Lecture 15 - The pn Junction Diode (I)

I-V Characteristics

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Reading assignment:

Howe and Sodini, Ch. 6, §§6.1-6.3
Key questions

- Why does the pn junction diode exhibit current rectification?
- Why does the junction current in forward bias increase as $\sim \exp \frac{qV}{kT}$?
- What are the leading dependences of the saturation current (the factor in front of the exponential)?
1. PN junction under bias

Focus on intrinsic region:

Upon application of voltage:

- electrostatics upset: depletion region widens or shrinks
- current flows (with rectifying behavior)
- carrier charge storage
Carrier profiles in thermal equilibrium:

Inside SCR in thermal equilibrium: dynamic balance between drift and diffusion for electrons and holes.

\[ |J_{\text{drift}}| = |J_{\text{diff}}| \]
Carrier concentrations in pn junction under bias:

- for $V > 0$, $\phi_B - V \downarrow \Rightarrow |E_{SCR}| \downarrow \Rightarrow |J_{drift}| \downarrow$

Current balance in SCR broken:

$$|J_{drift}| < |J_{diff}|$$

Net diffusion current in SCR

$\Rightarrow$ minority carrier injection into QNR’s

$\Rightarrow$ excess minority carrier concentrations in QNR’s

Lots of majority carriers in QNR’s $\Rightarrow$ current can be high.
• for $V < 0$, $\phi_B - V \uparrow \Rightarrow |E_{SCR}| \uparrow \Rightarrow |J_{drift}| \uparrow$

Current balance in SCR broken:

$$|J_{drift}| > |J_{diff}|$$

Net drift current in SCR
⇒ minority carrier extraction from QNR’s
⇒ defect of minority carrier concentrations in QNR’s

Few minority carriers in QNR’s ⇒ current small.
What happens if minority carrier concentrations in QNR change from equilibrium?

⇒ Balance between generation and recombination broken

- In thermal equilibrium: rate of break up of Si-Si bonds balanced by rate of formation of bonds

\[ \text{Si-Si bond} \quad \begin{array}{c} \text{generation} \\ \text{recombination} \end{array} \quad n_0 + p_0 \]

- If minority carrier injection:
  ⇒ carrier concentration above equilibrium
  ⇒ recombination prevails

\[ \text{Si-Si bond} \quad \begin{array}{c} \text{recombination} \\ \text{generation} \end{array} \quad n + p \]

- If minority carrier extraction:
  ⇒ carrier concentrations below equilibrium
  ⇒ generation prevails

\[ \text{Si-Si bond} \quad \begin{array}{c} \text{generation} \\ \text{recombination} \end{array} \quad n + p \]
Where does generation and recombination take place?

In modern devices, recombination mainly takes place at surfaces:

- perfect crystalline periodicity broken at a surface $\Rightarrow$ lots of broken bonds: generation and recombination centers
- modern devices are very small $\Rightarrow$ high area to volume ratio.

High generation and recombination activity at surfaces $\Rightarrow$ carrier concentrations cannot deviate much from equilibrium values:

$$n(s) \simeq n_o, \quad p(s) \simeq p_o$$
Complete physical picture for pn diode under bias:

- **Forward bias**: injected minority carriers diffuse through QNR \( \Rightarrow \) recombine at semiconductor surface

- **Reverse bias**: minority carriers extracted by SCR \( \Rightarrow \) generated at surface and diffuse through QNR
The current view:

- **Forward bias:**

  \[ I = I_n + I_p \]

- **Reverse bias:**

  \[ I = I_n + I_p \]
What limits the magnitude of the diode current?

- **not** generation or recombination rate at surfaces
- **not** injection or extraction rates through SCR
- diffusion rate through QNR’s

![Diode Diagram]

Development of analytical current model:

1. Calculate concentration of minority carriers at edges of SCR, \( p(x_n) \) and \( n(-x_p) \)
2. calculate minority carrier diffusion current in each QNR, \( I_n \) and \( I_p \)
3. sum electron and hole diffusion currents, \( I = I_n + I_p \)
2. I-V characteristics

\(\square\) **STEP 1**: computation of minority carrier boundary conditions at edges of SCR

In thermal equilibrium in SCR, \(|J_{\text{drift}}| = |J_{\text{diff}}|\), and

\[
\frac{n_o(x_1)}{n_o(x_2)} = \exp \frac{q[\phi(x_1) - \phi(x_2)]}{kT}
\]

and

\[
\frac{p_o(x_1)}{p_o(x_2)} = \exp \frac{-q[\phi(x_1) - \phi(x_2)]}{kT}
\]

Under bias in SCR, \(|J_{\text{drift}}| \neq |J_{\text{diff}}|\), but if difference small with respect to absolute values of current:

\[
\frac{n(x_1)}{n(x_2)} \approx \exp \frac{q[\phi(x_1) - \phi(x_2)]}{kT}
\]

and

\[
\frac{p(x_1)}{p(x_2)} \approx \exp \frac{-q[\phi(x_1) - \phi(x_2)]}{kT}
\]

This is called *quasi-equilibrium*. 
At edges of SCR, then:

\[
\frac{n(x_n)}{n(-x_p)} \approx \exp \left[ \frac{q[\phi(x_n) - \phi(-x_p)]}{kT} \right] = \exp \frac{q(\phi_B - V)}{kT}
\]

and

\[
\frac{p(x_n)}{p(-x_p)} \approx \exp \left[ -\frac{q[\phi(x_n) - \phi(-x_p)]}{kT} \right] = \exp \frac{-q(\phi_B - V)}{kT}
\]

But:

\[ p(-x_p) \approx N_a \quad \text{and} \quad n(x_n) \approx N_d \]

This is the low-level injection approximation [will discuss in more detail next time].
Then:

\[ n(-x_p) \simeq N_d \exp \frac{q(V - \phi_B)}{kT} \]

and

\[ p(x_n) \simeq N_a \exp \frac{q(V - \phi_B)}{kT} \]

Built-in potential:

\[ \phi_B = \frac{kT}{q} \ln \frac{N_d N_a}{n_i^2} \]

Plug in above and get:

\[ n(-x_p) \simeq \frac{n_i^2}{N_a} \exp \frac{qV}{kT} \]

and

\[ p(x_n) \simeq \frac{n_i^2}{N_d} \exp \frac{qV}{kT} \]
Voltage dependence:

- **Equilibrium** \((V = 0)\):
  \[
  n(-x_p) = \frac{n_i^2}{N_a} \quad p(x_n) = \frac{n_i^2}{N_d}
  \]

- **Forward** \((V > 0)\):
  \[
  n(-x_p) \gg \frac{n_i^2}{N_a} \quad p(x_n) \gg \frac{n_i^2}{N_d}
  \]
  Lots of carriers available for injection:
  \(\Rightarrow V \uparrow \rightarrow\) concentration of injected carriers \(\uparrow\)
  \(\Rightarrow\) forward current can be high.

- **Reverse** \((V < 0)\):
  \[
  n(-x_p) \ll \frac{n_i^2}{N_a} \quad p(x_n) \ll \frac{n_i^2}{N_d}
  \]
  Few carriers available for extraction:
  \(\Rightarrow\) reverse current is small.
  There is limit to how low minority carrier concentrations drop in reverse bias: zero!
  \(\Rightarrow\) reverse current saturates.

Rectification property of pn diode arises from minority-carrier boundary conditions at edges of SCR.
Step 2: Diffusion current in QNR:

Diffusion equation (for electrons in p-QNR):

\[ J_n = qD_n \frac{dn}{dx} \]

Inside p-QNR, electrons diffuse to reach and recombine at contact \( \Rightarrow J_n \) constant in p-QNR \( \Rightarrow n(x) \) linear.

Boundary conditions:

\[ n(x = -W_p) = n_o = \frac{n_i^2}{N_a} \quad n(-x_p) = \frac{n_i^2}{N_a} \exp \frac{qV}{kT} \]

Electron profile:

\[ n_p(x) = n_p(-x_p) + \frac{n_p(-x_p) - n_p(-W_p)}{-x_p + W_p}(x + x_p) \]
\[ n_p(x) = n_p(-x_p) + \frac{n_p(-x_p) - n_p(-W_p)}{-x_p + W_p}(x + x_p) \]

Electron current density:

\[ J_n = qD_n \frac{dn}{dx} = qD_n \frac{n_p(-x_p) - n_p(-W_p)}{W_p - x_p} \]

\[ = qD_n \frac{n_i^2}{N_a} \exp \frac{qV}{kT} - \frac{n_i^2}{N_a} \]

or

\[ J_n = q \frac{n_i^2}{N_a} \frac{D_n}{W_p - x_p} \left( \exp \frac{qV}{kT} - 1 \right) \]
Similarly for hole flow in n-QNR:

\[ J_p = q \frac{n_i^2}{N_d W_n - x_n} \frac{D_p}{(\exp \frac{qV}{kT} - 1)} \]
\[ \square \text{Step 3: sum both current components:} \]

\[ J = J_n + J_p = qn_i^2 \left( \frac{1}{N_a W_p - x_p} + \frac{1}{N_d W_n - x_n} \right) (\exp \frac{qV}{kT} - 1) \]

Current:

\[ I = qA n_i^2 \left( \frac{D_n}{N_a w_p - x_p} + \frac{D_p}{N_d w_n - x_n} \right) (\exp \frac{qV}{kT} - 1) \]

often written as:

\[ I = I_o (\exp \frac{qV}{kT} - 1) \]

with

\[ I_o \equiv \text{saturation current [A]} \]

B.C.'s contain both forward and reverse bias
⇒ equation valid in forward and reverse bias.

[will discuss this result in detail next time]
Key conclusions

- Application of voltage to pn junction results in disruption of balance between drift and diffusion in SCR:
  - in forward bias, minority carriers are \textit{injected} into quasi-neutral regions
  - in reverse bias, minority carriers are \textit{extracted} from quasi-neutral regions
- In forward bias, injected minority carriers recombine at surface.
- In reverse bias, extracted minority carriers are generated at surface.
- Computation of boundary conditions across SCR exploits \textit{quasi-equilibrium}: balance between diffusion and drift in SCR disturbed very little.
- Rate limiting step to current flow: diffusion through quasi-neutral regions.
- I-V characteristics of p-n diode:
  \[ I = I_o \left( \exp \frac{qV}{kT} - 1 \right) \]