PHY404- Solid State Physics II

Assoc.Prof. Yeşim Moğulkoç

Content

- Pseudopotential (Effective Potential)

- Basics of selected semiconductor devices
  - p-n junction
  - Bipolar transistors
  - Tunnel diodes
  - Semiconductor lasers

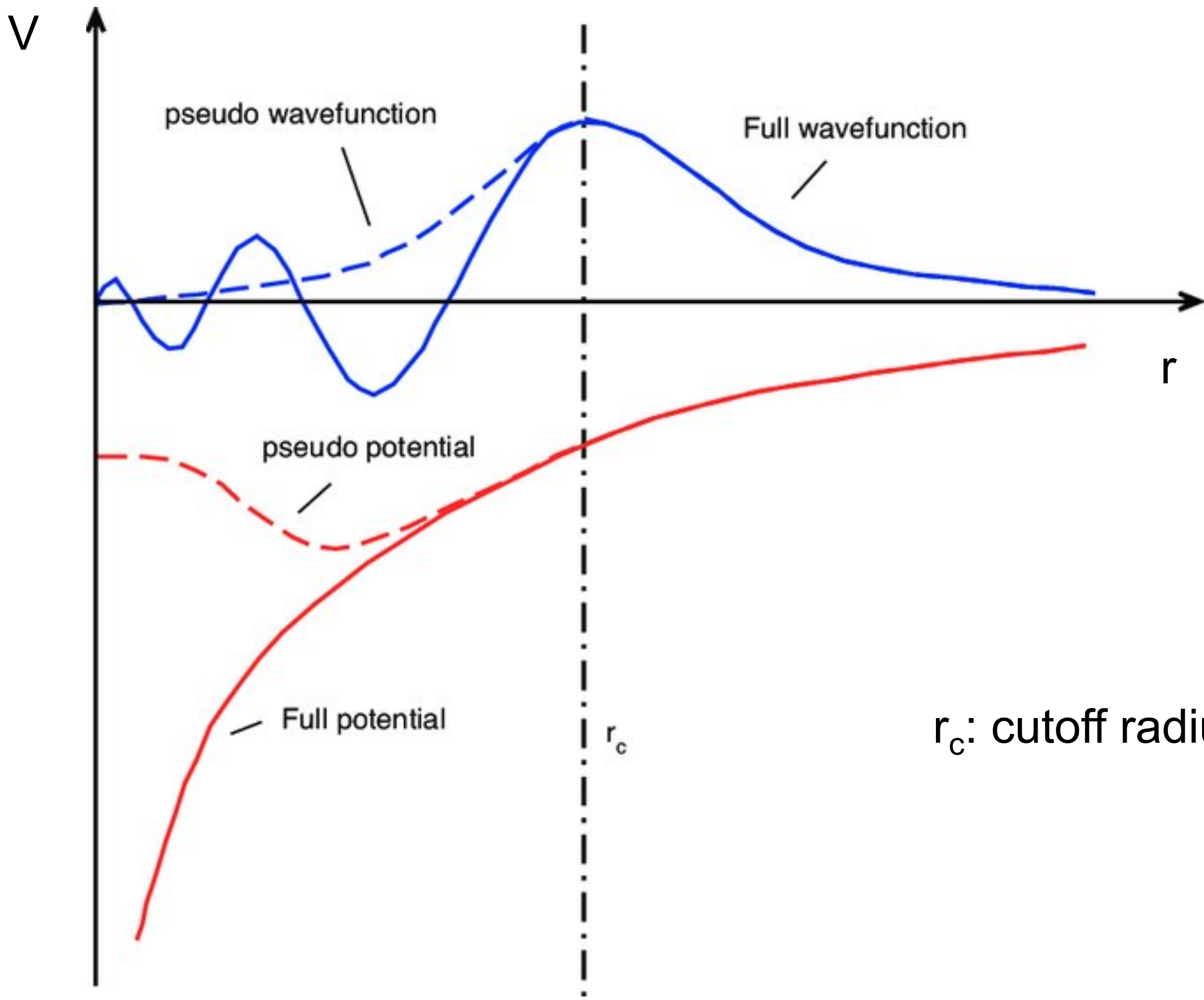
Pseudopotential (Effective potential)

- The concept of a pseudopotential is related to replacing the effects of the core electrons with an effective potential.

- This method simplifies the description of complex systems.

- The strong true potential of the ions is replaced by a weaker potential valid for the valence electrons.

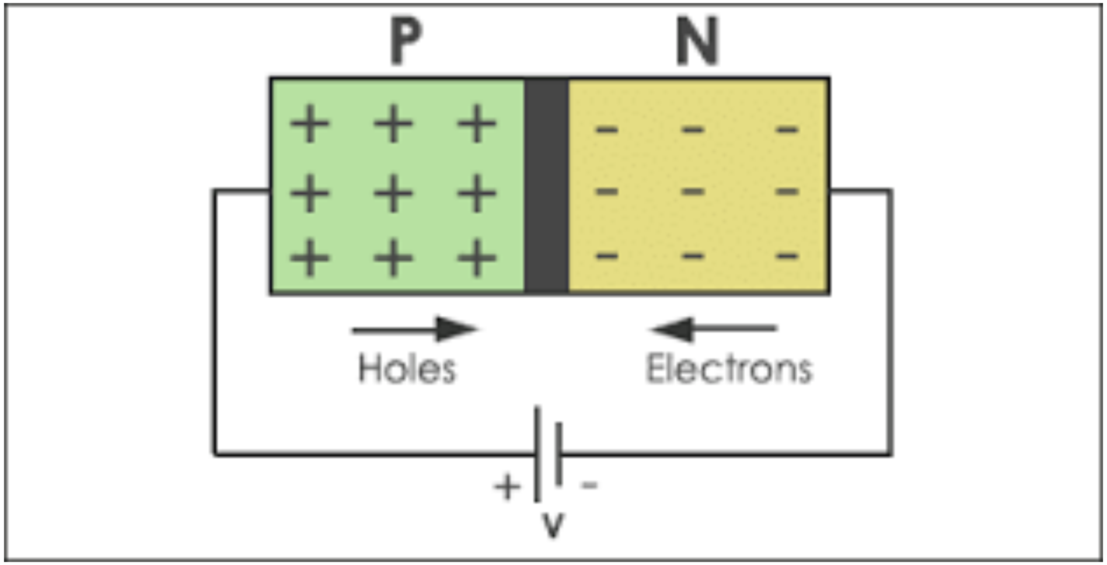
Pseudopotential (Effective potential)

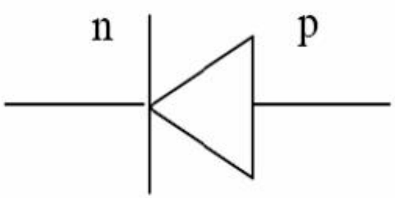


r_c: cutoff radius

Basics of selected semiconductor devices

p-n junction

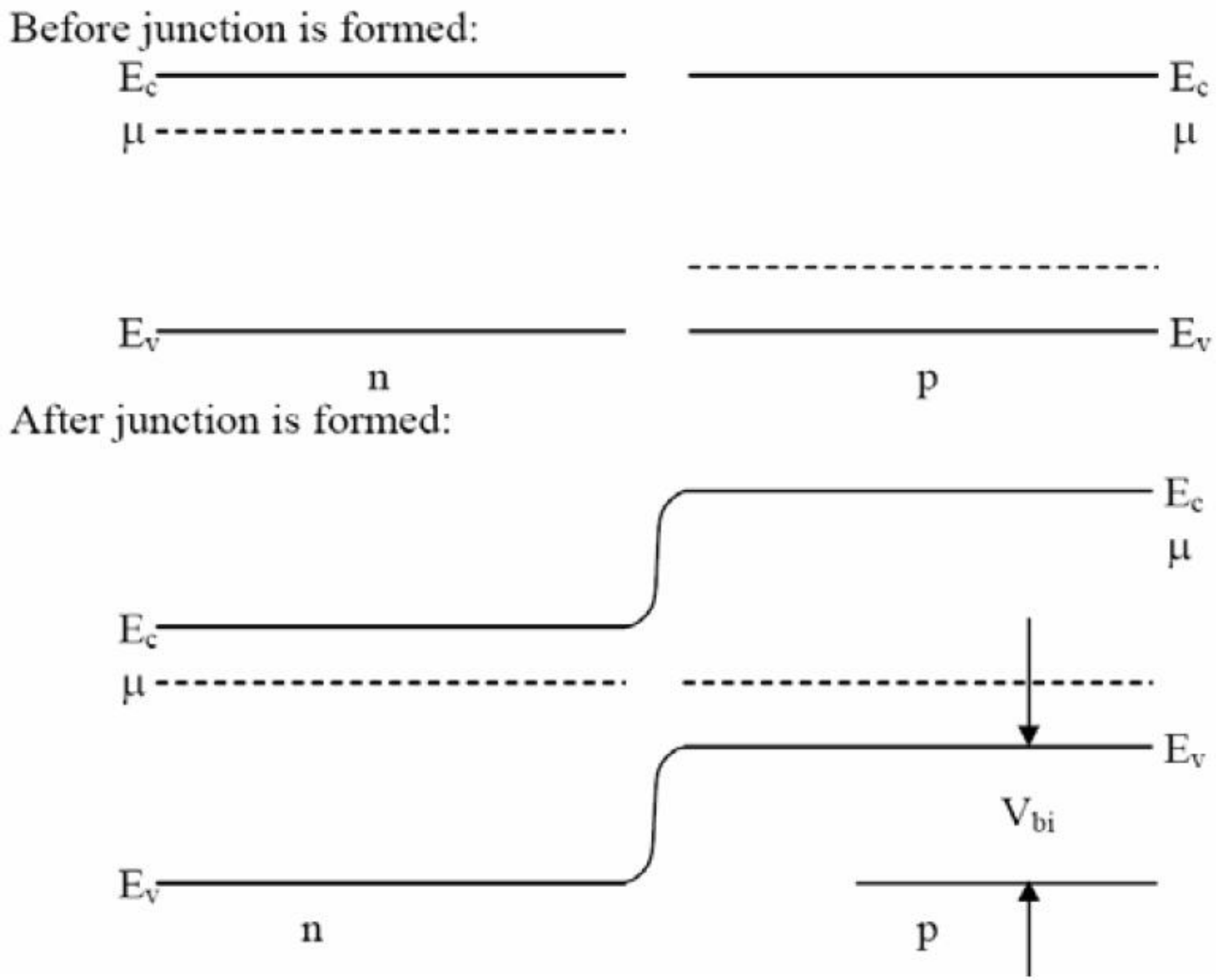




Charge density near the junction is not uniform:
electrons (majority carriers) from the n-side
and holes (majority carriers) from the p-side
will migrate to the other side through the junction.

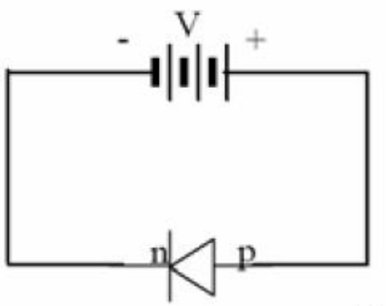
These migrated particles leave the ionized impurities behind:
a charged region is formed

In equilibrium, at zero bias, the chemical potential has to be the same at both sides: bending of the conduction and valance bands

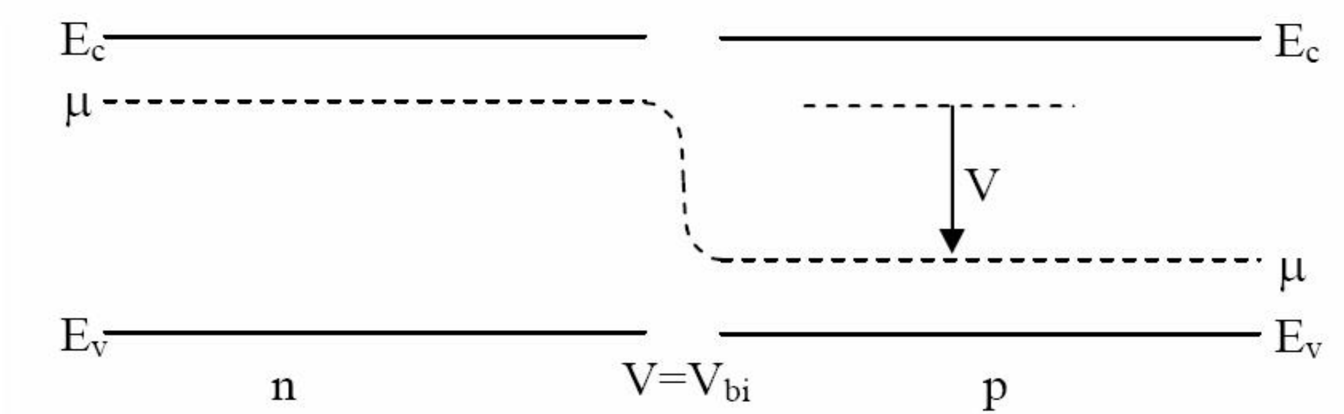


The band edge shift across the junction is called the *built in voltage* V_{bi}.

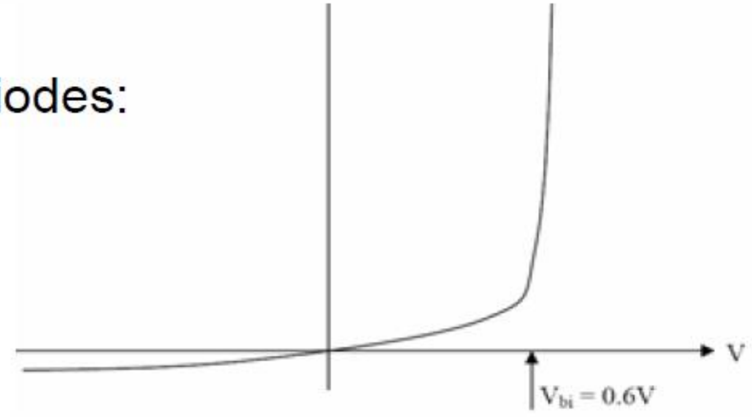
Forward bias



"pushes" electrons in the n-side and holes in the p-side towards the junction. The depletion width will become thinner → current flows



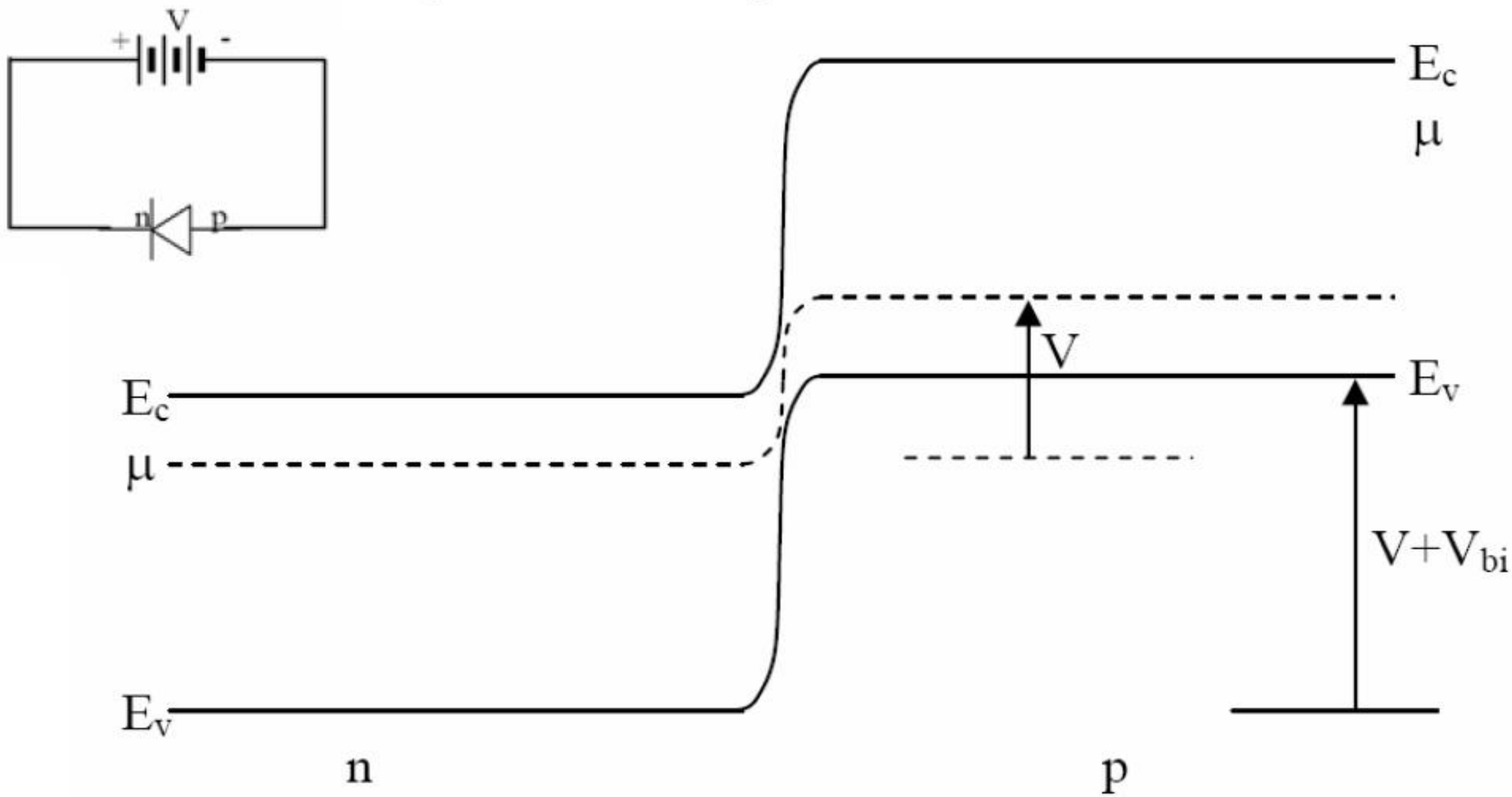
For most diodes:



Reverse bias

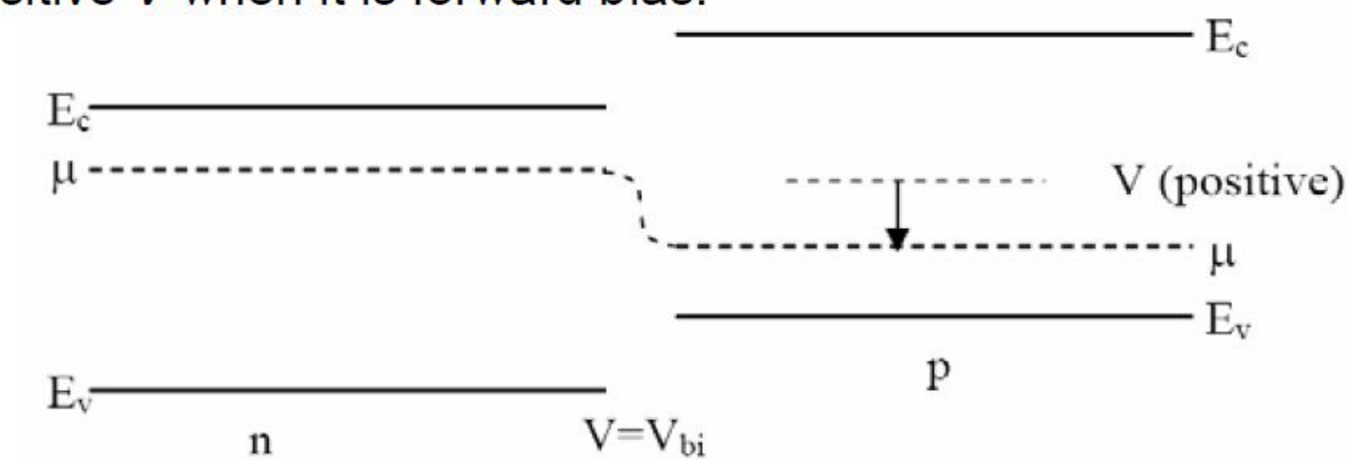
draws electrons and holes away from the *n*-side and holes from the *p*-side.

The depletion width grows and the junction resistance increases.



I-V characteristics of a p-n junction

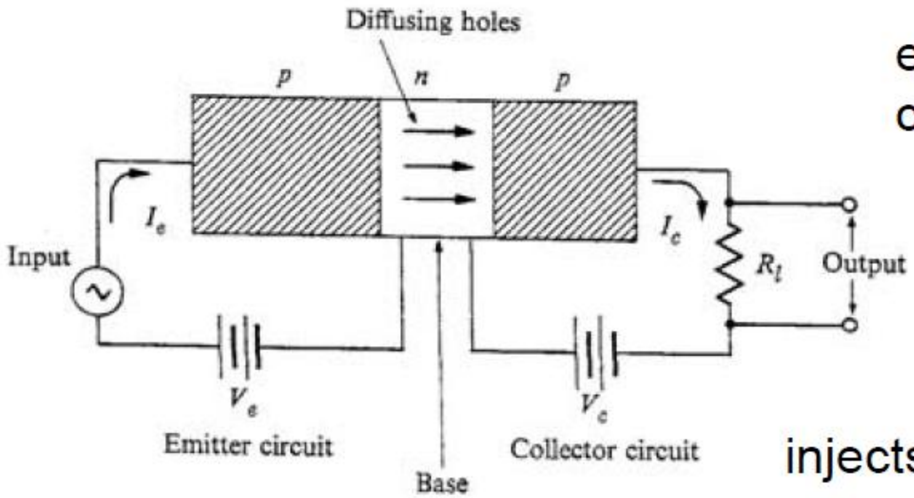
Assume positive *V* when it is forward bias:



There are two currents from two types of majority carriers, j_{n} and j_{p}

$E \sim 0$ at area outside the depletion layer $\Rightarrow$ mostly diffusion current outside the depletion layer.

Bipolar junction transistor



emitter circuit – forward biased
collector circuit – reverse biased

Emitter current:

$$I_e = I_{e0} e^{eV_e/kT}$$

injects holes into the base (n-region)

Holes diffuse through the base; some of them decay.

Collector current: $I_c = I_{c0} + \alpha I_e$ (α - fraction of holes that survive)

I_{c0} is very small $\rightarrow$ ca write $I_c \approx \alpha I_e$

Voltage drop across the load is: $V_l = \alpha R_l I_e$ *amplification*

Voltage gain $$\frac{dV_l}{dV_e} = \frac{dV_l}{dI_e}\frac{dI_e}{dV_e} = \frac{\alpha R_l I_e}{kT/e}$$

Power gain:
$$\frac{dP_l}{dP_e} = \frac{2\alpha^2 R_l I_e}{1+\ln(I_c/I_{e0})kT/e}$$

If we take $I_e = 10$ mA, $I_{e0} = 10$ μA, $kT = 25$ meV at 300 K, $\alpha \approx 1$, and $R_l = 2$ kΩ,

get voltage and power gains ~800 and 200, respectively.

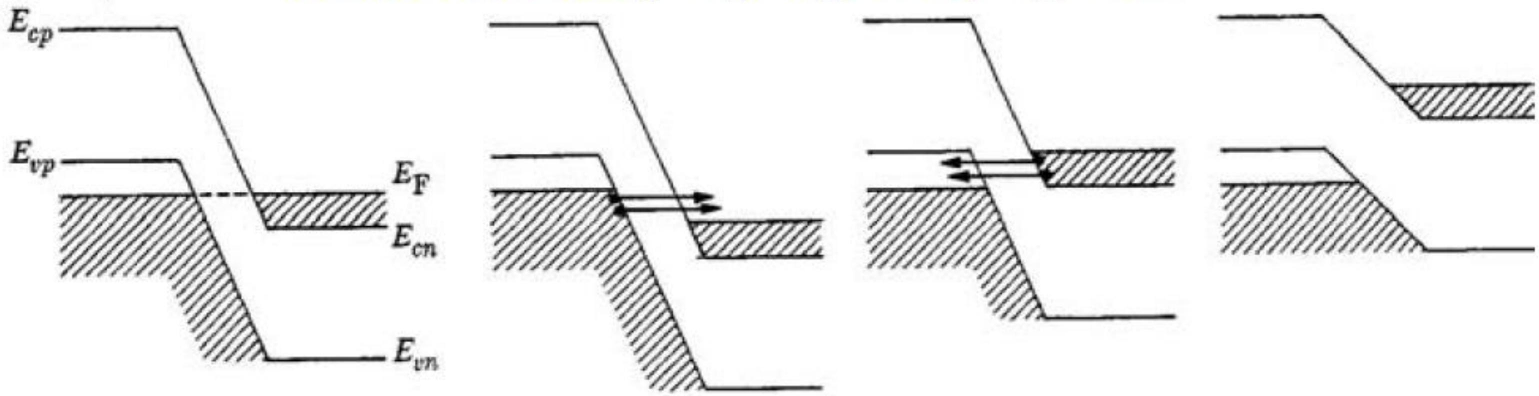
Fundamental limitation of bipolar junction transistor – low frequency – determined by diffusion of holes (electrons in *npn* case) into the base

The high-frequency limit beyond which the device cannot function properly, usually lies in the range of tens – hundreds of MHz

Other types of transistors are needed for higher-frequency range

Tunnel diode symbol

Tunnel diode (very high doping leve

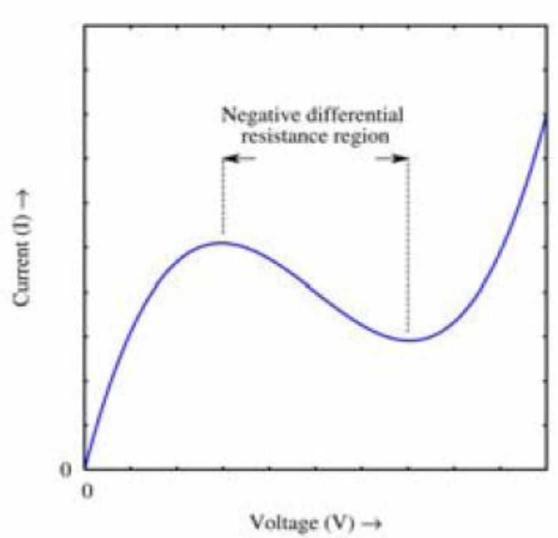


a) equilibrium

b) Reverse bias - large tunneling current

c) Small forward bias - some tunneling current

c) Large forward bias - no tunneling current



←*I*-*V* characteristics

tunneling process is very fast – can operate at high frequencies (e.g. 10 GHz)

Summary of the semiconductors section

- *p-n* junction: both electrons and holes diffuse across the junction – potential barrier develops, called *built in voltage* V_{bi} :

$$V_{\mathrm{bi}} = kT \ln \frac{N_A N_D}{n_i^2}$$

- The junction acts as rectifier. The current vs applied voltage V is

$I = I_0(e^{eV_e/kT} - 1)$ Forward: $I \approx I_0 e^{eV_e/kT}$ Reverse: $I \approx -I_0$

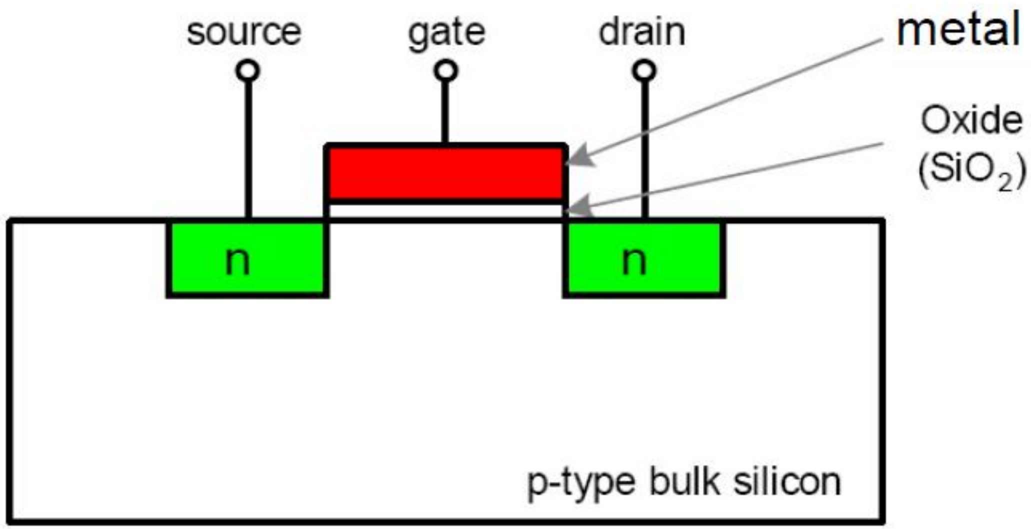
- Bipolar junction transistor – two back to back junctions: emitter is forward biased, collector is reverse biased

  Works as amplifier: when a signal is applied at the emitter, a current pulse passes through the base-collector circuit. The voltage gain is:

$$\frac{dV_l}{dV_e} = \frac{dV_l}{dI_e}\frac{dI_e}{dV_e} = \frac{\alpha R_l I_e}{kT/e}$$

- Tunnel diode is realized when the doping levels in a *p-n* junction are very high, so the junction width is very small – tunneling occur.
  A region of negative differential resistance exists in forward bias.

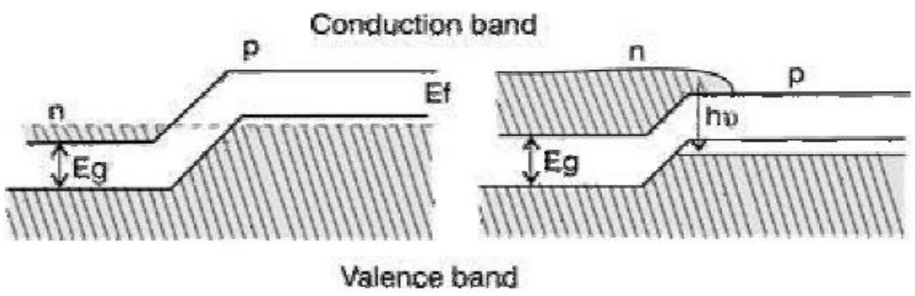
Field effect transistor



Body is commonly tied to ground (0 V)

- When the gate is at a low voltage
  - *p*-type body is at low voltage
  - Source-body and drain-body diodes are OFF (reverse bias)
  - Depletion region between n and p bulk: no current can flow, transistor is OFF
- When the gate is at a high voltage
  - Positive charge on gate of MOS capacitor
  - Negative charge attracted to oxide in the body (under the gate)
  - Inverts channel under the gate to n-type
  - Now current can flow through this n-type channel between source and drain
  - Transistor is ON

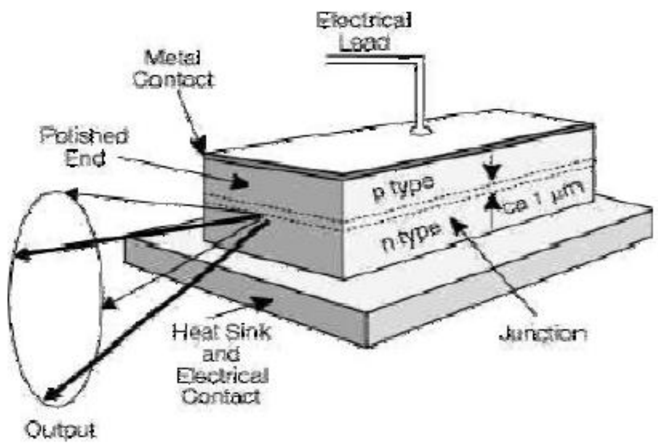
Emission of Light by Semiconductor Diodes



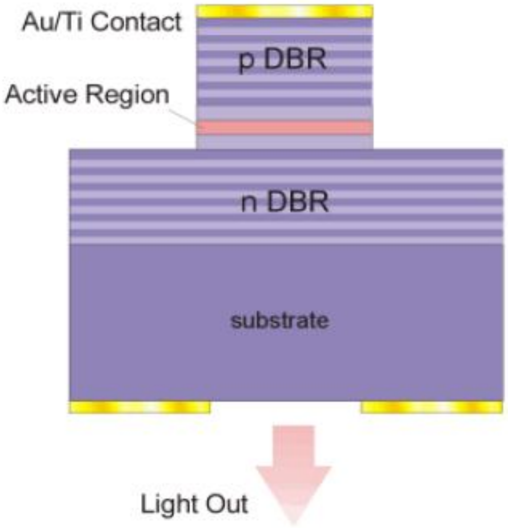
In a forward-biased p-n junction fabricated from a direct band gap material, the recombination of the electron-hole pairs injected into the depletion region causes the emission of electromagnetic radiation - a *light emitting diode*

If mirrors are provided and the concentration of the electron hole pairs (called the injection level) exceeds some critical value → a semiconductor laser

Edge-emitting laser



vertical cavity surface-emitting laser



Thank you for your attention