Photodiodes review

MEMS and Microsensors,   a.a. 2017/2018,   M.Sc. in Electronics Engineering

Outline

- **Semiconductors**

- *pn* Junction

- Photodiodes

- Quantum Efficiency and Responsivity

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Charge Carriers in Solids

- Atoms have only allowed energy levels for electrons called **shells**.

  ▪ Atom's electrical properties are determined by electrons in the outermost shell, called **valence electrons**.

- Solids have only allowed energy levels for electrons called **bands**.

  ▪ Solid's electrical properties are determined by electrons in the outermost band.

  ▪ Electrons can't be treated as belonging to their parent atoms. They belong to the crystal as a whole.
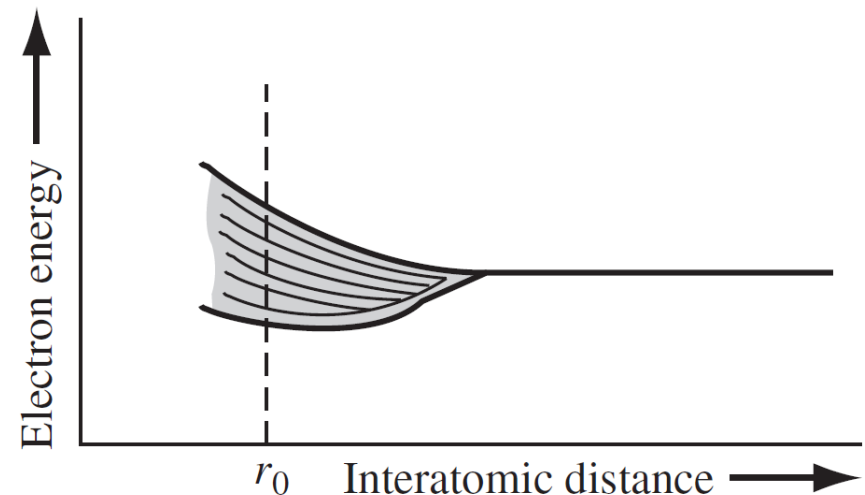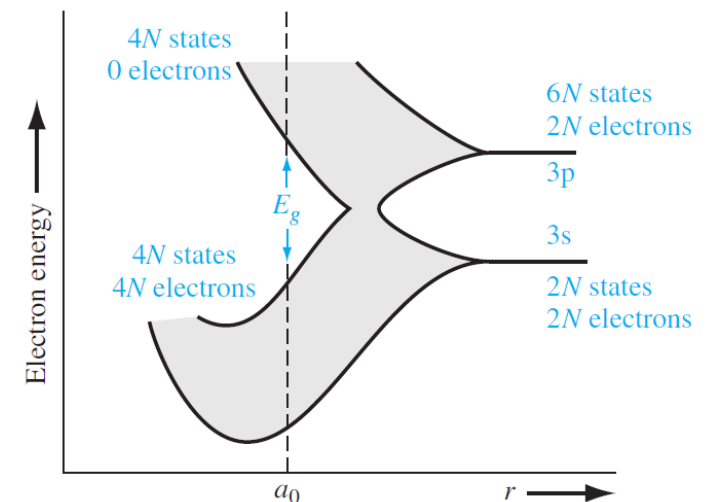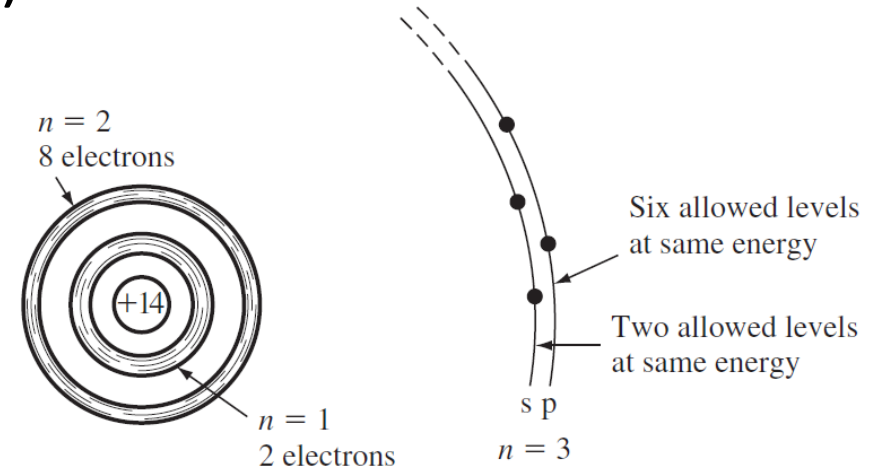
Silicon

- **Silicon** atom: 4 valence electrons.

- Each atom shares one valence electron with its neighbors, thereby completing its own shell and those of the neighbors. The *bond* thus formed between atoms is called a *covalent bond* to emphasize the sharing of valence electrons.
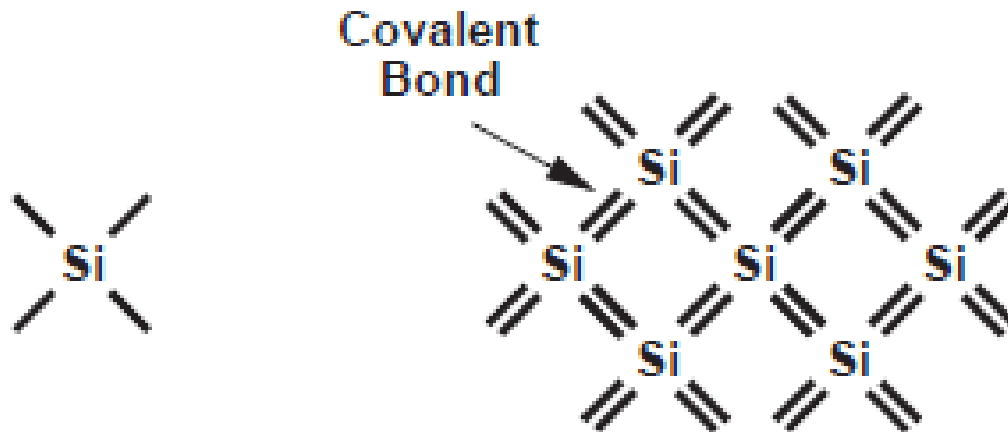
# Band Model

- Valence electrons (shell $n = 3$)

- 1 silicon atom

  - 8 states

  - 4 electrons

- N silicon atoms

  - 8·N states split in two bands

  - 4·N electrons

- The highest full energy band is called **valence band** (VB).

- The lowest empty energy band is called **conduction band** (CB).

Electrical Properties

- Does silicon carry current in response to a voltage?

- At temperatures near absolute zero, electrons in the *valence band* are confined to their respective covalent bonds, refusing to move freely. In other words, the silicon crystal behaves as an insulator for $T = 0$ K.

- At higher temperatures, **thermal vibrations** may break the covalent bonds. In terms of bands, when a bond is broken, an electron is **promoted** to the *conduction band*. An electron in the CB is *free* to move and also to respond to electric fields since there are plenty of neighboring empty energy levels.

$T = 0$ K

T

Conduction band

E_g

Valence band

Electrons and Holes
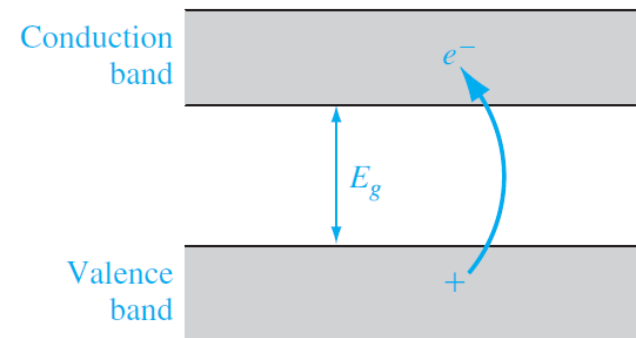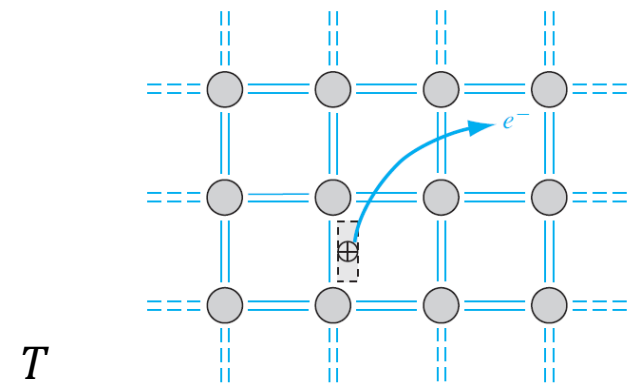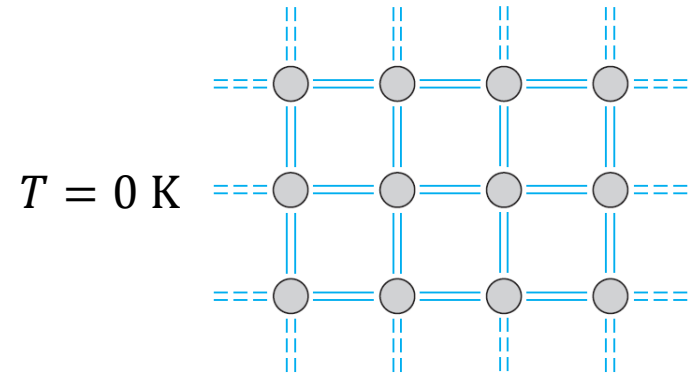
- When a valence electron in silicon becomes a free electron, an electron *void* is left in the covalent bond. Such a *void* can be filled by one of the neighboring electrons → there's a shift of the void location.

- We may consider this deficiency as a particle similar to an electron. This fictitious particle is called a **hole**. It carries a positive charge and moves, under the influence of an applied electric field, in the direction opposite to that of an electron. Both electrons and holes contribute to the total electric current.

- The concept of a hole is analogous to that of a bubble in a liquid: although it is actually the liquid that moves, it is easier to talk about the motion of the bubble in the opposite direction.
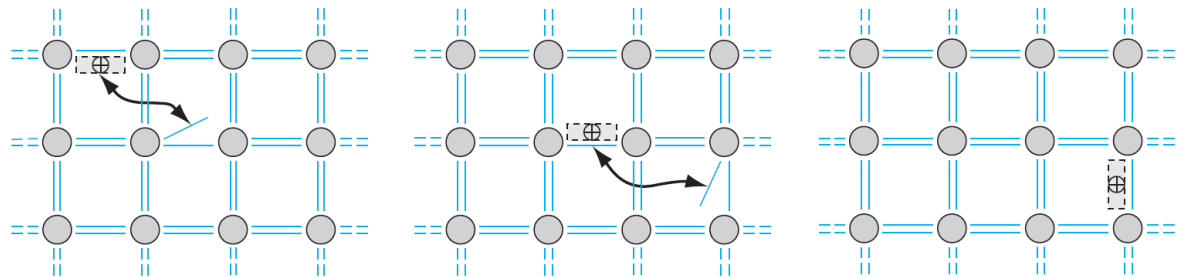
- When an electron is *promoted* to CB: *electron-hole pair (EHP) generation*.

- When a CB electron falls in VB: *electron-hole recombination*.

Bandgap Energy

- What makes an electron 'jump' from the VB to the CB? **Energy**!
- There's a minimum energy required to promote an electron, called **bandgap energy** (E_g). For silicon, $E_g = 1.12$ eV.
- Effect of bands / bandgap energy on the conductivity:
  - *Conductors* have a partially filled CB / VB and CB overlap: electrons are 'free'.
  - *Semiconductors* exhibit a moderate E_g, typically ranging from 1 to 1.5 eV.
  - *Insulators* display a high E_g; for example, $E_g = 2.5$ eV for diamond.
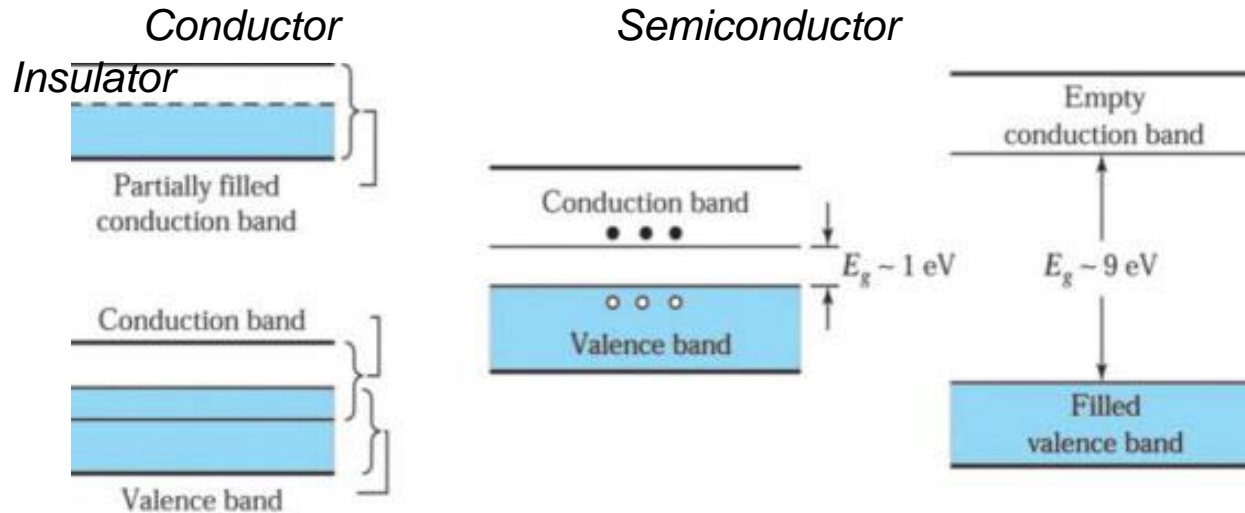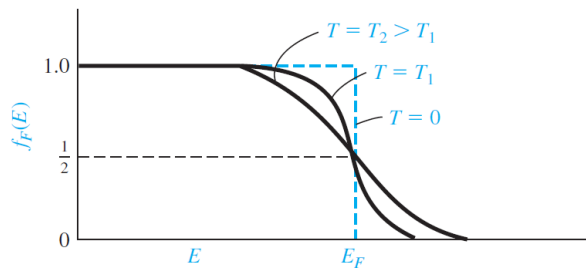

$$1 \text{ eV} = 1.6 \cdot 10^{-19} \text{ J}$$

Thermal Energy
$$kT = 25.8 \text{ meV}$$

Band Model

- Density of states: $g(E)$
- Probability that an electron occupies a state: $f(E)$, Fermi–Dirac distribution function

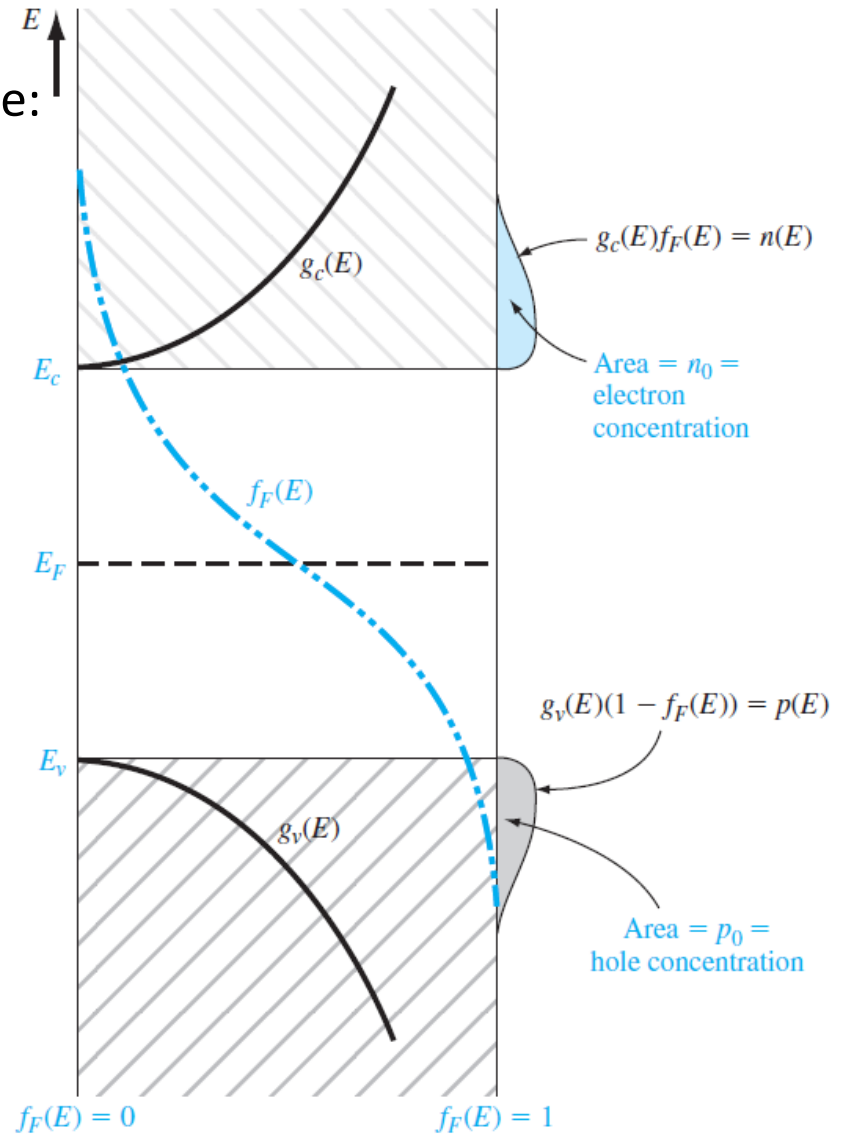$$f(E) = \frac{1}{1 + e^{\frac{E - E_F}{kT}}}$$

  - Fermi level: $f(E_F) = 50\%$.

- Number of electrons in the CB n

$$n = \int g(E) f(E) dE$$

- At $T = 0$ K, 100% electrons in VB: $n = 0$

- $g_c(E) f_F(E) = n(E)$
- $g_c(E)$
- Area $= n_0 =$ electron concentration
- $f_F(E)$
- E_c
- E_F
- $g_v(E)(1 - f_F(E)) = p(E)$
- E_v
- $g_v(E)$
- Area $= p_0 =$ hole concentration
- $f_F(E) = 0$
- $f_F(E) = 1$

Charge Density

- How many free electrons are created at a given temperature?
- At room temperature ($T = 300$ K), in silicon:
$$n_i \simeq 10^{10} \text{ electrons/cm}^3$$
- The density of electrons in a crystal depends on E_g and T:
  - A greater E_g yields fewer electrons.
  - A higher T yields more electrons.

- Remember that silicon has $5 \cdot 10^{22}$ atoms/cm^3!
Poor conductor!

- In an intrinsic semiconductor, the electron density $n = n_i$ is equal to the hole density, $p = n_i$. We have
$$np = n_i^2$$

Doping

- How can we make silicon more useful?

- It is possible to modify the resistivity of silicon by replacing some of the atoms in the crystal with atoms of another material.

- The controlled addition of an *impurity* to an intrinsic semiconductor is called **doping**, the impure atom itself is called a *dopant*, and the semiconductor becomes *extrinsic*.

n-type Doping

- Phosphorus (P) contains five valence electrons. What happens if some P atoms are introduced in a silicon crystal? Each P atom shares four electrons with the neighboring silicon atoms, leaving the fifth electron unattached. This electron is free to move, serving as a charge carrier. Thus, if N_D phosphorus atoms are uniformly introduced in each cubic centimeter of a silicon crystal, then **the density of free electrons rises** by the same amount.

  - $n = N_D$

  - $p = \dfrac{n_i^2}{n} = \dfrac{n_i^2}{N_D}$

  > It can be demonstrated that, even with impurities, $np = n_i^2$

- In an *n*-type semiconductor, electrons are called **majority carriers** and holes are called **minority carriers**.

- Typical doping densities fall in the range of 10^{15} to 10^{18} atoms/cm^3.

p-type Doping

- Boron (B) contains three valence electrons. If some B atoms are introduced in a silicon crystal, each B atom shares three electrons with the neighboring silicon atoms; the fourth bond contains a hole, free to move in the VB. If N_A boron atoms are uniformly introduced in a silicon crystal, **the density of holes rises** by the same amount.

  - $p = N_A$ (**majority carriers**)

 - $n = \dfrac{n_i^2}{p} = \dfrac{n_i^2}{N_A}$ (**minority carriers**)
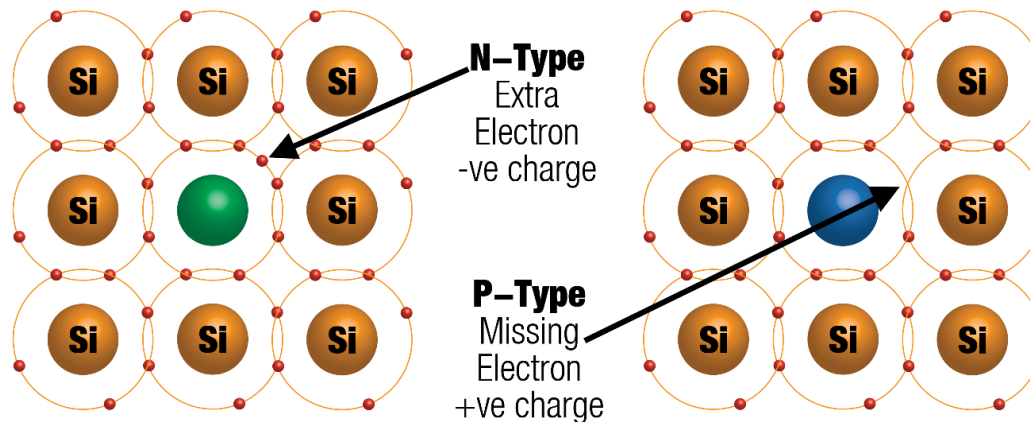
Band Model

- The Fermi level depends on the impurity concentration.

- For example, in a *n*-type semiconductor, the Fermi level turns out to be closer to the conduction band.

- As expected, electrons concentration is much larger than the hole concentration.

a) Intrinsic semiconductor

b) n-type semiconductor
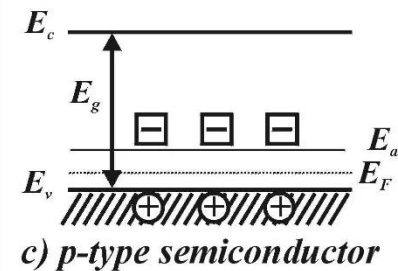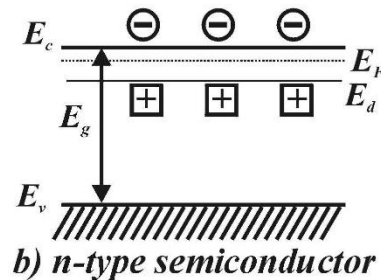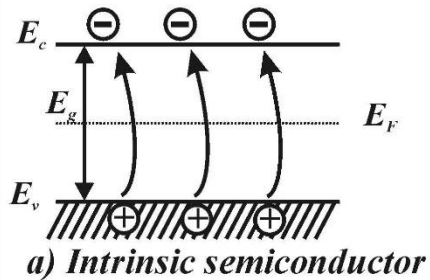
⊖ Electrons in conduction band (mobile)
⊕ Holes in the valence band (mobile)
⊞ Positive ions (imobile donors)
⊟ Negative ions (imobile acceptors)

c) p-type semiconductor
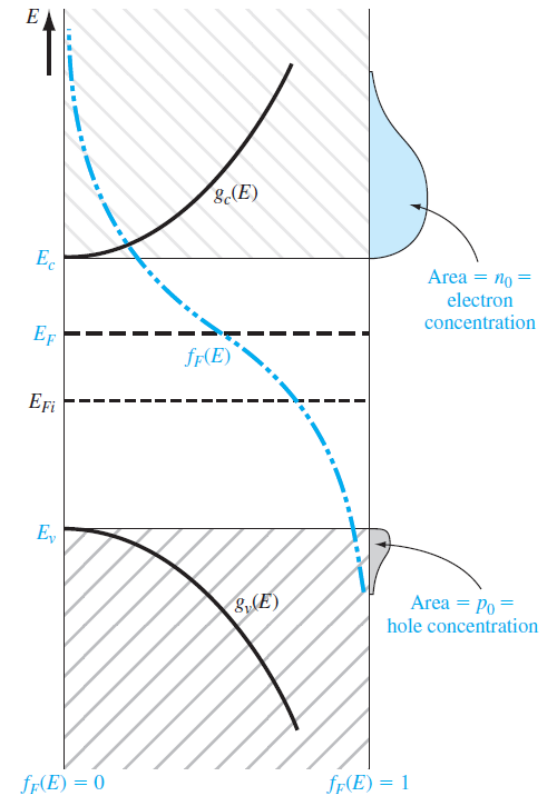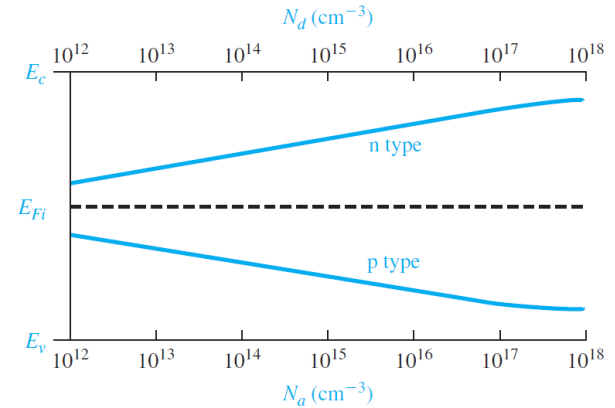
Current

- Two sources of current flow

$$I = \frac{dQ}{dt}$$

- **Drift**
  - Movements of charges due to an **electric field**
- **Diffusion**
  - Movements of charges due to a **concentration gradient**

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Absorption

- Are there other sources of energy that could contribute to the promotions of electrons? Light!
$$E = h\nu$$

$$h = 6.6 \cdot 10^{-34} \text{ Js}$$

$$\nu = \frac{c}{\lambda}$$

- What happens when a photon has *enough* energy to break the covalent bond? An electron in the VB **absorbs** the energy of the photon and gains sufficient energy to surmount the energy gap and to reach the CB: **EHP generation**.
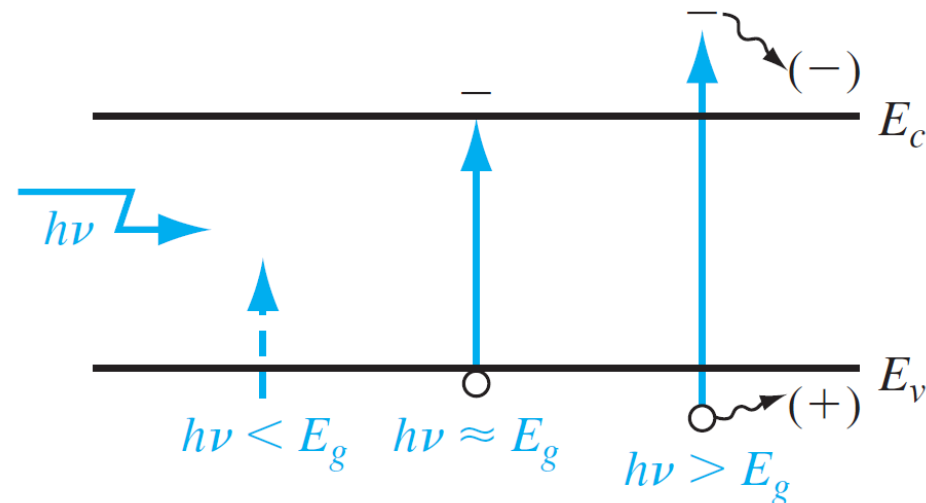
- Cut off wavelength:

$$\lambda_c = \frac{hc}{E_g} = \frac{1.24 \text{ [µm·eV]}}{E_g}$$

For silicon: $\lambda_c = 1.11$ µm

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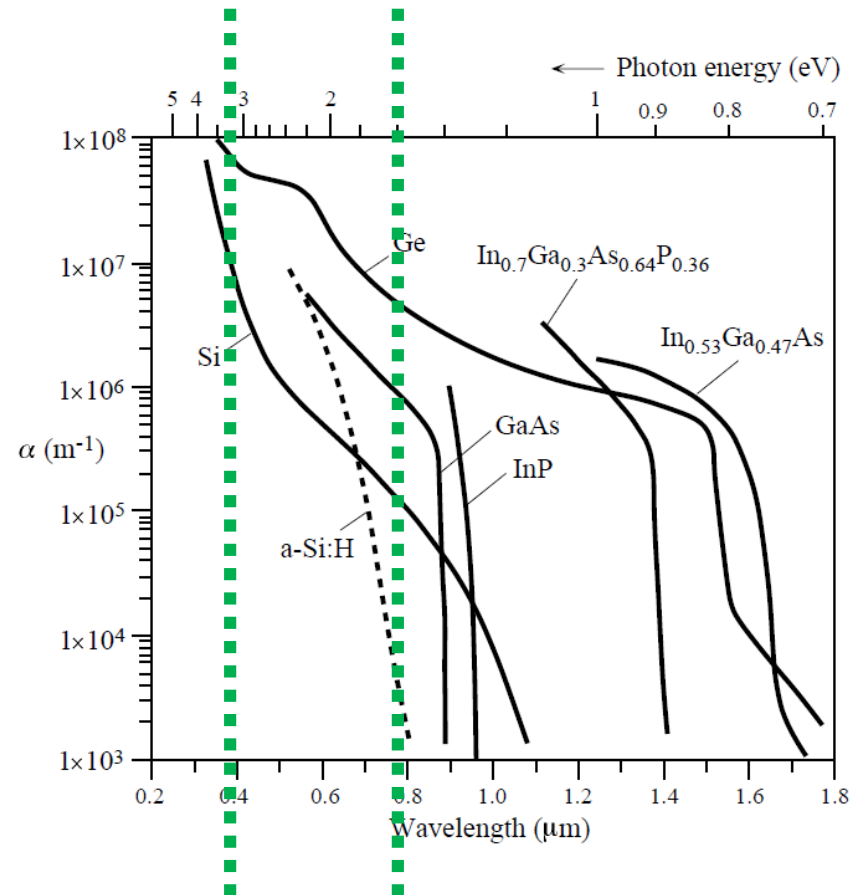
Absorption Coefficient

- Fractional change in the intensity I of light per unit distance along the propagation direction:

$$\alpha = -\frac{dI}{I dx}$$

- α depends on
  - material
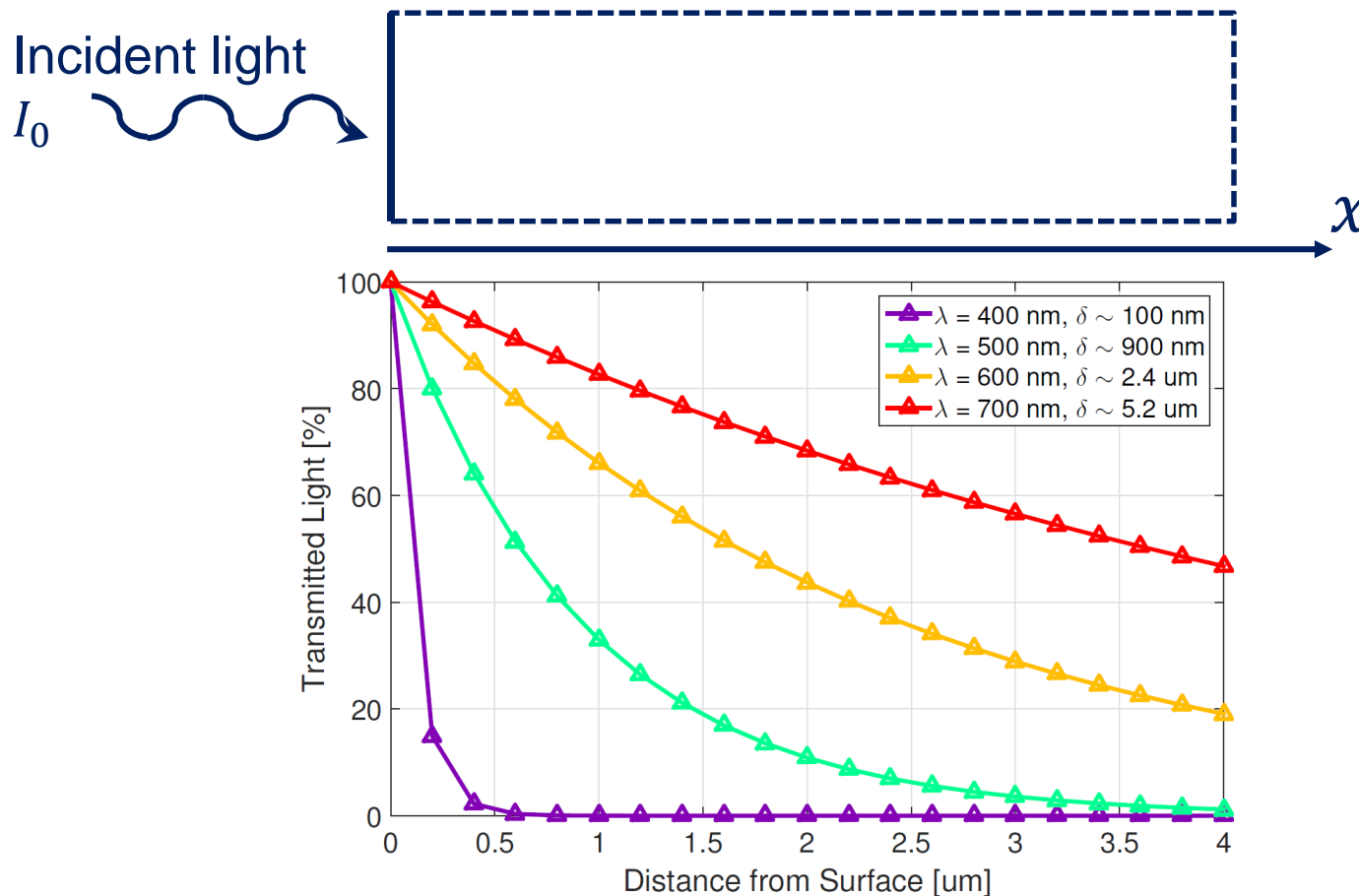 - photon energy (or wavelength λ)

$$\alpha = \alpha(\lambda)$$

- 63% of the photon absorption occurs over a distance $\delta = 1/\alpha$, called *penetration depth*.
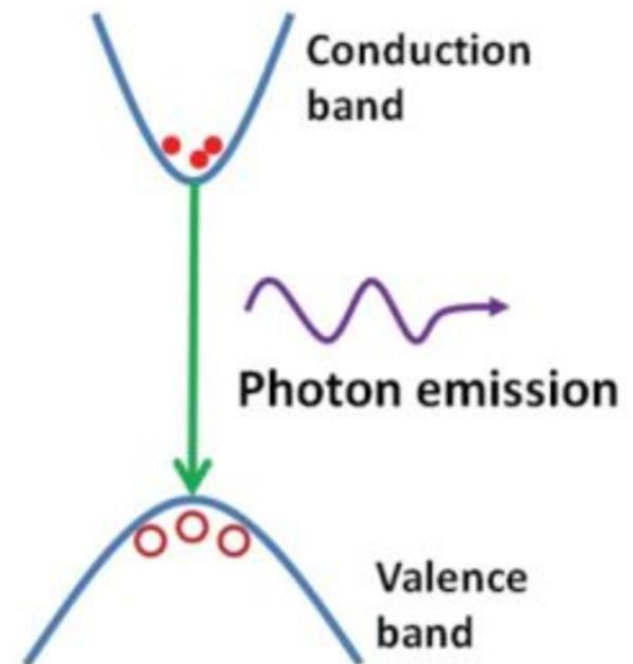
Absorption in Silicon

- Light intensity at a certain distance from the surface

$$I(x) = I_0 \mathrm{e}^{-\alpha x}$$

Incident light
I_0

x

Emission

- Absorption is reversible: when an electron and a hole recombine, energy is freed, and can be freed in form of photon **emission** (light).

- The photon energy will be equal to the bandgap energy! $E = h\nu = E_g$

- LEDs exploit this principle.

Outline

- **Semiconductors**

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pn Junction

- When an *n*-type region and an *p*-type region are in contact, due to the concentration gradient:
  - electrons diffuse from *n* to *p*-side and recombine with holes;
  - holes diffuse from *p* to *n*-side and recombine with electrons.

- The *n*-side has exposed donor (**+**) ions.

- The *p*-side has exposed acceptor (**-**) ions.

- The region across the junction becomes depleted of free carriers.
  - There is a **space charge region** (or **depletion region**) around the junction.
 - Other regions are called **bulk regions.**
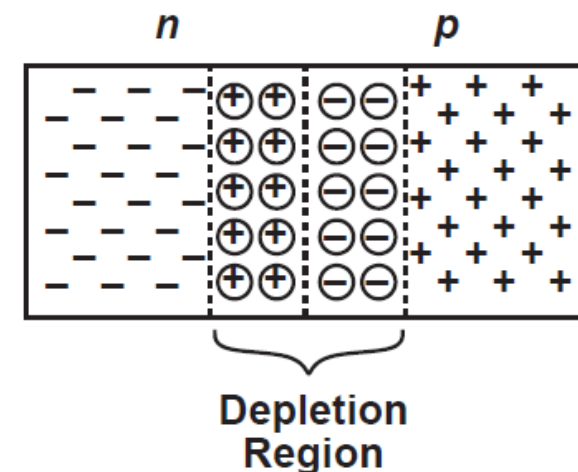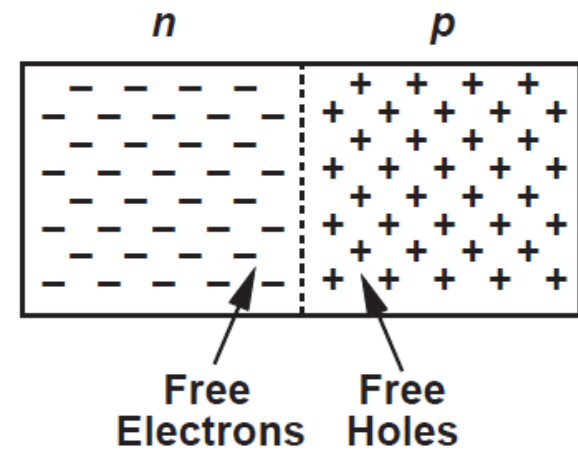
Electric Field

- An object carrying a nonzero charge creates an **electric field**. With the formation of the depletion region, an electric field emerges.

- The field profile can be found by the integration of the space charge density (Gauss law).

- This electric field is maximum at the junction and it tends to force positive (+) charges to flow from left to right, while the concentration gradient would force them from right to left.

- Once **equilibrium** is obtained, the electric field is strong enough to completely stop the diffusion currents. Said in other words, in equilibrium **the drift current exactly cancels the diffusion current**.

1D Gauss law:
$$\frac{dE}{dx} = \frac{\rho}{\varepsilon}$$
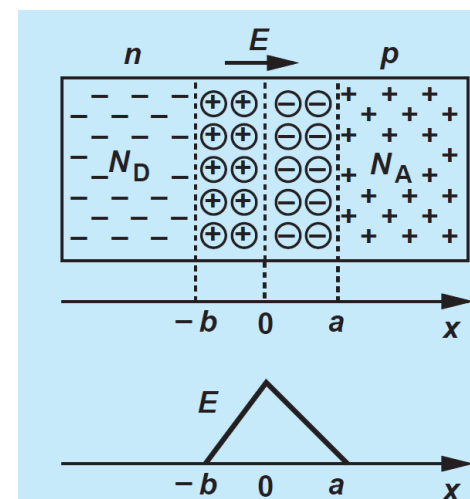
Potential

- The potential $V(x)$ at any point can be found by integrating the electric field.

- The potential difference between *p* and *n* bulk regions is called **built-in potential**

$$V_{bi} = \frac{kT}{q} \ln \left(\frac{N_A N_D}{n_i^2} \right)$$

- The built-in voltage is the potential across a *pn* junction in an open circuit. It is **not** the voltage across the diode, that is made up also of the contact potentials of the electrodes at the metal to semiconductor junctions.
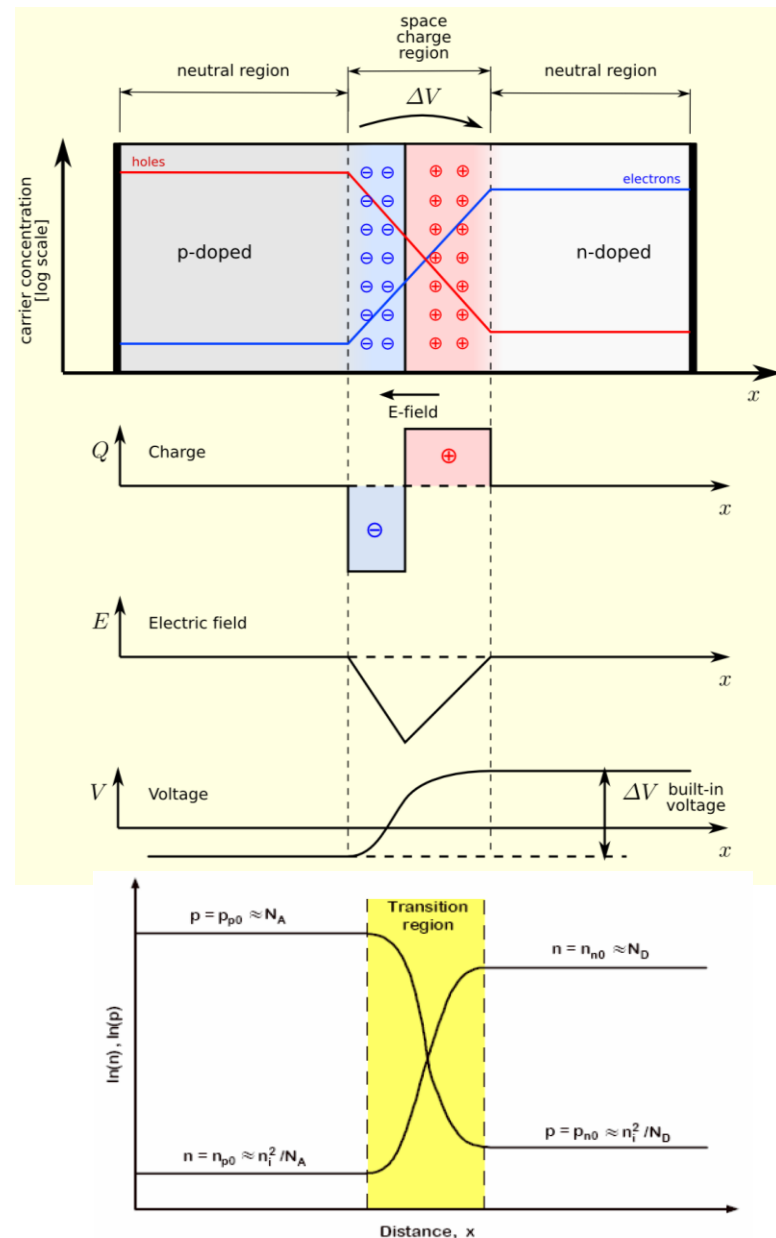
Band Diagram

- For a system in equilibrium the average energy must be constant. This means that the **Fermi level must be constant**.

- Away from the junction, bulk conditions dominate and the band diagram is unaffected.

- Close to the junction **the bands bend** due to the constant Fermi level.
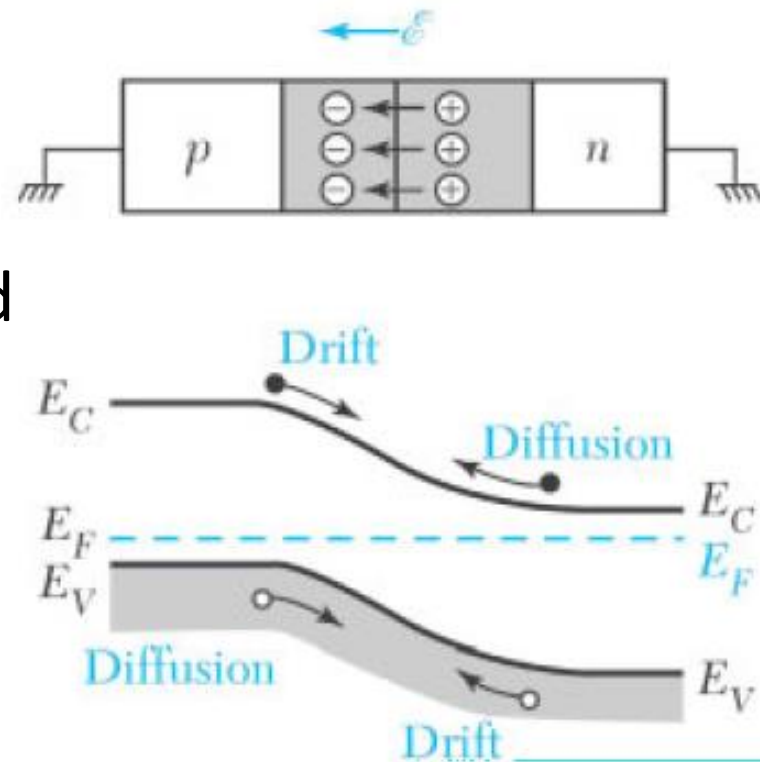
Depletion Region Width

- Three unknowns: W_p, W_n, E_0

- Three equations:

1. Charge neutrality

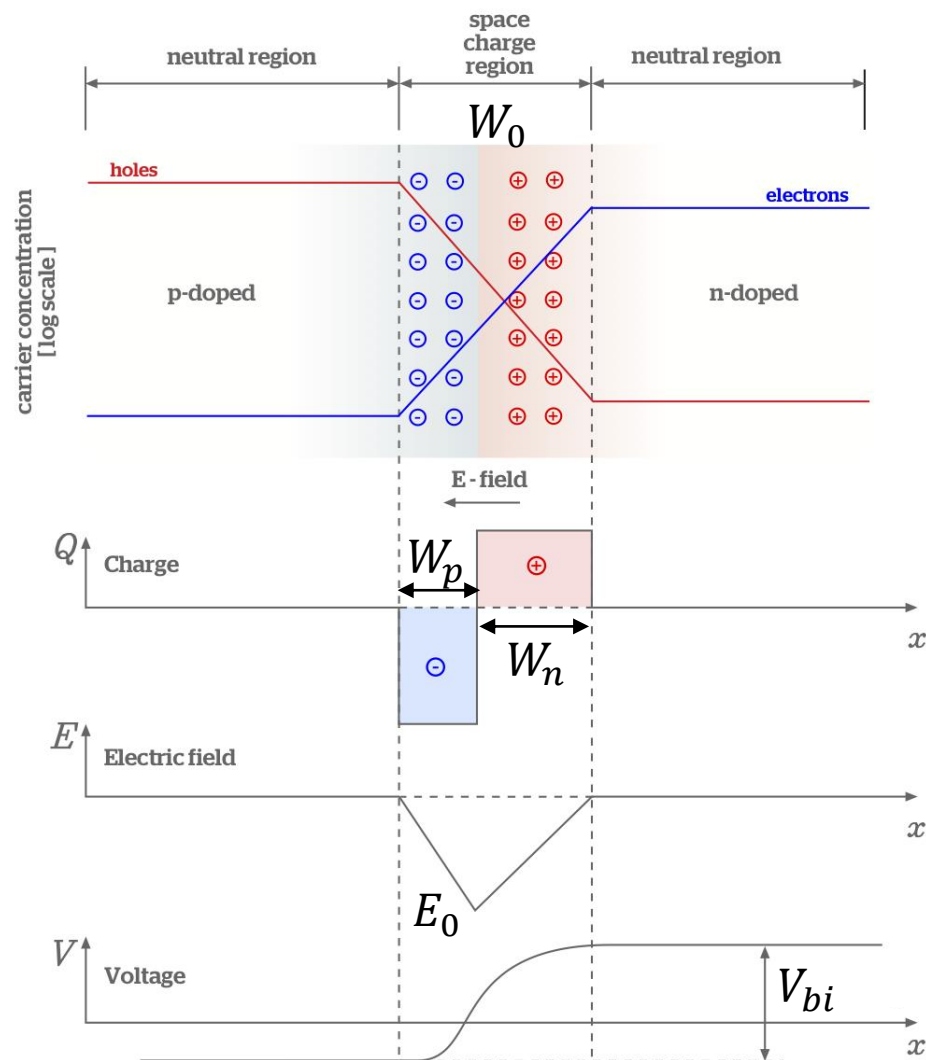$$N_D W_n = N_A W_p$$

2. Field at the junction

$$E_0 = E(x = 0) = -\frac{q N_A W_p}{\varepsilon}$$

3. Built in potential

$$V_{bi} = \frac{1}{2} W_0 E_0$$

- Depletion width $W_0 = W_p + W_n$

$$W_0 = \sqrt{\frac{2\varepsilon V_{bi}}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)}$$

One-sided Junction

- Usually, we have one region with a doping much higher than the other.

- Due to overall charge neutrality
$$W_n N_D = W_p N_A$$

- If $N_A \gg N_D$, the junction is said *one-sided*, and the depletion region **penetrates more on the lightly doped side** than the highly doped side ($W_p \ll W_n$)
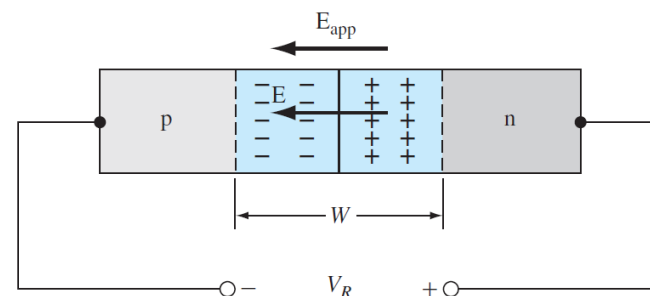
$$W_0 \simeq W_n = \sqrt{\frac{2\varepsilon V_{bi}}{qN_D}}$$

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Reverse Bias

- When a *pn* junction is reverse biased, with the *n*-side more positive, the applied voltage (V_R) mainly drops across the depletion region
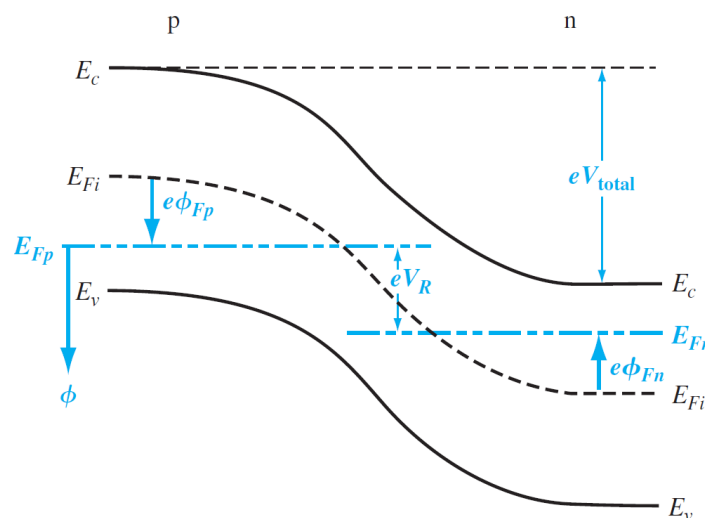   - the electric field increases
    - **the depletion region becomes wider**

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

- The reverse current is typically very low (ideally zero).

- Two sources of *reverse (dark) current*:
    - minority carriers diffusion, due to a gradient in the bulk regions
        - strongly temperature dependent, independent on V_R
    - thermal generation of EHPs
        - depends on V_R

Depletion Capacitance

- The depletion region of a *pn* junction has positive and negative charges separated over a distance W similar to a parallel plate capacitor, with
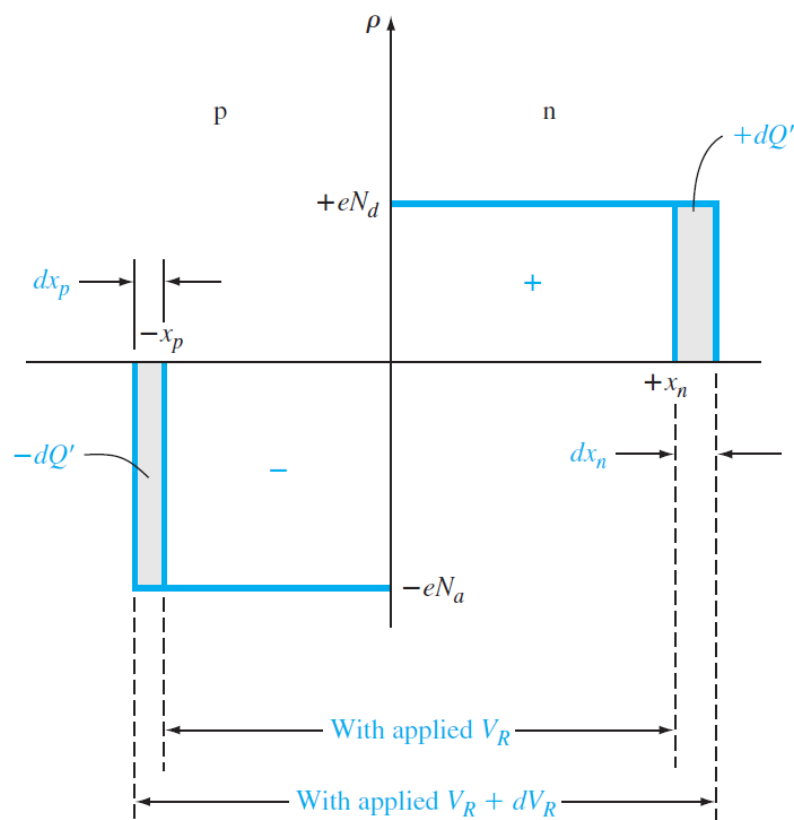 $+Q = qN_D W_n A$ on the *n*-side and
  $-Q = -qN_A W_p A$ on the *p*-side.

- We can define an incremental capacitance, i.e. the **depletion layer capacitance**:

$$C_{dep} = \left| \frac{dQ}{dV} \right| = \frac{\varepsilon A}{W} = \frac{A}{\sqrt{V_{bi} + V_R}} \sqrt{\frac{q\varepsilon N_A N_D}{2(N_A + N_D)}}$$

- Q does not depend linearly on the voltage V !

# Outline

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Photodetection

- Photodetectors **convert** a light signal into an electrical signal.

- This conversion is typically achieved by the **creation of electron hole pairs** by the absorption of photons, i.e. by creating electrons in the CB and photons in the VB.

- We will consider *pn* junction based photodiode type devices.

Typical Photodiode

- One-sided: $N_A \gg N_D$
  - "p+n junction"
  - depletion region in the n-side
- Window to allow photons enter the device
- Anti reflection coating to reduce light reflections
- Reverse biased
- Field exists in the depletion region and it's not uniform!
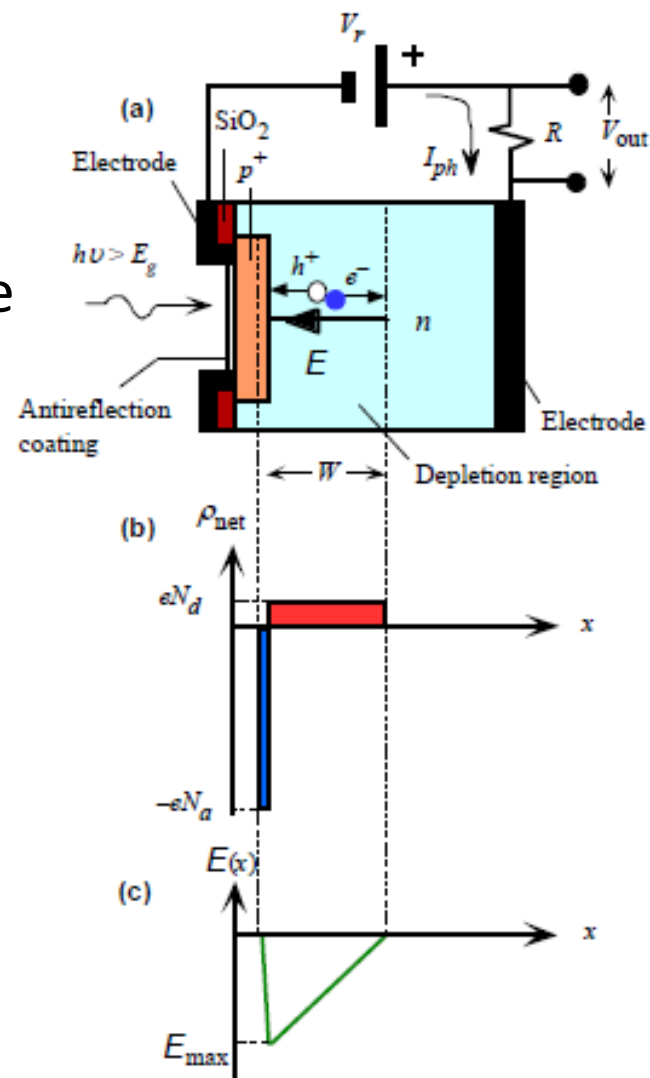
Working principle

- When a photon with an energy greater than E_g is incident, it becomes absorbed to **photogenerate** ar EHP.

- The field E then separates the EHP and drifts them.

- *Only the EHPs generated in the depletion region are separated by the electric field!*

- Drifting carriers generate a **photocurrent** I_{ph} in the external circuit.

$$I_{ph} = qN'_{EHPs} = qn'_{EHPs}WA$$

- I_{ph} depends on the rate of EHPs photogenerated.

- I_{ph} **does not depend on the wavelength of the photon.**

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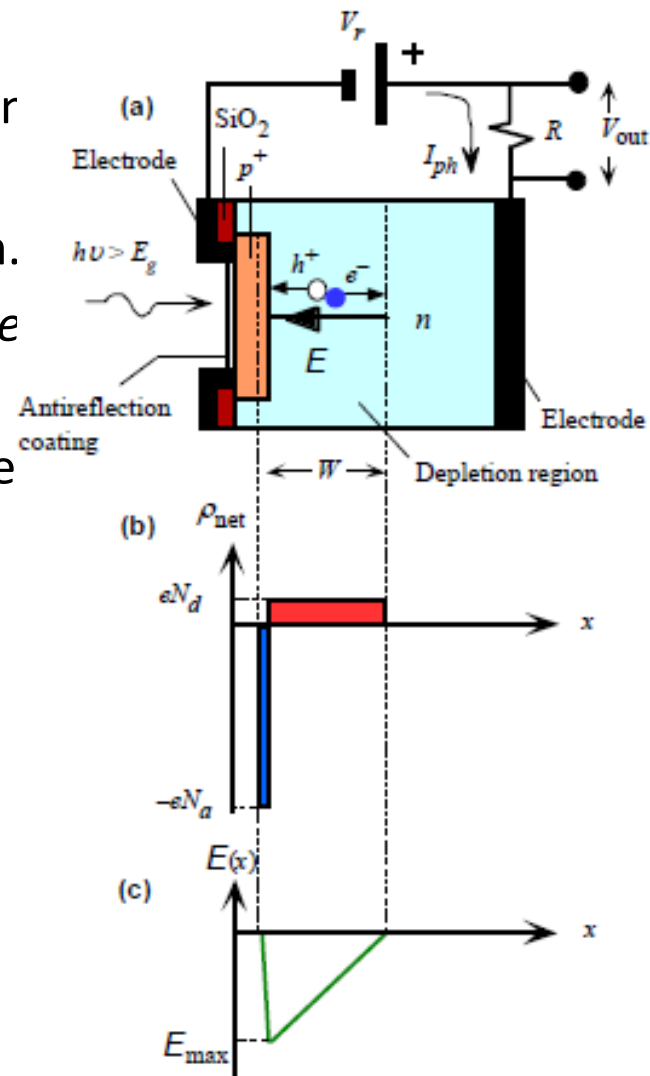
Working principle

- Photons absorbed outside the depletion region generate charges which are not separated by the field. They might either
  - recombine without contributing to the photocurrent;
  - slowly diffuse to the depletion layer.
- The diffusion length is the average distance that a carrier can travel before recombining:

$$L = \sqrt{D\tau}$$

  - τ is the average recombination time
  - D is the diffusion coefficient

$$I_{ph} = qN'_{EHPS} = qn'_{EHPS}(W + L_n + L_p)A$$

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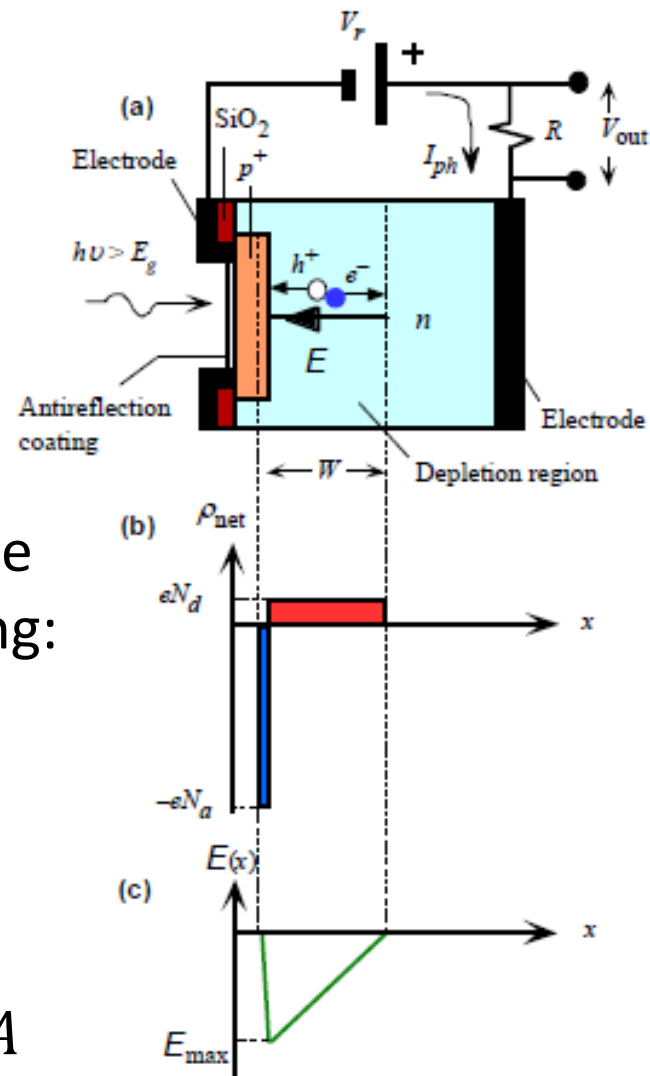
Choice of the Photodiode

- The choice of the material for a photodiode must be such that the photon energies are greater than E_g.

- At the wavelength of radiation, the absorption should occur over a depth covering the depletion region so that photogenerated EHPs can be separated by the field.

  ▪ If α is too big, absorption will occur near to the surface of the p⁺ layer, which is outside the depletion region.

  ▪ If α is too small, only a small portion of the photons will be absorbed in the depletion region.
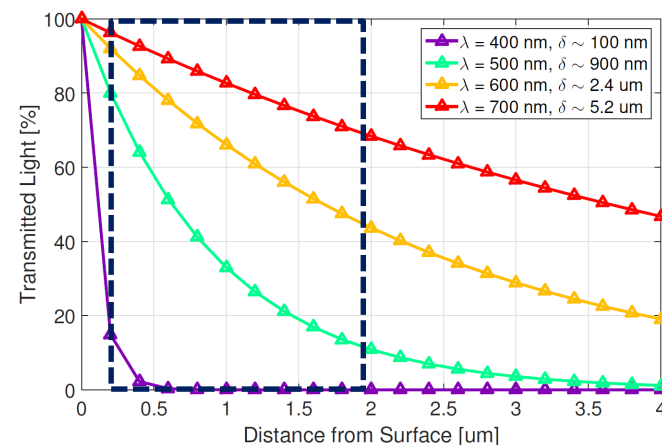
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Quantum Efficiency

- Not all incident photons are absorbed to create free EHPs that give rise to a photocurrent.

- Efficiency of conversions, or **quantum efficiency**:

$$\eta = \frac{\text{\# free EHPs generated and collected}}{\text{\# incident photons}}$$

- The rate of collected electrons is I_{ph}/q.

- If P_0 is the optical power, the rate of photons is $P_0/h\nu$. The quantum efficiency is:

$$\eta = \frac{I_{ph}/q}{P_0/h\nu}$$

Quantum Efficiency

- Not all absorbed photons may photogenerate EHPs.

- Some EHPs may recombine before being collected.

- If $W_0 \simeq \delta$, not all photons will be absorbed in the depletion region.

- Photons can be reflected at the surface.

$$\boldsymbol{\eta < 100}\%$$

Quantum Efficiency
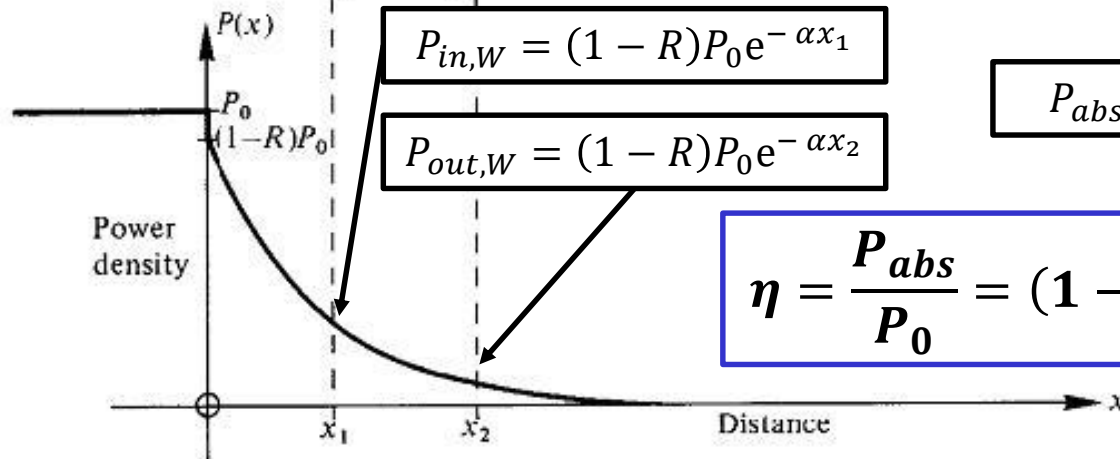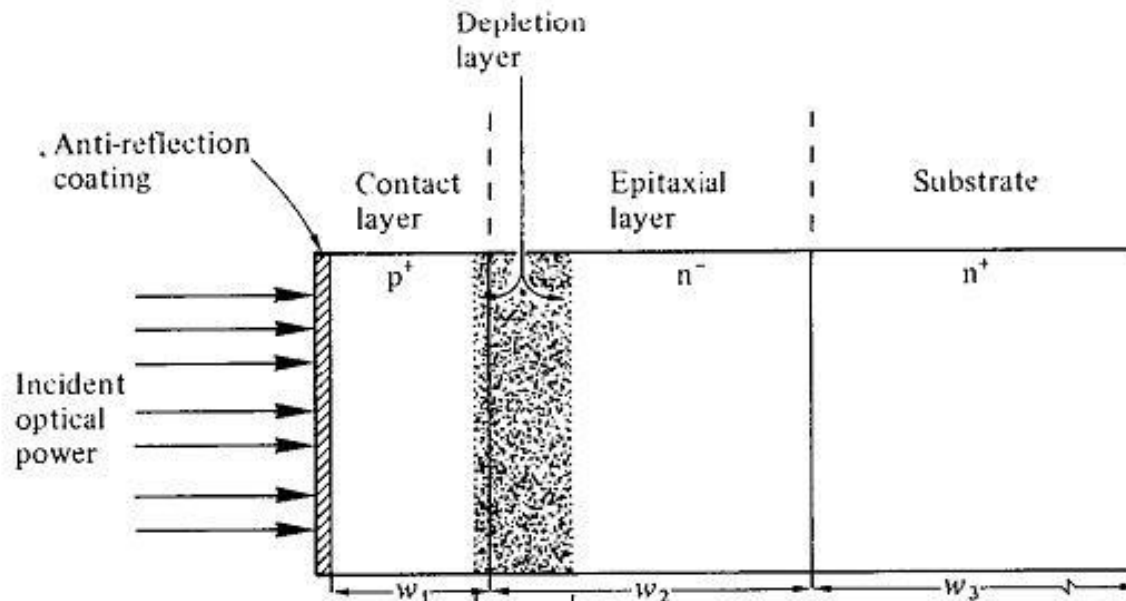
$$P_{in,W} = (1-R)P_0 e^{-\alpha x_1}$$

$$P_{out,W} = (1-R)P_0 e^{-\alpha x_2}$$

$$P_{abs} = P_{in,W} - P_{out,W}$$

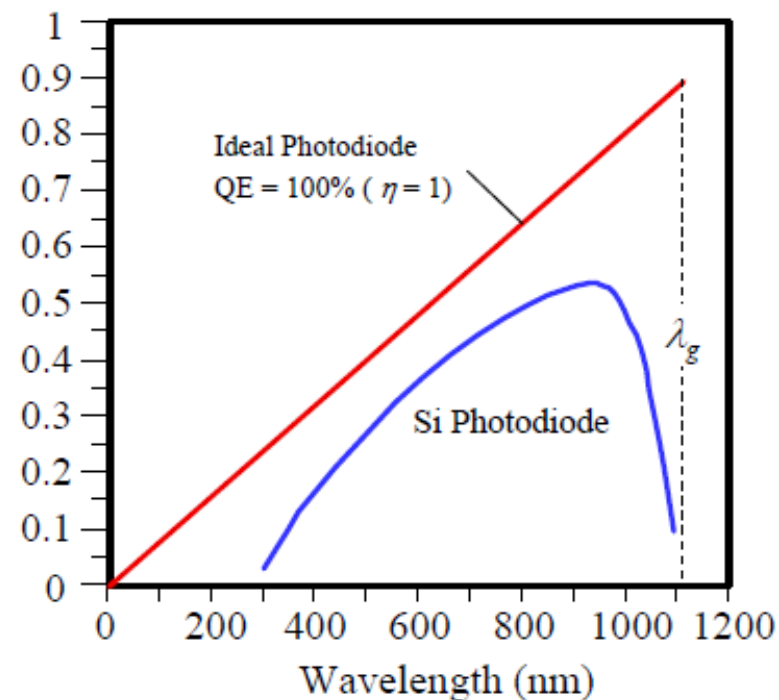$$\eta = \frac{P_{abs}}{P_0} = (1-R)e^{-\alpha x_1}(1 - e^{-\alpha W})$$

Responsivity

- The **responsivity** of a photodiode relates the photocurrent generated with the incident optical power.

$$R = \frac{I_{ph}}{P_0} = \frac{\eta q}{h \nu} = \frac{\eta q}{hc} \lambda$$

- With $\eta = 1$, R should be a ramp until λ_c.

- Real R vs λ characteristics repr the spectral response of the photodiode.

Responsivity (A/W)

Ideal Photodiode
QE = 100% ($\eta = 1$)

λ_g

Si Photodiode

Wavelength (nm)

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References

- S. O. Kasap, *Optoelectronics and Photonics (2nd Edition),* Prentice Hall, 2012

- D. A. Neamen, *Semiconductor Physics And Devices - Basic Principles (4th Edition),* McGraw-Hill, 2011