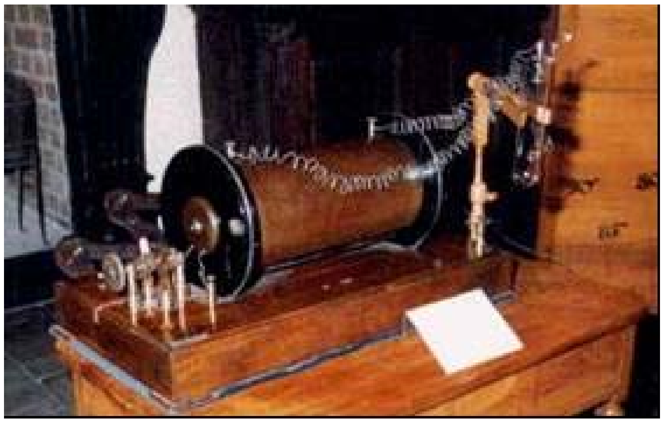
X-Ray Detectors

- Film: sensitivity is very low, it would require too high a dose to the patient
- Film + screen: conventional radiography
- Image intensifier (I.I.): fluoroscopy
- Photosensitive phosphor (computed radiography)
- **Flat panel detectors**
- **Direct digital radiography (semiconductor)**

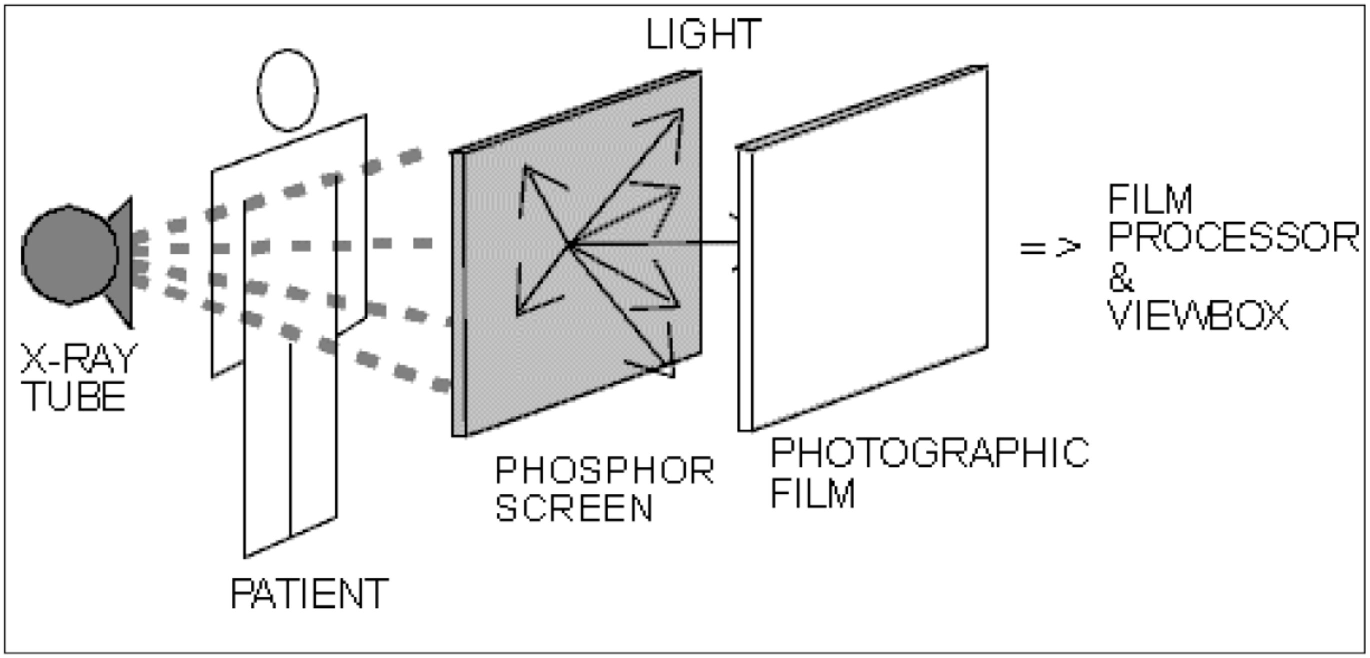
Roentgen's X-ray Setup (1895)



Roentgen's experimental apparatus (Crookes tube) that led to the discovery of the new radiation on 8 Nov. 1895 – he demonstrated that the radiation was not due to charged particles, but due to an as yet unknown source, hence "x" radiation or "x-rays"

Known as "the radiograph of Bera Roentgen's hand" taken 22 Dec. 1895

X-Ray Film-screen Detectors



Film-Screen Radiography:

- Phosphor screen emits light in response to x-rays absorption.
- The resulting optical image is used to expose a photographic film

Currently most diagnostic radiographic systems (such as chest and breast imaging) are based on a phosphor screen.

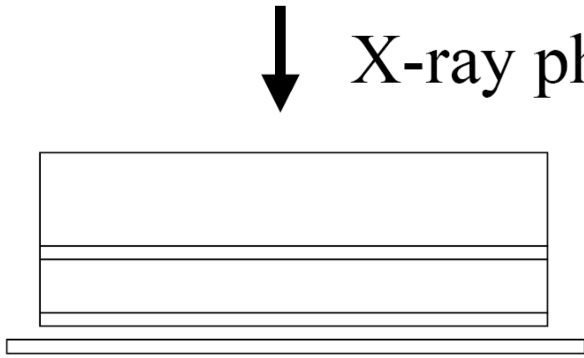
X-Ray Film-screen Detectors

Film Screen Detectors

- Film relatively insensitive to x-rays, requires a lot of x-ray energy to produced a properly exposed x-ray film
- Patient receives a large dose
- To reduce dose and exposure times, screens are used
    - Screens made of scintillating material: phosphor
    - When x-rays interact with phosphor, visible or UV light is emitted
    - Light emitted darkens the film
- Screen-film detectors are considered an Indirect detector

Using film-screen versus film only reduces radiation dose to patient up to 50X

X-Ray Film-screen Detectors



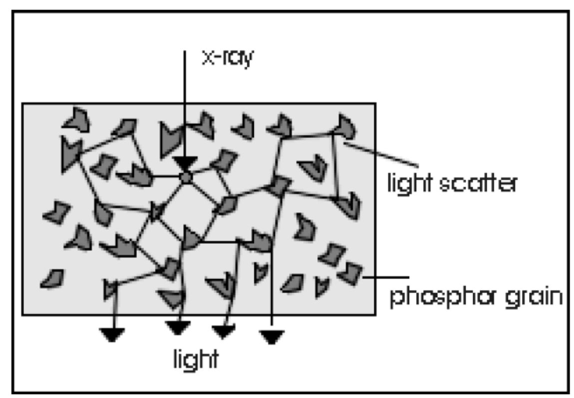
Screen Types: **$CaWO_4$, 430 nm blue**
Gd_2O_2S, 410 nm blue

Screen Sensitivity ~ thickness

Increased X-ray Absorption

=> more visible photons

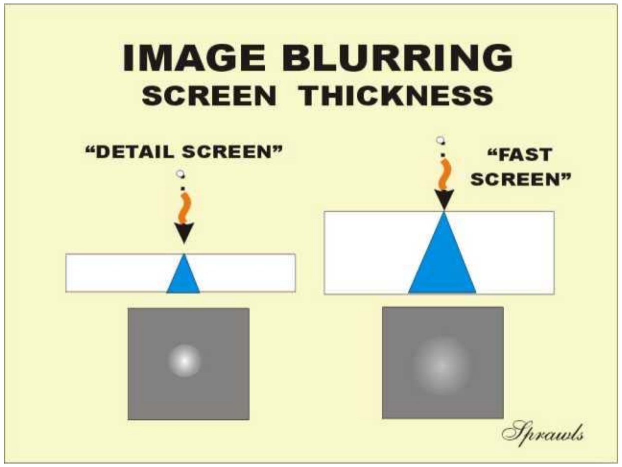
Screen Resolution ~ 1/thickness



X-Ray Film-screen Detectors

As screen thickness ↑ QDE ↑ and screen sensitivity ↑, but light-diffusion increases

Basic limitations for imaging performance: Compromise between sensitivity and resolution



c.f. http://www.sprawls.org/resources/RADDETAIL/classroom.htm

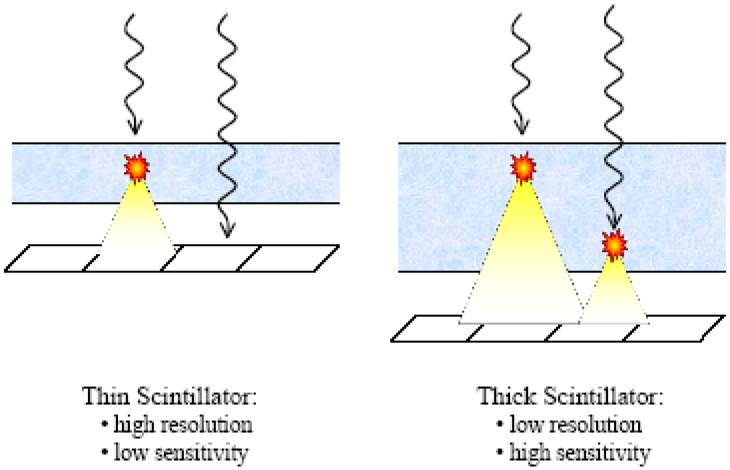
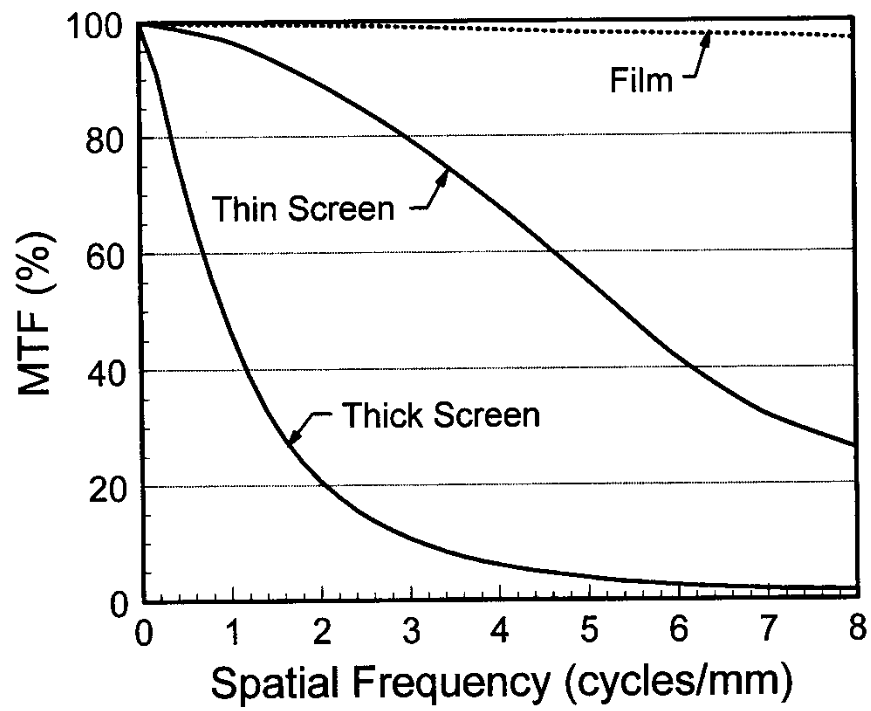


Figure 1: Sensitivity vs. Resolution Tradeoff

c.f. http://www.rad-icon.com/pdf/Radicon_AN07.pdf

X-Ray Film-screen Detectors

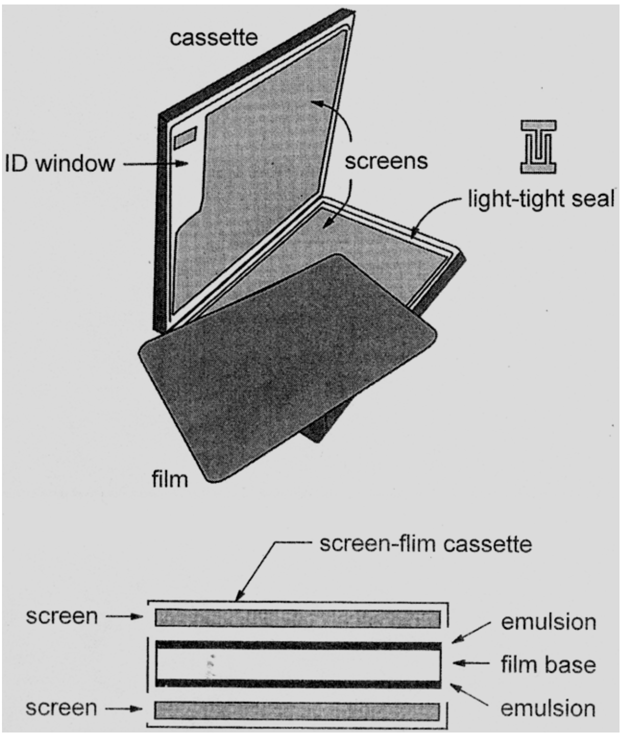
- **Modulation Transfer Function** (MTF) describes the resolution properties of an imaging system
- The MTF illustrates the fraction (or %) of an object's contrast that is recorded by the imaging system as a function of object size (spatial frequency)
- F (linepairs or cycles/mm)
- $F=1/2\Delta$, Δ = object size
- As screen thickness ↑ MTF ↓



c.f. Bushberg, et al. The Essential Physics of Medical Imaging, 2nd ed., p 152.

X-Ray Film-screen Detectors

Radiographic Cassettes



Light-tight and ensures screen contact with film

- Front surface - carbon fiber
- ID flash card area on back
- 1 or 2 Intensifying Screens
- Mounted on layers of compressed foam (produces force)

Sheet of film

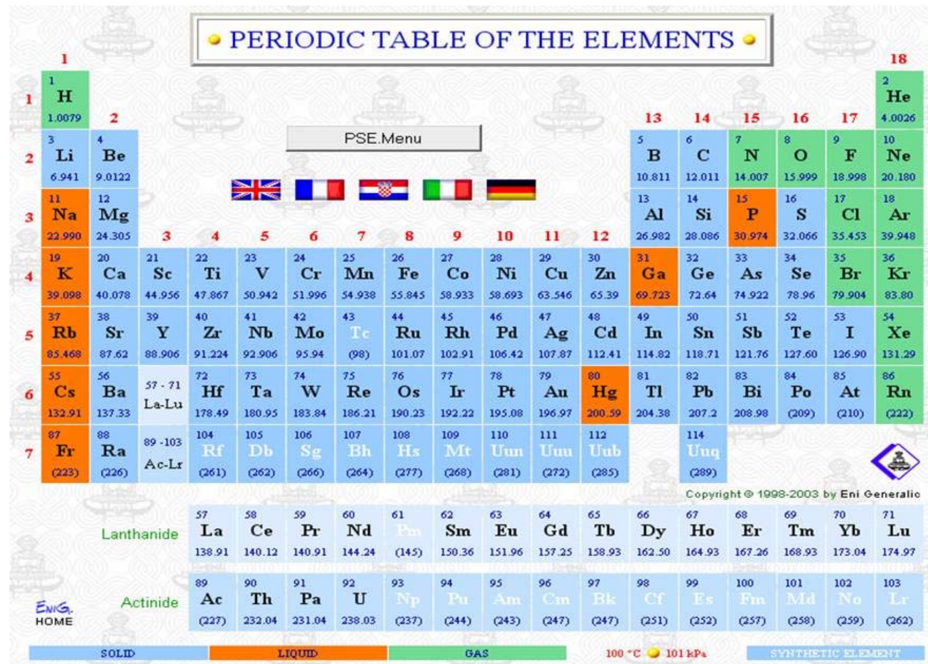
- Register the x-ray distribution
- Chemically processed
- Storage and display

X-Ray Film-screen Detectors

Phosphor Material

Early 20th century: calcium tungstate, $CaWO_4$

Since early 70's: rare earth phosphor was developed based on Lanthanide series elements with: Z = 57 – 71



Gd_2O_2S:Tb (gadolinium oxysulfide: terbium) - common

- LaOBr:Tm (lanthanum oxybromide: thulium)
- $YTaO_4$:Nb (yttrium tantalate: niobium)

X-Ray Film-screen Detectors

Radiographic Cassettes

- Function: absorb x-rays, convert to visible or UV light which exposes the film emulsion
- Conversion efficiency of a phosphor = fraction of absorbed energy emitted as UV or visible light
- $CaWO_4 \approx 5\%$ intrinsic conversion efficiency
- $Gd_2O_2S:Tb \approx 15\%$ intrinsic conversion efficiency

    50,000 eV x-ray x 0.15 = 7500 eV

    Green light, 2.7 eV

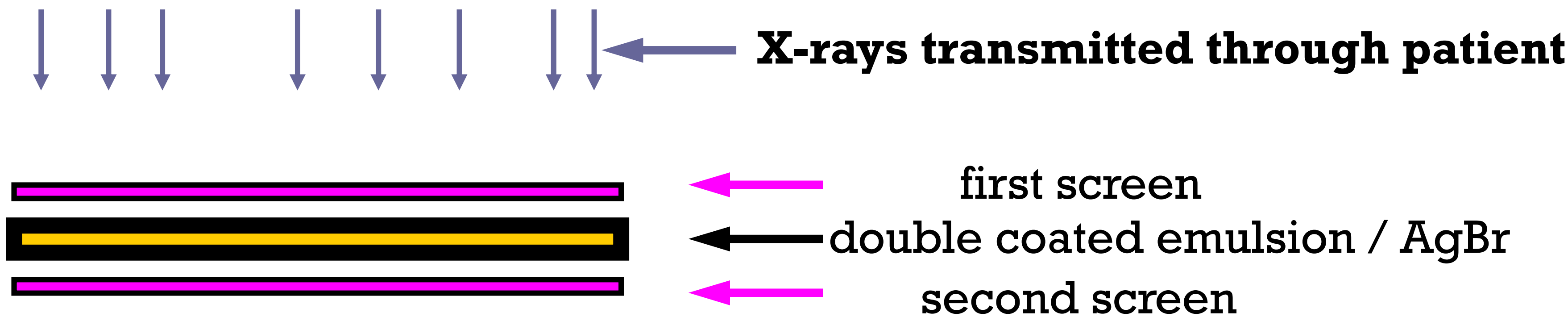
    7500 eV / 2.7 eV/photon

    = 2,800 photons

- 200-1000 photons reach film after diffusing through phosphor layer and being reflected at the interface layers

1 X-ray photon => 20-100 silver particles to be developed.

X-Ray Film-Screen Detectors



- **About 50% of the photons convert in the film-screen, mostly (95%) in the two screens**
- **The film exposure is mainly due to the blue-green light emitted by the phosphorescent screens ($CaWO_4$, Gd_2O_2S:Tb, etc.)**
- **Film-screen systems are classified according to their speed, with faster systems requiring less incident radiation to obtain same optical density**
- **The standard speed is = 100, slower (50) and faster (200, 400, 600) speed film-screen systems are commonly used**

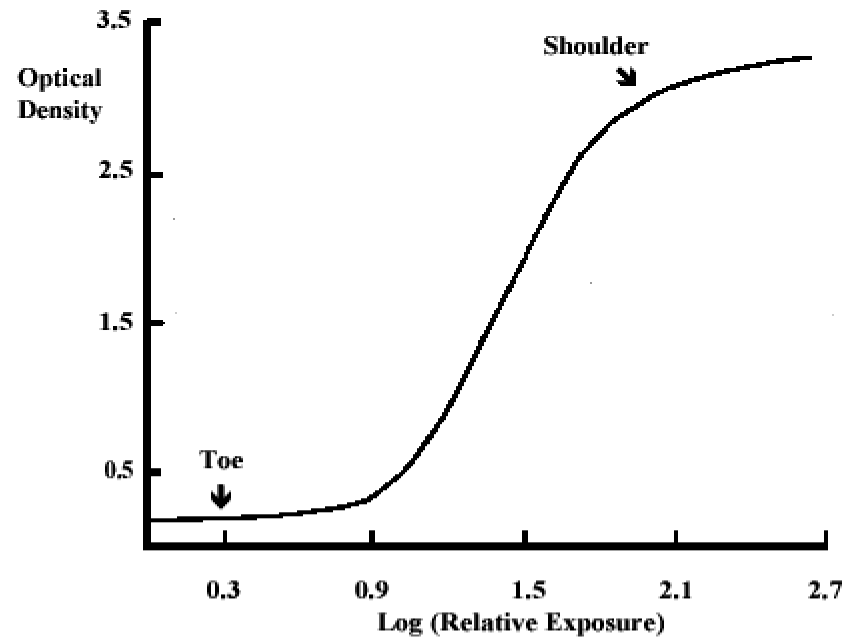
Exposure and Optical Density

Radiographic film blackening radiografico (mostly due to visible light emitted by screens) may be quantified by **optical density** (D):

$$D = -\log(T)$$

where T is the **transmission**:

$$T = I_1/I_0$$



Useful optical density goes from 0.2 to 2.5-3.0

Exposure X quantifies the number of incoming x-rays

Exposure and Optical Density

Relation between optical density D and exposure X:

1) Film-screen:

$$D = cX^{\gamma}$$

highly nonlinear, constants depend on film speed

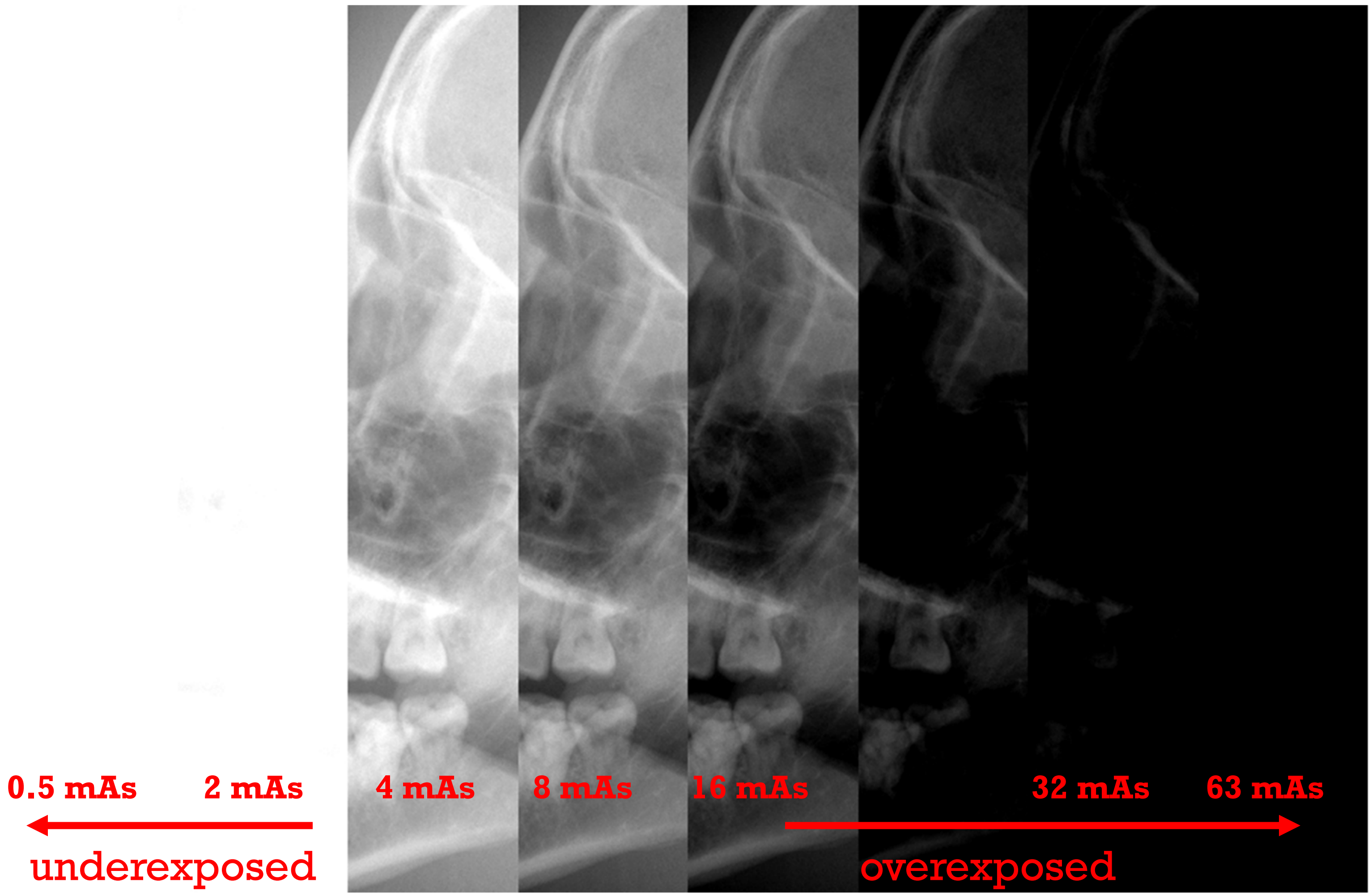
Transm. T	D = -log(T)	
1.000	**0.0**	100% transm.
0.741	**0.13**	base
0.100	**1.0**	good exposure
0.010	**2.0**	lung
0.001	**3.0**	very dark
0.0003	**3.5**	maximum darkness

2) Electronic detector (e.g. phosphor + photodiode):

$$D = kX$$

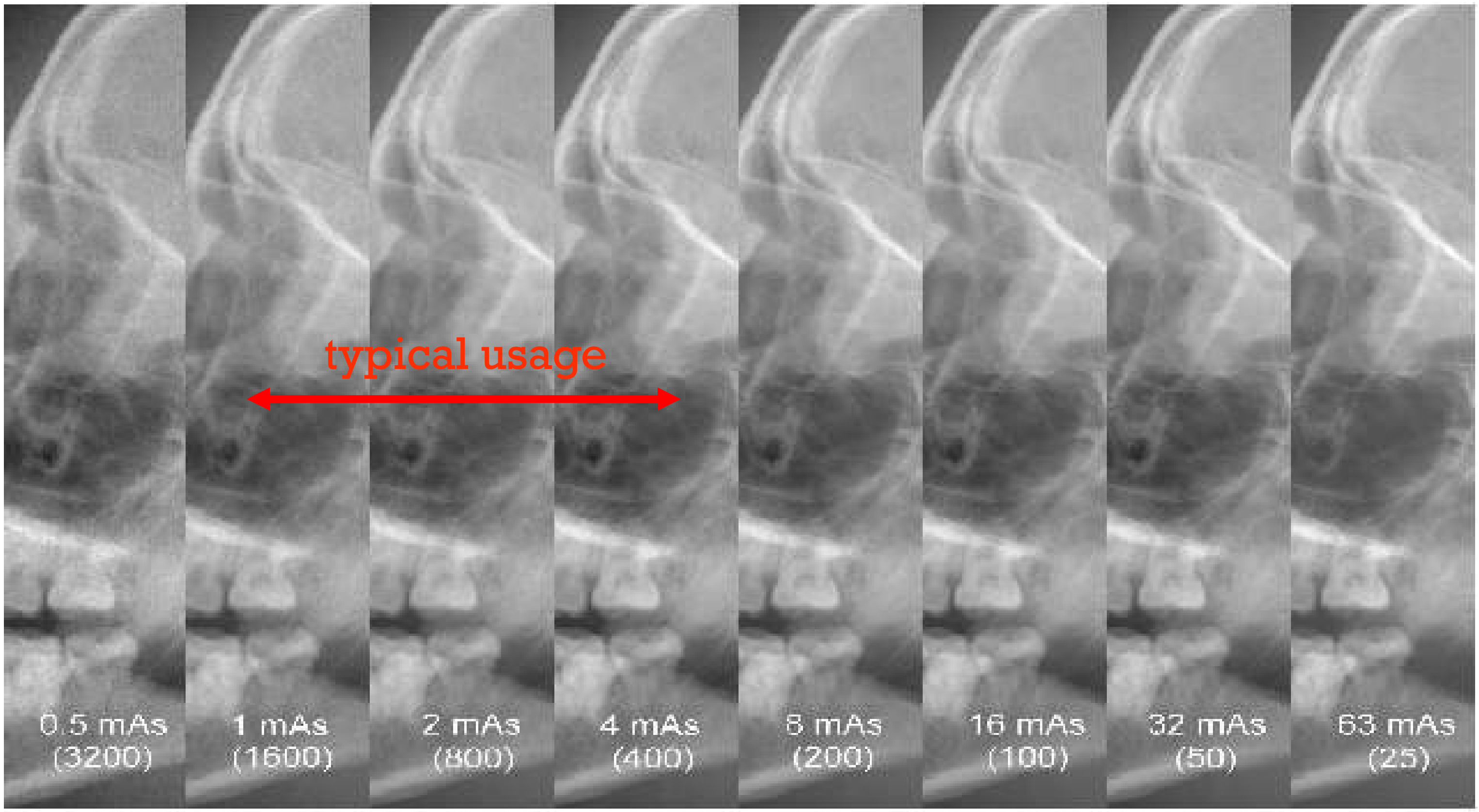
linear (image may be subsequently processed to "emulate" film of any given speed)

X-ray film: dynamical range



M. Overdick (PHILIPS), 11/09/2002, IWORID 2002, Amsterdam

Flat panel detector: dynamical range

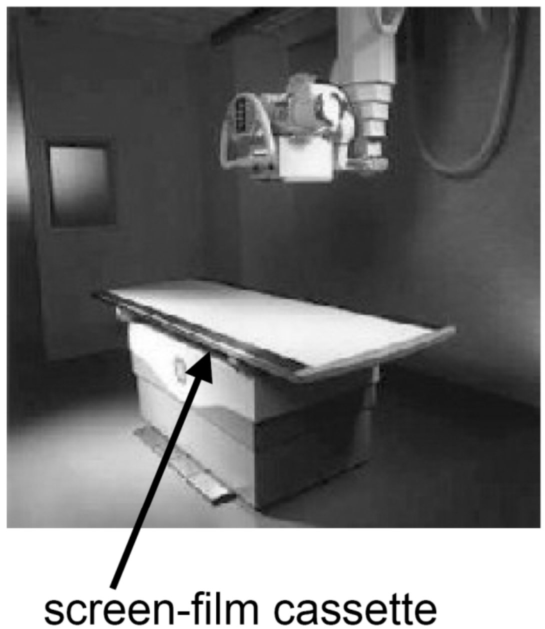


Digital Diagnost (PHILIPS) 43 cm x 43 cm, 143μm x 143 μm

M. Overdick (PHILIPS), 11/09/2002, IWORID 2002, Amsterdam

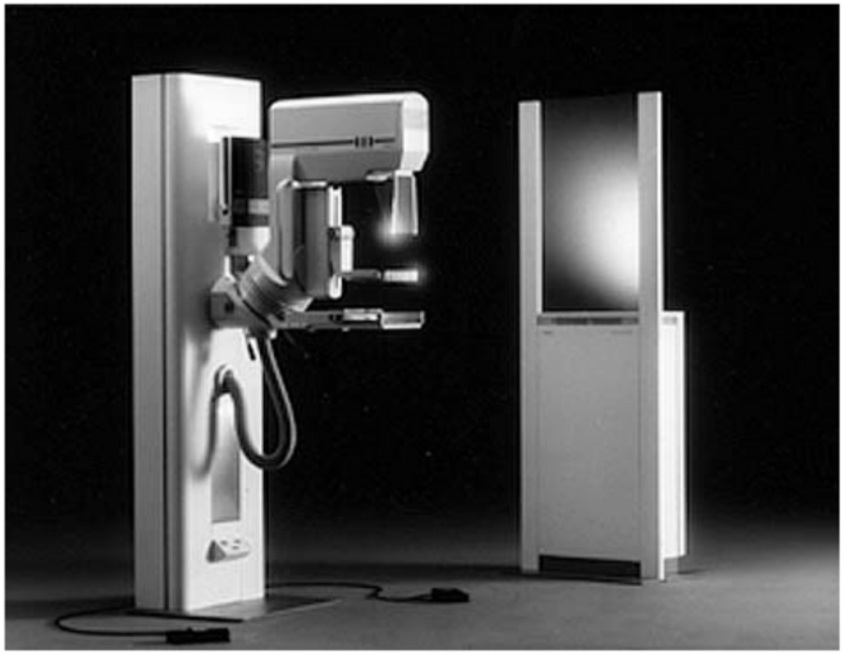
Film-screen based X-Ray Radiology

General Radiographic System:



designed for a wide range of examinations: (table, wall stand, ...)

Film-screen based X-Ray Radiology

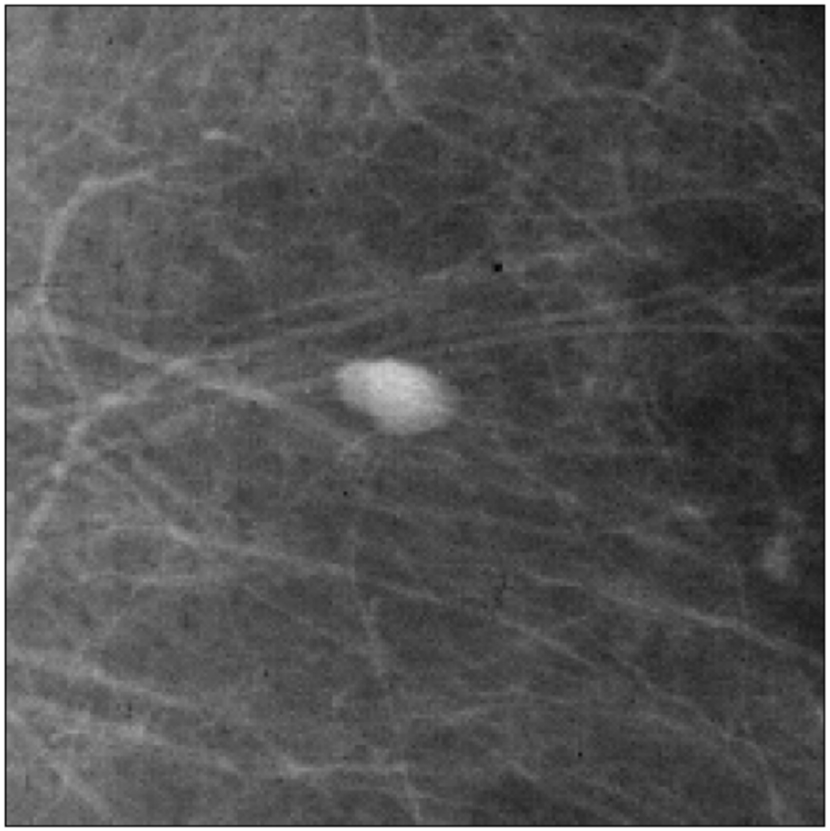


Requirements:

- Low energy x-ray photons for better soft tissue differentiation.
- High resolution (0.1 mm) for diagnosing micro-calcifications.

Breast compression
=> short exposure time

Film-screen based X-Ray Radiology



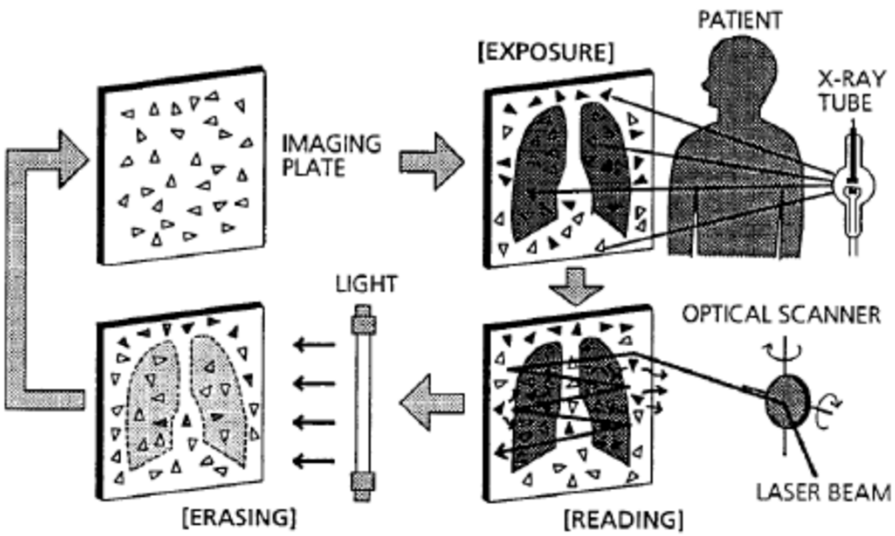
Screening Mammogram:

Close up view of mammogram shows a small, well circumscribed lesion.

UNC Radiology Teaching File (Mammography Section),

Image Plate based X-Ray Radiology

Digital X-ray image acquisition systems for projection radiography.



Stimulatable Phosphor System

- Imaging plate (stimulable phosphor) is exposed forming a latent image (”traps” in phosphor).
- latent image is read via laser scanning --> stored energy is released in form of “photostimulated luminescence light” proportional to the local X-ray exposure.
- The luminescence signal is converted to an electrical signal and is digitized.

Image Plate X-Ray Detector

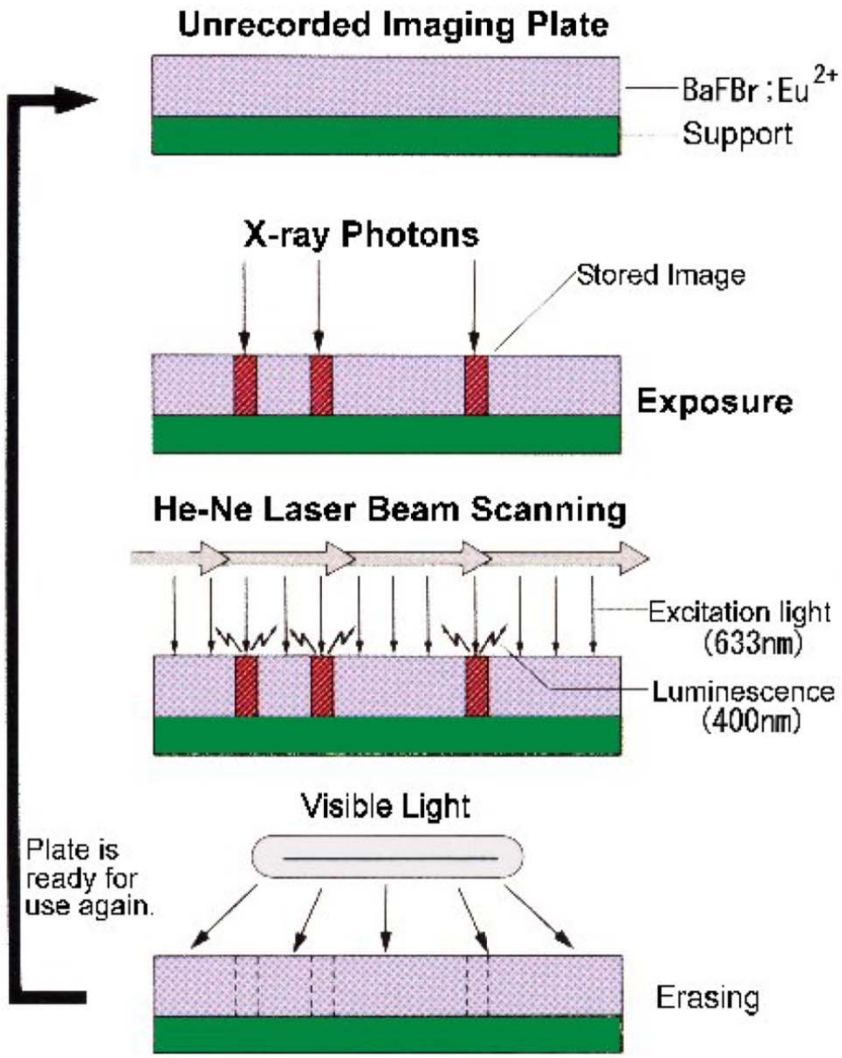


Image Plate X-Ray Detector

Success of CR:

– high dynamic range (> 104)

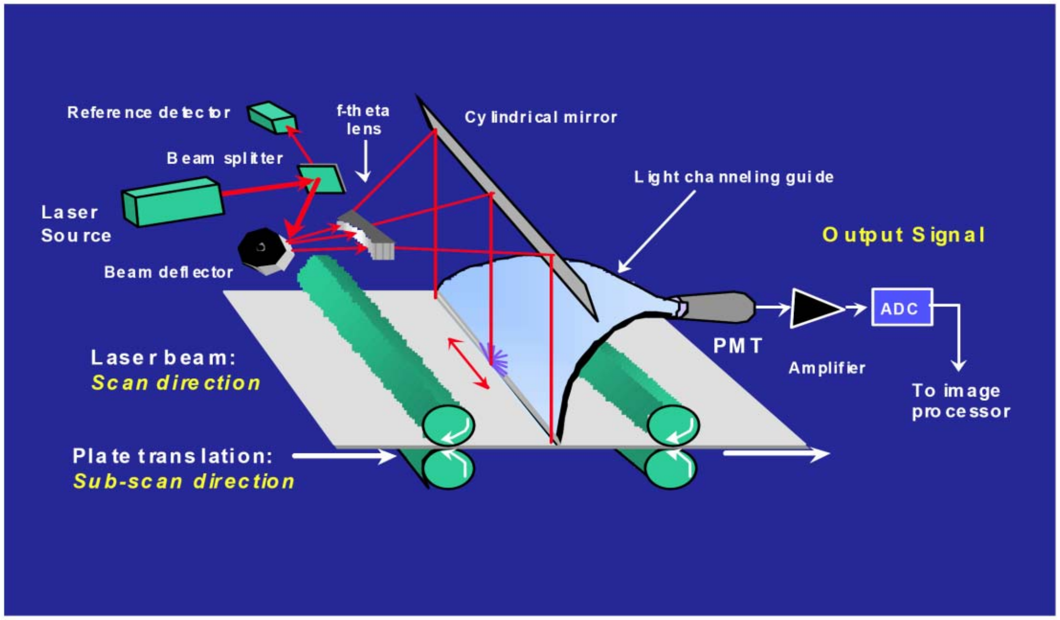
– digital nature

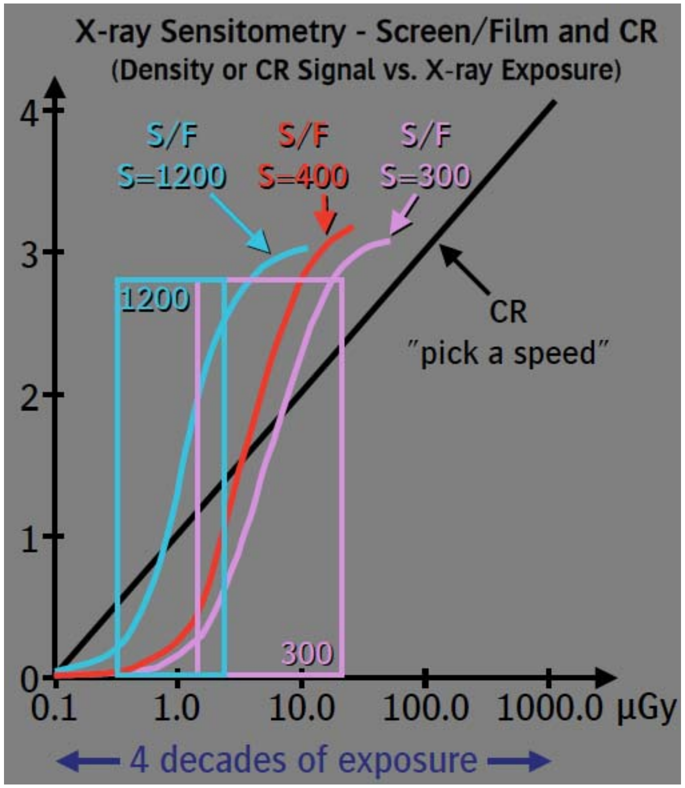
– easy to introduce

– relative low cost

– improvements for more than 25 years

– **but not for image or dose performances !**

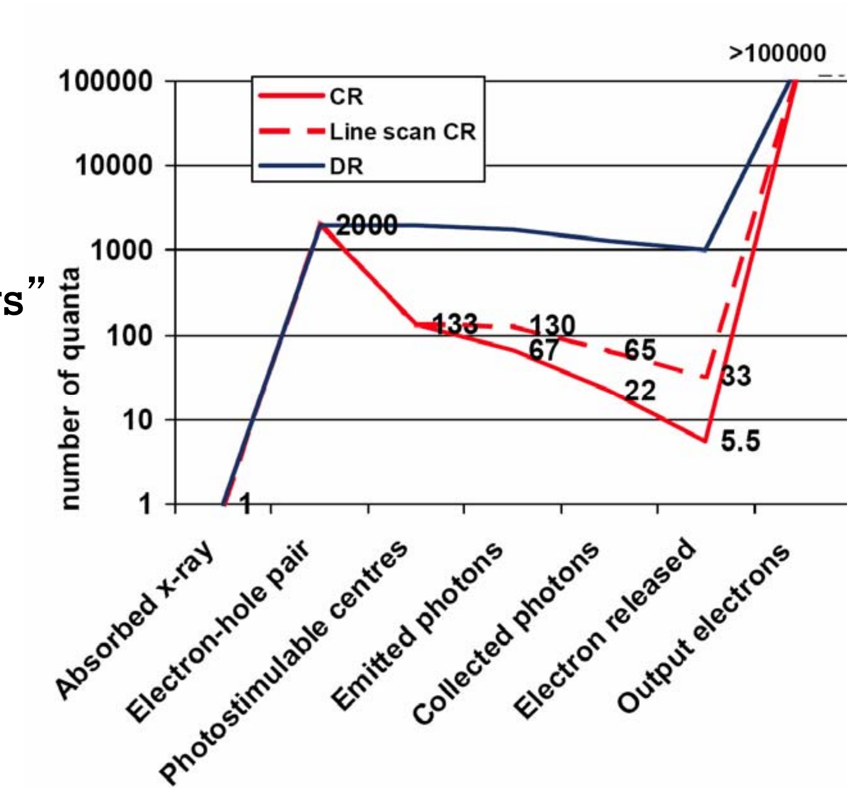




Limitation of Image Plate X-Ray Detector

Relatively small of "information carriers" created per x-ray photon.

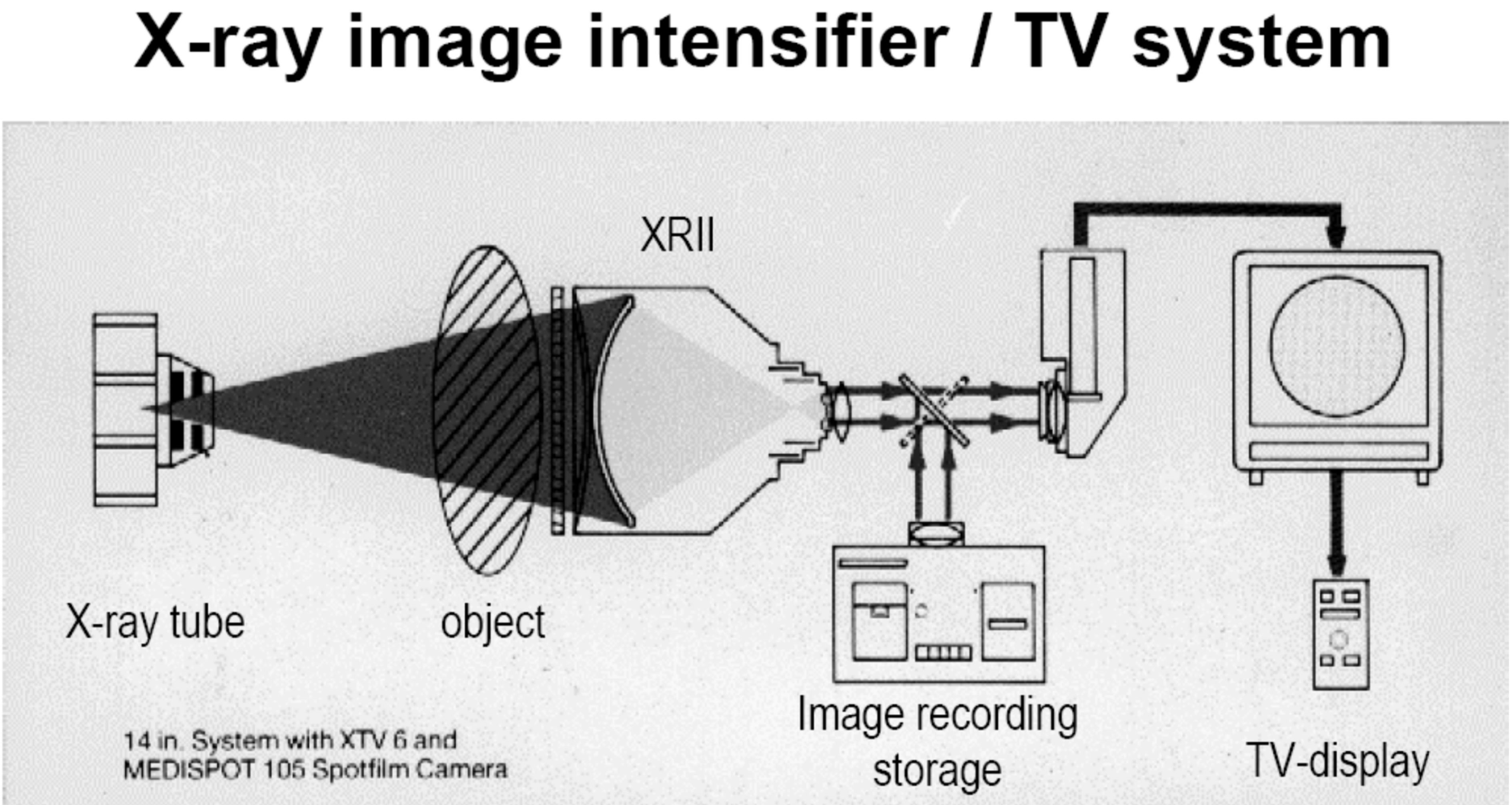
— Low signal to noise ratio (SNR)



X-Ray Image Intensifier (X-ray II)

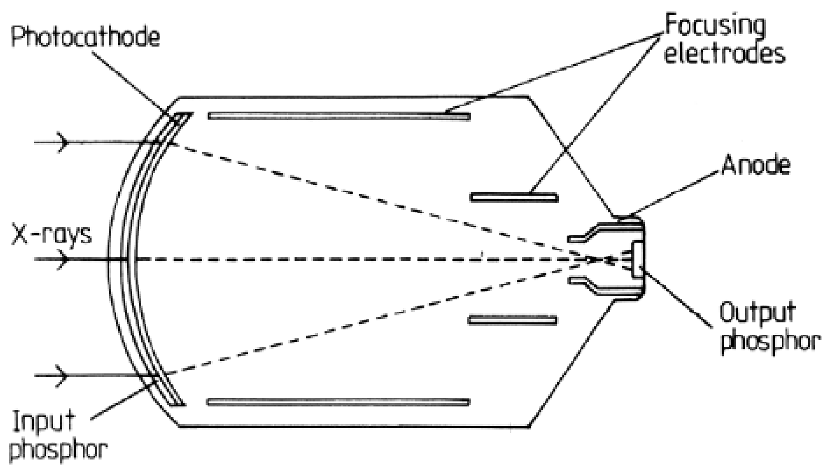
X-ray II is the standard detector for current projection radiography system

X-Ray Image Intensifier (X-ray II)



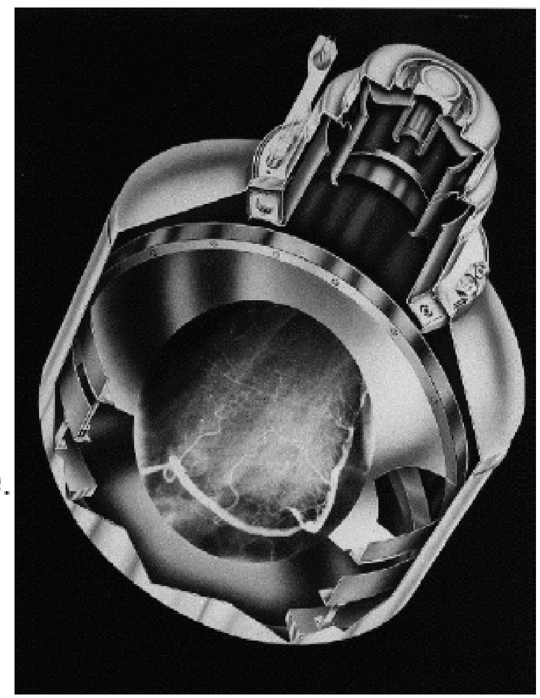
X-Ray Image Intensifier (X-ray II)

Principle Operation of XRII



Construction of the image intensifier.

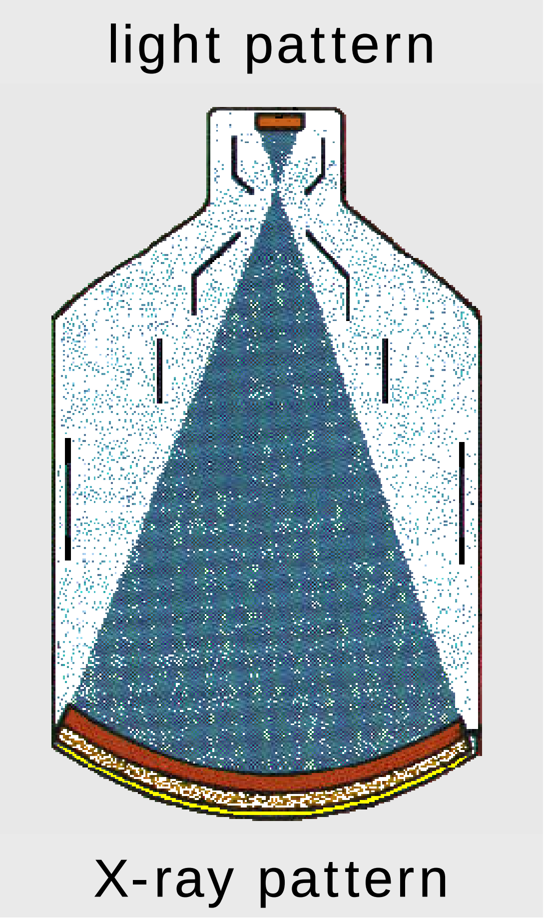
- X-rays are absorbed in CsI input phosphor.
- Emitted light is converted to electrons by photocathode.
- Electrons are focused and accelerated to output phosphor and converted to light..
- Bright light image at output window is imaged by TV-camera.



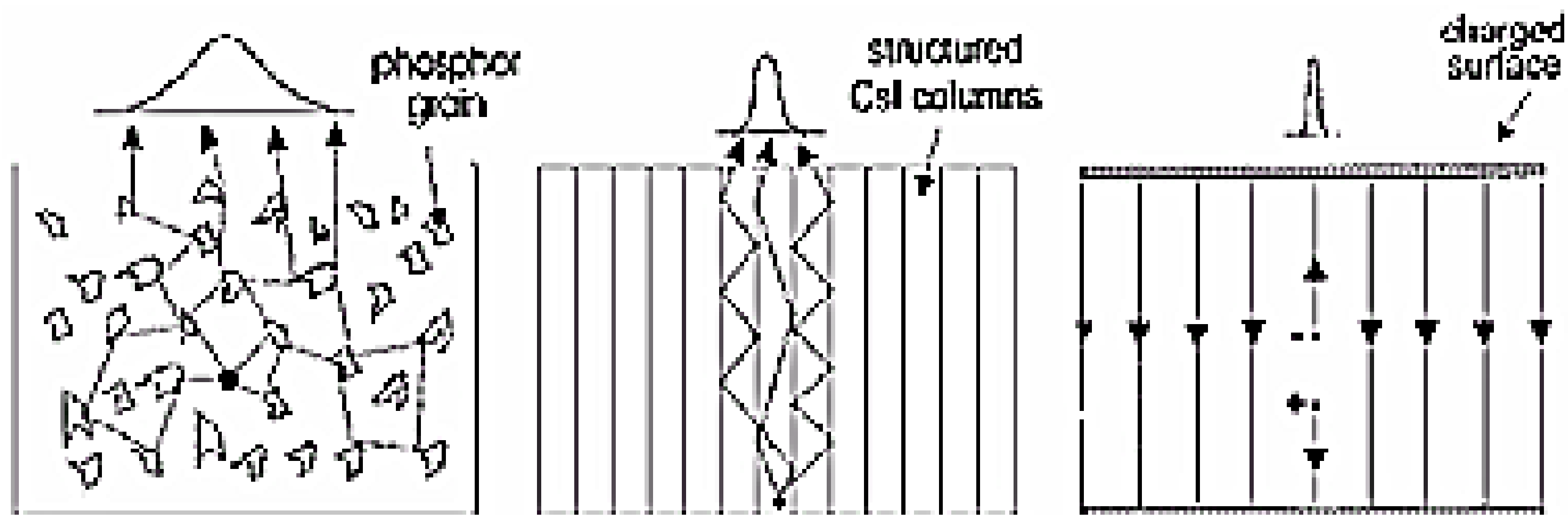
Medical Image Processing (Med Img 1) 39

X-ray II – Gain

- Ability of II to ↑ illumination
- Sequence of changes
  - Attenuated x-ray beam (dim)
  - Converted to light
  - Light used to emit e^-
  - e^- pattern focused & minified as it is attracted to anode
  - e^- strike output screen & converted back to light (bright)

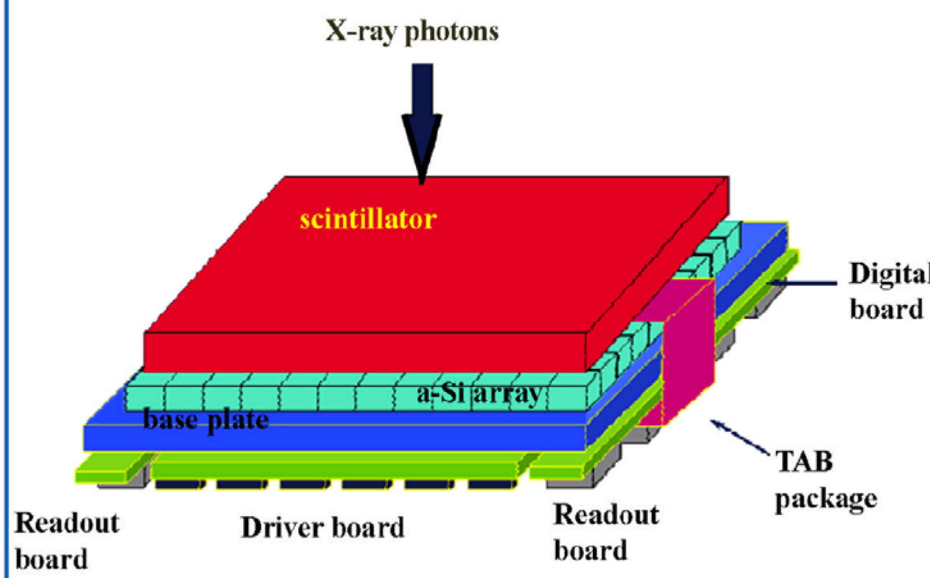


Signal Generation in X-Ray Detectors



Flat Panel Detectors

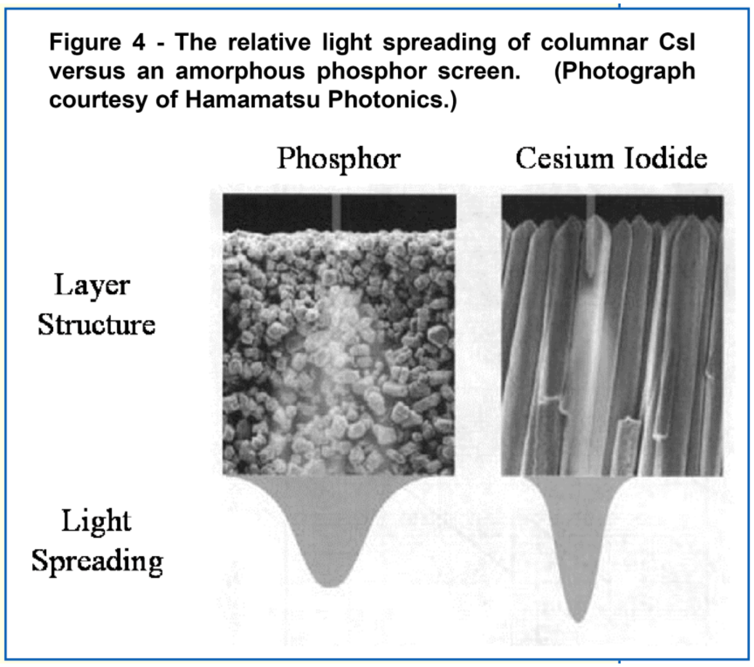
Figure 2 - Flat panel detector internal architecture.



The construction of FPDs is similar in many ways to flat panel displays, and uses many of the same technologies. Figure 2 shows the construction of a typical FPD. At the core is an amorphous-silicon TFT/photodiode array. Closely coupled to the array is the X-ray scintillator.

http://www.varian.com/xray/pdf/Flat%20Panel%20Xray%20Imaging%2017-11-04.pdf

Scintillation Material as Detection Media



- CsI(Tl) scintillator: density 4.6g/cm^3, emission peak ~550nm.
- Columnar structure of up to 3mm thick to provide an adequate stopping power and a reduced light spread.

http://www.varian.com/xray/pdf/Flat%20Panel%20Xray%20Imaging%2017-11-04.pdf

Readout Electronics for Plat Panel Detectors

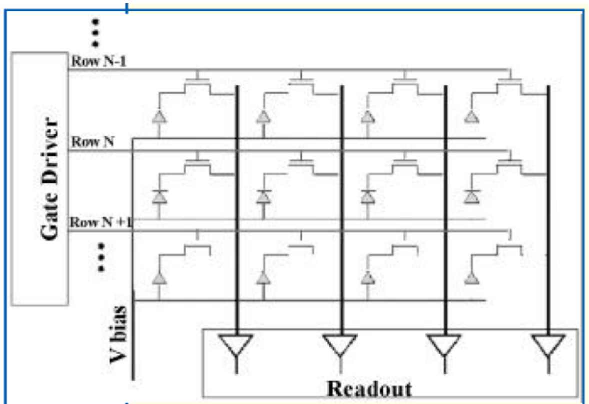
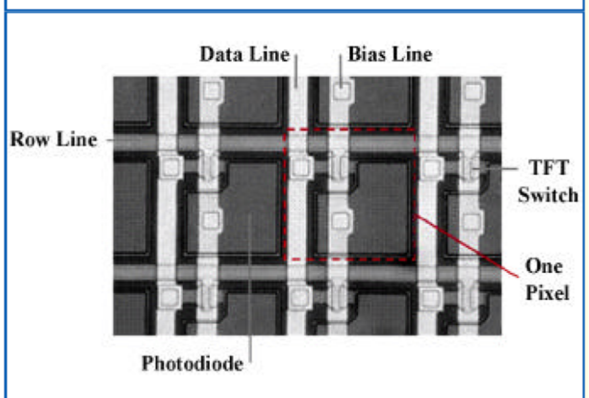


Figure 5 - TFT/Photodiode array schematic and view of a single 127µm pixel.

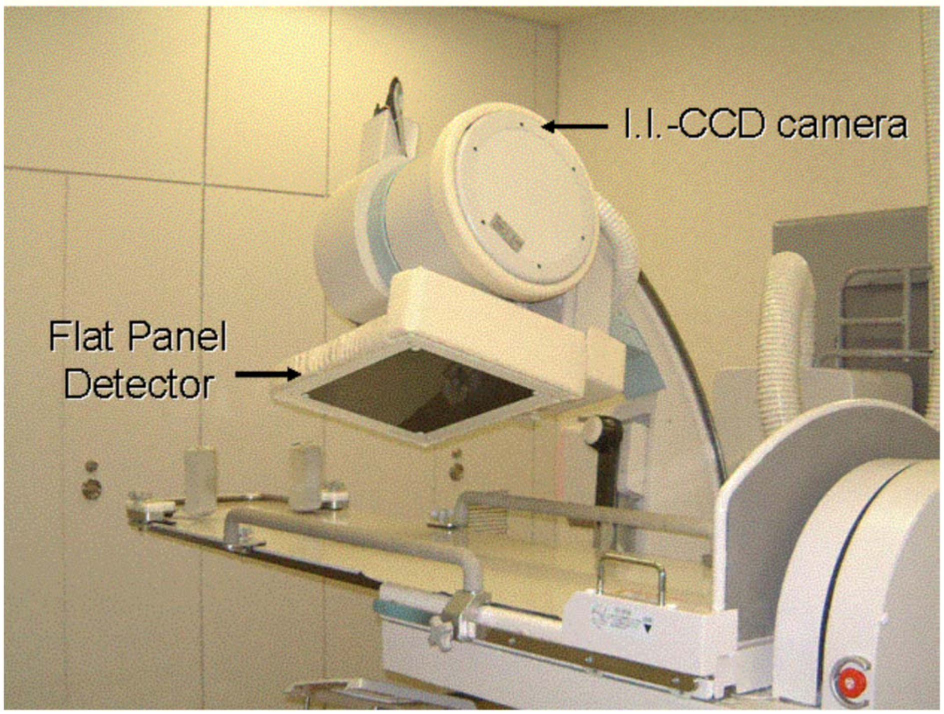


- scanned progressively, one line at a time from top to bottom. The TFTs are essentially switches.
- When a large positive voltage is applied to one of the gate lines, the switches (TFTs) in the selected row are closed, causing them to conduct electricity.
- With the TFTs energized, each pixel in the selected row discharges the stored signal electrons onto the dataline. At the end of each dataline is a charge integrating amplifier which converts the charge packet to a voltage.
- a programmable gain stage and an Analog-to-Digital Converter (ADC), which converts the voltage to a digital number.

http://www.varian.com/xray/pdf/Flat%20Panel%20Xray%20Imaging%2017-11-04.pdf

Advantages of Plat Panel Detectors

Figure 7 - This is experimental R&F equipment used by Hitachi in a clinical evaluation of flat panel technology. Here a 12”x16” (active area) FPD is mounted on the side of a 12” Image Intensifier Tube (IIT). With this system, either the FPD or IIT could be rotated into place, facilitating straightforward comparison images.

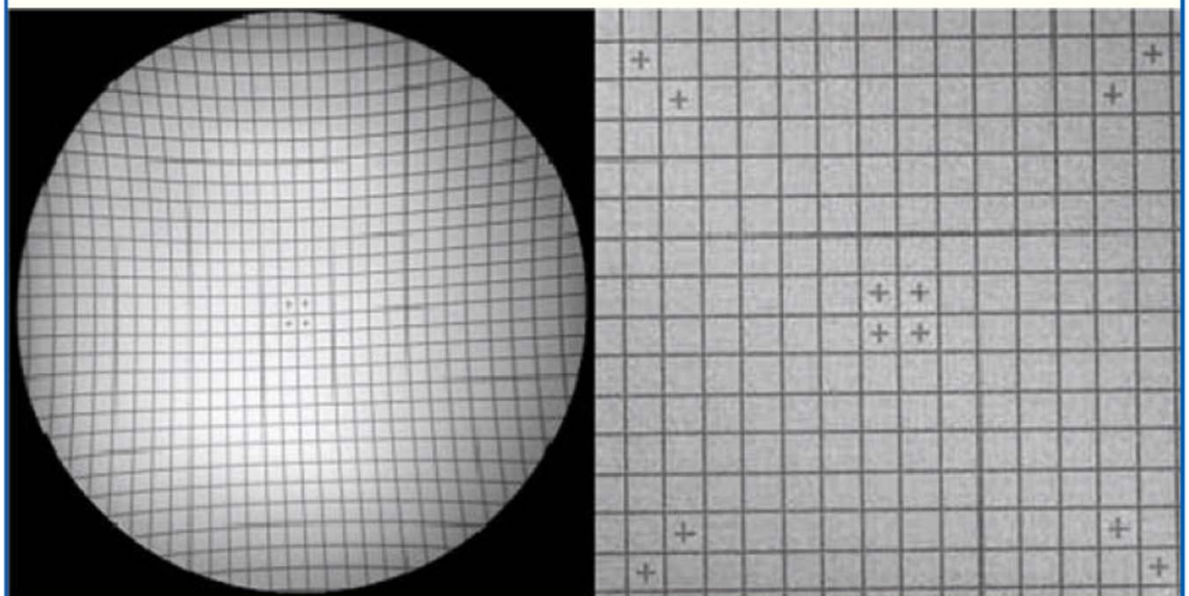


- Greatly reduced size over IIs.

http://www.varian.com/xray/pdf/Flat%20Panel%20Xray%20Imaging%2017-11-04.pdf

Advantages of Plat Panel Detectors

Figure 9 - Comparison between a 12" IIT system and GE's 20cm Revolution flat panel detector. Clearly the image intensifier has both distortion and brightness non-uniformity which is absent from the flat panel detector. (Image courtesy of GE Medical Systems.)



- Less distortion.

http://www.varian.com/xray/pdf/Flat%20Panel%20Xray%20Imaging%2017-11-04.pdf

Advantages of Plat Panel Detectors

Improved SNR over X-ray IIs

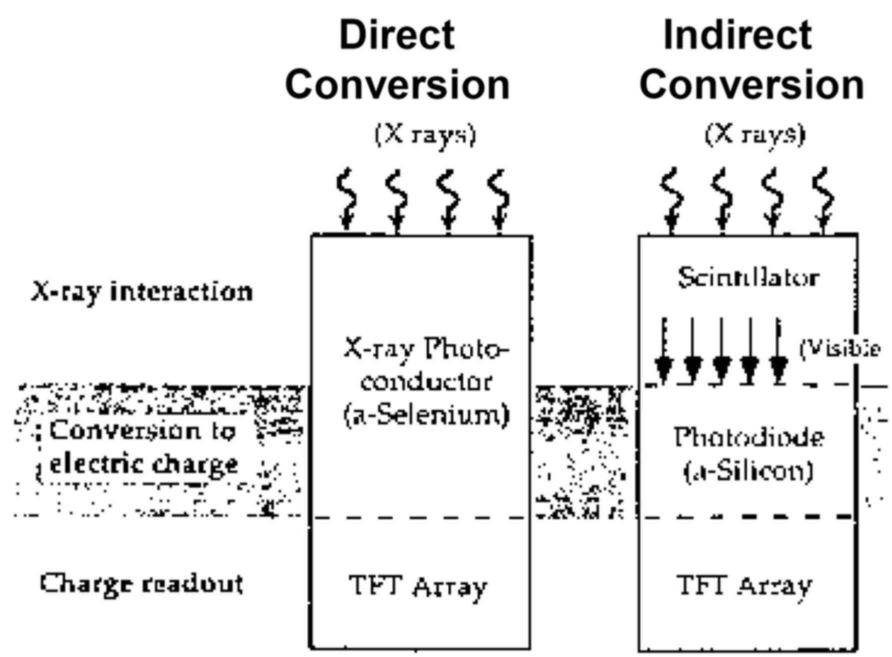
- The FPD contributes electronic noise to the image.
- However, if the electronic noise is low enough, the statistical noise in the X-ray beam is dominant.
- The noise in the beam follows Poisson statistics. In other words, the noise is equal to the square root of the number of incident X-ray photons.

http://www.varian.com/xray/pdf/Flat%20Panel%20Xray%20Imaging%2017-11-04.pdf

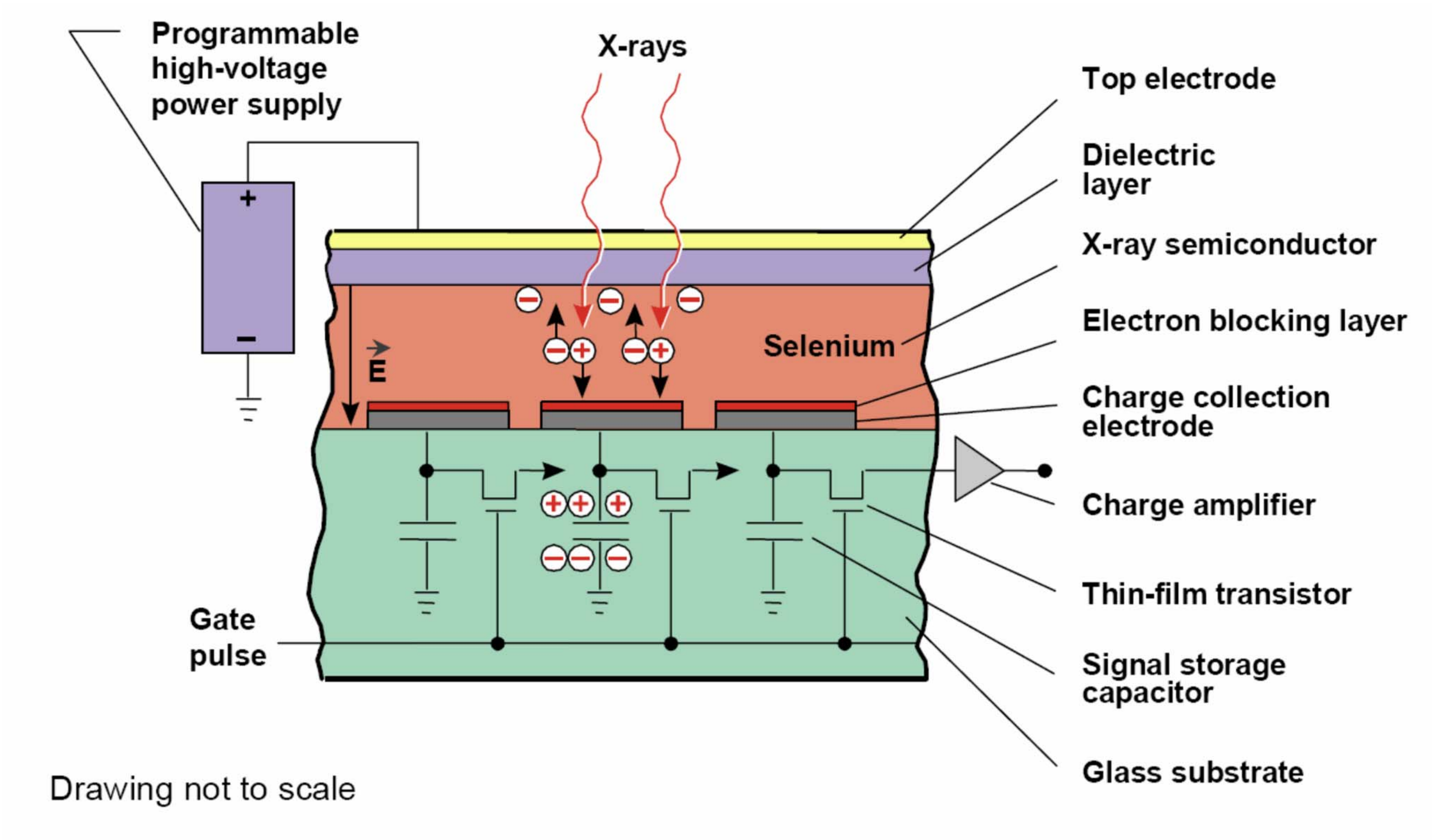
Direct Radiography (DR)

AMFPI (Active Matrix Flat Panel Imager) is composed of:
– a x-ray detection layer
– an AMA (Active Matrix Array) of TFT (Thin Film Transistors) layer

• Two type of x-ray detectors are today mainly used:
– Selenium (photoconductor)
– CsI(Tl) (scintillator)



Direct Radiography (DR)



The Energy Band Structures in Solids

- The energy of any electron within the pure material must be confined to one of these energy bands, which may be separated by gaps or ranges of forbidden energies.
  - **Valence band**: corresponds to outer shell electrons that are bound to specific lattice sites.
  - **Conduction band**: represents electrons that are free to migrate through the crystal → conductivity of the material.
  - **Band gap**: the minimum difference in the energies that can be possessed by electrons in the valence band and the conduction band.

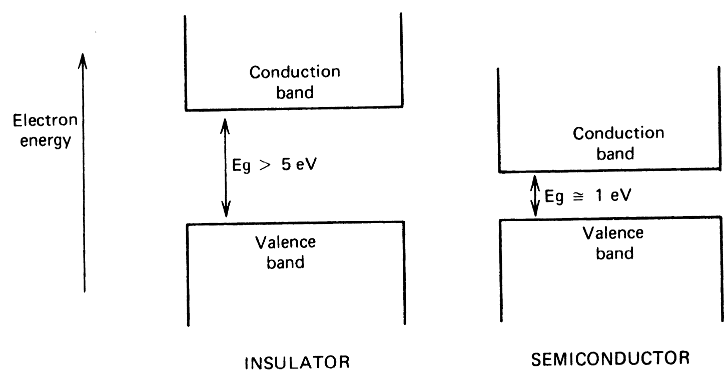
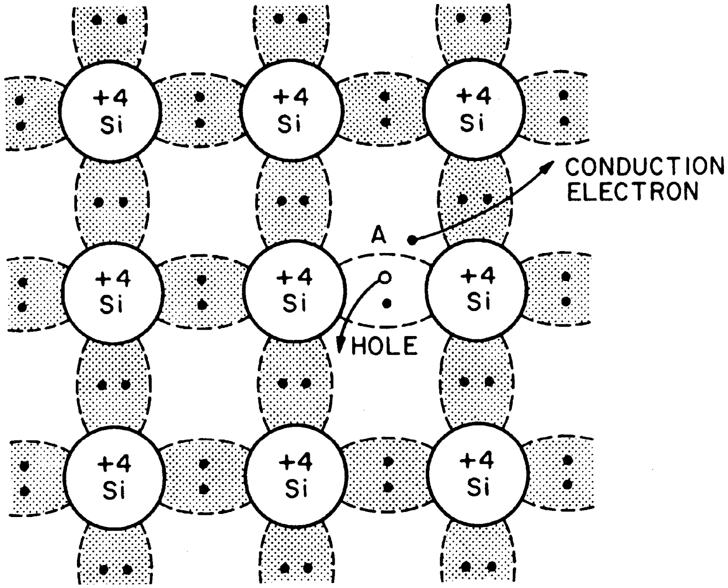
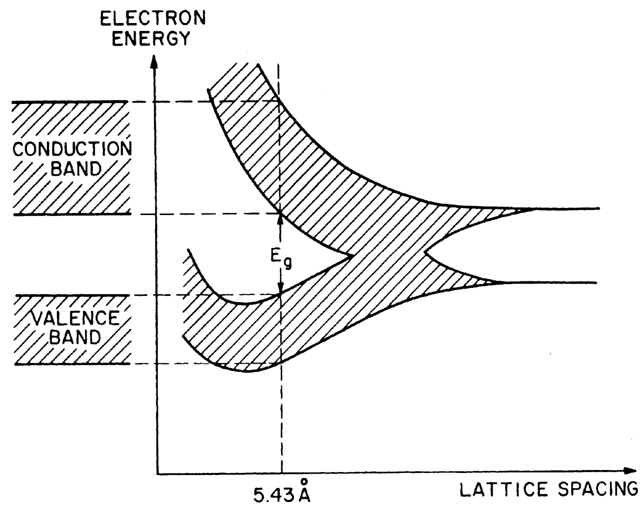


Figure 11.1 Band structure for electron energies in insulators and semiconductors.

The Energy Band Structures in Solids



Schematic bond representation of a single crystal with one broken bond in the center. (After Sze 1985, p9, Fig 7)



Energy levels of silicon atoms arranged in a diamond structure as a function of lattice spacing. (After Sze 1985, p9, Fig 7)

The Energy Band Structures in Solids

Insulator, semiconductor and conductor

☞ Insulator and semiconductor materials:

→ the number of electrons in the crystal is just adequate to fill all available sites in the valence band

→ electrons can not move freely in the valence band

→ no thermal excitation, no conductivity

→ band gap>5eV: insulator, otherwise semiconductor.

→ examples: band gap of diamond is 5.4eV → insulator

band gap of silicon is 1.14eV → semiconductor

☞ Conductor:

→ the number of electrons in the crystal is NOT enough to fill all available sites in the valence band

→ electrons can move freely in the valence band under external electric field, which give rise to the electrical conductivity.

The Energy Band Structures in Solids

- In metallic solid, the average number of electrons per quantum states of energy E in the electron gas is given by

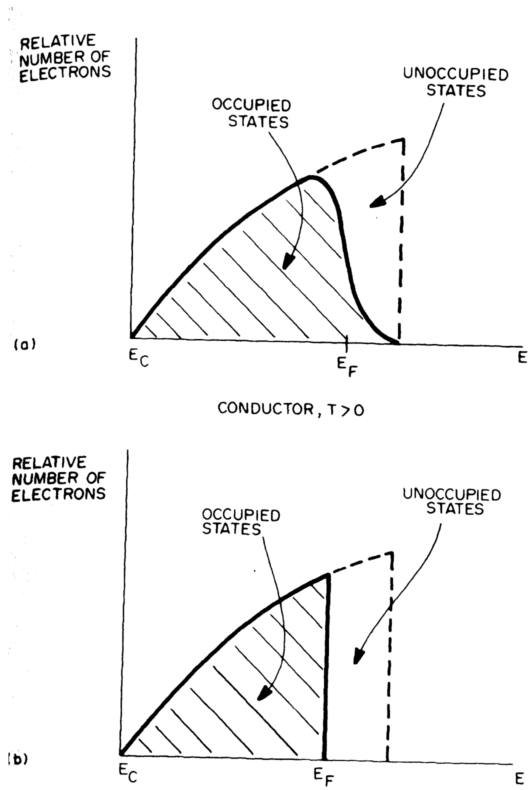


FIGURE 10.12. Relative number of electrons in the conduction band of a conductor at absolute temperatures (a) $T > 0$ and (b) $T = 0$.

$$N = \frac{1}{e^{(E - E_F)/kT} + 1}$$

where k is the Boltzmann constant, T is the absolute temperature, and E_F denotes the Fermi energy.

For further reference, please refer to Section 10.2, p249-251 and Section 2.9, p39-40, Atoms, Radiation and Radiation Protection.

The Energy Band Structures in Solids

- In semiconductors, the relatively small band gap may permit a small number of electrons to possess energies in the conduction band.
- The **number of electrons in the conduction band** is equal to the number of holes in the valence band.
- **Fermi energy** lies midway in the forbidden gap at an energy $E_0 + E_G/2$.

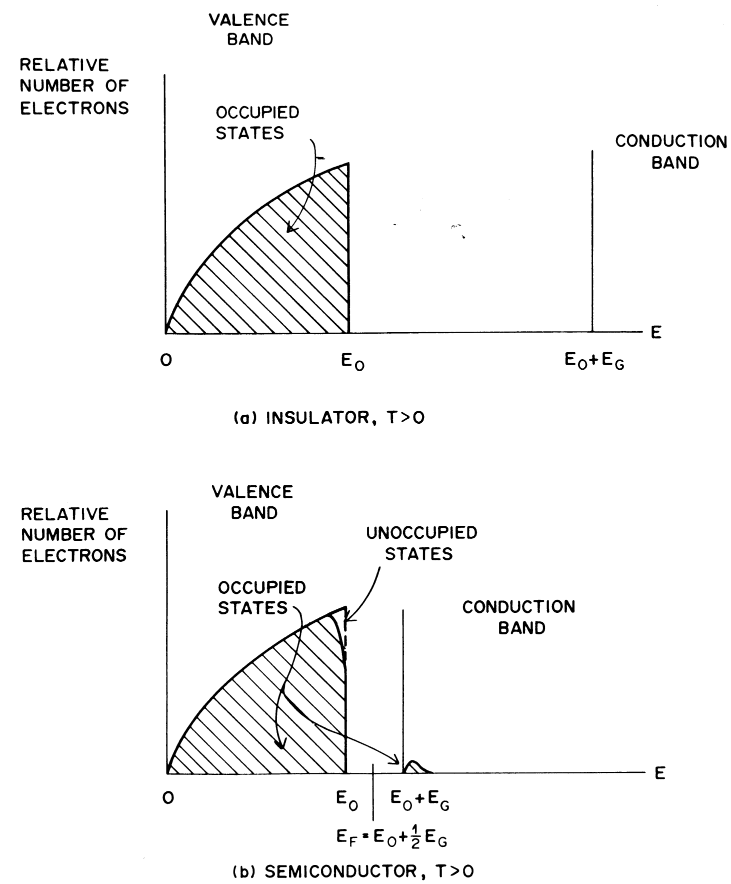


FIGURE 10.13. Relative number of electrons in valence and conduction bands of (a) an insulator and (b) a semiconductor with $T > 0$.

The Energy Band Structures in Solids

- In semiconductors, a small number of electrons are elevated to the conduction band and leaving the same number of holes in the valence band.
- At room temperature, the density of electrons in the conduction band is 1.5×10^{10}cm^{-3} in Si and 2.4×10^{13}cm^{-3} in Ge.

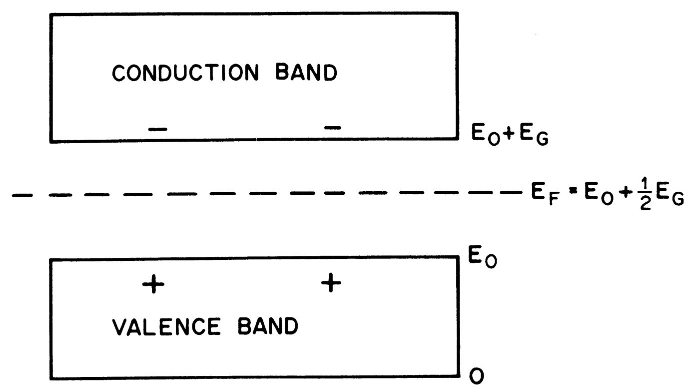


FIGURE 10.14. Occupation of energy states in an intrinsic semiconductor at room temperature. A relatively small number of electrons (−) are thermally excited into the conduction band, leaving an equal number of holes (+) in the valence band. The Fermi energy E_F lies at the middle of the forbidden gap.

The Energy Band Structures in Solids

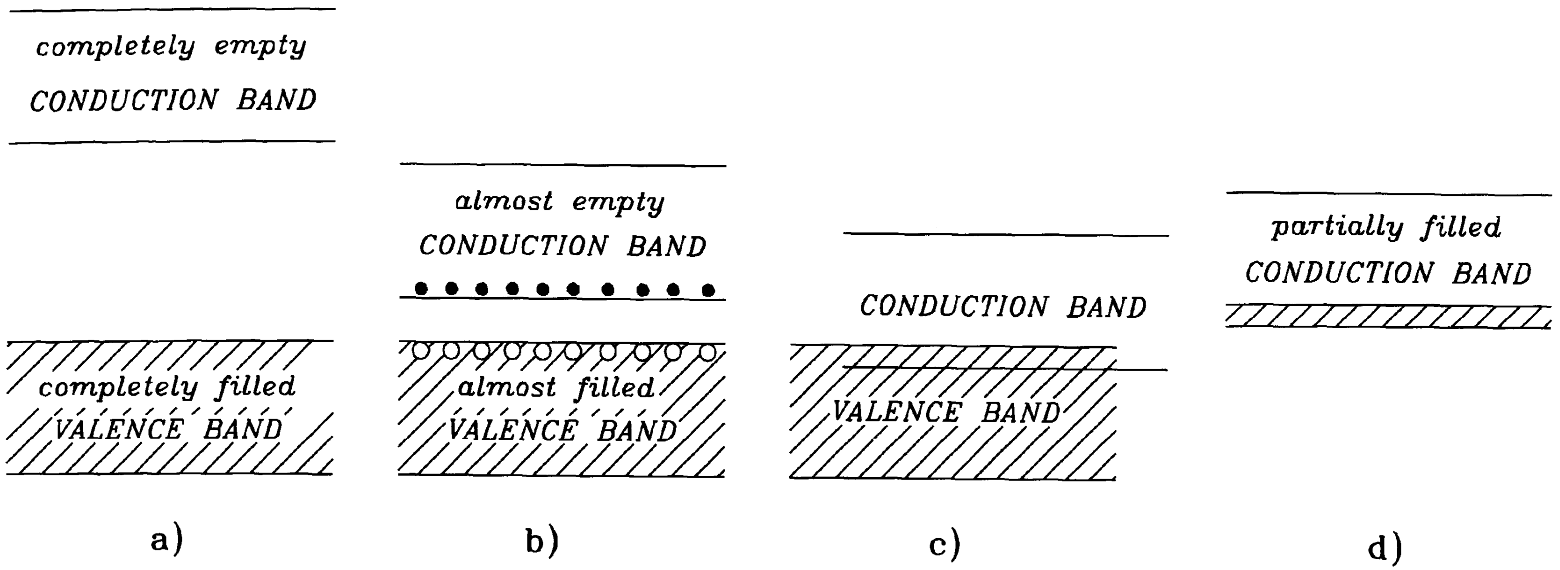


Fig. 2.5a–d. Energy band structure of insulators (a) semiconductors (b) and conductors (c,d)

Charge Carriers in Semiconductor Materials

The so-called **charge carriers** in semiconductors consist of the following two components

- **Electrons** elevated to the conduction band.
- **Vacancies** in the valence band. The migration of electrons in the valence band results in a net effect of moving positive charges (**hole**).

The **probability per unit time that an electron-hole pair is thermally generated** is given by

$$p(T) = CT^{3/2} \exp\left(-\frac{E_g}{2kT}\right)$$

where

T = absolute temperature

E_g = bandgap energy

k = Boltzmann constant

C = proportionality constant characteristic of the material

Effect of Impurities and Dopants – Intrinsic Semiconductors

An example from Knoll, p. 360.

The leakage current (I) through a detector, of area A and thickness t, is related to the resistivity of the material as

$$I = \frac{A \cdot V}{\rho \cdot t} \text{ or } \rho = \frac{A \cdot V}{I \cdot t}$$

be their sum, with each term given by the product of the area, intrinsic carrier density, electronic charge e, and the drift velocity of the charge carrier. Thus

$$I = I_e + I_h = An_i e(v_e + v_h)$$

From Eqs. 11.2 and 11.3

$$I = An_i e \mathscr{E}(\mu_e + \mu_h) = An_i e \frac{V}{t}(\mu_e + \mu_h)$$

Combining

$$\rho = \frac{1}{en_i(\mu_e + \mu_h)} \tag{11.8}$$

Effect of Impurities and Dopants – Intrinsic Semiconductors

An example from Knoll, p. 360.

$$I = \frac{A \cdot V}{\rho \cdot t} \text{ or } \rho = \frac{A \cdot V}{I \cdot t}$$

Inserting numerical values for intrinsic silicon at room temperature:

$$\rho = \frac{1}{(1.6 \times 10^{-19} C)(1.5 \times 10^{10}/\mathrm{cm}^3)(1350 + 480)\ \mathrm{cm}^2/V \cdot s}$$

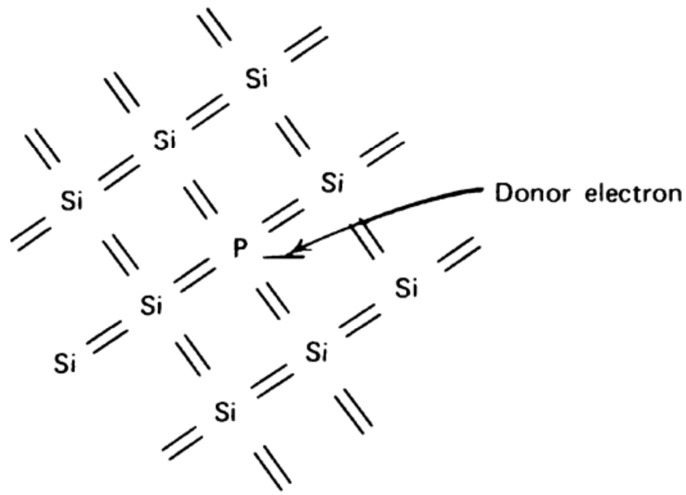
$$\rho = 2.3 \times 10^5 \frac{V \cdot s \cdot \mathrm{cm}}{C} = 230{,}000\ \Omega \cdot \mathrm{cm}$$

Presently available silicon material of the highest purity falls short of achieving this resistivity value because of the effect (discussed in the following sections) of residual impurities.

Effect of Impurities and Dopants – n-Type Semiconductors

n-Type semiconductors:

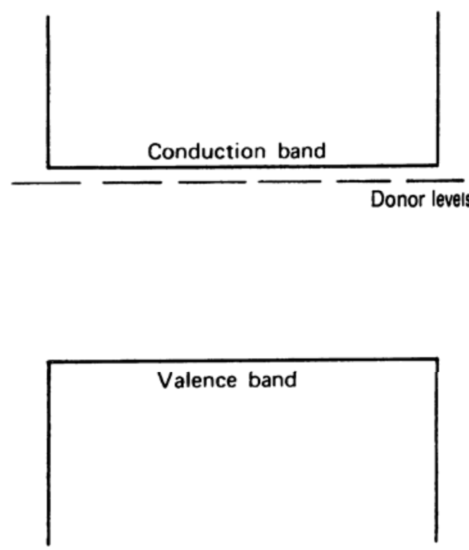
- A **small amount of impurity** may be present either as a residual amount after the best purification processes, or as a small amount intentionally added to the material to tailor its properties.
- The impurity atom (of the order of a few parts per million or less) will occupy a substitution site within the lattice, taking the place of a normal silicon atom.



Effect of Impurities and Dopants – n-Type Semiconductors

n-Type semiconductors:

- There are **extra electrons** in the impurity atom after forming covalent bonds with surrounding silicon atoms. The extra electron is **lightly bound** to the original impurity site.
- The extra electron associated with the donor impurity can occupy a position within the normally forbidden gap. They will have a energy near the top of the gap.

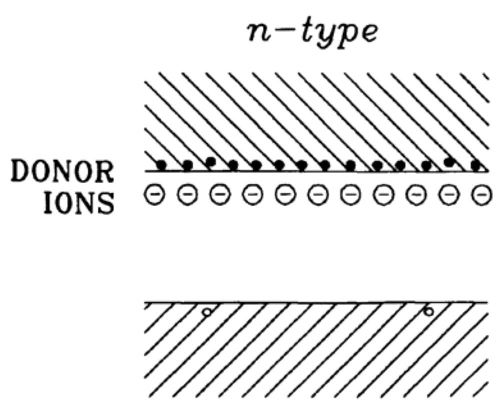


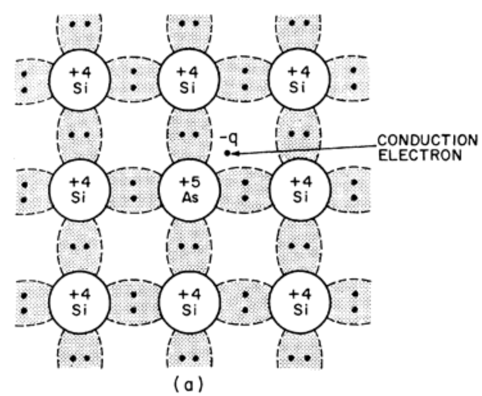
Effect of Impurities and Dopants – n-Type Semiconductors

n-Type semiconductors:

- It takes very little energy to dislodge the extra electron and to form a conductive electron, without leaving a hole in the valence band.
- Since the concentration of impurity N_D is large compared with the concentration of electrons expected in the conduction band for the intrinsic material, the **number of electrons in the conduction band (n) is dominated by the contribution from the donor impurity**,

$$n \cong N_D$$





Effect of Impurities and Dopants – p-Type Semiconductors

p-Type semiconductors:

- The addition of a trivalent impurity such as an element from group III of the periodical table to a silicon lattice results in a p-type semiconductor.

The impurity occupying a substitution site has one fewer valence electron than the surrounding silicon atoms – one covalent bond is left unsaturated.

Acceptor impurity.

An electron filling this hole is slightly less firmly attached than a typical valence electron.

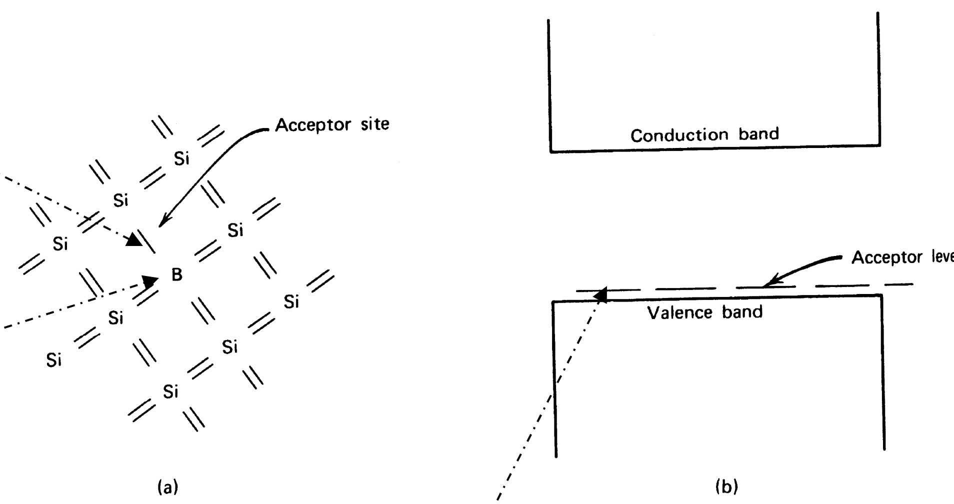


Figure 11.4 (*a*) Representation of an acceptor impurity (boron) occupying a substitutional site in a silicon crystal. (*b*) Corresponding acceptor levels created in the silicon bandgap.

Electron filling the hole possess an energy slightly above the maximum energy of a valence band electron.

Comparison of Intrinsic and Extrinsic Semiconductors

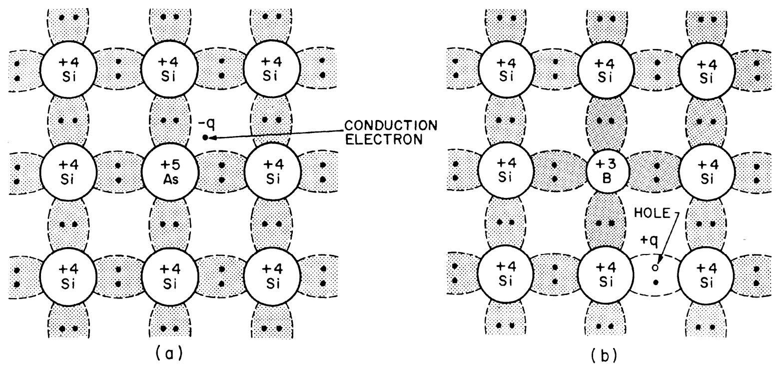


Fig. 2.8a,b. Bond representation of n-type (a) and p-type (b) semiconductors. (After Sze 1985, p. 21 Fig. 21)

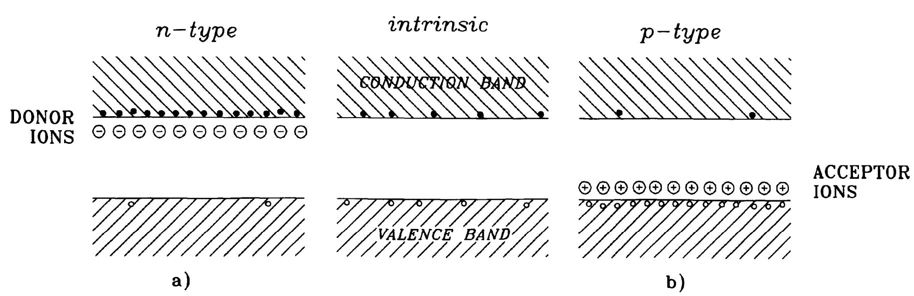


Fig. 2.9a,b. Schematic energy band representation of extrinsic n-type (a) and p-type (b) semiconductors

Effect of Impurities and Dopants

- The concentration of holes greatly exceeds the concentration of electrons in the conduction band.
- The concentration of holes (p) is completely dominated by the contribution from the acceptor impurity, so that

$$p \cong N_A$$

- Similarly, the concentration of electrons and holes is given by

$$np = n_i p_i$$

Comparison of Intrinsic and Extrinsic Semiconductors

- The increase of majority carriers electrons in the case of n-type material and holes in the case of p-type materials) is accompanied by a decrease of minority carriers according to the following law

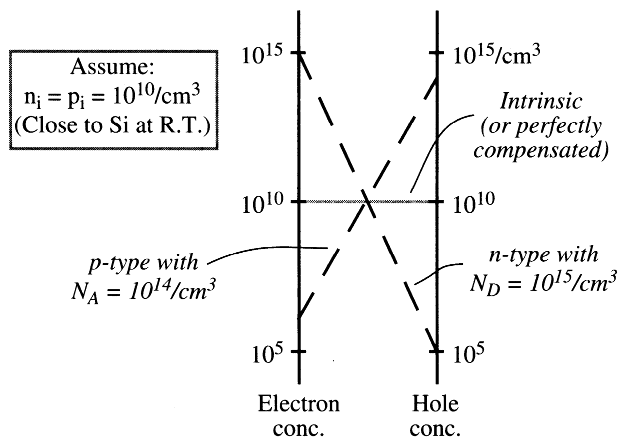


Figure 11.5 Nomogram showing the relationship between electron and hole concentrations in a semiconductor. Lines connecting points on the two logarithmic scales always pass through the center of the diagram for any type or degree of doping.

Comparison of Intrinsic and Extrinsic Semiconductors

- The increase of majority carriers (electrons in the case of n-type material and holes in the case of p-type materials) also leads to an increased conductivity in the material

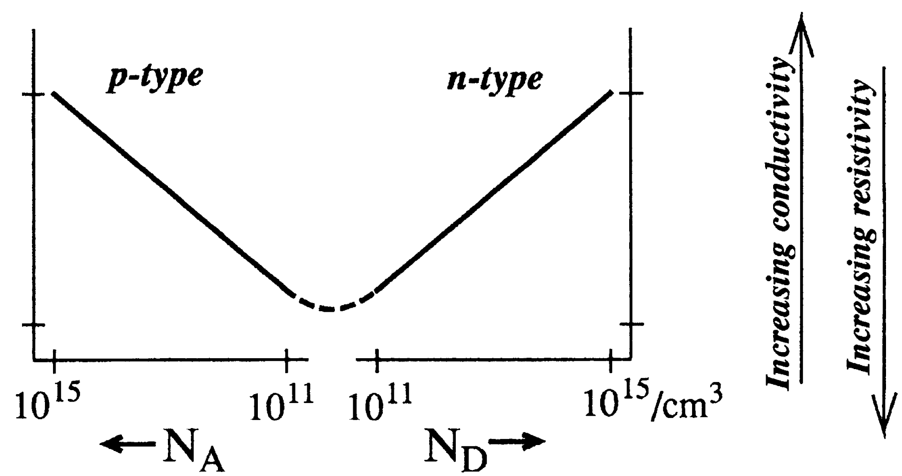


Figure 11.6 Plot using logarithmic scales of the conductivity of a semiconductor as a function of the net concentration of acceptors (N_A) or donors (N_D).

Effect of Impurities and Dopants – Intrinsic Semiconductors

An example from Knoll, p. 360.

The leakage current (I) through a detector, of area A and thickness t, is related to the resistivity of the material as

$$I = \frac{A \cdot V}{\rho \cdot t} \text{ or } \rho = \frac{A \cdot V}{I \cdot t}$$

be their sum, with each term given by the product of the area, intrinsic carrier density, electronic charge e, and the drift velocity of the charge carrier. Thus

$$I = I_e + I_h = An_i e(v_e + v_h)$$

From Eqs. 11.2 and 11.3

$$I = An_i e \mathscr{E} (\mu_e + \mu_h) = An_i e \frac{V}{t}(\mu_e + \mu_h)$$

Combining

$$\rho = \frac{1}{en_i(\mu_e + \mu_h)} \tag{11.8}$$

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Inserting numerical values for intrinsic silicon at room temperature:

$$\rho = \frac{1}{(1.6 \times 10^{-19} C)(1.5 \times 10^{10}/\mathrm{cm}^3)(1350 + 480)\ \mathrm{cm}^2/V \cdot s}$$

$$\rho = 2.3 \times 10^5 \frac{V \cdot s \cdot \mathrm{cm}}{C} = 230{,}000\ \Omega \cdot \mathrm{cm}$$

Presently available silicon material of the highest purity falls short of achieving this resistivity value because of the effect (discussed in the following sections) of residual impurities.

Semiconductors Junctions

- The usefulness of semiconductors as radiation detectors stems from the special properties created at a junction where n- and p- type semiconductors are brought into good thermodynamic contact.

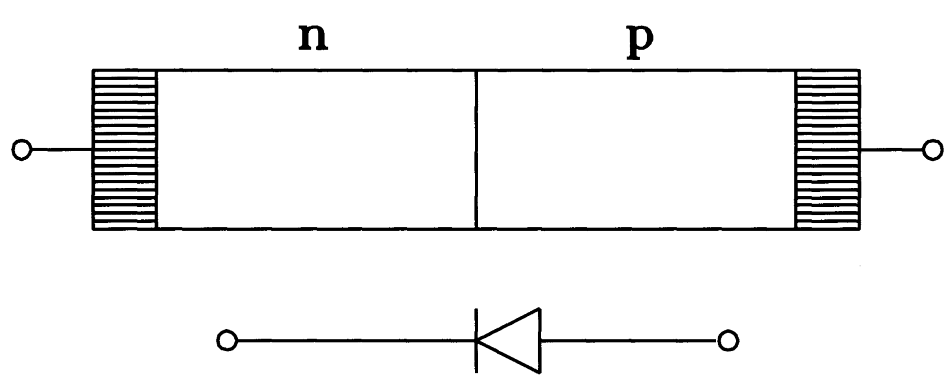


Fig. 3.1. A p–n diode junction: structure and device schematic

Semiconductors Junctions

Formation process

- ☞ Begins with crystals that has been doped with a uniform concentration of donor (n-type) and acceptor (p-type) impurities.

- ☞ When the n-type material is joining p-type material with a **good thermodynamic contact** → a p-n junction is formed due to the diffusion of majority carriers …

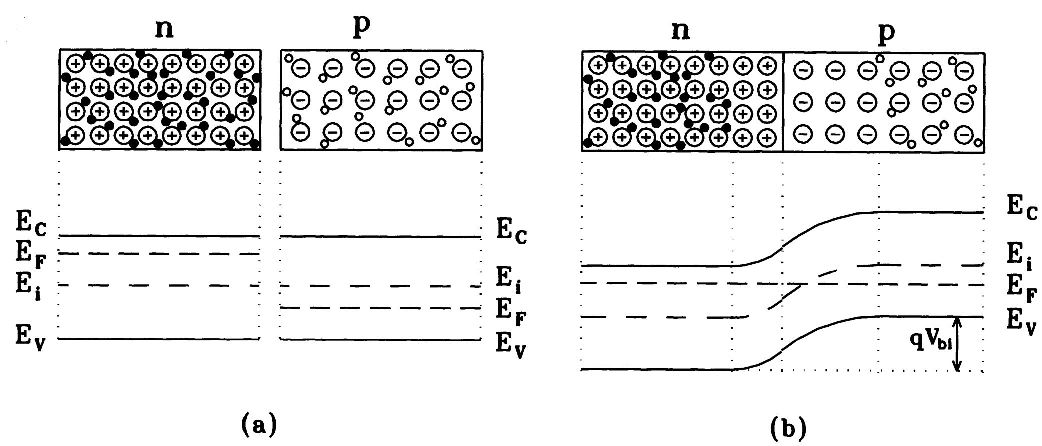
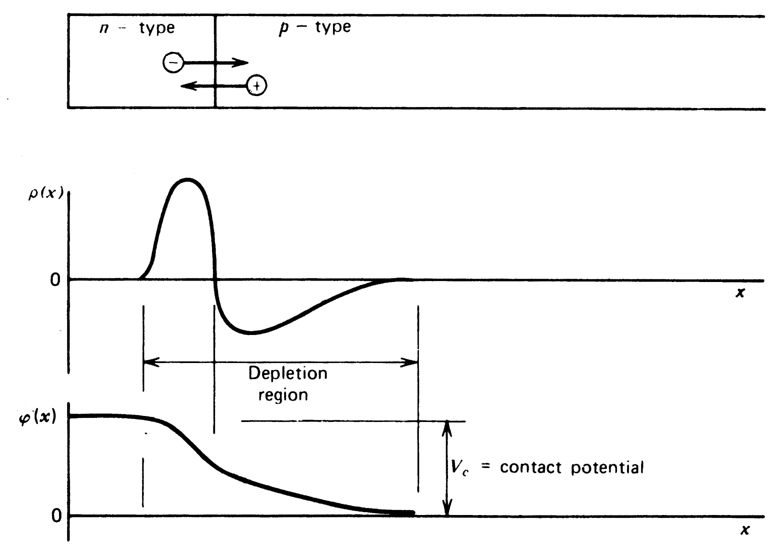


Fig. 3.2a,b. A p–n diode junction in thermal equilibrium, with its parts separated (a) and brought together (b)

Semiconductors Junctions

- The build up of net charge within the region of the junction leads to the establishment of an electric potential difference across the junction (called the **contact potential**). The value of the potential φ at any point can be found by the solution o Poisson's equation:



$$\nabla^2\varphi = -\frac{\rho}{\epsilon} \qquad (11.14)$$

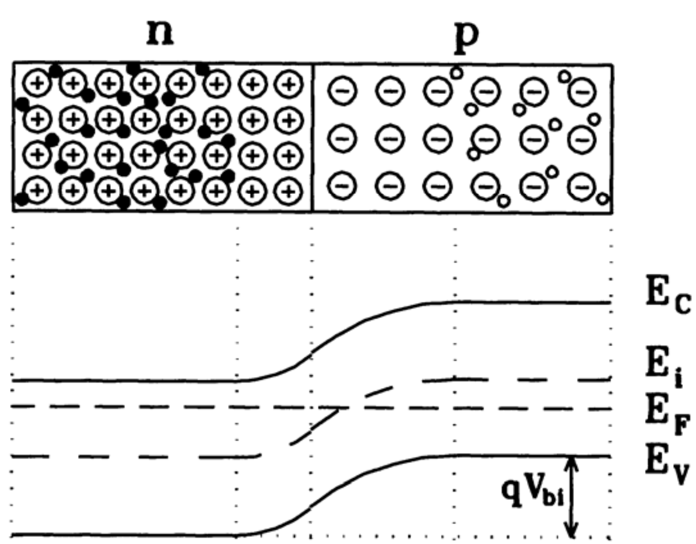
where ϵ is the dielectric constant of the medium, and ρ is the net charge density. In one dimension, Eq. (11.14) takes the form

$$\frac{d^2\varphi}{dx^2} = -\frac{\rho(x)}{\epsilon} \qquad (11.15)$$

Semiconductors Junctions

The depletion region corresponds to the basic active volume for the detection of radiation:

- ☞ The depletion region has a much higher resistivity compared to n- or p- type materials, because of the very low concentration of mobile charge carriers.
- ☞ Thermal generation of electron-hole pairs will continue to take place, contributing a component called **generation current** to the observed **leakage current**.



Biased Semiconductors Junctions

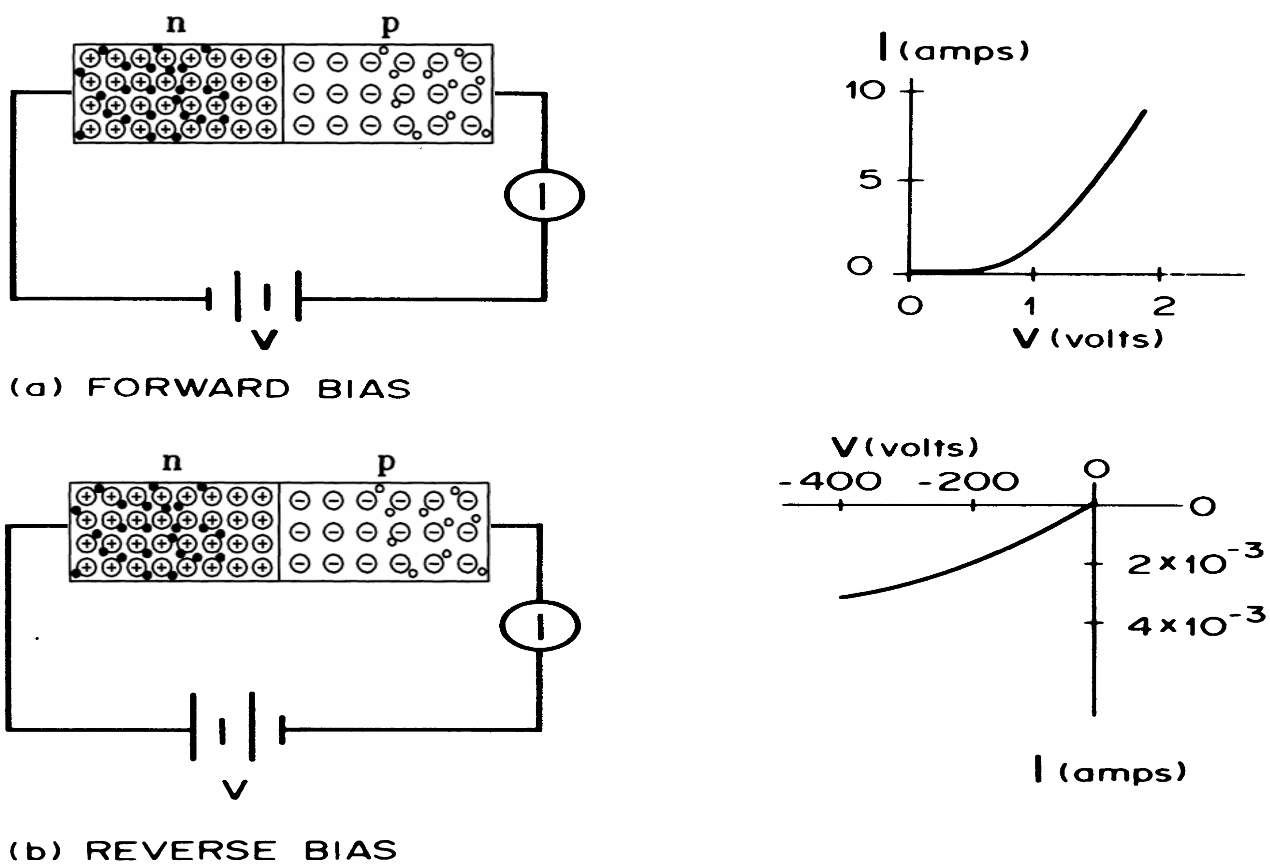
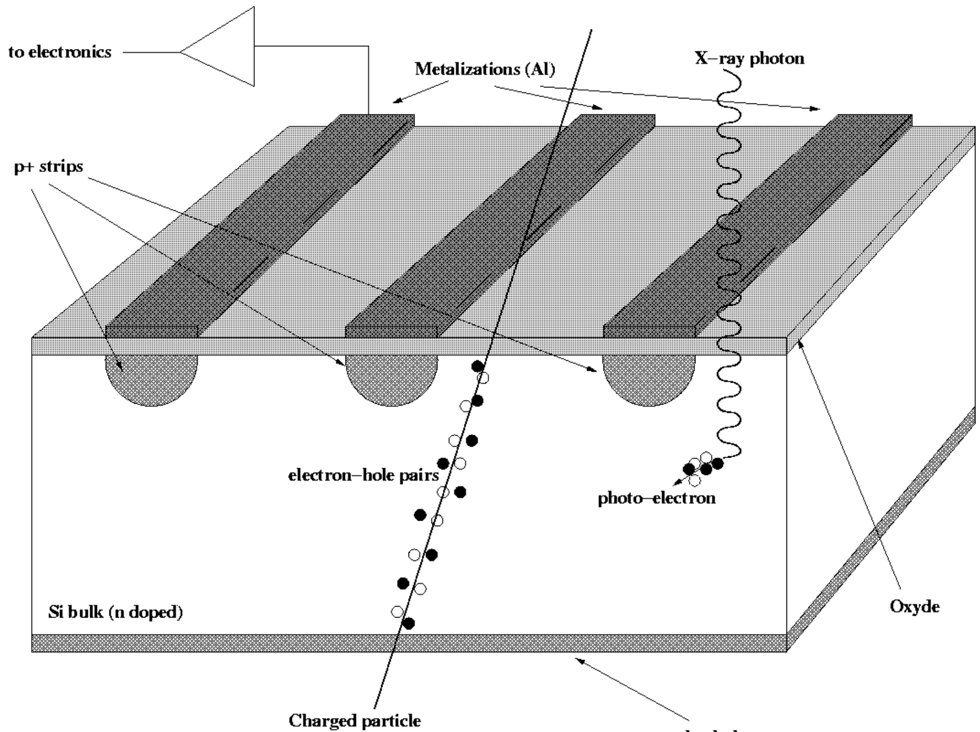


FIGURE 10.19. (a) Forward- and (b) reverse-biased n–p junctions and typical curves of current vs. voltage. Note the very different scales used for the two curves. Such an n–p junction is a good rectifier.

The microstrip detector



$$C = \frac{\varepsilon}{d} \qquad C = \left(\frac{\varepsilon e N_D}{2V_B} \right)^{1/2}$$

SIGNAL = number of electron-hole pairs:

$$n_{e\text{-}h} = DE/W,$$

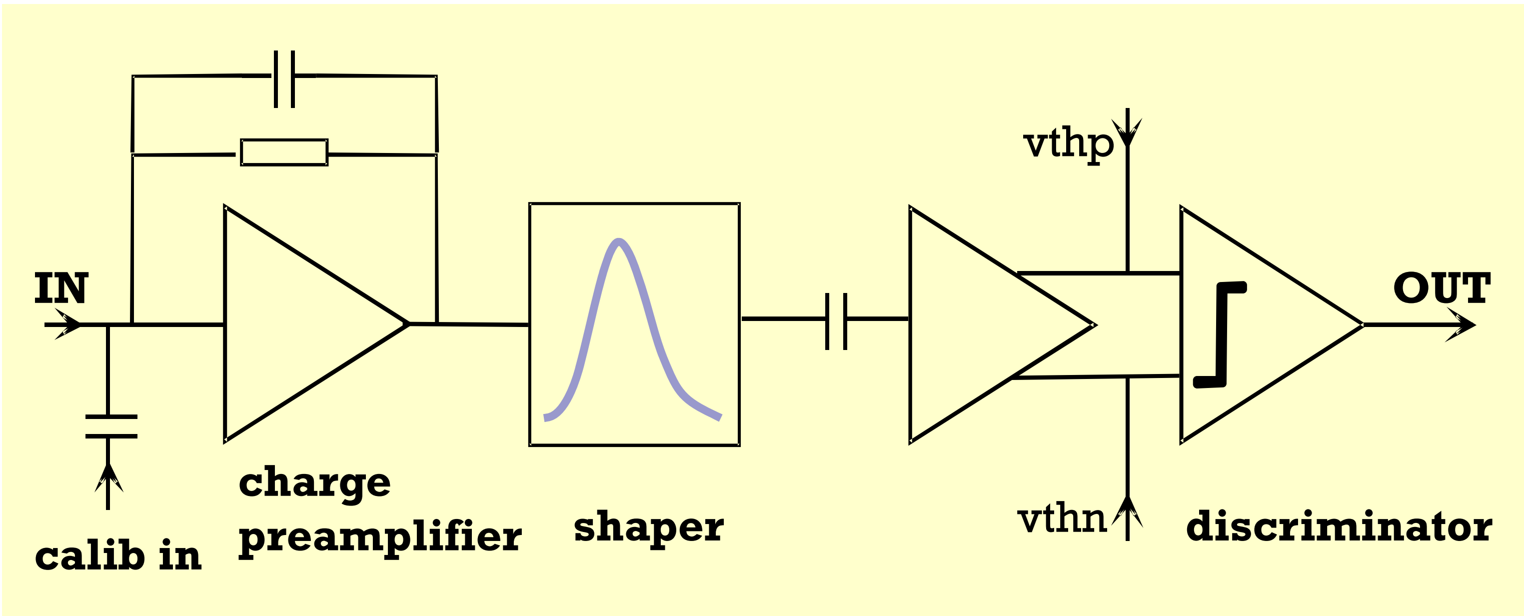
where W=3.62 eV for silicon

REVERSE POLARIZED DIODE

- **Depletion region** => free from charge carriers: e-h pairs may be detected
- **Reverse Bias voltage** (V_B) => controls diode depletion thickness, i.e. active volume
- **p-n junction capacitance** per unit area **C**:

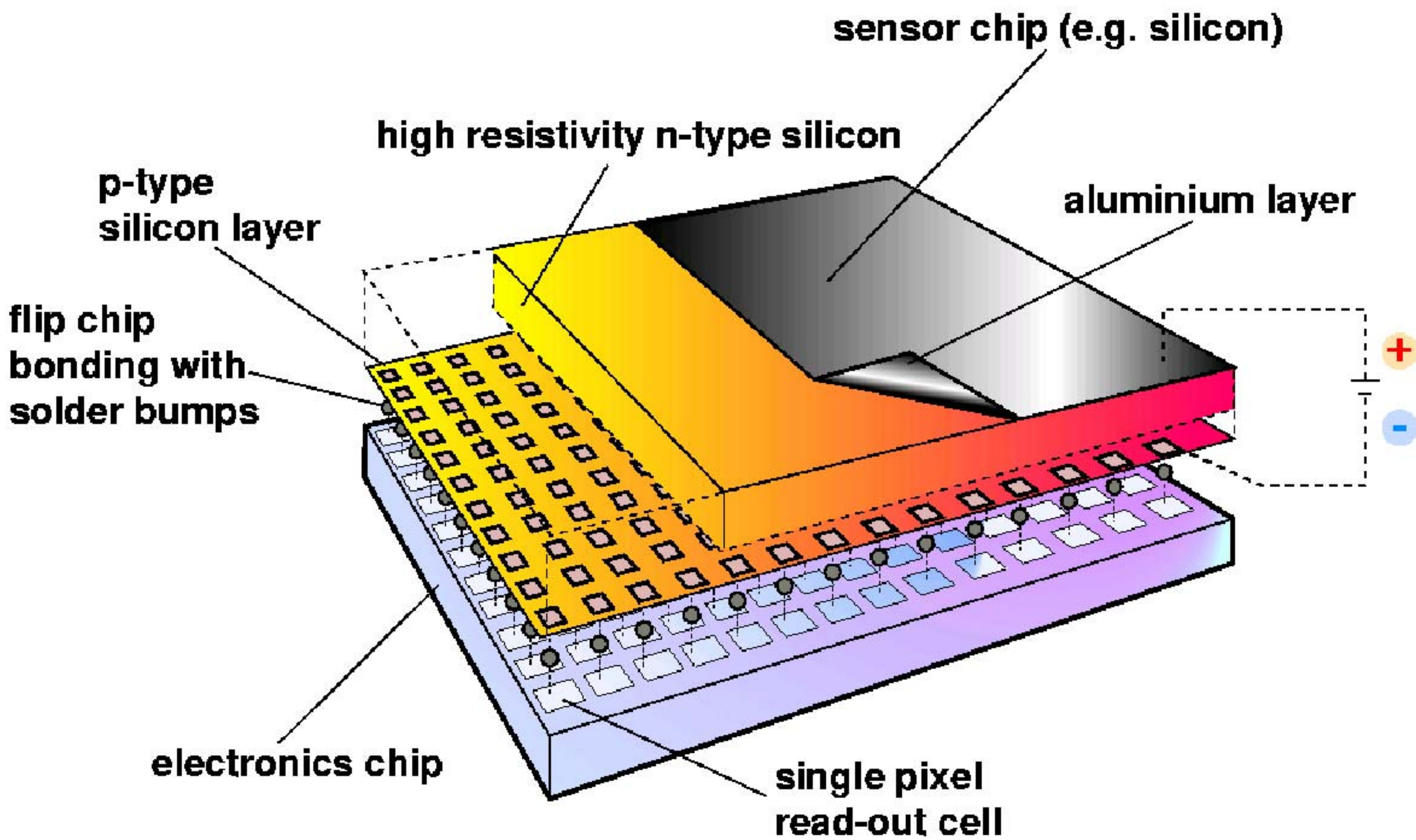
$1/C^2$ grows linearly with V_B =>
C-V measurement determines full depletion voltage V_{FD}

A Readout Chain



- This is just one possibility, the **binary** readout scheme – another one is to put an **ADC** instead of the discriminator, preserving the full analog information

Medipix: Hybrid Pixel Detector



M. Campbell, V. Rosso, Rome IEEE NSS-MIC 2004 conference