CCD and CMOS Imaging Devices for Large Ground Based Telescopes

Slides from Veljko Radeka – Brookhaven National Lab

"Large Telescopes"

		Survey telescope	Deep probe
Primary Mirror	*dia.*=D_m, *Area*= ***A***	***Large (~8m)***	***Very large (~30m)***
f-number	***f /#***	***~ 1/1.2***	***~ 1/30-40***
Focal Plane Array *dia.*= D_f		***Large (~60cm)***	***Medium (~20cm)***
Field of View	$\Omega\ \alpha\ D_f / D_m$	***~3-4 degrees***	***~20 arc min***
Etendue	$A\Omega$	***~330m²deg²***	
Plate Scale	arcsec/µm	***0.2***	

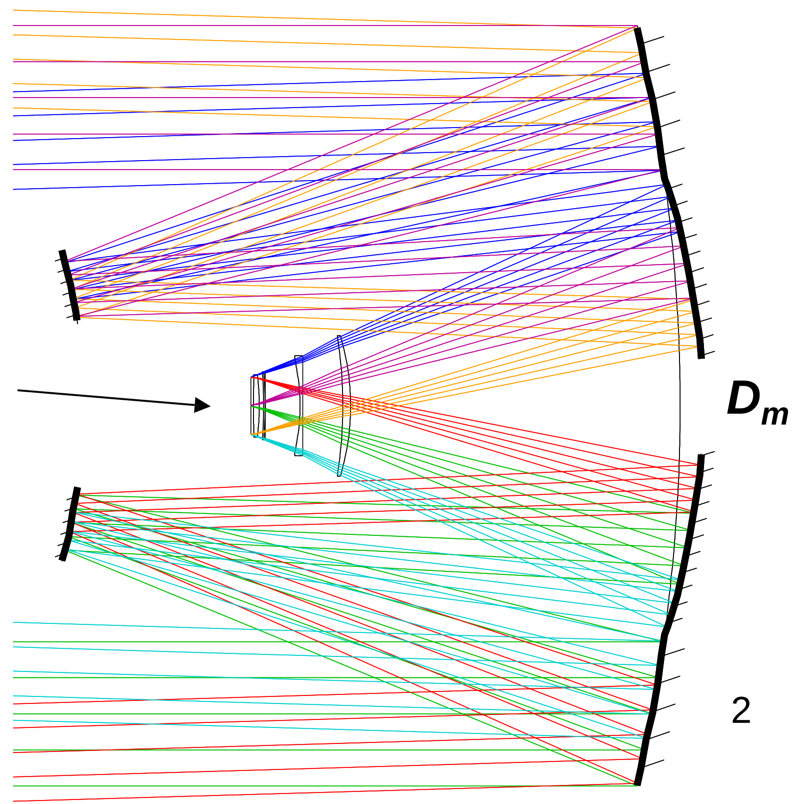
Science Drivers: Wide area surveys for dark energy studies

FPA Requirements:

- Increase Area
- Increase QE in near IR
- Reduce PSF (diffusion and pixel size)
- Increase readout speed

e.g., Pan STARRS, LSST

FPA, D_f



Growth of mosaics

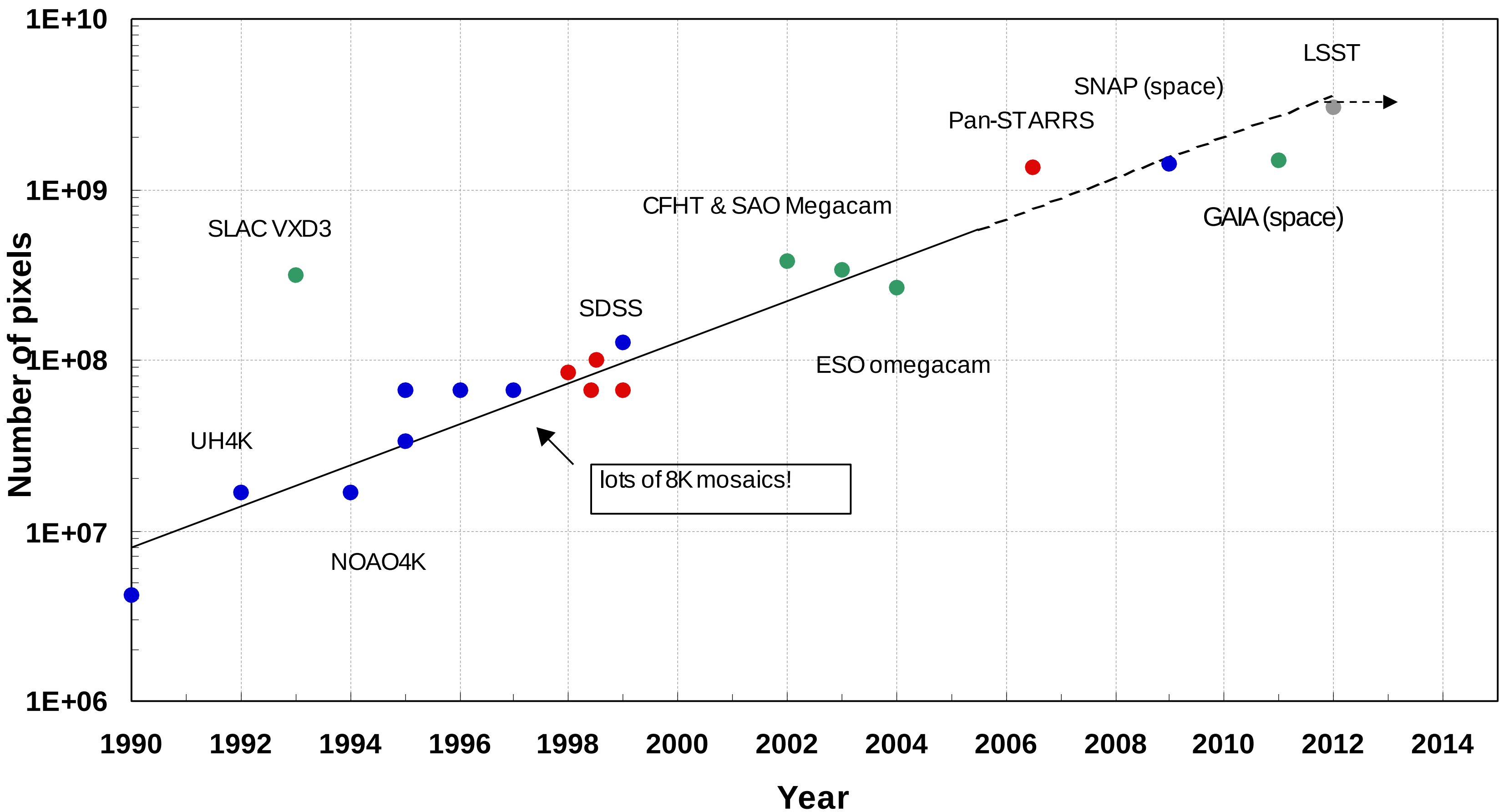
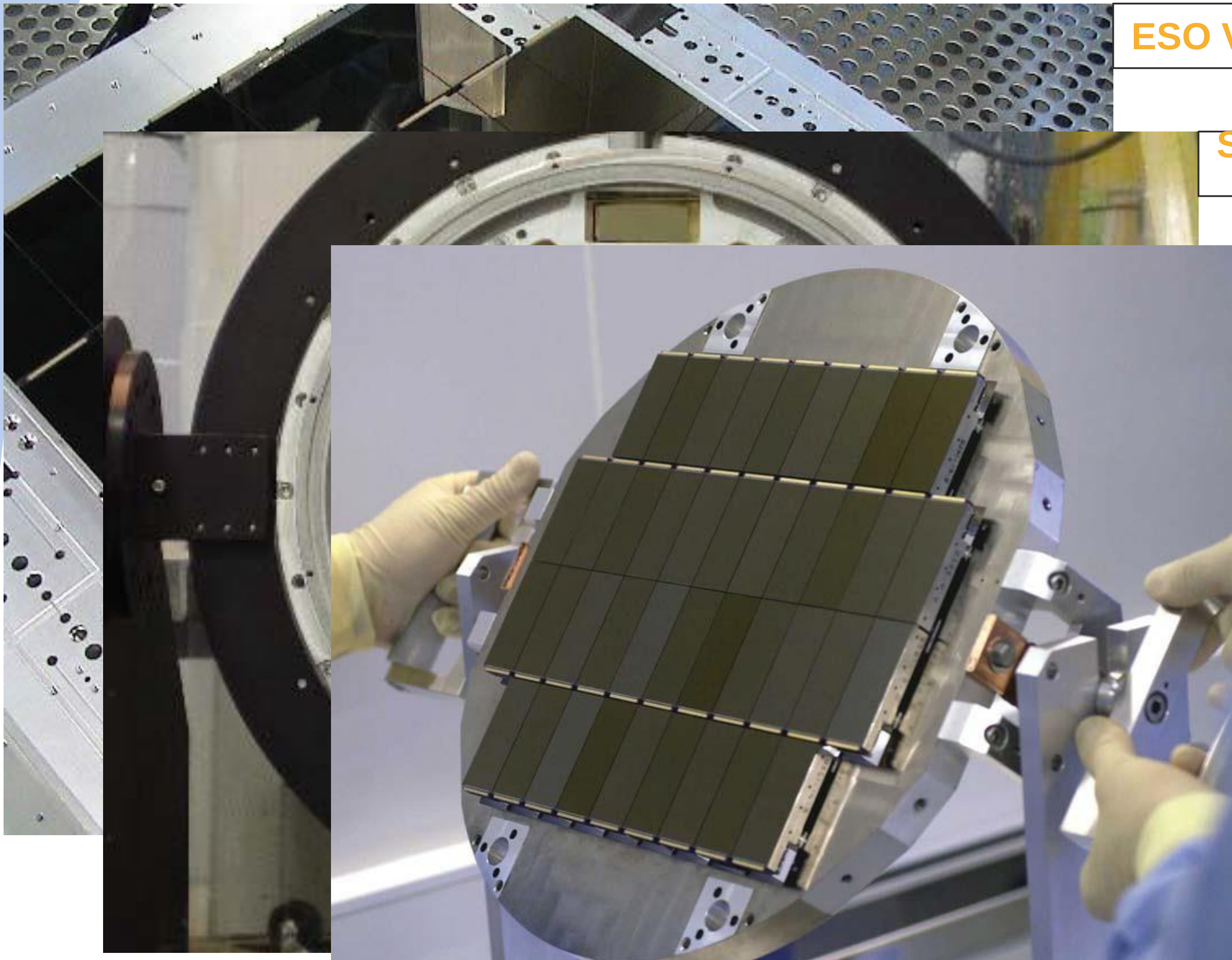


Illustration of focal plane sizes, from Luppino/Burke 'Moores' law

Focal plane size doubles every 2.5 years

From: Burke, Jorden, Vu, SDW Taormina 2005

Ground-based mosaics-3



ESO VST Omegacam

SAO MMT Megacam

CFHT Megacam

Operational- April 2003

SAO MMT Megacam

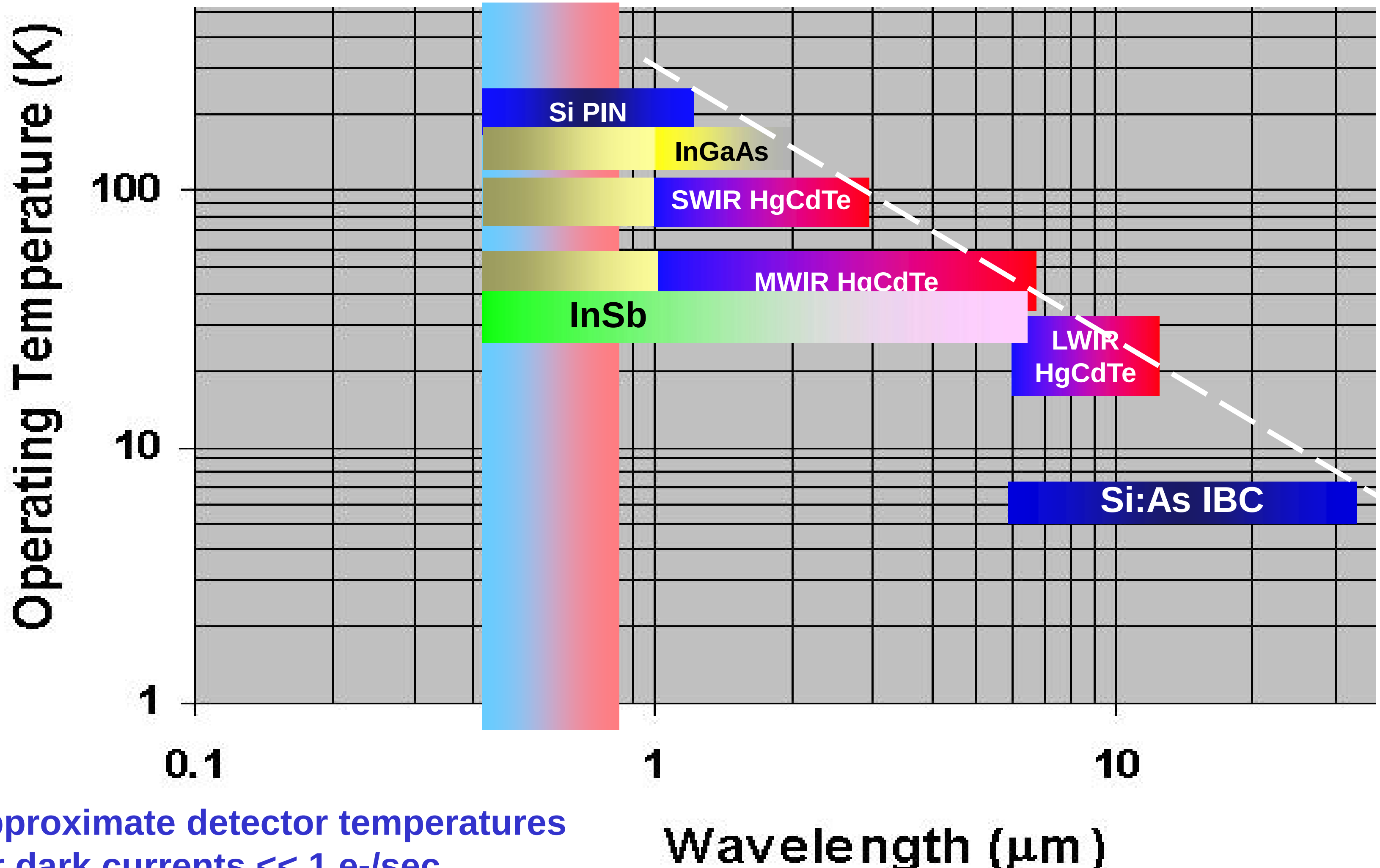
4x9

E2v CCD42-90

2048x4608 13.5 micron pixels

200kHz

Temperature and Wavelengths of High Performance Detector Materials



Approximate detector temperatures for dark currents << 1 e-/sec

From: Loose, Hoffman, Suntharalingam, SDW, Taormina 2005

Solid State Device

- *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: Charge-Coupled Device*
  - *CMOS: Complementary Metal-Oxide Semiconductor*
  - *IRFPA: Infrared Focal Plane Array*
- *Basic Operating Principle*
- *Performance of Solid State Detectors*
- *Observation with Solid State Detectors*

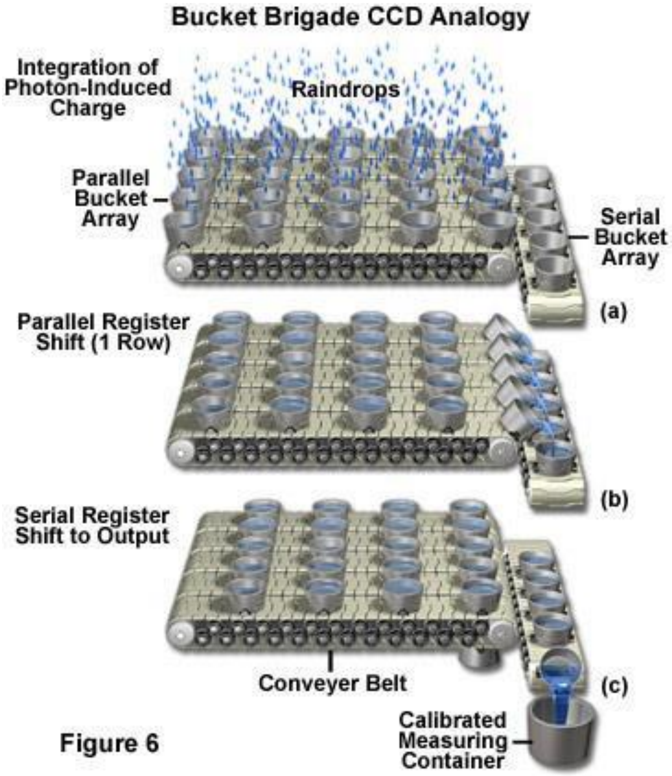
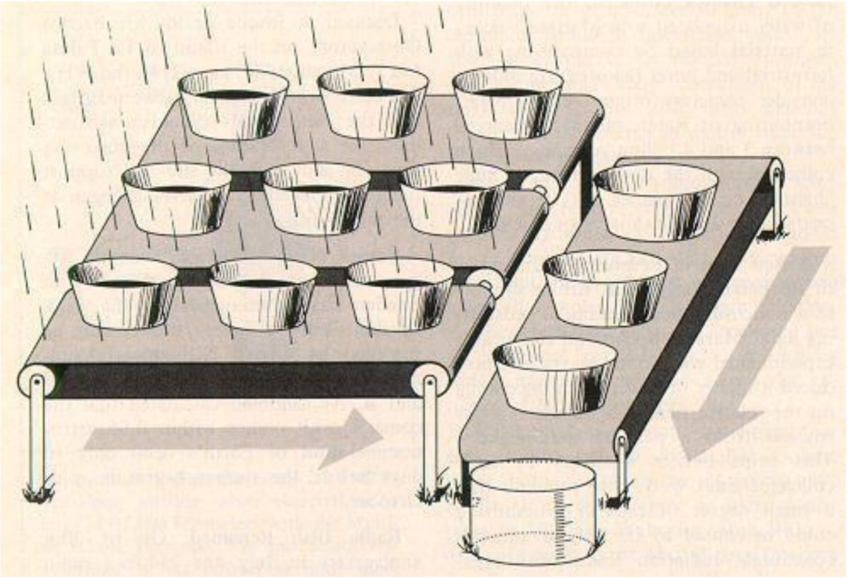


Figure 6

CCD Basic Operating Principle – Bucket Brigade

- ***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***

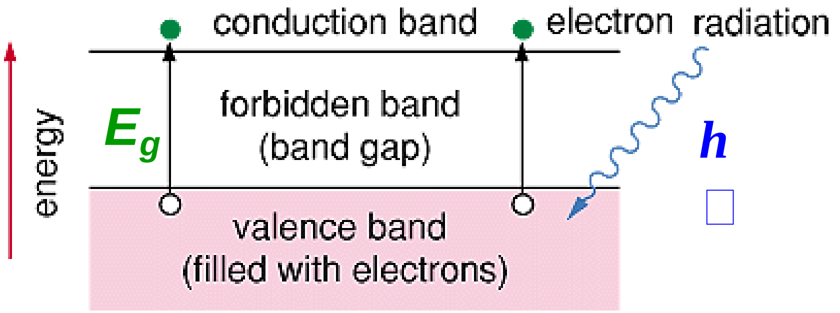


Charge Generation in Capacitive Pixel

- *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)*
  - □ **= c /** □ *(Frequency of light)*
  - *E_g**:** electron-volts (Energy gap of material)*



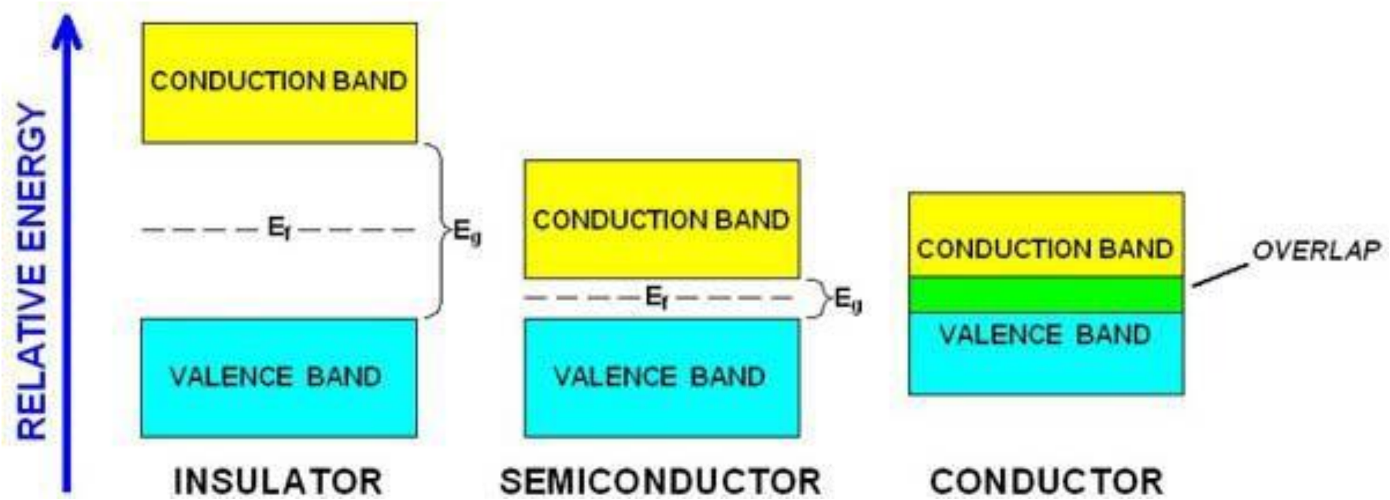
- *Long wavelength cut-off*

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

Silicon: E_g = 1.12 eV $\lambda_{\textbf{cut-off}}$ *= 1.1 micron*

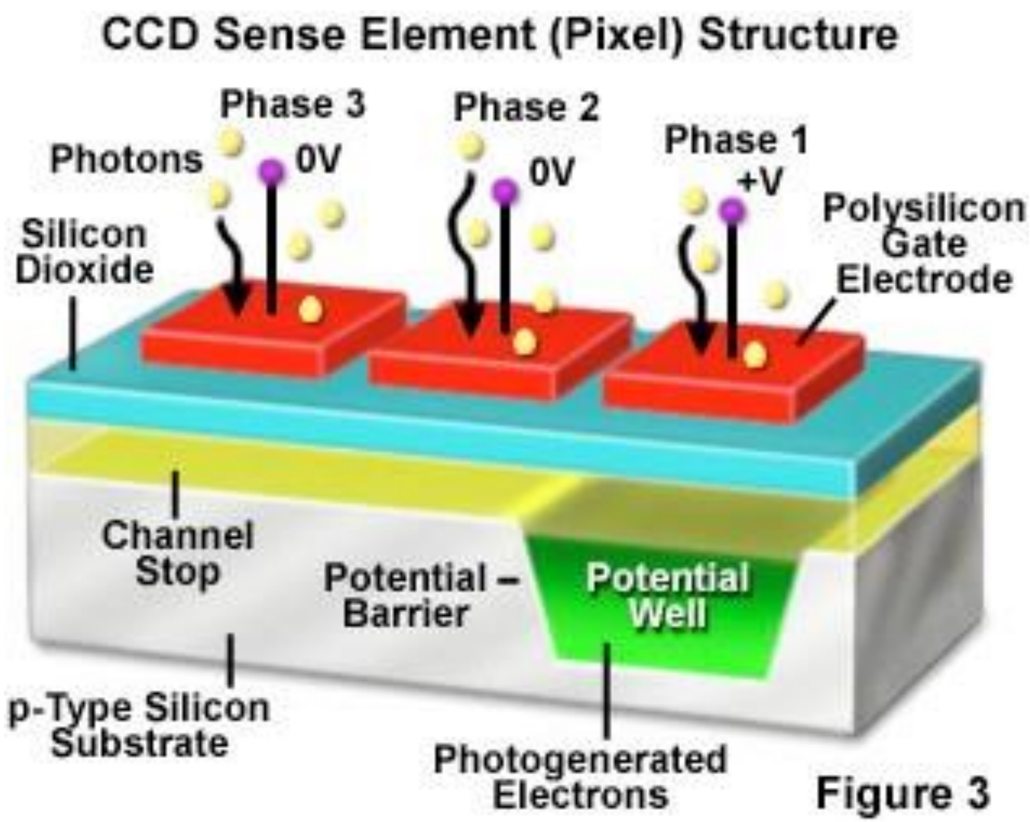
Band Gap Energy

- *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).*

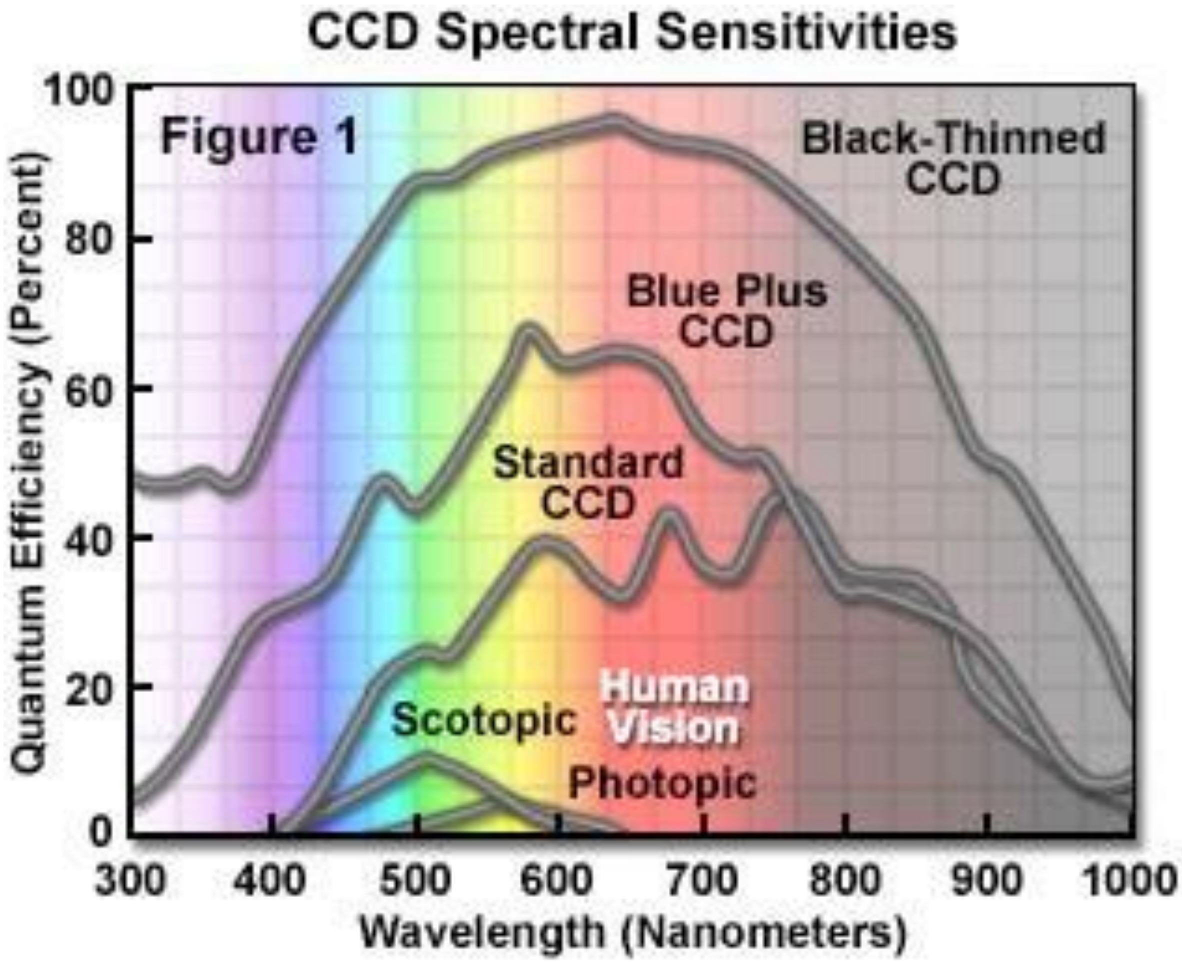
CCD readout



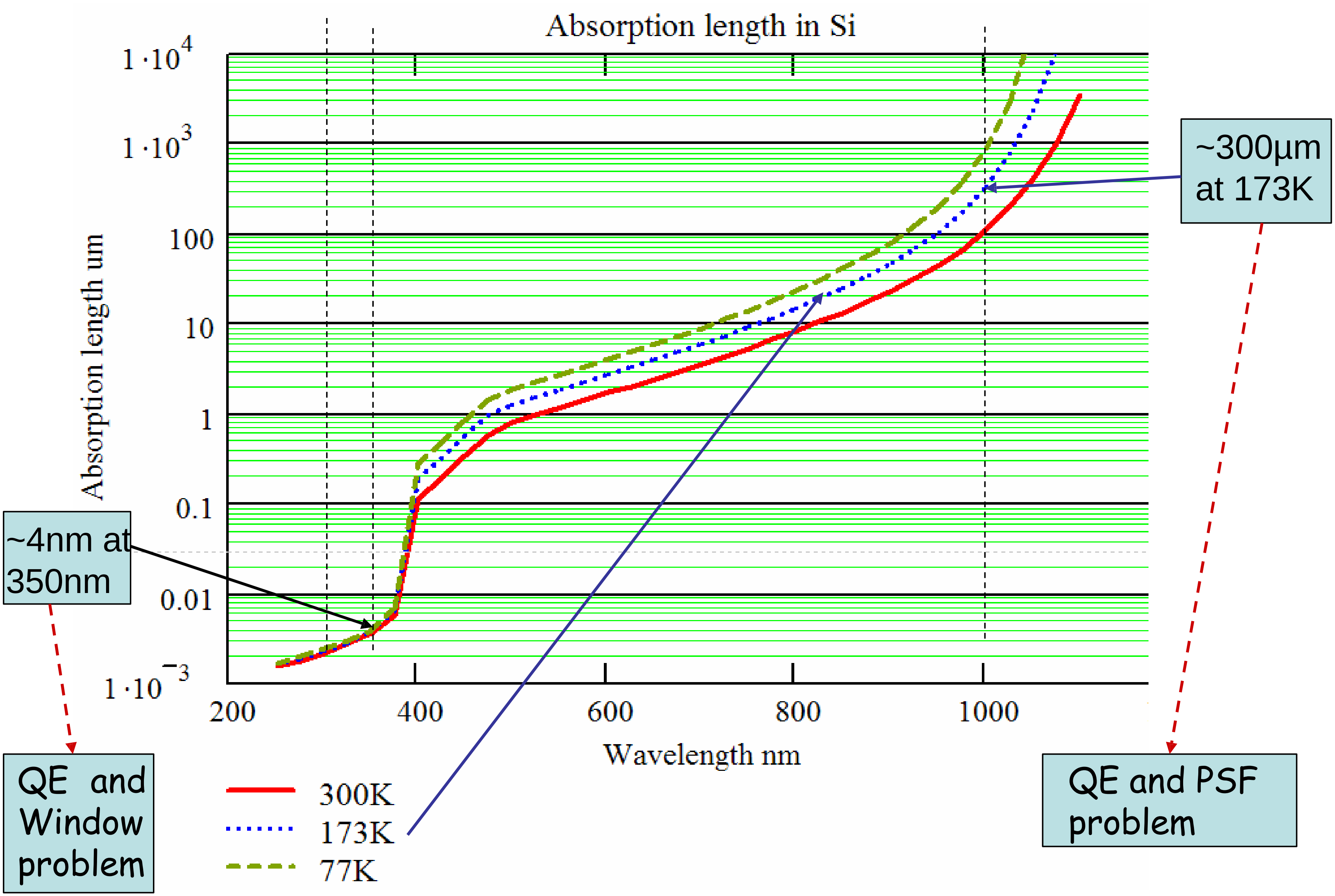
Schematic of typical 3-phase operation.
Charge is held by voltage potential until end of integration, then shifted, one pixel at a time, row by row to output.
Large CCDs move charge through thousands of pixels (c.f., CTE, multiple amplifiers)

CCD Properties

- Quantum Efficiency is the percentage of photons striking the CCD that are actually collected.

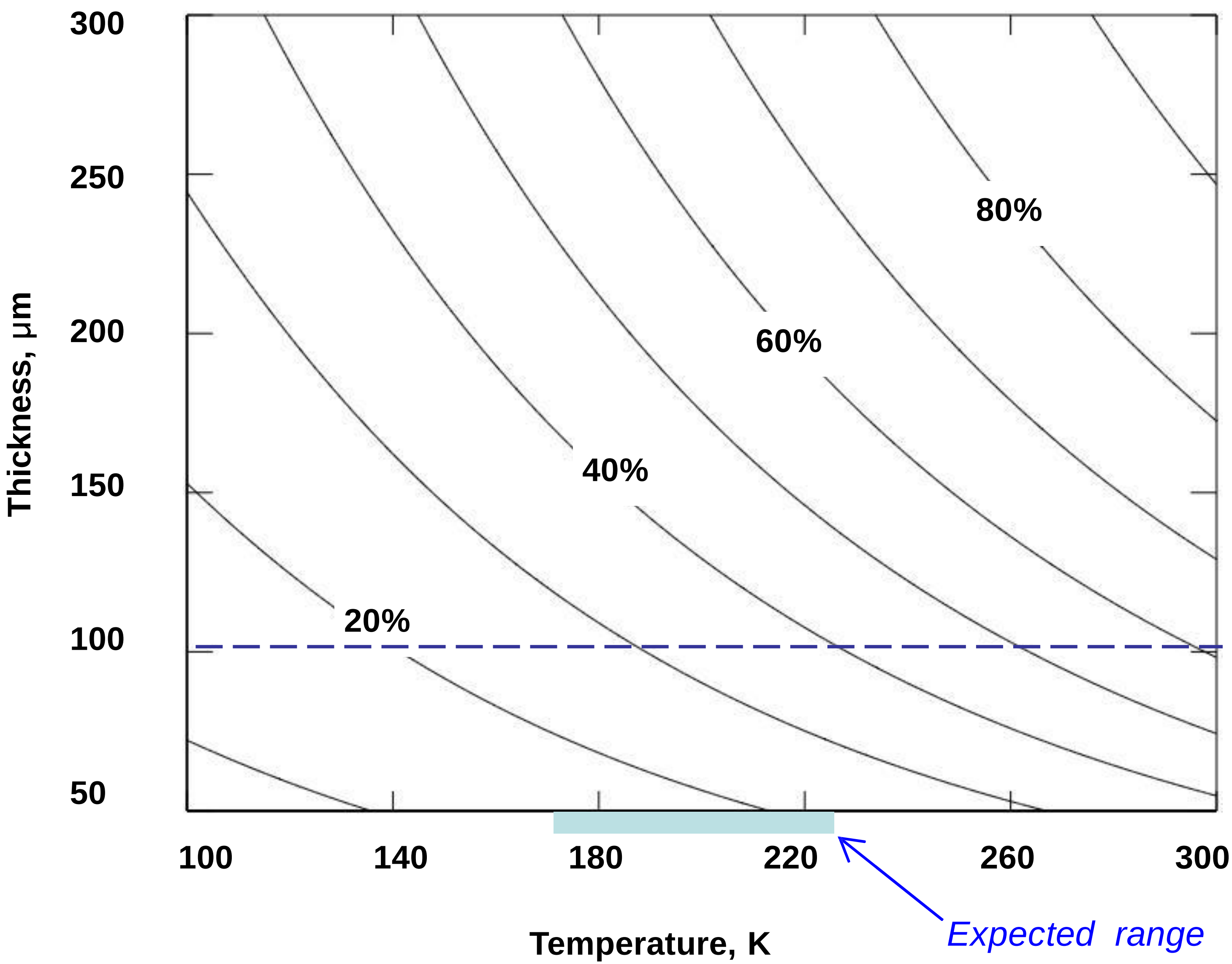


Scotopic vision is low light conditions (rod cells) , Photopic is daytime (cone cells)

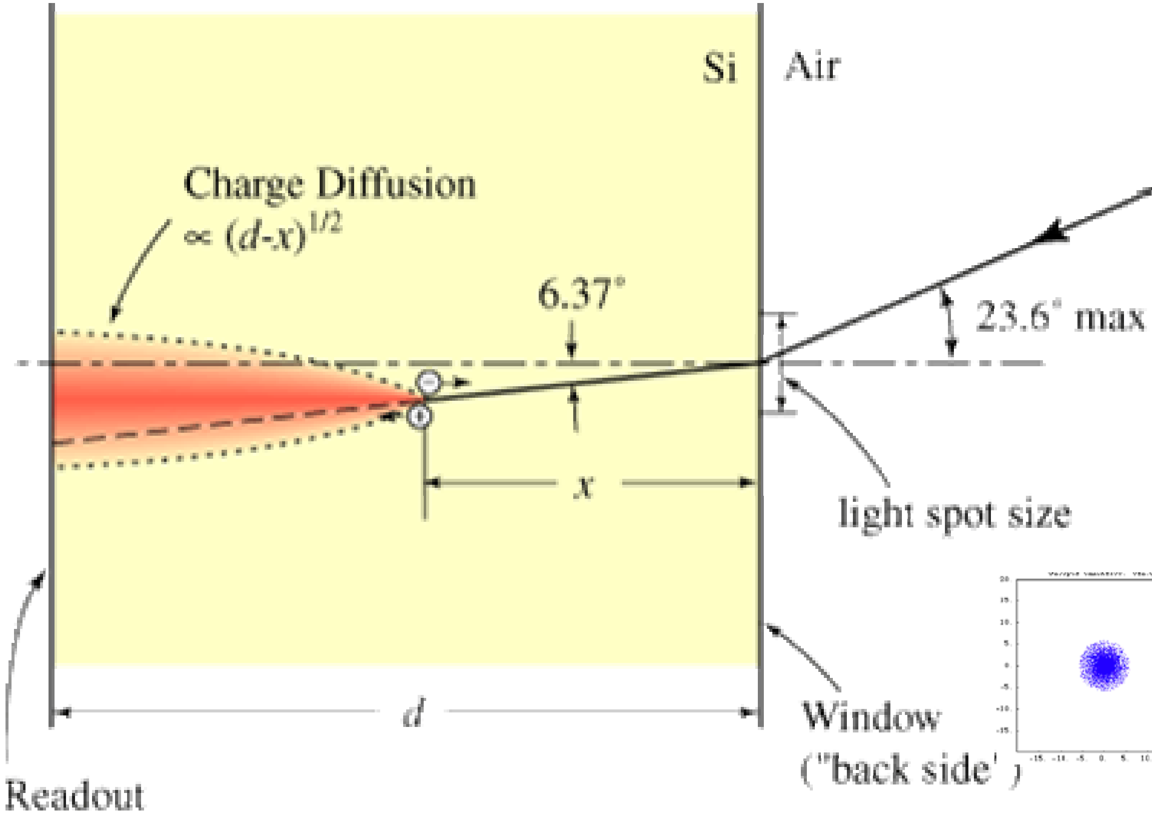


Absorption length in Si
Absorption length um
1·10^4
1·10^3
100
10
1
0.1
0.01
1·10^-3
200
400
600
800
1000
Wavelength nm
300K
173K
77K
~300µm at 173K
~4nm at 350nm
QE and Window problem
QE and PSF problem

Internal QE vs temperature and silicon thickness, for ***1000nm*** wavelength.

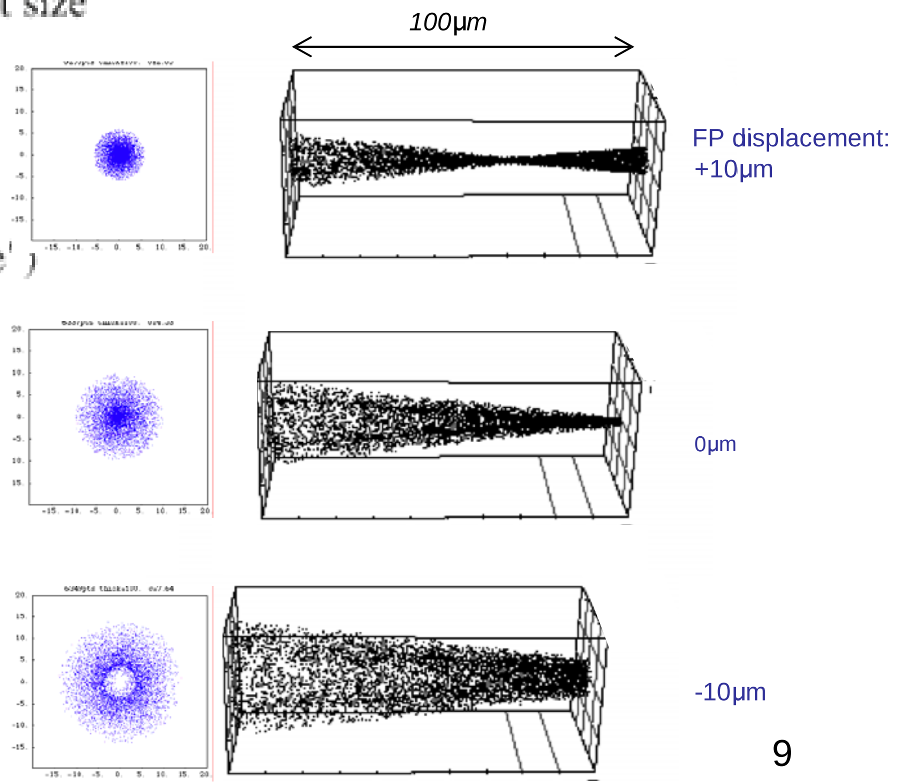


Point Spread Function (PSF) in Si



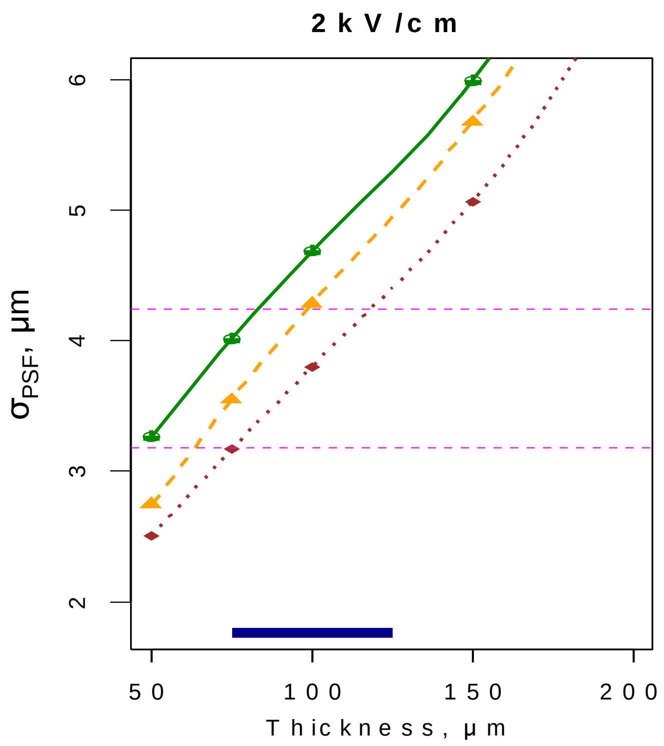
LSST (f~1.2!)

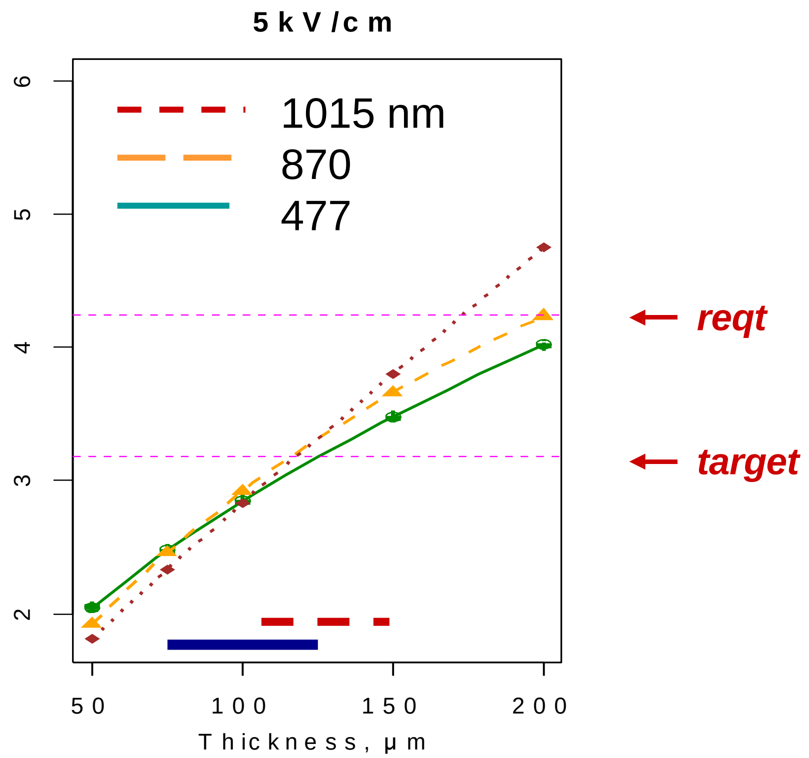
Simulation by P. Takacs, BNL:



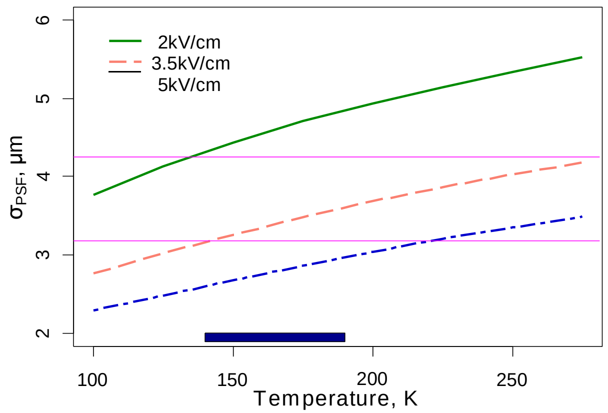
Light spot, cone, absorption→ionization, charge diffusion → PSF

Monochromatic PSF rms vs. thickness and electric field





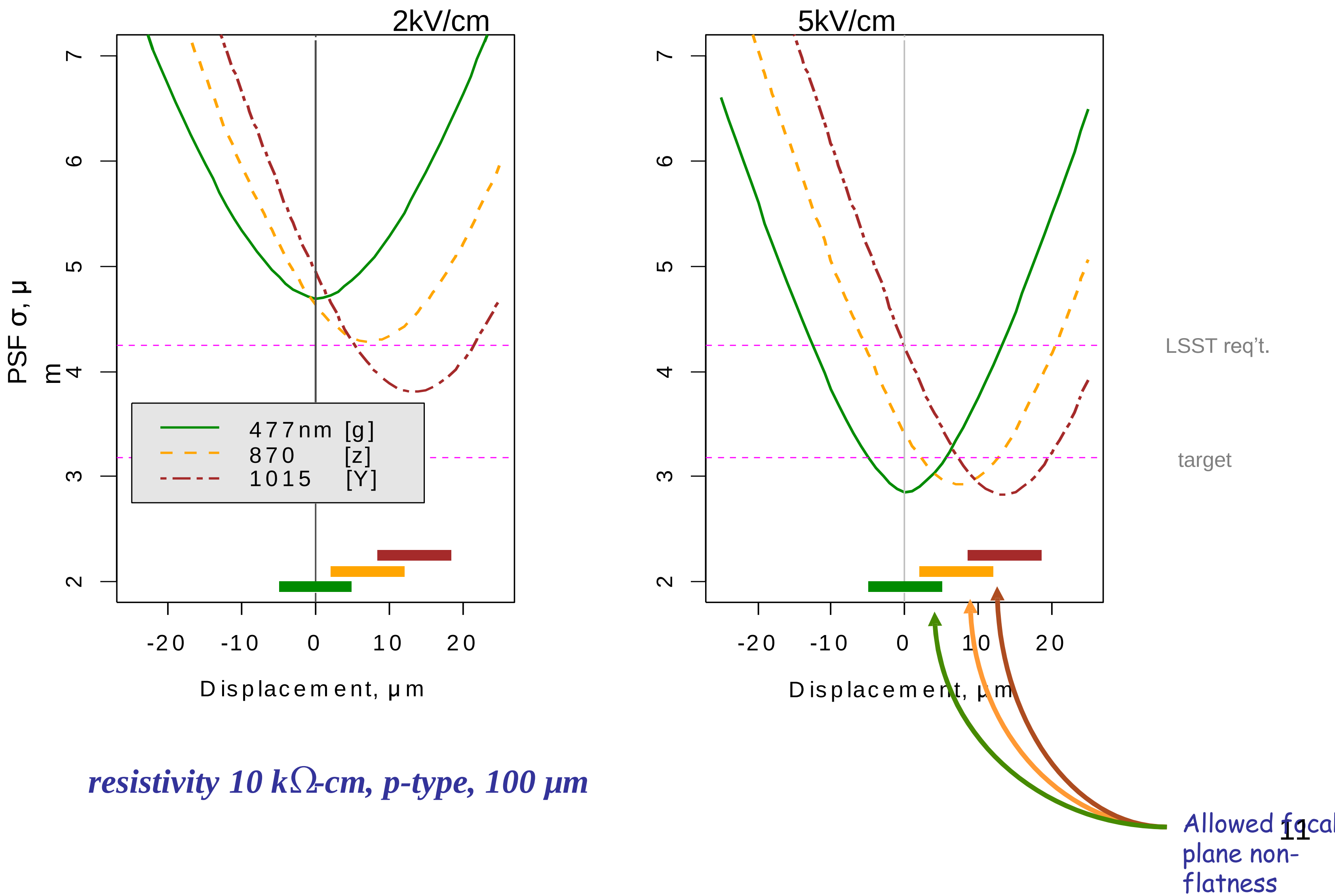
PSF vs T and E for electrons



- Includes effects of **diffusion** and **divergence**.
- ***Velocity saturation effects included***
- ***Focal plane position adjusted*** at each thickness and wavelength for minimum overall PSF.

resistivity 10 kΩ-cm, p-type, overdepleted

Optimal focal plane position varies with wavelength due to divergence of f/1.2 beam



resistivity 10 kΩ-cm, p-type, 100 μm

Partial vs Full Depletion

- **Conventional CCDs 15-20 µm thick on 20-100 ohmcm silicon cannot be fully depleted with 15-20 volts.**
  PSF (rms) **~** ***thickness of undepleted region*** **(≥~6-7 µm)**

- **Full depletion essential for minimal charge spreading,** ***PSF (rms) < ~ 4 µm***

- **Methods to ensure full depletion:**
  - ***High-resistivity substrate*** **>5 kohm cm**
  - ***Bias on p+ (n+) back-surface*** **(30-50 volts on 100 µm)**

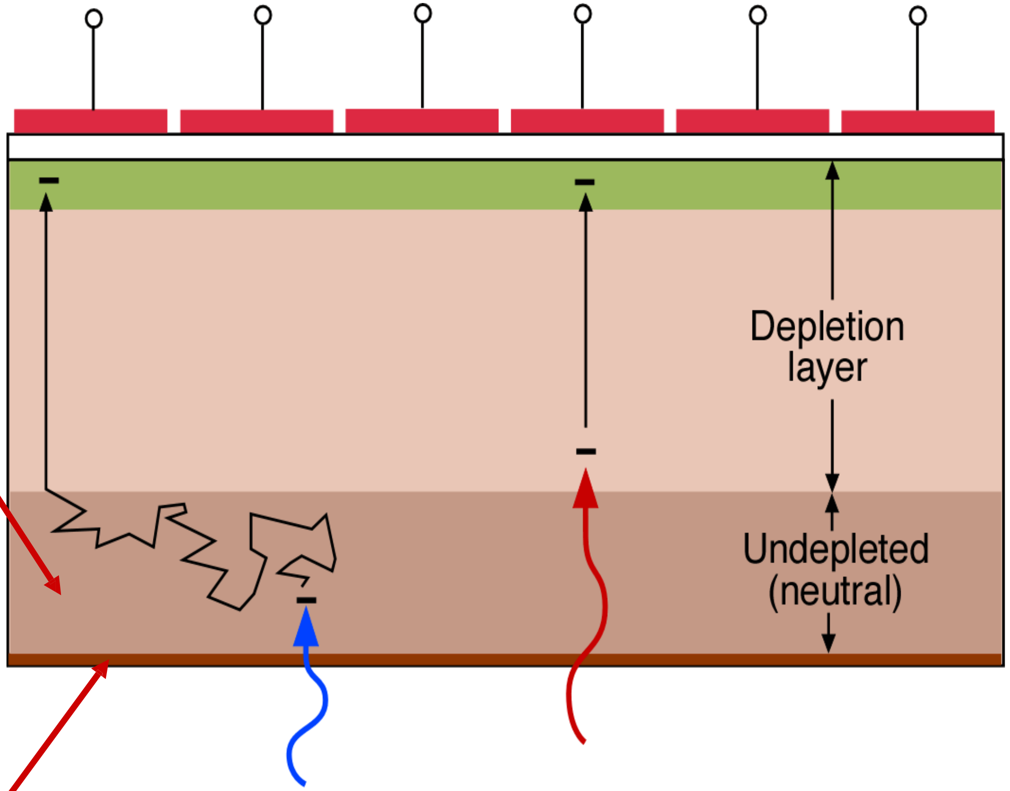
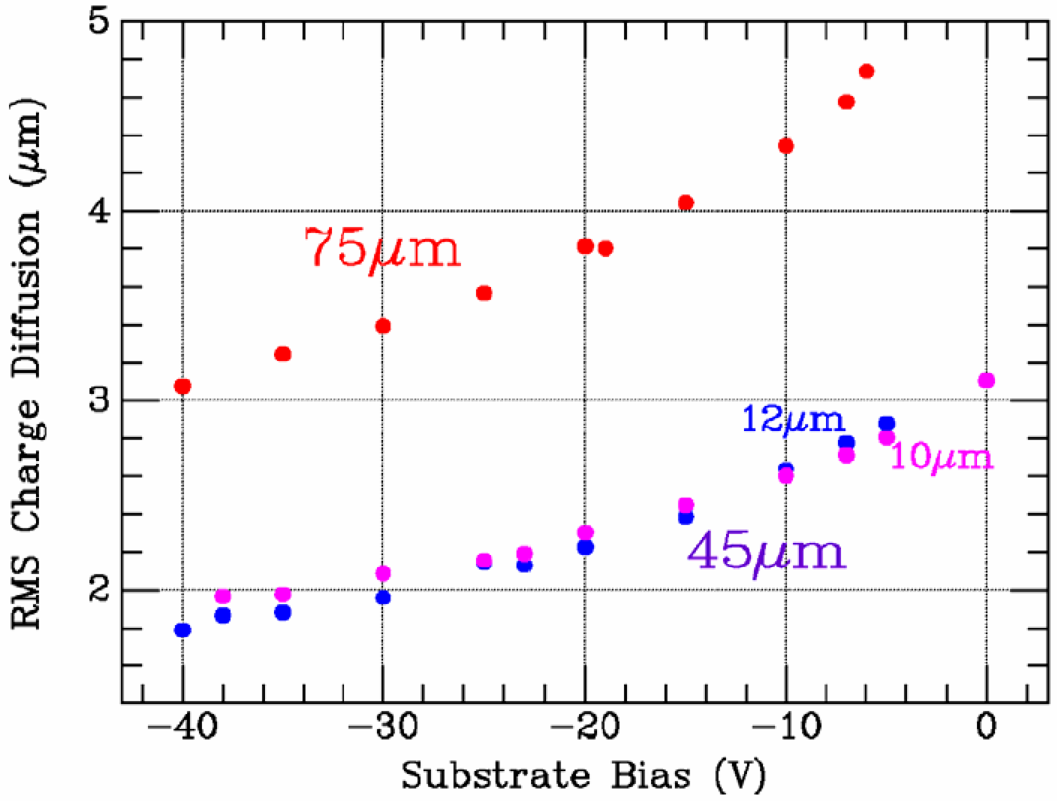


Illustration from: Barry Burke

Can the predicted small diffusion be achieved?

CCDs developed at LL for PanSTARRS.
B. Burke, J. Tonry, et al. results:



Calculation incl.velocity saturation effects predicts ~2.5 μ m rms at 40 volts for electrons (p-substrate).

For LBNL/SNAP CCD results see S.Holland, this conference

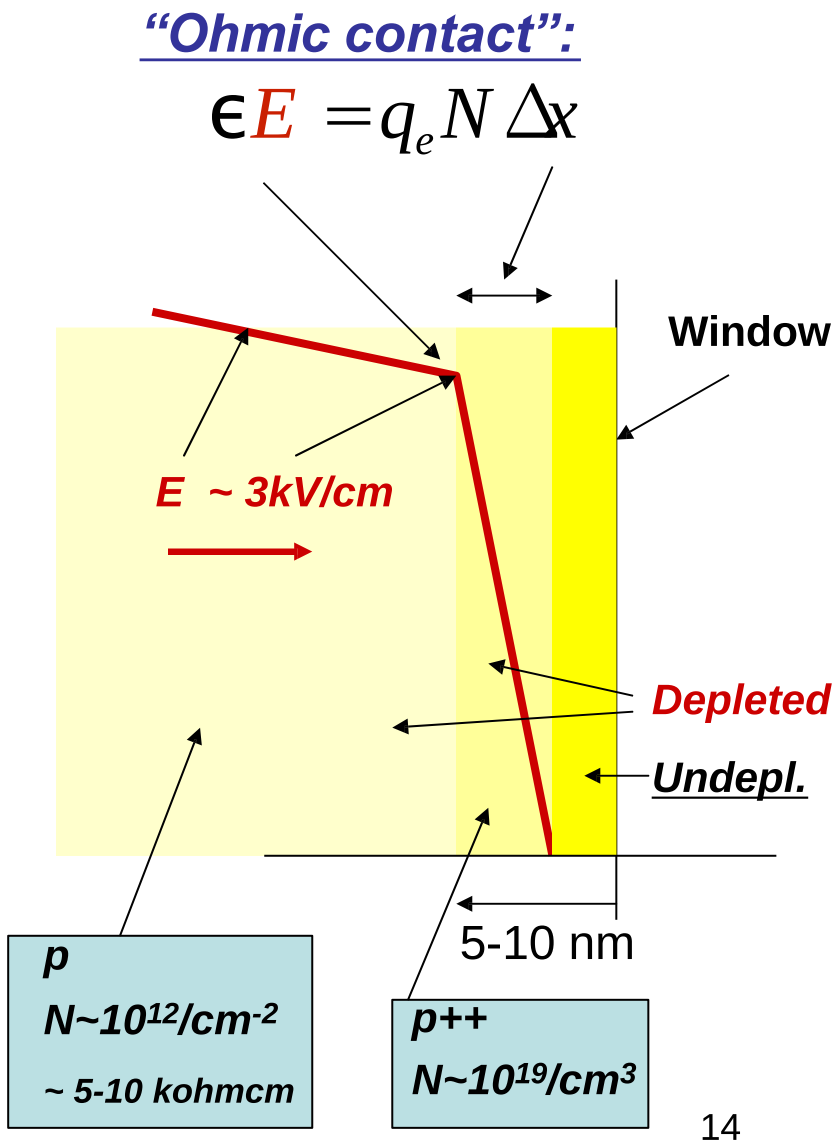
Window Technology

A highly doped layer at the window required to terminate the field and leave a thin conductive layer at the surface.

Highly doped layer thickness <~10 nm to allow uv light into the sensitive (depleted) region.

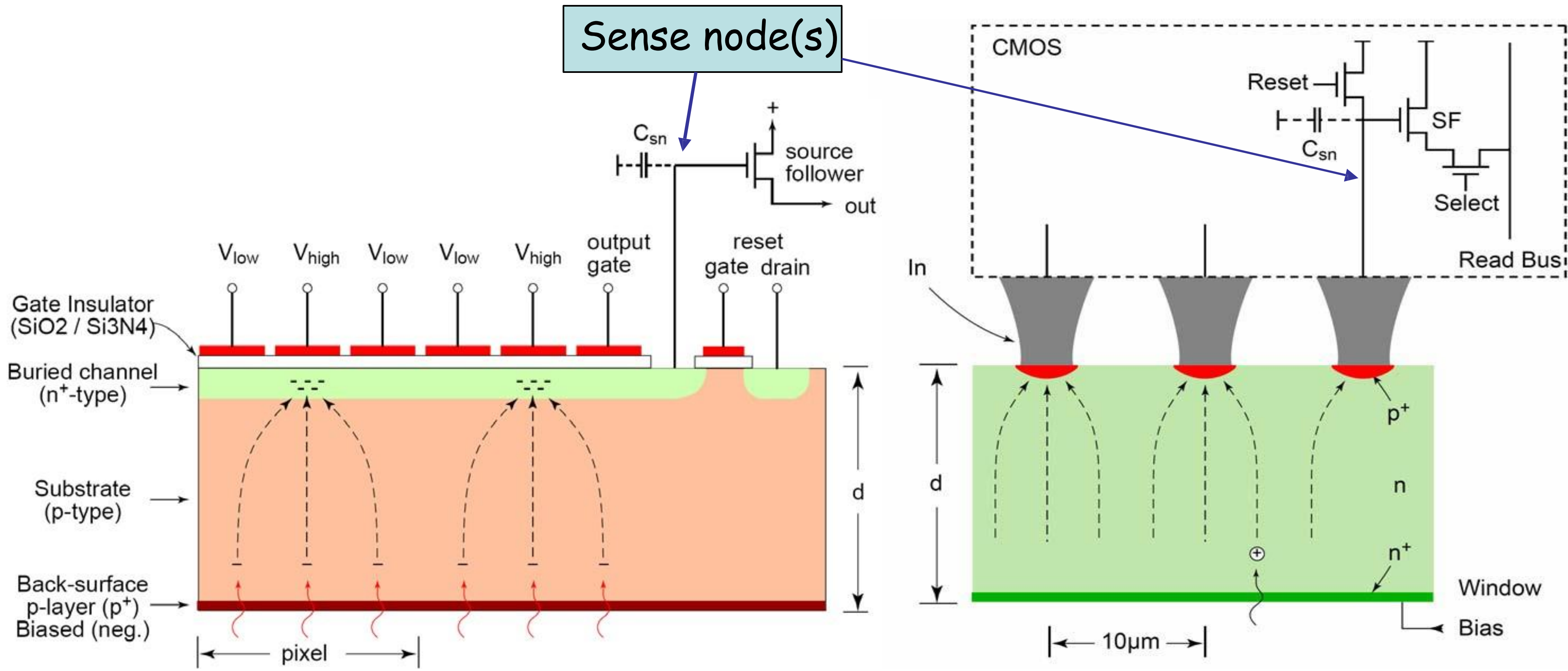
Technologies under development (must be compatible with antireflective coating):

- Ion implantation followed by laser annealing - low T process (LL)
- Doped polysilicon deposition – high T process (LBNL), presentation by S. Holland
- Chemisorption charging – very good for uv response, but no conductive layer (ITL)



CCD

Hybrid PIN-CMOS



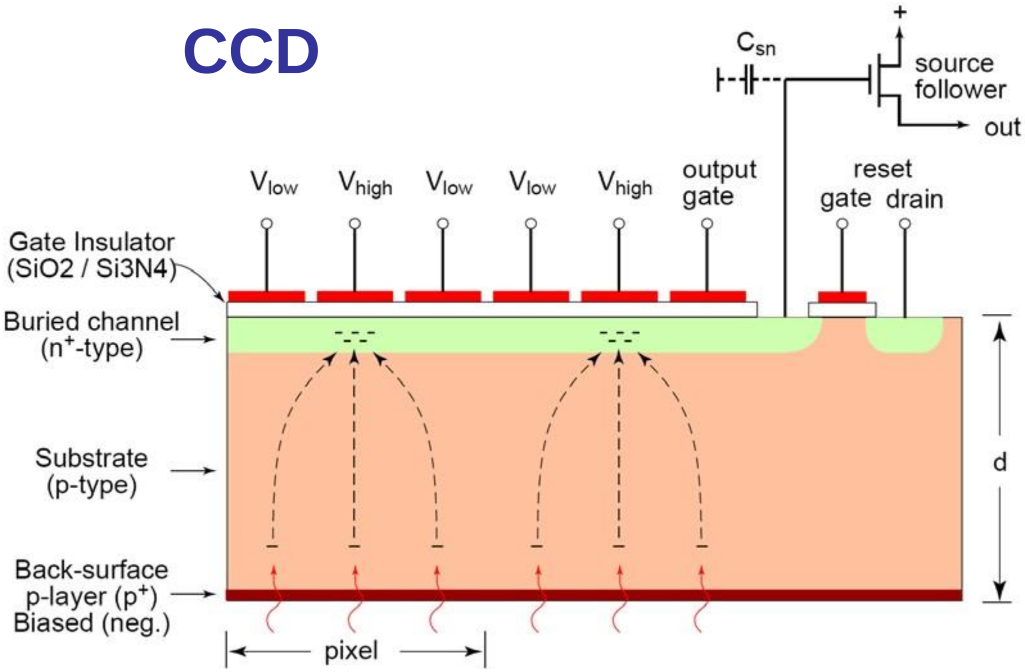
•In a CCD, the signal charge is transferred ***serially*** by a noiseless process (very high CTE) to ***a single sense node,*** where it is converted to a signal voltage.

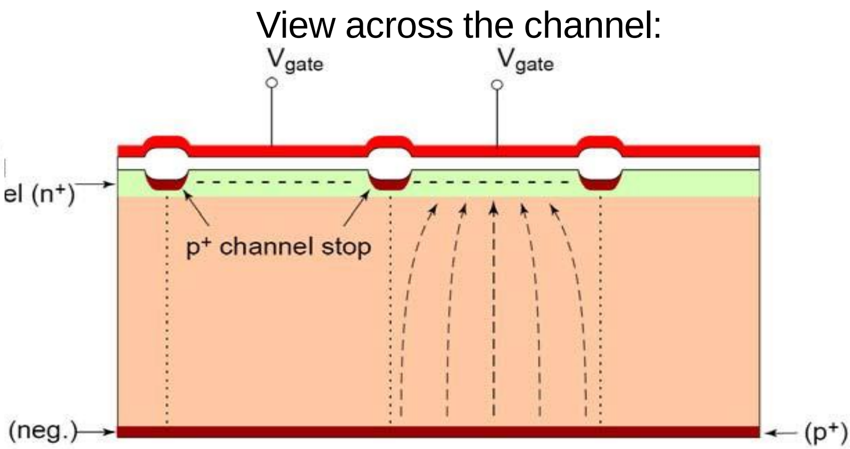
•Pixels are read out ***after*** the integration is completed.

•In a PIN CMOS sensor, the charge to voltage conversion takes place ***in parallel at the sense node of each pixel***.

•The signal voltage can be read out “up the ramp” ***during*** integration.

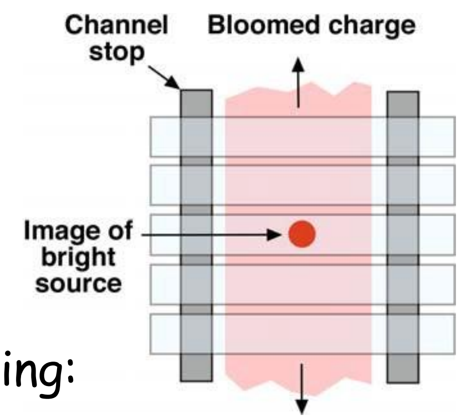
CCD





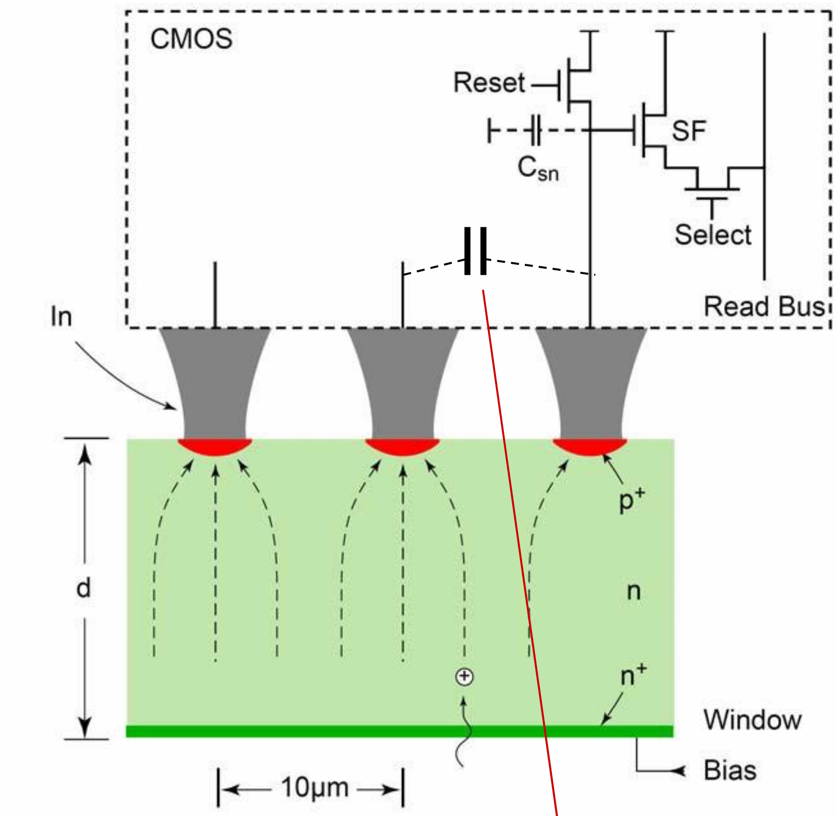
- Photoresponse non-uniformity <1%
- Dark current in inversion mode ~0.001 e/pixel sec
- Correlated double sampling each clock cycle
- More complex clock amplitude and phasing requirements
- High power dissipation with segmented readout
- Independent window biasing→design constraints

- Blooming:

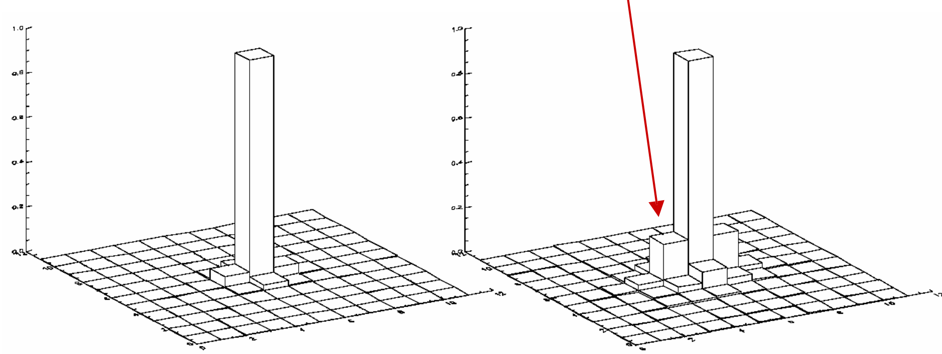


PIN-CMOS

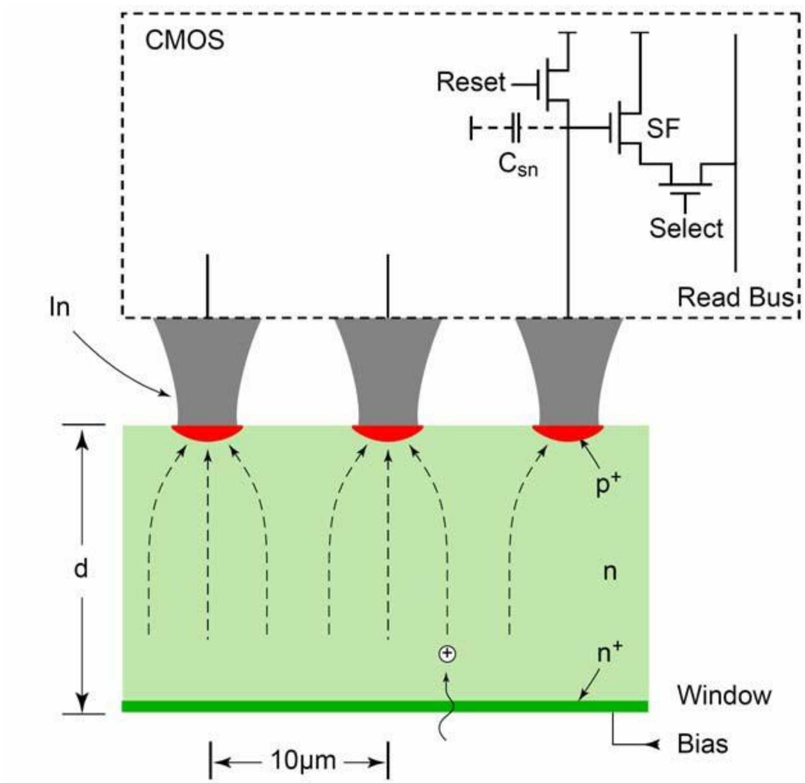
- Independent optimization of the PIN and CMOS design and processing
- Electronic shutter by reset transistors
- Blooming control
- Large dynamic range by readout "up the ramp"; addressable guider readout
- Lower power dissipation, low voltage for CMOS
- Fixed pattern noise
- pixel-to-pixel (stable) gain differences due to amplifier per pixel
- capacitive (deterministic) crosstalk to adjacent pixels
- CDS over longer time intervals

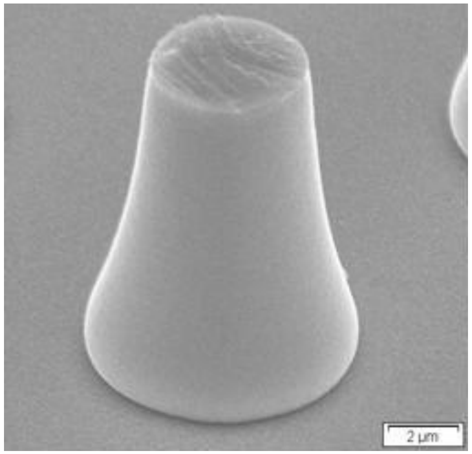


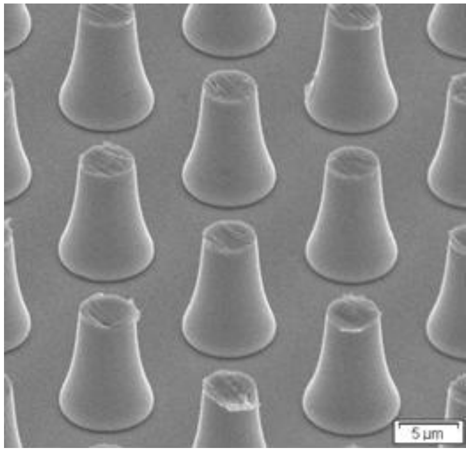
J. Beletic. Et al.:



Indium Bump Bonding

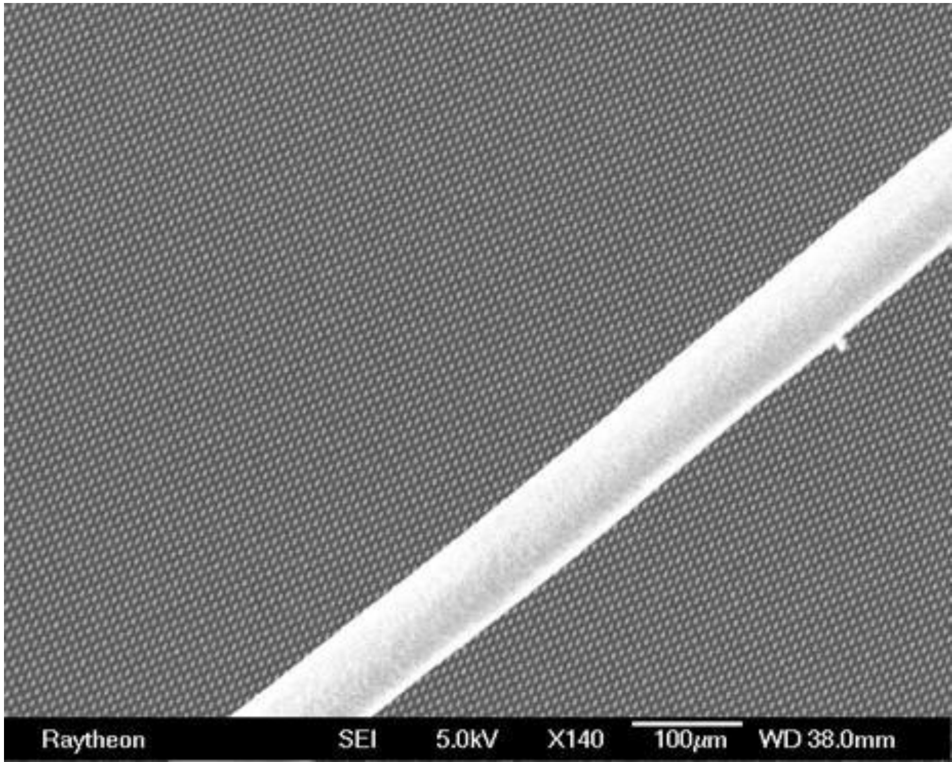






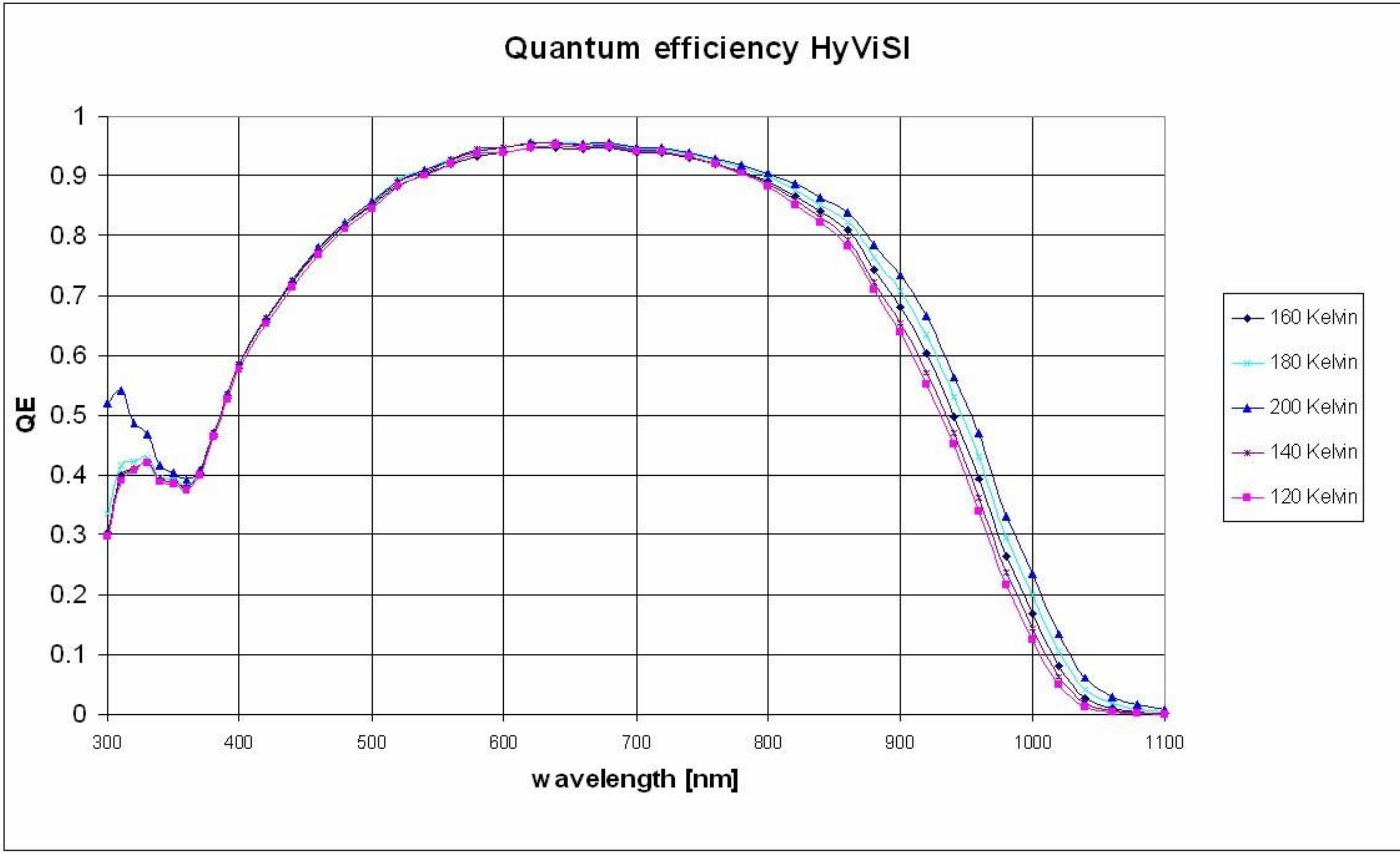
Bond yield by RVS and RSC >0.999

Indium interconnect array on 8 um centers compared to a human hair.



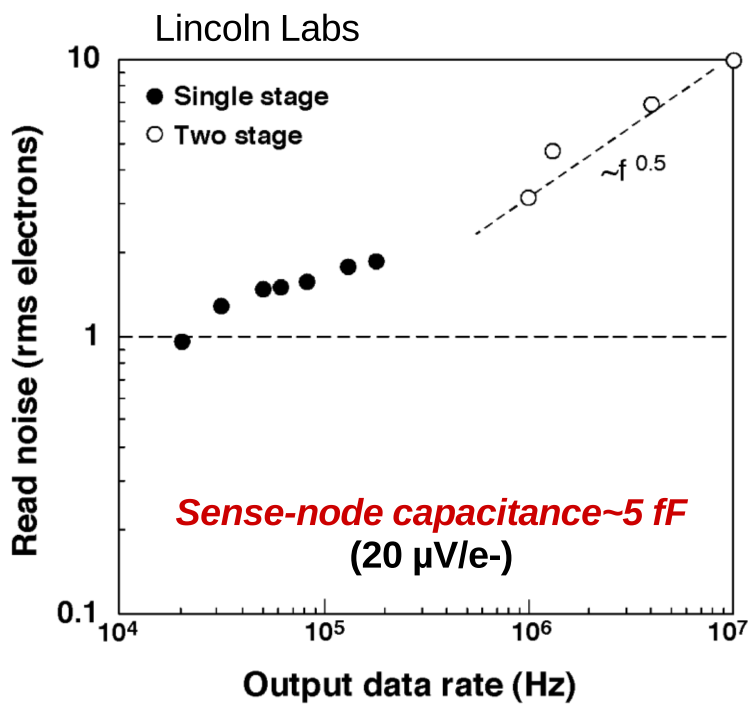
From: K.T. Veeder et al., "Enabling Technologies for Large Hybrid Focal Plane Arrays with Small Pixels", Raytheon Vision Systems

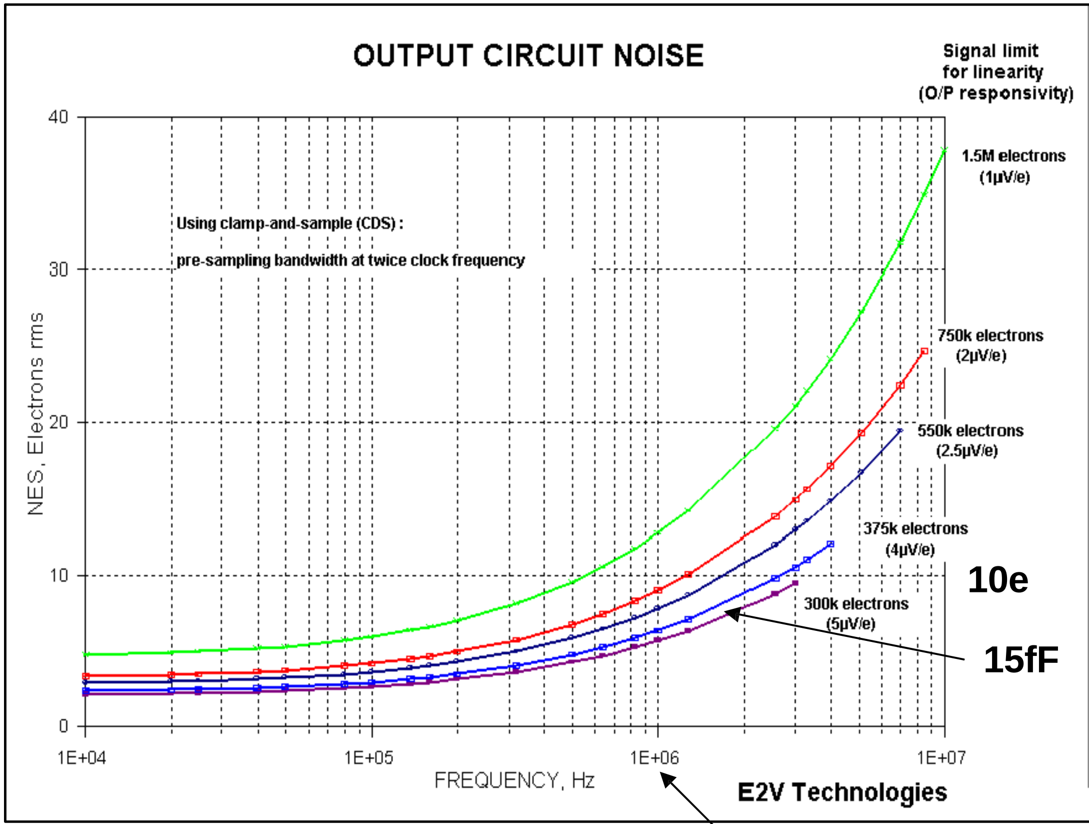
Teledyne RSC - H2RG (2Kx2K, 18 μm pixel) HyViSI Measured quantum efficiency (courtesy Reinhold Dorn, ESO).



This HyViSI array has a detector layer that is 75 microns thick and a single layer anti-reflection coating of SiO_2 that is 1200Å thick.

Readout Noise in CCDs



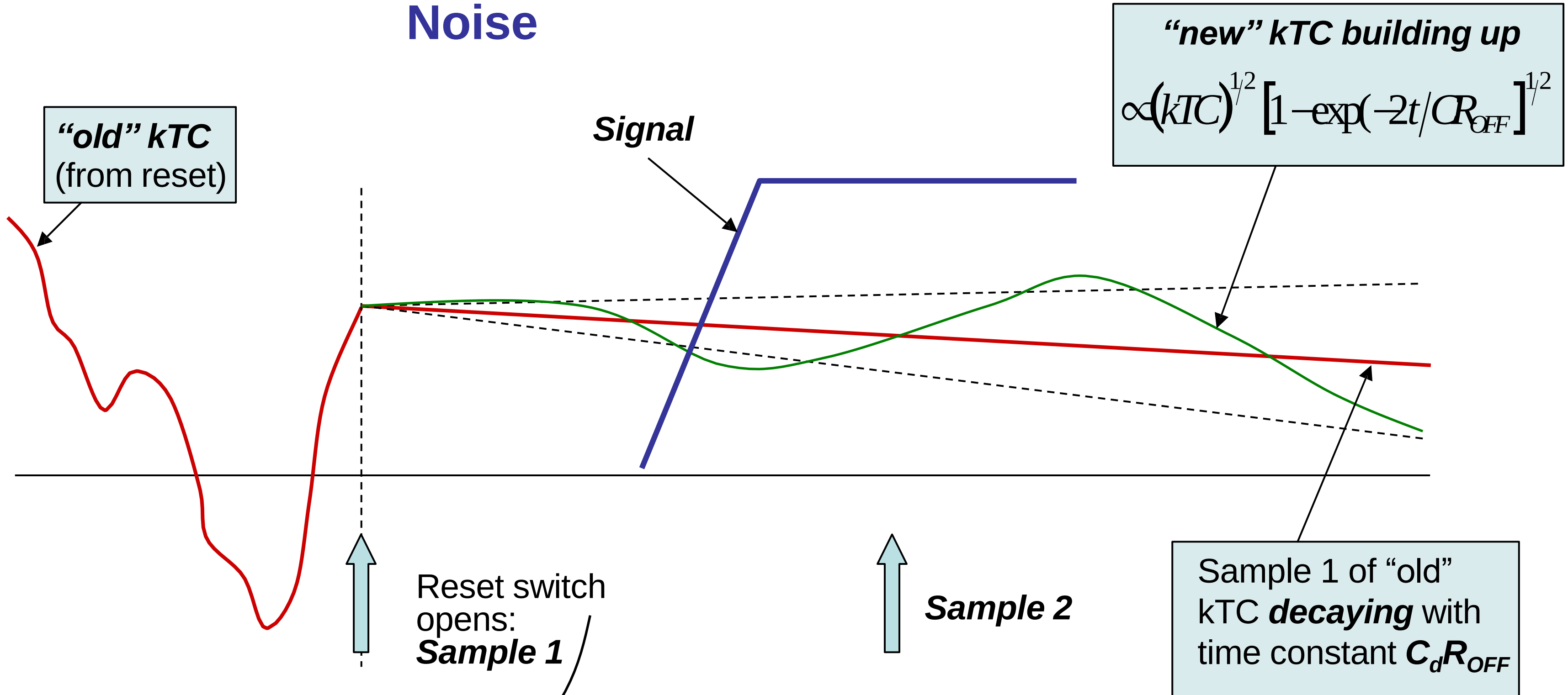


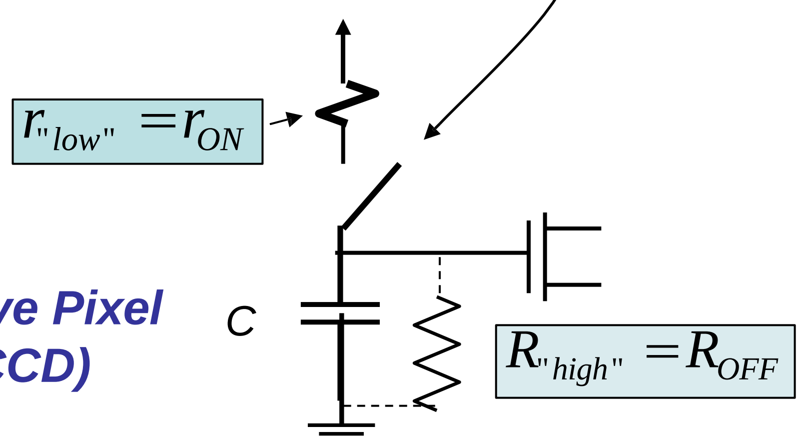
Source Follower transistor:	By CCD process:	MOS(P):
Channel length L:	~4-6 µm	~0.4-0.5 µm
Channel width W:	~45 µm	~10 µm
Power:	***5-10 mW***	***<100 µW***

For equal noise!

Results From: Burke, Jorden, Vu, SDW Taormina 2005

Correlated Double Sampling (CDS) and *kTC* Noise





Active Pixel (or CCD)

$R_{OFF} / r_{ON} \approx 10^6 - 10^{11}$

Example:

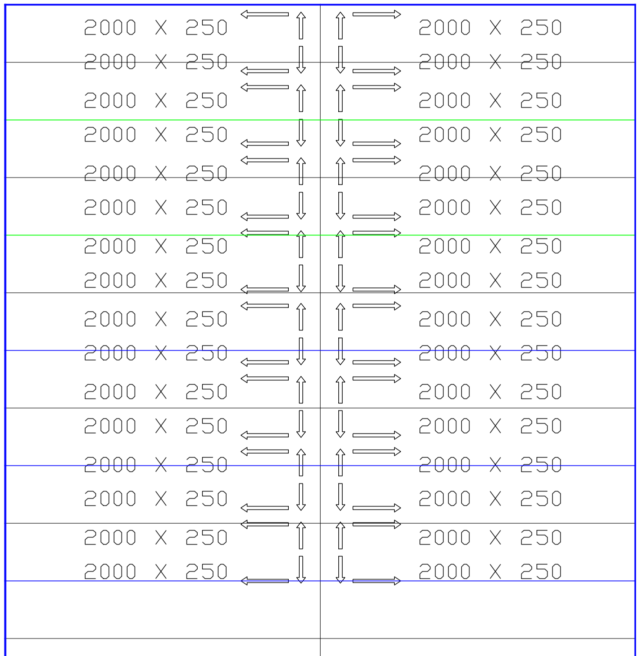
C ~ 20 fF → *kTC~40 e rms!*

r_{ON}~ 10^3 ohms $\quad$ $r_{ON}C$ ~ 20 ps

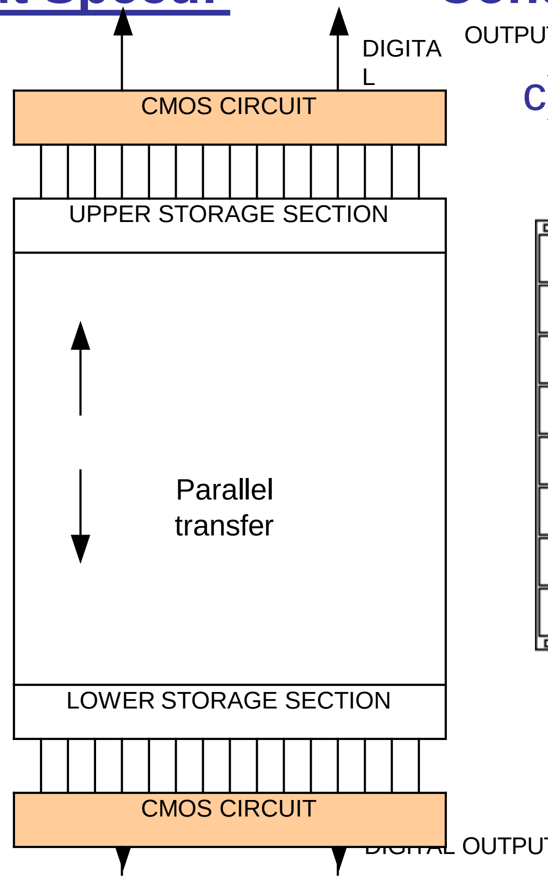
R_{OFF}~ 10^{13} ohms $\quad$ $R_{OFF}C$ = 0.2 s

Segmenting CCDs for Readout Speed: Condition: < 5 e rms

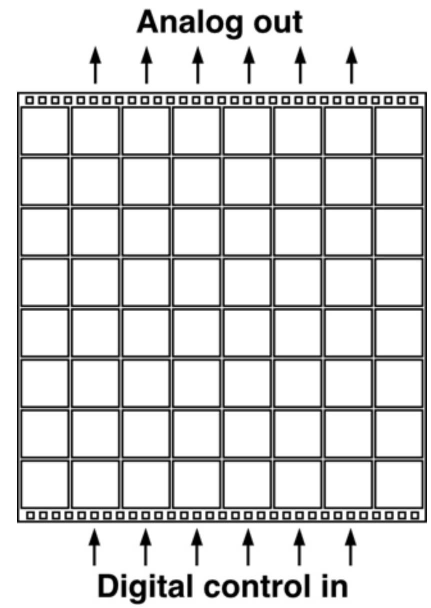
a)



b)



c)



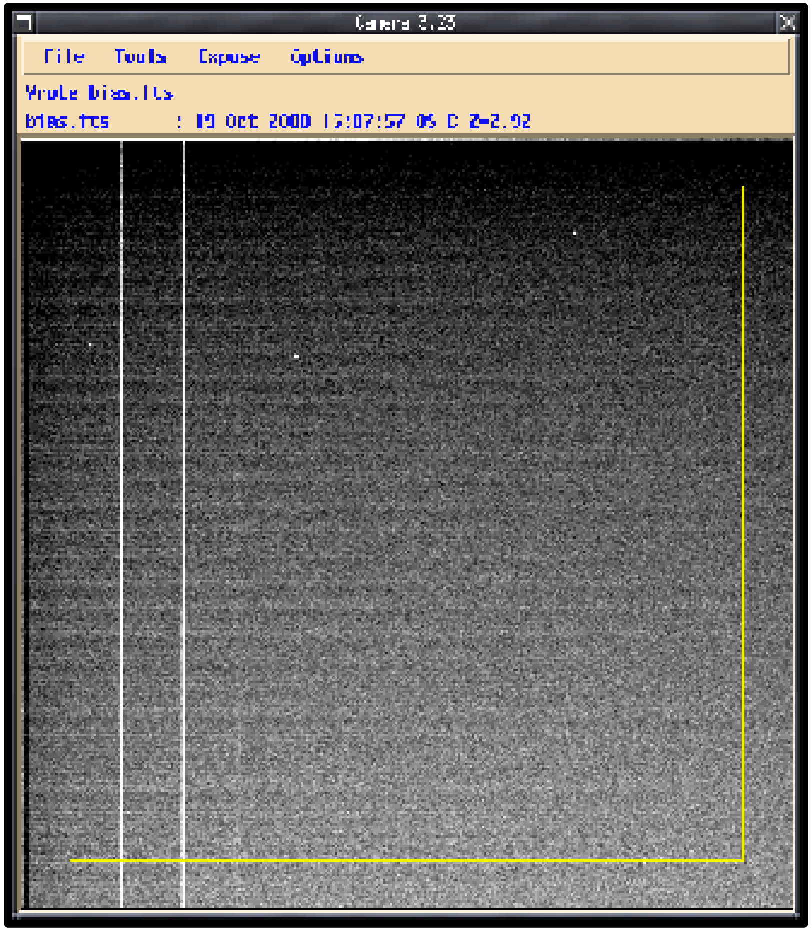
All arrays 4kx4k=16 Mpixels

	a)	b)	c)
Segments:	Up to 32	Up to 2x4k!	64 (or more)
Advantages:	Short columns – -blooming localized	High frame rate	Combination of a) and b) if not an OTA
Disadvantages:	Non-contiguous imaging due to serial registers	Long columns (blooming)	Density of outputs too low for direct bump bonding to CMOS readout
Application:	LSST-like telescopes	X-ray detectors	
Source followers:	on CCD	On or off CCD	On CCD (Pan STARRS), or off

CCD Observations

- 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)

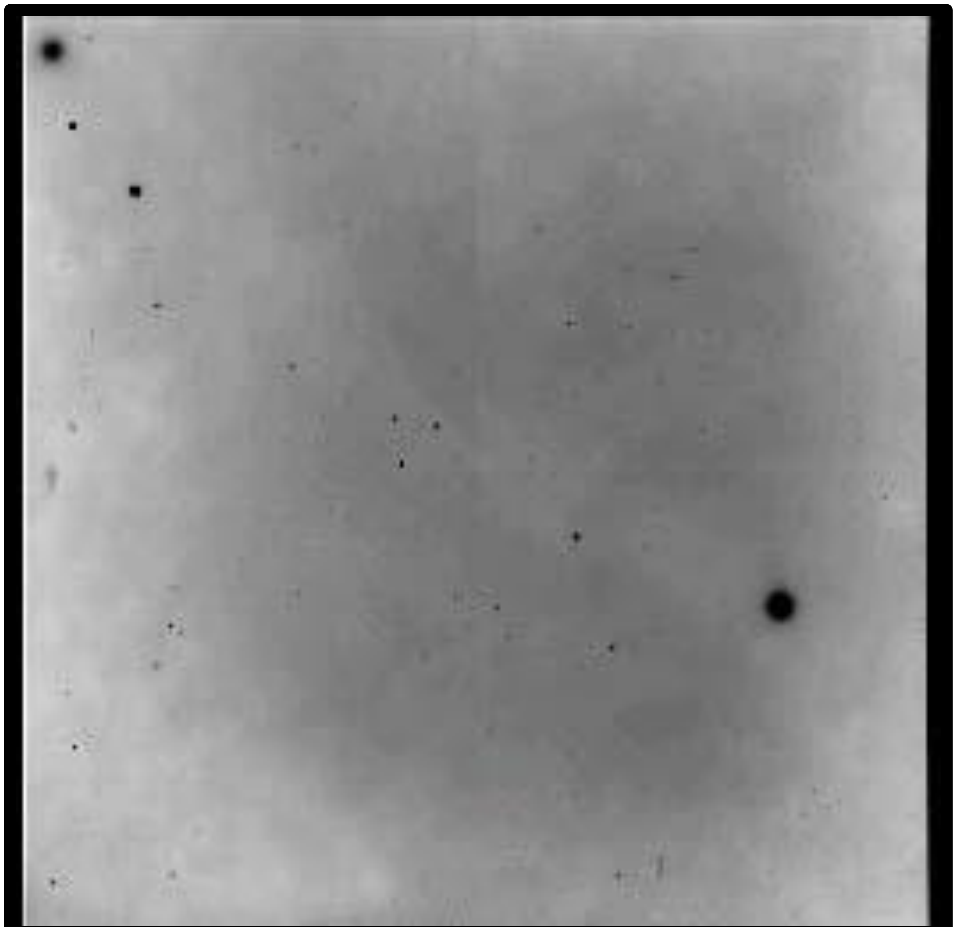
CCD Image Types – Bias Frame



- 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

CCD Image Types – Flat Field

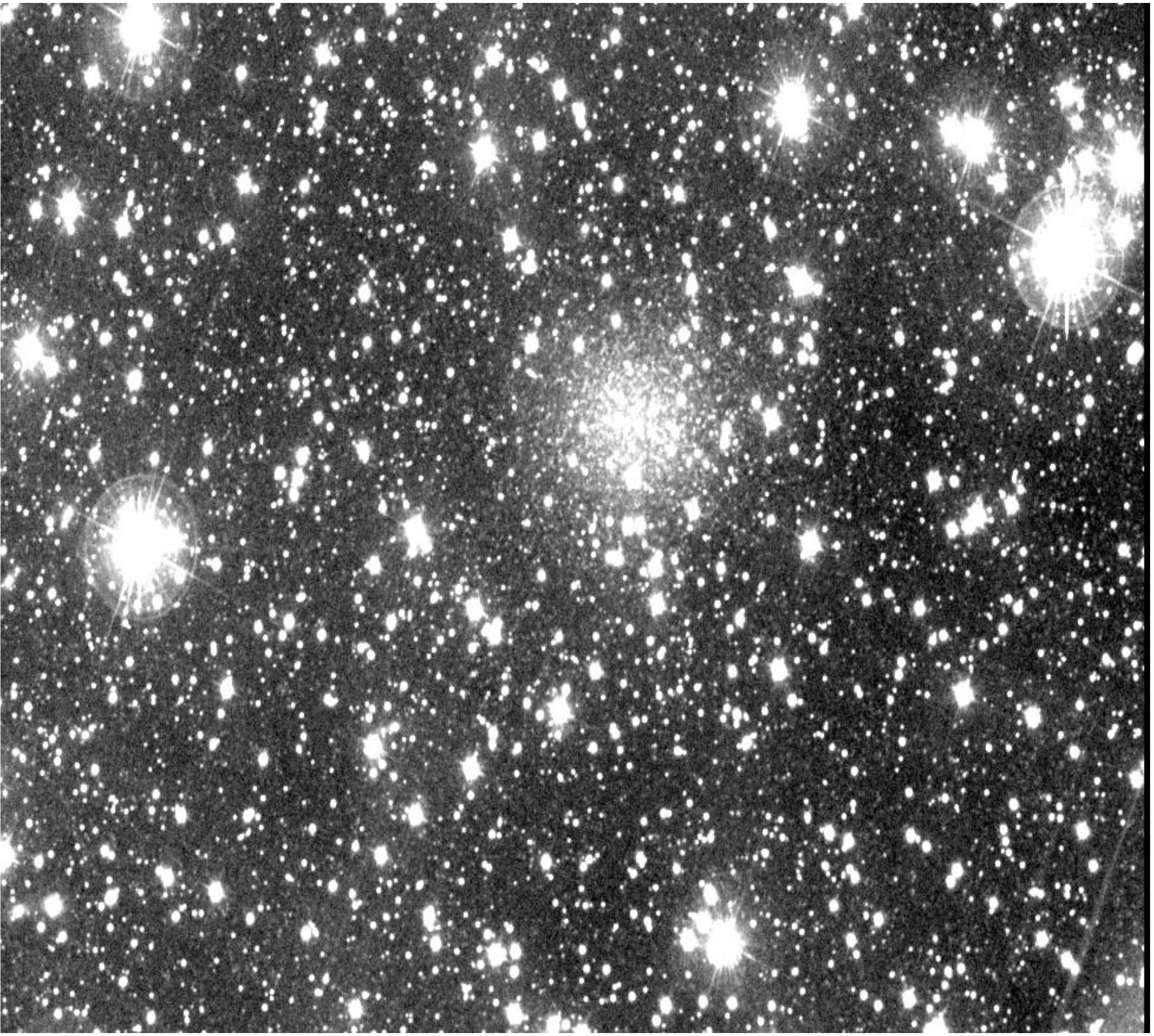


- **FLAT FIELD - calib.**
  - A flat field image is used to determine the relative QE of each pixel in the array
  - Flat field images are obtained from dome screens, the sky, or quartz lamps projected in to a spectrograph

Basic CCD data reduction

- Minimal set of images: bias, flat, and object
- Darks needed if dark current an issue
- All frames include overscan
- Additional steps needed for specific CCDs and specific observations – instrument manuals should provide details
- Basic reduction
  - (Object – Mean Zero) / Mean Flat
- LOOK AT YOUR DATA – Does it make sense?

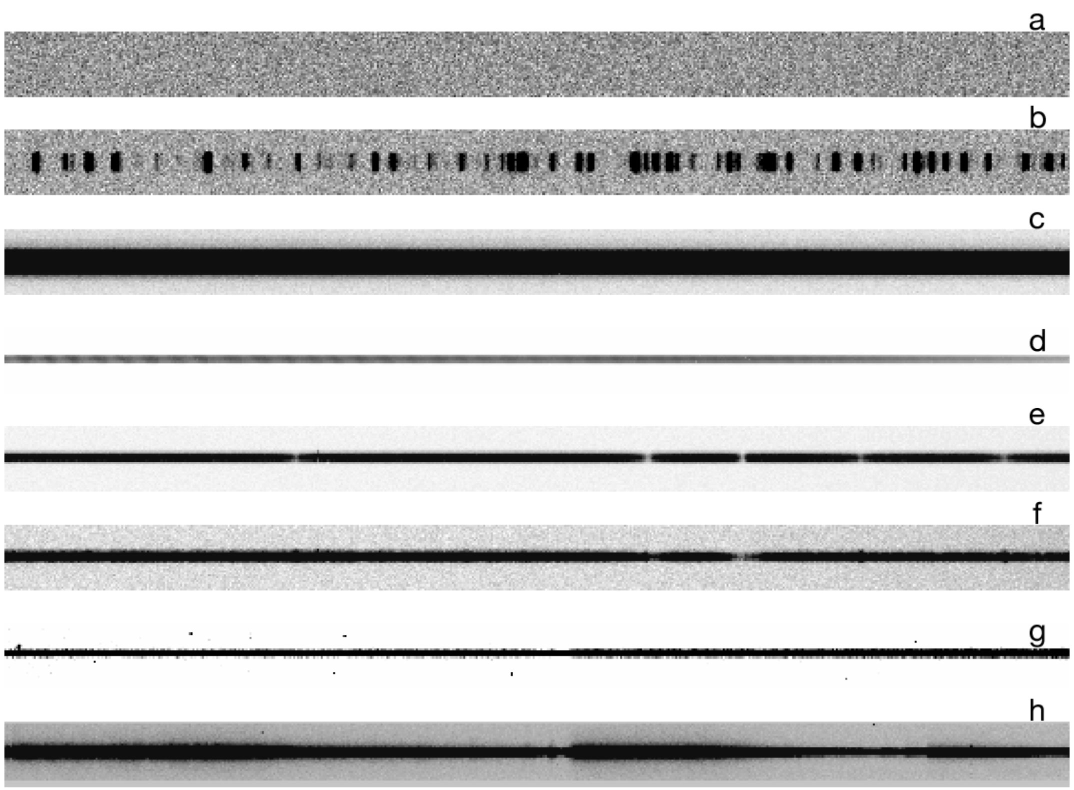
CCD Image Types



Object

– CCD images are grey scale representations of the collected and stored ADUs.

CCD Image Types



- **SPECTROSCOPY**

Spectra - light dispersed into pixels that correspond to colors.

Trends:

- CCDs ~75-200 μm thick for astronomy (more for x-rays) –-being developed by several manufacturers.
- Conventional CCD readout will be limited to a small number of segments (power dissipation, number of connections).
- Silicon PIN CMOS remain to be proven and accepted in astronomy. If so, will prevail for short readout times. CCDs will still be best for long integration times.
- Pixel size will bottom out (full well charge, readout time, …).
- CCD-CMOS hybrids need to be explored for high performance imaging in astronomy (they are being actively developed for other fields).