Lecture 20: PN diodes (forward bias), small signal model, BJTs

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Context

This lecture will discuss

- Diode Currents in forward and reverse bias (6.1-6.3)
- Small signal models for diodes

And if we have some time, we will start:

- BJTs (Bipolar Junction Transistors)

Reading

- The midterm covers chapters 1-4, plus phasors, linear circuits, and Bode plots
- Today we will be covering the material in chapter 6, PN diodes
- Wednesdays lecture will be review, example problems, and answers to any last minute questions.
- After the midterm, we will be covering chapter 7, Bipolar Junction Transistors (BJT's)

Lecture Outline

- Diode applications
- Forward currents in diodes
- Diode Small Signal Model
- Diode Charge Storage (6.4.4)
- Types of diodes
- The BJT (7.1)
- BJT Physics (7.2)

Diode applications

- Varactor Tuner
- Rectification
- Envelope Detector (AM demodulator, for instance)
- Phase modulator
- Voltage reference/Limiters/Regulators
- Diode Clamp
- ESD (electrostatic discharge) protection circuits
- Voltage multipliers (doublers, etc)

More Diode applications

- High frequency up-converter mixers
- Down-conversion mixers
- Tunnel diode oscillator
- GUNN diode oscillator
- Light emitting diodes
- Laser diodes
- Light detectors
  - Solar cells
  - PIN diodes
  - Avalanche diodes

Minority carrier injection

- In the last lecture, we discussed the ideal diode equation, and how it treats the minority carriers as if they always make it all the way across the junction, but then disappear once they have gotten across (we didn't account for the possibility that they wandered back, for instance)
- Now, we will more accurately account for the transport of the minority carriers.

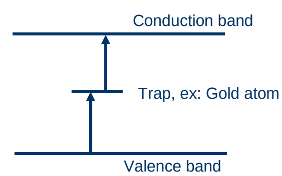
Including:

- Diffusion
- Recombination/Generation

Generation and Recombination

- The processes which cause the electron and hole populations to come into equilibrium with each other are rather slow in silicon, so we can make some approximations:
- Generation and recombination will be neglected inside the depletion zone, for one.

Sidebar:
It is possible to add atoms to silicon which greatly enhance generation and recombination, such as gold and copper. The are called traps. Except for very pure silicon, impurities will dominate carrier recombination



Minority Carriers at Junction Edges

minority carrier concentration at boundaries of depletion region increase as barrier lowers. This is called minority carrier injection. If we neglect generation and recombination inside the depletion regions, the number of carriers function is approximately the density of carriers on the other side of the barrier at the *equivalent energy*:

$$\frac{p_n(x = x_n)}{p_p(x = -x_p)} = \frac{\text{(minority) hole conc. on n-side of barrier}}{\text{(majority) hole conc. on p-side of barrier}} = e^{-(Barrier\ Energy)/kT}$$

$$\frac{p_n(x = x_n)}{N_A} = e^{-q(\phi_B - V_D)/kT}$$

The minority carrier concentrations at the edges of the depletion region will then be given by:

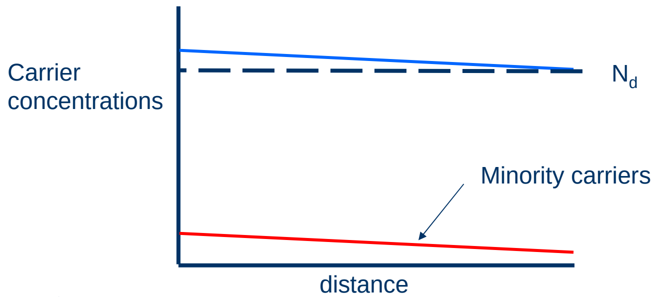
$$p_n(x = x_n) = N_A e^{-q(\phi_B - V_D)/kT}$$

$$n_p(x = -x_p) = N_D e^{-q(\phi_B - V_D)/kT}$$

Note: N_A and N_D are the majority carrier concentrations on the *other* side of the junction, with the assumption that $p_n << N_D$ and $n_p << N_A$

Quasi-Neutrality

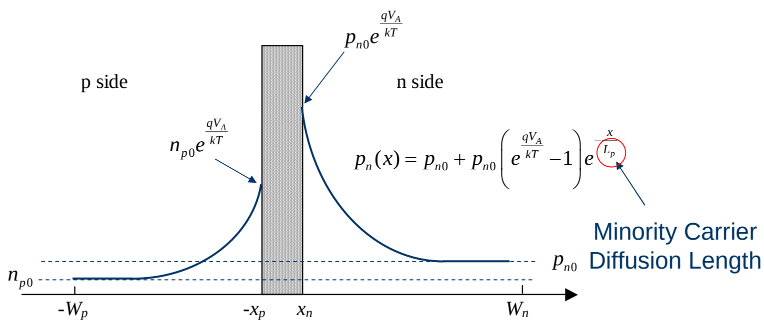
- Since the regions outside the depletion regions are going to be very close to electrically neutral (called quasi-neutrality) the number of majority carriers will increase slightly as well (slightly because there are usually many more majority carriers than minority carriers anyway)



Diffuse and Recombine

- Once the minority carriers have been injected across the depletion region, they will diffuse, and they will recombine.
- They will recombine, because now $pn > n_i^2$ and since recombination is proportional to pn, it will now cause carriers to recombine at a rate faster than they are generated.
- They will also diffuse into the other side, because there are more of them (the minority carriers) at the edge of the depletion region than there are further in.

Excess injected minority carriers



Once the minority carriers are injected into the other side of the junction, the minority carrier concentration in the bulk region for forward bias is a decaying exponential.

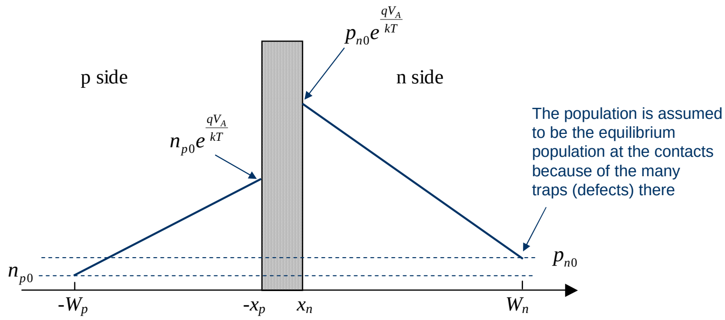
Ambipolar diffusion

- The diffusion constant for minority carriers is complicated by the fact that the minority carriers are dragged on (or pulled!) by the majority carriers, in a mechanism called ambipolar diffusion
- There is a small E field which keeps the excess holes and electrons together.
- The ambipolar diffusion constant for minority carriers comes out to be the diffusion constant for the *other*, *majority* carriers, in the cases where the majority carriers greatly outnumber the minority carriers. In other words, minority holes diffuse with D_n and electrons with D_p!
- The minority diffusion length is a function of the ambipolar diffusion constant for the minority carriers, as well as the variability in the lifetime, etc. We will just take it to be a number!

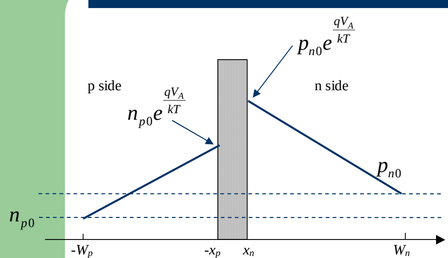
Steady-State Concentrations

$$L_{n,p} >> W_{n,p}$$

In silicon, it is easy for the diffusion lengths to be much longer than the distance to the contacts, if none of the diffusing holes and electrons recombine until they get to the contacts → get a linear concentration gradient.



Diode Current Densities



$$\frac{dn_p}{dx}(x) \approx \frac{n_{p0}e^{\frac{qV_A}{kT}} - n_{p0}}{-x_p - (-W_p)}$$

$$n_{p0} = \frac{n_i^2}{N_a}$$

Under this linear approximation, we can calculate the current due to the holes diffusing into the N side, and the electrons diffusing into the P side. Notice that we are using the electron diffusion constant for the minority holes, and visa versa.

$$J_n^{diff} = qD_n \left.\frac{dn_p}{dx}\right|_{x=-x_p} \approx q\frac{D_n}{W_p} n_{p0}\left(e^{\frac{qV_A}{kT}} - 1\right)$$

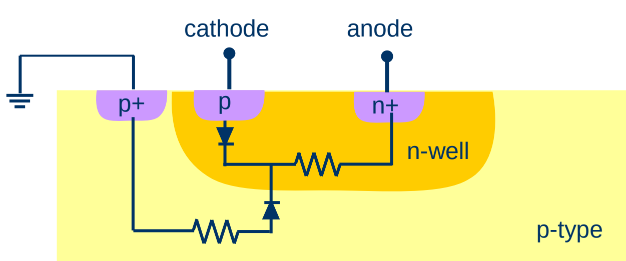
$$J_p^{diff} = -qD_p \left.\frac{dp_n}{dx}\right|_{x=x_n} \approx -q\frac{D_p}{W_n} p_{n0}\left(1 - e^{\frac{qV_A}{kT}}\right)$$

Net forward current (short device)

The total current is the sum of the currents carried by the minority carriers on each side:

$$J^{diff} = qn_i^2\left(\frac{D_p}{N_d W_n} + \frac{D_n}{N_a W_p}\right)\left(e^{\frac{qV_A}{kT}} - 1\right)$$

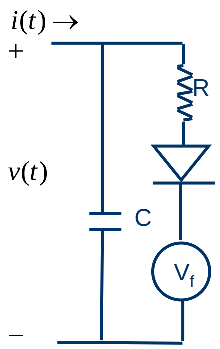
Fabrication of IC Diodes



- Start with p-type substrate
- Create n-well to house diode
- p and n+ diffusion regions are the cathode and anode
- N-well must be reverse biased from substrate
- Parasitic resistance due to well resistance

Diode large signal model

- It is inconvenient to use the exponential current model in a circuit, so a diode is often modeled with an approximation. One possible large signal model is:



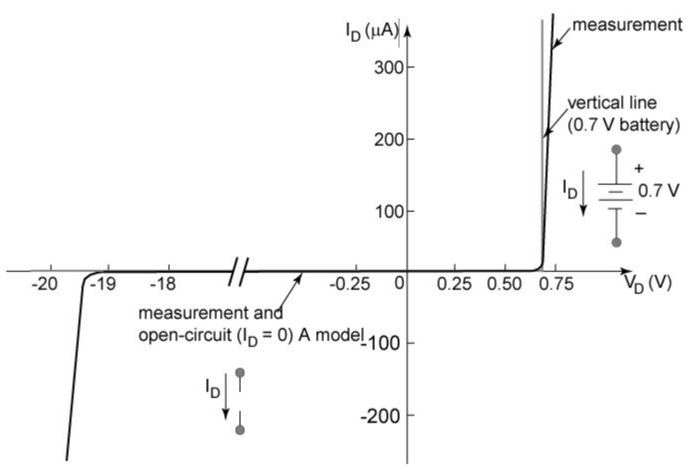
The resistance R is the forward resistance at large currents

The forward voltage drop Vf is about .7 volts because that is about where the forward current goes from negligible to very large!

The diode in the model is a perfect diode, perfect conductor when forward biased, open when reverse biased

The choice of capacitance C depends on which is most important, the capacitance under forward or reverse bias conditions.

Large-Signal Model



Diode Small Signal Model

- The I-V relation of a diode can be linearized

$$I_D + i_D = I_S\left(e^{\frac{q(V_d+v_d)}{kT}} - 1\right) \approx I_S e^{\frac{qV_d}{kT}} e^{\frac{qv_d}{kT}}$$

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots$$

$$I_D + i_D \approx I_D\left(1 + \frac{qv_d}{kT} + \cdots\right)$$

$$I_D = I_S e^{\frac{qV_d}{kT}} \qquad i_D \approx \frac{qI_D}{kT} v_d = g_d v_d$$

The small signal model of a diode in forward bias is a resistance in parallel with a capacitance. In reverse, it is just a capacitance. (the reverse leakage current is constant, thus no contribution to small signal)

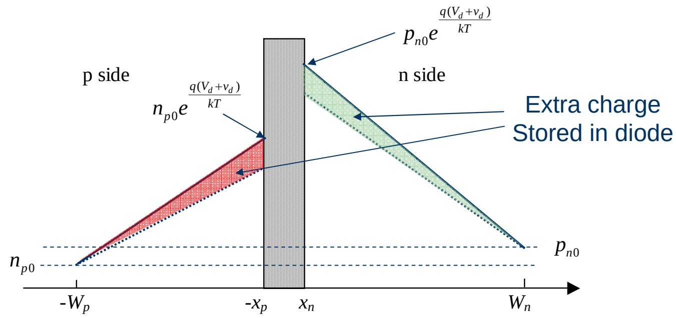
Forward Diode Capacitance

- We have already seen that a reverse biased diode acts like a capacitor since the depletion region grows and shrinks in response to the applied field. the junction capacitance in *forward bias* is given by

$$C_j = A\frac{\varepsilon_S}{X_{dep}} \approx 1.4 C_{j0}$$

- But another charge storage mechanism comes into play in forward bias:
- Minority carriers injected into p and n regions must be built up, which takes current×time, and they must also be extracted as the voltage is lowered.
- The effect is additional charge is stored in diode

Charge Storage

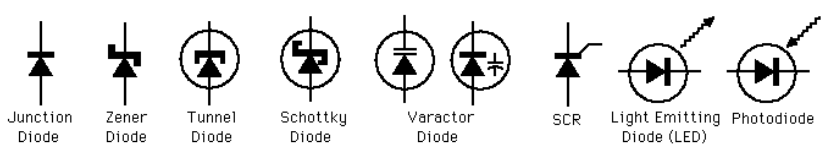


- Increasing forward bias increases minority charge density
- A detailed analysis yields: $C_d = \frac{1}{2}\frac{qI_d}{kT}\tau_T$

Time to cross junction (or minority carrier lifetime)

$$\rightarrow \quad C_d = \frac{1}{2} g_d \tau_T$$

Symbols



The PIN Diode

- The PIN diode has heavily doped p-type and n-type regions separated by an intrinsic region. When reverse biased, it acts like an almost constant capacitance and when forward biased it behaves as a variable resistor.
- The built in field stretches over the intrinsic region, causing minority carriers to be swept out by the field over a larger volume. It is often used for light detectors, and some high efficiency solar cells.

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Schottky Diode

- Metal junction with a (typically) n-type semiconductor.
- Mainly used in high frequency circuits or high speed digital circuits.
- There are no holes (minority carriers), so the conduction quickly stops upon change to reverse bias.
- Schottky diodes find application as rectifiers for high frequency signals.

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Step Recovery Diode

- In the step-recovery diode the doping level is gradually decreased as the junction is approached.
- This reduces the switching time since the smaller amount of stored charge near the junction can be released more rapidly when changing from forward to reverse bias.
- The forward current can also be established more rapidly than in the ordinary junction diode.
- This diode is used in fast switching applications, such as high frequency mixers

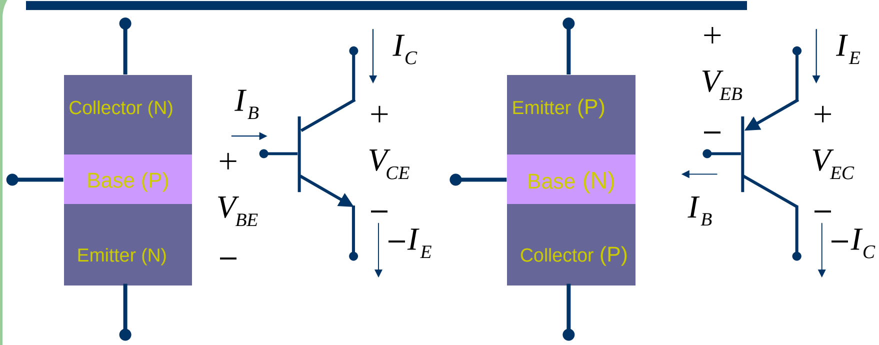
Zener diodes

- Diodes which are called Zener diodes do not use the Zener effect (tunneling) but are avalanche breakdown devices.
- With the application of sufficient reverse voltage, a p-n junction will experience a rapid avalanche breakdown and conduct current in the reverse direction.
- Under a high electric field, high energy carriers can cause the generation of more electron hole pairs, and the subsequent collisions quickly become an avalanche. When this process is taking place, very small changes in voltage can cause very large changes in current.
- Zener diodes can be made which break down at precise voltages from about 4 volts to several hundred volts. The avalanche breakdown occurs at a particular field strength, so the high field region just needs to be the correct length
- Avalanche breakdown does not damage the diode as long as power dissipation limits are not exceeded.

Bipolar Junction Transistor (BJT)

- A BJT is physically just two back to back PN diodes, with three contacts, but the current between the emitter and the collector is a *minority carrier current in the base.*
- Essentially, a forward biased diode is used to create a minority current, most of which then goes all the way across to the depletion region of another, reverse biased diode.
- The geometry can be such that almost all the current goes across to the second diode, so that the controlling electrode doesn't have to supply much of the current, maybe 1:100 to 1:400

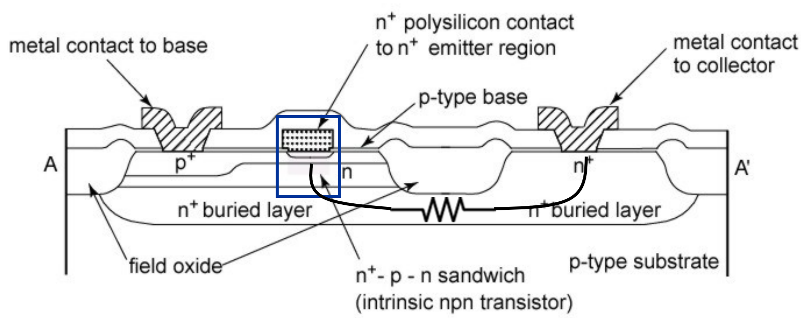
Ideal BJT Structure



- NPN or PNP sandwich (Two back-to-back diodes)
- How does current flow? Minority carriers diffusing across the base, which is thin so most go across
- A good BJT satisfies the following $I_C \approx -I_E$

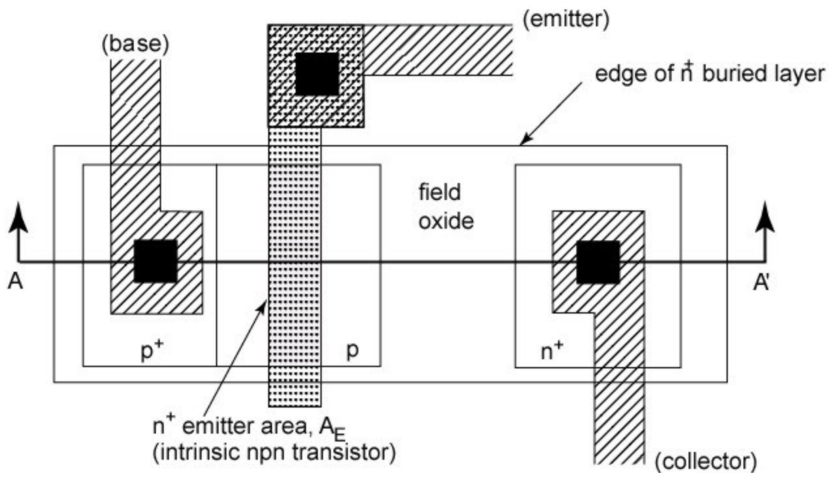
$$I_C >> I_B \qquad I_C \approx I_S e^{\frac{qV_{BE}}{kT}}$$

Actual BJT Cross Section



- Vertical npn sandwich (pnp is usually a lateral structure)
- n+ buried layout is a low resistance contact to collector
- Base width determined by vertical distance between emitter diffusion and base diffusion

BJT Layout

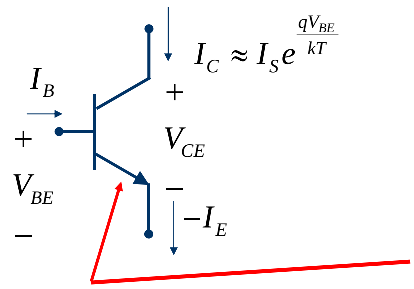


- Emitter area most important layout parameter
- Multi-finger device also possible for reduced base resistance

BJT Schematic Symbol

$$I_C = \beta I_B$$

$$I_C \approx I_S e^{\frac{qV_{BE}}{kT}}$$

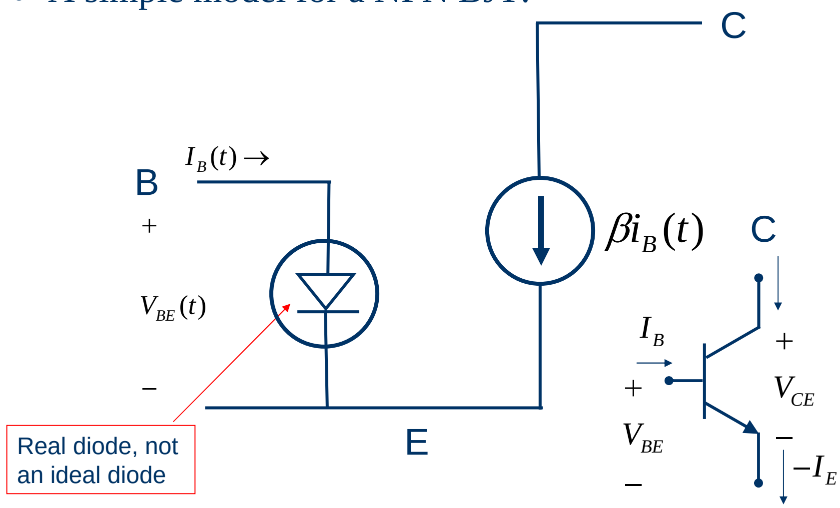


The arrow on the symbol shows the controlling diode.

- Collector current is control by base current linearly, a typical value would be $\beta = 100$, because only one in 100 electrons would stop in the base instead of making it across to the collector
- Collector is controlled by base-emitter voltage exponentially

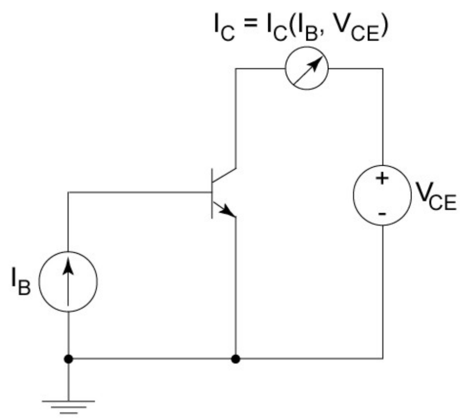
Simple NPN BJT model

- A simple model for a NPN BJT:



BJT Collector Characteristic

- Ground emitter
- Fix V_{CE}
- Drive base with fixed current I_B
- Measure the collector current



Collector Characteristics (I_B)