Chapter 2

PN junction and diodes

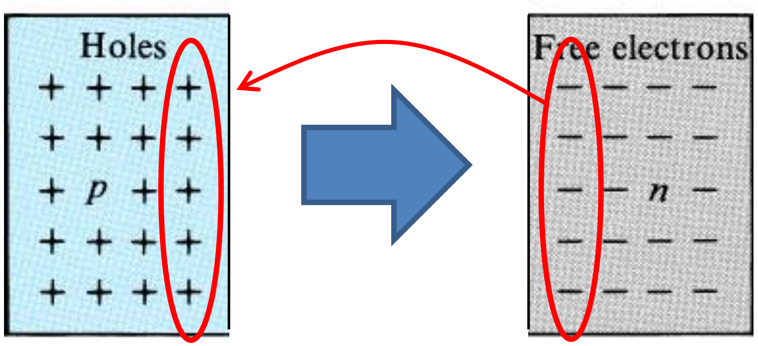
PN junction and diodes

Outline

- PN junction
  - What happens in a PN junction
  - Currents through the PN junction
  - Properties of the depletion region
- Diodes
  - Diode I/V characteristics
  - PN junction under reverse bias
  - PN junction in breakdown region
  - PN junction under forward bias
- Circuits with diodes
  - DC restorer
  - Voltage doubler
  - Voltage multiplier

PN junction

What happens at the transition region ?



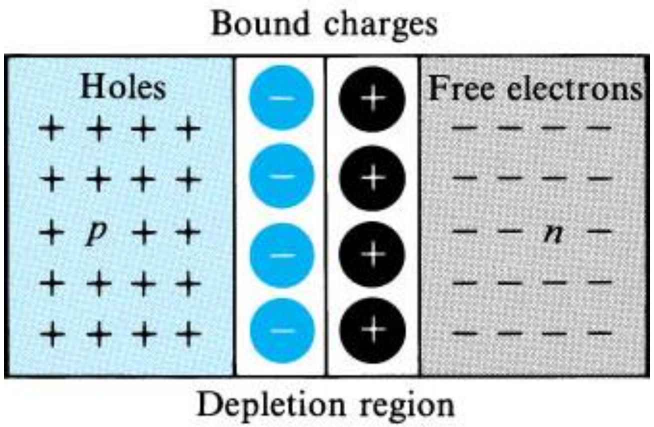
p-type, majority holes n-type, majority electrons

At the transition region, the majority holes are neutralized by an equal amount of majority electrons

=> this reveals the bound charges (ions)

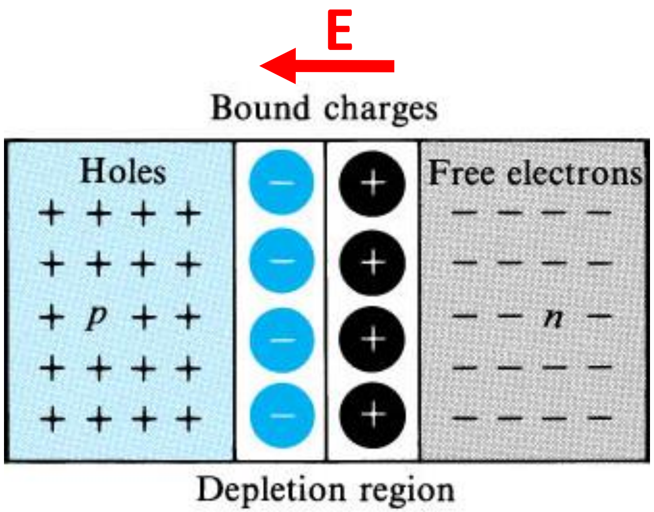
that are in the crystal

=> the bound charges create an E-field



PN junction

Effect of the E-field



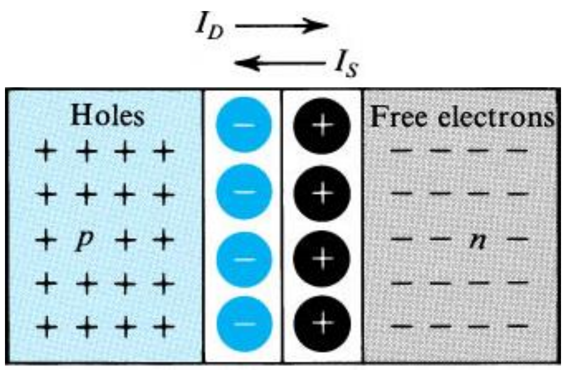
- The E-field « pushes » the holes in the p-region
- The E-field « pushes » the electrons in the n-region
- Holes/electrons need more energy to pass the depletion region
- An equilibrium appears, where the size of the depletion region no longer changes

PN junction

Currents through the depletion region

- Diffusion current I_D:
  - majority holes/electrons in the p/n-region that have enough energy to overcome the E-field
- Diffusion current I_S:
  - minority electrons/holes in the p/n-region (created through thermal ionization)

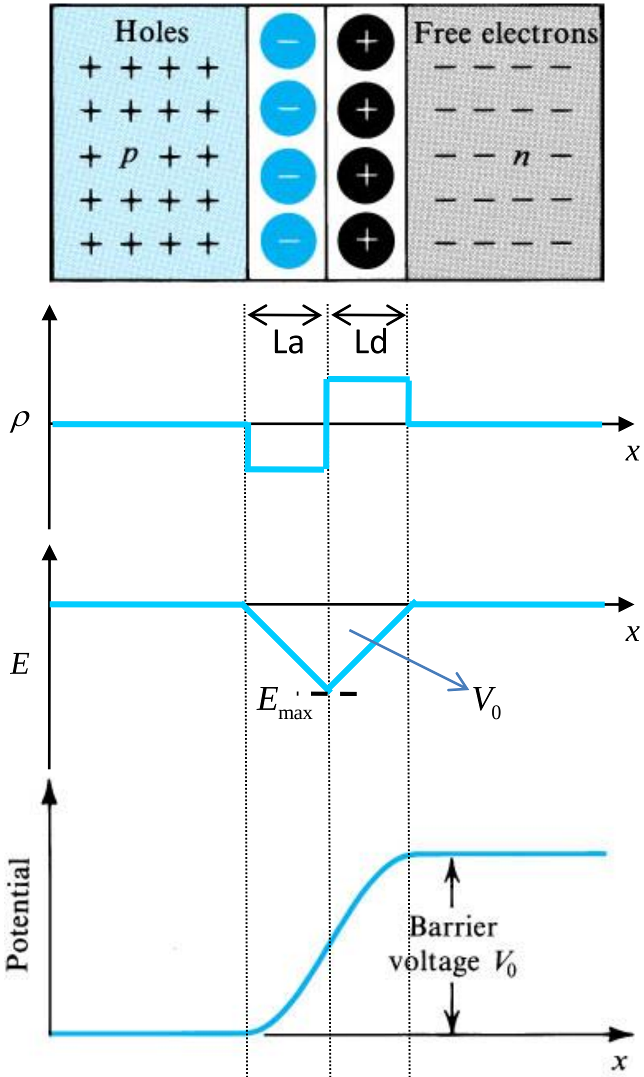
  $\Rightarrow$ Swept through the depletion region by the E-field



- No external current exists => $I_D = I_S$

PN junction

Width and barrier voltage of the depletion region



$$\boxed{\begin{aligned} \operatorname{div} E &= \frac{\rho}{\varepsilon} \\ E &= -\operatorname{grad} V \end{aligned}}$$

Global depletion region must be electrically neutral => $\boxed{N_a L_a = N_d L_d}$

$$\operatorname{div} E = \frac{\rho}{\varepsilon} \quad \Rightarrow \quad \boxed{E_{\max} = \frac{qN_a L_a}{\varepsilon} = \frac{qN_d L_d}{\varepsilon}}$$

$$E = -\operatorname{grad} V \quad \Rightarrow \quad V_0 = E_{\max} \frac{L_a + L_d}{2} = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

$$\boxed{L_a + L_d = \sqrt{\frac{2\varepsilon}{q} V_0 \left(\frac{1}{N_a} + \frac{1}{N_d}\right)}}$$

PN junction

Width and barrier voltage of the depletion region

- For silicon at room temperature:

$$V_0 \approx 0.6 - 0.8\mathrm{V}$$

- Typically, the depth of the depletion region ranges from 0.1 µm to 1 µm

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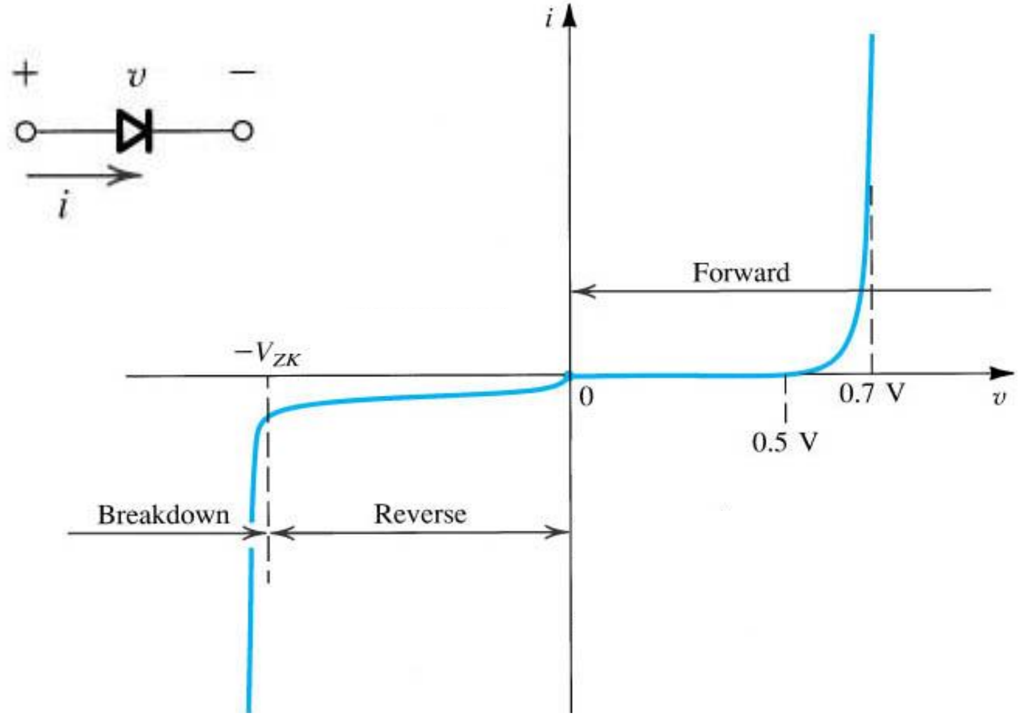
Diodes

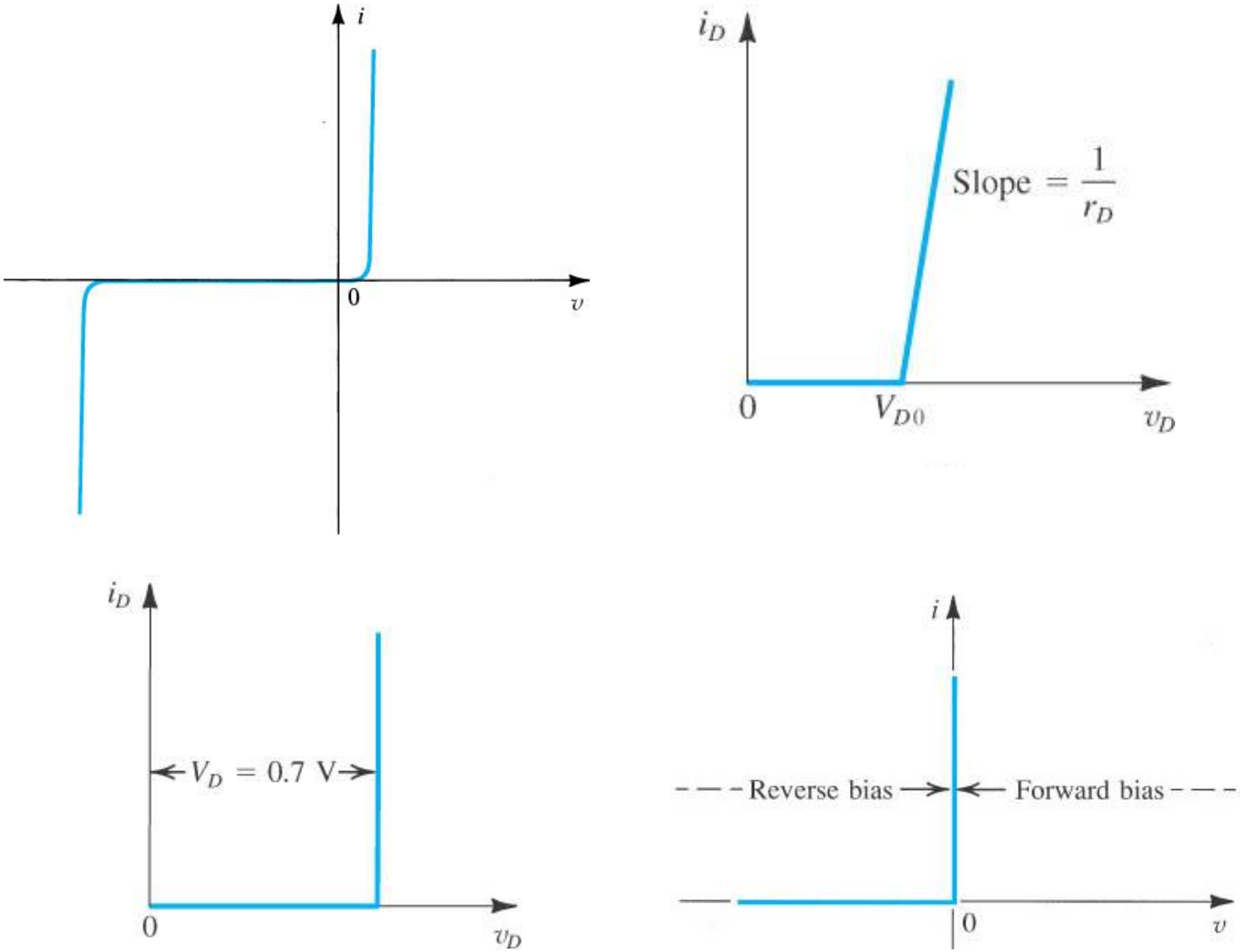
I-V characteristics

- A diode is merely a PN-junction (with terminals connected at both ends)
- Reminder from ELEC-H301
  - 3 regions: forward bias, reverse bias and breakdown



Diodes

Several levels of simplification …



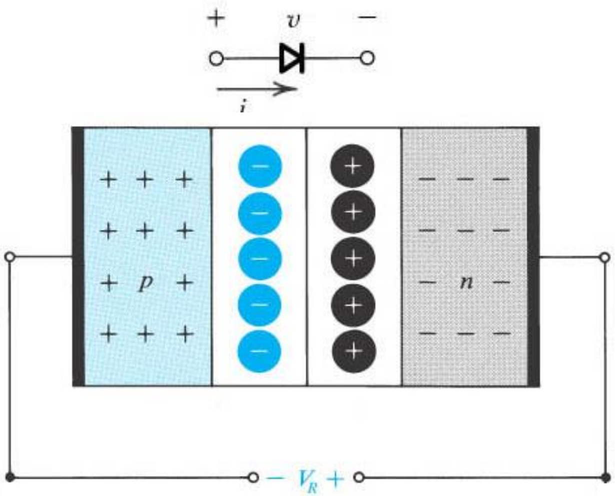
Diodes: PN junction under reverse bias

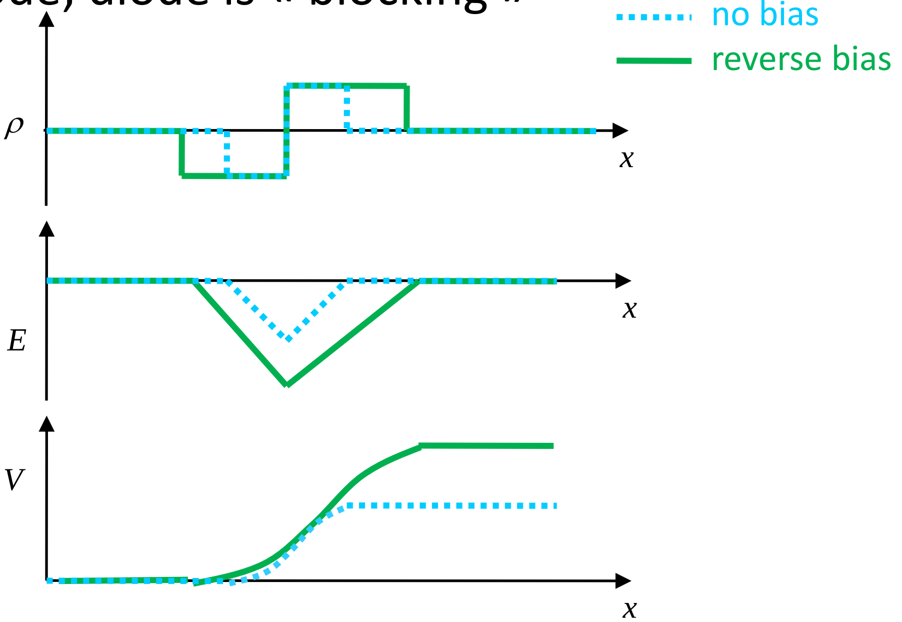
The depletion region widens

- Voltage source pulls electrons from n-region and holes from p-region around the depletion region
- Depletion region widens => barrier voltage V_0 increases

  $\Rightarrow$ It becomes even harder for holes/electrons from the p/n region to get through the depletion region =>

  $\Rightarrow$ no current goes through the diode; diode is « blocking »



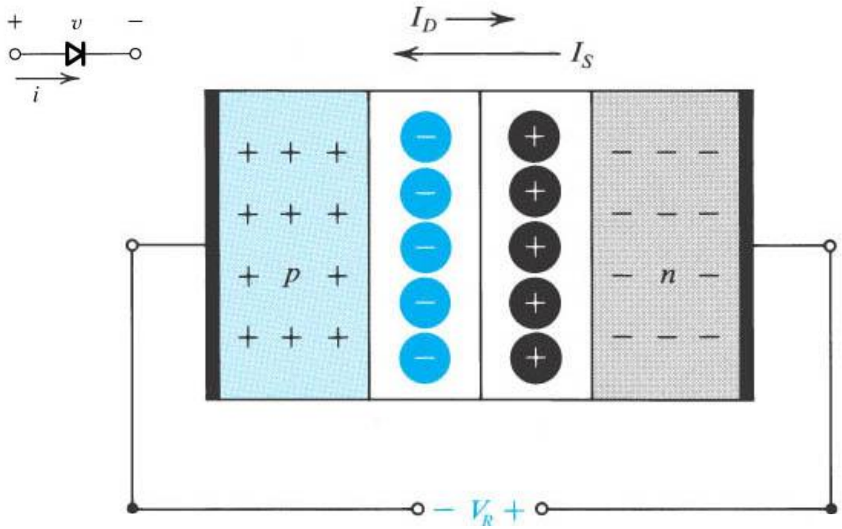


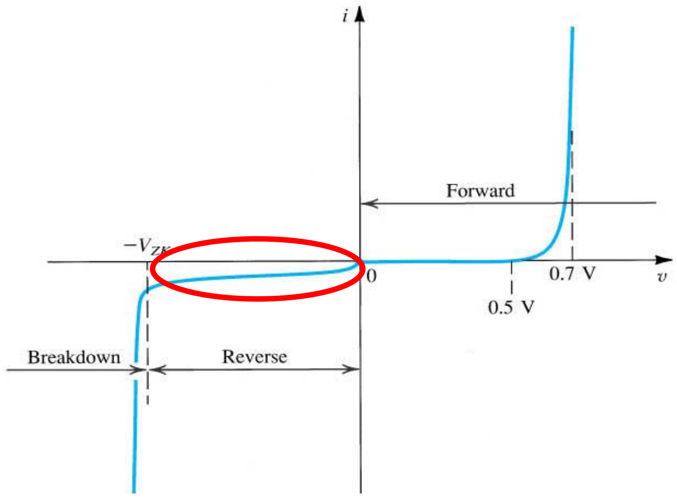
Diodes: PN junction under reverse bias

Reverse current is due to minority carriers

- Since the barrier voltage of the depletion region increases, the diffusion current I_D (due to majority holes/electrons in the p/n region) will decrease
- However, the diffusion current I_S (due to minority electrons/holes in the p/n region) will not change

=> a slight reverse current will appear, due to **minority carriers**





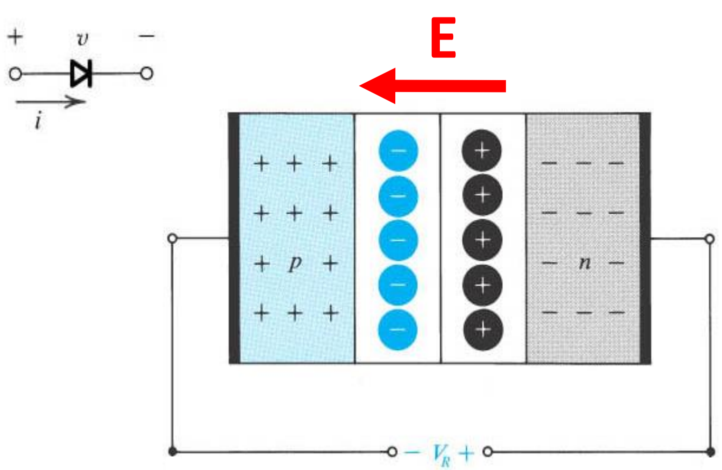
Diodes: PN junction in the breakdown region

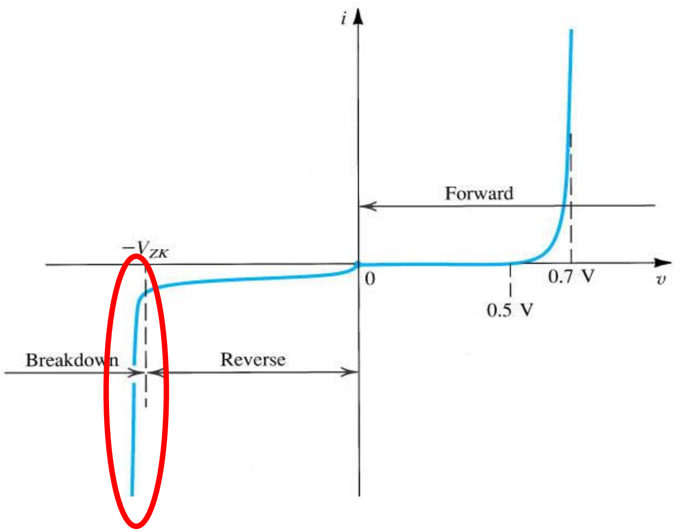
Reverse voltage keeps increasing

The electric field in the depletion region keeps increasing

1st effect:

- $\Rightarrow$ E-field is able to break covalent bonds in the depletion region (« Zenner effect ») , with negligible increase in junction voltage
- $\Rightarrow$ Reverse current will increase



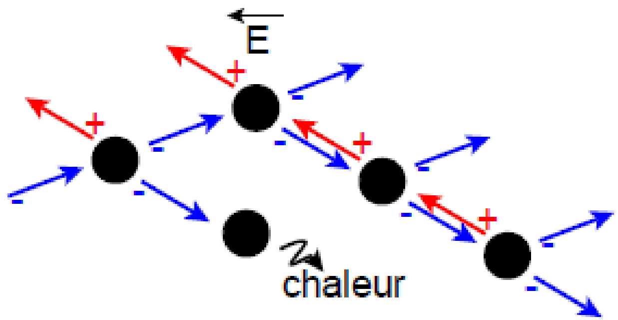


Diodes: PN junction in the breakdown region

Reverse voltage keeps increasing

The electric field in the depletion region keeps increasing

2nd effect:



$\Rightarrow$ Minority carriers going through depletion region have so much kinetic energy that they are able to break covalent bonds

$\Rightarrow$ Each liberated electron has sufficient energy to cause another ionizing collision (« Avalanche effect »)

$\Rightarrow$ reverse current increases fast

Diodes: PN junction in the breakdown region

PN breakdown is not a destructive process as such

- When decreasing the reverse voltage, diode will return to its original state

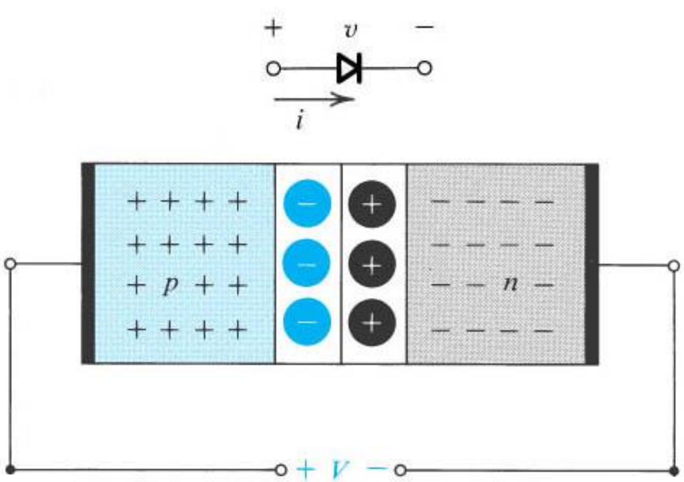
However… reverse current can cause high power dissipation

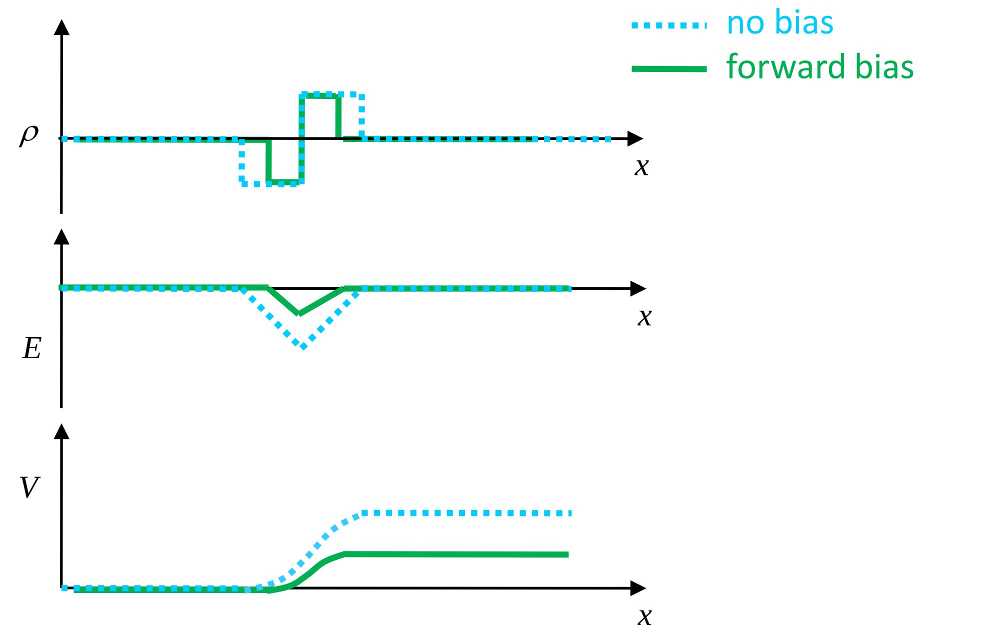
$\Rightarrow$ This power dissipation can degrade the PN junction irreversably, maybe even cause the Silicon to fuse

Diodes: PN junction under forward bias

Depletion regions narrows

- Voltage source pushes holes in the p-region and electrons in the n-region closer to the depletion region
  - $\Rightarrow$ Depletion region narrows
  - $\Rightarrow$ Barrier voltage V_0 decreases
  - $\Rightarrow$ Holes from p-region / electrons from n-region are injected accross the junction

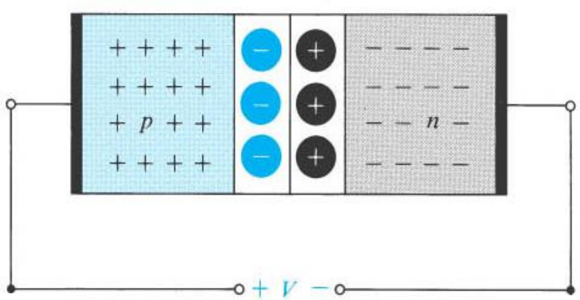


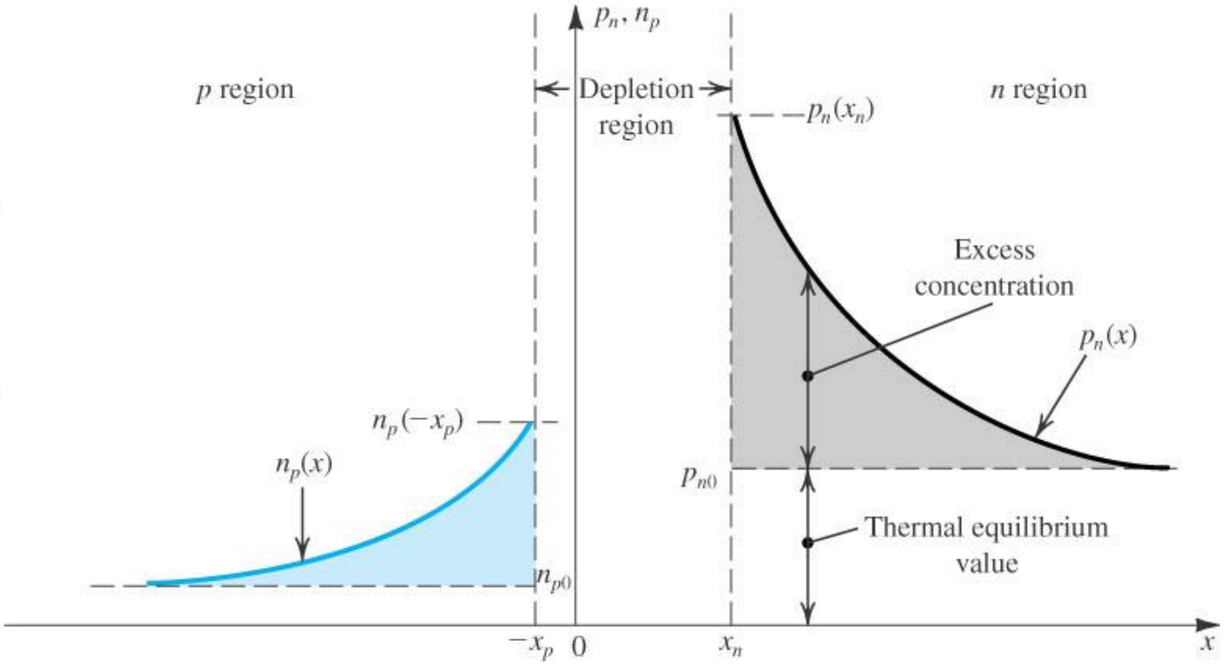


Diodes: PN junction under forward bias

Minority carrier concentration increases

- Holes from p-region are injected accross the junction
  - $\Rightarrow$ Increase minority carrier concentration in the n-region
  - $\Rightarrow$ Holes recombine with majority electron in n-region
  - $\Rightarrow$ Highest concentration of minority carriers close to junction
- Similar for electrons from the n-region





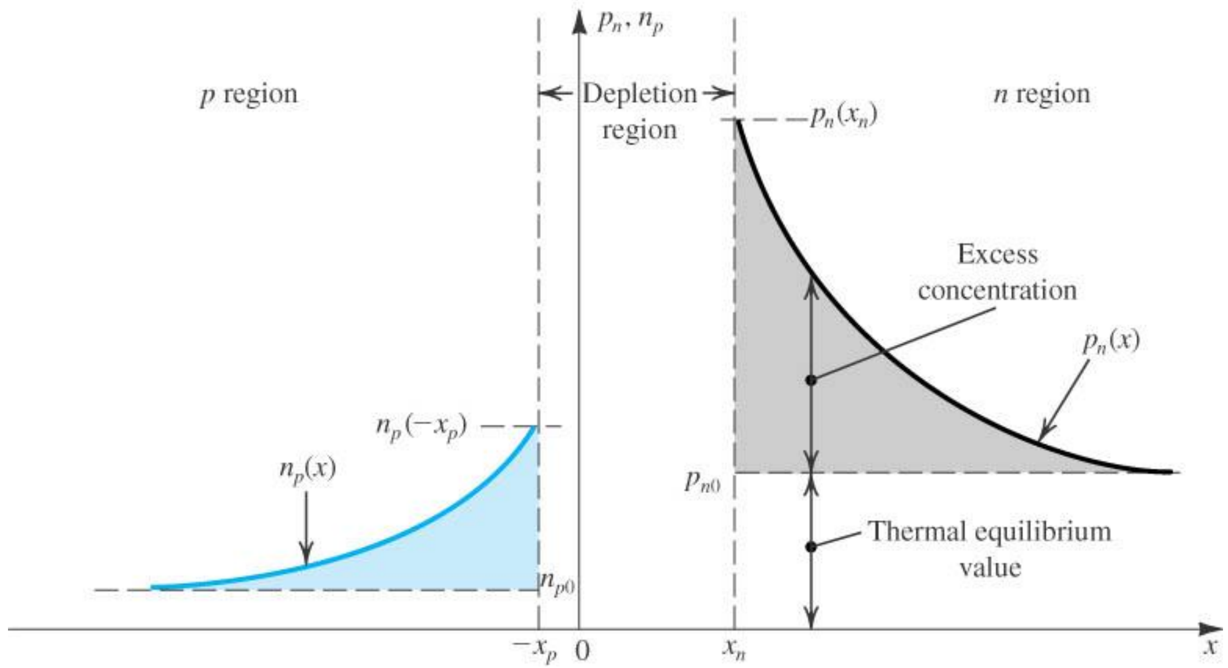
Diodes: PN junction under forward bias

Excess minority carrier concentration causes current

- Highest concentration of minority carriers close to junction

  $\Rightarrow$ from semiconductor physics: $p_n(x_n) = p_{n0}e^{V/V_T}$

  $\Rightarrow$ concentration of carriers: $p_n(x) = p_{n0} + [p_n(x_n) - p_{n0}]e^{-(x-x_n)/L_p}$



Diodes: PN junction under forward bias

Excess minority carrier concentration causes current

- Gradient in minority charge carriers causes diffusion current:

$$J_p = qD_p \frac{dp_n(x)}{dx}$$

$$= q\frac{D_p}{L_p} p_{n0}\left(e^{V/V_T} - 1\right) e^{-(x-x_n)/L_p}$$

at $x = x_n$: $J_p = q\frac{D_p}{L_p} p_{n0}\left(e^{V/V_T} - 1\right)$

- Similarly, for minority electrons in p-region: $J_n = q\frac{D_n}{L_n} n_{p0}\left(e^{V/V_T} - 1\right)$

=> Total current for cross-section *A :*

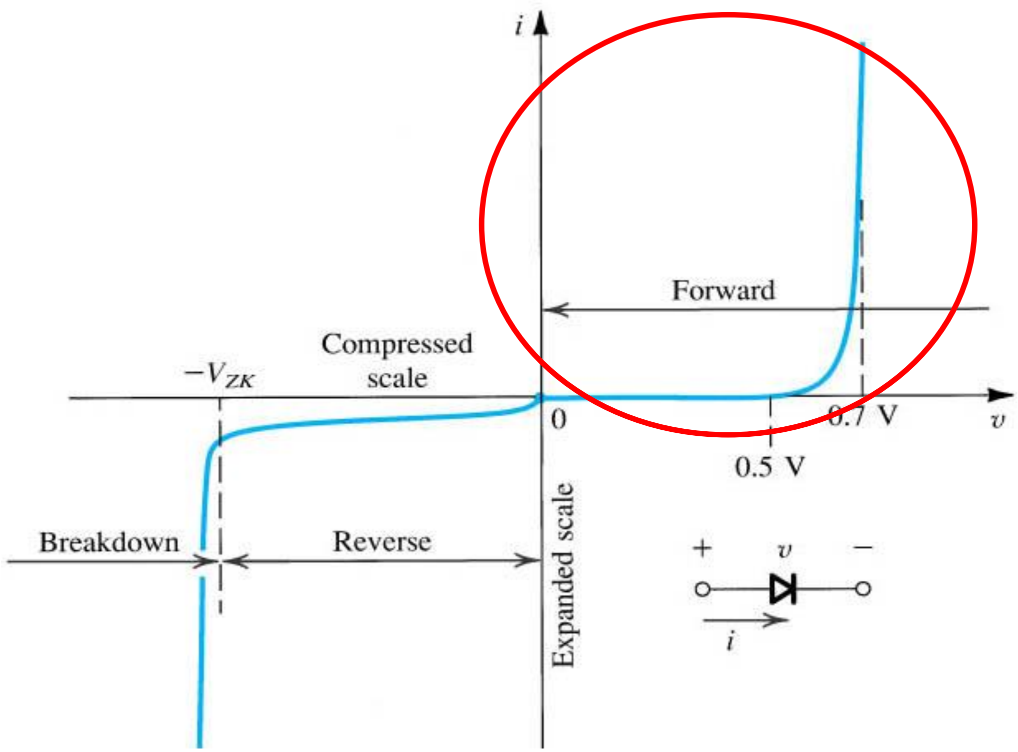
$$I = A\underbrace{\left(q\frac{D_p}{L_p} p_{n0} + q\frac{D_n}{L_n} n_{p0}\right)}_{=I_S}\left(e^{V/V_T} - 1\right)$$

Diodes: PN junction under forward bias

Excess minority carrier concentration causes current

- Total current for cross-section *A* : $I = I_S\left(e^{V/V_T} - 1\right)$

$\Rightarrow$ diode characteristic I-V equation in the forward bias region



Diodes: PN junction under forward bias

Excess minority carrier lifetime

- When turning of the forward voltage, it takes some time for the excess minority carriers to recombine with majority carriers: $p_n(x) = p_{n0} + \left(\left[p_n(x_n) - p_{n0} \right] e^{-(x-x_n)/L_p} \right) e^{-t/\tau_p}$
- This excess minority carrier lifetime is linked to the diffusion length: $\boxed{L_p = \sqrt{D_p \tau_p}}$ $\boxed{L_n = \sqrt{D_n \tau_n}}$

L_p ranges from 1um to 100um

τ_p ranges from 1 ns to 10000 ns

$\Rightarrow$ determines the speed of diode switching

$\Rightarrow$ τ_p can be reduced by increasing crystal purity, or by doping with Au or Pt

PN junctions: conclusions

Summary

- Forward bias
  - Depletion area narrows and more majority carriers cross junction
  - Cause excess minority carriers

  $\Rightarrow$ create diffusion current

  $\Rightarrow$ Diffusion current exponential with forward voltage

- Reverse bias
  - Depletion area widens and less majority carriers cross junction
  - Minority carriers still cross junction

  $\Rightarrow$ I_S (due to minority carriers) becomes larger than I_D (due to majority carriers)

  $\Rightarrow$ Small reverse current

PN junctions: conclusions

Summary

- Breakdown region
  - Zenner effect: large E-field breaks covalent bonds

  $\Rightarrow$ Large reverse current

  - Large E-field: minority carriers have enough kinetic energy to break covalent bonds

  $\Rightarrow$ Freed electrons also break other covalent bonds (Avalanche effect)

  $\Rightarrow$ Large reverse current

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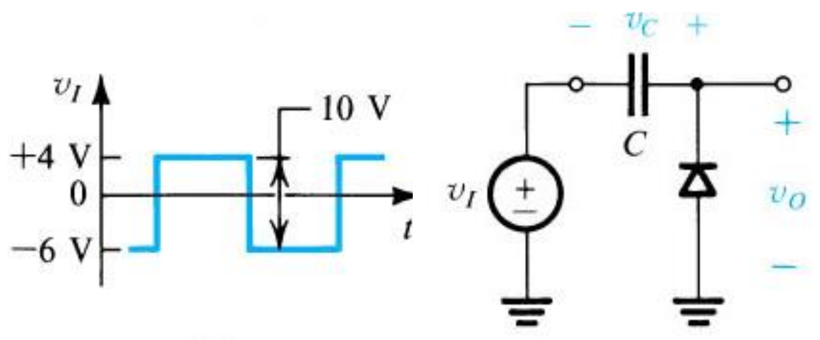
  - Voltage multiplier

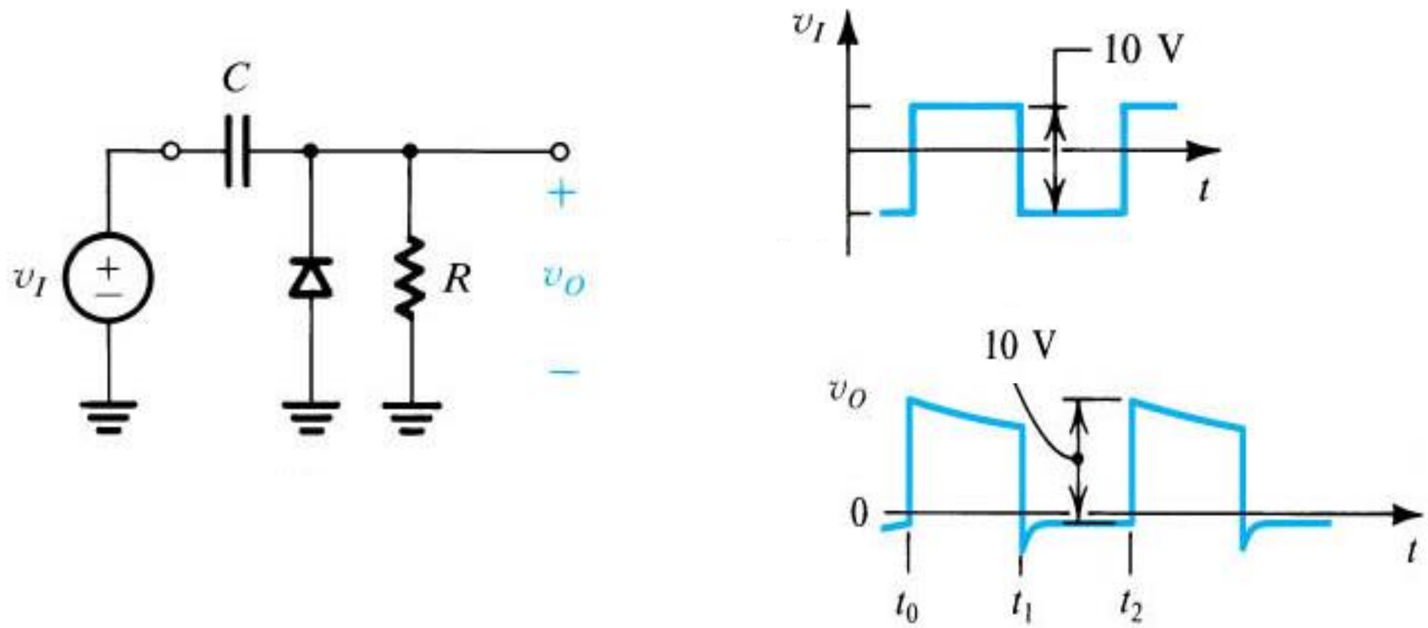
Circuits with diodes: DC restorer

adds a DC component to an AC signal



Circuits with diodes: DC restorer

When adding a load, capacitor discharges sligthy

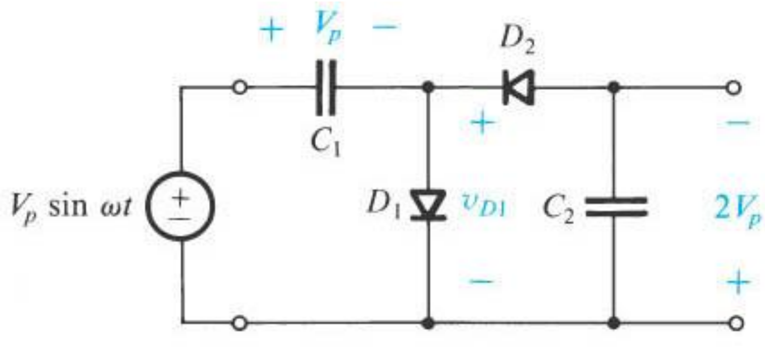


$\Rightarrow$ Choose RC constant wisely with respect to signal period!

Circuits with diodes: voltage doubler

Double AC voltage to DC voltage

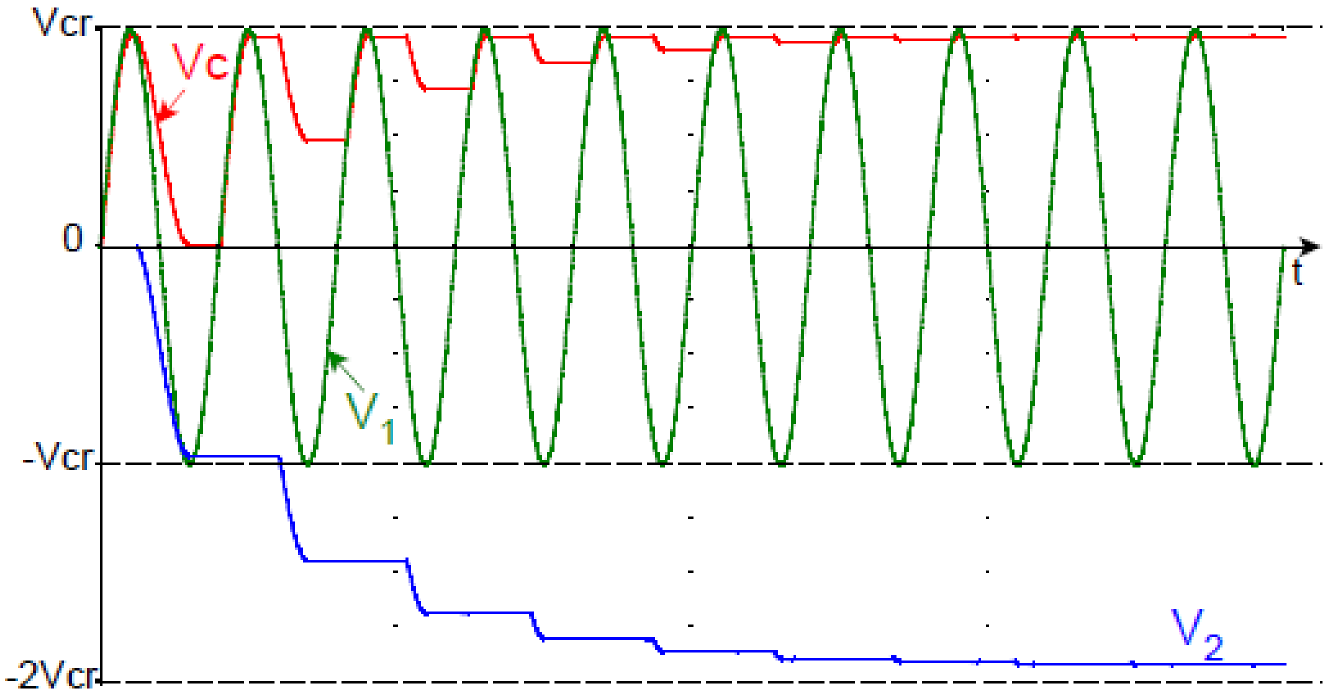
- Output is DC voltage twice the amplitude of AC input



Circuits with diodes: voltage doubler

PSpice simulation

- Capacitor takes a few cycles to be fully charged
- Treshold voltage diode causes slight voltage reduction



Circuits with diodes: voltage multiplier

previous circuit can be generalized

- V_{cr} is the amplitude of the source
- Every diode has to be able to sustain a reverse voltage of $2V_{cr}$ without going into avalanche