ECE 340 Lectures 25
Semiconductor Electronics

Spring 2022
10:00-10:50am
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Today’s Discussion

• Reverse bias
• Breakdown voltage
• Breakdown mechanisms
  – Zener effect
  – Avalanche
Details of particle flows \( (N_D > N_A) \)

Particle flow

- Current consists only of majority holes
- Current consists of majority holes and minority electrons with recombination occurring
- Practically all excess minority electrons have recombined

Assumption of no recombination

- Current consists of majority electrons and minority electrons with recombination occurring
- Practically all excess minority holes have recombined

(Remember: current is the same at each location)
Reverse saturation current

Reverse bias $V = -V_r$

$$I = I_0 \left[ \exp \left( -\frac{qV_r}{k_B T} \right) - 1 \right]$$

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

Reverse bias \( V = -V_r \) with \( V_r \gg k_B T / q \)

\[
\Delta p_n = p_n \left[ \exp \left( -\frac{qV_r}{k_B T} \right) - 1 \right] \approx -p_n
\]

\[
\Delta n_p = n_p \left[ \exp \left( -\frac{qV_r}{k_B T} \right) - 1 \right] \approx -n_p
\]
Reverse bias minority carriers

\[ \Delta n_p \approx -n_p \]

\[ V = -V_r \]

\[ p(x_n) \]

\[ \Delta p_n \approx -p_n \]
Reverse bias carrier distributions

Note: these are logarithmic scales

\[ n_p \exp \left( -\frac{qV_r}{k_B T} \right) \]

\[ p_n \exp \left( -\frac{qV_r}{k_B T} \right) \]
Quasi-Fermi level reminder

\[ n = n_i \exp\left(\frac{F_n - E_i}{k_B T}\right) \]

\[ p = n_i \exp\left(\frac{E_i - F_p}{k_B T}\right) \]

\[ pn = n_i^2 \exp\left(\frac{F_n - E_i + E_i - F_p}{k_B T}\right) \]

\[ = n_i^2 \exp\left(\frac{F_n - F_p}{k_B T}\right) \]
Reverse bias minority carriers

\[ pn = n_i^2 \exp\left(\frac{F_n - F_p}{k_B T}\right) \approx 0 \]
The following summary slides are adapted from the most recent edition (2006) of a classic comprehensive book on semiconductor devices. This book can be downloaded through the University Library:

S.M. Sze and K.K. Ng “Physics of Semiconductor Devices”

from the Wiley Online Library. For students who are interested in continuing with semiconductors or who simply want to have the standard reference which most professionals have used since the 1970’s, this is highly recommended.
Forward bias  Reverse bias

Adapted from S.M. Sze and K.K. Ng “Physics of Semiconductor Devices”
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• Consider an abrupt $p$-$n$ junction with cross-sectional area $A = 1 \text{ mm}^2$ at $T = 300K$, with:

\begin{align*}
\text{$p$-side} & & \text{$n$-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\text{s} & \tau_p &= 1.0 \mu\text{s}
\end{align*}

• Find the reverse saturation current
Exercise

• Reverse saturation current

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

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

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

\[ (D_p)_n = \frac{k_B T}{q} (\mu_p)_n = 0.0259 \times 150 = 3.89 \text{cm}^2 \text{s} \]

\[ (D_n)_p = \frac{k_B T}{q} (\mu_n)_p = 0.0259 \times 1000 = 25.9 \text{cm}^2 \text{s} \]
Exercise

• Reverse saturation current

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

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

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

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

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

\[ = -1.839 \times 10^{-13} \text{A} \]
$p$-$n$ junction $I$-$V$ curve under reverse bias

Circuit considerations:
The resistor $R$ helps constrain the current in the reverse breakdown regime.

(Remember ECE 110)
Compare with forward bias: same current magnitude, same resistance (same slope).

Which condition uses more power?
Reverse breakdown (A) = Zener effect

Tunneling through a narrow barrier

At higher doping levels, bands are steeper
Reverse breakdown (A) = Zener effect

In reverse bias the depletion width is wider but space separation between band edges is actually narrower, making tunneling more likely.
At shallow doping the depletion region is not sufficiently wide to allow tunneling between bands and there is no appreciable Zener effect.
Reverse breakdown (A) = Zener effect

At shallow doping the distance between bands is not sufficiently wide to allow tunneling.
Reverse breakdown (B) = Avalanche

At relatively higher reverse voltages [about $q(V_0 - V_r) > E_g$], avalanche generation dominates, due to a high energy scattering mechanism called “impact ionization”.
Both energetic electrons and holes may have multiple impact ionization collisions. Secondary electrons and holes with sufficient energy may also experience impact ionization collisions. An so on until carriers exit the depletion region...
Reverse breakdown (B) = Avalanche

\[ M_n = \frac{n_{out}}{n_{in}} \]
Reverse breakdown (B) = Avalanche

\[ n_{in} \text{ primary electrons} \rightarrow \text{depletion region } W \rightarrow n_{out} \text{ electrons} \]

**Simple model**  \[ P = \text{probability of impact ionization within } W \]

- primary \( n_{in} \)
- secondary \( n_{in} P \)
- tertiary \( n_{in} P^2 \)
- quaternary \( n_{in} P^3 \)
- \( \ldots \ldots \)
- \( n \)-ary \( n_{in} P^n \)

\[ n_{out} = n_{in} (1 + P + P^2 + P^3 + \ldots) = n_{in} \frac{1}{1 - P} \]

**multiplication factor**  \[ M_{in} = \frac{n_{out}}{n_{in}} = \frac{1}{1 - P} \]

NOTE: recombinations are neglected in this simple model
Reverse breakdown (B) = Avalanche

\[ M_n = \frac{n_{\text{out}}}{n_{\text{in}}} = \frac{1}{1 - P} \]

In this simple model, since \( P \) is close to unity, carrier multiplication essentially could grow without limit. The external circuit, as seen earlier, actually limits the current and there should also be a dependence on bias.

Empirical relation from experimental observations where \( n \) depends on the material and is between 3 and 6

\[ M_{\text{exp}} = \frac{1}{1 - \left( \frac{V}{V_{\text{br}}} \right)^n} \]
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 $V_{br}$
Reverse breakdown (B):

- $p + n$ junction

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 are largely based on avalanche generation effects, although these devices are often referred to as 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.
Example:

\[ V_{\text{in}} = 12 \text{ V} \text{ (available)} \]
\[ V_{\text{out}} = 5 \text{ V} \text{ (wanted)} \]

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

Calculate:

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

(a) \( I_{Z\text{max}} = \frac{2\text{ W}}{5\text{ V}} = 400 \text{ mA} \)
(b) \( R_{S\text{min}} = \frac{(V_{\text{in}} - V_{\text{out}})}{I_{Z\text{max}}} = \frac{(12 - 5)}{0.4} = 17.5 \text{ \Omega} \)
(c) \( I_L = \frac{V_{\text{out}}}{R_L} = \frac{5}{1000} = 5\text{ mA} \)
(d) \( I_Z = I_S - I_L = 400\text{ mA} - 5\text{ mA} = 395\text{ mA} \)
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

<table>
<thead>
<tr>
<th>ZBX55 Zener Diode Power Rating 500mW</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.4V</td>
</tr>
<tr>
<td>5.1V</td>
</tr>
<tr>
<td>11V</td>
</tr>
<tr>
<td>24V</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BZX85 Zener Diode Power Rating 1.3W</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3V</td>
</tr>
<tr>
<td>6.8V</td>
</tr>
<tr>
<td>15V</td>
</tr>
<tr>
<td>33V</td>
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</tbody>
</table>
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 breakdown, the other one is a forward biased diode adding 0.6 to 0.7 V)