R_{12} is always less than R_1. Why?

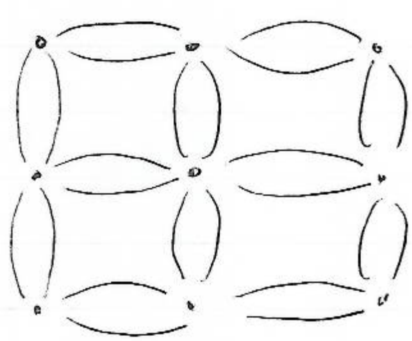
$$\tau' = \frac{R_2}{R_1 + R_2} \tau_{in}$$

$$\tau' < \tau.$$

Semiconductor Physics

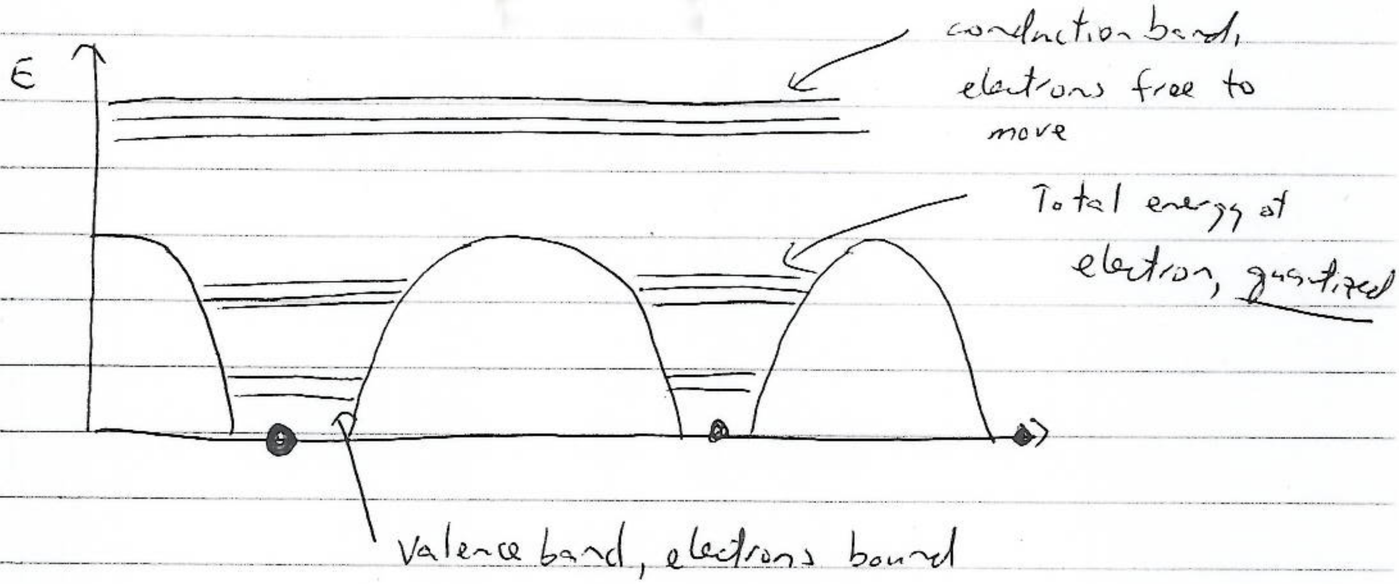
Types of matter

- gas - atoms interact only via hard collisions
- liquid - weak interaction
- plasma - ionized gas
- solid - rigid lattice
- crystal



amorphous - not regular pattern

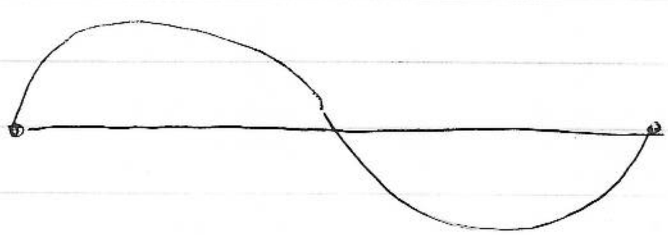
Potential energy of electron in crystal



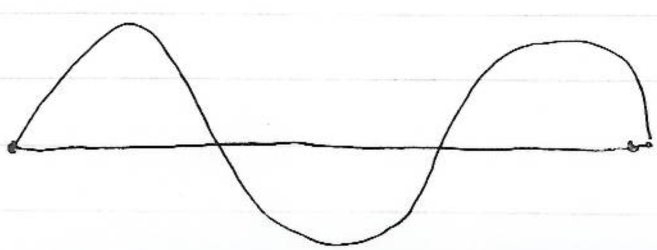
Quantization:

Consider a string with both ends tied

$\lambda = 2L$



$\lambda = L$



$\frac{3}{2}\lambda = L$

$\lambda = \frac{2}{3}L$

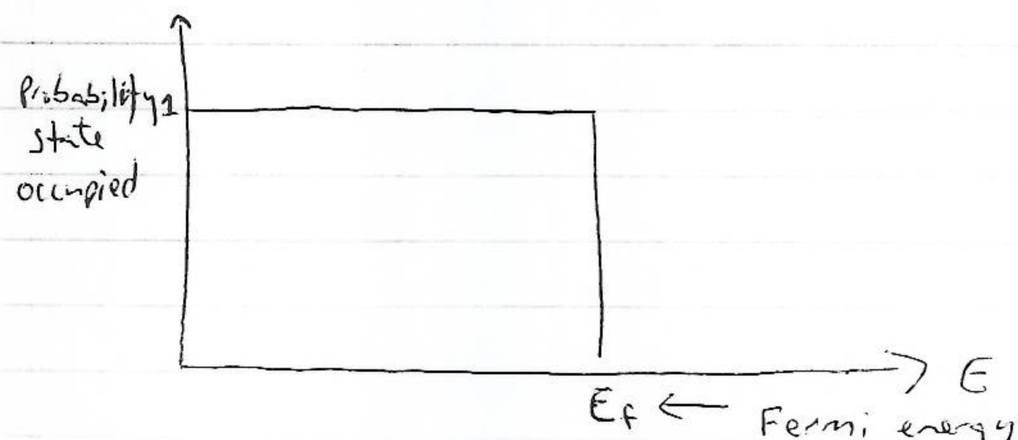
Never have $\lambda = 3.1415\, L$.

Electrons are <u>fermions</u>

fermions: spin 1/2, 3/2, 5/2
No two can occupy the same state

bosons: spin 0, 1, 2, 3
Can occupy the same state

④ At low T, electrons fill lowest states first



At $T \neq 0$, electrons not all packed in lowest levels

Careful treatment

Probability a state occupied:

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

k : Boltzmann's constant

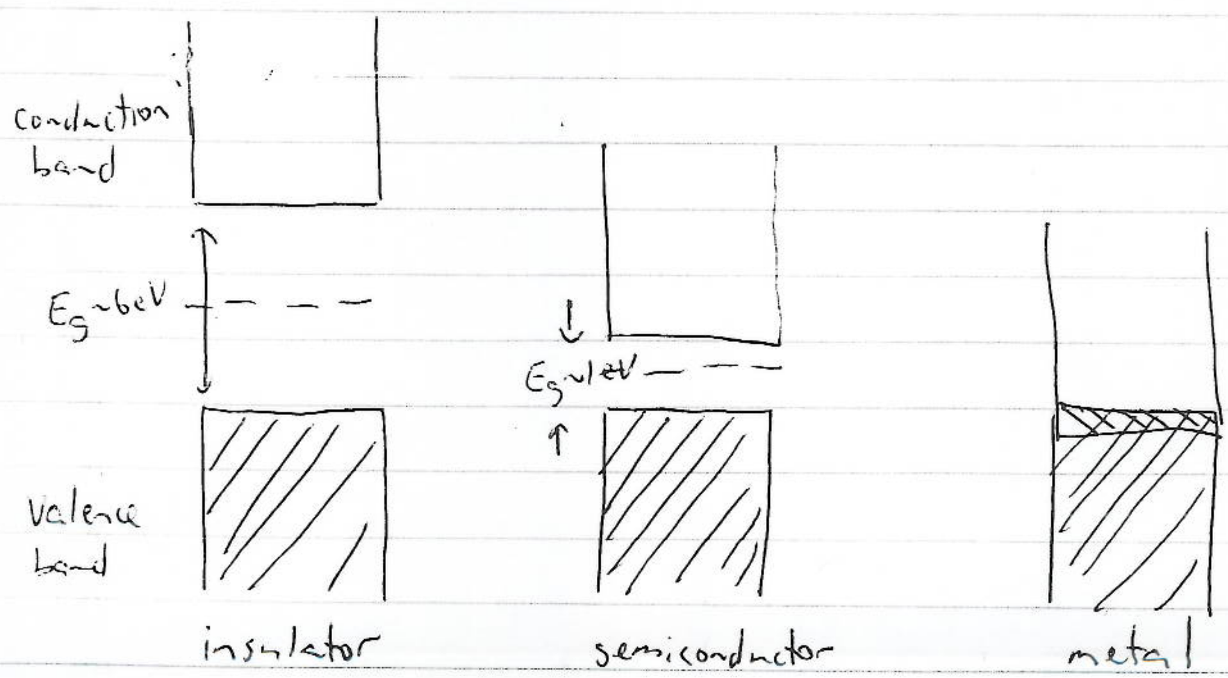
at room temp $kT \sim \frac{1}{40}$ eV

Number of electrons in a range $[E, E+dE]$

$$N(E)dE = \rho(E)\,dE\;F(E)$$

$\rho(E)$: number of states per unit energy

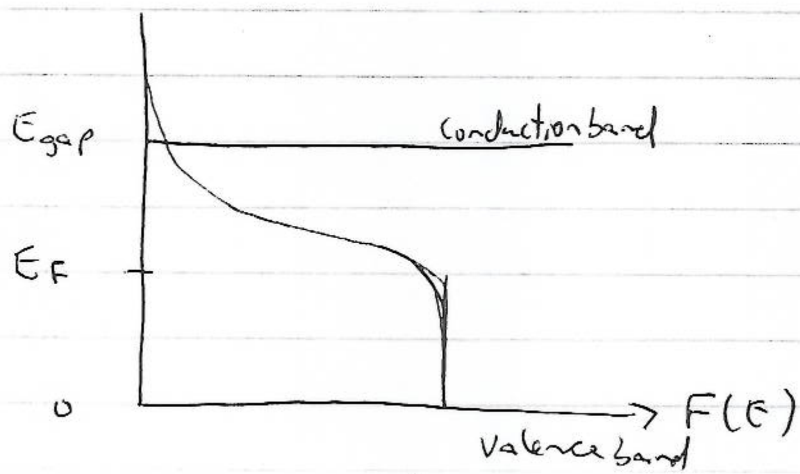
$F(E)$: Probability they are occupied

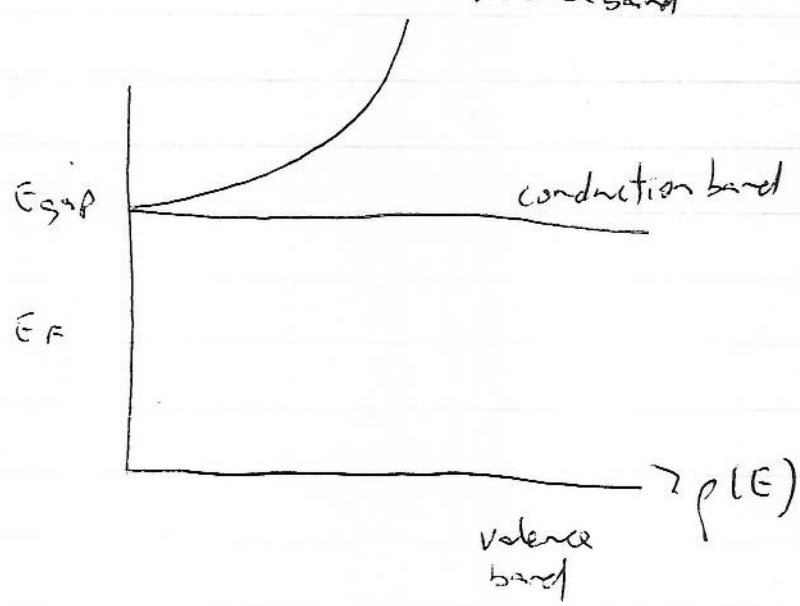


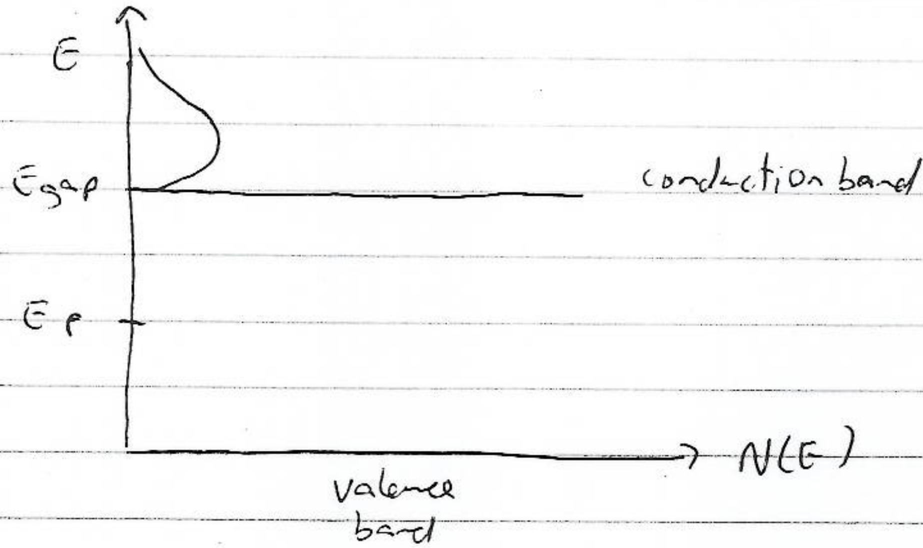
Define $E=0$ at top of valence band

$$\rho(E) \propto (E - E_{gap})^{1/2}$$

Semiconductor at finite T

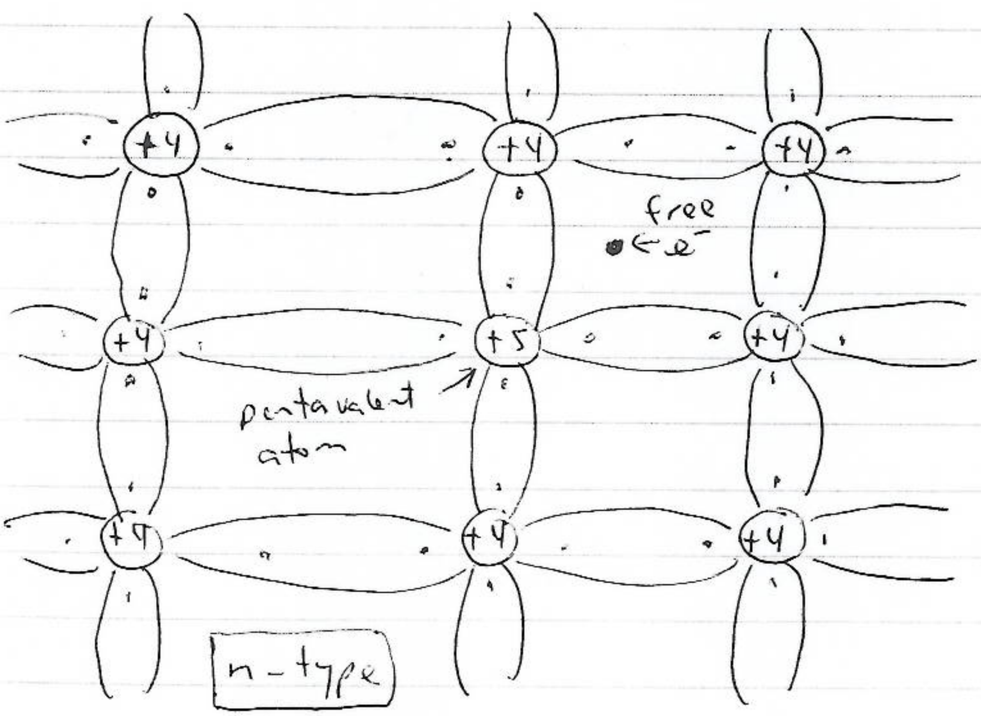






Doping

Insert carriers into lattice



+5 N

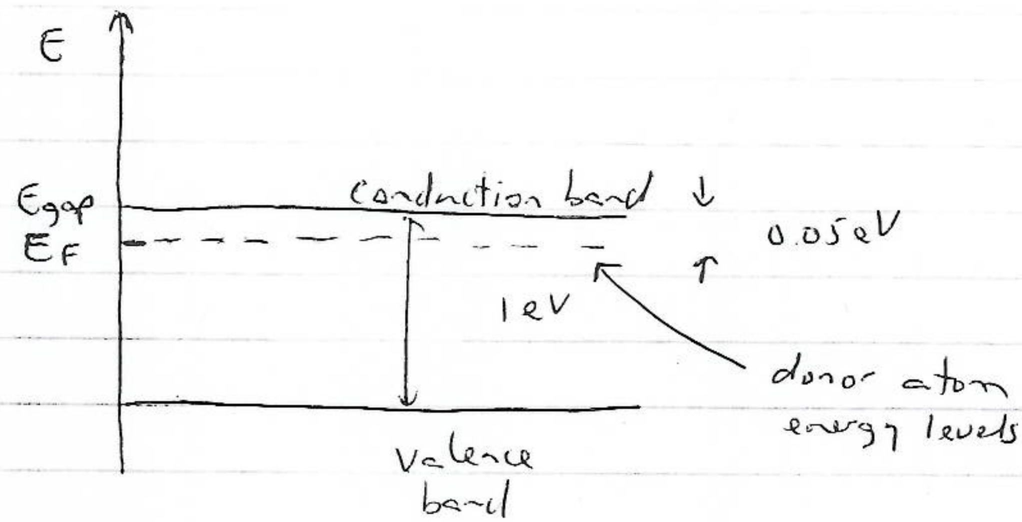
P

As

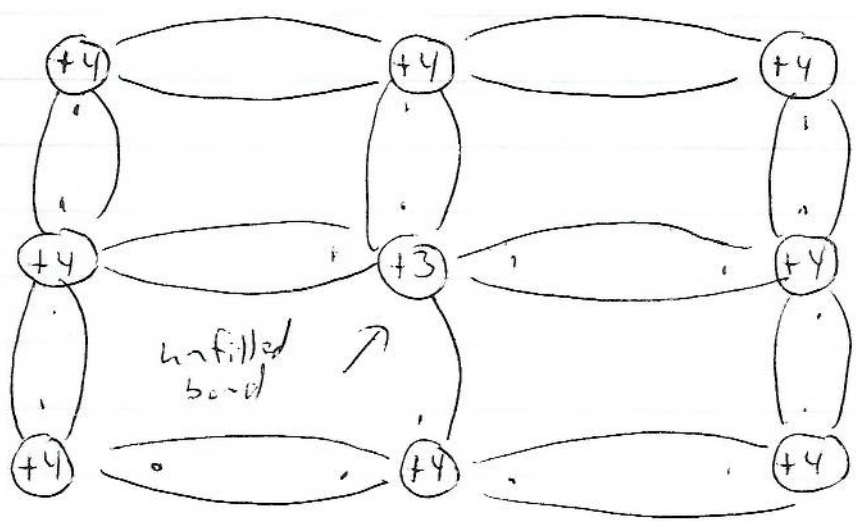
Sb

— carriers

n-type



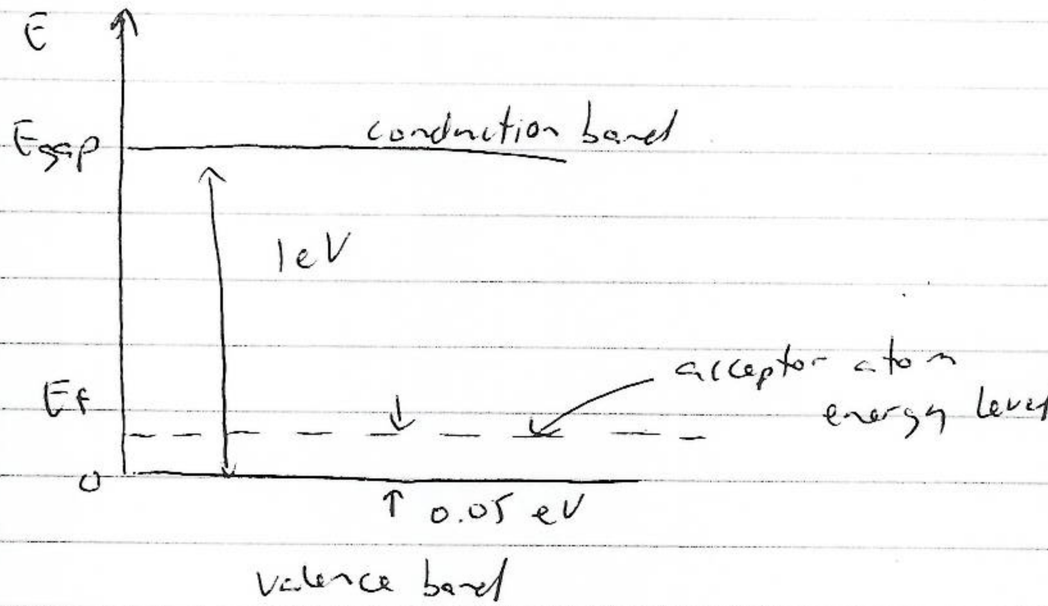
p-type



+3 B
Al
Ga
In

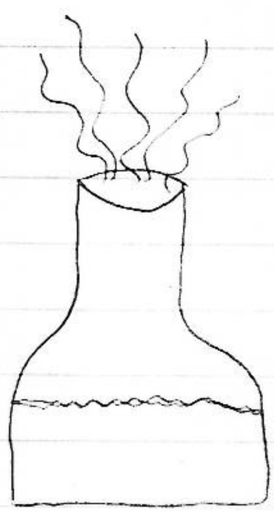
+ carriers (holes)

P-type



P-N Junctions

Consider an open bottle of perfume

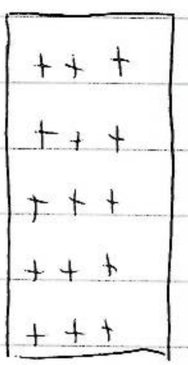


Diffuses from high density to low density

N-type

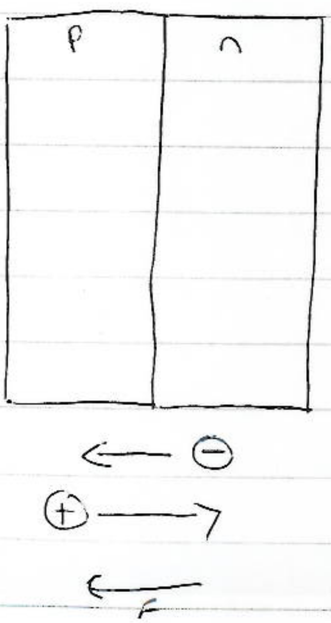
total charge = 0, but ⊖ can move

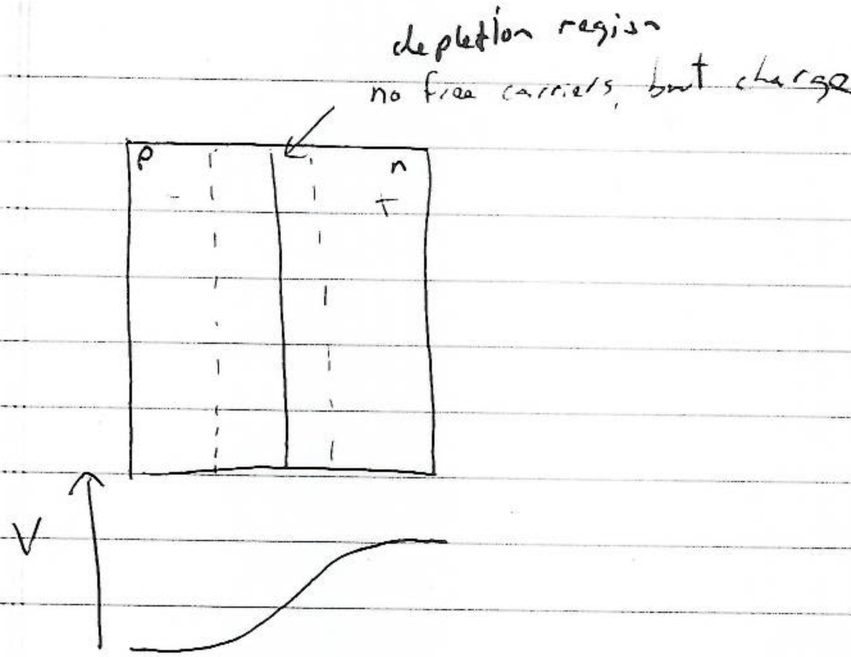
P-type



total charge = 0, but ⊕ can move

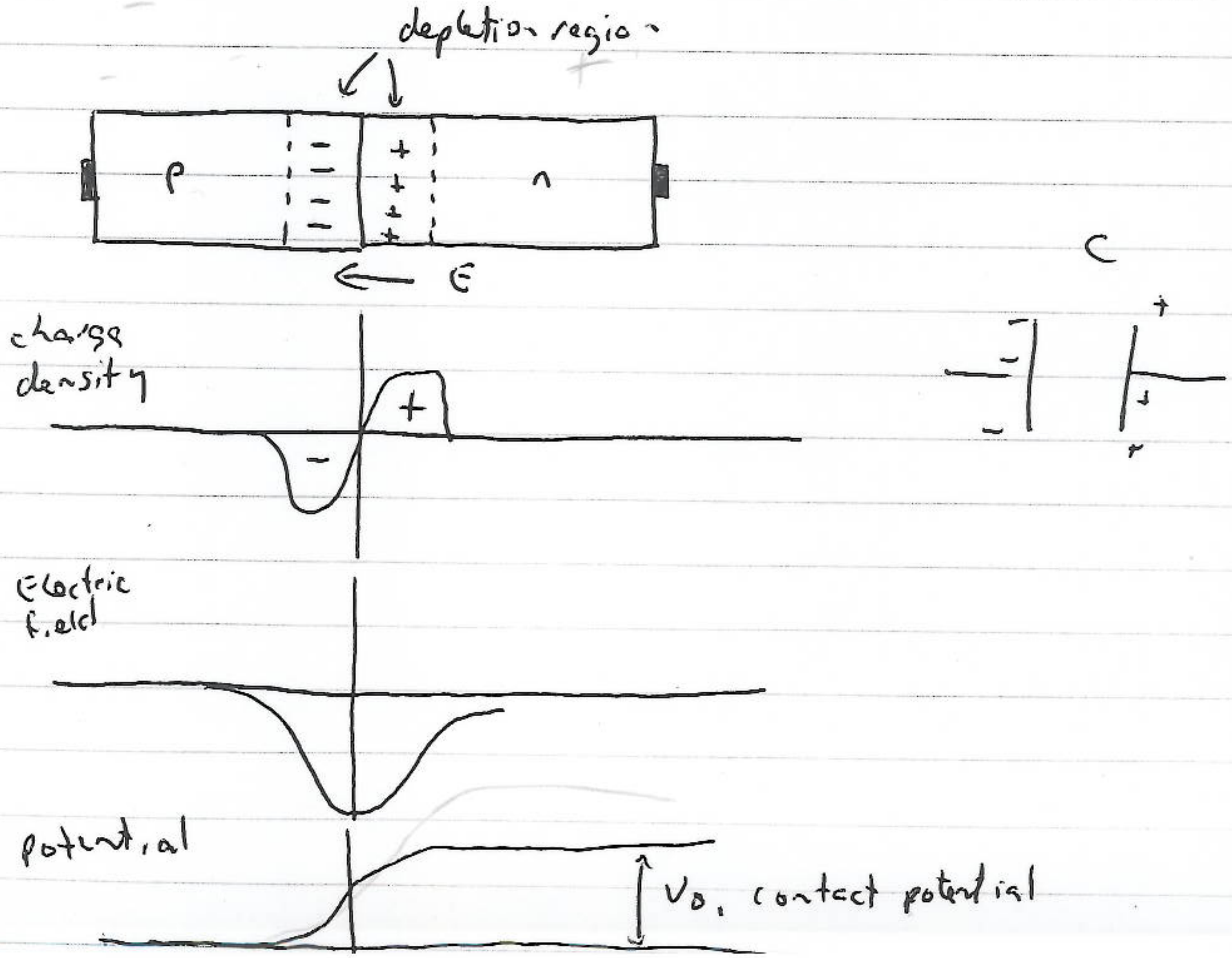
Put them together





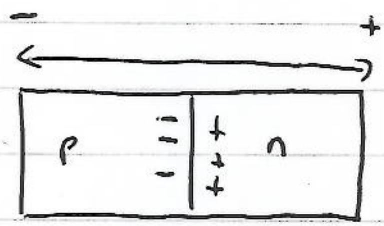
(f) Particle easily flows ←, but not →

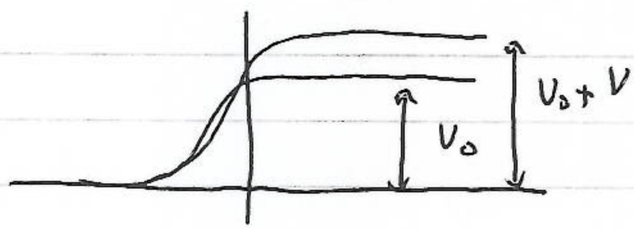
Open circuit



Diode acts as one-way valve for current

Reverse bias

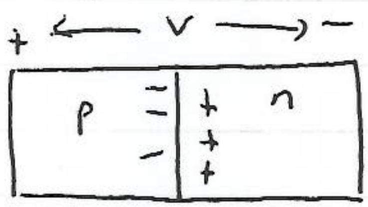


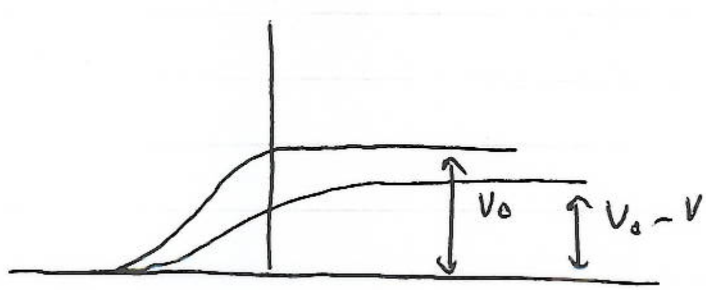


- Bigger depletion region
- p side + charges can move - see large potential barrier
- n " − " " "

Need kinetic energy > $e(V_0 + V)$ to conduct
Temperature dependent.

Forward bias



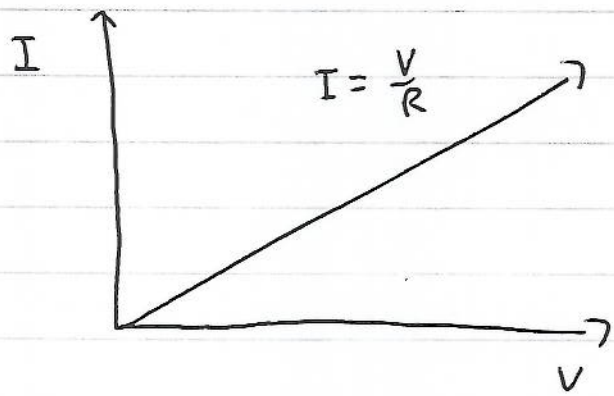


- Potential barrier decreased
- Depletion region decreased
- When $V > V_0 \rightarrow$ conduction

$V_0 \sim 0.5V$ for Si . Depends on T

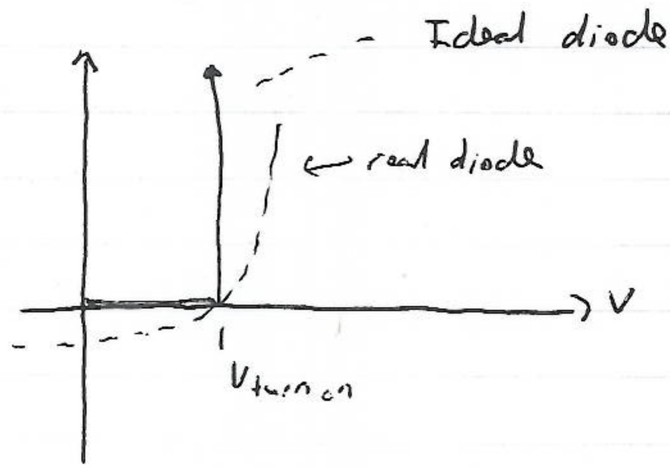
$$I = \frac{V - V_{turn\,on}}{R}$$ R: external resistance

Recall Ohms law



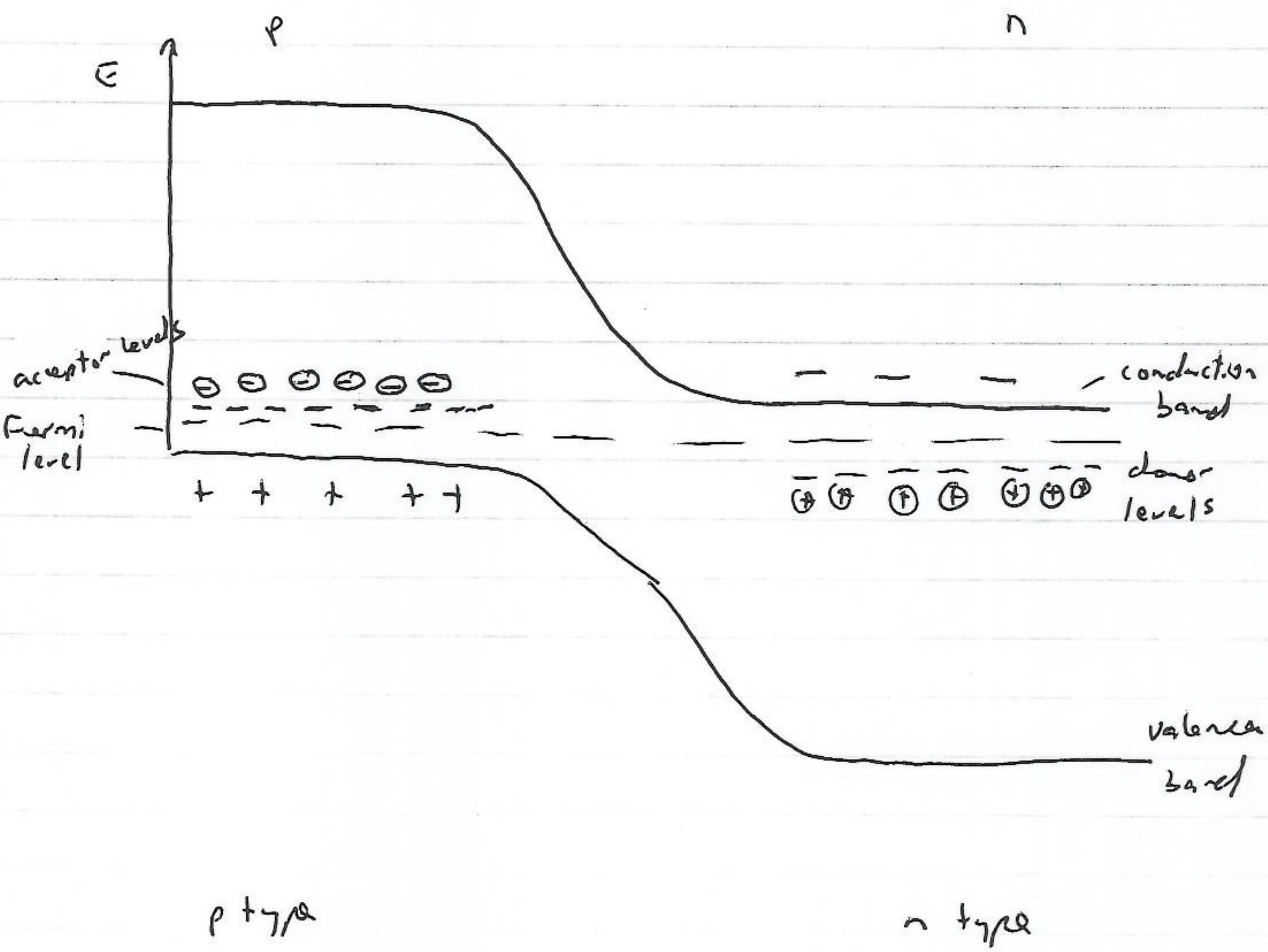
slope: $\frac{1}{R}$

Now we have



rectification

Energy level picture



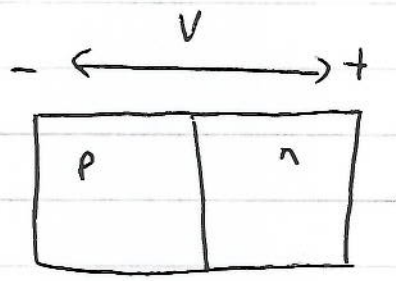
Electrons in C.B can't move ⟵

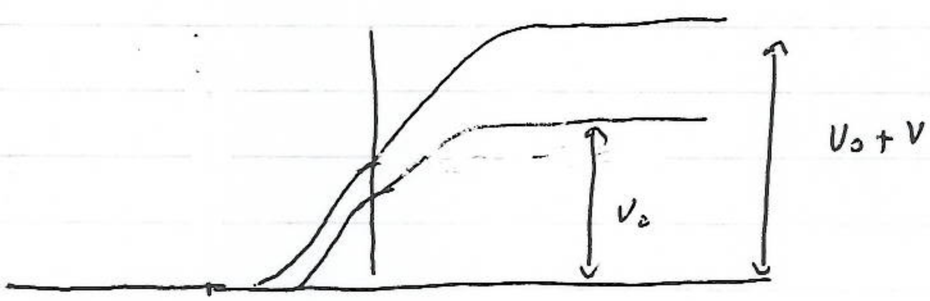
Holes in V.B can't move ⟶

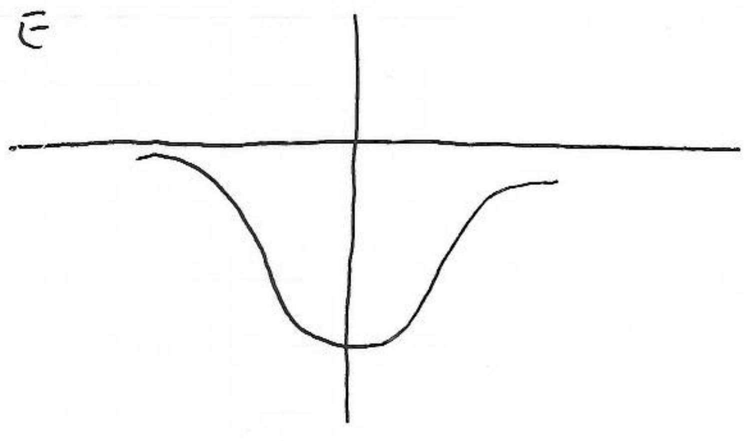
Zener diode (avalanche, reference, breakdown diode)

Reverse bias:

Recall





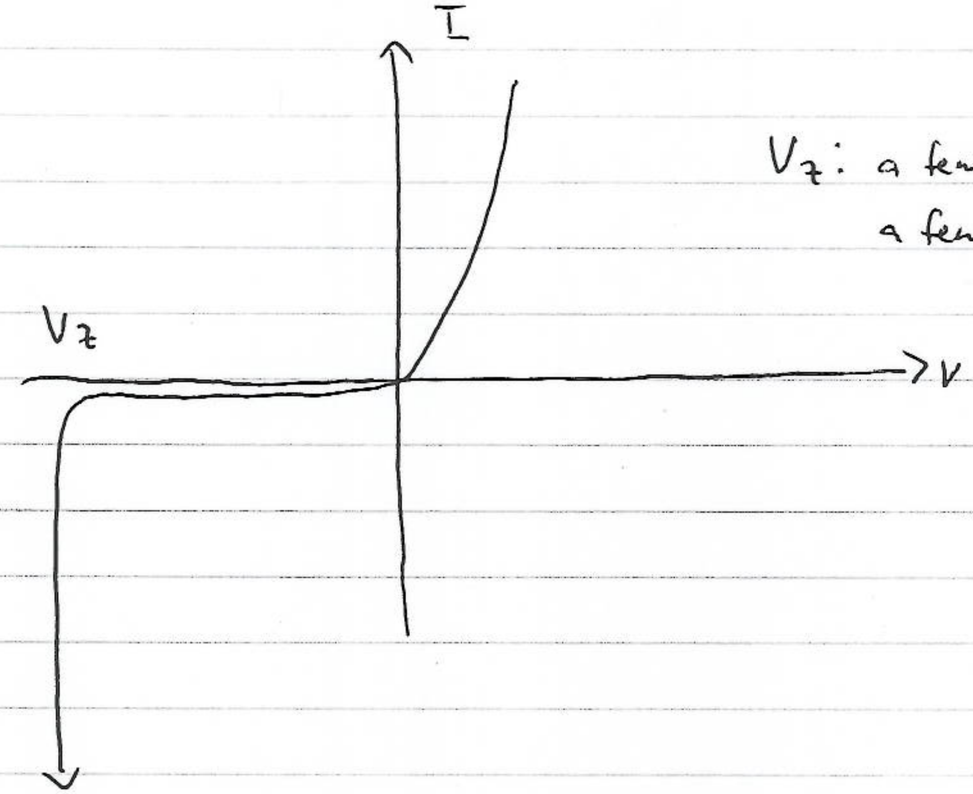


$E = -\nabla V$

bigger

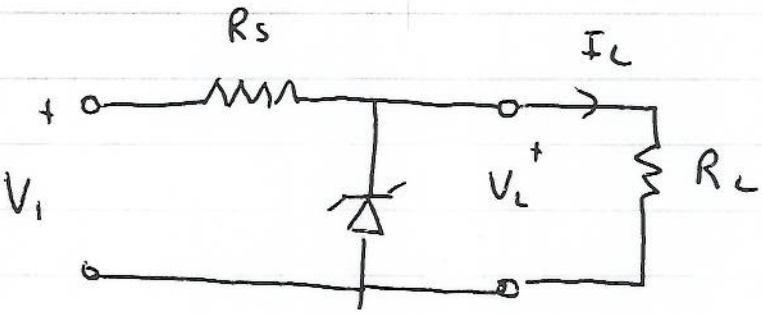
e^-'s pulled out of covalent bonds (ionized)

→ These electrons ionize others → avalanche



V_Z: a few volts to a few hundred volts

Zener diode Voltage Regulator

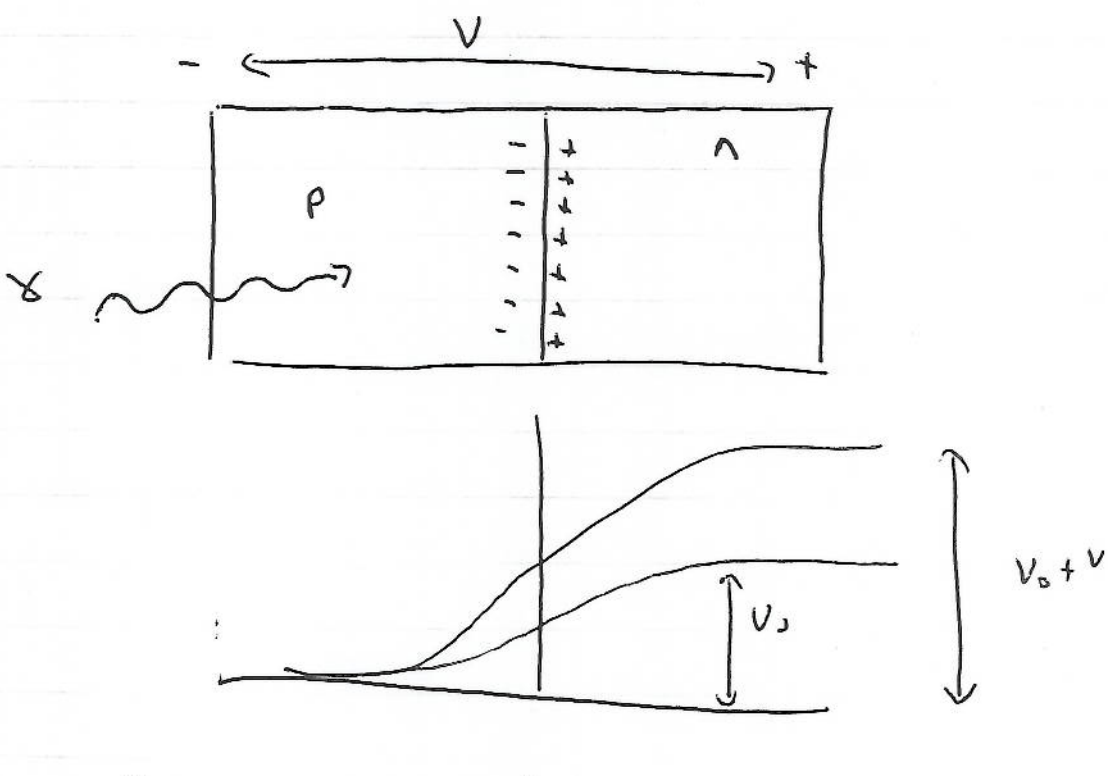


Zener keeps V_L from exceeding V_Z

Tunnel diode

The Photovoltaic diode

reverse bias

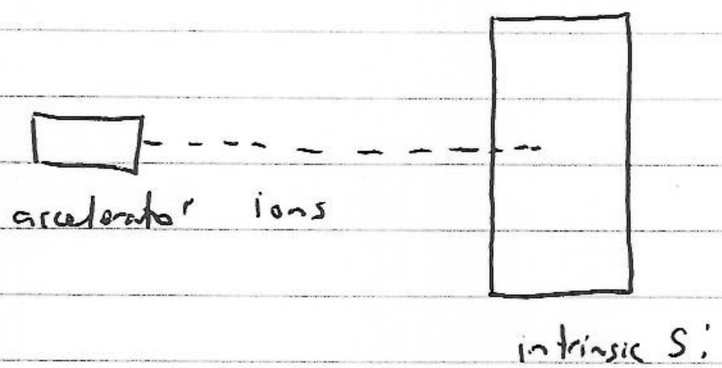


Photon creates e^--hole pair
swept by field in depletion region

Fabricatination Techniques

Method I

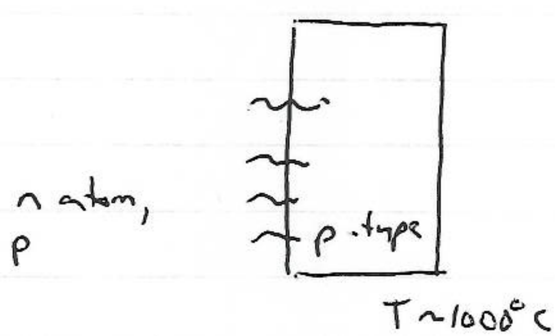
Ion implanted



Beam energy gives depth of penetration

Must be annealed

Method II

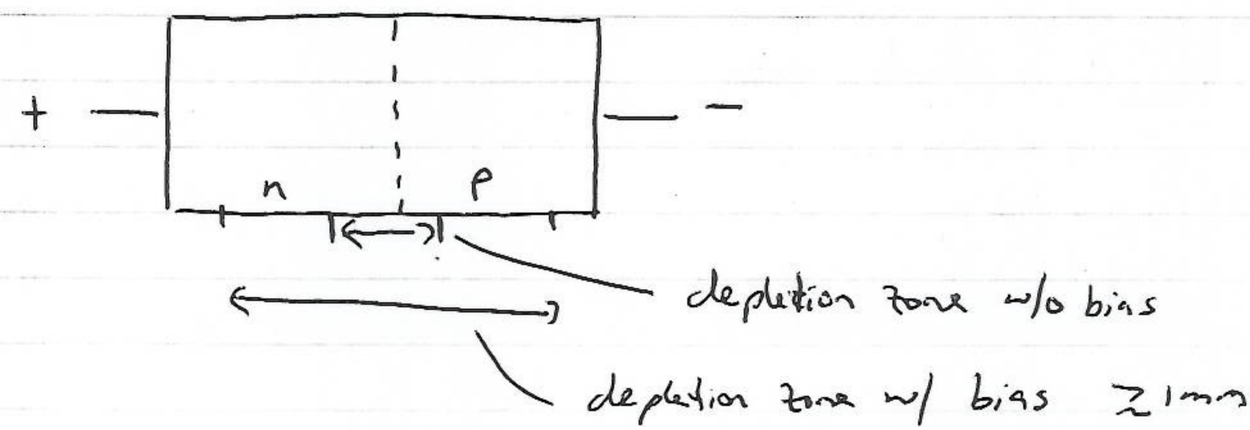


diffuse n-atom in

Junction depths controlled by
· concentrations
· diffusion time

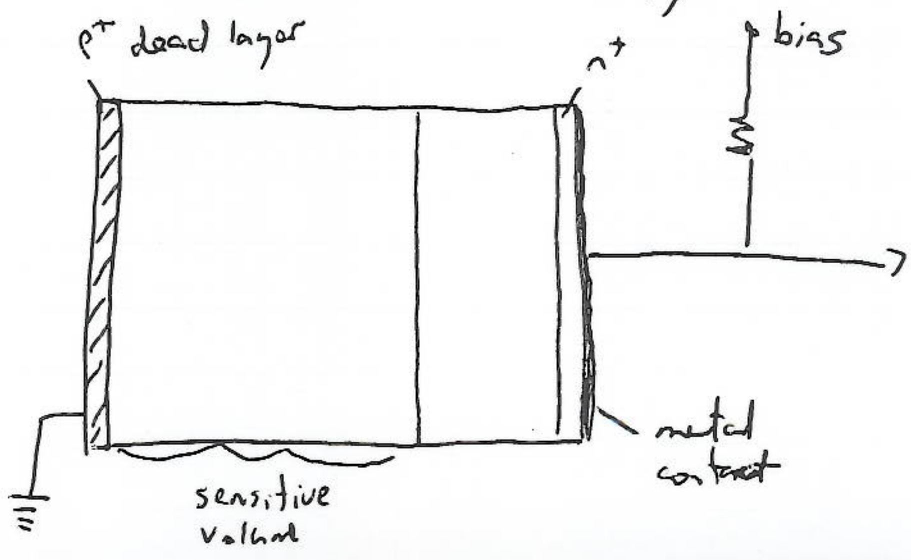
Particle detectors

Recall diode junction



Reverse bias increases depletion layer

Charged particle entering depletion layer ionizes
→ signal size ∝ to energy



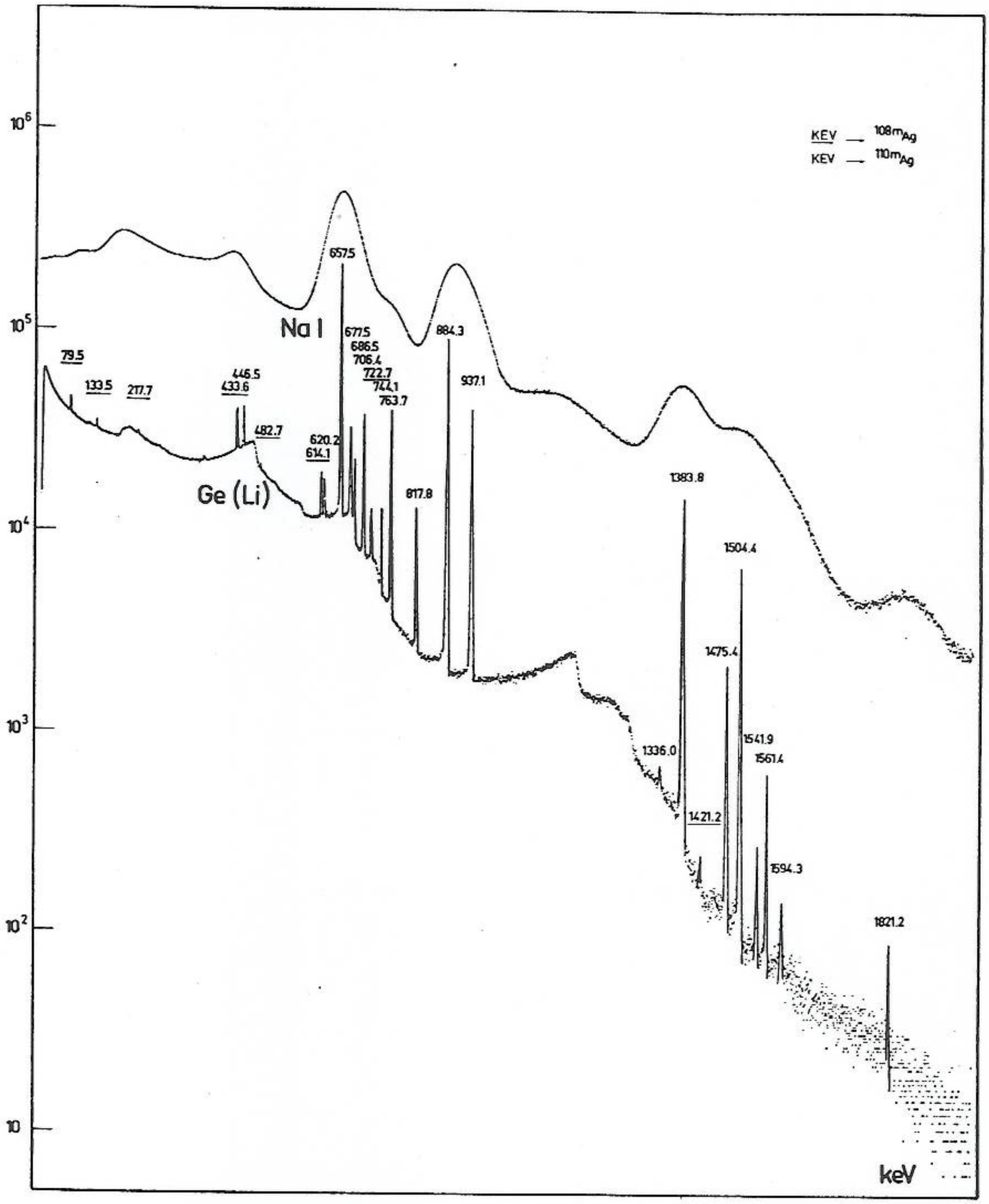


Figure 12-6 Comparative pulse height spectra recorded using a sodium iodide scintillator and a Ge(Li) detector. The source was gamma radiation from the decay of ^{108m}Ag and ^{110m}Ag. Energies of peaks are labeled in keV. (From Philippot.[9])

Diode Applications

Rectifiers:

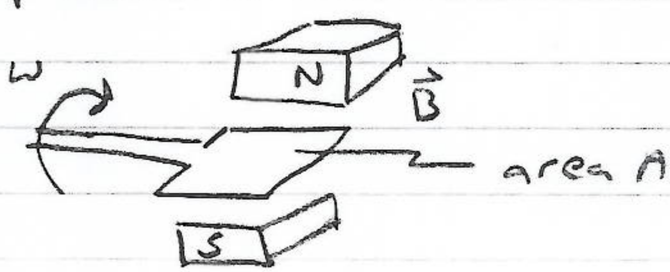
(1) Most power is delivered as AC

(2) Many devices need D.C.

Why (1)?

Reason 1:

Power production

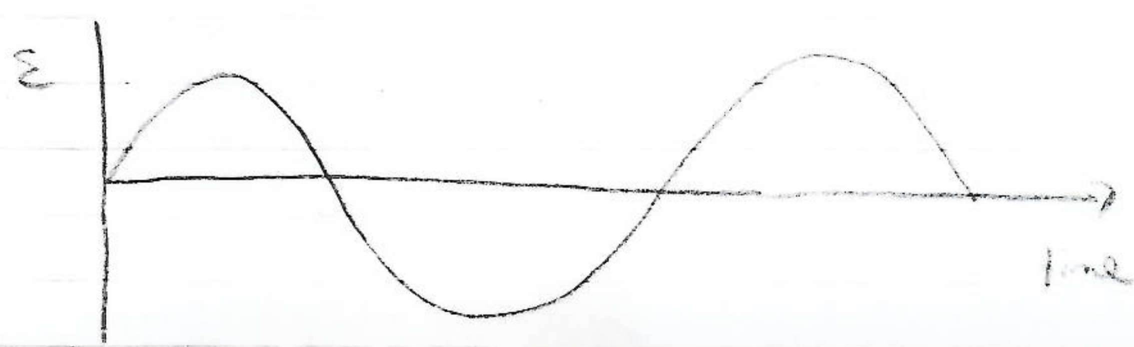


Rotate loop in B field

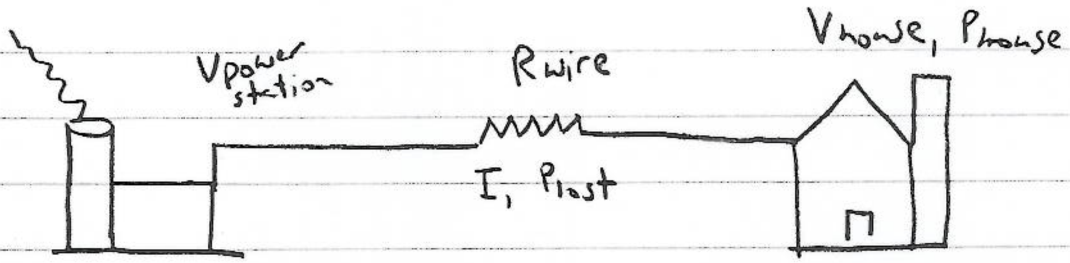
Faraday says

$$\mathcal{E} = -\frac{d\Phi}{dt} \qquad \Phi = BA\cos\omega t$$

$$\mathcal{E} = BA\omega \sin\omega t$$



Why not rectify (ie make it DC) at the power plant?



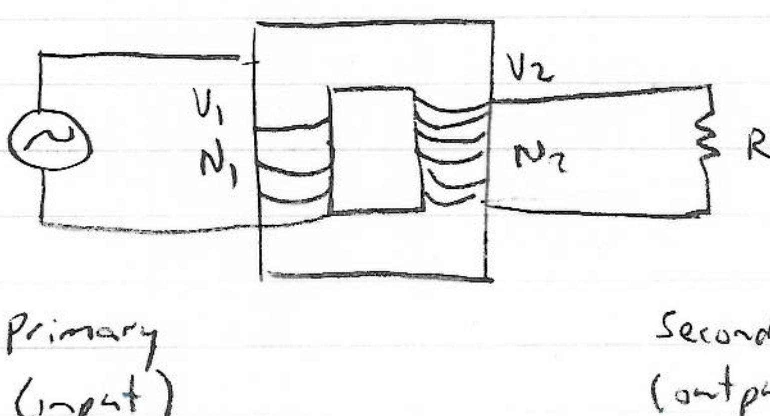
$$P_{lost} = I^2 R_{wire}$$
$$P_{house} = I V_{house}$$
$$= I V_{power\ station} - I^2 R_{wire}$$

For fixed R_{wire}, want high voltage, low current

Want to transmit at high voltage

Transformers

Increase or decrease A.C. voltage as needed



schematic

$$V_1 = -N_1 \frac{d\Phi}{dt}$$

$$V_2 = -N_2 \frac{d\Phi}{dt}$$

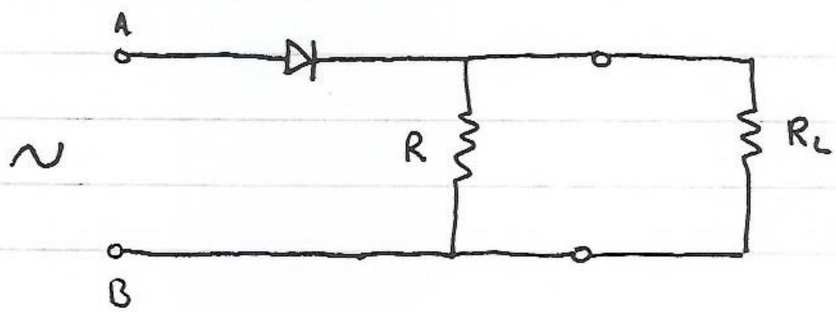
$$\frac{V_2}{V_1} = \frac{N_2}{N_1}$$

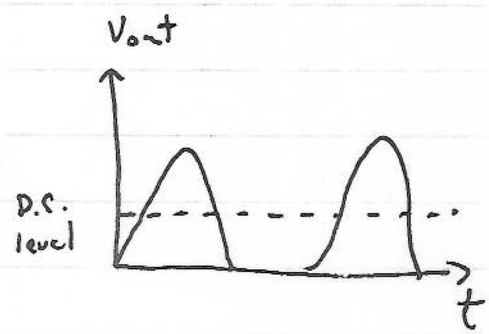
$N_2 > N_1$ step up

$N_2 < N_1$ step down transformer

<u>Rectifiers</u>

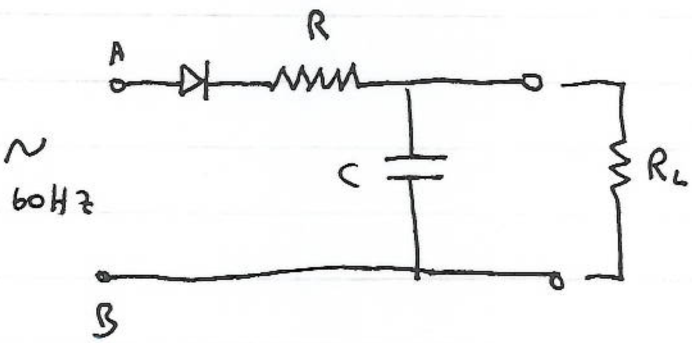
- half wave

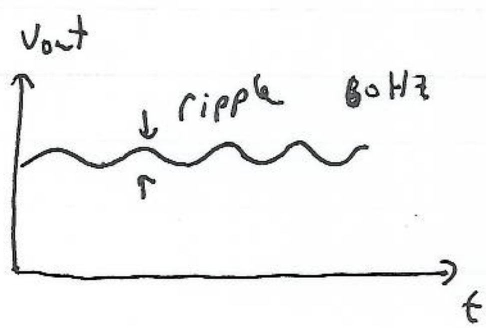




Half wave: $V(t) = V_0\left(\frac{1}{\pi} + \frac{1}{2}\cos\omega t + \frac{2}{3\pi}\cos 2\omega t + \ldots\right)$

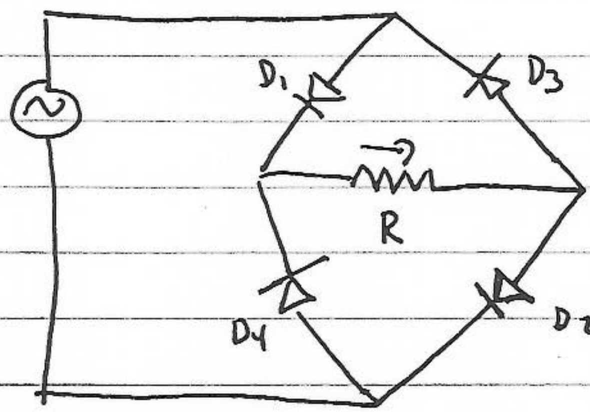
w/ low pass filter

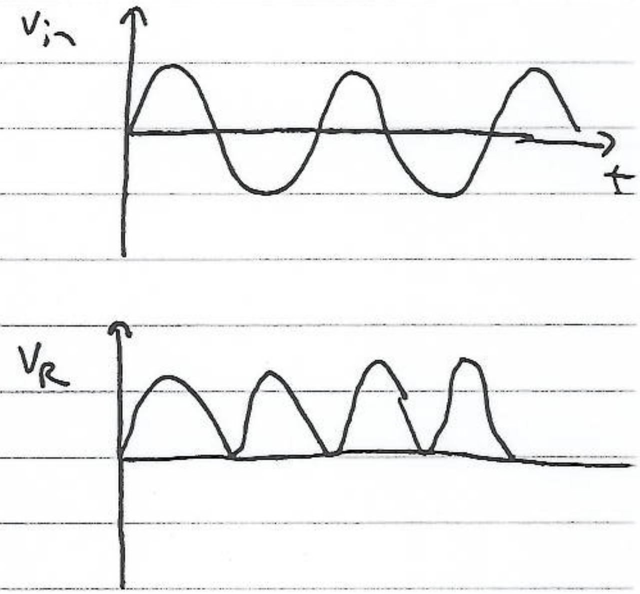




Not efficient

Full wave rectification

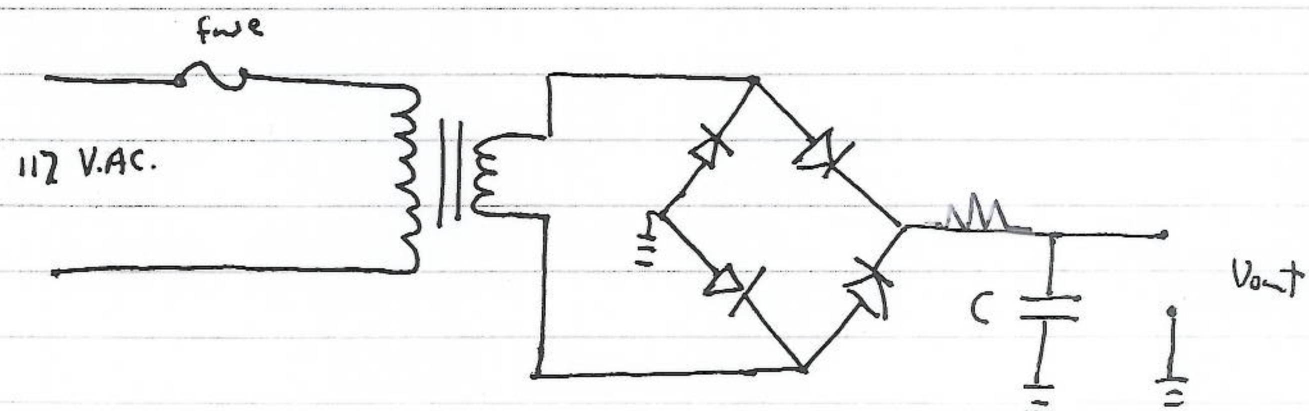


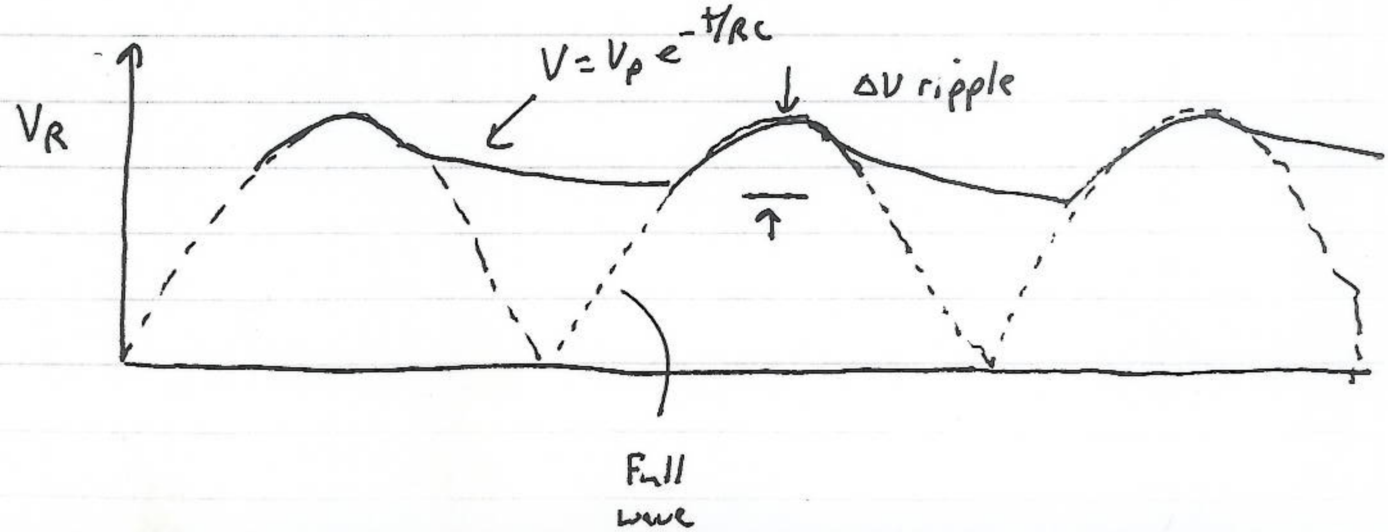


Full wave

$$V(t) = V_0\left(\frac{2}{\pi} + 0 + \frac{4}{3\pi}\cos 2\omega t + \dots\right)$$

w/ low pass filter

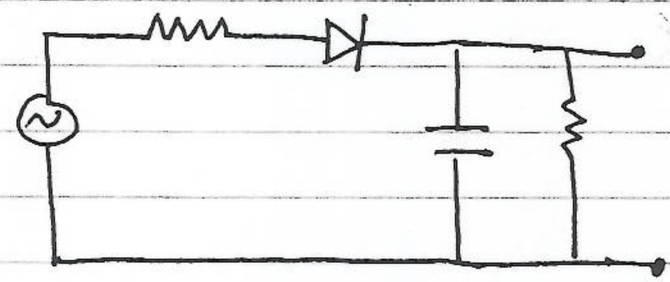


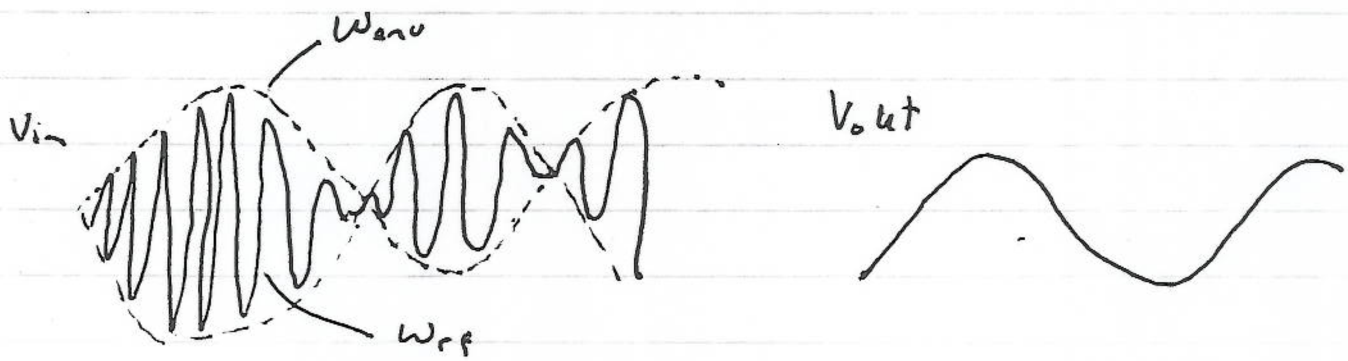


Let's say we want $\Delta V = 2V$ for $1 Amp$

$$C \approx \frac{I\, t_0}{\Delta V} = \frac{1 \times \frac{1}{120\,sec}}{2V} = 4166\,\mu F$$

Peak detector – r.f. signals





Diode rectifies

Low pass filter choose $W_{rf} \gg \frac{1}{RC}$

but

$W_{env} < \frac{1}{RC}$

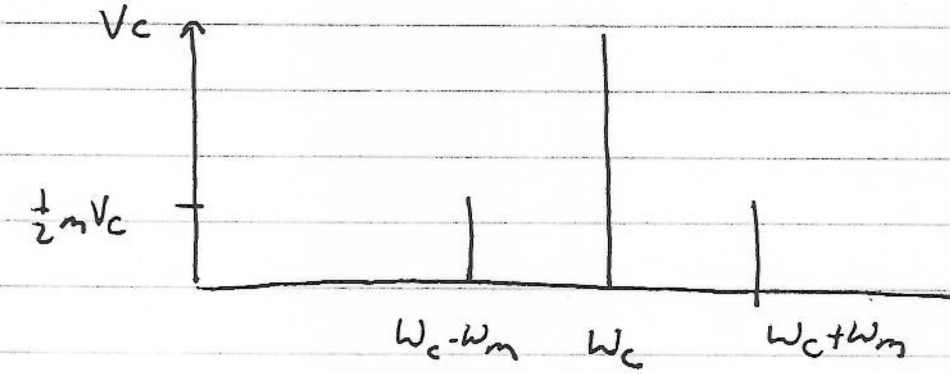
AM

$$V_{AM} = (1 + m \sin\omega_m t) V_c \sin\omega_c t$$

$$m = V_m / V_c$$

$$V_{AM} = V_c \sin\omega_c t + m V_c \sin\omega_m t \sin\omega_c t$$

$$= V_c \sin\omega_c t + \tfrac{1}{2} m V_c \cos(\omega_c - \omega_m)t - \tfrac{1}{2} m V_c \cos(\omega_c + \omega_m)t$$



FM frequency modulation

$$V_{FM} = \cos(\omega_c + k f(t))t$$

PM phase modulation

$$V_{PM} = \cos(\omega_c t + k f(t))$$

} angle modulation

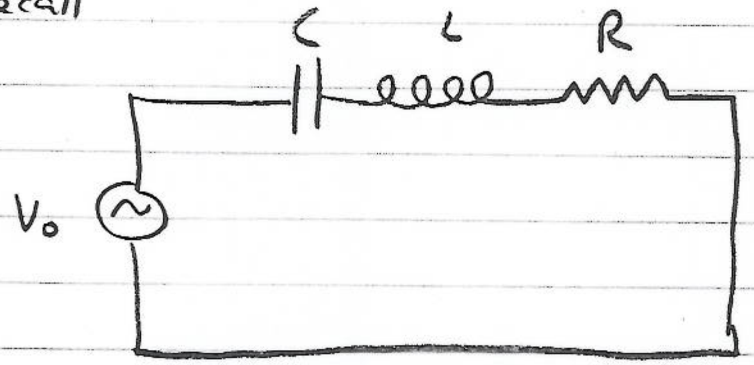
FM 88 - 108 MHz Δf 75 kHz

AM 0.54 - 1.6 MHz

FM not used on AM band → only 6 stations

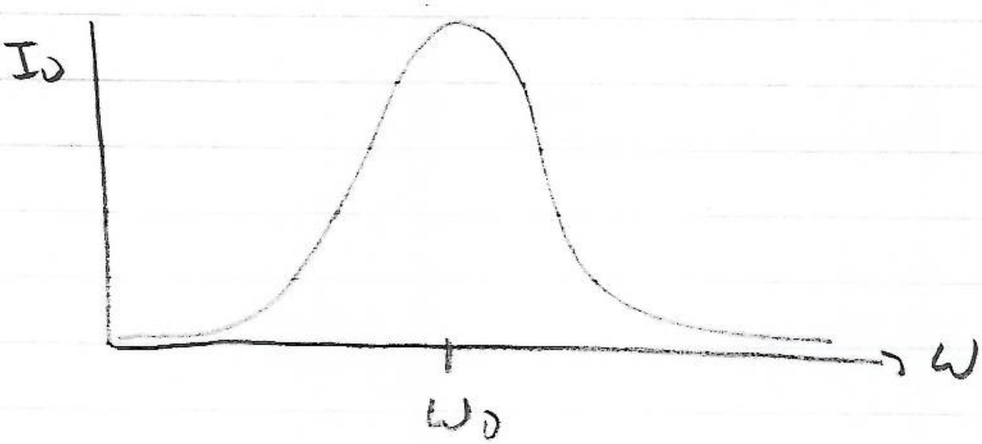
FM detector

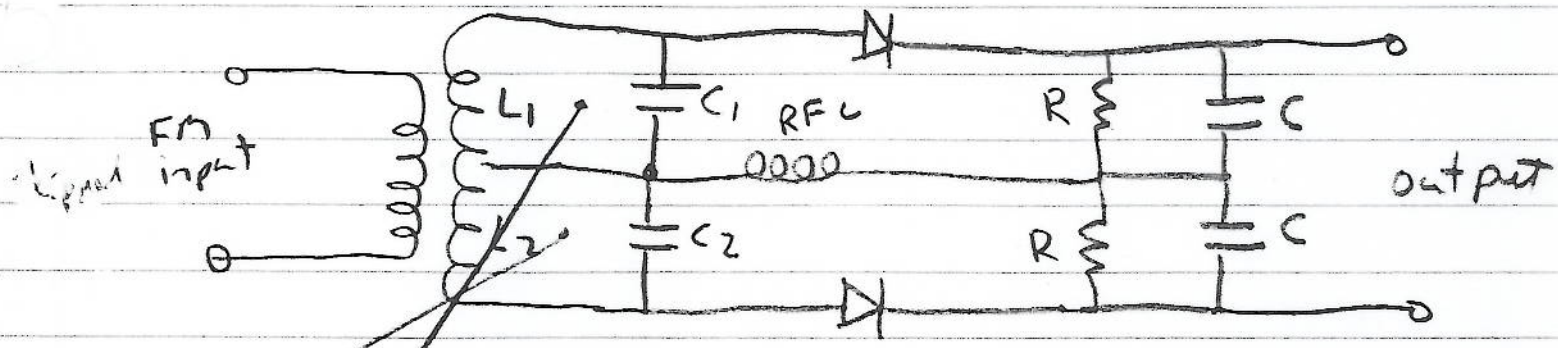
Recall



$$I_0 = \frac{V_0}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}$$

$$\omega_0 = \frac{1}{\sqrt{LC}}$$



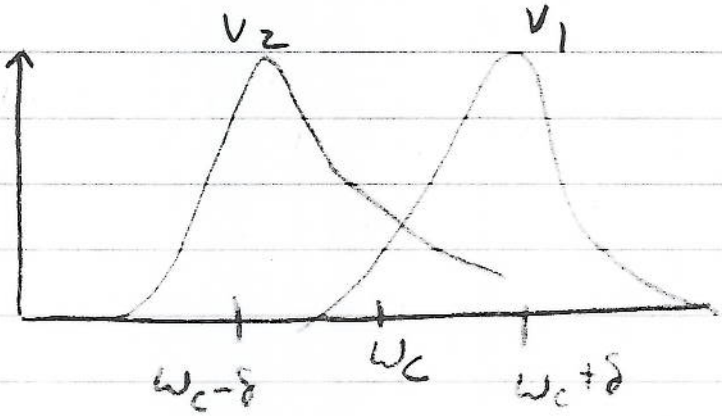


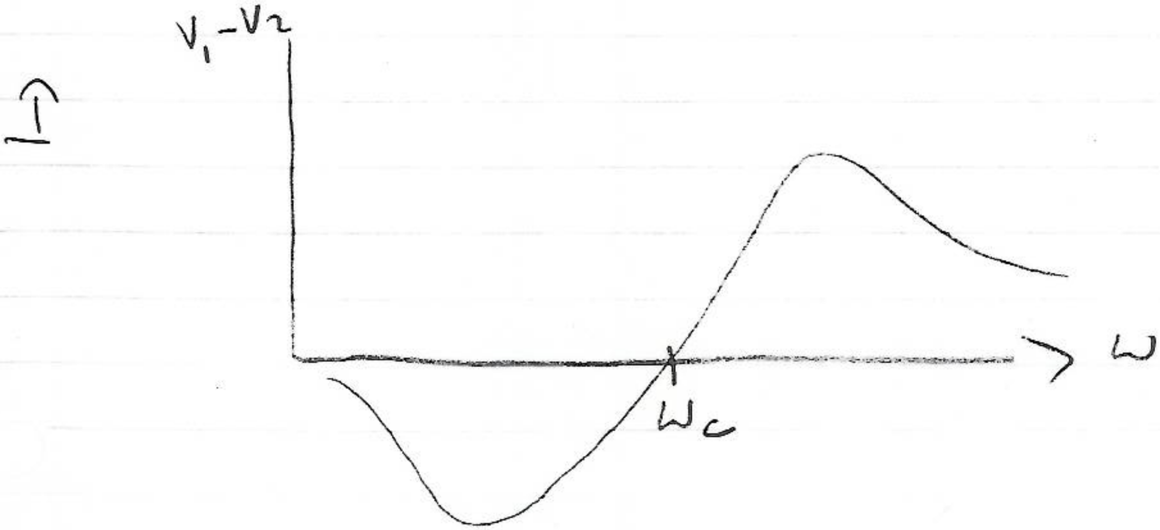
$T_c \ll RC \ll T_m$

$\omega_c \gg \frac{1}{RC} \gg \omega_m$

resonates at $\omega_1 = \frac{1}{\sqrt{L_1 C_1}} = \omega_c + \delta$

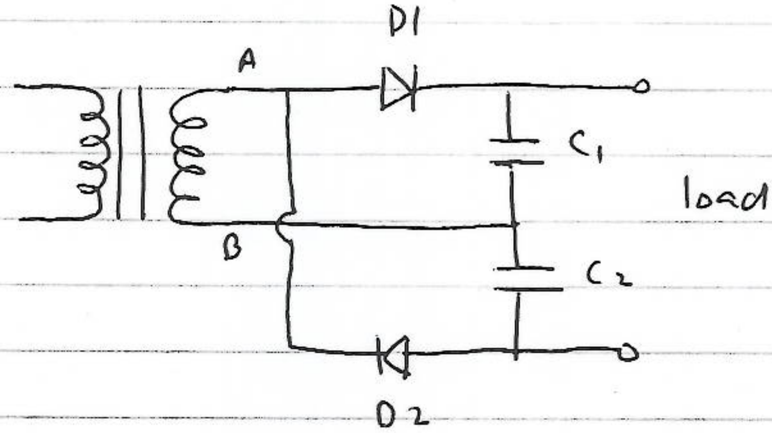
$\omega_2 = \frac{1}{\sqrt{L_2 C_2}} = \omega_c - \delta$





Voltage doubler

did

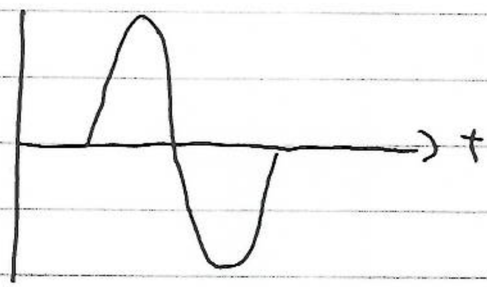


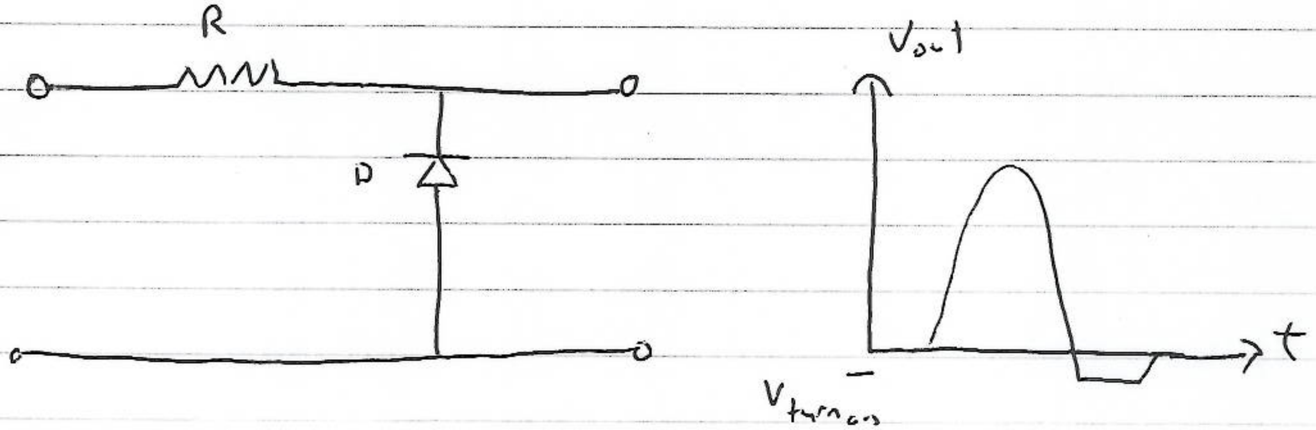
A+ → C_1 charges D1 conducts

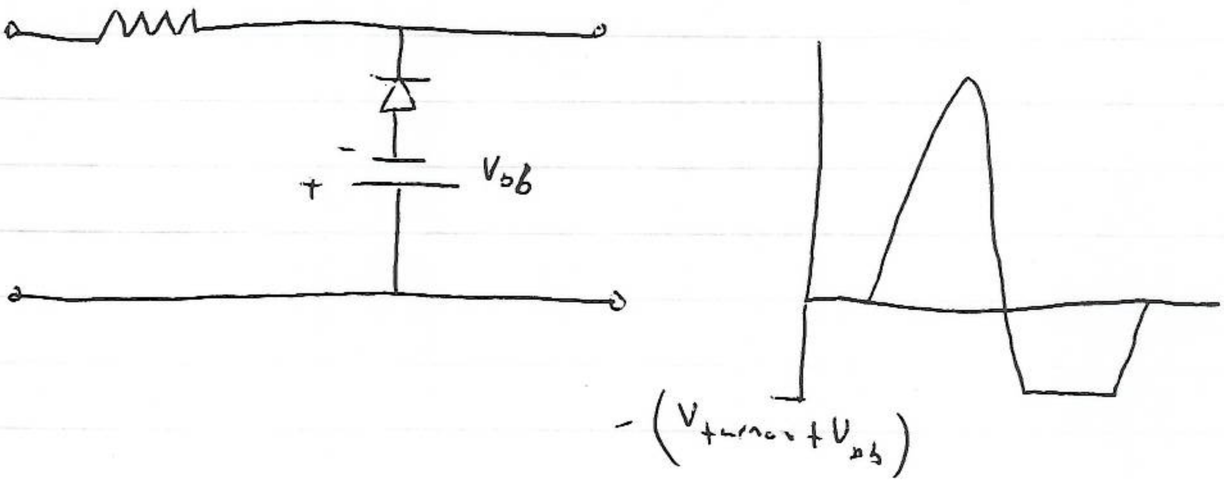
A− D_2 conducts C_2 charges

Clipping circuit

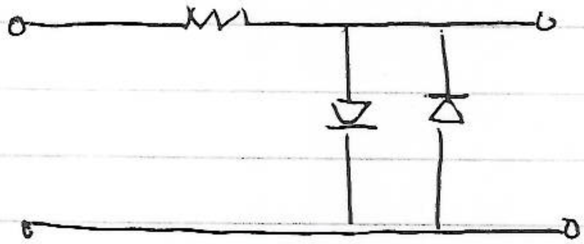
did

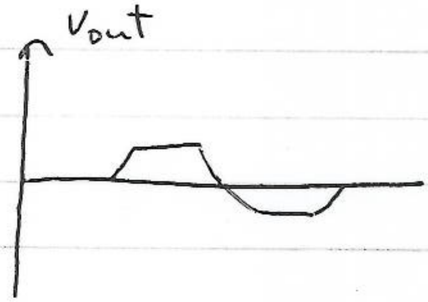




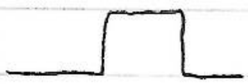


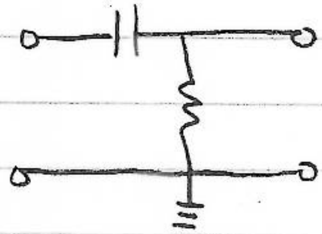
skip

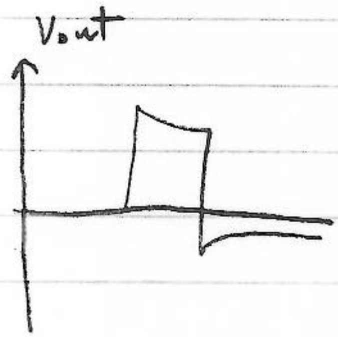


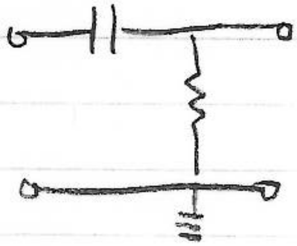


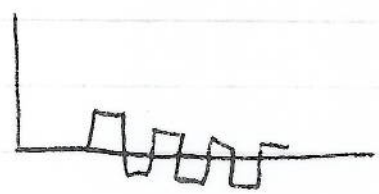
Baseline restoration

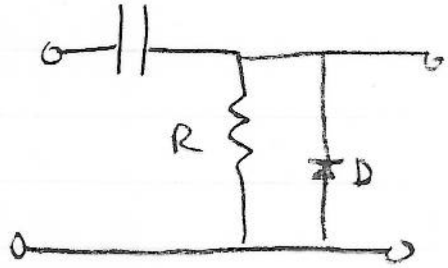


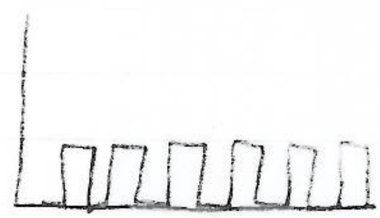










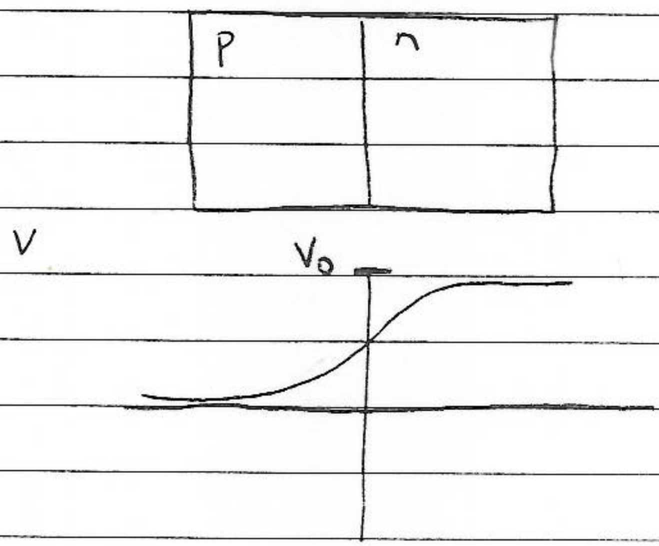


The Bipolar transistor

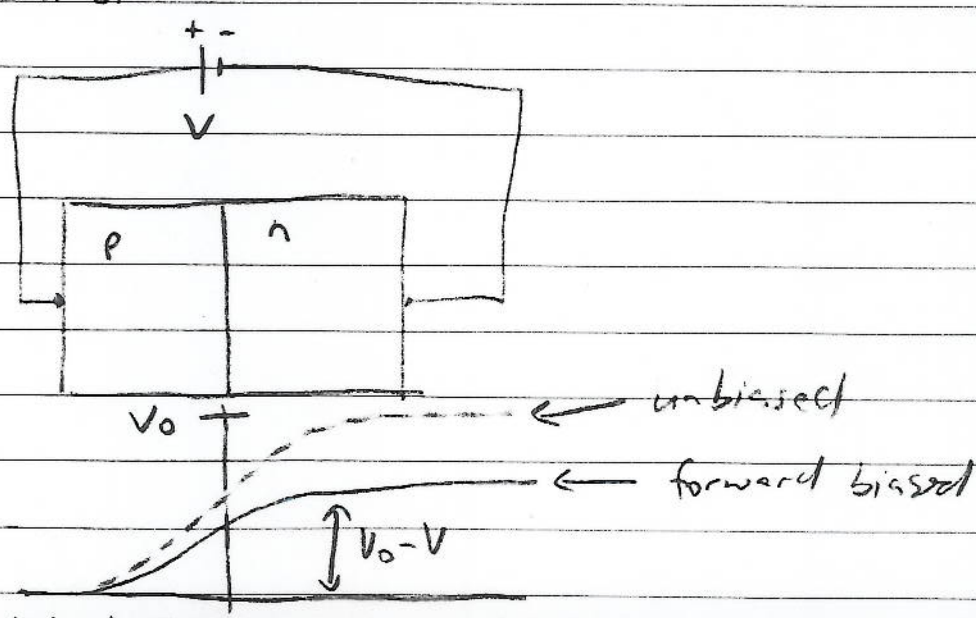
Punchline: Control a large current w/ a small one.

Recall n-p junction

unbiased

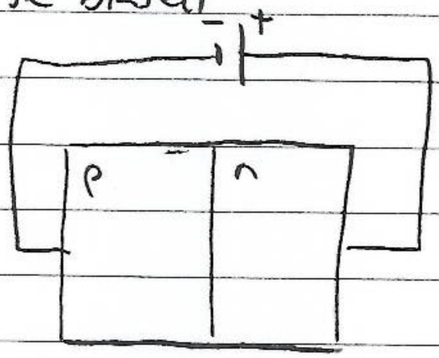


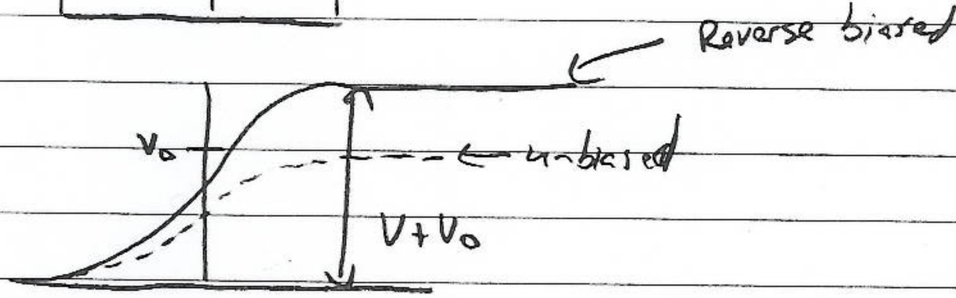
Forward biased



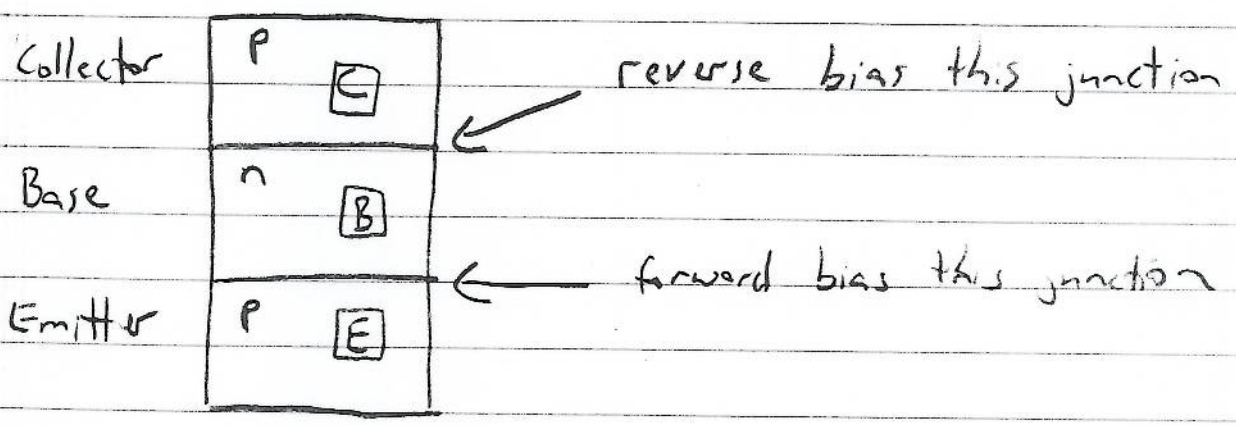
If $|V| > |V_0|$ → conduction

b Reverse biased

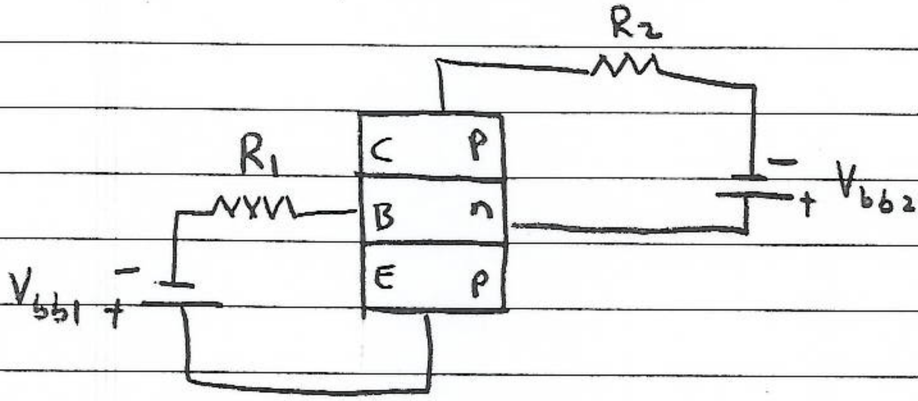




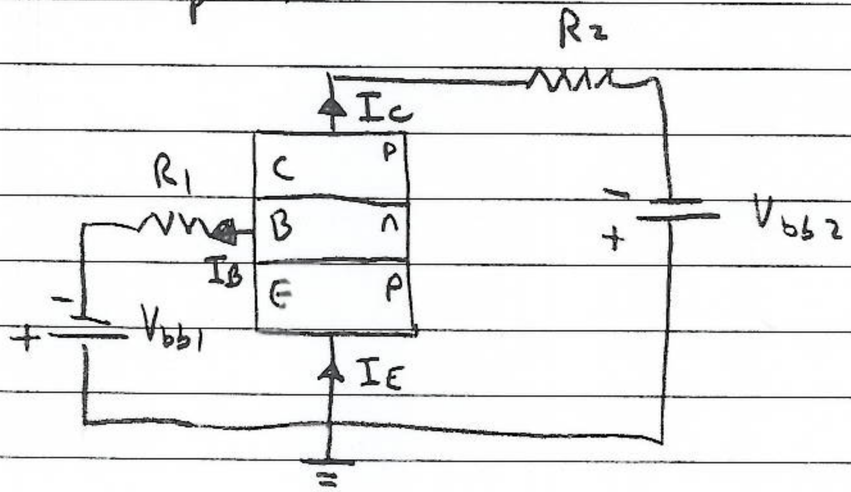
Now consider two junctions as follows



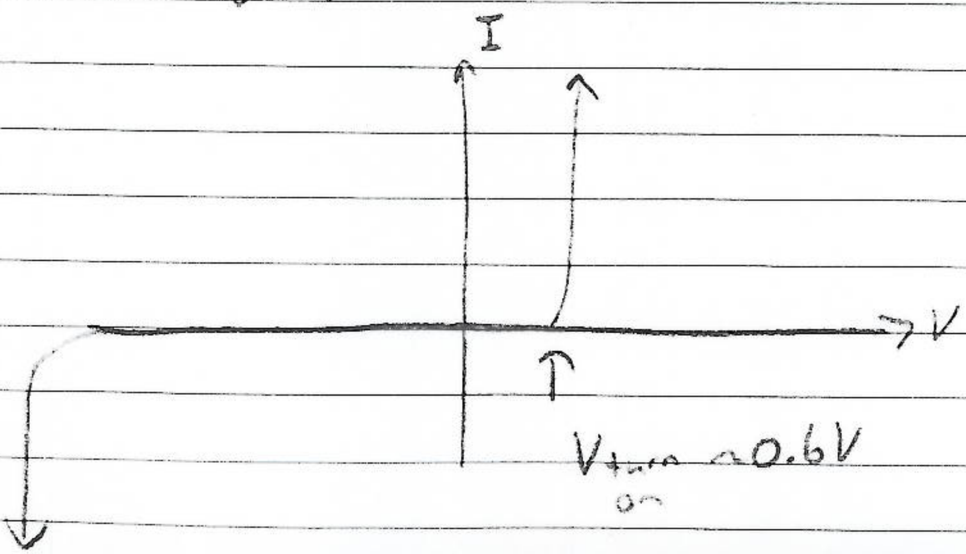
One way to realise this



In practice



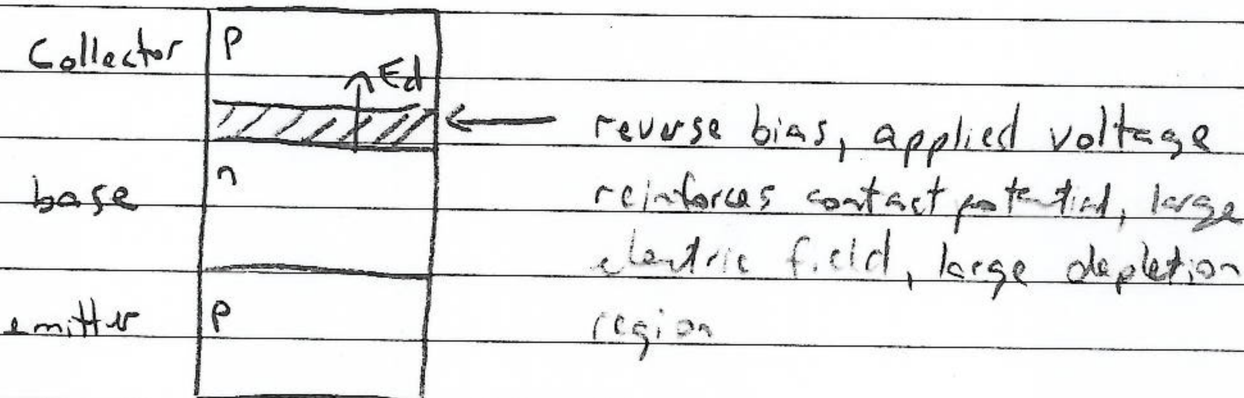
These two circuits are almost the same Why?
Recall diode



Since B−E junction is forward biased $V_{BE} \sim 0.6V$ (small)

Observations:

(1) Resistance between B & E is small (forward biased)
(2) Resistance between B & C is large (reverse biased):



(3) $I_E = I_B + I_C$

Might expect I_B to be large compared to I_C but, we do a trick to make the reverse true

$I_B \ll I_C$

How do we do this?

Consider holes injected into emitter. Three things can happen

1) Combine w/ free electrons in base
2) Diffuse thru base, combine w/ electrons at wire lead attached to base

} give I_B

3) Diffuse across base to collector, be swept by Ed into collector

Fabrication trick:

Make base thickness small

$t_{base} \ll$ mean free path of holes

* Holes usually are across C−B boundary before they have chance to recombine

Typically $I_B \sim 0.02\, I_E$

Define $\alpha = I_c / I_E \quad (\cong 0.99)$

$$I_E = I_B + I_c$$

$$\frac{I_c}{\alpha} = I_B + I_c$$

$$I_c\left(\frac{1}{\alpha} - 1\right) = I_B$$

$$\frac{I_c}{I_B} = \frac{\alpha}{1-\alpha}$$

$$I_B = I_E - I_c = I_E(1-\alpha)$$

$$I_c = \alpha I_E$$

Also define $\beta = \frac{\alpha}{1-\alpha}$

$I_C = \beta I_B$ β : 20 – 200

- I_B is small
- Change I_B a little, I_C changes a lot.
- If I_B considered input → I_C is amplified version of I_B

Amplification:

output > input

Voltage gain

$$A_v = \frac{V_{out}}{V_{in}}$$

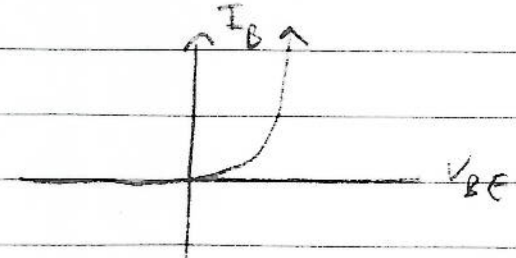
power gain

$$A_p = \frac{P_{out}}{P_{in}}$$

current gain

$$A_i = \frac{I_{out}}{I_{in}}$$

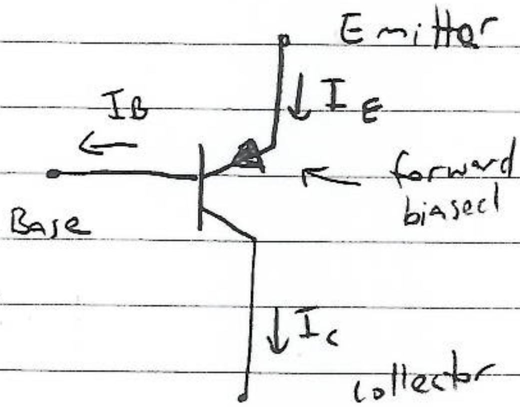
E-B junction forward biased:

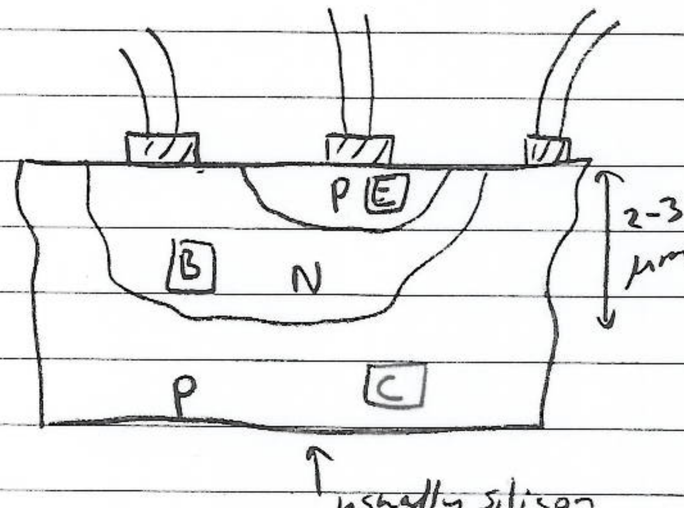


Small ΔV_{EB} → large I_B → even larger I_C

($I_C = \beta I_B$)

Fabrication - PNP



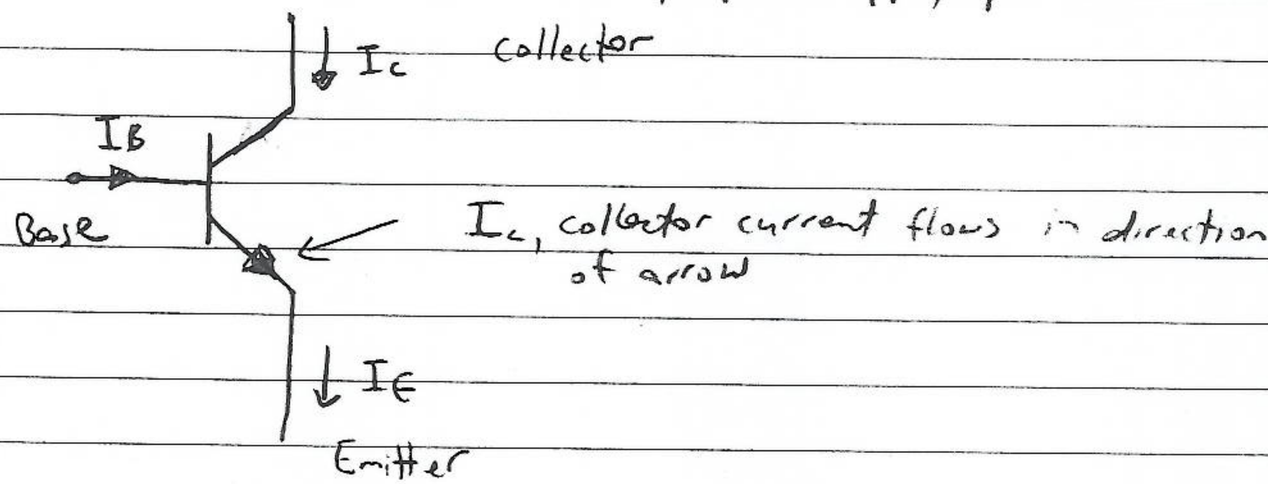


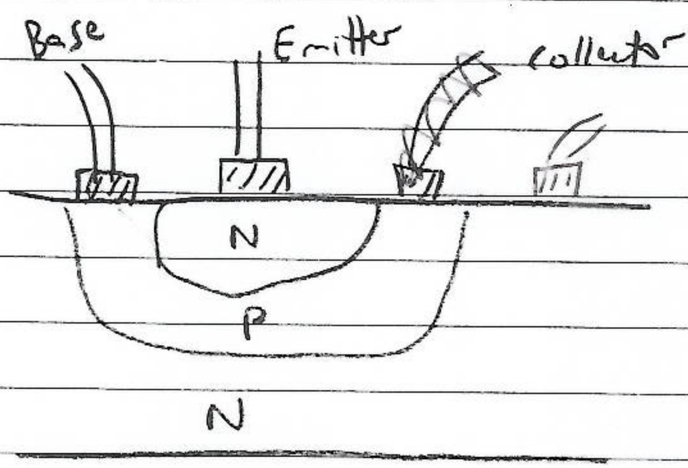
Collector is big
- I_c big
- Lot of heat to dissipate

Emitter doping is larger
- More holes going from emitter to base than electrons in base
- Minimizes recombination (1) & (2)
- Gives larger α & β

Can also have NPN

· Work like PNP's w/ power supply polarities reversed





Transistor is:

· 3 terminal device

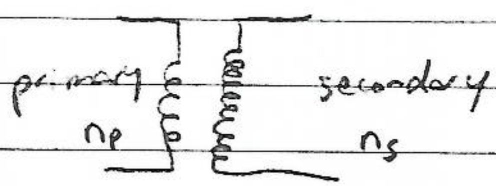
· We are interested in I-V curve between two of the terminals

· 3^{rd} terminal controls device

→ different I-V curve for each condition of 3 terminal

· active device - power gain (with power supply)

Ex of passive device:
Transformer



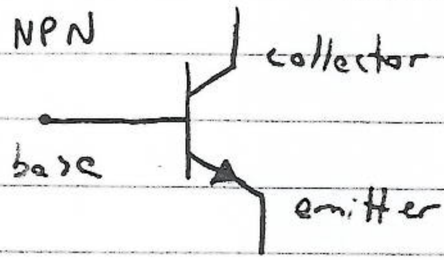
Voltage gain $\dfrac{V_s}{V_p} = \dfrac{n_s}{n_p}$

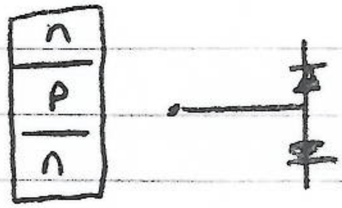
But no power gain

$\dfrac{I_s}{I_p} = \dfrac{n_p}{n_s}$ $P_p = P_s$, passive device

BJT

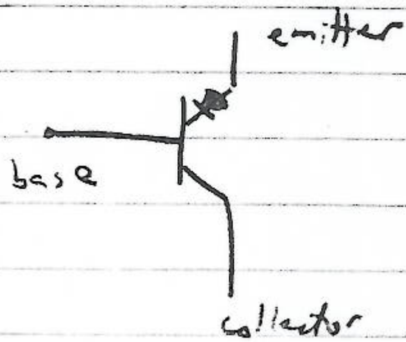
NPN

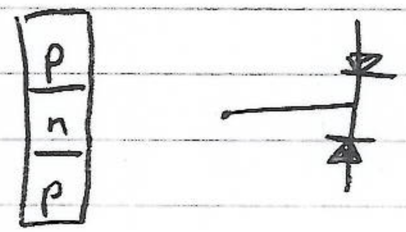




"never points in"

PNP

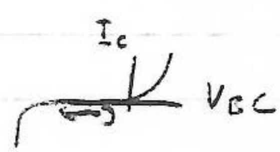




NPN

BE diode forward biased

BC diode reversed biased



EC current flows in direction of arrow

Biasing and Graphical Treatment of BJT

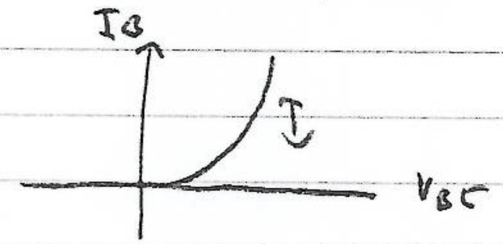
transistor - 3 terminals
input & output

1) common emitter
2) common collector
3) common base

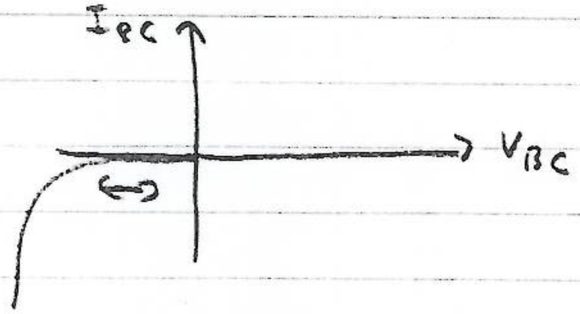
Common Emitter characteristics npn

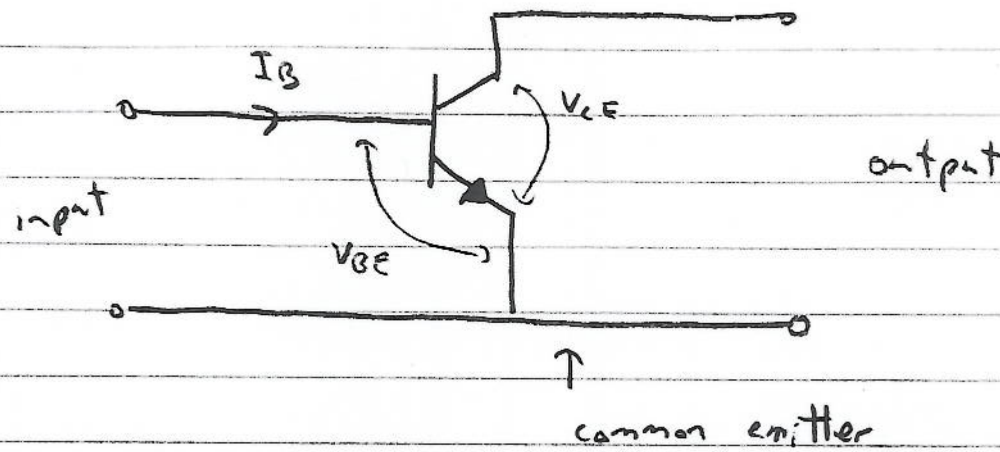
$V_{BE} \sim 0.6\ V$

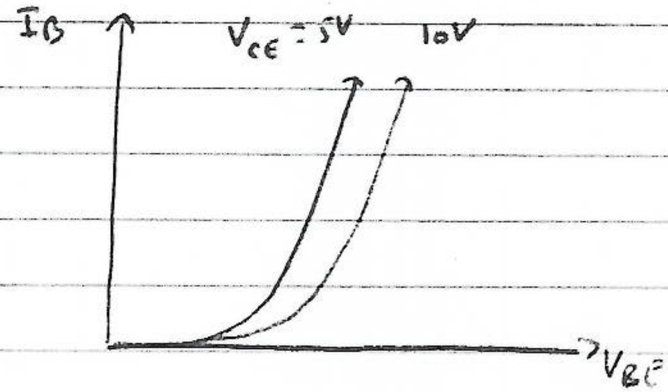
I_B varies a lot, look at it

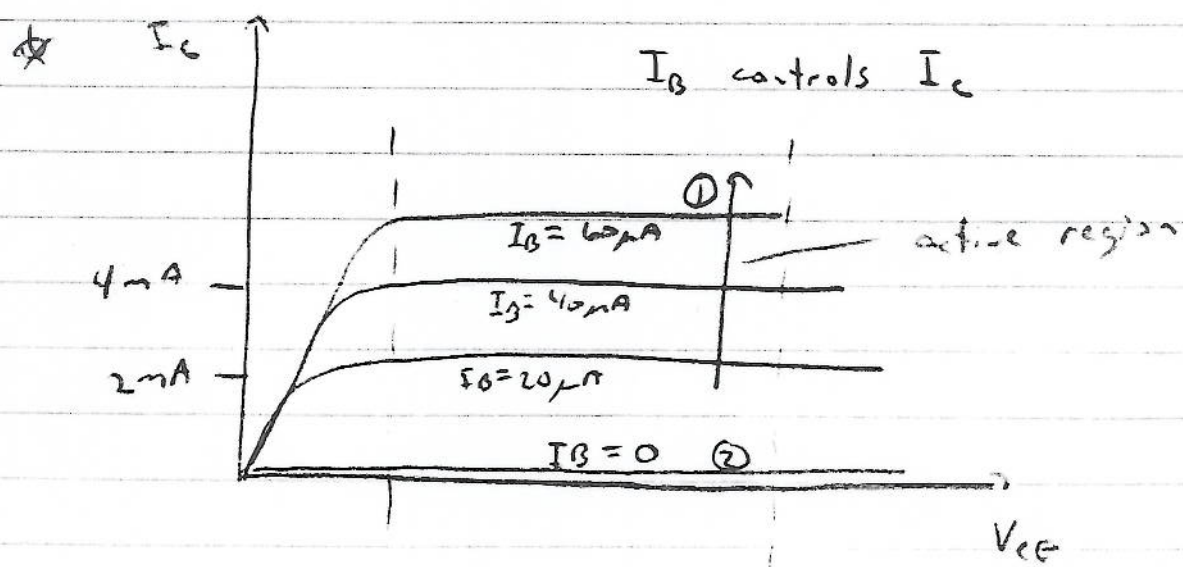


Also, focus on V_{BC}









I_C independent of V_{CE}, but increases if I_B increases

3 regions of operation

* (1) active region

$$I_C = \beta I_B$$

(2) cutoff region

$I_C \to 0$ EC open circuit

(3) saturation region

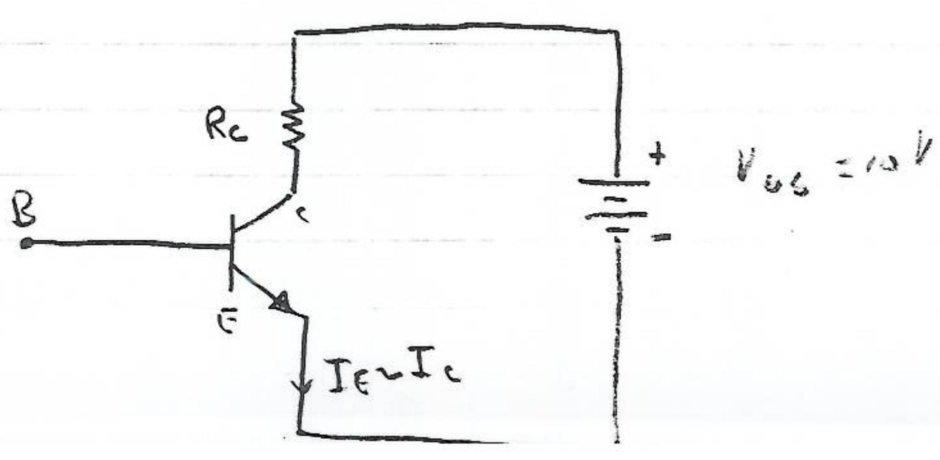
$V_{BC} \to 0$ EC short circuit

V_{CE} cannot supply enough current

☆ Current amplification

(1) base emitter forward biased
(2) base collector reverse biased
(3) stable (temperature, small perturbations in input, perturbations in transistor parameters)

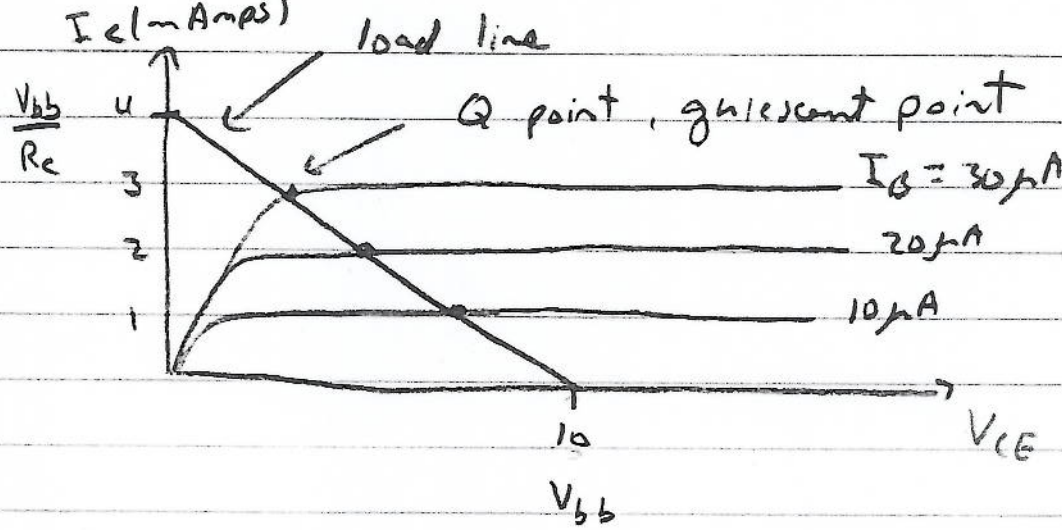
Consider



Kirchhoff

$$V_{bb} - V_{CE} - I_c R_c = 0$$

$$I_c = \frac{V_{bb}}{R_c} - \frac{V_{CE}}{R_c}$$ must be satisfied



$I_c = \frac{V_{bb}}{R_c}$ transistor fully turned on

$R_{transistor} = 0$ all voltage across the resistor

$V_{CE} = V_{bb}$ $R_{transistor} = \infty$ turned off

$I_c = 0$ no voltage across resistor

Can read current gain off graph

$$\text{current gain} = \frac{I_C}{I_B}$$

Large current gain – steep load line
R_C: small

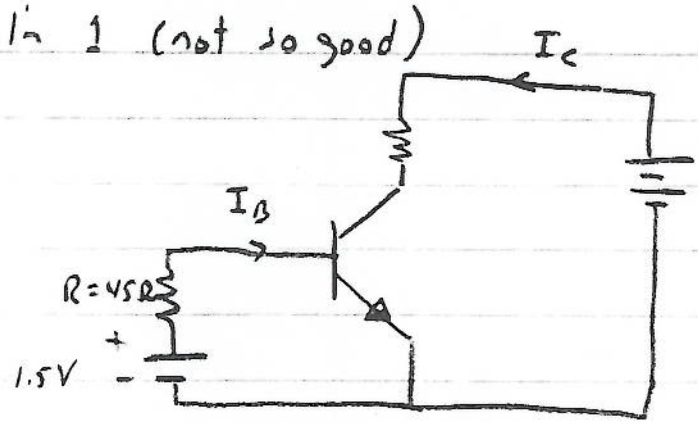
Large V_{CE} gain – flat load line
R_C: large

(*) <u>Stability of operating point</u>

Remember I_B controls I_C

How do we fix I_B?

Soln 1 (not so good)



why this R & V?

Kirchhoff

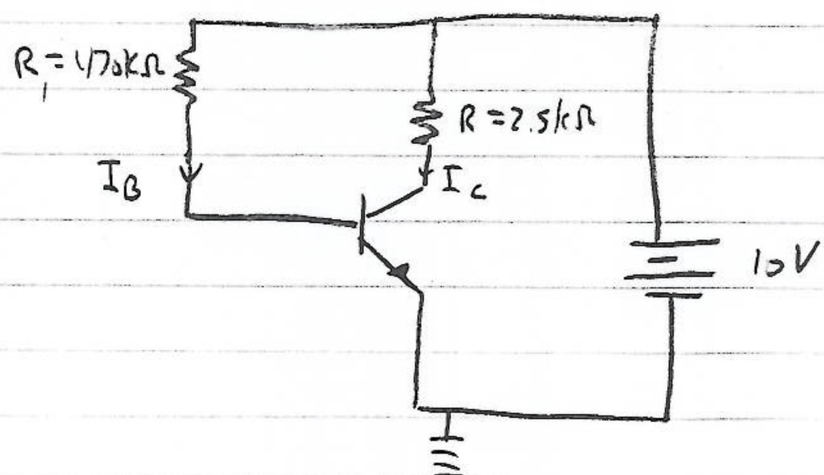
$$1.5V - 0.6V - I_B R = 0$$

If $R = 45k\Omega$ $I_B = 20\mu Amps$

This sets I_B

Bads things about this setup
- (1) two batteries
- (2) temperature instability
- (3) sensitive to β

Better solution



To forward bias BE $V_{BE} \sim 0.6V$

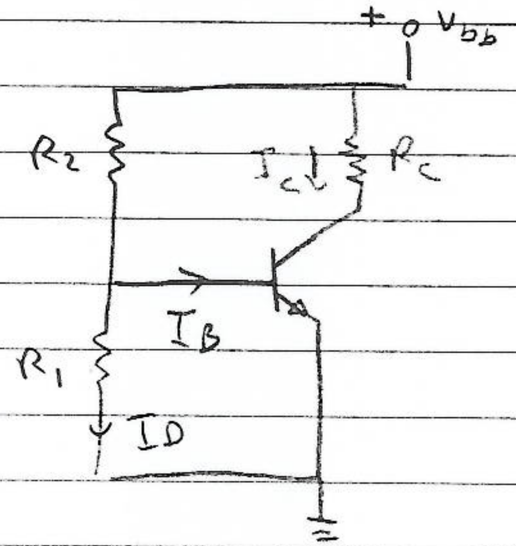
$\beta = 100$

If $I_c = 2mA$, $I_B = I_c/\beta = 20\mu A$

$$R_1 = \frac{V_{bb} - V_B}{I_B} = \frac{10V - 0.6V}{20\mu A} = 470\,k\Omega$$

β dependence still there
T dependence.

To lessen T dep.



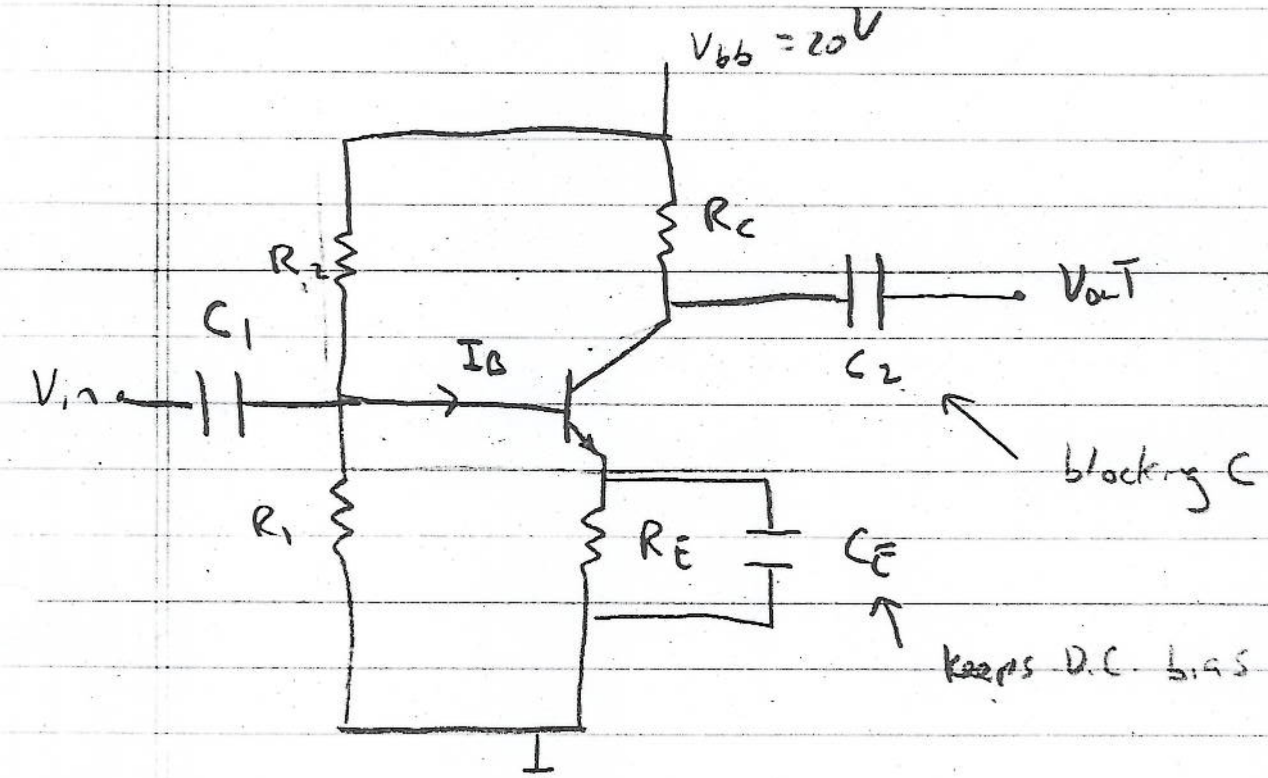
$$V_B \simeq \frac{R_1}{R_1 + R_2} V_{bb}$$

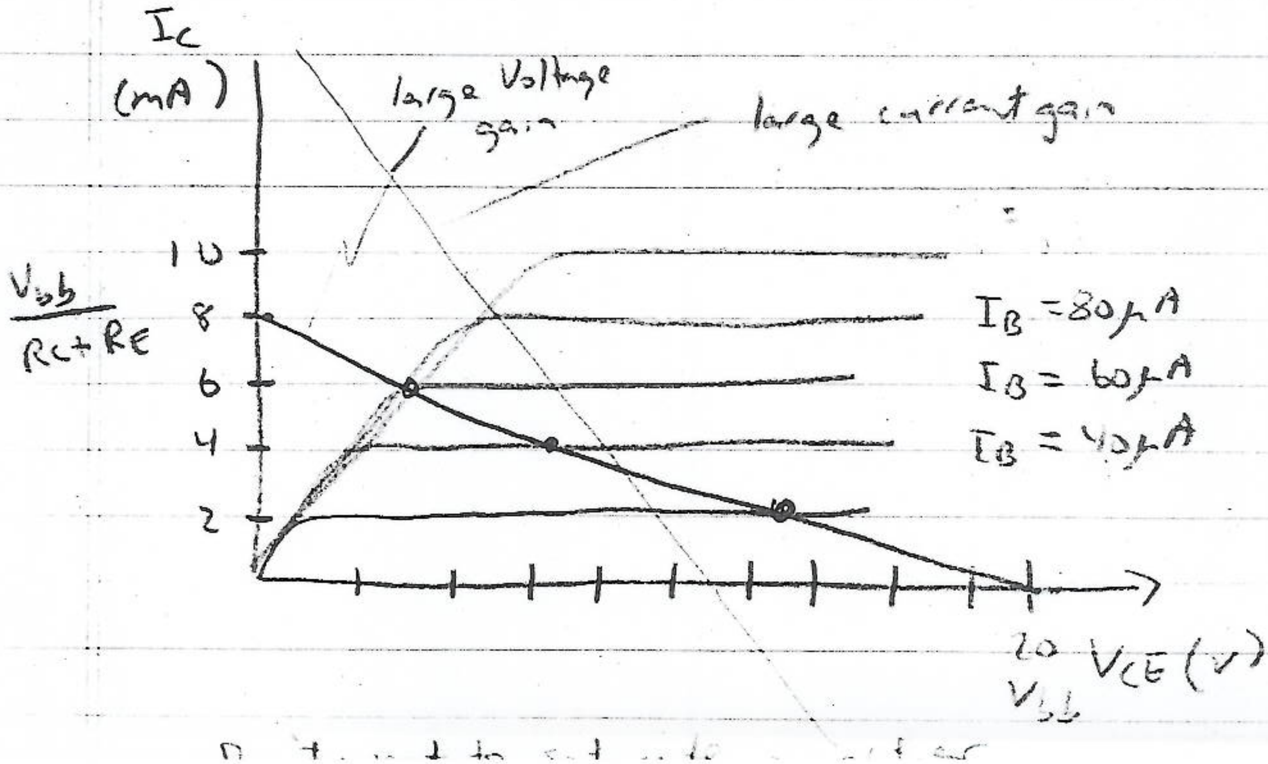
since I_D small

Ratio of R's matter → vary w/ T in the same way

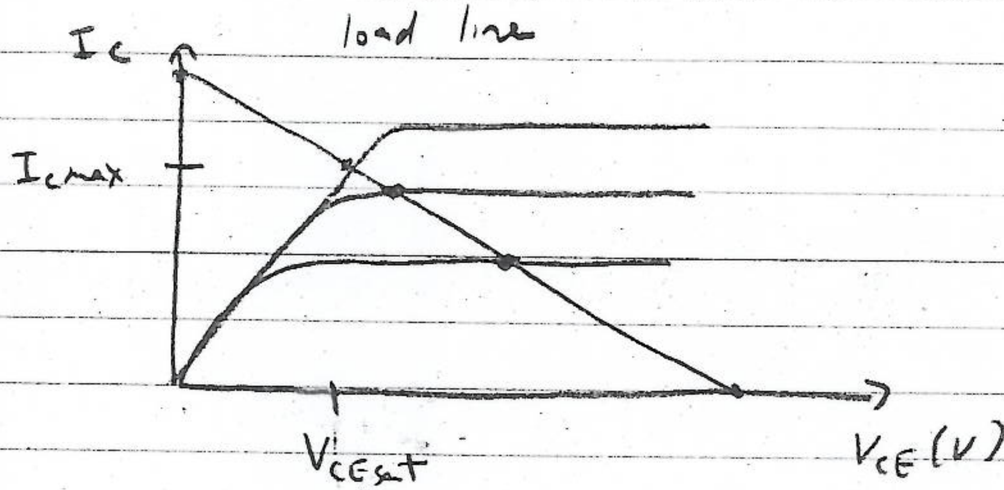
→ Temp still affects transistor

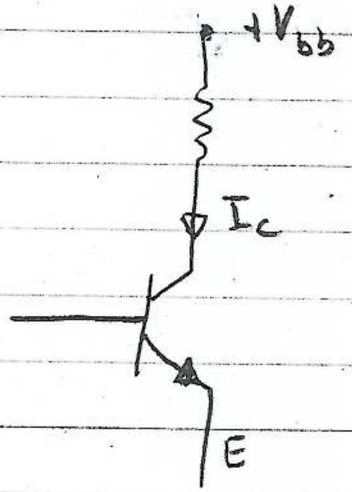
Amplifying AC signal





Transistor switches





$V_b = 0 \quad I_c = 0$ <u>off</u>

Load line says V_{CE} not below $V_{CE\,sat}$
I_c not above $I_{c\,max}$

Saturation

B-C junction forward biased
I_B increase does not increase I_C
$I_C \neq \beta I_B$

} $V_c \sim 0.2V$ $V_b \sim 0.6V$

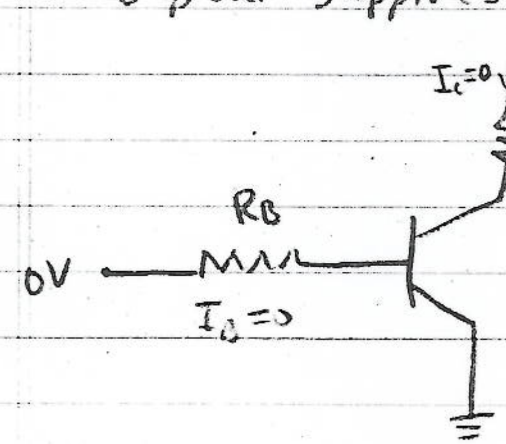
B-C junction reverse biased (amplifiers)

$I_C = \beta I_B$

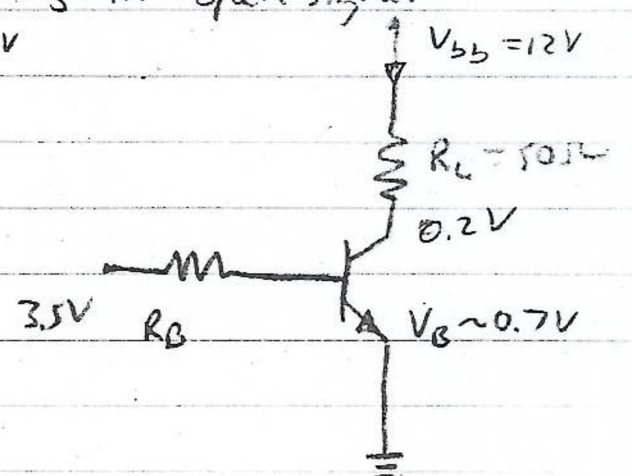
* Switch example:

Solenoid valve $R_L = 50\,\Omega$ $I = 200mA$ to open

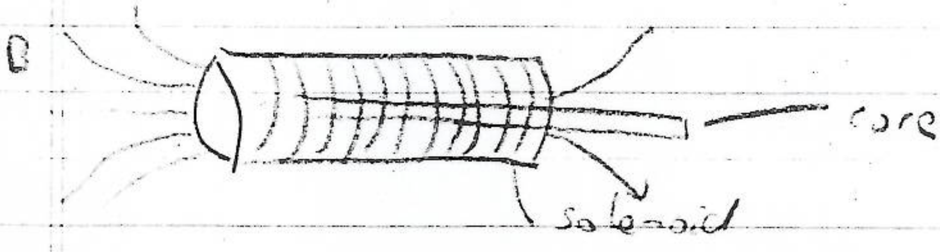
Computer supplies 3.5V 5mA open signal



off



on



(*)

$\beta = 50$

$V_L = 50\Omega\,(.20A) = 10V$

$\rightarrow V_{bb} = 12V$

<u>OFF</u>

$I_B = 0 \quad I_C \sim 0$

<u>ON</u>

$V_B = 3.5V$

$$I_B = \frac{3.5V - V_B}{R_B} = \frac{3.5V - 0.7V}{R_B}$$

$R_B \downarrow \quad I_B \uparrow \qquad I_C = \beta I_B$ even larger <u>if</u> not saturated

* For npn when $I_C = I_{C\,max}$ $V_C = 0.7V$

$$I_{C\,max} = \frac{V_{bb} - V_C}{R_L} = \frac{12V - 0.2V}{50\Omega} = 236mA$$

$$I_B = \frac{I_{C\,max}}{\beta} = \frac{236}{50} = 4.72mA$$

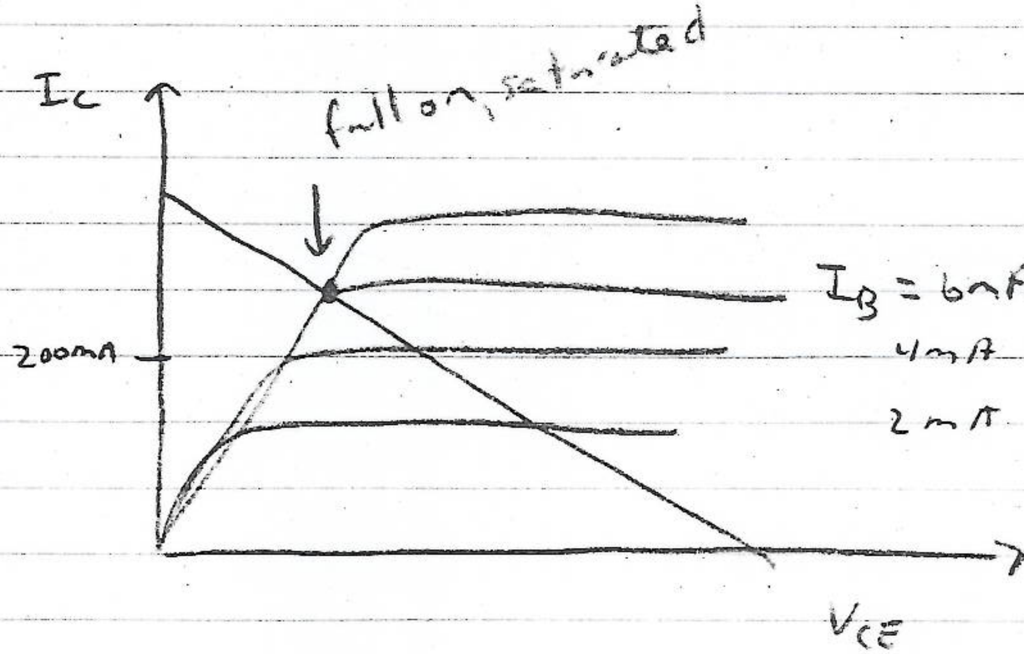
computer can supply 5mA → o.k

$$R_B = \frac{3.5V - 0.7V}{4.72mA} = 590\,\Omega$$

$R_B = 590\,\Omega$ allows input to drive transistor to edge of saturation

(*) <u>The point</u>

Changing V_B
→ gives I_B
→ choose R_B so I_B is big enough to make $I_C = 200mA$



If $I_B < 4mA$, $I_C < 200mA$, solenoid won't open