ECE 340
Lecture 28 : Photodiodes

Class Outline:

- I-V in an Illuminated Junction
- Solar Cells
- Photodetectors

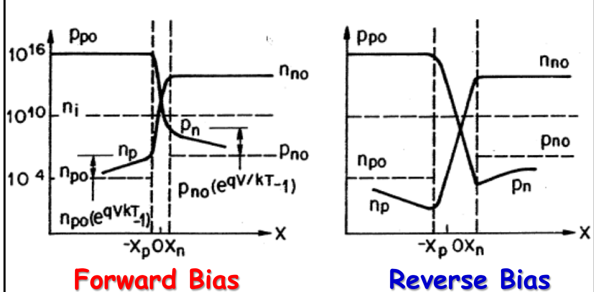
Things you should know when you leave…

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?

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?



Physics of Semiconductor Devices, S.M. Sze, Wiley-Interscience

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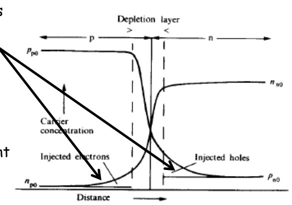
I-V in an Illuminated Junction

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.



I-V in an Illuminated Junction

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.

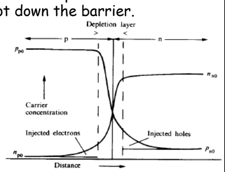
•Minority carriers wander too close to the space charge region and are swept across.

•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.



•EHPs generated within L_p or L_N of the SCR will participate.

•Referred to as **generation current**.

I-V in an Illuminated Junction

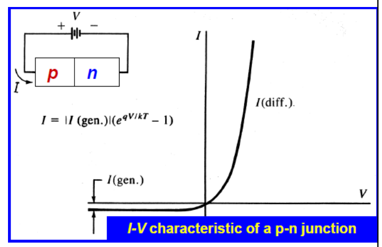
The end result produced the now familiar p-n junction I-V characteristic…

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

$$I = I_0(e^{qV/kT} - 1)$$

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

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



Analyze the carrier concentrations to get the diode equation…

Total Current… $I = qA\left(\frac{D_p}{L_p}p_n + \frac{D_n}{L_n}n_p\right)(e^{qV/kT} - 1) = I_0(e^{qV/kT} - 1)$

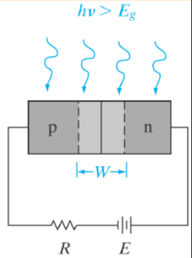
I-V of an Illuminated Junction

So we understand the operation…

•In reverse bias, the current is due mostly to the drift of minority carriers.

•Carriers arise mainly from thermal generation near the depletion region, W.

•If they are created within one diffusion length of the depletion region, they are swept across the junction by the electric field.



What happens when we add light?

•An added generation rate, g_{op}, participates in the current

AL_pG_{op} Extra holes generated on the n-side

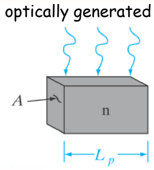
AL_nG_{op} Extra electrons generated on the p-side

AWG_{op} Extra carriers generated within the depletion region.

I-V in an Illuminated Junction

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

$$I_{op} = qAg_{op}(L_p + L_n + W)$$



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 → $I_0(e^{qV/kT} - 1)$ → $I_{th}(e^{qV/kT} - 1) - I_{op}$

$\delta p_{op} = g_{op}\tau_p$

Current directed from the n to the p

$I_{op} = q\,AL_pg_{op}$

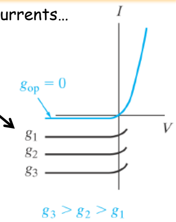
$I_{op} = q \times g_{op} \times (\text{generation volume})$

$$I = qn_i^2A\left[\frac{D_n}{L_nN_A} + \frac{D_p}{L_pN_D}\right](e^{qV/kT} - 1) - I_{op}$$

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)?

$$I = qn_i^2 A\left[\frac{D_n}{L_n N_A} + \frac{D_p}{L_p N_D}\right](e^{qV/kT} - 1) - I_{op} \longrightarrow -\mathbf{I_{op}}$$

Now what happens when we open circuit the device (I = 0)?

An open circuit voltage, V_{OC}, appears across the junction

$$V_{oc} = \frac{kT}{q}\ln[I_{op}/I_{th} + 1]$$
$$= \frac{kT}{q}\ln\left[\frac{L_p + L_n + W}{(L_p/\tau_p)p_n + (L_n/\tau_n)n_p} \cdot g_{op} + 1\right]$$

I-V in an Illuminated Junction

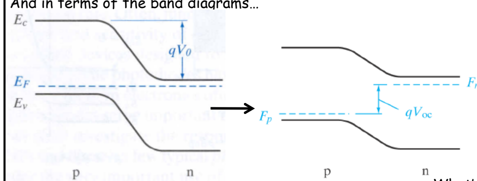
Wonderful, another complicated equation to deal with! Can we simplify it?

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…

$$V_{oc} \simeq \frac{kT}{q}\ln\frac{g_{op}}{g_{th}} \quad \text{for } g_{op} \gg g_{th}$$

Where $G_{th} = p_n / \tau_n$

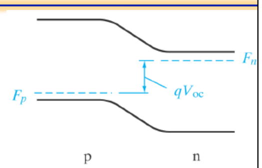
And in terms of the band diagrams…



What's happening ??

I-V of an Illuminated Junction

What is happening in our semiconductor?



- The minority carrier concentration is increased by the optical generation of EHPs.
- The lifetime, τ_n, is decreased.
- This increases the ratio p_n / τ_n.

So, V_{OC} cannot increase indefinitely.

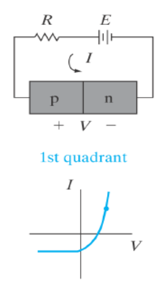
- In fact, it cannot increase beyond the equilibrium contact potential since the contact potential is the maximum forward bias that can appear across a junction.
- The appearance of a forward voltage across an illuminated junction is known as the **photovoltaic effect**.

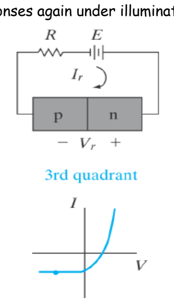
This is interesting, but how can we make this effect into something useful?

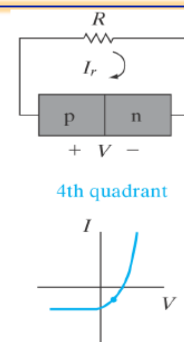
I-V in an Illuminated Junction

Well, it depends on the application.

Let's look at the I-V responses again under illumination…







Power delivered from the circuit to the junction.

Power delivered from the circuit to the junction.

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.
  •In Si ~ 1V.

•Current generated is ~ 10-100 mA for 1cm^2 illuminated area.

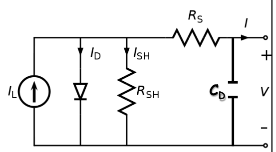
•One device won't cut it, but many might generate enough power.

Let's look at the equivalent circuit for a photodiode…

•Internal characteristics are represented by shunt resistor R_{sh} and capacitor, C_D and R_s is the series resistance of the diode.

•Connect to a high resistance load RL to use as a photocell.

•Connect to a high resistance load and power supply to use this device as a detector.



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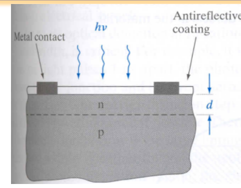
Solar Cells

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 Ln, 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 .

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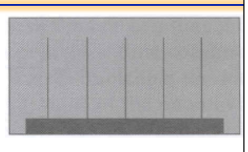
Solar Cells

But we haven't made contacts yet…

•We have a large area so we can make the resistivity of the p-body small.

•But if we make contact along the edge of the thin n layer, we get a large series resistance.

•To prevent this we distribute the contact over the n-layer using small contact fingers.



Do we know how to design them yet?

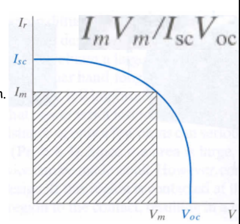
•Operate the device in the 4th quadrant.

•Determine I_{SC} and V_{OC} for a given amount of illumination.

•Maximum power delivered VI is a maximum.

•Area of rectangle gives the maximum power.

•A figure of merit in designing these devices is the fill factor.



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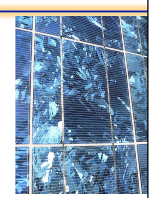
Solar Cells

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 10^{15} BTUs) 80% of which comes from fossil fuels.

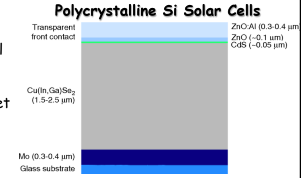
•There is ~ 600 TW of solar energy available worldwide.



Polycrystalline Si Solar Cells

•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.



Copper Indium Gallium Selenide

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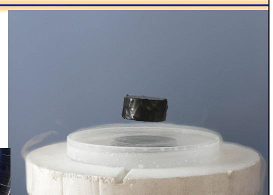
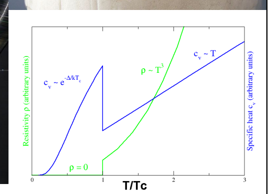
Solar Cells

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.

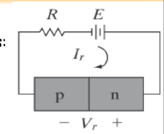
What if we want to detect a series of pulses 1 ns apart?

•Photogenerated carriers must diffuse to the junction and swept across in a time much less than 1 ns.

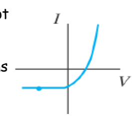
•W of depletion region should be large enough that most photons are absorbed there.

•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.



3rd quadrant



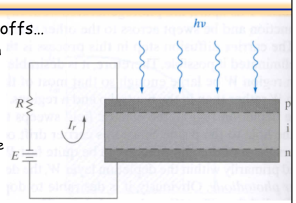
Photodetectors

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.

$$\eta_Q = (J_{op}/q)(P_{op}/hv)$$

External quantum efficiency

J_{op}/q → Carriers per unit area per second.

P_{op}/hv → Photons per unit area per second.

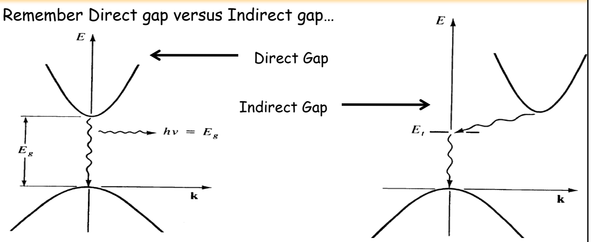
•Circuit with no gain, max is unity.

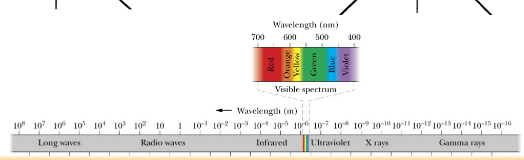
•If we operate close to avalanche breakdown, then each photogenerated carrier causes a huge change in current.

•This leads to efficiencies greater than 100%

Photodetectors

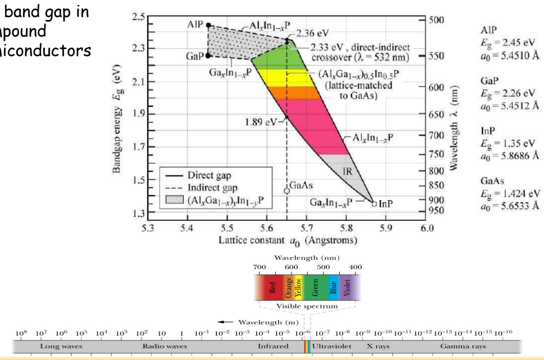
Remember Direct gap versus Indirect gap…





Photodetectors

We can tailor the band gap in compound semiconductors



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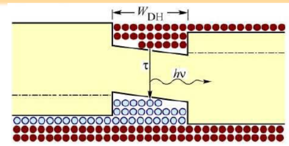
Photodetectors

Can we tailor them to suit our needs?



In Silicon,

- Photons with $E < E_G$ are not absorbed.
- Photons with $E \gg E_G$ 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.

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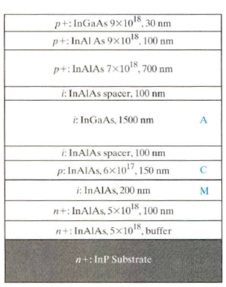
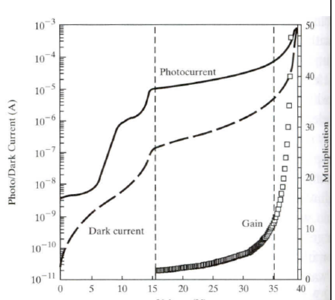
Photodiodes

Here is an actual example of an avalanche photodiode…





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