Lecture 6

Biased PN Junction Diodes and Current Flow

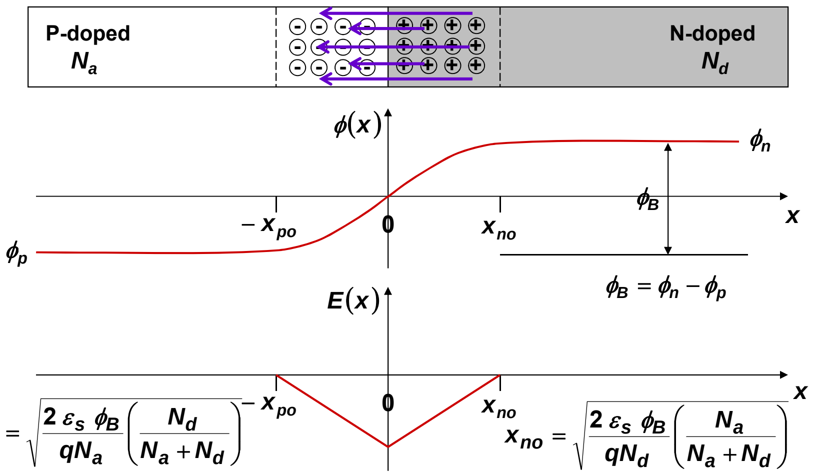
In this lecture you will learn:

- Biased PN junction diodes (forward biased and reverse biased PN diodes)
- Depletion capacitance of PN junction diodes
- Minority and majority carrier distributions in a biased PN junction diodes
- Carrier transport and current flow in biased PN junction diodes

---

Review: A PN Junction Diode in Thermal Equilibrium

- You have already seen a PN Junction diode in thermal equilibrium:

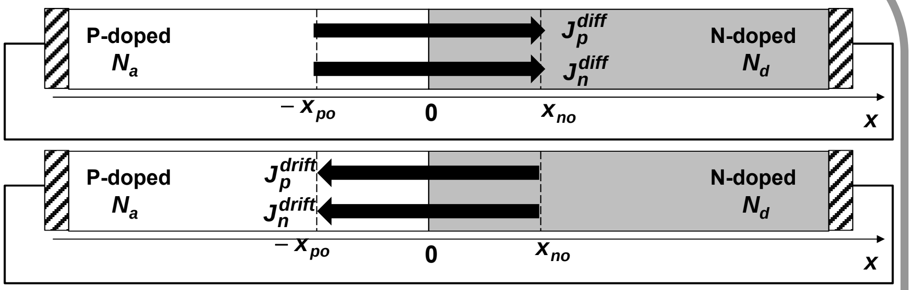


$$x_{po} = \sqrt{\frac{2\,\varepsilon_s\,\phi_B}{qN_a}\left(\frac{N_d}{N_a+N_d}\right)}$$

$$x_{no} = \sqrt{\frac{2\,\varepsilon_s\,\phi_B}{qN_d}\left(\frac{N_a}{N_a+N_d}\right)}$$

- In thermal equilibrium no net current flows in either left or right direction

Drift and Diffusion Currents in Thermal Equilibrium



In thermal equilibrium:

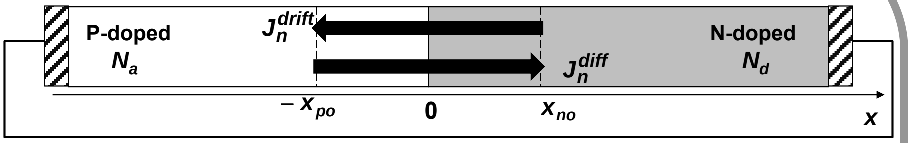
- The electron diffusion current is balanced by the equal and opposite electron drift current
- The hole diffusion current is balanced by the equal and opposite hole drift current

So the net currents of both the electrons as well as the holes are zero!

In thermal equilibrium:

$$J_p(x) = J_p^{drift}(x) + J_p^{diff}(x) = 0 \qquad J_n(x) = J_n^{drift}(x) + J_n^{diff}(x) = 0$$

Some Thermal Equilibrium Relations



- Total electron current is zero in thermal equilibrium:

$$J_n(x) = q\, n(x)\, \mu_n\, E(x) + q\, D_n \frac{d\, n(x)}{dx} = 0$$

In thermal equilibrium, these two components balance each other exactly at every point in space so that there is no total electron current anywhere

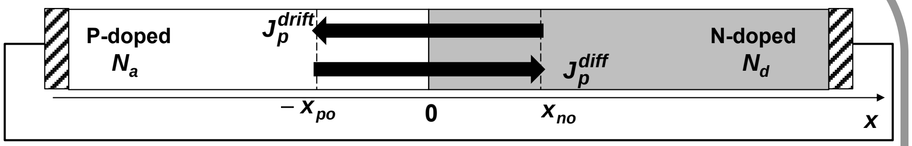
$$\Rightarrow q\, n(x)\, \mu_n\, E(x) = -q\, D_n \frac{d\, n(x)}{dx}$$

$$\Rightarrow -n(x)\, \mu_n \frac{d\,\phi(x)}{dx} = -D_n \frac{d\, n(x)}{dx}$$

$$\Rightarrow \frac{\mu_n}{D_n} \frac{d\,\phi(x)}{dx} = \frac{d \log[n(x)]}{dx}$$

$$\Rightarrow \frac{q}{KT} \frac{d\,\phi(x)}{dx} = \frac{d \log[n(x)]}{dx} \quad \Rightarrow \quad \boxed{n(x) = n_i\, e^{\frac{q\phi(x)}{KT}}}$$

Some Thermal Equilibrium Relations



- Total hole current is zero in thermal equilibrium:

$$J_p(x) = q\,p(x)\,\mu_p\,E(x) - q\,D_p\,\frac{d\,p(x)}{dx} = 0$$

In thermal equilibrium, these two components balance each other exactly at every point in space so that there is no total hole current anywhere

$$\Rightarrow\ q\,p(x)\,\mu_p\,E(x) = q\,D_p\,\frac{d\,p(x)}{dx}$$

$$\Rightarrow\ -p(x)\,\mu_p\,\frac{d\,\phi(x)}{dx} = D_p\,\frac{d\,p(x)}{dx}$$

$$\Rightarrow\ -\frac{\mu_p}{D_p}\frac{d\,\phi(x)}{dx} = \frac{d\log[p(x)]}{dx}$$

$$\Rightarrow\ -\frac{q}{KT}\frac{d\,\phi(x)}{dx} = \frac{d\log[p(x)]}{dx} \quad \Rightarrow\ \boxed{p(x) = n_i\,e^{-\frac{q\phi(x)}{KT}}}$$

Carrier Concentrations in Thermal Equilibrium

$$\boxed{n(x) = n_i\,e^{\frac{q\phi(x)}{KT}}}$$

$$\boxed{p(x) = n_i\,e^{-\frac{q\phi(x)}{KT}}}$$

$$\left[\begin{array}{l} n(x_1) = n_i\,e^{\frac{q\varphi(x_1)}{KT}} \\ n(x_2) = n_i\,e^{\frac{q\varphi(x_2)}{KT}} \end{array}\right.$$

Another way to write the same equations is:

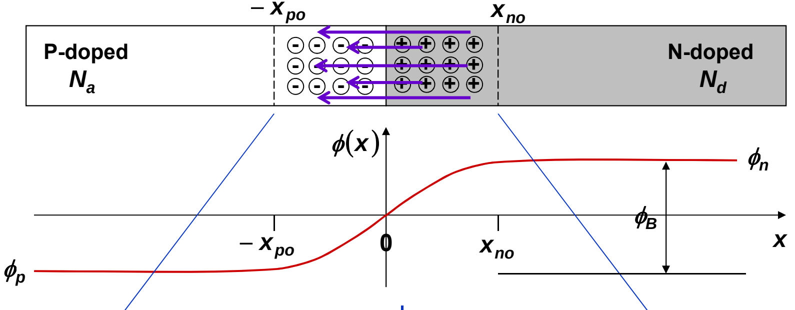
$$\boxed{n(x_2) = n(x_1)\,e^{\frac{q[\phi(x_2)-\phi(x_1)]}{KT}}}$$

$$\boxed{p(x_2) = p(x_1)\,e^{-\frac{q[\phi(x_2)-\phi(x_1)]}{KT}}}$$

In thermal equilibrium, electron and hole concentrations at different points are related exponentially to the potential difference at these points

A PN Junction Diode in Thermal Equilibrium

- **Minority carrier concentrations at the edges of the depletion region:**



$$n(-x_{po}) = \frac{n_i^2}{N_a} = n_i\, e^{\frac{q\phi_p}{KT}} = n_i\, e^{\frac{q\phi_n}{KT}} e^{\frac{q[\phi_p - \phi_n]}{KT}}$$

$$= n(x_{no})\, e^{\frac{q[\phi_p - \phi_n]}{KT}}$$

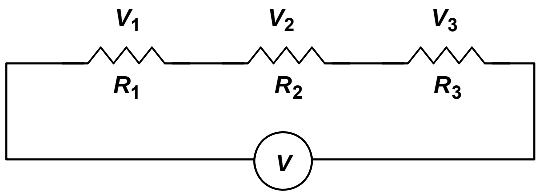
$$= N_d\, e^{-\frac{q\phi_B}{KT}}$$

$$p(x_{no}) = \frac{n_i^2}{N_d} = n_i\, e^{-\frac{q\phi_n}{KT}} = n_i\, e^{-\frac{q\phi_p}{KT}} e^{-\frac{q[\phi_n - \phi_p]}{KT}}$$

$$= p(-x_{po})\, e^{-\frac{q[\phi_n - \phi_p]}{KT}}$$

$$= N_a\, e^{-\frac{q\phi_B}{KT}}$$

Voltage Drops in Resistive Networks



Most of the voltage drops across the largest resistor in series

Suppose:

$$R_2 >> R_1$$

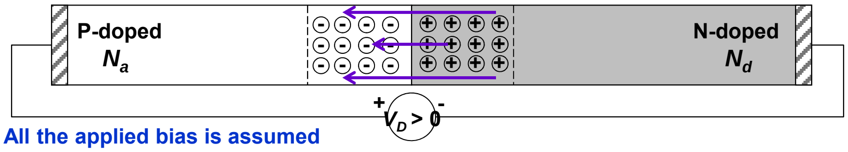
$$R_2 >> R_3$$

Then:

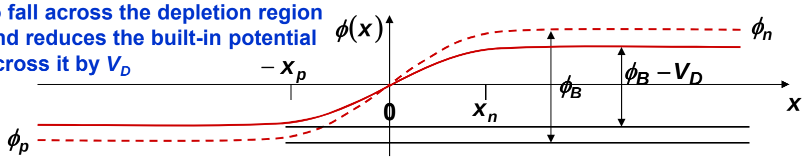
$$V_2 = V\,\frac{R_2}{R_1 + R_2 + R_3} \approx V$$

A Forward Biased PN Junction Diode

- Now apply a forward bias with an external voltage source V_D:

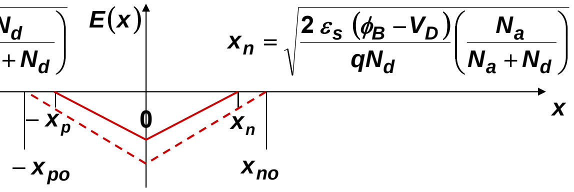


All the applied bias is assumed to fall across the depletion region and reduces the built-in potential across it by V_D



$$x_p = \sqrt{\frac{2\,\varepsilon_s\,(\phi_B - V_D)}{qN_a}\left(\frac{N_d}{N_a+N_d}\right)}$$

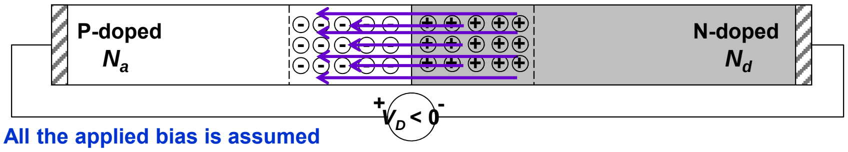
$$x_n = \sqrt{\frac{2\,\varepsilon_s\,(\phi_B - V_D)}{qN_d}\left(\frac{N_a}{N_a+N_d}\right)}$$



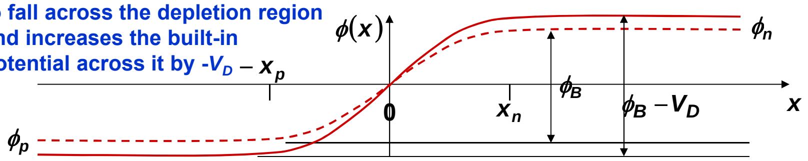
- In forward bias, the depletion regions shrink, and the electric field in the junction also decreases in magnitude

A Reversed Biased PN Junction Diode

- Now apply a bias with an external voltage source V_D (where $V_D < 0$):

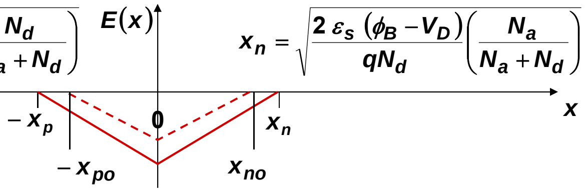


All the applied bias is assumed to fall across the depletion region and increases the built-in potential across it by $-V_D$



$$x_p = \sqrt{\frac{2\,\varepsilon_s\,(\phi_B - V_D)}{qN_a}\left(\frac{N_d}{N_a+N_d}\right)}$$

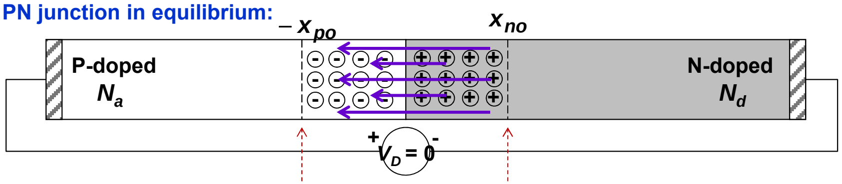
$$x_n = \sqrt{\frac{2\,\varepsilon_s\,(\phi_B - V_D)}{qN_d}\left(\frac{N_a}{N_a+N_d}\right)}$$



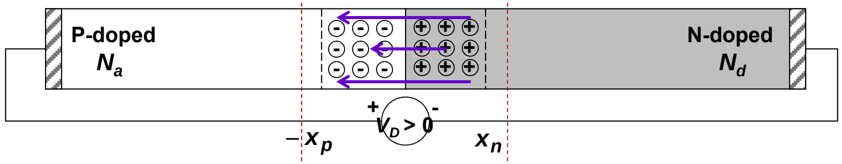
- In reverse bias, the depletion regions become larger, and the electric field in the junction also increases in magnitude

Junction Depletion Region Capacitance

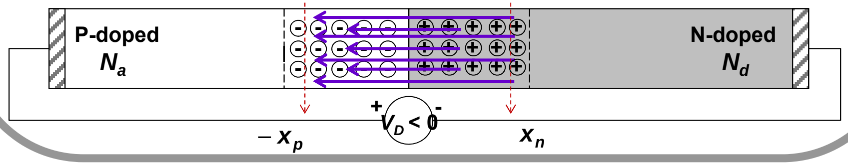
A PN junction in equilibrium:



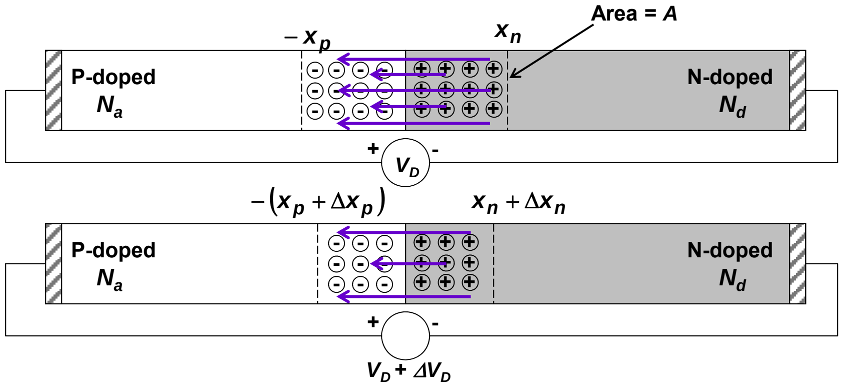
A PN junction in forward bias (depletion region shrinks):



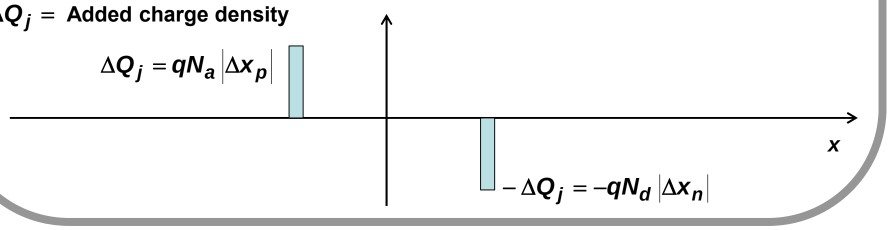
A PN junction in reverse bias (depletion region widens):



Junction Depletion Region Capacitance



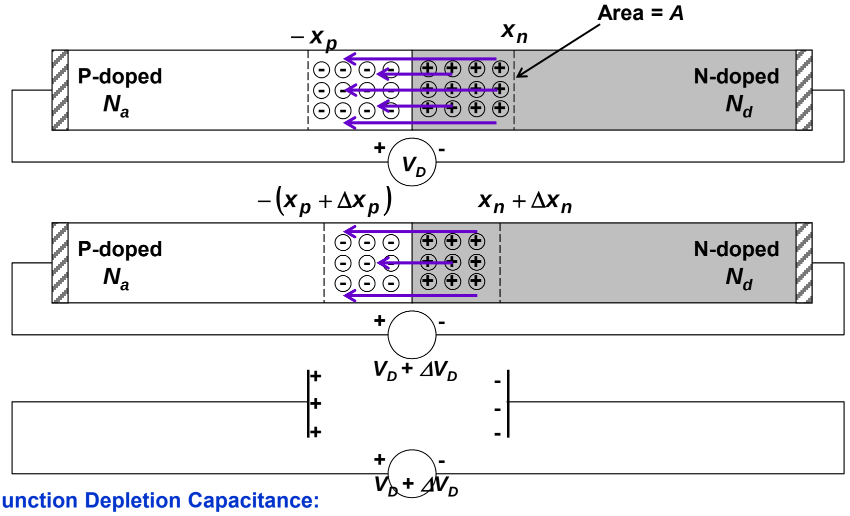
$\Delta Q_j =$ Added charge density



$\Delta Q_j = qN_a |\Delta x_p|$

$-\Delta Q_j = -qN_d |\Delta x_n|$

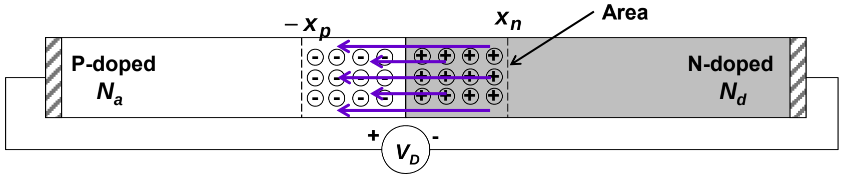
Junction Depletion Region Capacitance



Junction Depletion Capacitance:

$$C_j = \frac{\Delta Q_j}{\Delta V_D} = \frac{dQ_j}{dV_D} = \frac{d(-qN_a x_p A)}{dV_D} = -\frac{d(+qN_d x_n A)}{dV_D} = \frac{\varepsilon_s A}{(x_p + x_n)}$$

Junction Depletion Region Capacitance



Since:

$$x_p + x_n = \sqrt{\frac{2\,\varepsilon_s\,(\phi_B - V_D)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)}$$

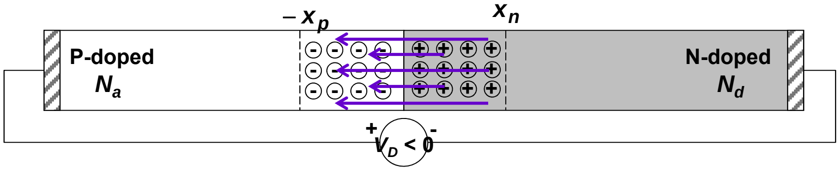
The depletion region capacitance becomes:

Zero voltage junction capacitance

$$C_j = \frac{\varepsilon_s A}{(x_p + x_n)} = A\sqrt{\frac{q\varepsilon_s}{2\,(\phi_B - V_D)}\left(\frac{N_a N_d}{N_a + N_d}\right)} = \frac{C_{jo}}{\sqrt{1 - \frac{V_D}{\phi_B}}}$$

The depletion capacitance is mostly contributed by the side with the lower doping that has the larger depletion region thickness

Junction Breakdown in Reverse Bias



In the presence of very large electric fields, the generation rate G of electrons and holes can increase dramatically from the equilibrium value G_o

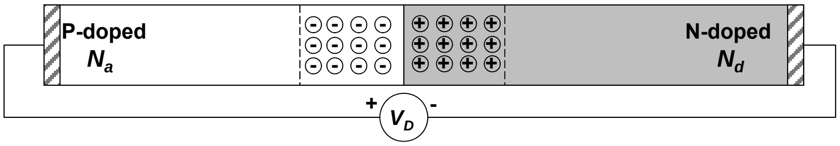
In the presence of large electric fields, electrons and holes accelerate to large velocities and then give off their kinetic energies to create more electrons and holes (impact ionization) which in turn accelerate and create even more electrons and holes leading to an avalanche effect and resulting in very large currents

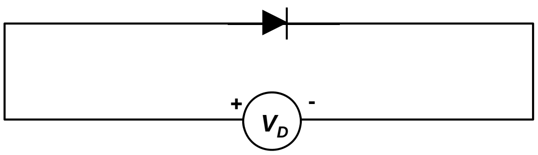
The minimum electric field at which breakdown occurs is called the "breakdown field"

In Silicon, the breakdown field is around 3×10^5 V/cm

PN diodes exhibit breakdown under large reverse biases - when the maximum field in the junction becomes equal to the breakdown field value

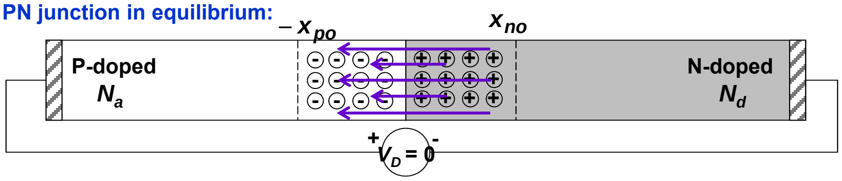
Circuit Symbol for a PN Junction Diode



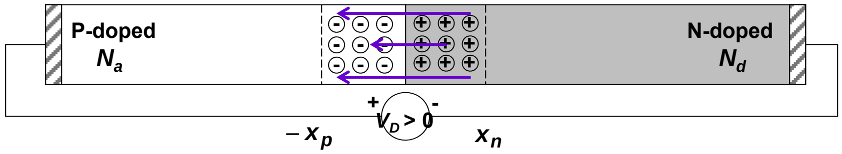


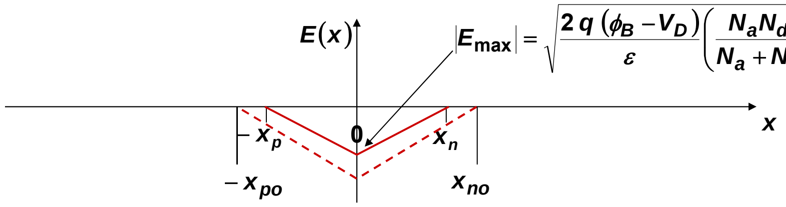
Current Flow in a Forward Biased PN Junction Diode

A PN junction in equilibrium:



A PN junction in forward bias (junction field decreases and depletion region shrinks):

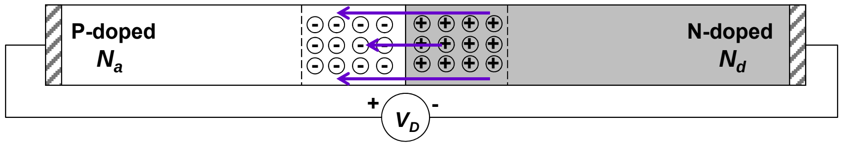




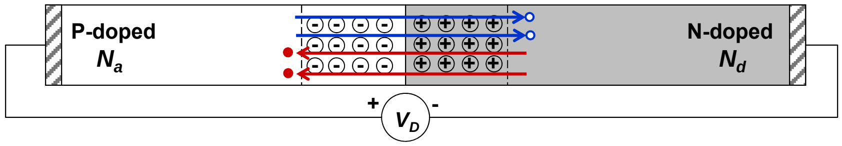
$$|E_{\max}| = \sqrt{\frac{2q\,(\phi_B - V_D)}{\varepsilon}\left(\frac{N_a N_d}{N_a + N_d}\right)}$$

Current Flow in a Forward Biased PN Junction Diode: Balance of Drift Diffusion Currents is Broken

Drift current of both electrons and holes is reduced in forward bias (because the electric field is reduced)



Diffusion current of both electrons and holes in approximately the same as in equilibrium

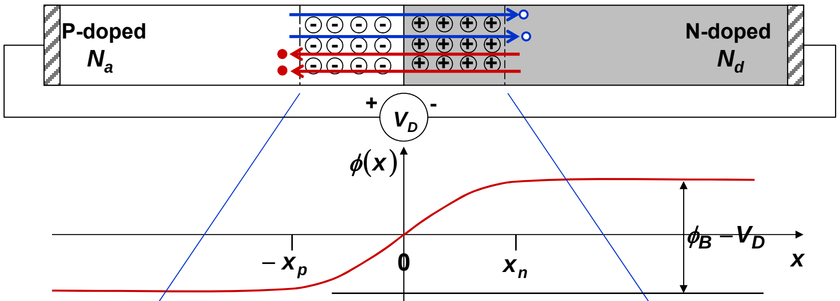


- **Consequently, the total electron and hole currents are no longer zero; diffusion exceeds drift!!**

- **There is net current due to electron diffusion flow from the N-side to the P-side, and due to hole diffusion flow from the P-side to the N-side**

Carrier Injection in a Forward Biased PN Junction Diode

- **Minority carrier concentrations** at the edges of the depletion region in forward bias:



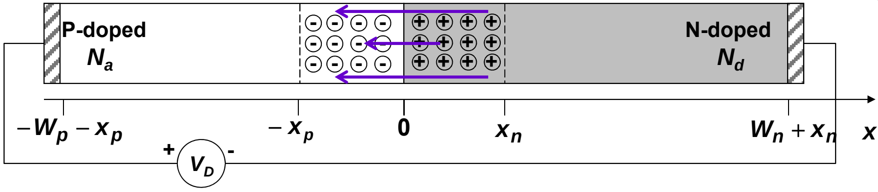
$$n(-x_p) = N_d\, e^{-\frac{q(\phi_B - V_D)}{KT}} = \frac{n_i^2}{N_a}\, e^{\frac{qV_D}{KT}}$$

$$p(x_n) = N_a\, e^{-\frac{q(\phi_B - V_D)}{KT}} = \frac{n_i^2}{N_d}\, e^{\frac{qV_D}{KT}}$$

In forward bias, the minority carrier concentrations increase exponentially at the edges of the depletion region

---

Fundamental Assumptions In Modeling Carrier Transport



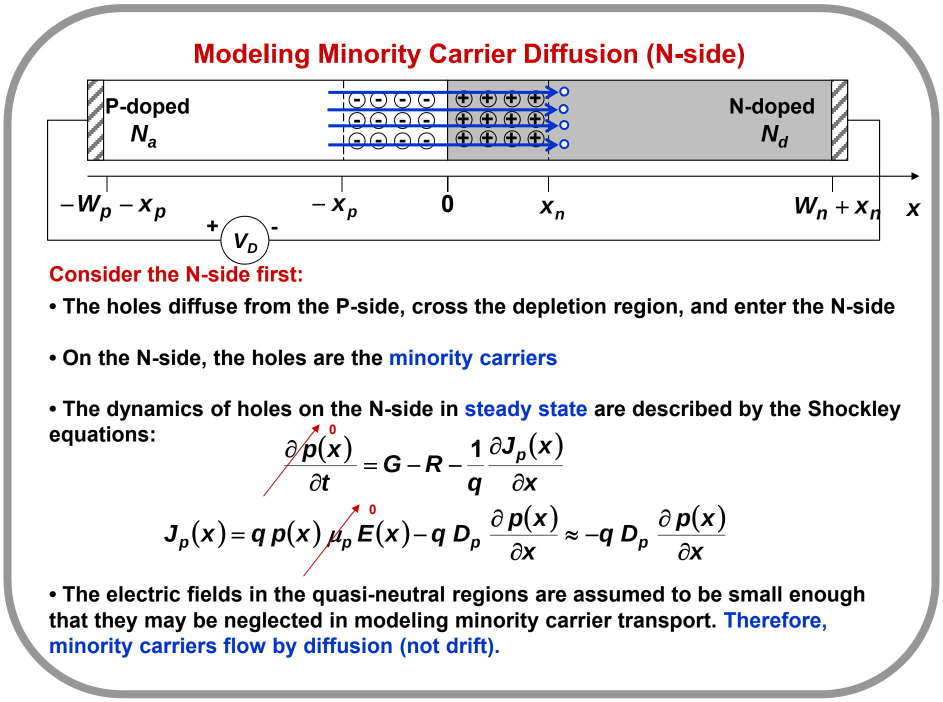
- In forward bias, the main obstacle to current flow is not the depletion region but carrier diffusion in the N- and the P-sides

This assumption implies that it is enough to study current flow in the N- and P-sides and not worry about what happens inside the depletion region

- The N-side and the P-side are “quasi-neutral”

The word “quasi-neutral” implies that there is almost no net charge densities inside these regions and, by Gauss’s law, almost zero electric fields inside these regions

This assumption is not 100% accurate. The physical reason behind this assumption is that when a material is highly conducting (like the N- and P-sides) the electric field inside it is usually small. How small is small…….see the next slide….



Modeling Minority Carrier Diffusion (N-side)

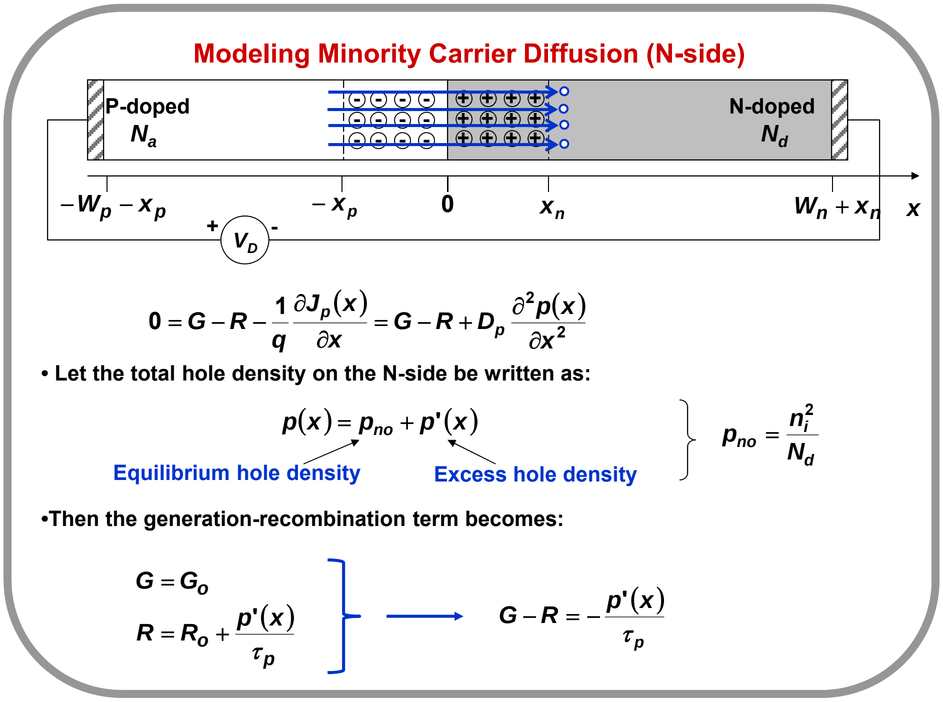
Consider the N-side first:

- The holes diffuse from the P-side, cross the depletion region, and enter the N-side
- On the N-side, the holes are the minority carriers
- The dynamics of holes on the N-side in steady state are described by the Shockley equations:

$$\cancelto{0}{\frac{\partial p(x)}{\partial t}} = G - R - \frac{1}{q}\frac{\partial J_p(x)}{\partial x}$$

$$J_p(x) = q\,p(x)\,\cancelto{0}{\mu_p}\,E(x) - q\,D_p\frac{\partial p(x)}{\partial x} \approx -q\,D_p\frac{\partial p(x)}{\partial x}$$

- The electric fields in the quasi-neutral regions are assumed to be small enough that they may be neglected in modeling minority carrier transport. Therefore, minority carriers flow by diffusion (not drift).



Modeling Minority Carrier Diffusion (N-side)

$$0 = G - R - \frac{1}{q}\frac{\partial J_p(x)}{\partial x} = G - R + D_p\frac{\partial^2 p(x)}{\partial x^2}$$

- Let the total hole density on the N-side be written as:

$$p(x) = p_{no} + p'(x) \qquad p_{no} = \frac{n_i^2}{N_d}$$

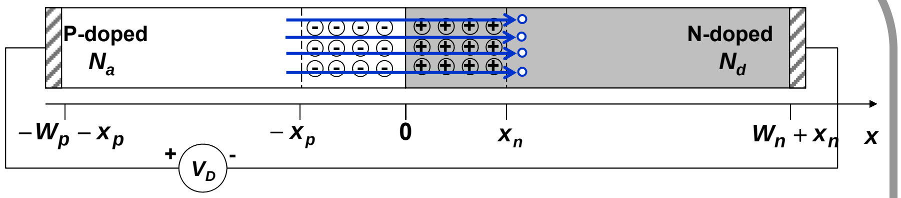
Equilibrium hole density

Excess hole density

- Then the generation-recombination term becomes:

$$\left.\begin{aligned} G &= G_o \\ R &= R_o + \frac{p'(x)}{\tau_p} \end{aligned}\right\} \longrightarrow \quad G - R = -\frac{p'(x)}{\tau_p}$$

Modeling Minority Carrier Diffusion (N-side)



$$0 = G - R - \frac{1}{q}\frac{\partial J_p(x)}{\partial x} = G - R + D_p \frac{\partial^2 p(x)}{\partial x^2}$$

- Let the total hole density on the N-side be written as:

$$p(x) = p_{no} + p'(x) \quad \Big\} \quad p_{no} = \frac{n_i^2}{N_d}$$

Equilibrium hole density

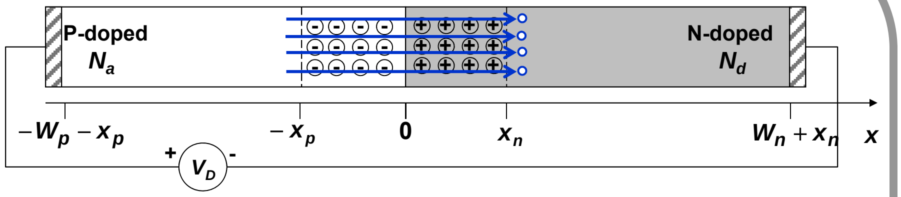
Excess hole density

•And we get:

$$\boxed{\frac{\partial^2 p'(x)}{\partial x^2} - \frac{p'(x)}{D_p \tau_p} = 0} \longrightarrow$$

Diffusion equation for the excess hole density

Modeling Minority Carrier Diffusion (N-side)



- We need to solve the second order diffusion equation: $\frac{\partial^2 p'(x)}{\partial x^2} - \frac{p'(x)}{D_p \tau_p} = 0$

with the boundary condition:

$$p'(x_n) = p(x_n) - p_{no} = \frac{n_i^2}{N_d} e^{\frac{qV_D}{KT}} - \frac{n_i^2}{N_d} = \frac{n_i^2}{N_d}\left(e^{\frac{qV_D}{KT}} - 1\right)$$

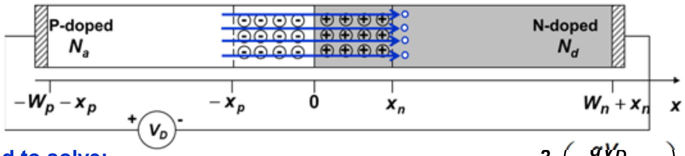
- But it is a second order differential equation, so we need a second boundary condition!

The minority carrier lifetime τ_p is assumed to be zero at the metal contacts.

- Consequently, there cannot be any excess hole density at the right metal contact. This gives us the second boundary condition:

$$p'(W_n + x_n) = 0$$

Modeling Minority Carrier Diffusion (N-side)



We need to solve:

$$\frac{\partial^2 p'(x)}{\partial x^2} - \frac{p'(x)}{D_p \tau_p} = 0$$

$$p'(x_n) = \frac{n_i^2}{N_d}\left(e^{\frac{qV_D}{KT}} - 1\right)$$

$$p'(W_n + x_n) = 0$$

Define a **"minority carrier diffusion length"** L_p for holes as: $L_p = \sqrt{D_p \tau_p}$

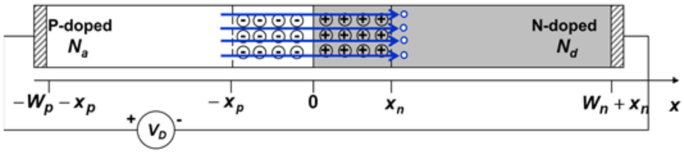
We need to solve:

$$\frac{\partial^2 p'(x)}{\partial x^2} - \frac{p'(x)}{L_p^2} = 0$$

$$p'(x_n) = \frac{n_i^2}{N_d}\left(e^{\frac{qV_D}{KT}} - 1\right)$$

$$p'(W_n + x_n) = 0$$

Modeling Minority Carrier Diffusion (N-side)



We need to solve:

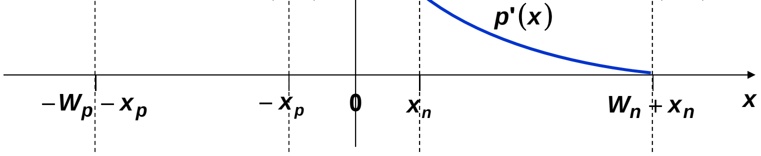
$$\frac{\partial^2 p'(x)}{\partial x^2} - \frac{p'(x)}{L_p^2} = 0$$

$$p'(x_n) = \frac{n_i^2}{N_d}\left(e^{\frac{qV_D}{KT}} - 1\right)$$

$$p'(W_n + x_n) = 0$$

And the solution is:

$$p'(x) = p'(x_n)\frac{\sinh\left(\frac{W_n + x_n - x}{L_p}\right)}{\sinh\left(\frac{W_n}{L_p}\right)} = \frac{n_i^2}{N_d}\left(e^{\frac{qV_D}{KT}} - 1\right)\frac{\sinh\left(\frac{W_n + x_n - x}{L_p}\right)}{\sinh\left(\frac{W_n}{L_p}\right)}$$



The Minority Carrier Diffusion Length (N-Side)

The minority carrier diffusion length L_p is the average length a hole injected into the N-side will diffuse before it finds an electron and recombines with it

- **Long Base Limit:**

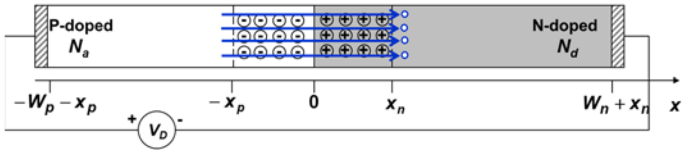
If $L_p << W_n$ then pretty much all the holes injected into the N-side recombine with electrons before they are able to cross the N-side

- **Short Base Limit:**

If $L_p >> W_n$ then pretty much all the holes injected into the N-side do not recombine with the electrons and are able to cross the N-side

---

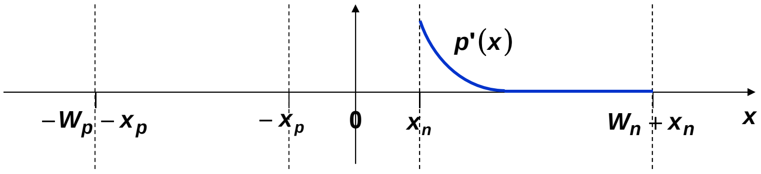
Modeling Minority Carrier Diffusion (N-side)



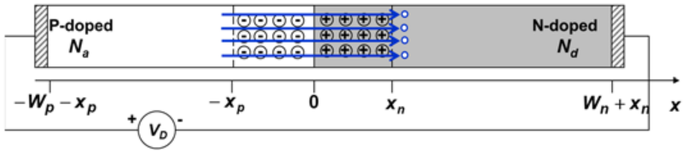
Long Base Limit:

If $L_p << W_n$ then the solution is:

$$p'(x) = \frac{n_i^2}{N_d}\left(e^{\frac{qV_D}{KT}} - 1\right)\frac{\sinh\left(\frac{W_n + x_n - x}{L_p}\right)}{\sinh\left(\frac{W_n}{L_p}\right)} \approx \frac{n_i^2}{N_d}\left(e^{\frac{qV_D}{KT}} - 1\right)e^{-\frac{(x - x_n)}{L_p}}$$



Modeling Minority Carrier Diffusion (N-side)



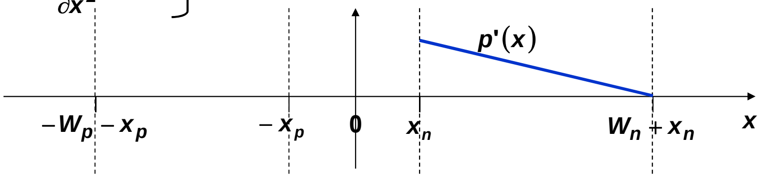
Short Base Limit:

If $L_p >> W_n$ then the solution is:

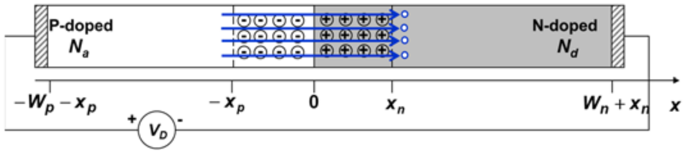
$$p'(x) = \frac{n_i^2}{N_d}\left(e^{\frac{qV_D}{KT}} - 1\right)\frac{\sinh\left(\frac{W_n + x_n - x}{L_p}\right)}{\sinh\left(\frac{W_n}{L_p}\right)} \approx \frac{n_i^2}{N_d}\left(e^{\frac{qV_D}{KT}} - 1\right)\left(\frac{W_n + x_n - x}{W_n}\right)$$

Could have just solved:

$$\left.\frac{\partial^2 p'(x)}{\partial x^2} = 0\right\}$$



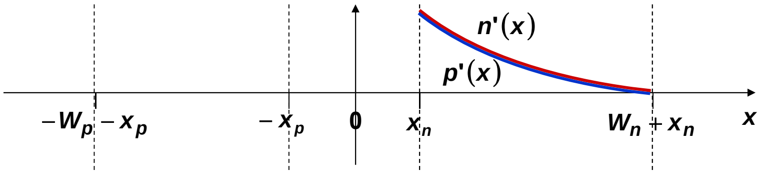
Charge Neutrality and Majority Carrier Distribution (N-side)



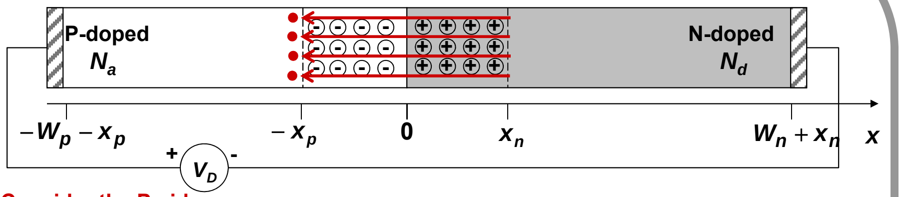
- The assumption of **quasi-neutrality** implies that charge neutrality in the conducting N-doped region holds even when out of equilibrium
- Let the excess majority carrier distribution (i.e. of electrons on the N-side) be written as:

$$\left.\begin{matrix} n(x) = n_{no} + n'(x) \\ \text{Equilibrium electron density} \quad \text{Excess electron density} \end{matrix}\right\} \quad n_{no} = N_d$$

- Then charge neutrality implies: $n'(x) = p'(x)$



Modeling Minority Carrier Diffusion (P-side)



Consider the P-side now:

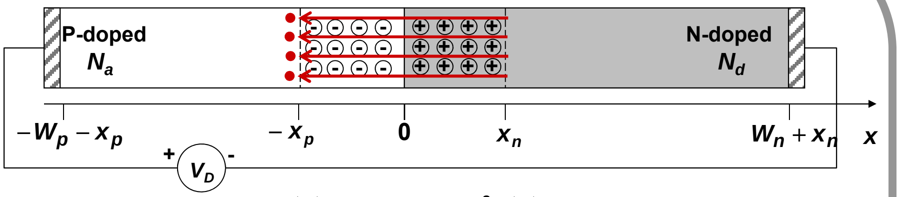
- The electrons diffuse from the N-side, cross the depletion region, and enter the P-side
- On the P-side, the electrons are the minority carriers
- The dynamics of electrons on the P-side in steady state are described by the Shockley equations:

$$\cancelto{0}{\frac{\partial n(x)}{\partial t}} = G - R + \frac{1}{q}\frac{\partial J_n(x)}{\partial x}$$

$$J_n(x) = q\,n(x)\,\mu_n \cancelto{0}{E(x)} + q\,D_n\frac{\partial n(x)}{\partial x} \approx q\,D_n\frac{\partial n(x)}{\partial x}$$

- The electric fields in the quasi-neutral regions are assumed to be small enough that they may be neglected in modeling minority carrier transport. Therefore, minority carriers flow by diffusion (not drift).

Modeling Minority Carrier Diffusion (P-side)



$$0 = G - R + \frac{1}{q}\frac{\partial J_n(x)}{\partial x} = G - R + D_n\frac{\partial^2 n(x)}{\partial x^2}$$

- Let the total electron density on the P-side be written as:

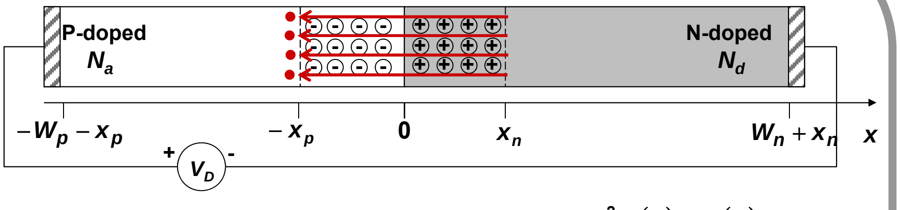
$$\left. n(x) = \underset{\text{Equilibrium electron density}}{n_{po}} + \underset{\text{Excess electron density}}{n'(x)} \right\} \quad n_{po} = \frac{n_i^2}{N_a}$$

- Then the generation-recombination term becomes: $G - R = -\dfrac{n'(x)}{\tau_n}$
- And we get:

$$\boxed{\frac{\partial^2 n'(x)}{\partial x^2} - \frac{n'(x)}{D_n\tau_n} = 0} \longrightarrow$$

Diffusion equation for the excess electron density

Modeling Minority Carrier Diffusion (P-side)



- We need to solve the second order diffusion equation: $\frac{\partial^2 n'(x)}{\partial x^2} - \frac{n'(x)}{D_n \tau_n} = 0$

with the boundary condition: $n'(-x_p) = \frac{n_i^2}{N_a}\left(e^{\frac{qV_D}{KT}} - 1\right)$

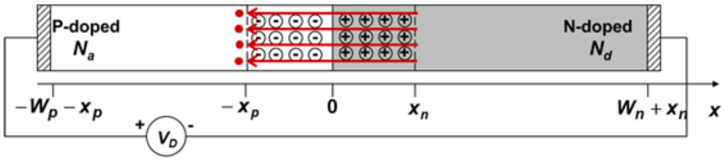
- But it is a second order differential equation, so we need a second boundary condition!

The minority carrier lifetime τ_n is assumed to be zero at the metal contacts.

- Consequently, there cannot be any excess electron density at the left metal contact. This gives us the second boundary condition:

$$n'(-W_p - x_p) = 0$$

Modeling Minority Carrier Diffusion (P-side)



We need to solve:

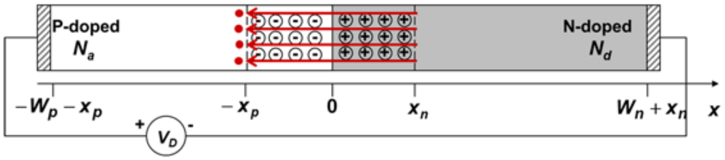
$$\frac{\partial^2 n'(x)}{\partial x^2} - \frac{n'(x)}{D_n \tau_n} = 0 \quad \left\} \quad \begin{array}{l} n'(-x_p) = \frac{n_i^2}{N_a}\left(e^{\frac{qV_D}{KT}} - 1\right) \\ n'(-W_p - x_p) = 0 \end{array} \right.$$

Define a "minority carrier diffusion length" L_n for electrons as: $L_n = \sqrt{D_n \tau_n}$

We need to solve:

$$\frac{\partial^2 n'(x)}{\partial x^2} - \frac{n'(x)}{L_n^2} = 0 \quad \left\} \quad \begin{array}{l} n'(-x_p) = \frac{n_i^2}{N_a}\left(e^{\frac{qV_D}{KT}} - 1\right) \\ n'(-W_p - x_p) = 0 \end{array} \right.$$

Modeling Minority Carrier Diffusion (P-side)

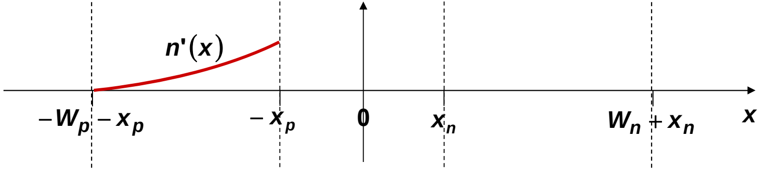


We need to solve:

$$\frac{\partial^2 n'(x)}{\partial x^2} - \frac{n'(x)}{L_n^2} = 0 \quad \Bigg\} \quad \begin{cases} n'(-x_p) = \dfrac{n_i^2}{N_a}\left(e^{\frac{qV_D}{KT}} - 1\right) \\ n'(-W_p - x_p) = 0 \end{cases}$$

And the solution is:

$$n'(x) = n'(-x_p)\frac{\sinh\left(\dfrac{W_p + x_p + x}{L_n}\right)}{\sinh\left(\dfrac{W_p}{L_n}\right)} = \frac{n_i^2}{N_a}\left(e^{\frac{qV_D}{KT}} - 1\right)\frac{\sinh\left(\dfrac{W_p + x_p + x}{L_n}\right)}{\sinh\left(\dfrac{W_p}{L_n}\right)}$$



The Minority Carrier Diffusion Length (P-Side)

The minority carrier diffusion length L_n is the average length an electron injected into the P-side will diffuse before it finds a hole and recombines with it

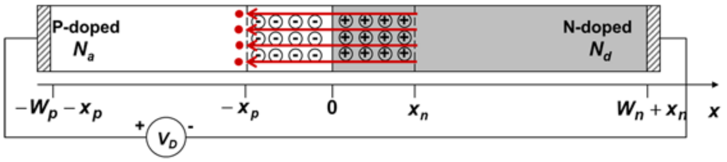
- **Long Base Limit:**

If $L_n << W_p$ then pretty much all the electrons injected into the P-side recombine with holes before they are able to cross the P-side

- **Short Base Limit:**

If $L_n >> W_p$ then pretty much all the electrons injected into the P-side do not recombine with the holes and are able to cross the P-side

Charge Neutrality and Majority Carrier Distribution (P-side)



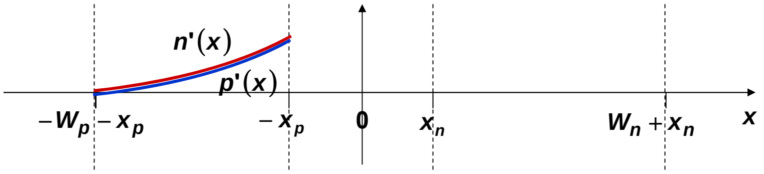
- The assumption of quasi-neutrality implies that charge neutrality pretty much holds even when out of equilibrium
- Let the excess majority carrier distribution (i.e. of holes on the P-side) be written as:

$$p(x) = p_{po} + p'(x) \qquad \Big\} \; p_{po} = N_a$$

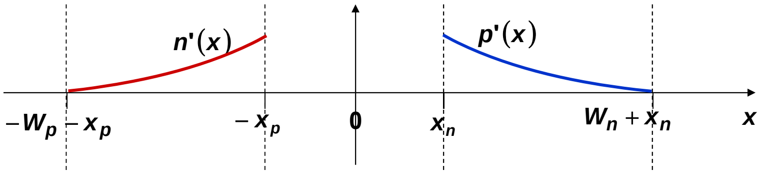
Equilibrium hole density

Excess hole density

- Then charge neutrality implies: $p'(x) = n'(x)$



Minority Carrier Current Flow



Electron current on the P-side:

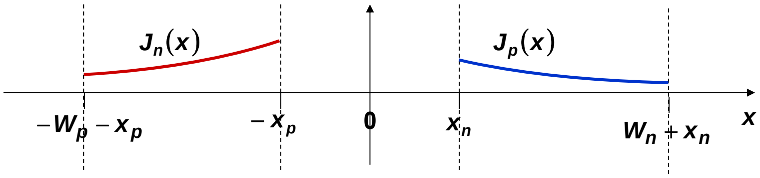
$$J_n(x) \approx J_n^{diff}(x) = q\, D_n \frac{\partial n'(x)}{\partial x}$$

$$J_n(x) = q n_i^2 \frac{D_n}{N_a L_n}\left(e^{\frac{qV_D}{KT}} - 1\right) \frac{\cosh\left(\frac{W_p + x_p + x}{L_n}\right)}{\sinh\left(\frac{W_p}{L_n}\right)}$$

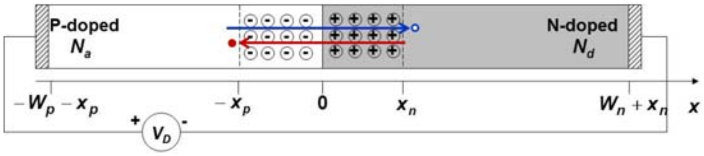
Hole current on the N-side:

$$J_p(x) \approx J_p^{diff}(x) = -q\, D_p \frac{\partial p'(x)}{\partial x}$$

$$J_p(x) = q n_i^2 \frac{D_p}{N_d L_p}\left(e^{\frac{qV_D}{KT}} - 1\right) \frac{\cosh\left(\frac{W_n + x_n - x}{L_p}\right)}{\sinh\left(\frac{W_n}{L_p}\right)}$$



Total Current Flow



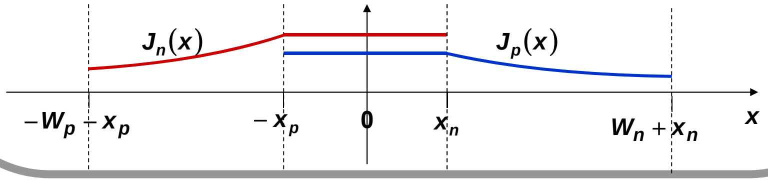
- The total current in steady state is the sum of electron and hole currents and is independent of position:

$$J_T = J_n(x) + J_p(x)$$

- So we can compute the total current in forward bias if we know the total electron current (drift and diffusion components) and the total hole current at any one location in the device – wherever that location might be.

- **Assumption:** the minority carrier diffusion currents inside the depletion region are constant (valid if there is no recombination in the depletion region), i.e.:

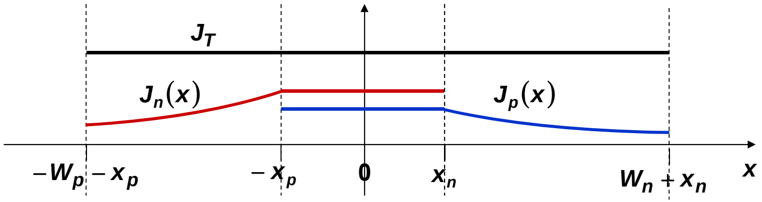
$$J_n(-x_p) = J_n(x_n) \qquad J_p(x_n) = J_p(-x_p)$$



Total Current Flow

- Now using: $J_T = J_n(x) + J_p(x)$

with "*x*" anywhere inside the depletion region, we can calculate the total current



$$J_n(-x_p) = q n_i^2 \frac{D_n}{N_a L_n}\left(e^{\frac{qV_D}{KT}} - 1\right)\coth\left(\frac{W_p}{L_n}\right)$$

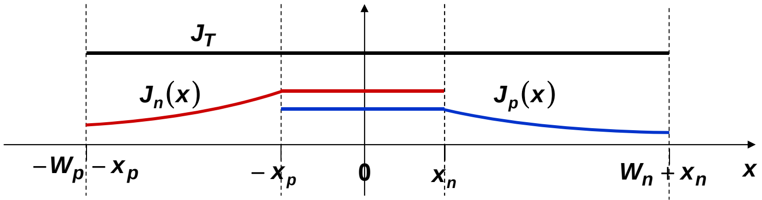
$$J_p(x_n) = q n_i^2 \frac{D_p}{N_d L_p}\left(e^{\frac{qV_D}{KT}} - 1\right)\coth\left(\frac{W_n}{L_p}\right)$$

$$J_T = J_n(x_n) + J_p(x_n) = J_n(-x_p) + J_p(x_n)$$

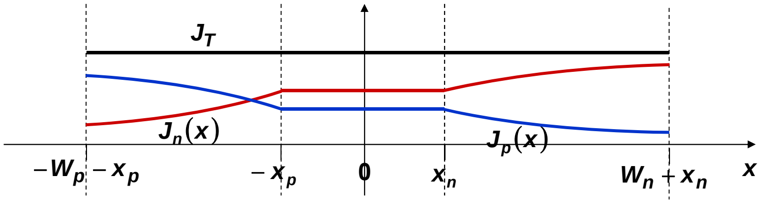
$$J_T = q n_i^2\left(\frac{D_n}{N_a L_n}\coth\left(\frac{W_p}{L_n}\right) + \frac{D_p}{N_d L_p}\coth\left(\frac{W_n}{L_p}\right)\right)\left(e^{\frac{qV_D}{KT}} - 1\right)$$

Majority Carrier Current Flow

- So far we have assumed that minority carrier current is entirely due to diffusion
- With the above assumption, we were able to calculate the total current

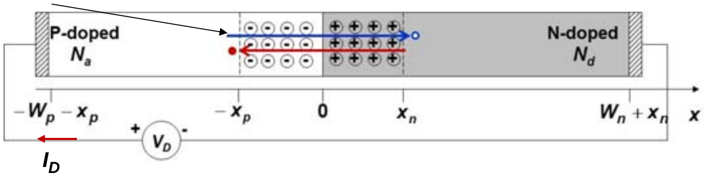


- Now we want to see how the majority carriers contribute to the total current
- Since we already know the total current everywhere, and the minority carrier current everywhere, the difference must be the majority carrier current



- The majority carriers flow by both drift and diffusion

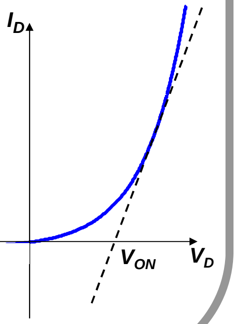
Current Flow in a PN Junction Diode



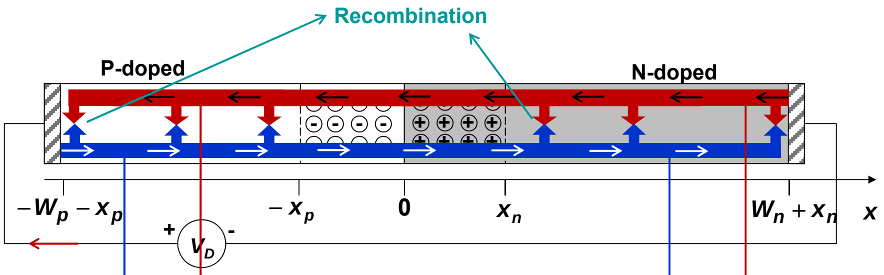
$$J_T = q n_i^2 \left(\frac{D_n}{N_a L_n} \coth\left(\frac{W_p}{L_n}\right) + \frac{D_p}{N_d L_p} \coth\left(\frac{W_n}{L_p}\right) \right) \left(e^{\frac{qV_D}{KT}} - 1 \right)$$

$$I_D = A J_T = I_o \left(e^{\frac{qV_D}{KT}} - 1 \right)$$

$$I_o = q n_i^2 A \left(\frac{D_n}{N_a L_n} \coth\left(\frac{W_p}{L_n}\right) + \frac{D_p}{N_d L_p} \coth\left(\frac{W_n}{L_p}\right) \right)$$



Carrier Flow Diagram in Steady State Forward Bias



Holes (majority carriers) flowing via drift and diffusion

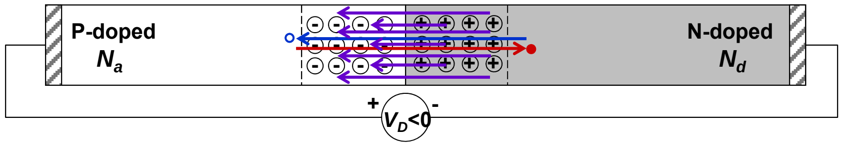
Holes (minority carriers) flowing via diffusion

Electrons (minority carriers) flowing via diffusion

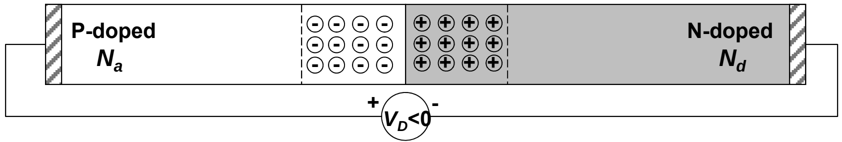
Electrons (majority carriers) flowing via drift and diffusion

Current Flow in a Reverse Biased PN Junction Diode: Balance of Drift Diffusion Currents is Broken

Drift current of both electrons and holes increases in reverse bias (because the junction electric field increases)



Diffusion current of both electrons and holes in approximately the same as in equilibrium



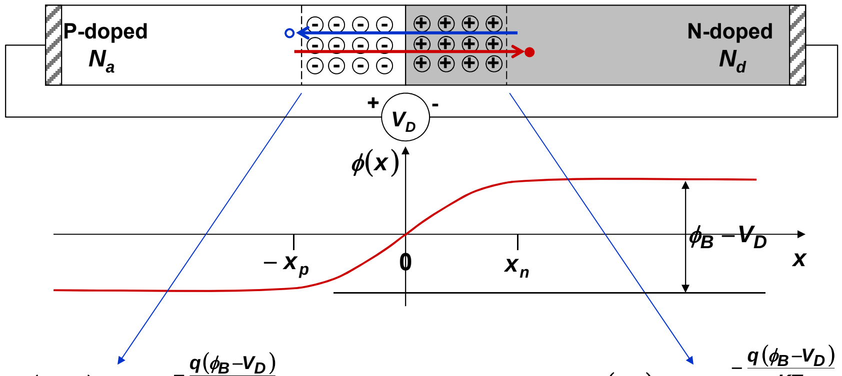
- Consequently, the total electron and hole currents are no longer zero; drift exceeds diffusion!!

- There is net current due to electron drift flow from the P-side to the N-side, and due to hole drift flow from the N-side to the P-side

- But the P-side dos not have very many electrons and the N-side does not have very many holes!!

A Reverse Biased PN Junction Diode

- **Minority carrier concentrations** at the edges of the depletion region in reverse bias:

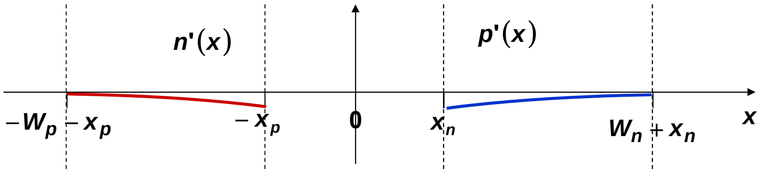


$$n(-x_p) = N_d\, e^{-\frac{q(\phi_B - V_D)}{KT}} = \frac{n_i^2}{N_a} e^{\frac{qV_D}{KT}}$$

$$p(x_n) = N_a\, e^{-\frac{q(\phi_B - V_D)}{KT}} = \frac{n_i^2}{N_d} e^{\frac{qV_D}{KT}}$$

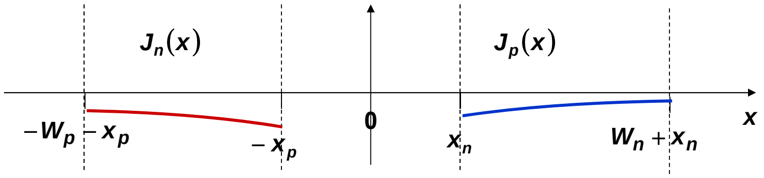
In reverse bias, the minority carrier concentrations decrease exponentially at the edges of the depletion region

Excess Minority Carrier Distributions in Reverse Bias



Same equations, as in the forward bias case, work in the reverse bias:

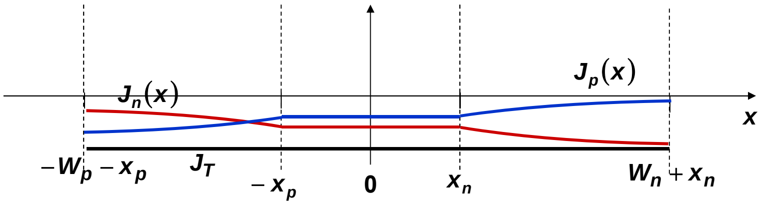
$$n'(x) = \frac{n_i^2}{N_a}\left(e^{\frac{qV_D}{KT}} - 1\right)\frac{\sinh\left(\frac{W_p + x_p + x}{L_n}\right)}{\sinh\left(\frac{W_p}{L_n}\right)} \qquad p'(x) = \frac{n_i^2}{N_d}\left(e^{\frac{qV_D}{KT}} - 1\right)\frac{\sinh\left(\frac{W_n + x_n - x}{L_p}\right)}{\sinh\left(\frac{W_n}{L_p}\right)}$$



Total Current Flow in Reverse Bias

- **Now using:** $J_T = J_n(x) + J_p(x)$

with "*x*" anywhere inside the depletion region, we can calculate the total current



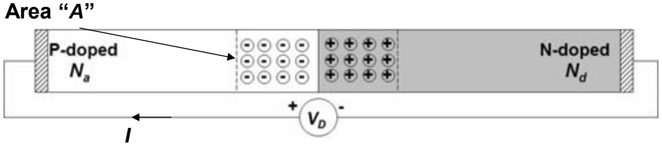
$$J_n(-x_p) = qn_i^2 \frac{D_n}{N_a L_n}\left(e^{\frac{qV_D}{KT}} - 1\right)\coth\left(\frac{W_p}{L_n}\right)$$

$$J_p(x_n) = qn_i^2 \frac{D_p}{N_d L_p}\left(e^{\frac{qV_D}{KT}} - 1\right)\coth\left(\frac{W_n}{L_p}\right)$$

$$J_T = J_n(x_n) + J_p(x_n) = J_n(-x_p) + J_p(x_n)$$

$$J_T = qn_i^2\left(\frac{D_n}{N_a L_n}\coth\left(\frac{W_p}{L_n}\right) + \frac{D_p}{N_d L_p}\coth\left(\frac{W_n}{L_p}\right)\right)\left(e^{\frac{qV_D}{KT}} - 1\right)$$

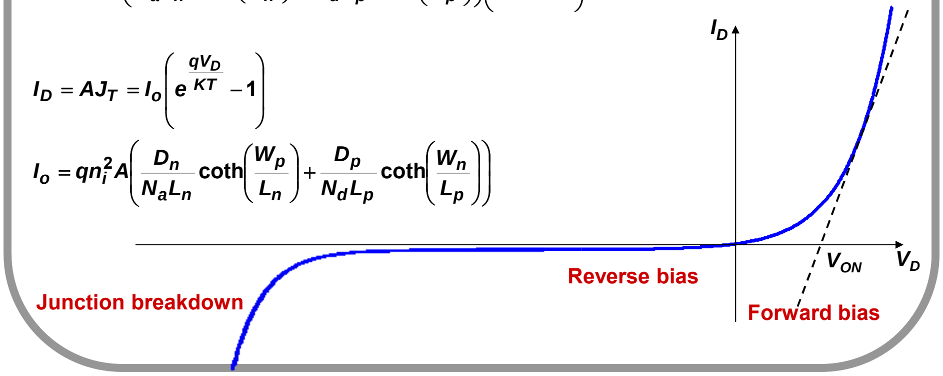
Current Flow in a PN Junction Diode



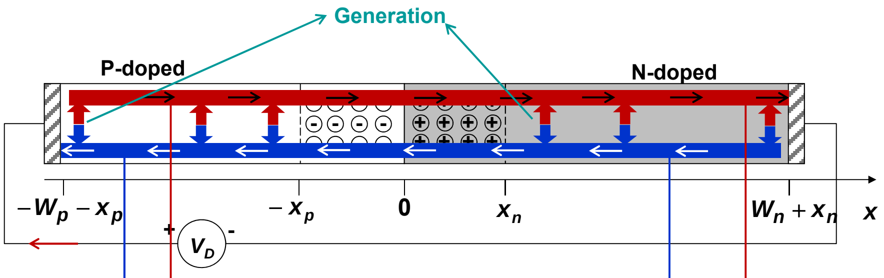
$$J_T = qn_i^2\left(\frac{D_n}{N_a L_n}\coth\left(\frac{W_p}{L_n}\right) + \frac{D_p}{N_d L_p}\coth\left(\frac{W_n}{L_p}\right)\right)\left(e^{\frac{qV_D}{KT}} - 1\right)$$

$$I_D = AJ_T = I_o\left(e^{\frac{qV_D}{KT}} - 1\right)$$

$$I_o = qn_i^2 A\left(\frac{D_n}{N_a L_n}\coth\left(\frac{W_p}{L_n}\right) + \frac{D_p}{N_d L_p}\coth\left(\frac{W_n}{L_p}\right)\right)$$



Carrier Flow Diagram in Steady State Reverse Bias



Holes (majority carriers) flowing via drift and diffusion

Holes (minority carriers) flowing via diffusion

Electrons (minority carriers) flowing via diffusion

Electrons (majority carriers) flowing via drift and diffusion