Lec 3 – Diodes

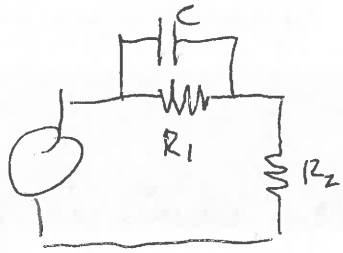
Intro
- Backlog AC ckt
- why diodes
- Edification vs. knowing

Bands to Current
- Justify exp. current
- what's a band
- Fermi
- Doping

Silicon Picture & C_j
- Space charge showing eq.
- integrals for E_{max} & V_{bi}
- Note about breakdown & avalanche, E_{crit}

Switch Model & Examples
- switch model
- light an LED
- 1/2 wave rect? full for HW? env. det HW?

Let's revisit last few AC ckt.



$$V_{DC} = \frac{R_2}{R_1+R_2} V$$

$$V_{AC} = V$$

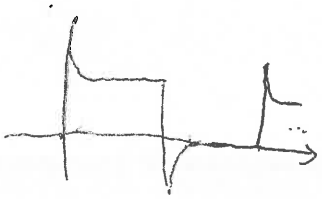
$$\tau = (R_1 \| R_2) C$$

- Thevenize from cap to find τ fast
- τ set by pole & not zero

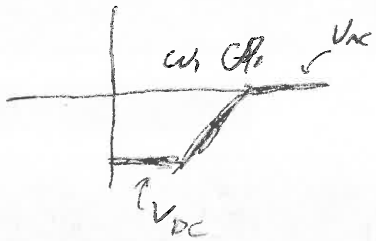
$$v_o = \frac{R_2}{R_2 + \frac{R_1/Cs}{R_1 + 1/Cs}}$$

$$= \frac{R_2(R_1Cs+1)}{R_2(R_1Cs+1)+R_1}$$

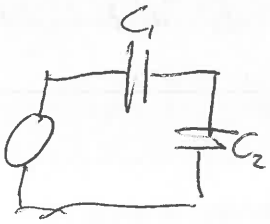
$$= \frac{R_2}{R_1+R_2} \frac{R_1Cs+1}{1+\frac{R_2R_1}{R_1+R_2}Cs}$$



- Standard form for Xfer fn (easy to get DC gain & "back solve")



- AC response also has V_{AC} & V_{DC}
- pole zero sep related to gain

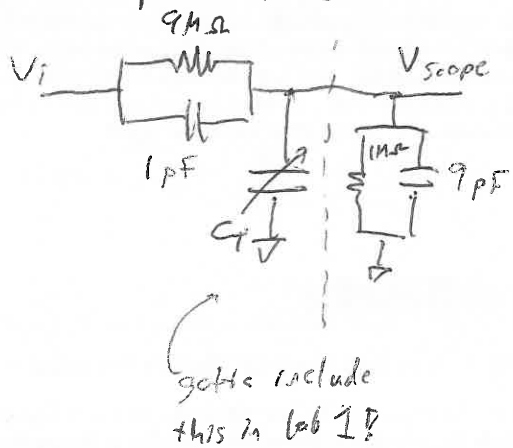


$$V_o = \frac{\frac{1}{sC_2}}{\frac{1}{sC_1} + \frac{1}{sC_2}}$$

$$= \frac{C_1}{C_1+C_2}$$

- frequency indept.
- nominally works @ DC input!
- But output is DC floating susceptible to all sorts of perturbation (scope probe?)

Oscilloscope Probes



- At DC $V_o/V_i = \frac{1}{10}$, so called 10x probe
- scope needs to multiply by 10 internally
- At AC, gain is also 1/10
- Can get flat response from DC to AC
- see much less cap @ input b/c of this design, so probe won't disturb circuit.

- Feel free to talk to me about mystery box once you've taken a crack at it.

Diodes

- up until now we've been working on "good at circuits" & "good at dynamics" learning goals
- Diodes are our 1st non-linear element
- Start of "large-signal" (which secretly means DC) analysis
- This lecture is about convincing you that diodes come from real physics
  - ↳ most isn't testable, won't be quizzed, edifying
  - ↳ semiconductors are pretty mysterious, ask questions!
- Do a bit of handy modeling @ end of lecture

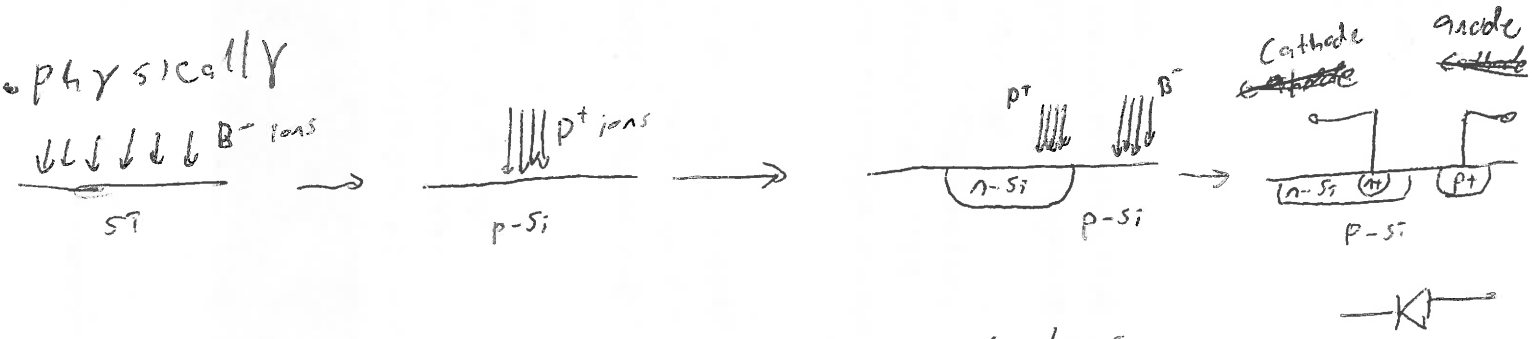
What are diodes?

↳ exponential i-v devices

↳ one way current gates

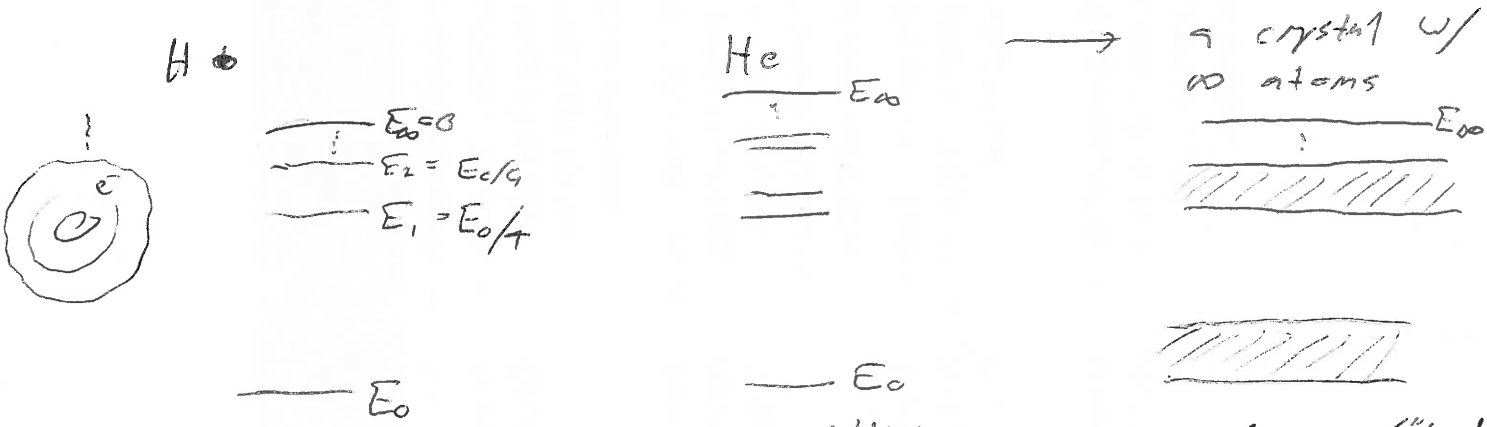
↳ pn junctions → differently doped pieces of semiconductor (impurity added)

• physically



• How do we calculate current in semiconductors

↳ figure out how many e^- are moving between energy states



• Band splitting

• more densely packed states

• wind up w/ "bands" of states each infinitely dense

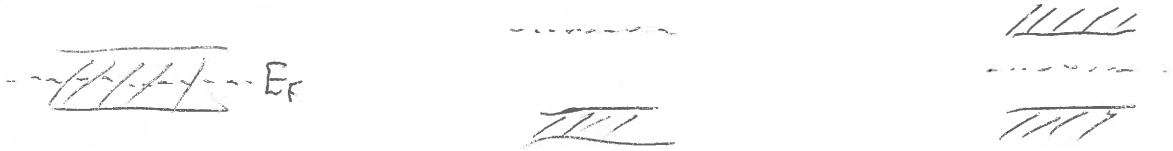
• "band gaps" between them

• Fermi ~~Energy~~ Level is the energy e^- would occupy @ absolute zero

~ "chemical potential" of electrons

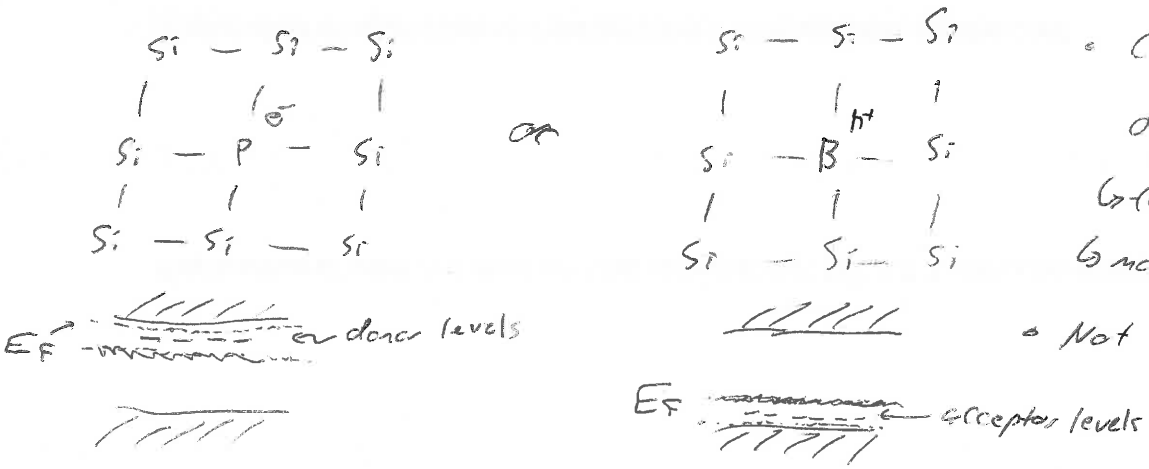
~ Energy required to add one e^-

Let's consider some materials



- e^- can easily find new states & move "conductor"
- bottom band full (valence band) top band (conduction band) far away "insulator"
- ~~Gap Band~~ Valence band full but conduction band close "semiconductor"

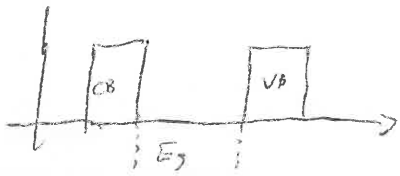
- Doping
  - adds or takes away free e^-



- Change in # of e^- obviously affects E_F
  - ↳ fewer e^-, easy to add
  - ↳ more e^-, hard to add
- Not conducting yet, but only takes a little E push

- Temperature
  - Adds a little energy to system
  - e^- have "probability" of being in different spots

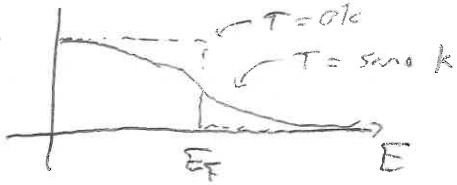
DOS



Fermi Fn.

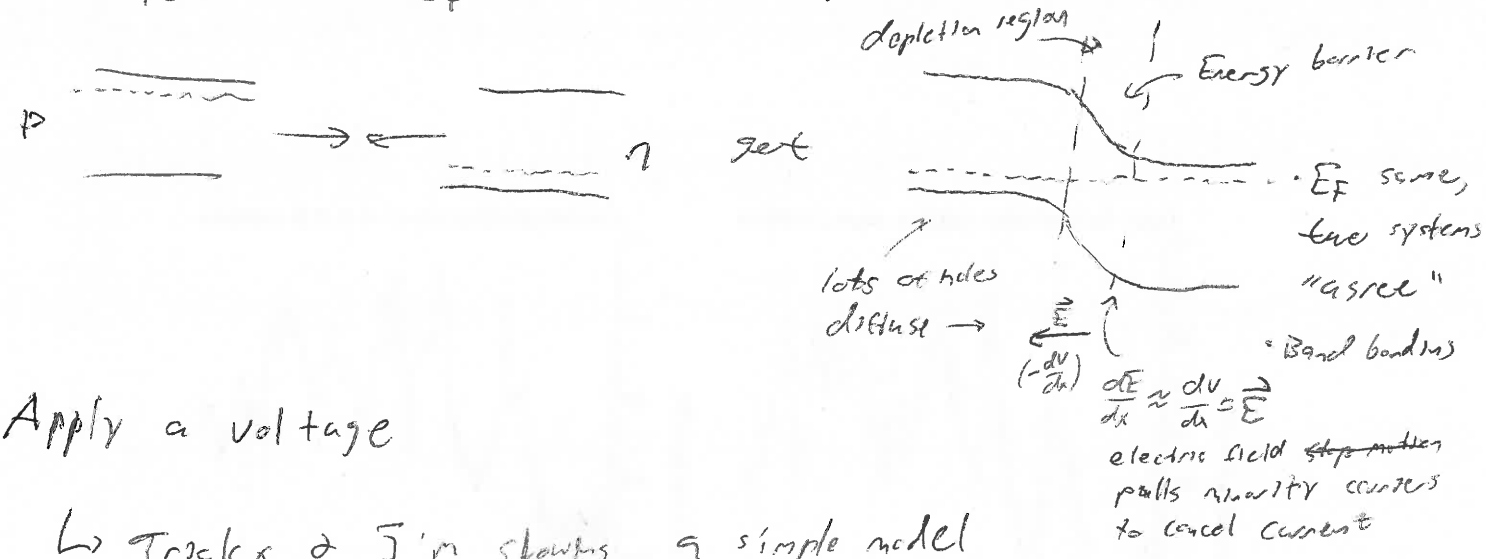
$$F(E) = \frac{1}{1 + e^{\frac{E - E_F}{kT}}}$$

$P(e^-)$



- DOS × $P(e^-)$ gives you probability of e^- in a state
- # of free e^- to move
- suggests # e^- ~ exponential in temperature

- pn junctions
  - ↳ recall that E_F is a chemical potential, represents equilibrium



- Apply a voltage
  - ↳ Tracking a I in showing a simple model
  - ↳ Voltage is "like" potential, shifts bands

fwd. bias ← voltage on dev. moves p band down

rev. bias moves p up

  - ↳ quasi-fermi levels for e^- & holes

- From this we have

$$I_d = I_s\left(e^{qV/nkT} - 1\right)$$

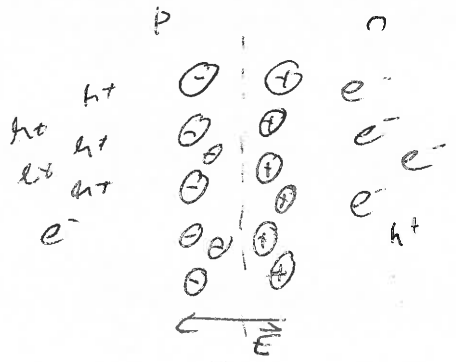
V/ϕ_{TH} ← thermal voltage ~ 26mV @ RT

n ← non-ideality factor

exponential in voltage & temp

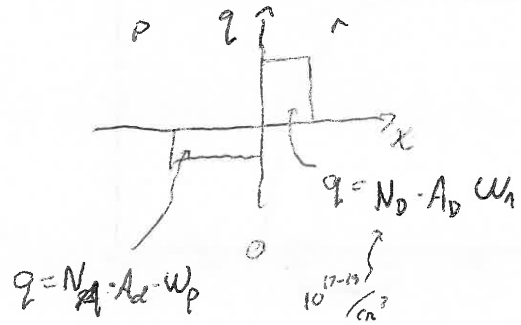
drift current in rev. bias

- Let's look at the silicon picture again to make this concrete



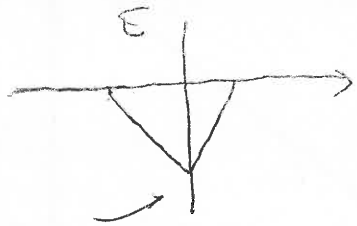
recombination leaves behind fixed charge

- depletion or space-charge region
- $\vec{E}$ field points + to −, cancels diffusion pressure of majority carriers



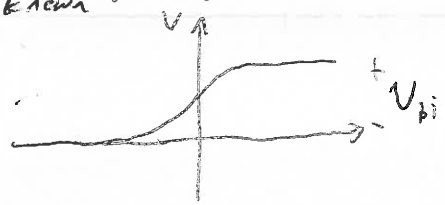
- Charge must balance b/c extra carriers o/w (leftover from recomb)
- depletion mostly on lightly doped side
- Si atoms ~ $10^{20}/cm^3$, intrinsic holes ~ $10^{10}/cm^3$, typical p or e^- dope $10^{15}/cm^3$

  degenerate dope $10^{19}/cm^3$
- Depletion width interesting, comes from diff eq.



- E_{crit} causes breakdown
- fast e^- release more e^-
- known voltage reference

- $\nabla \cdot \vec{E} = \rho/\varepsilon$ ← not ε_0 b/c in Si
- integrate q to get $\vec{E}$
- high peak field in depl. region
- peaks are way

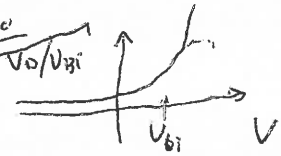


- $\vec{E} = -\nabla V = -\frac{dV}{dx}$ for us
- integrate again to get V
- built-in voltage same as energy barrier

total q idea?

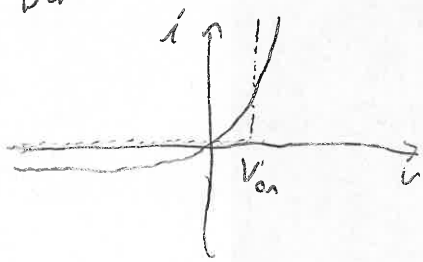
- Width changes w/ applied voltage ~ more diffusion pressure
  - ↳ fwd bias shrinks (weak peak field!) rev grows (stronger field! pushes more carriers away)
- implies there's a $\frac{dq}{dV}$ → non-linear cap

$$C_j = \frac{C_{j0}}{\sqrt{1 - V_0/V_{bi}}}$$



- Dealing w/ exponentials in calculations is hard
  - ↳ why do we do hand calcs? Quick understanding → in meeting → know before you run
  - ↳ work w/ them in detail on Monday

- But we can make a quick & serviceable model

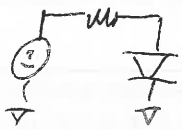


- approximate exponential as brick wall
- $V_{on} \neq V_{bd}$, artificial thing
- Note: both models passive, solar cells, LEDs
- eq. ckt is switch + V src.

- V_{on} = 0.7 for Si, 1.7V for red, 2.3 V for green, 3.1 V for blue

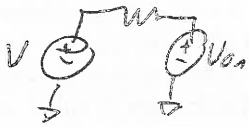
  Increasing V across rainbow

- set current in diode:



- Why need R? Blowup o/w

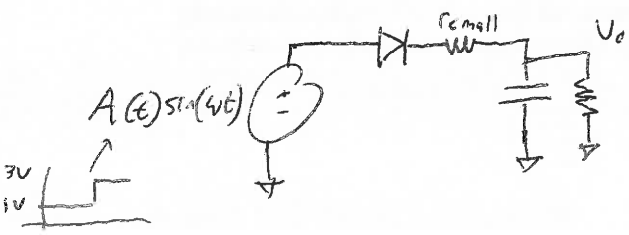
- solve by assuming diode state - On ⇝

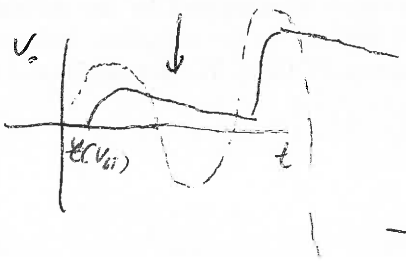


$i = \frac{V - V_{on}}{R}$

  ↳ check assumption at end!

- Common use: envelope detector
  - sine stone approx
  - straight line N/2 approx!





- Height follows envelope
- fast charge & slow discharge
- rectifies DC to AC!