Handout #5
Digital Radiography

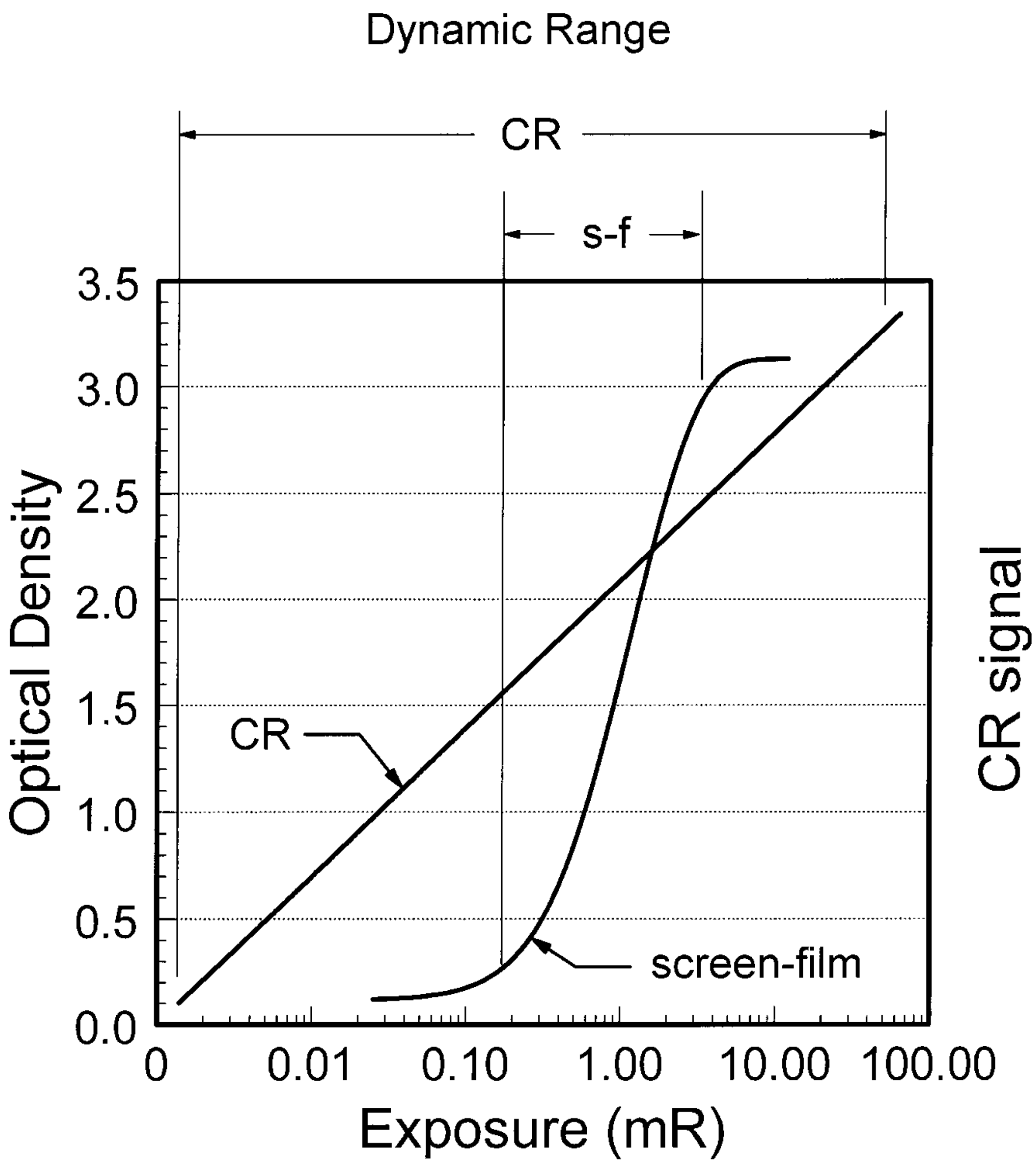
5.1 Background

❖ In recent years radiology has undergone a revolutionary change from screen-film-based radiology to digital radiology, which uses optoelectronic detectors to record images.

Advantage of digital radiography

- Wider dynamic range
- Immediate availability of digital data for image manipulation, transmission and archiving
- Lower patient dose can potentially be achieved through fewer repeat examinations

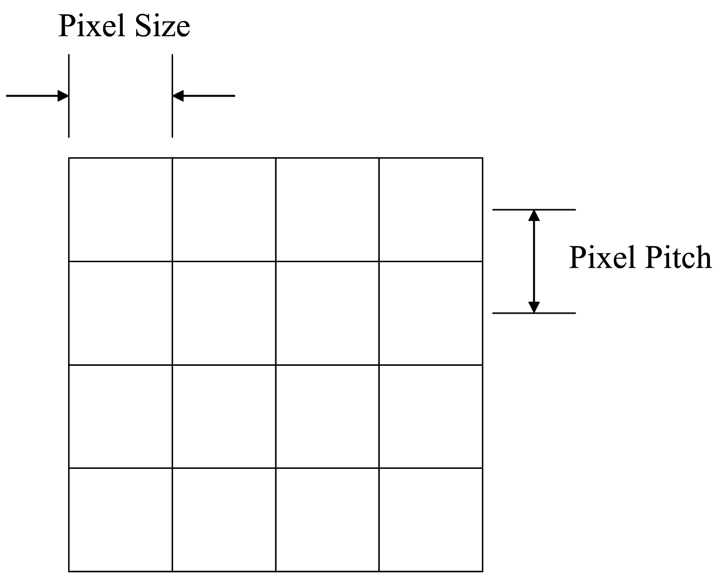
Separate detector and display device



Dynamic Range
CR
s-f
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Optical Density
CR
screen-film
CR signal
0
0.01
0.10
1.00
10.00
100.00
Exposure (mR)

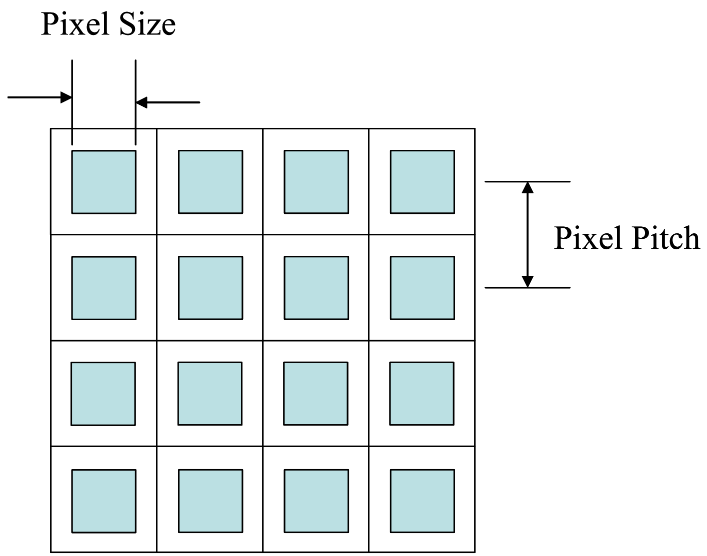
Figure 1

(1) A digital image detector detects X-ray (or Optical) image pixel by pixel, thus, the digital image appears as an array of pixels.



Pixel -

- Pixel pitch: Δ x (mm)
- Spatial resolution (lp/mm) = 1 / (2 $\times$ Δx) (lp/mm)
- Resolution format
  1024 $\times$ 1024 (1k $\times$ 1k)
  2048 $\times$ 2048 (2k $\times$ 2k)
  Other formats



Fill factor

- The ratio of the light-sensitive area to the entire area of each detector element (pixel) is called the fill factor..

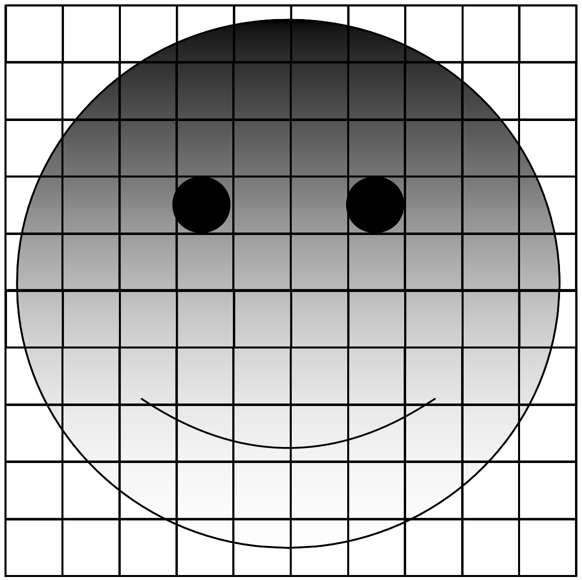
(2) Pixel values

Figure 2 shows an example of how a simple one-dimensional image would appear in **analogy and digital format**.

Figure 2

Pixel values and gray-levels

256 gray levels ~ 2^8 ~ 8 bits
4096 gray levels ~ 2^{12} ~ 12 bits
65536 gray levels ~ 2^{16} ~ 16 bits



(3) Various optoelectronic detectors have been developed and successfully applied in clinical imaging practice.

- Charge-coupled device (**CCD**) detector systems or complementary metal-oxide semiconductor (**CMOS**) detectors
- Flat-panel thin-film transistor (**TFT**) detector systems,
- Photostimulable phosphor imaging plate detector systems (computed radiography---**CR**).

5.2 Principles of CCD Operation

(1) Basic structure

- ❖ A two-dimensional **CCD** is a matrix of millions of picture elements (pixels) made from silicon. (Fig. 3).
- ❖ The size of each pixel ranges from a few micrometers to tens of micrometers.
- ❖ An image that is projected on the photosensitive surface of a **CCD** produces an optical intensity pattern.

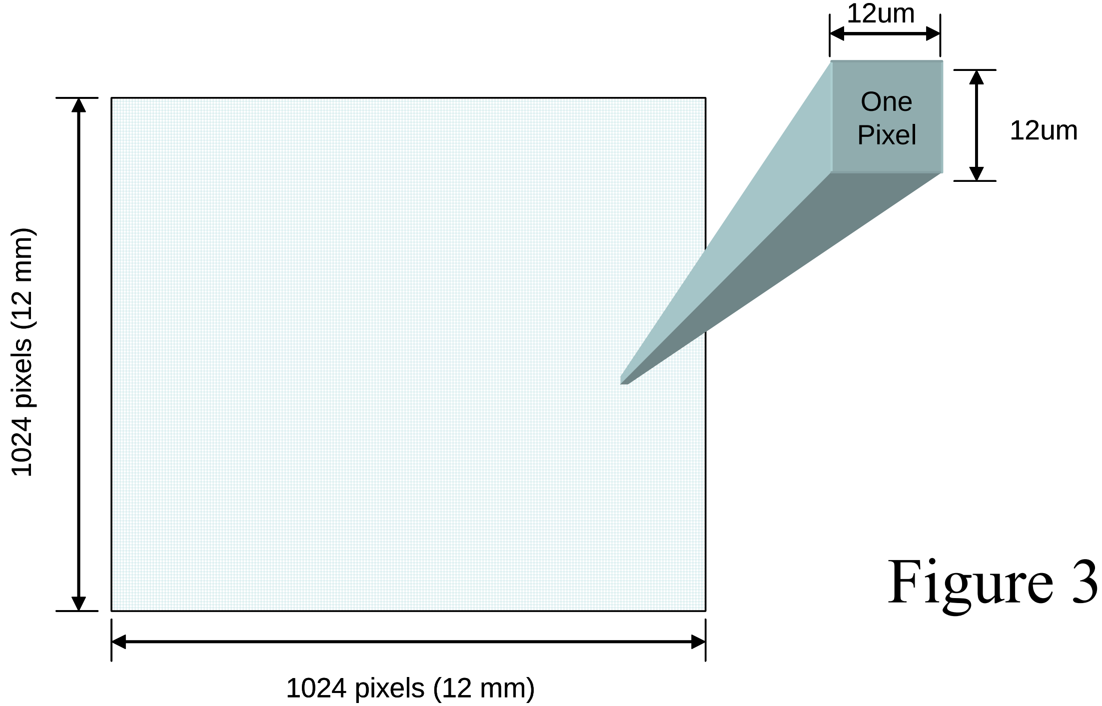


Figure 3

(2) Exposure

- During the exposure period, each pixel converts the incident photons into a proportional quantity of electron charges.
- These electron charges are then stored in a metal-oxide semiconductor (**MOS**) capacitor (potential well) associated with each pixel (Fig.4).

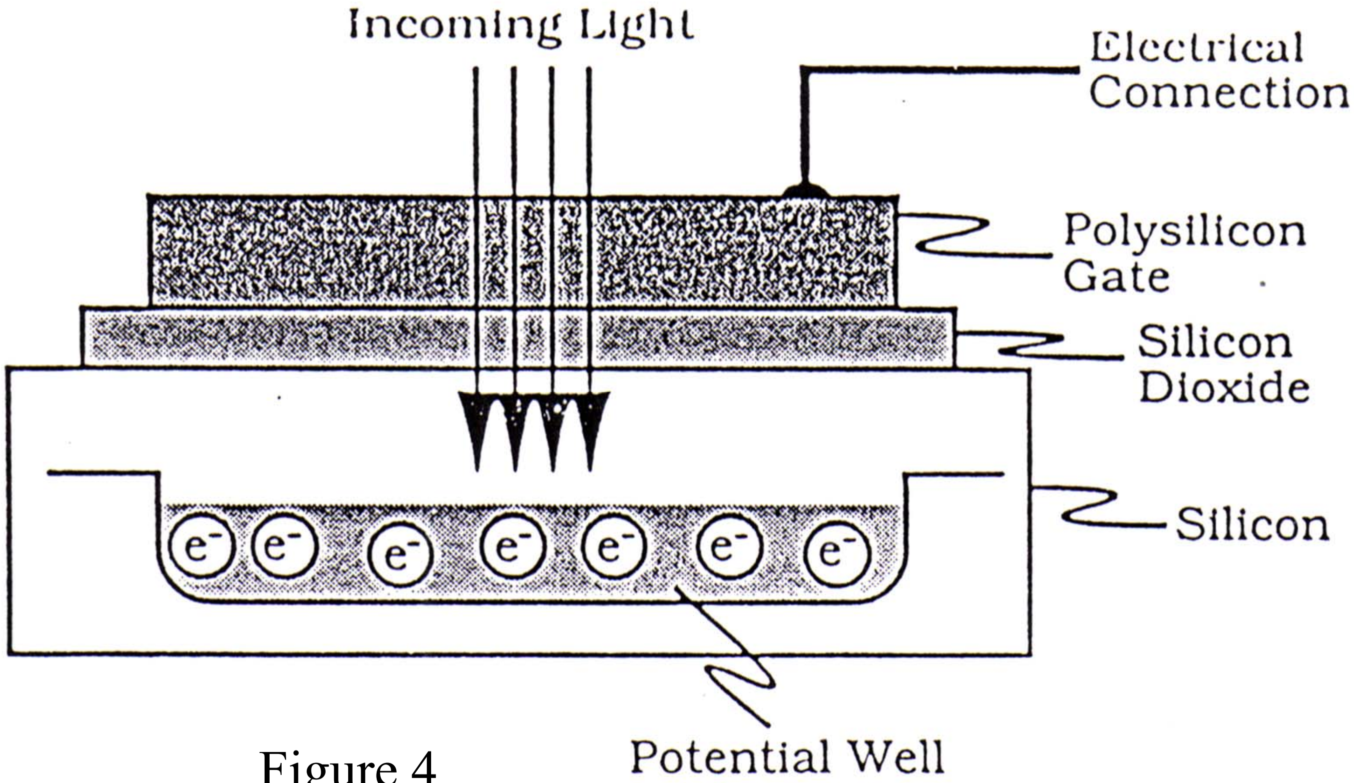


Figure 4

(3) After exposure

- After the exposure period, a programmed sequence shifts the accumulated charge packet of each pixel row by row to a readout stage (usually called serial register).
- As each pixel is clocked out of the serial register, each charge packet is converted into a proportional voltage signal (Fig.5).
- Additional sampling and amplification gives the low impedance video signal.
- For a **CCD** imager, the whole readout of a pixel array may requires several seconds. It should be noted that **CCDs** with faster readout rate are available

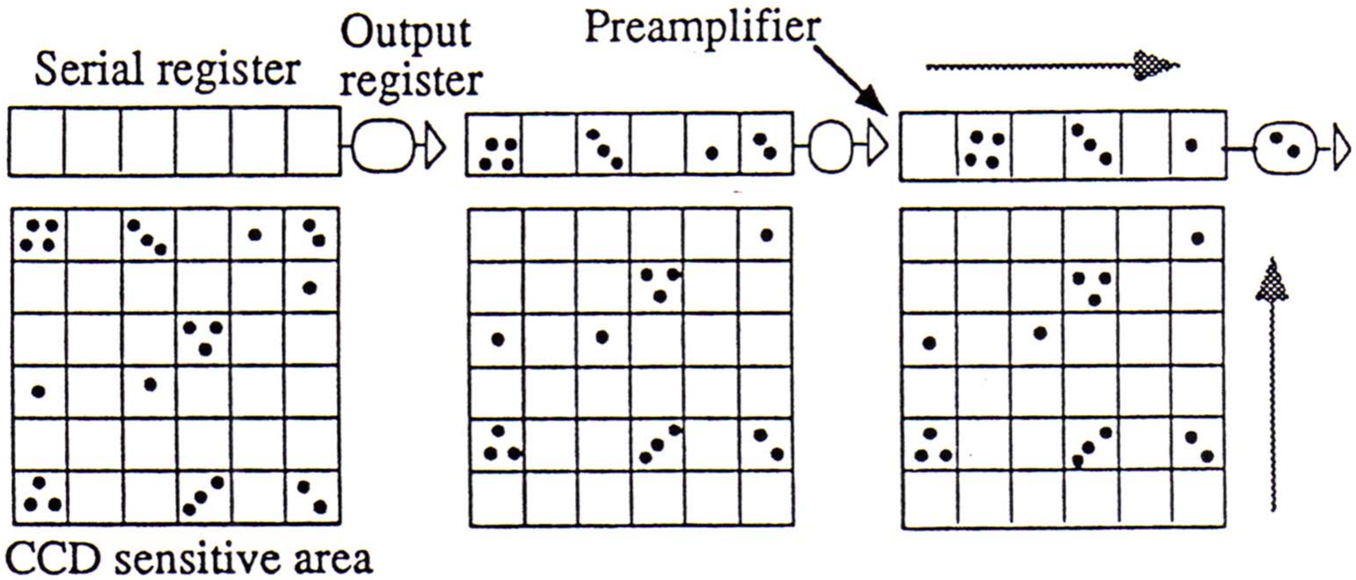


Figure 5

(4) CCD performance

The following is a brief description of these features and their impact on image clarity.

(a) Spatial resolution

- The spatial resolution of a **CCD** camera is determined by the geometry of the specific **CCD** being used. A picture element, or pixel, varies in size from a few micrometers up to tens of micrometers.
- Most scientific grade **CCDs** have square pixels.
- In full frame **CCD** imagers, there is no dead space between the square photosensitive pixels. In other words, the sampling distance and the sampling aperture of this digital imager are almost the same.
- A scientific-grade **CCD** with square discrete pixels and a fixed geometry exhibits nearly ideal behavior in terms of sampling theory.

Therefore the **Nyquist spatial resolution** (lp/mm) of the **CCD** is determined by:

$$f_q = \frac{1}{2\Delta x} \quad (5.1)$$

where Δx is the pitch of the discrete pixel in mm.

Example:

The CCD shown in the previous slide has a format of 1024 by 1024 pixels array. The pixel pitch is 0.012mm. What is the Nyquist spatial resolution in lp/mm of the detector?

Solution:

$$f_q = \frac{1}{2\Delta x} = \frac{1}{2 \times 12 \times 10^{-3}} = 41(lp/mm)$$

(b) Quantum efficiency

Quantum efficiency is a measure of the sensor's efficiency in generating electronic charge from incident photons,

$$\text{Quantum efficiency} = \frac{\text{Number of electrons generated per pixel}}{\text{Number of incident photons per pixel}}$$

This photon to electron conversion factor is a function of wavelength. Fig.6 shows the spectral quantum efficiency of the Ford aerospace CCD in conjunction with the spectral emission of a Kodak Lanex (rare earth) intensifying screen.

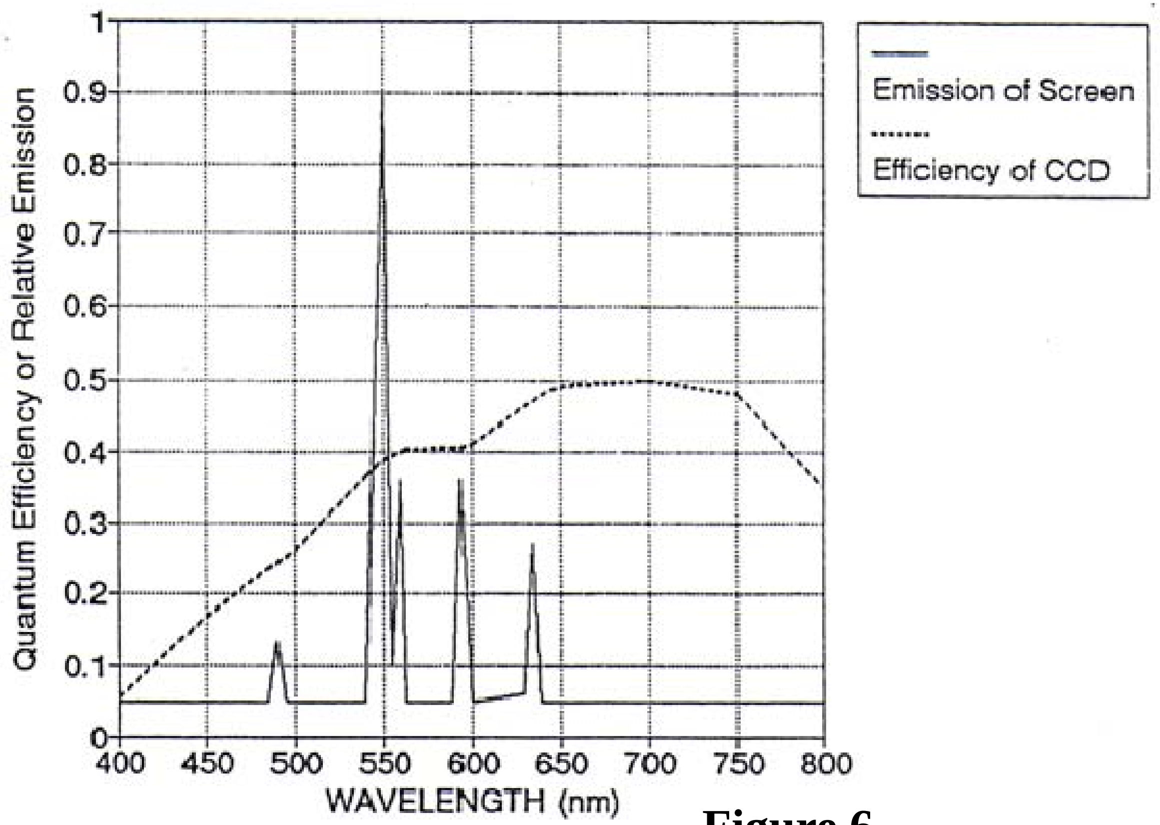


Figure 6

- ❖Within the visible spectrum, the optimal **CCD** quantum efficiency ranges from 30% to 70%, depending on the quality and or types of the **CCD**.
- ❖According to Fig.6, this **CCD** imager has a quantum efficiency of 35% at 550nm.

(c) Detector noise

- At high light exposure levels, system noise is dominated by photon **Poisson** counting statistics,
- But at low light exposure levels, the additive noise, primarily the preamplifier noise, begins to dominate. As the light exposure continues to decrease, it may reach to a point where the signals become "lost in the noise".
- **CCD** imagers have demonstrated a very low additive noise level. Noise levels as low as 2~20 electrons rms (root-mean-square) are attainable in high quality **CCDs**.
- In comparison, the additive noise level of a TV camera can be a few hundreds electrons rms (root-mean-square) or even higher.

(d) Sensitivity

- Sensitivity is a measure of the minimum detectable signal a **CCD** can produce.
- The sensitivity of a **CCD** imager to light is affected by quantum efficiency, detector noise levels.

(e) Dynamic range

- The term dynamic range refers to the ratio of the saturation charge to the imager's noise level.
- The dynamic range is often represented as **a *log* ratio** of well depth to the readout noise in decibels.
- In general, a **CCD's** noise level may vary between a few electrons and tens of electrons.
- The saturation charge of a **CCD** is limited by the **well capacity** (capacity of the potential wells) and varies with architecture and pixel size of the device.
- For scientific grade **CCDs**, a well capacity of >100,000 electrons is available.
- In comparison, the dynamic range of a TV tube is usually much smaller.

Example:

A system has a well depth of 85,000 electrons and a readout noise of 12 electrons. What is its dynamic range?

Solution:

$$\text{Dynamic range} = 20 \times \log (85000/12) = 77 \text{ (dB)}$$

Example:

Table 1 Characteristics of a 1K by 1K CCD

Pixel size	12μm × 12μm
Sensitive area	1024 × 1024 pixels, 12mm × 12mm
Quantum efficiency	30% ~ 35% at 550nm
Quantization	12 bits per pixel
Readout rate	40MHz
Readout noise	Approx. 1.75 electrons per pixel

(5) CCD based digital X-ray imaging systems

❖ Systems for small field radiography applications

Such as specimen radiography systems
or systems for assisting breast cancer biopsy

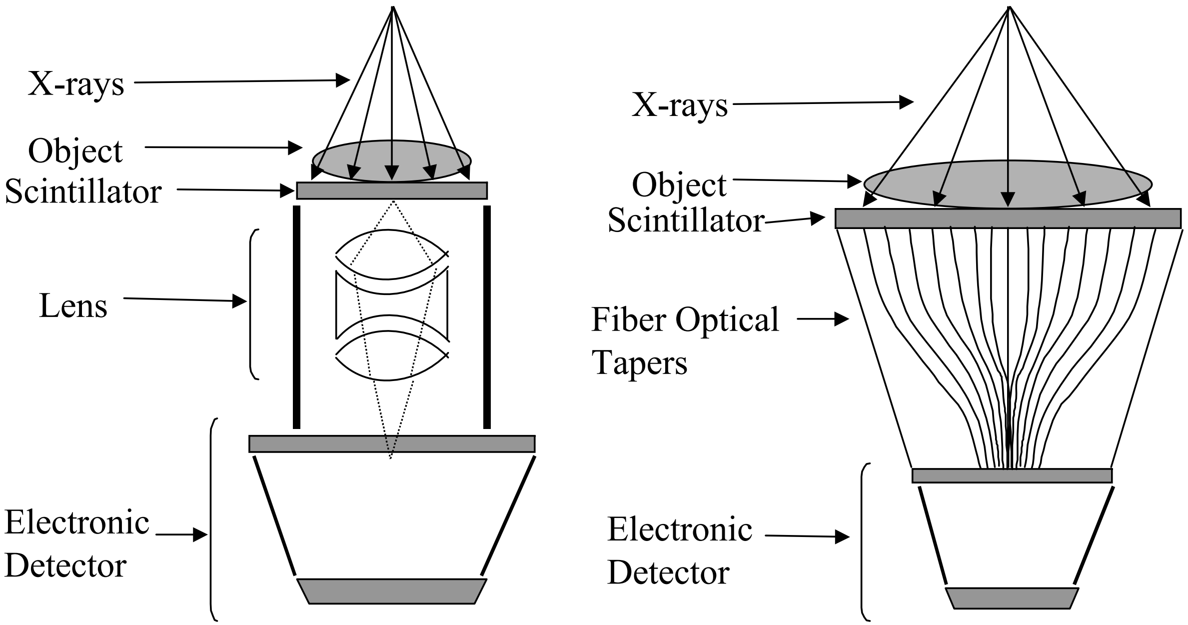


Figure 7

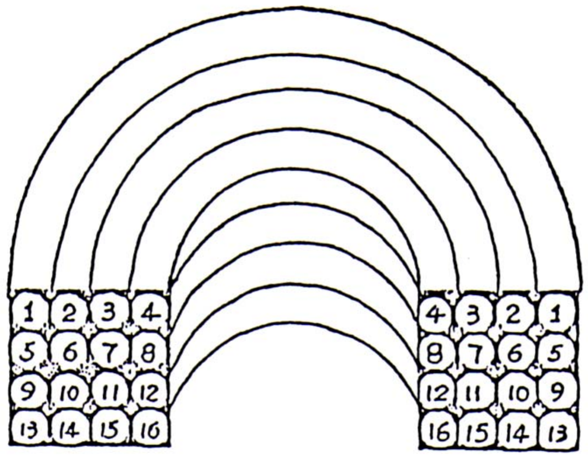
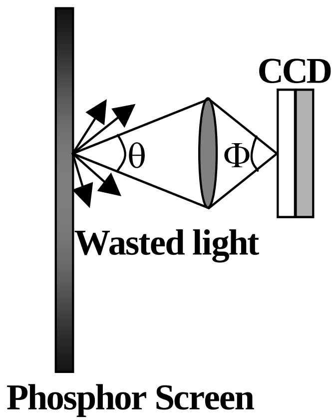


Figure 8

Optical Lens Coupling



Fiber Optic Coupling

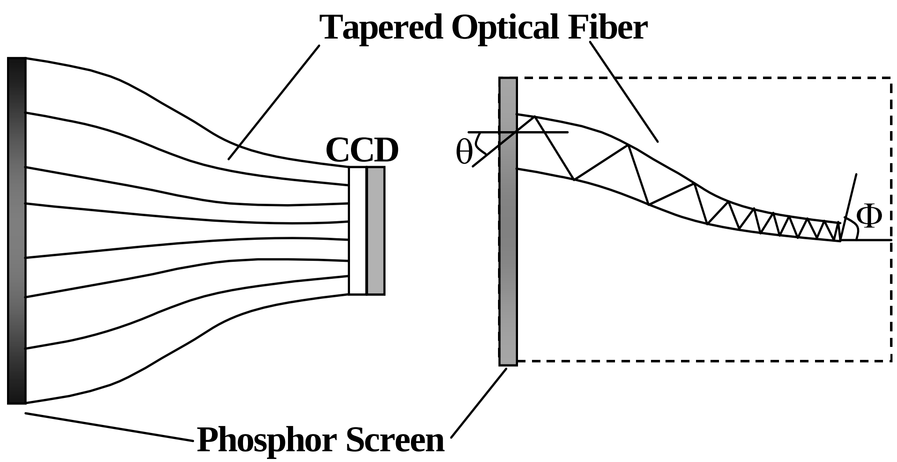


Figure 9

Full field digital mammography systems

❖ CCD scanning, radiation shielding technique

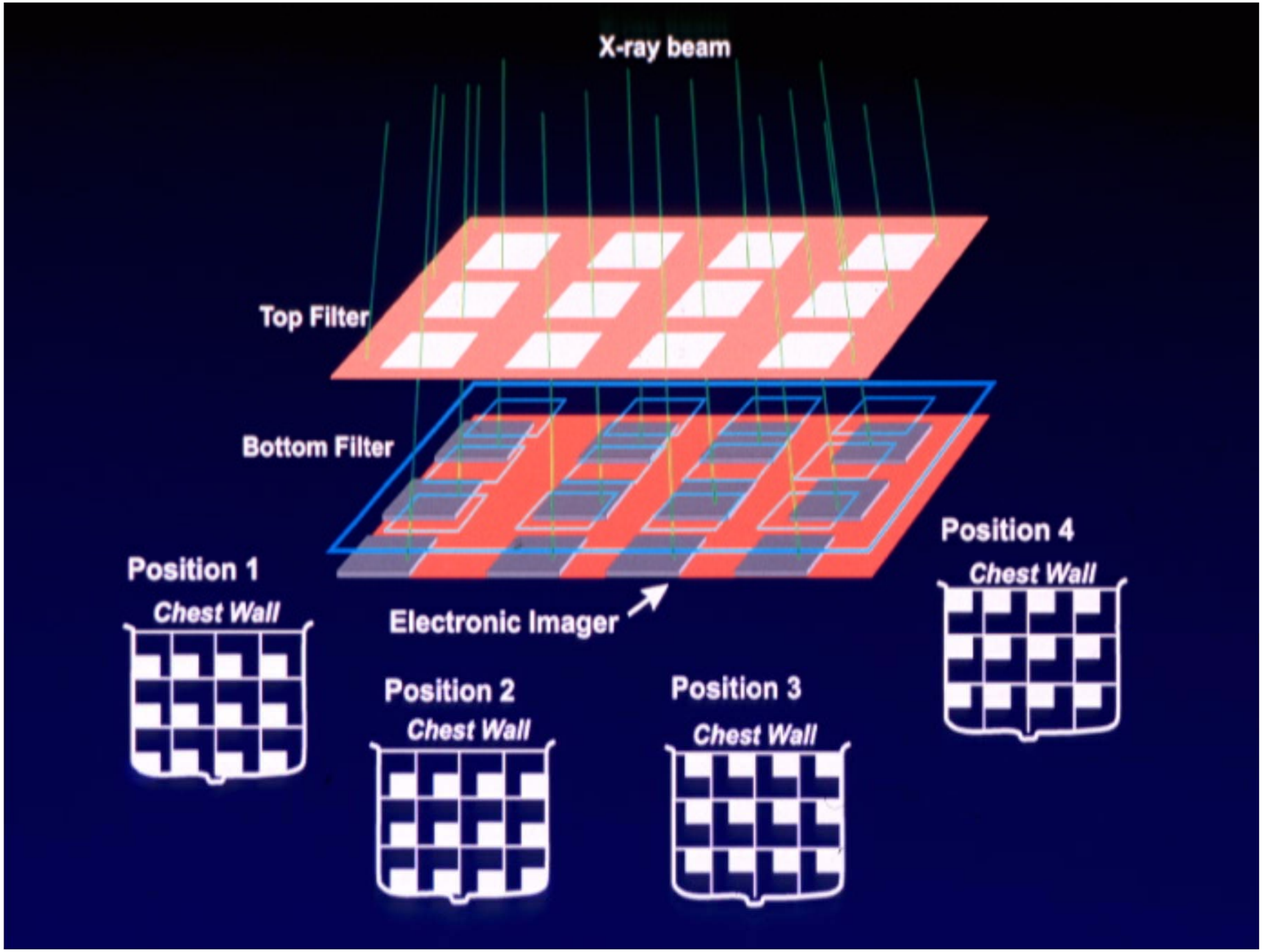


Figure 10

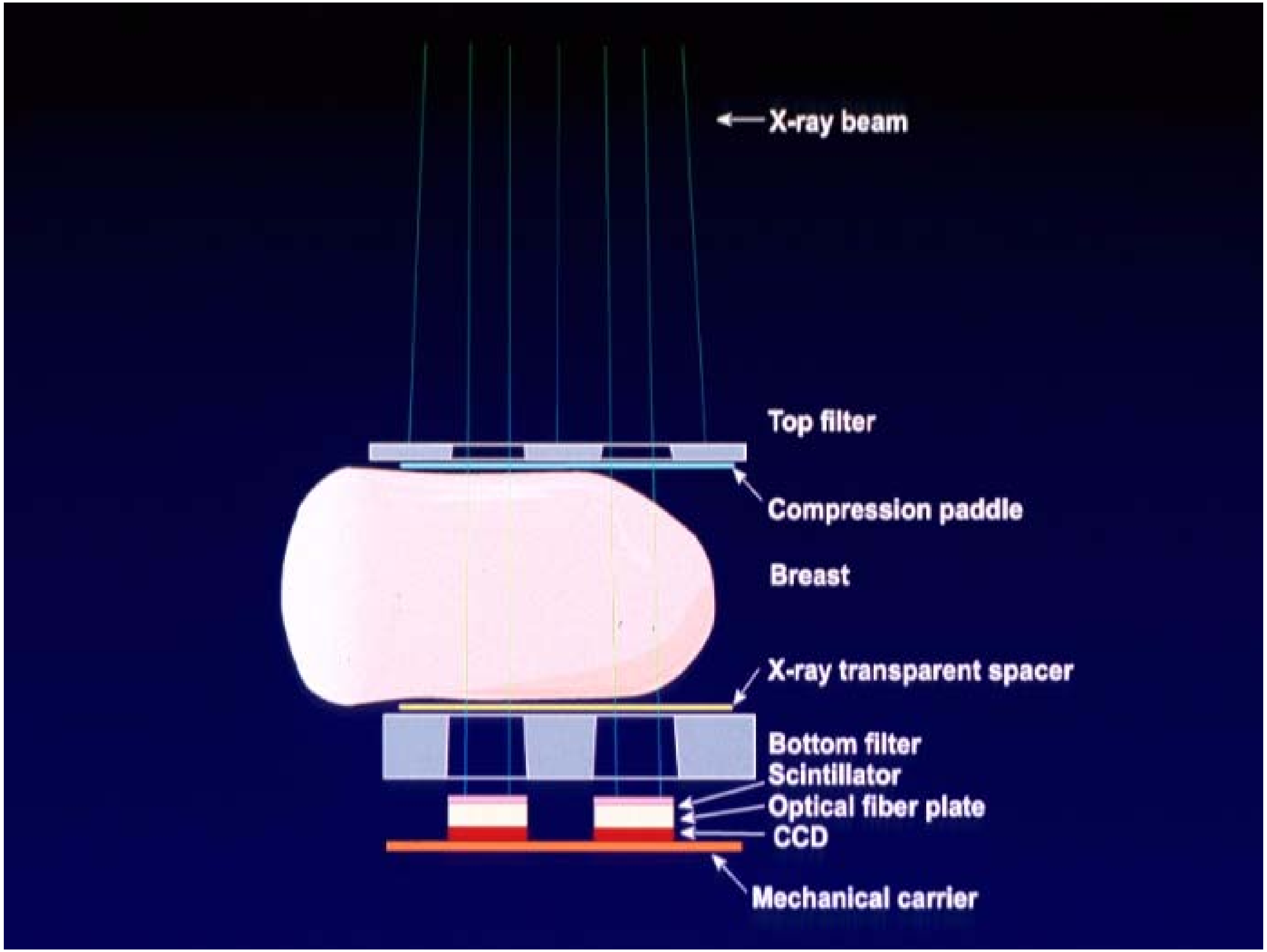

X-ray beam
Top filter
Compression paddle
Breast
X-ray transparent spacer
Bottom filter
Scintillator
Optical fiber plate
CCD
Mechanical carrier

Figure 11

5.3 Flat Panel Detectors

Flat-panel digital radiography x-ray detectors can be divided into two classes: **direct conversion detectors**, in which x-ray energy is converted directly into electric charge, and **indirect conversion detectors**, in which x-ray energy is first converted to light by an x-ray scintillator.

(1) Indirect detection flat panel systems

❖ Indirect flat panel detectors are sensitive to visible light, and an x-ray intensifying screen, typically Gd_2O_2S(Gadolinium Oxide Sulfide) or CsI (Cesium Iodide), is used to convert incident x-rays to light, which is then detected by the **flat panel thin film transistor (TFT) detector array**, as shown in Figure 12.

❖ The term "indirect" comes from the fact that x-rays are absorbed in the screen, and the absorbed x-ray energy is then relayed to the photodetector by visible light photons.

❖ This indirect detection strategy is analogous to a screen-film system, except that the electronic sensor replaces the light-sensitive film emulsion.

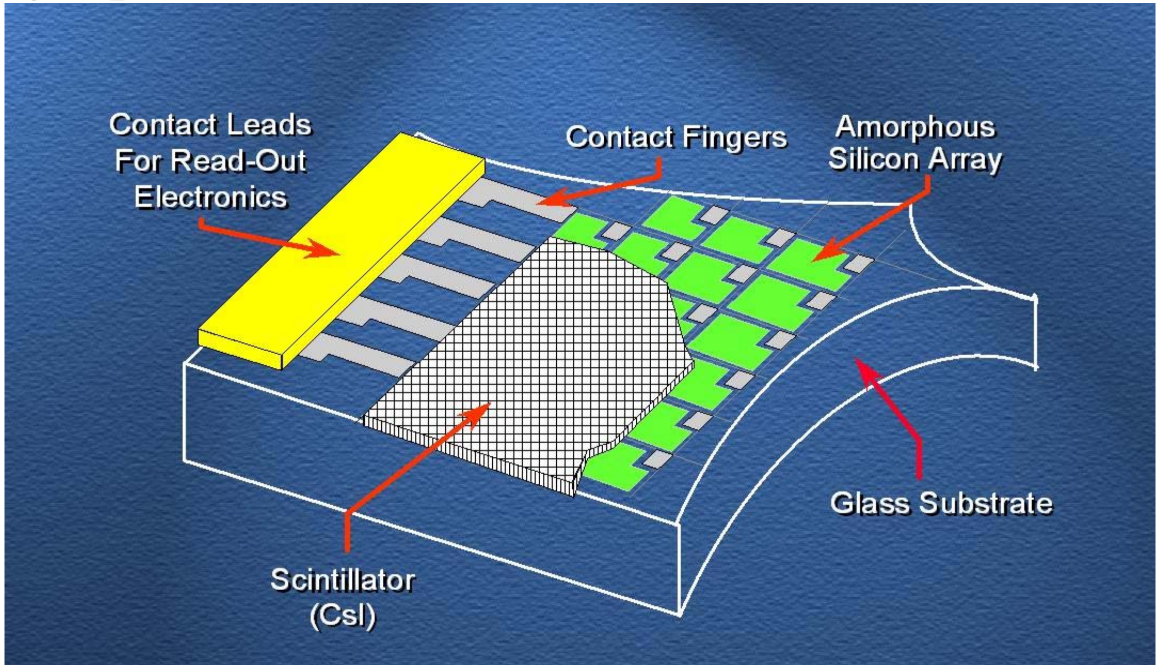


Figure 12

Typical **flat panel TFT detector** configuration is shown in Fig. 13.

- ❖The flat panel comprises a large number of individual detector elements, each one capable of storing charge in response to exposure.
- ❖Each detector element has a light-sensitive region, and a small corner of it contains the electronics.
- ❖The light-sensitive region is a photoconductor, and electrons are released when the photoconductor region is exposured to visible light.

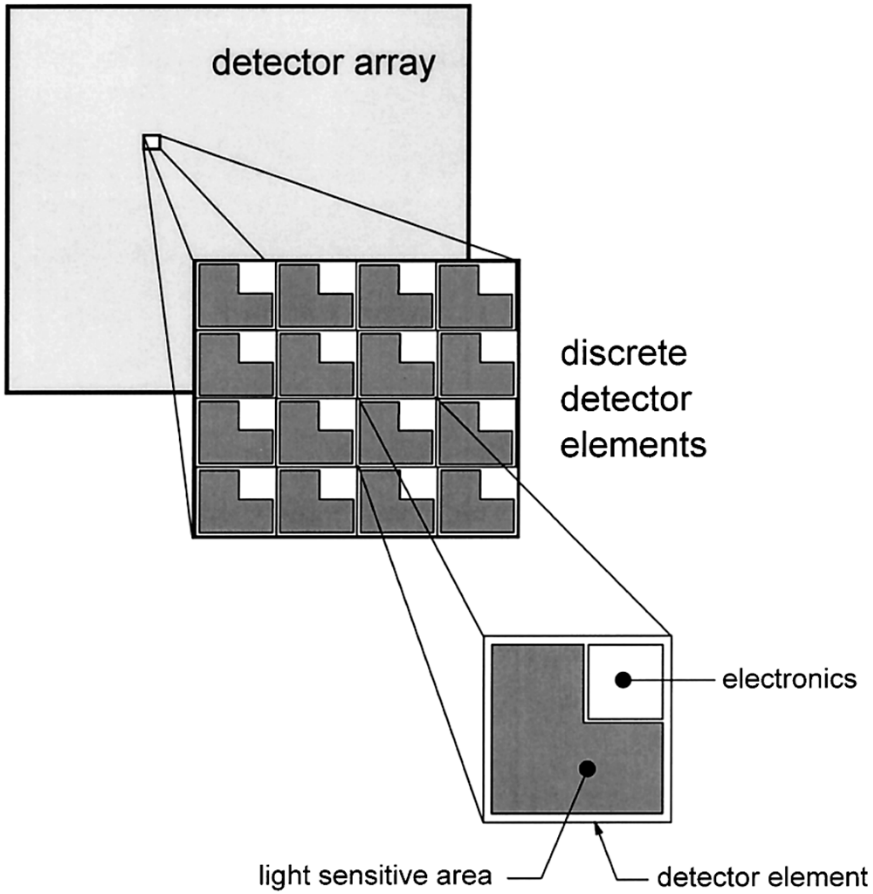
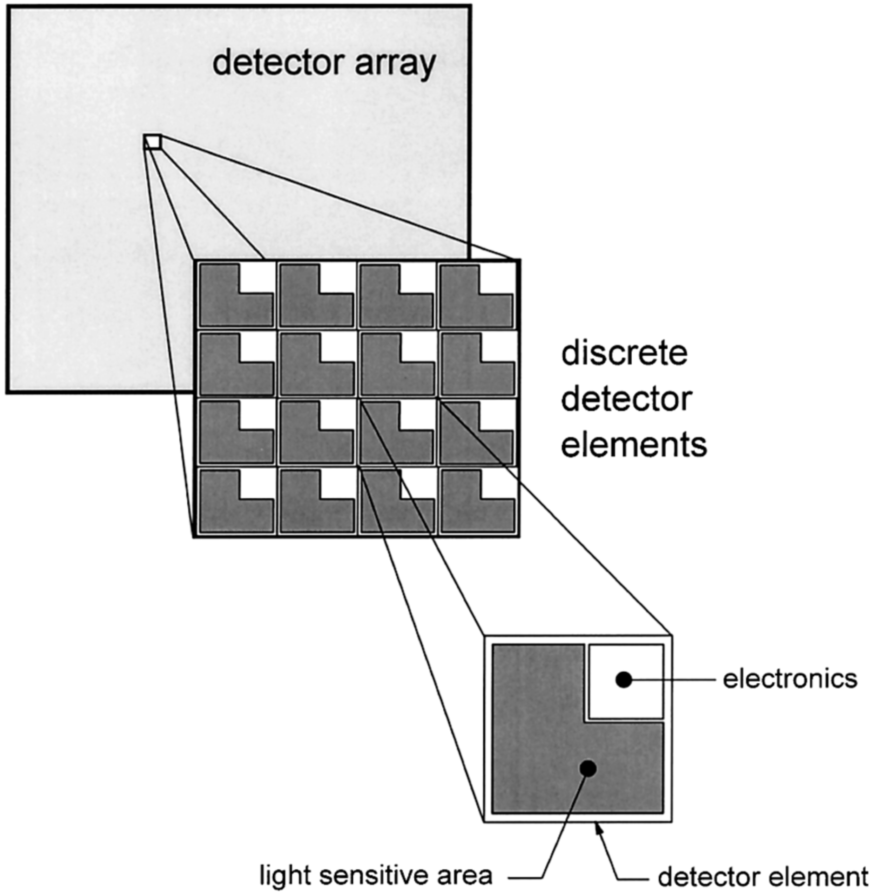


Figure 13

- During exposure, charge is built up in each detector element and is held there by the capacitor.
- After exposure, the charge in each detector element is read out using electronics.
- Because each detector element has a transistor, and the device is manufactured using thin-film deposition technology, these flat panel systems are called **thin-film transistor** (TFT) image receptors.



The readout procedure occurs as follows.

- During exposure, negative voltage is applied to all gate lines, causing all of the transistor switches on the flat panel imager to be turned off.
- During readout, positive voltage is sequentially applied to each gate line (e.g., R1, R2, R3, as shown in Fig. 14), one gate line at a time.
- The multiplexer (top of Fig.14) is a device with a series of switches in which one switch is opened at a time.
- The multiplexer sequentially connects each vertical wire (e.g., C1, C2, C3), via switches (S1, S2, S3), to the digitizer, allowing each detector element along each row to be read out.

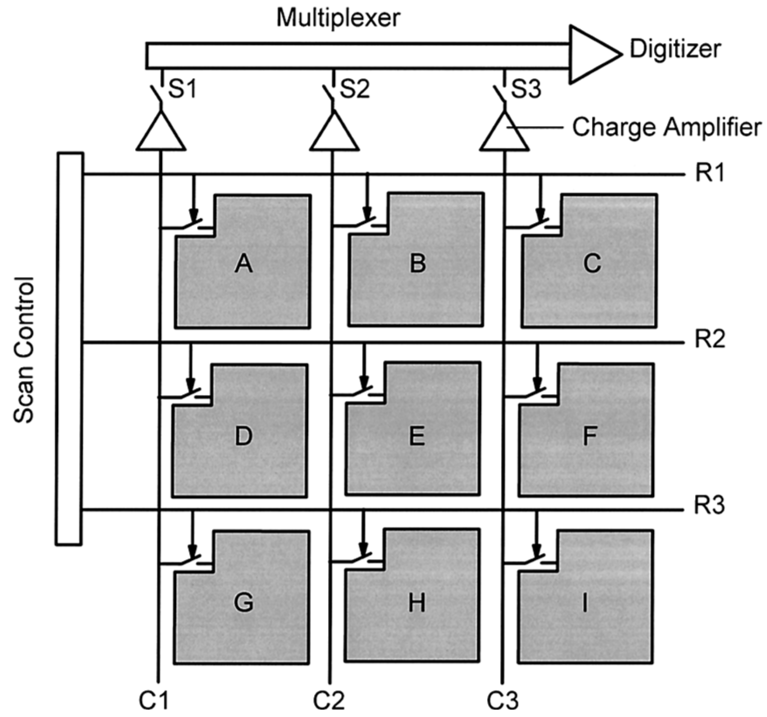


Figure 14

- Notice that in this procedure the signal from each detector element does not pass through any other detector elements, as it does in a CCD camera. This means that the charge transfer efficiency in a flat panel imager needs only to be good **(approximately 98%), whereas for a CCD the charge transfer efficiency needs to be excellent (greater than 99.99%).**
- Therefore, flat panel systems are less susceptible to imperfections that occur during fabrication. This translates into improved manufacturing cost efficiency.

The spatial resolution of the detector system

- The pixel pitch on a flat panel detector system largely determines the spatial resolution of the detector system.
- For example, for a flat panel with 0.15×0.15 mm pixels pitch, the maximum spatial frequency that can be conveyed in the image (the Nyquist frequency) is:

$$f_q = \frac{1}{2 \times 0.15} = 3.3(lp/mm)$$

More about the fill factor

- The ratio of the light-sensitive area to the entire area of each detector element (pixel) is called the fill factor (Fig. 15). It is desirable to have a high fill factor, because light photons that are not detected do not contribute to the image.
- However, the electronics (e.g., the switch, capacitor, etc.) of each detector element (pixel) of TFT detector array takes up a certain (**fixed**) amount of the area, so, for flat panels with smaller detector elements, a larger fraction of the detector element's area is not sensitive to light. Therefore, the light collection efficiency decreases as the detector elements get smaller.
- It is a technical challenge to develop flat panel detector system with high fill factor and high spatial resolution.

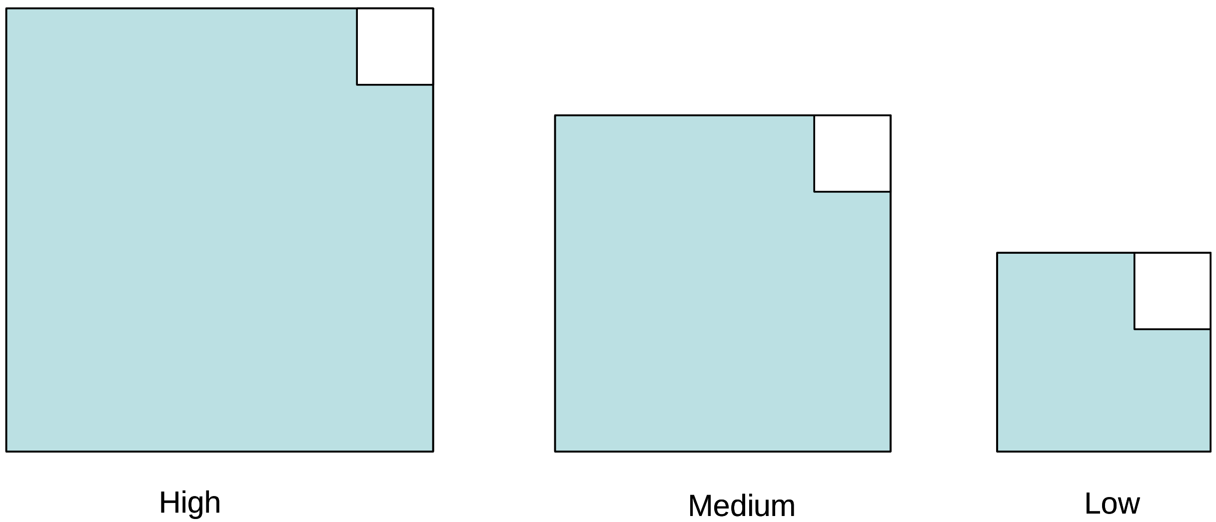


Figure 15

(2) Direct detection flat panel systems

❖ Direct flat panel detectors are made from a layer of photoconductor material on top of a TFT array, as shown in figure 16.

❖ These photoconductor materials have many of the same properties as silicon, except they have higher atomic numbers. Selenium is commonly used as the photoconductor.

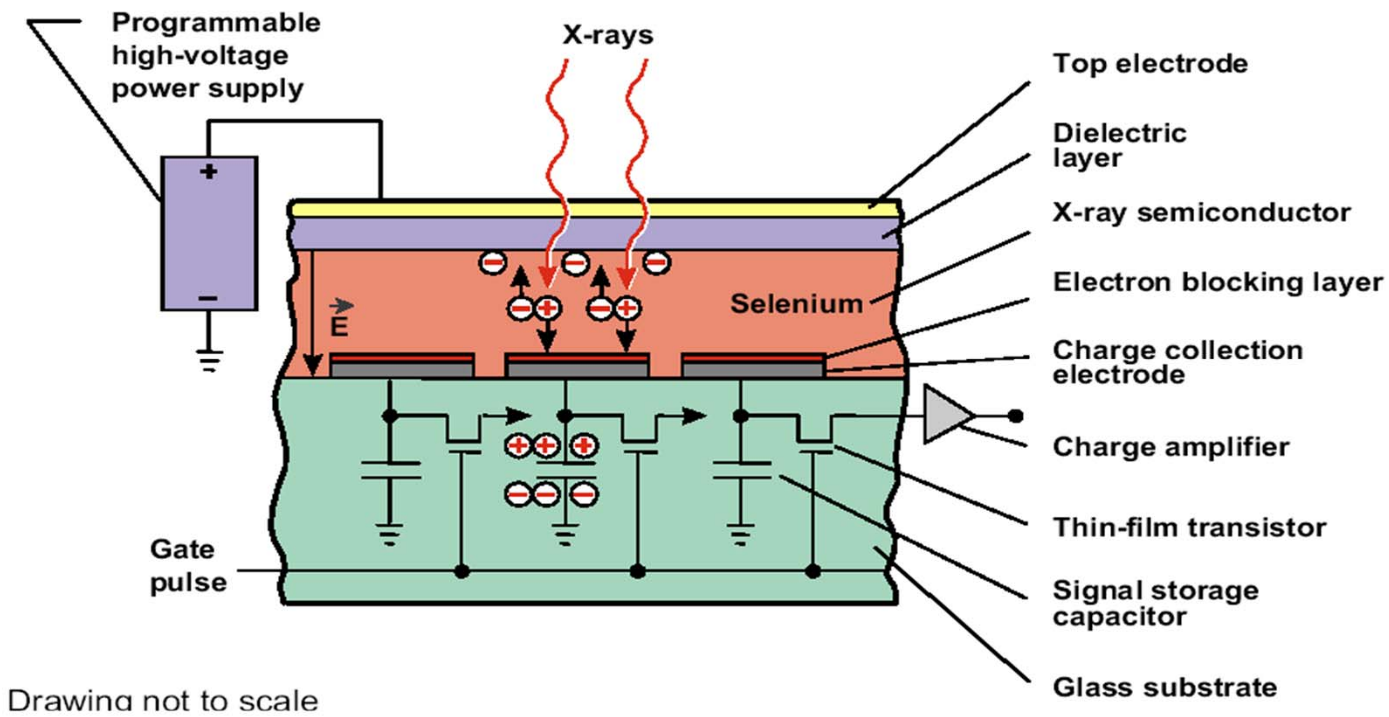


Figure 16

- During x-ray exposure, x-ray interactions in the selenium layer liberate electrons that migrate through the selenium matrix under the influence of the applied electric field and are collected on the detector elements.
- With direct detectors, the electrons released in the detector layer from x-ray interactions are used to form the image directly. Light photons from a scintillator are not used.
- After exposure, the detector elements are read out with the same line-and-gate readout logic, as described earlier for indirect systems.

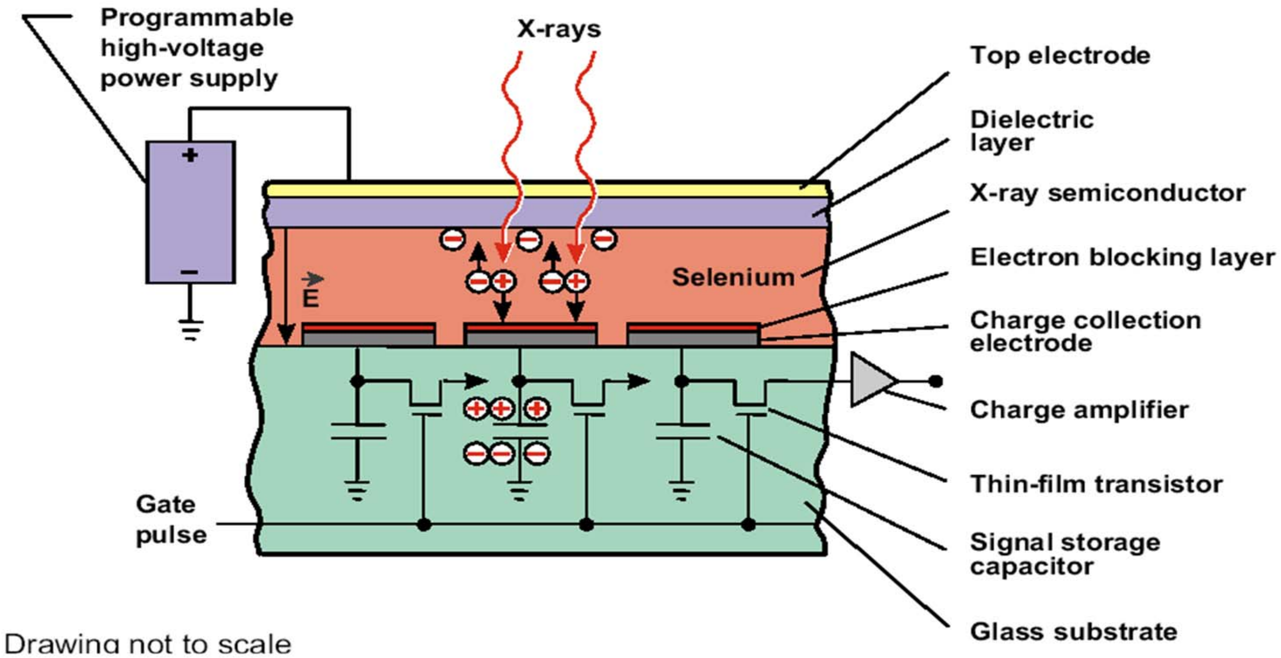
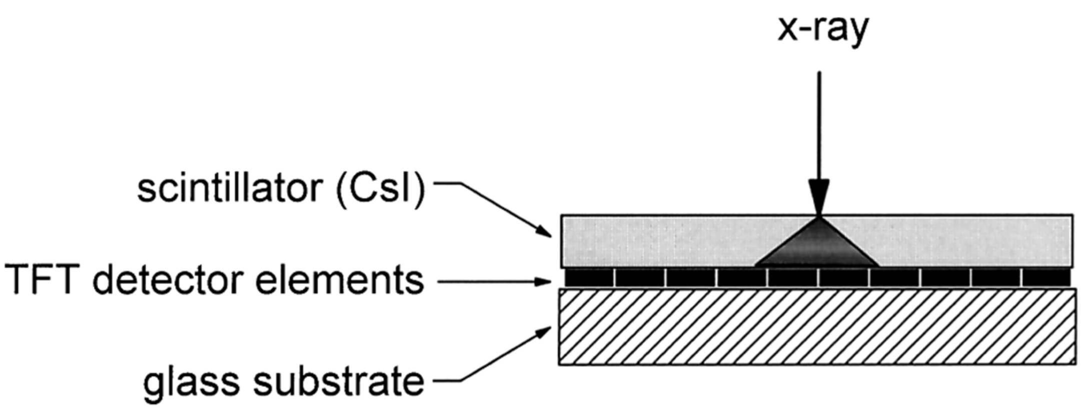


Figure 16

(3) Imaging blurring

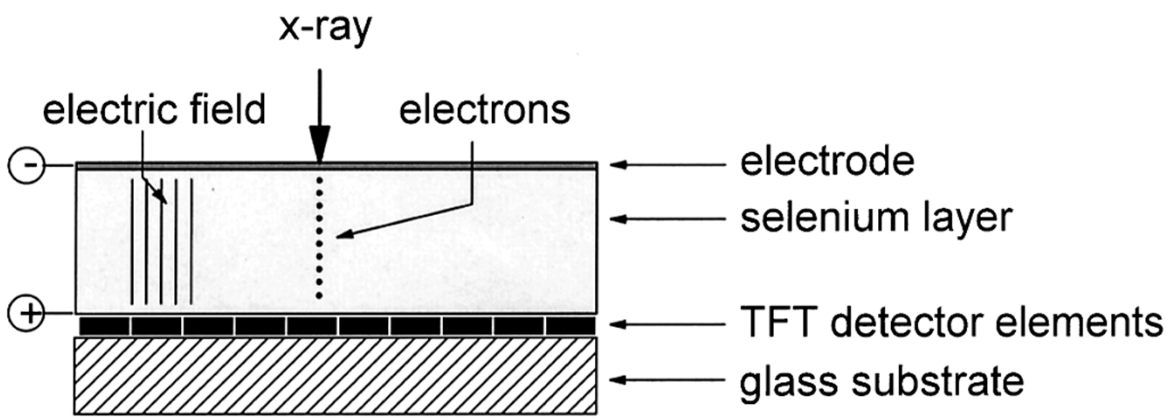
For indirect systems

- With **indirect systems**, the light that is released in the intensifying screen diffuses as it propagates to the TFT array, and this causes a certain amount of blurring.
- This blurring is identical to that experienced in screen-film detectors.
- For indirect flat panel detectors, the columnar structure of CsI (Cesium Iodide) is often exploited to help direct the light photons toward the detector and reduce lateral spread. This approach works well, but an amount of lateral blurring does still occur.



For direct systems

- For **direct detection systems,** in contrast, electrons are the secondary quanta that carry the signal. Electrons can be made to travel with a high degree of directionality by the application of an electric field.
- Therefore, virtually no blurring occurs in direct detection flat panel systems.
- Because of the ability to direct the path of electrons in direct detection flat panel systems, the spatial resolution is typically limited only by the dimensions of the detector element.



5.4 Computed Radiography (CR)

(1) Basics of CR technology

- Computed radiography (CR) is a marketing term for photostimulable phosphor (**PSP**) detector systems.
- Phosphors used in screen-film radiography, such as Gd_2O_2S (Gadolinium Oxide Sulfide) emit light promptly (virtually instantaneously) when struck by an x-ray beam.
- When x-rays are absorbed by photostimulable phosphors, some light is also promptly emitted, but much of the absorbed x-ray energy is trapped in the PSP screen and can be read out later.
- For this reason, PSP screens are also called storage phosphors or imaging plates.

(2) The operation of CR

(a) X-ray image acquisition

- ❖ CR imaging plates are made of BaFBr (Barium Fluoro-Bromide) and BaFI (Barium Fluoro-Iodide). A CR plate is a flexible screen that is enclosed in a cassette similar to a screen-film cassette.
- ❖ The imaging plate is exposed in a procedure identical to screen-film radiography, and the **CR cassette** is then brought to a CR reader unit.

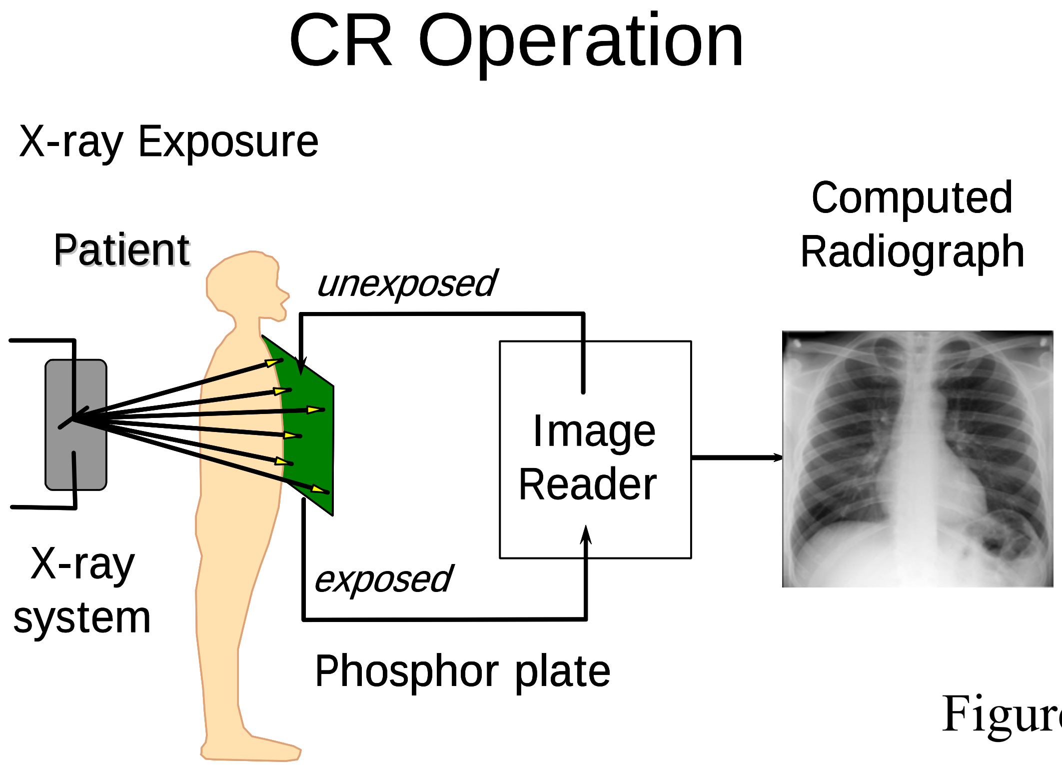


Figure 17

(b) Readout process

The cassette is placed in the reader unit, and several processing steps then take place:

- ❖ The cassette is moved into the reader unit and the imaging plate is mechanically removed from the cassette.
- ❖ The imaging plate is translated across a moving stage and scanned by a laser beam.
- ❖ The laser light stimulates the emission of trapped energy in the imaging plate, and visible light is released from the plate.

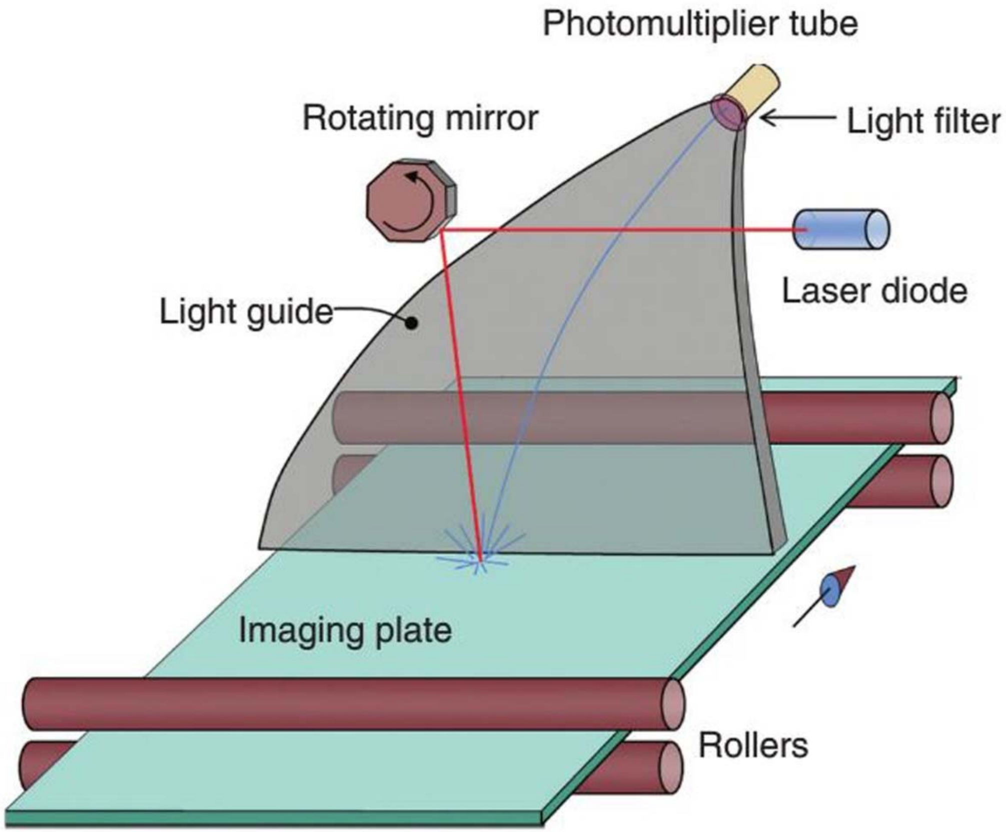
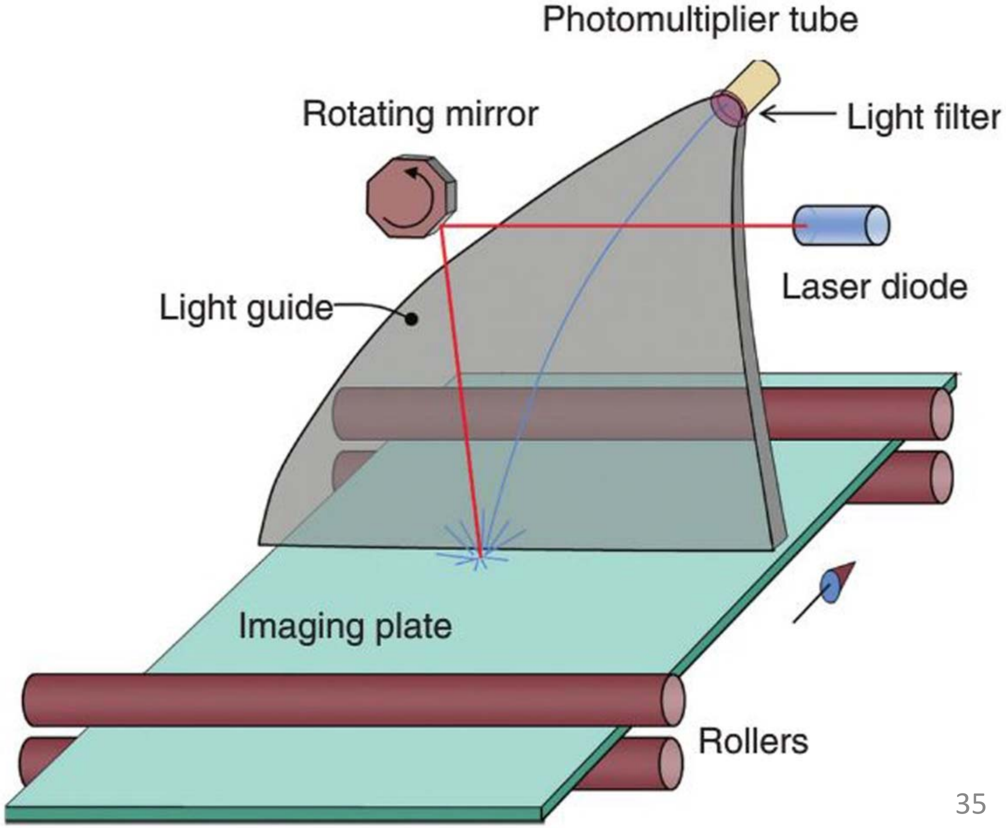


Fig 18.

- The light released from the plate is collected by a fiber optic light guide and strikes a photomultiplier tube (PMT), where it produces an electronic signal.
- The electronic signal is **digitized and stored**.
- The plate is then exposed to bright white light to erase any residual trapped energy.
- The imaging plate is then returned to the cassette and is ready for reuse.



(3) Principle of storage phosphors

(a) How to record x-ray images

- ❖ Figure 19 describes how stimulable phosphors work. A small mass of screen material is shown being exposed to x-rays. Typical imaging plates are composed of about 85% BaFBr (Barium Fluoro-Bromide) and 15% BaFI (Barium Fluoro-Iodide), activated with a small quantity of europium.

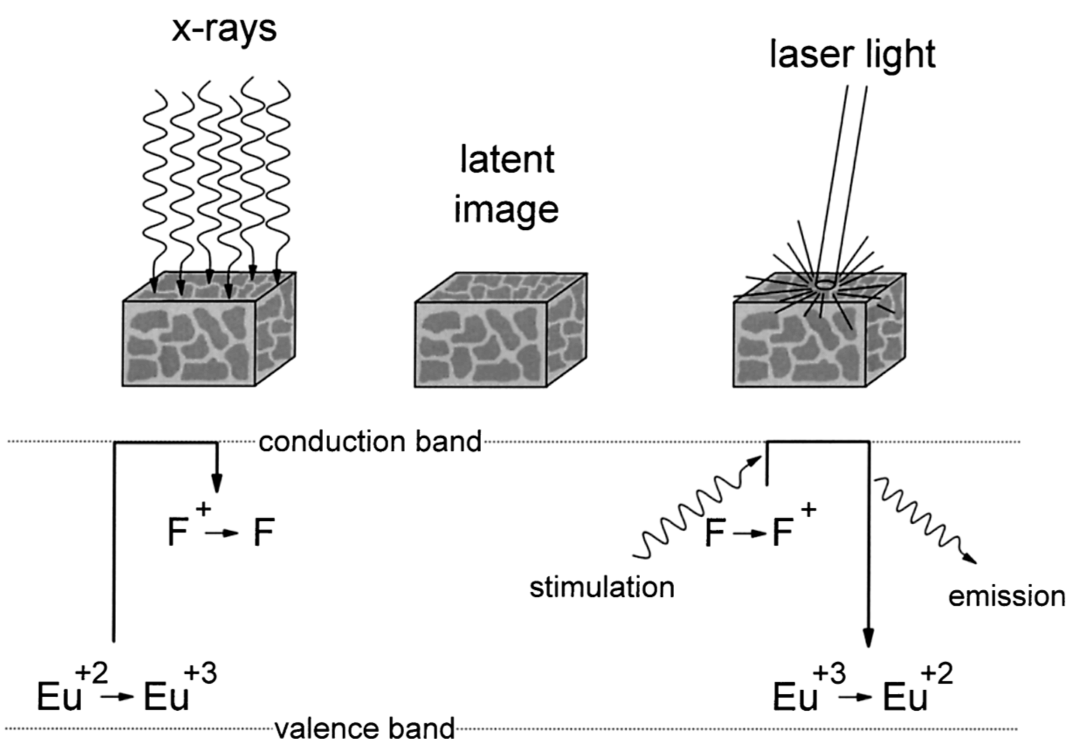
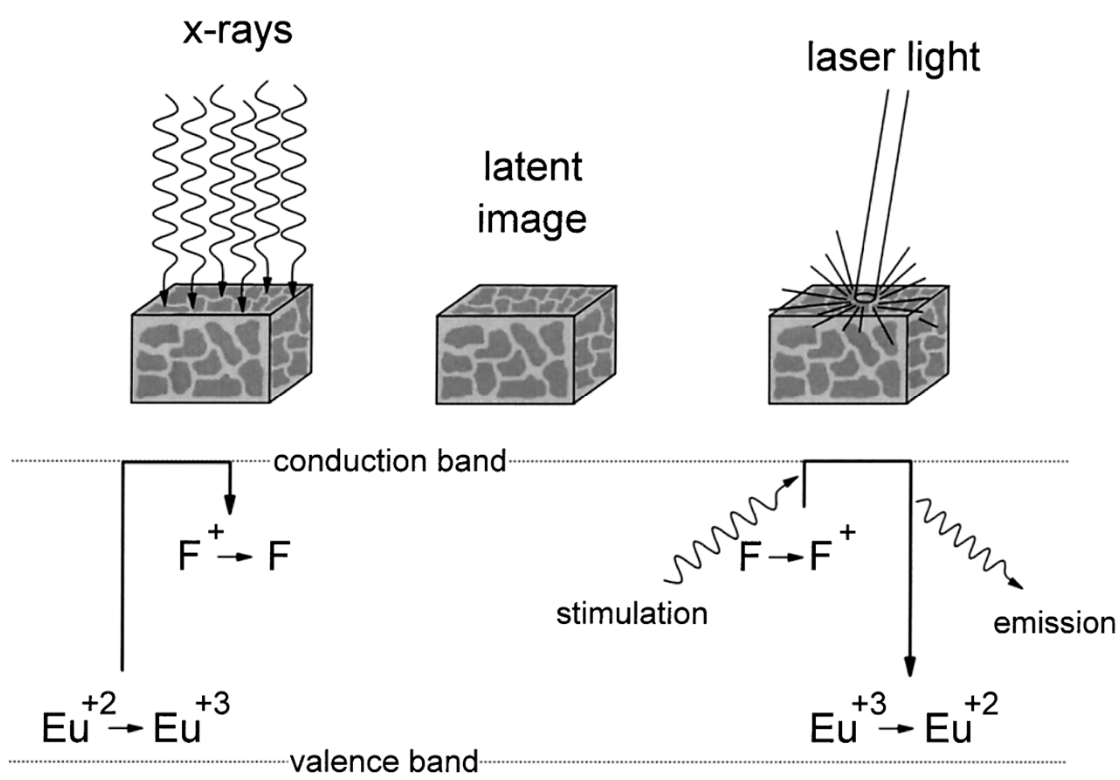


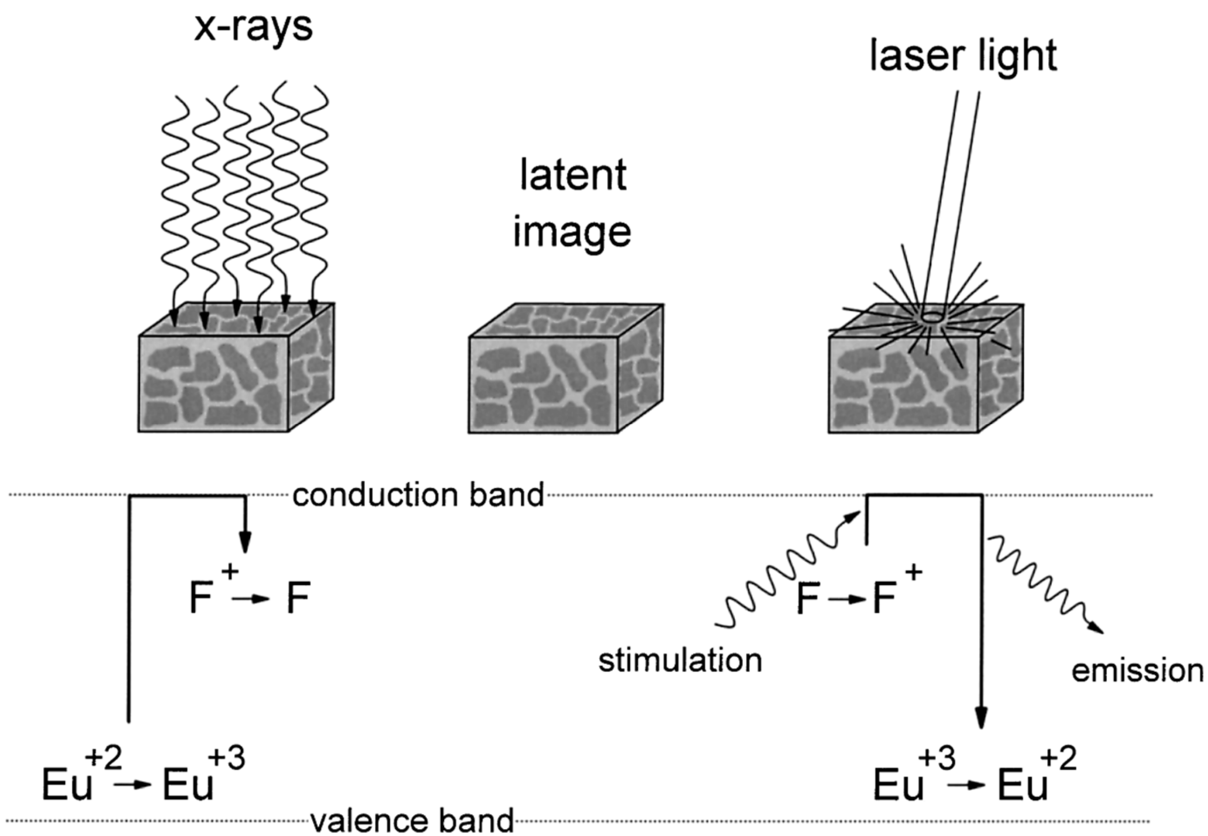
Fig 19

❖When the x-ray energy is absorbed by the BaFBr phosphor, the absorbed energy excites electrons associated with the europium atoms, causing divalent europium atoms (Eu^{+2}) to be oxidized and changed to the trivalent state (Eu^{+3}).

❖The excited electrons become mobile, and some fraction of them interact with a so-called **F-center**. The F-center traps these electrons in a higher-energy, metastable state, where they can remain for days to weeks, with some fading over time.



- ❖ The latent image that exists on the imaging plate after x-ray exposure, but before readout, as billions of electrons trapped in F-centers.
- ❖ The number of trapped electrons per unit area of the imaging plate is proportional to the intensity of x-rays incident at each location during the exposure.



(b) How to readout digital images (laser light stimulates emission)

❖When the **red laser light** scans the exposed imaging plate, the red light is absorbed at the F-center, where the energy of the red light is transferred to the electron.

❖Many of these electrons then become de-excited by releasing **blue-green** light as they become reabsorbed by the trivalent europium atoms (Eu^{+3}), converting them back to the divalent state(Eu^{+2}), see Fig. 19.

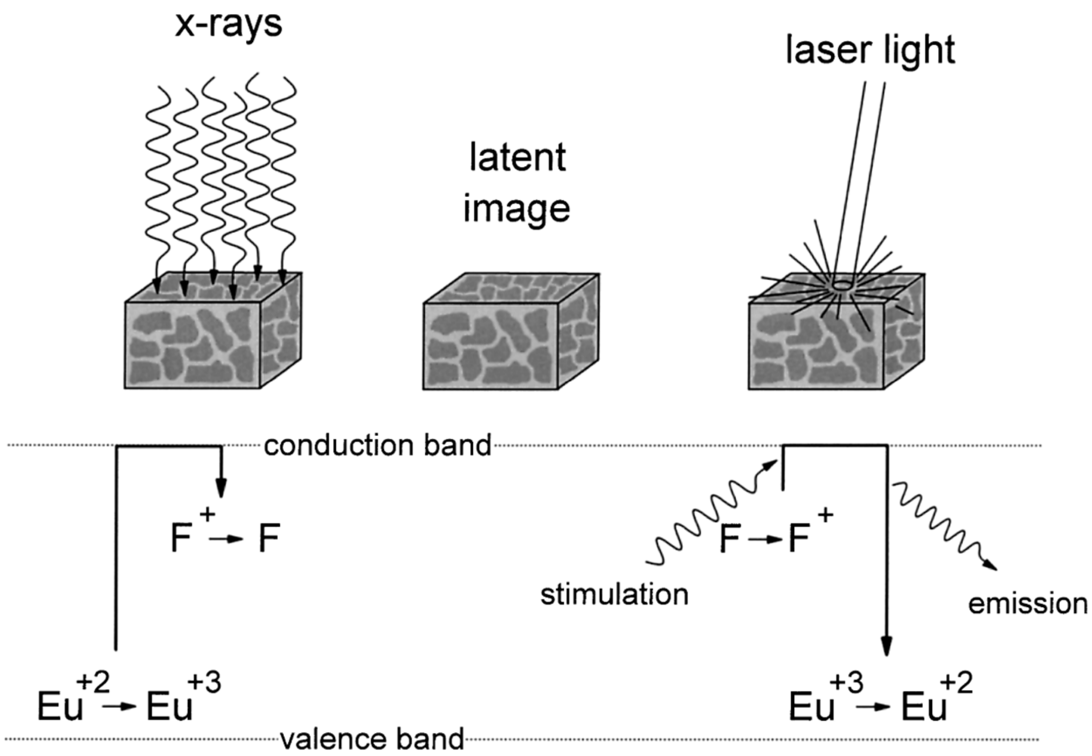


Fig.19

The optical spectra of stimulating light and emission light

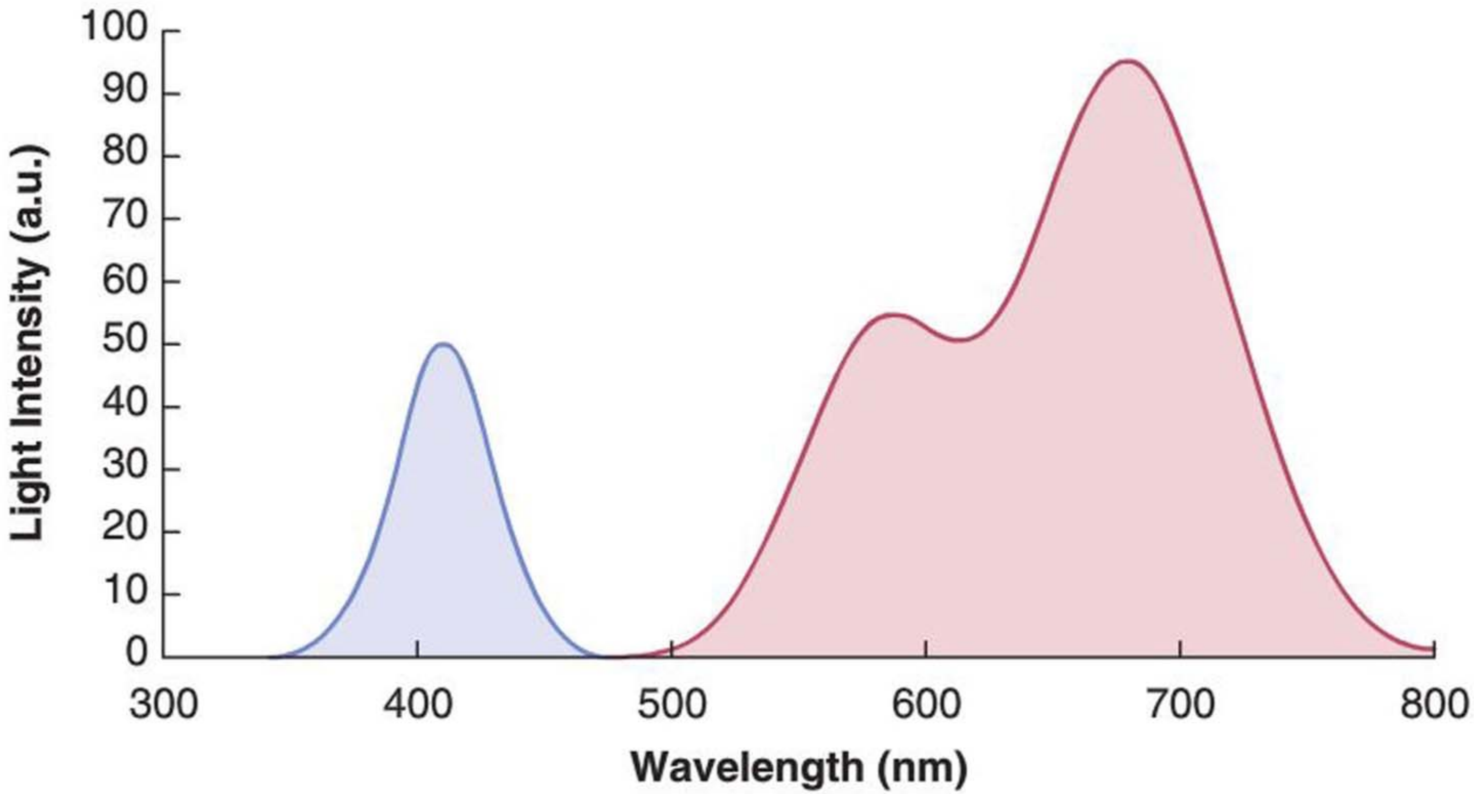
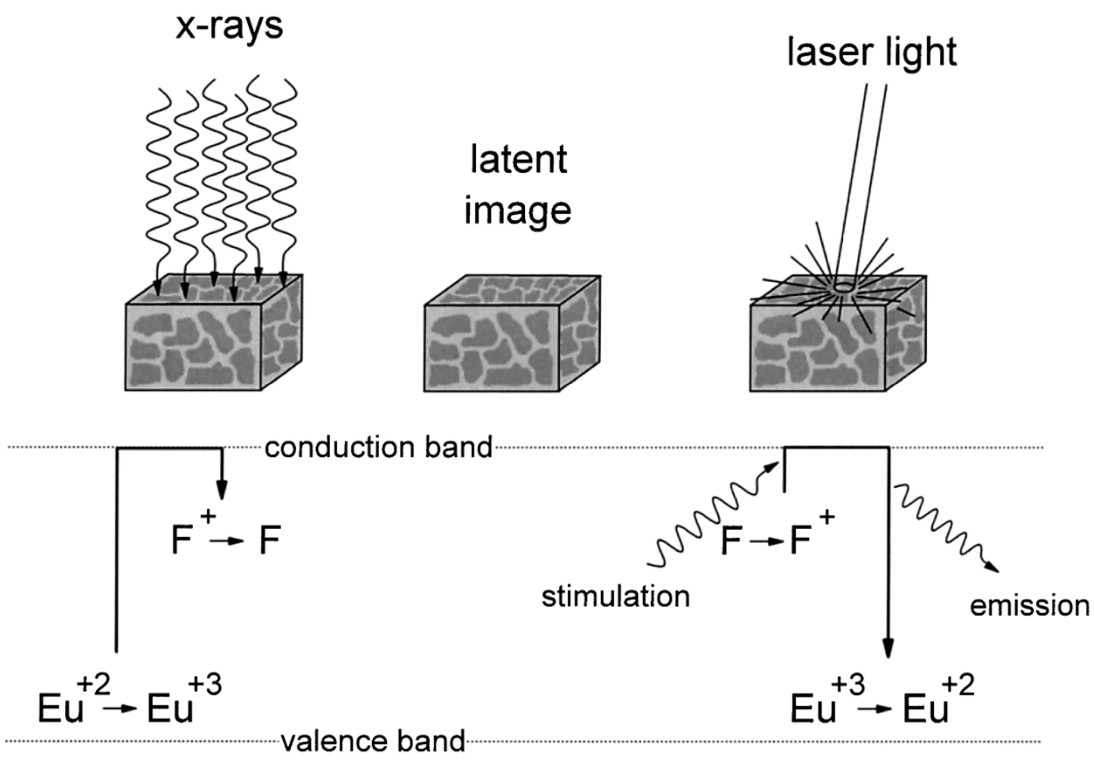


Fig. 20.

❖ To erase the latent image so that the imaging plate can be reused for another exposure without ghosting, the plate is exposed to a very bright light source, which flushes almost all of the metastable electrons to their ground state, emptying most of the F-centers.



Summary:

1. The concepts of spatial resolution, dynamic range, fill factor of digital detectors

2. Some characteristics of several different detectors and digital radiography systems

   CCD based digital radiography systems:

   High spatial resolution, low noise, small FOV

   Flat panel detector digital radiography systems:

   Large FOV, moderate spatial resolution, higher noise as compared to **CCD**

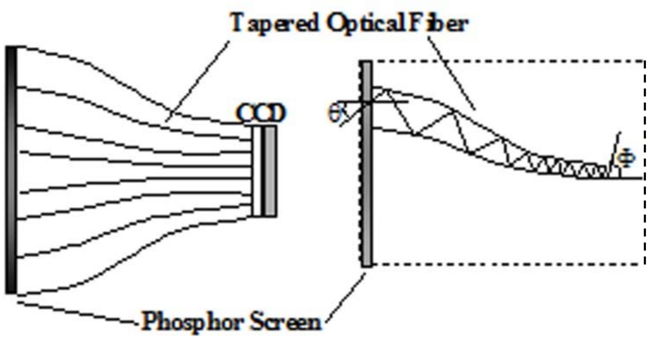
   CR using storage phosphor plates

   Large FOV, moderate spatial resolution, two-steps operation in image acquisition and readout

Homework #4_B

1. A fiber optically coupled CCD x-ray imaging system is schematically shown as follows. The CCD detector is a 1024 × 1024 pixel array, and each pixel is 0.025mm × 0.025mm in dimension. The fill factor of the CCD detector is assumed to be 100%. A 2:1 optical fiber taper is used to relay images from a scintillating screen to the CCD detector. Assuming the x-ray source used in this system is a "point" source (with very small focal spot) and the scintillating screen is very thin. Therefore these two components have no significant impact to the limiting spatial resolution of the overall x-ray imaging system.
   (1) Please determine the limiting spatial resolution of the overall x-ray imaging system.
   (2) Also determine the field of view (FOV) of the system.

Fiber Optic Coupling



2. A CCD detector system has a well depth of 100,000 electrons and a readout noise of 10 electrons. What is its dynamic range in dB?

3. Please describe, in your own words and/or schematics, the principle of a storage phosphor in recording x-ray images (how x-ray images is recorded by storage phosphor?)

4. A direct flat panel detector system was built with 60% overall quantum efficiency for x-ray imaging in the diagnostic energy range. It has a 75% fill factor. The same type of the direct flat panel detector system was re-designed to offer higher spatial resolution. It now has a 50% fill factor. Please determine the overall quantum efficiency of the second system for x-ray imaging in the same diagnostic energy range.

5. What are the most important advantages of digital radiography as compared with the screen-film based radiography?

6. Will less than perfect fill factor of electronic detectors affect the overall quantum efficiency of an X-ray imaging system, why?