Bipolar Junction Transistors (BJT)

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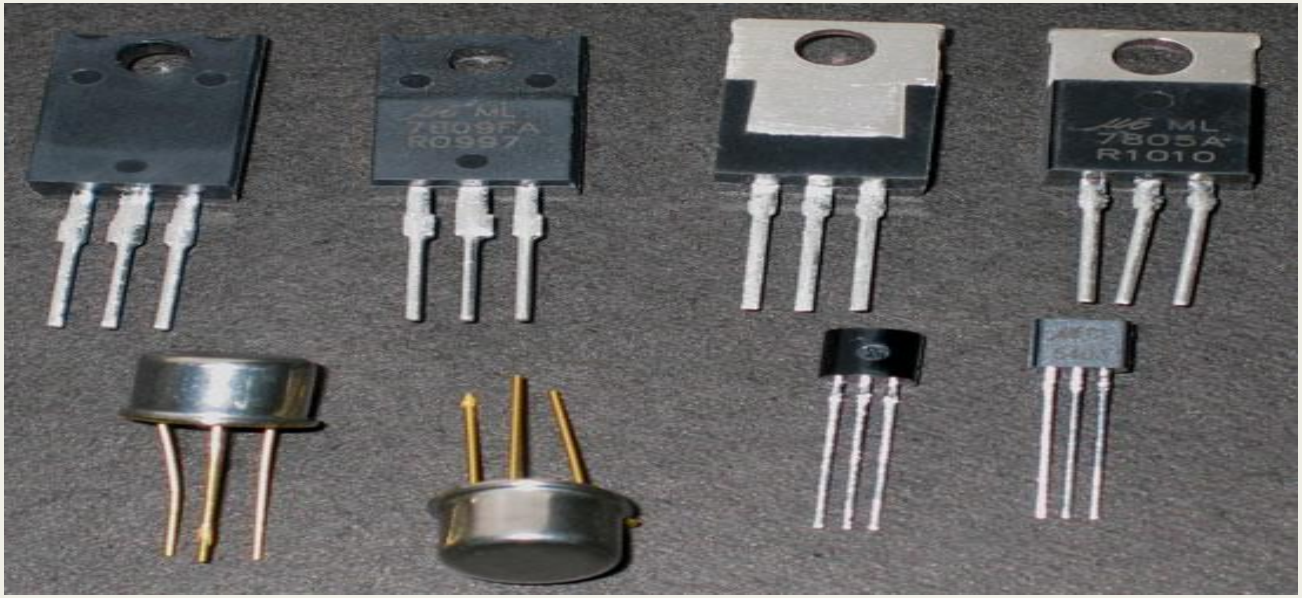
Syllabus

Module – 3: Bipolar Junction Transistors:

- PNP and NPN transistors,
- Energy band diagram,
- Working principle of transistor,
- cut-off, active and saturation,
- Current components in active mode,
- Transistor characteristics, CE, CB, CC configurations,
- Transistor as an amplifier and a switch,
- Biasing and bias stability,
- CE *h*-parameter model, and analyses of amplifiers using *h*-parameter model.

What is a transistor?

- A transistor is a 3 terminal electronic device made of semiconductor material.
- Transistors have many uses, including amplification, switching, voltage regulation, and the modulation of signals.



The History

- **Before transistors were invented, circuits used vacuum tubes:**
- **Fragile, large in size, heavy, generate large quantities of heat, require a large amount of power.**
- **The first transistors were created at Bell Telephone Laboratories in 1947.**
- **William Shockley, John Bardeen, and Walter Brattain created the transistors in and effort to develop a technology that would overcome the problems of tubes.**

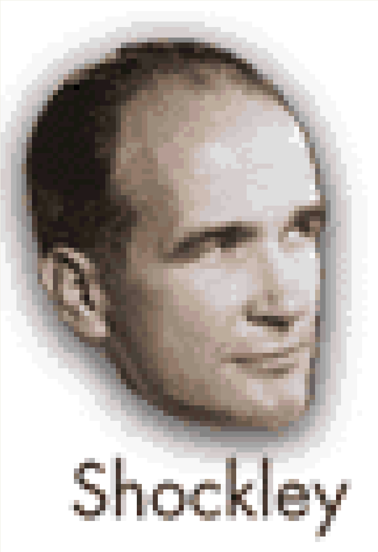
1926 & 1928

- The first patents for the principle of a field effect transistor were registered in 1926 by Julius Edgar Lilienfeld. With improved device he again registered another patent in 1928.
- Shockley, Bardeen, and Brattain had referenced this material in their work.
- The word "transistor" is a combination of the terms "transconductance" and "variable resistor".
- Today an advanced microprocessor can have as many as 1.7 billion transistors.

1936

- Mervin Kelly Bell Lab's director of research. He felt that to provide the best phone service it will need a better amplifier;
- The answer might lie in semiconductors.
- And he formed a department dedicated to solid state science.

1945

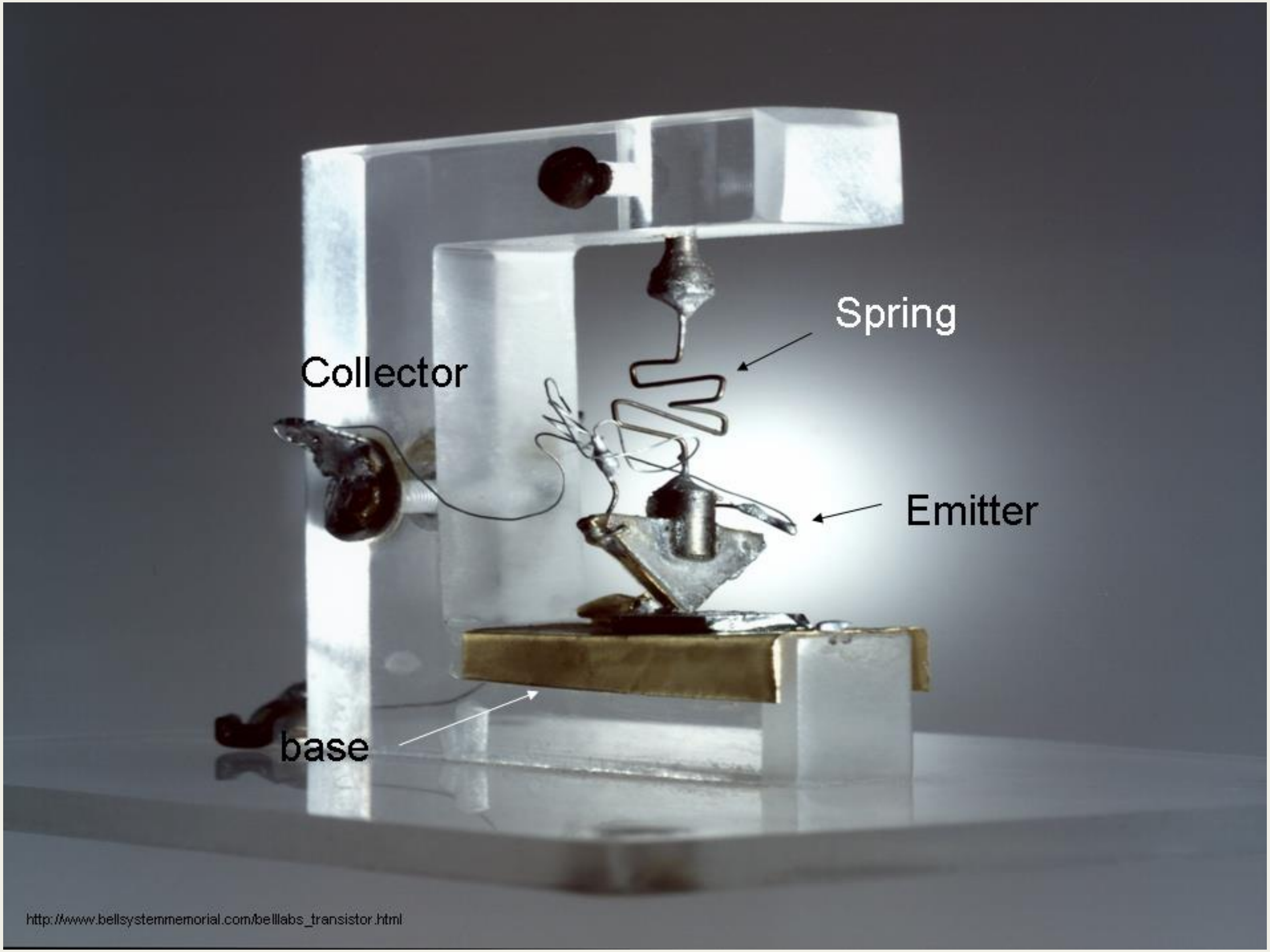


- Bill Shockley the team leader of the solid state department (Hell's Bell Lab) hired Walter Brattain and John Bardeen.
- He designed the first semiconductor amplifier, relying on the field effect.
- His device was a small cylinder coated thinly with silicon, mounted close to a small, metal plate.
- The device didn't work, and Shockley assigned Bardeen and Brattain to find out why.

1947

- **Bardeen and Brattain built the point contact transistor.**
- **They made it from strips of gold foil on a plastic triangle, pushed down into contact with slab of germanium.**

1947 (continued)

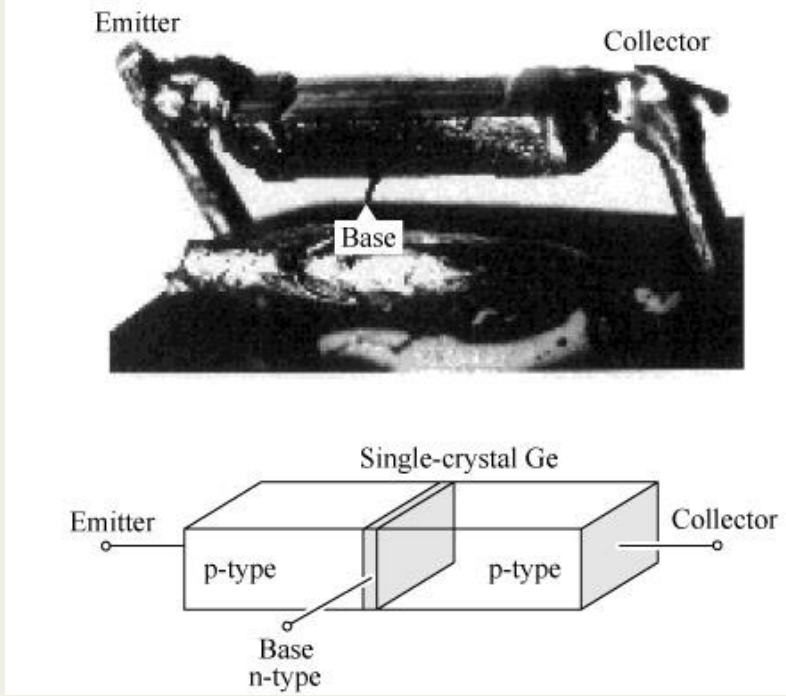


1947 (continued)

- **Shockley make the Junction transistor (sandwich).**
- **This transistor was more practical and easier to fabricate.**
- **The Junction Transistor became the central device of the electronic age.**

The First Junction Transistor

First transistor with diffused pn junctions by *William Shockley*
Bell Laboratories, Murray Hill, New Jersey (1949)



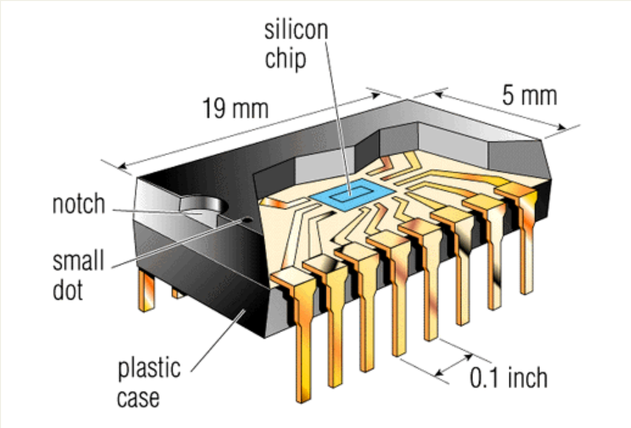
1948

- Bells Lab unveil the transistor.
- They decided to name it transistor instead of Point-contact solid state amplifier.
- John Pierce invented the name, combining transresistance with the ending common to devices, like varistor and thermistor.

1958

- Jack Kilby of Texas Instruments
  - Invent the Integrated Circuit (IC)
  - It occurred to him that all parts of a circuit could be made out of the same piece of silicon
  - The entire circuit could be built out of a single crystal
    - Reducing the size
    - Easier to produce

1958 (continued) – Integrated Circuit

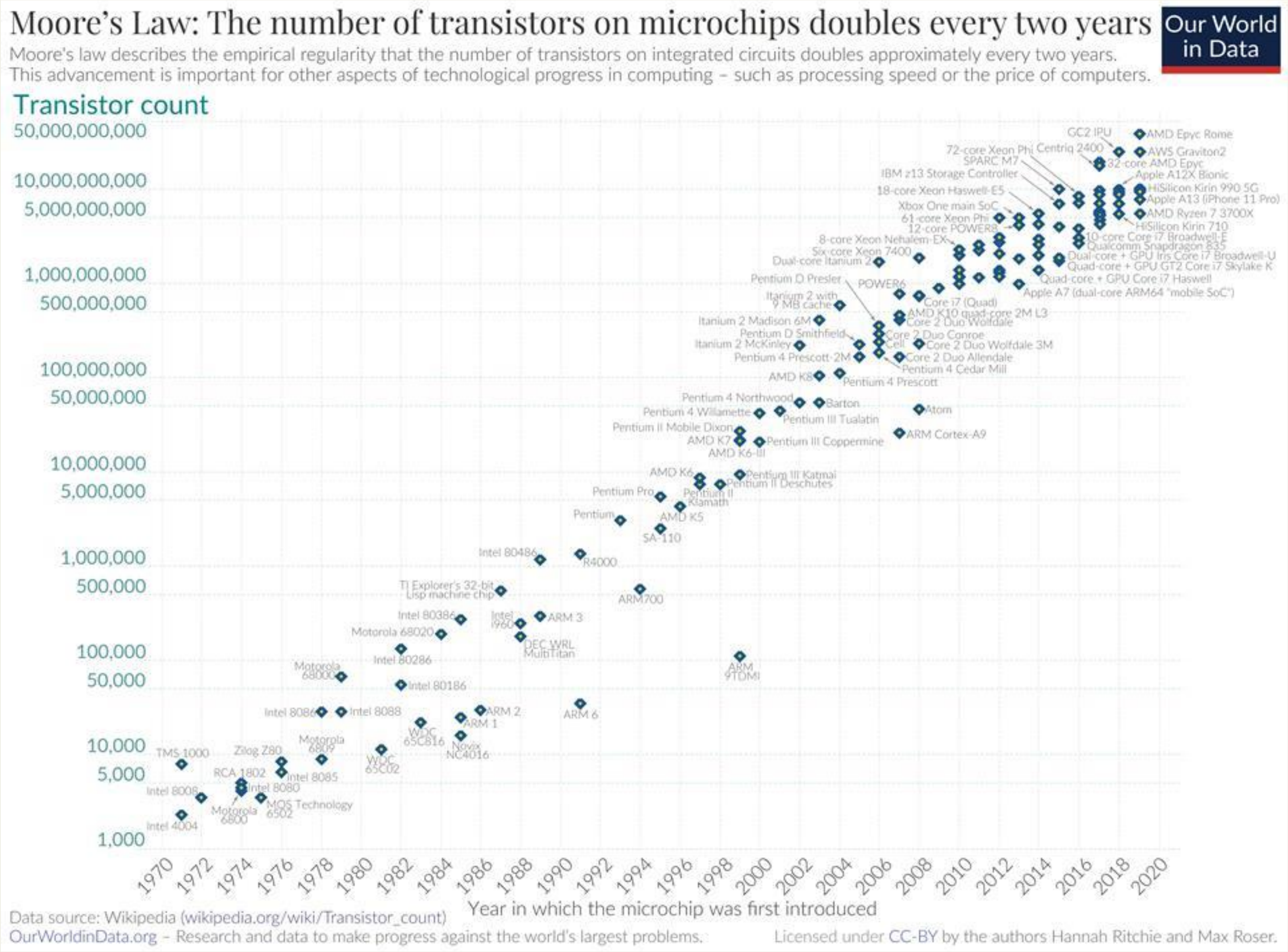


- **A single device that contains an interconnected array of elements like transistors, resistors, capacitors, and electrical circuits contained in a silicon wafer.**

Moore's Law

- In 1965, Gordon E. Moore, the co-founder of Intel predicted that the number of transistors inside a dense Integrated Circuit, could be doubled every 24 months.
- At the density that also minimized the cost of a transistor to be halved.
- He made this observation that became known as Moore's Law.
- Moore's law is an observation and projection of a historical trend. Rather than a law of physics, it is an empirical relationship linked to gains from experience in production.

Moore's Law



Moore's Law: The number of transistors on microchips doubles every two years
Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years.
This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.
Our World in Data
Transistor count
Year in which the microchip was first introduced
Data source: Wikipedia (wikipedia.org/wiki/Transistor_count)
OurWorldinData.org – Research and data to make progress against the world's largest problems.
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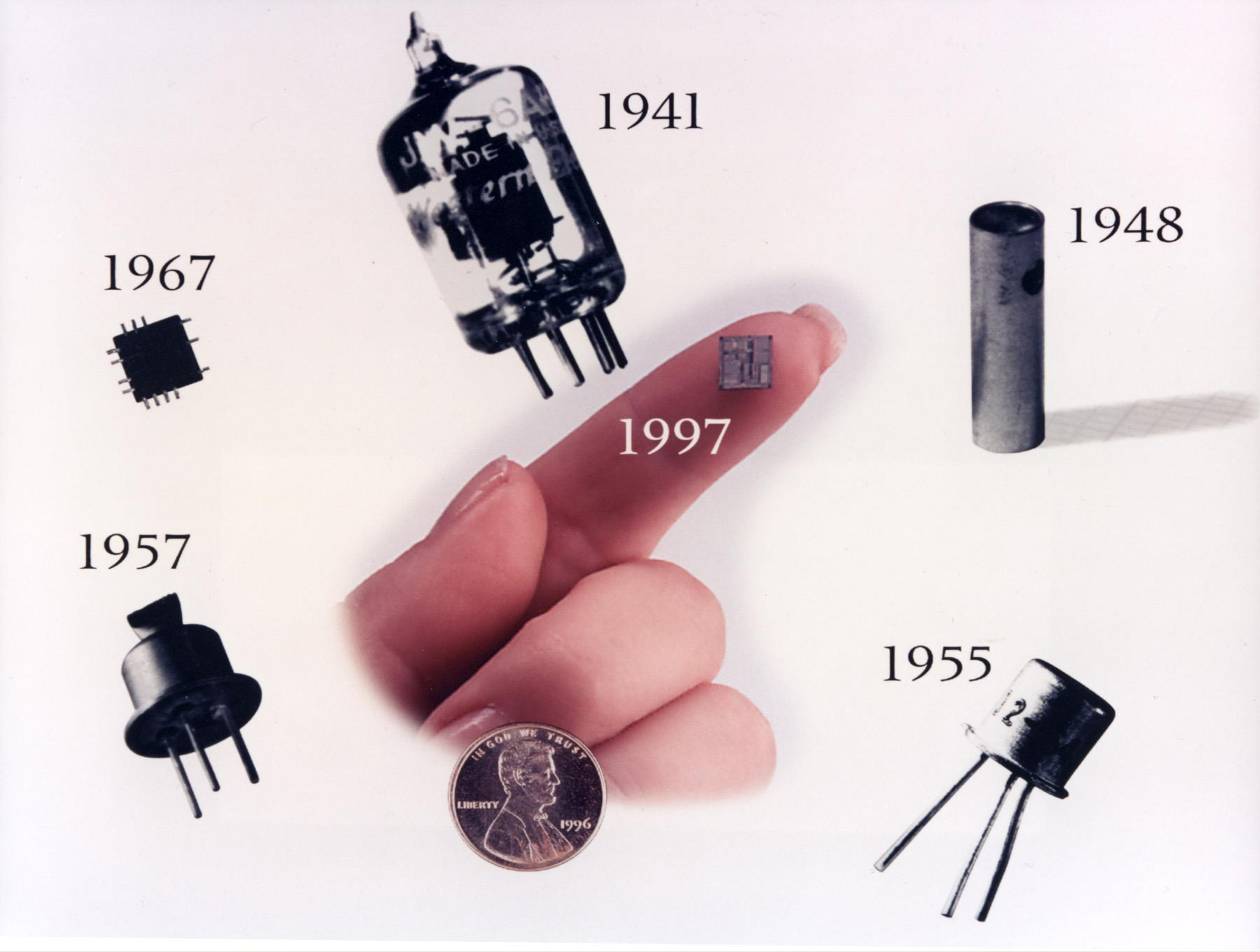
Transistor problems

- Power density increased
- Device variability
- Reliability
- Complexity
- Leakage
- Power dissipation limits device density
- Transistor will operate near ultimate limits of size and quality
  - Eventually, no transistor can be fundamentally better.

Pictorial History of Transistors



Background Science

- Conductors
  - Ex: Metals
  - Flow of electricity governed by motion of free electrons
  - As temperature increases, conductivity decreases due to more lattice atom collisions of electrons
  - Idea of superconductivity
- Insulators
  - Ex: Plastics
  - Flow of electricity governed by motion of ions that break free
  - As temperature increases, conductivity increases due to lattice vibrations breaking free ions
  - Irrelevant because conductive temperature beyond melting point

Transistor types

- **MOS - Metal Oxide Semiconductor**
- **FET - Field Effect Transistor**
- **BJT - Bipolar Junction Transistor**

How a Transistor Works?

- The transistor can function as:
- – An insulator
- – A conductor
- The transistor's ability to fluctuate between these two states that enables to switch or amplify.
- The transistor has many applications, but only two basic functions: switching and modulation (amplification).

Transistor materials

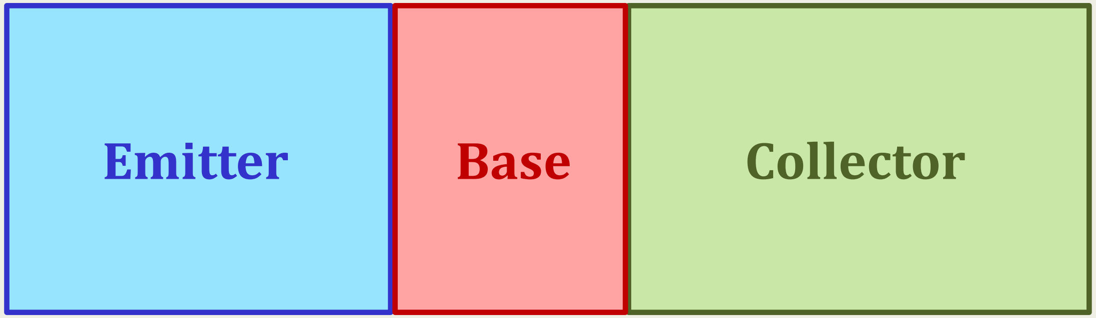
- **Transistors are made of semiconductors such as silicon and gallium arsenide.**
- **These materials carry electricity not well enough to be called conductors; not badly enough to be called insulators.**
- **Hence their name semiconductor.**
- **The importance of a transistor is in its ability to control its own semi conductance, namely acting like a conductor when needed, or as an insulator (nonconductor) when that is needed.**

Transistors are Made of Silicon

- Silicon is a grey colored element with crystalline structure.
- It is the second most abundant element in the earth's crust, after oxygen.
- Silicon is always found in combined form in nature, often with oxygen as quartz, and is found in rocks and silica sand.
- To be able to use silicon as a semiconductor, it needs to be in a very pure form.
- If there is more than one impure particle in a million, the silicon can not be used.
- Silicon is the most frequently used semiconducting material today.

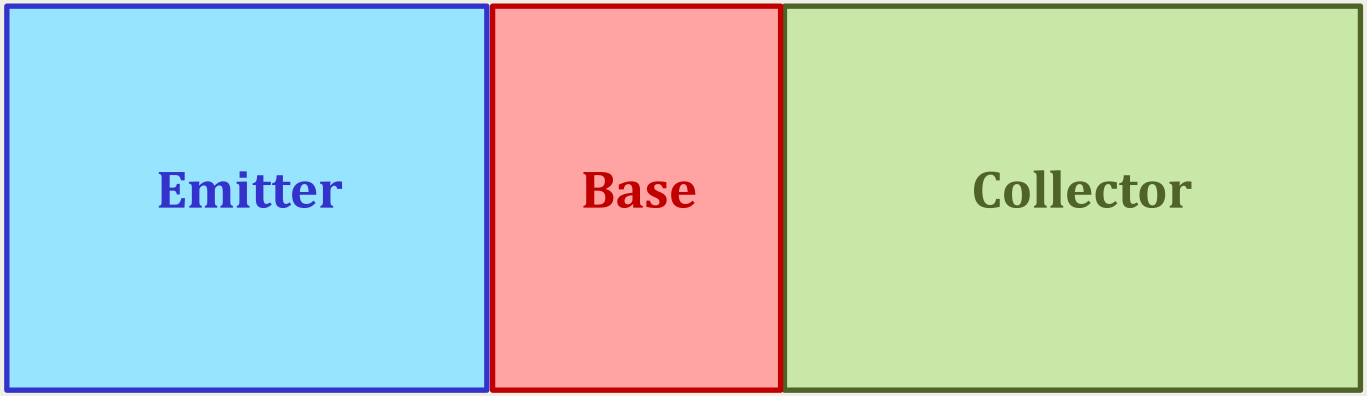
Bipolar Junction Transistors (BJTs)

- The bipolar junction transistor is a semiconductor device constructed with three doped regions.
- These regions essentially form two ‘back-to-back’ *p-n* junctions in the same block of semiconductor material (silicon or germanium).
- The most common use of the BJT is in linear amplifier circuits (linear means that the output is proportional to input).
- It can also be used as a switch (as for example, in logic circuits).



BJT Structure

- **The three regions are known as the emitter, base and collector regions.**
- **Electrical connections are made to each of these regions.**



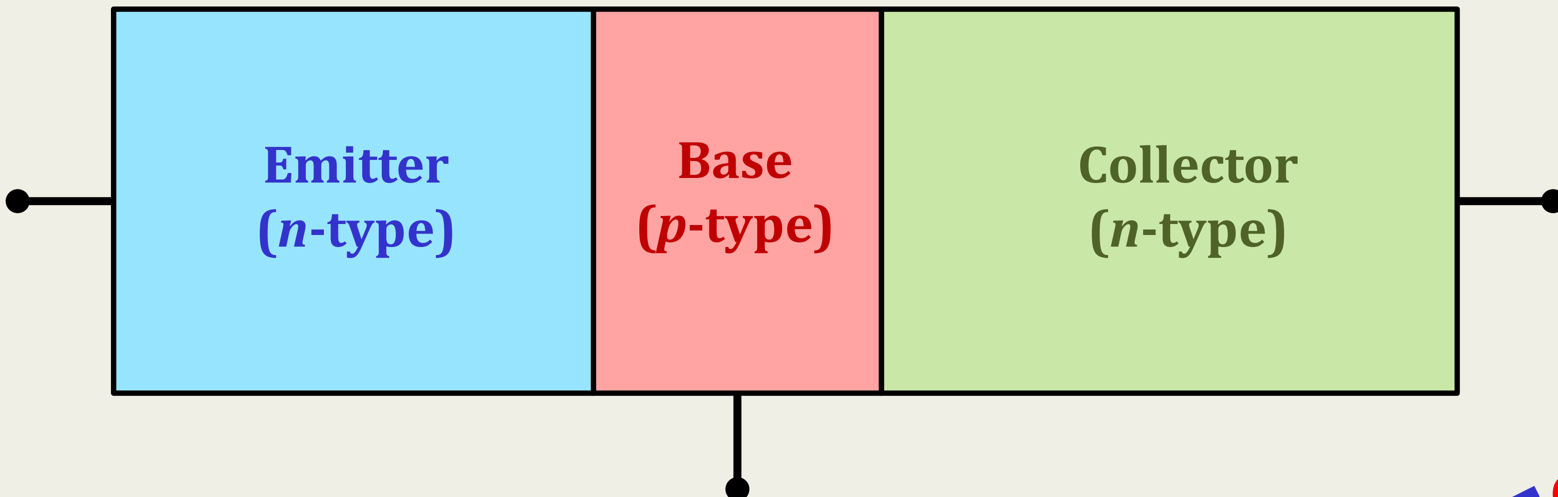
- **The emitter (E) and is *heavily doped*.**
- **The base (B) is *lightly doped* with opposite type to the emitter and collector.**
- **The doping of the collector region is of same type of emitter and is *intermediate* between the emitter and the base.**

Doping Profile and Physical Dimension of BJT

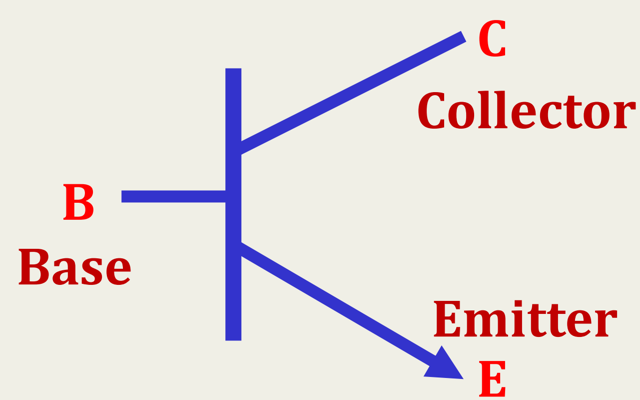
- The emitter region is *heavily doped*. and the base region is very lightly doped, and is made physically very thin.
- The base region is very lightly doped, and is made physically very thin.
- The doping of the collector region is *intermediate* between the emitter and the base.
- The collector region is made *physically larger* than the remitter region since it is required to dissipate more heat.
- Although the emitter and collector regions are of the same type, their functions cannot be interchanged.
- The two regions have different physical and electrical properties.

npn-BJT Structure & Symbol

- **The '*npn*' version of the BJT consists of two *n* regions separated by a *p* region (as the name suggests).**
- **A schematic of an *npn* transistor is shown.**

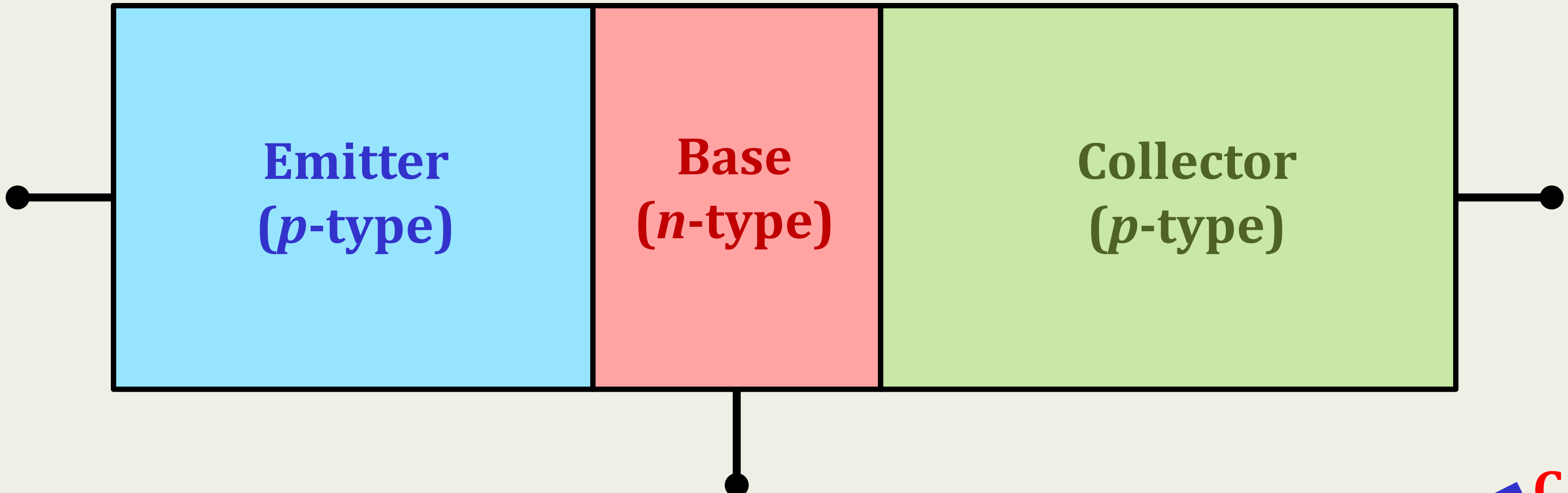


- **In the symbol for an *npn* BJT transistor, the direction of the arrow on the emitter is the direction of current flow.**

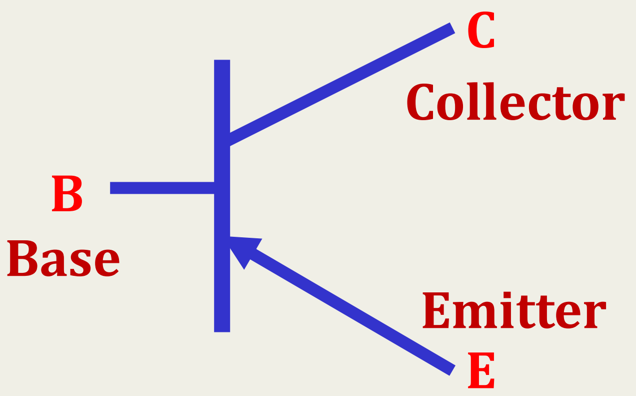


pnp-BJT Structure & Symbol

- The '*pnp*' version of the BJT consists of two *p* regions separated by an *n* region (as the name suggests).
- A schematic of an *pnp* transistor is shown.



- In the symbol for a *pnp* BJT transistor, the direction of the arrow on the emitter is the direction of current flow, which is just reversed of that in the *npn* BJT transistor.



E-B and C-B Junctions

- **A transistor has two p-n junctions.**
- **The *p-n* junction between the emitter and base regions is called the *emitter-base* (E-B) *junction* or *base-emitter* (B-E) *junction* (it doesn't really matter), or simply the *emitter junction*.**
- **The *p-n* junction between the collector and base regions is called the *collector-base* (C-B) *junction* or *base-collector* (B-C) *junction*, or simply the *collector junction*.**
- **Thus, a transistor is like two *p-n* junction diodes connected back-to-back but in the block of same semiconducting material.**

Surprising Action of a Transistor

- **Transistor has two *p-n* junctions – an emitter junction (E-B junction) and a collector junction (C-B junction).**
- **Therefore, there are four possible ways of biasing these two junctions (see the Table below).**
- **Of these combinations, at the moment we put our attention only on the condition I, where emitter (E-B) junction is forward-biased and collector (C-B) junction is reverse-biased. This condition is often described as forward-reverse (FR).**

Table

Condition		*Emitter Junction*	*Collector Junction*	*Region of Operation*
I	FR	Forward-biased	Reverse-biased	Active
II	FF	Forward-biased	Forward-biased	Saturation
III	RR	Reverse-biased	Reverse-biased	Cutoff
IV	RF	Reverse-biased	Forward-biased	Inverted

Surprising Action of a Transistor (continued)

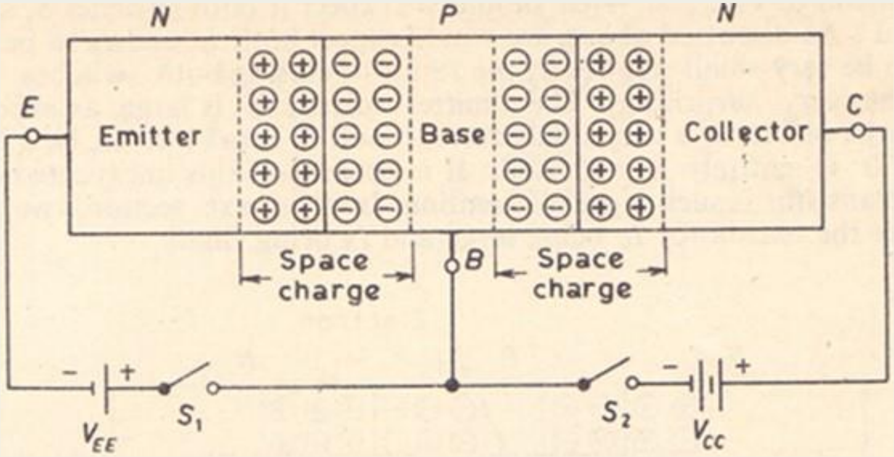


Fig. : Biasing an NPN transistor for active operation.

- **Let us consider an *npn* transistor biased for active operation.**
- **The battery V_{EE} acts to forward bias the emitter junction, and the battery V_{CC} acts to reverse bias the collector junction. Therefore, there are four possible ways of biasing these two junctions (see the Table below).**
- **When the both the switches S_1 and S_2 are open, both the emitter and collector junctions are unbiased.**
- **Therefore, depletion or space-charge regions are developed across the two junctions.**

Surprising Action of a Transistor (continued)

- **When the switch S_1 is closed and the switch S_2 is open, the emitter junction is forward-biased.**
- **The potential barrier at the emitter junction is reduced.**

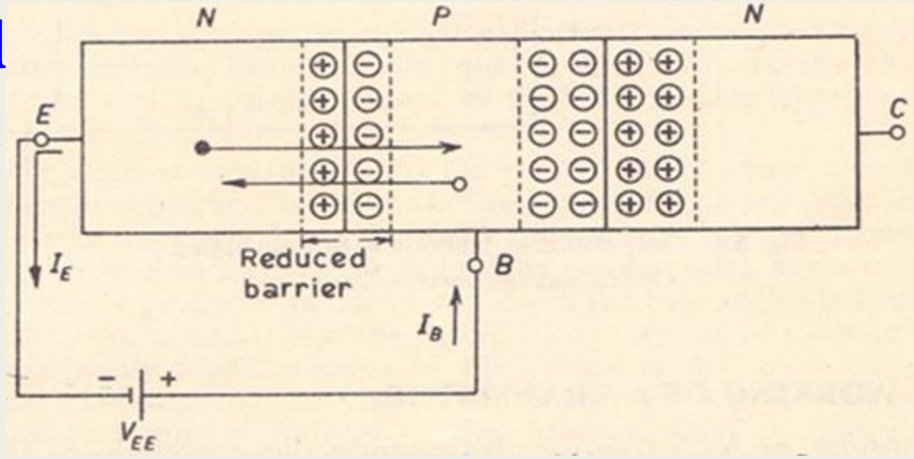


Fig. : Only emitter junction is forward biased- a large current flows.

- **Thus, a large current flows across the forward-biased emitter junction.**
- **This current consists of majority carries diffusing across the junction. That is electrons diffusing from the emitter to the base, and holes from the base to the emitter.**

Surprising Action of a Transistor (continued)

- The total current flowing across the emitter junction is the sum of the electron diffusion current and the hole diffusion current.

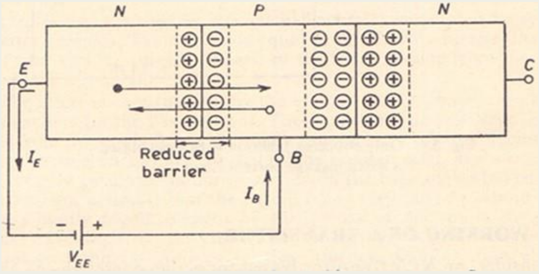


Fig. : Only emitter junction is forward biased- a large current flows.

- Since the base region is very lightly doped compared to the emitter region, there are very few holes in the base region compared to enormous electrons in the emitter region.
- As a result, over 99% of the total current is carried by the electrons (diffusing from the emitter to the base).
- This current flowing out of the emitter terminal and into the base terminal is quite large. There is no collector current ($I_C = 0$) in this case.

Surprising Action of a Transistor (continued)

- When the switch S_2 is closed and the switch S_1 is open, the collector junction is reverse-biased.
- The potential barrier at the collector junction is increased.

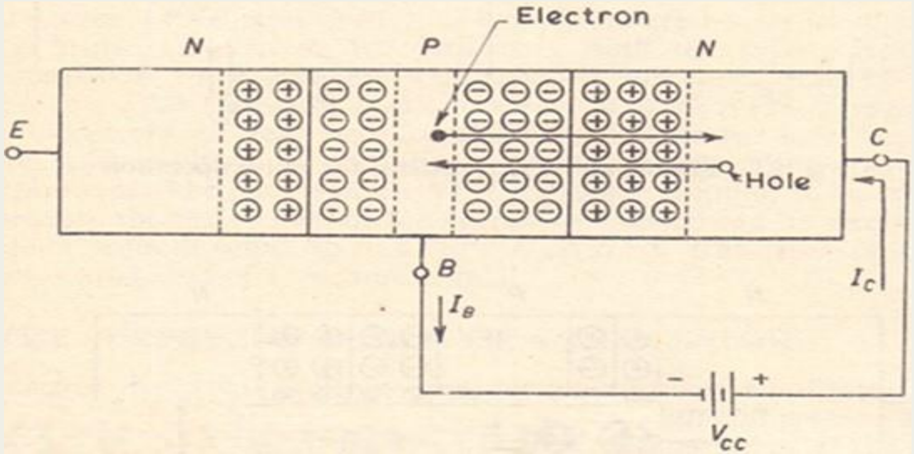


Fig. : Only collector junction is reverse biased- a small current flows.

- Thus, a very small current known as reverse leakage current flows across this reverse-biased collector junction.
- This reverse leakage current consists of minority carries diffusing across the junction. That is electrons diffusing from the base to the collector, and holes from the collector to the base.

Surprising Action of a Transistor (continued)

- This reverse leakage current consists of minority carries diffusing across the junction. That is electrons diffusing from the base to the collector, and holes from the collector to the base.

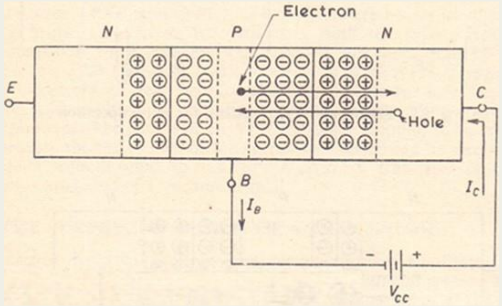


Fig. : Only collector junction is reverse biased- a small current flows.

- This leakage current flows into the collector terminal and out of the base terminal. There is no emitter current ($I_E = 0$) in this case.
- This leakage current is very much temperature dependent.
- This small collector leakage current is denoted by I_{CBO}. Subscripts *CBO* in this symbol signifies that it is a current between the collector and the base, the emitter is open.

Surprising Action of a Transistor (continued)

- **When both the switches S_1 and S_2 are closed simultaneously what one would expect?**
- **One would expect both I_E and I_B to be large and I_C to be very small.**

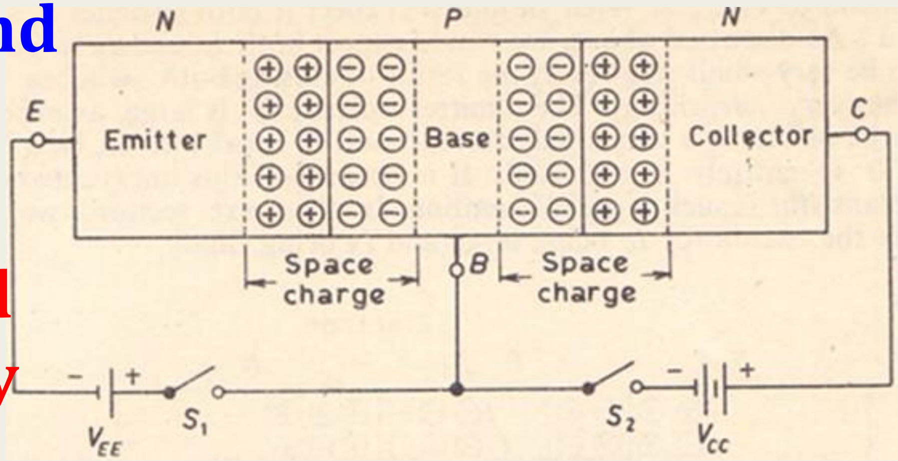


Fig. : Biasing an NPN transistor for active operation.

- **But, the result of closing both the switches turns out to be very surprising.**
- **The emitter current I_E is large, as expected, but the base current I_B turns out to be very small, and the collector current I_C turns out to be large. This is entirely unexpected.**
- **Because of this unexpected result the transistor is such a great invention.**

Working of a Transistor

- Let us consider an *npn* transistor biased for active operation.

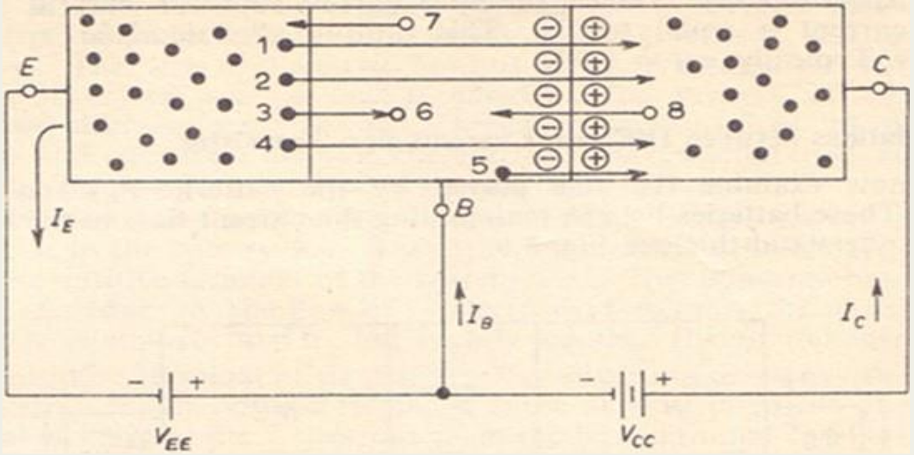


Fig. : An NPN transistor biased for active operation.

- When both the switches S_1 and S_2 are closed simultaneously, the emitter-base junction is forward biased by V_{EE} and the collector-base junction is reverse biased by V_{CC}.
- The directions of various currents that flow in the transistor are indicated.
- To understand the transistor action, some of the electrons and holes are numbered. This will simplify the description.

Working of a Transistor (contd. ...)

- **Since the E-B junction is forward biased, the barrier potential is reduced and the depletion or space-charge region becomes narrow.**

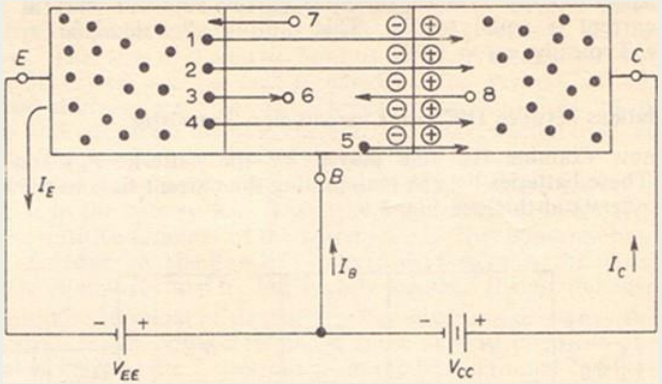


Fig. : An NPN transistor biased for active operation.

- **The majority charge carriers diffuse across the E-B junction.**
- **The resulting current consists of electrons diffusing from the emitter (n-type) to the base (p-type) and holes diffusing from the base to the emitter.**

Working of a Transistor (continued)

- Only the electrons crossing the E-B junction and thus electron current is useful in the action of the transistor as the holes crossing the E-B junction does not contribute to the carriers those reach the collector and constitutes collector current.

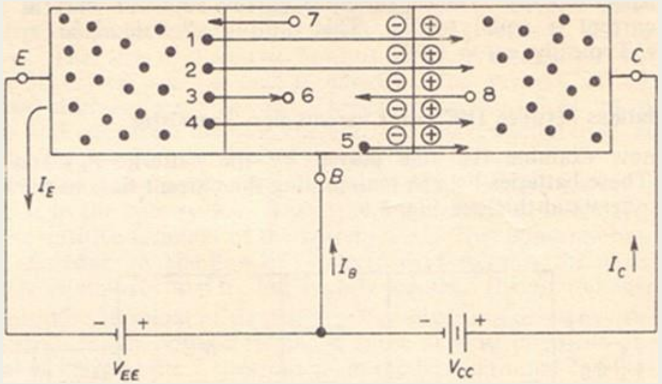


Fig. : An NPN transistor biased for active operation.

- For this reason in an *npn* transistor, the electron current is made larger than the hole current.
- This is accomplished by doping the emitter region more heavily compared to the more lightly doped base region.

Working of a Transistor (continued)

- It is seen that the electrons (like 1, 2, 3, and 4) and cross the junction from the emitter to the base and the holes (like 7) cross the junction from the base to the emitter.

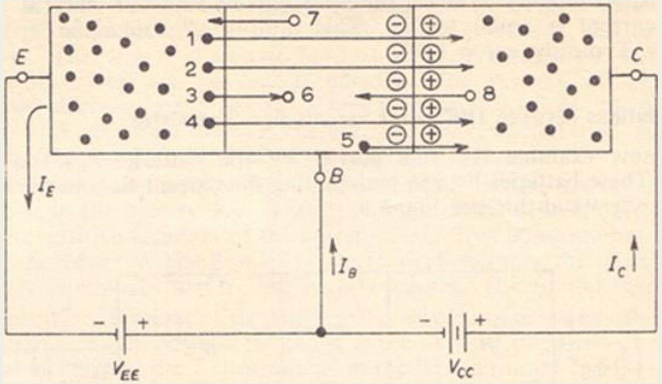


Fig. : An NPN transistor biased for active operation.

- The sum of these charge carriers movement constitutes the total emitter current I_E flowing out the E-terminal.
- Only a portion of this emitter current I_E is due to the movement of the electrons (like 1, 2, 3, and 4) from the emitter to the base.

Working of a Transistor (continued)

- The ratio of the electron current I_{nE} to the total emitter current I_E is known as the *emitter injection ratio*, or the *emitter efficiency*. This ratio is denoted by the symbol γ.

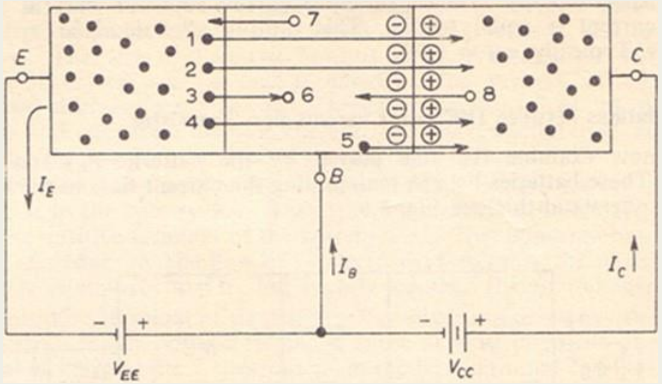


Fig. : An NPN transistor biased for active operation.

- Typically, $\gamma = 0.995$. This means that only 0.5% of the emitter current consists of the holes diffusing from the base to the emitter.

$$\gamma = \frac{I_{nE}}{I_E}$$

Working of a Transistor (continued)

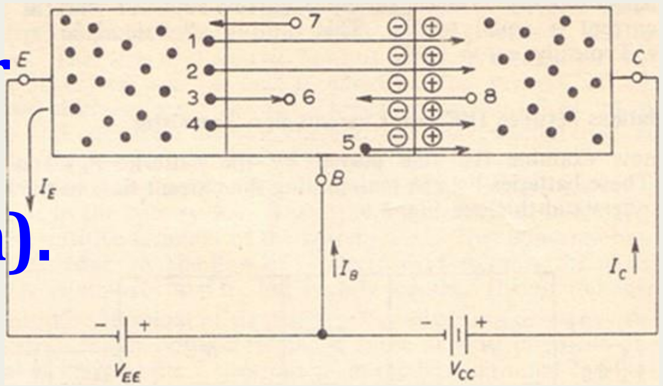


Fig. : An NPN transistor biased for active operation.

- Once the electrons from the emitter reach the base, they become minority carries (in the base region).
- Since the base is made very thin (about 25μm, less than the diffusion length of the carriers) and is very lightly doped,
- most of the electrons (minority carries in the base) injected from the emitter do not recombine with the holes in the base region and
- they (like electrons 1, 2, and 4) simply pass through the reverse-biased C-B junction and reach the collector.
- Only a few electrons (like 3) may recombine with the holes (like 6).

Working of a Transistor (continued)

- **The ratio of the number of electrons (like 1, 2, and 4) arriving at the collector to the number of emitted electrons (like 1, 2, 3, and 4) is known as the *base transportation factor*. It is denoted by the symbol β′.**

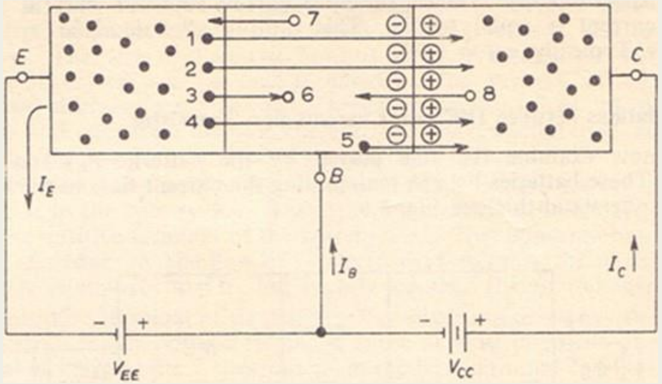


Fig. : An NPN transistor biased for active operation.

- **Typically, β′ = 0.995.**
- **The movement of the minority carriers, holes (like 8) from the collector and electrons (like 5) from the base constitute the collector leakage current, denoted by I_{CBO}.**
- **Movement of the majority carriers electrons (like 3) and the holes (like 7) constitute a part of the emitter current I_E.**

Working of a Transistor (continued)

- The number of electrons (like 3) and holes (like 7) crossing the E-B junction is much more than the number of electrons (like 5) and holes (like 8) crossing the C-B junction.

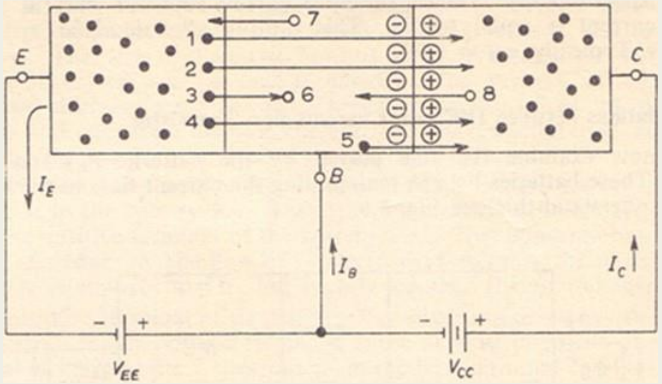


Fig. : An NPN transistor biased for active operation.

- The difference of these two currents in the base region constitutes the base current flowing into the base terminal.
- The collector current I_C is due to the movement of the majority carriers electrons (like 1, 2, and 4) and the minority carriers electrons (like 5) holes (like 8).

Working of a Transistor (continued)

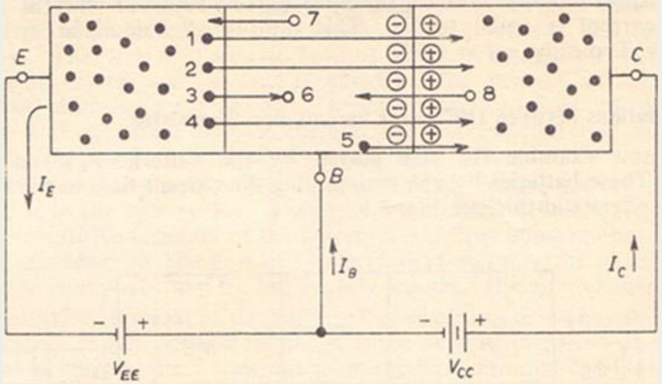


Fig. : An NPN transistor biased for active operation.

- The collector current I_C is less than the emitter current I_E. There are two reasons.
- Firstly, a part of the emitter current consists of holes (like 7) that do not contribute to the collector current;
- Secondly, not all the electrons (like 3) injected into the base are successful in reaching the collector.

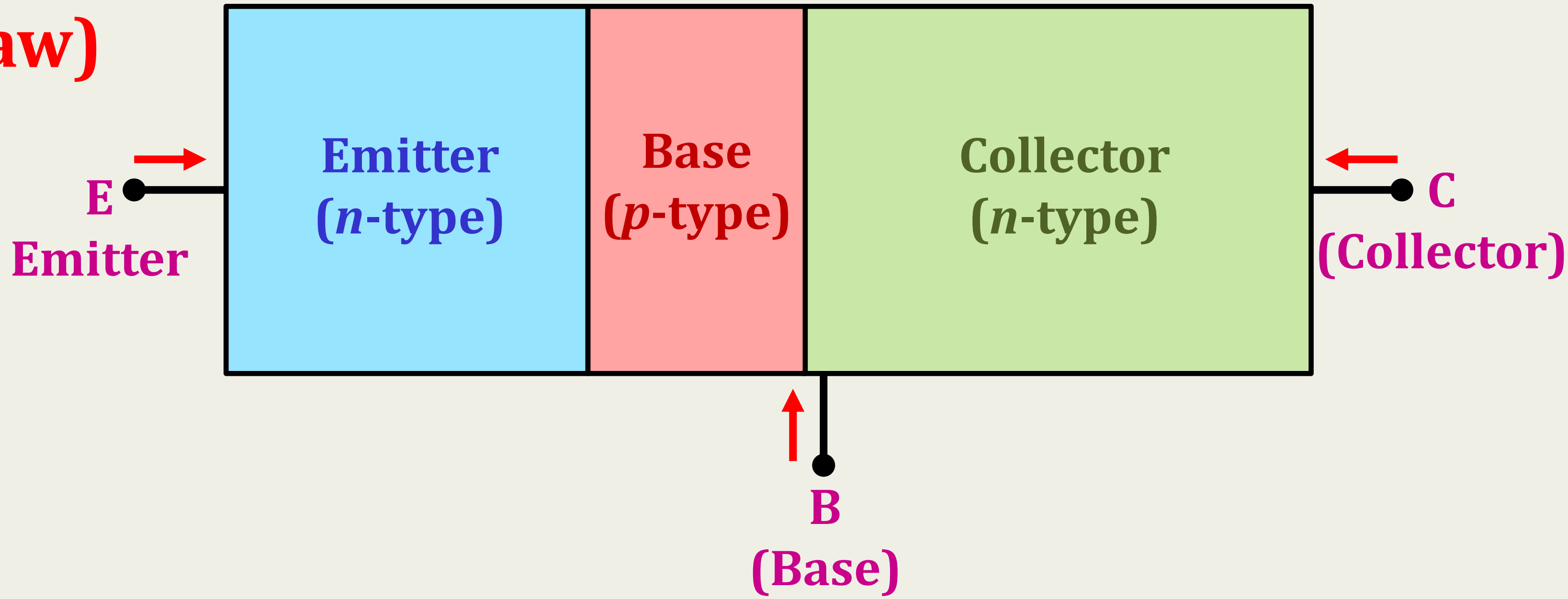
Working of a Transistor (continued)

- **The first factor is represented by the emitter injection ratio γ, and the second factor, by the base transportation ratio β'.**
- **Hence, the ratio of the collector current to the emitter current is equal to $\gamma\beta'$.**
- **This ratio is denoted by the symbol α and is called the dc α (α_{dc}) of the transistor.**
- **Typically, $\alpha_{dc} = 0.99$.**

$$\alpha_{dc} = \frac{I_C}{I_E}$$

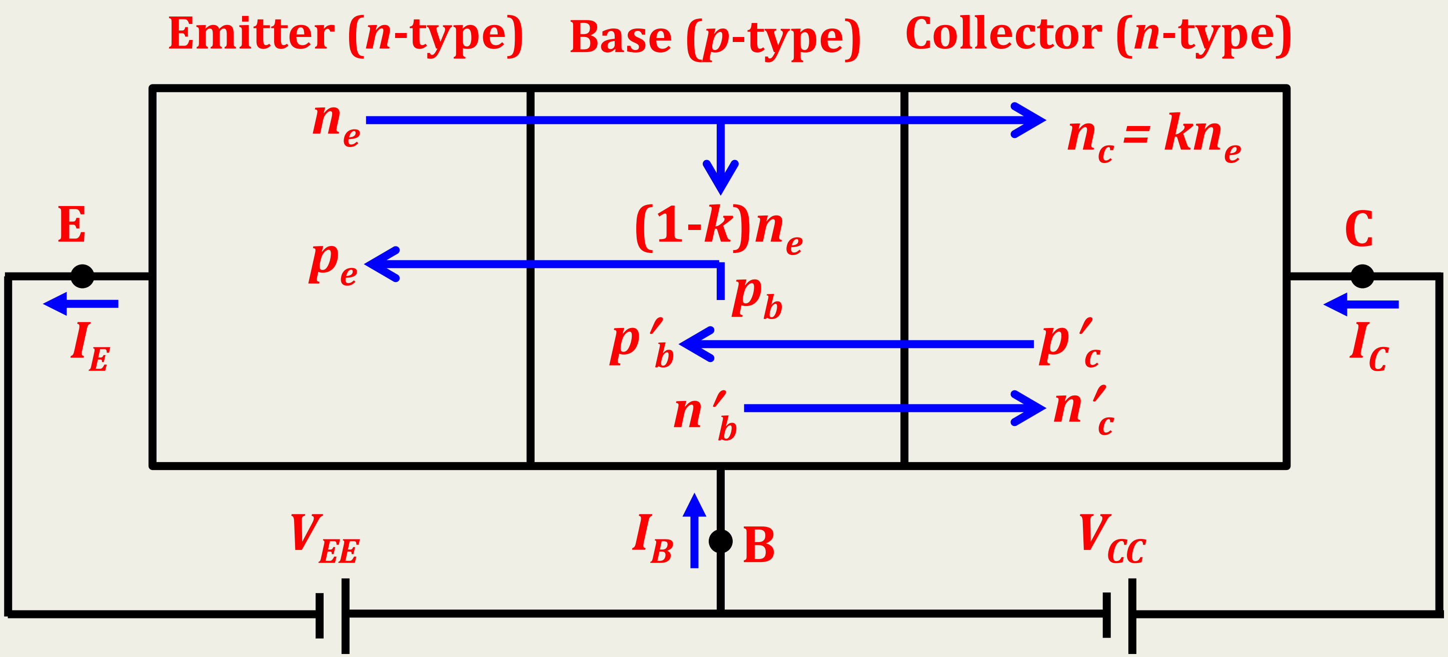
Current Directions (Convention)

- The current directions are such that the collector current (I_C) and base current (I_B) flow *into* the device whereas the emitter current (I_E) flows *out* of the device.
- *This is important*; the transistor is treated as a current node and thus: $I_C + I_B = I_E$ (Kirchhoff current law)



Current Components in a Transistor

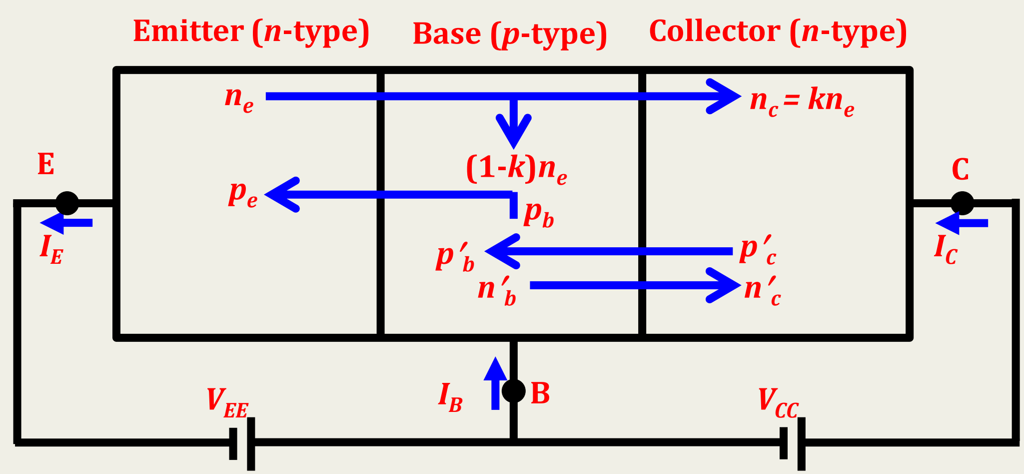
- **Let us take into account the flow of various charge carriers across the forward-biased emitter-base junction and the reverse-biased collector-base junction and the resulting currents at E, B, and C terminals of an *npn* transistor.**



Current Components in a Transistor

- **At the Emitter:**

(1) Electrons n_e injected by the emitter into the base, give rise to a current I_{ne} coming out of the emitter terminal.

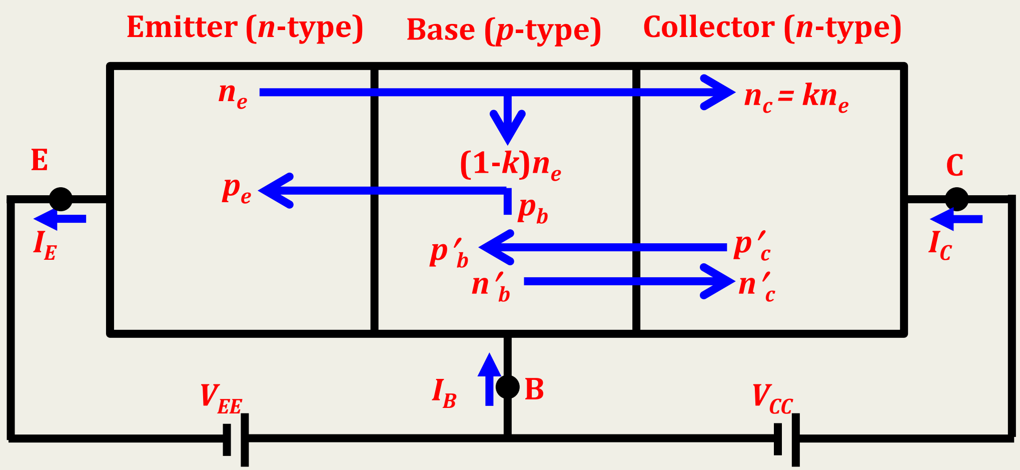


(2) Holes p_b (= p_e) injected by the base into the emitter, give rise to a current I_{pe} coming out of the emitter terminal E.

- **Therefore, the emitter current, $I_E = I_{ne} + I_{pb}$ . . . (1a)**
- **As the emitter doping is much higher than base doping, $I_{ne} > I_{pb}$, so the emitter current arises almost entirely from the injected electrons. This is desirable since the injected holes from the base to the emitter does not contribute carriers which can reach the collector.**

Current Components in a Transistor

- **At the Base:**



(1) Out of n_e electrons injected from the emitter most of them, say kn_e crossing both the E-B and C-B junctions and diffuse into the collector. The remaining $(1-k)n_e$ electrons recombine with the holes in the base to give rise to a current $(1-k)I_{ne}$ flowing into the base terminal B.

(2) Holes p_b ($= p_e$) injected from the base into the emitter, give rise to a current I_{pb} into the base terminal B.

(3) Thermally generated electrons (minority carriers in the base) n'_b ($= n'_c$) diffuse into the collector, give rise to a current $I_{n'b}$ coming out of the base terminal B.

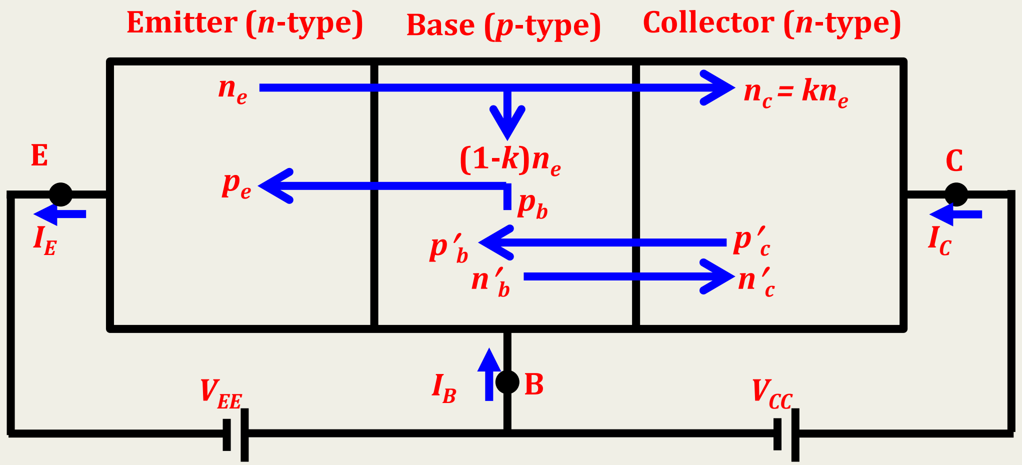
(4) Thermally generated holes (minority carriers in the collector) p'_c ($= p'_b$) diffuse into the base, give rise to a current $I_{p'b}$ out of the base terminal B.

- **Therefore, the base current, $I_B = (1-k)I_{ne} + I_{pb} - I_{n'b} - I_{p'b}$ . . . (1b)**

Current Components in a Transistor

- **At the Collector:**

(1) Diffused electrons $n_c = kn_e$ from the base give rise to a current $I_{nc} = kI_{ne}$ flowing into the collector terminal C.

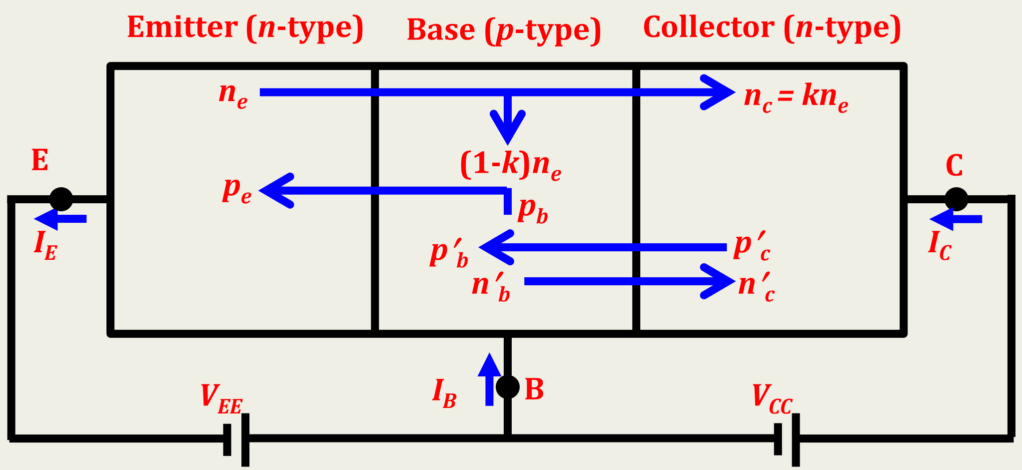


(2) Thermally generated holes (minority carriers in the collector) p'_c $(= p'_b)$ from the collector diffuse into the base, give rise to a current $I_{p'c}$ flowing into the collector terminal C.

(3) Thermally generated electrons (minority carriers in the base) n'_b $(= n'_c)$ from the base diffuse into the collector, give rise to a current $I_{n'c}$ flowing into the collector terminal C.

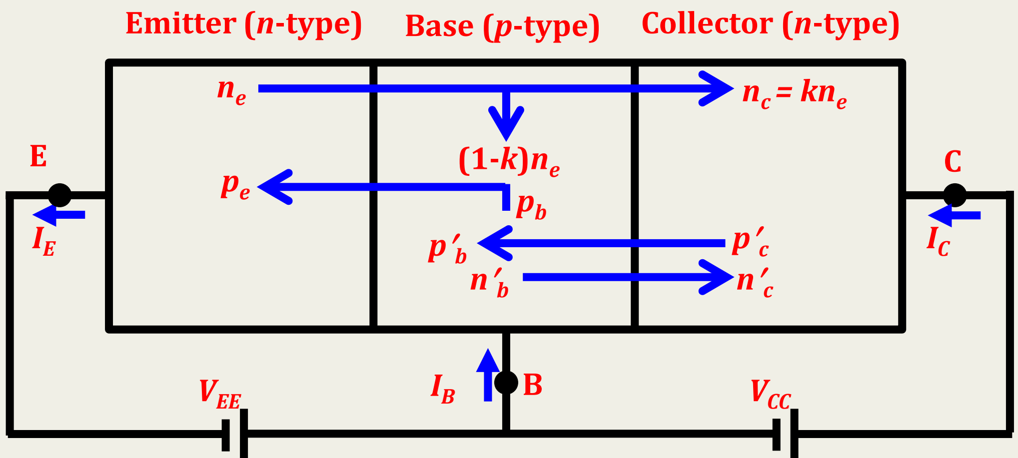
- **Therefore, the collector current, $I_C = kI_{ne} + I_{p'c} + I_{n'c}$ . . . (1c)**

Current Components in a Transistor



- Therefore, the total current in an *npn* transistor, when the E-B junction is forward-biased and the C-B junction is reverse-biased, is:
- $I_B + I_C = (1\text{-}k)I_{ne} + I_{pb} - I_{n'b} - I_{p'b} + kI_{ne} + I_{p'c} + I_{n'c}$ ... (1d)
- Since, $I_{n'b} = I_{n'c}$ and $I_{p'b} = I_{p'c}$,
- Therefore, $I_B + I_C = I_{ne} + I_{pb} = I_E$ ... (2)

Current Components in a Transistor



- Thermally generated electrons n'_b (= n'_c) from the base and holes p'_c (= p'_b) from the collector crossing the reverse-biased C-B junction constitute a collector current defined as reverse saturation current I_{CO}.
- This reverse saturation current arises also when the emitter is open, i.e. the E-B junction is open-circuited and so it is also denoted by I_{CBO}.
- Thus, the collector current in (1c) can be written as:

$$I_C = I_{nc} + I_{CBO} \quad \ldots (3)$$

where, $k = I_{nc}/I_{ne}$.

THANK YOU!