ELEC 424 Lesson Plan
July 22, 2008

Objective – fold up Chapter 5, Streetman

Begin at 5.3.2 – Quantitative Derivation of the Diode Equation

Remembering 5.3.1

Project figure 5-13

V_o is contact potential
V_f lowers the built in potential barrier
V_r increases the built in potential barrier

<u>Majority</u> carriers will <u>diffuse</u> from the majority side to become minority carriers in the opposing side. More can make the jump if the barrier is lower.

<u>Minority</u> carriers will <u>drift</u> with the E-field from the minority side to become a fraction of the majority on the other side. This does not depend on barrier magnitude, but rather on the quantity of minority carriers to begin with.

<u>Total current is composed of Diffusion Current and Drift Current</u>

Interestingly Diffusion Current is a function of external bias

> As a forward bias lowers the contact potential of the junction, more diffusion results

BUT, drift current is relatively insensitive to external bias because

> The thermally generated EHPs within a single diffusion length of the transition region are relatively constant. While bias does not increase this population, photons or thermal energy can.
>
> The diode equation results where the current increases exponentially with forward bias but remains fairly flat in the reverse direction.
>
> I_0 is called "generation current" since it is dependent on the generation of EHPs

Discuss on white board in terms of figures on pp 50-51 of Neudeck, Volume II

Bottom line on section 5.3.2 is that equation 5-36 and 5-25 (from 5.3.1) are the same. Remember that V can be either $V_{forward}$ or $-V_{reverse}$. <u>The polarity of V is important to making the equation work.</u>

Draw figure 5-17 on the board in pieces. Point out that the minority carrier current on one side stems from majority on the other. No change in transition region.

5.3.3 is 5.3.2 for reverse bias. Minority carriers deplete at the edge of the transition region. This is called <u>carrier extraction</u> as opposed to <u>carrier injection</u> in 5.3.2

5.4 <u>Reverse Breakdown</u>

Non destructive if current limited.

Can be of Zener or Avalanche in type.

Zener
Heavily doped junction results in a band diagram with the conduction band bottom in the n side being lower than the valance band top on the p side. Electrons can cross the gap in this "field ionization". Requires a large number of electrons separated from a large number of empty states by a relatively narrow energy band. Means this must be a rather abrupt junction, with neither side too lightly doped.

Zener – abrupt heavily doped junction, relatively low voltage.

Avalanche – caused by impact ionization with a carrier multiplication effect.

DRAW figure 5-21 b and c, pp 199

<u>5.4.3</u>

You learned this in electronics, but there are material characteristics at play.

For example a high bandgap material will have less thermally generated EHPs at a given temperature and therefore less leakage (generation) current … a good thing.

BUT that same material will have more bulk resistivity with shallower slope (less ideality) to the forward IV characteristic.

For another example light doping increases the avalanche breakdown voltage but also imparts slope (as above) to the forward IV characteristic.

Geometry can help…guard rings and beveled junctions are discussed in figure 5.24 and 5.25.

Power handling is heavily packaging dependent.

5.5.1 <u>Time Variation</u>

AC analysis is important as a primary use of PN junctions is to create switching devices.

The transition region is a dielectric and stores charge just like a capacitor. Charge lags current (current flows into a capacitor until charge builds up to stop it, and current flows out of a capacitor until charge is exhausted), or as shown in 5-47

$$I(t) = Q_p(t)/\tau_p + d\, Q_p(t)/dt$$

For a long n region when hole current is injected at $x_n = 0$ and is 0 at $x_n = \infty$

$Q_p(t)/\tau_p$ is the recombination term, τ_p is known as carrier lifetime
$d\, Q_p(t)/dt$ is the buildup or depletion of charge

5-47 is solved by Laplace transforms for specific stimuli. 5-48 is the solution for a common case, the step function.

$$Q_p(t) = I\, \tau_p e^{-t/\tau_p}$$

Look at figure 5-27, exponential decay of charge after current ceases.

Note that with no additional charge available after I = 0, so the excess carrier concentration (δ_p in this case) must be flat at $x_n = 0$. This makes an exact solution of V(t) difficult so an exponential relaxation curve is used to yield a quasi steady state solution [5-53] on p 208.

<u>5-53 shows us that junction voltage does not and cannot turn off instantly…therefore switching speed limitations. This stored charge dependence is another thing for solid state device designers to contend with. Narrow junctions switch faster, but are difficult to make and are more E-field sensitive. No free lunch. Sometimes fast switching devices are made by purposely adding impurities, such as gold, to act as recombination centers.</u>

5.5.2 <u>Reverse Recovery Time</u>

So…the PN junction cannot just turn off, but has transient voltage decay.

Therefore when the bias across a diode is reversed, the current cannot immediately drop to the reverse saturation (generation current) level, but instead falls through a period of $-V/R$ (ohmic) behavior into an exponential decay toward $-I_0$. The duration of the ohmic region is dependent on carrier lifetime and is called storage delay time (t_{sd}). <u>Discuss figure 5-29, p 210.</u>

5.5.3 <u>Switching Diodes</u>

Rectifiers have minimal R_f to reduce power losses and are also designed for low reverse currents. A switching application may require different optimization. We just saw how τ, *lifetime* affects switching, so diodes doped to shorten lifetimes might be good for switching applications. 10^{14} gold atoms/cm^3 can reduce τ by a factor of 10, and 10^{15} gold atoms/cm^3will bring it down another order of magnitude.

HOMEWORK ASSIGNMENT, due Tuesday May 13, 2006

5-2 Formation of a junction
5-3 Junction depth
5-9 Fermi Energy Levels
5-12 Forward Bias Current
5-19 Junction Characteristics
5-29 Breakdown and Punch-through (Bonus Problem)

BREAK

5.5.4 PN Junction Capacitance

Two components

Reverse Bias or Depletion capacitance derives from the depleted region of the junction, analogous to the dielectric role in a traditional parallel plate capacitor.

C = absolute value of dQ/dV

We know that in diodes W changes with V

Equations 5-56 and 5-57 are expressions of W in equilibrium and bias situations

Examining 5-57 reveals that W increases as V_r increases (feels good).

5-63 is 5-61 simplified for a P^+-N junction, where the extension of the depletion region into the heavily doped P side is ignored.

IMPORTANT POINT: This clear relationship allows us to deduce doping densities quite accurately from capacitance measurements for abrupt junctions (P^+-N and N^+-P). All we need is the junction area.

REMEMBER FIELD TRIP TO TOUR TEST BOX?

Forward Bias or Diffusion capacitance varies with respect to the diode length as compared to the carrier diffusion length. This is the capacitance relating to the reclamation of the stored charge. It is negligible above V_0.

<u>See figures 5-30 and 5-31.</u>

<u>Example 5-6</u> Pull the equation from the back cover and plug and chug (note ε in denominator of bracketed term, which causes the leading square root of ε term).

5.5.5 Varactor Diode (short for variable reactor)

In abrupt junction capacitance is proportional to $V_R^{1/2}$
Graded junctions are similar, but not as predictable, thus less useful.
Most varactors are constructed with epitaxially grown or implanted (not diffused) junctions.

These are voltage-variable capacitors, and are the solid state replacements for the tunable air capacitors used in early radio and TV tuners. SHOW AND TELL

5.5.6 Deviations from the Simple Model

Most important deviations are

1. Carrier injection is influenced by band gap and by carrier concentration under forward bias. Low temperature I-V curves of heavily doped diodes with various band gaps show sharper, more square conducting knees, Figure 5-33.
2. The model does not consider recombination and generation within the transition region. Long and short devices will display different IV characteristics because of this shortcoming.
3. Ohmic (IR drop) effects are not included in the simple model.
4. Graded junction effects are not included in the simple model.

Let's look at #2 a bit closer (section 5.3.2)

We model W as a depleted region, but recombination occurs during conduction. This is handled pragmatically with what is known as an "ideality" factor. Example: http://www.intel.com/design/intarch/datashts/27326801.pdf, n = ideality factor and varies between 1 and 2

(5-740 $I = I_0'(e^{qV/nkT} - 1)$, when n = 1, things are ideal!

Forward Bias: When n > 1, we get more current than expected because at low injection recombination effects dominate. So n may vary from ~2 (less current than expected) to ~1 as forward bias increases.

Generation plays a similar screwy role under reverse bias. Let's look through it in Figures 5-35 and 5-36.

SWITCH TO EDITION 5

5.6.3 Ohmic Losses

The diode equation assumed that the device voltage drop appeared entirely across the junction, neglecting any drop across neutral regions or contacts. Equation 5-76 summarizes voltage drops across the neutral N and P regions plus an external voltage.

Ohmic losses are designed out with choices in doping and geometry.

LOOK AT FIGURE 5-37 in edition 5 and words on prior page bottom.

5.6.4 Graded Junctions

The ideal equation works much better for abrupt junctions, but enough is known about graded junctions to compensate. This section provides general guidance on the deviations to be expected when predicting the behavior of a graded junction (diffused) device.

5.7 Metal Semiconductor Junctions

The simplest of P-N junctions can be formed with a properly chosen metal to semiconductor connection. Conversely, we must take care to make sure that junctions meant to be ohmic (non-rectifying) are indeed so.

5.7.1 Schottky Barriers

Metal work function and semiconductor type can be harmonized to create Schottky barrier diodes.

Just as with a PN junction, when a metal of one work function is combined with a semiconductor of another, the Fermi energy levels will align. Thus if the metal has a work function larger than that of an n-type semiconductor, an energy diagram as shown in Figure 5-40 will result in combination. NOTE that the semiconductor work function is measured from its Fermi level, the same as the metal, BUT that the metal's Fermi level is at its surface. In this figure, alignment of the Fermi levels means that the energy band of the n-type semiconductor must be bent upwards toward the junction. The metal is a source of electrons, so positively biasing the metal forward biases the structure and conduction takes place. Conversely, since the semiconductor is n-type and has on a few minority positive carriers, it can be positively biased with only a small generation current result.

Figure 5-41 shows a Schottky barrier diode constructed of a metal with a lesser work function than its p-type semiconductor mate.

Figure 5-42 shows the IV curve of the metal/n-type Schottky barrier diode.

5.7.2 Ohmic Contact See Figure 5.43

Conversely, a metal/n-type construction where the metal work function is less than that of the n-type will be ohmic in nature as will be the situation where the metal work function is greater than a partner p-type semiconductor.

A final practical approach to insuring ohmic contacts is to dope the semiconductor heavily at the metal interface. This will make any barrier super thin (extension into the semiconductor is limited by doping density) and allow carriers to tunnel through regardless.

5.7.4 and 5.8 Just read highlights out of 5th edition