Course on Basic Electronics and Instrumentation

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Outline of the Course

- ❑ Basic Instrumentation.
  - a. What is instrumentation, why bother about it?
  - b. What are the basic things that we can measure.
    (All about circuits and components)
  - a. Challenges/Limitations etc.
- ❑ Semiconductors in instrumentation technology.
  - a. Semiconductors: A materialistic story.
    (Crystal lattice, Band structure, etc…)
  - a. Bending semiconductors to our will (doping).
  - b. The most basic semiconductor device: Diode.
  - c. When two diodes are better than one: Bipolar Junction Transistor.
  - d. Diodes, BJTs and their brethren in instrumentation technology.
    (Basics of amplifiers, their role in instrumentation, etc…)
- ❑ Instrumentation in the digital world.
  - a. Short intro to digital electronics.
  - b. Need for digitization in instrumentation technology.
  - c. Language of the digital world: Binary number system.
  - d. Mathematics with binary numbers.

Semiconductors in instrumentation technology

Q: What makes any material conduct electricity?
A: If it has free electrons that can be moved around by applying an external electric field (bias/potential).

In simple terms: Higher the number of electrons, better the conductivity.

There are 3 classes of materials depending on the availability of free electrons.
In decreasing order of free electrons:

METALS → **SEMICONDUCTORS** → **INSULATORS**

Now…
Suppose you put in some effort and synthesize a new material in your lab…
~~WHO~~ WHAT decides the fate of your material's free electrons??

It's the band structure…

Origin of band structure

To understand what is a band, first we have to look into the physical structure of our material. We have to note:

a. **The elements that make up our material.**
b. **How the atoms of each element are arranged.**
c. **What is the electronic configuration of the constituent atoms.**
d. **What kind of chemical bonds do the adjacent atoms make with each other.**

And so on…

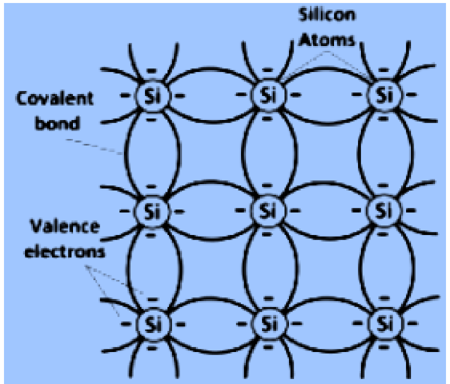
As an example, let's consider a material only made of silicon atoms…

- **The atomic configuration of Si is: [Ne] $3s^2$ $3p^2$, *i.e.*, it's valence shell has 4 electrons.**
- **To make our material, each silicon atom needs to make covalent bonds with neighbouring silicon atoms (to complete the valence shell).**

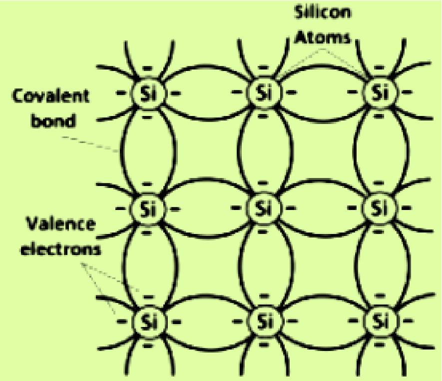
sp^3 hybridization for chemistry folks

A factually incorrect cartoon to show what the arrangement could look like…

Note that this arrangement extends to 3D!



Origin of band structure: Crystal lattice



Remembering this factually incorrect cartoon…

- Any (infinitely) periodic arrangement of atoms in three dimensions is a crystal

(This is the simplest definition, better definitions will be available online… please check)

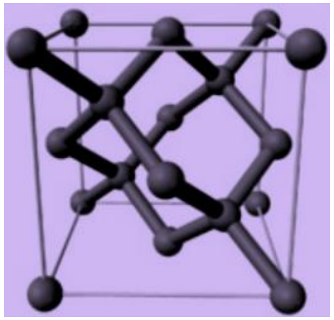
- Lattice refers to the arrangement of atoms in a crystal. This arrangement is dictated by the orientation of chemical bonds between adjacent atoms.

(Again, check for better definitions online/books etc…)

- The smallest arrangement of atoms that can be repeatedly stacked together to form the whole crystal is called the unit cell. The properties of an unit cell is enough to tell us about the structure of the entire crystal.

This what the unit cell of silicon (diamond cubic) looks like

Spheres indicate the atoms and sticks indicate the bonds
(Won't get into more details…)



Some tips for the experimentalists out there…

- If you want to know if your material is crystalline, do XRD
- From XRD you can get info about the unit cell, spacings etc.
- If your material is a very thin film (few nm), high resolution TEM can also give you the lattice structure.

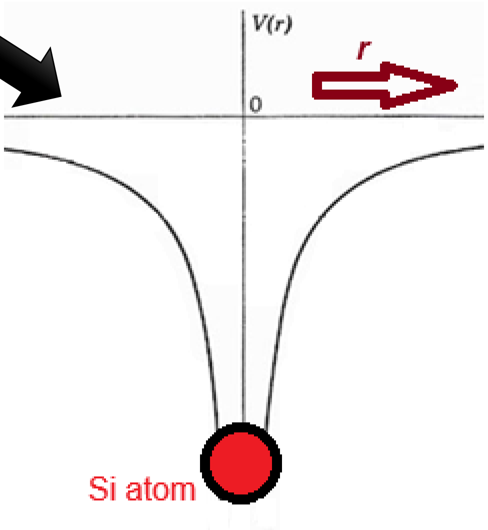
From crystal lattice to band structure

Why do we need the crystal lattice when our concern is with the band structure??

To put it simply, a band is the energy landscape faced by an electron when moving about within the crystal. So, this landscape is directly dependent on the arrangement of atoms, *i.e.*, the crystal/lattice structure.

But, how does one get this energy landscape?

Consider a silicon atom. An electron orbiting its nucleus will feel an attractive potential of the form ‘*1/r*’ called the Coulomb potential

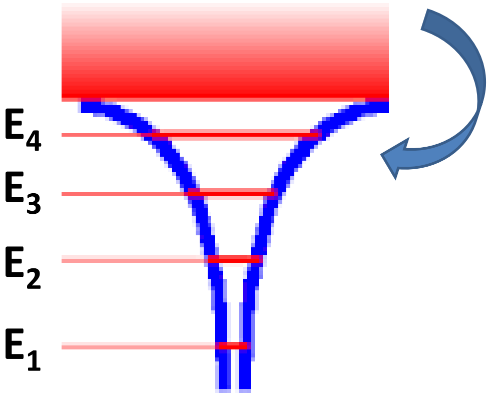


Schrodinger’s equation would indicate discrete energy states if the electron was strongly confined in the potential, whereas continuous if unconfined

In general,

$$E_n \propto \frac{\hbar^2 n^2}{2m}$$

n = 1, 2, 3…



From crystal lattice to band structure

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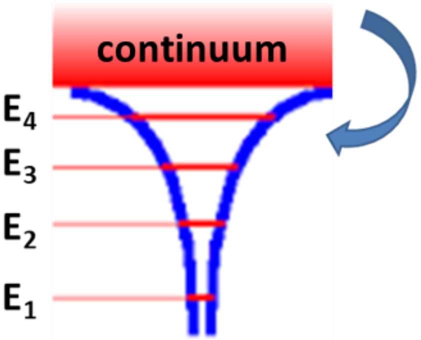
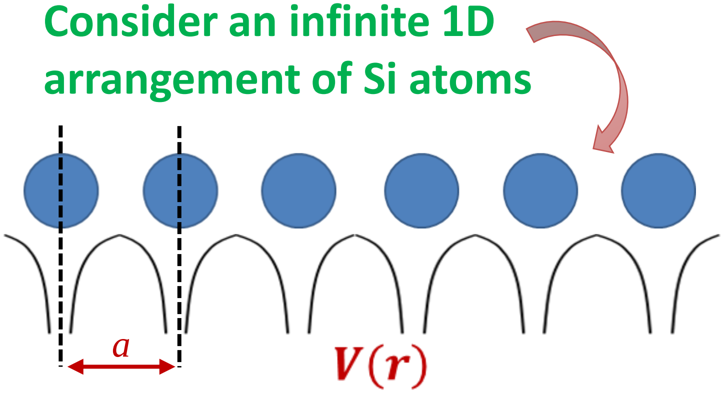


Keeping this in mind...
Consider an infinite 1D arrangement of Si atoms



The potential at any point '*r*' follows the rule:

$$V(r+a) = V(r)$$

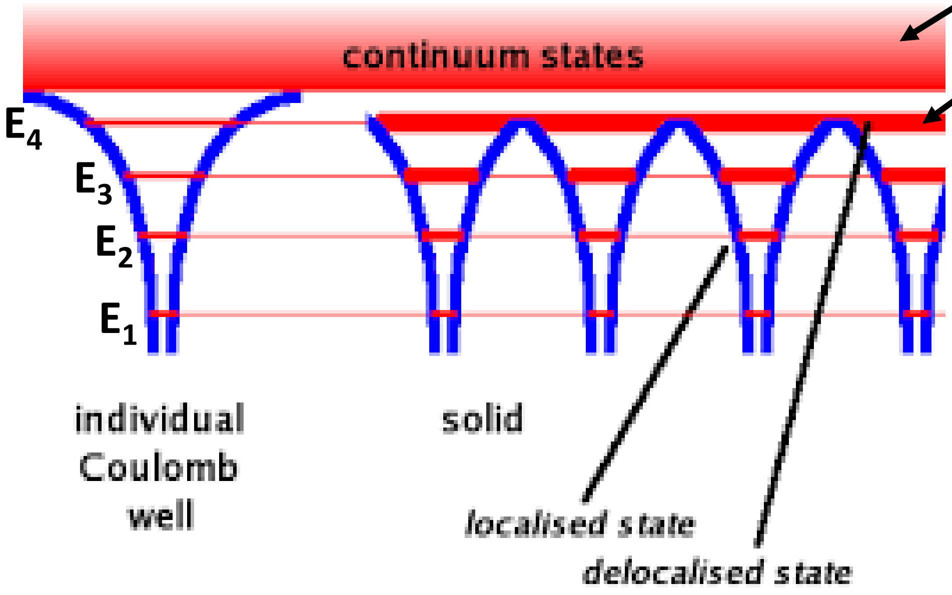
This is called a periodic potential.

The periodicity depends on the arrangement of atoms (crystal structure)

From a physical point of view, the following occurs:

- Orbitals from neighbouring atoms overlap.
- Due to overlap, a single atomic state is now replaced by multiple closely placed energy states, *i.e.*, atomic orbital → molecular orbital.
- Instead of individual energy states, there are now a range of energy states available to the electron.

Band Structure!!!



Electrons here are free

Electrons here are very weakly bound, shared across neighbouring atoms.

Electrons having these energies are bound to their respective atoms.

The energy levels are not discrete but have a certain spread…

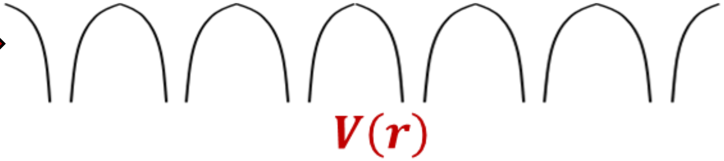
You could say that it's a 'band' of energies…

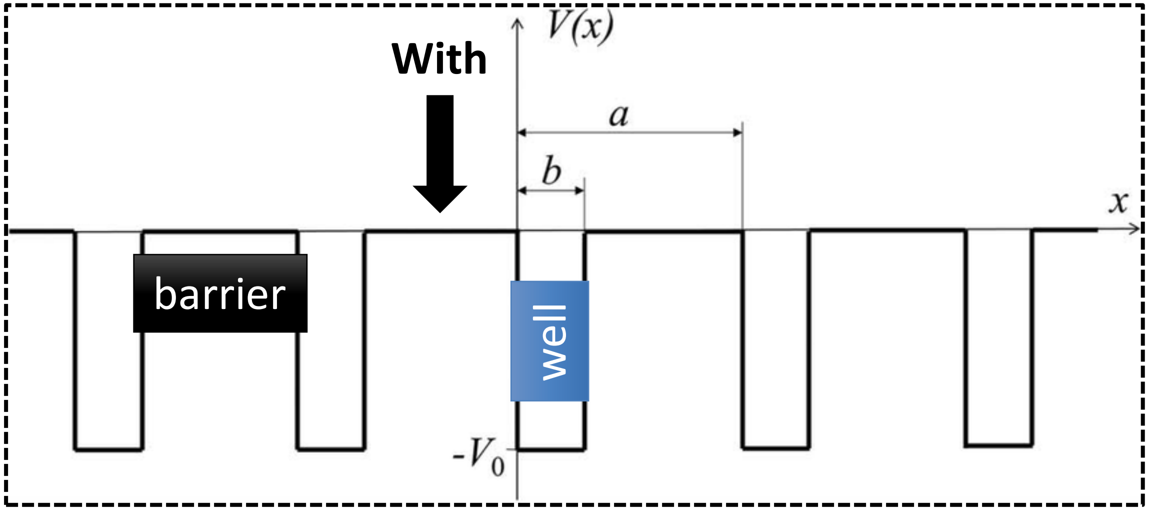
Now, to make any predictions about our material's free electron situation, we need to mathematically quantify the band structure…

Since we want to just get the simple idea of a band, let's simplify our periodic potential

Band Structure!!!

Replace





****Bloch's theorem, Wavefunction in a periodic potential is of the form:**

$$\Psi(x) = e^{ikx}u(x)$$
$$u(x+a) = u(x)$$
$$\Psi(x+a) = \Psi(x)$$

- **Physicists, R. Kronig and W. Penny, considered this kind of infinite square well potential.**
- **They wanted to find out what kind of energy states would be available to electrons.**
- **So they solved the Schrodinger equation for this kind of potential.**

(We won't go into details…)

Band Structure!!!

What did Kronig and Penney find??

They did a lot of mathematics and came to an expression (with some assumptions of course),

$$\cos(ka) = \cos(\alpha a) + \frac{P\sin(\alpha a)}{\alpha a}$$

Other variations of this relation are there online

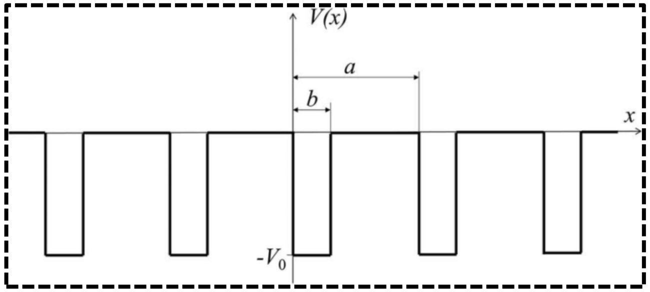
Unknown wave vector from Bloch's theorem

Momentum (p) = $\hbar k$

$$P = \frac{2mV_0ba}{\hbar^2}$$

Known momentum (p) = $\hbar\alpha$ *for a given energy E*

$$\alpha = \sqrt{\frac{2mE}{\hbar^2}}$$

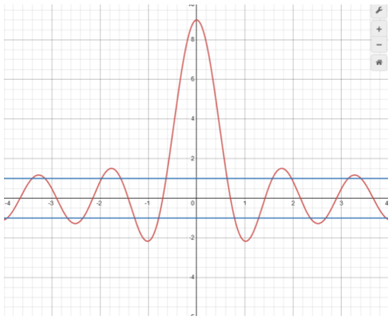


- ☐ **This momentum is actually modulated by the lattice (crystal momentum).**
- ☐ **To know the band, we must know the relation between E and k.**

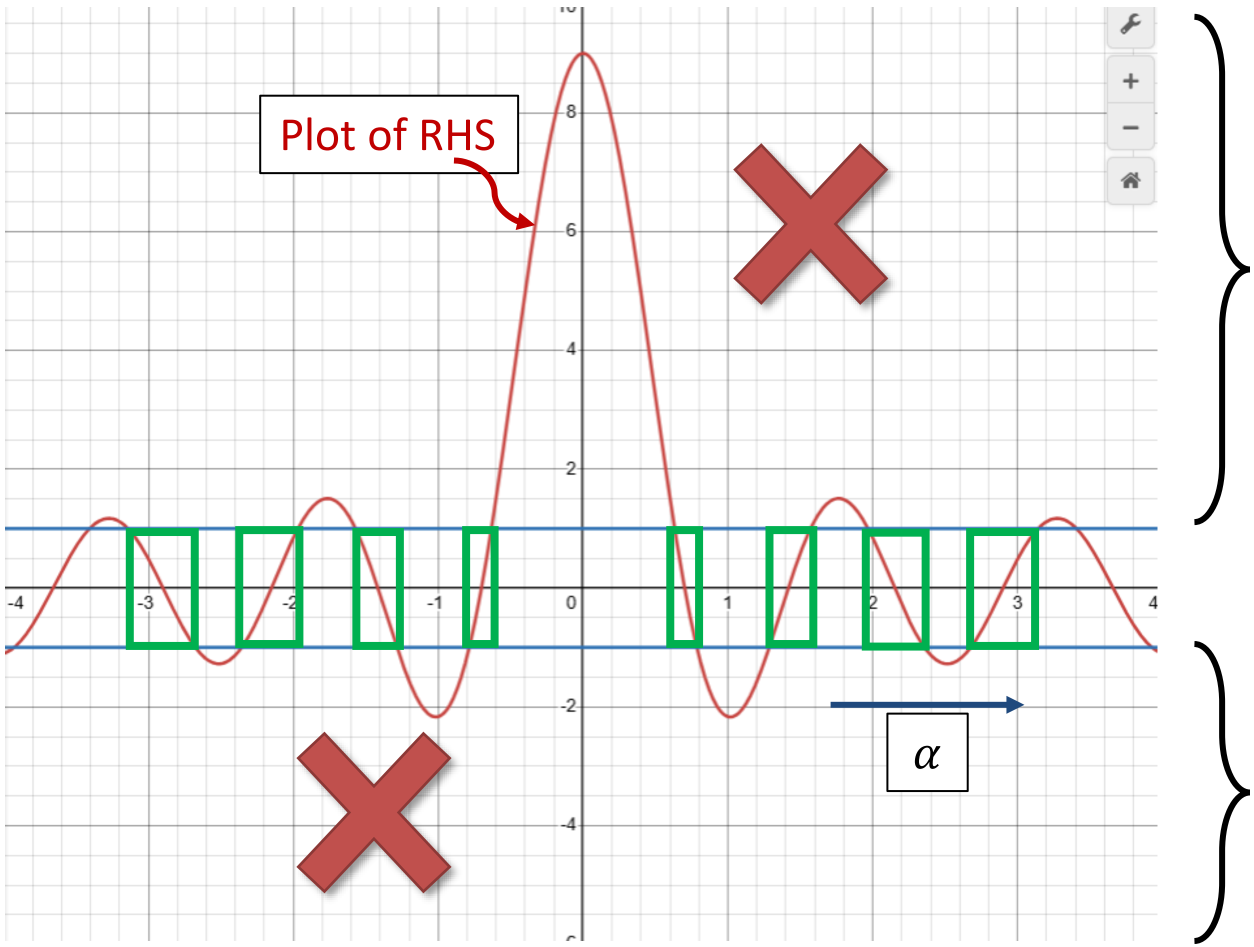
LHS has the term $\cos(ka)$. For any value of 'k', the value of LHS is limited to the range:

$$-1 \le \cos(ka) \le 1$$

Now, plot RHS with respect to α, *i.e.*, Energy (E)



Band Structure!!!

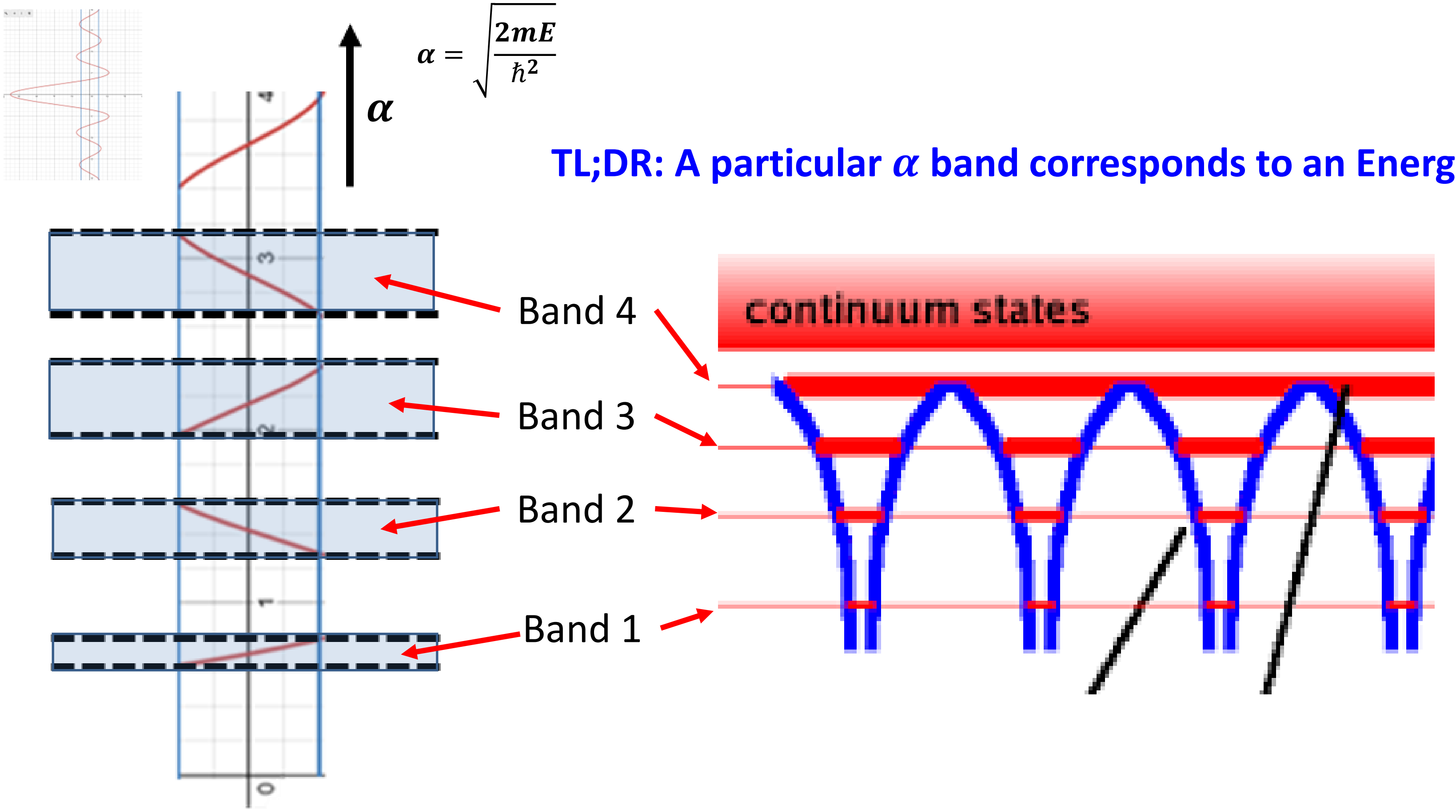


These parts do not contribute to any solution as LHS value cannot go beyond +/- 1

Only those regions enclosed by green boxes yield valid relations between k and α

But these boxes only cover specific regions of α, *i.e.*, E

Band Structure!!!



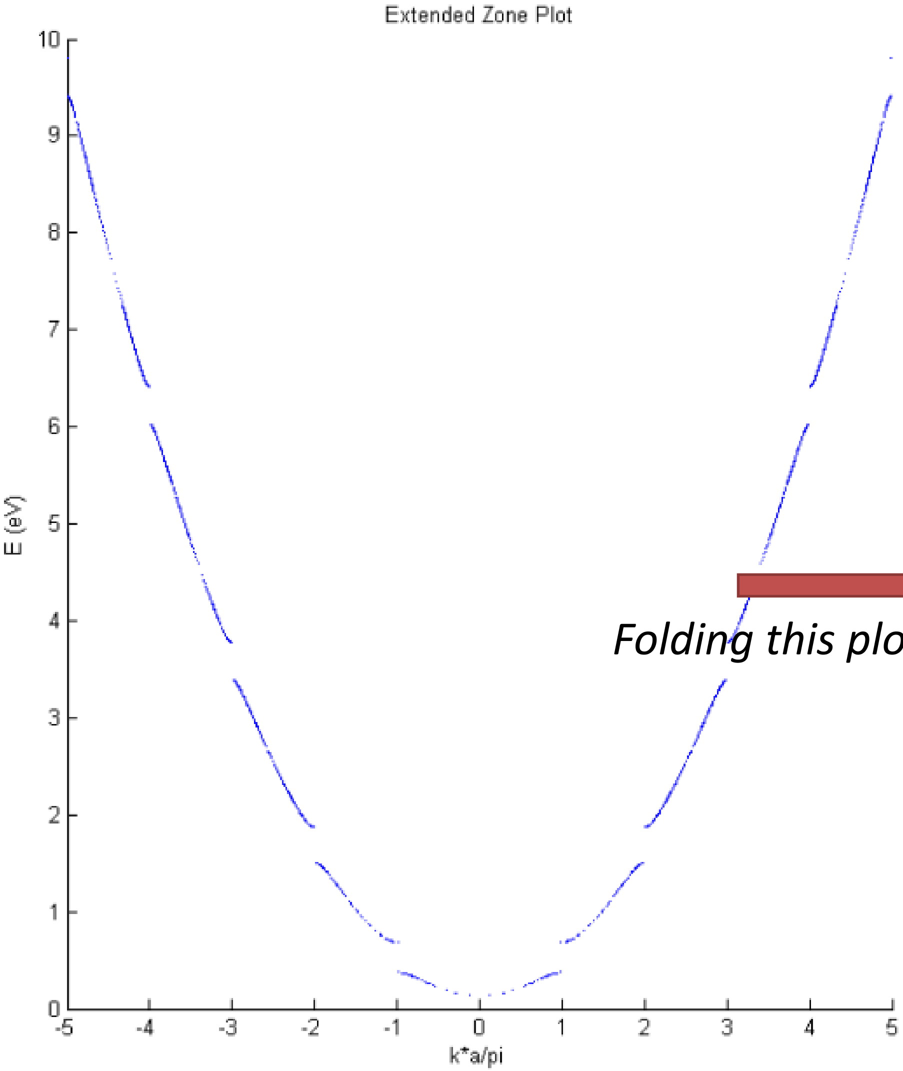
$$\alpha = \sqrt{\frac{2mE}{\hbar^2}}$$

TL;DR: A particular α band corresponds to an Energy band

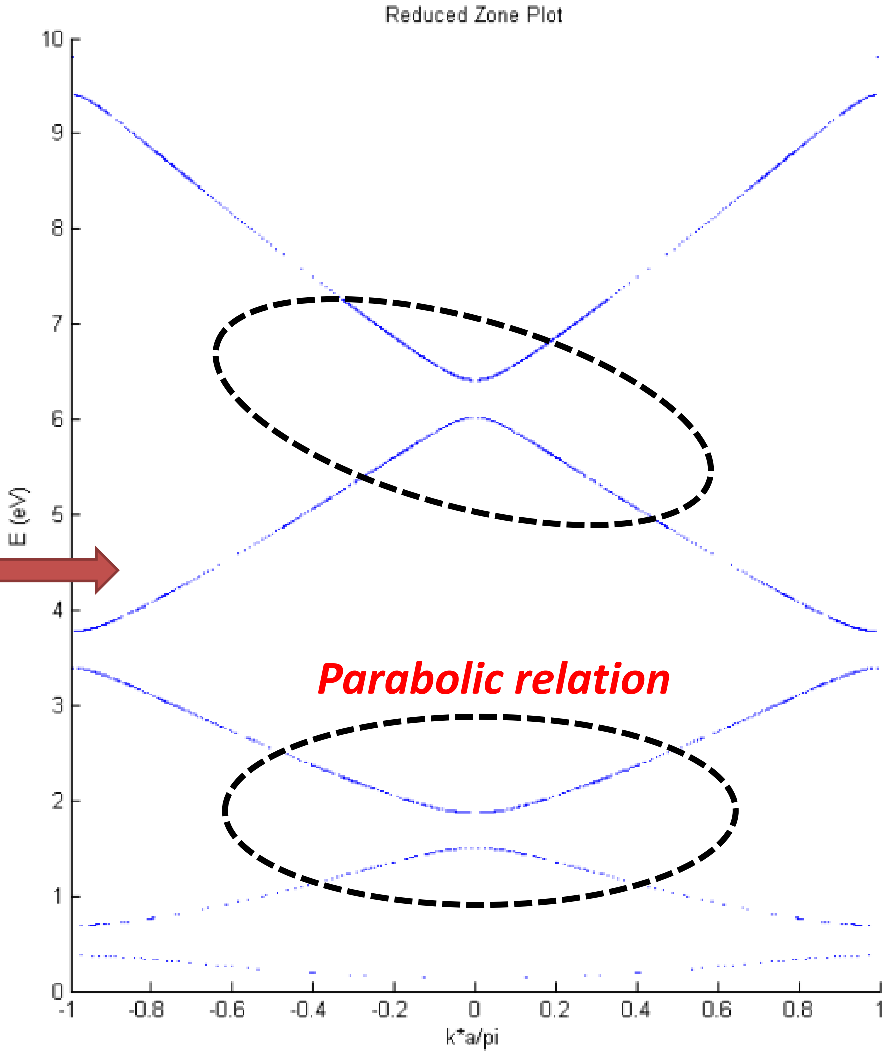
So, our physical intuition is validated by (physics backed) mathematical formulations!

We can now definitely say that any periodic arrangement of atoms can create a potential arrangement that leads to energy hybridization → energy band formation.

The E vs k relation



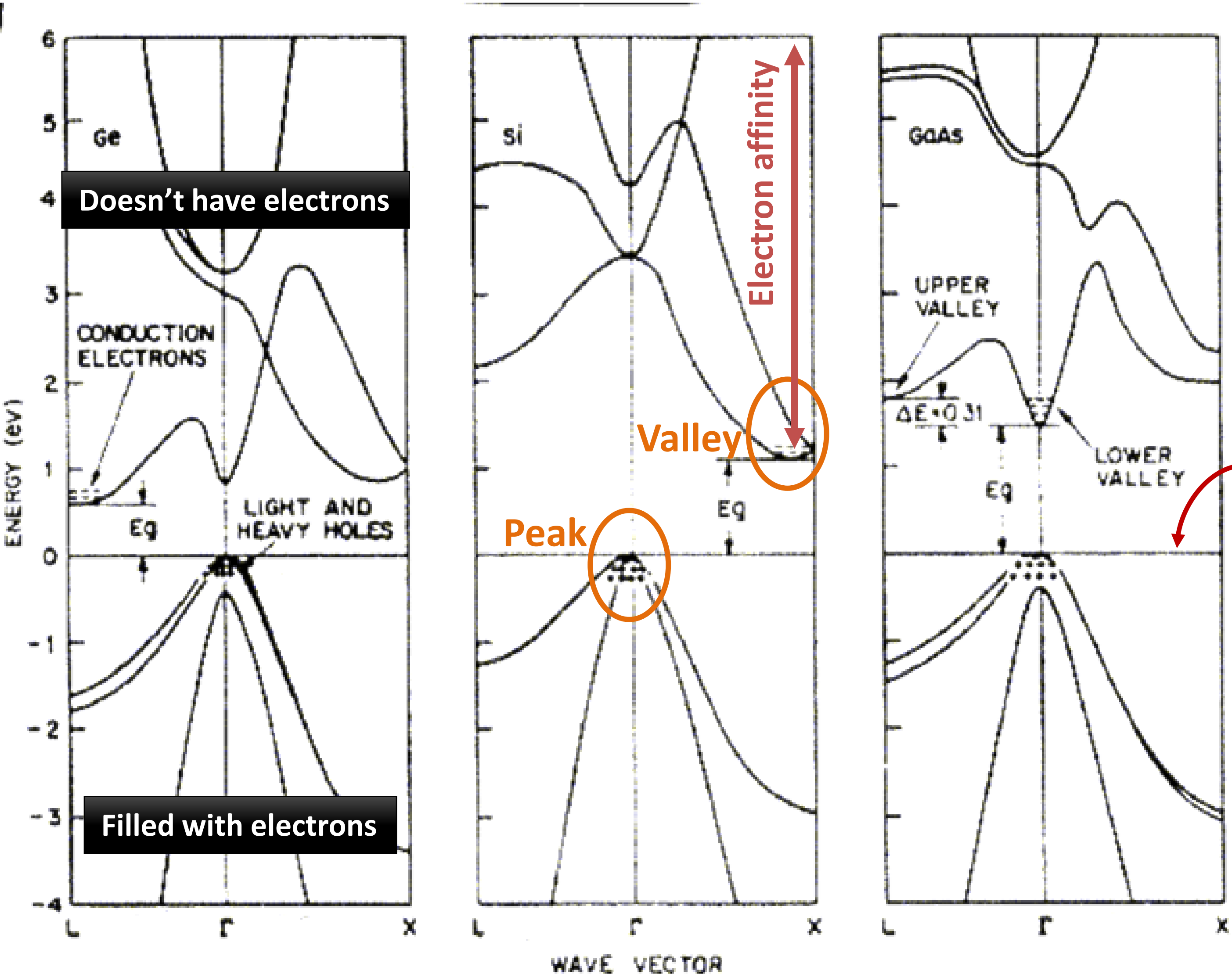
Folding this plot



Parabolic relation

Band Structure in the material realm…

- Looking back at our silicon crystal, it has a 3D arrangement of atoms.
- So, momentum (k) will be three dimensional as well. Now what?



Valley	k_x	k_y	k_z
Γ	0	0	0
X			
L			

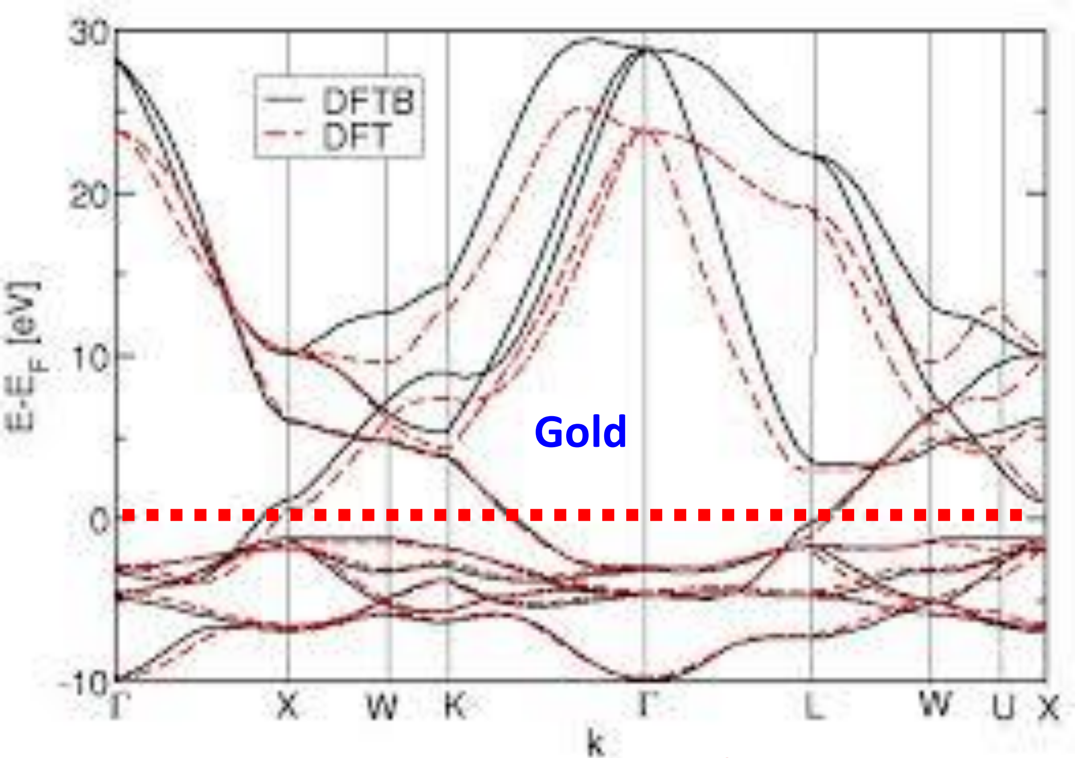
Chemical potential (arbitrary reference value)

For making devices, info of only the valence band (VB) maximum and conduction band (CB) minimum are enough.

- A completely filled/empty band will not conduct current.
- Partially filled bands will.

Some whataboutery…

- ➢ In case of semiconductors the band gaps are small enough to enable electron transfer from valence to conduction band (in previous slide).
- ➢ But… What about metals and insulators??

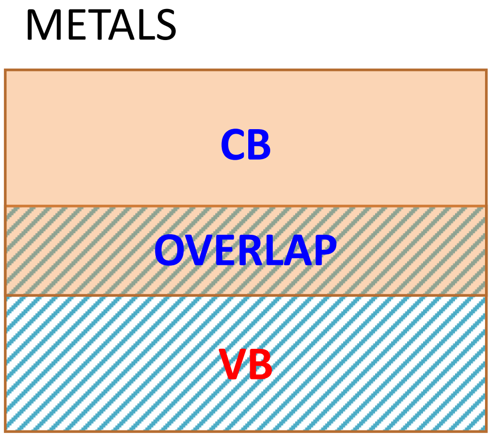


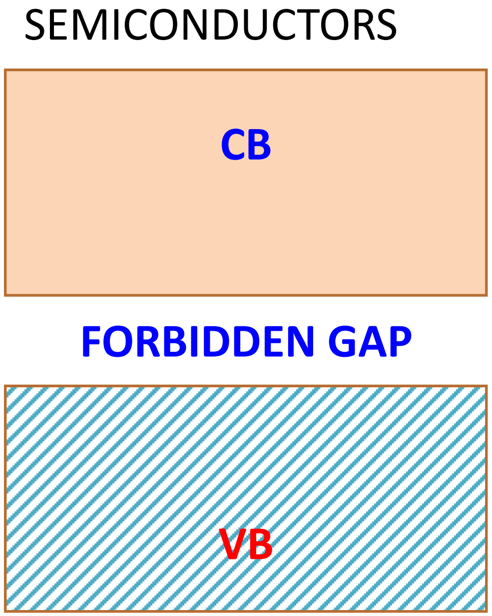
In metals, there is no such gap, the VB and CB overlap.

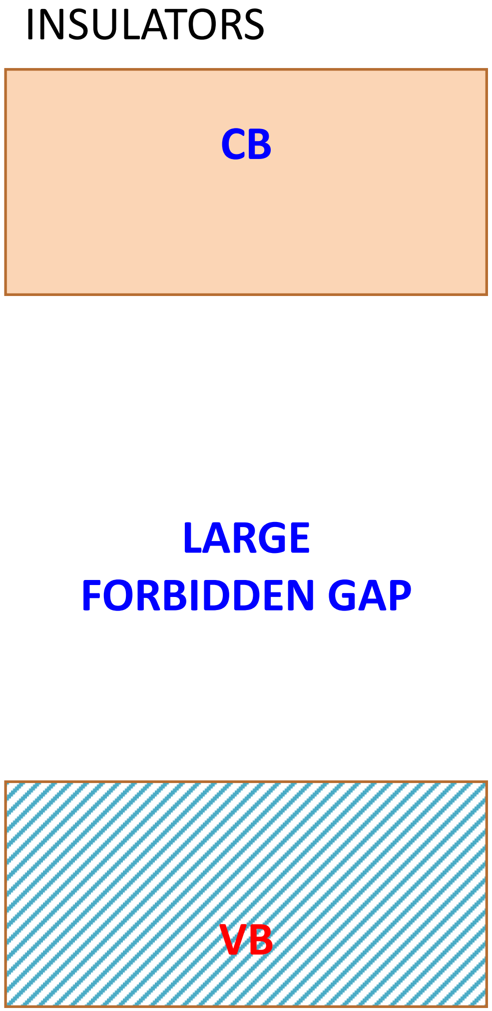
In insulators, the gap is so high that researchers don't even bother with the band structure

- When electrons are excited from the valence band of a semiconductor to the conduction band, it leaves behind a positively charged atom.
- Migration of this positive charge by exchange of valence electrons from neighboring atoms enables the flow of electricity. This positive charge is a hole.

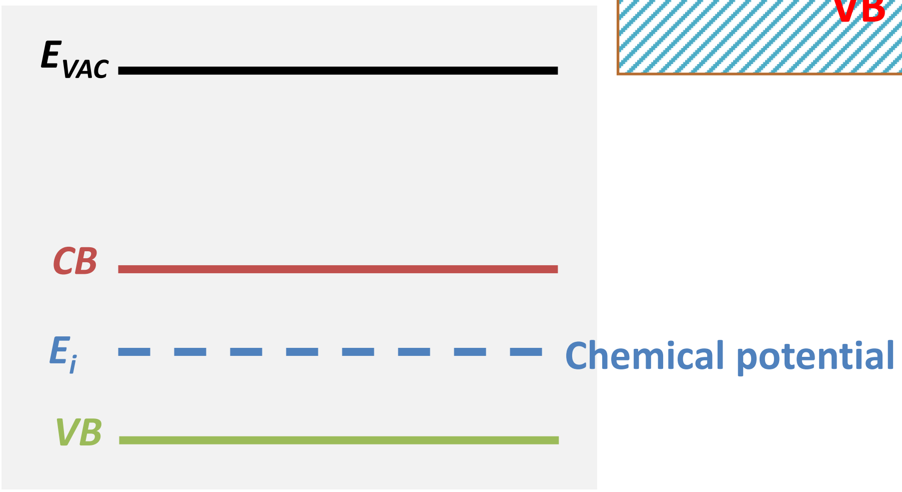
To make things simpler…







*****Pure semiconductor***



Lekin picture abhi baki hai…

Bending semiconductors to our will…

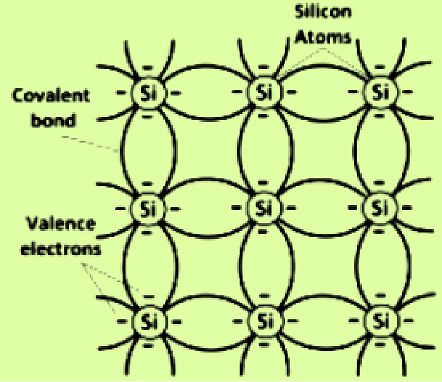
- **For making our devices, to control the flow of current etc… just any pure slab of semiconductor won't do.**

- **To control the flow of electrons/holes we need to artificially alter the position of the bands and the electron/hole populations.**
- **We introduce impurities in pure semiconductors for this purpose.**
- **The process of introducing impurities is called doping.**
- **Pure semiconductor => intrinsic; Impure semiconductor => extrinsic.**

By doping, we can create:

i. **Semiconductor with electron conc. > hole conc. -> *n*-type**

ii. **Semiconductor with hole conc. > electron conc. -> *p*-type**



Going back to our factually incorrect pure Si lattice…

- ***We get free electrons by breaking covalent bonds.***
- ***The absence of electrons is a hole.***
- ***In thermal equilibrium, number of electrons = number of holes.***
- ***But their number is very few.***

We need a way to artificially introduce free charge carriers!

Bending semiconductors to our will…

- First… the missing link!

Chemical potential

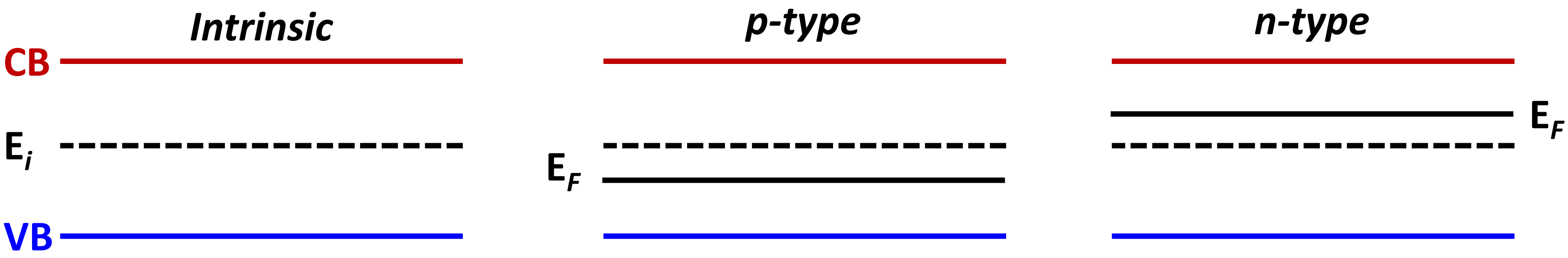
What is it?? Khay na mathay dae??

Possible definitions?

•

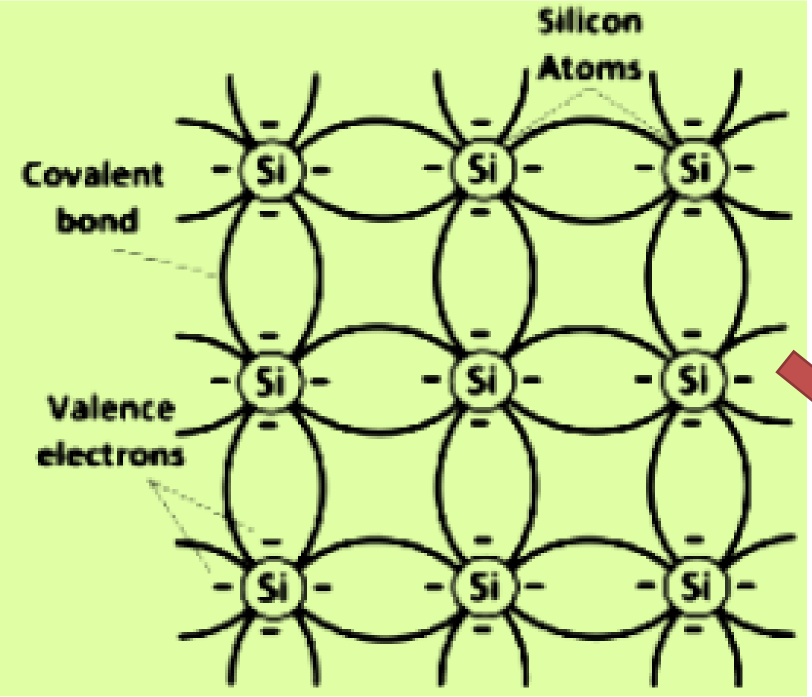
•

- For us, chemical potential is the Fermi level.
- It is the average energy of electrons and holes of the system.
- For intrinsic semiconductor it lies exactly between the conduction and valence band (midgap).

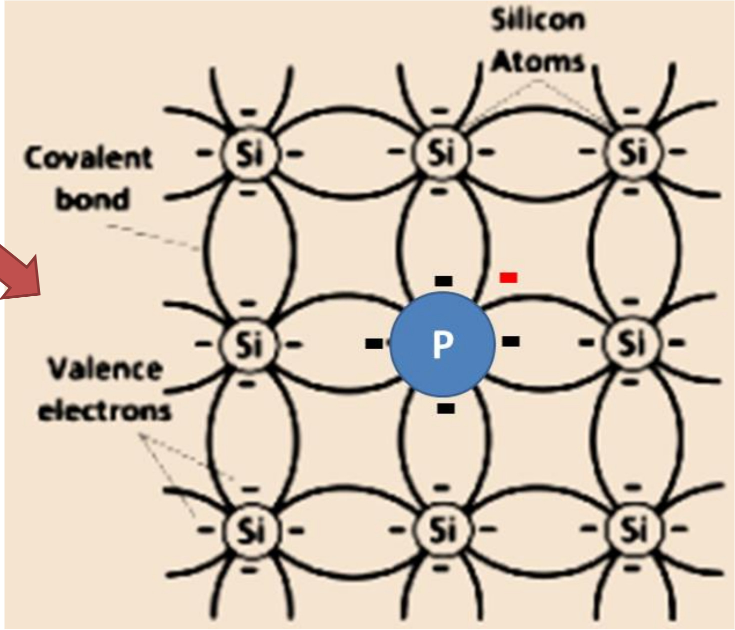


Bending semiconductors to our will…

But how does a dopant really work??
Let's start with our (factually incorrect) silicon lattice…



Suppose one of the silicon atoms is replaced by a pentavalent atom (impurity) like phosphorus.

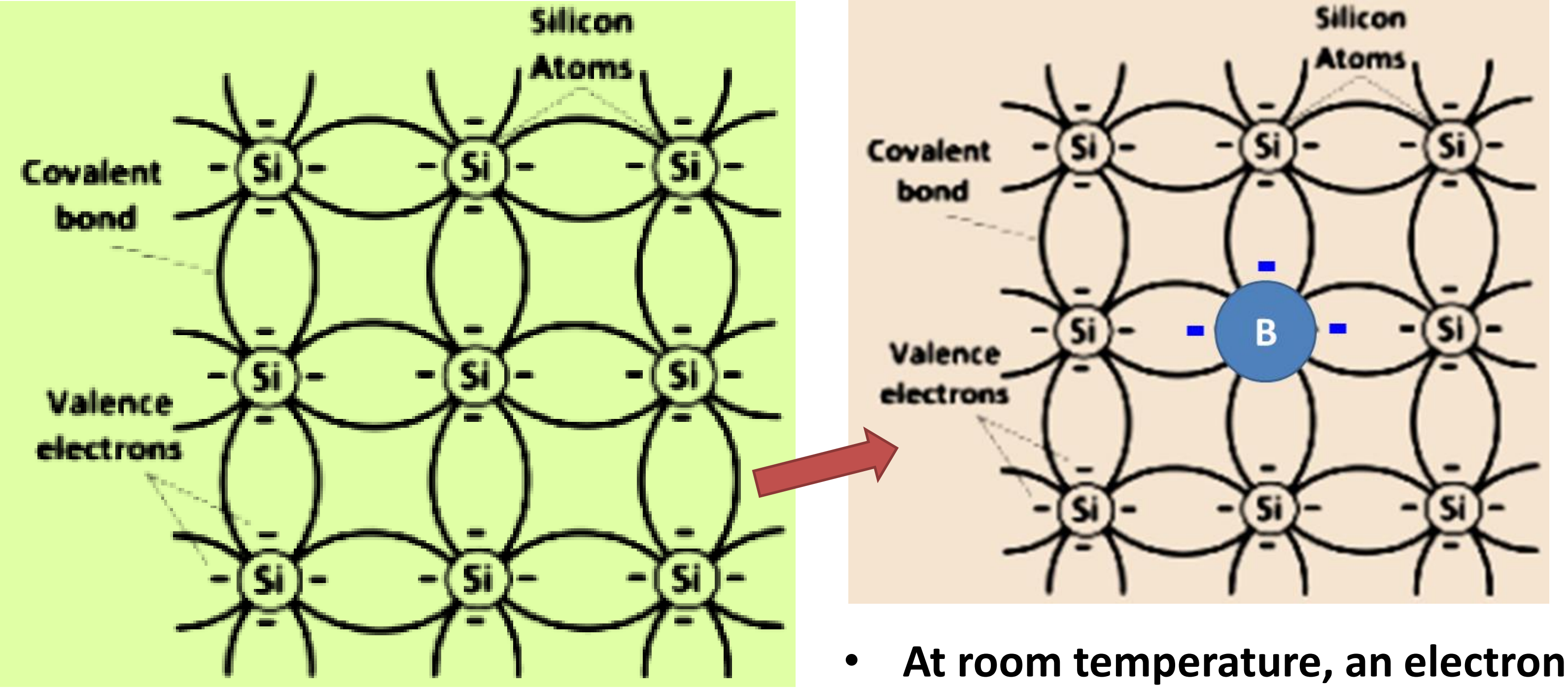


- **4 electrons of phosphorus make covalent bonds with neighboring Si atoms.**
- **One extra loosely bound electron remains, with energy just below the conduction band minimum. (Donor state)**

- **At room temperature, most of these electrons are transferred to the conduction band, leaving behind positively charged impurity atoms (Donor atoms).**

Bending semiconductors to our will…

What if we introduced a trivalent atom like Boron??



- 3 electrons of boron make covalent bonds with neighboring Si atoms.
- One empty slot remains that can possibly accept an electron. (Acceptor state)
- These acceptor states lie just above the valence band (45 meV).

- At room temperature, an electron from a neighboring silicon atom is transferred from the valence band to acceptor states
- Positive charge left on silicon atom that can migrate.
- Negatively charged boron atom (Acceptor atoms).

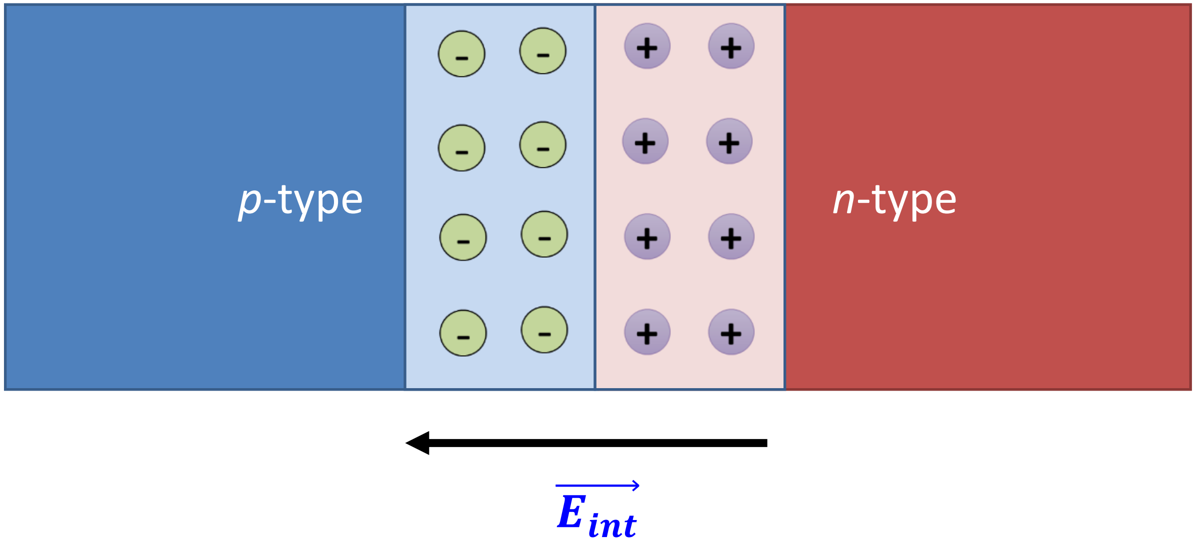
This maintains charge neutrality!

Joining p- and n-type together: *pn* junction

What if a p-type and a n-type semiconductor are metallurgically joined?

- ☐ **Majority carriers from either side will diffuse… and instead recombine.**
- ☐ **This will leave the immobile donor/acceptor atoms behind**
- ☐ **The chemical potentials of either side will shift till equilibrium is reached.**

When will equilibrium be reached??



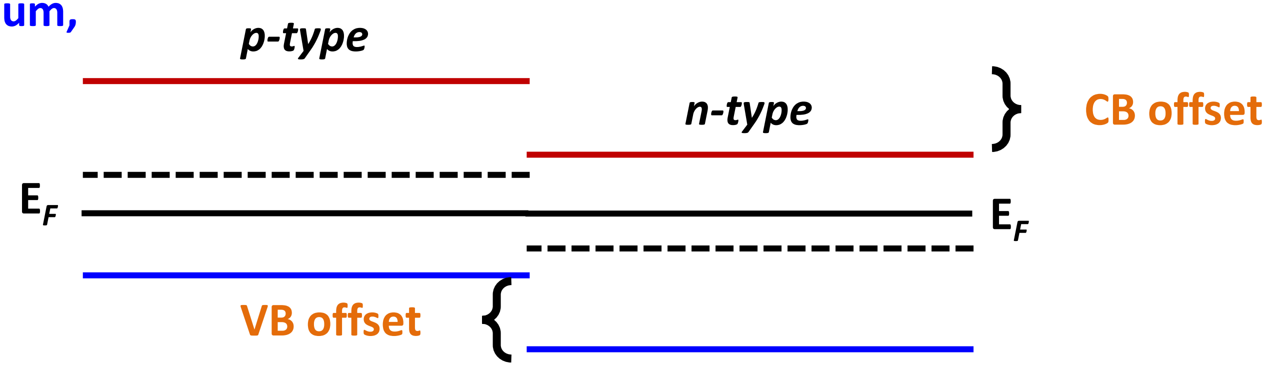
When the internal field is strong enough to prevent majority carrier diffusion.

The new layer at the junction is depleted of mobile charge carriers => depletion layer

p-n junction band diagram

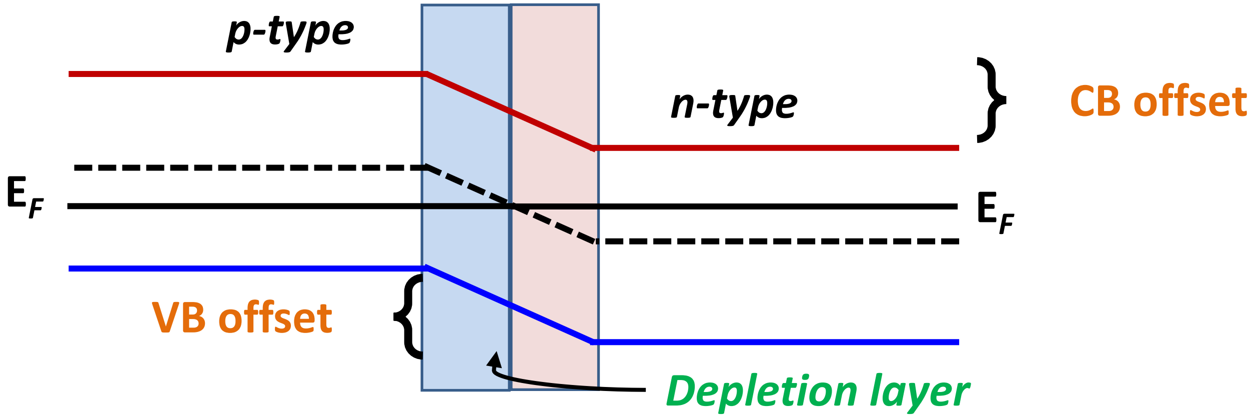
At equilibrium,

Expected band diagram



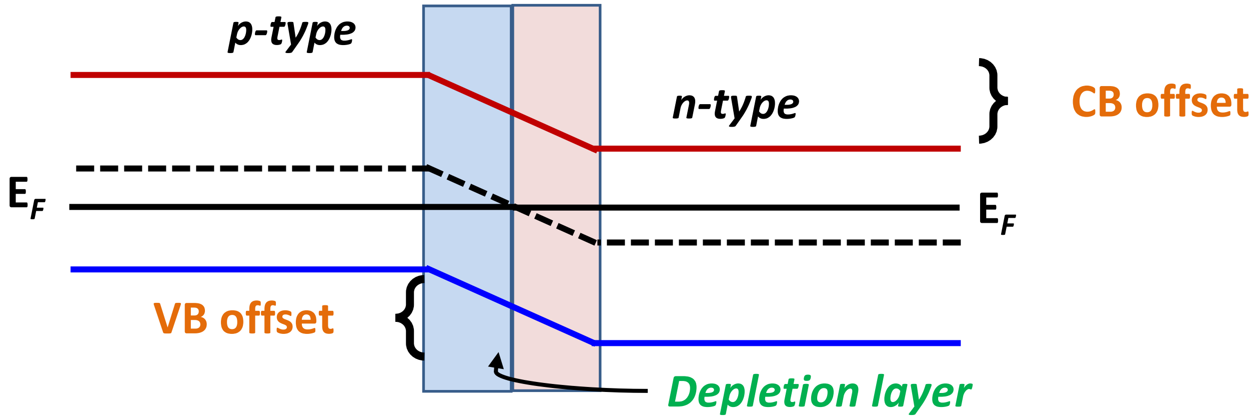
BUT!!

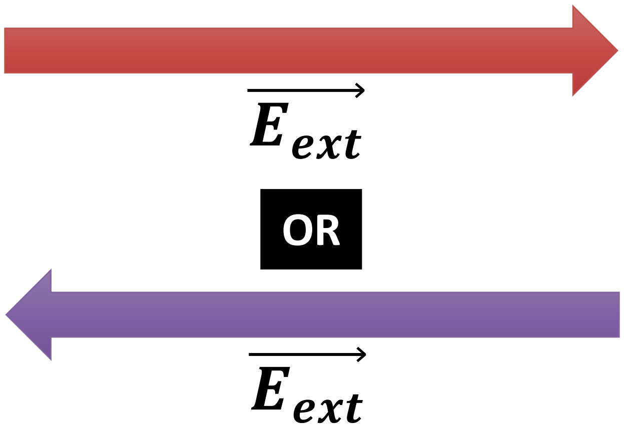
Due to depletion layer (with fixed charge density), the change in band offset is gradual



- **The drawing is incomplete tho… need a reference vacuum level.**
- ***Kids, always remember to draw your vacuum levels first!***

p-n junction with external fields

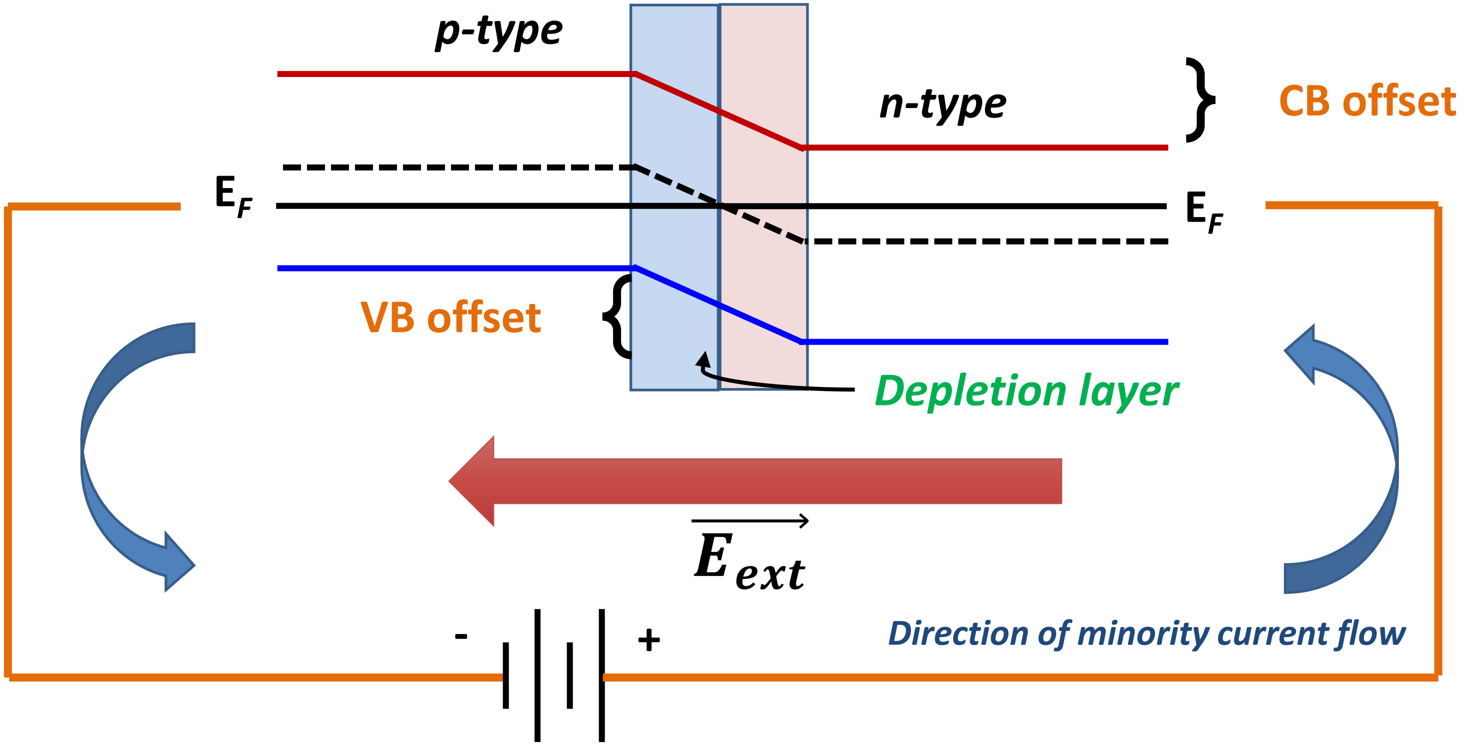




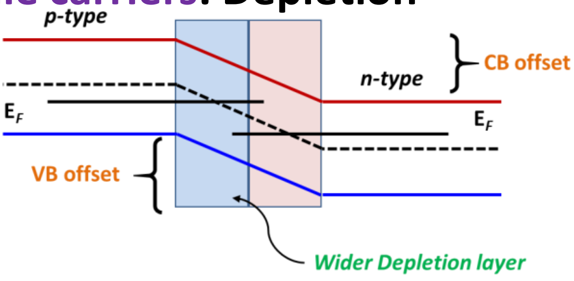
You can exert the external field by applying a voltage across the junction.

p-n junction with external fields

Case – 1: Electric field directed from *n*-type to *p*-type

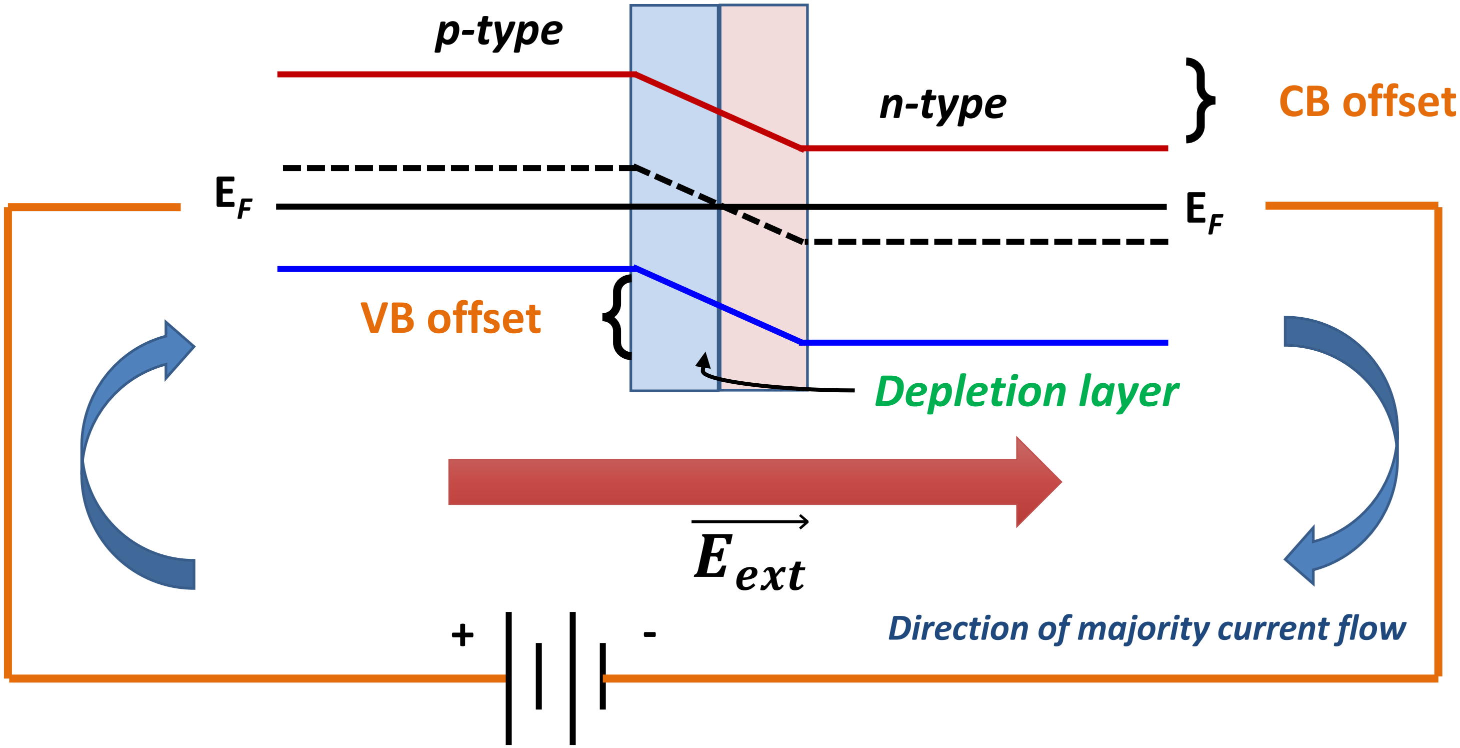


- ➢ **Removes the majority carriers away from the junction.**
- ➢ **The barrier at depletion region is increased for both mobile carriers. Depletion width increases.**
- ➢ **Current conduction due to minority carrier flow.**
- ➢ **Reverse bias.**

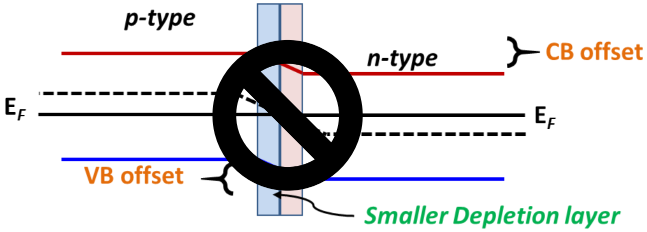


p-n junction with external fields

Case – 2: Electric field directed from *p*-type to *n*-type

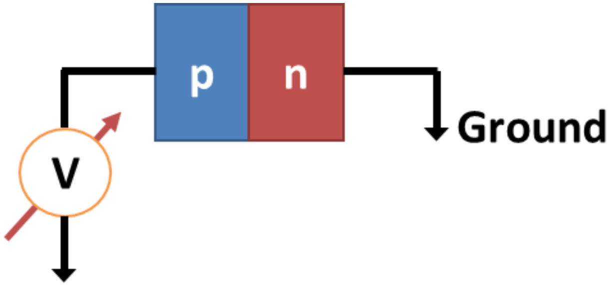


- Facilitates movement of electrons (hole) from n-type (p-type) to p-type (n-type).
- The barrier at depletion region is lowered for both mobile carriers. Depletion width decreases.
- Current conduction due to majority carrier flow.
- Forward bias.



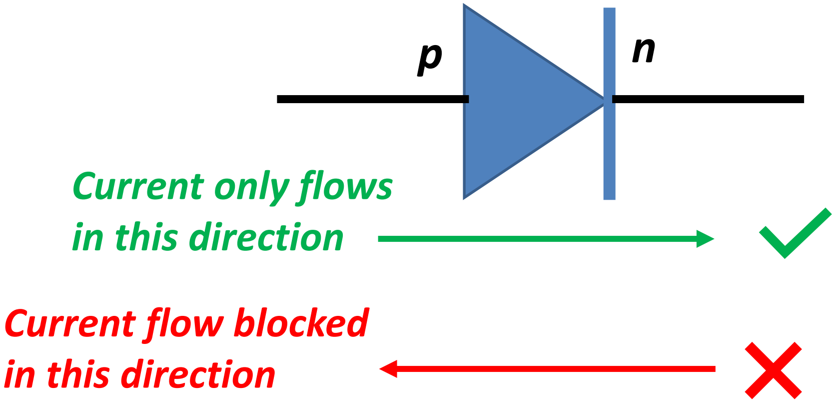
Response of *p-n* junction to voltage sweep

- **Start with connecting *n*-type side to ground and p-type to a voltage source.**



- **When *p*-type is negative with respect to *n*-type, the electric field points from *n* to *p*.**
- **Reverse bias condition, <u>minority</u> carrier current. (Very small value).**
- **When *p*-type is positive with respect to *n*-type, the electric field points from *p* to *n.***
- **Forward bias condition, <u>majority</u> carrier current. (Large value).**

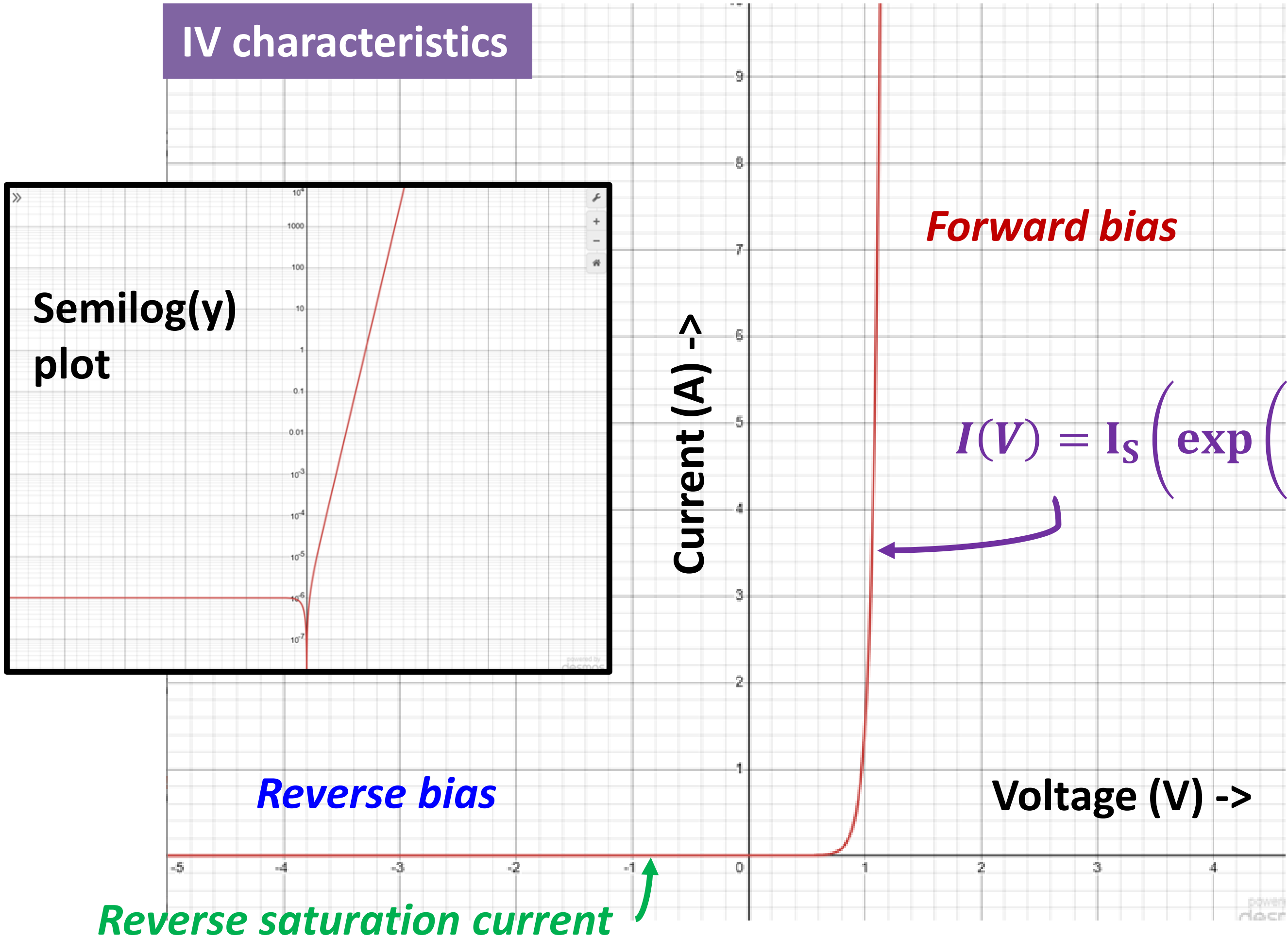
Let's plot the current with respect to the applied voltage…



Current only flows in this direction

Current flow blocked in this direction

Response of *p-n* junction to voltage sweep



IV characteristics

Semilog(y) plot

Current (A) ->

Forward bias

Shockley equation

$$I(V) = \mathbf{I_S}\left(\exp\left(\frac{qV}{\eta k_B T}\right) - 1\right)$$

Reverse bias

Voltage (V) ->

Reverse saturation current

Performance params: Rectification ratio, reverse saturation current, ideality factor, series/dynamic resistance

What to do with a diode??

- Make a one way valve in any circuit…
- To do stuff with alternating current (voltage) signals.
- Protection to circuits.
- Provide reference voltages (Zener diode).

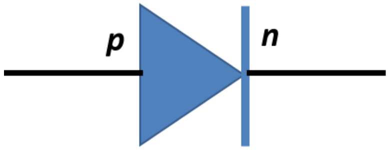
….

- Diodes with photo sensitive semiconductors can be photodetectors.

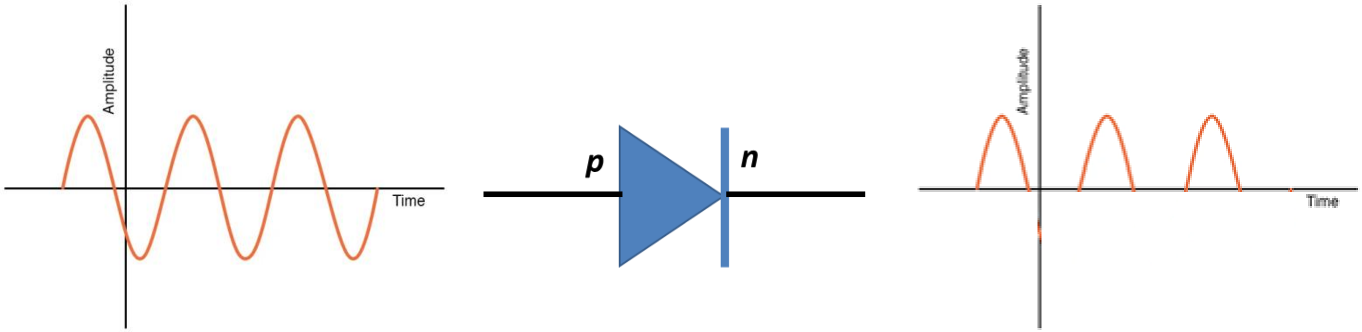
…And tons of other stuff I couldn’t think of…

Diodes and alternating current

Take a



Give an AC signal at input…



Again… khabo na mathay debo??

Q. How about using the rectifying property to convert the AC in mains voltage to DC?

A. Virtually every electronic gadget/instrument utilizes some form of rectifier to convert AC to DC…

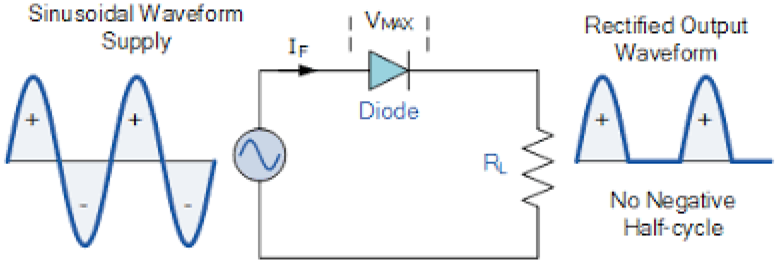
Half-wave rectifier

Full-wave rectifier

As regulated voltage source: Zener diode choto kore…

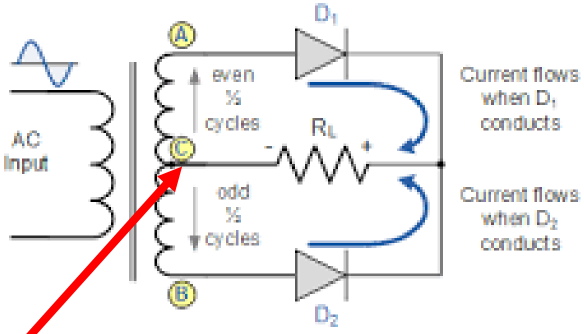
Diodes and alternating current

Half-wave rectifier



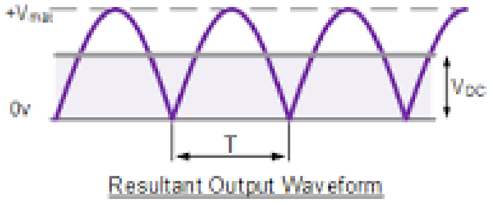
Diode is conducting in only one half of the input cycle

Full-wave rectifier



Each diode conducts in their respective half cycle.

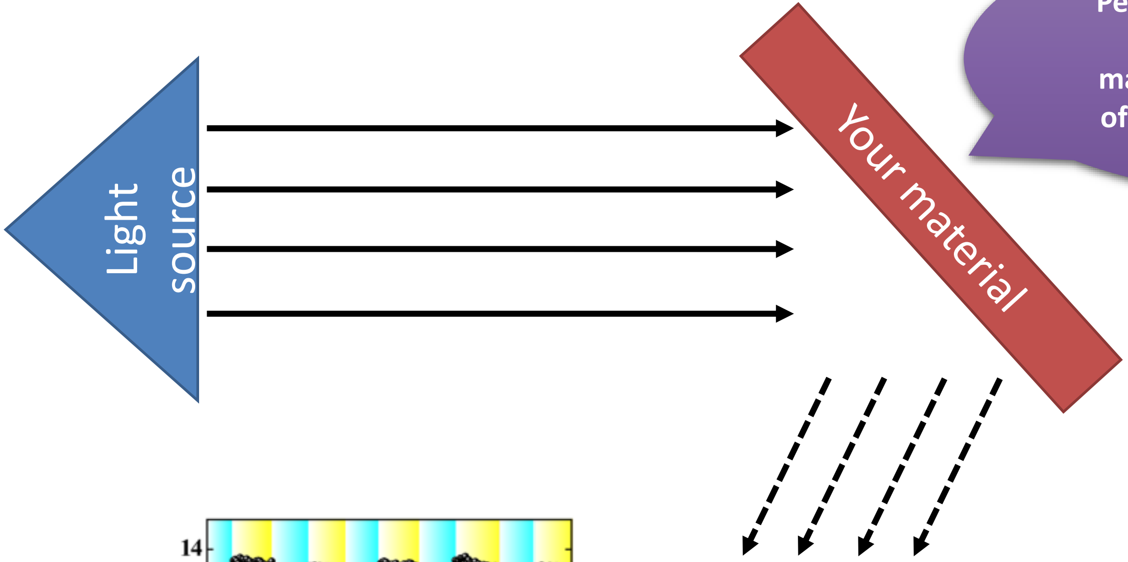
Reference (0 volt) using a Center-tap



Diodes for photodetection

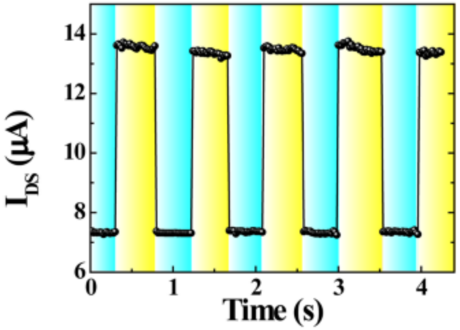
Many of you perform absorption spectroscopy to find the band-gap of your materials…

But how does absorption spectroscopy work??



Peak in absorbance corresponds to the wavelength at which the material absorbs the most amount of light => might be the bandgap…

Detector ⬅ **Photodetector**



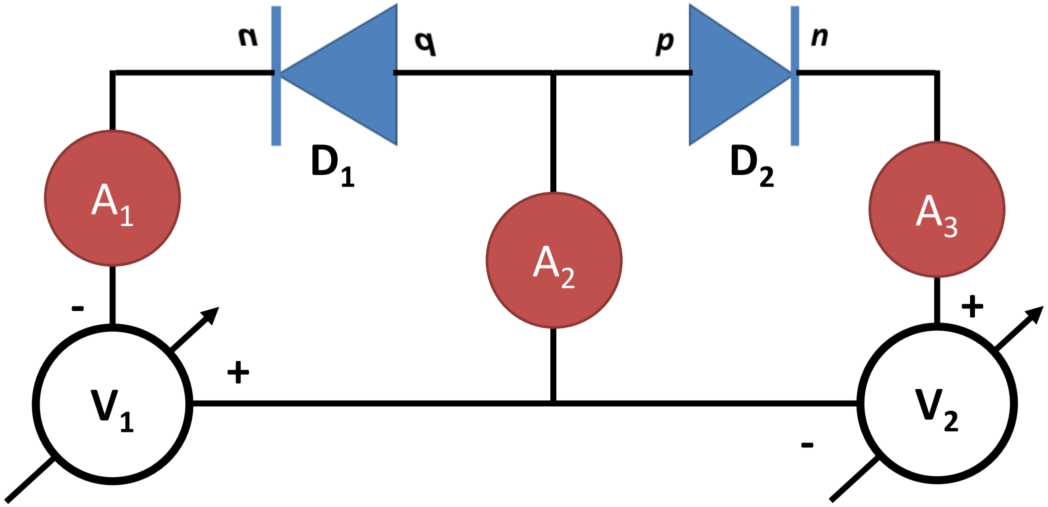
Use in reverse bias condition

Typically:
Si
InGaAs
GaAs…

When two diodes are better than one

We make a connection between two p-n junction diodes…

Why? To try to actively control the flow of current in the circuit!



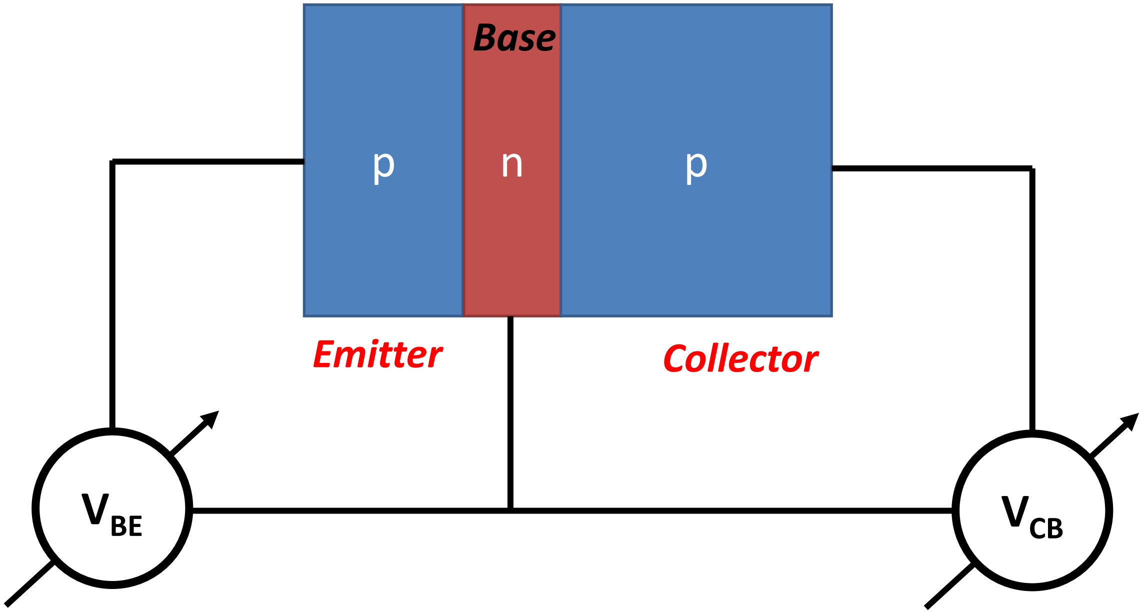
Suppose…

When D_1 is forward biased and D_2 is reverse biased.

- ☐ Majority carrier current will flow through ammeter A_1 and A_2.
- ☐ Minority carrier current will flow through ammeter A_3. Its contribution is negligible.
- ☐ If V_1 is increased the current in A_1 and A_2 will increase. But it will not affect the current through A_3.
- ☐ There is no versatility in the circuit.

When two ~~diodes~~ p-n junctions are better than one

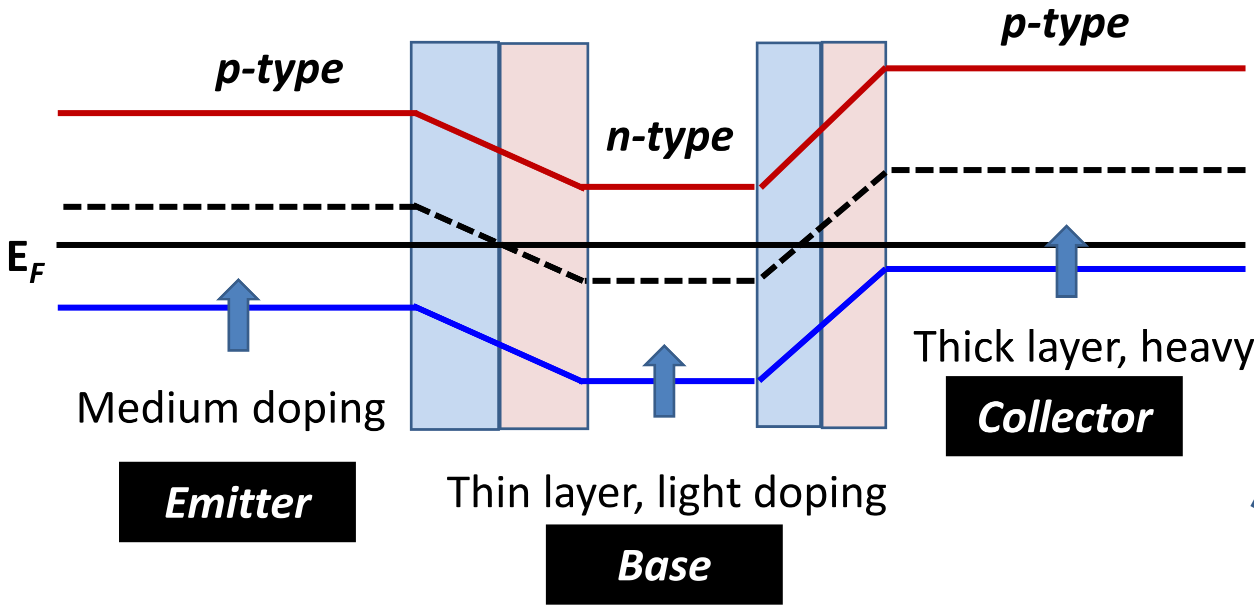
So we make two p-n junctions in a single slab of silicon…



- A very thin base region (*n*-type) sandwiched between two p-type regions.
- A slightly thicker *p*-type region called emitter.
- A thick *p*-type region called collector.

Similar device can be made by sandwiching a p-type material in between two n-type pieces.

When two *p-n* junctions are better than one



Medium doping

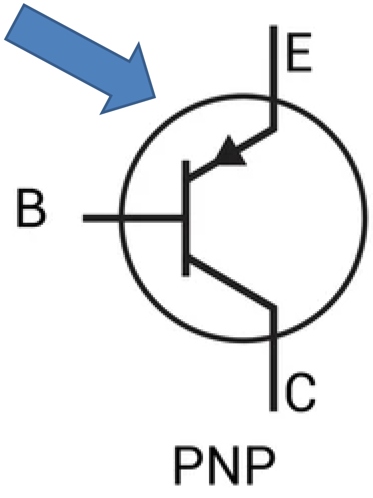
Emitter

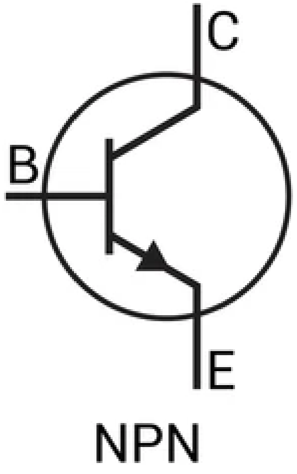
Thin layer, light doping

Base

Thick layer, heavy doping

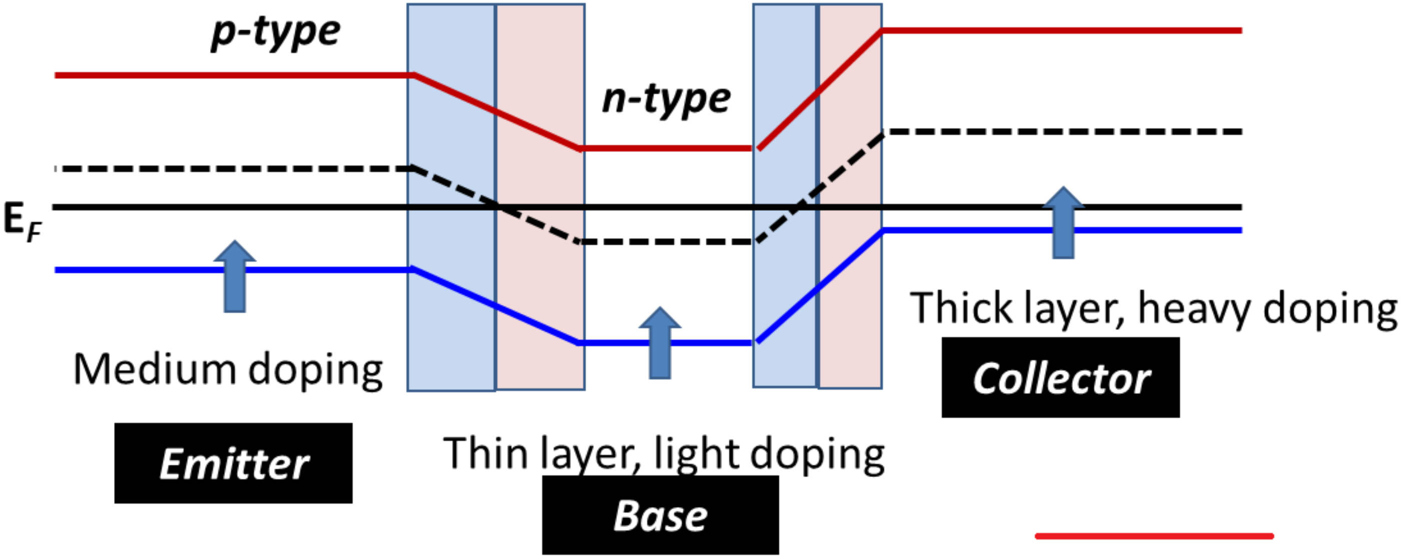
Collector

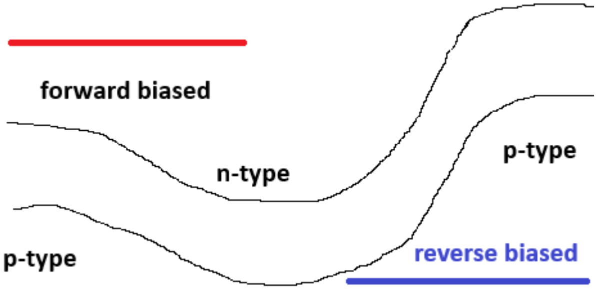




Note:
When drawing the symbol, diode should be between emitter and base

When two *p-n* junctions are better than one





Suppose:

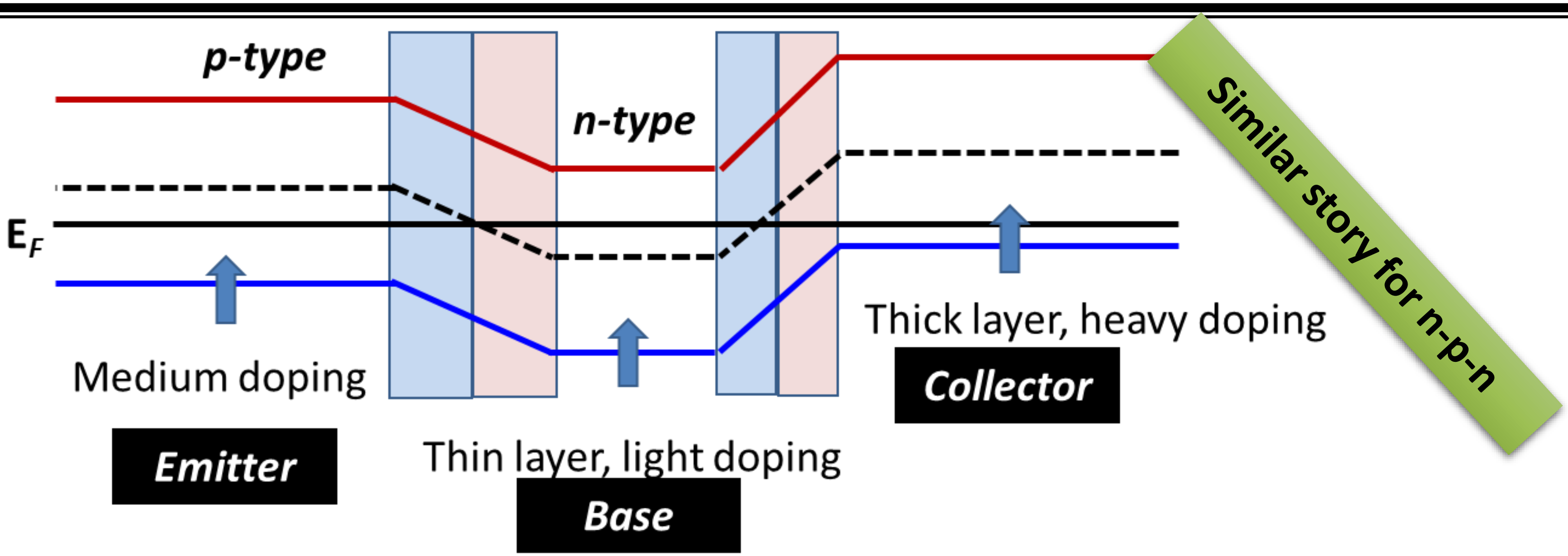
a. Emitter is forward biased with respect to base.

b. Collector is reverse biased with respect to base.

- ☐ **In the emitter-base region, forward current (majority carriers) will flow.**
- ☐ **But what about the base-collector region?**

Lets look at the motion of carriers…

When two *p-n* junctions are better than one

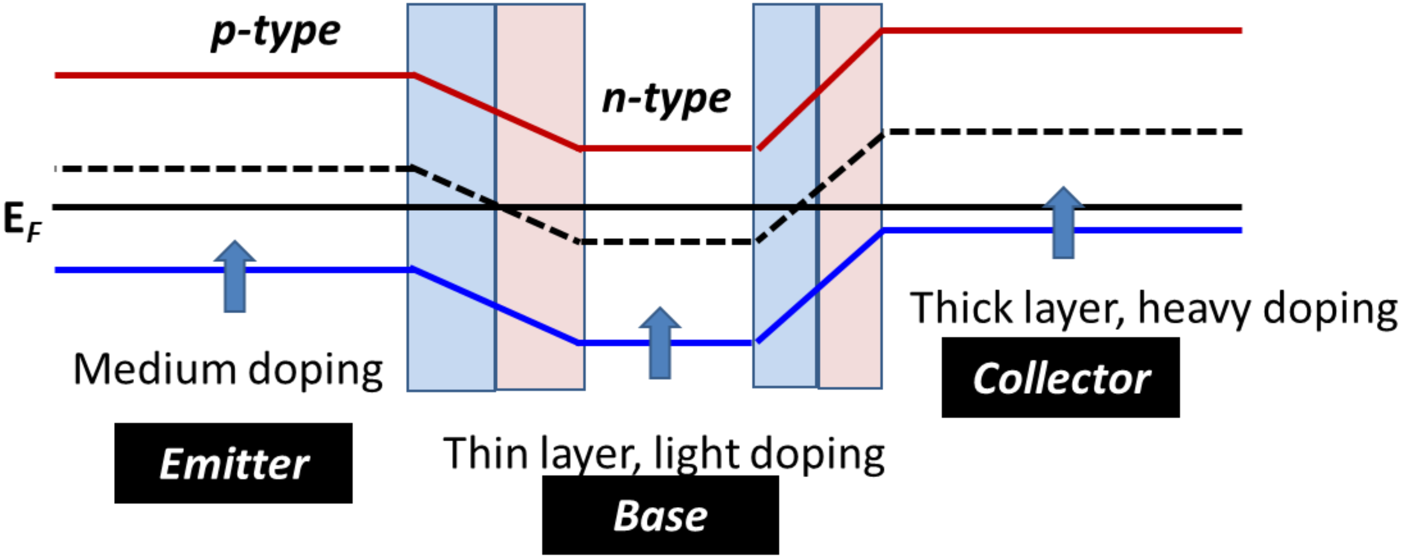


- ❑ Holes will flow from emitter -> base
- ❑ Due to thin base region + reverse bias field, these holes will flow from base -> collector.

- ❑ Electrons will flow from base -> emitter.
- ❑ Minority electrons in collector will also flow to base.

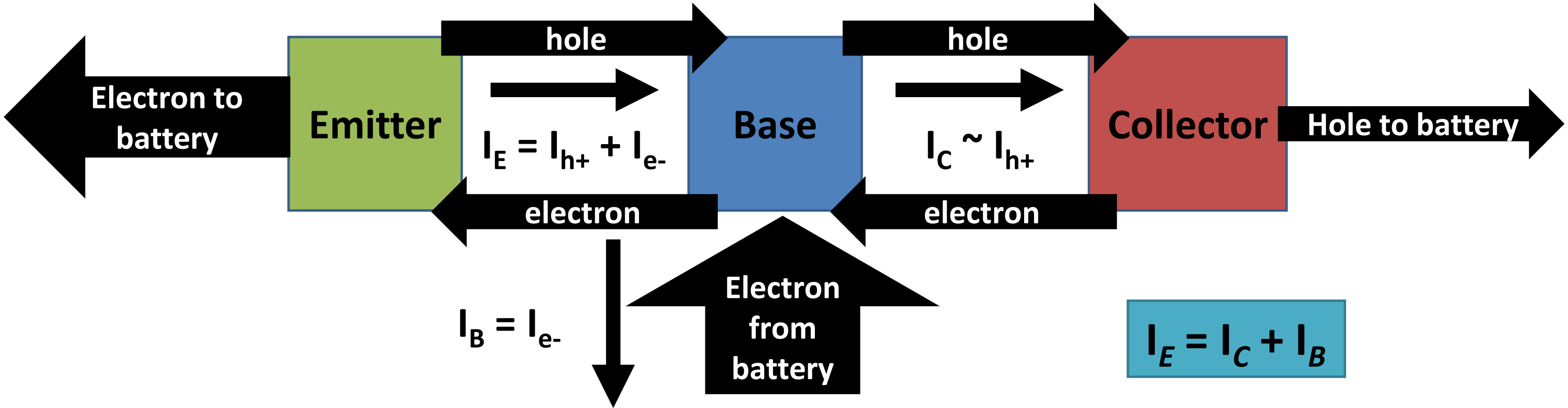
- ❑ Due to forward bias between emitter-base, electrons will be injected into base from the battery.
- ❑ These contribute to electron current. Since the base region is very thin, recombination probability is low.

Carrier flow in p-n-p junctions



- **Let's think about the current…**

(Rule of thumb: Current flows in opposite direction to electrons)



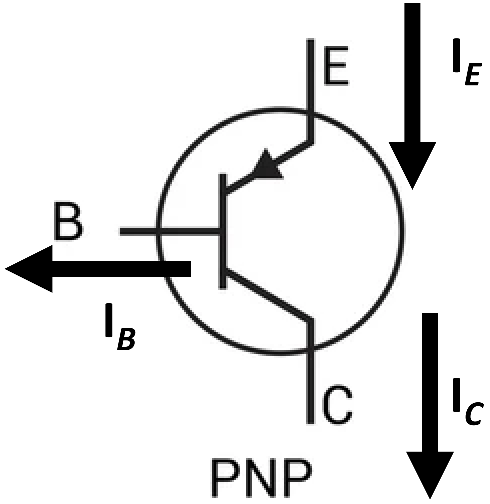
$I_E = I_{h+} + I_{e-}$

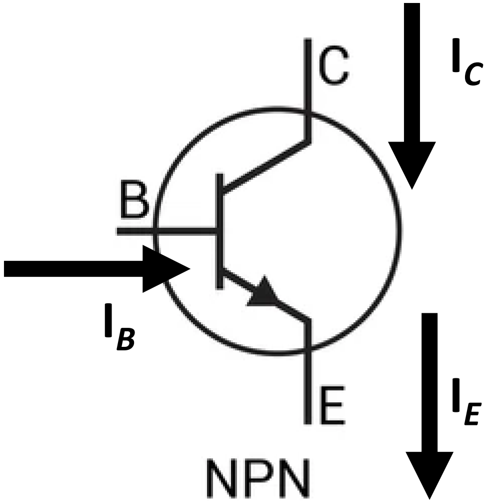
$I_C \sim I_{h+}$

$I_B = I_{e-}$

$I_E = I_C + I_B$

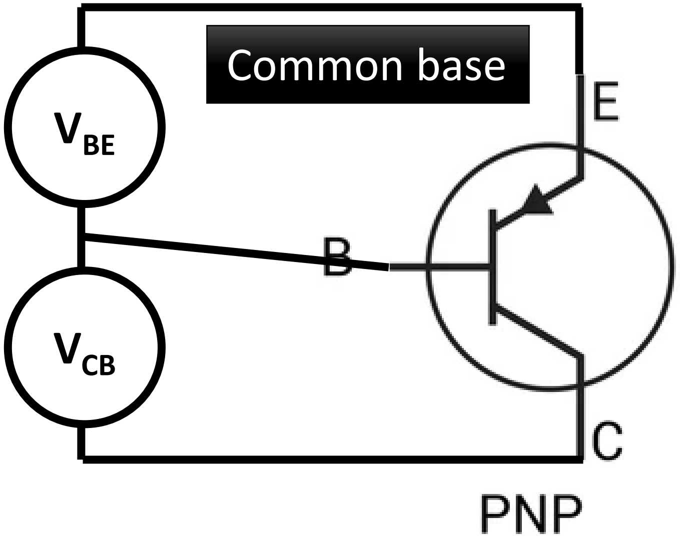
Carrier flow in p-n-p junctions

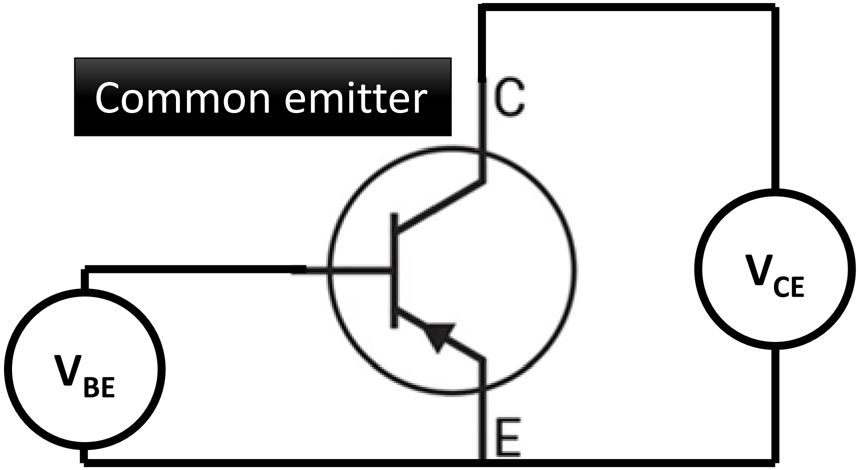




$I_E = I_C + I_B$

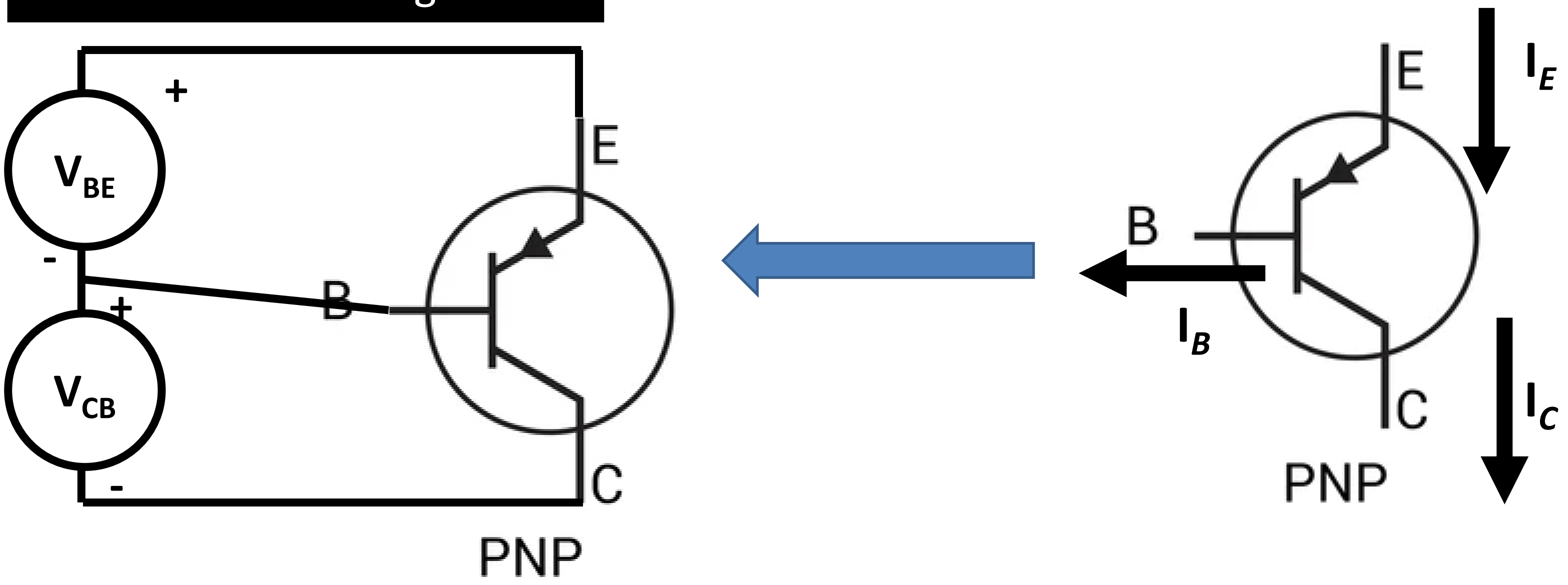
Maybe we could control the collector current using the base current??



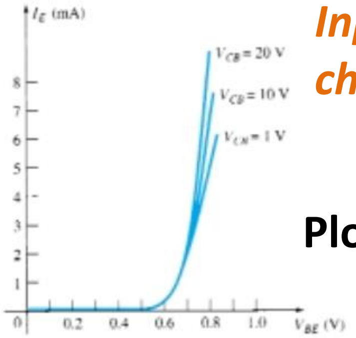


The transistor

Common base configuration



- ☐ Since small number of electrons are injected from base to emitter, consider the E-B region as the input side. (small since the base region is by definition thin)
- ☐ Consider the C-B region as the output side.

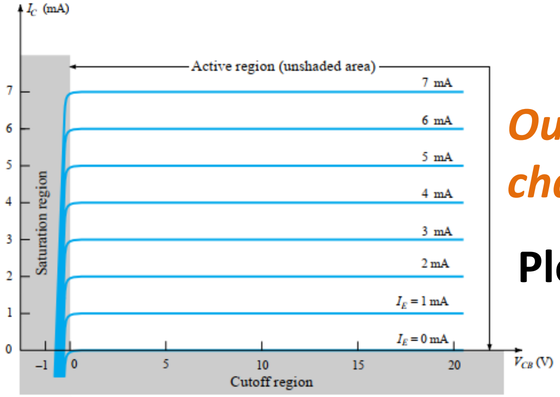


Input characteristics

Plot I_E vs V_{BE}

$I_C \leq I_E$

$I_C = \alpha I_E$



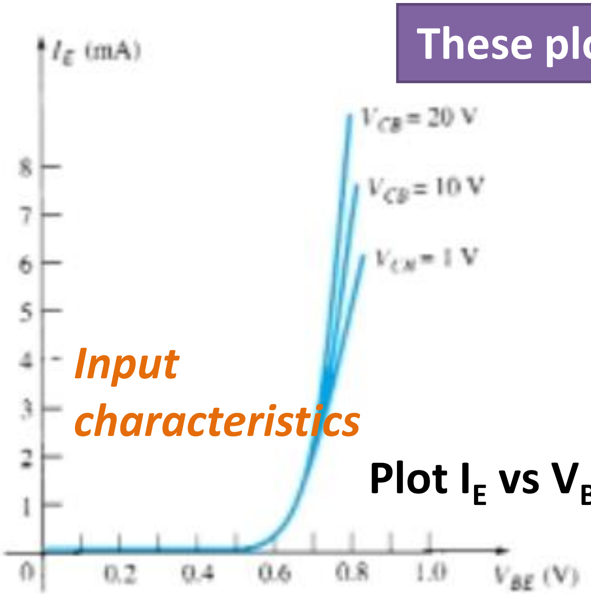
Output characteristics

Plot I_C vs V_{CB}

The transistor

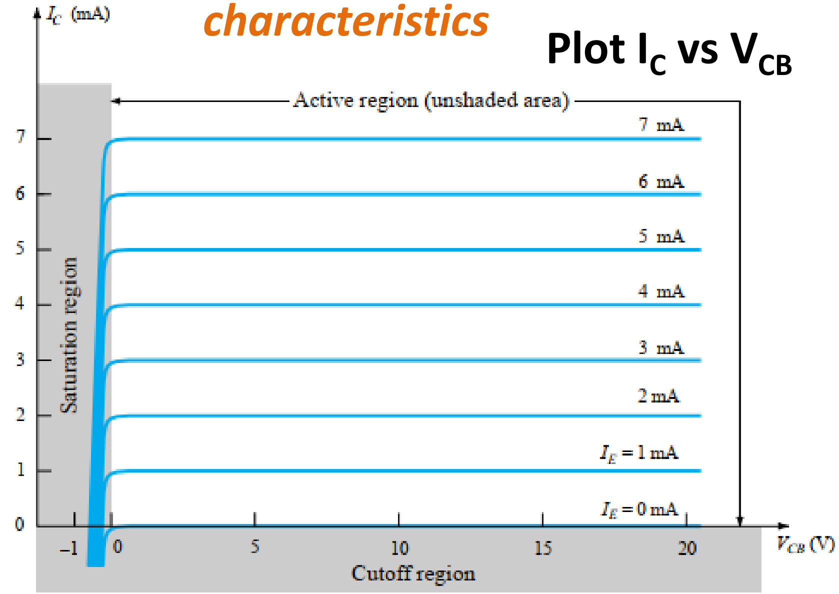
Common base configuration

These plots are for n-p-n



Input characteristics

Plot I_E vs V_{BE}



Output characteristics

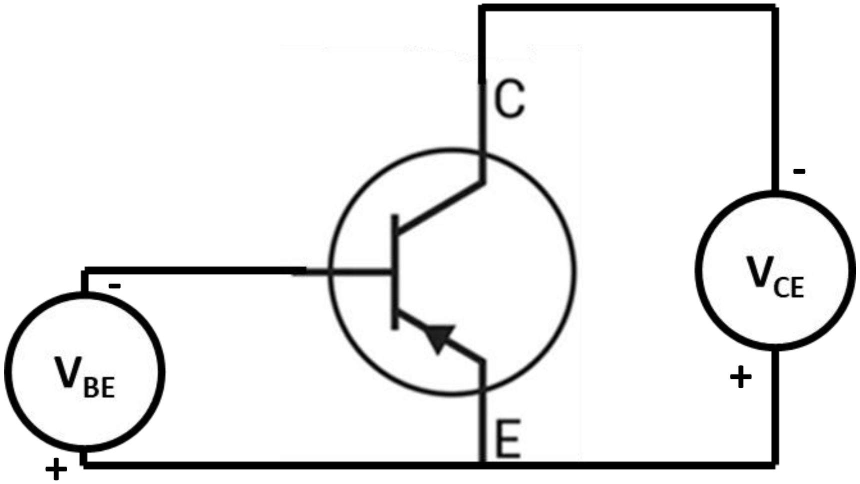
Plot I_C vs V_{CB}

- ❑ **In the input characteristics, the dynamic resistance is LOW.**
- ❑ **In the output characteristics, the active region resistance is HIGH.**
- ❑ **By changing the input resistance, we can tune the output resistance.**
- ❑ **Hence transfer-resistor, i.e., *transistor*.**

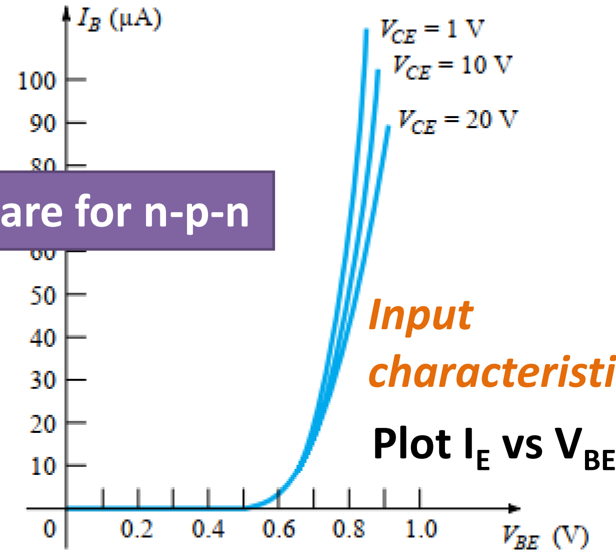
Although current is not amplified, the voltage drop across input side is amplified at the output side!

The transistor

Common emitter configuration



These plots are for n-p-n



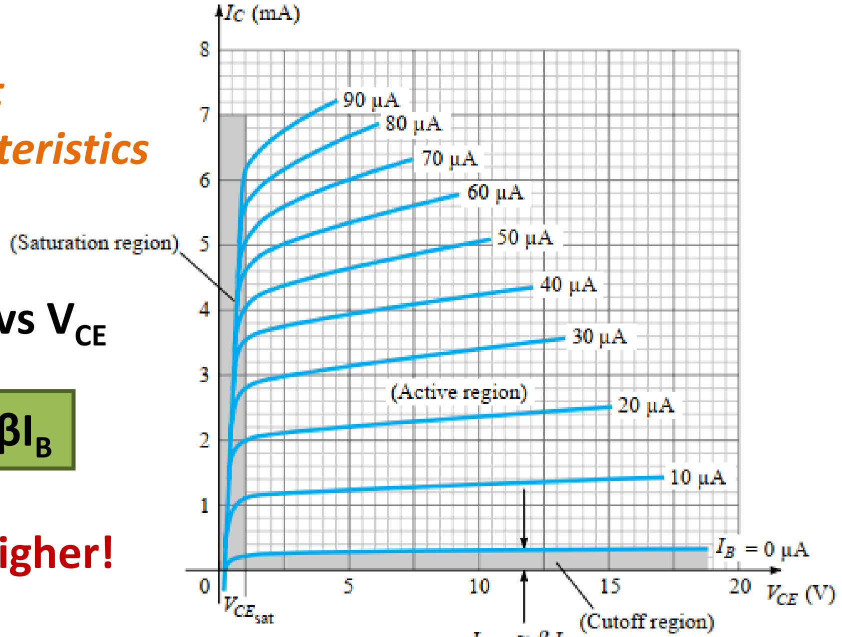
Input characteristics

Plot I_E vs V_{BE}

Output characteristics

Plot I_C vs V_{CE}

$I_C = \beta I_B$



- ❑ Very small base current.
- ❑ Orders of magnitude larger collector current.
- ❑ Current amplification!

β~ 25 – 150 or even higher!