Lecture 15

The pn Junction Diode (II)

Outline

- I-V characteristics
  - Forward Bias
  - Reverse Bias

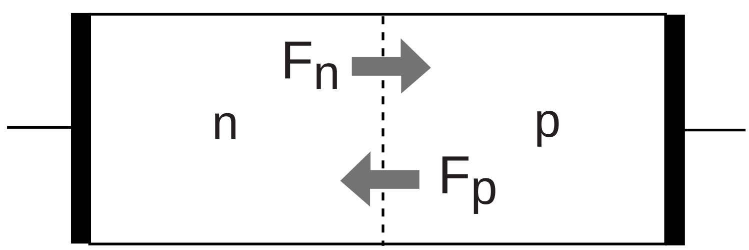
Reading Assignment:
Howe and Sodini; Chapter 6, Sections 6.4 - 6.5

1. I-V Characteristics (contd.)

Diode Current equation:

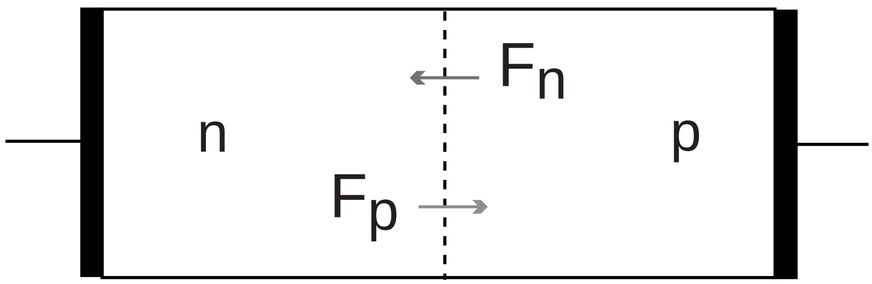
$$I = I_o\left(e^{\left[\frac{V}{V_{th}}\right]} - 1\right)$$

Physics of forward bias:



- Potential drop across SCR reduced by V
  - $\Rightarrow$ minority carrier injection in QNRs
- Minority carrier diffusion through QNRs
- Minority carrier recombination at contacts to the QNRs (and surfaces)
- Large supply of carriers injected into the QNRs

$\Rightarrow$ $$\boldsymbol{I \propto e^{\left[\frac{V}{V_{th}}\right]}}$$



Physics of reverse bias:

- Potential drop across SCR increased by V
  - $\Rightarrow$ minority carrier extraction from QNRs
- Minority carrier diffusion through QNRs
- Minority carrier generation at surfaces & contacts of QNRs
- Very small supply of carriers available for extraction
  - $\Rightarrow$ I saturates to small value

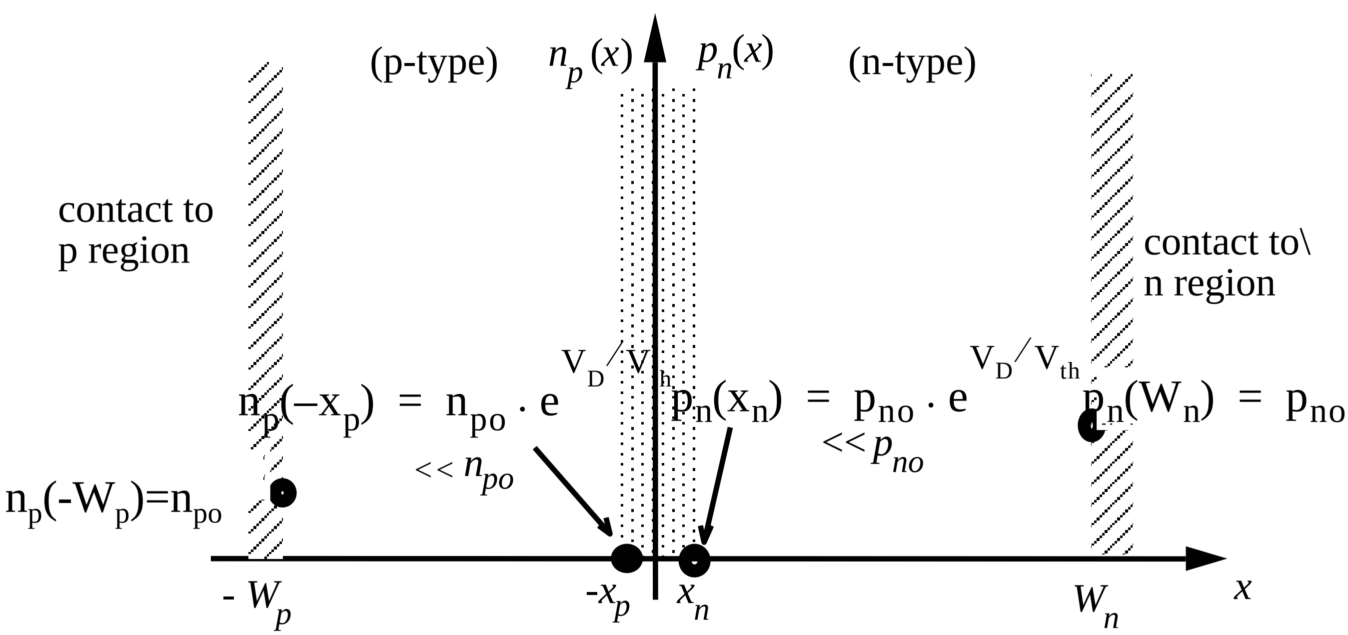
Development of analytical current model:

1. Calculate the concentration of minority carriers at edges of SCR;

2. Find the spatial distribution of the minority carrier concentrations in each QNR;

3. Calculate minority carrier diffusion current at SCR edge.

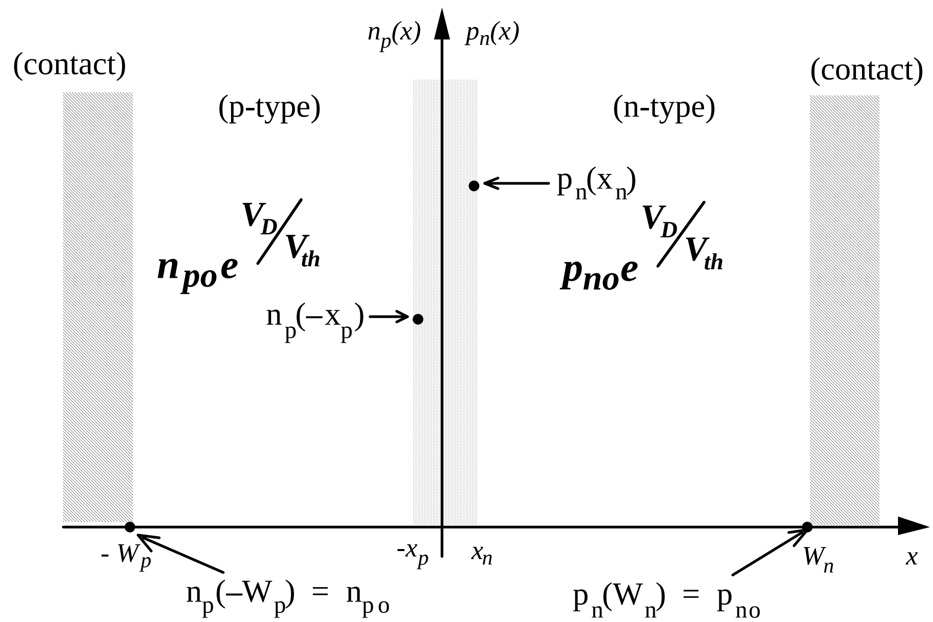
4. Sum minority carrier electron and hole diffusion currents at SCR edge.



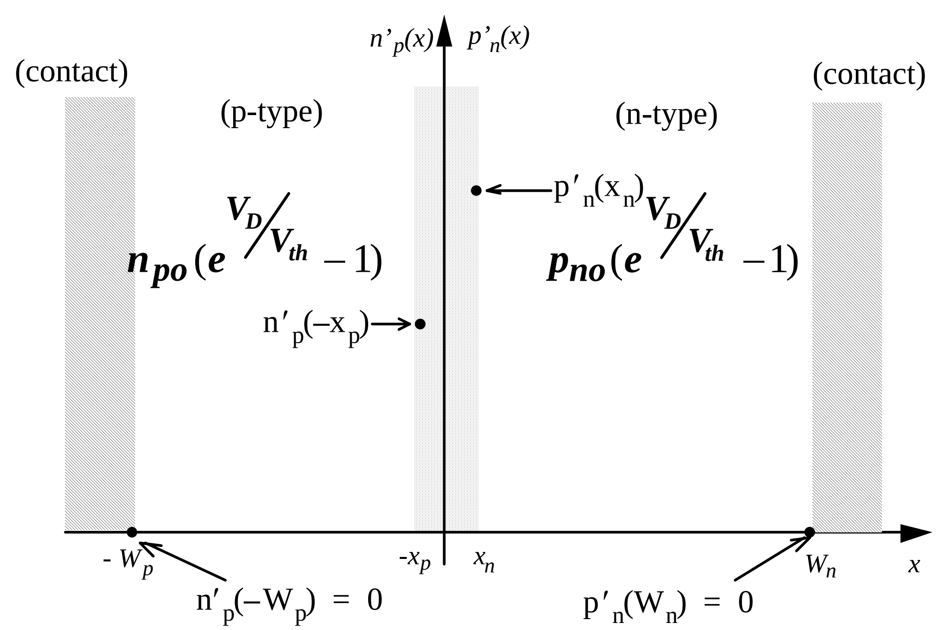
Reverse Bias

Total and Excess Concentrations Forward Bias (Step 1)

Total Carrier Concentration (n & p)

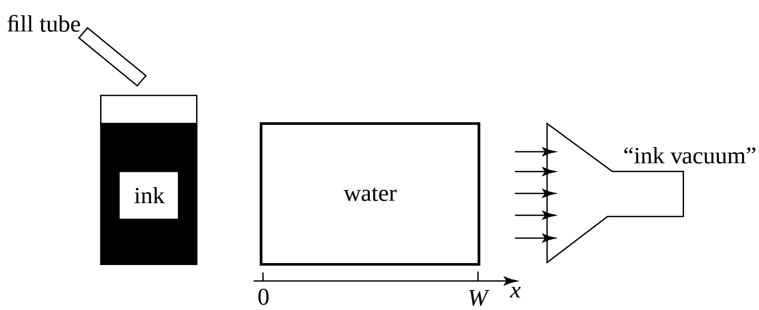


Excess Carrier Concentration (n' & p') - Subtract n_{po} and p_{no}



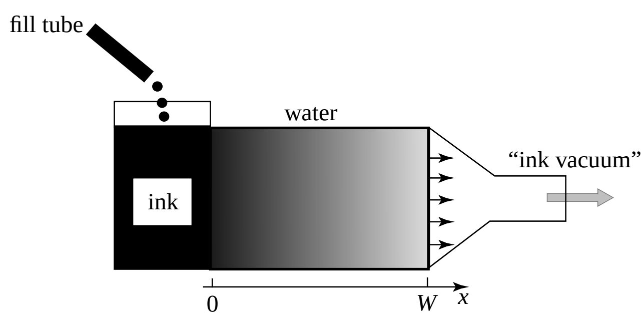
Steady-State Diffusion
Ink Diffusion Example

- Flux is number of ink molecules passing a plane/cm^2-sec
- No molecules vanish in the water (NO recombination)
- Ink concentration is a constant at x = 0
- Ink concentration is zero at x = W (ohmic contact)
- Result - Ink concentration falls linearly from x=0 to x=W



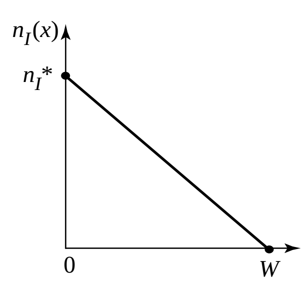
(a)

Injects minority carriers



Carriers recombine at ohmic contact

(b)



(c)

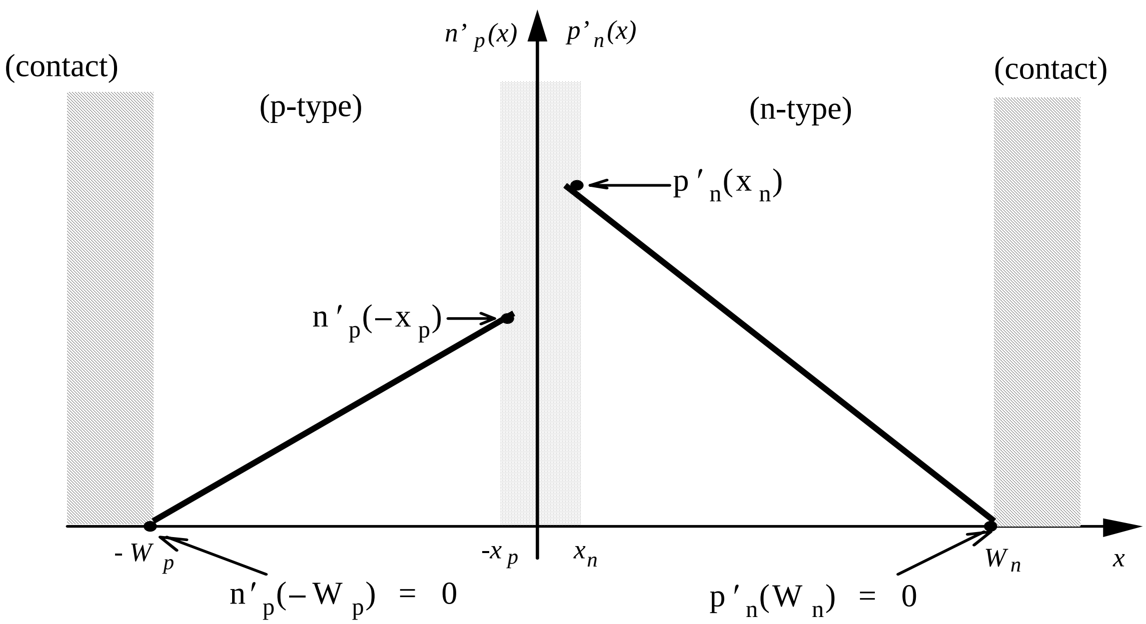
Minority Carrier Spatial Distribution

(Step 2)

- Concentration linearly decreases from SCR edge to ohmic contact. The expressions assumes no recombination in the QNR.

$$n'_p(x) = n'_p(-x_p) + \left(\frac{n'_p(-x_p)}{W_p - x_p} \right) \bullet (x + x_p)$$

$$p'_n(x) = p'_n(x_n) - \left(\frac{p'_n(x_n)}{W_n - x_n} \right) \bullet (x - x_n)$$



Steady-state---> minority carriers are continuously injected across the junction to maintain the value at the SCR edge set by the applied bias. The same number continuously recombine at ohmic contact.

Minority Carrier Diffusion Current at SCR Edge (Step 3)

- Gradient in minority carrier concentrations across the n & p QNRs
- $n = n_o + n'$ ---> $dn/dx = dn'/dx$
- Transport occurs by diffusion
- Ignore drift component since minority carriers

At $-x_p$ electron diffusion current:

$$J_n = qD_n \frac{dn'_p}{dx} = qD_n \left(\frac{n'_p(-x_p) - 0}{W_p - x_p} \right)$$

$$J_n = qD_n \left[\frac{n_{po}\left(e^{\left[\frac{V}{V_{th}}\right]} - 1\right)}{W_p - x_p} \right]$$

$$J_n = q \frac{n_i^2}{N_a} \bullet \frac{D_n}{W_p - x_p} \bullet \left[e^{\left(\frac{V}{V_{th}}\right)} - 1 \right]$$

Sum minority carrier diffusion currents at SCR edge (Step 4)

Hole diffusion current at x_n by same reasoning:

$$J_p = q\frac{n_i^2}{N_d} \bullet \frac{D_p}{W_n - x_n} \bullet \left[e^{\left(\frac{qV}{kT}\right)} - 1 \right]$$

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

Current is:

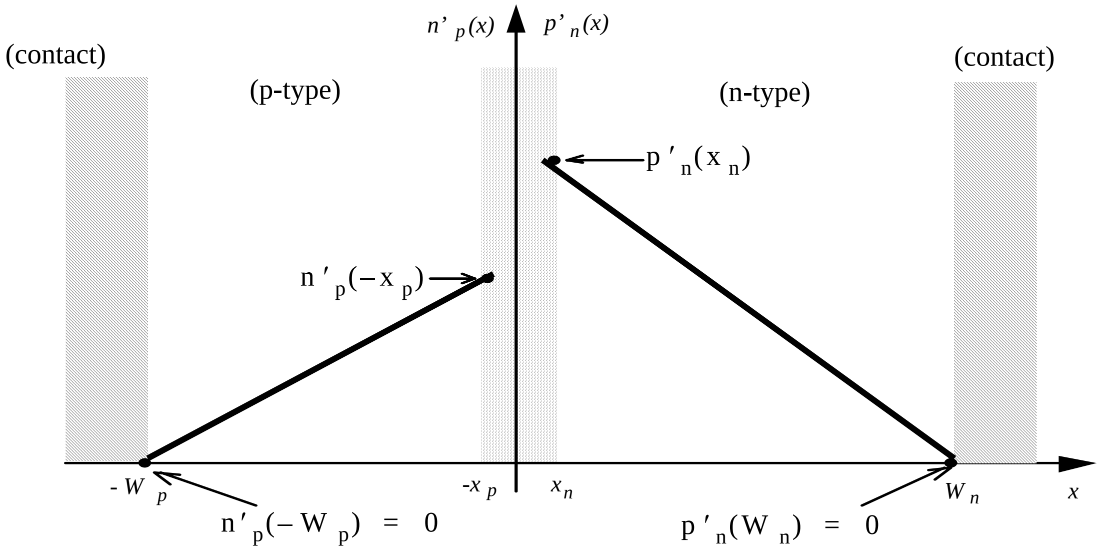
$$I = qAn_i^2 \left(\frac{1}{N_a} \bullet \frac{D_n}{W_p - x_p} + \frac{1}{N_d} \bullet \frac{D_p}{W_n - x_n} \right) \bullet \left[e^{\left(\frac{qV}{kT}\right)} - 1 \right]$$

Often written as:

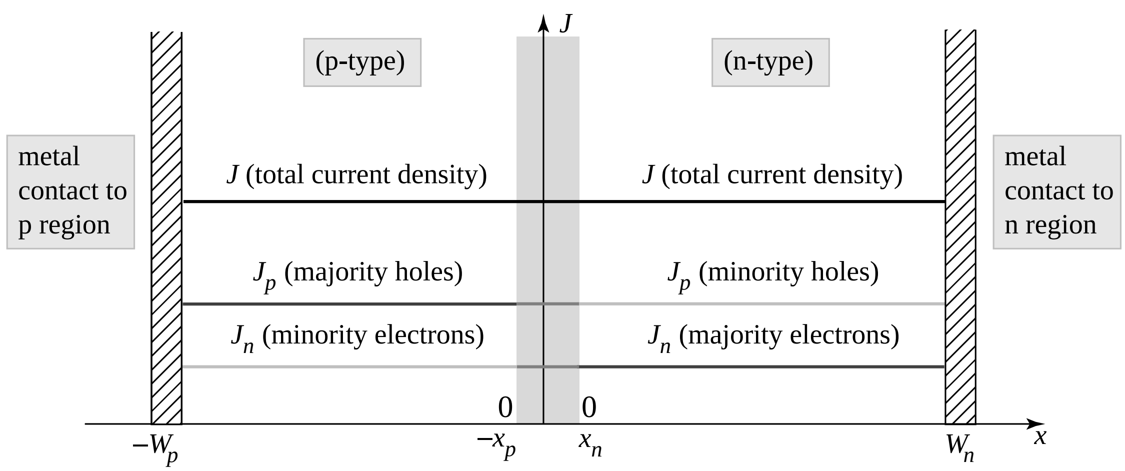
$$I = I_o \left[e^{\left(\frac{qV}{kT}\right)} - 1 \right]$$

Picture of Total Diode Current
Forward Bias

- Minority carriers are injected from the other side of the junction
- Minority carriers diffuse from SCR edge to the ohmic contact with no recombination and recombine at contact
- Total current found by summing the minority carrier diffusion currents at SCR edges and assuming no recombination in SCR

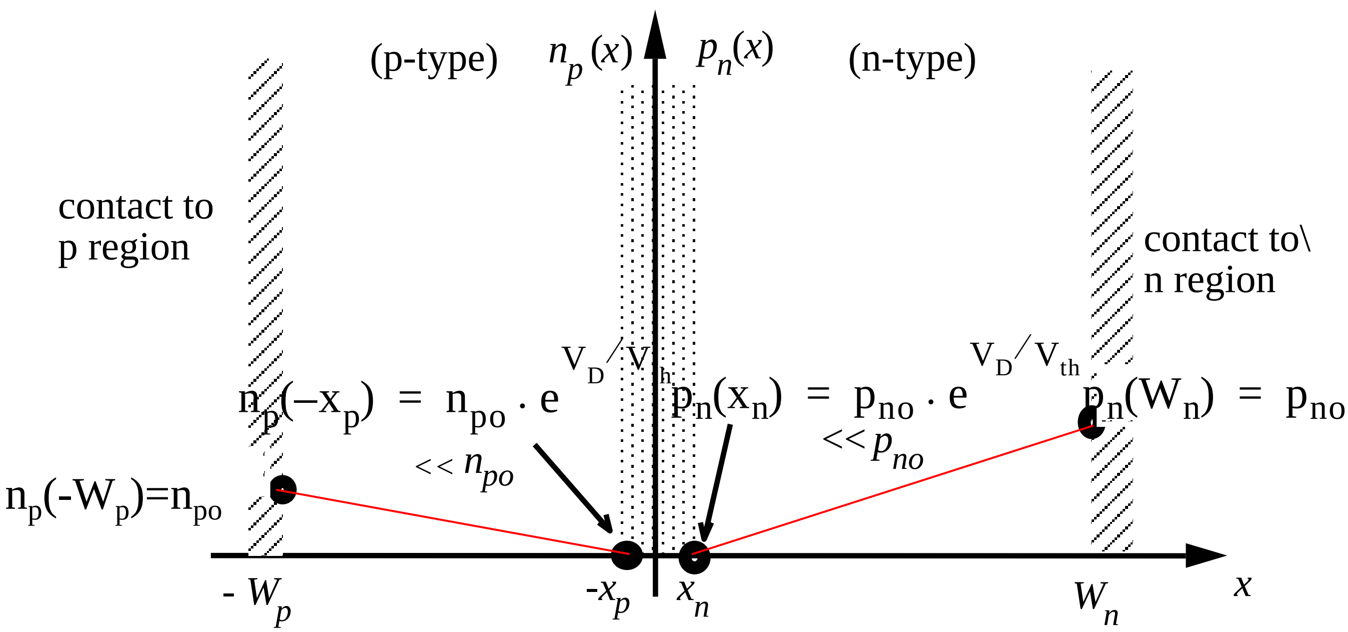


•Majority carriers are transported to the junction from the ohmic contact by drift and diffusion.



Minority Carrier Spatial Distribution (Reverse Bias)

- Diode current derivation same for forward and reverse bias. (same equations for spatial distribution)
- Minority carrier concentration at SCR is near zero under reverse bias.
- Concentration linearly increases from SCR edge to ohmic contact.
- Minority carriers flow from contacts to SCR and are swept across the junction.

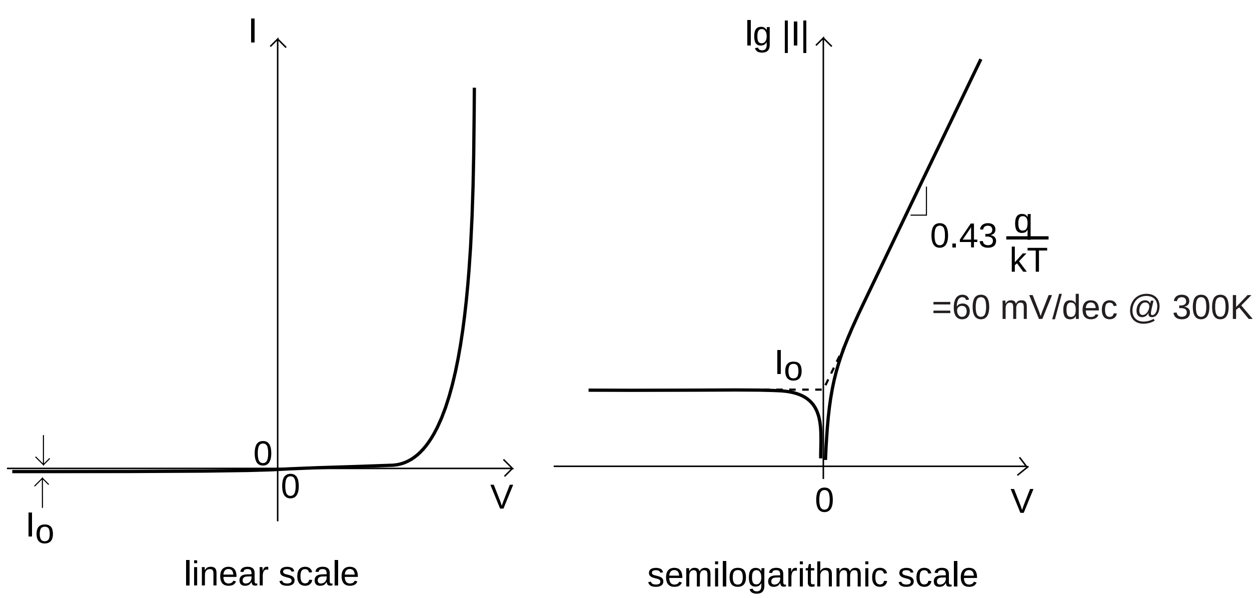


Steady-state---> minority carriers are continuously *extracted* across the junction to maintain the value at the SCR edge set by the applied bias. The same number continuously are *generated* at ohmic contact.

I-V Characteristics

Diode Current equation:

$$I = I_o\left[e^{\left(\frac{V}{V_{th}}\right)} - 1\right]$$



What did we learn today?

Summary of Key Concepts

- *Diode Current can be analytically determined by summing the minority carrier current at both sides of SCR*

$$I = I_o\left(e^{\left[\frac{qV}{kT}\right]} - 1\right)$$

- *Under forward bias:*
  - *Minority carriers are **injected** across the junction and diffuse to the contact where they **recombine***
- *Under reverse bias:*
  - *Minority carriers are **generated** at the contact and diffuse to the junction where they are **extracted** across the junction*