Electronics Imaging System for the Synchrotron Light Source

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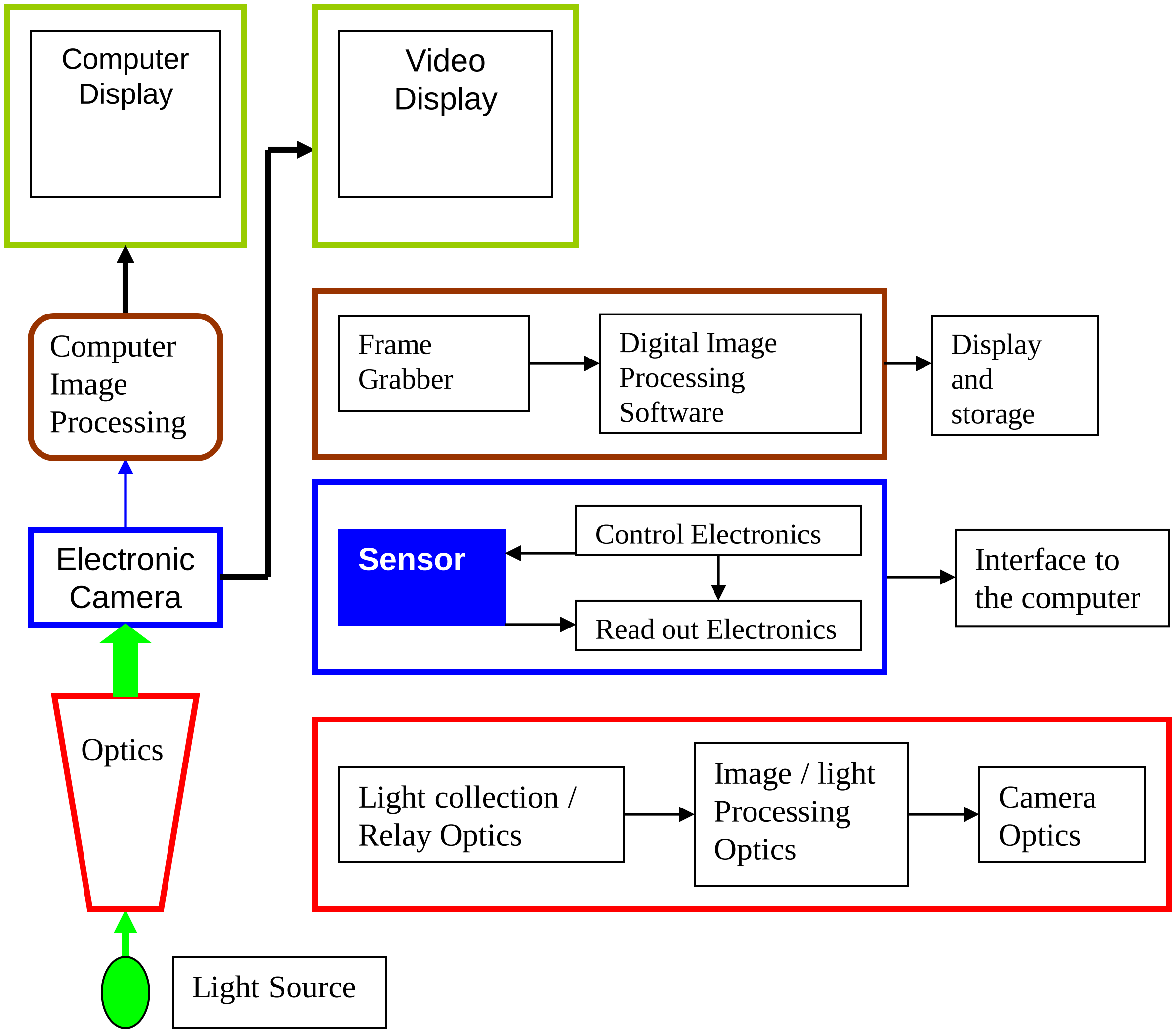
The key components of an Electronic Imaging System for a synchrotron light source



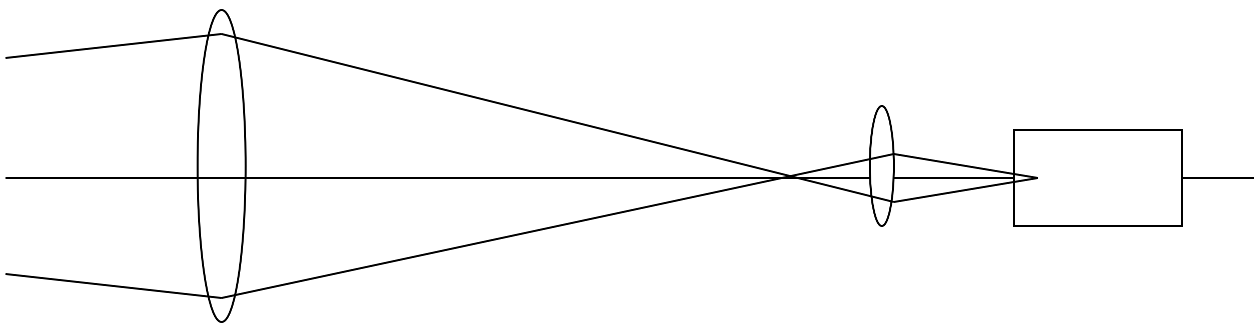
Key components of an electronic imaging system

- The ***source*** – what is coming out of the Synchrotron?
- The ***optics*** – to transform the light from the source for detection
- The ***camera*** – to detect the transformed light
- Digital ***image processing*** – to extract and store information

Visible Beam Source Characterization

- Vertical beam size – Interferometer, CCD camera
- Cross section /vertical / horizontal– CCD camera
- Axial beam size – temporal beam size, Streak camera.
- Time history of the beam – Scanning mirror imaging system, amplitude variation over time

Optical design for imaging the beam cross-section



Demagnification Lens

6 inch lens or 6 inch mirror to select the beam size for experiment

Magnification Lens

Long working distance microscope objective with magnification filling up the area of the sensor

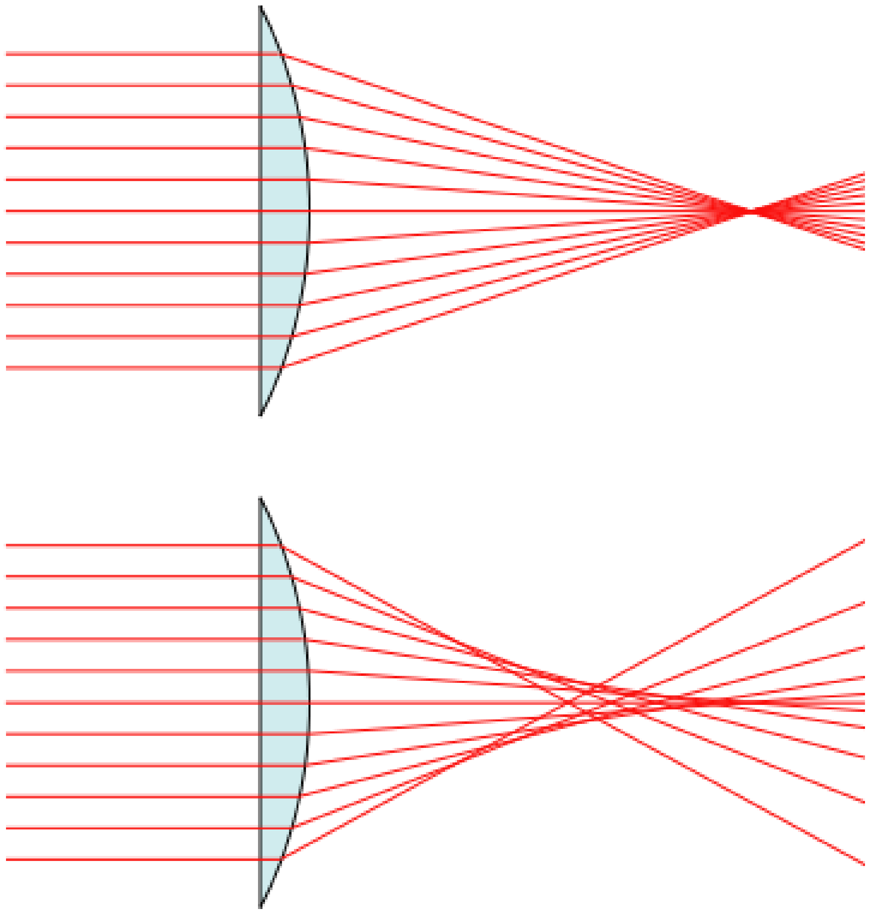
Optical design

- Polarization change due to reflection – variation of the X- and Y-components of the
- Wave front deterioration causing variation in beam size
- Reflective optics – advantage, wide band, spherical aberation, focal length varies with aperture
- Refractive optics – chromatic aberration, variation in focus for different color of light

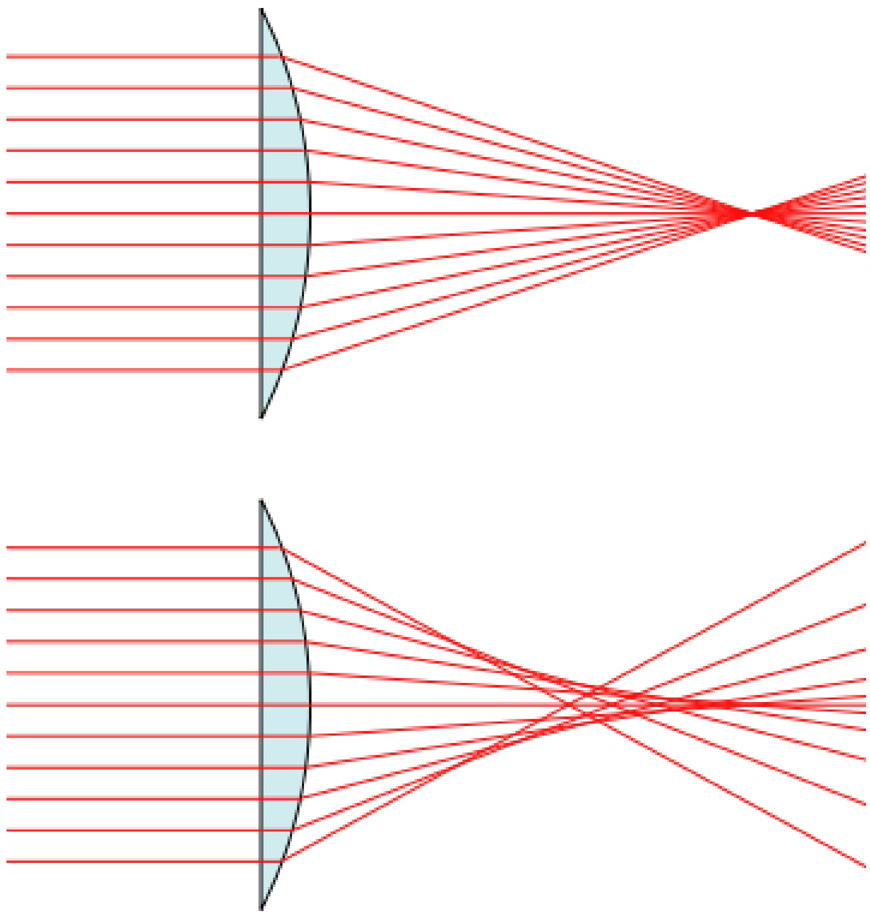
Speed

- Processing time
- Rise time- 10, 300 ps, 5 ns
- Fall time - ns

Spherical aberration- broadening the image image



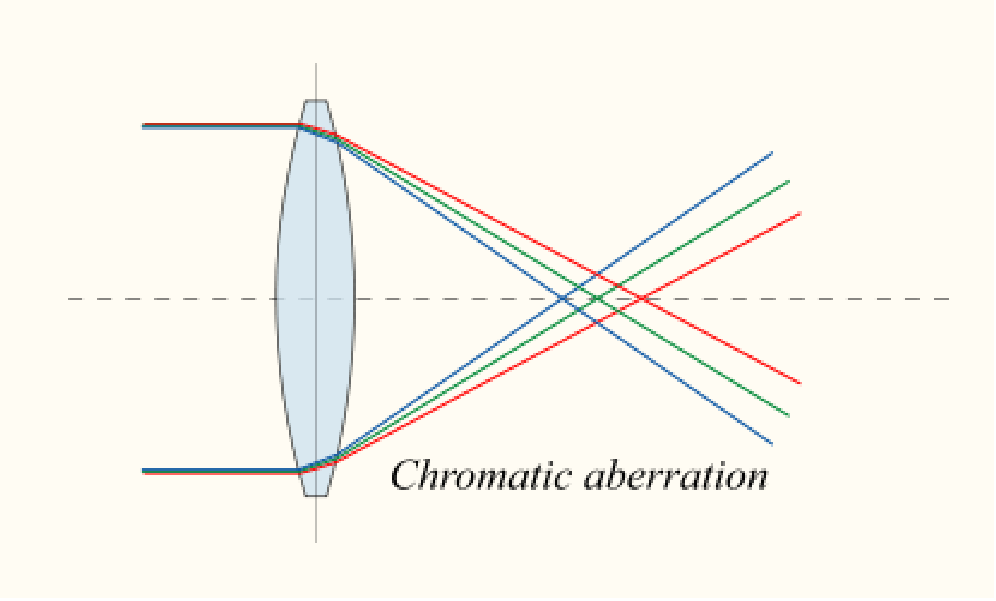
Reduction of Spherical aberration-Use only the center portion of the lens or mirror



Chromatic aberration of a single lens causes different

wavelengths of light to have differing focal lengths

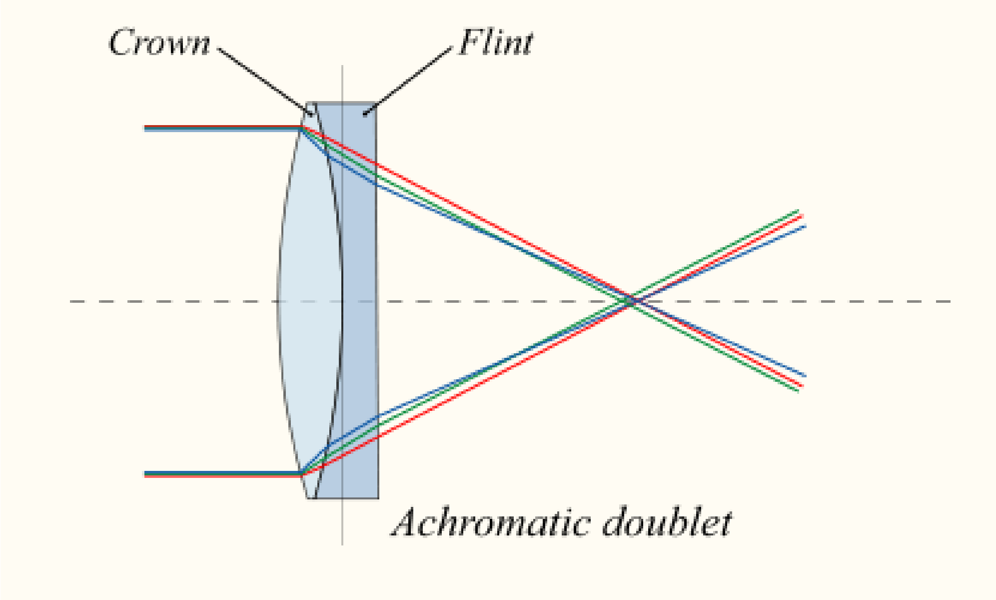
Broadening of image



Reduction of chromatic aberration –Achromatic doublet

visible wavelengths have approximately the same focal length

The IR UV are not compensated



Narrow band color filter, limit the operation with single wave length.

PI-MAX Data Acquisition

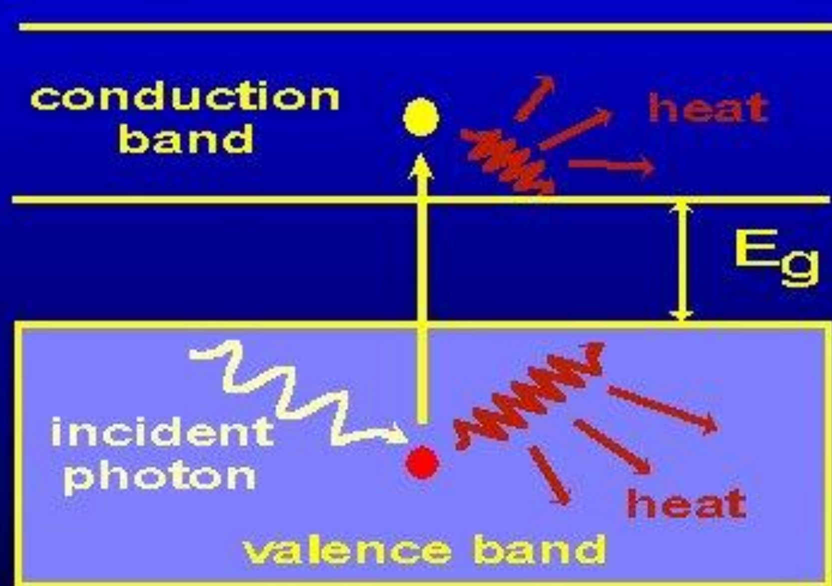
- Major components of the Intensified-CCD
- PI-Max Data Acquisition system
- Operation of PI-Max Data Acquisition system
- Application in synchrotron light imaging.

Different Kinds of Imaging Sensors

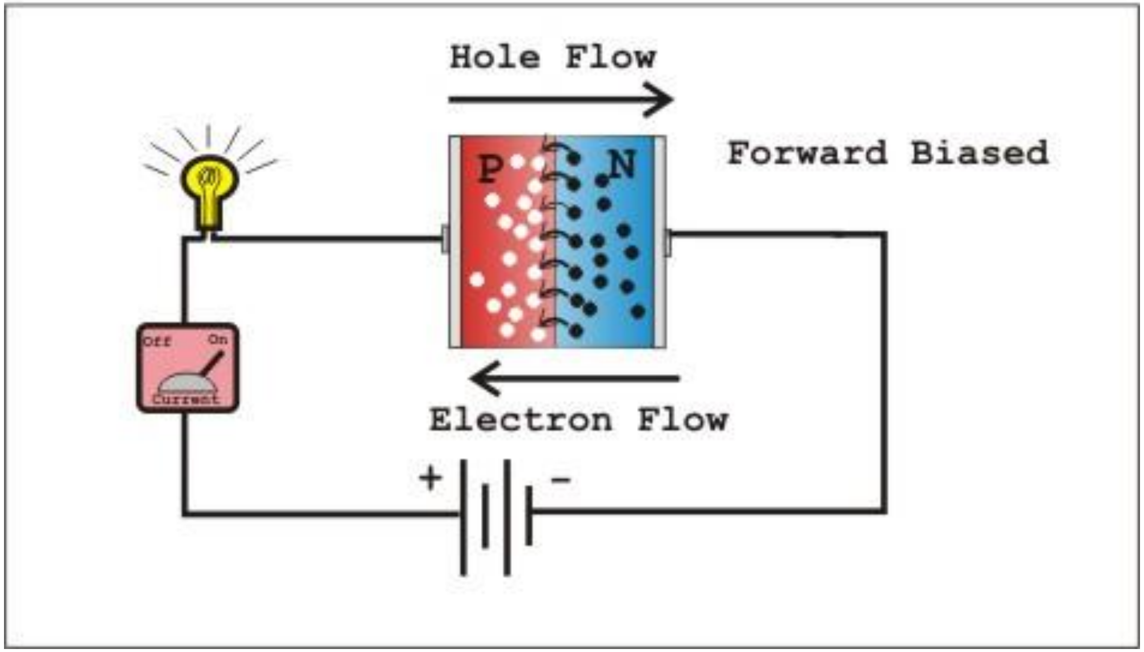
- CCD – Charge Coupled Device
- ICCD – Intensified CCD
- EMCCD – Electron Multiplying CCD
- CMOS – Complementary Metal Oxide Semiconductor

How is CCD different from CMOS ?

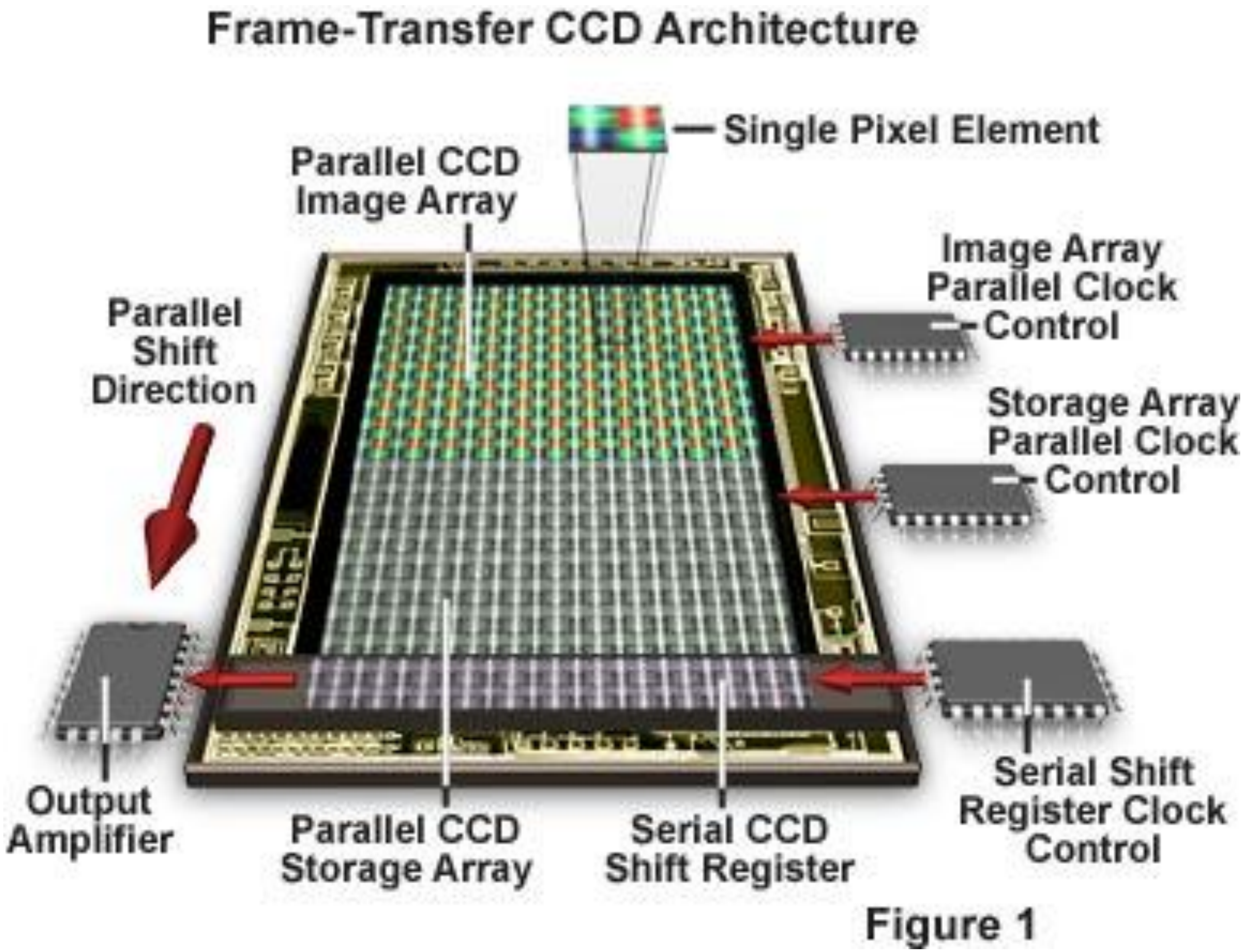
The generation of electron-hole pairs by light



Principle of electronic sensor

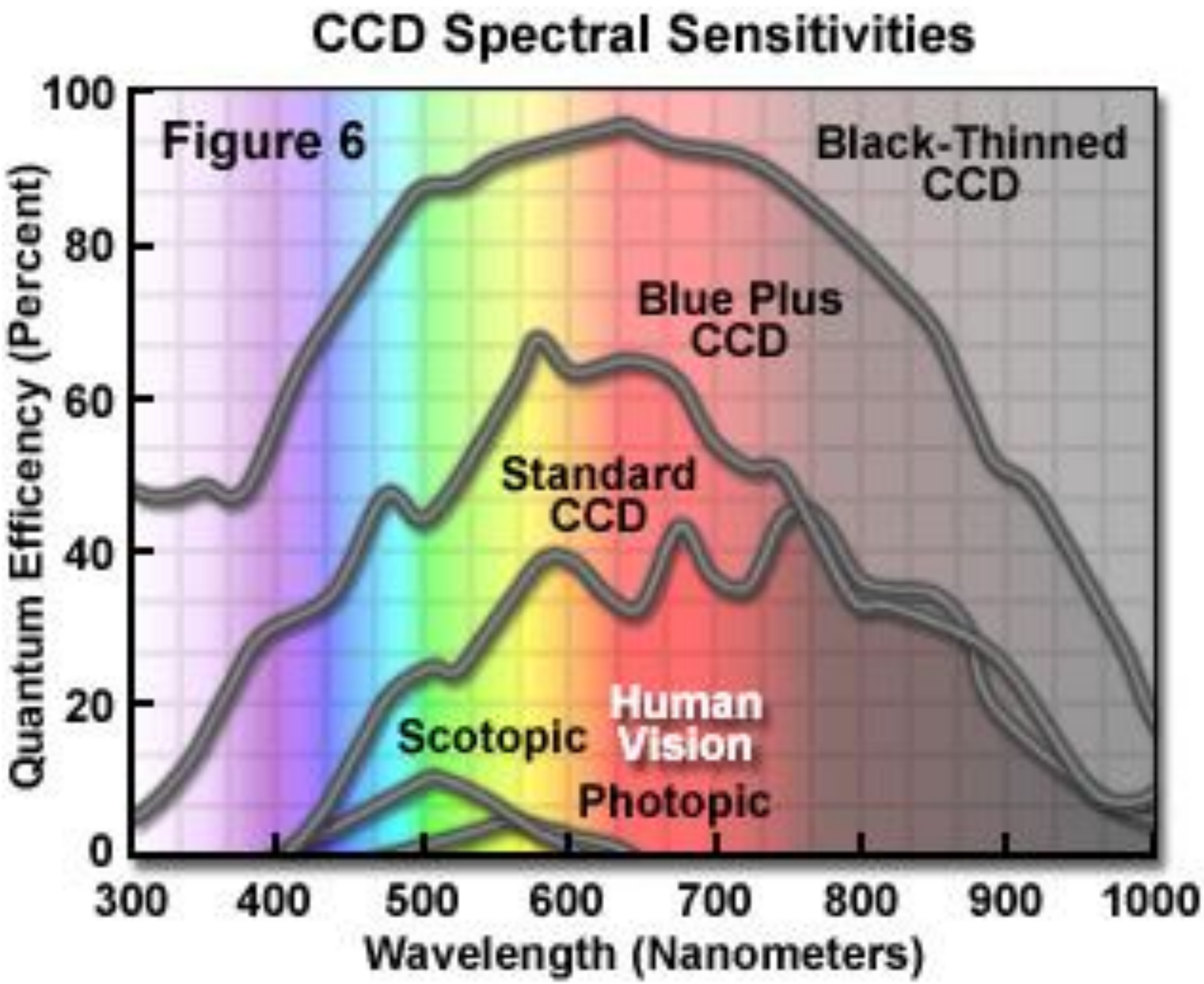


CCD 2-Dimension array



Choosing a sensor

- Spectral response
  - Energy band gap
  - Silicon 1.15 ev fro vis UV and nir
  - Germanium for IR
- Window material
  - Quartz – UV transmission
  - AR coating : VIS
  - BK7 glass: UV Fluoresce
  - Germanium: for IR
- Substrate thickness
  - 7 -10 micron for soft x-ray
  - 3 micron for back illumination, high speed
- CCD IR, VIS, UV, Soft X-ray


CCD Spectral Sensitivities
Figure 6
Black-Thinned CCD
Blue Plus CCD
Standard CCD
Human Vision
Scotopic
Photopic
Quantum Efficency (Percent)
0
20
40
60
80
100
300
400
500
600
700
800
900
1000
Wavelength (Nanometers)

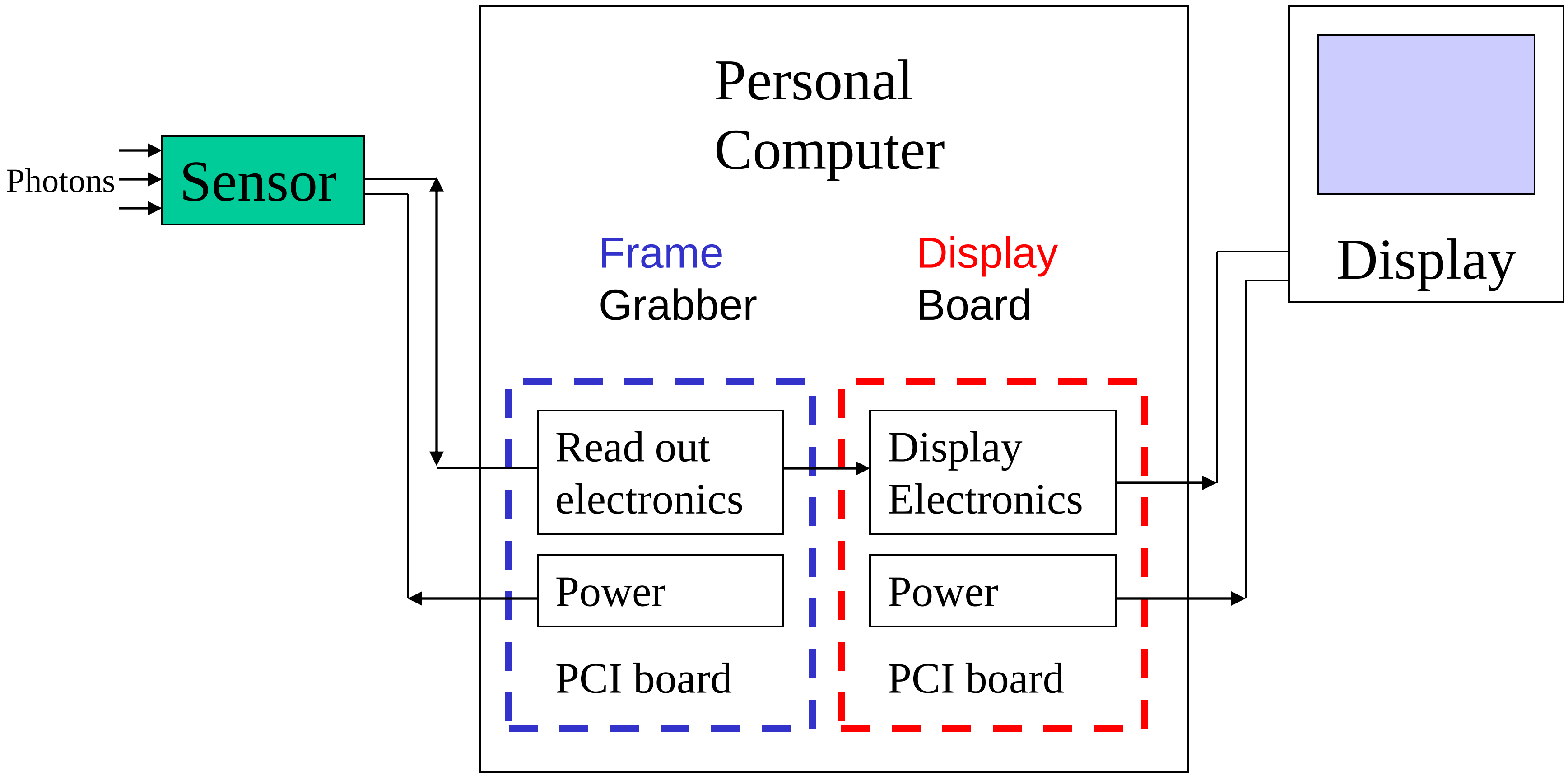
Sensitivity

- Quantum efficiency – number of charges generated per photon as a function of wave length in %
- Dynamic Range – response to weak and strong light
- Linearity – Out put voltage as function of the intensity of the light
- Resolution –
  - Number of pixel, 1600 X 1200, 640 X 480, 2048 X 1536,
  - 2592 X 1944, 3072 X 2304
  - Pixel size
  - Geometry of the pixel size, square pixel

How imaging sensor properties are related to user's requirements

Image Sensor properties	User's requirements
Quantum efficiency	Spectral sensitivity
Fill factor	Intensity Sensitivity, image fidelity
Number of pixel	Resolution
Pixel size	Resolution, size of the chip
Pixel separation (center to center)	Resolution
Pixel geometry	Image fidelity [square pixel]
Full well capacity	Dynamic range
Fix picture noise	Uniformity
Charge collection efficiency	Resolution, Anti-blooming, fidelity
Charge transfer	Data Acquisition Speed
Charge measurement	Noise level, S/N

Electronic Imaging System



The four operational tasks to generate an electronic image

1. Charge generation-intercept of incoming photon to generate charges by photo-electric effect in Silicon
2. Charge collection – localize the charge where the photon hits and area large enough to cover the details
3. Charge transfer – transport the charge to the output amplifier without loss
4. Charge measurement – charge → voltage linearly with little electrical noise

Operation of a semiconductor sensor

2. collection of charges

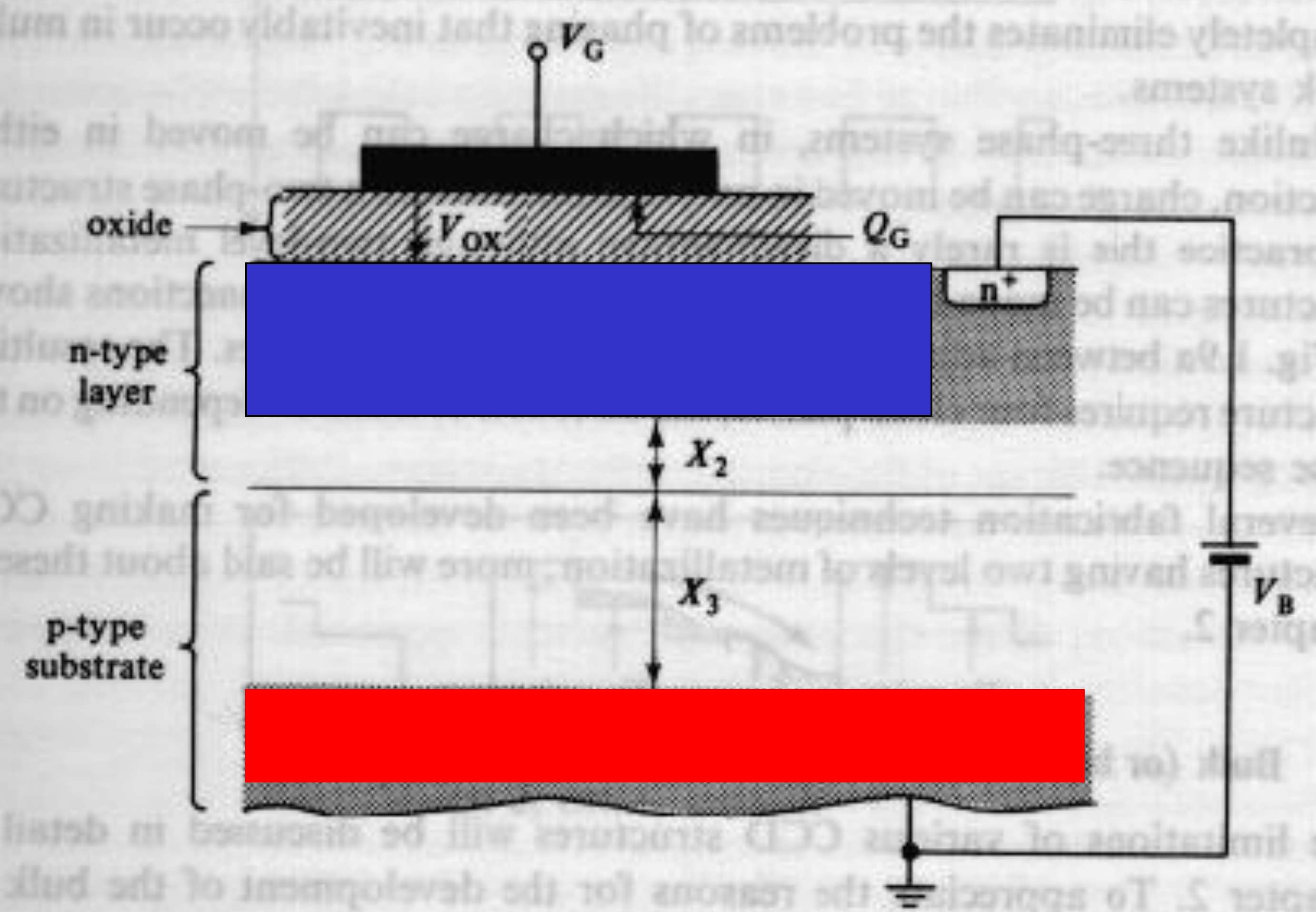


Fig. 1.11 Section through part of a BCCD showing formation of field-induced and junction depletion regions.

Operation of a semiconductor sensor

1.Charges generation

Silicon

•Energy band gap of silicon = 1.14 ev.

• Electron-hole pair generation, photon energy > 1.14 ev.

• Average life time of *e-h* = 100 *microseconds*

• 5 ev > Photon energy > 1.1 ev generates single e-h pair

•Photon Energy > 5 ev produces multiple pairs

•Useful for soft-X ray detection

Limitations

•Photon energy < 1.1 ev (wave length=1.2 micron) passes through

•Photon energy > 10 kev , low probability of interaction

• Photon energy =10 ev generates 3 e-h pair

• IR detection use Germanium Energy band gap = 0.55 ev

Architecture of a semiconductor sensor

2. collection of charges

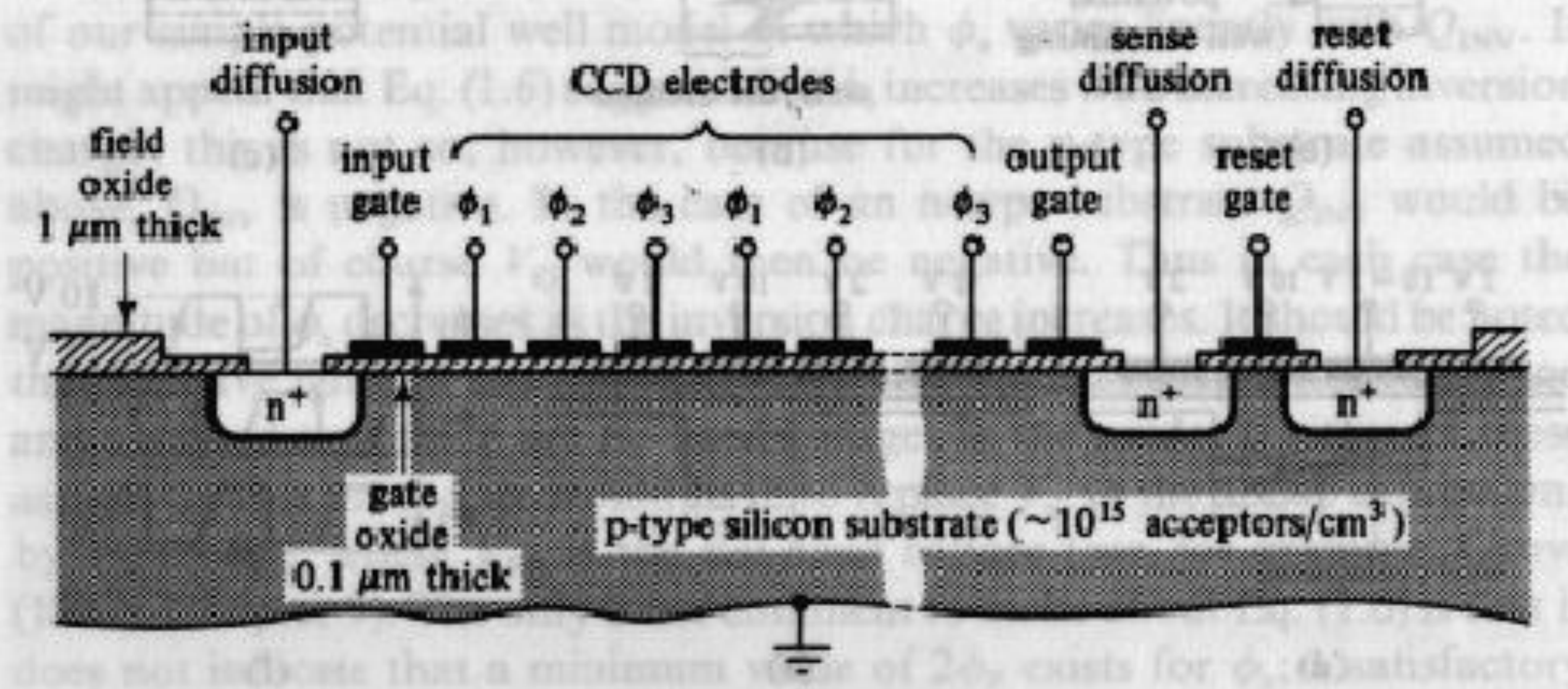


Fig. 1.8 Diagrammatic representation of a complete CCD system, including input and output circuitry (n^+ denotes heavily doped n-region).

2. CHARGE COLLECTION:

Ability of the sensor to accurately reproduce an image after electrons are generated.

- Number of Pixel on the chip

  Both CCD holds the record number of pixel and CMOS achieve large number of pixels, CMOS 4000 x 4000

- Full well capacity-

  The number of signal charges a pixel can hold

  - CMOS & CCD are equivalent, CCD, driven by higher clock voltage, has

- Fix Picture Noise

  The variation in sensitivity from pixel to pixel

  - size variation in pixel geometry, deign, manufacturing process, uniformity 1%, both CCD & CMOS

- Charge Collection Efficiency

  The ability of a pixel to collect carriers efficiently without loss to its neighbor

  - CCE. It defines the spatial resolution of the detector

  Ideally, the electrons generated due to photon exposure should remain in the target pixel.

2. CHARGE COLLECTION:

Ability of the sensor to accurately reproduce an image after electrons are generated.

- **<u>Degradation</u>**
- *Thermal diffusion* makes the image appear out of focus and increases as pixel size shrinks
- *Pixel cross talk* is most conspicuous for near-IR and soft x-ray photons that penetrate deep into the sensor, where very weak electric fields exist.

- **<u>Enhancement</u>**

  Increase of the electric field depth is achieved by:
- *High-resistivity* silicon wafer
- *High voltage clocking* to take advantage of the fact that the electric field depth varies as a function of the square root of resistivity and applied voltage.
- CCD electric fields typically extend 7 – 10 microns allow full coverage into the near IR spectral region (700 – 1100 nm)

2. CHARGE COLLECTION:

<u>CCD</u>:

- High resisitivity,
- High clocking voltage
- Deep field for good collection

<u>CMOS</u>:

- Low resisitivity
- Low clocking voltage
- Shallow field → diffusion loss.
- Additional problems – Single event upsets and ground bounce related to on chip logic circuitry becomes pronounced as silicon resisitivity increases.

3. Charges Transfer

Multiple charges transfer by the shift register

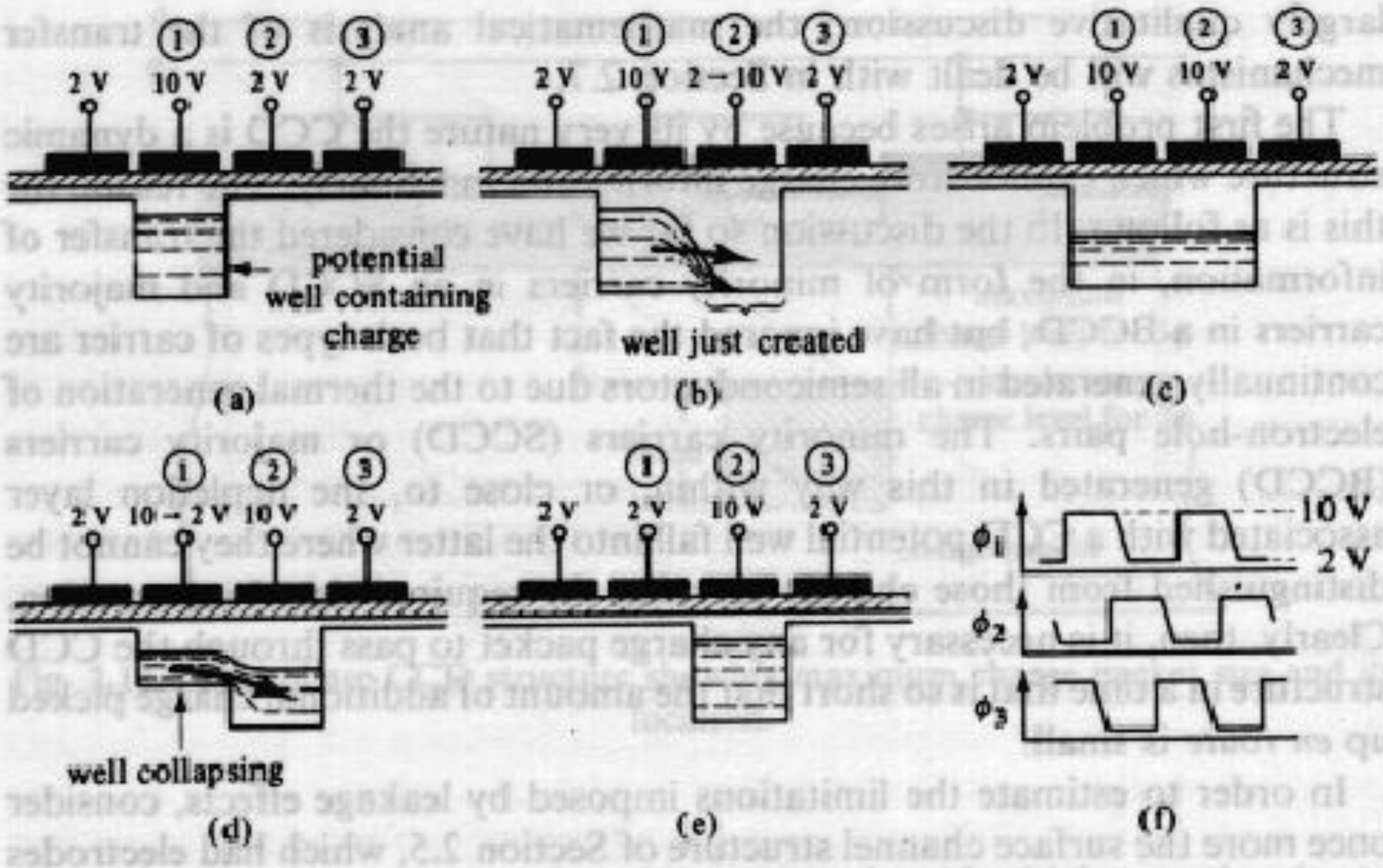
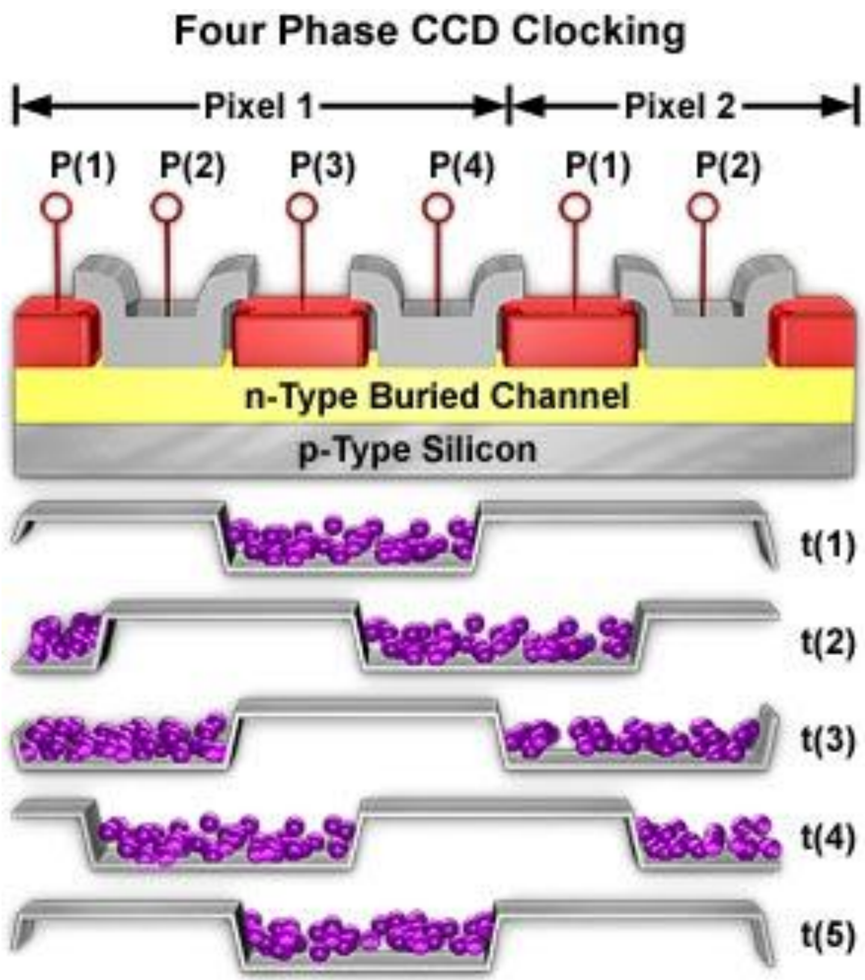


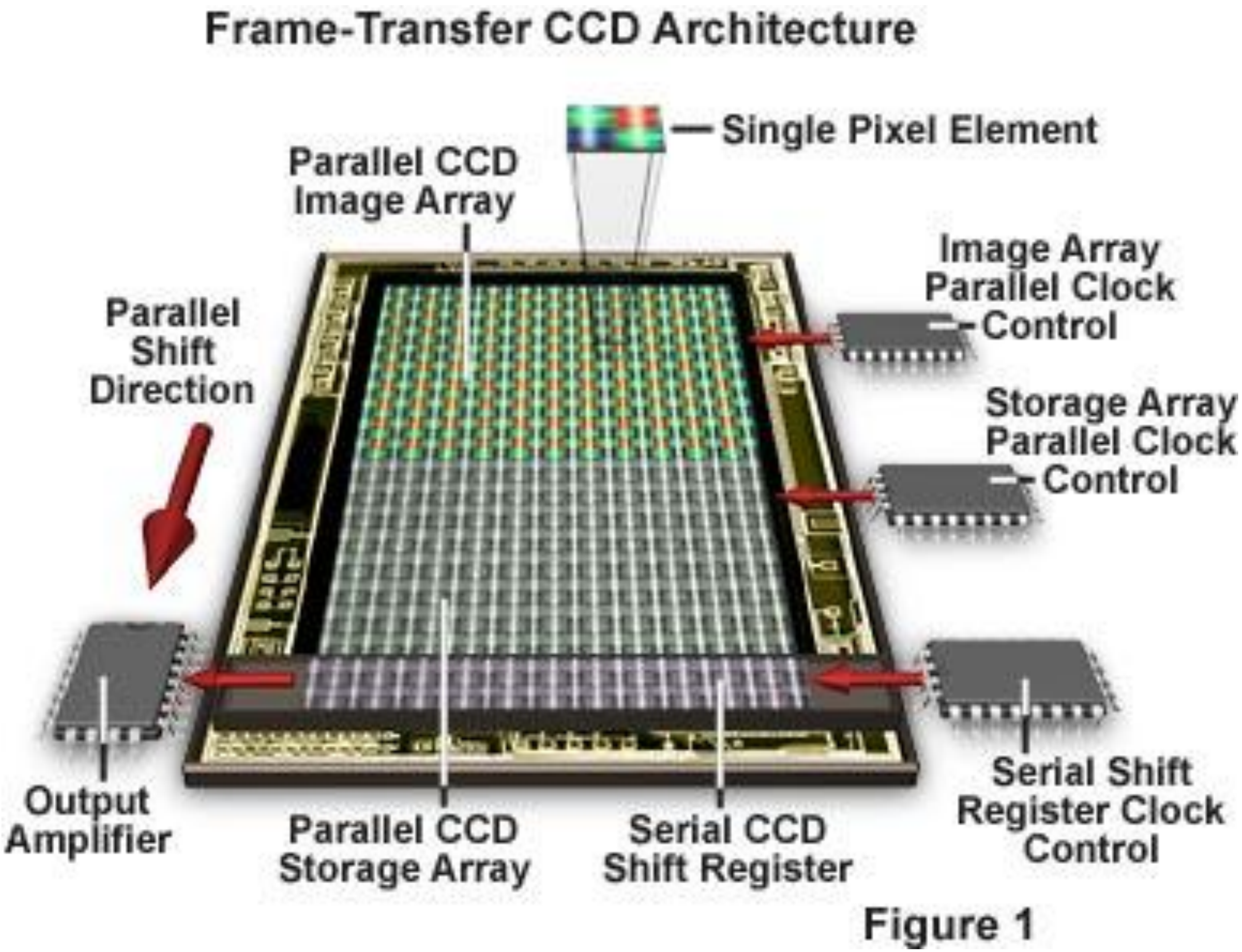
Fig. 2.15 (a)–(e) Movement of potential well and associated charge packet by clocking of electrode voltages; (f) clocking waveforms for a three-phase CCD.



Four Phase CCD Clocking
Pixel 1
Pixel 2
P(1)
P(2)
P(3)
P(4)
P(1)
P(2)
n-Type Buried Channel
p-Type Silicon
t(1)
t(2)
t(3)
t(4)
t(5)

Figure 1

CCD 2-Dimension array



3.CHARGE TRANSFER

- The signal channel must be void of electron traps induced by flaws in the design, processing

  or even the silicon itself.
- It is critically important to CCD operation. A small charge packet may need to transfer through over thousands of gate well in the silicon layer to reach the output amplifier.
- CCD: high clocking voltage achieves 99.9999% transfer efficiency.

http://learn.hamamatsu.com/tutorials/fourphase/

Operation of a semiconductor sensor

Detection of charges by MOSFET

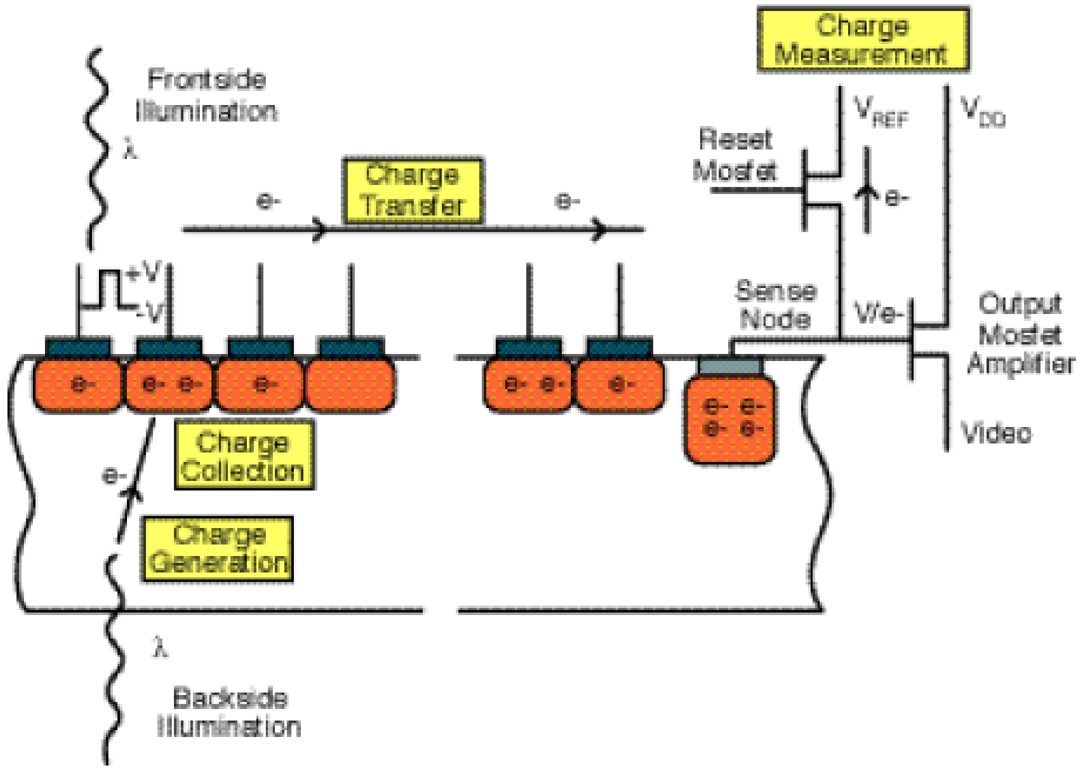
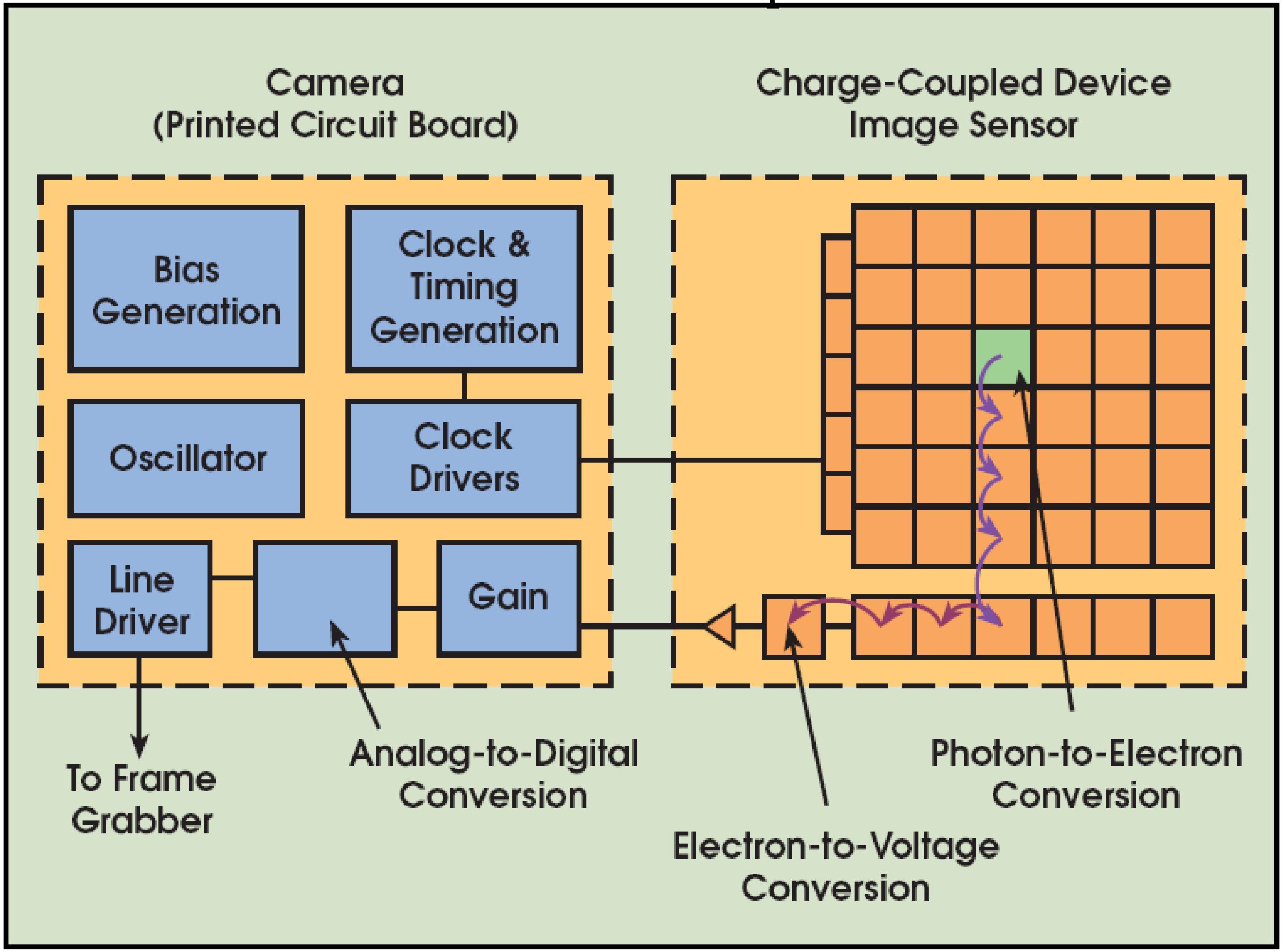


FIGURE 2 A cross-section of a CCD pixel shows the four major functions required to generate an image.

Architecture of a CCD image sensor

The electron to voltage conversion and the photon to electron conversion are not in the same pixel.



Architecture of a CMOS image sensor
The electron to voltage conversion and the photon to electron conversion are in the same pixel.

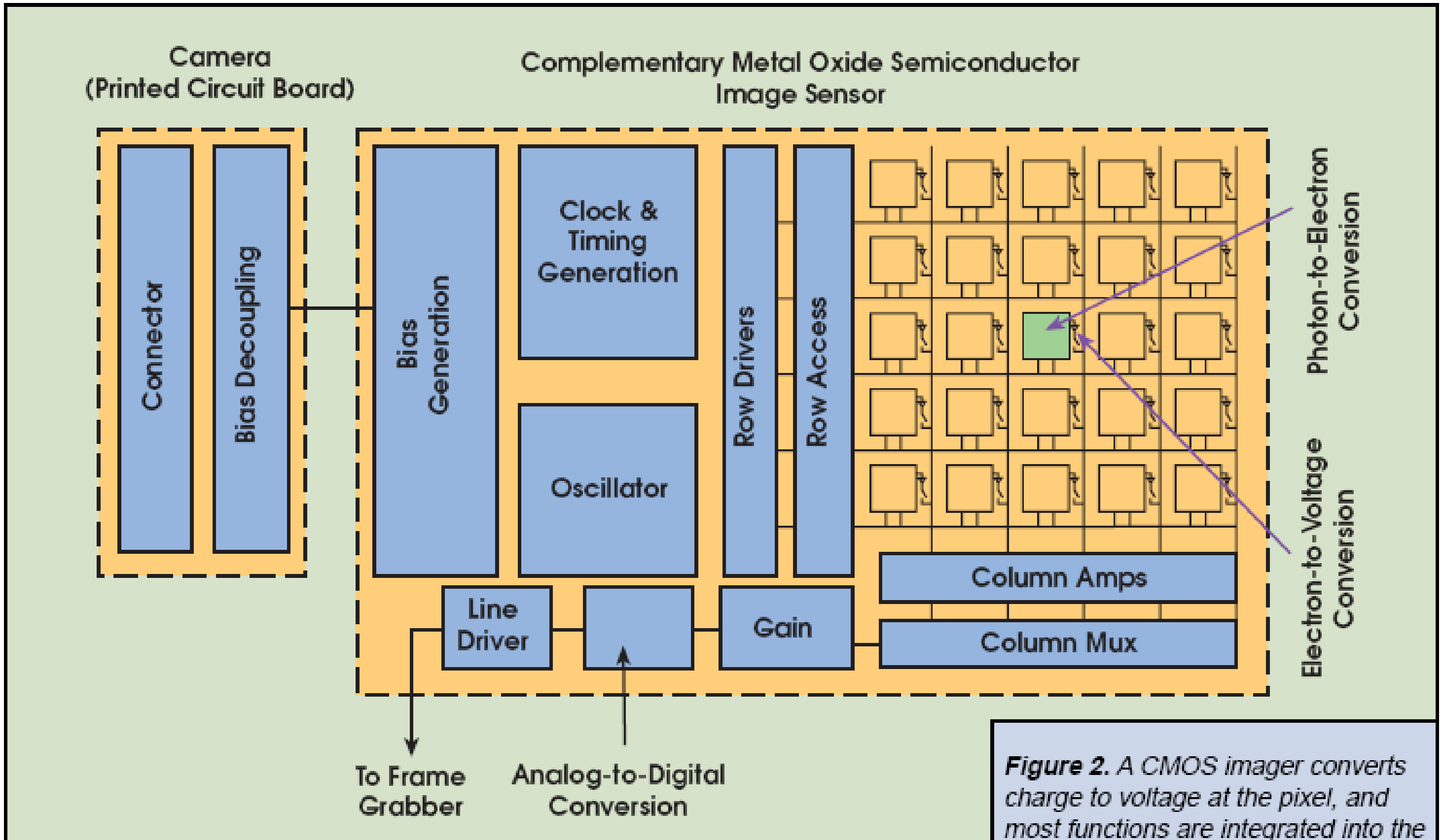


Figure 2. *A CMOS imager converts charge to voltage at the pixel, and most functions are integrated into the chip. This makes imager functions less flexible but, for applications in rugged environments, a CMOS camera can be more reliable.*

Two types of camera based on the semiconductor sensor *charge transfer architecture* from the *photo region* to the *read-out region*.

CMOS – single charge transfer

Photon→Charge→out put amp.

CCD – multiple charge transfer

Photon → Charge → [Shift Register] → out put amp.

- CMOS: pixels are directly addressable and thus avoid many charge-transfer issues. A single transfer is involved.

4. CHARGE MEASUREMENT

The *readout process* for CMOS and CCD is identical. A capacitor connected to an output MOSFET amplifier converts signal charge to voltage. Making this capacitor small will increase gain and output signal over noise source.

- CMOS has considerably more difficulty achieving low-noise performance because analog process circuit is on-chip. Additional filters would yield an excessively large chip.
- More flexibility for the CCD to minimize the noise in the read out process because there is no readout amplifier in the pixel.
- Thermal noise is reduced by cooling down the image sensor.

Charge Collection: Ability to reproduce an image accurately after electrons are generated

- Number of Pixel on the chip–

  Both CCD holds the record number of pixel and CMOS achieve large number of pixels, CMOS 4000 x 4000

- The number of signal charges a pixel can hold *Full Well Capacity*

  CMOS & CCD are equivalent, CCD, driven by higher clock voltage, has deeper well

- The variation in sensitivity from pixel to pixel *Fix Picture Noise* -

  size variation in pixel geometry, deign, manufacturing process, uniformity – 1%, both CCD & CMOS

- The ability of a pixel to collect carriers efficiently without loss to its neighbor *Charge Collection Efficiency*- CCE.

  It defines the spatial resolution of the detector Ideally, the electrons generate due to photon exposure should remain in the target pixel.

Parameters to measure sensor performance

- Charge generation – ***Quantum efficiency*** -
- Charge collection – Ability of the sensor to accurately reproduce the image
  - ***Resolution*** **-** The number of pixels (picture elements)on the chip
  - ***Full well capacity*** - The number of signal charges a pixel can hold
  - ***Pixel uniformity*** **-**The variation of sensitivity f pixel to pixel
  - ***Charge Collection Efficiency*** - The ability of a pixel to collect charge efficiently
- Charge transfer – ***Charge transfer efficiency*** **–**
- Charge measurement – ***Read noise***

Scientific Imaging Sensor Selection

Performance	CCD	CMOS
Pixel signal	Electron packet	Voltage
Chip signal	Analog	Digital
Fill factor	High	Moderate
Responsivity	Moderate	Moderate – High
Noise level	Low	Moderate – High
Dynamic range	High	Moderate
Uniform	High	Low
Resolution	Low – High	Low-high
Speed	Moderate –High	High
Power consumption	Low	Moderate-High
Complexity	Low	Moderate
Cost	Moderate	Moderate
Design Flexibility	Yes	No
Spectral band width	Broad	Visible

Photo-electric effect in silicon, X-ray detection

Silicon exhibits an energy gap of 1.14 eV.

Incoming photons with energy greater than this can excite valence electrons into the conduction band thus creating electron-hole pairs. These pairs diffuse through the silicon lattice structure. The average lifetime for these carriers is 100 micro-sec. After this time the e-h pair will recombine.

Photons with energy of 1.1 to 5 eV generate single e-h pairs. Photons with energy > 5 eV produce multiple pairs. Example: a 10 eV photon (Lyman alpha) will produce 3 e-h pairs, on average, for every incident photon.

Soft X-ray photons can generate thousands of signal electrons make it possible for a CCD to detect single photons. Limits in Silicon Detectors: Photons with energy less than 1.1 eV (about 1.2 microns) pass through silicon unimpeded. Photons with energy greater than 10 kev have such small wave length that the probability of interaction is very small. To use as an infrared imager, CCDs must be made of other material like germanium (band gap 0.55 eV).