Lecture 13: Direct Imaging 1

Outline

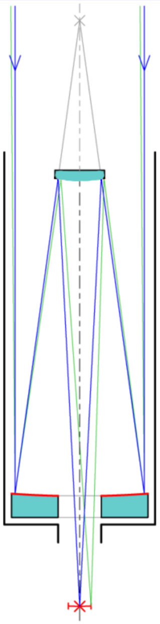
1. Overview
2. Photoconductive Detection
3. Charge Coupled Devices
4. CMOS and CMOS Hybrid Devices

Christoph U. Keller, Utrecht University, C.U.Keller@uu.nl

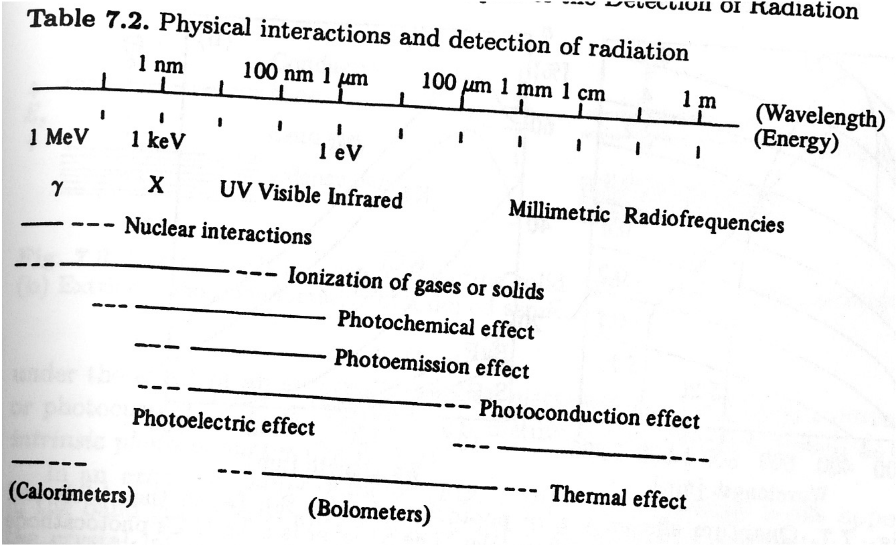
Overview

Direct Imaging

- telescope transforms angular information into positional information
- most common approach at optical wavelengths
- filters, spectrographs in image plane
- electronic imaging detectors (this lecture)
- image analysis (next lecture)



Photon Detection at Different Wavelengths

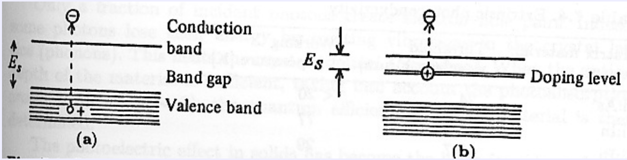


the Detection of Radiation

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$\cdot$m^{-1} and σ_0 in Ohm$^{-1}\cdot$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: mobilities μ_n for electrons and μ_p, $\mu_n \approx 3\mu_p$

  $$\vec{j} = -nq\vec{v_n} + pq\vec{v_p}$$

  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

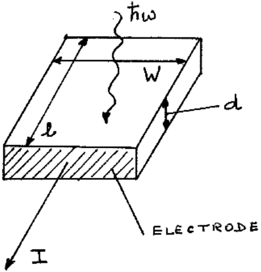
Photoconductive Gain

- fixed bias voltage V_B across photoconductor
- relative change in conductivity $\Delta\sigma/\sigma$ related to relative change in current $\Delta I/I_0$ and resistance $\Delta R/R_0$:

$$\frac{\Delta\sigma_0}{\sigma_0} = -\frac{\Delta R}{R_0} = \frac{\Delta I}{I_0} = \frac{I_{pc}}{I_0}$$

- I_0, R_0 represent photoconductor DC-current/resistance without radiation
- $\Delta I = I_{pc}$ is photon-generated *photo-current*

Photoconductive Gain (continued)



- detector width W, length l ($A = l \cdot W$)

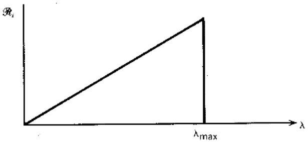
$$I_0 = Wd\,|\vec{j}|$$

- and hence

$$I_{pc} = I_0\,\frac{\Delta\sigma_0}{\sigma_0} = \frac{\eta_{\lambda_0} q \lambda_0}{hc} \cdot \frac{\tau_l \mu_n V_B}{l^2} \cdot \Phi(\lambda_0)$$

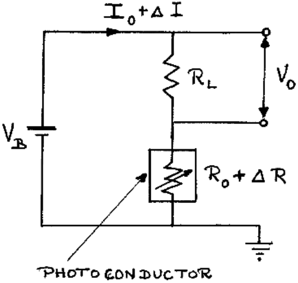
- $\tau_l \mu_n V_B / l^2$ is *photoconductive gain G*
- transition time τ_{tr} of free charge carriers across photoconductor length l ($\tau_{tr} = \frac{l^2}{\mu_n V_B}$), G gives ratio between carrier life time against recombination in photoconductor and its transition time, i.e. $G = \tau_l / \tau_{tr}$

Responsivity



ideal responsivity as function of wavelength

for constant η_{λ_0}



- *current responsivity* $R^I_{pc}(\lambda_0)$ follows from

$$R^I_{pc}(\lambda_0) = \frac{I_{pc}}{\Phi(\lambda_0)} = G\eta q\,\frac{\lambda_0}{hc}$$

  in Ampere/Watt

- in practice, photocurrent I_{pc} measured over load resistance R_L in series with photoconductor resistance R_0, translating I_{pc} into voltage V_0
- *spectral voltage responsivity*

$$R^V_{pc}(\lambda_0) = \frac{R_L R_0}{R_L + R_0}\,G\eta_{\lambda_0} q\,\frac{\lambda_0}{hc}$$

  in Volt/Watt

Responsivity (continued)

to raise responsivity of photoconductor, one should

- enhance quantum efficiency η_{λ_0} by minimizing reflections at interfaces through anti-reflection coatings, creating larger cross-section for internal photo-electric effect
- increase carrier life time $\Rightarrow$ raises photoconductive gain G
- enlarge carrier mobility μ_c (n-type charge carriers have substantially higher mobility than p-type)
- increase bias voltage $V_B \Rightarrow$ lowers transition time τ_{tr}

Charge Coupled Devices (CCD)

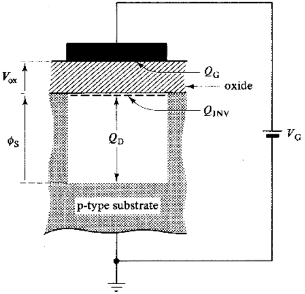
Operation Principle

- 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

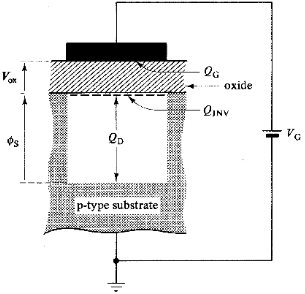
Single CCD Electrode



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 increasingly positive

Single CCD Electrode (continued)



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

- voltage high enough $\Rightarrow$ 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 μm 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

Potential Well

- calculate variation of surface potential ϕ_S with gate voltage V_G and surface-charge density Q_{Inv} in inversion layer
- p-type substrate grounded, oxide layer at V_{ox}:

$$V_G = V_{\mathrm{ox}} + \phi_S$$

- charge neutrality demands

$$Q_G = -(Q_{Inv} + Q_D)$$

- $Q_D = -qN_a x_D$ is surface charge density in depletion layer
- volume charge density $-qN_a$ integrated over thickness of depletion layer x_D
- N_a is density of acceptor doping in p-type semiconductor, q is the elementary charge

Potential Well (continued)

- voltage and charge balance from before

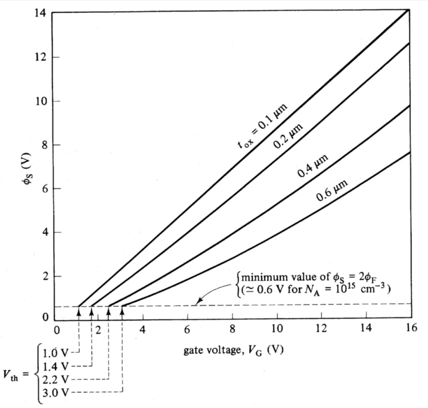
$$\begin{aligned} V_G &= V_{ox} + \phi_S \\ Q_G &= -(Q_{Inv} + Q_D) \end{aligned}$$

- integration of Poisson equation (electrostatics), $x_D = 2\epsilon\phi_s / qN_a$, with ϵ the dielectric constant ($\epsilon = \epsilon_0\epsilon_r$).
- substituting in Q_D and writing $Q_G = V_{ox}C_{ox}$ (C_{ox} is oxide capacitance per unit area ($C_{ox} = \epsilon/t_{ox}$ with oxide thickness t_{ox})), surface potential is:

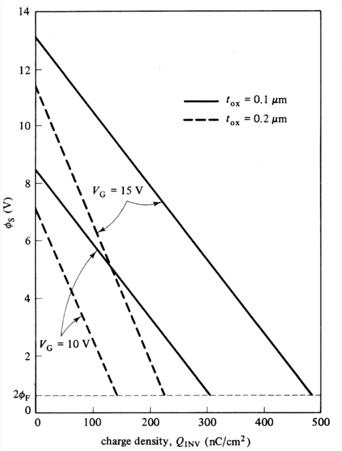
$$\phi_S = V_G + V_0 + \frac{Q_{Inv}}{C_{ox}} - \sqrt{2\left(V_G + \frac{Q_{Inv}}{C_{ox}}\right)V_0 + V_0^2}$$

- V_0 is a constant ($q\epsilon N_a / C_{ox}^2$) in Volts

Potential Well (continued)



Surface potential ϕ_S as function of gate voltage V_G for different values of oxide thickness t_{ox}. charge in inversion layer Q_{Inv} is zero in all cases (from Beynon & Lamb, 1980)



Surface potential ϕ_S as function of inversion charge Q_{Inv} for two values of gate voltage V_G and of oxide thickness t_{ox} (from Beynon & Lamb, 1980)

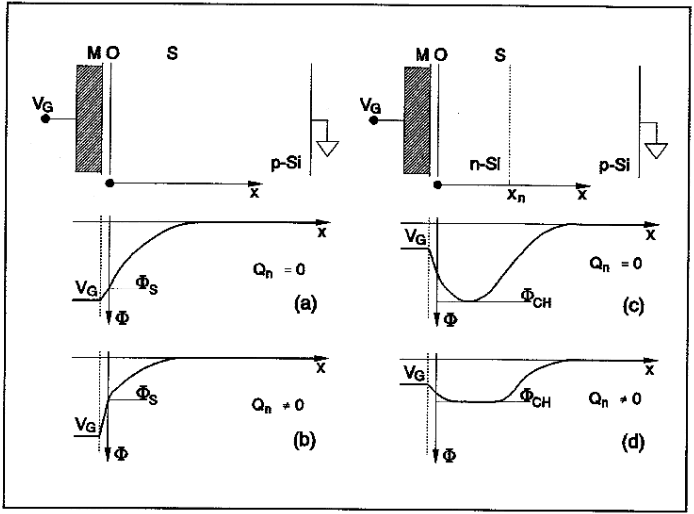
Potential Well (continued)

- surface potential ϕ_S interpreted as *potential well*
- well depth given by magnitude of inversion charge packet Q_{Inv}
- ϕ_s practically linear function of Q_{Inv} and V_G, since constant V_0 is small compared to typical values for V_G; i.e. V_0 = 0.14 Volt for 0.1 μm thick oxide layer
- since V_G= 10 - 15 Volt:

$$\phi_S = V_G + \frac{Q_{Inv}}{C_{ox}} \qquad \text{in good approximation}$$

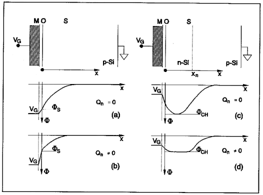
- storage of charge at the Si-SiO$_2$ interface leads to some charge losses during charge transport due to charge trapping in atomic surface states
- prevent losses, keep charge packet should at potential minimum separate from Si-SiO$_2$ interface, i.e. create minimum in bulk-silicon
- achieve this by n-type layer on top of p-type silicon; positive ions

SCCD vs BCCD



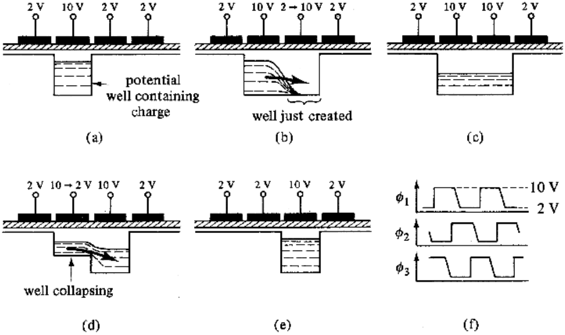
Surface and channel potential for a SCCD ((a) and (b)) and a BCCD ((c) and (d)), with empty ((a) and (c)) and filled ((b) and (d)) wells (from Theuwissen, 1995)

SCCD vs BCCD



- electron-potential minimum at interface vs. away from interface
- potential well in n-type Si: minimum deeper in bulk Si (BCCD)
- charge stored and transported in channel embedded in bulk silicon, not subject to charge loss at surface states
- comparison between empty and partly filled SCCD, (a) and (b), and empty and partly filled BCCD, (c) and (d)
- in BCCD, charge packet flattens minimum of potential well ("neutral layer" that increases in width if it becomes filled with charges)

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 Process

- equations for charge transfer process based on current density and continuity equation
- for n-type channel (electron charge):

$$\begin{aligned} j(x,t) &= q\mu_n n(x,t)\frac{\partial\phi(x,t)}{\partial x} + qD_n\frac{\partial n(x,t)}{\partial x} \\ \frac{\partial n(x,t)}{\partial t} &= \frac{1}{q}\,\frac{\partial j(x,t)}{\partial x} \end{aligned}$$

- charge propagation in x direction (no vector treatment)
- $n(x,t)$ is electron density, μ_n electron mobility, and D_n electron diffusion coefficient
- first right-hand term refers to drift of charge packet under gradient in electric potential
- second term refers to thermal diffusion under presence of a density gradient

Charge Transfer Process (continued)

- diffusion coefficient related to mobility of charge carriers μ_n

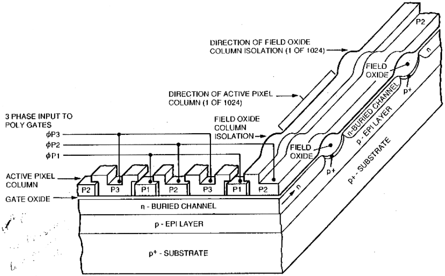
$$\frac{D_n}{\mu_n} = \frac{kT}{q}$$

- drift due to
    - *self-induced fields*: in gradient in charge concentration, charges of same type will mutually repel and reshuffle concentration of charge carriers in such a way that gradient becomes zero
    - *fringing fields*: charges are forced to move due to the existence of electric fields generated by the various voltage levels on the gates
- equalizing of charge concentration under electrodes two and three governed by drift speed due to self-induced fields and thermal diffusion
- effective diffusion coefficient $D_{n,eff}$ describes both processes
- for large charge packets mainly self-induced drift
- for small charge packets (e.g. $<$ 1% of well charge capacity) mainly thermal diffusion dominates and slows the transfer

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 and quenches surfaces potential ϕ_S so that 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 (rows)

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:

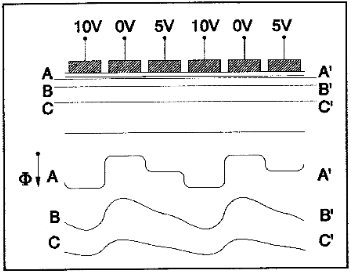
$$A_{elec}C_{ox} = \frac{Q_{Inv}}{V_G} \qquad \Longrightarrow \qquad Q_{Inv} = A_{elec}C_{ox}V_G$$

- C_{ox} is oxide capacitance per unit area, A_{elec} is electrode geometric area
- with A_{elec} = 10 $\times$ 20μm^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

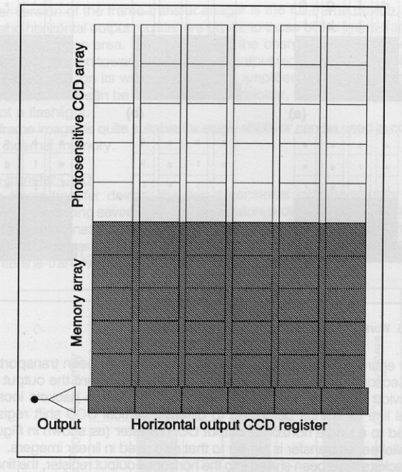
Fringing Fields



Fringing fields at Si-SiO_2 interface at several depths (from Beynon & Lamb, 1980)

- for BCCD, speed dominated by fringing field of neighboring gate due to depth of charge channel
- potential levels do not exhibit flat structure of Si-SiO_2 interface but have continuous gradient along which charge can drift
- BCCDs, with usually smaller charge packets, can be read out at much higher frequencies, up to 300 MHz, with acceptable CTE

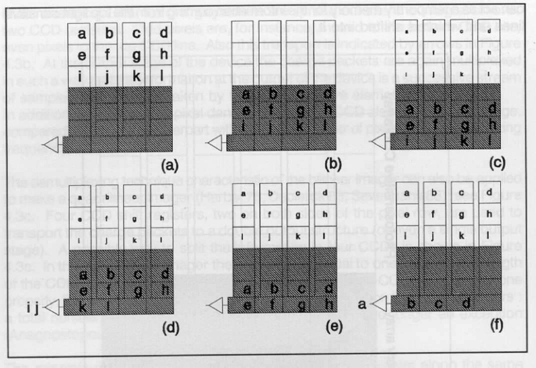
Focal Plane Architectures



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

Modulation Transfer Function

- pixel size Δx, sampling of image is array of normalized window functions $\frac{1}{\Delta x}\Pi\left(\frac{x}{\Delta x}\right)$
- spatial frequencies (s) associated with window function from its Fourier transform $\mathrm{sinc}(s\Delta x)$
- pixel pitch in image plane $x_0 \Rightarrow$ Nyquist frequency $s_N = \frac{1}{2x_0}$
- normalizing spatial frequency s with s_N yields geometrical MTF for linear array of pixels Δx with pitch x_0 ($s_0 = s/s_N$)

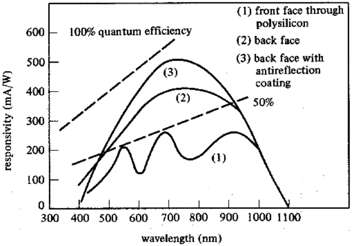
$$MTF_{geo} = \mathrm{sinc}\frac{s_0\Delta x}{2x_0}$$

- for contiguous pixels (e.g. frame-transfer CCD array), $\Delta x \approx x_0$ yielding:

$$MTF_{FT} = \mathrm{sinc}\frac{s_0}{2}$$

with $MTF_{FT} = 0$ for $s_0 = 2$, i.e. $s = 2s_N$

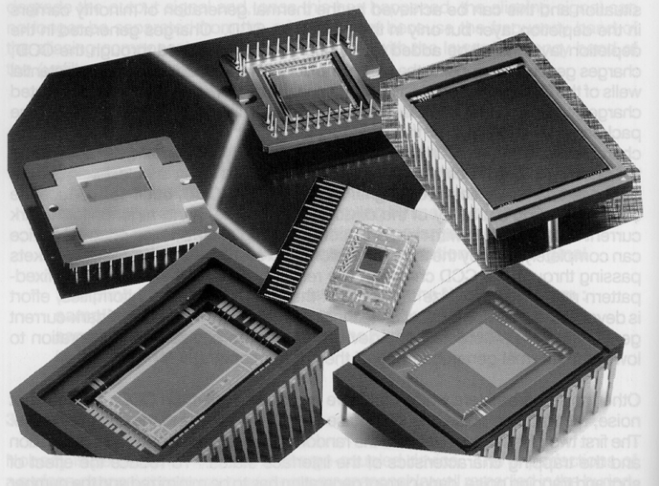
Wavelength response of CCDs



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

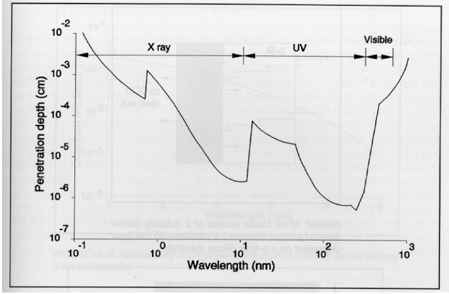


Top left: back-side illuminated FT imager with 1260 × 1152 pixels. Top right: a full frame CCD with 3k × 2k pixels, each of 9 μm × 9 μm. Middle: a low-cost FT sensor with 270,000 pixels, total diameter of the image section is 3.2 mm. Bottom left: HDTV IT image sensor with 2M pixels, 11 mm diagonal. Bottom 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 $> 1\ \mu$m: photo-electric absorption coefficient in silicon is too low ($h\nu_{IR} <$ bandgap) $\Rightarrow$ all photons pass through silicon
- wavelengths $< 0.4\ \mu$m, $> 10\ nm$: 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 an 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