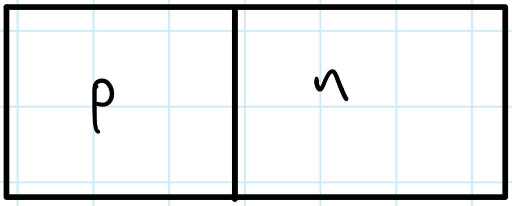
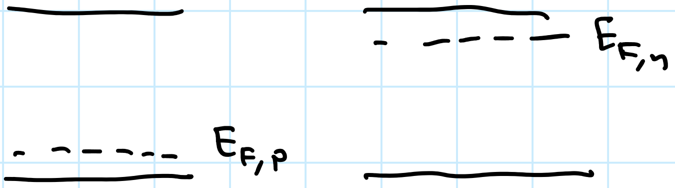
Section 7: Solar Cell Nonidealities

Saturday, November 13, 2021 12:50 AM

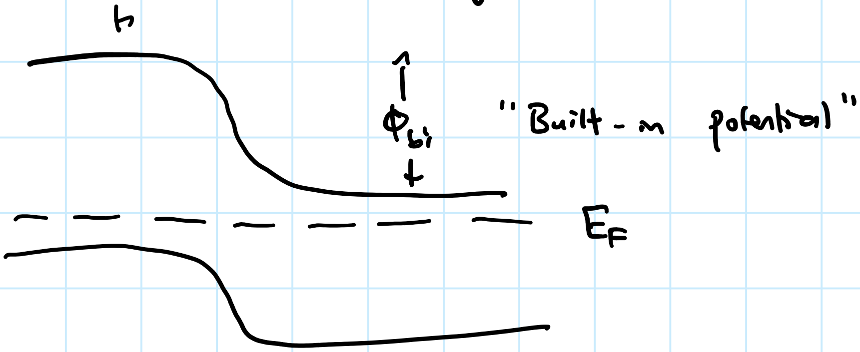
I. Solar Cell Operation

a) pn junction





"One Fermi level in equilibrium"



Physically, what happens?

- Concentration gradient cause holes on p-side to diffuse to n-side, electrons on n-side to diffuse to p-side.
- This "uncovers" the charged dopant ions

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Q: What charge is dopant ion in p-side? n-side?

A: p-side has acceptors, which upon giving up a hole become negatively charged. Similarly, n-side has donors which upon giving up an electron become positively charged.

- This separation of charge forms an electric field that opposes the diffusion.

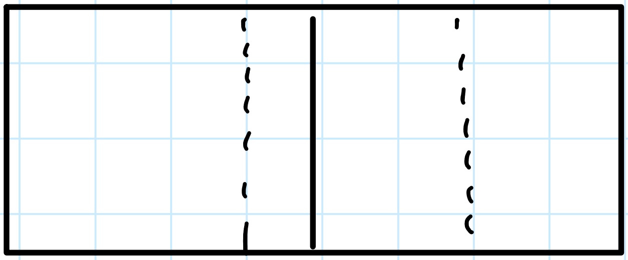
$\Longrightarrow$ Built-in potential

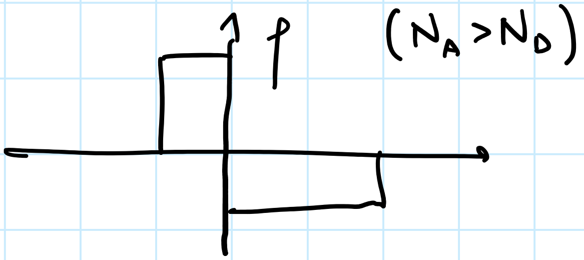
- Depletion-layer model: $n \approx 0, p \approx 0$ in this "depletion region" in the middle, where the dopant ions have been left uncovered.

Q: Relative size of the depletion region on the n vs p sides?

A: Can argue based on charge conservation that intuitively, the more heavily doped region needs one heavily doped region needs "less depletion width" for a given charge. In fact,

$$N_A|x_p| = N_D|x_n|$$





b) I-V Characteristics

Note: built-in potential

$$\phi_{bi} = \frac{kT}{q} \ln \frac{N_D N_A}{n_i^2}$$

Q: What happens to ϕ_{bi} if N_D, N_A held constant but E_g increases?

A: Expect n_i to go down, and thus ϕ_{bi} to go up. Does this match what you observed in lab, roughly?

- Shockley-Diode Equation

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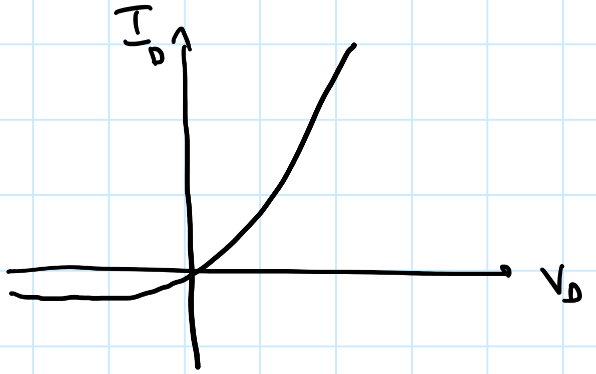
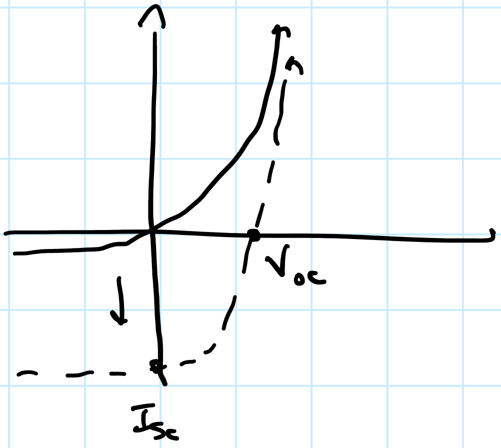
$$I_D = I_s\left(e^{qV_D/k_BT} - 1\right)$$

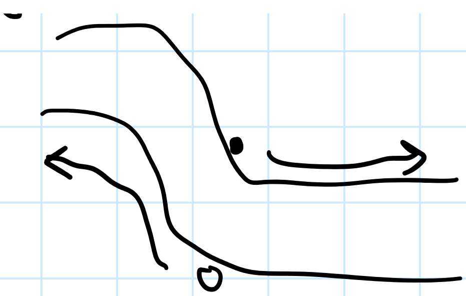


- With illumination:

$$I_D = I_0\left(e^{qV/k_BT} - 1\right) - I_{sc}$$



Physically, incident light photogenerates electron hole pairs. If they are within the depletion region (or within ~ depletion length $\sqrt{D\tau}$ such that they can diffuse into the depletion region), the built-in field will sweep the charge carriers out of the junction, causing a current to flow.



c) Various figures of merit

- efficiency (complex)
  - fill factor $\frac{V_{sc} I_{oc}}{V_M I_M}$
  - external quantum efficiency (consider absorption, reflection)
  - internal quantum efficiency (e.g. how many carriers recombine before being collected?)
- cost

II. Nonidealities and Potential Solutions

We've already talked a bit about how solar cell performance can be enhanced, whether by improving absorption (mirrors, texturization), new materials, multi-junction cells, etc.

But another important consideration should be, how do we combat nonidealities that degrade operation?

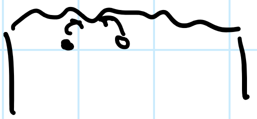
a) Degraded Carrier Lifetimes

Q: Do we want long or short carrier lifetimes?

A: In general, long ——— so carriers have time to reach depletion region instead of recombining immediately after being generated.

However, various mechanisms can degrade carrier lifetimes from theoretical maxima.

For example, defects at the <u>surface</u> of material create dangling bonds that become recombination centers ⟶ quantified by quantity known as the "surface recombination velocity" (large = recombines quickly, bad!)



Can "plug" these dangling bonds with a cladding layer or via chemical treatment:

- oxidation + HF etch ⟹ Si - H bonds
  (Yablonovitch PRL, 1986)
- room-temperature polymer treatment :

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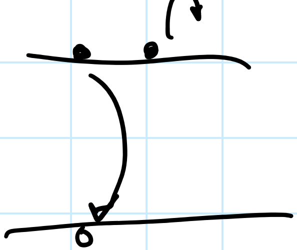
Nafion (strong Lewis acidity) ⟶ interfacial charge transfer

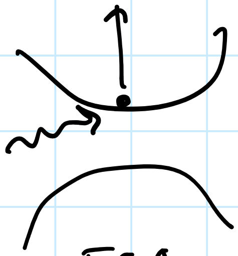
↳ accepts electrons

(Ji et al., ACS Nano, 2019)

Even without considering the surface, other mechanisms can degrade carrier lifetime as well. High doping concentrations are often used to assist the assymetric collection of carriers (i.e. holes on one side, electrons on the other). However, heavy doping can degrade carrier lifetime via Auger recombination (electron-hole pair gives up energy to nearby carrier) as well as absorption due to free-carrier absorption effects.



Auger



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One solution is to simply use dopant-free contacts by choosing the work function of the contact materials carefully.

(Bullock et al, Nature Energy, 2016)

b) Heating

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Heating degrades solar cell efficiency, primarily by decreasing V_{oc} (roughly, this can be seen as stemming from E_g decreasing as temperature increases).

$$\text{c-Si}: \frac{d\eta}{dT} \sim 0.45\% \text{ per Kelvin}$$

Lots of structural techniques to address this (e.g. putting solar cells on good dissipators of heat). One more esoteric way is to use a technique called "radiative cooling" — basically, outer space is used as a heat sink. To do this, the blackbody radiation should emit in the "atmospheric transparency window" of ~ 8 - 13 um while still allowing solar wavelengths to be absorbed. The idea is then to design a layer of thermal emitter placed atop the solar cell that satisfies those constraints.

(Zhu et al., Optica, 2014)

Alternatively, going to the extreme one could try using a combined thermo-optical effect to generate energy. This is the idea behind a thermophotovoltaic cell (TPV), which aims to collect blackbody radiation emitted by high-T sources (e.g. a car). Perhaps unimaginatively the efficiency can be boosted by using a mirror — however, the effect is actually two fold. Above-bandgap thermal photons get multipassed (as we saw before), and below-bandgap photons get reflected back to the heat source, which will reabsorb the photon (since it's a blackbody). Thus, the photon gets "recycled" and has a chance to be re-emitted at a higher energy!

(Omair et al., PNAS, 2019)