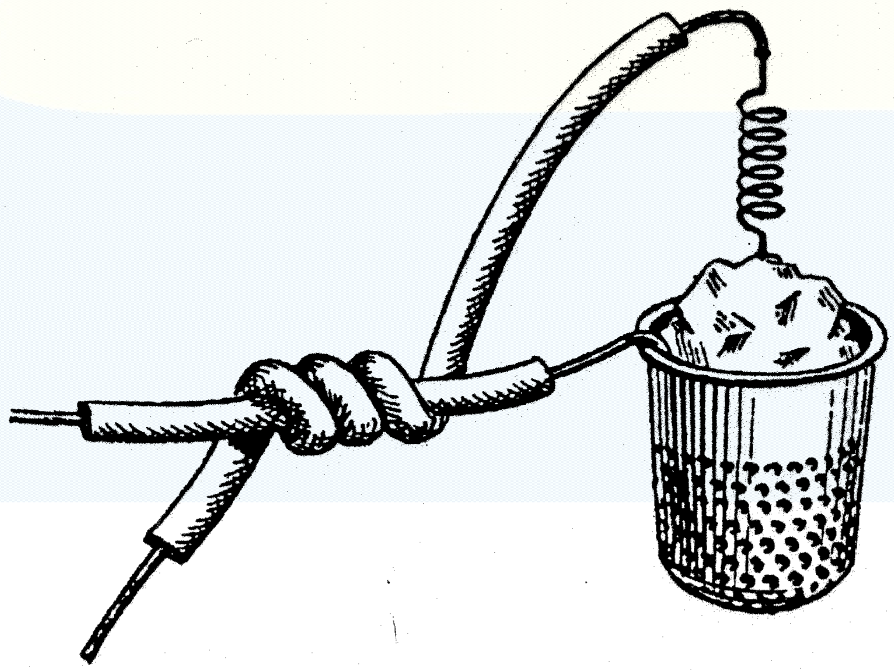
Sensor devices



Outline

- 6 Radiation Sensor
  - Introduction
  - Interaction of radiation with matter
  - Semiconductor physics
  - Semiconductor processing
  - Semiconductor Detectors
  - Photo Detectors

Introduction

- Radiant detectors detect signals originate in atomic or nuclear processes
- The radiation can be of type; electromagnetic, neutrons, kinetic electrons or heavy-charge particles
- Electromagnetic radiation typical
  - **Light (visible, UV, IR)**
  - **X-ray photons “transition of orbital electrons”**
  - **Gamma photons “de excitations processes in nuclei, nuclear reaction and pair production”**

Interaction of radiation with matter

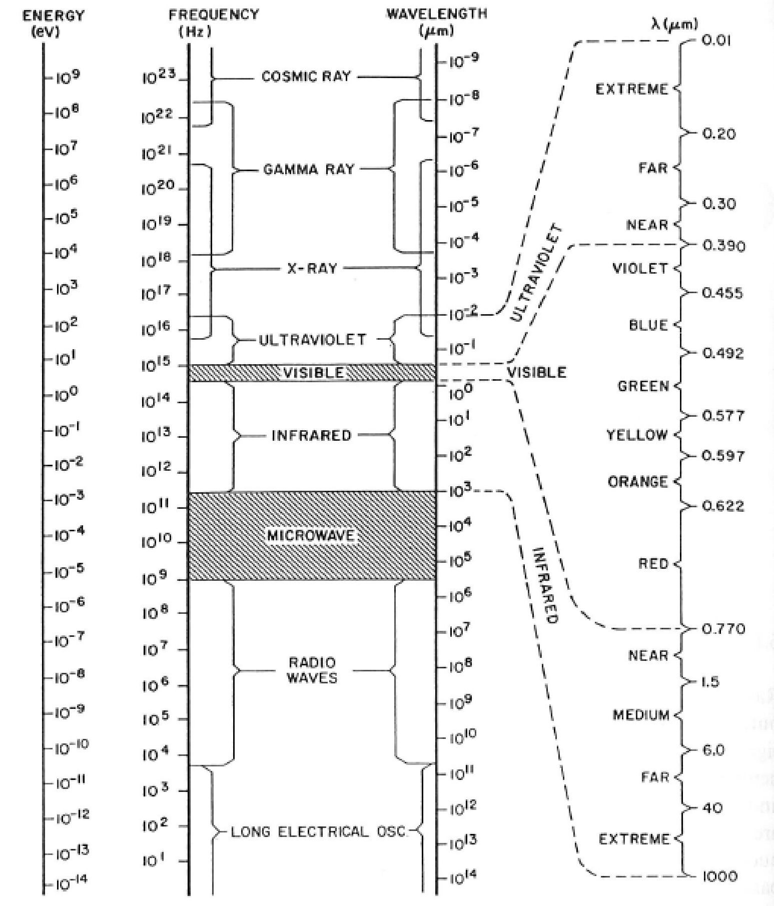


Fig. 1 Chart of electromagnetic spectrum. (After Ref. 4)

Electromanetic spectra

$$E = h\nu.$$

$$h = 6.626 \times 10^{-34} \text{ J-s.}$$

E=energy

ν=frequency

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Interaction of radiation with matter

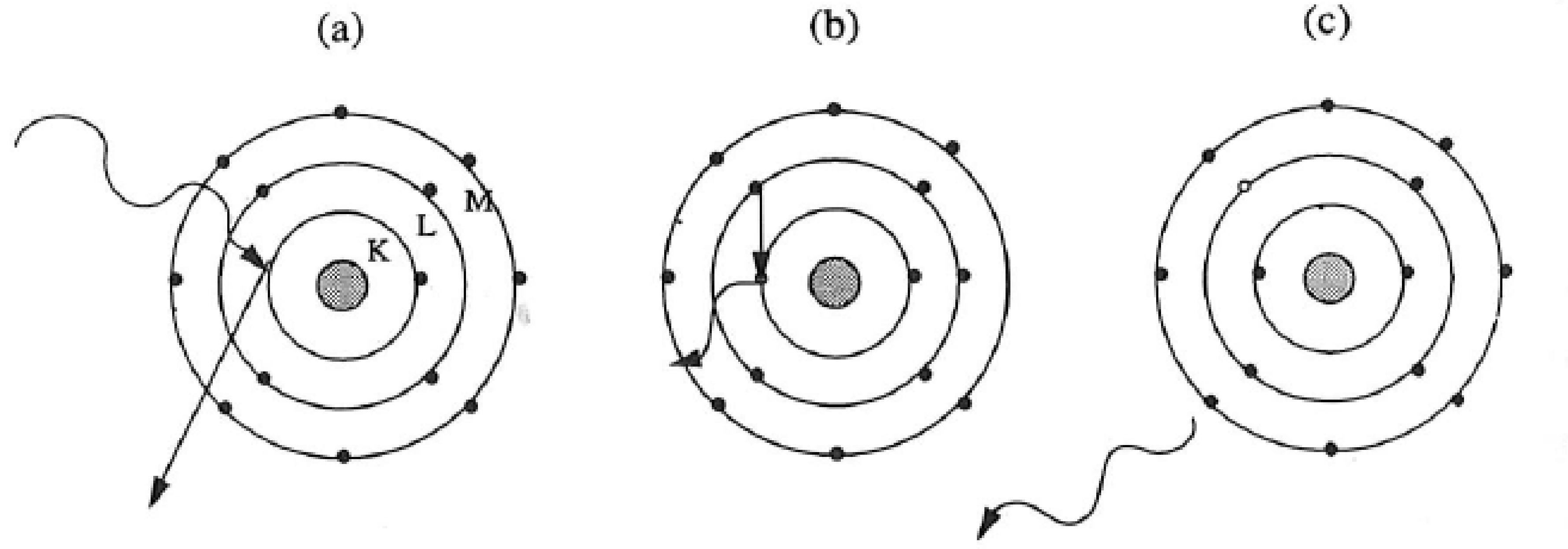
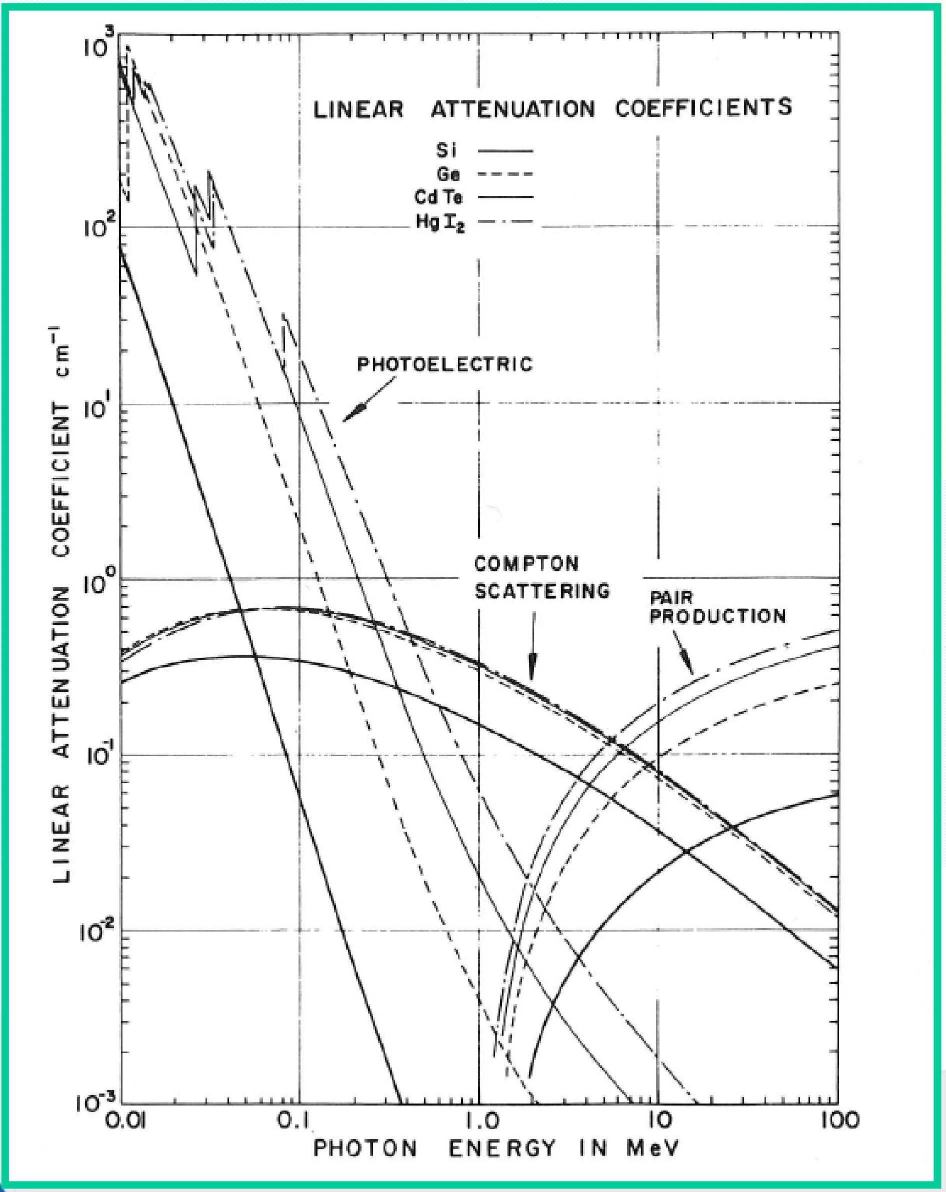


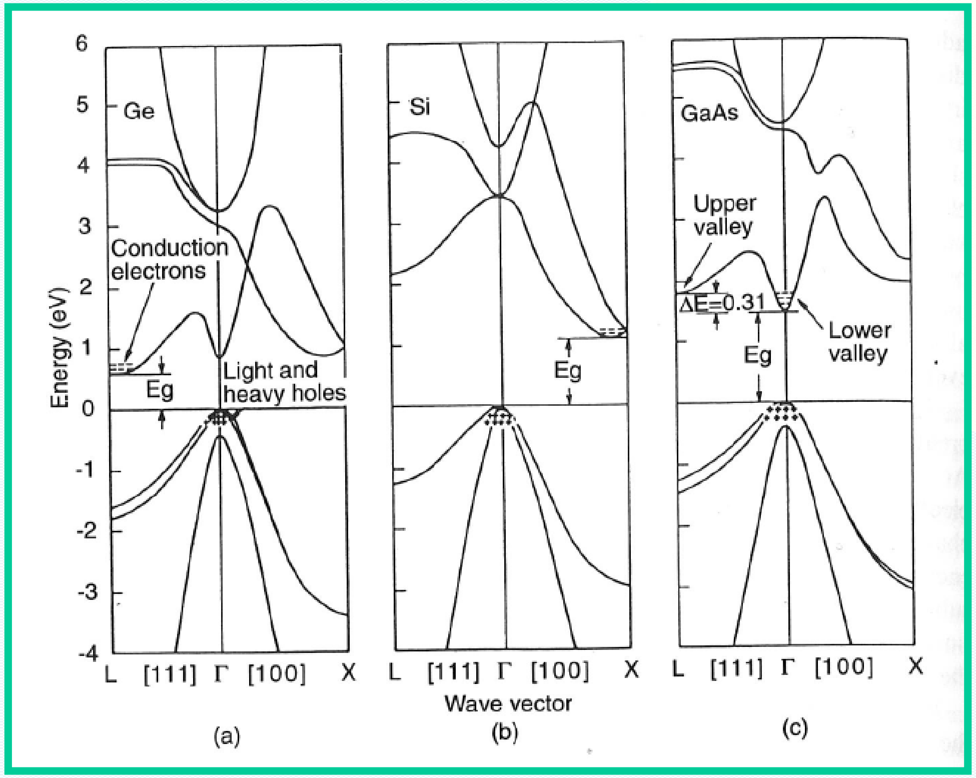
Fig. 2 (a) Incident photon interaction with a K-shell electron. (b) The de-excitation process in which an electron transition occurs from the outer L-shell to the inner K-shell. (c) Emission of a characteristic secondary X-ray photon.

Interaction of radiation with matter



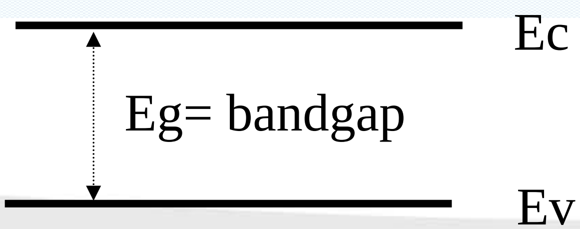
- Absorption processes in semiconductor for higher photon energies
  - **Photoelectric effects**
    - Photon is completely absorbed in one interaction, resulting in an energetic photoelectron
  - **Compton scattering**
    - Photon energy is partly transferred to a recoil electron and a lower energetic scatter photon
  - **Pair production**
    - Energy exceeding rest mass of an electron, 1.02 MeV. A electron-positron pair is created. General two annihilation photons are generated caused by the absorption of positron.

Interaction of radiation with matter

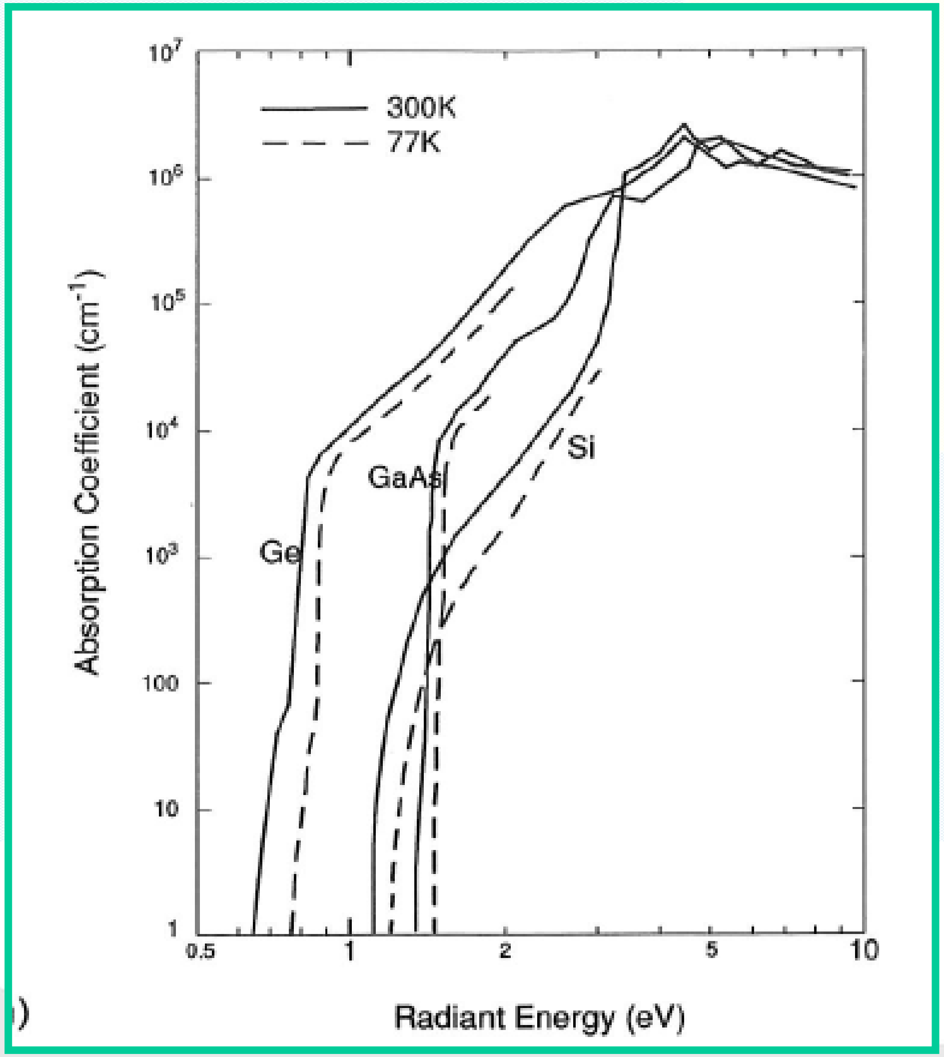


- One atom have a nuclei with orbital electrons. The energy levels describing the orbital electrons are discrete.
- When several atoms are ordered in a lattice, as in silicon, the discrete energies are combined into energy bands. The energy bands have normally a complicated structure as can be seen in the figure (green).
- Conduction band host free electrons and valence band host free positive charges "holes"

Simplified band structure



Interaction of radiation with matter



- Depending of the properties of the band structure the absorption of a “low” energy photon is strongly depended of the energy
- The lowest photon energy which can be detected is equal with the energy –bandgap. Si Eg=1.12 eV, Ge Eg=0.67eV, GaAs, Eg=1.42 eV
- At lower energy one photon generate one e/h-pair, when the energy increase ~3 times the energy bandgap, impact ionisation result in more than one e/h pair generation

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Interaction of radiation with matter

Ionised particle stopping mechanism

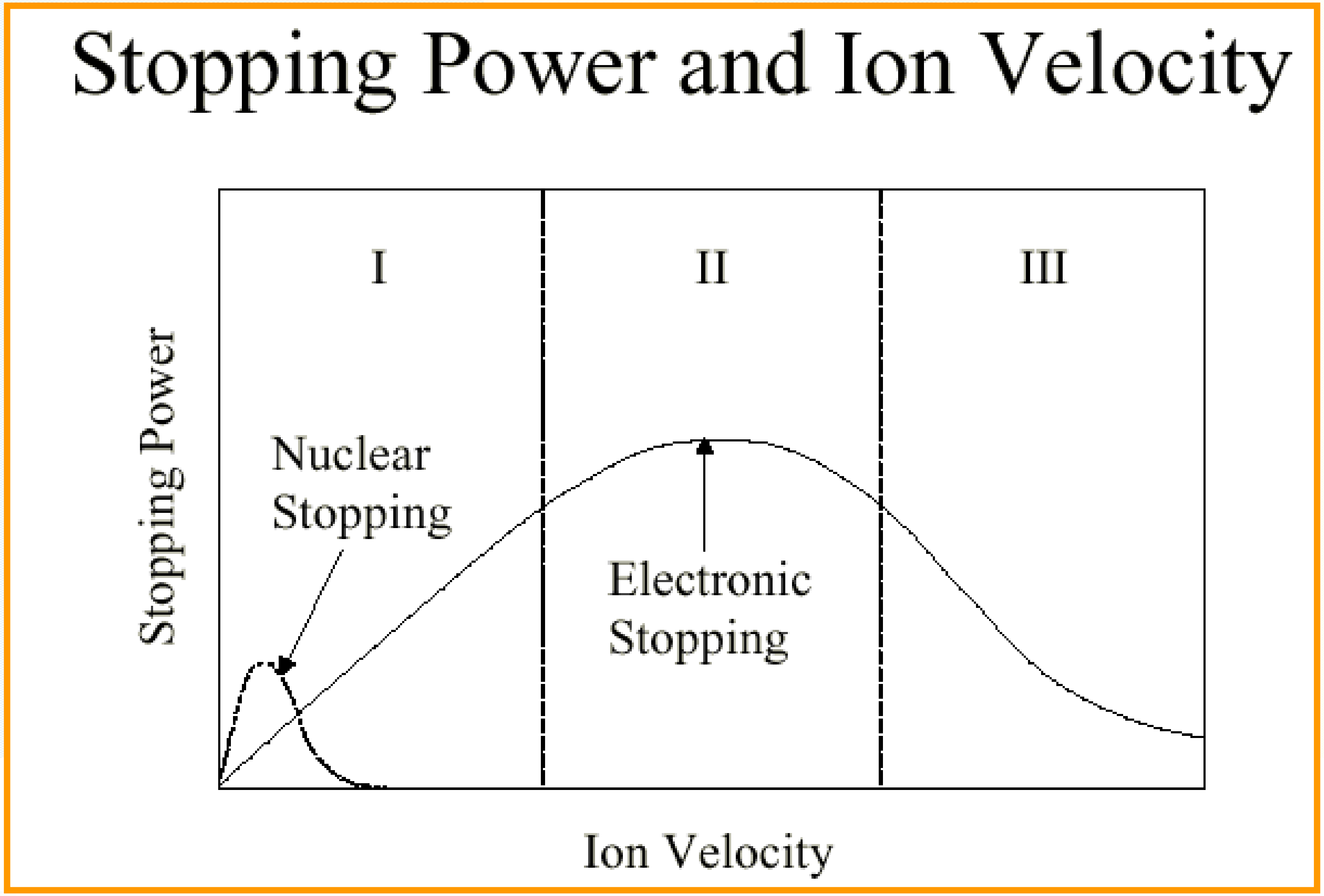
Stopping Mechanism

- The total stopping power

$$S_{total} = S_n + S_e$$

- S_n: nuclear stopping, S_e: electronic stopping
- Low E, high A ion implantation: mainly nuclear stopping
- High E, low A ion implantation, electronic stopping mechanism is more important

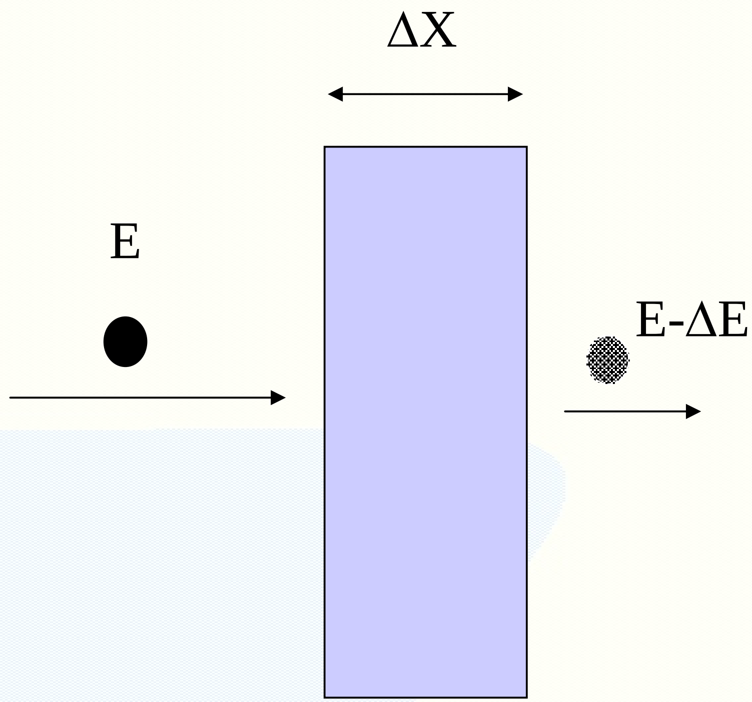
Interaction of radiation with matter



Interaction of radiation with matter

$$\frac{dE}{dx} = \left.\frac{dE}{dx}\right|_e + \left.\frac{dE}{dx}\right|_n$$

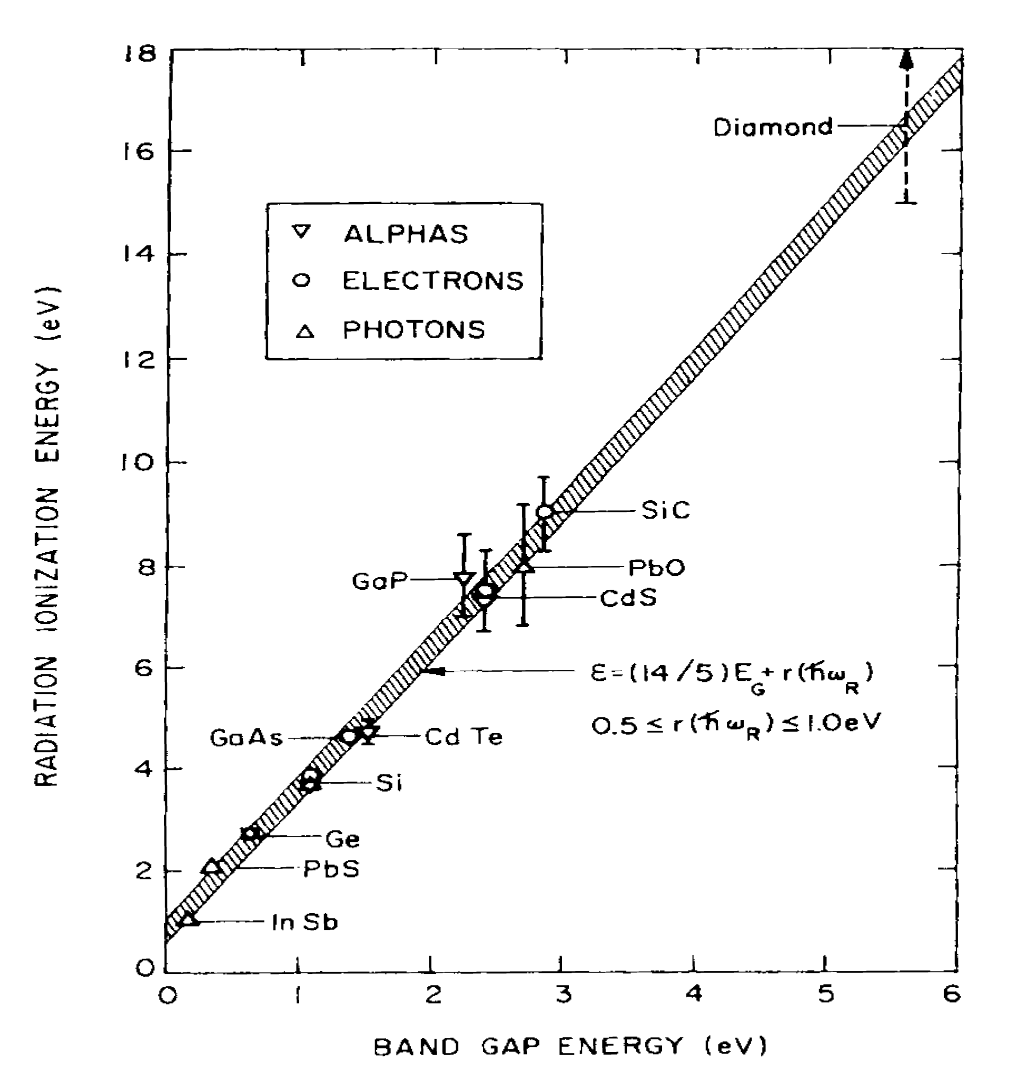
$$\Delta E = \int_0^{\Delta x} \left(\frac{dE}{dx} \right) dx$$



Simulation of stopping power can be done with SRIM software “SRIM.org”

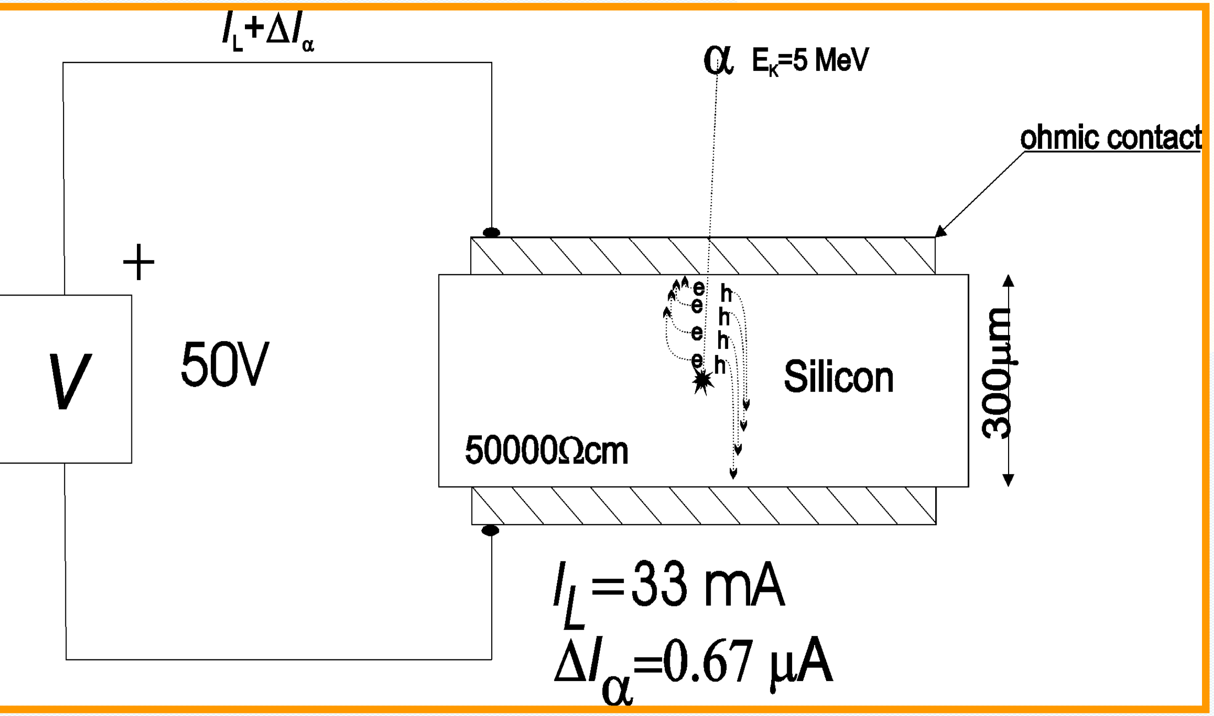
Interaction of radiation with matter

- Ionisation of semiconductor
  - **Particle and high energy photons (x-ray,gamma) result in an generation of one e/h-pair /~3Eg**
  - **For silicon is needed 3.6eV to generate one e/h-pair**

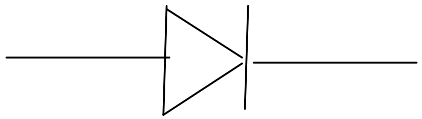


– **Picture; C. A. Klein, J. Appl. Phys.,** 39**, No.4, 2029, (1968)**

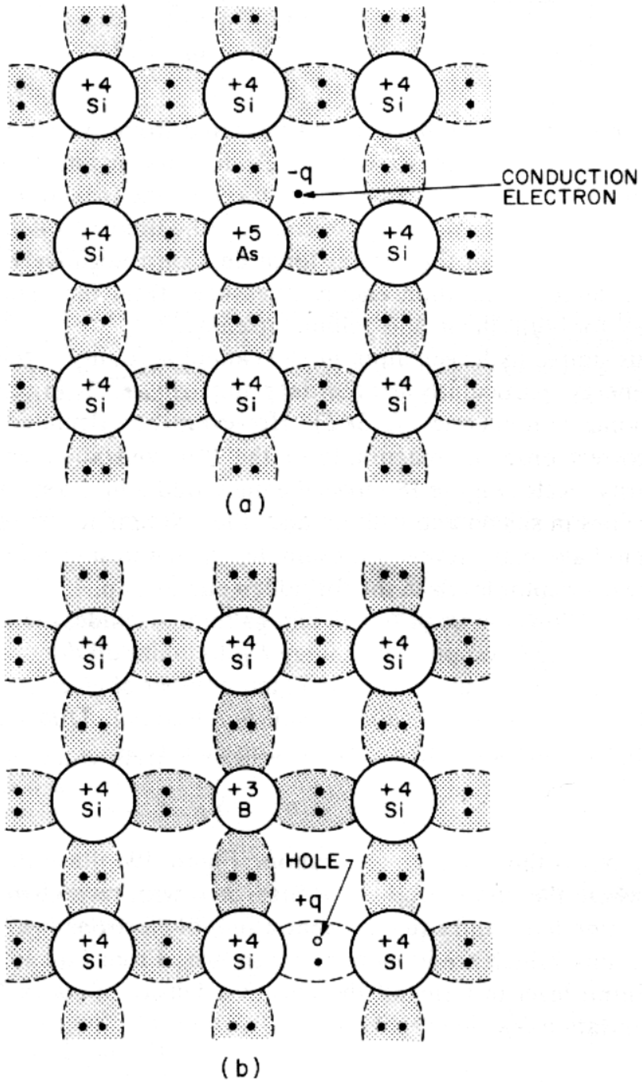
Interaction of radiation with matter



- Detection of radiation
- Necessary properties of a detector
- Normally is the produced excess charge to small compared to the leakage current. Therefore a blocking contact must be introduced

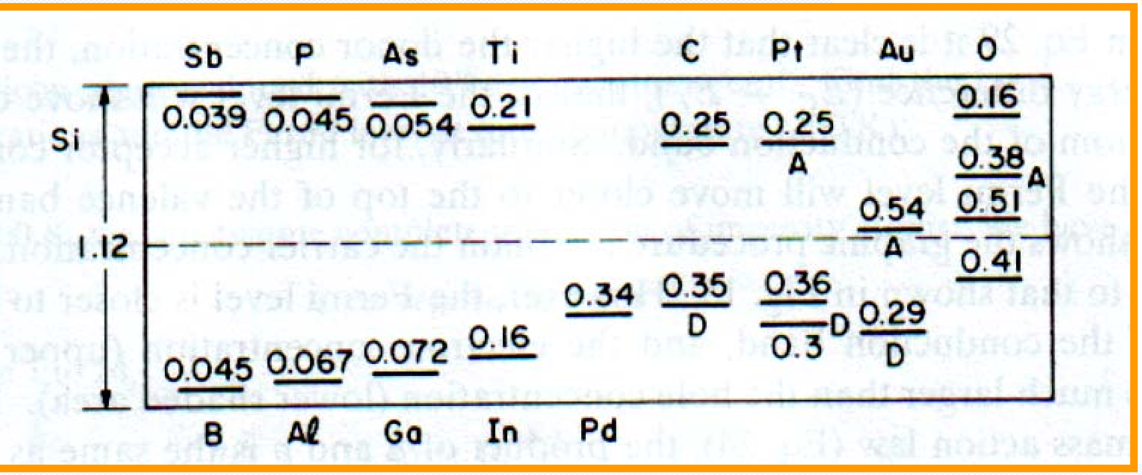


Semiconductor physics

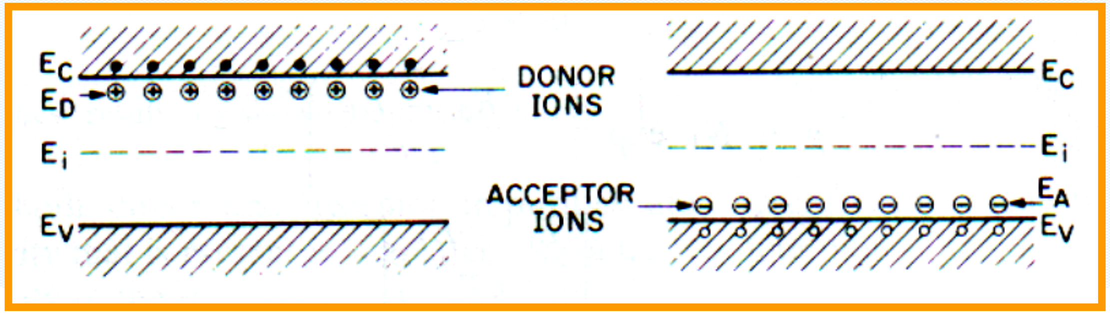


- Doping
  - N type ”free electron”
  - P type “lost of a valence electron”

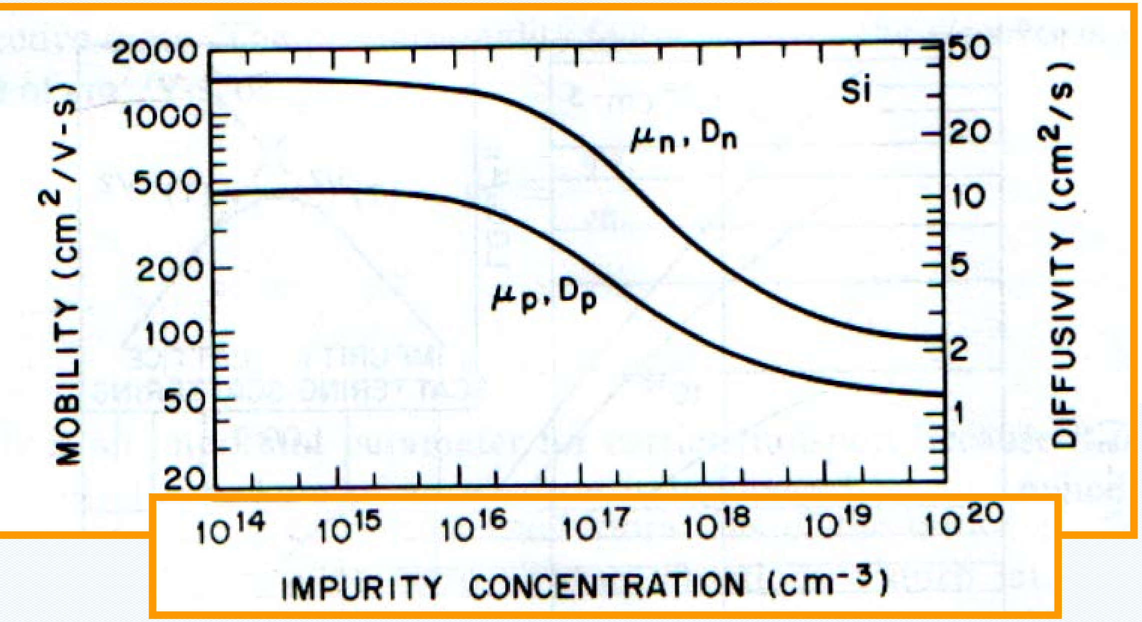
Semiconductor physics



- Energy band gap
  - **Levels of some donors and acceptor ions**



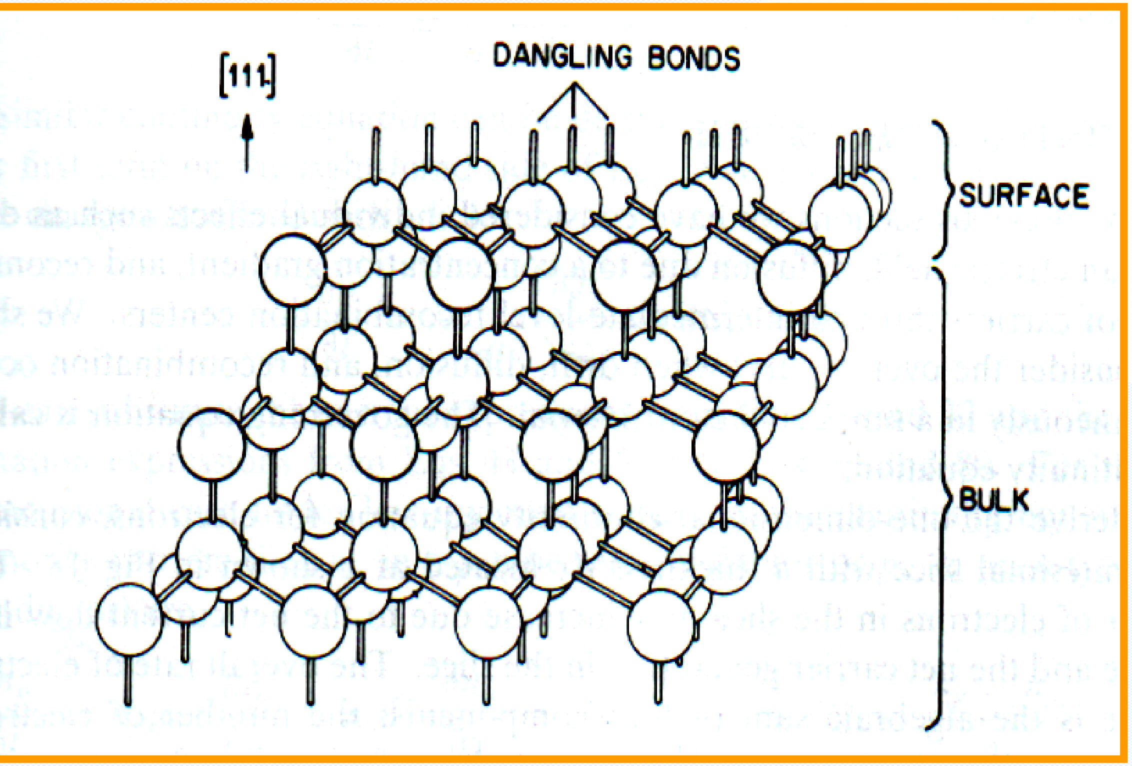
Semiconductor physics



Mobility as a function of impurity concentration

Semiconductor physics

Silicon surfaces, dangling bonds



Semiconductor physics

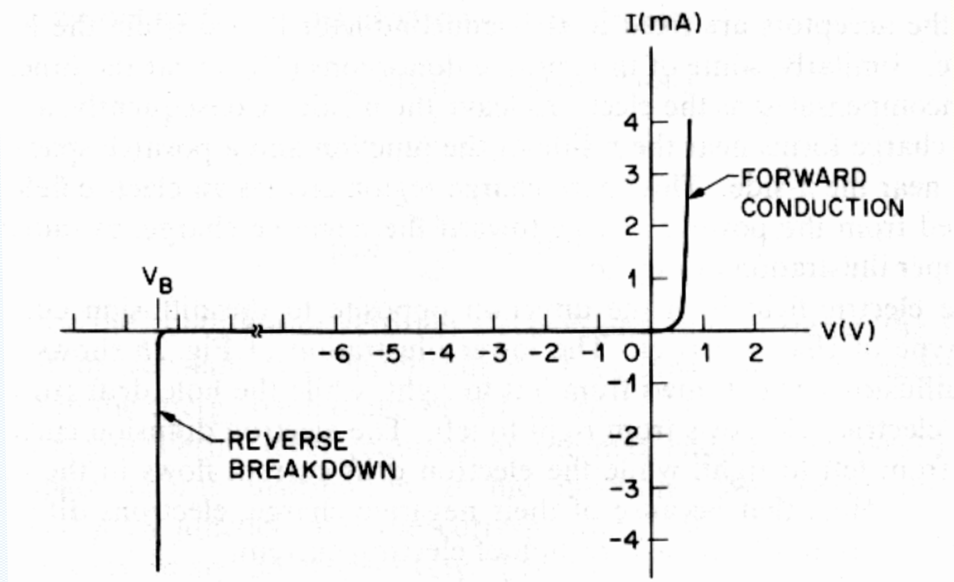
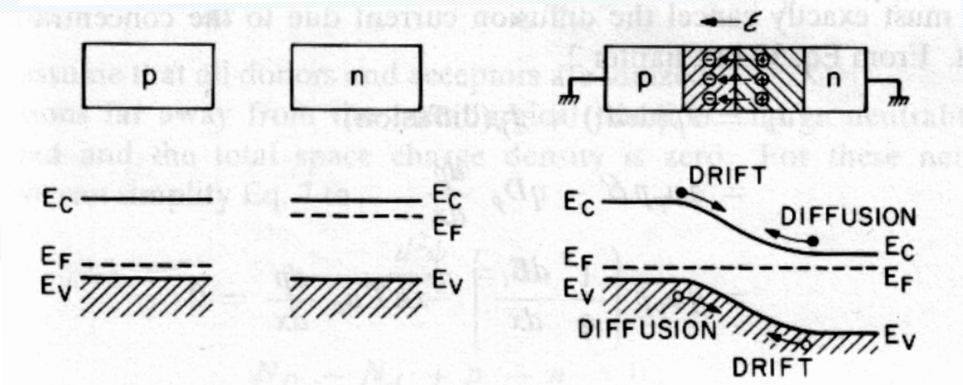
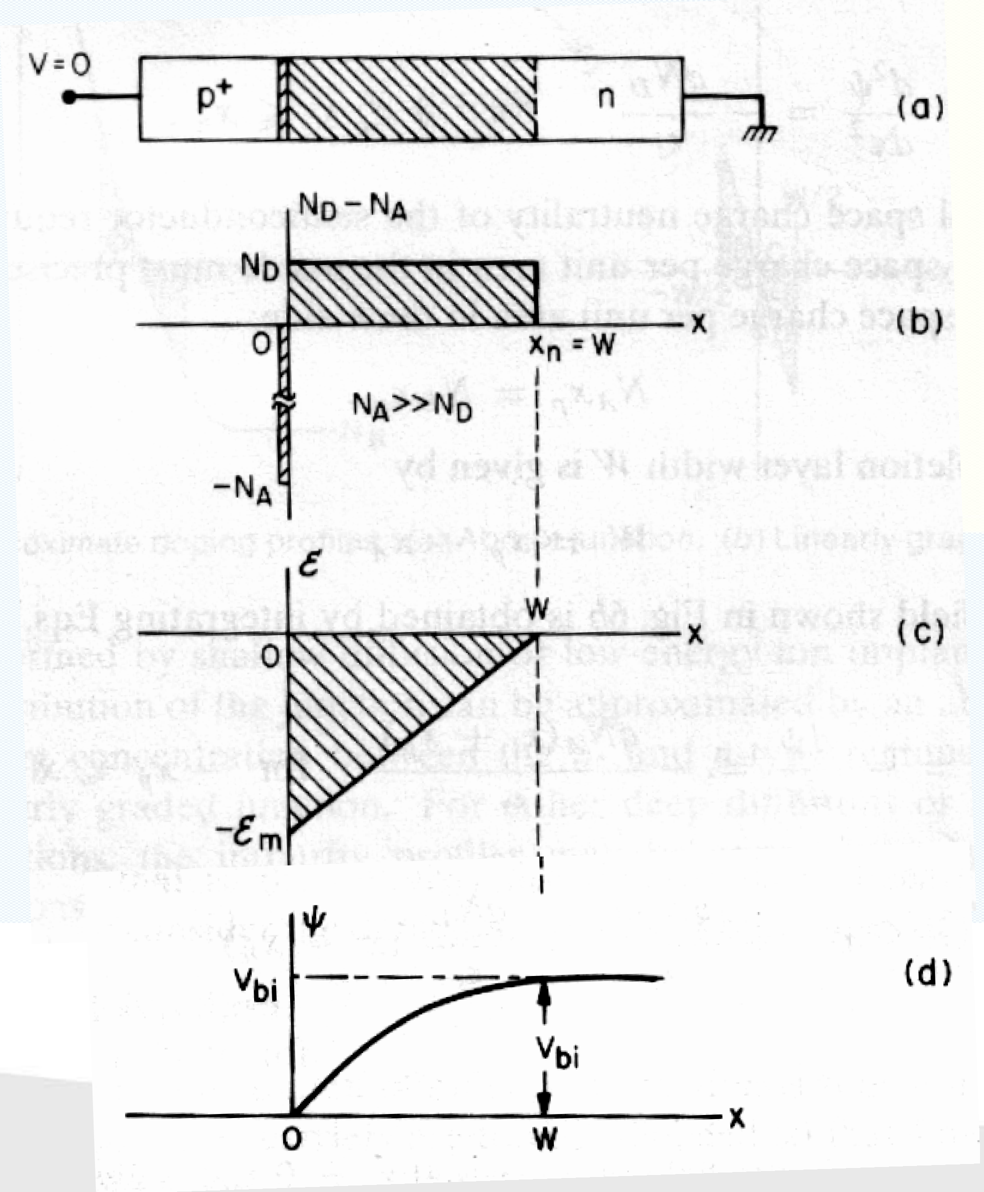


Fig. 1 Current–voltage characteristics of a typical silicon *p*–*n* junction.



- Basic properties diode
  - **Expected IV-characteristic**
  - **Formation of a 1-dim. diode**

Semiconductor physics



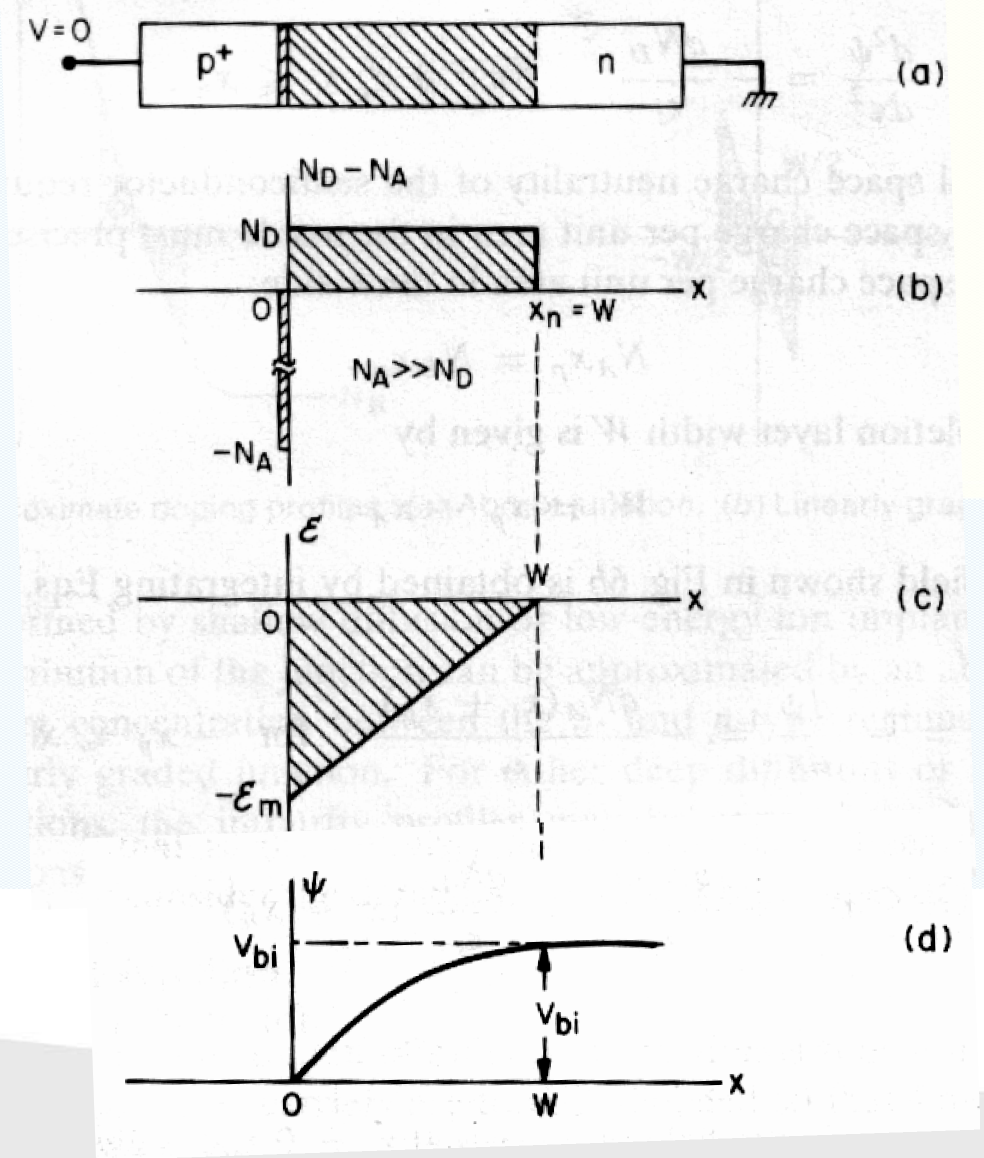
Abrupt junction one side heavily doped

$$W = \sqrt{\frac{2\epsilon_s}{q}\left[\frac{N_A + N_D}{N_A N_D}\right] V_{bi}}\ .$$

Result in

$$W \simeq x_n = \sqrt{\frac{2\epsilon_s V_{bi}}{q N_D}}\ .$$

Semiconductor physics



Abrupt junction one side heavily doped

$$W = \sqrt{\frac{2\epsilon_s}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)V_{bi}}\ .$$

Result in

$$W \simeq x_n = \sqrt{\frac{2\epsilon_s V_{bi}}{qN_D}}\ .$$

Semiconductor physics

$$C_j \equiv \frac{dQ}{dV} = \frac{dQ}{W\dfrac{dQ}{\epsilon_s}} = \frac{\epsilon_s}{W} \qquad \mathrm{F/cm^2}.$$

Capacitance of a diode

$$C_j = \frac{\epsilon_s}{W} = \sqrt{\frac{q\epsilon_s N_B}{2(V_{bi} - V)}}$$

$$\frac{1}{C_j^2} = \frac{2(V_{bi} - V)}{q\epsilon_s N_B}.$$

Capacitance versus voltage, one side abrupt junction

$$N(W) = \frac{2}{q\epsilon_s}\left[\frac{1}{d(1/C_j^2)/dV}\right].$$

Doping concentration versus depletion width

Semiconductor physics

$$J = J_p(x_n) + J_n(-x_p) = J_s(e^{qV/kT} - 1)$$

$$J_s \equiv \frac{qD_p p_{no}}{L_p} + \frac{qD_n n_{po}}{L_n}$$

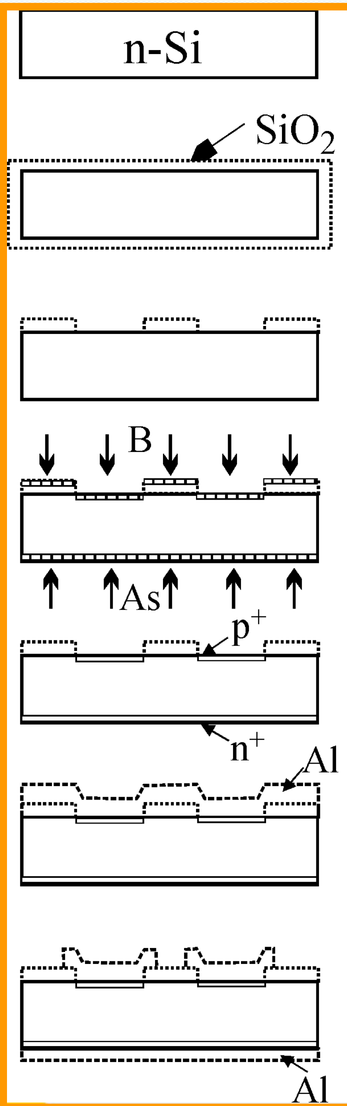
$$J_R \simeq q\sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_D} + \frac{qn_i W}{\tau_g}.$$

$$J_F = q\sqrt{\frac{D_p}{\tau_p}}\frac{n_i^2}{N_D}e^{qV/kT} + \frac{qWn_i}{2\tau_r}e^{qV/2kT}.$$

$$J_F \sim \exp\left(\frac{qV}{\eta kT}\right)$$

- IV characteristic
  - –**Ideal diode equation**
  - –**Reverse current, contribution from generation of carrier, abrupt junction p$^+$n**
  - –**Forward current, diffusion + recombination**
  - – **n ideal factor, n=1 diffusion, n=2 recombination, 1<n<2 !**

Semiconductor Processing



n-Si Wafer

Oxide passivation

Opening of windows

Doping by ion implantation
B 15 keV $5x10^{14}$ cm^{-2}
As 30 keV $5x10^{15}$ cm^{-2}

Annealing at $600^{o}C$, 30 min

Al metallisation

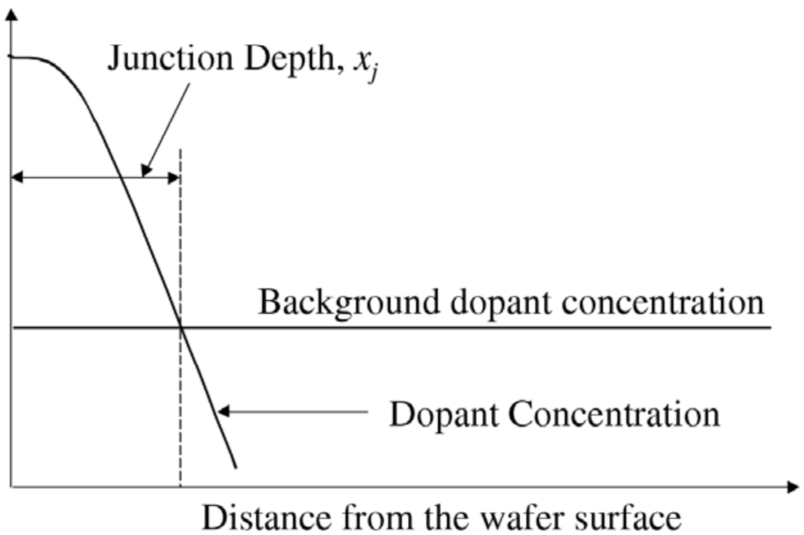
Al pattering at the front
Al-rear contact

- Passivated, silicon planar diode detector
- Almost operated with reverse bias voltage, (except photodiodes normally operated with zero bias voltage)

- J. Kemmer, Nucl. Instr. and Meth. **226**, 45, (1984)

Semiconductor Processing

Definition of Junction depth



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Semiconductor Processing

Basic diffusion

Constant surface-concentration

$$C(x,t) = C_s erfc\left[\frac{x}{2\sqrt{Dt}}\right]$$

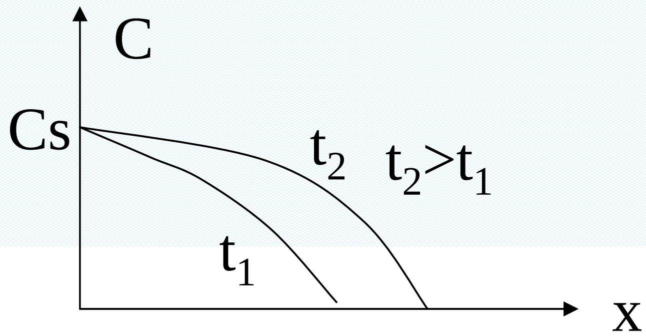
D= Diffusion coefficient (cm^2/s)

t=time (s)

t=0 C(x,0)=0

boundary conditions: C(0,t)=Cs where Cs=surface-concentration (cm^{-3})

C(∞,t)=0 ”at large depth”



Semiconductor Processing

Constant dose (quantity)

$$C(x,t) = \frac{S}{\sqrt{\pi D t}} \exp\left[-\frac{x^2}{4Dt}\right]$$

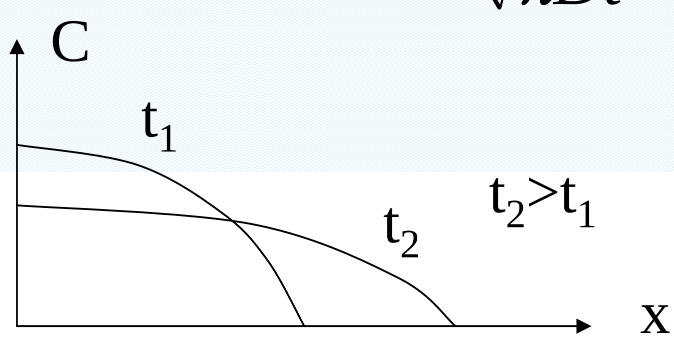
S= dopants per surface unit (cm^{-2})

boundary conditions : $\int_0^\infty C(x,t)\,dx = S$

$$C(\infty,t) = 0$$

x=0 lead to $C_s(t) = \frac{S}{\sqrt{\pi D t}}$

t increase, Cs decrease Cs !



Equal Area below the curves

Semiconductor Processing

Diffusion coefficient

$$D = D_0 \exp\left[-\frac{E_a}{kT}\right]$$

T= temperature in Kelvin

k=8.617·10^{-5} (eV/K) ”Boltzmans-constant”

E_a= activation energy (eV)

D_0= Diffusion coefficient

extrapolated for infinity temperature

D is the intrinsic diffusion coefficient and is valid when $C<n_i$

n_i=intrinsic charge carrier concentration for a specified temperature.

When $C>=n_i$ then D is extrinsic diffusion

Semiconductor Processing

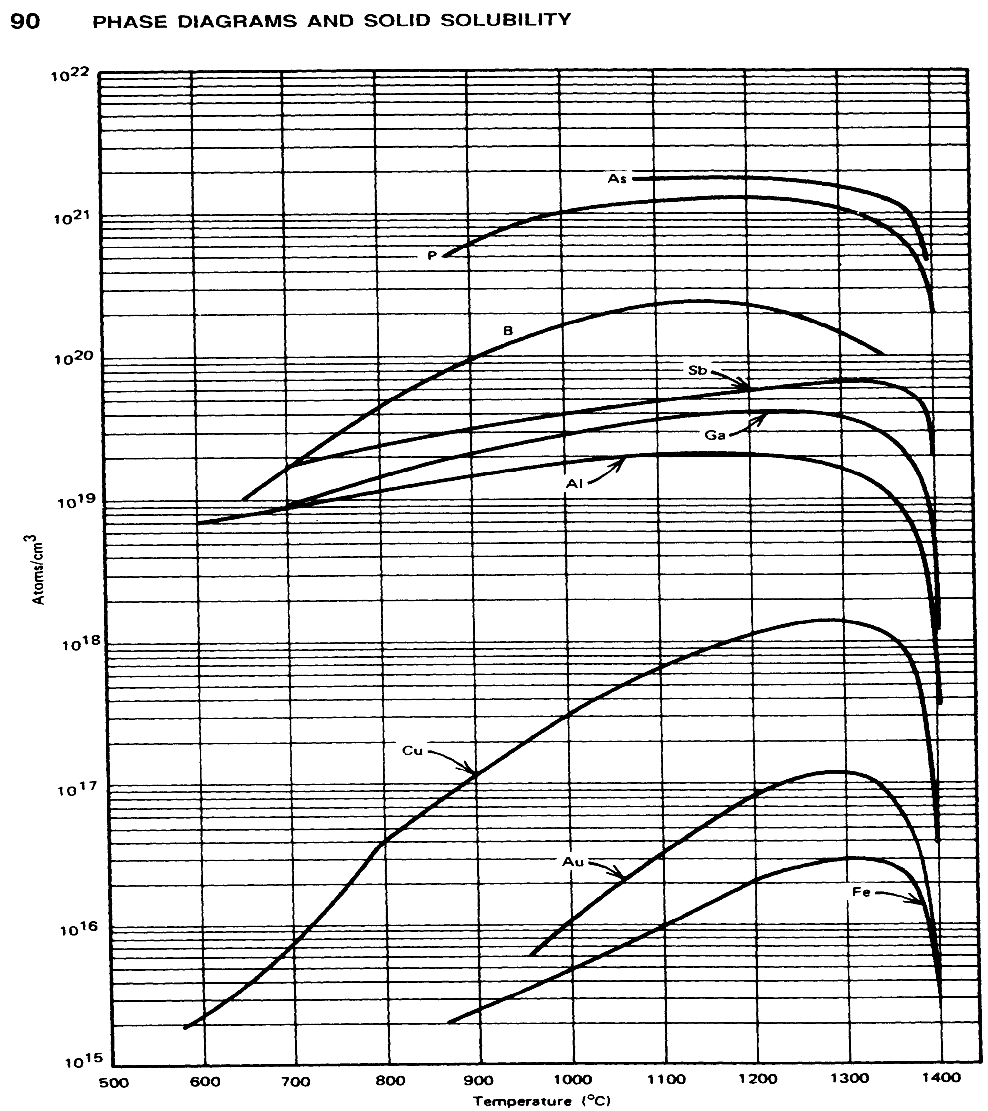
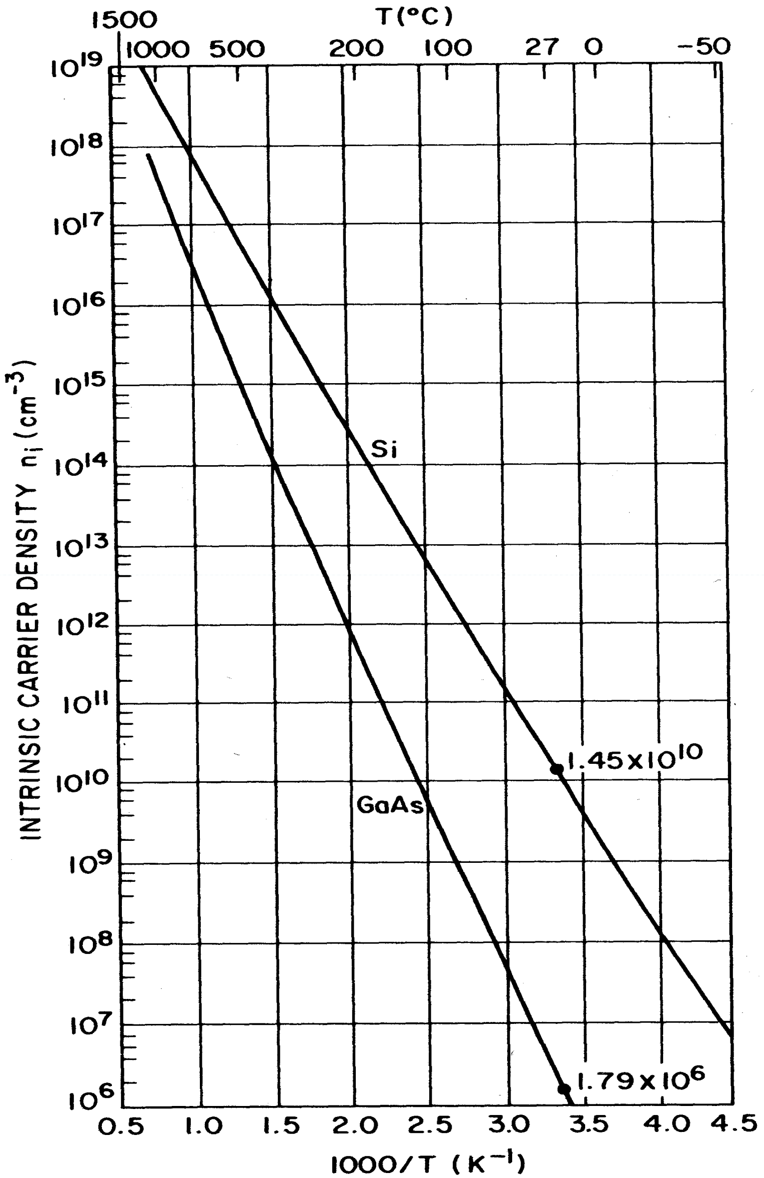


Fig. 2.20 The solid solubility of impurities in silicon.

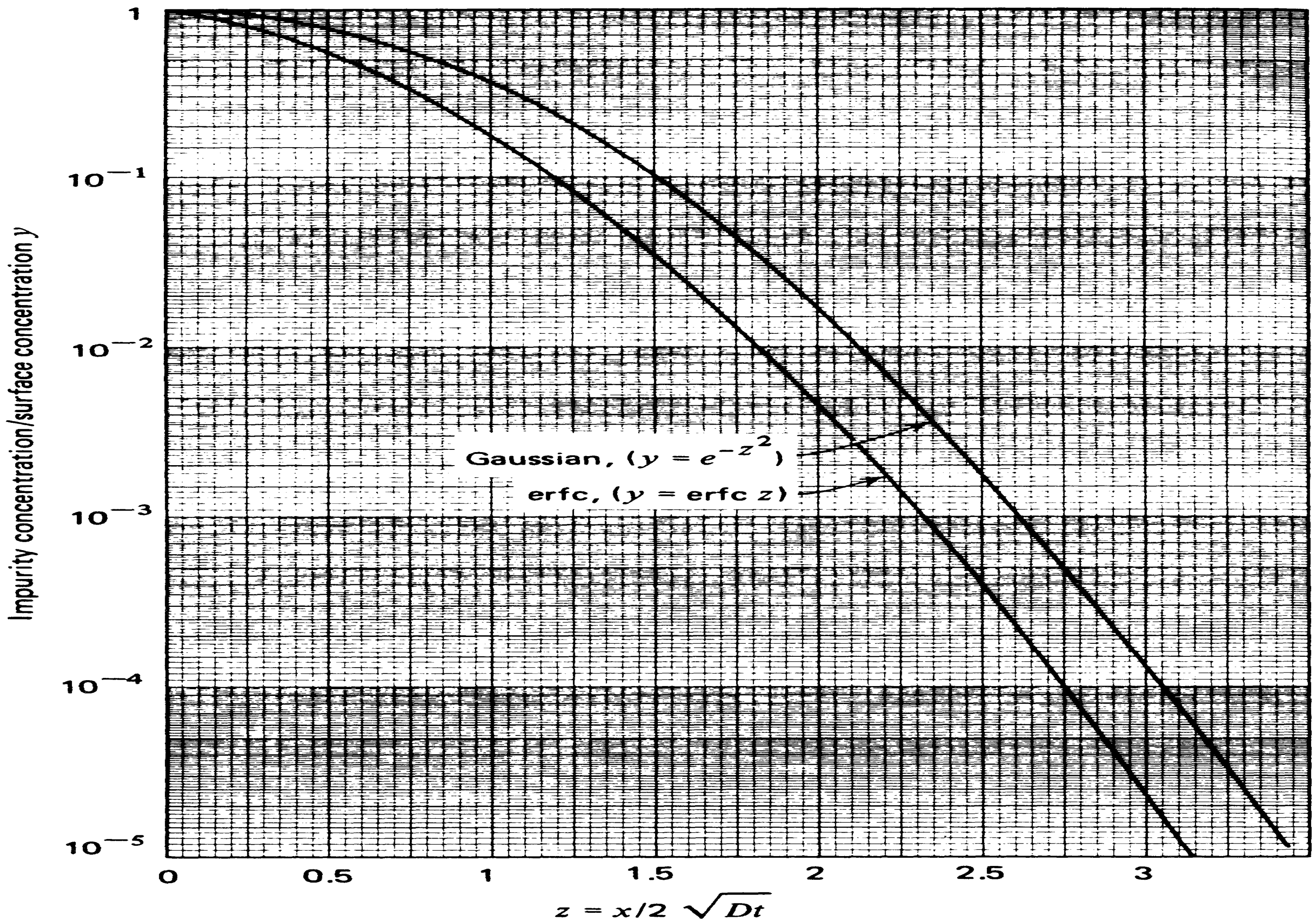
Solid solubility

Semiconductor Processing



Intrinsic carrier concentration

Semiconductor Processing



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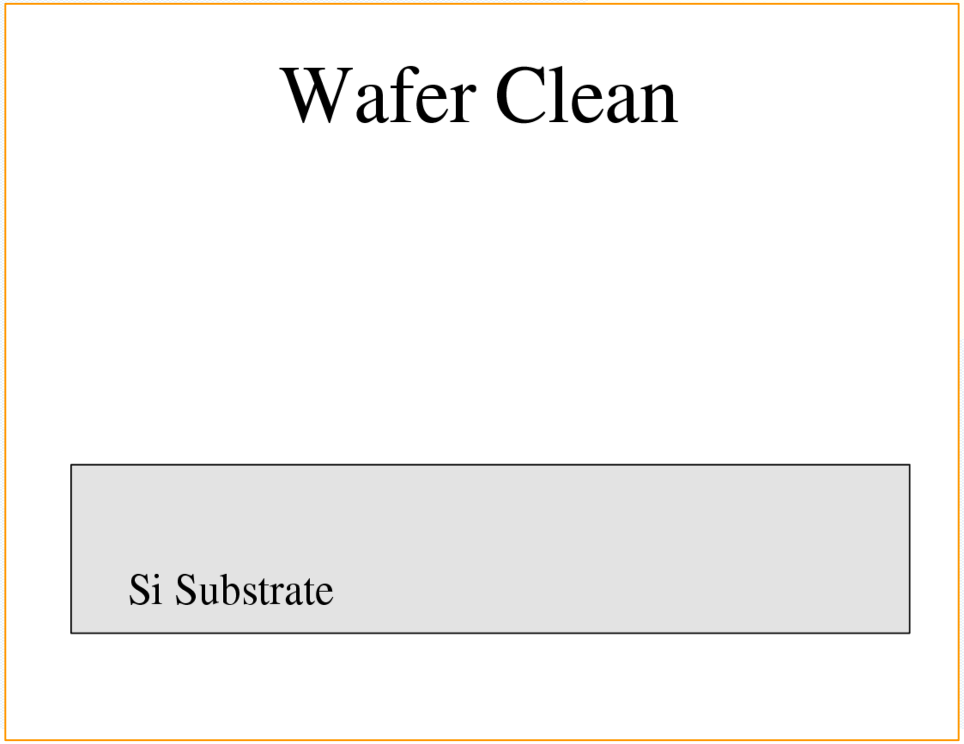
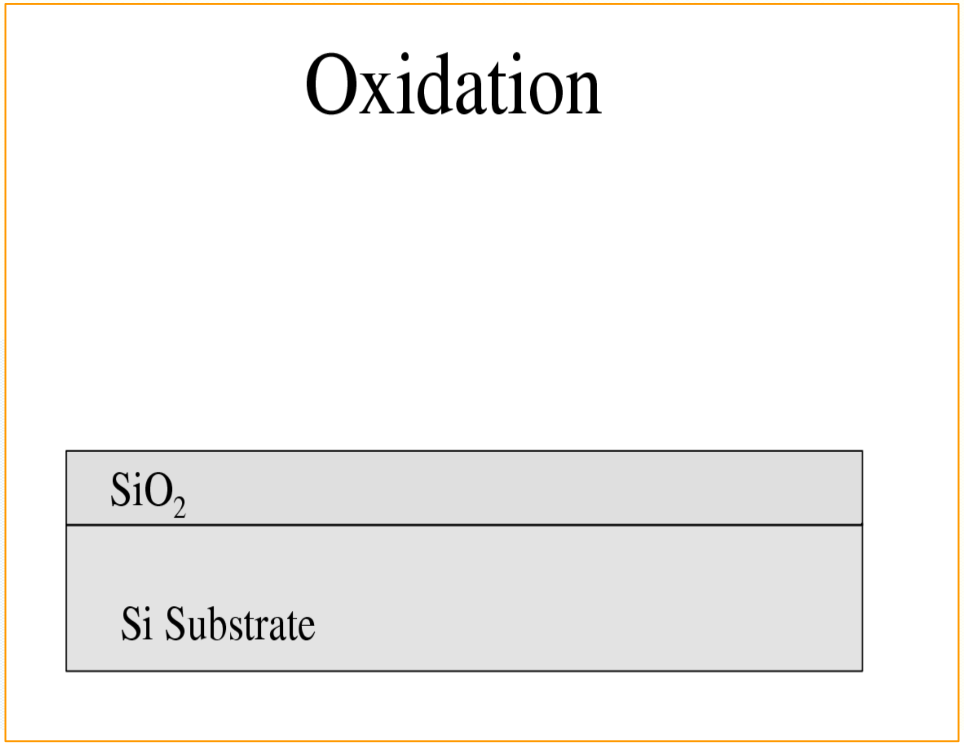
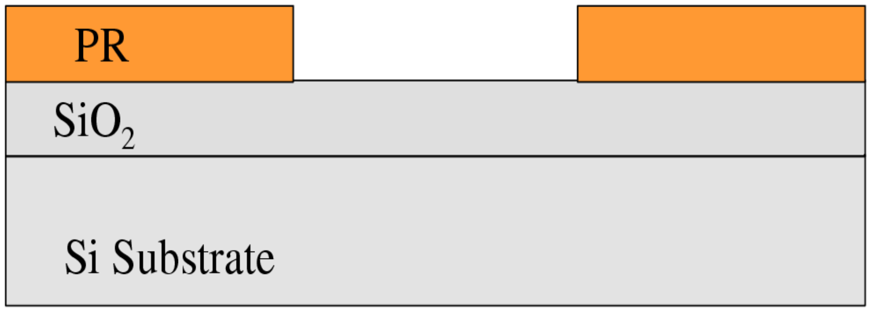
Semiconductor Processing



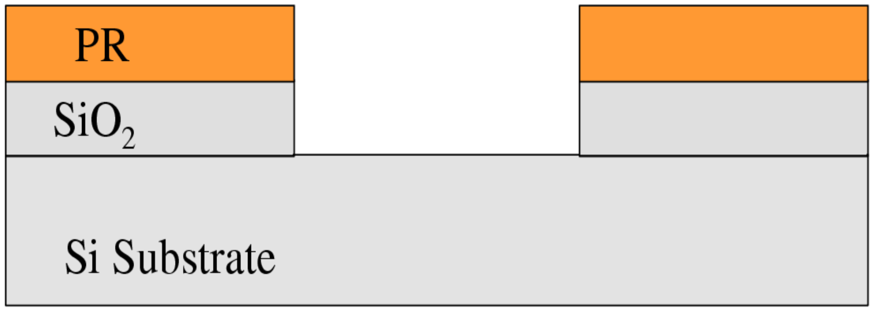


Semiconductor Processing

Doped Area Patterning

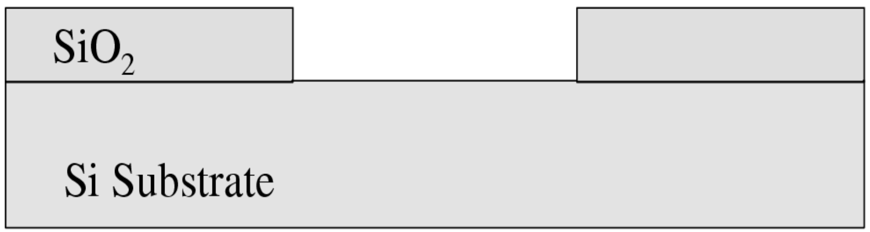


Etch Silicon Dioxide

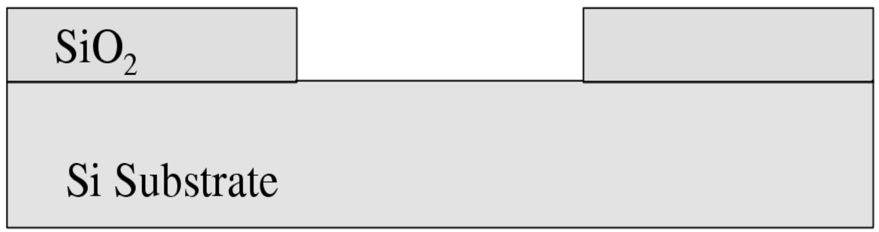


Semiconductor Processing

Strip Photoresist

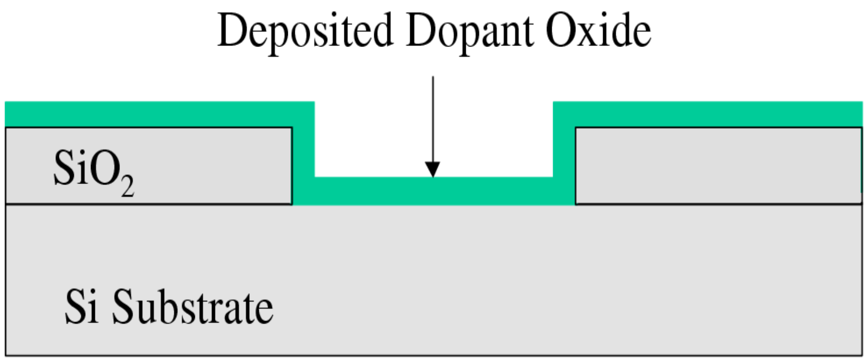


Wafer Clean

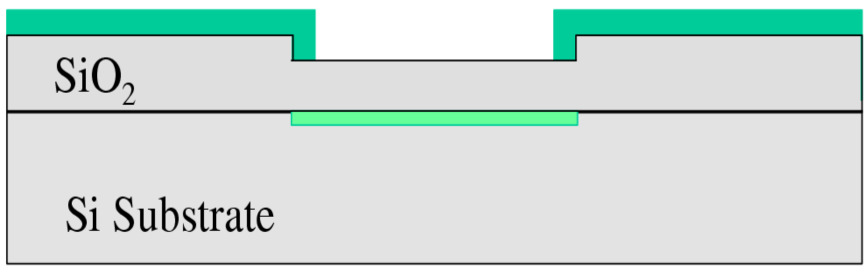


Semiconductor Processing

Dopant Oxide Deposition

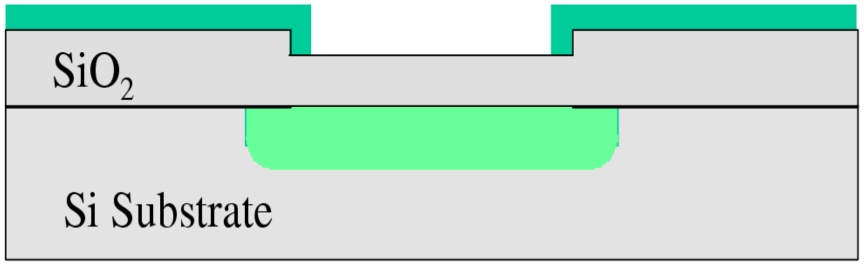


Cap Oxidation

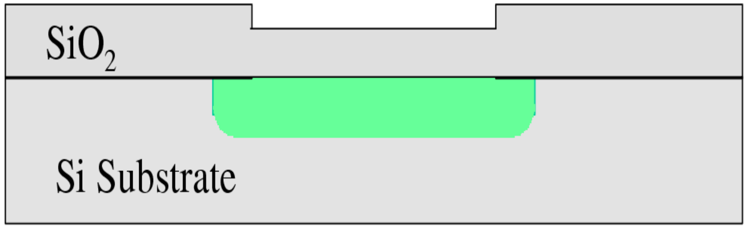


Semiconductor Processing

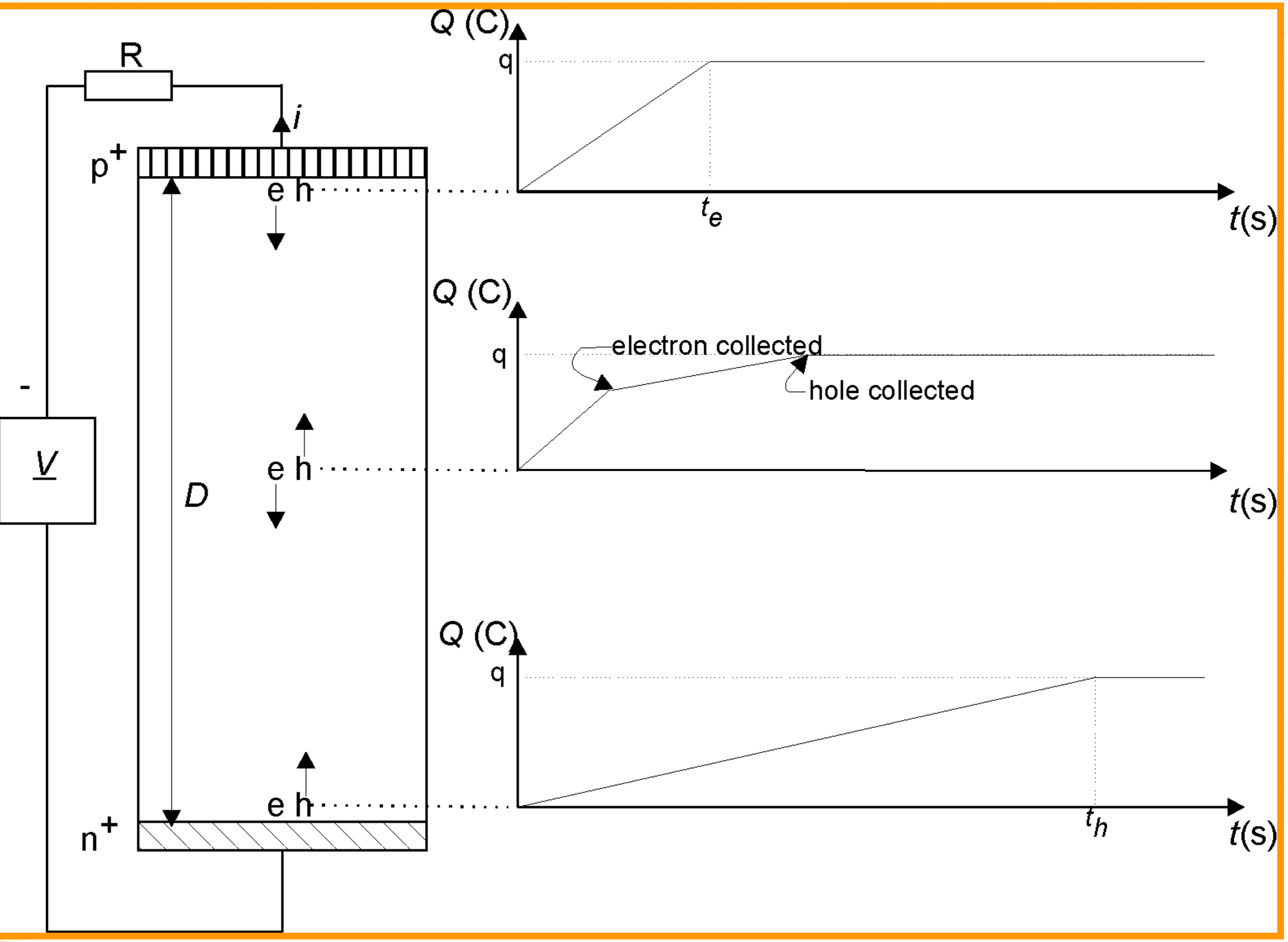
Drive-in



Strip Oxide, Ready for Next Step



Semiconductor Detector

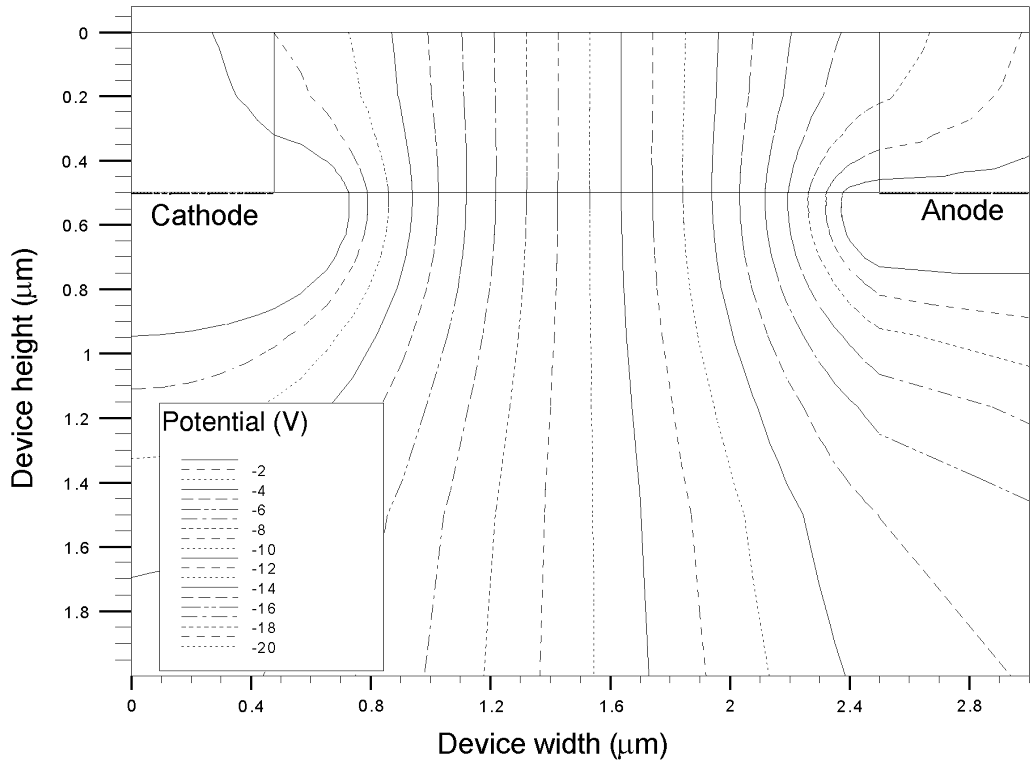


- Drift of generated carrier in the detector

$$v = \mu \cdot \overline{E} \quad \text{for } v<vs$$

- Fast current pulse-high electric field in the detector
- High mobility for holes and electrons
- The mobility for holes are in most cases lower than electrons.

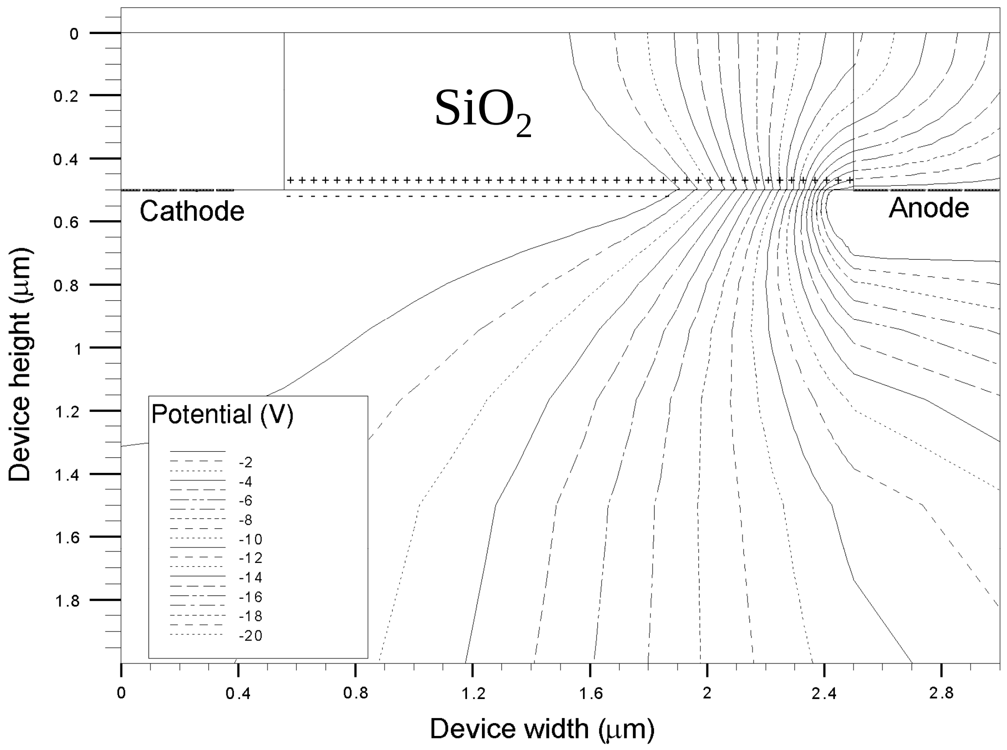
Semiconductor Detector



High reverse bias in the detector generate high electric field

Reverse bias 20 V

Semiconductor Detector

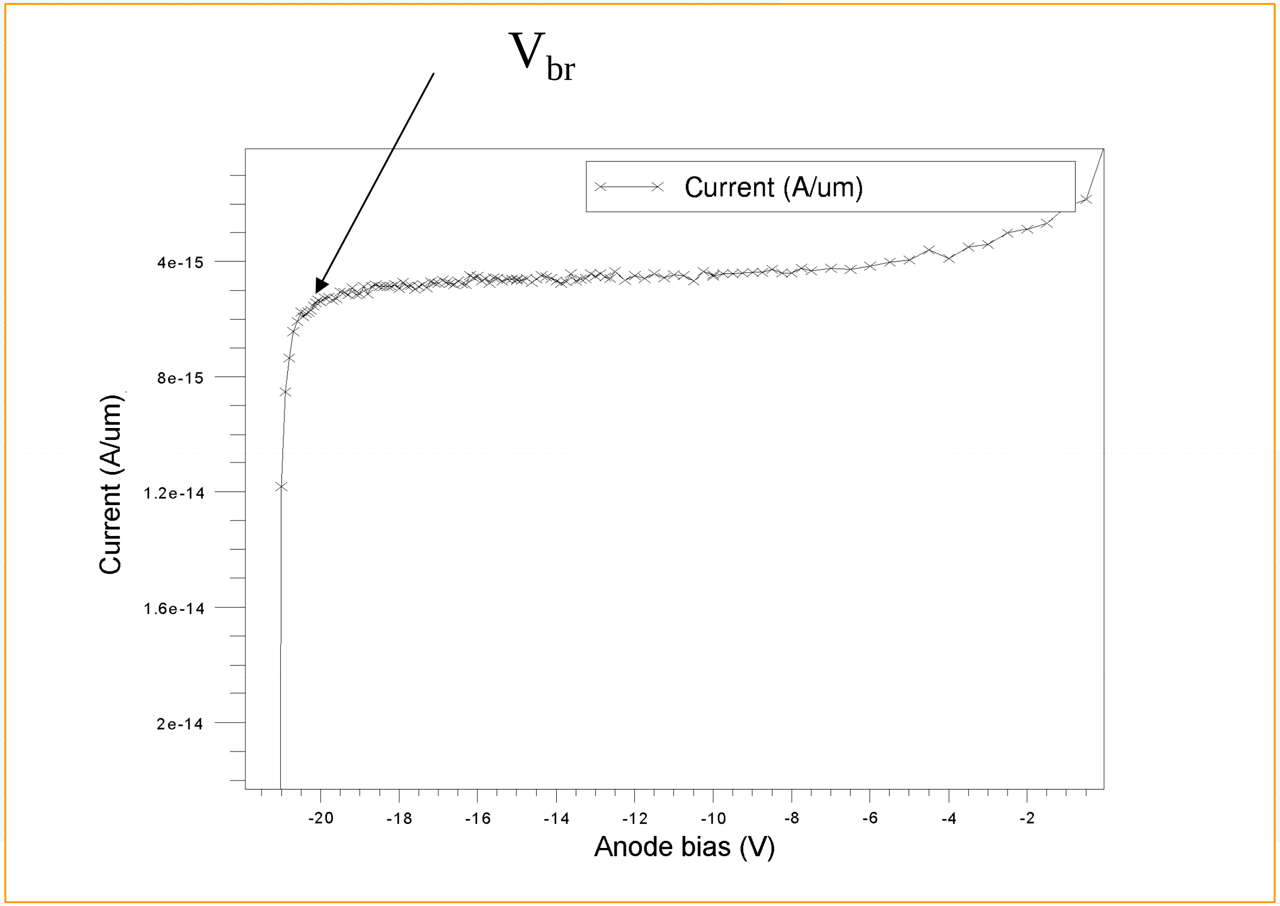


$Qf=2{\cdot}10^{12}$ q/cm^2

Vr=20V

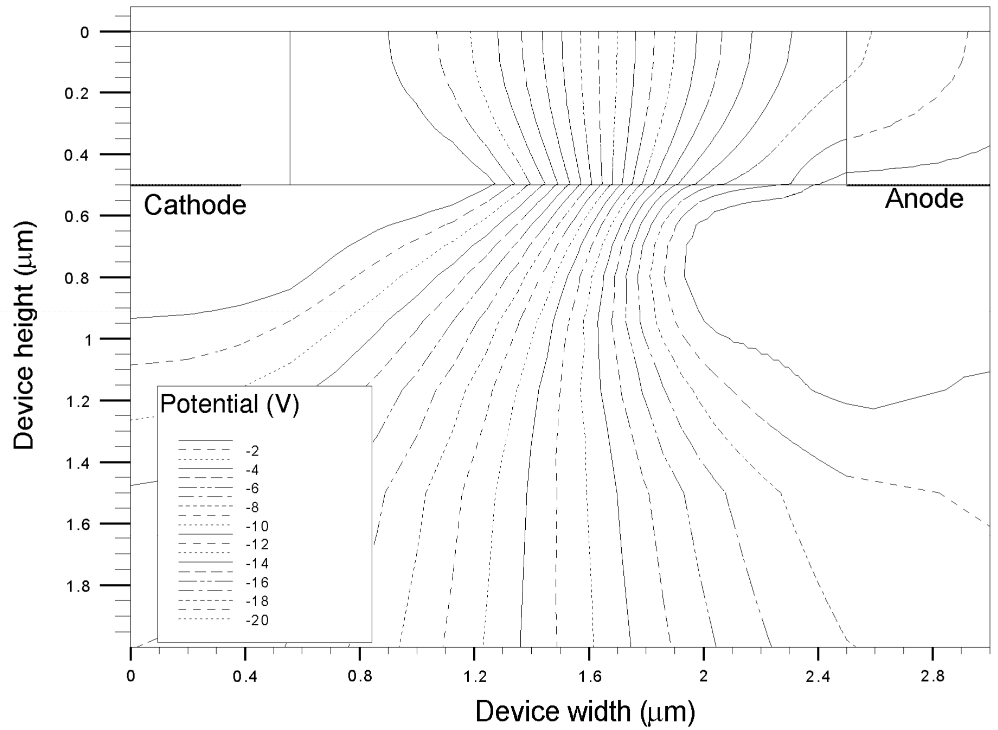
Result in high electric field at anode

Semiconductor Detector



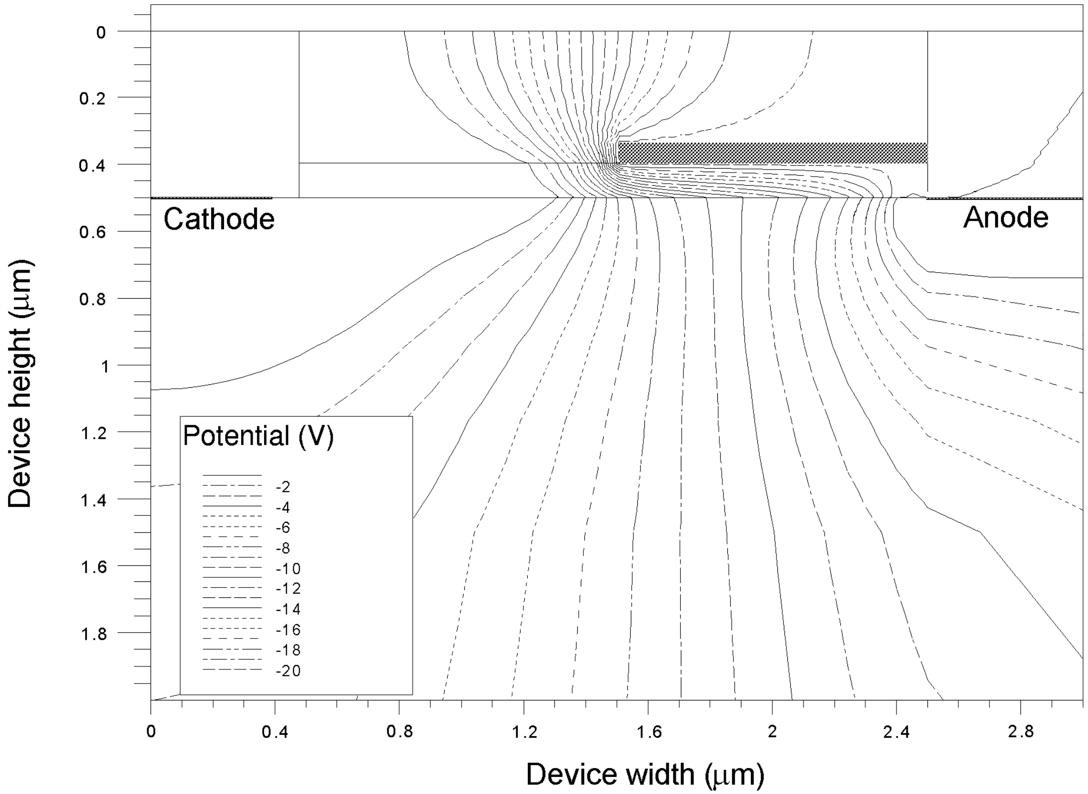
And surface avalanche breakdown

Semiconductor Detector



- Edge termination
  - Edge implantation (edge of anode) or diffusion drive in

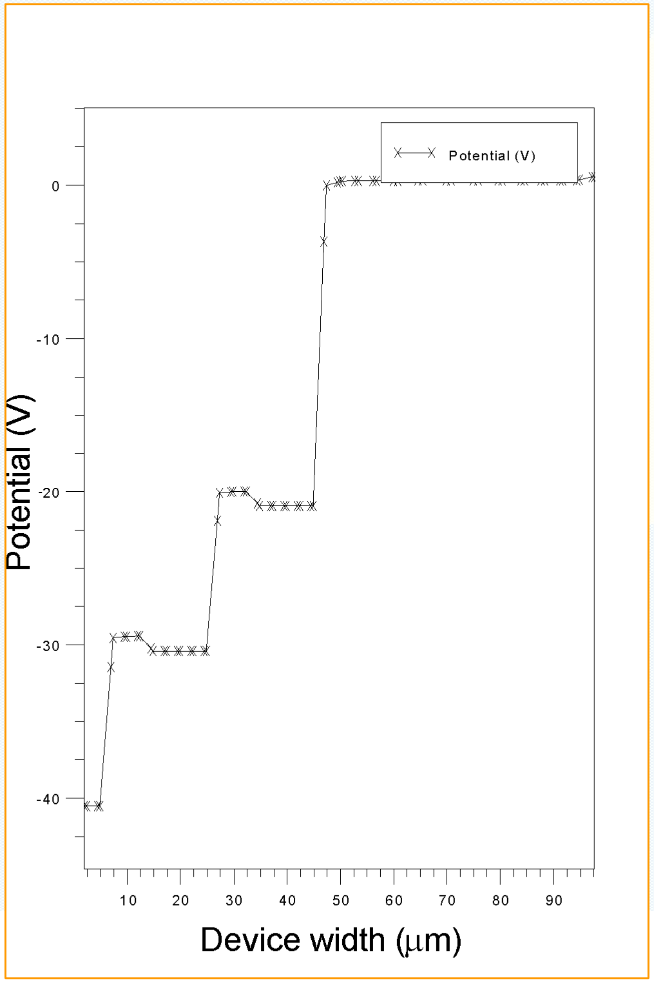
Semiconductor Detector



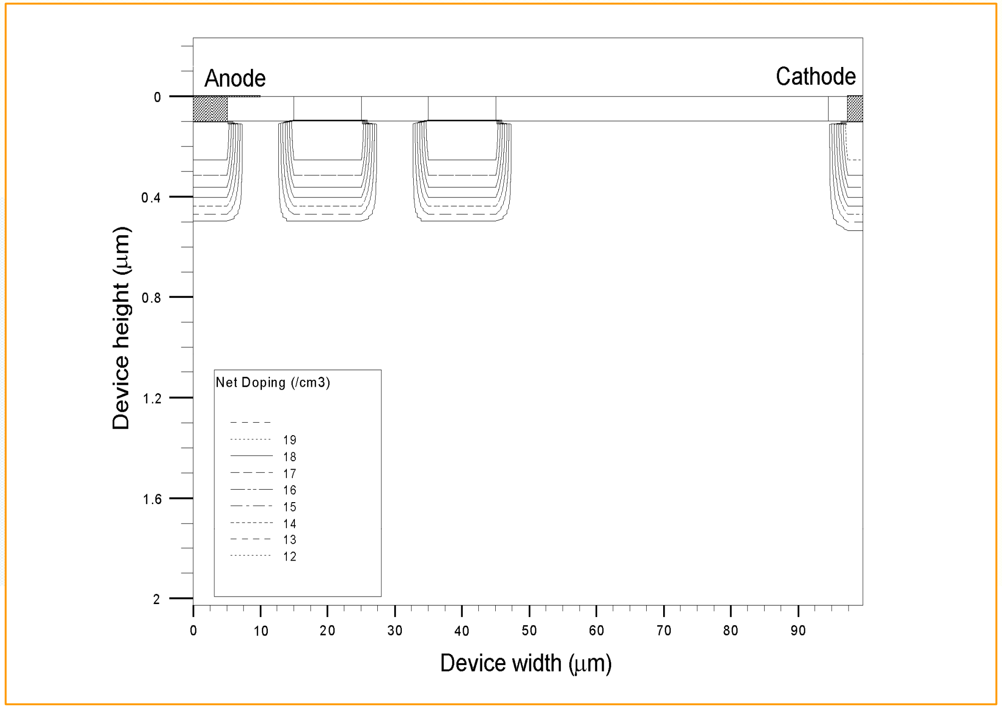
Edge termination

– **Field plate**

Semiconductor Detector

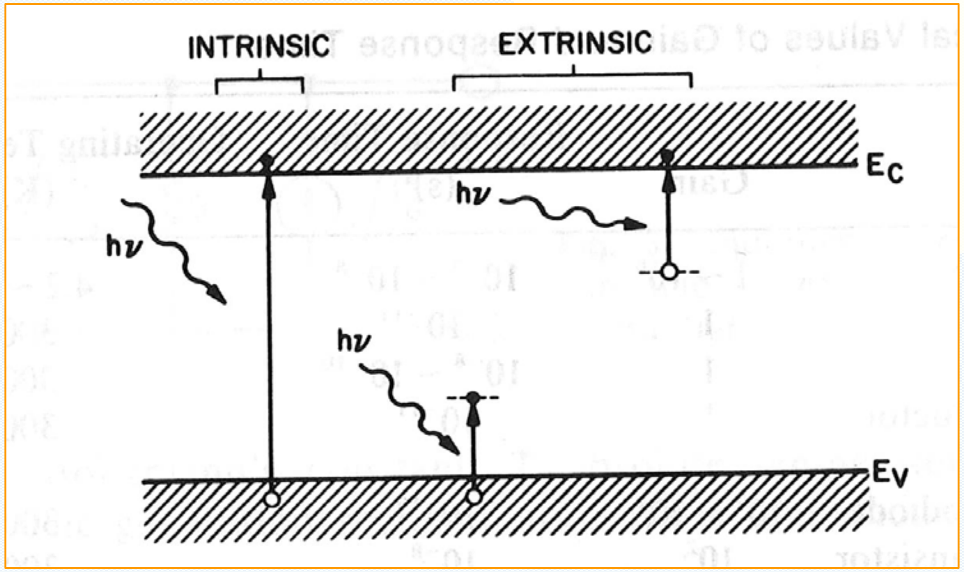


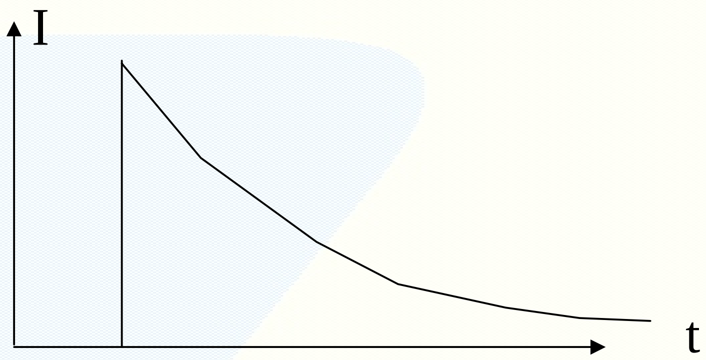
- Edge termination
  - –Floating guard rings, reverse bias 40 V , Qf=2·10^{12} q/cm^{2}



Photoconductor

$$n = n_0 e^{-t/\tau}$$





Photoconductor

Generation rate of carrier per unit volume

$$G = \frac{n}{\tau} = \frac{\eta(P_{opt}/h\nu)}{WLD}$$

Photocurrent flowing between contacts

$$I_p = (\sigma\mathscr{E})WD = (q\mu_n n\mathscr{E})WD = (qnv_d)WD$$

$$=$$

$$I_p = q\left(\eta\frac{P_{opt}}{h\nu}\right)\left(\frac{\mu_n\tau\mathscr{E}}{L}\right).$$

Primary photocurrent

$$I_{ph} \equiv q\left(\eta\frac{P_{opt}}{h\nu}\right)$$

Photocurrent gain

$$\text{gain} = \frac{I_p}{I_{ph}} = \frac{\mu_n\tau\mathscr{E}}{L} = \frac{\tau}{t_r}$$

$t_r = L/v_d$ is the carrier transit time.

Photoconductor

Table 1 Typical Values of Gain and Response Time

Photodetector	Gain	Response Time (s)	Operating Temperature (K)
Photoconductor	$1 \sim 10^6$	$10^{-3} \sim 10^{-8}$	$4.2 \sim 300$
p-*n* junction	1	10^{-11}	300
p-*i*-*n* junction	1	$10^{-8} \sim 10^{-10}$	300
Metal–semiconductor diode	1	10^{-11}	300
Avalanche photodiode	$10^2 \sim 10^4$	10^{-10}	300
Bipolar phototransistor	10^2	10^{-8}	300
Field-effect phototransistor	10^2	10^{-7}	300

Photoconductor

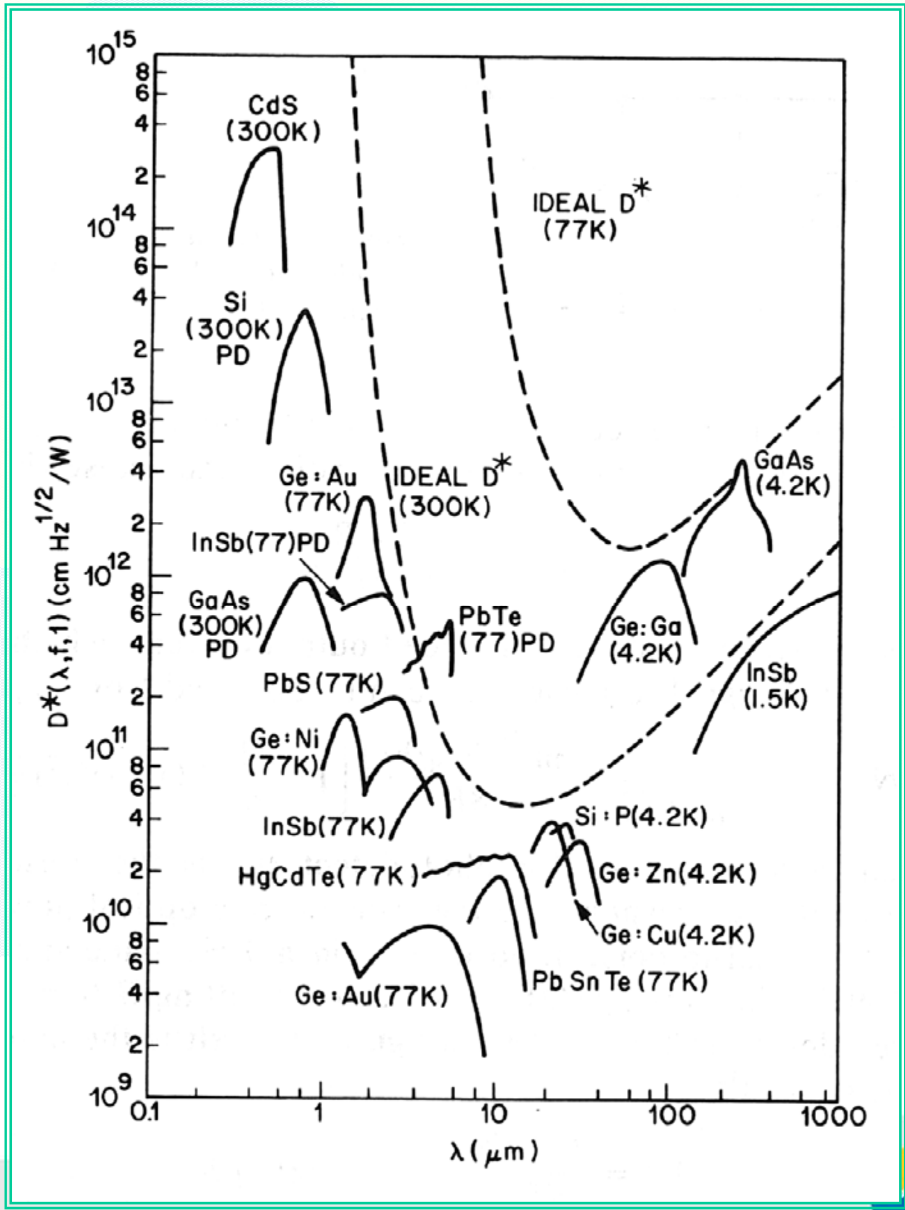
Detectivity

$$D^* = \frac{A^{1/2}B^{1/2}}{NEP} \quad \text{cm(Hz)}^{1/2}/\text{W}.$$

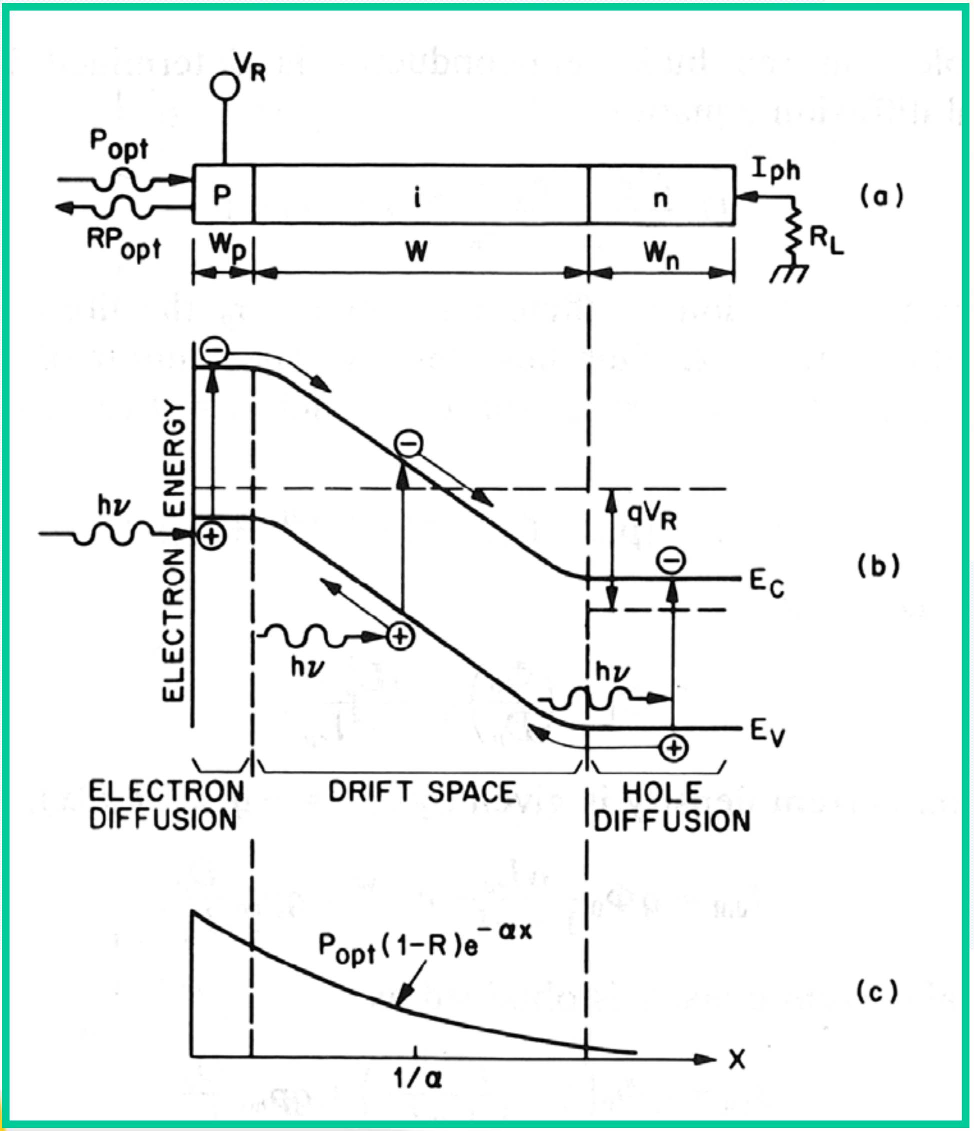
A=area of detector

B=bandwidth

NEP=noise equivalent power



Photodiode



- Responsivity 1
  - **Antireflective coating,** minimize reflection
  - **SiO_2-Si interface (if silicon),** effect short wavelength responsivity
  - **Effective depth of device** (effect long Wavelength responsivity)
- Internal quantum efficiency

$$\eta = (I_p/q)/(P_{opt}/h\nu)$$

- External quantum effiency
  - **Include optical properties: Reflection, absorption and transmission**
- Responsivity 2

$$R = \frac{I_p}{P_{opt}} = \frac{\eta\lambda(\mu m)}{1.24} \quad (A/W)$$

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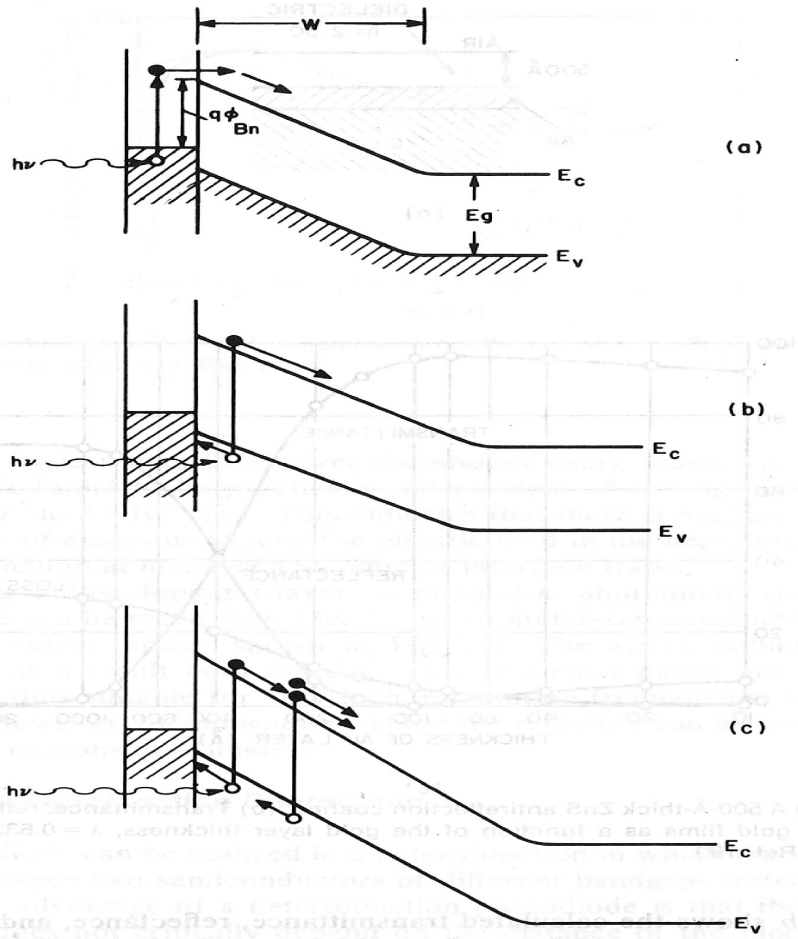
Schottky diode



Thin metal (~100Å) on a semiconductor surface

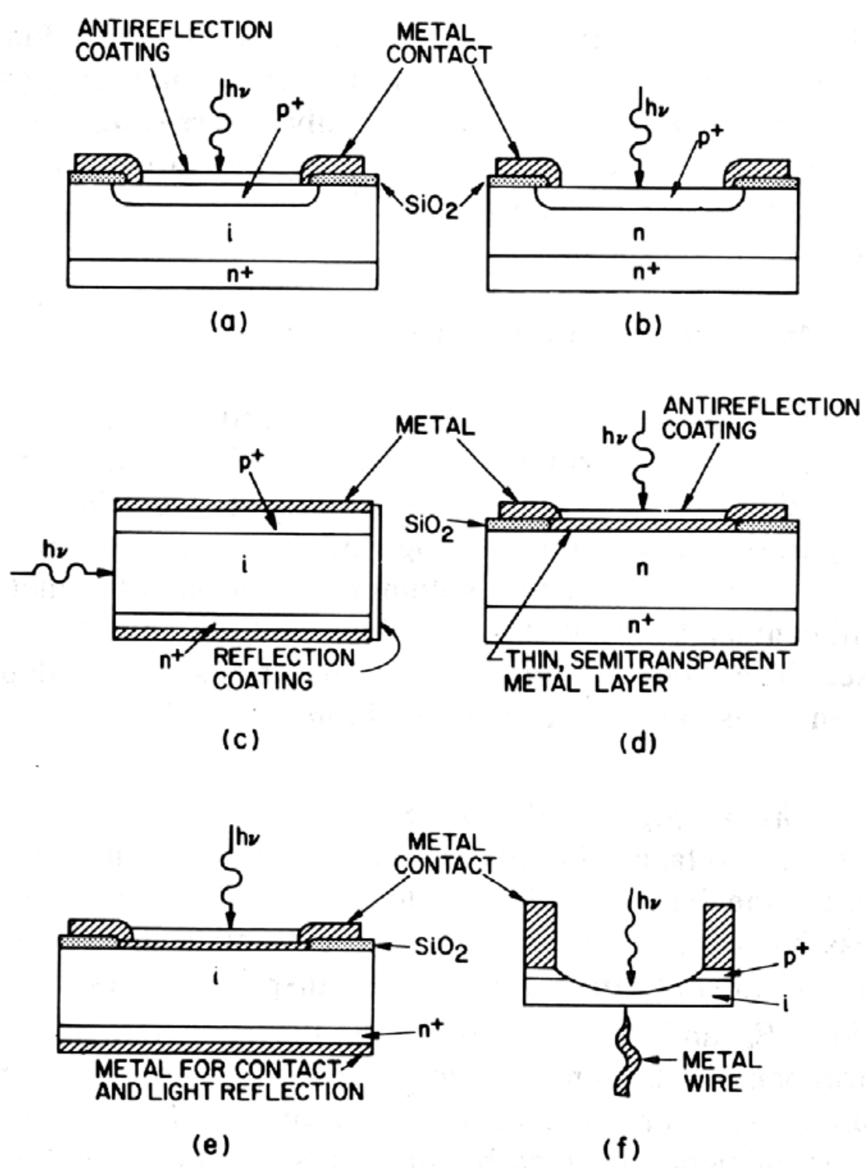
1 For $E_g > h\nu > q\phi_{Bn}$ and $V < V_B$, Fig. 14*a*, where V_B is the avalanche breakdown voltage, the photoexcited electrons in the metal can surmount the barrier and be collected by the semiconductor. This process has been used extensively to determine the Schottky-barrier height and to study the hot-electron transport in metal films.[20]

2 For $h\nu > E_g$ and $V < V_B$, Fig. 14*b*, the radiation produces hole–electron pairs in the semiconductor, and the general characteristics of the diode are very similar to those of a *p-i-n* photodiode. The quantum efficiency is given by an expression identical to Eq. 29.

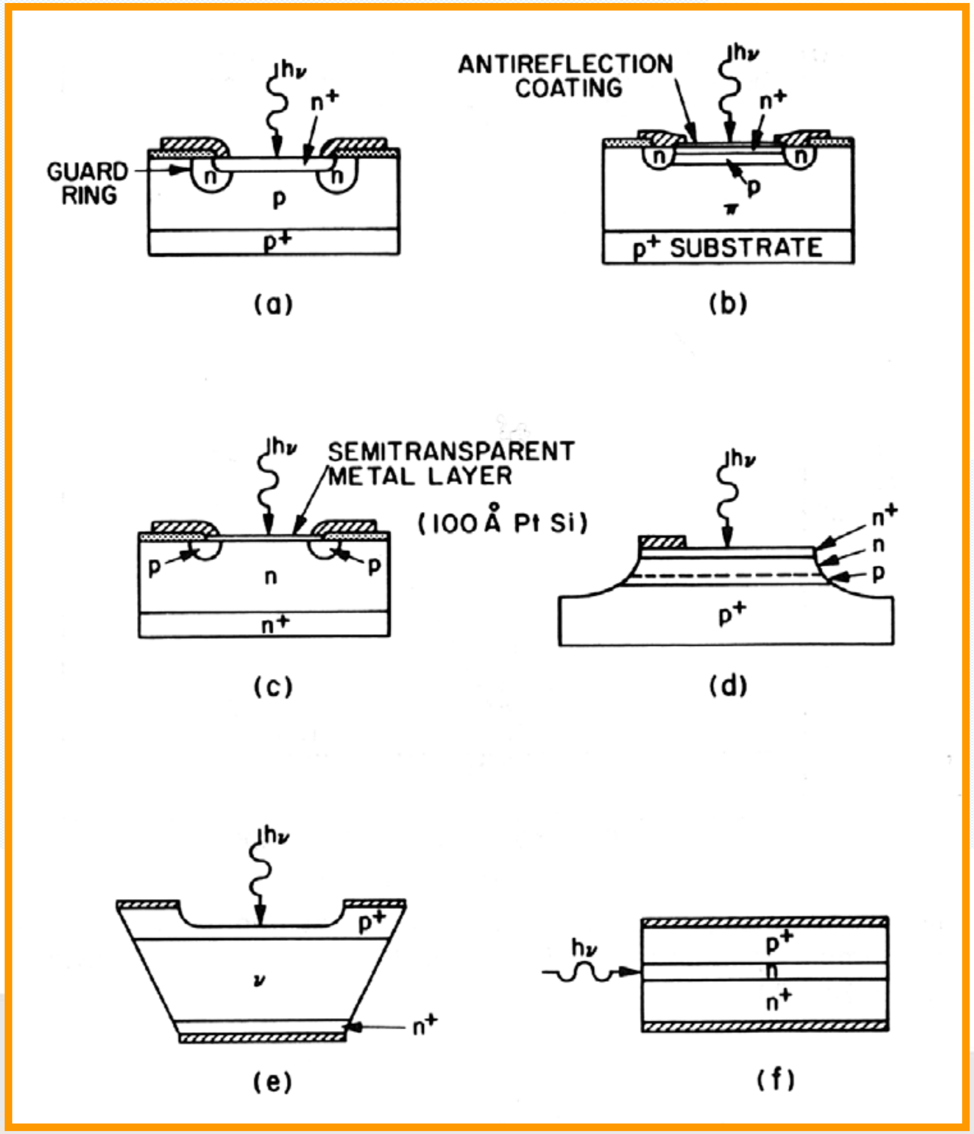
3 For $h\nu > E_g$ and $V \simeq V_B$ (high reverse-bias voltage), Fig. 14*c*, the diode can be operated as an avalanche photodiode (discussed in Section 13.4).

Schottky diode

a,b,c pn-junction
d,e,f schottky-junction



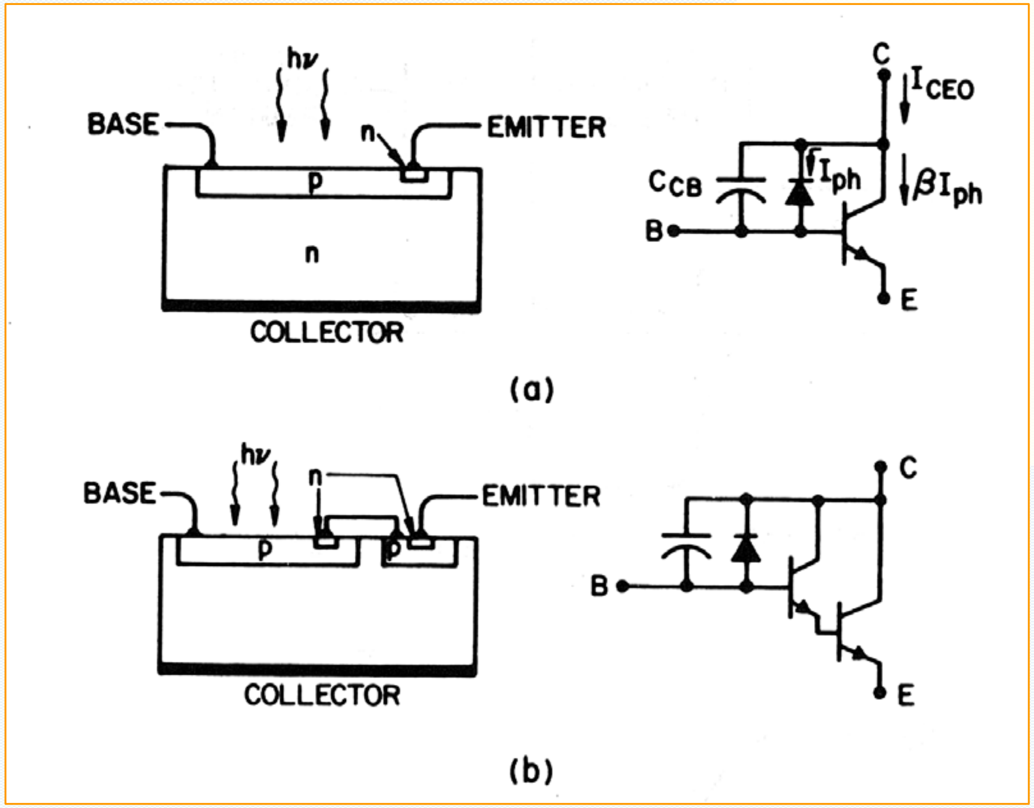
Avalanche photodiode



Operated at high reverse bias voltage where avalanche multiplication occur.

Problem to achieve uniform avalanche multiplication in entire light sensitive area

Phototransistor



High gain through the transistor action

Slower response-time compared with photodiode

pn-diode 0.01us

Ph-trans. 5 us

Ph darlington 50 us

Exercise

7. A collimated 10 keV X-ray bean is incident upon a fully depleted silicon sensor 0.05 cm thick with an active area of 30 mm^2. The sensor is cooled to a temperature of 77 K.

a) What percentage of the incident radiation will be absorbed within the sensitive volume, assuming no radiation is absorbed in the space between the source and the sensor?

b) Given that an incident X-ray interacts with a silicon atom, which type of interaction is most likely to occur?

c) What is the most probable origin of the photoelectron ejected by the silicon atom following the interaction with the 10 keV X-ray?

d) What is the energy of the ejected photoelectron?

e) Given that the energy of an incident X-ray is fully absorbed within the sensitive volume of the silicon sensor, how many electron/hole pairs will be created?

f) How many electron/hole pairs would be created if a 10 keV X-ray were fully absorbed within a fully depleted high-purity germanium sensor 0.05 cm thick with an active area of 30 mm^2 cooled to a temperature of 77 K?

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Exercise

9. a) What is the primary interaction of heavy charged particles and fast electrons with matter?

b) Explain the difference between excitation and ionization of the absorber atom.

c) What is the definition of the range and the mean range of a charged particle in matter?

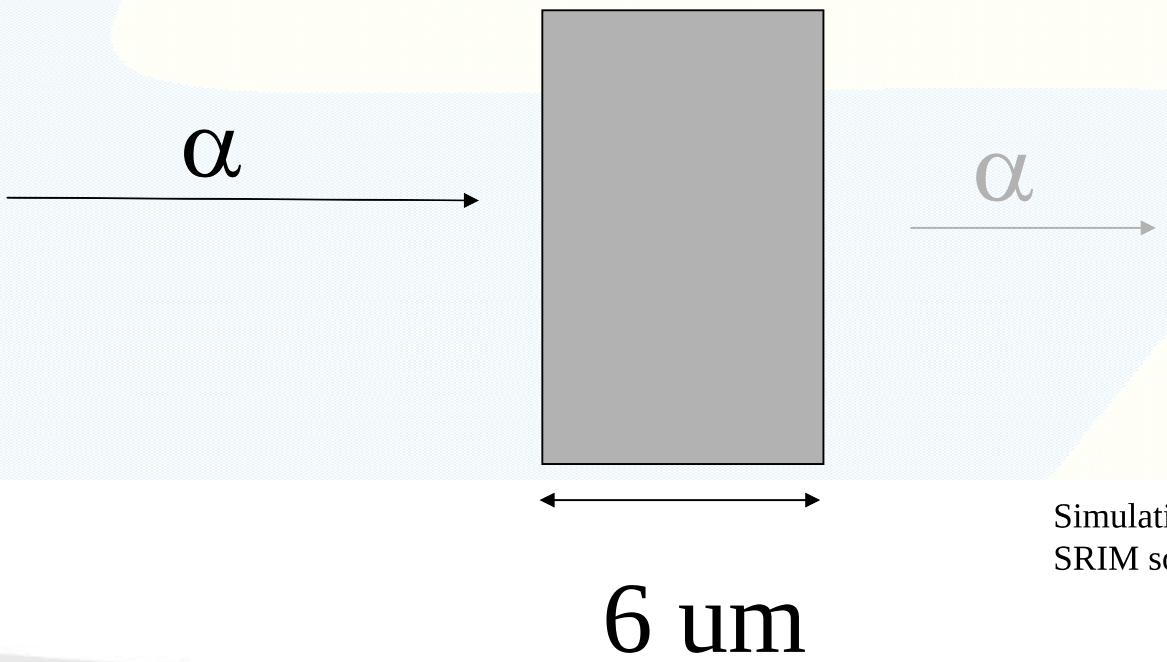
10. a) Given a high-purity silicon sensor with an active area of 30 mm^2 0.02 cm thick operating at room temperature, what substrate doping density is necessary if a voltage of 300 V is needed for full depletion?

b) The structure of the sensor is that shown in Fig. 10. What is the output capacitance of the detector given that the geometry of the output anode is 0.05×0.05 cm^2?

c) What should the input capacitance of the preamplifier be to minimize the system noise and to obtain the best energy resolution?

Exercise

11) Calculate and simulate (both) the deposited energy of an alfa particle with energy 5MeV in the thin silicon film? What energy have the leaving alfa particle.



Simulation of stopping power can be done with SRIM software “SRIM.org”