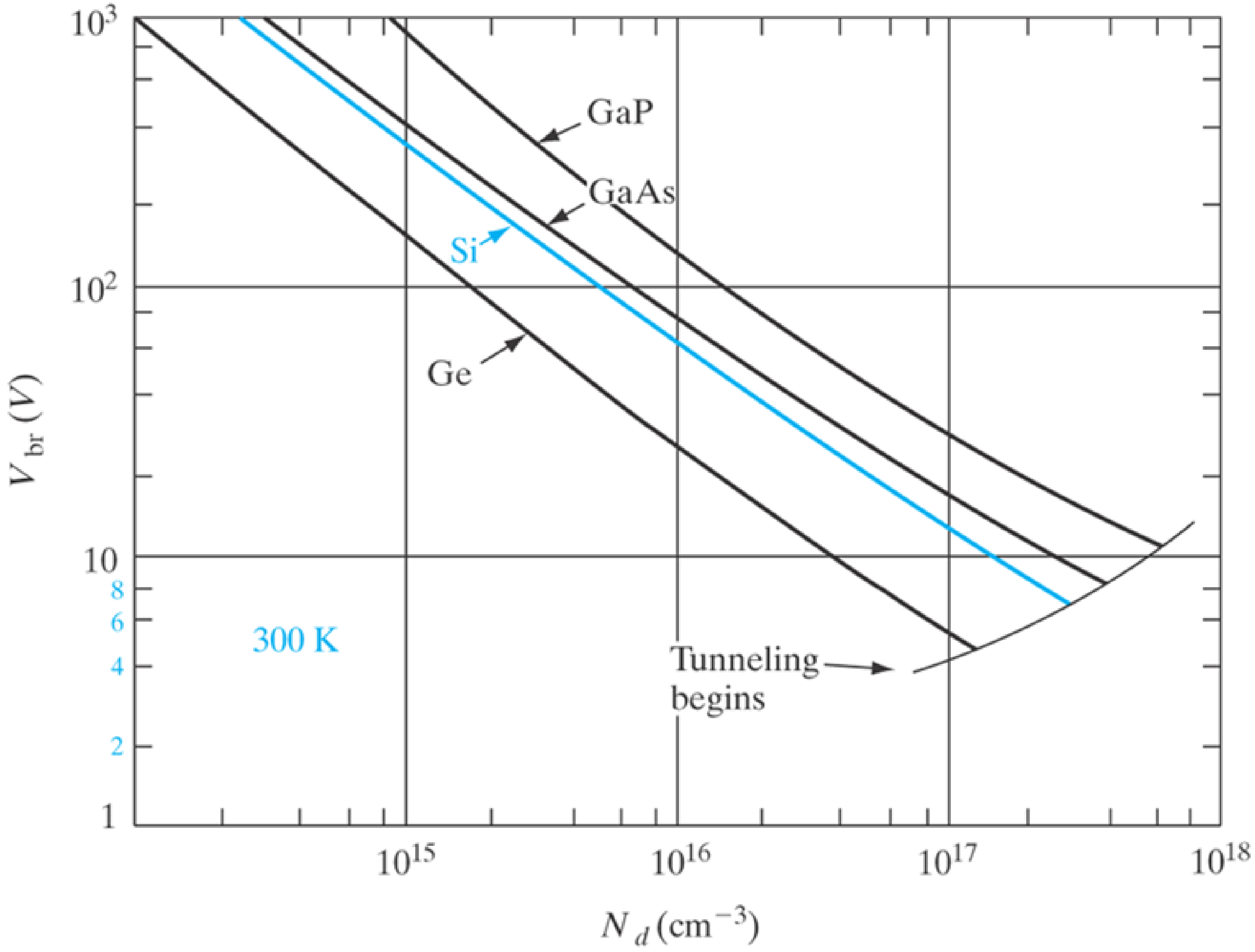
ECE 340 Lectures 26
Semiconductor Electronics

Spring 2022
10:00-10:50am
Professor Umberto Ravaioli
Department of Electrical and Computer Engineering
2062 ECE Building

Today's Discussion

- **Example applications of Zener diodes**
- **Capacitance of *p-n* junctions**
- **Stored charge**
- **Junction capacitance**
- **Diffusion capacitance**

Reverse breakdown (B): *p^+-n junction*



These results were calculated numerically by Sze and Gibbons, Applied Phys Lett, vol. 8, p.111, 1996

Values should be intended as upper limits for V_{br}

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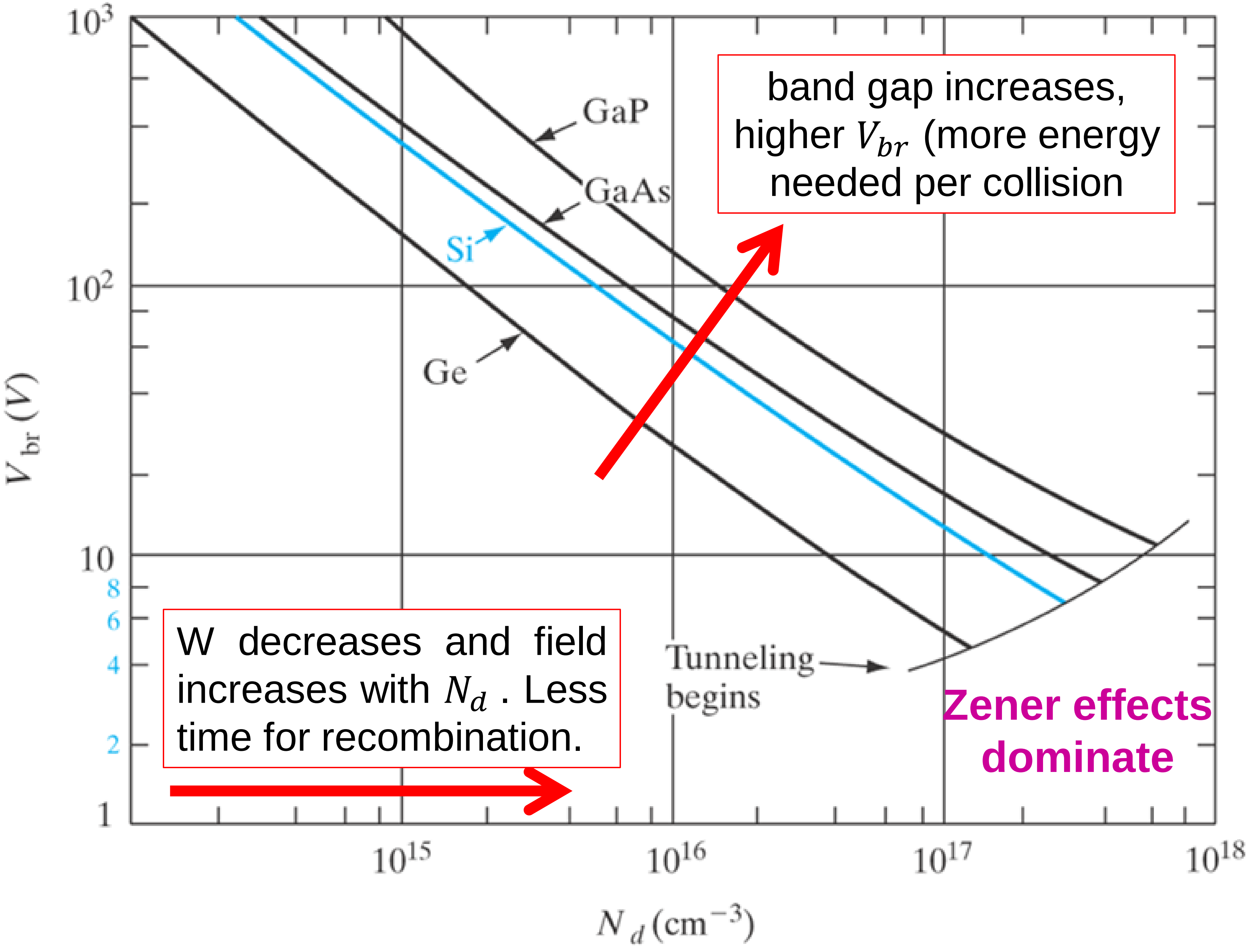


band gap increases, higher V_{br} (more energy needed per collision

W decreases and field increases with N_d . Less time for recombination.

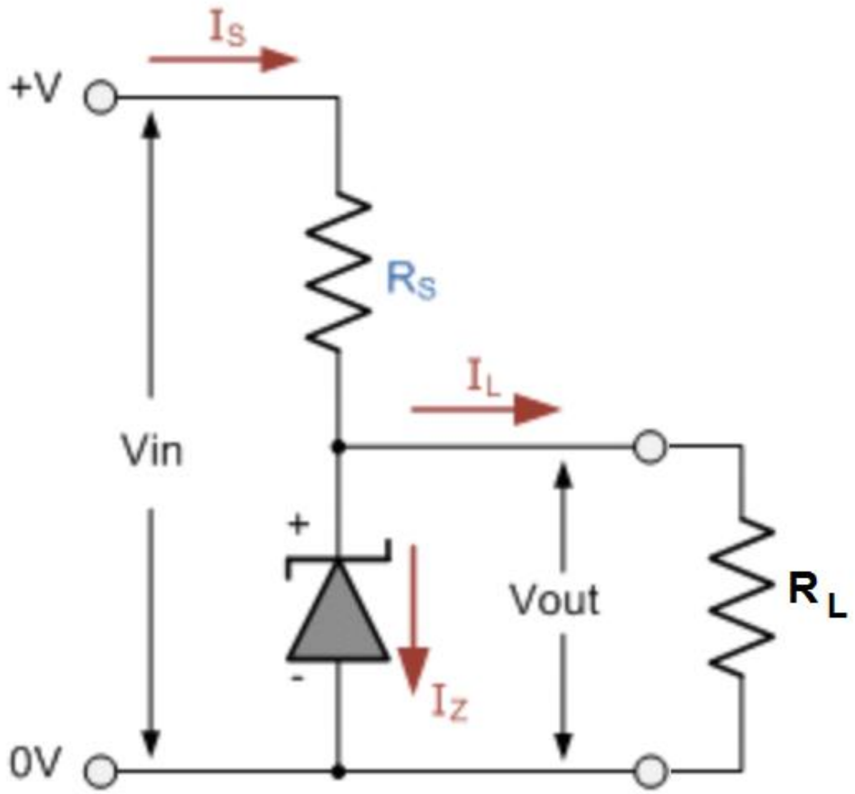
Zener effects dominate

Breakdown diodes

Breakdown diodes are largely based on avalanche generation effects, although these devices are often referred to an Zener diodes. This is historical, due to misinterpretations in early observations of breakdown in p-n junctions.

Zener tunnelling is only effective up to several volts in highly doped junctions. Diodes which are rated for breakdown at tens to hundreds of volts, experience primarily avalanche generation.

EXTRA – voltage reference in circuits



Example:

$V_{in} = 12\text{ V}$ (available)

$V_{out} = 5\text{ V}$ (wanted)

Maximum power rating of the breakdown diode $P_{max} = 2\text{ W}$.

Calculate:

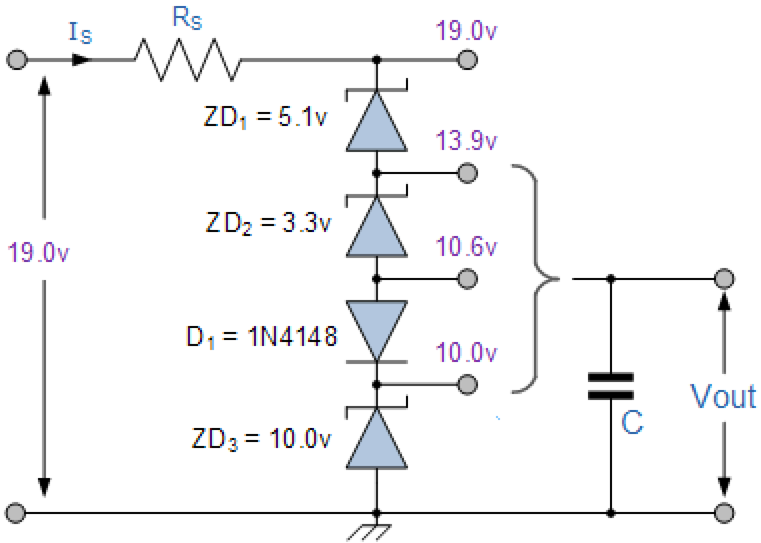
(a) maximum breakdown current
(b) Minimum value of R_S
(c) Current I_L with load $R_L = 1\ k\Omega$
(d) Diode current I_Z with load & R_{Smin}

(a) $I_{Zmax} = 2\text{W}/5\text{V} = 400\text{ mA}$
(b) $R_{Smin} = (V_{in} - V_{out})/I_{Zmax} = (12 - 5)/0.4 = 17.5\ \Omega$
(c) $I_L = (V_{out}/R_L) = 5/1000 = 5\text{mA}$
(d) $I_Z = I_S - I_L = 400\text{mA} - 5\text{mA} = 395\text{mA}$

EXTRA – Breakdown Diodes in series

More voltage options with diodes in series.

Standard forward biased Si diodes may be included to add ~ 0.6 to 0.7 V increments



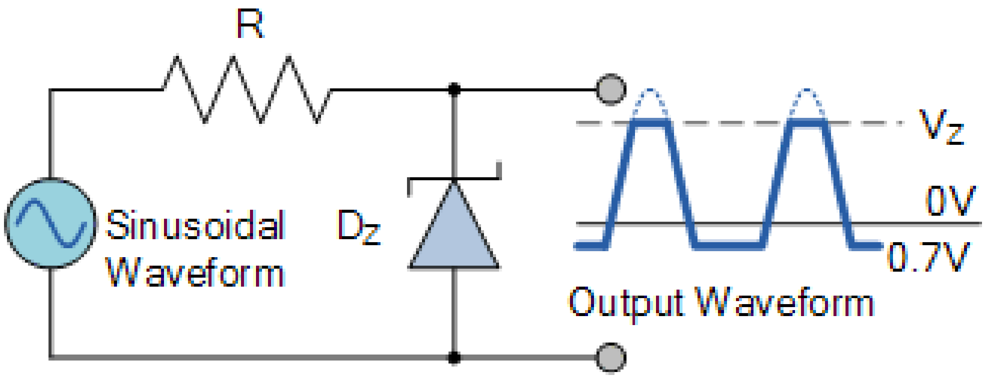
Example - Commercial diodes

BZX55 Zener Diode Power Rating 500mW							
2.4V	2.7V	3.0V	3.3V	3.6V	3.9V	4.3V	4.7V
5.1V	5.6V	6.2V	6.8V	7.5V	8.2V	9.1V	10V
11V	12V	13V	15V	16V	18V	20V	22V
24V	27V	30V	33V	36V	39V	43V	47V

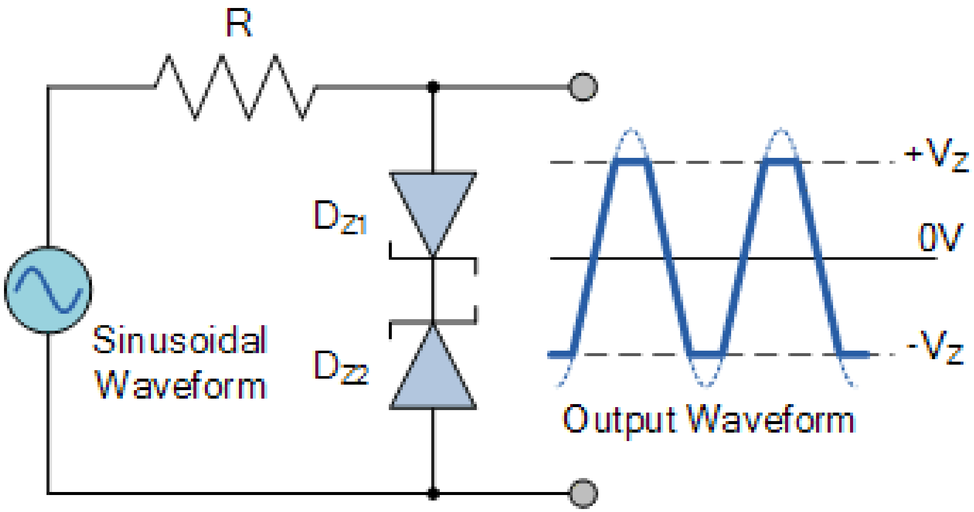
BZX85 Zener Diode Power Rating 1.3W							
3.3V	3.6V	3.9V	4.3V	4.7V	5.1V	5.6	6.2V
6.8V	7.5V	8.2V	9.1V	10V	11V	12V	13V
15V	16V	18V	20V	22V	24V	27V	30V
33V	36V	39V	43V	47V	51V	56V	62V

EXTRA - More options for voltage clippers

Single breakdown diode clipper (in forward bias it behaves like a regular diode)

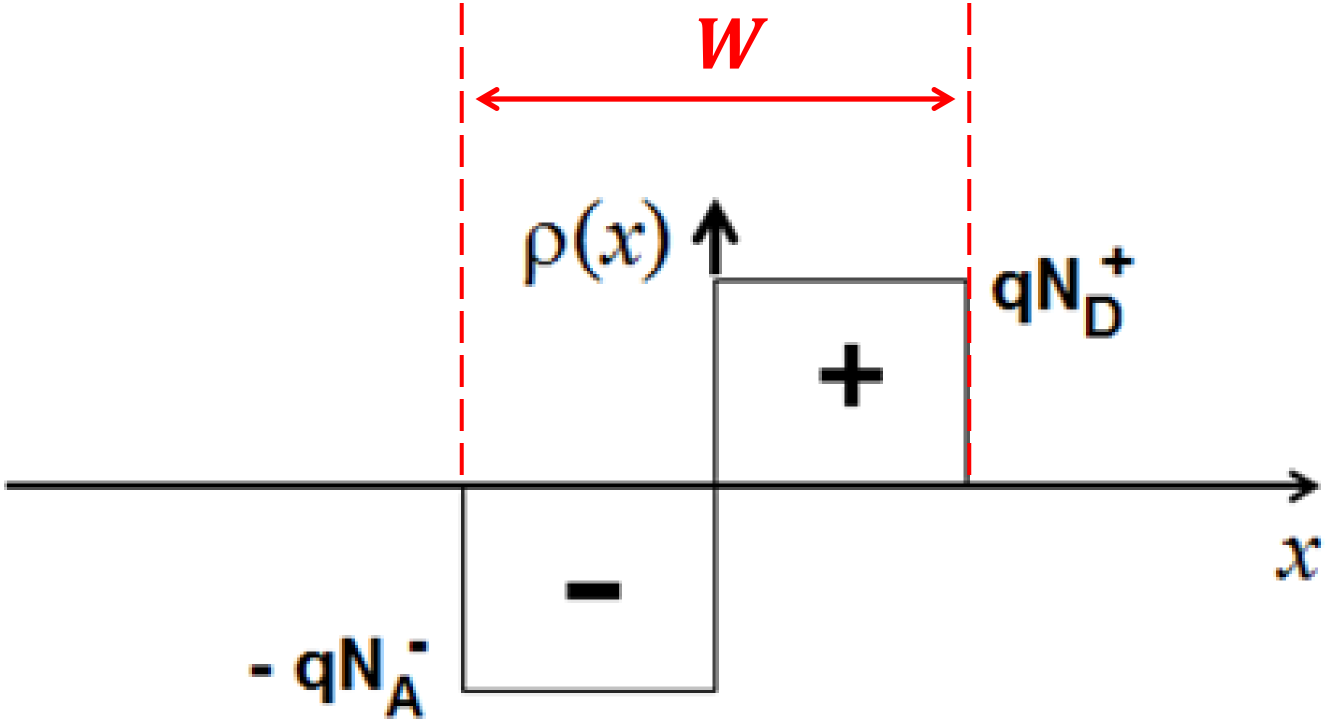


Double breakdown diode clipper (for each half wave one diode is at beakdown, the other one is a forward biased diode adding 0.6 to 0.7 V)



Recall the Depletion Width in equilibrium

$$\boxed{W = \sqrt{\frac{2\varepsilon V_o}{q}\frac{N_A + N_D}{N_A N_D}}}$$



p-n junction as capacitance

- **The space charge at the junction of a *p-n* diode varies in response to applied bias, so it behaves like a capacitor.**
- **This capacitor is *non-linear* as one can deduce from the depletion width expression**

$$\boxed{W = \sqrt{\frac{2\varepsilon(V_0 - \overset{\substack{\textbf{bias}\\ \downarrow}}{V})}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)}}$$

Differential form of the capacitance

- **The general expression for capacitance is used for the nonlinear case**

$$\boxed{C = \frac{dQ}{dV}}$$

- **We obtained earlier these expressions**

$$|Q| = qAx_{n0}N_D = qAx_{p0}N_A$$

$$x_{n0} = \frac{N_A}{N_A + N_D}W \qquad x_{p0} = \frac{N_D}{N_A + N_D}W$$

Junction (or Depletion) capacitance

$$|Q| = qA\frac{N_D N_A}{N_A + N_D}W =$$

$$= qA\frac{N_D N_A}{N_A + N_D}\underbrace{\sqrt{\frac{2\varepsilon(V_0 - V)}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)}}_{W}$$

$$= \varepsilon A\sqrt{\frac{2q}{\epsilon}(V_0 - V)\frac{N_D N_A}{N_A + N_D}}$$

Junction (or Depletion) capacitance

$$|Q| = \epsilon A \sqrt{\frac{2q}{\epsilon}(V_0 - V)\frac{N_D N_A}{N_A + N_D}}$$

$$C_j = \left|\frac{dQ}{d(V_0 - V)}\right| =$$

$$= \epsilon A \sqrt{\frac{2q}{\epsilon}\frac{N_D N_A}{N_A + N_D}}\left|\frac{d}{d(V_0 - V)}\sqrt{(V_0 - V)}\right|$$

$$\frac{d}{d(V_0 - V)}\sqrt{(V_0 - V)} = \frac{1}{2\sqrt{(V_0 - V)}}$$

Junction (or Depletion) capacitance

$$C_j = \left|\frac{dQ}{d(V_0 - V)}\right| = \epsilon A \underbrace{\sqrt{\frac{q}{2\epsilon(V_0 - V)}\frac{N_D N_A}{N_A + N_D}}}_{W^{-1}}$$

$$C_j = \frac{\epsilon A}{W} \propto (V_0 - V)^{-\frac{1}{2}}$$

One-sided p^+-n junction

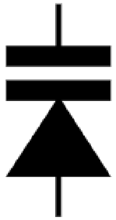
$$C_j = \epsilon A \sqrt{\frac{q}{2\epsilon(V_0 - V)}\frac{N_D N_A}{N_A + N_D}} = \epsilon A \sqrt{\frac{q N_D}{2\epsilon(V_0 - V)}}$$

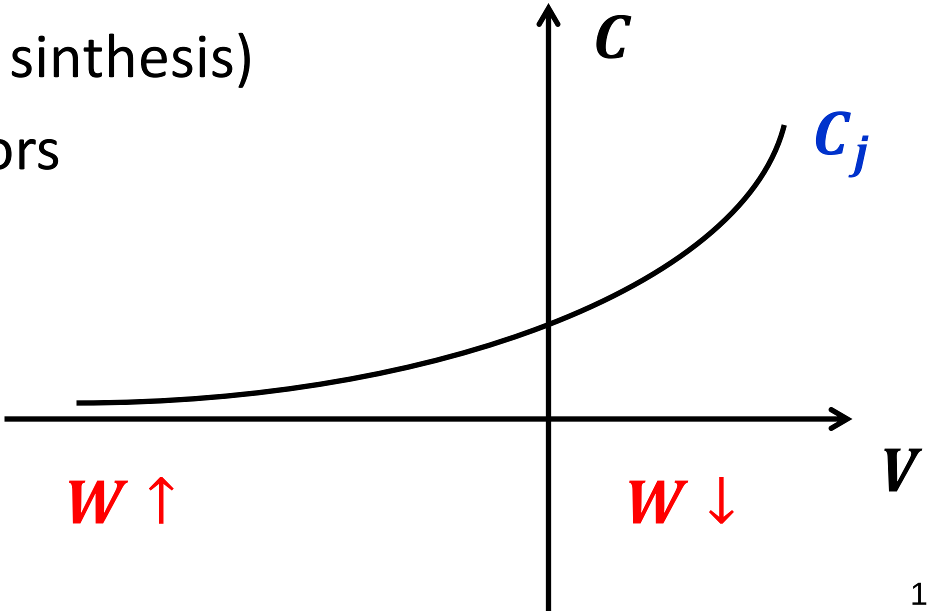
Junction (or Depletion) capacitance

Bias dependence – C_j dominates in reverse bias and small forward bias.

Varactor (a.k.a. Varicap) diodes are extensively used as miniaturized capacitors in RF applications:

- Voltage controlled oscillators
  (demodulators, frequency sinthesis)
- Frequency/Phase modulators
- RF Filters
- Tuners

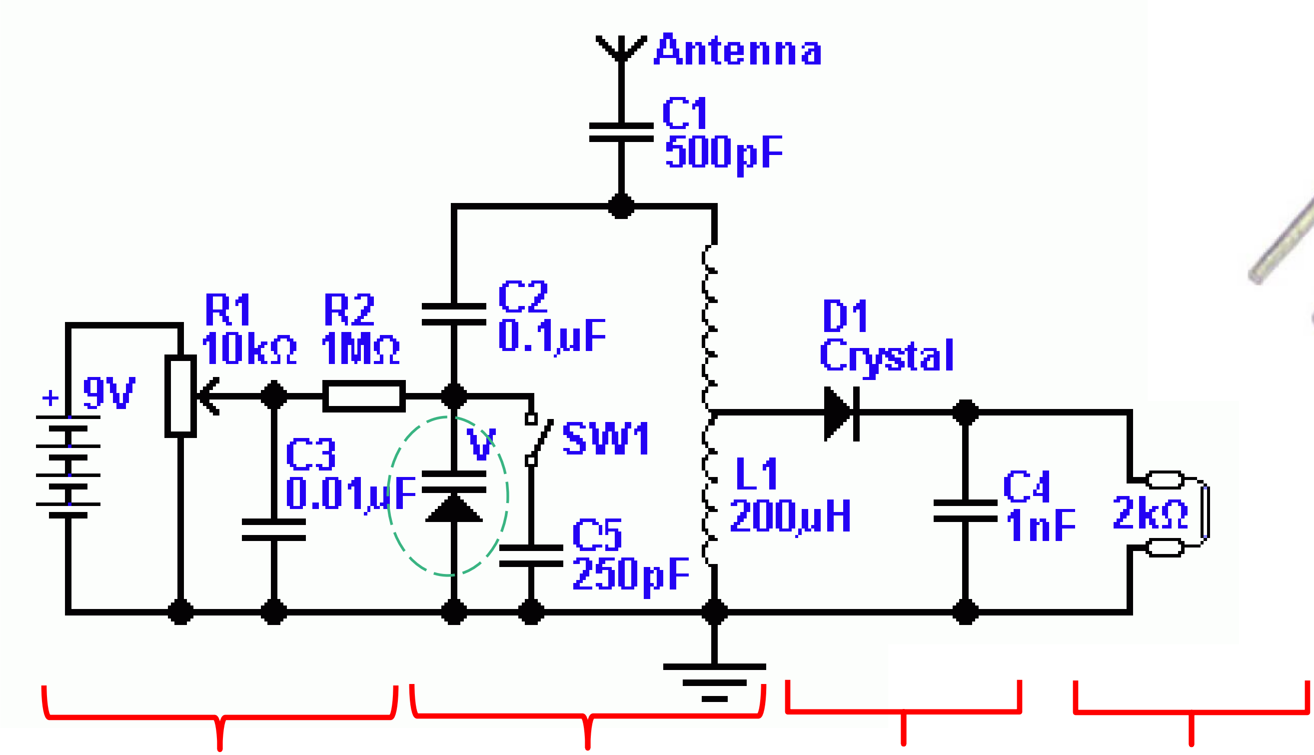


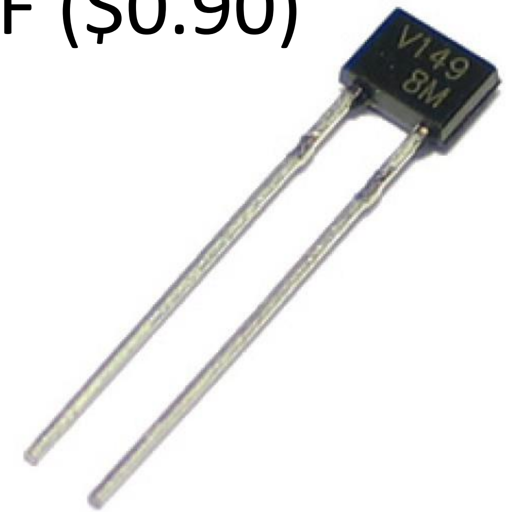


Varactor diode example application

- **1SV159** Varicap diode, 25 to 500pF ($0.90)

Suitable for AM band receivers





1V → 485 pF
8V → 25 pF

Voltage control for varicap diode

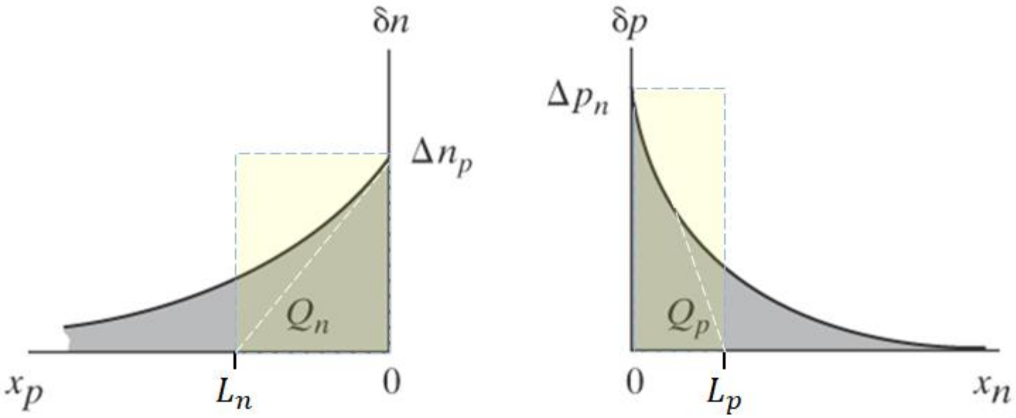
Resonant circuit

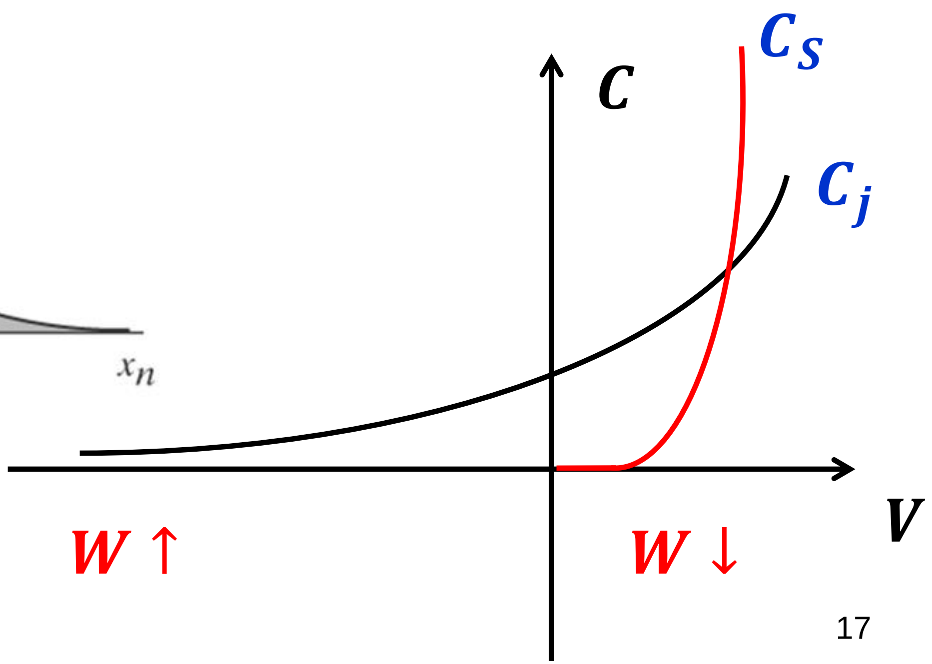
Rectifier for demodulation

High impedance earphones

Diffusion (a.k.a. Storage) capacitance

At sufficiently high forward bias, the **diffusion capacitance** C_S dominates. This is associated to the excess minority charge that accumulates at the boundaries of the depletion region.





Simple model for diffusion capacitance

Assume p^+-n junction in forward bias with current $I = \frac{Q_p}{\tau_p}$.

Charge storage for injected holes ($V \gg \frac{k_B T}{q}$):

$$Q_p = qA\Delta p_n L_P = qAL_p p_n \exp\left(\frac{qV}{k_B T}\right)$$

$$C_S = \frac{dQ_p}{dV} = \frac{q^2}{k_B T} AL_p p_n \exp\left(\frac{qV}{k_B T}\right)$$

$$C_S = \frac{q}{k_B T} Q_p = \frac{q}{k_B T} I\tau_p$$

(NOTE: Analogous results are obtained for electrons, if not negligible, and the contribution can be simply added to the model)

Simple model for diffusion capacitance

This result provides immediately also the a-c conductance of the junction since $I = \frac{Q_p}{\tau_p}$

$$G_S = \frac{dI}{dV} = \frac{1}{\tau_p}\frac{dQ_p}{dV} = \frac{q}{k_B T} I$$

Recall from the previous slide

$$\boxed{C_S = \frac{dQ_p}{dV} = \frac{q}{k_B T} I \tau_p}$$

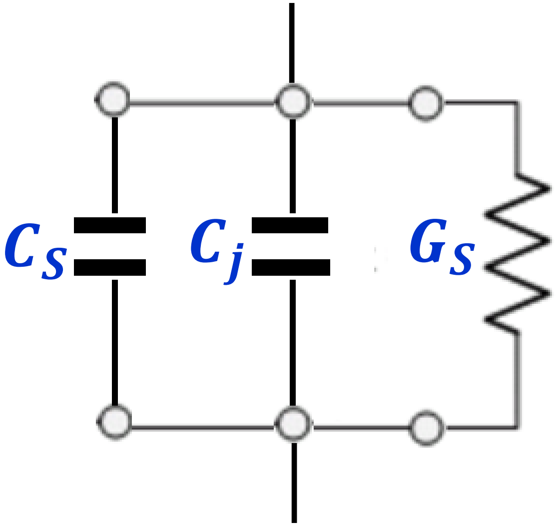
Simple model for diffusion capacitance

This result provides immediately also the a-c conductance of the junction since $I = \frac{Q_p}{\tau_p}$

$$G_S = \frac{dI}{dV} = \frac{1}{\tau_p}\frac{dQ_p}{dV} = \frac{q}{k_B T} I$$

Total capacitance

$$\boldsymbol{C = C_J + C_S}$$



small-signal equivalent circuit for the diode

Simple model for diffusion capacitance

This elementary model for diffusion does not involve the carrier distribution inside the depletion region.

A more in depth analysis based on numerical simulations with a complete drift-diffusion model (Laux and Hess, IEEE Trans. Electron Dev., 1999) indicates that a factor of ½ should be included:

$$C_S = \frac{dQ_p}{dV} = \frac{q^2}{\mathbf{2}k_B T} A L_p p_n \exp\left(\frac{qV}{k_B T}\right)$$

$$C_S = \frac{q}{\mathbf{2}k_B T} Q_p = \frac{q}{\mathbf{2}k_B T} I \tau_p$$

Diffusion capacitance

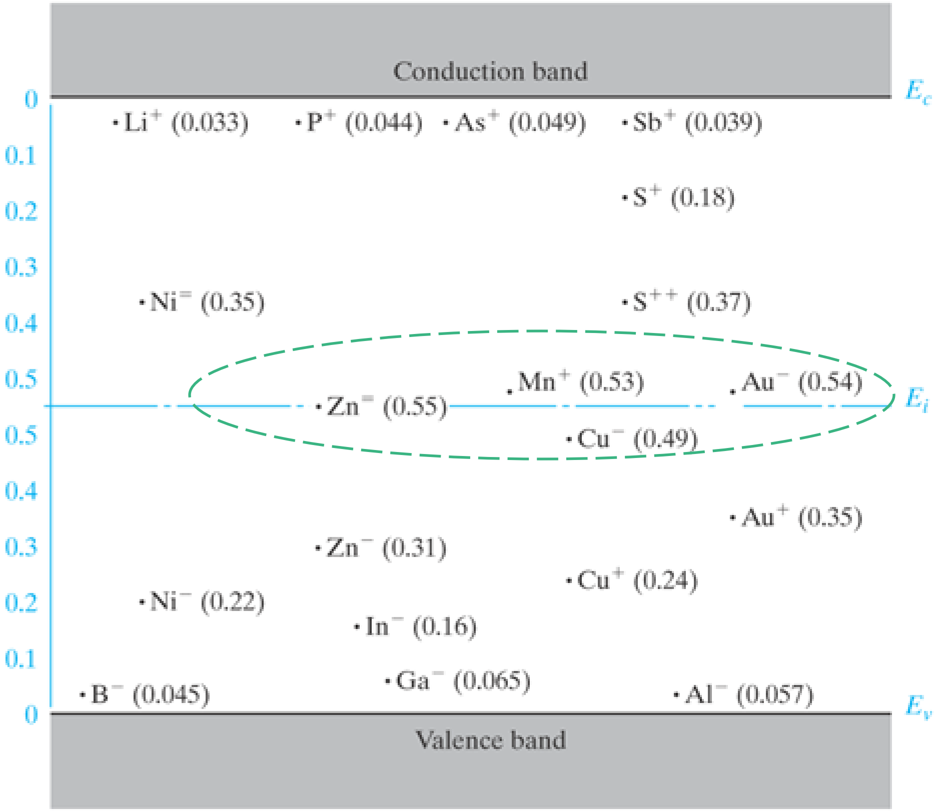
The capacitance due to charge storage is a limitation which may be serious in high frequency circuits involving forward biased p-n junctions. Additional capacitance tends to induce a delay in the response of a circuit

Frequency a-c response can be improved in general by reducing the carrier lifetime. We see that C_S is directly proportional to τ_p (and/or to $\tau_n$if a similar analysis is carried out for electrons).

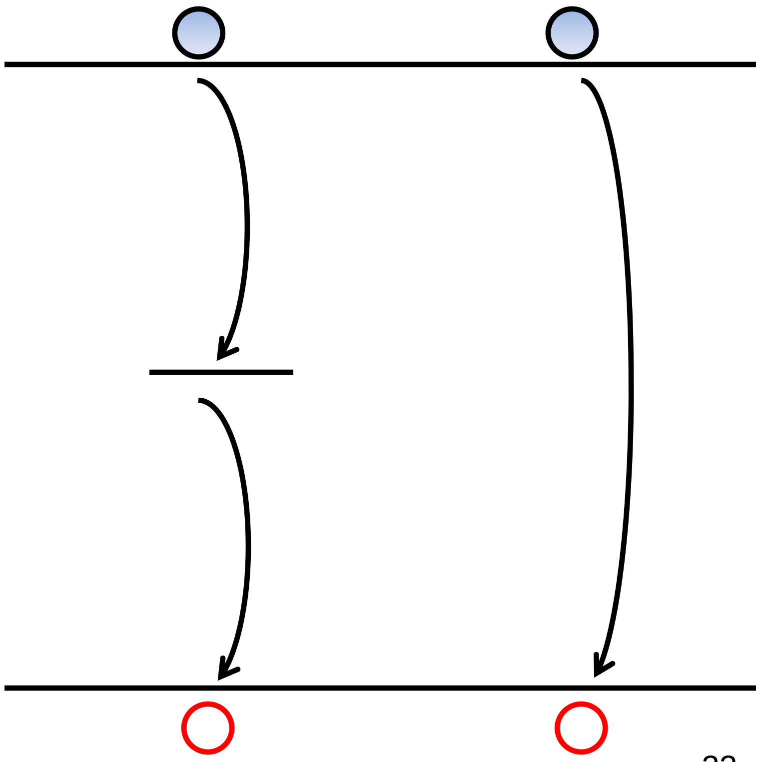
$$C_S = \frac{q}{2k_BT} I\tau_p$$

Shortening lifetimes

For instance, introduction of impurities with energy levels near the mid-gap can increase the probability of recombination, thus lowering the carrier lifetimes significantly.

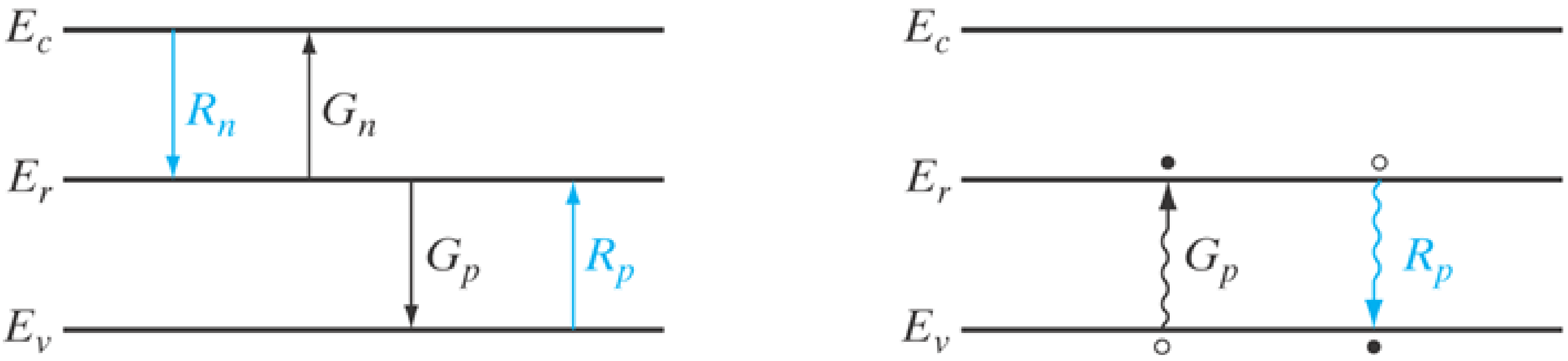


This transition is more probable



Capture and generation at recombination center

R_n — Electron capture
R_p — Hole capture
G_n — Electron generation
G_p — Hole generation



(a)

(b)

From *Solid State Electronic Devices,* Sixth Edition, by Ben G. Streetman and Sanjay Kumar Banerjee.
ISBN 0-13-149726-X.

Exercise (from last class)

- **Consider an abrupt *p-n* junction with cross-sectional area A = 1 mm^2 at T = 300K, with:**

p-side	*n*-side
$N_A = 10^{16}\text{cm}^{-3}$	$N_D = 10^{18}\text{cm}^{-3}$
$\mu_p = 370\text{cm}^2/\text{Vs}$	$\mu_n = 550\text{cm}^2/\text{Vs}$
$\mu_n = 1{,}000\text{cm}^2/\text{Vs}$	$\mu_p = 150\text{cm}^2/\text{Vs}$
$\tau_n = 1.0\ \mu s$	$\tau_p = 1.0\ \mu s$

- **Find the reverse saturation current**
- **Find the junction (depletion) capacitance at $-5V$**

Exercise (from last class)

- **Reverse saturation current**

$$I = -I_0 = -qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)$$

$$p_n = \frac{n_i^2}{n_n} = \frac{(1.5\times 10^{10})^2}{10^{18}} = 2.25\times 10^2\mathrm{cm}^{-3}$$

$$n_p = \frac{n_i^2}{p_p} = \frac{(1.5\times 10^{10})^2}{10^{16}} = 2.25\times 10^4\mathrm{cm}^{-3}$$

$$\left(D_p\right)_n = \frac{k_BT}{q}\left(\mu_p\right)_n = 0.0259\times 150 = 3.89\mathrm{cm}^2\mathrm{s}$$

$$(D_n)_p = \frac{k_BT}{q}(\mu_n)_p = 0.0259\times 1000 = 25.9\mathrm{cm}^2\mathrm{s}$$

Exercise (from last class)

- **Reverse saturation current**

$$I = -I_0 = -qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)$$

$$L_p = \sqrt{D_p\tau_p} = \sqrt{25.9 \times 10^{-6}} = 0.00197\text{cm}$$

$$L_n = \sqrt{D_n\tau_n} = \sqrt{3.89 \times 10^{-6}} = 0.00509\text{cm}$$

$$I = -1.602 \times 10^{-19} \times 10^{-2} \times$$

$$\times\left(\frac{3.89}{0.00197}2.25 \times 10^2 + \frac{25.9}{0.00509}2.25 \times 10^4\right)$$

$$= -1.839 \times 10^{-13}\text{A}$$

Exercise (now calculate capacitance)

- **Capacitance at $-5V$**

$$V_0 = \frac{k_B T}{q} \ln \frac{p_p}{p_n} = 0.0259 \times \ln \frac{10^{16}}{2.25 \times 10^2} = 0.8139\ \mathrm{V}$$

One-sided *p-n*⁺ junction

$$C_j = \epsilon A \sqrt{\frac{q}{2\epsilon(V_0 - V)} \frac{N_D N_A}{N_A + N_D}} = \sqrt{\epsilon} A \sqrt{\frac{q N_A}{2(V_0 - V)}}$$

$$= \sqrt{8.85 \times 10^{-14} \times 11.8} \times 10^{-2} \sqrt{\frac{1.6 \times 10^{-19} \times 10^{16}}{2(0.8139 + 5)}}$$

$$= 1.199 \times 10^{-10}\ \mathrm{F}$$