EE 331 Devices and Circuits I

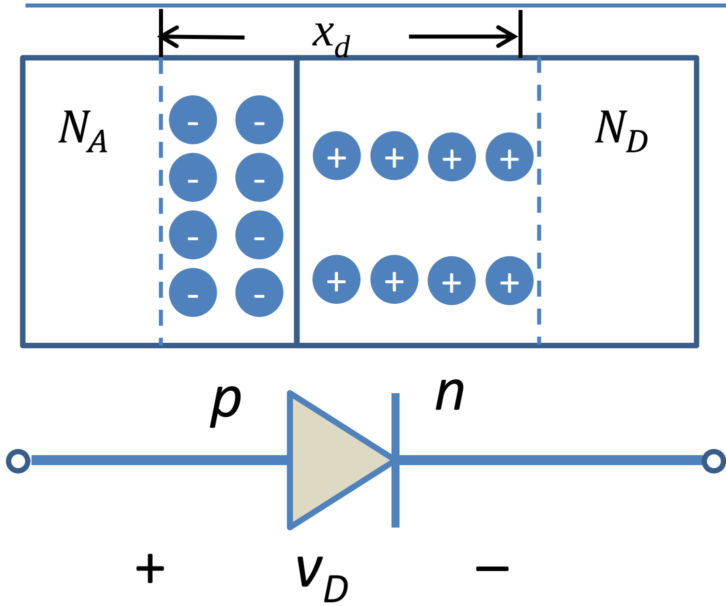
Chapter 3

Diodes – Switching and Photovoltaics

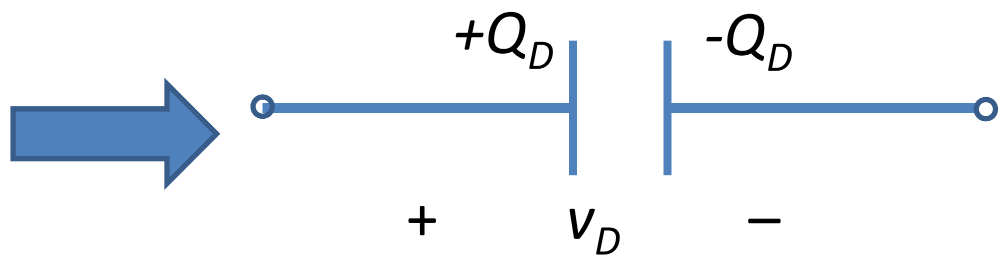
Announcements

- HW #3 due Friday in class. Make a copy if you want it for reference/studying.
- Exam #1 on Monday 4/28 (Semiconductors and Diodes, Chapters 2 and 3 plus notes).
- No lecture next Friday (4/25) due to Engineering Discovery Days.
- HW #3 due on 4/25 under door of my office by 12:30pm.

p-n junction capacitance



Depletion charge: $Q_D < 0$



Equal and opposite depletion charges produce a diode capacitance

- Normal linear capacitance (e.g. parallel plate):

$$C = \frac{Q}{V}$$

- "Depletion capacitance" or "junction capacitance" for diodes:

$$C_j = \frac{dQ_D}{dv_D}; \quad C_{javg} \cong \frac{\Delta Q_D}{\Delta v_D}$$

p-n junction capacitance

A: diode area [cm^2]

- Depletion capacitance:

$$Q_D = -qAx_pN_A \quad \Rightarrow \quad C_j = \frac{dQ_D}{dv_D} = \frac{\varepsilon_s A}{x_d}$$

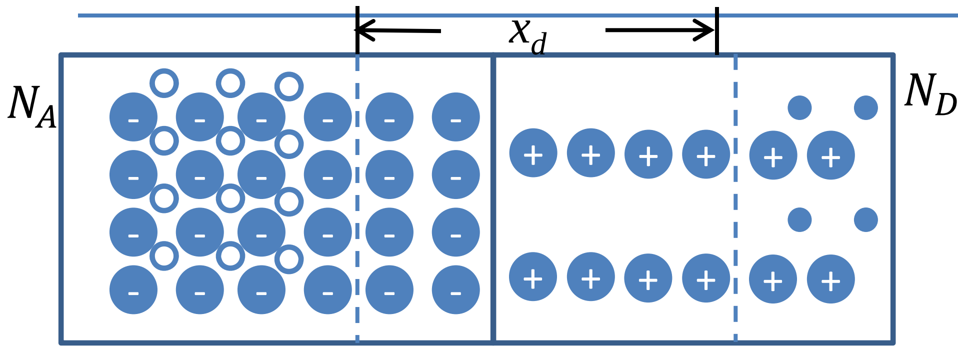
$$x_p = \sqrt{\frac{2\varepsilon_s\,(\varphi_j - v_D)}{qN_A(1+N_A/N_D)}}; \quad x_d = \sqrt{\frac{2\varepsilon(\varphi_j - v_D)}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)}$$

- Looks like a parallel-plate capacitor formula!
- As x_d varies with v_D, C_j also varies with v_D.
  - At zero bias, $C_{j0} = \frac{\varepsilon_s A}{x_{d0}}$
  - At a non zero bias, $C_j = \frac{\varepsilon_s A}{x_d} = C_{j0}\frac{x_{d0}}{x_d} = C_{j0}\sqrt{\frac{\varphi_j}{\varphi_j - v_D}}$

Voltage-dependent capacitor : "varactor"

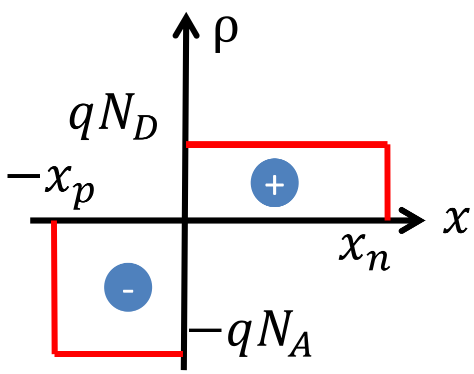
p-n Junction – Depletion Charge

$N_A > N_D$

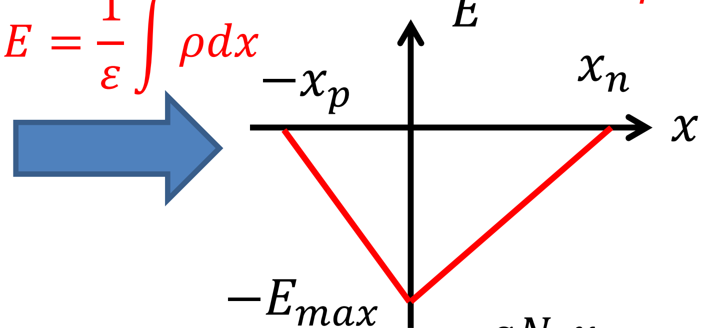


1D Poisson's Equation:

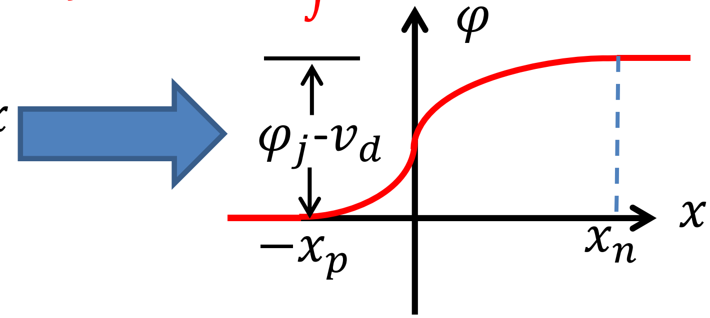
$$\frac{d^2\varphi}{dx^2} = -\frac{dE}{dx} = -\frac{\rho}{\varepsilon}$$



$$E = \frac{1}{\varepsilon}\int \rho dx$$



$$\varphi = \varphi_j - v_d = -\int E dx$$



Charges must be equal:

$$x_p N_A = x_n N_D$$

$$E_{max} = \frac{qN_A x_p}{\varepsilon} = \frac{qN_D x_n}{\varepsilon}$$

φ_j : built-in voltage

p-n Junction Under Applied Voltage

- Example: p-n junction with N_A = 2x10^{16} cm^{-3}, N_D = 5x10^{17} cm^{-3}. Find the depletion width x_d at 300 K under (a) zero bias (b) forward bias (v_D = +0.5 V) (c) reverse bias (v_D = - 5.0 V).
  - Under forward bias: $\varphi_j = 0.85\ V \rightarrow \varphi_j - V_D = 0.35\ \text{V}$

$$x_d = \sqrt{\frac{2\varepsilon(\varphi_j - v_D)}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)} = 154\ \text{nm} < 240\ \text{nm}$$

  - Under reverse bias: $\varphi_j \rightarrow \varphi_j - V_D = 5.85\ \text{V}$

$$x_d = \sqrt{\frac{2\varepsilon(\varphi_j - v_D)}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)} = 630\ \text{nm} > 240\ \text{nm}$$

Diffusion charge (forward bias)

Short base W_p<<L_n, W_n<<L_p:

$$Q_D = qAn_i^2\left[\frac{W_p}{2N_A}+\frac{W_n}{2N_D}\right]\left(e^{qv_d/kT}-1\right)$$

Long base W_p>>L_n, W_n>>L_p:

$$Q_D = qAn_i^2\left[\frac{L_n}{N_A}+\frac{L_p}{N_D}\right]\left(e^{qv_d/kT}-1\right)$$

Stored charge dominated by minority carrier injection into the lightly-doped and/or **wider** side.

Diffusion capacitance (forward bias)

- Additional charge stored in the neutral region near edges of spatial charge region.

$$Q_D = i_D \tau_T$$

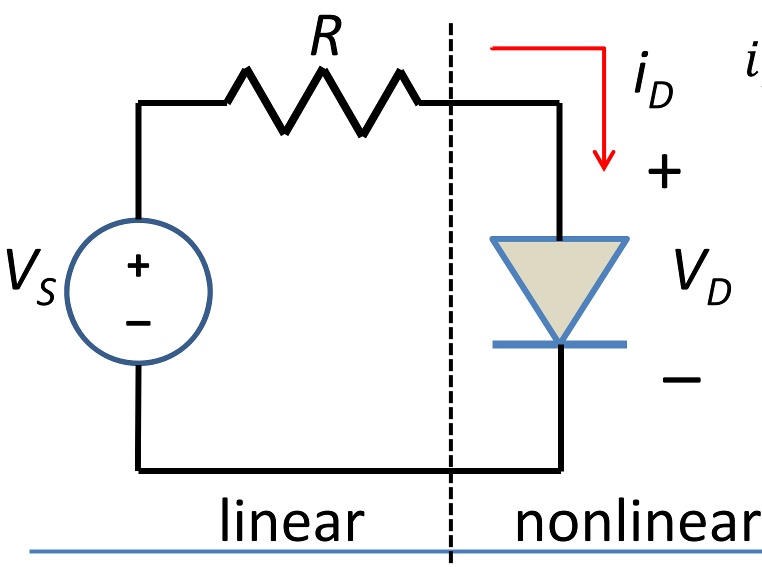
  - τ_T: transit time of diode (1 fs ~ 1us).
- Diffusion capacitance (forward bias):

$$C_D = \frac{dQ_D}{dv_D} = \frac{(i_D + I_S)\tau_T}{V_T} \cong \frac{i_D \tau_T}{V_T}$$

- Diffusion capacitance proportional to forward current (large at high forward bias)

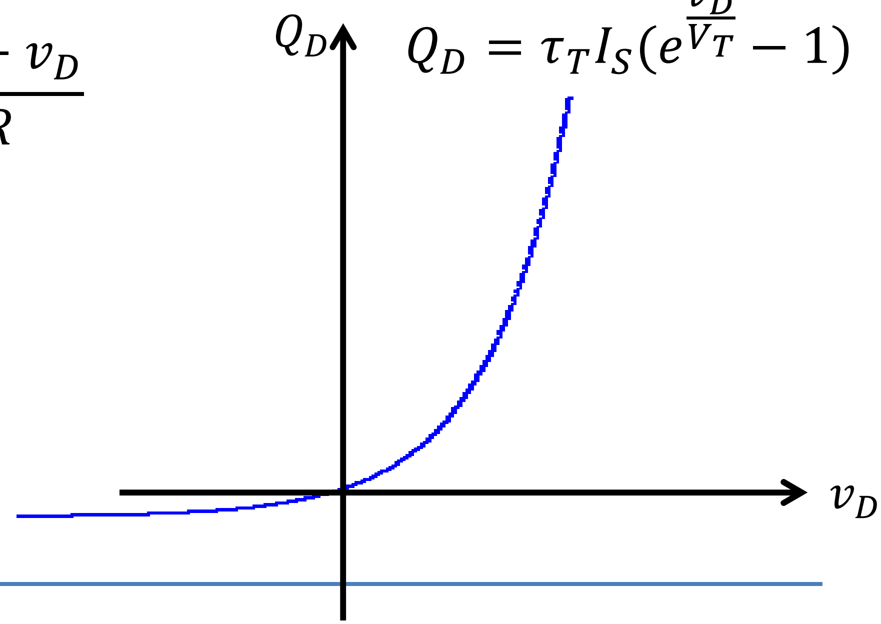
Diffusion Charge

- 98% of stored minority charge (diffusion charge) in final 100 mV of forward bias (90% in final 60 mV).
- Diffusion capacitance dominates near V_{on}. Depletion capacitance dominates for reverse and small forward bias.

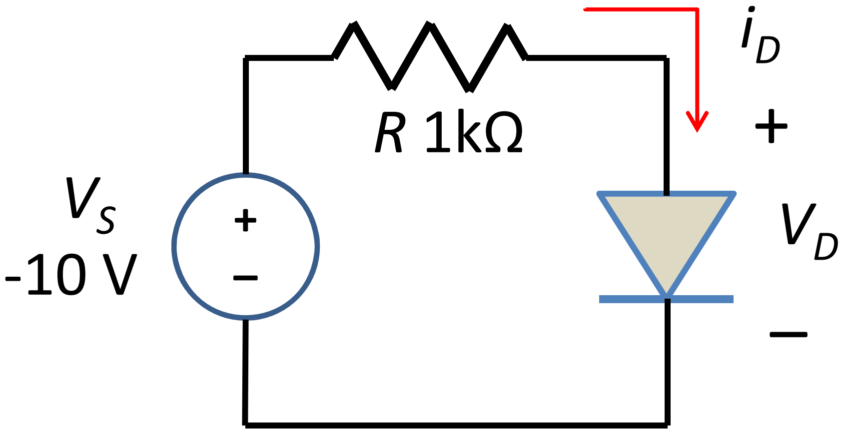


$$i_D = \frac{V_S - v_D}{R}$$

$$Q_D = \tau_T I_S\left(e^{\frac{v_D}{V_T}} - 1\right)$$



Diode Storage Time



$$i_D = \frac{V_S - v_D}{R}$$

$$I_R = \frac{V_S - v_D}{R} = -10.7 \text{ mA}$$

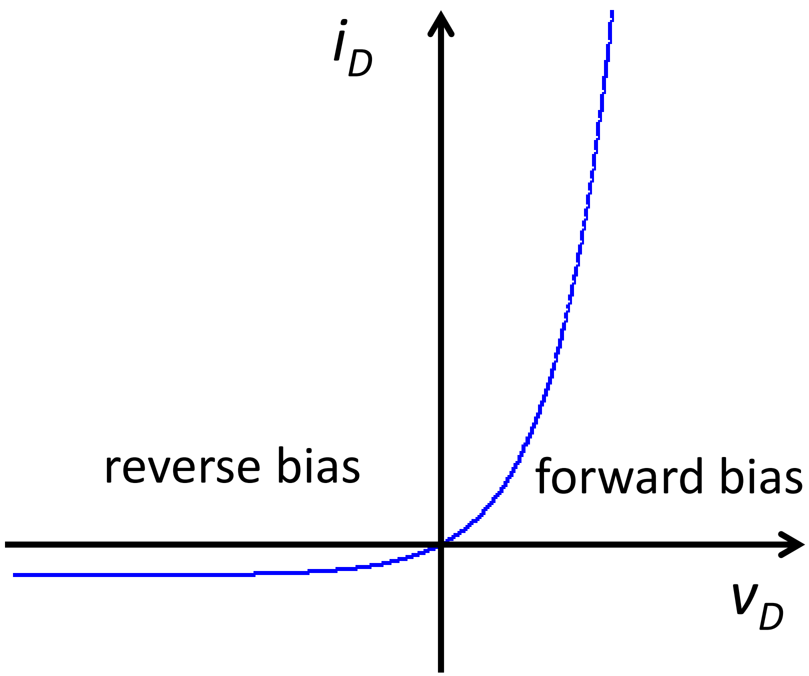
- To turn off diode, must first remove diffusion charge.

$$Q_D = i_D^{on}\tau_T = I_F\tau_T$$

- This results in storage time of:

$$\tau_S = \tau_T \ln\left(1 - \frac{I_F}{I_R}\right)$$

Diode I-V Characteristics



Let I_s=10^{-13}A, n=1. Then if i_D = 1 mA, v_d = 0.026 ln(10^{10}+1) = 0.60 V

- Shockley diode equation:

$$i_D = I_S(e^{\frac{v_D}{nV_T}} - 1)$$

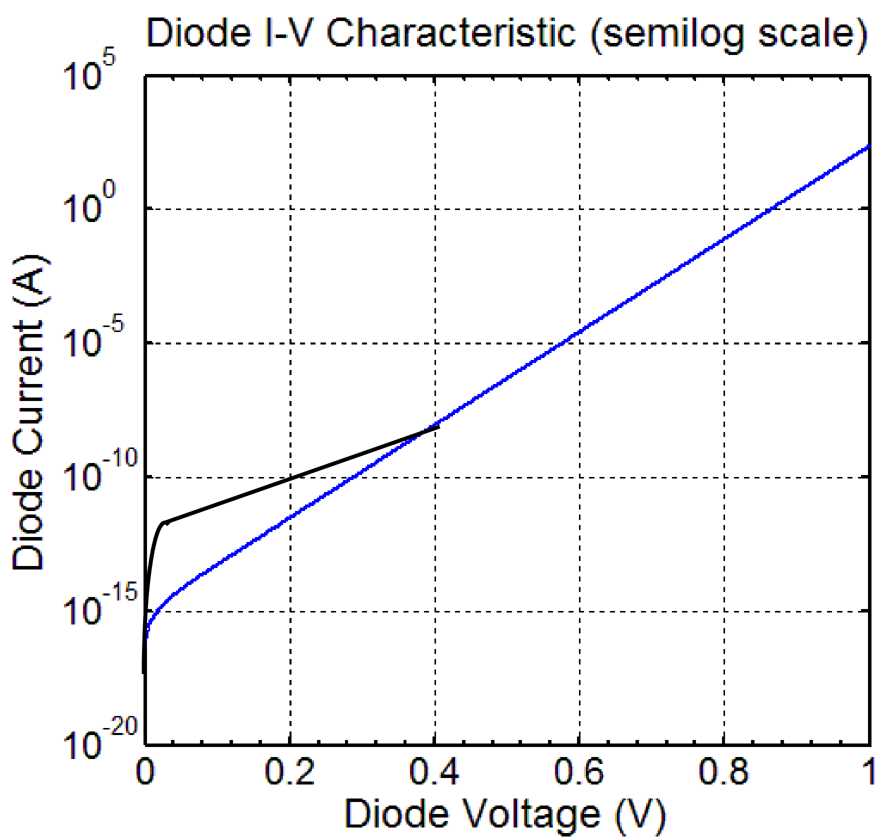
- I_S: Reverse saturation current

typically, $10^{-18}\ \mathrm{A} \leq I_S \leq 10^{-9}\ \mathrm{A}$ (small!)

- *n*: nonideality factor, *n*=1 for ideal diodes (Assume *n*=1 later on)
- V_T: thermal voltage
- Can solve for v_d:

$$v_D = nV_T \ln\left(\frac{i_D}{I_S} + 1\right)$$

Diode I-V Forward Bias



- Exponential increase

$$i_D = I_S e^{\frac{v_D}{nV_T}}$$

- ΔV_{decade}: Voltage increase required to increase current by a factor of 10.
  - $\Delta V_{\text{decade}} = V_T \ln 10$
  - n=1, $\Delta V_{\text{decade}} = 60\ \text{mV}$ =>

  A 60 mV increase in v_D gives a decade increase in i_D

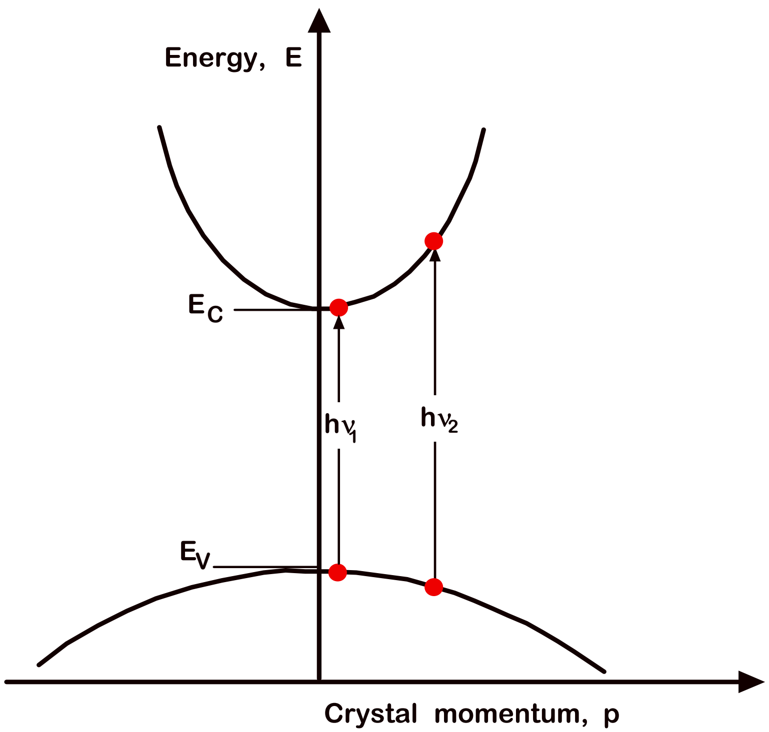
  (60n mV per decade if nonideal)

Recombination: Direct vs. Indirect

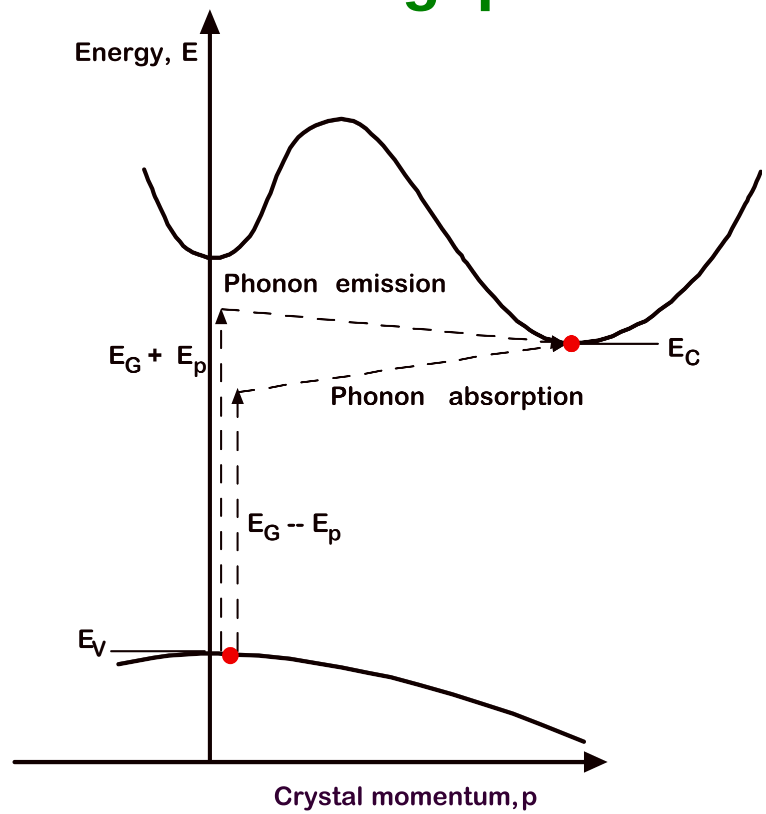
Recombination strongly affected determined by type of bandgap.

Photon = light (no mass); phonon = lattice vibration = heat.

Direct band gap



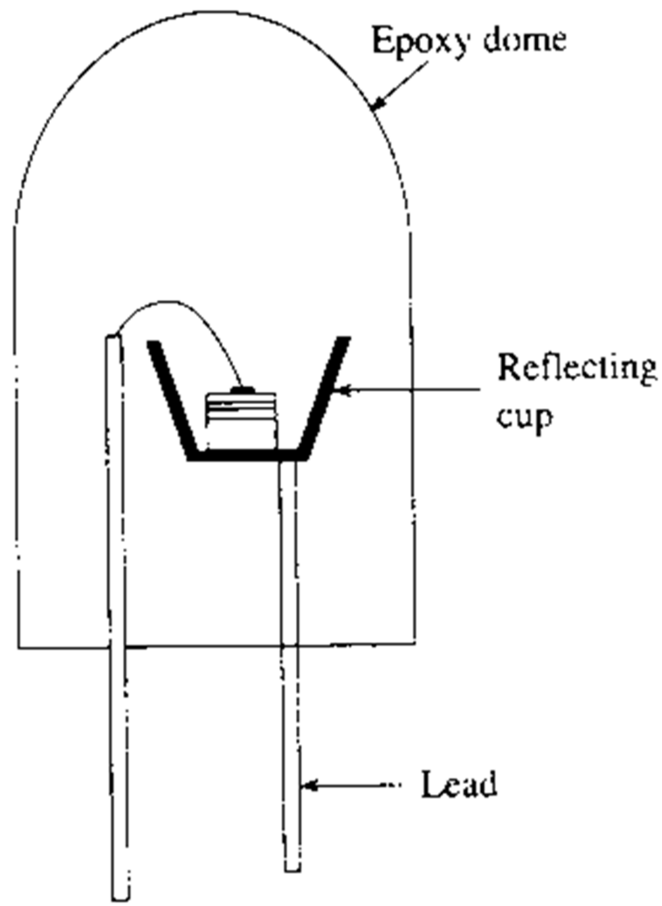
Indirect band gap



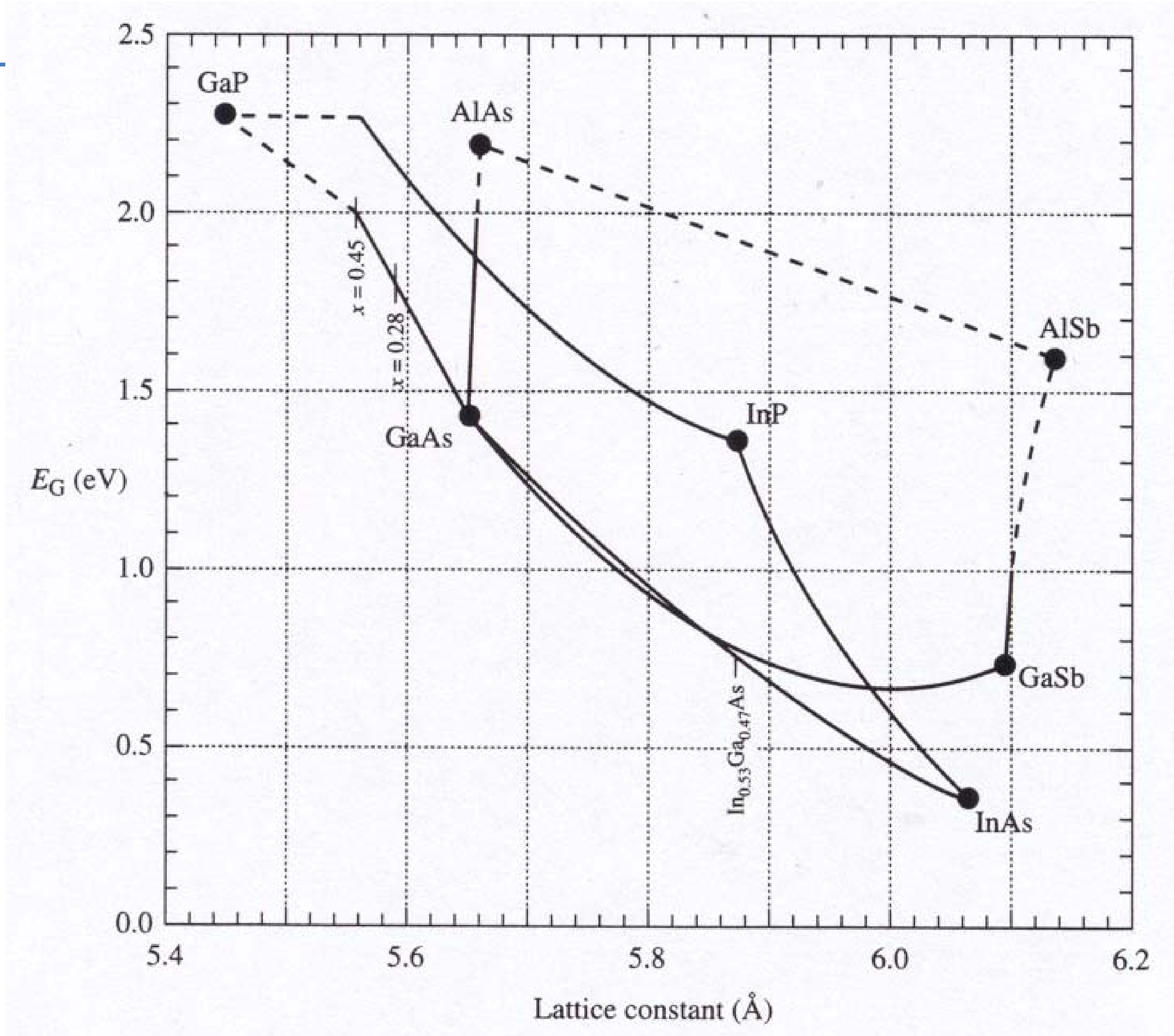
Light-emitting diodes

•When pn junction is forward biased, large number of carriers are injected across the junctions. These carriers recombine and emit light if the semiconductor has a direct bandgap.

•For visible light output, the bandgap should be between 1.6 and 3.1 eV.



Bandgap energy versus lattice constant of selected III-V compounds and alloys

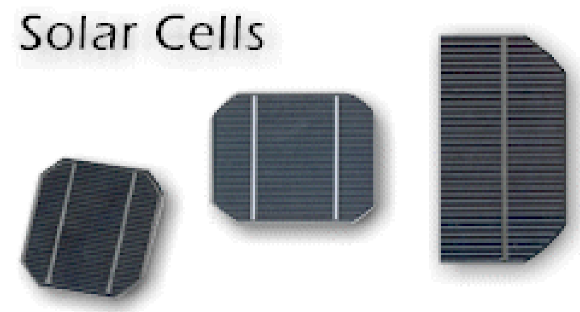


Characteristics of commercial LEDs

Semiconductor	*Color*	*Peak λ(μm)*	*External Efficiency η (%)*	*Performance (lumens/watt)*†
Established Materials				
$GaAs_{0.6}P_{0.4}$	Red	0.650	0.2	0.15
$GaAs_{0.35}P_{0.65}$:N	Orange-Red	0.630	0.7	1
$GaAs_{0.14}P_{0.86}$:N	Yellow	0.585	0.2	1
GaP:N	Green	0.565	0.4	2.5
GaP:Zn-O	Red	0.700	2	0.40
Recent Additions				
AlGaAs	Red	0.650	4–16	2–8
AlInGaP	Orange	0.620	6	20
AlInGaP	Yellow	0.585	5	20
AlInGaP	Green	0.570	1	6
SiC	Blue	0.470	0.02	0.04
GaN	Blue	0.450	2	0.6

What Is a Solar Cell?

- A device that converts solar energy directly to electricity by the photovoltaic effect
  - It supplies voltage and current to a resistive load (light, battery, motor)
  - It supplies DC power



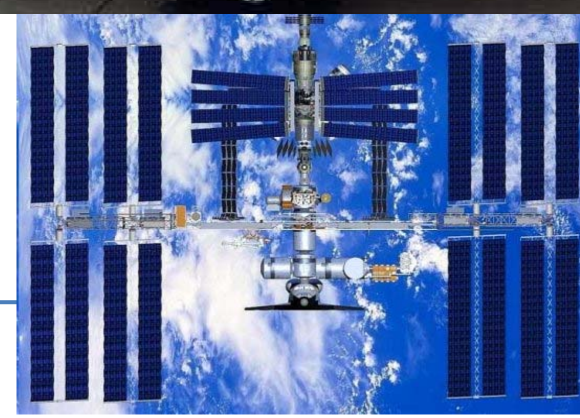
- Solar Module or Solar Panel
  - Solar Module: Solar cells are wired in series
  - Solar Panel: Solar Modules are assembled together and placed into a frame
- Fundamental functions of solar (photovoltaic) cell
  - Photogeneration of charge carriers (electrons and holes) in a light-absorbing semiconductor material
  - Separation of the charge carriers to a contact to transmit electricity
  - An array of solar cells converts solar energy into a usable amount of DC electricity

History

- 1839 Alexandre-Edmond Becquerel: Photovoltaic effect
  - Light dependant voltage immersing between two electrodes
- 1883 Carles Fritts: First solar cell
  - Coated semiconductor selenium with an extremely thin layer of gold to form the junctions
  - 1% efficiency
- 1941 Russell Ohl: First Si-based solar cell
  - Only a fraction better efficiency than selenium cells
  - Less expensive Si basis: a step towards greater efficiency
- 1954 Bell Laboratories: Beginning of modern solar cell research
  - Diffused Si p-n junction: Experimenting with semiconductors, accidentally found that Si doped with certain impurities was very sensitive to light
  - Array of thin Si strips: 6% efficiency

Applications of Solar Cells

- Renewable energy
- Can be powered for remote locations
- It’s free, limitless, and environmentally friendly…



Best Research-Cell Efficiencies

www.nrel.gov/ncpv/thin_film/docs/kaz_best_research_cells.ppt