ECE 340
Lecture 28 : Photodiodes

Class Outline:
• I-V in an Illuminated Junction
• Solar Cells
• Photodetectors

I-V in an Illuminated Junction
Remember the forward and reverse bias carrier concentrations in a p-n junction that resulted from the application of bias?

Forward Bias
Reverse Bias

I-V in an Illuminated Junction
The total current consists of a diffusion current?
• 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.

Key Questions
• How do the I-V characteristics change with illumination?
• How do solar cells operate?
• How do photodiodes operate?
• What are the important design considerations for each?
And, naturally, 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.
- Referred to as generation current.

The end result produced the now familiar p-n junction I-V characteristic...

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

I = \frac{I_d(e^{\frac{qV}{nKT}} - 1)}{1 + \frac{I_d}{I_{ref}}}

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

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

Total Current...

Analyze the carrier concentrations to get the diode equation...

Extra holes generated on the n-side
Extra electrons generated on the p-side
Extra carriers generated within the depletion region.

The resulting current is due to the collection of these optically generated carriers...

I_{op} = qA_{n,p}(g_{n} + g_{p} + W)

To find the total reverse current, we need to now modify the diode equation we derived previously to incorporate the new optical generation current...

Total current

I_{op} = qA_{n,p}g_{op}

Current directed from the n to the p

I_{op} = qA_{n,p}g_{op} \times \text{generation volume}
I-V of an Illuminated Junction

So this additional mechanism will change the output currents...

The I-V curve will be lowered in an amount proportional to the generation rate.

Now what happens when we short circuit the device (V = 0)?

An open circuit voltage, \( V_{OC} \), appears across the junction.

What is happening in our semiconductor?

- The minority carrier concentration is increased by the optical generation of EHPs.
- The lifetime, \( \tau_n \), is decreased.
- This increases the ratio \( p_n/\tau_n \).
- So, \( V_{OC} \) cannot increase indefinitely.
- In fact, it cannot increase beyond the equilibrium contact potential since the contact potential is the maximum forward bias that can appear across a junction.
- The appearance of a forward voltage across an illuminated junction is known as the photovoltaic effect.

This is interesting, but how can we make this effect into something useful?

I-V in an Illuminated Junction

Wonderful, another complicated equation to deal with! Can we simplify it?

Consider a symmetric junction, \( p_n = n_p \) and \( \tau_p = \tau_n \). Then we can rewrite the preceding equation in terms of the optical and thermal generation rates...

\[
V_{OC} = \frac{kT}{q} \ln \left( \frac{G_{op}}{G_{th}} \right)
\]

Where \( G_{th} = \frac{p_n}{\tau_n} \)

And in terms of the band diagrams...

What's happening??
Solar Cells

**How we use this technology?**

Let's operate in the 4th quadrant where the device gives energy to the circuit.
- The voltage is restricted to values less than the contact potential.
  - On Si ~ 1V.
- Current generated is ~ 10-100 mA for 1 cm² illuminated area.
- One device won't cut it, but many might generate enough power.

**Let's look at the equivalent circuit for a photodiode...**
- Internal characteristics are represented by shunt resistor $R_{sh}$ and capacitor $C_D$; $R_s$ is the series resistance of the diode.
- Connect to a high resistance load $R_L$ to use as a photocell.
- Connect to a high resistance load and power supply to use this device as a detector.

**But we need to design these carefully...**
- We need large area to collect light with a junction located near the surface.
- We must coat the surface with anti-reflective coating.
- Series resistance should be small (ohmic losses) but not too small or we don't get any output power.
- Depth must be less than $L_P$ in the n material to allow holes generated near the surface to diffuse to the junction without recombining.
- So there must be a match between $L_n$, the thickness of the p-region and the optical penetration depth.
- Need a large contact potential and this requires high doping.
- But we need long lifetimes, so we can't dope it too heavily.

**Solar Cells**

**Can we use these for power in an everyday sense?**
- According to Streetman, worldwide power generation is ~ 15 TW.
- This corresponds to an energy usage of 500 quads (500 x 10¹⁵ BTUs) 80% of which comes from fossil fuels.
- There is ~ 600 TW of solar energy available worldwide.
- But solar cells are not very efficient.
  - 25% solar energy conversion for well made cells.
  - 10% for cheap amorphous cells.
  - Need to cover 3% of the earth to get enough energy.
- And they cost ~ 10x more than current technology.

**Polycrystalline Si Solar Cells**

- Copper Indium Gallium Selenide

**M.J. Gilbert  ECE 340 - Lecture 28**
Solar Cells

But we still need to transport the energy somewhere...
We need room temperature superconductors!!

Photodetectors

What can we use these devices for beyond solar cells?
If we operate the device in the third quadrant the current is:
- Independent of applied voltage.
- Proportional to the optical generation rate.

What if we want to detect a series of pulses 1 ns apart?
- Photogenerated carriers must diffuse to the junction and swept across in a time much less than 1 ns.
- W of depletion region should be large enough that most photons are absorbed there.
- Then most EHPs created are swept across as drift current, which is very fast.
- We must dope one side lightly to allow for a large depletion region.

But again there are some design tradeoffs...
Choice of depletion width is a tradeoff between speed and sensitivity.
- Large W leads to a very sensitive device with a low RC time constant.
- But it also cannot be too large or the drift time will be excessive and lead to low speed.

To limit W, use a P-I-N structure...
- During reverse bias, most of the voltage is dropped across the I region.
- If carrier lifetime is large, most carriers will be collected in the n and p regions.

\[ \text{Carriers per unit area per second} = \text{Photons per unit area per second} \times \text{External quantum efficiency} \]

- Circuit with no gain, max is unity.
- If we operate close to avalanche breakdown, then each photogenerated carrier causes a huge change in current.
- This leads to efficiencies greater than 100%.

Remember Direct gap versus Indirect gap...
Photodetectors

We can tailor the band gap in compound semiconductors.

In Silicon:
- Photons with $E < E_G$ are not absorbed.
- Photons with $E >> E_G$ are absorbed near the surface where recombination is high.

Let's use a III-V material:
- We can tune the bandgap to absorb what we desire to detect.
- By using a heterojunction, we can limit the surface recombination by passing photons through a layer which has a larger bandgap and absorbing them deep in the heterostructure.
- We can also separate the absorption and multiplication layers to minimize the leakage.

Photodiodes

Here is an actual example of an avalanche photodiode...