CCD Digital Radiographic Detectors

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Outline

- Introduction
- CCD Fundamentals
- Characteristics related to imaging
- Implementations in Radiology
- Advantages and Disadvantages
- CMOS
- Conclusion

Introduction

- CCDs are quite widespread
  - used in digital cameras
  - videocameras
  - Astronomy
  - Photomicrography
- Some of original digital devices used in Radiology
- Relatively simple
- New offerings of CCD technology in Radiology

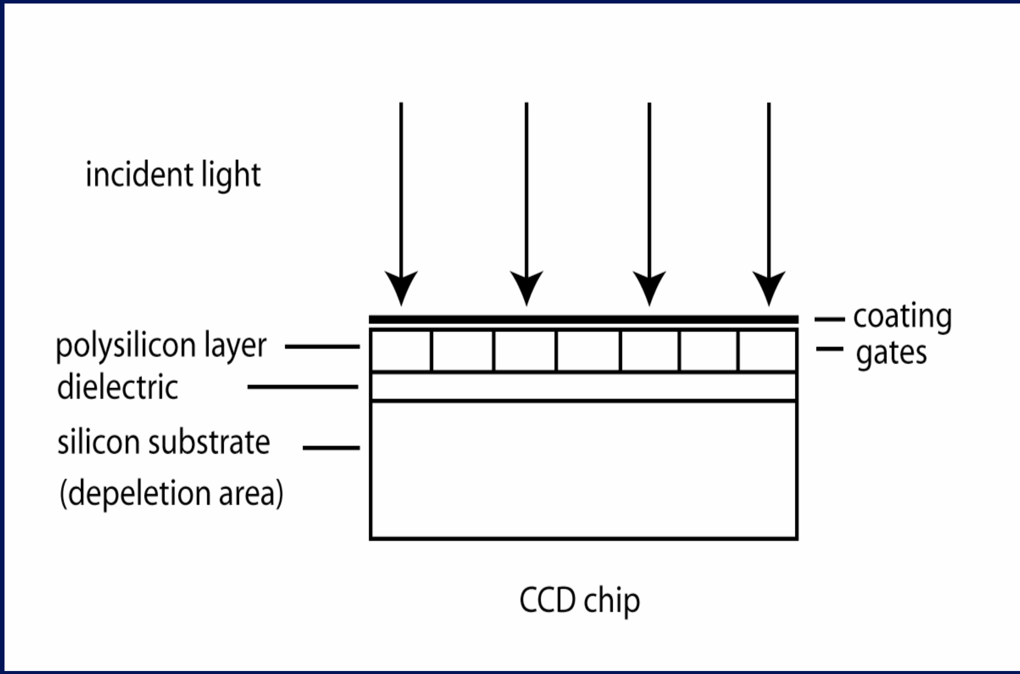
Introduction

- CCDs are limited in size
- CCDs are indirect type of digital receptor
- Have optical considerations in addition to usual considerations
- Related to disadvantage

CCD Fundamentals

- Device is a silicon chip
- Photosensitive layer
- Embedded electronics

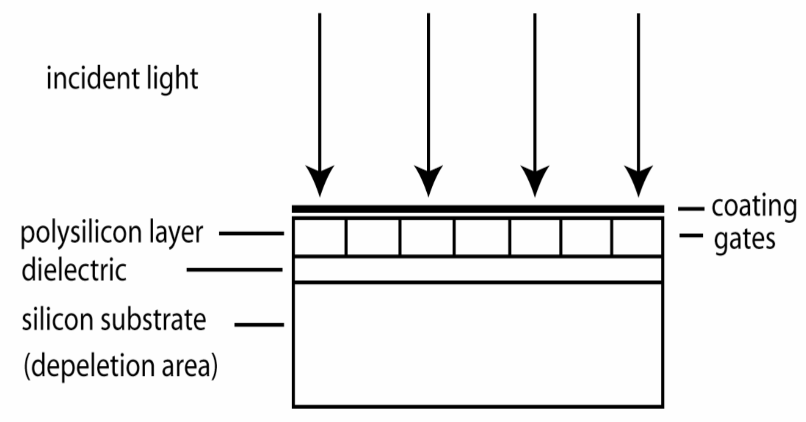
CCD Fundamentals



- **Polysilicon layer contains the gates (in essence the pixels)**
- **Silicon dioxide acts as an insulator**
- **Bulk silicon contains depletion area and charge storage area**

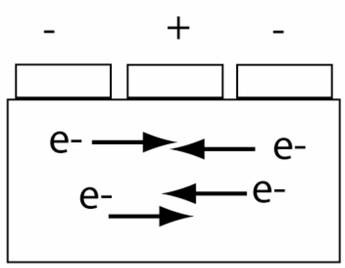
CCD Fundamentals -- Sequence of events

- Light strikes device
- Electron-hole pairs formed
- Electrons constrained to an area by electrostatic forces



CCD chip

- Each pixel contains 3 electrodes as shown
- Charge readout in "bucket brigade" fashion



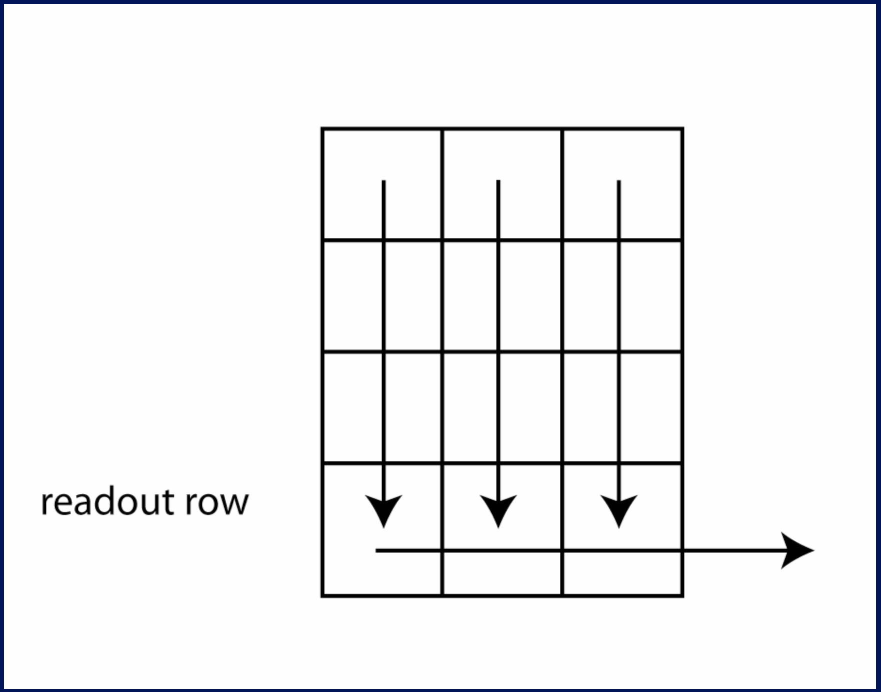
Single Pixel

CCD Architectures

- **Full-frame -- frame dumped out as a unit**
  - Simpler and used in general radiological applications
  - Entire surface area of chip utilized so fill factor = 100%
  - An entire scene is captured (e.g. x-ray exposure)
- **Interline -- readout and photo-detection in one area**
  - Readout is shielded and charge is transferred to the readout area at a given frame rate (shutter control)
  - High frame rates but fill factor is significantly reduced

CCD Fundamentals -- Readout
Full Frame

- Move charge down column using voltage sign changes
- Charge eventually reaches readout row
- Charge in readout row (serial register) is sequentially moved out to sense amplifier and digitized
- All of above takes place under control of clock signals

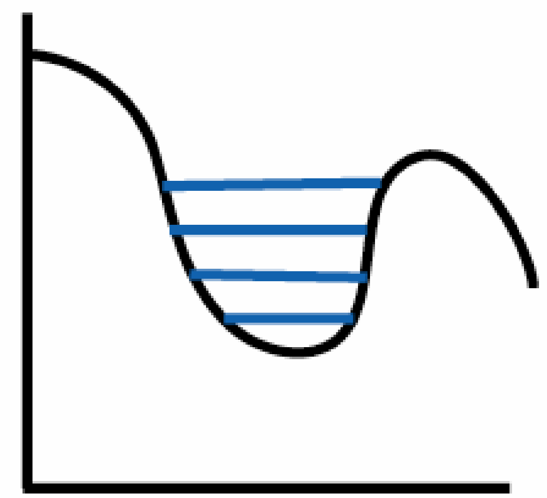


CCD and blooming

- Each cell has a given well depth for the storage of the charge
- If the charge exceeds the well depth, electrons will spill into adjoining cells
- Design chip to accommodate expected well depth
- In some applications overflow drains are incorporated into the chip

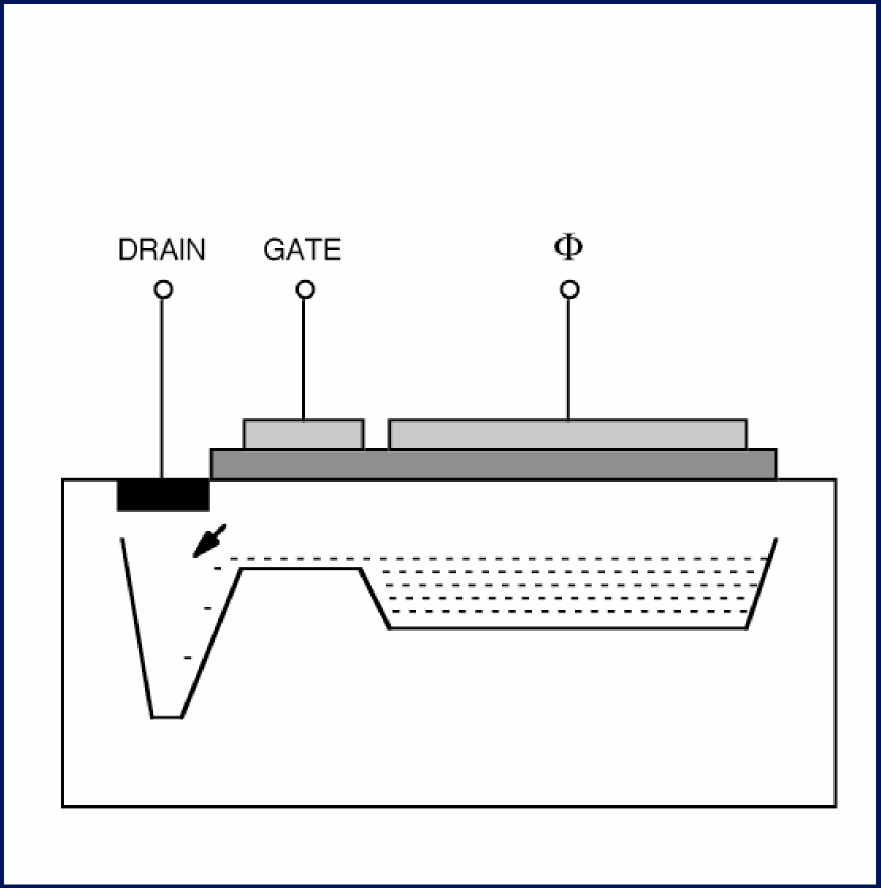
Vertical Overflow Drain

- Vertical -- set barrier with height less than surrounding
- adds to complexity and may reduce overall dynamic range
- (reduces original barrier height)



Lateral Overflow drain

- Lateral -- uses part of the chip to store the excess
- reduces fill-factor



Adapted from Kodak CCD Primer - #KCP-001

CCD Characteristics and Imaging

- CCD chip size is limited to a maximum of 5 x 5 cm
- Cost is dominant issue
  - Number of acceptable chips is low
  - Large chip quite expensive, acceptability rates low
  - Cheaper to make a large number of smaller chips
- Demagnification needed in most applications
  - Match light emission source and CCD size with optics (lenses or fiber optics)
- Amount of light incident and subsequently absorbed is very important

Important components and characteristics

- Scintillator -- amount of light input
- Optics -- capture of light and transmission to chip
- CCD quantum efficiency -- light absorption, spectral sensitivity
- Noise

Scintillator

- Absorption of x-rays and light conversion
- Spectrum of emitted light

- Characteristics are not unique to CCD
  - Spectrum is important to CCD
- Common to any indirect digital system
- CsI is common
  - "needle" crystalline structure advantageous

Optical considerations

- Light transport efficiency is critical issue
- Transmission of light through medium (will depend on spectrum)
- Focusing media
  - lenses
  - fiber optics
- Different issues for each

Lenses

- **Efficiency of transmission**
  - **~ 0.7 to 0.8 for CsI spectrum (550 nm)**
- **Focal length**
- **Demagnification factor**
- **Overall collection efficiency**

Collection efficiency for lenses

$$\eta_L = \frac{T_L}{1 + 4 \bullet f_{\#}^2 \bullet (1+m)^2}$$

- **Assuming Lambertian source of light**

T_L = transmission factor of lens

$f_{\#}$ = f-number of lens

m = demagnification factor

- **Note $f_{\#}$ and m appear as squared terms**

Example

$f_{\#}$ = 1.2, T_L = 0.8, and m = 2

η_L = 1.5%

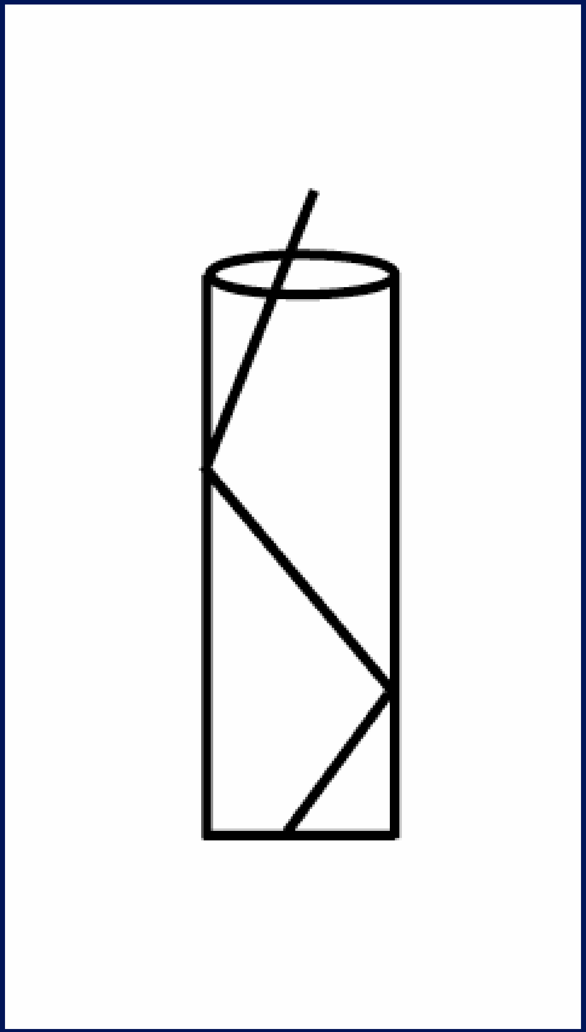
Other issues with lenses

- Geometric distortion
- Vignetting
- Veiling glare (light scatter)

- Main concern is coupling efficiency and creation of a secondary quantum sink
- Note: it is possible to avoid the above but much care and effort involved, especially at low exposure

Fiber optics

- Want to have 100% internal reflection
- For a bundle have to consider ratio of length-to-diameter (normally a high ratio)
- Any loss will be magnified



Collection efficiency -- fiber optic

$$\eta_{TFO} = \left(\frac{1}{m}\right)^2 \bullet \left(\frac{\left(n_2^2 - n_3^2\right)^{1/2}}{n_1}\right)^2 \bullet T_F \bullet (1 - L_R) \bullet F_C$$

assuming Lambertian source as before

m = demagnification factor

n_1 , n_2 , n_3 = refraction indices of source medium, fiber core and cladding

T_F = transmission factor

L_R = loss due to Fresnel reflection

F_C = fill factor of core

Example: m = 2; n_1 = 1; n_2 = 1.8; n_3 = 1.5; T_F = 0.8; F_C = .85; and L_R = 0

η = 15%

Quantum efficiency of CCD

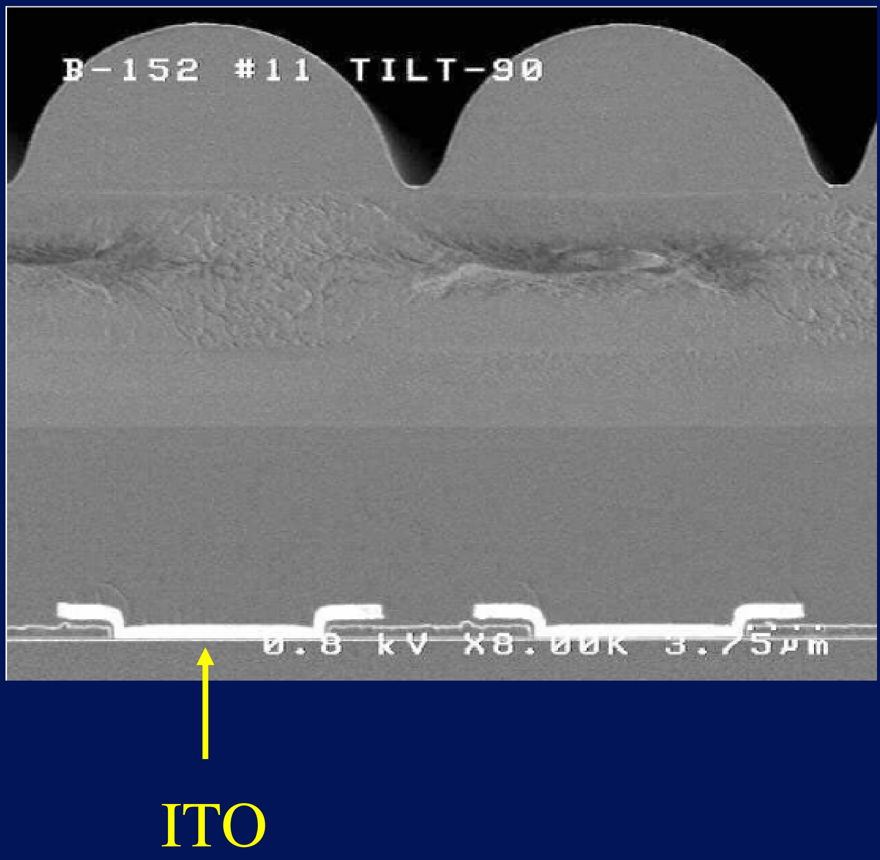
- QE = efficiency of system per photon incident on receptor
- Absolute efficiency relative to light collection and creation of electron within chip
- Not to be confused with DQE, though has influence

Quantum efficiency influences

- **Absorption of light**
  - Light needs to pass through polysilicon layers but not so deep that cannot be captured in potential well
  - Polysilicon layer needs to be relatively transparent
- **Spectrum sensitivity**
  - Can modify this with overlaying materials and doping to optimize to a given wavelength
- **Light collection**
  - microlens

Example Kodak Blue Plus CCD

- Indium Tin Oxide gate
- Microlens channels light to ITO gate (more sensitive)
- Chip has a peak spectral sensitivity in the range of 550 nm (flat over 575 to 650 nm)
- Matches the CsI peak
- quantum efficiency ~ 85%



Adapted from article by A. Ciccarelli, et al., Eastman Kodak Co.

Noise

- Quantum noise inherent with exposure
- “shot noise” -- related to number of photons reaching the CCD
- Dark current noise
  - Strong dependence on temperature particularly at the surface
  - Thermal radiation can move electron to near the conduction band, another can move it to the conduction band

Dark Noise Remedies

- Operate the chip in an inverted state
  - Populate the interface states with free carriers
  - Operate two or all three electrodes in inverted state
  - Accomplished by doping
  - Kodak uses this in the Blue Plus Chip mentioned earlier
- Over time dark noise will increase if readout has not occurred
- Can use cooling (peltier, thermoelectric cooling)
  - Especially needed for applications in astronomy

Cooling Effects

- Dark noise may be of the order of 10,000 e/pxl/sec at room temperature for unmodified CCD
- Drop of 40 degrees from room temperature will reduce dark noise by a factor of ~ 100
- So is an important consideration

Other noise sources

- noise associated with amplifiers in output stage
- Digitization noise
- Flat field correction
  - Correct for non-uniform response across chip
  - Dead pixels
  - Application of correction adds to system noise
- Above common to any digital system but noise is additive

Implementations in Radiology

- Digital Fluoroscopy
- Stereo breast biopsy
- Mammography
- General radiography

Digital Fluoroscopy

- Prevalent in II -- natural replacement for TV tube
  - Output of II of the order of 1 inch which matches the size of a CCD
  - Analogous readout to TV tube (data stream readout as lines)
- CCD has a linear response and a large dynamic range
  - Blooming is greatly reduced and can be managed by manipulation of the overflow pixel area of the chip
- Don't have the problems associated with electron scanning
- Significant brightness gain afforded by II so losses in coupling less of a problem
- Can operate at high frame rates

Stereotactic Biopsy

- Typical FOV is 5 x 5 cm
- Matches with CCD well
- Fischer and Lorad use 2.5 x 2.5 cm cameras
  - Fischer uses tapered fiber optics
  - Lorad uses lens
- Noise is a major issue
  - Use 27 to 28 kVp to increase photon flux reaching CCD
  - 1024 x 1024 matrix; pixel size 50 µm -- affects noise
  - CsI and special scintillators used to increase light output

Stereotactic Biopsy

- **Imaging characteristics**
  - DQE is low, unpublished values
  - New cameras and scintillators have been implemented
  - 512 matrix can help on contrast and noise
  - but main reason for doing x-ray biopsy is to find calcifications where resolution and noise is important

Digital Mammography

- Original -- tiled arrays with fiberoptic tapers to cover 18 x 24 cm, not used now replaced by flat panel arrays
- Current -- Fischer
  - Four rectangular CCDs
  - Operating in time-delay-integration mode
  - CsI scintillators to cover 1 cm x 22 cm area
  - Scanned over 30 cm width
  - Slot scanning affords significant scatter reduction
  - No grid used so increase in flux helps overcome photon limitations of CCD

Time delay integration

- Good for long narrow area of moving data
- Parallel register is clocked in step with the motion
- When data reaches serial register, data are transferred and stored in normal fashion

General Radiography

- Desire 14 x 17 inch coverage
- Demagnification issues significant
- CsI scintillator common to increase efficiency
- Many different implementations
  - Swissray
  - Imaging Dynamics Corporation

Swissray

- **four CCDs with fiberoptic tapers**
  - **Helps solve some of the demagnificagion issue**
- **10% overlap of each CCD**
  - **(stitching and balance of response)**

Imaging Dynamics

- single CCD
- Use a large high quality lens
- Have achieved high DQE, through many design features

Specialized -- Statscan (Lodox)

- 12 CCDs coupled to GdOS
- Cover an array of 1 x 66 cm
- X-ray tube and receptor array attached to C-arm
- Assembly can move longitudinally up to 180 cm
- Angle up to 100 degrees
- CCDs operated in time-delay-integration mode
- Slot scan -- no grid needed; increases photon flux
- Pixel size 60 µm unbinned; different binning possible
- Small area resolution of 3.6 lp/mm, Whole body 1.7 lp/mm

Advantages and Disadvantages

- Relatively simple
- Cheaper to replace if failure
- Modularity -- easy upgrades
- Detector costs cheaper

- Demagnification is a major concern
- Relates to potentially lower DQE

- Vary with application
- II -- CCD a natural replacement
- Stereotactic Biopsy -- demagnification less of a problem

Complimentary-Metal-Oxide Semiconductors (CMOS)

- Are being used in place of CCDs
- Development less mature
- Size is an issue as with CCDs (demagnification)
- Readout scheme -- more direct output
  - Each pixel is attached to a column and row output line
  - Direct readout of a pixel
- Tiled arrays
- Specimen radiography, small area digital radiography systems

CMOS

- Uniformity correction may be tied to kVp for tiled arrays
- Specimen biopsy radiograph system is set to a particular kVp. If change kVp, see the tiling structure unless one resets the “blank” calibration to that kVp.
- kVp range may be limited based on uniformity

Conclusion

- Demagnification is a concern and much care needed
- Lower DQE compared to flat panel, in general
- Certain advantages
  - Cost, modularity
- Based on cost and modularity, expected that systems will continue to find use in Digital Radiography
- New designs are competitive