Lecture 15 - The pn Junction Diode (I)

I-V Characteristics

November 1, 2005

Contents:

1. pn junction under bias
2. I-V characteristics

Reading assignment:

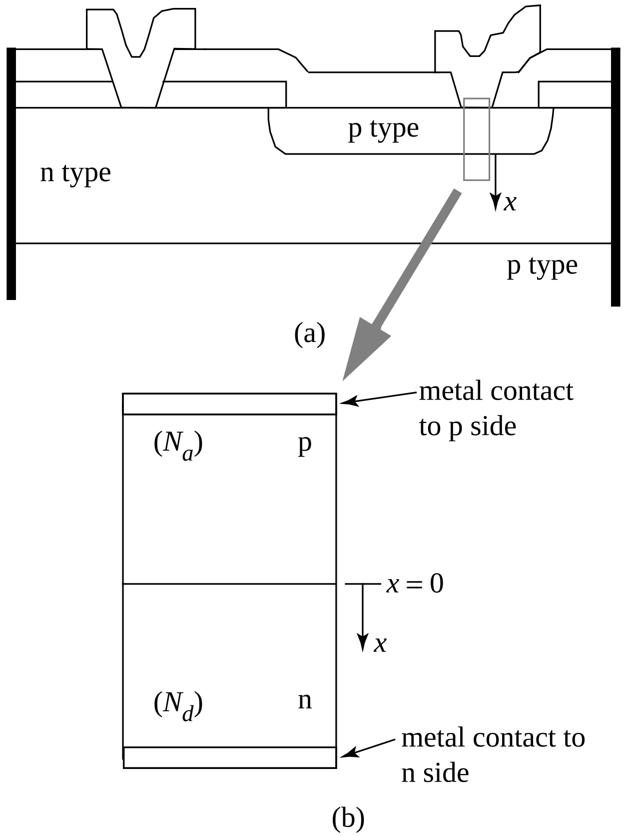
Howe and Sodini, Ch. 6, §§6.1-6.3

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

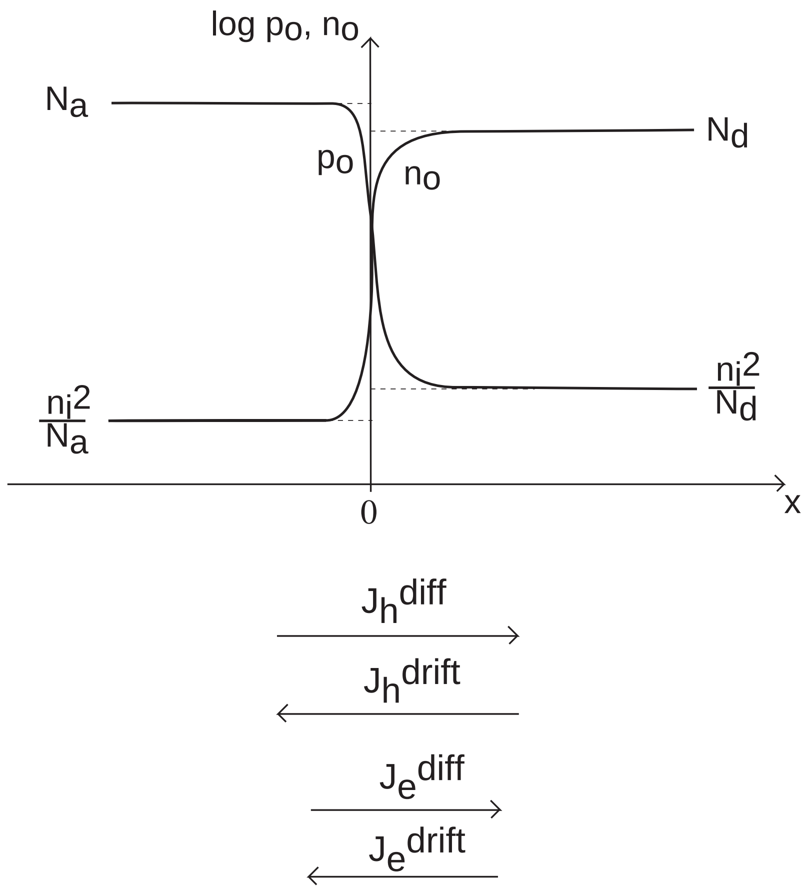
Focus on intrinsic region:



Upon application of voltage:

- electrostatics upset: depletion region widens or shrinks
- current flows (with rectifying behavior)
- carrier charge storage

Carrier profiles in thermal equilibrium:

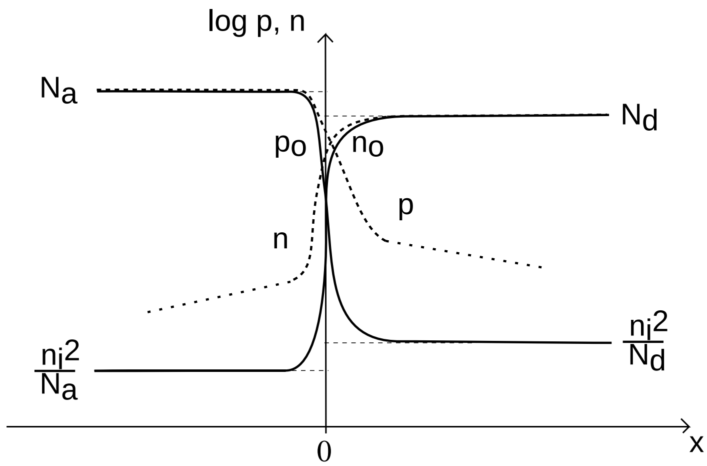


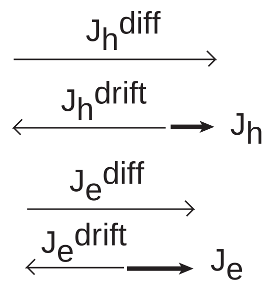
Inside SCR in thermal equilibrium: dynamic balance between drift and diffusion for electrons and holes.

$$|J_{drift}| = |J_{diff}|$$

Carrier concentrations in pn junction under bias:

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





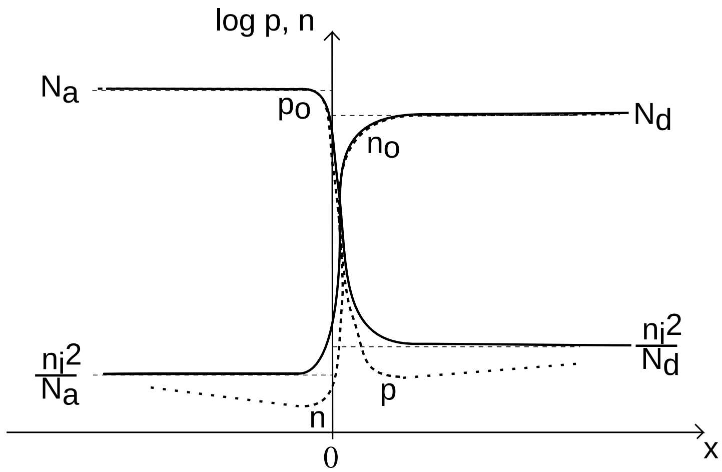
Current balance in SCR broken:

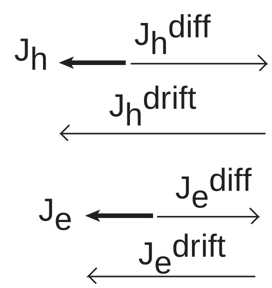
$$|J_{drift}| < |J_{diff}|$$

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
$\Rightarrow$ minority carrier *extraction* from QNR's
$\Rightarrow$ *deficit* of minority carrier concentrations in QNR's

Few minority carriers in QNR's $\Rightarrow$ 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

$$\text{Si-Si bond} \quad \underset{\text{recombination}}{\overset{\text{generation}}{\rightleftarrows}} \quad n_o + p_o$$

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

$$\text{Si-Si bond} \quad \xleftarrow[\text{recombination}]{} \quad n + p$$

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

$$\text{Si-Si bond} \quad \xrightarrow{\text{generation}} \quad n + p$$

Where does generation and recombination take place?

In modern devices, recombination mainly takes place at *surfaces*:

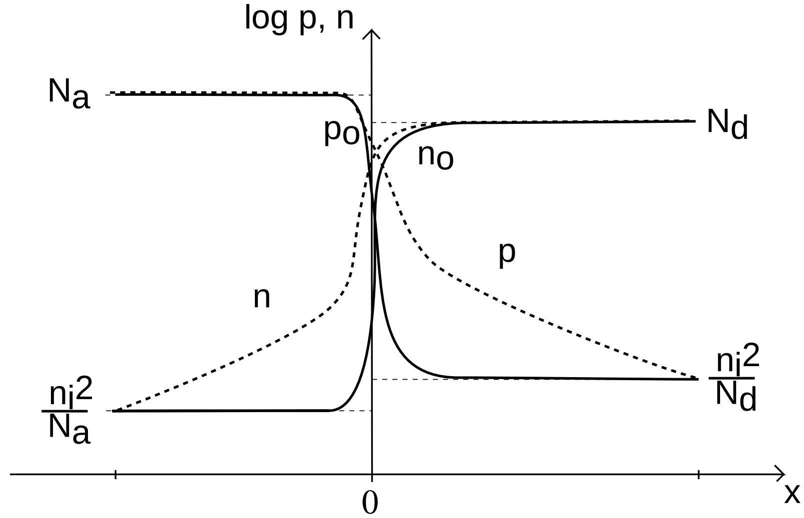
- perfect crystalline periodicity broken at a surface
  $\Rightarrow$ lots of broken bonds: generation and recombination centers
- modern devices are very small
  $\Rightarrow$ high area to volume ratio.

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

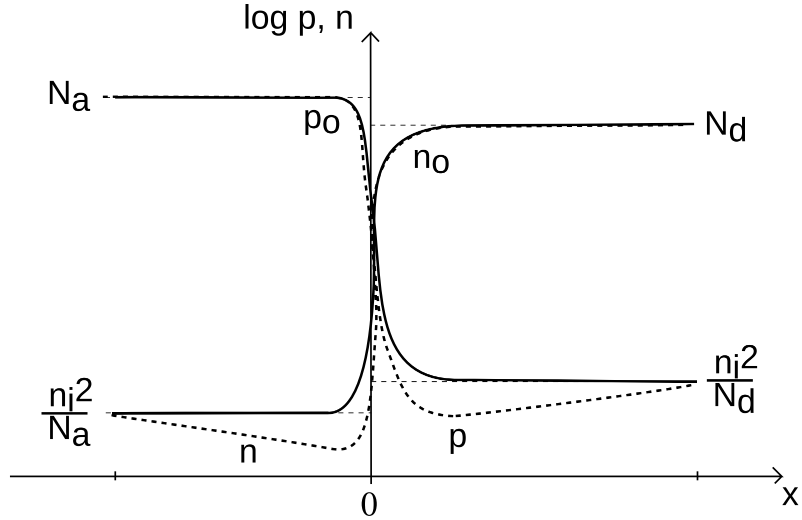
$$n(s) \simeq n_o, \quad p(s) \simeq p_o$$

Complete physical picture for pn diode under bias:

- Forward bias: injected minority carriers diffuse through QNR ⇒ recombine at semiconductor surface

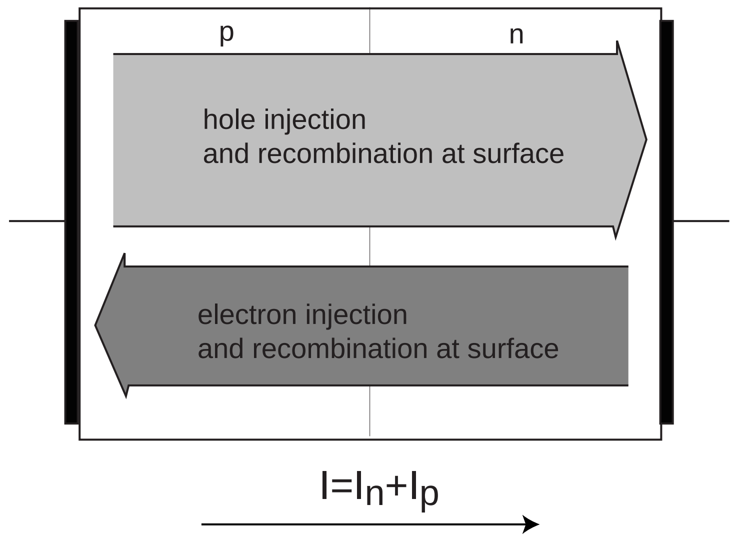


- Reverse bias: minority carriers extracted by SCR ⇒ generated at surface and diffuse through QNR

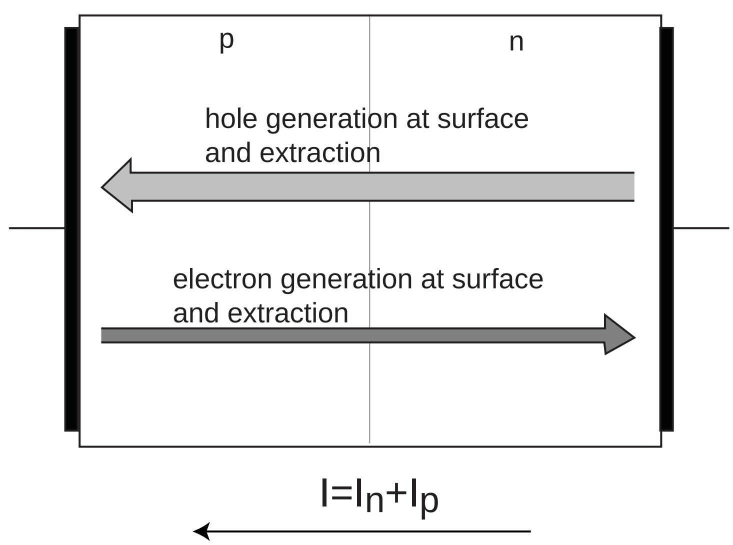


The current view:

- Forward bias:

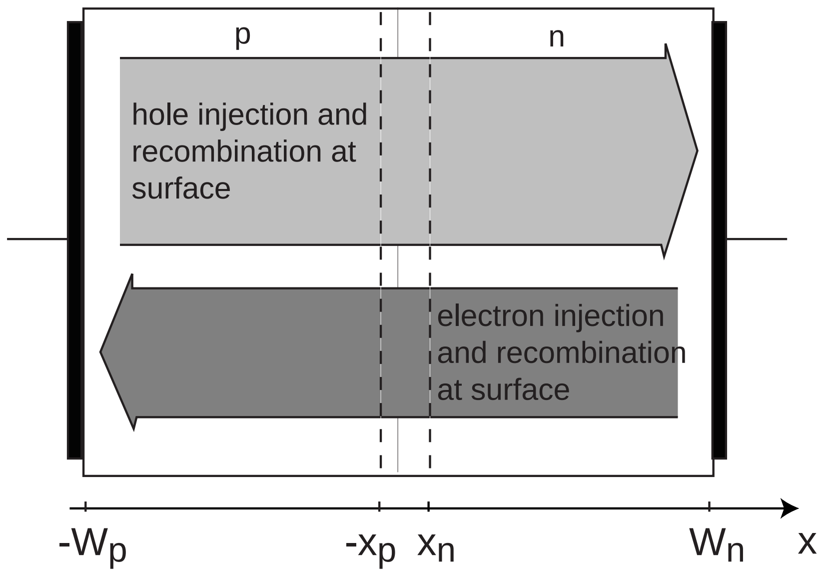


- Reverse bias:



What limits the magnitude of the diode current?

- <u>not</u> generation or recombination rate at surfaces
- <u>not</u> injection or extraction rates through SCR
- diffusion rate through QNR's



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

□ STEP 1: computation of minority carrier boundary conditions at edges of SCR

In thermal equilibrium in SCR, $|J_{drift}| = |J_{diff}|$, and

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

and

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

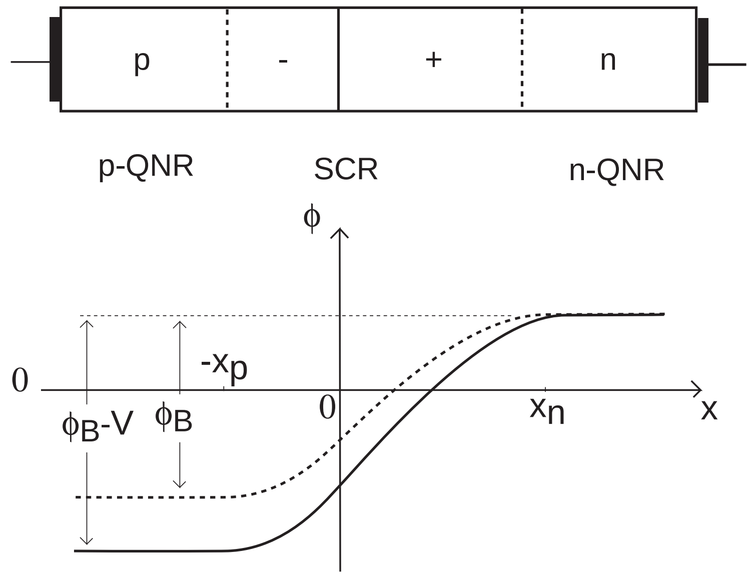
Under bias in SCR, $|J_{drift}| \neq |J_{diff}|$, but if difference small with respect to absolute values of current:

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

and

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

This is called *quasi-equilibrium.*



At edges of SCR, then:

$$\frac{n(x_n)}{n(-x_p)} \simeq \exp\frac{q[\phi(x_n) - \phi(-x_p)]}{kT} = \exp\frac{q(\phi_B - V)}{kT}$$

and

$$\frac{p(x_n)}{p(-x_p)} \simeq \exp\frac{-q[\phi(x_n) - \phi(-x_p)]}{kT} = \exp\frac{-q(\phi_B - V)}{kT}$$

But:

$$p(-x_p) \simeq N_a \quad \text{and} \quad n(x_n) \simeq N_d$$

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 ($V = 0$):

$$n(-x_p) = \frac{n_i^2}{N_a} \qquad p(x_n) = \frac{n_i^2}{N_d}$$

- Forward ($V > 0$):

$$n(-x_p) \gg \frac{n_i^2}{N_a} \qquad p(x_n) \gg \frac{n_i^2}{N_d}$$

  Lots of carriers available for injection:
  $\Rightarrow V \uparrow \rightarrow$ concentration of injected carriers $\uparrow$
  $\Rightarrow$ forward current can be high.

- Reverse ($V < 0$):

$$n(-x_p) \ll \frac{n_i^2}{N_a} \qquad p(x_n) \ll \frac{n_i^2}{N_d}$$

  Few carriers available for extraction:
  $\Rightarrow$ reverse current is small.

  Minority carrier concentration becomes vanishingly small:
  $\Rightarrow$ reverse current saturates.

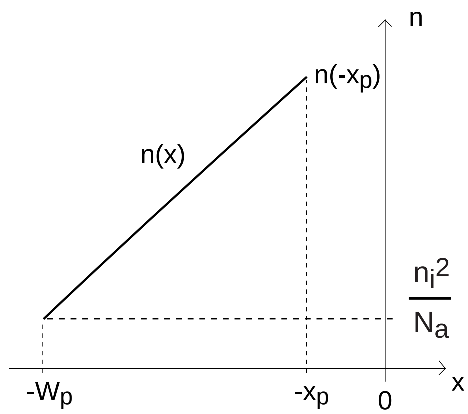
Rectification property of pn diode arises from minority-carrier boundary conditions at edges of SCR.

□ 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 ⇒ J_n constant in p-QNR⇒ $n(x)$ linear.



Boundary conditions:

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

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:

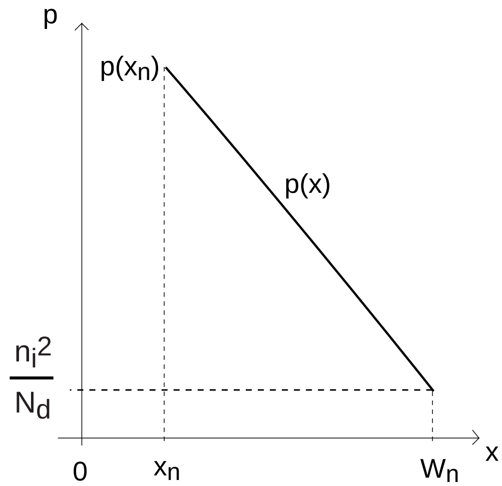
$$J_n = qD_n\frac{dn}{dx} = qD_n\frac{n_p(-x_p) - n_p(-W_p)}{W_p - x_p}$$

$$= qD_n\frac{\frac{n_i^2}{N_a}\exp\frac{qV}{kT} - \frac{n_i^2}{N_a}}{W_p - x_p}$$

or

$$J_n = q\frac{n_i^2}{N_a}\frac{D_n}{W_p - x_p}(\exp\frac{qV}{kT} - 1)$$

Similarly for hole flow in n-QNR:



Hole current density:

$$J_p = q\frac{n_i^2}{N_d}\frac{D_p}{W_n - x_n}(\exp\frac{qV}{kT} - 1)$$

□ STEP 3: sum both current components:

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

Current:

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

often written as:

$$I = I_o\left(\exp\frac{qV}{kT} - 1\right)$$

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 *injected* into quasi-neutral regions
  - in reverse bias, minority carriers are *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 *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:

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