ECE 340
Lecture 27 : Junction Capacitance

Class Outline:
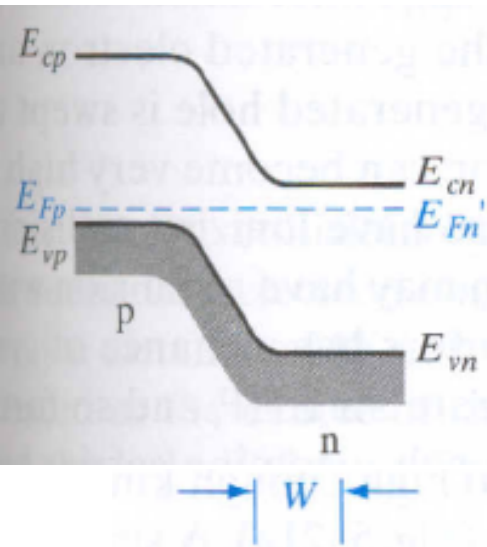
- Breakdown Review
- Junction Capacitance

Key Questions

- What types of capacitance are prevalent in p-n junctions?
- Which is important in forward bias?
- Which is important in reverse bias?
- How can I qualitatively describe them?

Zener Breakdown

Last time we talked about **zener breakdown**…

The **Zener effect** is the breakdown mechanism if the reverse bias required to force **breakdown occurs at low voltages**.

Consider the heavily doped p-n junction shown to the left and then apply a reverse bias to the junction.
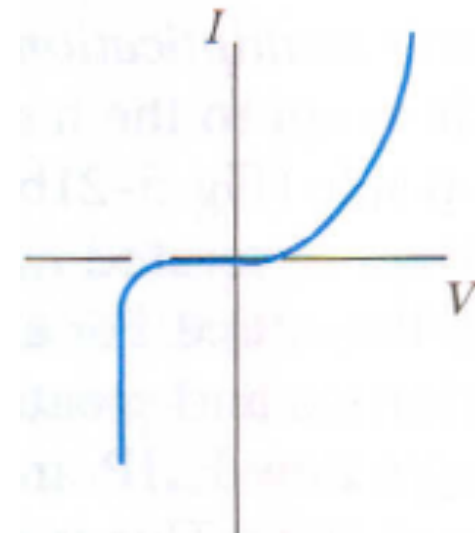
Reverse bias brings the conduction band very close to the valence band.

This brings many occupied states on the p-side into energetic alignment with vacant states on the n-side.
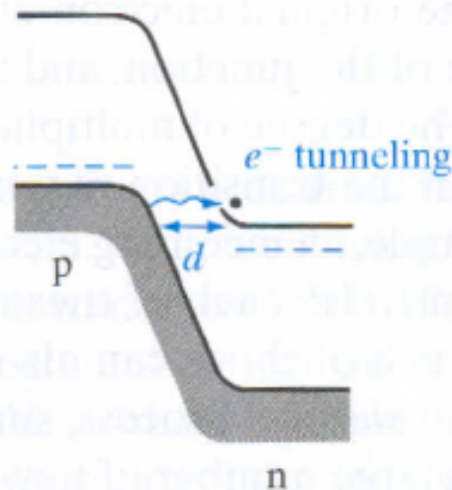
Electrons **tunnel** from the valence band to the conduction band giving rise to a reverse current.

This is the **Zener effect**.
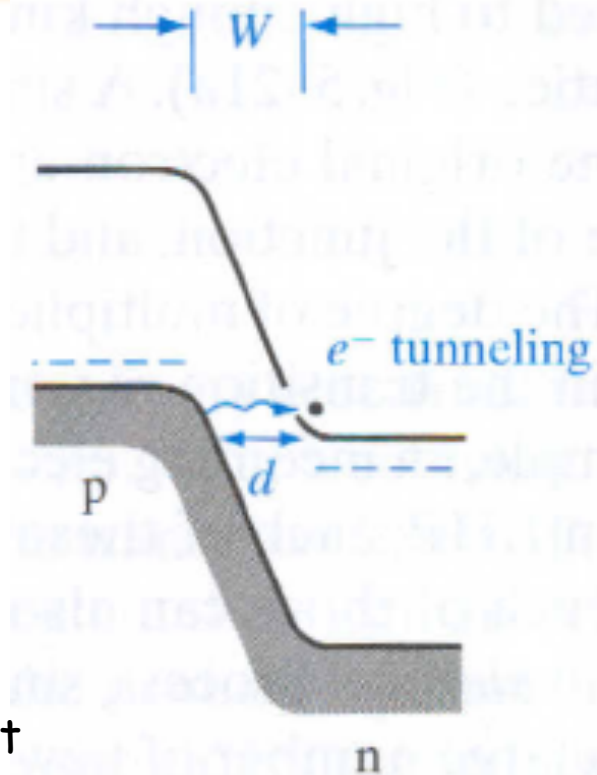
Zener Breakdown

So what do we need to cause **Zener breakdown**?

The basic requirements to drive a tunneling current are:

• A large number of electrons

• A large number of holes

• Separated by a narrow barrier of finite height.

Keep in mind…

• Tunneling depends heavily on the barrier width so we want to keep the junction sharp and doping high.

• This will ensure that the transition region W extends only a very short distance from each side of the junction.

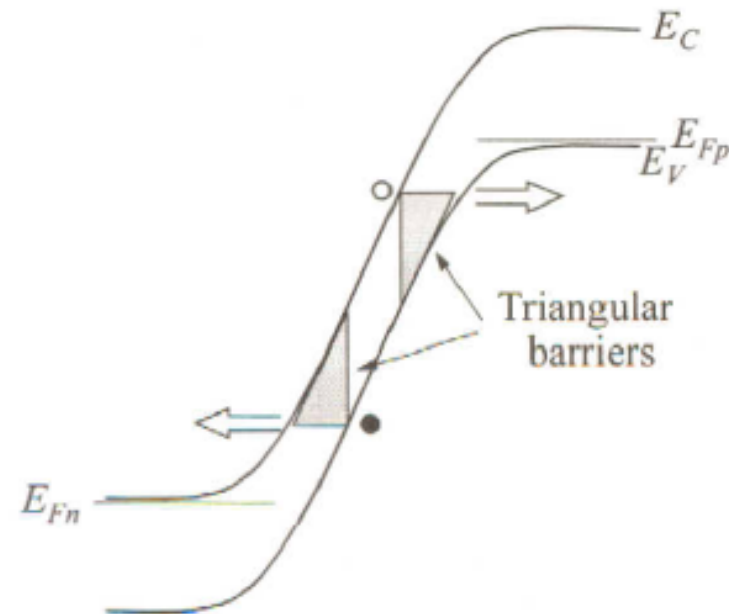• Failure to attain high doping or sharp junctions will result in no tunneling current.

Zener effect

Zener Breakdown

What else is important about the **Zener process**?

• As the reverse bias is increased the distance between the bands decreases.

• This is due to higher electric fields increasing the slopes of the bands.

• **We assume that the transition region, W, does not increase with bias which is valid for high doping and low voltage.**

What does the current look like...

$$J_t = \frac{\sqrt{2m^* q^3 \mathscr{E} V_R}}{4\pi^2 \hbar^2 \sqrt{E_g}} \exp\left(-\frac{4\sqrt{2m^* E_g^{3/2}}}{3q\mathscr{E}\hbar}\right)$$

Average electric field in junction

When does it happen...

• Occurs in Si for fields ~ 10^6 V/cm

• Must have high impurity concentrations

• Occurs in general for reverse biases of less than $4E_g/q$.
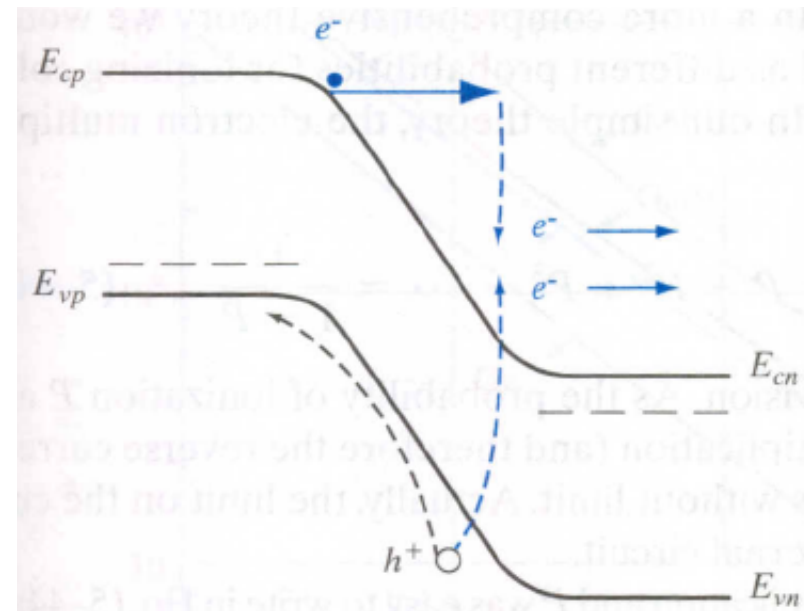
Avalanche Breakdown

For devices with **large breakdown voltages** or devices that are **lightly doped**, the major breakdown mechanism is **avalanche breakdown**.

In a lightly doped junction the tunneling is negligible due to the large distance between bands.

Instead, **breakdown is caused by impact ionization of the host atoms by energetic carriers.**

Normal lattice scattering can cause the creation of EHPs if the carrier being scattered has **sufficient energy**.

These single event scattering interactions are results in **carrier multiplication.**

Avalanche Breakdown

But we are not dealing with a **single collision**...

When the electron scatters it creates an EHP.

Each of these carriers then has a chance to be accelerated and collide with the lattice creating a new EHP.

This process may continue and is referred to as avalanche breakdown.

Let's make an **approximate** analysis of the physics...

• A carrier (either electron or hole) has some probability of having an ionizing collision with the lattice while being accelerated through the transition region, W.

• For n_{in} electrons entering from the p-side, there will be Pn_{in} ionizing collisions and an EHP generated for each collision.
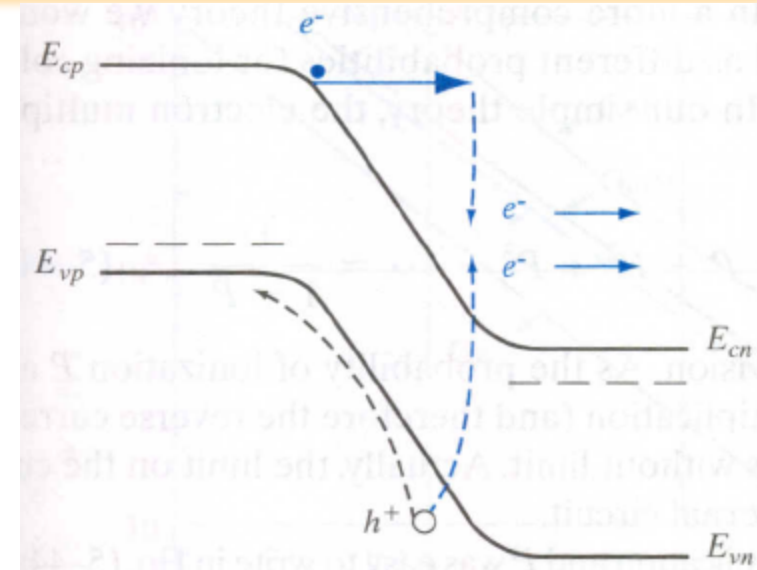
Avalanche Breakdown

The process continues…

After Pn_{in} collisions by the primary electrons, we have the primary plus the secondary electrons, $n_{in}(1 + P)$.

After a collision, each EHP moves a distance of W within the transition region. If the pair is created at the center, the electron will drift W/2 to n and the hole will drift –W/2 to p.

For $n_{in}P$ secondary electrons there will be $(n_{in}P)P$ collisions creating $n_{in}P^2$ tertiary pairs.

After n collisions we have: $n_{out} = n_{in}(1 + P + P^2 + P^3 + \cdots)$

Assume no recombination and equal probabilities of ionizing collisions, then the electron multiplication is…

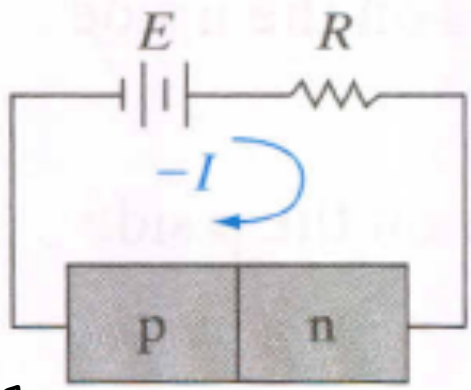$$M_n = \frac{n_{out}}{n_{in}} = 1 + P + P^2 + P^3 + \cdots = \frac{1}{1 - P}$$

Avalanche Breakdown

If the ionization probability approaches unity then the carrier multiplication becomes infinite!

So then what limits the current?　　　**External circuit**

But this was waaaaaay too easy...

•We assumed no recombination and equal ionization probabilities.

•We expect the probability to **increase with increasing electric field** so the **multiplication should depend on the reverse bias**...

We can determine an empirical relation...

$$M = \frac{1}{1 - (V/V_{br})^n}$$
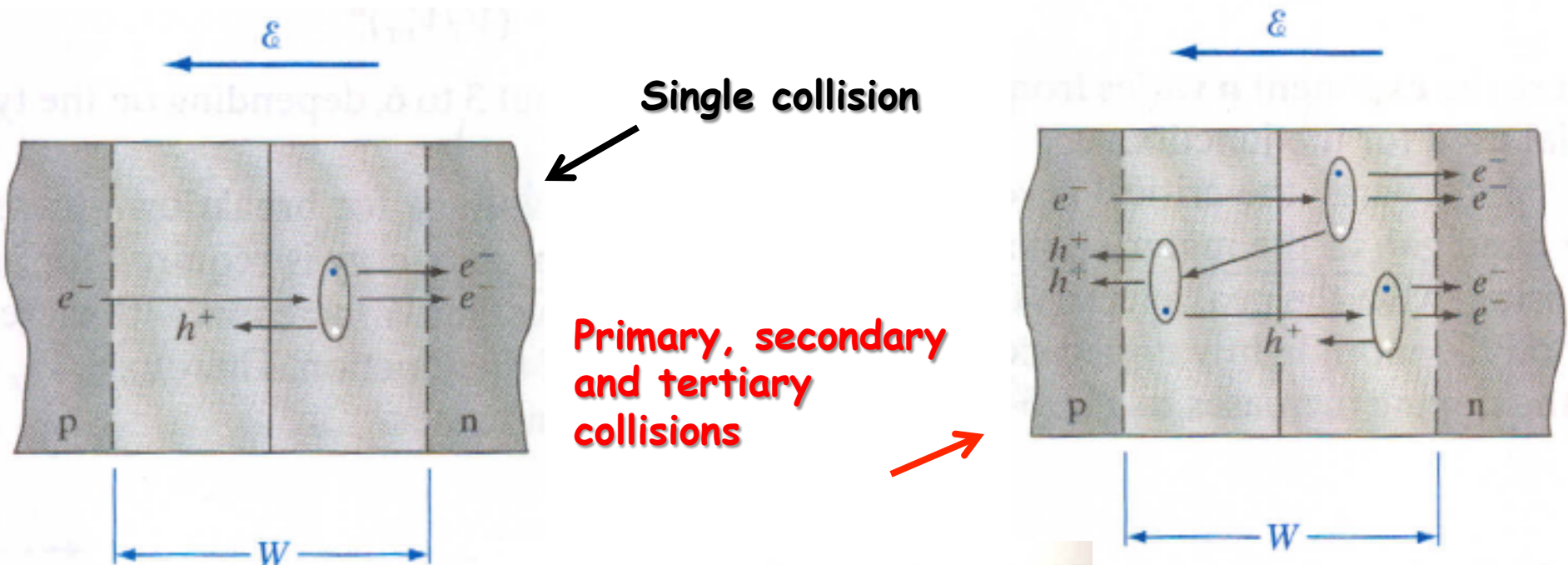
N is between 3-6 depending on the material.

In general:

•**Critical voltage for breakdown increases with bang gap.**
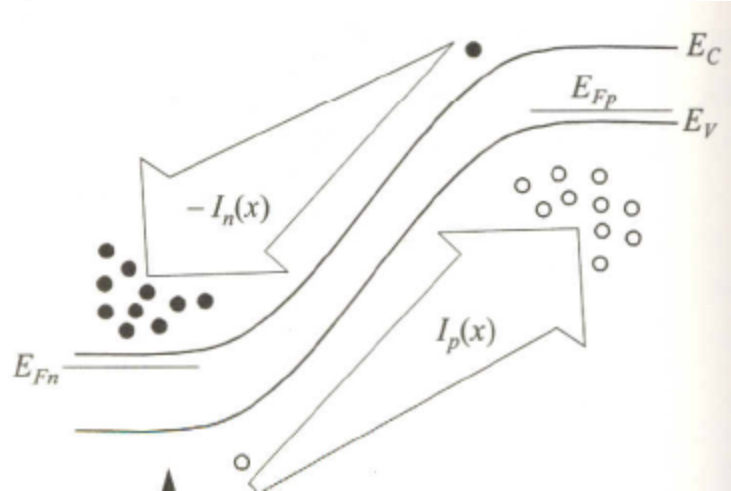•**Peak field in W increases with increased doping, thus Vbr decreases as doping increases.**

Avalanche Breakdown

In summary…

Single collision

Primary, secondary and tertiary collisions

Junction Capacitance

Basically, there are **two types of capacitance** associated with a p-n junction…

•The first is **junction capacitance**:

   •due to the **dipole in the transition region**.

   •Also called transition region capacitance or depletion layer capacitance.

   •**Dominates under reverse bias conditions**.

•The second is the **charge storage capacitance**:

   •Arises from the voltage lagging behind the current **due to charge storage effects**.
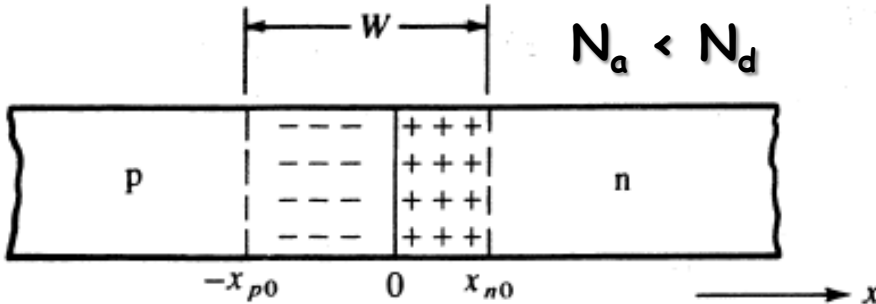
   •Also referred to as diffusion capacitance.

   •**Dominant when the junction is forward biased**.

Junction Capacitance

Junction capacitance is easy to visualize from the charge distribution…

•Uncompensated acceptor atoms on the p-side provide the negative charge.

•Uncompensated donor atoms on the n-side provide the positive charge.

$N_a < N_d$

Can we just use the expressions for parallel plate capacitance?

No

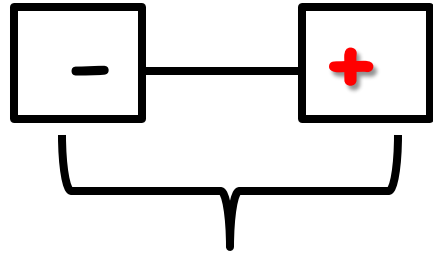We are forming a series of **dipoles at the junction**.

Why?

$$C = |Q/V|$$

Parallel plate capacitance

Assumes that we are dealing with a capacitor in which the charge is a linear function of the voltage.
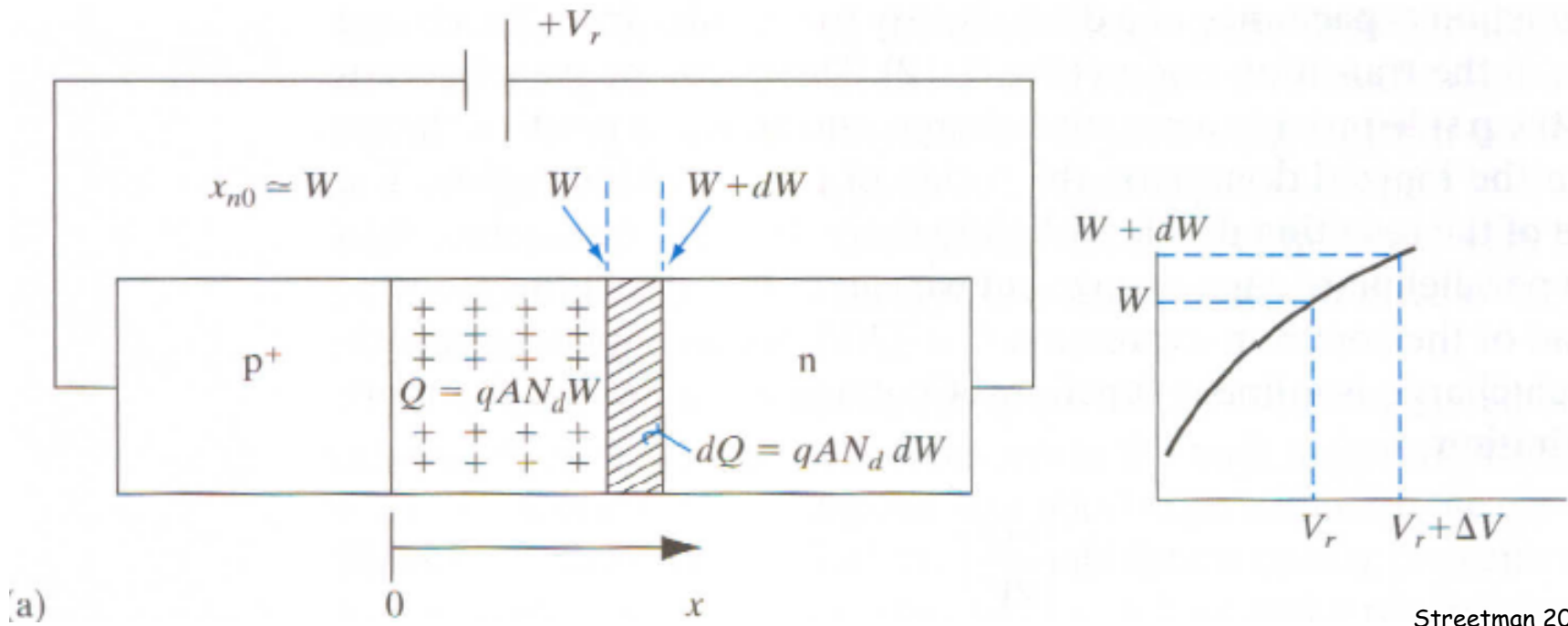
Junction Capacitance

So let's start from a more general definition and determine the **junction capacitance**...

Let's start with the general definition for the capacitance of a structure...

$$C = \left| \frac{dQ}{dV} \right|$$

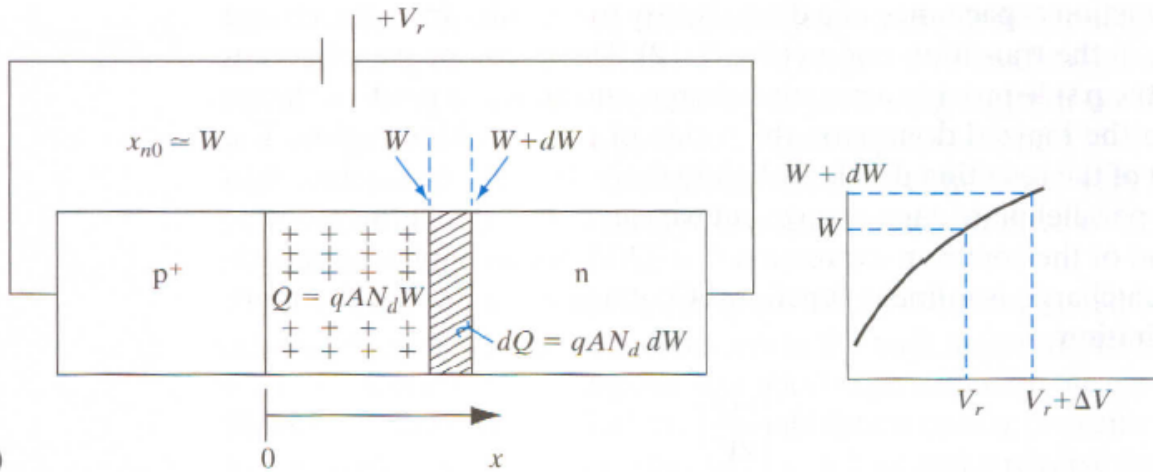Since we know the charge varies non-linearly with the applied voltage.

(a)

We know the equations for the variation of the **depletion width**…

In equilibrium…

$$W = \left[\frac{2\epsilon V_0}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$ (a)

And under applied bias…

$$W = \left[\frac{2\epsilon(V_0 - V)}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)\right]^{1/2}$$

$+V_r$

$x_{n0} \simeq W$ W $W + dW$

p^+ $+ + + +$ / $+ + + +$ / $+ + + +$ n
$Q = qAN_dW$
$dQ = qAN_d\,dW$

0 x

$W + dW$
W
V_r $V_r + \Delta V$

•The applied bias can either be positive or negative.

•Width of depletion region is increased for reverse bias and increased for forward bias.

•Uncompensated charge varies with depletion region width and applied voltage.

Now what? We already knew this…

Junction Capacitance

We can determine the **charge** from the doping concentrations and depletion region widths…

$$|Q| = qAx_{n0}N_d = qAx_{p0}N_a$$

Now we can relate the depletion region width to the individual widths…
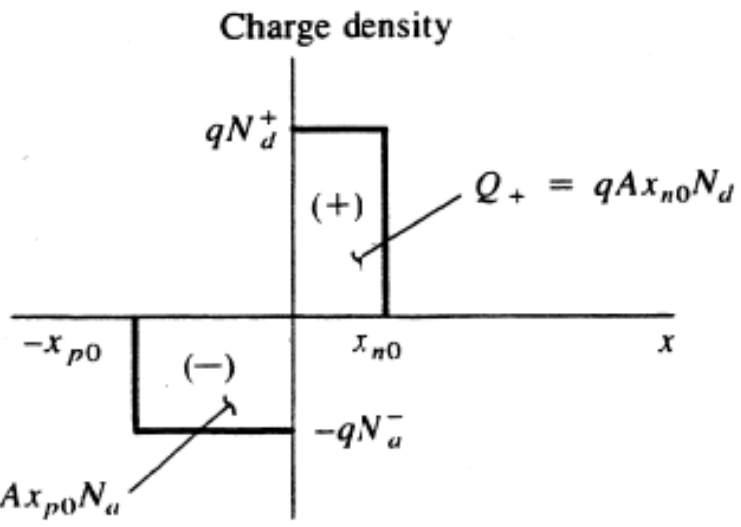
Charge density

$$x_{p0} = \frac{WN_d}{N_a + N_d} = \frac{W}{1 + N_a/N_d} = \left\{ \frac{2\epsilon V_0}{q} \left[\frac{N_d}{N_a(N_a + N_d)} \right] \right\}^{1/2}$$ N-type

$$x_{n0} = \frac{WN_a}{N_a + N_d} = \frac{W}{1 + N_d/N_a} = \left\{ \frac{2\epsilon V_0}{q} \left[\frac{N_a}{N_d(N_a + N_d)} \right] \right\}^{1/2}$$ **P-type**

So we have…

$$x_{n0} = \frac{N_a}{N_a + N_d}W$$ $$x_{p0} = \frac{N_d}{N_a + N_d}W$$ Now combine the equations…

Junction Capacitance

When combine the equations result in the charge on either side of the dipole…

Total charge:

$$|Q| = qA\frac{N_d N_a}{N_d + N_a}W = A\left[2q\epsilon(V_0 - V)\frac{N_d N_a}{N_d + N_a}\right]^{1/2}$$

Clearly a non-linear function of the applied voltage. Now apply the definition of the capacitance…

Junction Capacitance:

$$C_j = \left|\frac{dQ}{d(V_0 - V)}\right| = \frac{A}{2}\left[\frac{2q\epsilon}{(V_0 - V)}\frac{N_d N_a}{N_d + N_a}\right]^{1/2}$$

• The junction capacitance is a voltage-variable capacitance.

• It is used in devices called varactors which are useful in radios and filtering devices.

Junction Capacitance

When we use the expression for the junction capacitance and the depletion region width, we can obtain a familiar form for the capacitance.

$$C_j = \epsilon A \left[\frac{q}{2\epsilon(V_0 - V)} \frac{N_d N_a}{N_d + N_a} \right]^{1/2} = \frac{\epsilon A}{W}$$

Looks like a parallel plate capacitor with the depletion width acting as the separation between plates...
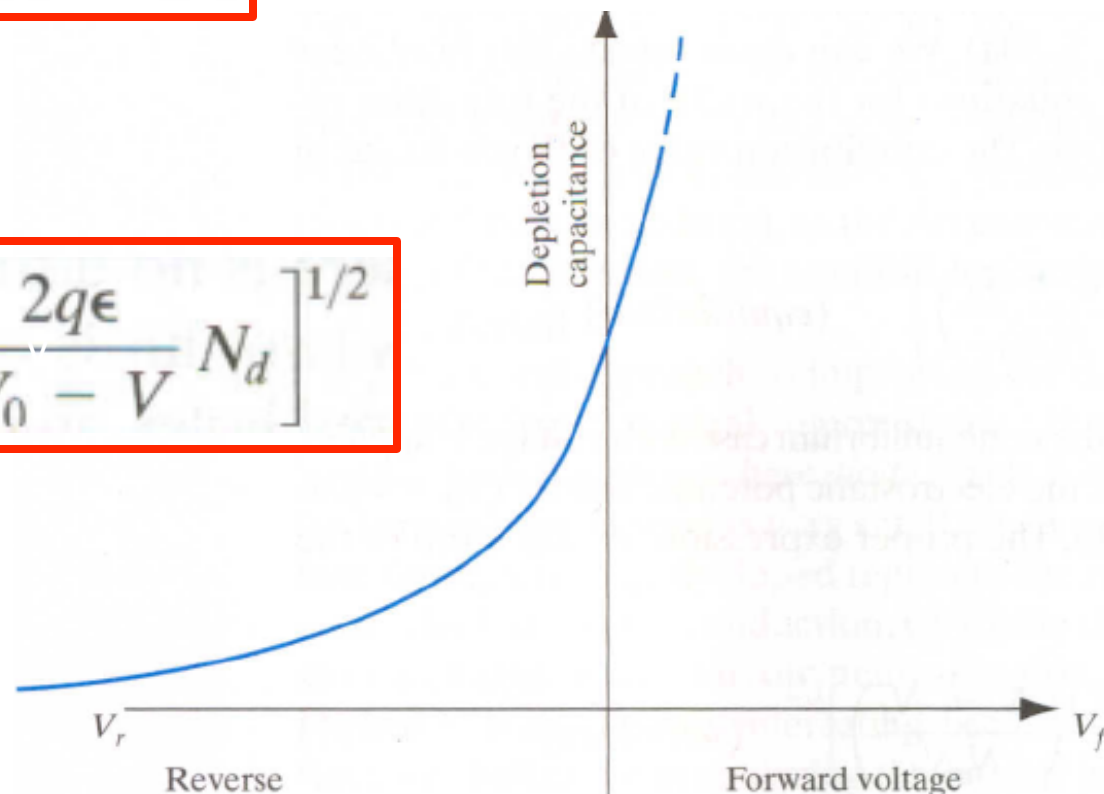
What about for a p+-n junction?

- $N_A \gg N_D$

- $x_{N0} = W$

- $x_{P0} = 0$

$$C_j = \frac{A}{2} \left[\frac{2q\epsilon}{V_0 - V} N_d \right]^{1/2}$$

So if we apply a bias much larger than the contact potential, we can determine the n-side doping.

Depletion capacitance vs. voltage. V_r Reverse, Forward voltage V_f

Junction Capacitance

Under forward bias conditions, the charge storage or diffusion capacitance dominates...
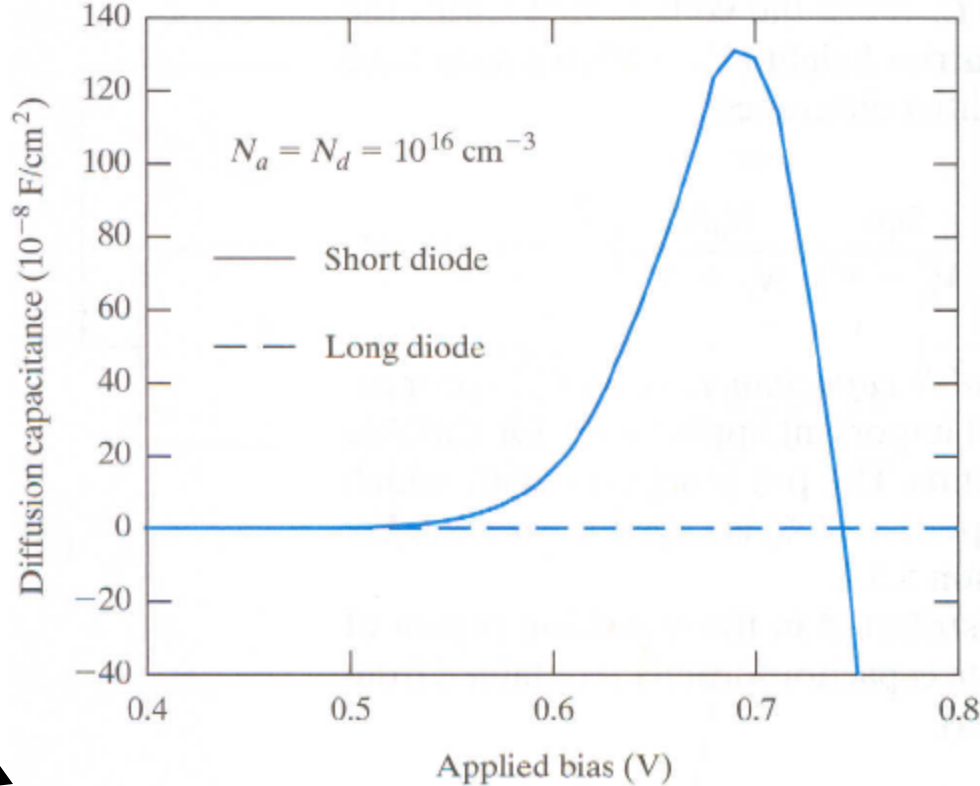
What affects the diffusion capacitance?
- Time-dependent currents.
- Boundary conditions.

We must specify where the relevant voltage drops occur and where the stored charges are extracted.

- For long junctions (longer than the diffusion lengths) there is no diffusion capacitance. (Laser diodes, short lifetime)

- For short junctions, the diffusion capacitance due to stored holes on the n-side (electrons on the p-side) (silicon p-n)

$N_a = N_d = 10^{16} \, \text{cm}^{-3}$

Diffusion capacitance $(10^{-8} \, \text{F/cm}^2)$

Applied bias (V)

—— Short diode

– – – Long diode

$$G_s = \frac{dI}{dV} = \frac{qAL_p p_n}{\tau_p} \frac{d}{dV}(e^{qV/kT}) = \frac{q}{kT}I$$

$$C_s = \frac{dQ_p}{dV} = \frac{1}{3}\frac{q^2}{kT}Acp_n e^{qV/kT}$$