ECE 440
Lecture 21: Qualitative Current Flow in a P-N Junction

Class Outline:

• Qualitative Current Flow in a P-N Junction
Key Questions

• What happens to a p-n junction under a forward bias?
• What happens to a p-n junction under a reverse bias?
• What physical processes are in play?
• What can I safely ignore when I apply a bias?
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What do we know about p-n junctions so far...

We know how to make them:

We can make interesting things out of them...

LED

Photocells

1. Oxidize the Si sample
2. Apply a layer of positive photoresist (PR)
3. Expose PR through mask A
4. Remove exposed PR
5. Use RIE to remove SiO₂ in windows
6. Implant boron through windows in the PR and SiO₂ layers
7. Remove PR and sputter Al onto the surface
8. Using PR and mask B, repeat steps 2-4; etch away Al except in p-contact areas
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We understand the electrostatics:

Energy bands

Electric Field

Charge Density

- $E_{vp}$
- $E_{Fp}$
- $E_{cn}$
- $E_{Fm}$
- $E_{vn}$

Charge Density

Exact

Depl. Approx.

Electrostatic potential

$V_0$

$V_n$
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We have a tentative game plan for solving p-n junction problems...

Plan for finding the **charge density**, **electric field**, and **potential**:

1. Find the **built-in potential**, $V_0$.

2. Use the **depletion approximation** to find the **charge density**.
   - Gives an easy solution to the Poisson equation.
   - Depletion layer widths are still unknown.

3. Integrate the **charge density** to find the **electric field**.
   - Be sure to use the appropriate boundary conditions $E(-x_p) = E(x_n) = 0$.

4. Integrate the **electric field** to find the **potential**.
   - Boundary conditions are $V(-x_p) = 0$ and $V(x_n) = V_0$.

5. Solve for the **depletion layer widths** ($-x_p$ and $x_n$).
   - Use the fact that for $E(x)$ to be continuous at $x = 0$, $N_A x_p = N_D x_n$. 

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**10/15/10**
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We know that currents flow in equilibrium...

Dashed Arrows = Particle Flow

Solid Arrows = Resulting Currents
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Now apply a bias. What do we know?

Things we know or will assume:

• We are assuming that the contacts to the p-n junction are ohmic.

• We are assuming that there is no voltage drop in the bulk of the p and n regions (low level injection).

• We assume that all of the voltage is dropped across the space charge region.

• We assume that $V_A < V_0$ otherwise we cannot assume low level injection.
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So what will happen to the potential...

Forward Bias ($V = V_F$):

- The potential barrier is lowered for a forward bias.

Reverse Bias ($V = -V_R$):

- The potential barrier is raised for a reverse bias.
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What will happen to the **electric field and space charge region**?

Forward Bias (V = V_F):

Reverse Bias (V = -V_R):

When we apply a bias we are changing the electric field which will change the space charge region as we still need the proper number of positive and negative charges.

- Apply a **positive bias** and we will **decrease the electric field** because the bias potential will oppose it. We also expect a **smaller space charge region** because of the smaller field with reduced uncompensated charge.

- Apply a **negative charge** and we will **increase the electric field** as the bias potential is now in the same direction as the field. We expect a **larger space charge region** because we now have more uncompensated charge to balance.
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What happens to the energy bands?

Equilibrium

Forward Bias ($V = V_F$): Reverse Bias ($V = -V_R$):

- We can already anticipate the change in the energy bands as a forward bias will bring the bands closer to one another.
- Naturally, if we then apply a reverse bias the energy bands, the bands will separate farther apart.
- The bias also separates the Fermi levels with $E_{FN} > E_{FP}$ by $V_F$ for forward bias and $E_{FN} < E_{FP}$ by $V_R$ for reverse bias.
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Let's summarize the electrostatic changes with applied bias...
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How should the **diffusion current** behave?

- The diffusion current is majority carriers on the n-side surmounting the barrier and crossing over to the p-side.
- Some high energy electrons can surmount the barrier at equilibrium.
- Under forward bias, both electrons and holes begin to diffuse creating a significant current.
- Under reverse bias, the barrier to diffusion is raised and very few carriers can diffuse from one region to another.
- Diffusion current is usually negligible for reverse bias.
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Taking a closer look at the forward and reverse bias carrier concentrations...

Forward Bias

Reverse Bias

Physics of Semiconductor Devices, S.M. Sze, Wiley-Interscience
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Where there is diffusion, there is also **drift current**...

- The drift current is relatively insensitive to the height of the potential barrier.
- The drift current is not limited by how fast carriers are swept down the barrier but instead it is **limited by how often** they are swept down the barrier.
- Minority carriers wander too close to the space charge region and are swept across.
- This leads to a drift current.
- But there are not many carriers available to be swept across so this leads to a small current.
- Every minority carrier that participates will be swept across regardless of the size of the barrier.
- Minority carriers are generated by thermal excitation of EHPs.

**EHPs generated within** $L_P$ or $L_N$ **of the SCR will participate.**

**Referred to as** generation current.
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Summarizing the total current in the p-n junction...

Equilibrium:
• No current flows

Reverse Bias:
• Both drift and diffusion currents are very small.
• Only current that flows is from the generation process.
• This current is bias independent.

Forward Bias:
• Large diffusion current from p to n
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Take a closer look at the forward bias regime...

Forward bias increases the probability of diffusion across the junction exponentially.

\[ I = I_0 \left( e^{qV/kT} - 1 \right) \]

Total current is the diffusion current minus the absolute value of the generation current.

At \( V = 0 \), the generation and diffusion currents cancel.

End result is a rectifying type of behavior seen in MS contacts.
Let's try to visualize what is going on...

Carrier motion in a material:

For this structure, we can use the dimensions to define the resistance:

\[ R = \frac{\rho L}{wt} = \frac{L}{\sigma wt} \]

- Carriers move in a group.
- Electrons move against the electric field.
- Holes move with the electric field.
- Convention makes the drift currents flow in the same direction.
- The contacts are considered ohmic
  - Perfect sources and sinks for carriers.
  - No tendency to inject either carrier.

*Electrons* are easy to visualize.

What happens to *holes* when they reach the contact?
What happens to the holes??

- As the hole reaches the end of the semiconductor, it recombines with an electron which must be supplied by the external circuit.
- As one hole disappears, another hole must appear at the entrance of the circuit to conserve charge neutrality.
- So, we have the generation of an electron-hole pair when an electron leaves the semiconductor sample.
- The hole flows in while the electron flows out.
Now look at the big picture of a p-n junction under bias...

R-G centers.

Minority carriers wander close to the depletion region and are swept away.

Excess minority carriers

- When electrons are swept across the junction they are replaced by an electron generated from an R-G center. Similar for holes.
- Excess minority carriers set up a local field pushing carriers to the contacts.
Let's solve a simple problem...

The electrostatic potential in the depletion region of a p-n junction under equilibrium conditions is determined to be:

\[ V(x) = \frac{V_{bi}}{2} \left[ 1 + \sin \left( \frac{\pi x}{W} \right) \right] \quad \text{for} \quad -\frac{W}{2} \leq x \leq \frac{W}{2} \]

(a) Establish a relationship for and sketch the electric field in the depletion region.

(b) Establish a relationship for the charge density and sketch it.

(c) Invoke the depletion approximation, determine and sketch \( N_D - N_A \) in the depletion region.
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Let's solve a hard problem...

A P-I-N diode is a three-region device with a middle region that is intrinsic and relatively narrow. Assuming that the p and n regions are uniformly doped and $N_D - N_A = 0$ in the intrinsic region:

(a) Sketch the expected charge density, electric field, electrostatic potential and band diagram.

(b) What is the built-in voltage drop between the p and n regions? Justify it.

(c) Establish a quantitative relationship for the charge density, electric field, potential and the depletion widths.