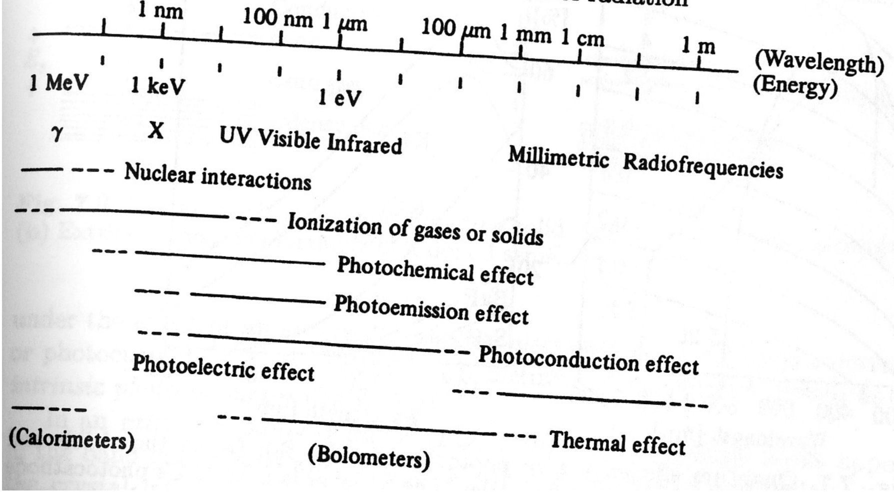
Lecture 13: Detectors 1

Outline

1. Overview
2. Photoconductive Detection
3. Charge Coupled Devices
4. CMOS and CMOS Hybrid Detectors
5. Array Detector Properties
6. Array Detector Data Reduction
7. Array Detector Problems

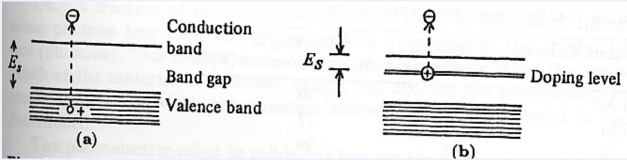
Photon Detection at Different Wavelengths

Table 7.2. Physical interactions and detection of radiation



from Lena et al., Observational Astrophysics, Second Edition

Photoconductive Detection



Operation Principle

- illumination changes conductance/resistance of photoconductor
- conductance σ_0 increases due to excess charge carriers in semiconductor
- *intrinsic* semiconductors: charge carriers = electron-hole pairs
- *extrinsic* semiconductors: charge carriers = electrons (n-type) or holes (p-type)
- spectral responsivity determined by *energy/band gap*
- only photons with energies $>$ gap are absorbed
- charge carriers create excess current flow

Responsivity of a Photoconductor

- material with conductivity σ_0 produces current density $\vec{j}$ given by

$$\vec{j} = \sigma_0 \vec{E}$$

  - $\vec{E}$: electric field from bias voltage V_B accross photoconductor
  - $|\vec{E}|$ in Volt·m^{-1}
  - σ_0 in Ohm^{-1}·m^{-1}
- current density $\vec{j}$ at microscopic scales

$$\vec{j} = Nq\vec{v}$$

  - N: volume density of free charge carriers
  - q: elementary charge
  - $\vec{v}$: drift velocity of charges in applied electric field
- drift velocity $\vec{v} = \mu_c \vec{E}$, μ_c the mobility of charge carrier

Conductivity

- *intrinsic semiconductor*: distinction between electron conduction and hole conduction
- mobility μ_n for electrons
- mobility μ_p for holes, $\mu_n \approx 3\mu_p$
- current density
  $$\vec{j} = -nq\vec{v_n} + pq\vec{v_p}$$
  with n, p electron/hole densities, $\vec{v_n}/\vec{v_p}$ electron/hole drift velocities (opposite directions)
- q: elementary charge, positive sign
- therefore
  $$\sigma_0 = q(n\mu_n + p\mu_p)$$
- reduces to $\sigma_0 = qn\mu_n$ and $\sigma_0 = qp\mu_p$ in case of heavily doped n-type, p-type extrinsic semiconductors

Light on Semiconductor

- monochromatic photon flux $F(\lambda_0)$ on n-type semiconductor
- equilibrium between generation rate of excess conduction electrons and recombination rate:

$$\frac{d\Delta n}{dt} = g - \frac{\Delta n}{\tau_l} = 0$$

  - Δn: equilibrium number of excess electrons per unit volume (= excess carrier concentration)
  - τ_l lifetime of electrons against recombination
- generation rate g:

$$g = \frac{\eta_{\lambda_0} F(\lambda_0)}{d}$$

  - η_{λ_0}: photon detection efficiency
  - d thickness of photoconductor material

Light on Semiconductor (continued)

- conductivity:

$$\sigma_0 = qn\mu_n$$

- equilibrium:

$$\frac{d\Delta n}{dt} = g - \frac{\Delta n}{\tau_l} = 0$$

- generation rate:

$$g = \frac{\eta_{\lambda_0} F(\lambda_0)}{d}$$

- increase in conductivity $\Delta\sigma = \sigma - \sigma_0$ from:

$$\Delta\sigma = q\mu_n \Delta n = \frac{q\mu_n \eta_{\lambda_0} F(\lambda_0)\tau_l}{d} = \frac{q\mu_n \eta_{\lambda_0} \tau_l}{Ad} \frac{\lambda_0}{hc} \Phi(\lambda_0)$$

  - $\Phi(\lambda_0)$: monochromatic radiation flux in Watt
  - A: illuminated area of the photoconductor
  - λ_0: wavelength of monochromatic photon flux

Charge Coupled Devices (CCD)

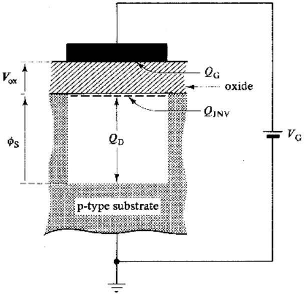
Operation Principle

- CCD: array of capacitors
- typically metal-oxide-semiconductor (MOS) capacitor made from silicon (Si) and silicon dioxide (SiO_2, insulator)
- charge position in capacitor electrostatically controlled by voltage levels
- dynamical application of voltages and relative phases:
  - injected charges due to electron-hole pairs generated by photons are stored in capacitor
  - built-up charge (charge packet) can be transferred across semiconductor substrate
- CCD arrays for imaging in near-infrared up to 1.1 μm, visible, and X-ray range

Charge Storage in a CCD

- 2 types of charge coupled structures
    - charge packets stored very close to interface between semi-conductor (Si) and overlaying insulator (SiO_2) (surface channel CCDs, SCCDs)
    - charge packets stored some distance away from surface of semiconductor (bulk or buried channel CCDs, BCCDs)
- both devices are very similar
- discuss SCCDs since their concept is easier to understand

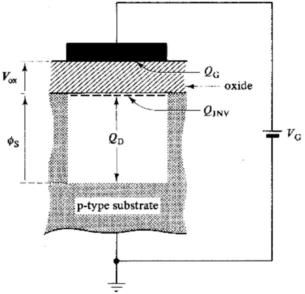
Single CCD Electrode



single CCD-electrode. V_G positive, Q_{Inv} and Q_D negative

- metal gate, separated by thin oxide layer (few 0.1 μm) from p-type semiconductor (hole-conduction)
- without voltage bias to gate, uniform distribution of holes (majority free charge carriers) in p-type semiconductor
- gate electrode positive, holes are repelled beneath gate
- *depletion layer* (devoid of free charge) is created
- increased gate voltage extends depletion region into semiconductor
- potential at semiconductor/insulator interface (ϕ_S) becomes positive

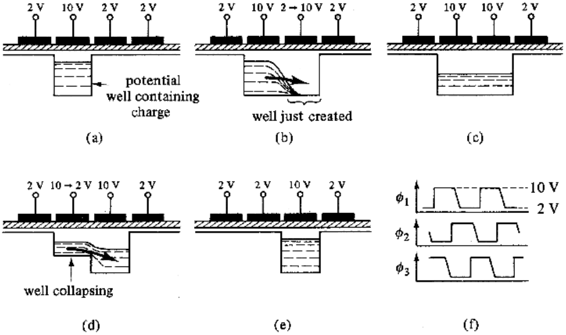
Single CCD Electrode (continued)



single CCD-electrode. V_G positive, Q_{Inv} and Q_D negative

- voltage high enough ⇒ surface potential ϕ_S attracts electrons (i.e. minority charge carriers in the p-type material) to surface
- electrons form extremely thin ($\approx 0.01\ \mu$m thick), but very (charge) dense layer, the *inversion layer*
- electrons reside in deep potential well at semiconductor surface, do not recombine with holes, since holes are repelled from depletion layer
- light on single CCD electrode creates electron-hole pair: electrons stored in inversion layer, holes repelled from depletion region

Charge Transport in a CCD



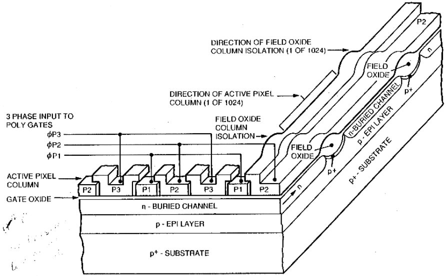
charge packet transport and clocking waveforms (from Beynon & Lamb, 1980)

- all CCD electrodes at minimum bias ($\approx$ 2 V) to ensure that each MOS capacitor operates in inversion-mode
- potential well under 10 V electrode is much deeper than those under the 2V electrodes

Charge Transfer Efficiency

- charge transfer mechanisms are not perfect
- *charge transfer efficiency (CTE)* is ratio of charge transferred to initial charge
- typical values of CTE are of the order 0.99999 for a good device

CCD Structure



- must limit extent of potential well in orthogonal direction
- *lateral confinement* with *channel-stop diffusion*, heavily doped region of semiconductor relative to neighboring regions
- region has large conductivity σ relative to surrounding material, quenches surfaces potential ϕ_S; no depletion region can be formed
- 1-D columns or rows are implemented in CCD structure along which charge transfer occurs, isolated from neighboring columns

Charge capacity and transfer speed in CCD structures

- maximum amount of charge in CCD pixel depends mainly on clock voltages and electrode area
- considering an SCCD, full-well storage capacity is in good approximation given by oxide capacity under gate electrode ($A_{elec}C_{ox}$) and gate voltage V_G:

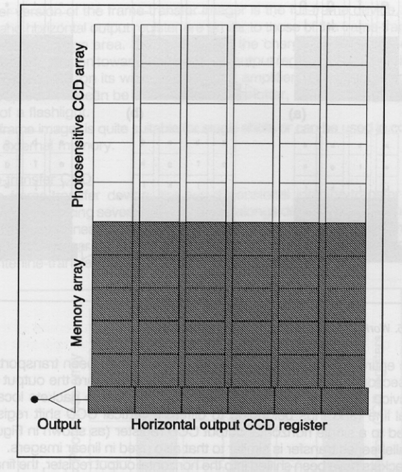
$$A_{elec}C_{ox} = \frac{Q_{Inv}}{V_G} \qquad \Longrightarrow \qquad Q_{Inv} = A_{elec}C_{ox}V_G$$

- C_{ox} is oxide capacitance per unit area, A_{elec} is electrode geometric area
- with A_{elec} = $10 \times 20 \mu\text{m}^2$, t_{ox} = 0.1 μm ($C_{ox} = \epsilon_{ox}/t_{ox}$) and V_G = 10 V: in that case Q_{Inv} = 0.6 pC $\approx 3.6 \cdot 10^6$ electrons.

Charge Transport

- intrinsic speed of charge transport in CCD governed by transport equation, depending on the time constants for self-induced drift, thermal diffusion and fringe field drift.
- in SCCD: time constant for self-induced drift is a function of charge density, C_{ox} and the interelectrode spacing.
- For C_{ox} = 1 pF, $Q_{Inv} = 10^{12}$ cm^2 and spacing 25 μm, the time constant τ_{Si} = 0.14 μs
- time constant for thermal diffusion of an electron packet ($D_n \approx 10$ cm$^2 \cdot$s^{-1}) amounts to 0.25 μs
- high frequency limit would appear to be a few MHz, however the fringing field of the neighboring gate electrodes aid the transfer considerably, especially when thermal diffusion is dominant and clocking frequencies up to 15 MHz can be used for SCCDs

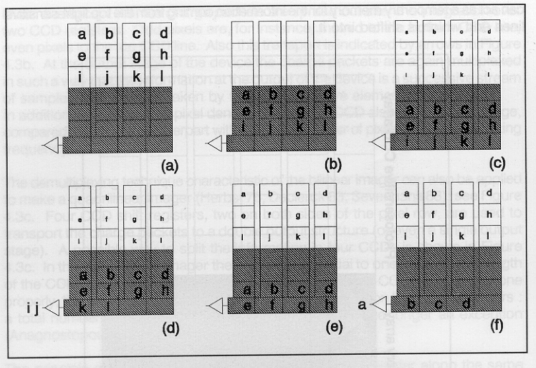
Focal Plane Architectures



Architecture of frame-transfer CCd array (from Theuwissen, 1995)

- astronomical CCD imaging arrays can be subdivided into *full-frame* and *frame-transfer* arrays
- *interline-transfer* arrays are often used in commercial CCD cameras
- CCD has photosensitive array and a memory array coupled to a linear output register
- *full-frame* device lacks storage section
- shutter interrupts illumination during readout

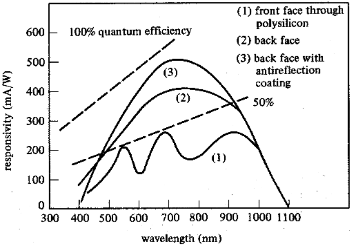
Frame Transfer Operation



Working principle of frame-transfer CCD (from Theuwissen, 1995)

- transfer needs to be done quickly to prevent disturbance by light falling on the image section during read-out
- during readout, all CCD cells in image array are again biased in integration mode

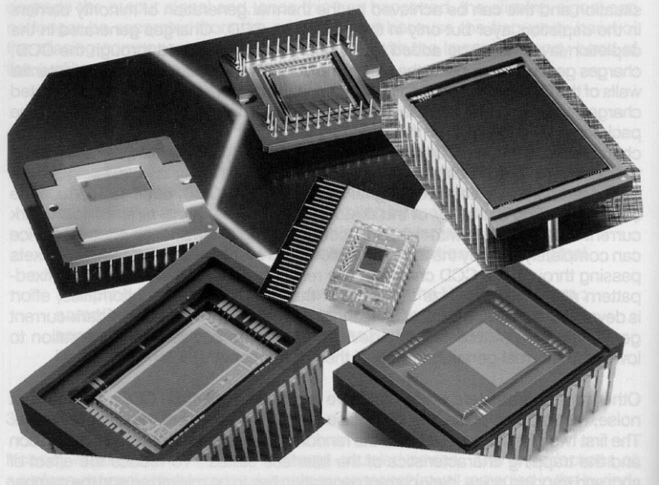
Wavelength response of CCDs



from Beynon & Lamb (1980)

- at optical wavelengths: illumination through front surface or back-surface (back-illumination)
- front illumination:
  - poly-silicon gate electrodes that transmit light
  - strongly wavelength dependent absorption and interference effects occurring in thin poly-silicon gate layer ($\approx 0.5\ \mu$m) and thin oxide layer ($\approx 0.1 - 0.2\ \mu$m)
  - blue-responsivity strongly suppressed by absorption in poly-silicon gate

CCDs

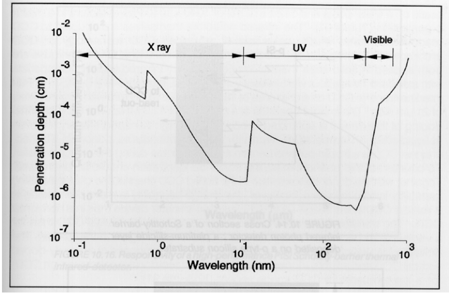


Top left: back-side illuminated FT imager with 1260 × 1152 pixels. Top right: a full frame CCD with 3k × 2k pixels, each of 9 μm × 9 μm. Middle: a low-cost FT sensor with 270,000 pixels, total diameter of the image section is 3.2 mm. Bottom left: HDTV IT image sensor with 2M pixels, 11 mm diagonal. Bottom right: FT CCD for broadcast applications with 500,000 pixels.

CCD Response

- back-illumination requires thinning of silicon substrate for photon-generated charges to reach potential wells
- charge transport can be aided by building an electric field gradient into the semi-conductor by increasing substrate doping concentration in regions close to silicon surface
- this accelerates photon-generated carriers towards front surface and potential wells
- particularly useful for increasing blue-responsivity where charge carriers are generated close to rear silicon surface
- response can be further improved by minimizing the reflection of light from back surface employing a $\lambda/4$ thick layer of silicon monoxide at wavelength of interest
- quantum efficiency of about 50 % with back-illumination can be raised to a peak efficiency of about 90% by using the proper antireflection coating

CCDs from X-rays to the Infrared



Penetration depth of silicon as a function of wavelength (from Theuwissen, 1995)

- wavelengths > 1 μm: photo-electric absorption coefficient in silicon is too low ($h\nu_{IR} <$ bandgap) $\Rightarrow$ all photons pass through silicon
- wavelengths < 0.4 μm, > 10 *nm*: absorption very high in silicon and silicon oxide layer

Infrared CCDs

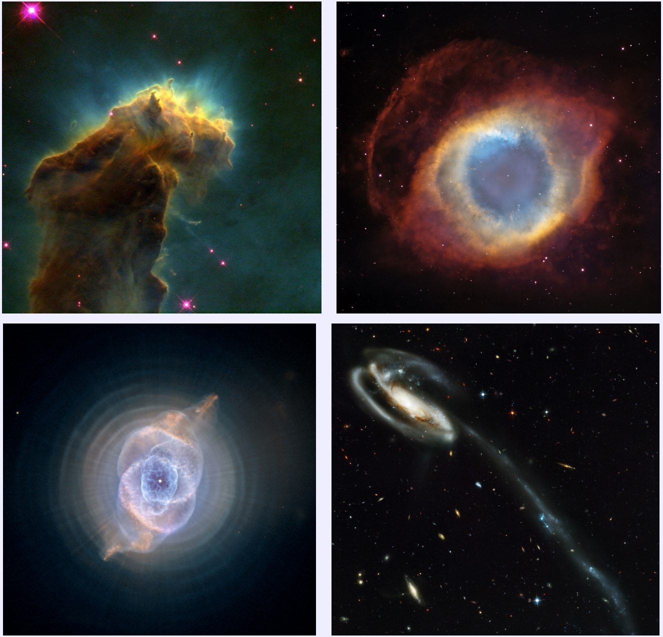
- wavelengths longer than 1 μm, for which the photo-electric absorption coefficient in silicon is too low ($h\nu_{IR} <$ bandgap) and all photons pass through silicon without being absorbed
- infrared photons need to be converted first into electrons, e.g. by means of so-called Schottky-barrier structures in which pixels are used made out of platinum-silicide (PtSi)
- array of these detectors is then coupled to a CCD read-out system
- responsivity in the thermal IR can theoretically be extended in this way to approximately 5.6 μm
- however, quantum efficincy of PtSi CCD detectors is only about 1%

CCDs at Ultraviolet Wavelengths

- UV-sensitive phosphor on top of active area: down-converts energy of UV-photons to longer wavelengths
- back-illumination: due to high absorption, substrate of CCD must be thinned to about 10 μm (expensive, difficult)
- deep depletion of lightly-doped, high-resistivity substrate: depletion region under CCD gates extends to back of siliconwafer
- charge carriers generated by UV illumination swept to front side into potential wells of deep depletion layer
- does not require extreme thinning: 50 μm adequate

CCDs for X-ray Astronomy

- CCDs useful for X-ray astronomy when X-ray photon flux sufficiently low to register (small) charge packet associated with single X-ray photon
- exposures with no more than one X-ray photon per 100 pixels to obtain both spectral and spatial information simultaneously
- magnitude of charge packet represents energy of absorbed X-ray photon
- deep depletion CCDs (30 – 50 μm) provide high quantum efficiency ($>$ 90%) over wide X-ray range (0.2 – 10 nm)
- ideal imaging spectrometer behind grazing incidence X-ray telescopes
- back-illumination avoids problem of penetrating the gate structure and oxide layer, superior response to low-energy X-rays (2 – 10 nm)
- deep depletion layer minimizes effect of charge diffusion of X-ray-generated charge cloud, since electric field causes cloud to quickly drift into potential well



hubblesite.org

Charge Coupled Device (CCD)

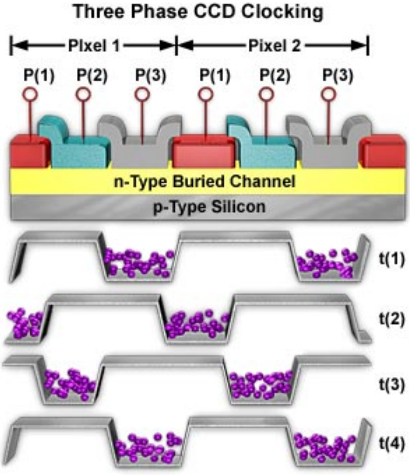


Figure 1

imagingu.com/articles/threephase.html

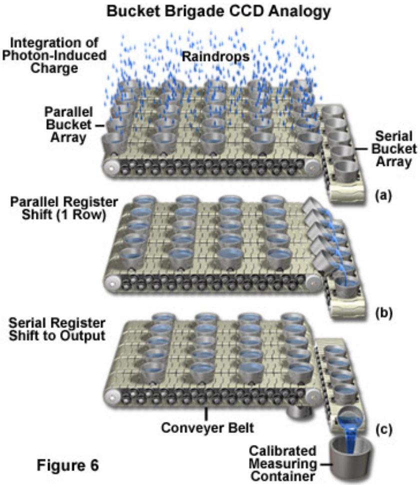
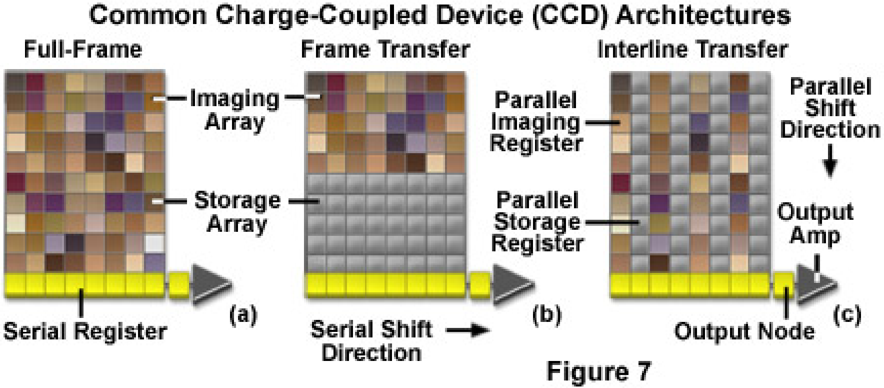


Figure 6

imagingu.com/articles/microscopyimaging.html

CCD Readout Architectures



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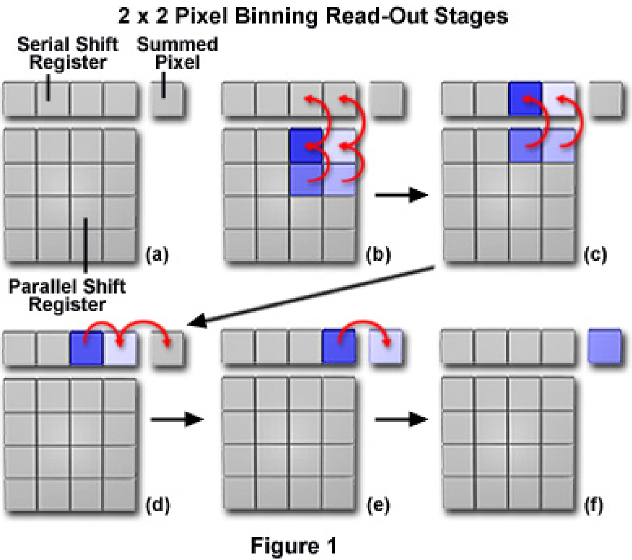
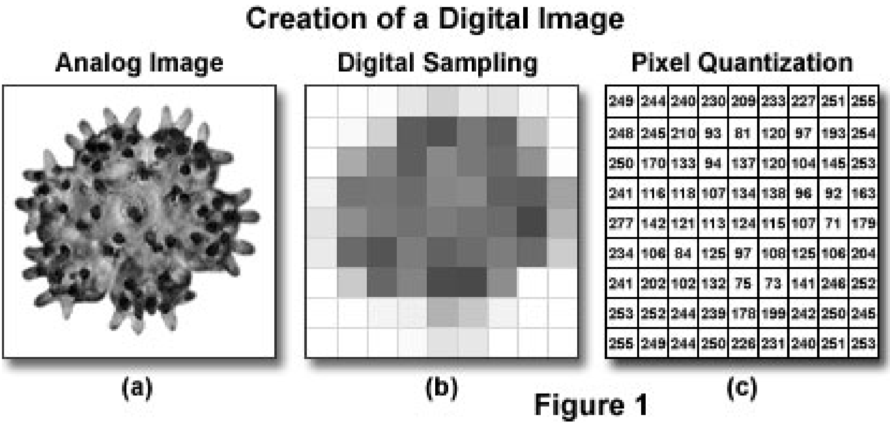
Binning



imagingu.com/articles/binning.html

Digital Imaging



249	244	240	230	209	233	227	251	255
248	245	210	93	81	120	97	193	254
250	170	133	94	137	120	104	145	253
241	116	118	107	134	138	96	92	163
277	142	121	113	124	115	107	71	179
234	106	84	125	97	108	125	106	204
241	202	102	132	75	73	141	248	252
253	252	244	239	178	199	242	250	245
255	249	244	250	228	231	240	251	253

imagingu.com/articles/digitalimagebasics.html

Complementary Metal Oxide Semiconductor (CMOS) Detectors

CMOS and CCD Pixels

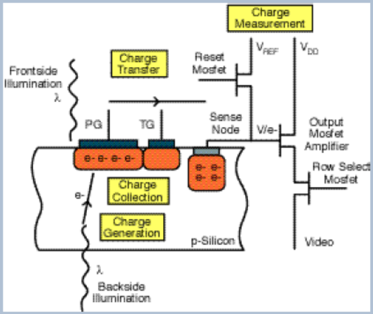


FIGURE 1 A cross-section of a CMOS pixel shows the four major functions required to generate an image.

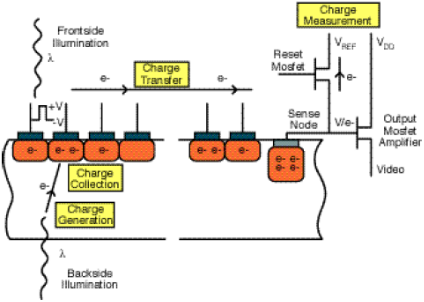
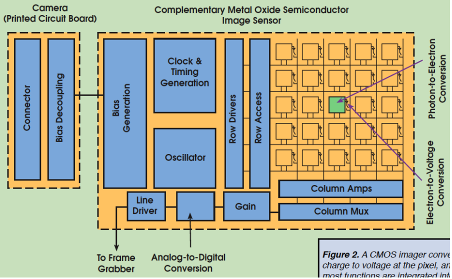
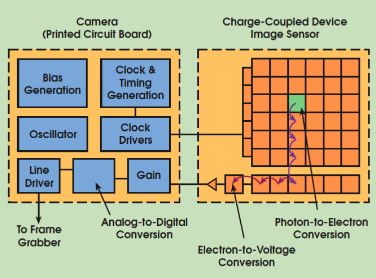


FIGURE 2 A cross-section of a CCD pixel shows the four major functions required to generate an image.

www.dalsa.com/shared/content/OE_Magazine_Dueling_Detectors_Janesick.pdf

CMOS and CCD Cameras



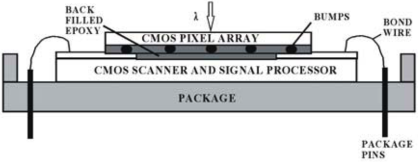


www.dalsa.com/shared/content/Photonics_Spectra_CCDvsCMOS_Litwiller.pdf

CMOS vs. CCD

- CMOS advantages over CCD:
  - standard semiconductor processing
  - low power consumption ($\approx$ 1% of CCD)
  - random access to regions of interest
  - blooming and streaking much reduced compared to CCDs
  - additional electronics can be integrated on chip and in pixel (smart sensor)
  - non-destructive readout
- CMOS disadvantages:
  - small geometric fill factor (microlenses can help)
  - typically larger read noise

CMOS Hybrid Detectors



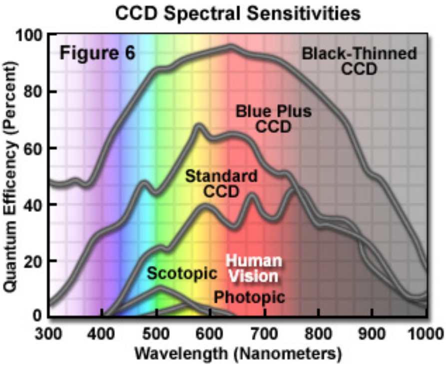
- combine CMOS readout multiplexer bonded to a photosensitive material layer pixel by pixel
- combines sensitivity of CCD with CMOS readout flexibility
- can also use HgCdTe or InSb for infrared sensitivity
- disadvantages:
    - expensive due to pixel-by-pixel bonding
    - differential thermal expansion of materials
    - image lag

Array Detector Properties

Overview

- quantum efficiency
- bias
- dark current
- flat field

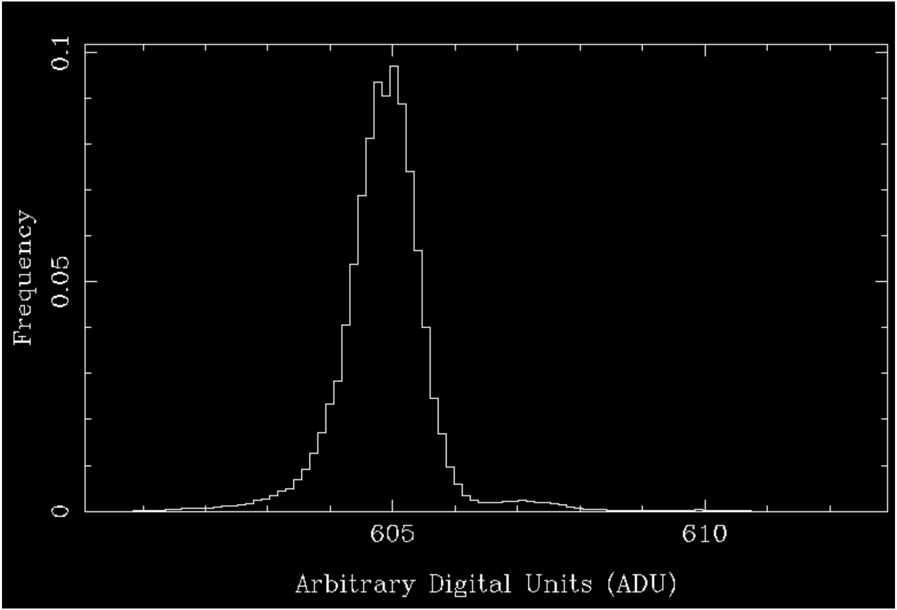
Quantum Efficiency



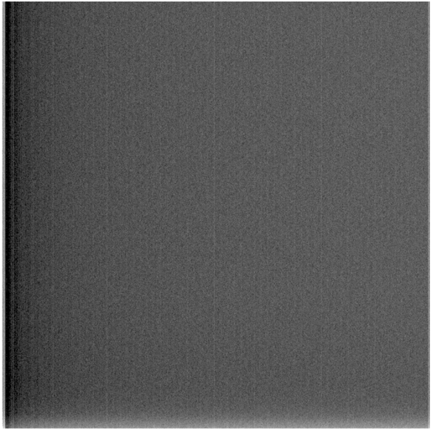
imagingu.com/articles/microscopyimaging.html

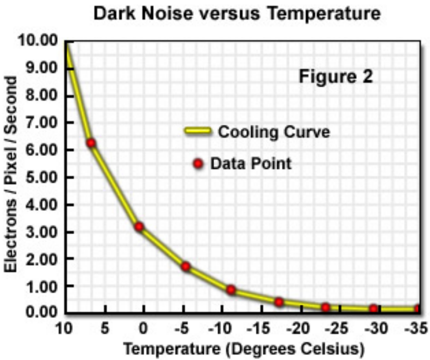
- quantum efficiency: conversion of photons ⇒ electrons
- absorption: avoid opically dead structures above or within pixel
- reflection: 70% loss at 250 nm without anti-reflective coating
- transmission: no photons generated in photosensitive volume (problem in near-infrared and soft X-rays)

Bias



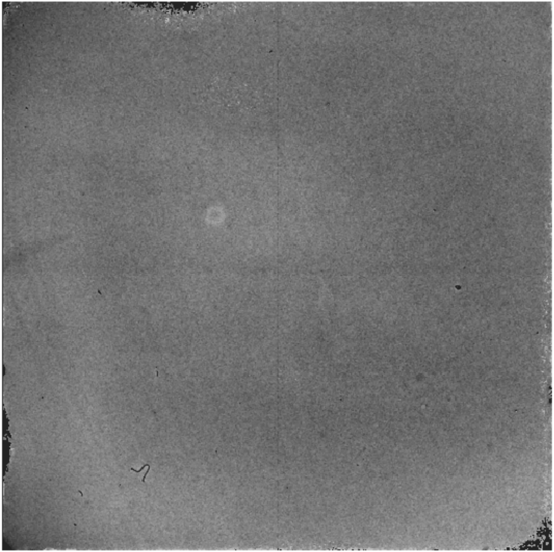
Dark Current





imagingu.com/articles/ccdsnr.html

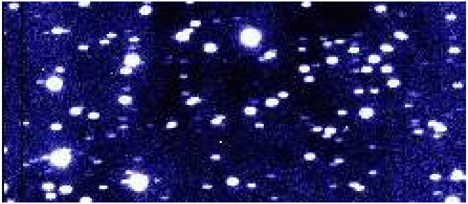
Flatfield



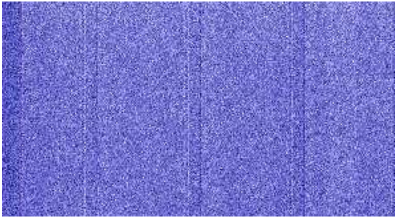
http://www.not.iac.es/instruments/notcam/sci-grade-arr.html

Array Detector Data Reduction

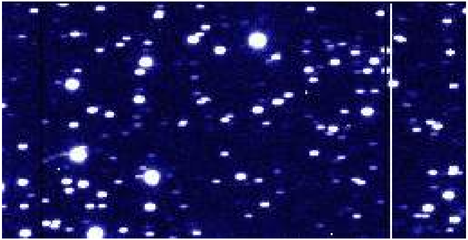
Raw Frame



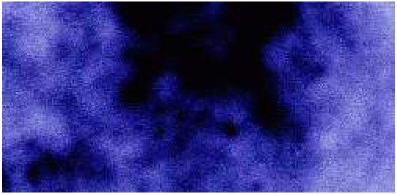
Bias + Dark



Reduced Frame



Flat Field



www.sc.eso.org/˜ohainaut/ccd/

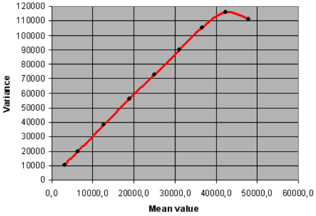
Typical Array Detector Data Reduction

- science frame S, exposure time t_S
- dark frame D, exposure time t_D
- bias frame B, zero exposure time
- flat field frame F, exposure time t_F
- corrected (calibrated) image

$$S' = \frac{S - \frac{t_S}{t_D}(D-B) - B}{F - \frac{t_F}{t_D}(D-B) - B}$$

- $F - \frac{t_F}{t_D}(D-B) - B$ often normalized such that mean of S' = mean of S

Gain, Read Noise, Saturation Determination



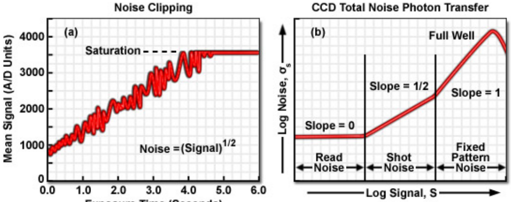


Figure 2

- gain (G) between arbitrary digital units (ADU, A) and number of photo-electrons (e): $A = G \cdot e$
- noise in e is given by $\sigma_e^2 = e$
- and therefore $\sigma_A^2 = G^2 \sigma_e^2 = G^2 e$
- gain G determined from $G = \frac{\sigma_A^2}{A}$

Array Detector Problems: Read Noise

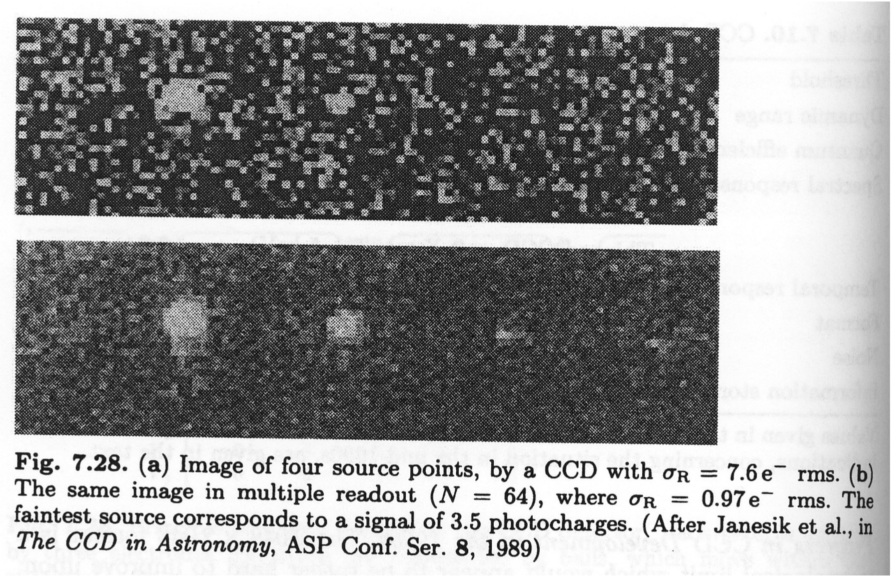
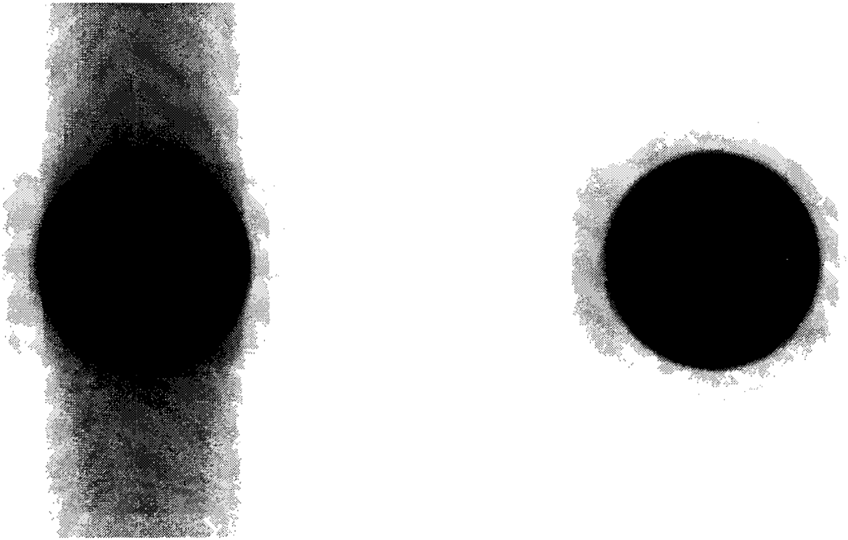


Fig. 7.28. (a) Image of four source points, by a CCD with $\sigma_R = 7.6\,e^-$ rms. (b) The same image in multiple readout ($N = 64$), where $\sigma_R = 0.97\,e^-$ rms. The faintest source corresponds to a signal of 3.5 photocharges. (After Janesik et al., in *The CCD in Astronomy*, ASP Conf. Ser. **8**, 1989)

Array Detector Problems: Bias Shift



Array Detector Problems: Cross Talk

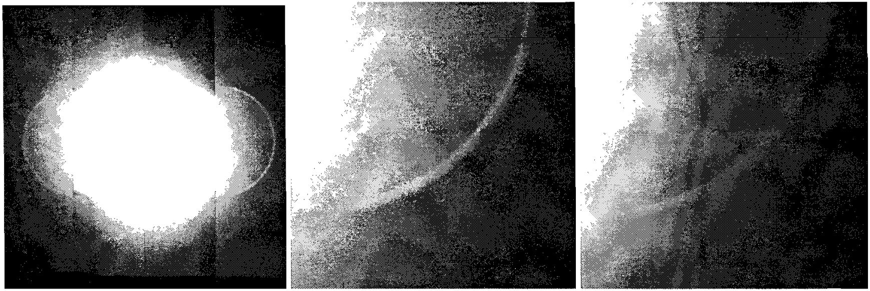


Figure 2: (left) Image similar to Figure 1 except shown in positive contrast and a range from 0 to 0.005 of the maximum illumination level. (center) Detail of left image channel 4 exposed at low light level. (right) Detail of channel 4 exposed at high light level.

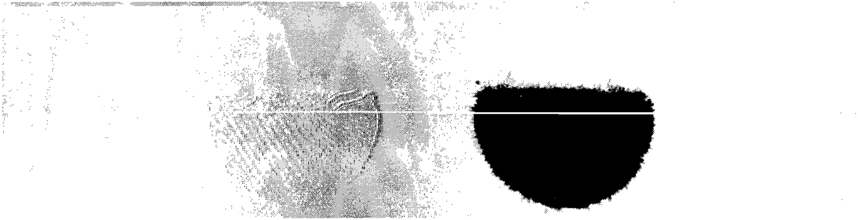
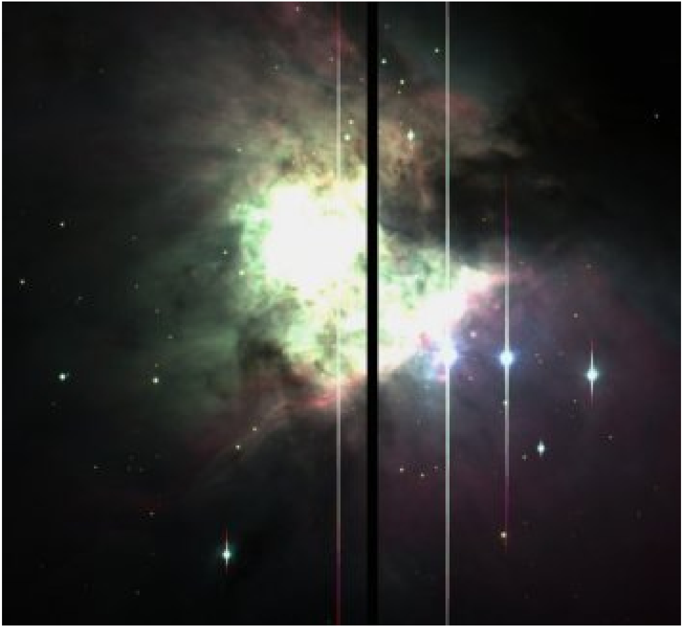
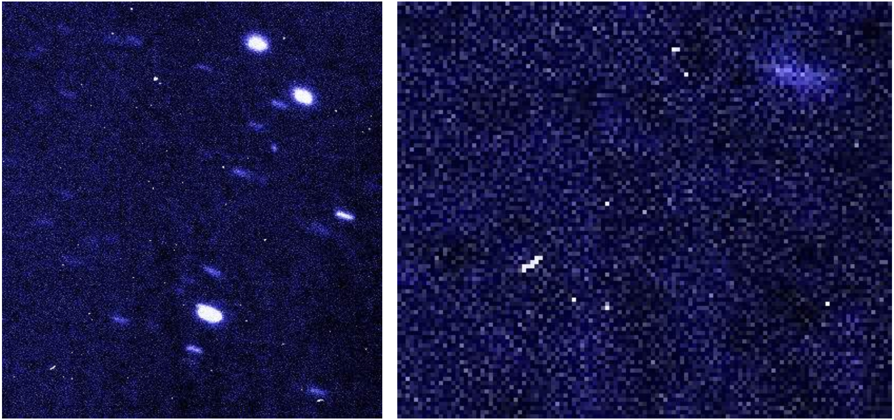


Figure 5: Negative contrast display of cross talk among four quadrants of a Rockwell Scientific Company HyViSI-1024 camera. The

Array Detector Problems: Blooming

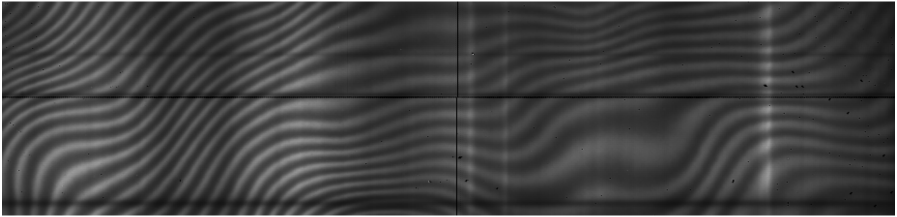


Cosmic Rays



www.sc.eso.org/õhainaut/ccd/CCD_artifacts.html

Array Detector Problems: Fringes



Other Array Detector Problems

- photon (shot) noise
- dark current noise; dark current is reduced by factor of 2 for every 7 K of cooling
- non-linearity of electronic amplification
- image lag