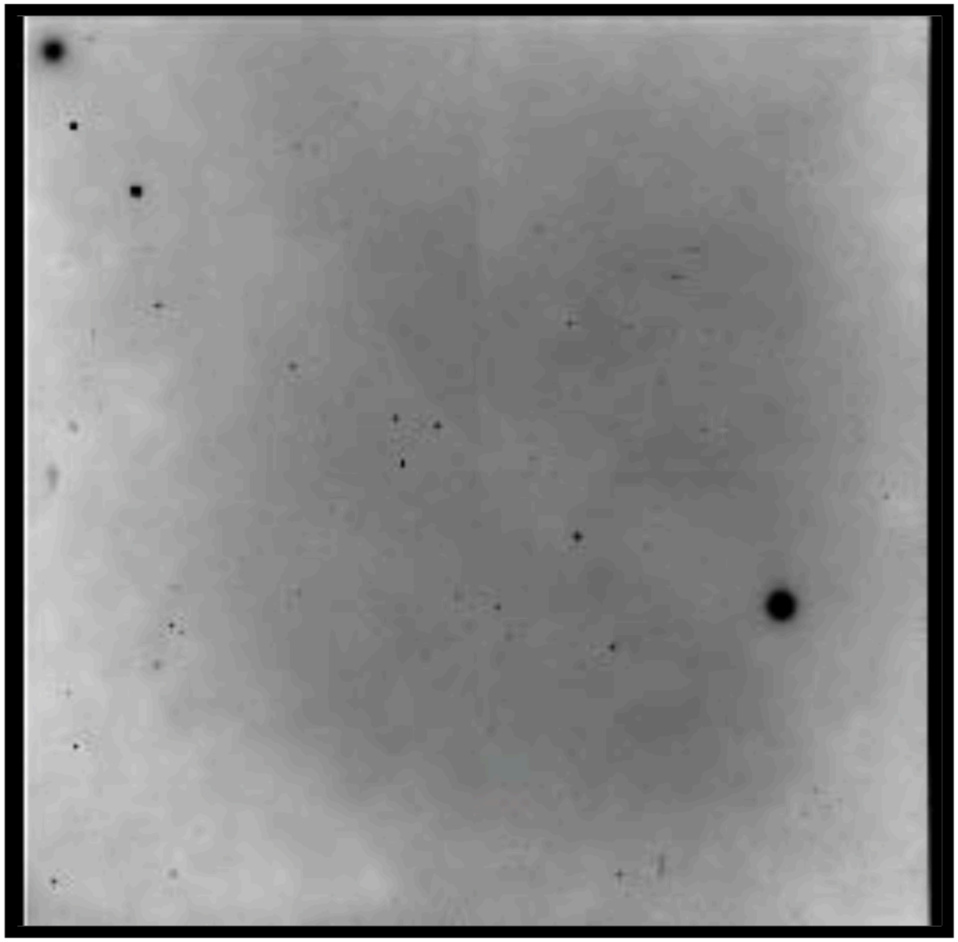
Dark frames

- To account for dark current

- Take an exposure of the same duration as the images to be processed, but keeping the **shutter to the CCD closed**

$$n_{dark} \sim t_{INT} T^2 e^{-E_\Delta / kT}$$

Flat field



- **FLAT FIELD - calib.**
  - A flat field image is used to determine the relative QE of each pixel in the array
  - Flat field images are obtained from dome screens, the sky, or quartz lamps projected in to a spectrograph

Usually, divide your science image by the flat field frame

Summary

For a typical CCD image, the steps in image reduction are:

1. Subtract average value of the overscan region from the image.
2. Trim away the overscan region.
3. Subtract bias frame to remove spatially dependent bias (optional).
4. Subtract dark frame scaled to exposure time (optional).
5. Divide by flat field (preferably night-sky flat).
6. Subtract constant sky value.

G. Bernstein (Penn)

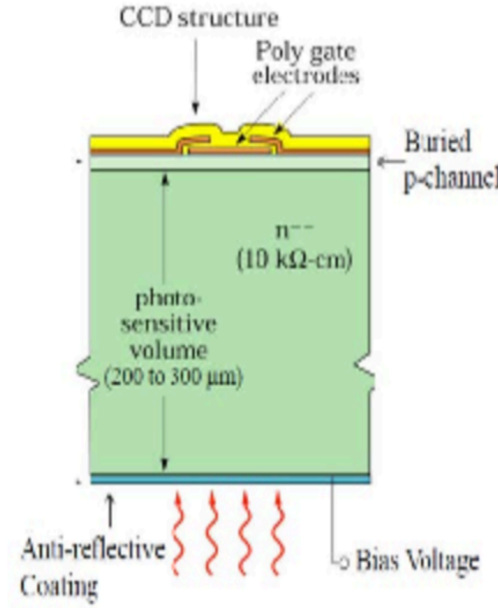
Fully depleted, back-illuminated, thick CCDs

Thick CCDs

- What if we had thick CCDs **AND** high QE in the red?

-But, what about the problems we mentioned before?

-Solution: high resistivity->can apply an E field along the whole Si substrate->the whole CCD has a depletion region: more chances to trap photons.

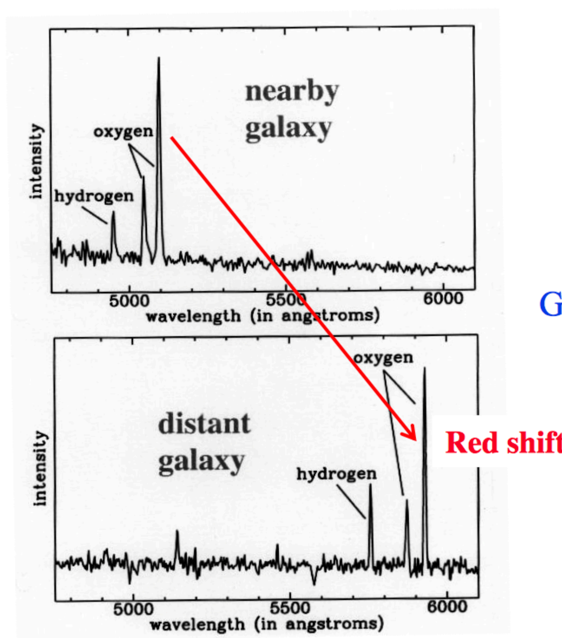


Thick (~100-250 microns), fully-depleted CCDs

- Scientific Motivation:

Why is near-infrared response important?

Light from distant astronomical objects is shifted to longer wavelengths due to the expansion of the Universe



Galaxy spectra measured with CCDs

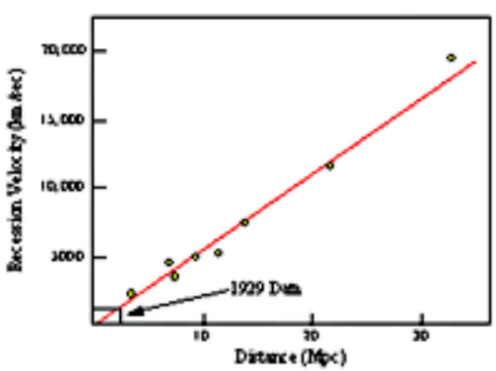
Motivation

Why is near-infrared response important?

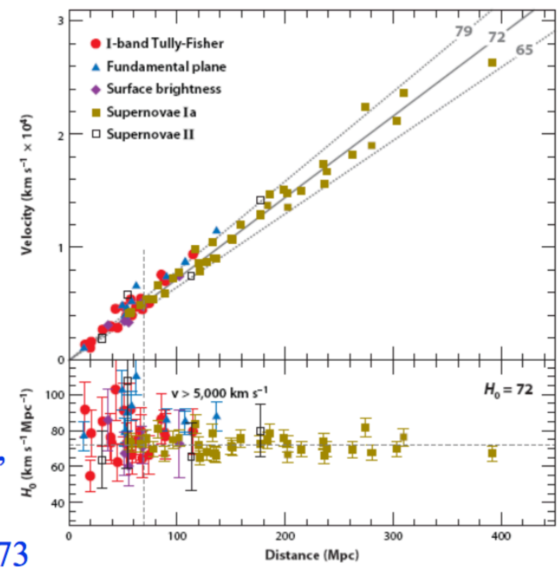
Light from distant astronomical objects is shifted to longer wavelengths due to the expansion of the Universe

$$z \equiv \frac{\lambda_{observed}}{\lambda_{at\,emission}} - 1 = \boxed{\frac{v}{c} = \frac{Hd}{c}}$$ Hubble's Law

Hubble & Humason (1931)

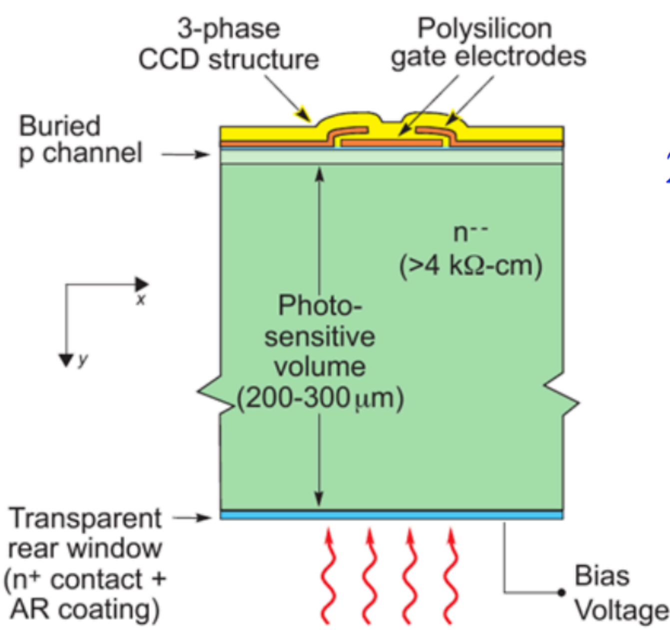


Freedman and Madore, "The Hubble Constant," Annu. Rev. Astron. Astrophys. , 2010, 48:673



HST

Fully depleted CCDs



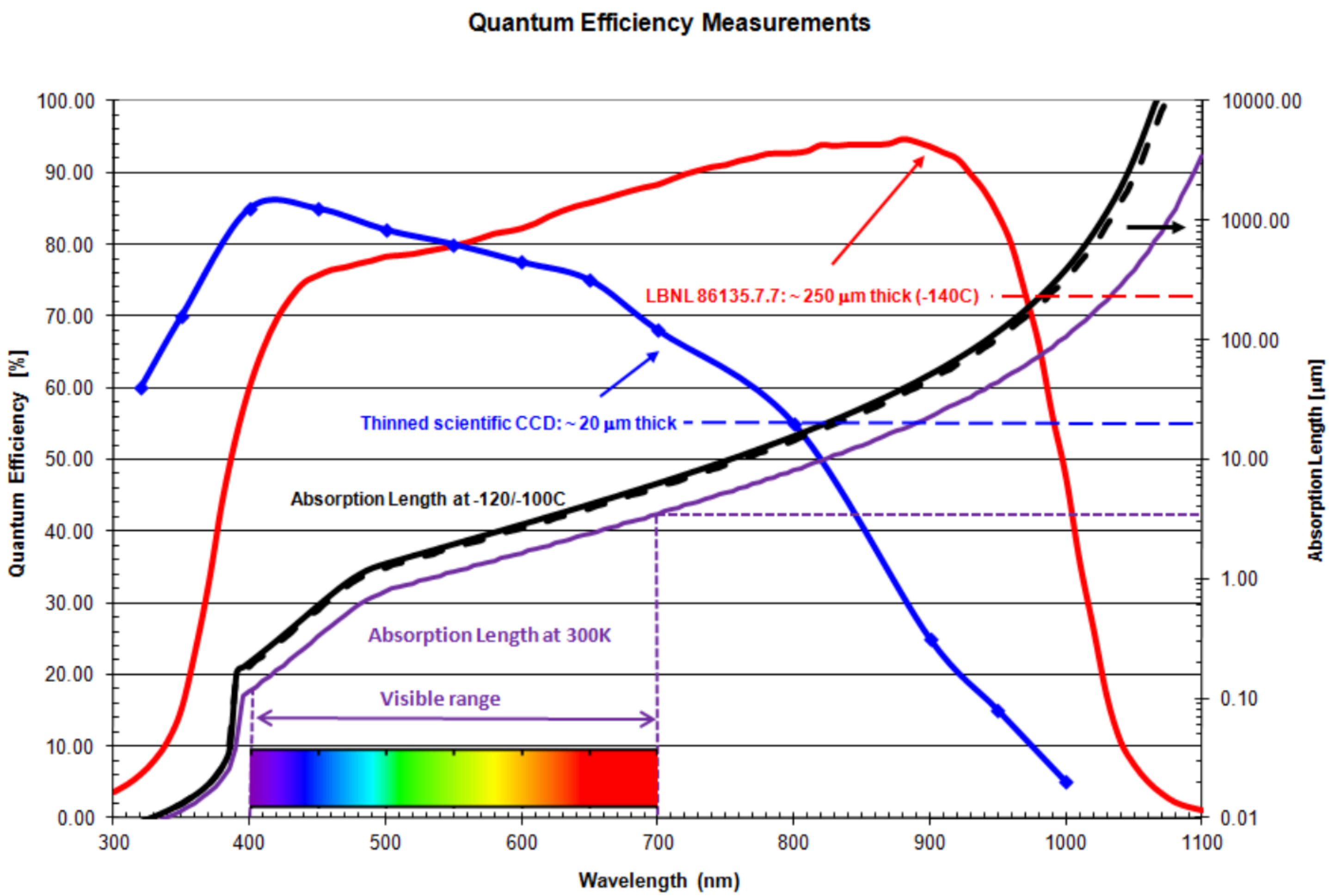
1) Concept: Fabricate a conventional CCD on a thick, high-resistivity Si substrate (> 4 kΩ-cm)
   200-250 µm typical

2) Use a substrate bias voltage to fully deplete the substrate of mobile charge carriers
   Merging of p-i-n and CCD technology
   High-ρ Si allows for low depletion voltages
   <u>Float-zone refined silicon</u>

3) The large thickness results in high near-infrared quantum efficiency and greatly reduced fringing

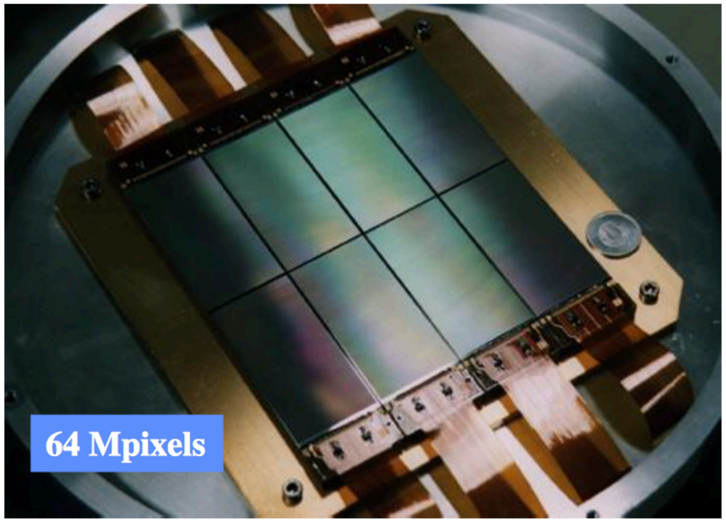
4) The fully depleted operation results in the ability to control the spatial resolution via the thickness and the substrate bias voltage

Fully depleted CCDs

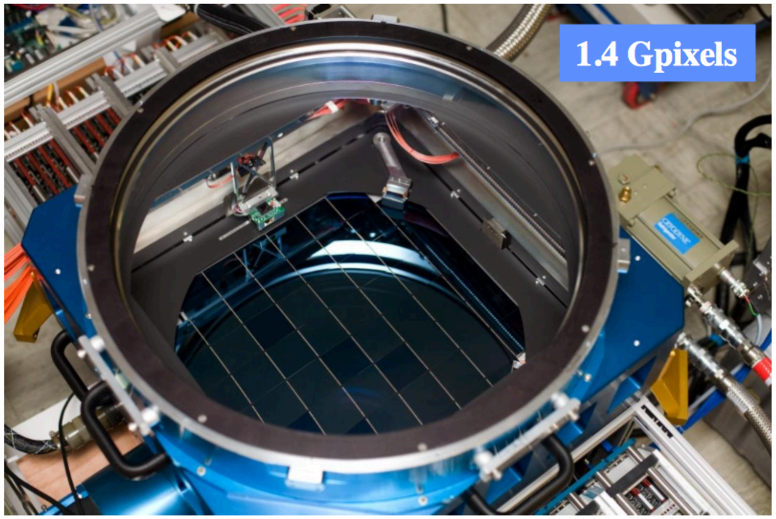


Visible range is 400 – 700 nm

Thick CCD Cameras



SuprimeCam – 8 2k x 4k, (15 μm)^2-pixel CCDs
Subaru 8-m Telescope (1998)

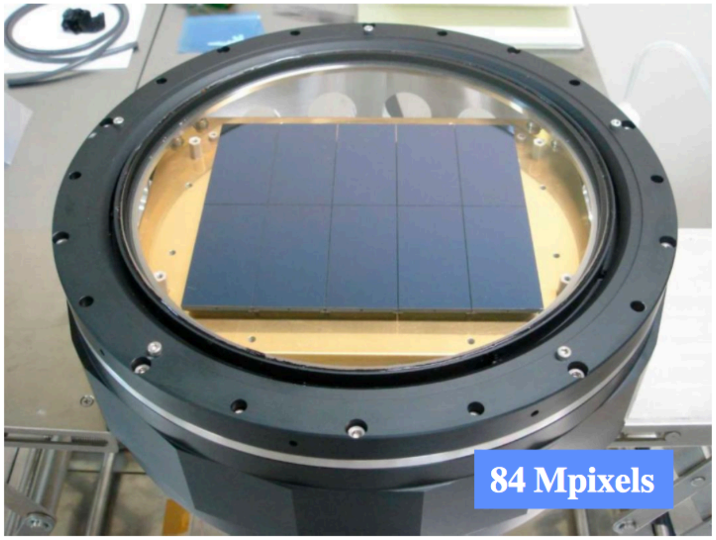


PS1 camera – 60 4.8k x 4.8k, (10 μm)^2-pixel CCDs
Pan-STARRS telescope (2010)

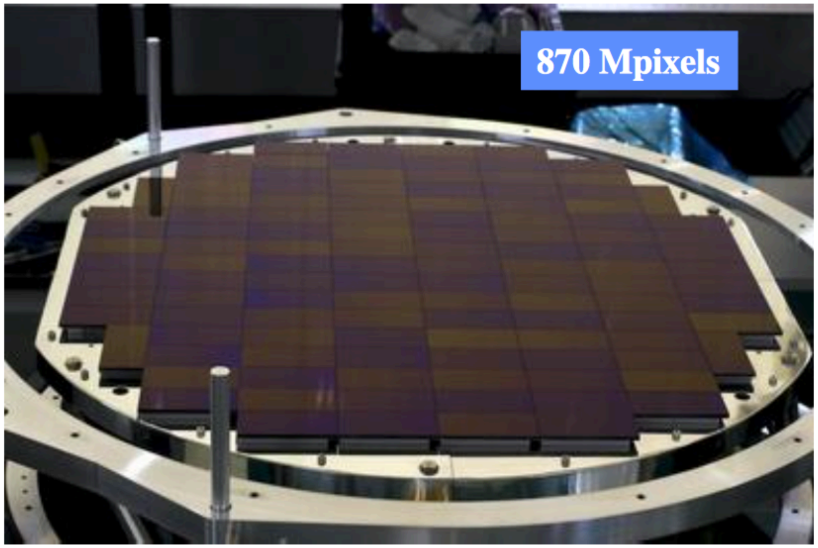
~ 40 μm thick, partially depleted and ~ 75 μm thick, fully depleted CCDs
(deep depletion CCDs)

MIT Lincoln Laboratory

Thick CCD Cameras



SuprimeCam – 10 2k x 4k, (15 μm)^2-pixel CCDs
Subaru 8-m Telescope (2008)

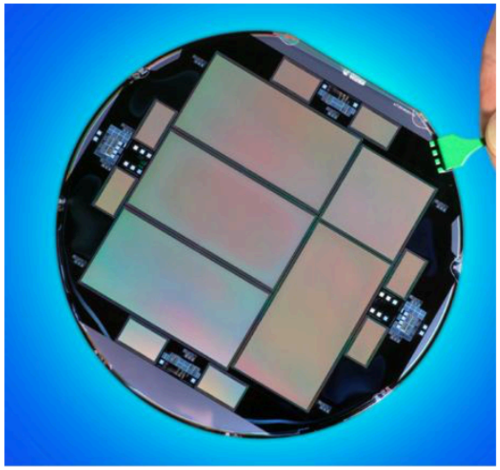


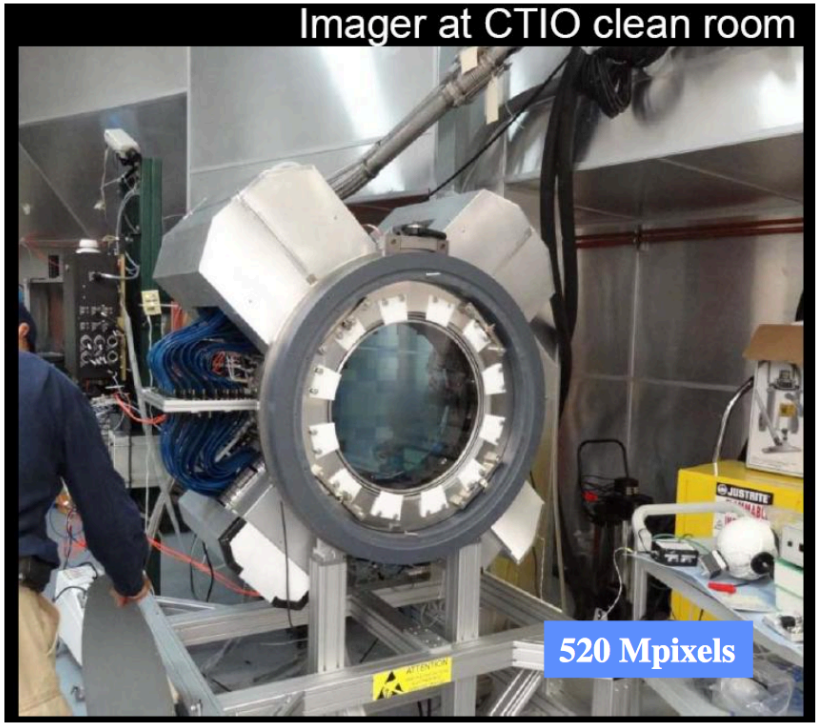
HyperSuprimeCam – 116 2k x 4k, (15 μm)^2-pixel CCDs
Subaru 8-m Telescope
1st light achieved 28Aug2012

~ 200 μm thick, fully depleted CCDs

Hamamatsu Corporation

Thick CCD Cameras

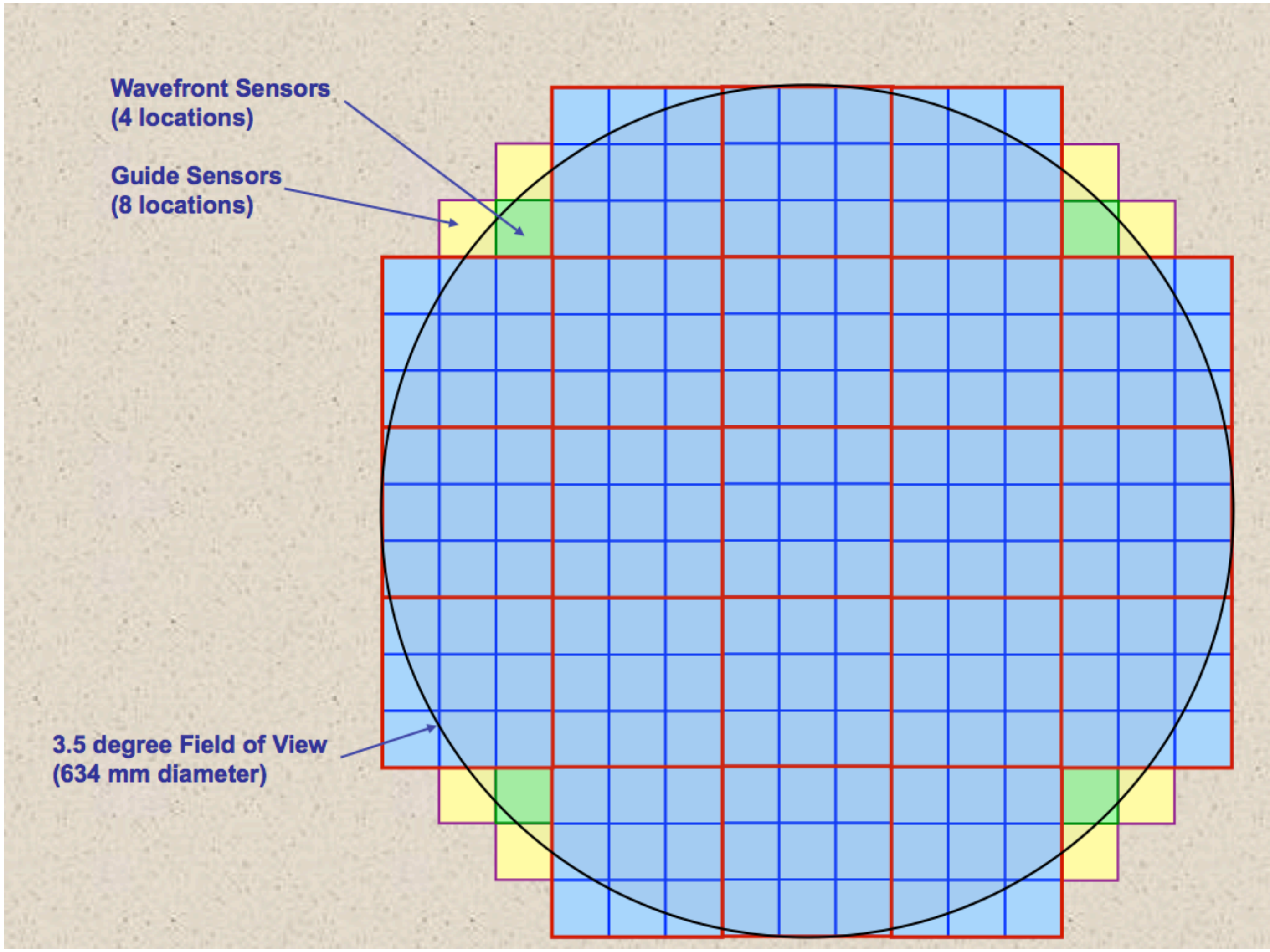




Dark Energy Survey Camera (DECam) – 62 2k x 4k, (15 μm)^2-pixel CCDs
NOAO Cerro Tololo Blanco 4-m Telescope (Fall 2012)

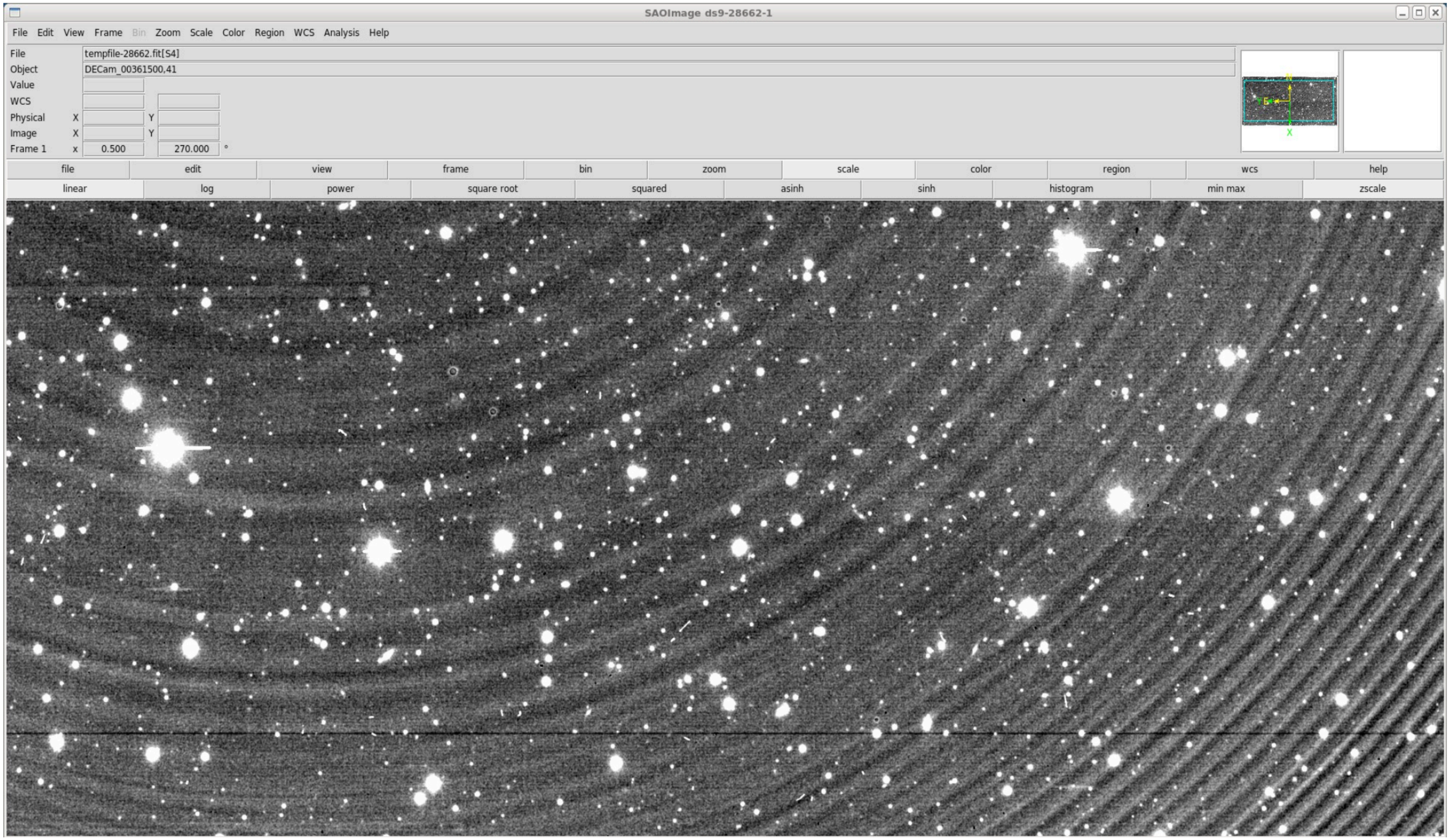
250 μm thick, fully depleted CCDs (DALSA/LBNL)

Thick CCD Cameras



Thick CCDs

- Thick CCDs have many advantages, and are being used and will continue to do so by several digital cameras (LSST, DESI)
- But they also suffer from certain type of effects that get **enhanced** due to the longer transfer time of the charge from its generation to the collecting well.
- Just until recently people have been investigating these and their connection to astrophysical observables: **tomorrow's lecture!**


SAOImage ds9-28662-1
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help
File tempfile-28662.fit[S4]
Object DECam_00361500,41
Value
WCS
Physical X Y
Image X Y
Frame 1 x 0.500 270.000 °
file edit view frame bin zoom scale color region wcs help
linear log power square root squared asinh sinh histogram min max zscale

References

- “Scientific Charge-Coupled Devices” J. Janesick: the “bible” of CCDs
- Handbook of CCD Astronomy
- **“Charge-coupled Devices In Astronomy” Craig Mackay (1986): good introduction**