# Lecture 14

## The pn Junction Diode (I)

### I-V Characteristics

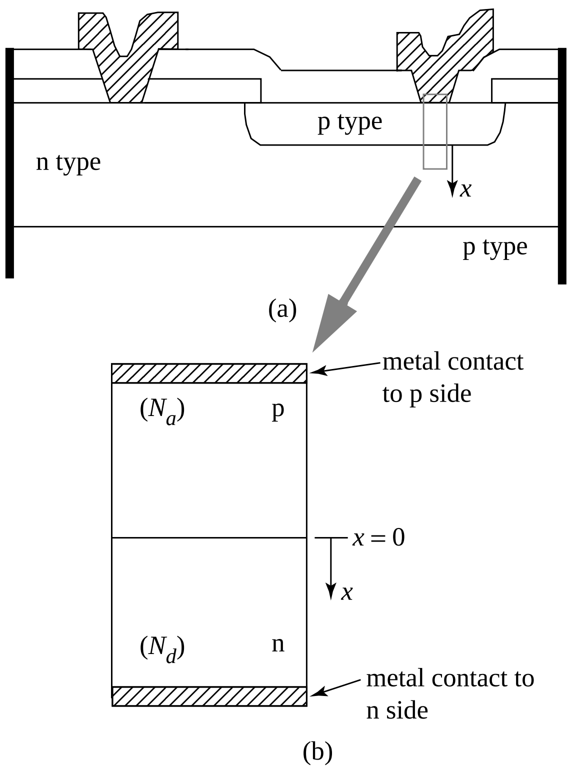
Outline

- pn junction under bias
- IV characteristics

**Reading Assignment:**
Howe and Sodini; Chapter 6, Sections 6.1-6.3

# 1. PN junction under bias

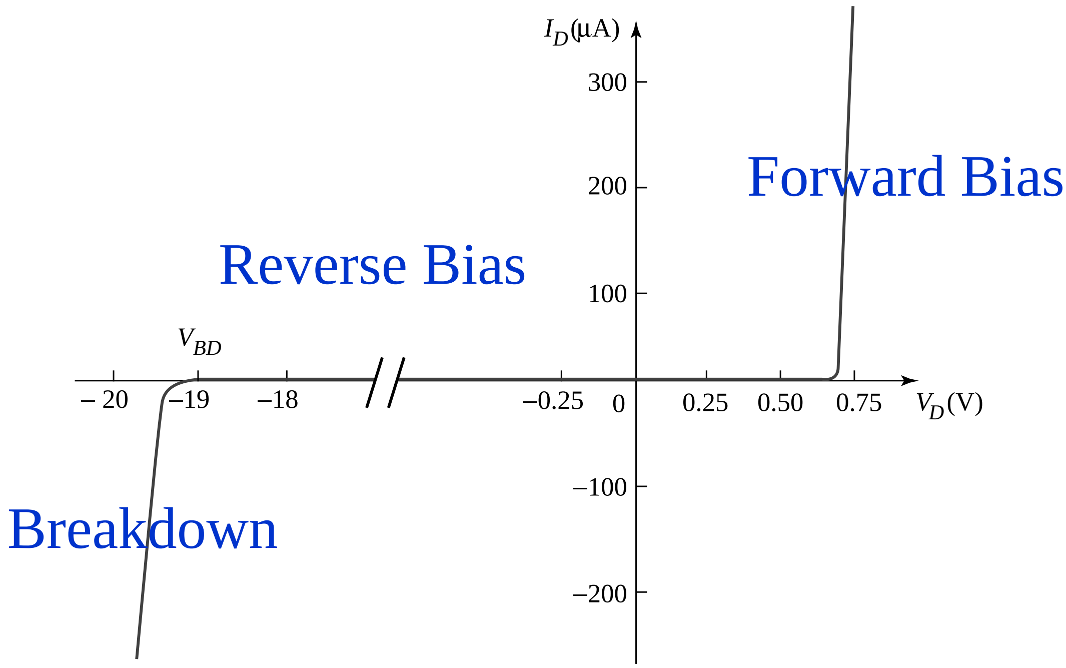
Focus on intrinsic region:



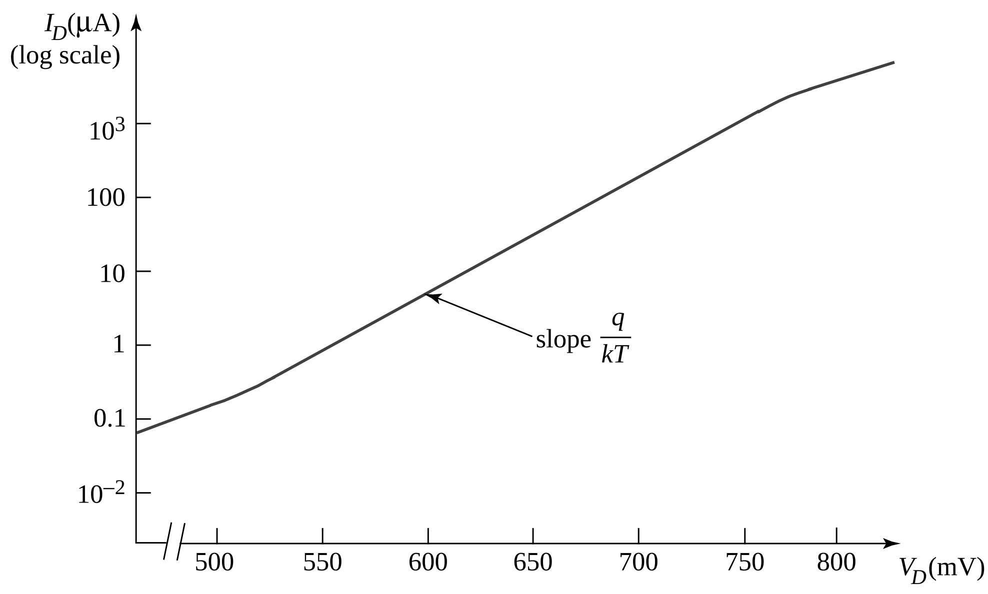

Upon application of voltage:

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

# I-V Characteristics




(a)

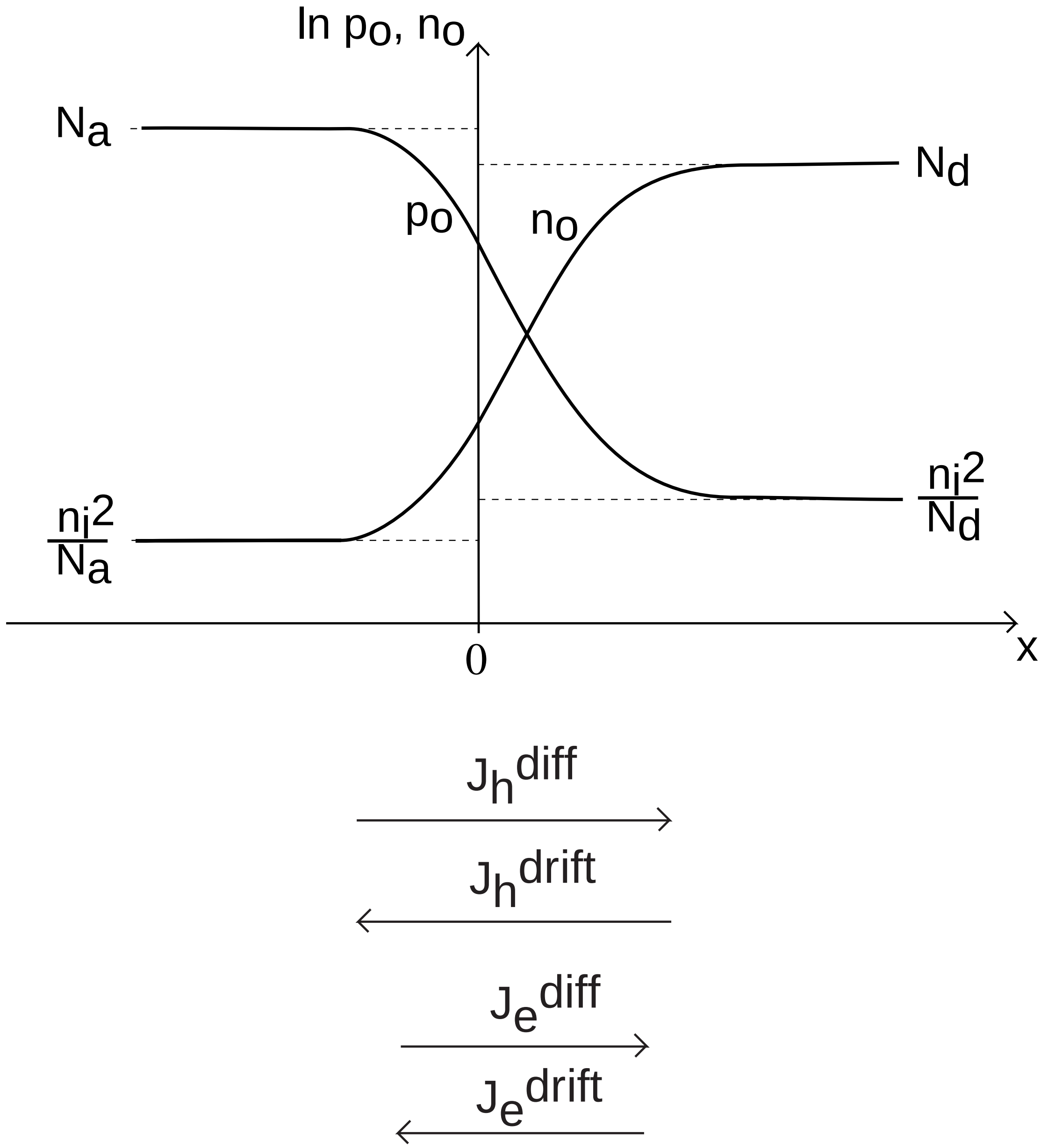



(b)

To model I-V characteristics we need 2 concepts

- The Law of the Junction
- Steady-State Diffusion

# Carrier Profiles: in thermal equilibrium

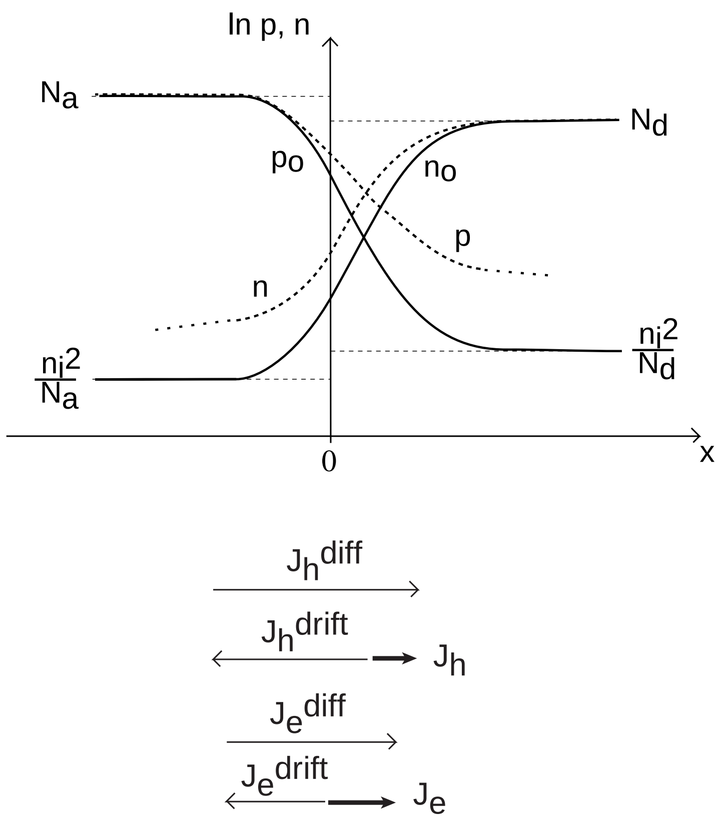



In equilibrium: dynamic balance between drift and diffusion for electrons and holes inside SCR.

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

# 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:

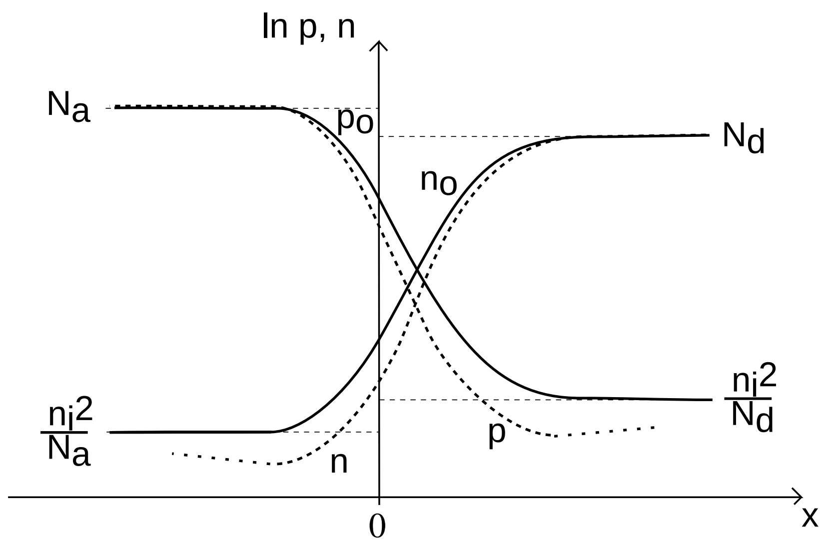
$$|J_{drift}| < |J_{diff}|$$

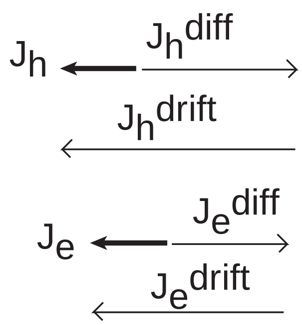
Net diffusion current in SCR ⇒ minority carrier ***injection*** into QNRs.

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 ↑ ⇒ $|E_{SCR}|$ ↑ ⇒ $|J_{drift}|$ ↑




Current balance in SCR broken:

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

Net drift current in SCR ⇒ 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?

$\Rightarrow$ 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

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

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

$$\text{Si-Si bond} \underset{\text{recombination}}{\longleftarrow} n + p$$

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

$$\text{Si-Si bond} \overset{\text{generation}}{\longrightarrow} n + p$$

## 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:

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

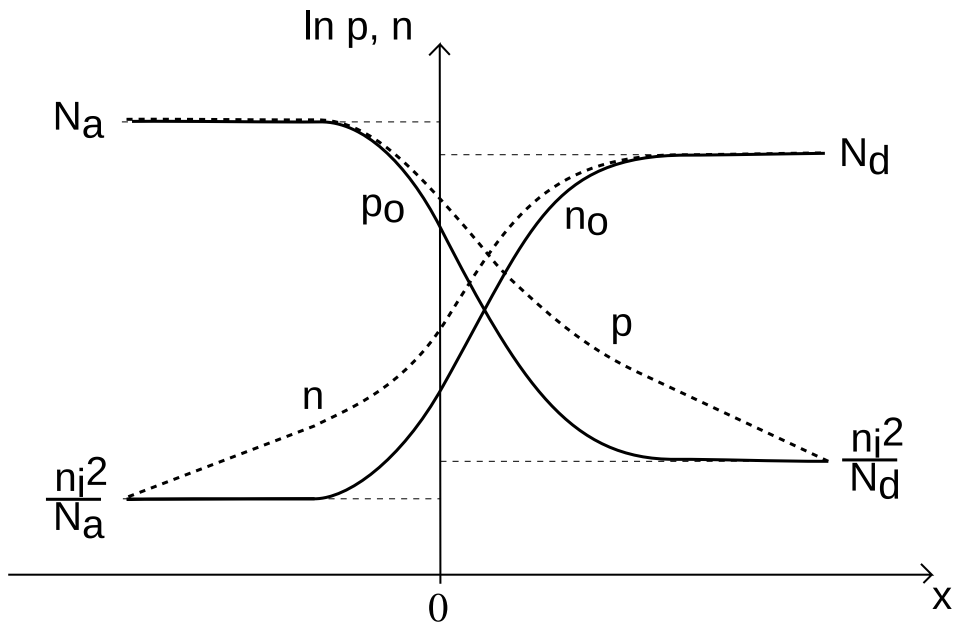
***Surfaces and contacts*** are very active generation and recombination centers
⇒ ***at contacts***, carrier concentrations cannot deviate from equilibrium:

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

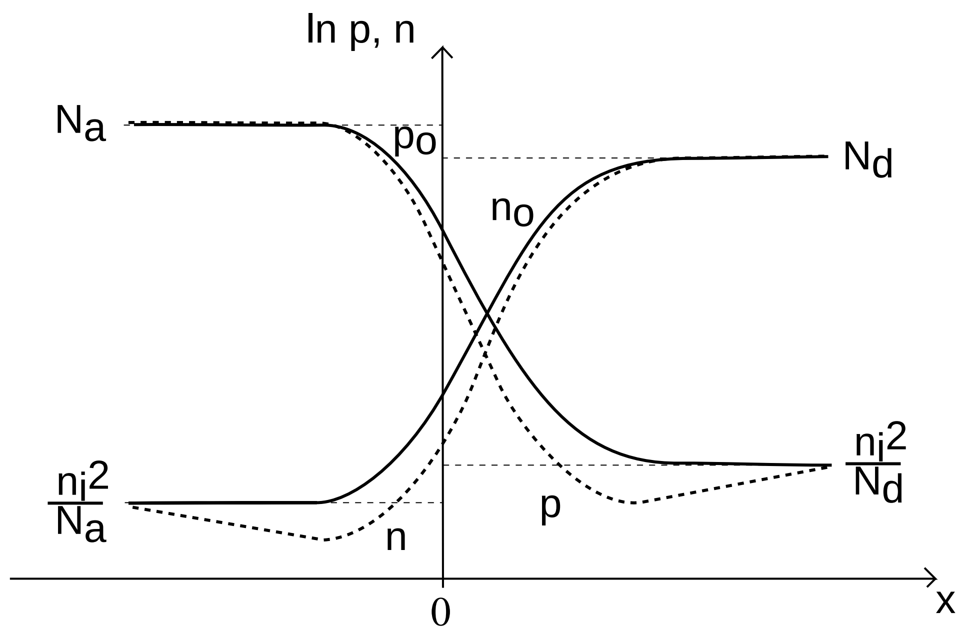
$$n(s) = n_o \; ; \qquad p(s) = p_o$$

## 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**, $|J_{drift}| = |J_{diff}|$

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

- Recall

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

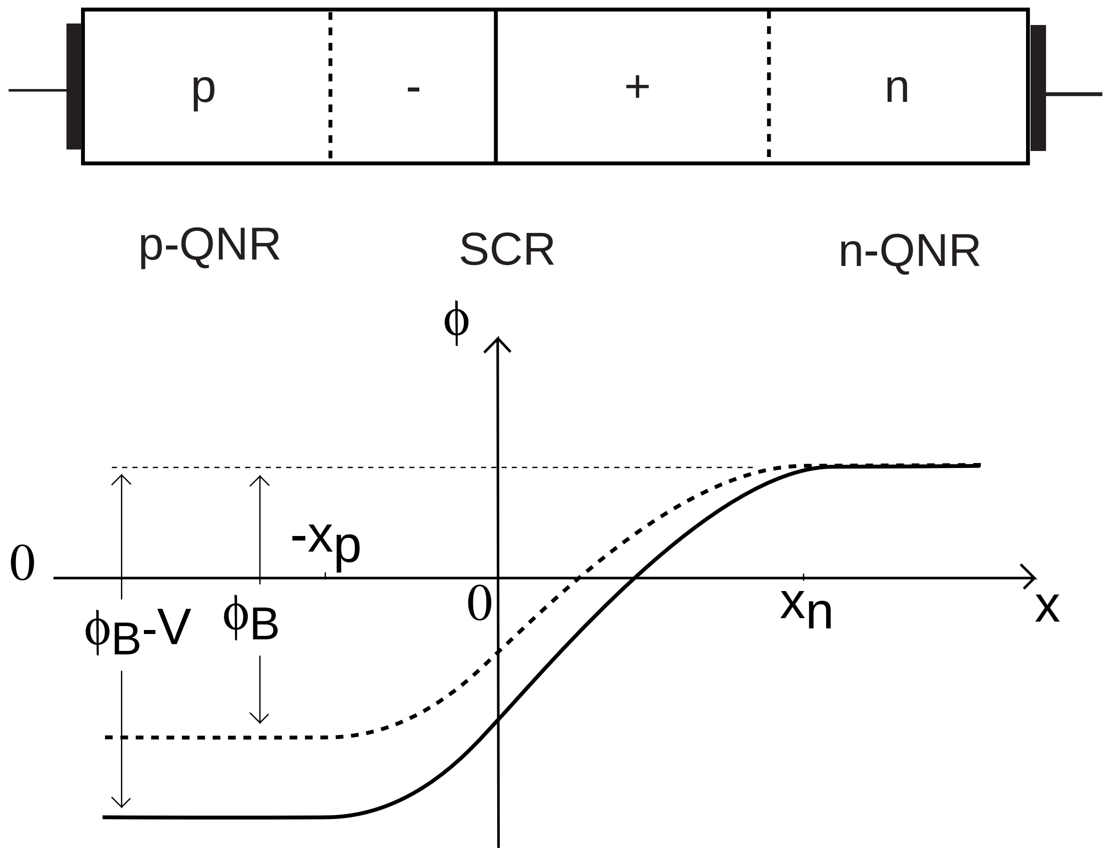
- Rewrite

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

- 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***

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

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

• 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.

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

# Voltage Dependence:

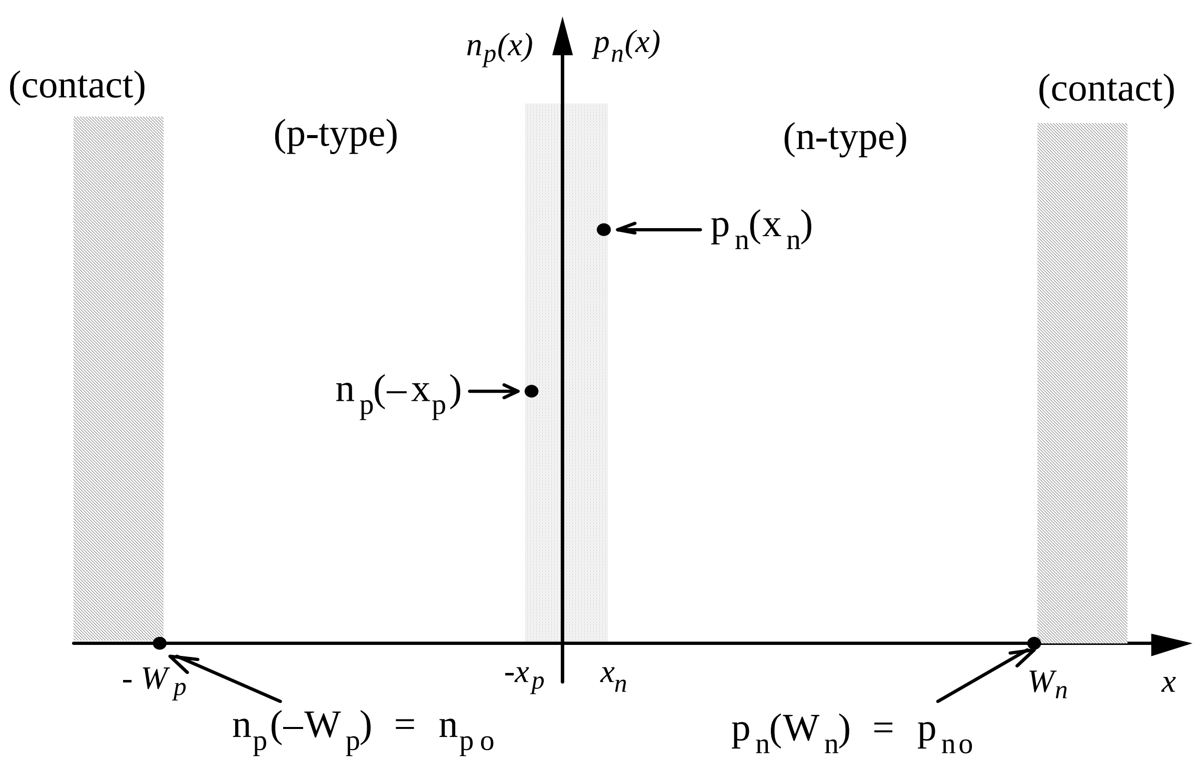
- **Forward bias (V>0):**

$$n_p(-x_p) >> n_{po}(-x_{po})$$

$$p_n(x_n) >> p_{no}(x_{no})$$

- 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):**

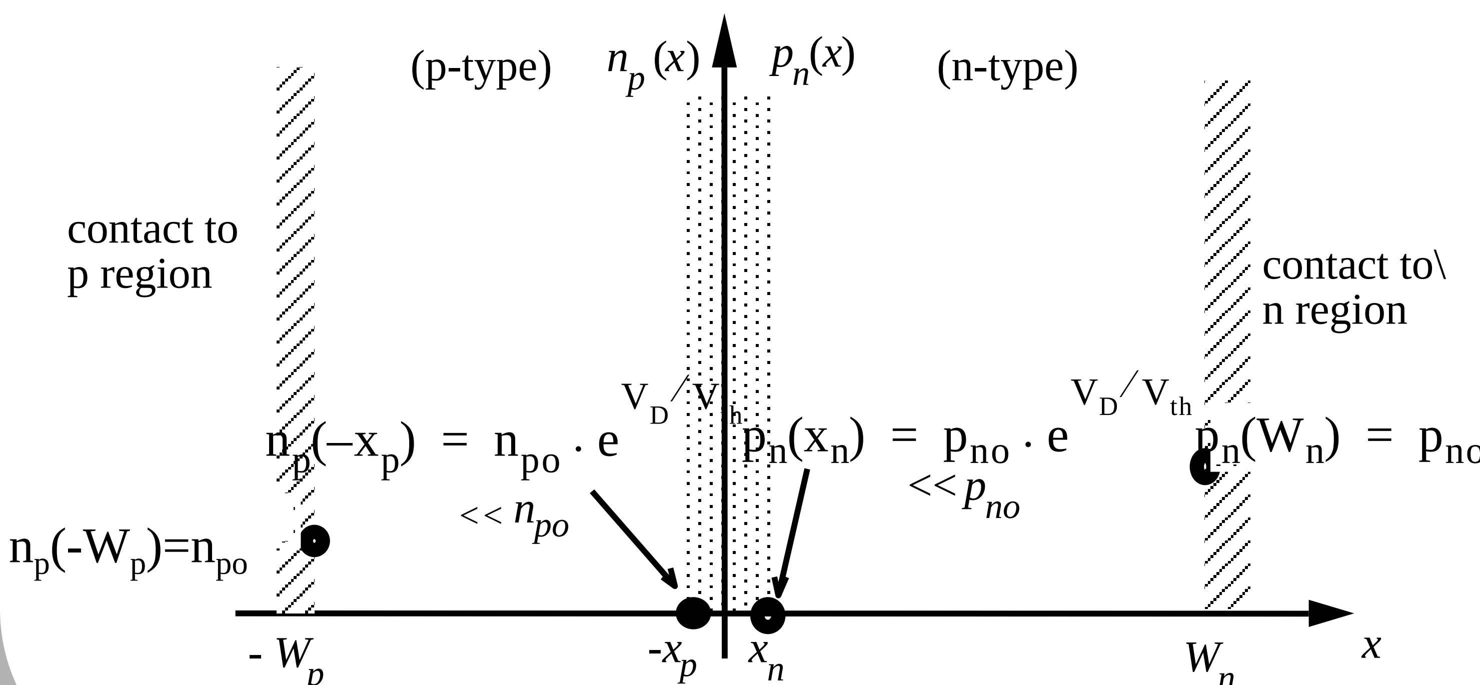
$$n_p(-x_p) << n_{po}(-x_{po})$$

$$p_n(x_n) << p_{no}(x_{no})$$

Few carriers available for extraction
⇒ 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

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