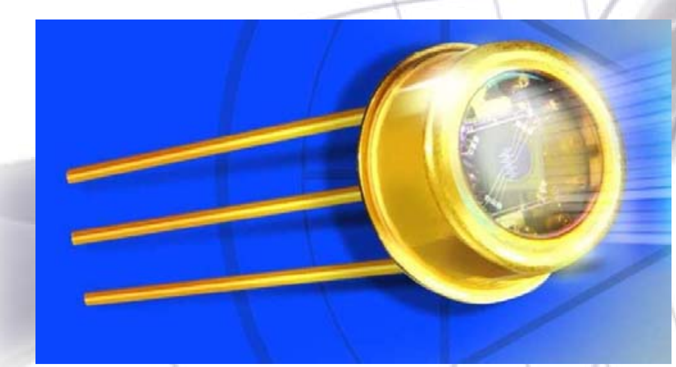
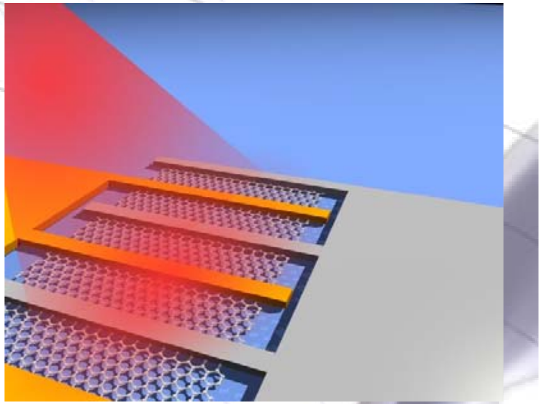




Lesson 9

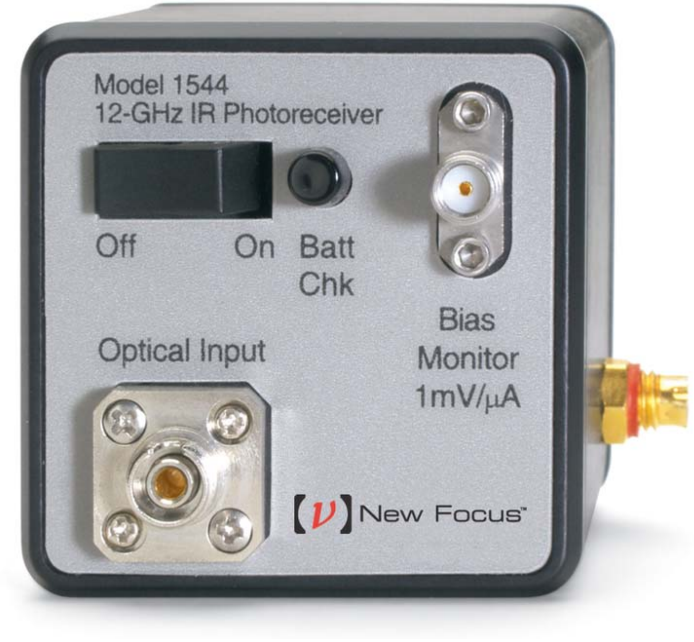
Photodetectors

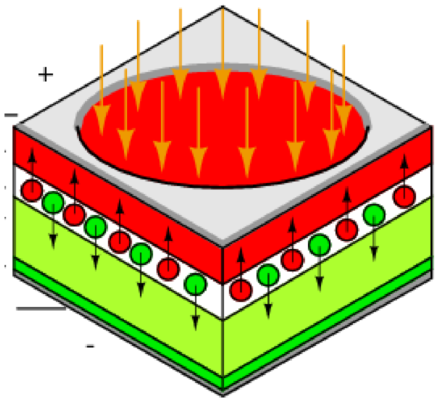
Chen-Bin Huang

Department of Electrical Engineering
National Tsing Hua University, Taiwan

Motivation and usage

- Modulators: E/O conversion
- PDs: convert optical signal to electrical signal
  - **O/E** conversion





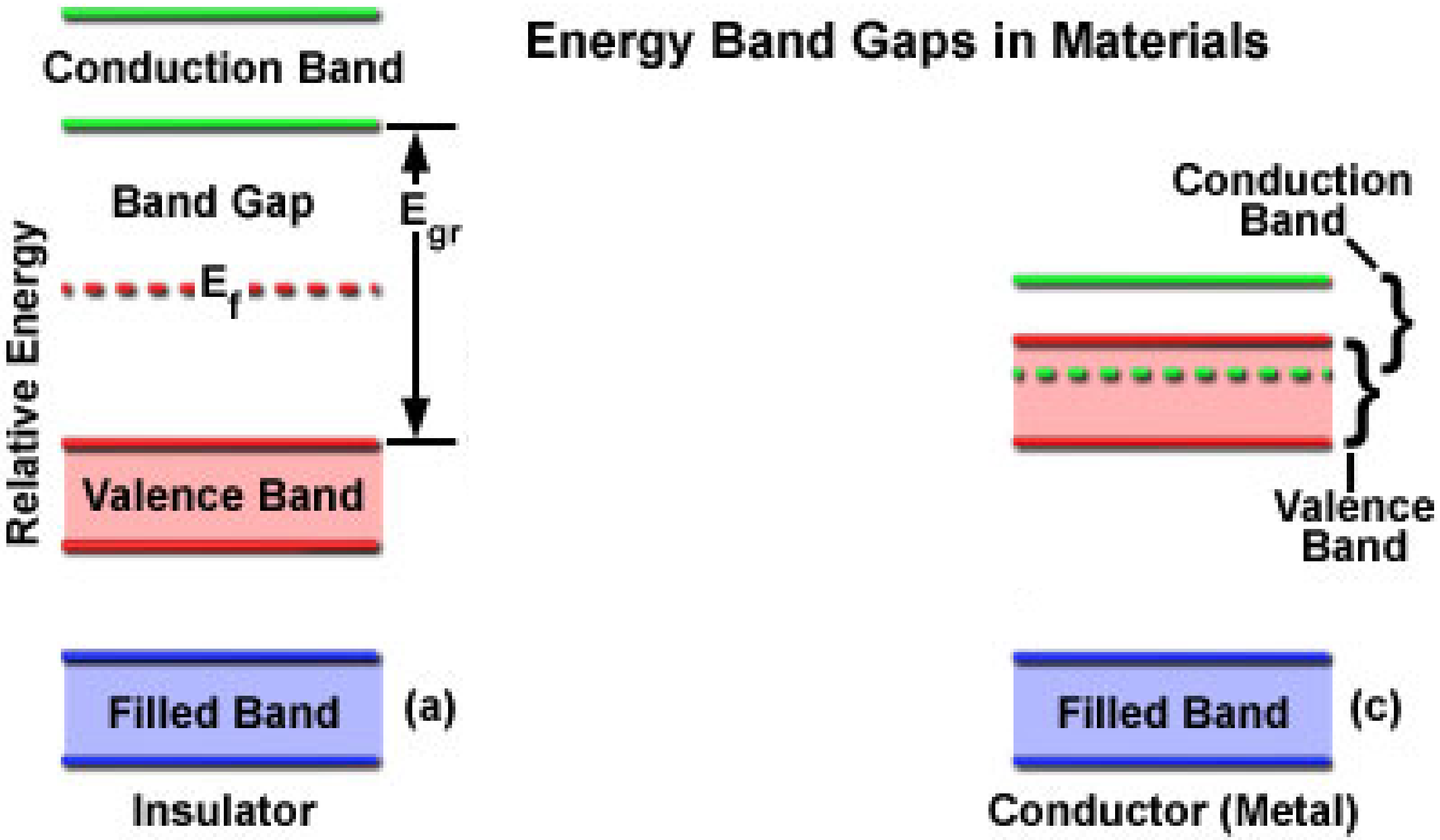
Outline

- Concept of semiconductor and energy bandgap

- pn junction
- Photodetector types
- Quantum efficiency

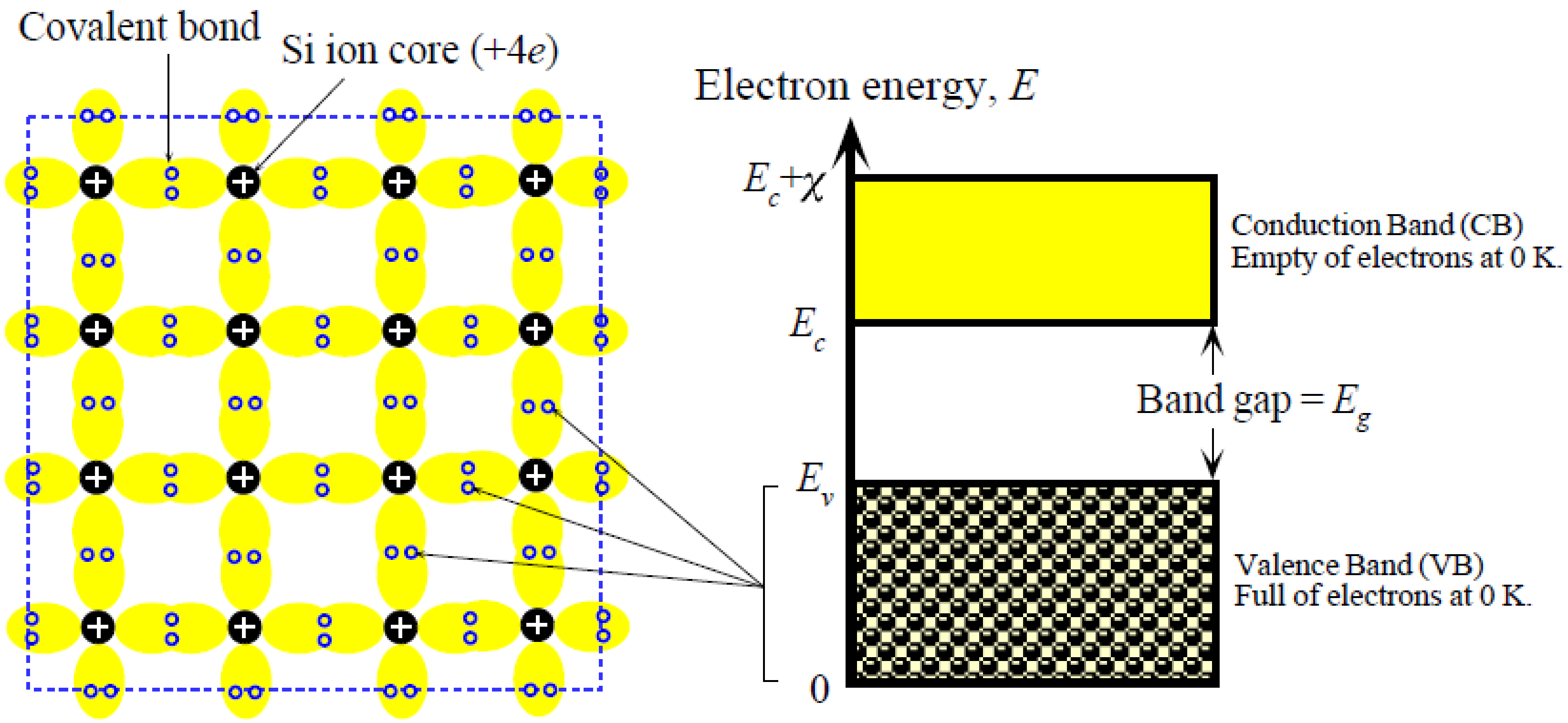
Materials classified by “bandgap”

- Insulator
- Conductor
- Semiconductor



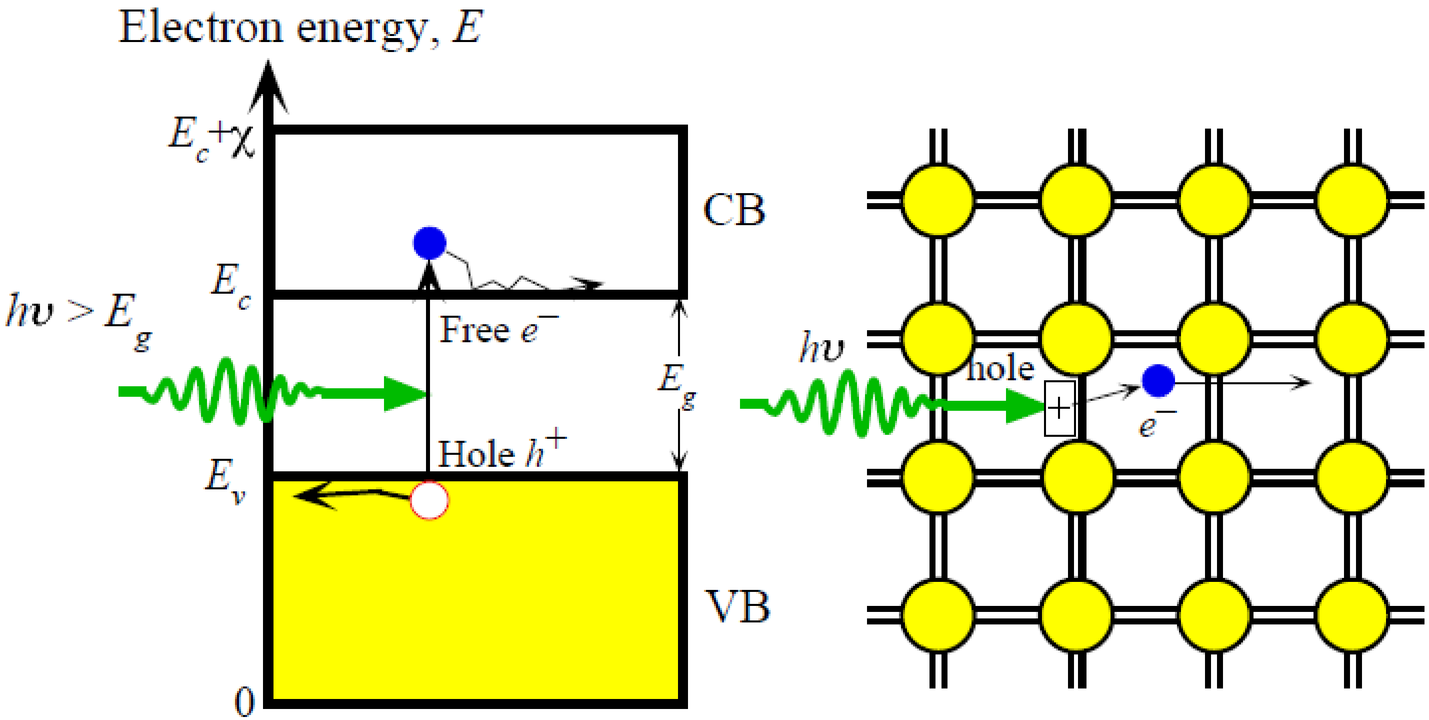
Energy bandgap of semiconductor

- Lattice defined



A photon can excite an electron: O/E conversion

- The photon energy needs to be grater than E_g
- The excited free electron-hole pair can wander freely
- Free electron and hole both contribute to photocurrent

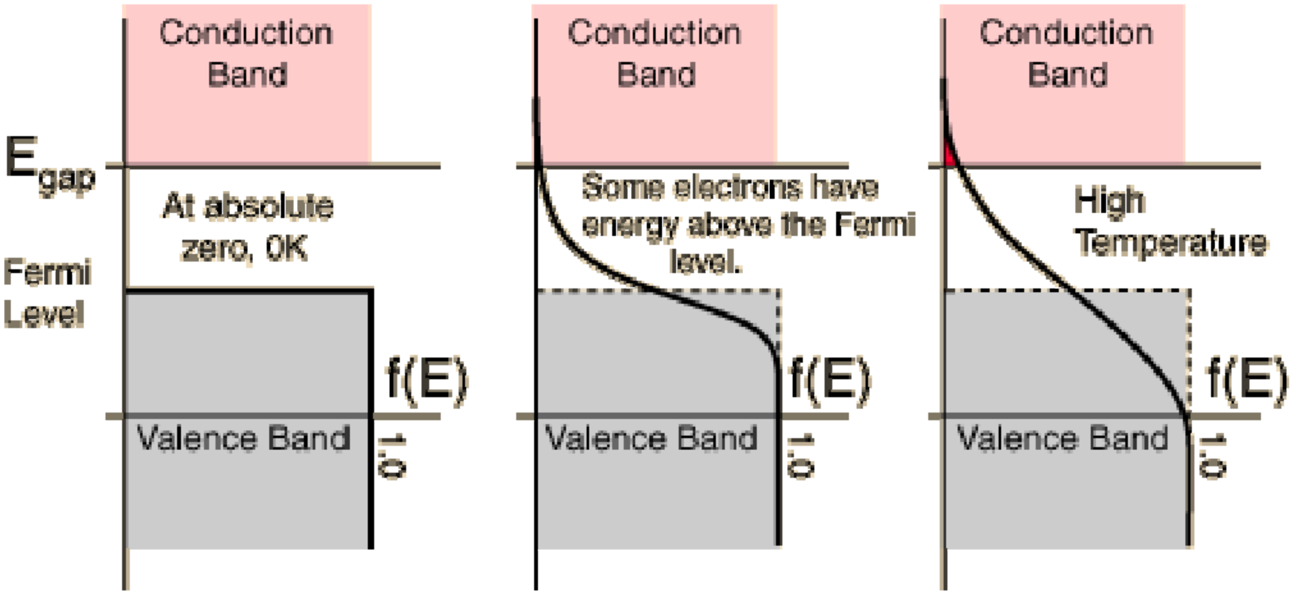


The Fermi level

- Determines the concentration of electron and hole

$$f(E)=\left[1+\exp\left(\frac{E-E_f}{k_BT}\right)\right]^{-1}$$

$$f(E_f)=0.5$$



No electrons can be above the valence band at 0K, since none have energy above the Fermi level and there are no available energy states in the band gap.

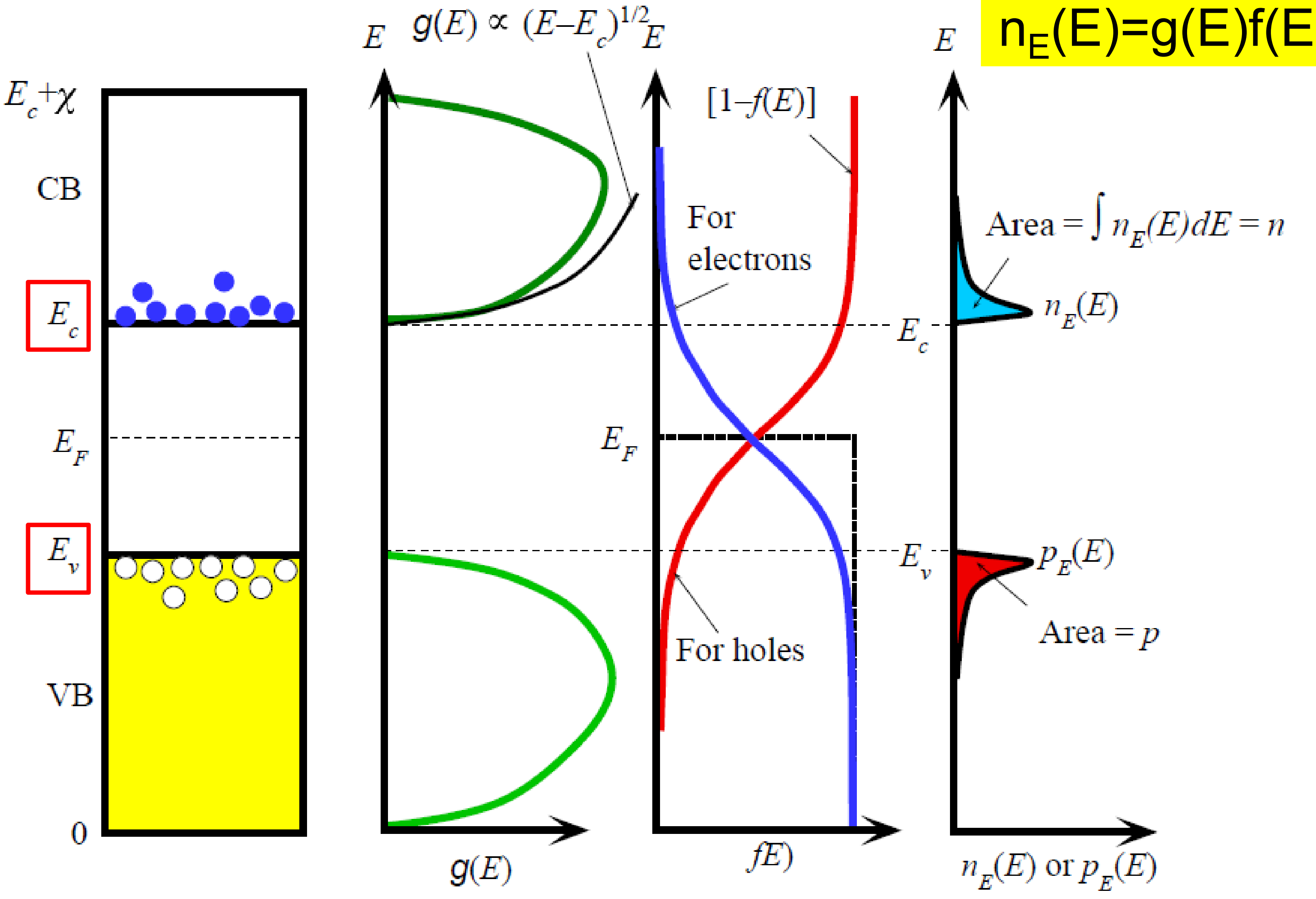
At high temperatures, some electrons can reach the conduction band and contribute to electric current.

Energy density

- Number of carriers per energy per volume

g(E): density of state

$n_E(E)=g(E)f(E)$



Number of carriers

- When $(E-E_f) >> k_B T$

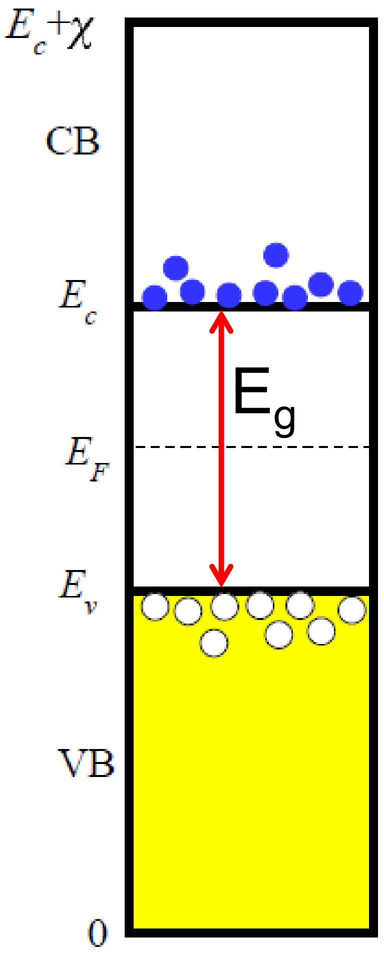
N_c, N_v: effective DOS

$$f(E)=\left[1+\exp\left(\frac{E-E_f}{k_B T}\right)\right]^{-1} \rightarrow \exp\left[-\frac{(E-E_f)}{k_B T}\right]$$

$$n=N_c \exp\left[-\frac{(E_c-E_f)}{k_B T}\right],\ N_c=2\left[\frac{2\pi m_e^* k_B T}{h^2}\right]^{3/2}$$

$$p=N_v \exp\left[-\frac{(E_f-E_v)}{k_B T}\right],\ N_v=2\left[\frac{2\pi m_h^* k_B T}{h^2}\right]^{3/2}$$

$$np=N_c N_v \exp\left[-\frac{E_g}{k_B T}\right]=n_i^2$$

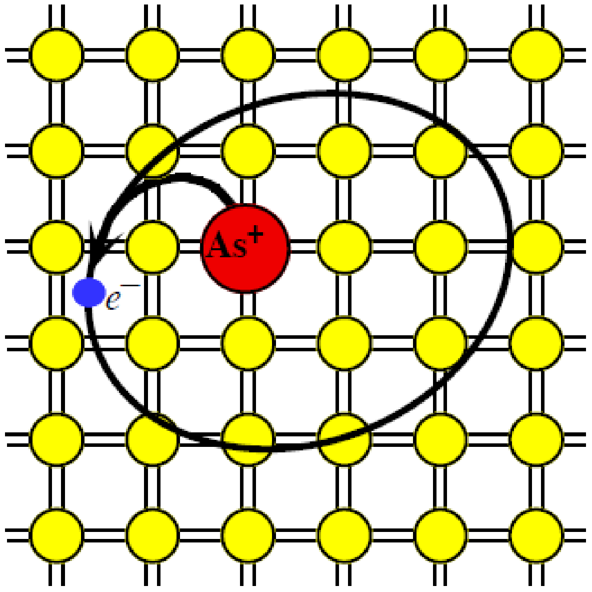


Changing the Fermi level

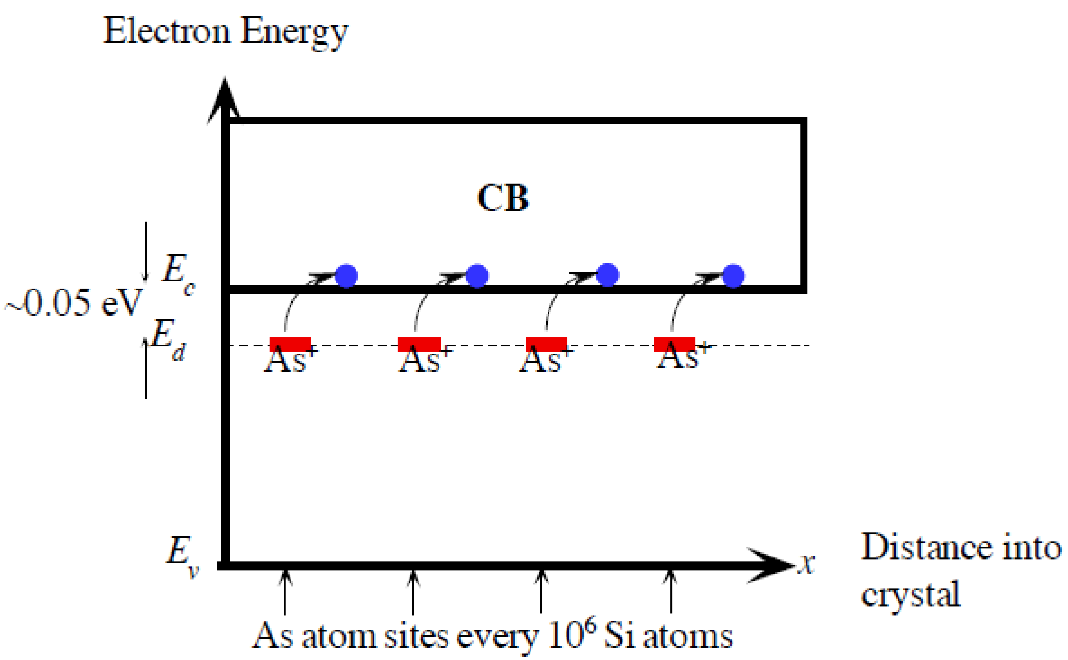
- Doping impurities with excess electrons (donor) N_d
  - Example: As into Si
- n-type semiconductor

$$n \simeq N_d, \ p = \frac{n_i^2}{N_d}$$

(a)



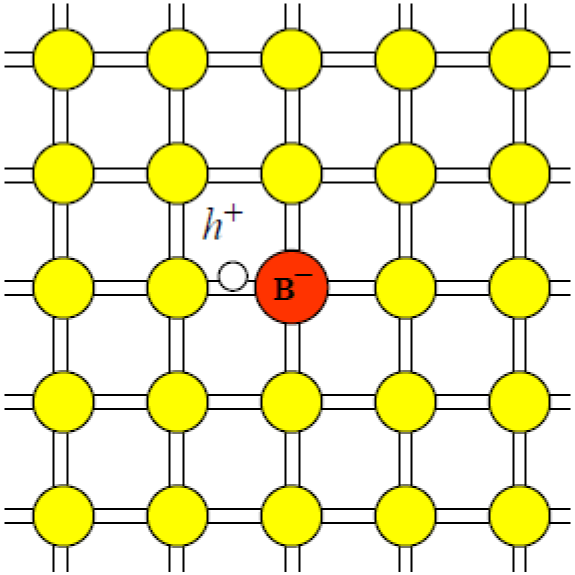
(b)

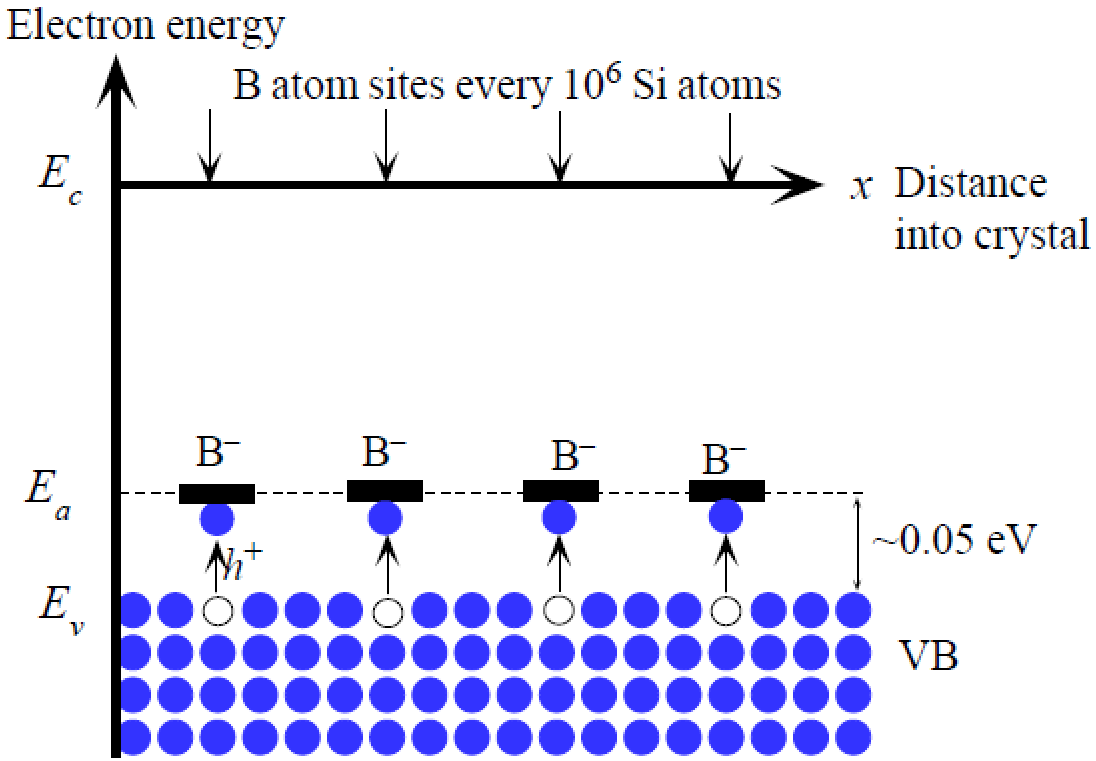


Changing the Fermi level

- Doping impurities with excess hole (acceptor) N_a
  - Example: B into Si
- p-type semiconductor

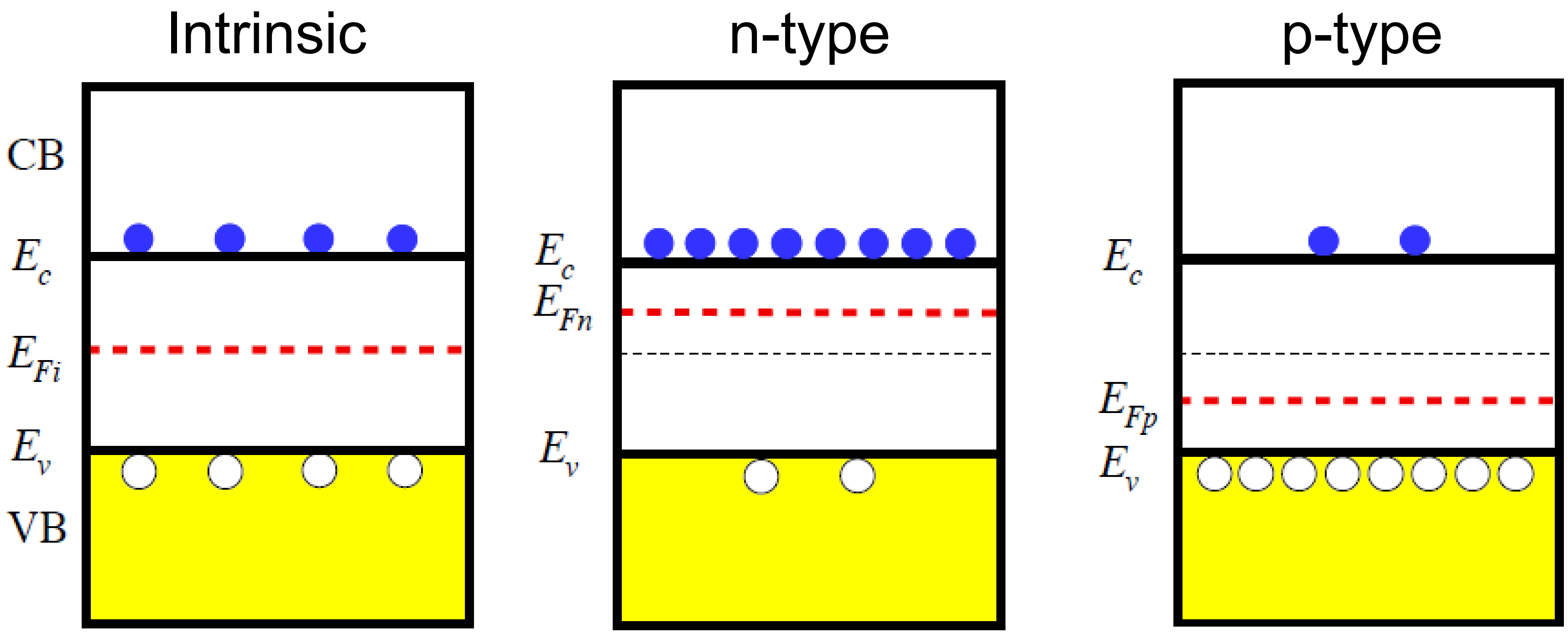
$$p \simeq N_a, \quad \mathrm{n} = \frac{n_i^2}{N_a}$$





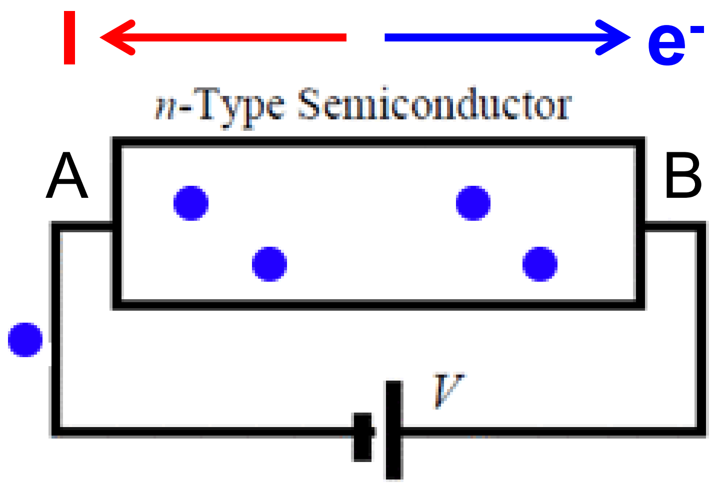
Energy band diagrams for semiconductors

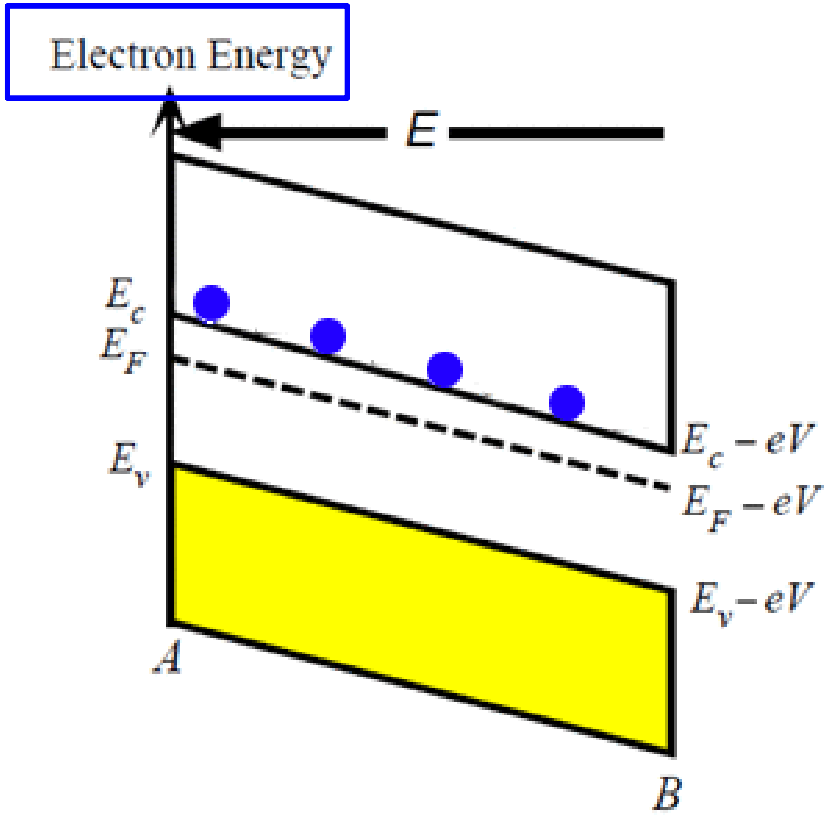
- Classified according to the Fermi level



When you apply an external field

- Bending of the band diagram
- Positive voltage ⇔ lower electron energy
- Electron flow: reverse direction of current flow





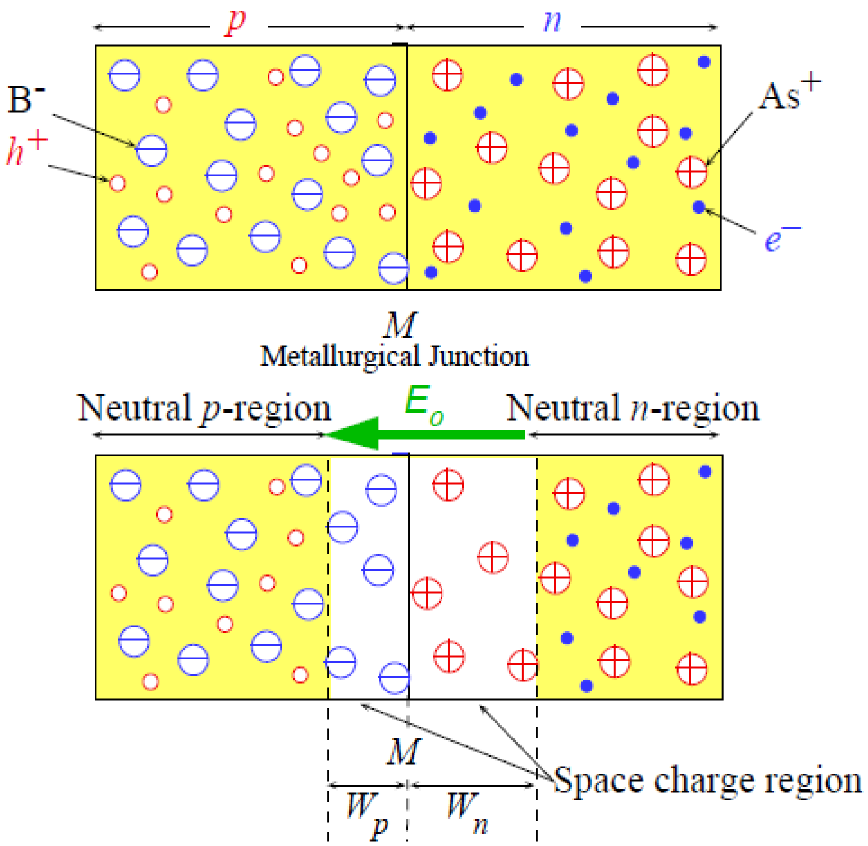
- Concept of semiconductor and energy bandgap

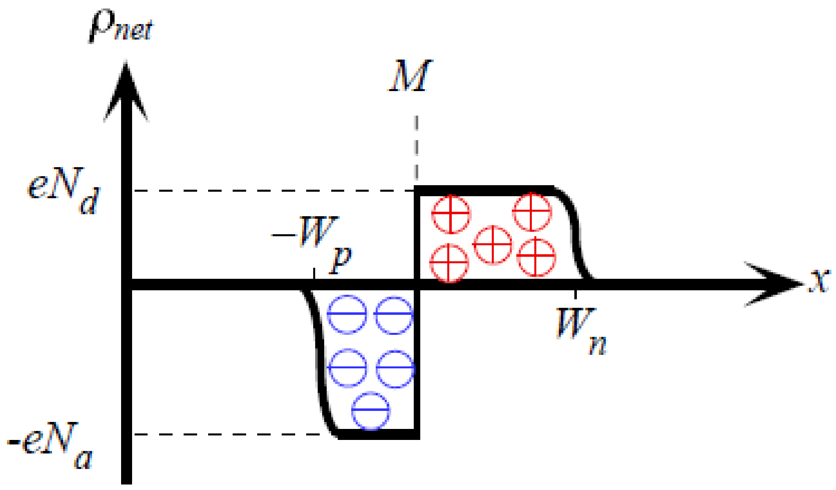
- pn junction
  - Depletion region
  - Built-in voltage
  - Biasing

- Photodetector types
- Quantum efficiency

pn-junction

- Formation of depletion region or space-charge layer





pn-junction

- Gives rise to a built-in voltage V_0

$$\frac{\partial \vec{E}}{\partial x} = \frac{\rho_{net}(x)}{\varepsilon} \quad \Rightarrow E = \int \frac{\rho_{net}(x)}{\varepsilon} \bullet dx$$

$$E_0 = -\frac{qN_D W_n}{\varepsilon} = -\frac{qN_A W_p}{\varepsilon}$$

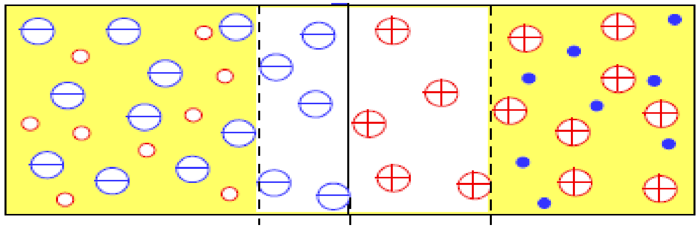
$$\vec{E} = -\nabla V = -\frac{\partial V}{\partial x} \quad \Rightarrow V = -\int E \bullet dx$$

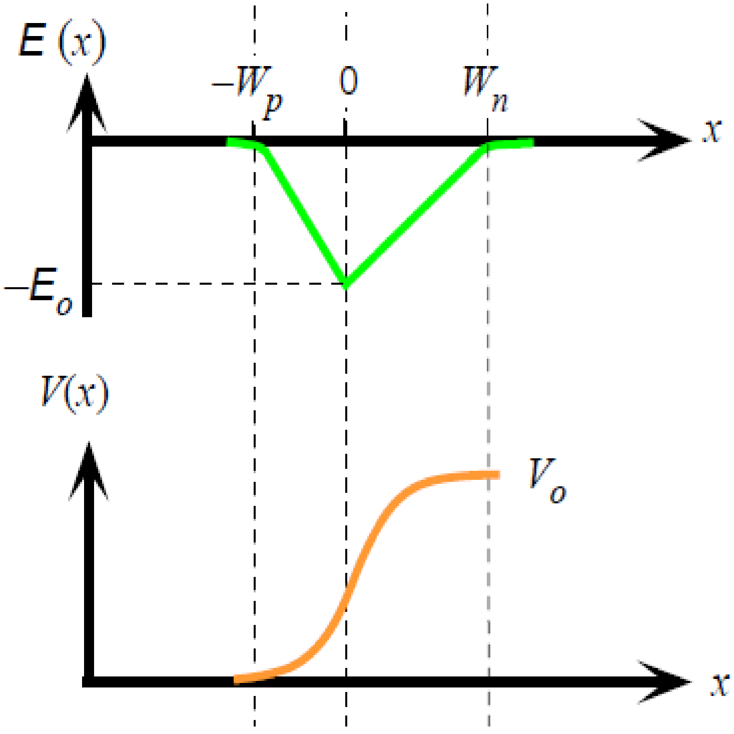
$$W_p = W_0 \frac{N_D}{N_A + N_D}; W_n = W_0 \frac{N_A}{N_A + N_D}$$

(charge neutrality)

$$V_0 = -\frac{1}{2} E_0 W_0 = \frac{qN_A N_D W_0^2}{2\varepsilon(N_A + N_D)}$$

$$\nabla \bullet \vec{D} = \rho_{net}$$





Built-in voltage

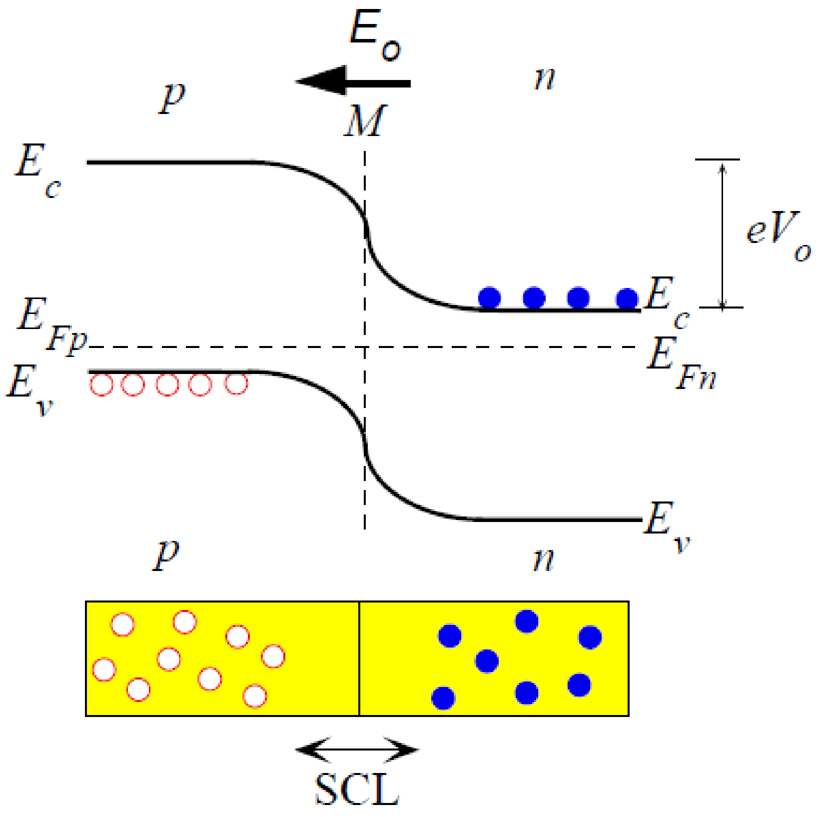
- Detailed derivations

$$qV_0 = [E_{cp} - E_{fp}] - [E_{cn} - E_{fn}]$$

$$\frac{n_i^2}{N_A} = N_C \exp[\frac{-(E_{cp} - E_{fp})}{kT}] \quad \Rightarrow (E_{cp} - E_{fp}) = kT \ln(\frac{N_A N_C}{n_i^2})$$

$$N_D = N_c \exp[\frac{-(E_{cn} - E_{fn})}{kT}]$$

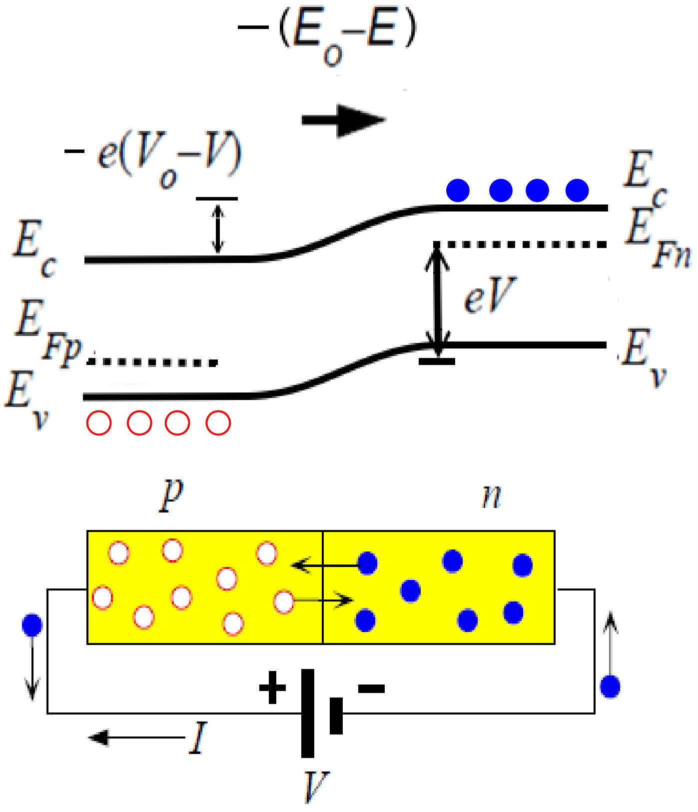
$$\Rightarrow (E_{cn} - E_{fn}) = kT \ln(\frac{N_C}{N_D})$$

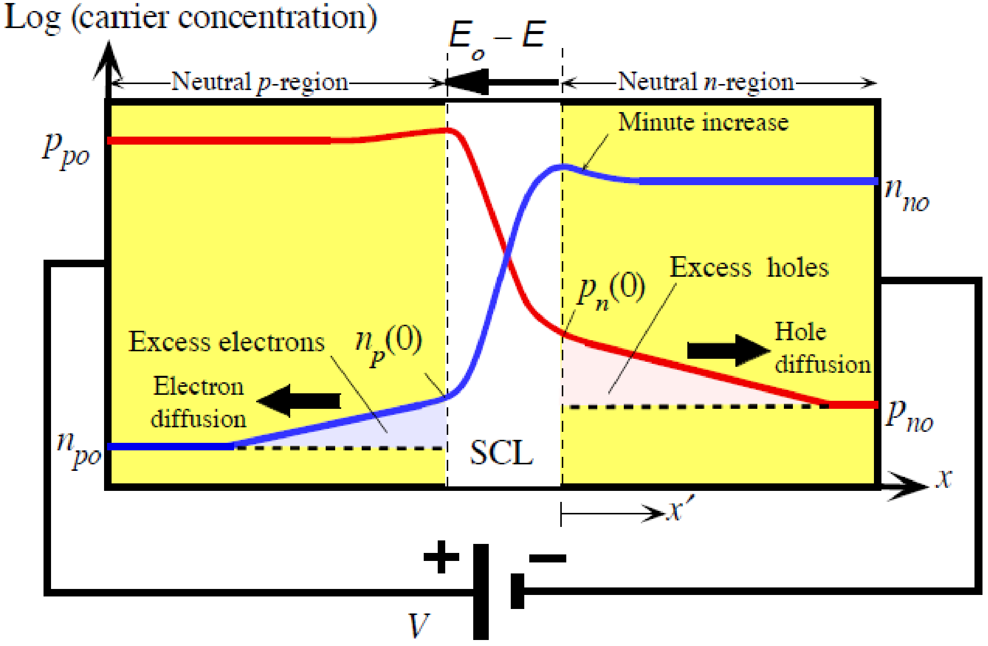


$$V_0 = \frac{kT}{q} \ln(\frac{N_A N_D}{n_i^2}) = \frac{qN_A N_D W_0^2}{2\varepsilon(N_A + N_D)}$$

Forward-bias the pn-junction

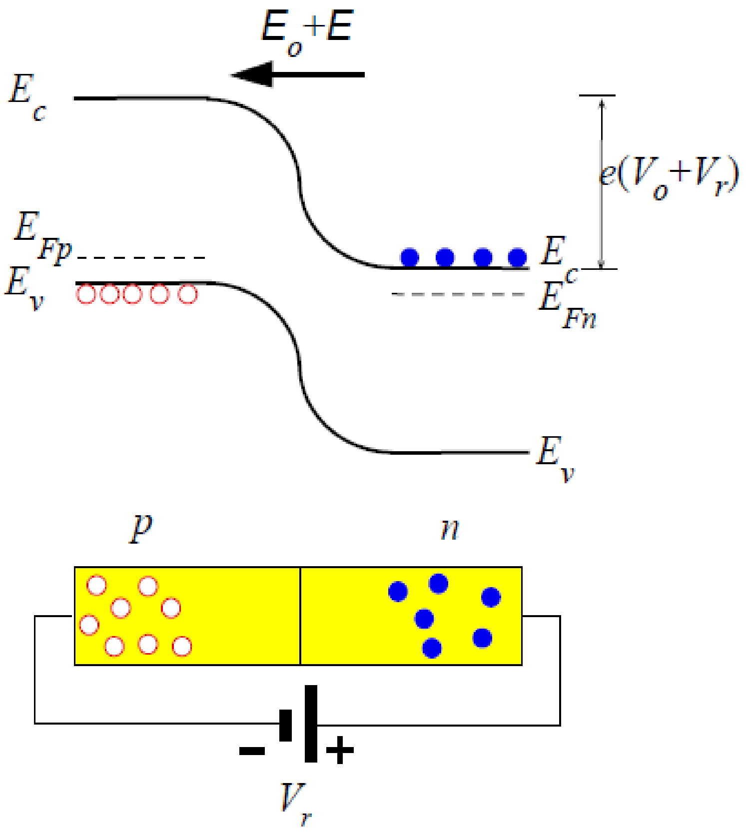
- Huge electrical current
  - Is this what we want?

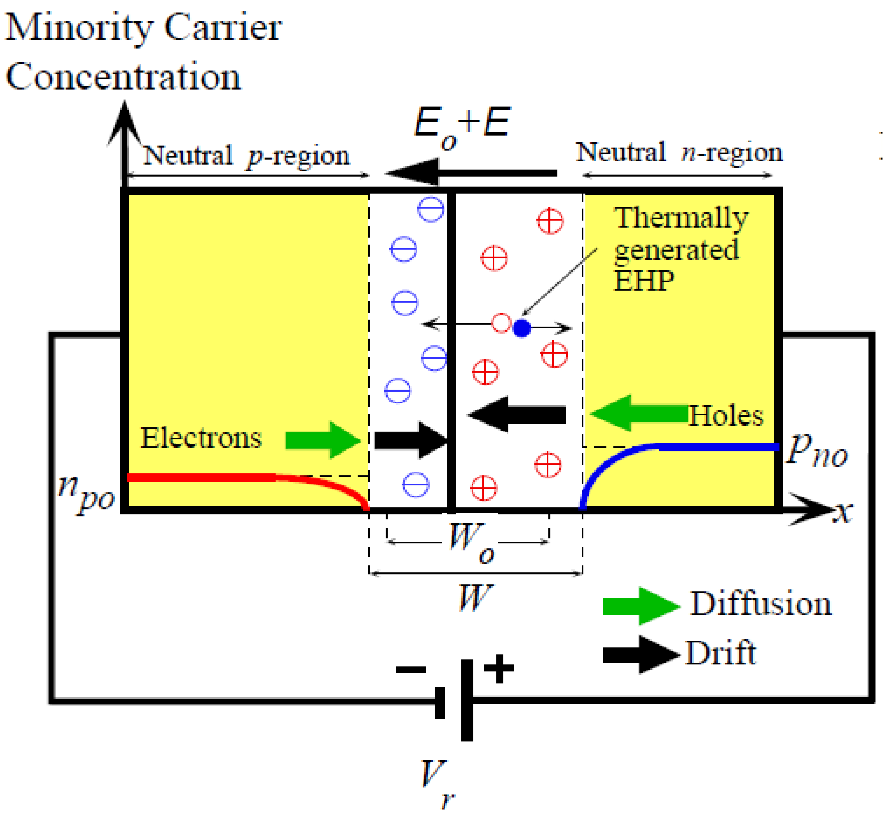




Reverse-bias the pn-junction

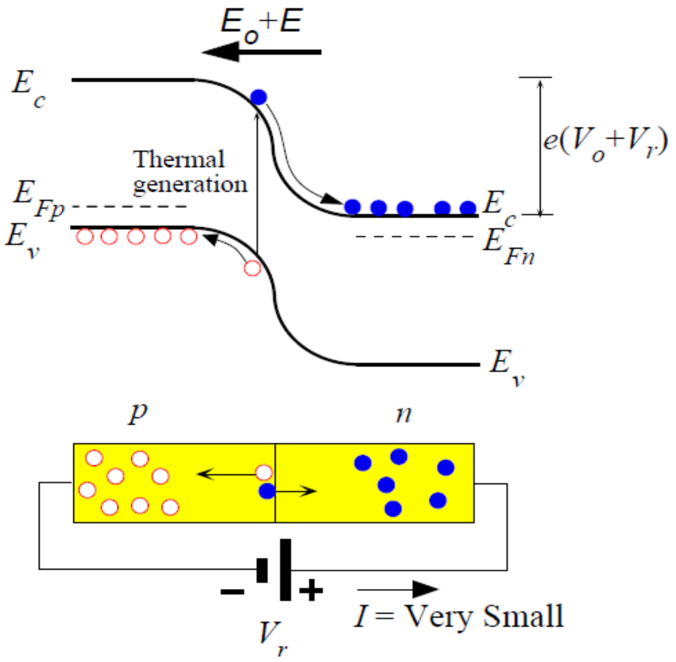
- For photodetection
  - Current only generated by photons
  - Increases depletion length

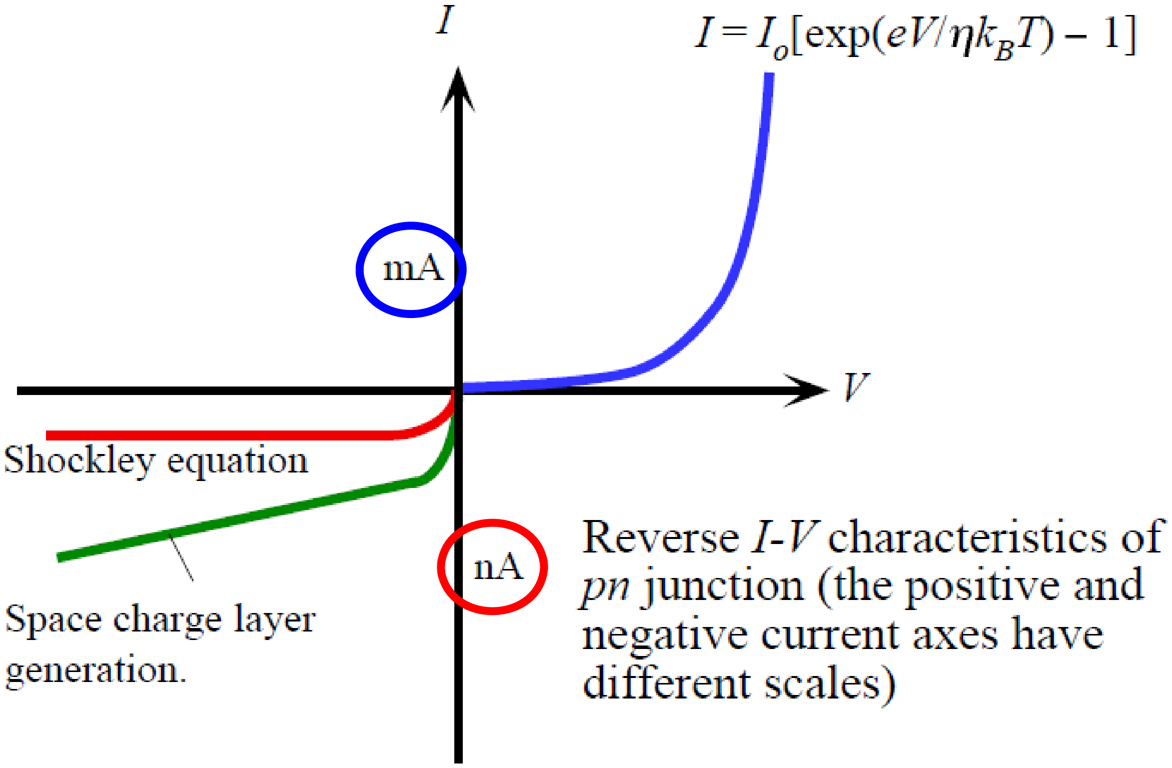




Current vs. bias voltage

- Diode characteristic





Reverse I-V characteristics of a *pn* junction (the positive and negative current axes have different scales)

- Concept of semiconductor and energy bandgap
- pn junction

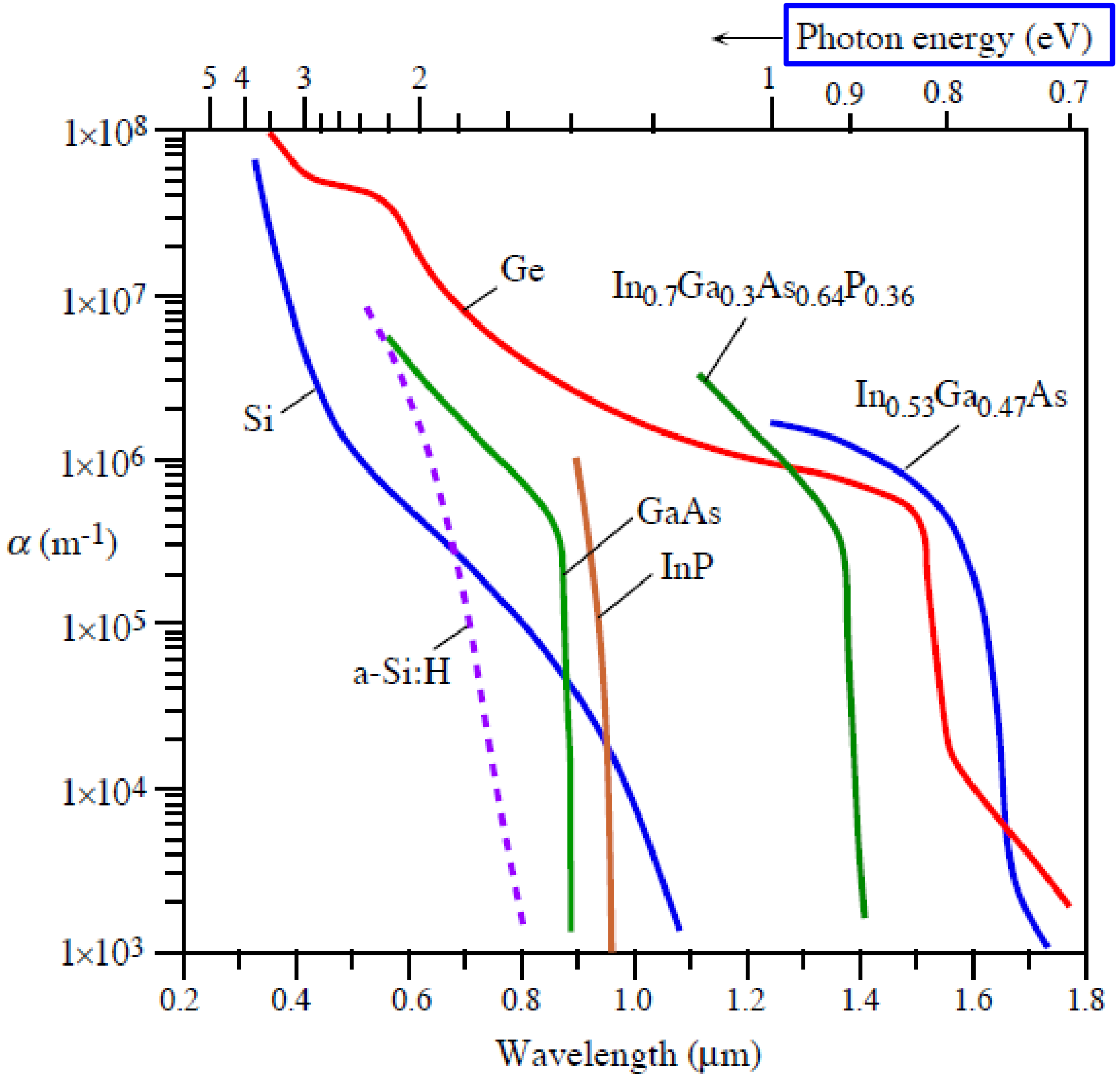
- Photodetector types
  - Absorption coefficient and materials
  - pn-junction photodiode
  - pin photodiode
  - Avalanche photodiode
  - Heterojunction photodiodes
  - Photoconductive photodiodes

- Quantum efficiency

Absorption coefficients of various materials

- Si: 400~1100 nm
- InGaAs: 900~1700 nm
- eV

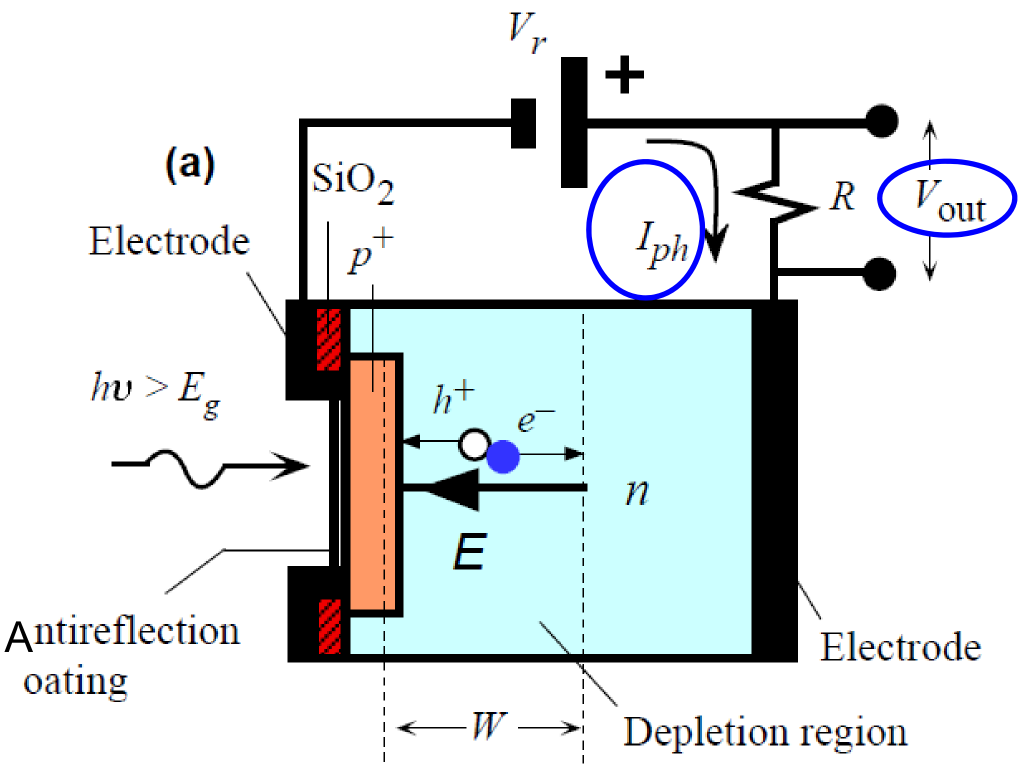
$$\frac{h\nu}{q} = \frac{hc}{q\lambda} \doteq \frac{1.24}{\lambda(\mu m)}$$

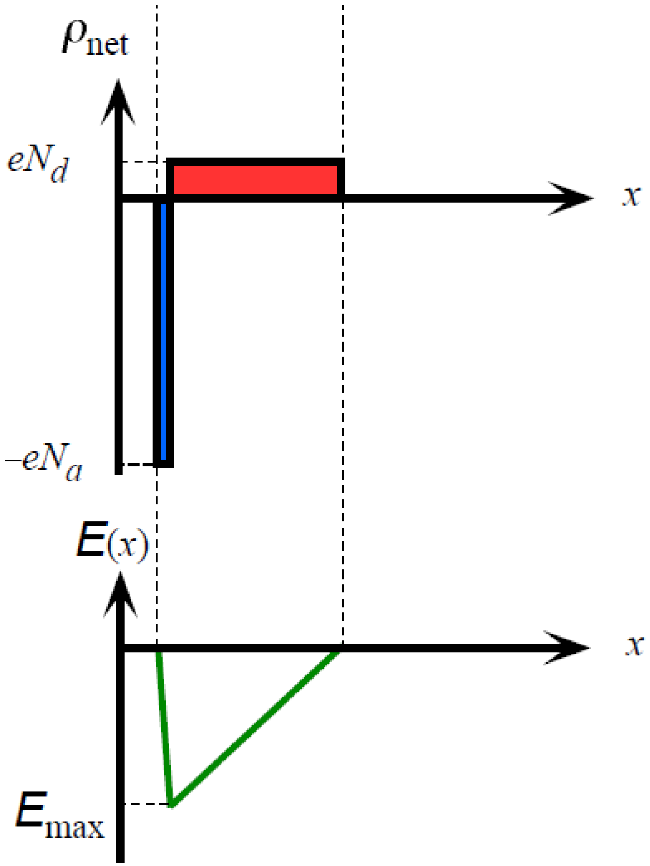


pn photodiodes (PD)

- Reverse-bias a pn-junction
- p+ layer thin, almost entirely depletion
- Photocurrent ➔ voltage
- Capacitance depends on bias

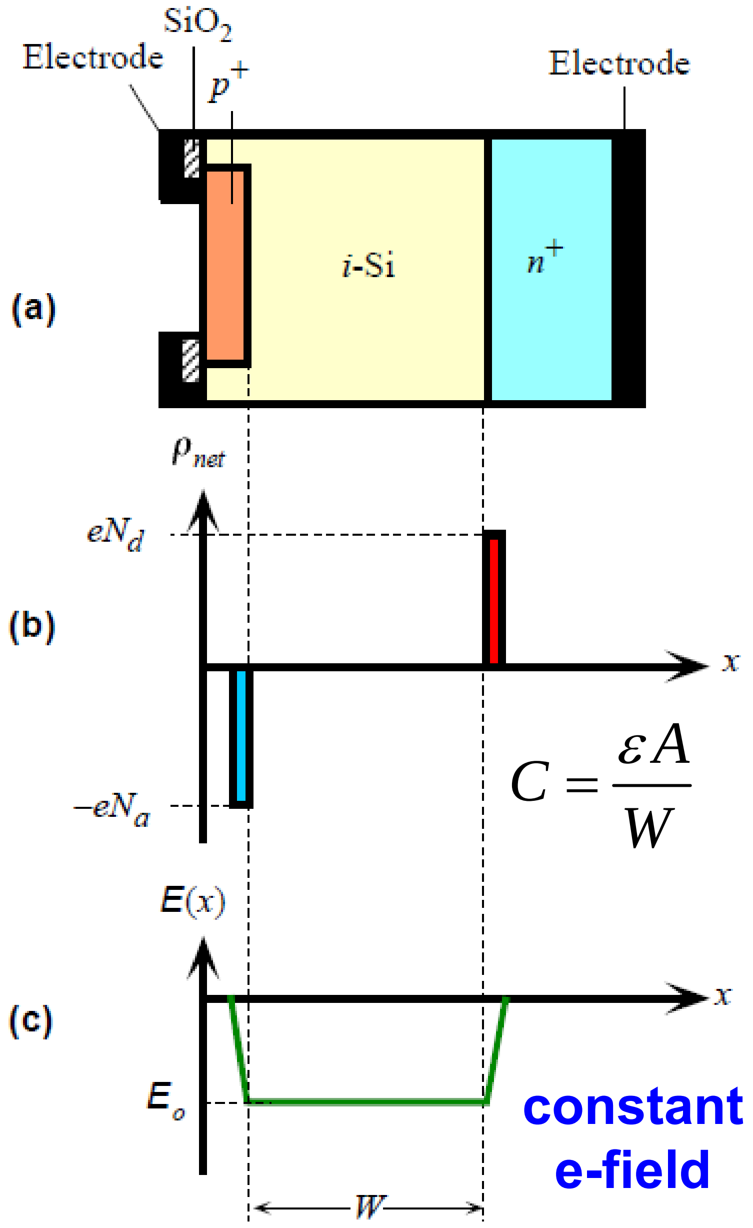
$$C = \frac{\varepsilon A}{W}$$





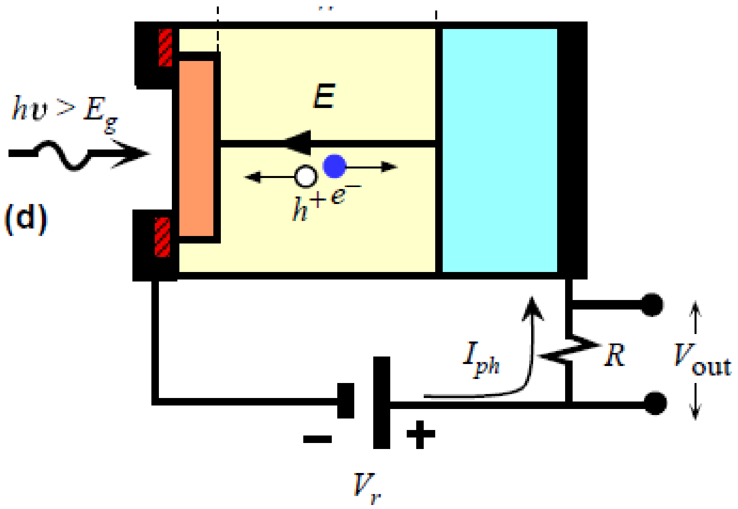
pin PDs

- A sandwiched intrinsic layer
  - Reduce capacitance
  - Longer absorption length
  - Constant e-field
  - Fixed junction capacitance



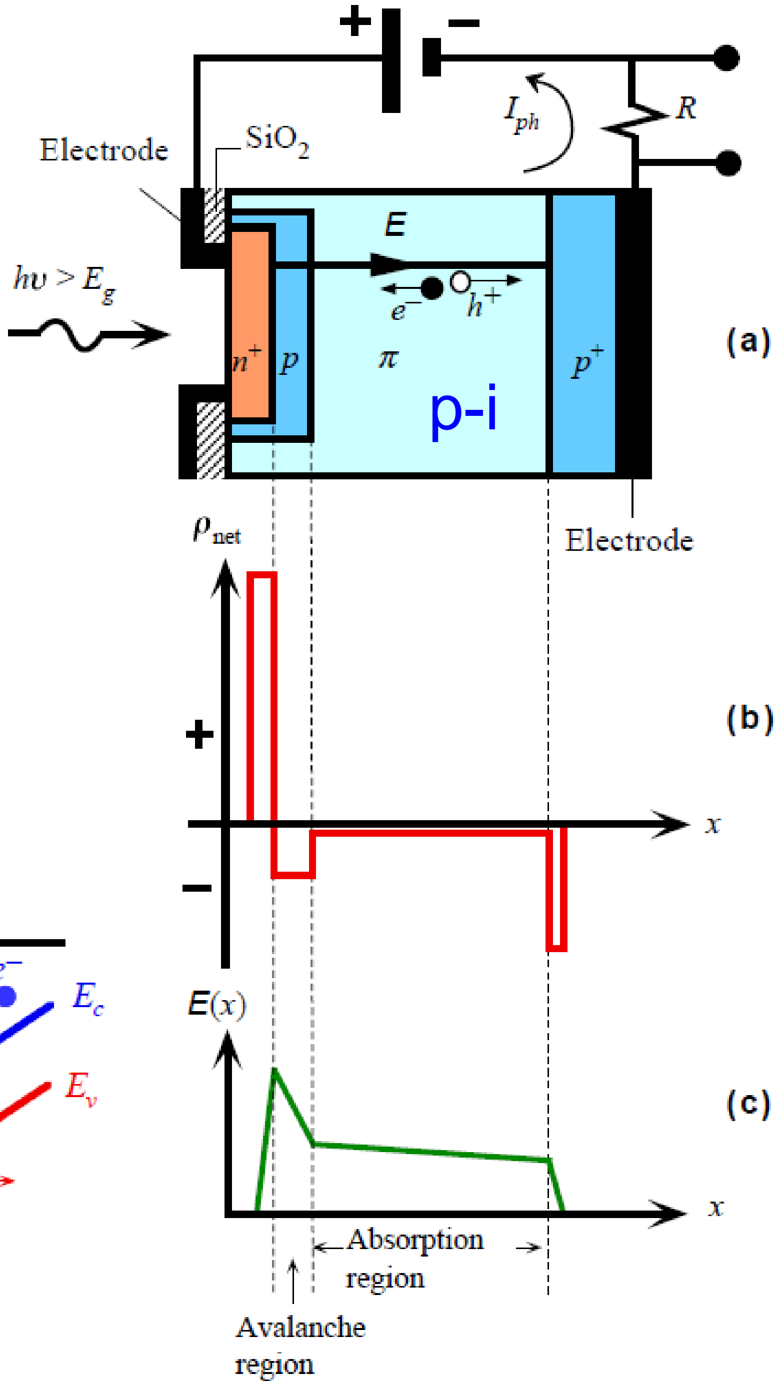
$$C = \frac{\varepsilon A}{W}$$

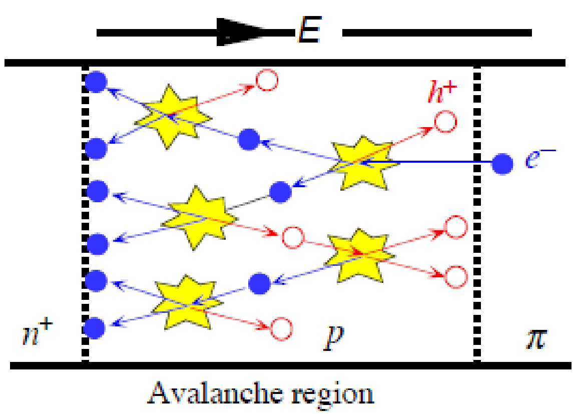
constant e-field

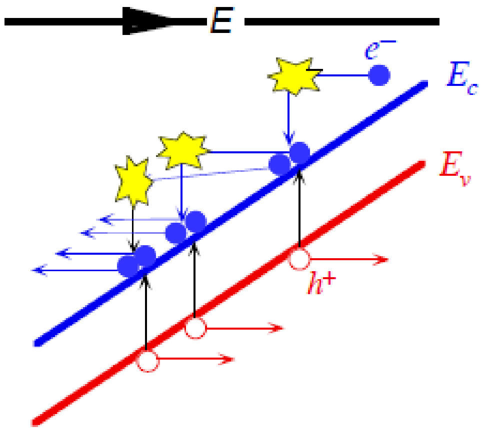


Avalanche PDs

- Current multiplication/gain
  - Acceleration ➔ impact ionization

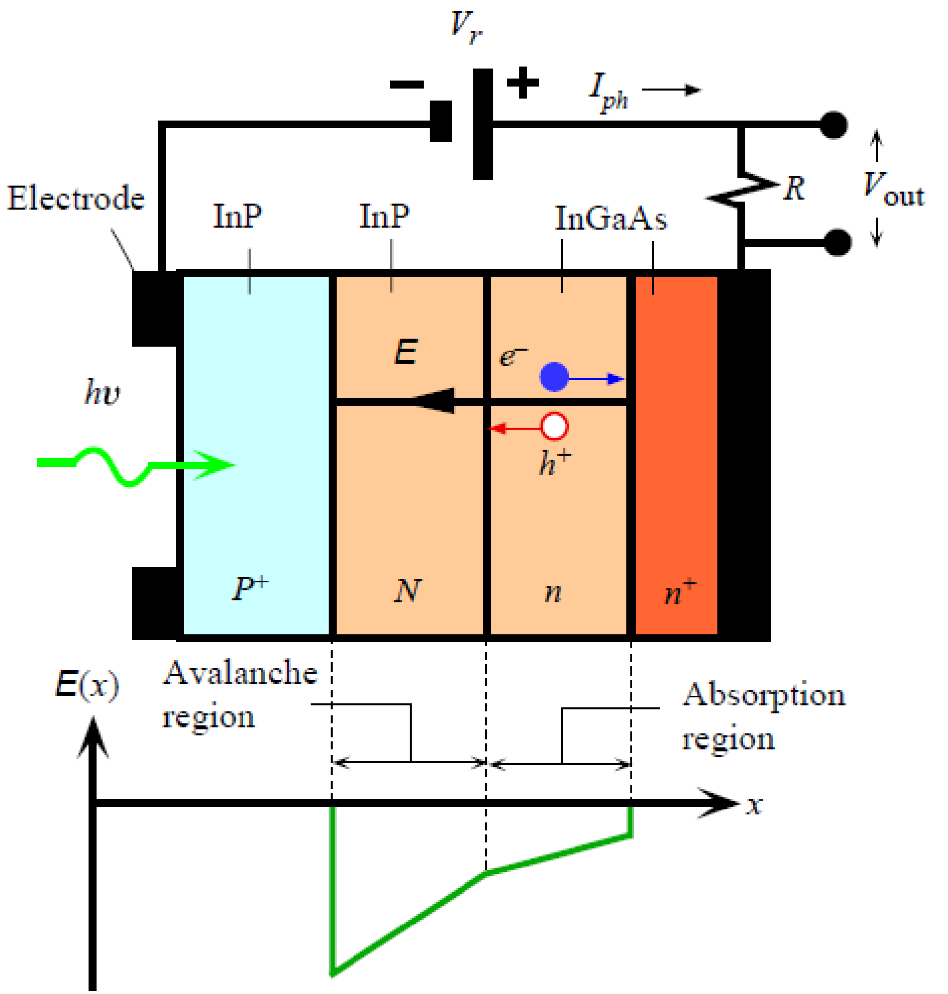






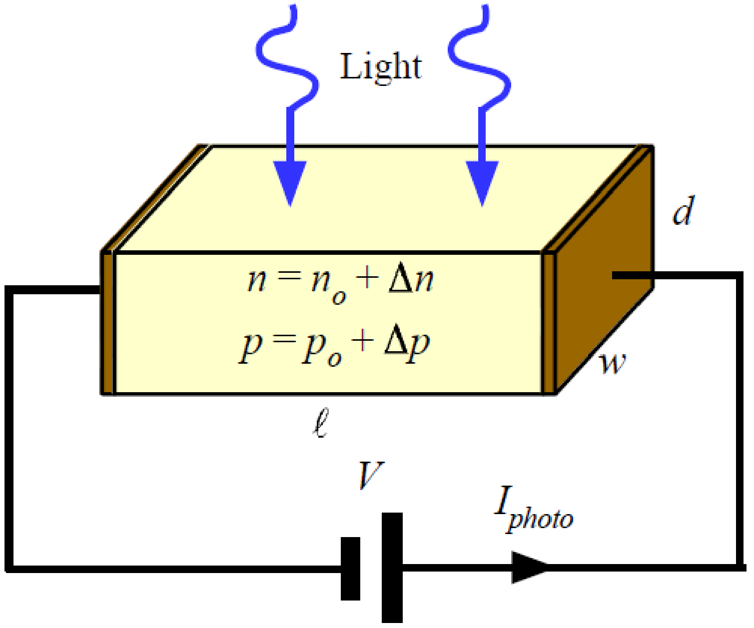
Heterojunction PDs

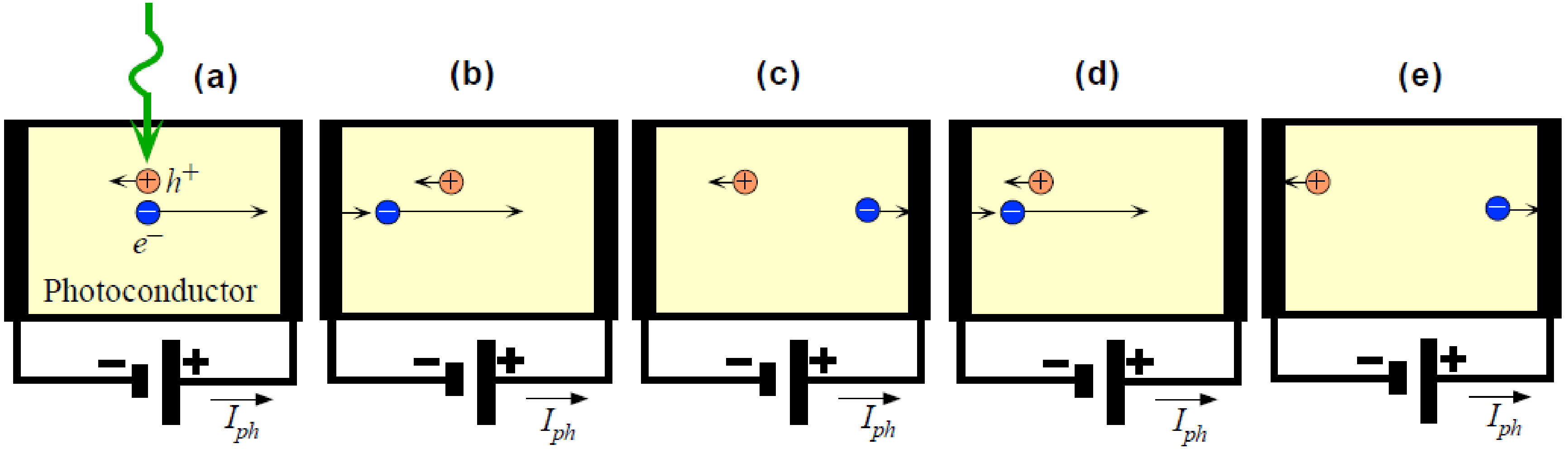
- $E_{g,InP} > E_{g,InGaAs}$
- Holes multiplied through avalanche process



Photoconductive PDs

- No junction
- Photoconductive gain
  - Electron mobility very fast
  - Charge neutrality needs be maintained





- Concept of semiconductor and energy bandgap
- pn junction
- Photodetector types

- Quantum efficiency

Responsivity (R)

- Quantum efficiency

$$\eta = \frac{\text{\# of free e-h pairs}}{\text{\# of input photons}} = \frac{I_{ph}/q}{I_0/h\upsilon} < 1$$

$$R = \frac{I_{ph}}{I_0} = \eta \frac{q}{h\upsilon}$$