ELECTRONIC MATERIALS - Devices
Chapter 6 from Prof. Kasap’s Book
Electrical Properties of Materials
Details of Electronic Devices
This section is designated as ch6B

MSE 433 Class Presentation
Spring Semester
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The Figures are mostly from Prof. Kasap’s book and I have added my additional notes. The equations have been typed at UNR from the Prof. Kasap’s book.
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http://Semiconductors.Usask.Ca
SEMICONDUCTING DEVICES
Chapter 6 – Kasap’s Book

6.1 p-n junctions... No Bias... Forward Bias and Reverse Bias
6.2 p-n junctions... Band Diagram
6.3 p-n junctions... Capacitance of the Depletion Layer
6.4 Diffusion Storage (Capacitance) and Dynamic Resistance
6.5 Reserve Bias breakdown: Avalanche and Zener Breakdown
6.6 Bipolar Common Transistors
6.7 Field Effect Transistors (FET) . Junction
6.9 Light Emitting Diodes
6.10 Photovoltaic Devices
6.11 Lasers and optical amplifiers
Two Types of Transistors

- *Bipolar Junction Transistors (BJT’s)
- **Field Effect Transistors (FET’s)

* William Shockley (Nobel Prize Winner) Proposed .... Principle of Transistor operation is mainly dictated by minority carrier injection

**FET work on a different principle .... Effect of Applied Field on Conducting Channel between two terminals
6.1 **p-n junctions** …No Bias and with Forward Bias and Reverse Bias

1. **Conc. Equation 6.1 Fig. 6.1**
   \[ N_a W_p = N_d W_n \]

   - \( N_a \) = Concentration of Acceptor
   - \( N_d \) = Concentration of donors
   - \( W_a \) = Width of space charge area
   - \( W_n = W_d \) = Width of space charge area

2. Electric Field and Net space charge Density, \( \rho_{net} \)
   \[
   \frac{dE}{dx} = \frac{\rho_{net}(x)}{\varepsilon}
   \]

   \( dE/dx \) = Electrostatic Charge at a point or Gauss’s Point Law
   \( \varepsilon = \varepsilon_o \cdot \kappa \) = Permittivity or Capacivity
   \( \varepsilon_o \) = Absolute Permittivity of free space = 8.854x10^-12 F/m
   \( \kappa \) = Relative Permittivity = Dielectric Constant
   (this is due to incorporation of a electrical insulator in between electrodes…it increases it’s permittivity by a factor \( \kappa \) or \( \varepsilon \), from \( \varepsilon_o \) with vacuum.

3. **Electric Field In Depletion region:**
   Eq. 6.2 –Figure 6.1 c
   \[
   E(x) = \frac{1}{\varepsilon} \int_{-W_p}^{x} \rho_{net}(x) \, dx
   \]

4. **Built In Electric Field**
   Eq. 6.3 –Figure 6.1 d
   \[
   E_0 = -\frac{eN_d W_n}{\varepsilon} = -\frac{eN_a W_p}{\varepsilon}
   \]

---

Fig. 6.1: Properties of the pn junction.

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Electric Field, $E(x)$, Built-in Voltage $V_0$, and Width of Depletion Region, $W$

Built-in Voltage, $V_0$, Eq. 6.4 – Figure 6.4 e., obtained by Integrating $E_x$ and using $x = W_n$ to evaluate potential $V(x)$

$$V_0 = -\frac{1}{2}E_0W_0 = \frac{eN_aN_dW_0^2}{2e(N_a + N_d)} \quad \text{Eq. 6.4}$$

Charge Carrier Ratios in Depleted Region

\[ \frac{n_2}{n_1} = \exp \left[ -\frac{(E_2 - E_1)}{kT} \right] \quad \text{N}_1 \text{ carriers at some } E_1 \text{ and } \text{N}_2 \text{ carriers at } E_2 \]

\[ \frac{n_{p0}}{n_{n0}} = \exp \left( -\frac{eV_0}{kT} \right) \quad \text{Eq. 6.5a- p-side far away from } M@E=0 \text{ p-side, } n=n_{p0} \]

\[ \frac{p_{n0}}{p_{p0}} = \exp \left( -\frac{eV_0}{kT} \right) \quad \text{Eq. 6.5b- n-side far away from } M@E=eV_0 \text{ n-side, } n=n_{n0} \]

Finally (after detailed derivation in the Book) the Built-in voltage is:

$$V_o = \frac{kT}{e} \ln \left( \frac{n_{n0}}{n_{p0}} \right) \quad V_o = \frac{kT}{e} \ln \left( \frac{p_{p0}}{p_{n0}} \right) \quad \text{and} \quad \frac{n_{n0}}{n_{p0}} = \frac{n_1^2}{N_d}$$

Equation 6.6–Dependence on $N_a$ and $N_d$}

Width of the Depletion region

$$W_o = \left[ \frac{2\varepsilon(N_a + N_d)W_o}{eN_aN_d} \right]^{1/2} \quad \text{Equation 6.7}$$

Properties of the pn junction. ($E_0$ is the electric field.)
### Built-in Potential for Ge, Si and GaAs at 300K

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>$E_g$ (eV)</th>
<th>$n_i$/cm$^3$</th>
<th>$V_o$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge</td>
<td>0.7</td>
<td>$2.4 \times 10^{13}$</td>
<td>0.37 V</td>
</tr>
<tr>
<td>Si</td>
<td>1.1</td>
<td>$1.45 \times 10^{11}$</td>
<td>0.76 V</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.4</td>
<td>$1.79 \times 10^{6}$</td>
<td>1.22 V</td>
</tr>
</tbody>
</table>

Note: $E_g$, $n_i$ are from Table 5.1 Page 334. We have just calculated the last column of this Table.

Ex: Find the Built In $(V_o)$ if Si, pn junction diode has a concentration, (acceptor) $10^{16}$ atoms/cm$^3$ (p-side) and $10^{17}$ donor atoms/cm$^3$ (n-side)

**Built-in voltage $V_o$ From Eq. 6.6**

$$V_o = \frac{kT}{e} \ln \left( \frac{N_a N_d}{n_i^2} \right)$$  

**Equation 6.6-Dependence on $N_a$ and $N_d$**

$N_a = 10^{16}$/cm$^3$

$N_d = 10^{17}$/cm$^3$

Intrinsic Electron Concentration

$n_i = 1.45 \times 10^{11}$/cm$^3$

$kT/e = 0.0259$ V

Note - units

$k = 8.62 \times 10^5$ eV/K

$e = 1.602 \times 10^{-19}$ C

Units: $\frac{kT}{e} = \frac{(eV / K).K}{C} = \frac{(C.V / K).K}{C}$ = V

$V_o$ for Si $\sim 0.76$ V
**FORWARD BIAS i.e. Battery connected with + pole connected to the p-side and the negative connected to n-side of the pn junction then estimate the Diffusion Current**

1. Applied Voltage = V
2. Reduction of Potential Barrier ($V_o$) is created by a value V or
3. The bulk regions have high Conductivities than depleted region in the middle.
4. Carriers are immobile in the depletion region
5. Thus V opposes the (built-in potential, $V_o$) across the width “W” that REDUCES THE DIFFUSION OF ELECTRONS
6. Thus the probability of “Hole” surmounting the potential barrier is proportional to $e^{(V_o-V)/kT}$
7. MANY HOLES CAN CROSS THE DEPLETED REGION AND DIFFUSE INTO n-SIDE…..resulting injection of EXCESS MINORITY charges holes in this case in the n-region.
8. At the n interface at $x'=0$ (Voltage determines how many holes arrive at n-side). “**LAWS OF JUNCTION**”

For Excess Holes on n-side: $p_n(x'=0) = p_{no}e^{eV/kT}$ Eq.6.9
For Excess Electrons on p-side: $n_p(x'=0) = n_{po}e^{eV/kT}$ Eq.6.10

Thus, if applied $V=0$ then, $p_n(x'=0) = p_{no}$

see the Figure to the left. Also look up Hole diffusion length Page 423.
Next Topic: *Ideal Diode (Shockley) Equation*

**1. HOLE DIFFUSION CURRENT DENSITY, $J_{D,\text{hole}}$**

$$J_{D,\text{hole}} = -eD_h \frac{dp_n(x')}{dx'} = -eD_h \frac{d\Delta p_n(x')}{dx'}$$

$$J = J_{\text{elec}} + J_h J_{D,\text{hole}} = eD_h \frac{dp_n(x')}{dx'}$$

Where:

- $J_{D,\text{hole}}$ Hole Diffusion Length
- $\tau_h$ Mean Hole Recombination Time or *Minority Carrier Lifetime*
- $D_h$ Diffusion Coefficient of the holes

*This equation is saying that the Hole diffusion depends on location*

But The total current depends on sum of Holes and electron contribution ….independent of $x$ (or $x'$)…..so a flat line on top (left Figure). Next slide shows more Equations
Shockley Equation

At $x' = 0$, just outside the depletion region

$$ J_{D,hole} = \left( \frac{eD_h}{L_h} \right) \Delta p_n(0) $$

Using Law of junction, $p_n$ in terms Volts

$$ \Delta p_n(0) = p_n(0) - p_{no} = p_{no} \left[ \exp\left( \frac{eV}{kT} \right) - 1 \right] $$

At $x' = 0$, just outside the depletion region

$$ J_{D,hole} = \left( \frac{eD_h p_{no}}{L_h} \right) \left[ \exp\left( \frac{eV}{kT} \right) - 1 \right] $$

But at thermal eq. this related to hole concentration

$$ p_{no} = \frac{n_i^2}{n_{no}} = \frac{n_i^2}{N_d} $$

In terms of $n_i$

$$ J_{D,hole} = \left( \frac{eD_h n_i^2}{L_h N_d} \right) \left[ \exp\left( \frac{eV}{kT} \right) - 1 \right] $$

Total Current Density is $J = J_{D,hole} + J_{D,electron}$

$$ J = \left( \frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a} \right) n_i^2 \left[ \exp\left( \frac{eV}{kT} \right) - 1 \right] $$

Shockley Equation

$$ J = J_{so} \left[ \exp\left( \frac{eV}{kT} \right) - 1 \right] \quad \text{Eq.6.12} $$

$J_{so}$ is const. but dependent on doping, $N_d$, $N_a$, and also on materials via $n_i, D_h, D_e$, and $L_h, L_e$

Constant $J_{so}$ is familiar Diode Eq.

$$ J_{so} = \left[ \frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a} \right] n_i^2 $$

INTRINSIC CONCENTRATION…Band Gap expressed in Volts:

$$ n_i^2 = (N_c N_v) \exp \left( -\frac{eV_g}{kT} \right) $$
The significance of this Diode equation is that voltage at, for example 0.1 mA, THE VOLTAGES OF Ge and Si, and GaAs are 0.2, 0.6, and 0.9V!

**Diode Current (J) and Band gap Energy (V_g)**

\[
J = J_1 \exp \left( -\frac{eV}{kT} \right) \left[ \exp \left( \frac{eV}{kT} \right) - 1 \right]
\]

Equation 6.13

\[
J = \frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a} \left( N_e N_v \right) \exp \left( -\frac{eV_c}{kT} \right) \left[ \exp \left( \frac{eV}{kT} \right) - 1 \right]
\]

where \( J_1 = \left( \frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a} \right) (N_e N_v) \)

\( N_c = \text{Effective Density of States at Conduction Band edge/m}^3 \)

\( N_v = \text{Effective Density of States at Valence Band edge/m}^3 \)

\[
L_n = \sqrt{D_n \tau_n}
\]

\[
\frac{d\Delta p_n(x')}{dx'} = -\frac{\left[ p_n(0) - p_{no} \right]}{l_n}
\]

Fig. 6.4: Schematic sketch of the I-V characteristics of G and GaAs pn Junctions
Example of depletion Width’s (W) and Built-in Voltage (Vo) Calculation depending on the amount of Doping in a pn Junction – This will give you a feel for actual widths and voltages involved that are dependent on $N_a$ and/or $N_d$ (from Kasap’s Book)

This problem relates to a heavily doped p-side of $p^+n$ junction. To find $V_o$ and depletion width (W)

Given: $N_d = 10^{16}/cm^3 = 10^{22}/m^3$, and $N_a = 10^{18}/cm^3 = 10^{24}/m^3$

Charge $Q = eN_aW_p = eN_dW_n$

where, $N_a$ and $N_d$ are acceptor and donor concentrations

Using Eq. 6.6 and 6.7: At 300K

$$V_o = \frac{kT}{e} \ln\left(\frac{N_aN_d}{n_i^2}\right)$$

$$V_o = (0.259V) \ln \left(\frac{10^{16} \cdot 10^{18}}{1.45 \times 10^{10}}\right) = 0.816V$$

$$W_o = \left[\frac{2\varepsilon(N_a + N_d)V_o}{eN_aN_d}\right]^{1/2}$$

if $Na >> Na$

$$W_o = \left[\frac{2\varepsilon(N_a)V_o}{eN_aN_d}\right]^{1/2}$$

$$W_o = \left[\frac{2 \times 11.9(10^{22} + 10^{24}) \times 0.816V}{1.6 \times 10^{19} \times 10^{22} \times 10^{24}}\right]^{1/2} = 3.3 \times 10^{-7} \text{ meters} = 0.33 \mu\text{m}$$

$\varepsilon_r = 11.9$ for Si Table 5.1 page 334
SHORT AND LONG DIODES

Minority Carrier Concentration

In Diode Eq. Lengths of p and n regions are very long

Let “$l_p$” be finite length p-side (outside depletion region)

Let “$l_n$” be finite length n-side (outside depletion region)

Also, assume that the $l_p$ and $l_n$ are Shorter than diffusion Lengths, $L_e$ and $L_h$

Remember, \[ L_h = \sqrt{D_h \tau_h} \]

Then we call this “Short Diode”

Note: the Minority Concentration Profile is almost linear in this region

If, $l_p$ and $l_n$ are Longer than diffusion Lengths, $L_e$ and $L_h$

Then we call this “Long Diode”

Note: the Minority Concentration Profile may not be linear in this region (see Fig.6.6)

Fig.6.5: Minority carrier injection and diffusion in a short diode.
Short Diode Equations for Current density ($J$)

Excess Minority carriers:

$$\frac{d\Delta p_n(x')}{dx'} = -\left[ p_n(0) - p_{no} \right] \frac{l_n}{l_n}$$

Current Density $J_{D,\text{hole}}$ due to injection and diffusion of holes in region as result of Forward Bias:

$$J_{D,\text{hole}} = -eD_h \frac{d\Delta p_n(x')}{dx'} = eD_h \left[ p_n(0) - p_{no} \right] \frac{l_n}{l_n}$$

Using Law of Junction: $p_n(0) = p_{no} \exp\left(\frac{eV}{kT}\right)$

Current Density for Short Diode - For $p_n(x'=0)$ or $p_n(0)$ (by combining a similar above eq. for $p$-region, $n_p(0)$)

Eq.6.14

$$J = \left( \frac{eD_h}{l_n N_d} + \frac{eD_e}{l_p N_a} \right) n_i^2 \left[ \exp\left(\frac{eV}{kT}\right) - 1 \right]$$
Forward Bias
Recombination and Total Current

At the Metallurgical Junction, C

The Minority Carriers, \( p_M = n_M \)

Mean Recombination Time for holes, \( \tau_h \)

\[
J_{\text{recom}} = \frac{eABC}{\tau_e} + \frac{eBCD}{\tau_h}
\]

The Area of the triangle ABC = \( \frac{1}{2} W_p n_M \) and DCB = \( \frac{1}{2} W_n p_M \). Current Density – Recomb. is:

\[
J_{\text{recom}} \approx \frac{e - \frac{1}{2} W_p n_M}{\tau_e} + \frac{e - \frac{1}{2} W_n p_M}{\tau_h}
\]

At “A” the Potential Energy = 0 and

At “M” the Potential Energy = \( \frac{1}{2} e. (V_o - V) \), and so

\[
\frac{p_M}{p_{po}} = \exp\left[ -\frac{e(V_o - V)}{2kT} \right]
\]

Cont’d on next page
Recombination Current Equation

And Final Diode “J” Equation

Note: \( V_o \) depends on the Dopant Concentration

- \( p_{po} = N_a \)
- \( n_{po} = \text{equilibrium majority hole carriers (holes/m}^3\)\)
- \( n_{no} = \text{equilibrium majority electron carriers (holes/m}^3\)\)
- \( N_a = \text{Acceptor Concentration/m}^3 \)
- \( n_{po} = \text{equilibrium minority hole carriers (holes/m}^3\)\)
- \( p_{no} = \text{equilibrium minority electron carriers (holes/m}^3\)\)

\[
P_M = n_i \exp\left(\frac{eV}{2kT}\right)
\]

\[
J_{\text{recom}} = \frac{en_i}{2} \left( \frac{W_p}{\tau_e} + \frac{W_n}{\tau_H} \right) \exp\left(\frac{eV}{2kT}\right)
\]

Eq. 6.15 or

\[
J_{\text{recom}} = J_{ro}[\exp(eV / 2kT) - 1]
\]

Eq. 6.16

Total Diode Current = Diffusion + Recombination Current

\[
J = J_{so} \exp\left(\frac{eV}{kT}\right) + J_{ro} \exp\left(\frac{eV}{2kT}\right) \left( V > kT \right)
\]

The Diode “J” Equation

where, \( \eta = \text{Ideality Factor} \)

- If current is due to Minority Diffusion carrier, \( \eta = 1 \)
- If current is due to Recombination, \( \eta = 2 \)
The Diode “J” Equation

\[ J = J_o \exp\left(\frac{eV}{\eta kT}\right) \left(\frac{kT}{e}\right) \]

where, \( \eta = \text{Ideality Factor} \)

If current is due to Minority Diffusion carrier, \( \eta = 1 \)

If current is due to Recombination, \( \eta = 2 \)

At High Currents Bulk resistance of neutral regions limits the current Flow

For Ge: \( \eta=1 \) .. mainly due to minority carrier diffusion (indirect Band gap)

For GaAs: \( \eta=2 \) .. current limited due to recombination (direct Band gap)

For Si: The \( \eta \) changes from 2 and 1 when current is increased .. due both these two processes. (indirect Band gap)

You are now on Page 428 of Prof. Kasap’s Book
Fig. 6.8: Reverse biased pn junction. (a) Minority carrier profiles and the origin of the reverse current. (b) Hole PE across the junction under reverse bias.

- **Applied Voltage Drop Mainly in Space Charge Region** – SCL (same as forward bias)
- **As electrons and holes are crossing the SCL layer**
- **There are more exposed positively charged donor ions** and **negatively charged acceptor ions** (thus wider Depletion SCL layer with reverse bias)
- **No electron from p-side to n-side and no hole from n-side to p-side (except for leakage current)**

**EHP (Electron Hole Pair) Generation in in SCL**

\[
J_{gen} = \frac{eWn_i}{\tau_g} \quad \text{Eq. 6.18}
\]

\[
\tau_g = \text{Mean time to generate electron-hole pair due to thermal vibrations (Phonons)}
\]
**Reverse Bias (Cont’d)**

\[ I = I_o e^{\left( \frac{eV}{nkT} \right)} \]

**Rev. Current @ V = -5V**

\[ J_{rev} = \left( \frac{eD_h}{L_h N_d} + \frac{eD_e}{L_e N_a} \right) n_i^2 + \frac{eWn_i}{\tau_g} \]

**Fig. 6.9:** (a) Reverse I-V characteristics of a pn junction (the positive and negative current axes have different scales). (b) Reverse diode current in a Ge pn junction as a function of temperature in a \( \ln(I_{rev}) \) vs \( 1/T \) plot. Above 238 K, \( I_{rev} \) is controlled by \( n_i^2 \), and below 238 K it is controlled by \( n_i \). The vertical axis is a logarithmic scale with actual current values. (From D. Scansen and S.O. Kasap, *Cnd. J. Physics*, **70**, 1070-1075, 1992.)

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Fig. 6.10: (a) Two isolated $p$ and $n$-type semiconductors (same material). (b) A $pn$ junction band diagram when the two semiconductors are in contact. The Fermi level must be uniform in equilibrium. The metallurgical junction is at M. The region around M contains the space charge layer (SCL). On the $n$-side of M, SCL has the exposed positively charged donors whereas on the $p$-side it has the exposed negatively charged acceptors.

Open Circuit
- $E_{fp}=E_{Fn}$ is same after $n$ and $p$ are joined
- Bending of Bands occurs as $E_c$ on $p$-side is different from $n$-side
- $V_o$ is built-in Potential (contact)

\[
V_o = -\frac{1}{2} E_0 W_0 = \frac{eN_a N_d W_0^2}{2e(N_a + N_d)} \quad \text{.........Eq. 6.4}
\]

Pl. Note: There is no net current flow in open circuit in spite of the built-in potential, so the diffusion currents of electrons from $n$- to $p$-side is balanced by the electron drift from the $p$- to $n$-side driven by built-in field.

Energy Band Diagram of pn Junction (Cont’d)

Fig. 6.11: Energy band diagrams for a pn junction under (a) open circuit, (b) forward bias and (c) reverse bias conditions. (d) Thermal generation of electron hole pairs in the depletion region results in a small reverse current.

Built-in Potential $E = eV_o$

J without any Bias i.e. Zero Bias

Or The Probability of Overcoming the PE barrier is Proportional to:

$$e \frac{eV_o}{kT}$$

$$J_{diff}(0) = B \exp \left(-\frac{eV_o}{kT}\right) \quad \text{Eq. 6.20}$$

$$J_{net}(0) = J_{diff}(0) + J_{drift}(0) = 0 \quad \text{Eq. 6.21}$$

Thus, $J_{diff}(0) = -J_{drift}(0)$

Clearly, Drift is opposing the diffusion

Zero Current Flow-No Bias

Forward Biased pn Junction

\[ E_o = -2 \left( \frac{V_o}{W_o} \right) \] \text{From Eq. 6.24}

**Majority of Voltage Drop in the SCL**

\( V_o \), applied Voltage is opposing the built-in potential \( V_o \).

The Potential Barrier reduces from \( eV_o \rightarrow e(V_o - V) \rightarrow \text{Elec. from n-side (right)} \)

can overcome the PE barrier and diffuse in p-side (left) marked by red arrow

Or The Probability of Overcoming the PE barrier is Proportional to: (less now)

\[ e \left( \frac{e(V_o - V)}{kT} \right) \]

Electron flow from Ec-n side to p-side

Vice versa for holes

**Net Current flow Forward bias Bias**
**COMPARISION OF PE**

**Zero Bias**

The Probability of Overcoming the PE barrier is Proportional to

\[ J_{\text{diff}}(0) = B \exp \left( -\frac{eV_o}{kT} \right) \]

\[ J_{\text{diff}} = \text{Diffusion Current Density} \]

\[ J_{\text{net}}(0) = J_{\text{diff}}(0) + J_{\text{drift}}(0) = 0 \]

\[ J_{\text{diff}}(0) = -J_{\text{drift}}(0) \]

**Forward Bias**

The field Decreases from E to E-Eo

\[ J_{\text{diff}}(V) = B \exp \left( -\frac{e(V_o-V)}{kT} \right) \exp \left( \frac{eV}{kT} \right) - 1 \]

\[ J(V) = J_o \left[ \exp \left( \frac{eV}{kT} \right) - 1 \right] \]

**Reverse Bias**

The field Increases from E to E+Eo

\[ J_{\text{net}}(V) \approx J_{\text{diff}}(V) + J_{\text{drift}}(0) \]

\[ J_{\text{net}}(V) = B \exp \left( -\frac{e(V_o-V)}{kT} \right) - b \exp \left( -\frac{eV_o}{kT} \right) \]

**Zero Current Flow**

Electron flow from E-c-n side to p-side

**Jo is Temp. Dependent**

**Thermal Excitation**

Small Reverse current

**No Current Flow**
Energy Band Diagram of pn Junction (Cont’d)

(a) Open Circuit
(b) Forward Bias
(c) Reverse Bias
(d) Thermal Generation

Reverse Biased and Thermal Excitation pn Junction

The Probability of Overcoming the PE barrier is Proportional is Low

Except for thermal excitation diffusion
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### Varactor Diodes (Varicaps) - pn Junctions as Variable Voltage Depletion Layer Capacitors

1. Recall Parallel plate capacitor – review next page (charges across a plate)
2. SCL, depletion layer creates a special capacitor with charges on both sides expect here we have voltage dependence.
3. Width of SLC is given by:

   \[
   W = \left[ \frac{2\varepsilon(N_a + N_d)(V_o - V)}{eN_a N_d} \right]^{1/2} \quad \text{Eq. 6.22}
   \]

**Depletion Layer Capacitance** $(C_{dep})$:

\[
C_{dep} = \frac{|dQ|}{dV}
\]

**Amount of Charge** $|Q| = eN_a W_n A = eN_a W_p A$

\[
C_{dep} = \frac{\varepsilon A}{W} = \frac{A}{(V_o - V)^{1/2}} \left[ \frac{e\varepsilon (N_a N_d)}{2(N_a + N_d)} \right]^{1/2}
\]

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**Equation 6.23**

\[
dQ = \text{Incremental charge}
\]

**Equation 6.24**

\[
	ext{Space charge region}
\]

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**Fig. 6.12:** The depletion region behaves like a capacitor. (a) The charge in the depletion region depends on the applied voltage just as in a capacitor (b) The incremental capacitance of the depletion region increases with forward bias and decreases with reverse bias. Its value is typically in the range of picofarads per mm$^2$ of device area.

**Same as parallel plate**

**Permittivity of a medium** $\varepsilon = \varepsilon_0 \cdot \varepsilon_r \quad \text{units (C/V.m or F/m)}$
Definition of Permittivity (Capacivity)

of Free space (in Vacuum):

\[ \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m or } [\text{C/V.m}] \]

When a dielectric material is placed between the two parallel plates, then the capacitance of the capacitor increases by \( \varepsilon_r \) (or Materials Scientists call this \( \kappa \)) …this is called Dielectric constant.

For a parallel plate capacitor:

This \( C = \kappa \cdot \varepsilon_0 \cdot \frac{A}{d} = \varepsilon_r \cdot \varepsilon_0 \cdot \frac{A}{d} \ldots \) this implies that if you use materials with high \( \varepsilon_r \) value then one can use a small sized capacitor.

- \( \varepsilon_r \) = Relative permittivity: Typically 10 and, for Si it is 11.9 , for \( \text{Al}_2\text{O}_3 \sim 9 \)

Note: Capacitance \( C = \frac{q}{V} \), \( V \) = Applied voltage, \( q \) = Charge

\( A \) = area of the plate, \( d \) = distance between two plates

\( C = \varepsilon_0 \cdot \frac{A}{d} \)

Typical areas with \( A \) (vacuum) = 0.021 m\(^2\) and \( A \) (dielectric material) = 0.00235 m\(^2\)

With \( \varepsilon_r \) (Dielectric Material) = 9 , \( \varepsilon_r \) (vacuum) = 1, and \( V = 8000 \text{ volts Potential to store } 5 \times 10^{-6} \text{ C} \) (F or mF)

Permittivity of a medium \[ \varepsilon = \varepsilon_0 \cdot \varepsilon_r \ldots \text{units} (\text{C/V.m or F/m}) \]
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Injected Minority Carrier Charge

\[ Q = \tau_h I = \tau_h I_0 \left[ \exp\left(\frac{eV}{kT}\right) - 1 \right] \]

This is telling us that at a Voltage, injected positive charge Q on the n-side is disappearing by recombination at a rate of \( Q/\tau_h \)

Eq. Minority Carriers/m³ is given by:

\[ p_n'(0) = p_n'(x'=0) \text{ with increased voltage } (V+dV) \]

\[ p_n(0) = p_n(x'=0) \text{ with a voltage } (V) \]

\[ C_{\text{diff}} = \frac{dQ}{dV} = \frac{\tau_h e l}{kT} = \frac{\tau_h l (mA)}{25} \]

Diffusion Capacitance \( (C_{\text{diff}}) \) is much greater than C-depletion layer \( (C_{\text{dep}}) \) in nano Farad range
Diffusion Storage Capacitance and Dynamic Resistance (dV/dI) cont’d

Thus the resistance of the circuit varies with the tangent to the slope of the I-V curve…very interesting!!

Dynamic Resistance \( r_d \) of the Diode is given by:

\[
\frac{dV}{dI} = \frac{kT}{eI} = \frac{25}{I(mA)}
\]

Slope of I-V curve gives, \( 1/r_d = \) Dynamic Conductance “\( g_d \)” is given by:

\[
g_d = \frac{dI}{dV} = \frac{1}{r_d}
\]

\[
r_d C_{diff} = \tau_h
\]

Forward Bias small ac signals around 25 mV (kT/e) changes the \( r_d \) at room temperature

Fig. 6.14: The dynamic resistance of the diode is defined as \( dV/dI \) which is the inverse of the tangent at \( I \).

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Reverse Bias: Avalanche and Zener Diodes

Fig. 6.15: Reverse $I$-$V$ characteristics of a $pn$ junction.


When all the donor electron are in conduction band and you keep increasing the Reverse bias voltage to a critical value ($V_{br}$) → The valence electrons from the VB begin to jump to the CB, and there is an avalanche ...as there are infinite amount of electrons from Si

When all the donor electron are in conduction band and you keep increasing the Reverse bias voltage to a critical value ($V_{br}$)

Multiplier Eq.

$$M = \frac{I}{I - (\frac{V_r}{V_{br}})^n} \quad \cdots \cdots \cdots \cdots n = 3 \text{to} 5$$

Fig. 6.16: Avalanche breakdown by impact ionization.


- With this process the device may burn down to melting of contacts etc.
- To avoid this, we put a resistor* and make use of this (Zener Diode) device
- Used in Automobiles for AC to DC conversion
Resistor to Prevent burn out of the device

Note: I = Vr - V_{br} for Alternators it is -14V, but for other applications it is typically -10V

Small Increases in Reverse Bias leads to Dramatic increases in multiplication (M) processes

V_{br} = Breakdown voltage
V_r = Applied Rev. Bias Voltage
n ~ 3 to 5

\[ M = \frac{1}{1 - \left( \frac{V_r}{V_{br}} \right)^n} \]

Fig. 6.17: If the reverse breakdown current when V_r > V_{br} is limited by an external resistance, R, to prevent destructive power dissipation then the diode can be used to clamp the voltage between A and B to remain approximately V_{br}.

Fig. 6.18: Zener breakdown involves electrons tunneling from the VB of the p-side to the CB of the n-side when the reverse bias reduces $E_C$ up with $E_V$.

Note:
- If heavily doped the $E_C$ is lowered below the $E_V$ of VB of the Si.
- The Depletion layer becomes very thin
Thus making an easy passage for the VB electrons in CB of n-type Si.

- the tunneling of electrons from VB to CB.

From VB$_{\text{electrons of Si}}$ on p$\rightarrow$ CB on n-side

Note the level of CB of the n-side; it is lower than that of pside $E_V$.

Zener Breakdown Field $E_{br}$ as function of Dopant Concentration

Electrons Tunnel to the p-side called Zener Effect

Fig. 6.19: The breakdown field $E_{br}$ in the depletion layer for the onset of reverse breakdown vs. doping concentration $N_d$ in the lightly doped region in a one-sided ($p^+n$ or $pn^+$) abrupt $pn$ junction. Avalanche and tunneling mechanisms are separated by the arrow [data extracted from M. Sze and G. Gibbons, Solid. State. Electronics, 9, 831 (1966)]

Reverse breakdown and Conc. Of dopant charges make this diode work on either tunneling or by avalanche.

Usually, p$^+n$ or np$^+$

**Tunneling is usually referred to as Zener Effect**