

Lecture 14

The pn Junction Diode (I)

I-V Characteristics

Outline

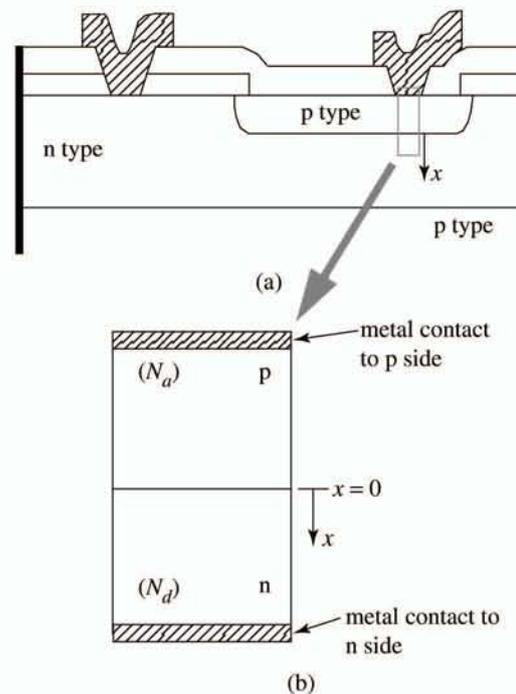
- pn junction under bias
- IV characteristics

Reading Assignment:

Howe and Sodini; Chapter 6, Sections 6.1-6.3

1. PN junction under bias

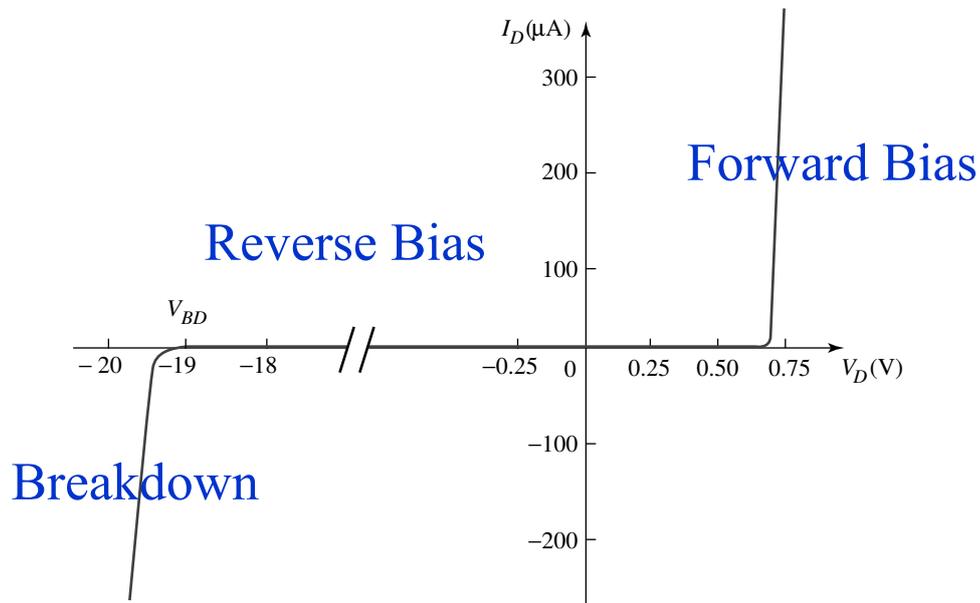
Focus on intrinsic region:



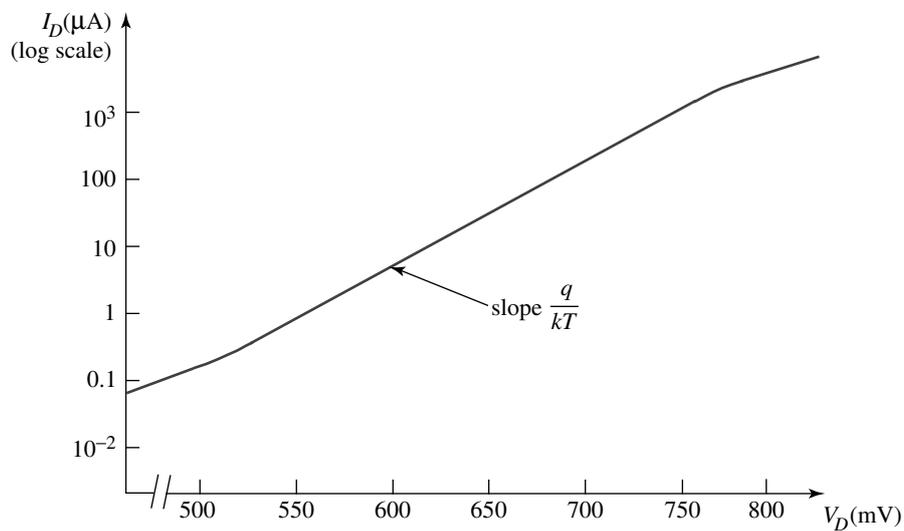
Upon application of voltage:

- Electrostatics upset:
 - depletion region widens or shrinks
- Current flows
 - With rectifying behavior
- Carrier charge storage

I-V Characteristics



(a)

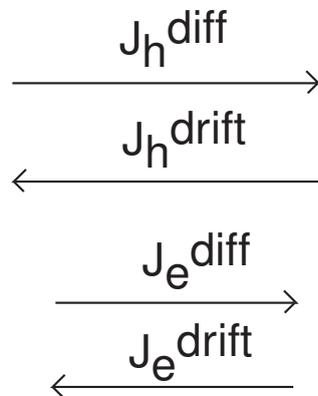
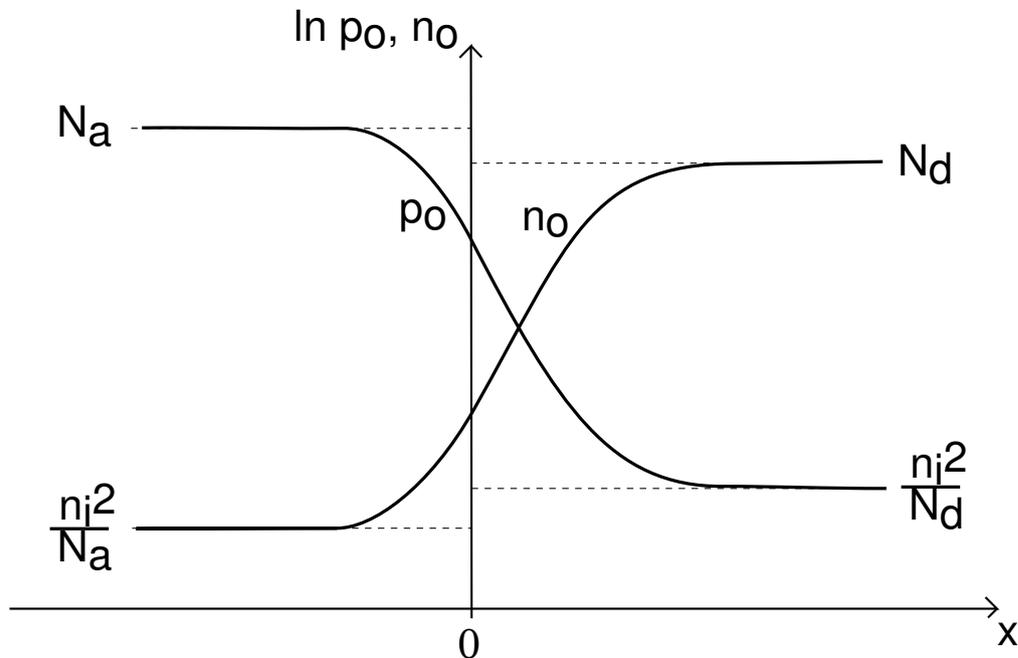


(b)

To model I-V characteristics we need 2 concepts

- The Law of the Junction
- Steady-State Diffusion

Carrier Profiles: in thermal equilibrium

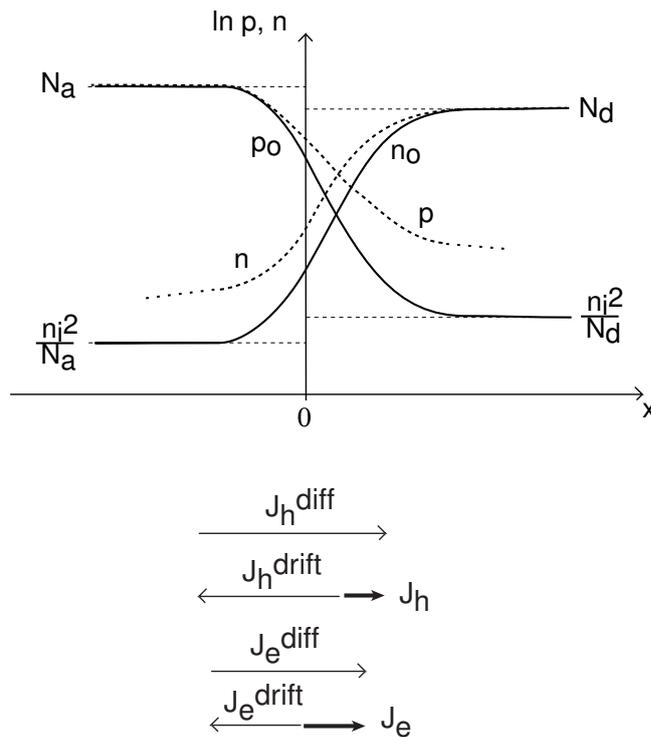


In equilibrium: dynamic balance between drift and diffusion for electrons and holes inside SCR.

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

Carrier Profiles: under forward bias

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



Current balance in SCR broken:

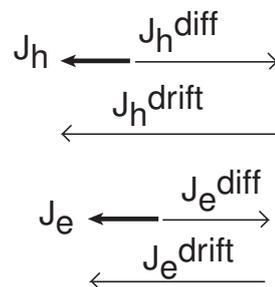
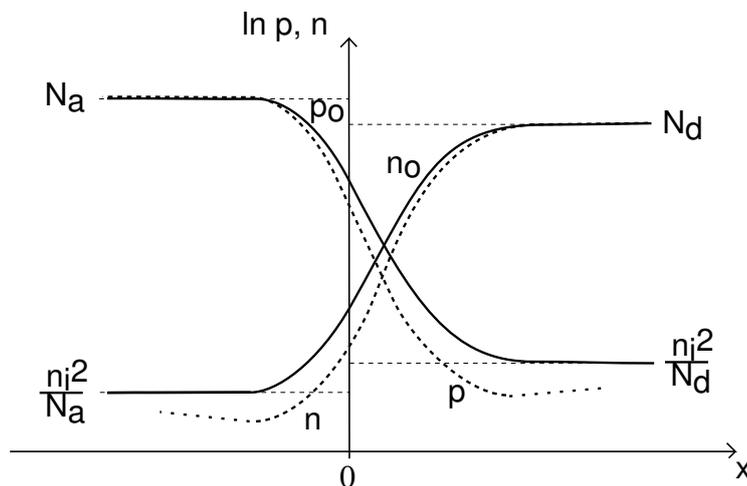
$$|J_{drift}| < |J_{diff}|$$

Net diffusion current in SCR \Rightarrow minority carrier **injection** into QNRs.

Carrier flow can be high because lots of minority carriers are injected into QNRs from the majority side.

Carrier Profiles: under reverse bias

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 QNRs.

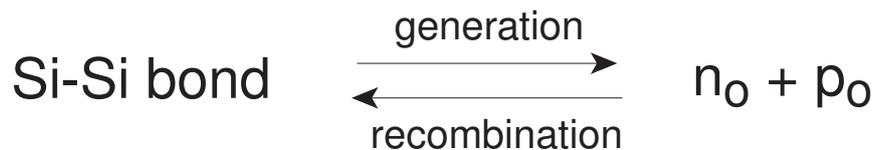
Carrier flow is small because there are few minority carriers extracted from QNRs from the minority side.

Minority Carrier Concentrations: in QNR

What happens if minority carrier concentrations in QNR changed from equilibrium?

⇒ Balance between generation and recombination is broken

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



- **If minority carrier injection:** carrier concentration above equilibrium and recombination prevails



- **If minority carrier extraction:** carrier concentrations below equilibrium and generation prevails



Where does generation and recombination take place?

1. Semiconductor bulk
2. Semiconductor surfaces & contacts

In modern silicon pn-junction devices, surface & contact recombination dominates because:

- Perfect crystalline periodicity broken at the surface
 - \Rightarrow lots of generation and recombination centers;
- Modern devices are small
 - \Rightarrow high surface area to volume ratio.

Surfaces and contacts are very active generation and recombination centers

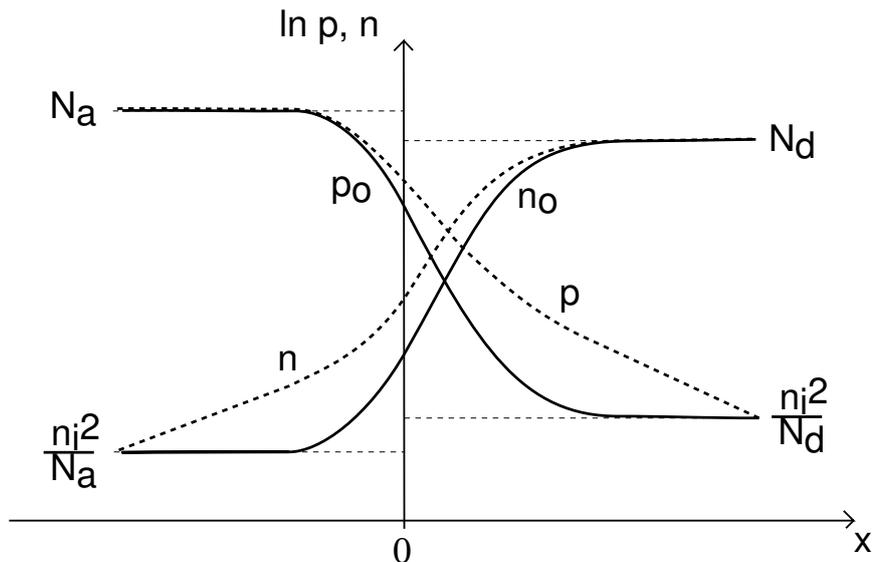
\Rightarrow *at contacts*, carrier concentrations cannot deviate from equilibrium:

In general, it is assumed that at contacts, the rate at which generation/recombination takes place is *infinite*.

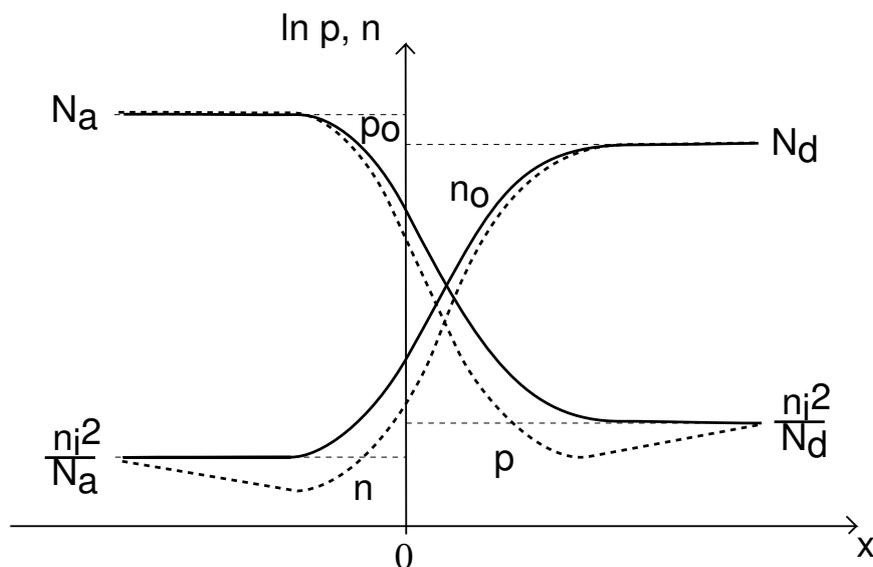
$$n_c = n_o ; \quad p_c = p_o$$

Complete physical picture for pn diode under bias:

- **In forward bias**, injected minority carriers diffuse through QNR and recombine at semiconductor surface.



- **In reverse bias**, minority carriers generated at the semiconductor surface, diffuse through the QNR, and extracted by SCR.



What is the barrier (**Bottleneck**) to current flow?

- Not generation or recombination at surfaces,
- Not injection or extraction through SCR
- But minority carrier *diffusion* through the QNRs

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.

2. I-V Characteristics

STEP 1: Computation of minority carrier boundary conditions at the edges of the SCR

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

- Define $p_{\text{no}} = n_i^2/N_d$ and $n_{\text{po}} = n_i^2/N_a$

- Recall

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

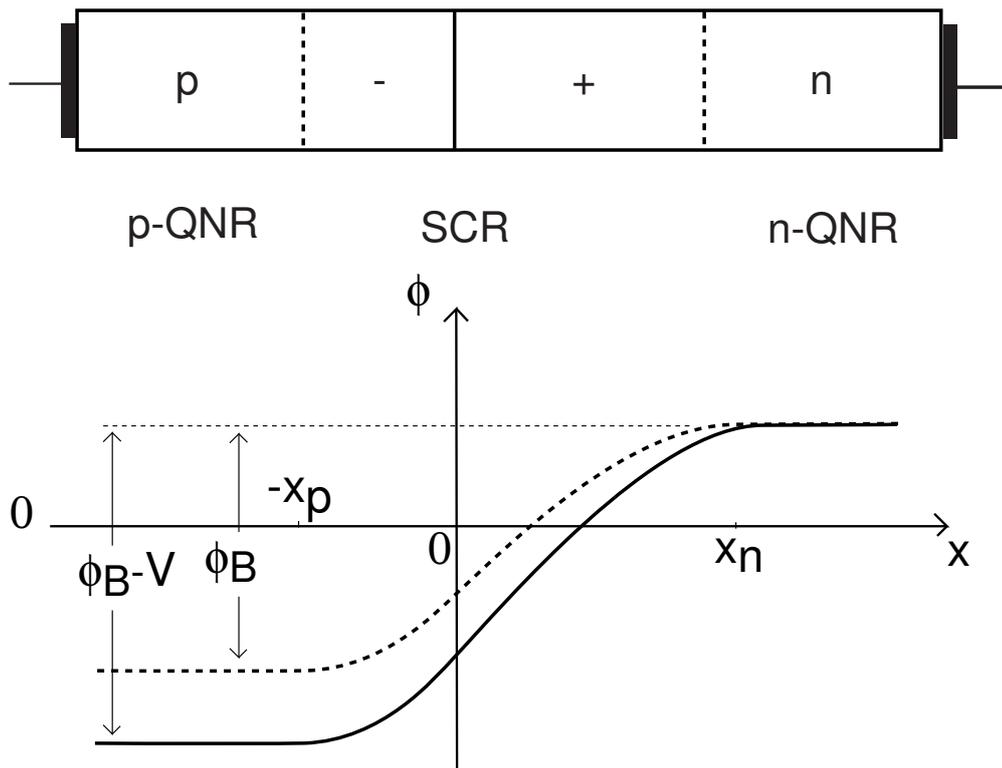
- Rewrite

$$\phi_B = V_{th} \ln\left(\frac{N_d}{n_{po}}\right) \quad \text{and} \quad \phi_B = V_{th} \ln\left(\frac{N_a}{p_{no}}\right)$$

- Solving for the equilibrium minority carrier concentrations in terms of the built-in potential,

$$p_{no} = N_a e^{-\frac{\phi_B}{V_{th}}} \quad \text{and} \quad n_{po} = N_d e^{-\frac{\phi_B}{V_{th}}}$$

This result relates the **minority carrier concentration** on one side of the junction to the **majority carrier concentration** on the *other side* of the junction



- The new potential barrier $\phi_j = (\phi_B - V_D)$ is substituted for the thermal equilibrium barrier to find the new minority carrier concentrations at the SCR edges.
- **Assume the detailed balance between drift and diffusion is not significantly perturbed.** This says **electrons are in equilibrium with each other across the junction.** SAME for holes.

$$n_p(-x_p) = N_d e^{\frac{-\phi_j}{V_{th}}} = N_d e^{\frac{-(\phi_B - V_D)}{V_{th}}}$$

and

$$p_n(x_n) = N_a e^{\frac{-\phi_j}{V_{th}}} = N_a e^{\frac{-(\phi_B - V_D)}{V_{th}}}$$

Law of the Junction

$$n_p(-x_p) = N_d e^{\left[\frac{-\phi_B}{V_{th}}\right]} e^{\left[\frac{V_D}{V_{th}}\right]} = n_{po} e^{\left[\frac{V_D}{V_{th}}\right]}$$

and

$$p_n(x_n) = N_a e^{\left[\frac{-\phi_B}{V_{th}}\right]} e^{\left[\frac{V_D}{V_{th}}\right]} = p_{no} e^{\left[\frac{V_D}{V_{th}}\right]}$$

$$\text{where } n_{po} = \frac{n_i^2}{N_a} \quad \text{and} \quad p_{no} = \frac{n_i^2}{N_d}$$

- The minority carrier concentration at the SCR is an exponential function of applied bias. It changes one **decade for every 60mV** change in V_D .

- Law of the Junction is valid if minority carrier concentration is less than equilibrium majority concentration. This condition is called **Low Level Injection**.

$$p_n < n_{no} \quad \text{and} \quad n_p < p_{po}$$

Voltage Dependence:

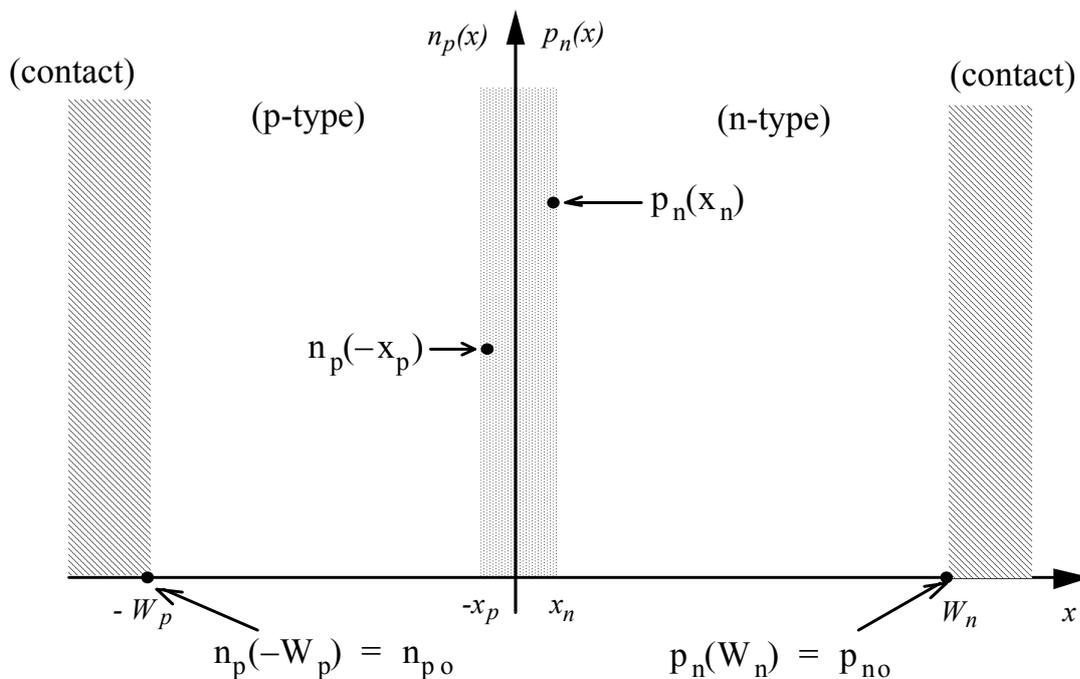
- **Forward bias ($V > 0$):**

$$n_p(-x_p) \gg n_{po}(-x_{po})$$

$$p_n(x_n) \gg p_{no}(x_{no})$$

- Lots of carriers available for injection, the higher V , the higher the concentration of injected carriers
 \Rightarrow forward current can be high.

- Minority carrier concentration is maintained at thermal equilibrium at the ohmic contacts. All **excess carriers recombine at ohmic contact.**



- **Reverse bias ($V < 0$):**

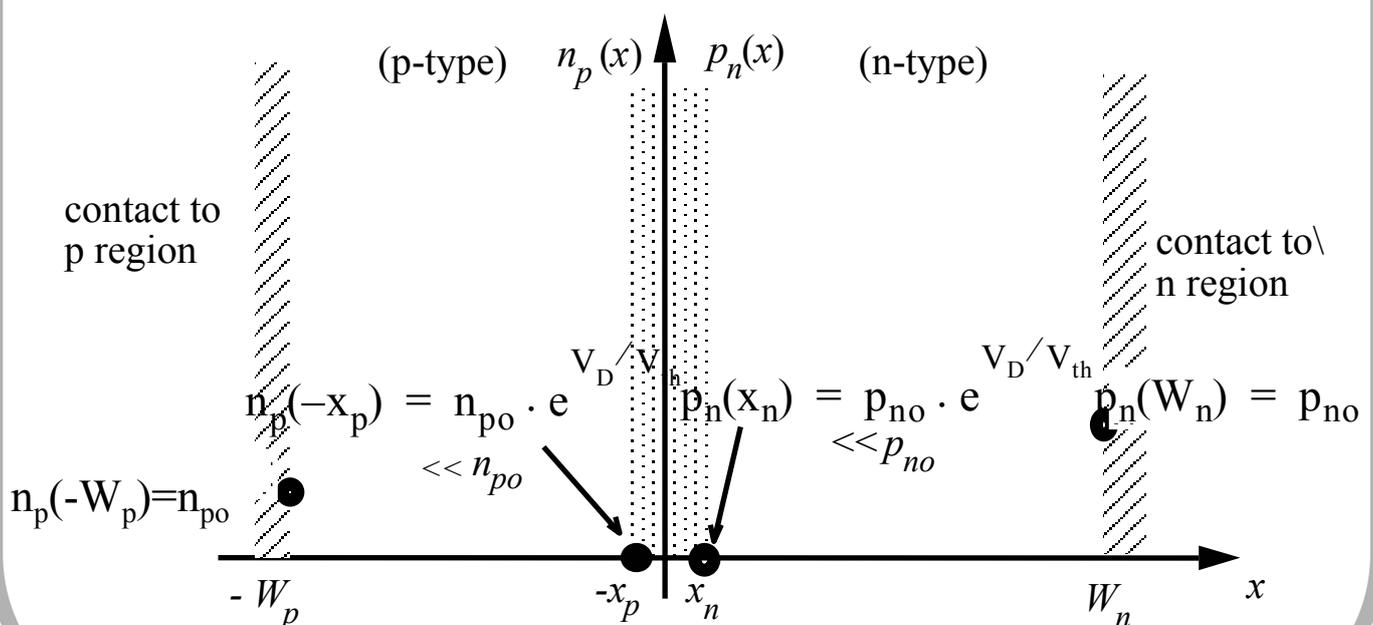
$$n_p(-x_p) \ll n_{po}(-x_{po})$$

$$p_n(x_n) \ll p_{no}(x_{no})$$

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

There is limit in reverse bias to how low minority carrier concentrations at SCR edge can be: **zero!**

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



What did we learn today?

Summary of Key Concepts

- 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 the quasi-neutral regions
- In forward bias, injected minority carriers recombine at the surface (contacts).
- In reverse bias, extracted minority carriers are generated at the surface (contacts).
- Computation of boundary conditions across SCR exploits *quasi-equilibrium*: balance between diffusion and drift in SCR disturbed very little
- IV characteristics of p-n diode: **Next Time**

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

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Spring 2009

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