EE 330
Lecture 18

Bipolar Devices

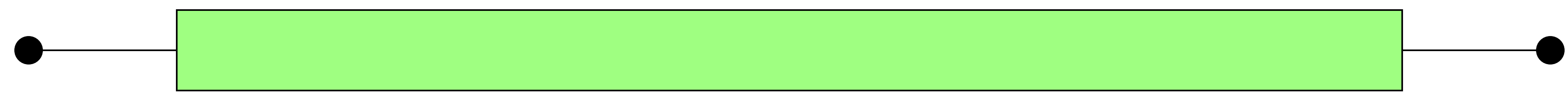
Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT

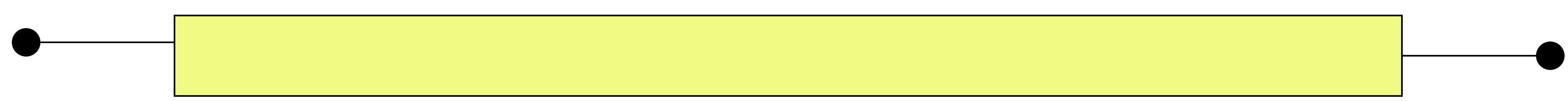
Bipolar Junction Transistors

- Operation
- Modeling

Carriers in Doped Semiconductors

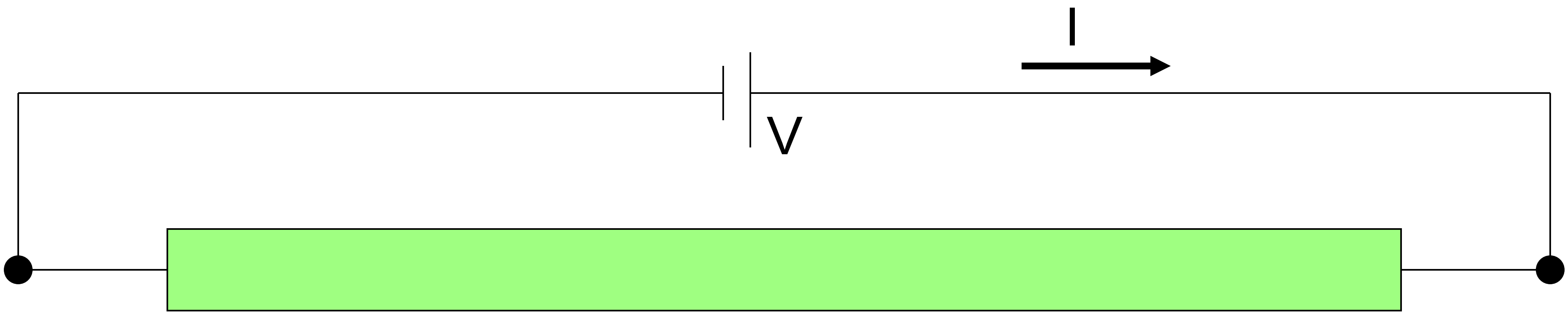


n-type



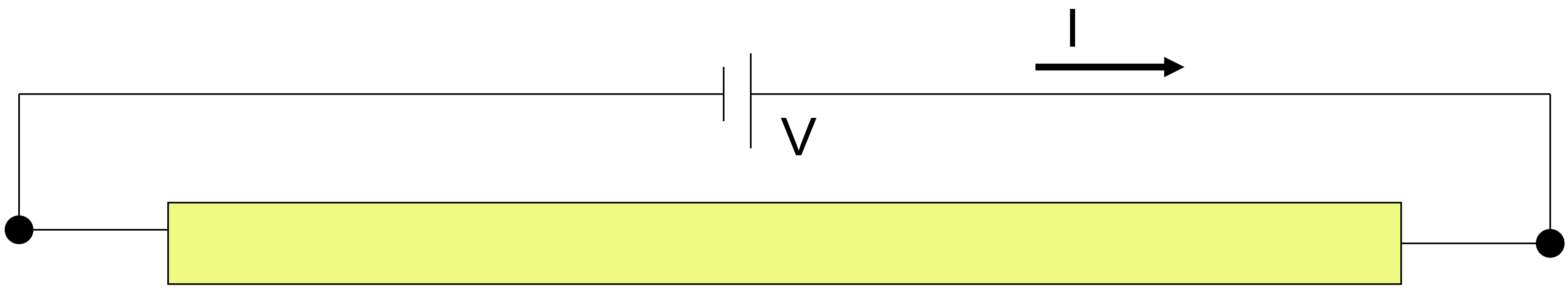
p-type

Carriers in Doped Semiconductors



Current carriers are <u>dominantly</u> electrons

Small number of holes are short-term carriers



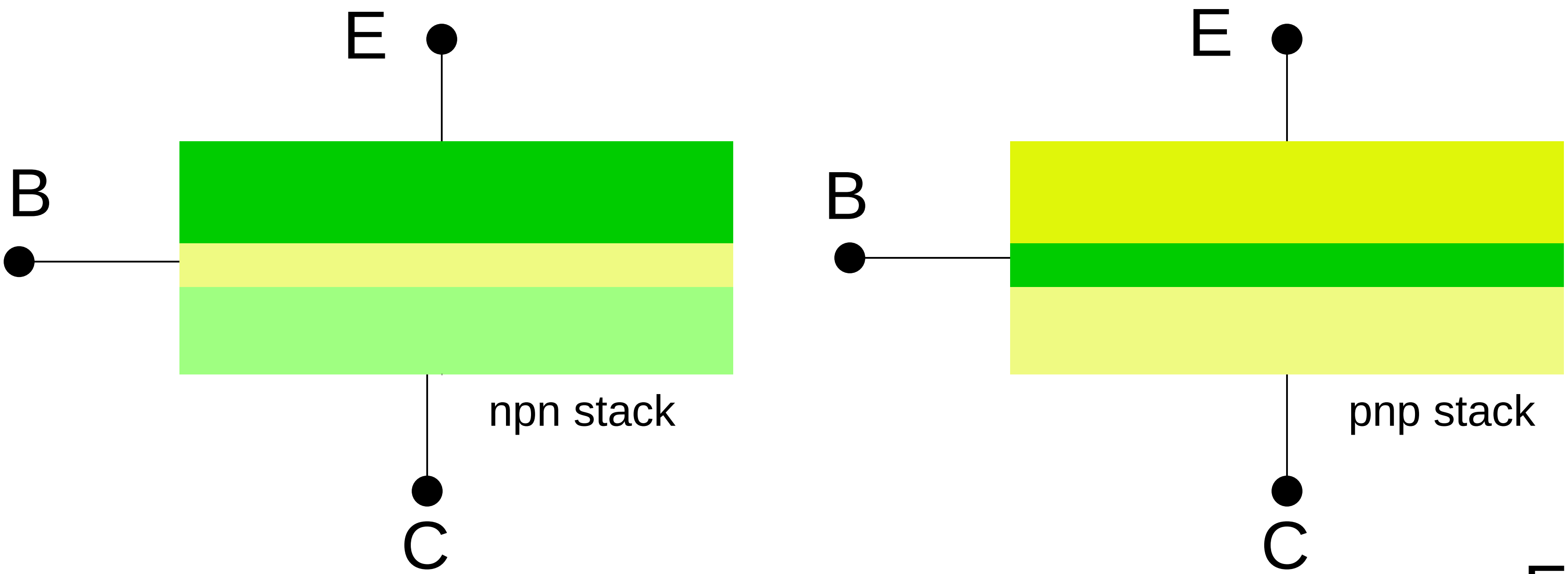
Current carriers are <u>dominantly</u> holes

Small number of electrons are short-term carriers

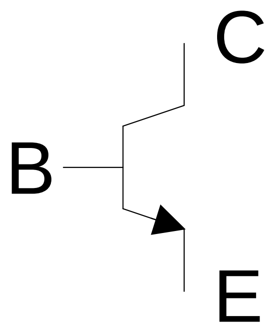
Carriers in Doped Semiconductors

	Majority Carriers	Minority Carriers
n-type	electrons	holes
p-type	holes	electrons

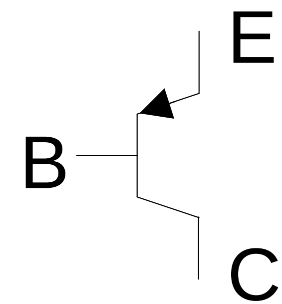
Bipolar Transistors



- **Bipolar Devices Show Basic Symmetry**
- **Electrical Properties not Symmetric**
- **Designation of C and E critical**



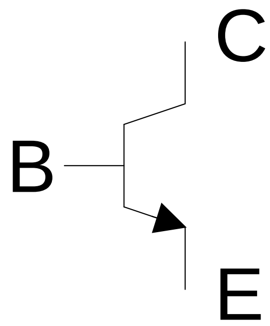
npn transistor



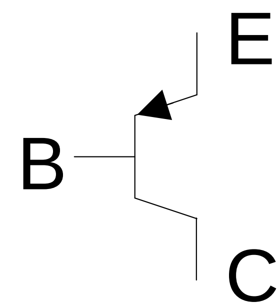
pnp transistor

With proper doping and device sizing these form Bipolar Transistors

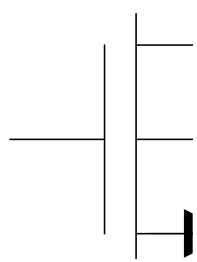
Bipolar Transistors

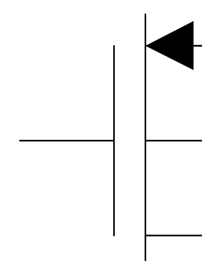


npn transistor



pnp transistor

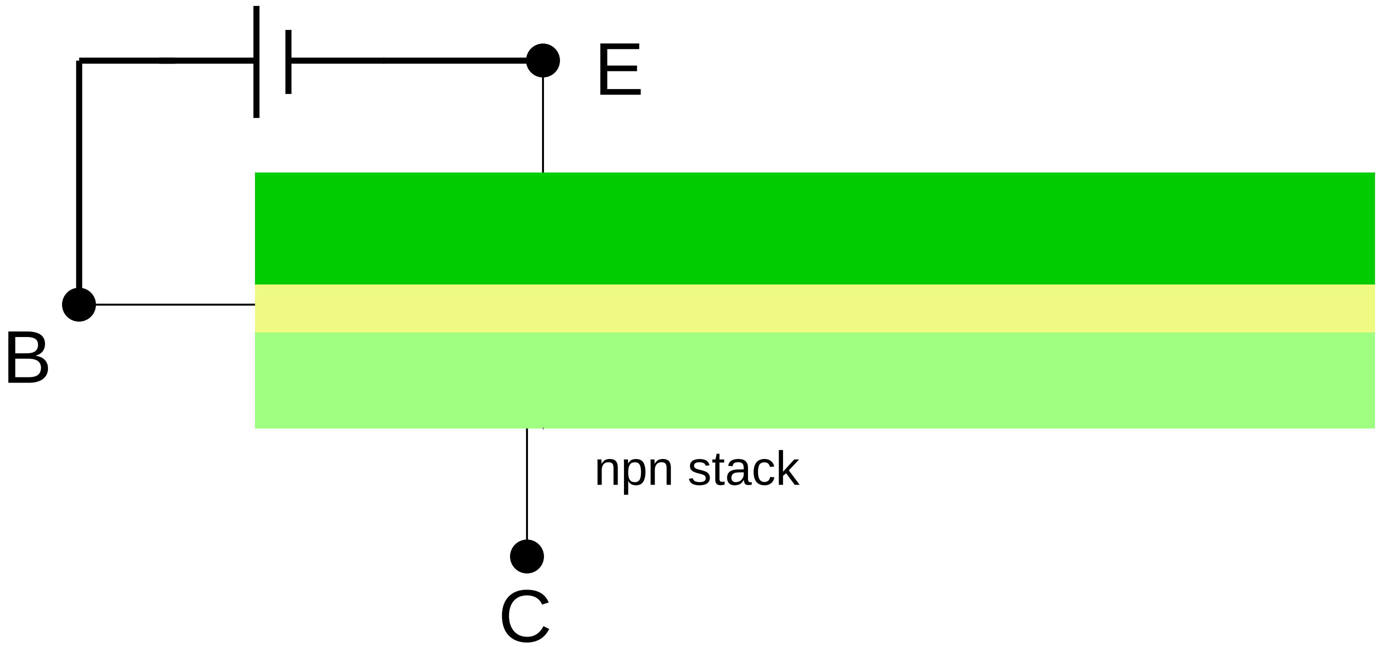

n-channel MOSFET


p-channel MOSFET

In contrast to a MOSFET which has 4 terminals, a BJT only has 3 terminals

Bipolar Operation

Consider npn transistor – Forward Active Operation



Under **forward bias** current flow into base and out of emitter

Current flow is governed by the diode equation

Carriers in emitter are electrons (majority carriers)

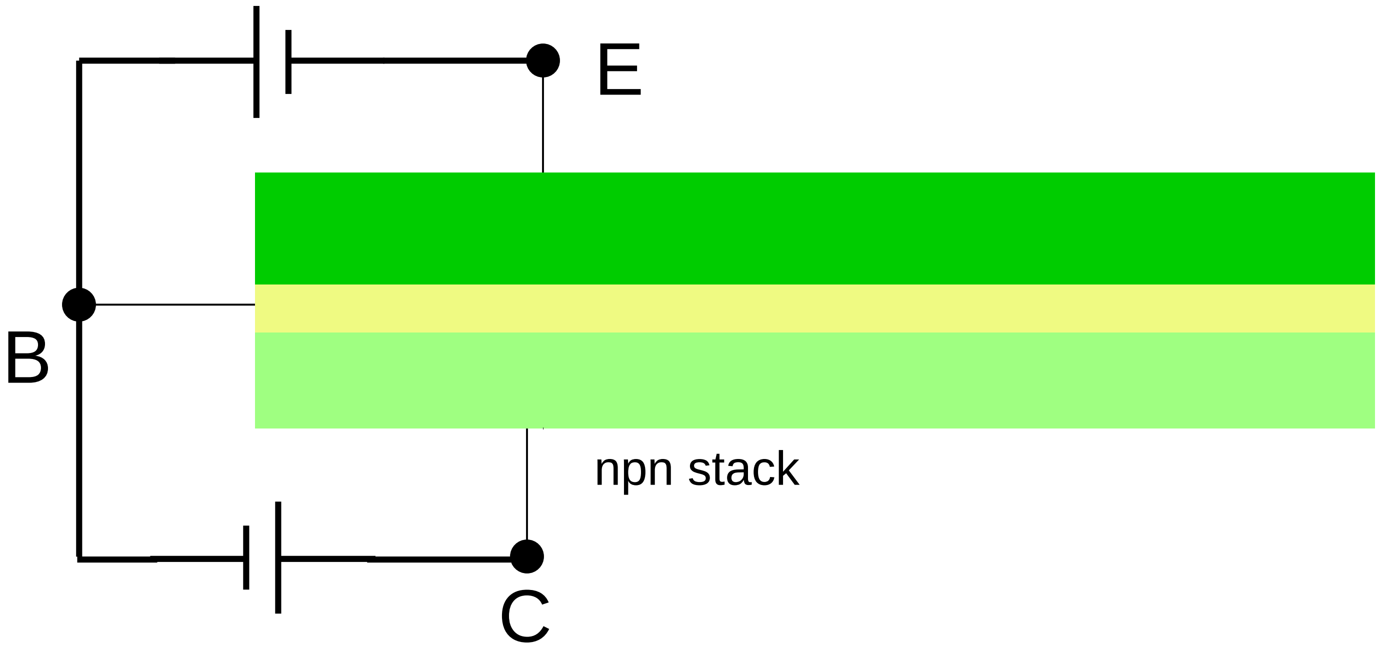
When electrons pass into the base they become minority carriers

Quickly recombine with holes to create holes base region

Dominant current flow in base is holes (majority carriers)

Bipolar Operation

Consider npn transistor – Forward Active Operation



Under forward BE bias and reverse BC bias current flows into base **region**

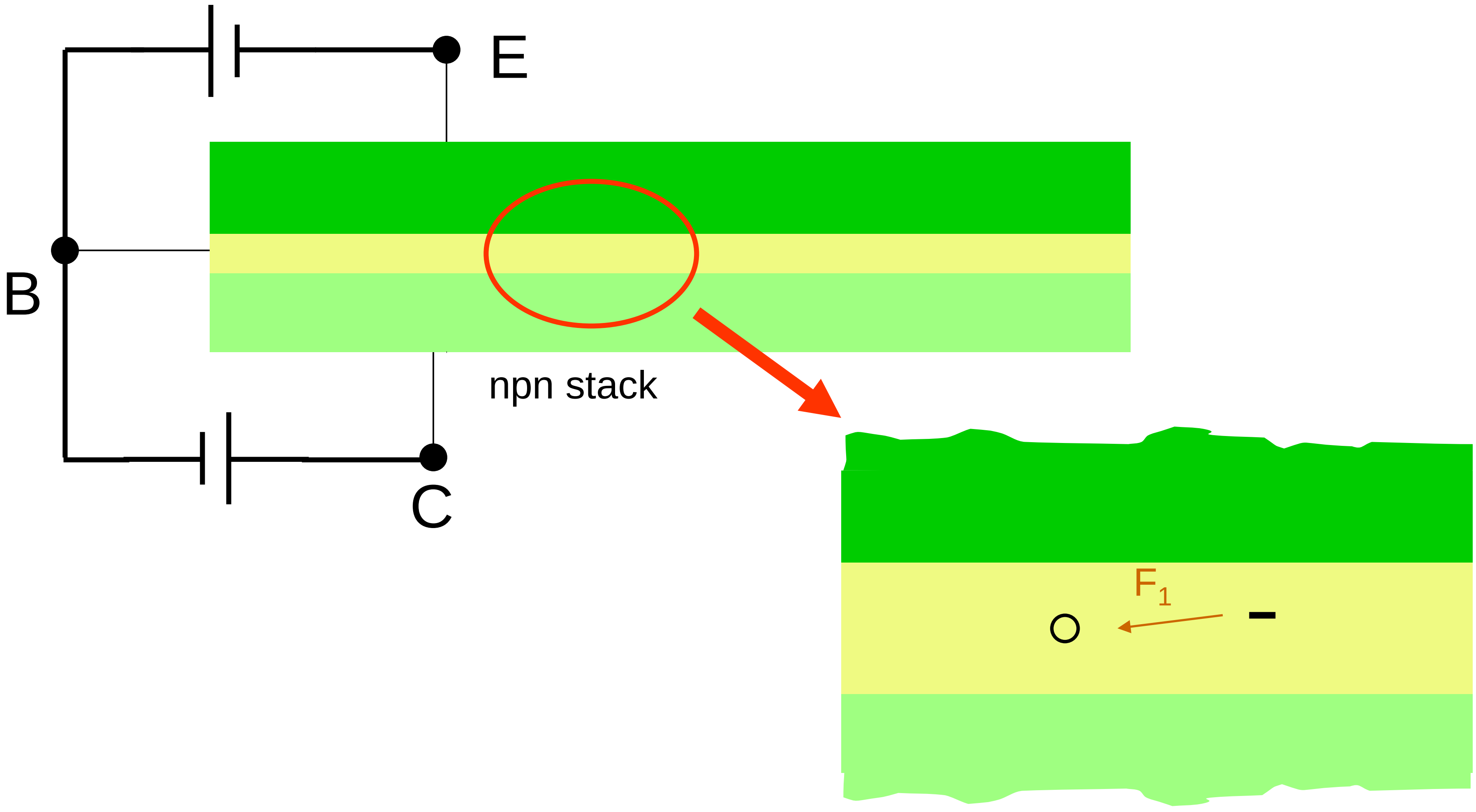
Carriers in emitter are electrons (majority carriers)

When electrons pass into the base they become minority carriers

When minority carriers are present in the base they can be attracted to collector

Bipolar Operation

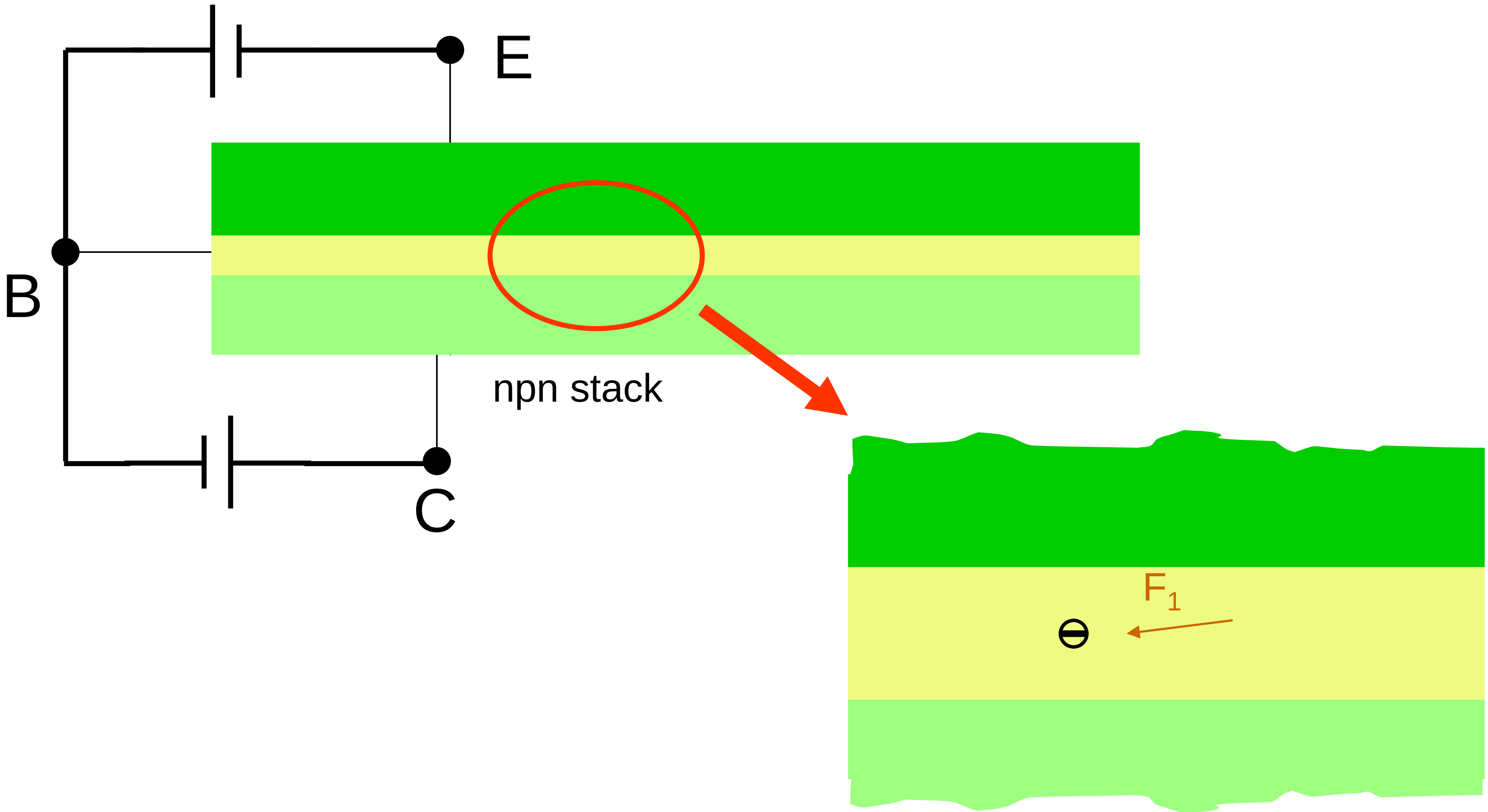
Consider npn transistor – Forward Active Operation



If no force on electron is applied by collector, electron will contribute to base current

Bipolar Operation

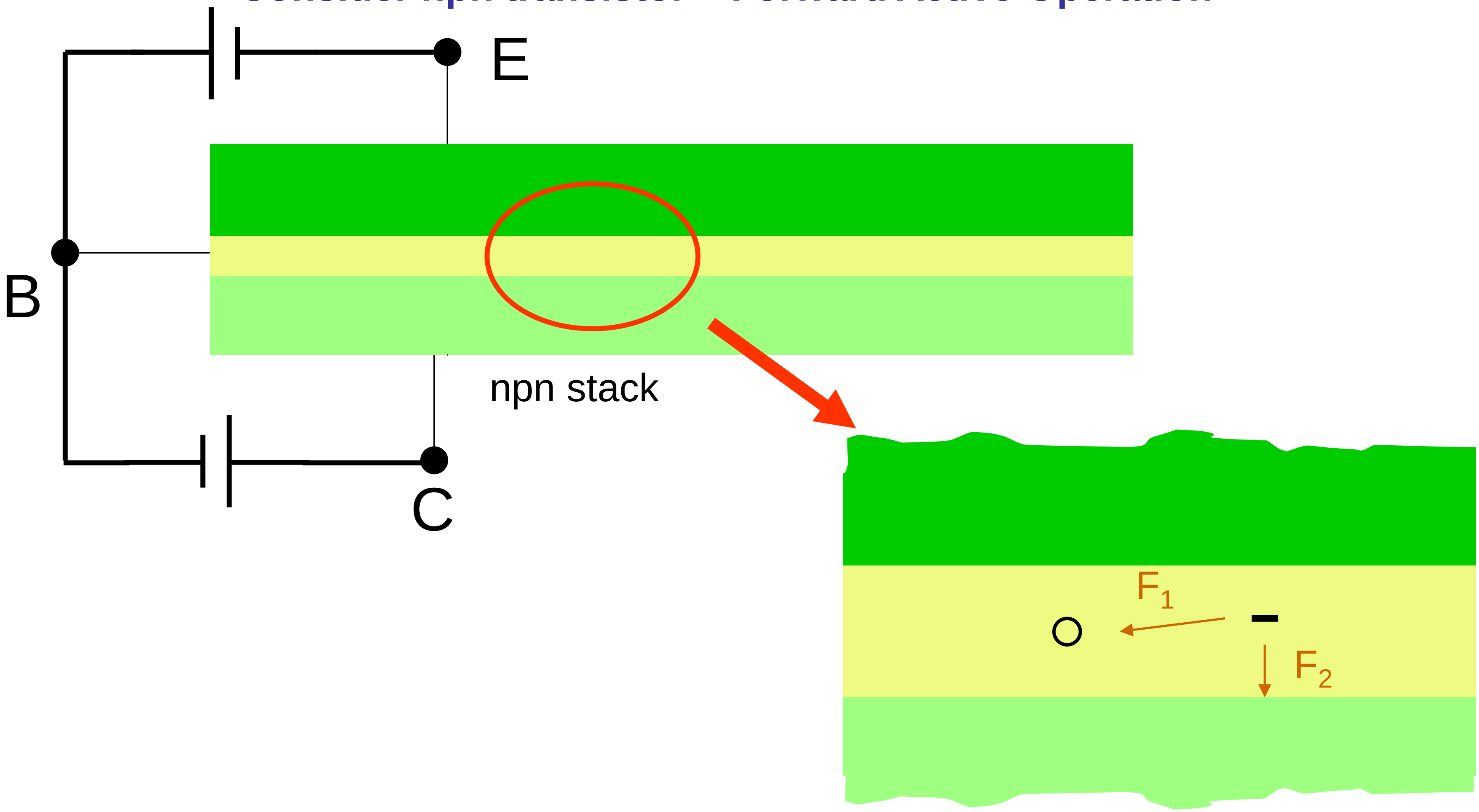
Consider npn transistor – Forward Active Operation



If no force on electron is applied by collector, electron will contribute to base current
Electron will recombine with a hole so dominant current flow in base will be by majority carriers

Bipolar Operation

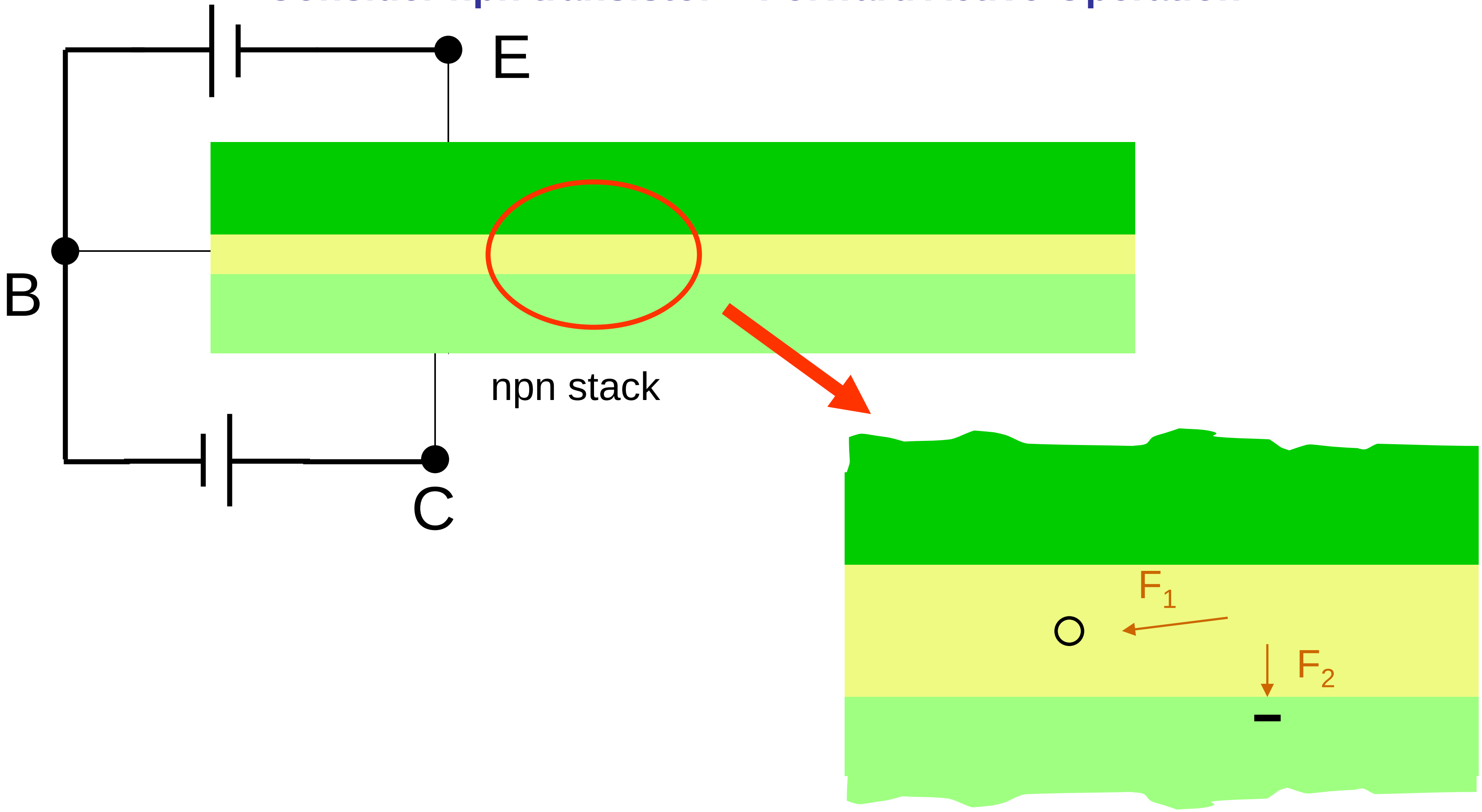
Consider npn transistor – Forward Active Operation



When minority carriers are present in the base they can be attracted to collector with reverse-bias of BC junction and can move across BC junction

Bipolar Operation

Consider npn transistor – Forward Active Operation

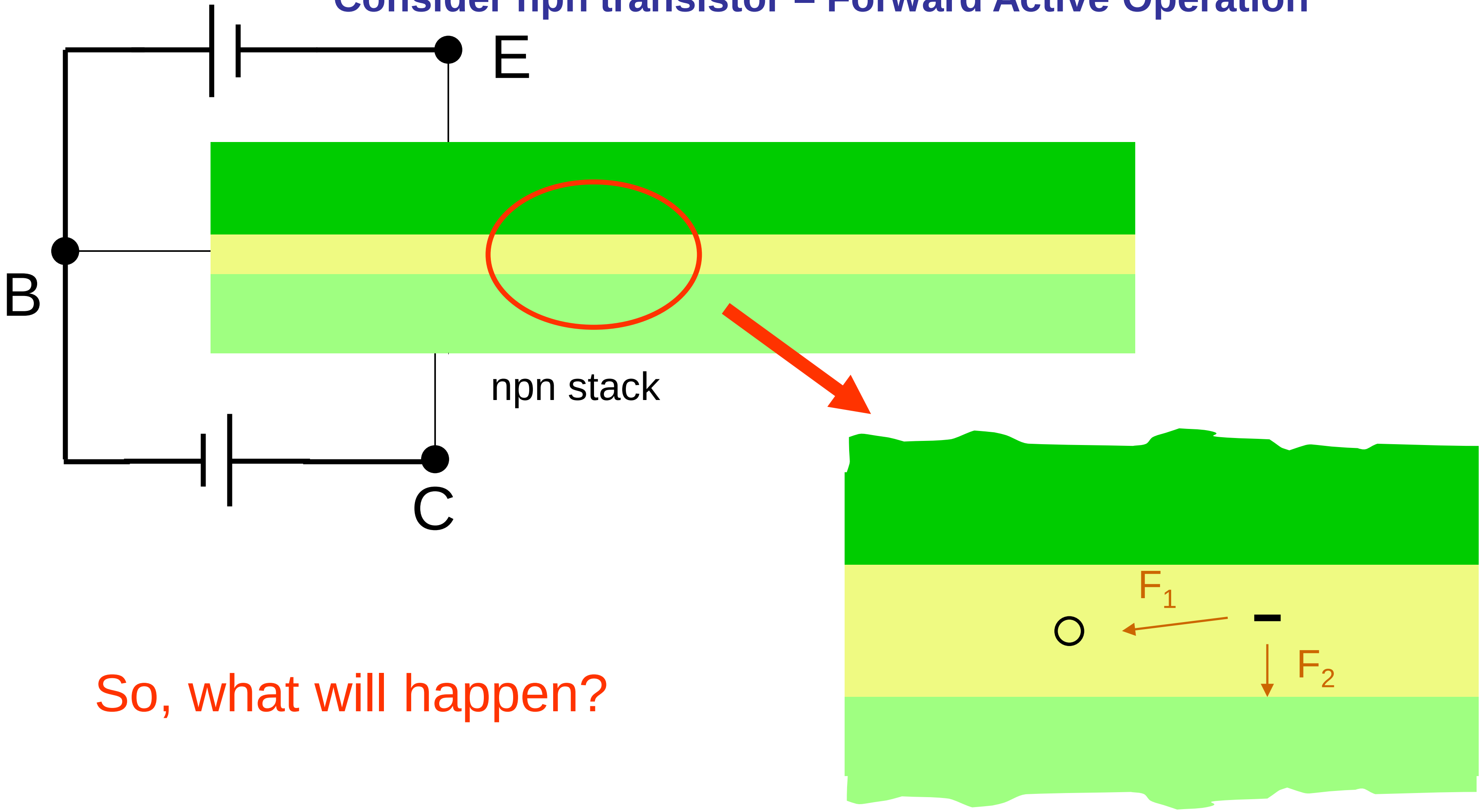


When minority carriers are present in the base they can be attracted to collector with reverse-bias of BC junction and can move across BC junction

Will contribute to collector current flow as majority carriers

Bipolar Operation

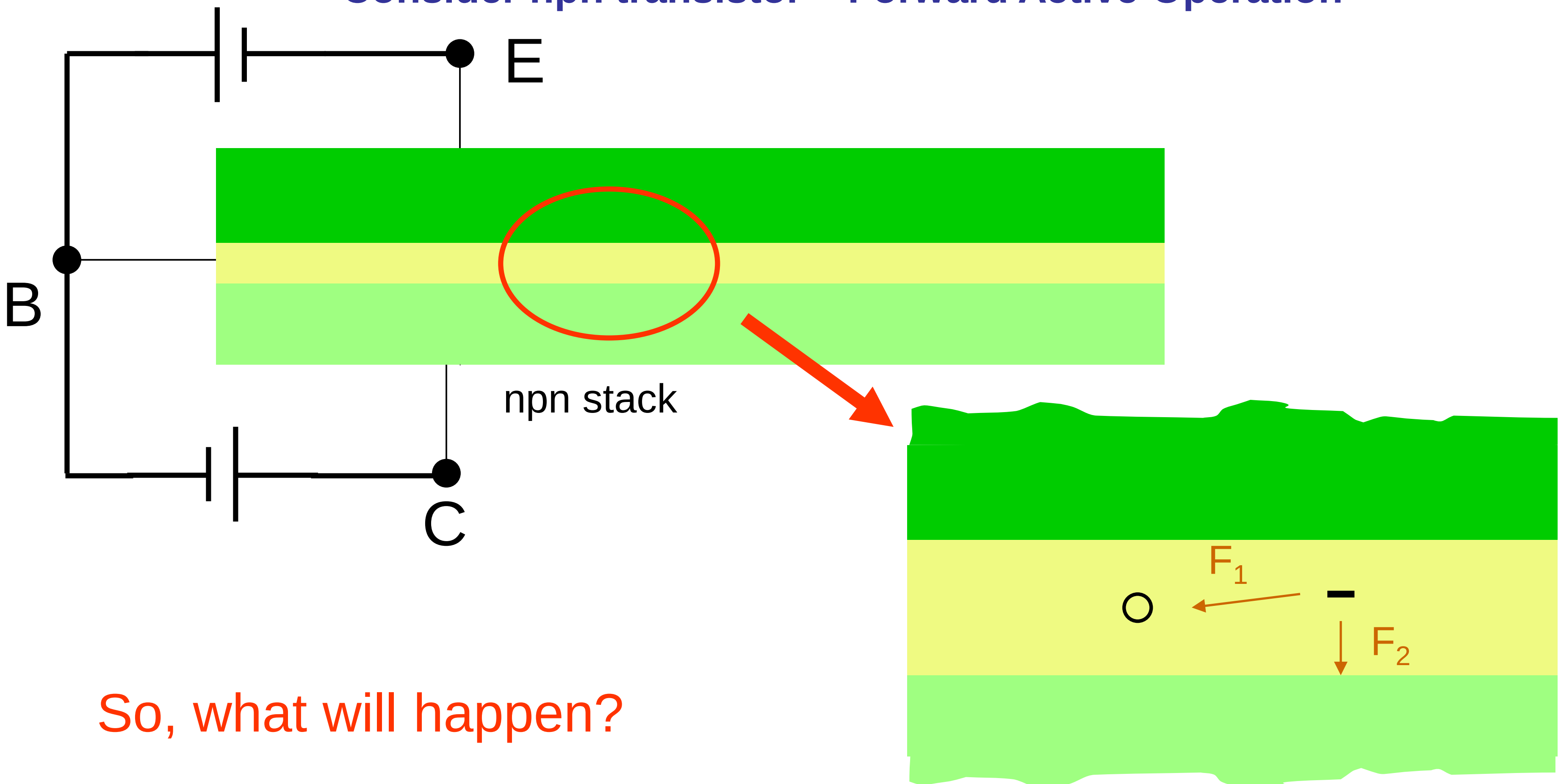
Consider npn transistor – Forward Active Operation



So, what will happen?

Bipolar Operation

Consider npn transistor – Forward Active Operation



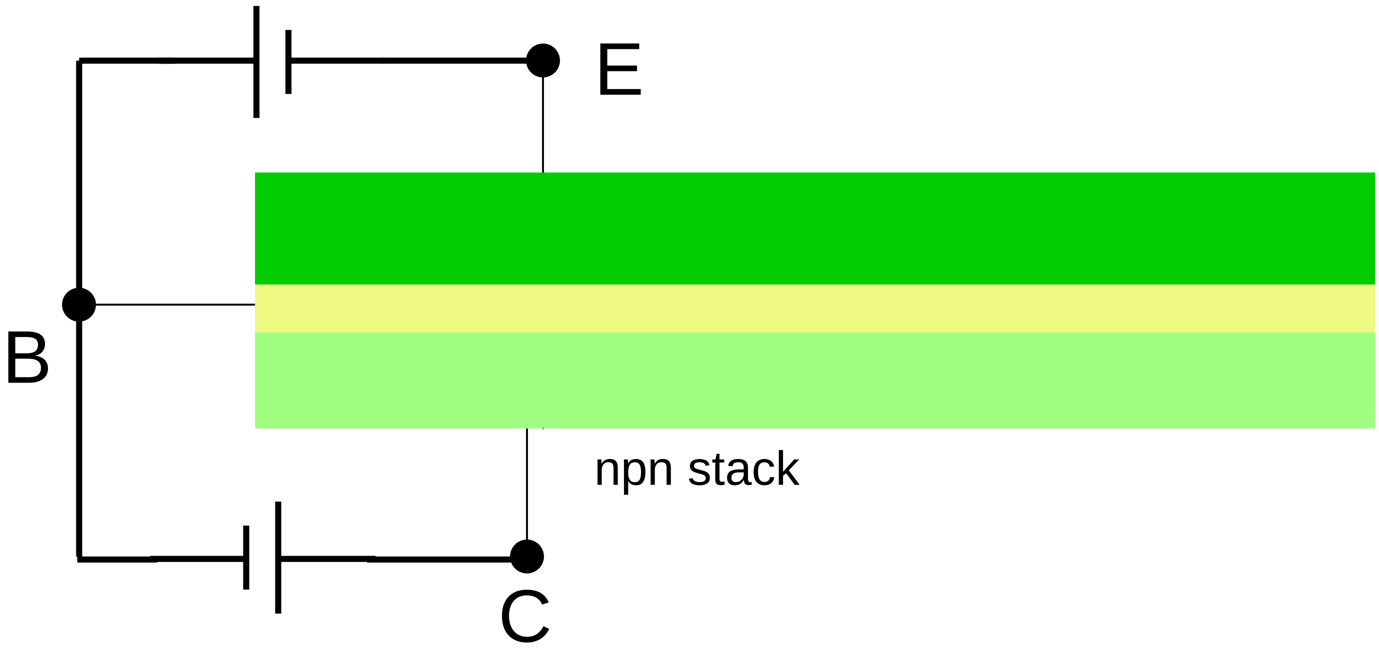
So, what will happen?

Some will recombine with holes and contribute to base current and some will be attracted across BC junction and contribute to collector

Size and thickness of base region and relative doping levels will play key role in percent of minority carriers injected into base contributing to collector current

Bipolar Operation

Consider npn transistor – Forward Active operation



Under forward BE bias and reverse BC bias current flows into base **region**

Carriers in emitter are electrons (majority carriers)

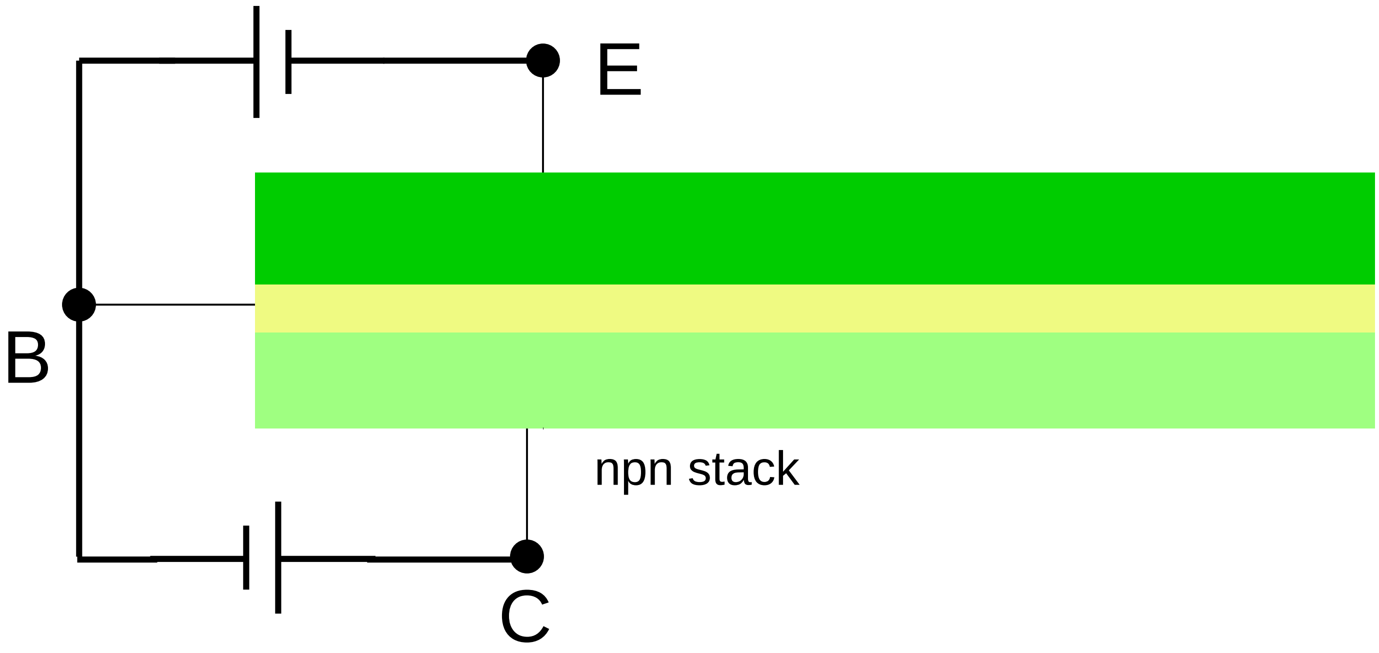
When electrons pass into the base they become minority carriers

When minority carriers are present in the base they can be attracted to collector

Minority carriers either recombine with holes and contribute to base current
or are attracted into collector region and contribute to collector current

Bipolar Operation

Consider npn transistor - Forward Active Operation



Under forward BE bias and reverse BC bias current flows into base **region**

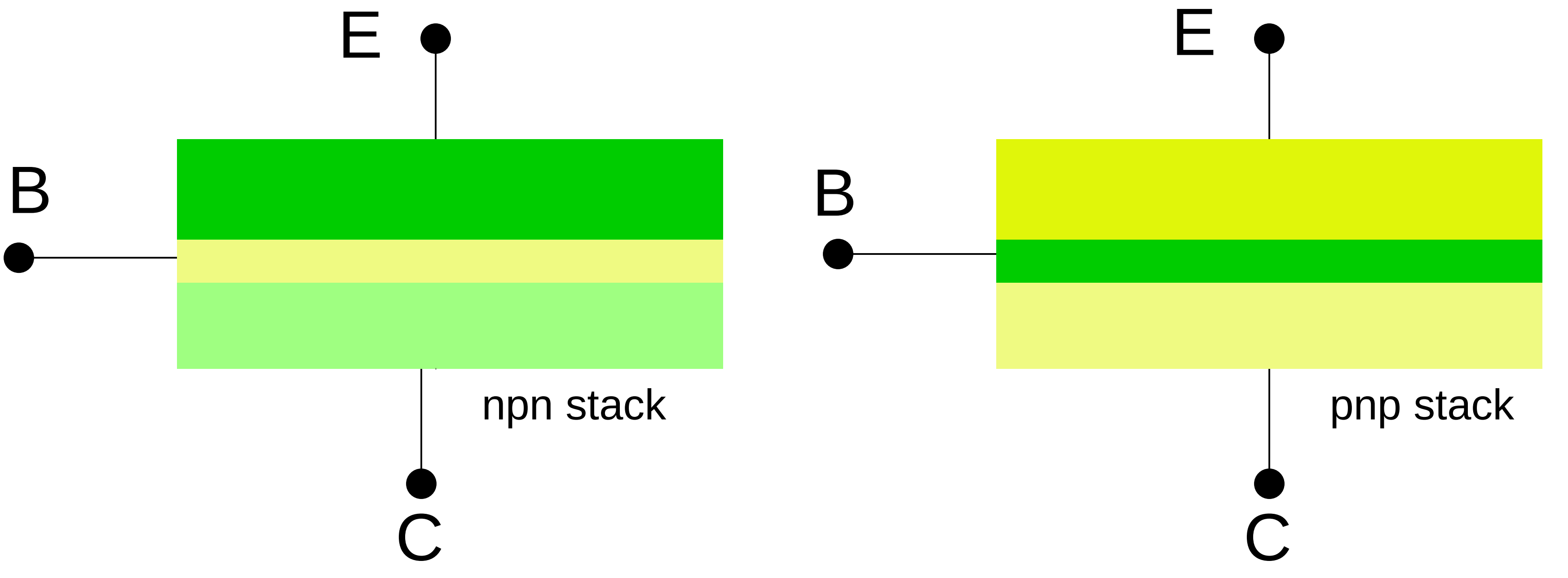
Efficiency at which minority carriers injected into base region and contribute to collector current is termed α

α is always less than 1 but for a good transistor, it is very close to 1

For good transistors $.99 < \alpha < .999$

Making the base region very thin makes α large

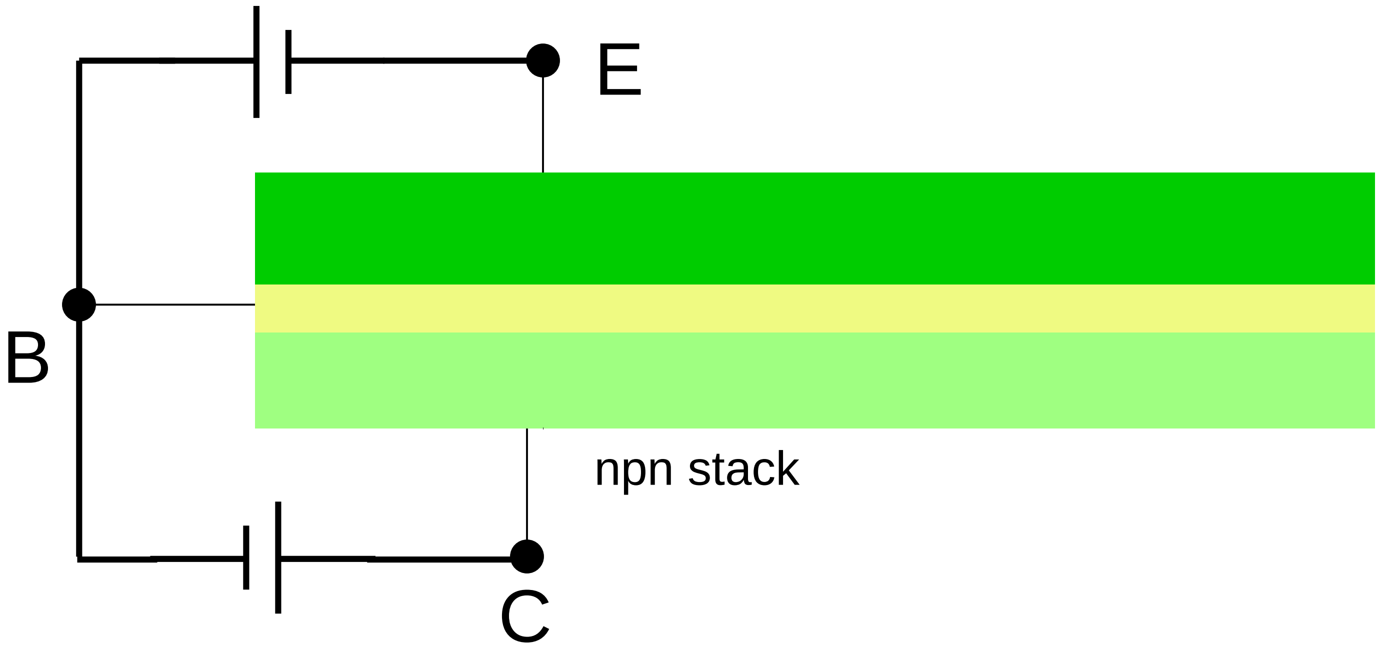
Bipolar Transistors



- principle of operation of pnp and npn transistors are the same
- minority carriers in base of pnp are holes
- npn usually have modestly superior properties because mobility of electrons is larger than mobility of holes

Bipolar Operation

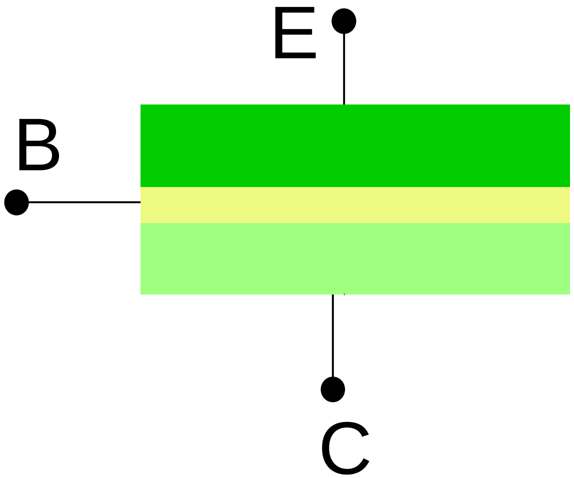
Consider npn transistor – Forward Active Operation

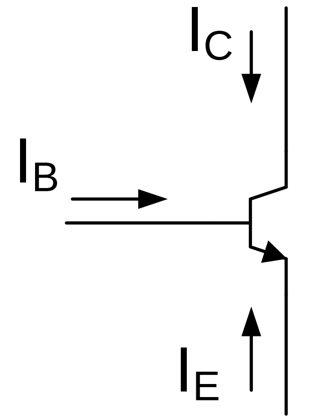


In contrast to MOS devices where current flow in channel is by majority carriers, current flow in the critical base region of bipolar transistors is by minority carriers

Bipolar Operation

Consider npn transistor – Forward Active Operation





$$\left.\begin{aligned} I_C + I_B &= -I_E \\ I_C &= -\alpha I_E \end{aligned}\right\}$$

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

$$\beta \overset{defn}{=} \frac{\alpha}{1-\alpha}$$

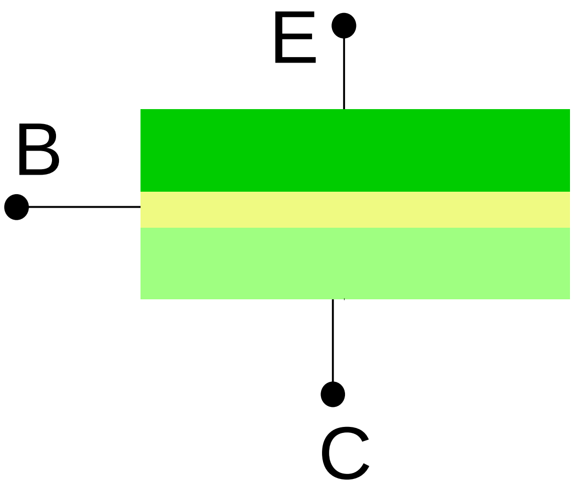
$$I_C = \beta I_B$$

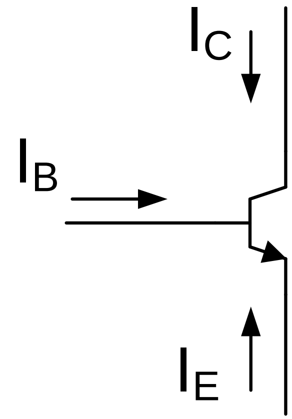
β is typically very large

often 50<β<999

Bipolar Operation

Consider npn transistor – Forward Active Operation





$$I_C = \beta I_B$$

β is typically very large

Bipolar transistor can be thought of a current amplifier with a large current gain

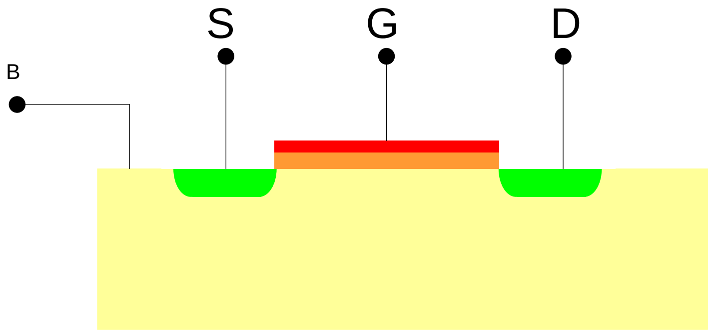
In contrast, MOS transistor is inherently a tramsconductance amplifier

Current flow in base is governed by the diode equation $$I_B = \tilde{I}_S e^{\frac{V_{BE}}{V_t}}$$

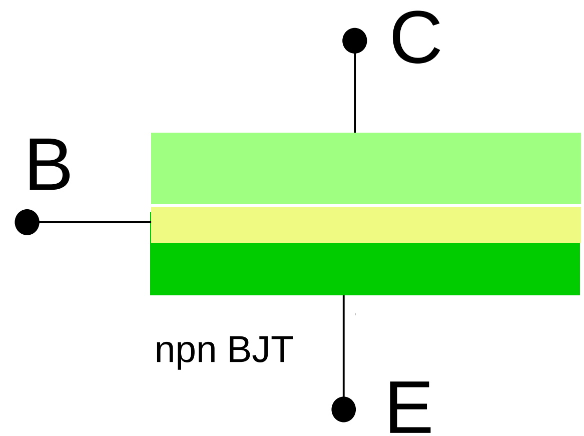
Collector current thus varies exponentially with V_{BE} $$I_C = \beta \tilde{I}_S e^{\frac{V_{BE}}{V_t}}$$

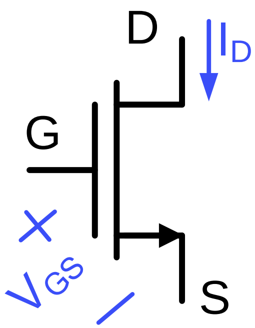
Preliminary Comparison of MOSFET and BJT

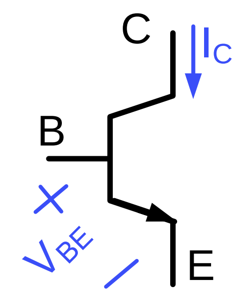
(Saturation vs Forward Active)



n-channel MOSFET







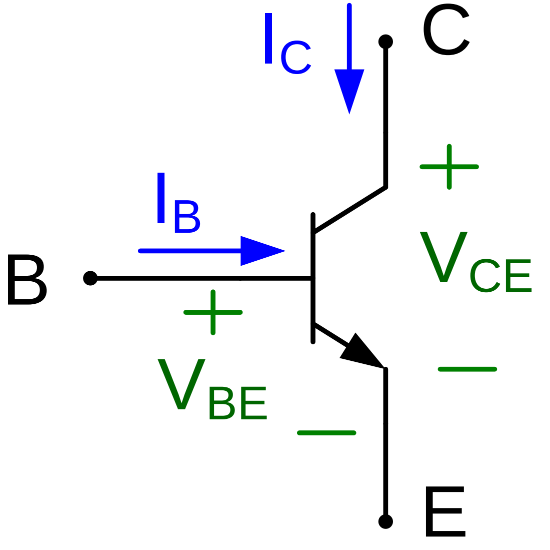
$$I_D = \frac{\mu C_{OX} W}{2L}\left(V_{GS} - V_{TH}\right)^2$$

$$I_C = \beta \tilde{I}_S e^{\frac{V_{BE}}{V_t}}$$

- The BJT I/O relationship is exponential in contrast to square-law for MOSFET
- Provides a very large "gain" for the BJT (assuming input is voltage and output is current)
- This property is very useful for many applications

Bipolar Models

Simple dc Model



Following convention, pick I_C and I_B as dependent variables and V_{BE} and V_{CE} as independent variables

Simple dc model

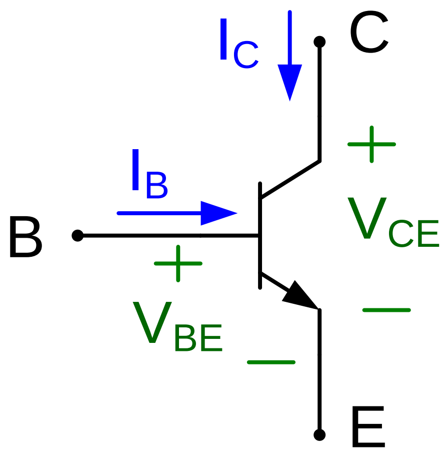
Consider npn transistor – Forward Active Operation

Summary:

$$I_B = \tilde{I}_S e^{\frac{V_{BE}}{V_t}}$$

$$I_C = \beta \tilde{I}_S e^{\frac{V_{BE}}{V_t}}$$

$$V_t = \frac{kT}{q}$$



This has the properties we are looking for but the variables we used in introducing these relationships are not standard

It can be shown that $\tilde{I}_S$ is proportional to the emitter area A_E

Define $\mathbf{J_S}$ by $\tilde{I}_S = \beta^{-1} \mathbf{J_S A_E}$ and substitute this into the above equations

Simple dc model

npn transistor – Forward Active Operation

$$I_B = \tilde{I}_S e^{\frac{V_{BE}}{V_t}}$$

$$I_C = \beta \tilde{I}_S e^{\frac{V_{BE}}{V_t}}$$

$$V_t = \frac{kT}{q}$$

$$\Longrightarrow$$

$$I_B = \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}}$$

$$I_C = J_S A_E e^{\frac{V_{BE}}{V_t}}$$

$$V_t = \frac{kT}{q}$$

$k/q = 8.62\text{x}10^{-5}$

J_S is termed the saturation current density

Process Parameters : J_S, β

Design Parameters: A_E

Environmental parameters and physical constants: k,T,q

At room temperature, V_t is around 26mV

J_S very small – around .25fA/u^2 at room temperature

Simple dc model

npn transistor – Forward Active Operation

$$\left.\begin{aligned} I_B &= \frac{J_S A_E}{\beta} e^{\frac{V_{BE}}{V_t}} \\ I_C &= J_S A_E e^{\frac{V_{BE}}{V_t}} \end{aligned}\right\}$$

$$V_t = \frac{kT}{q}$$

As with the diode, the parameter J_S is highly temperature dependent

$$J_S = J_{SX}\left[T^m e^{\frac{-V_{G0}}{V_t}}\right]$$

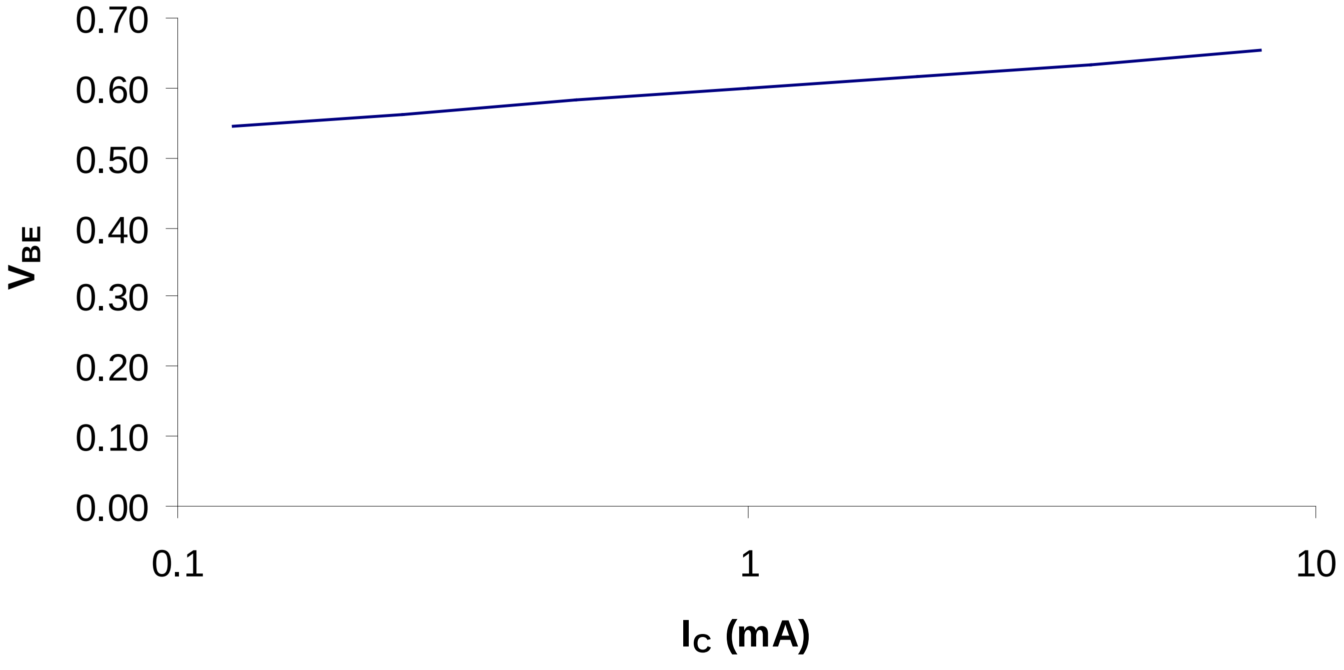
Typical values for parameters: J_{SX}=20mA/μ^2, V_{G0}=1.17V, m=2.3

The parameter β is also somewhat temperature dependent but much weaker temperature dependence than J_{SX}.

Transfer Characteristics

npn transistor – Forward Active Operation

J_S=.25fA/u^2
A_E=400u^2

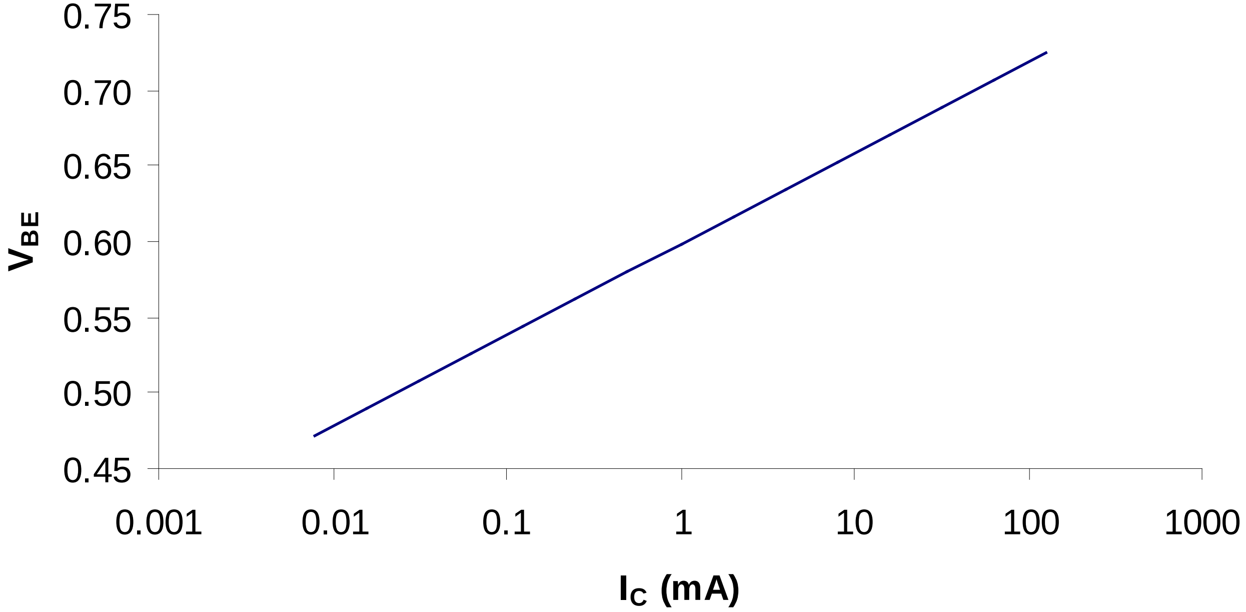


V_{BE} close to 0.6V for a two decade change in I_C around 1mA

Transfer Characteristics

npn transistor – Forward Active Operation

J_S=.25fA/u^2
A_E=400u^2

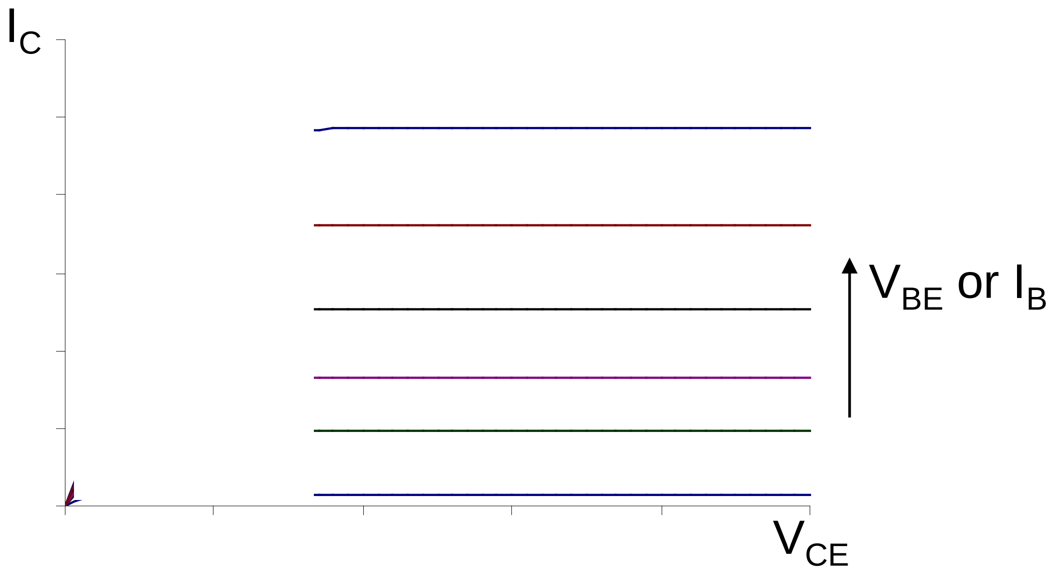


V_{BE} close to 0.6V for a four decade change in I_C around 1mA

Simple dc model

npn transistor – Forward Active Operation

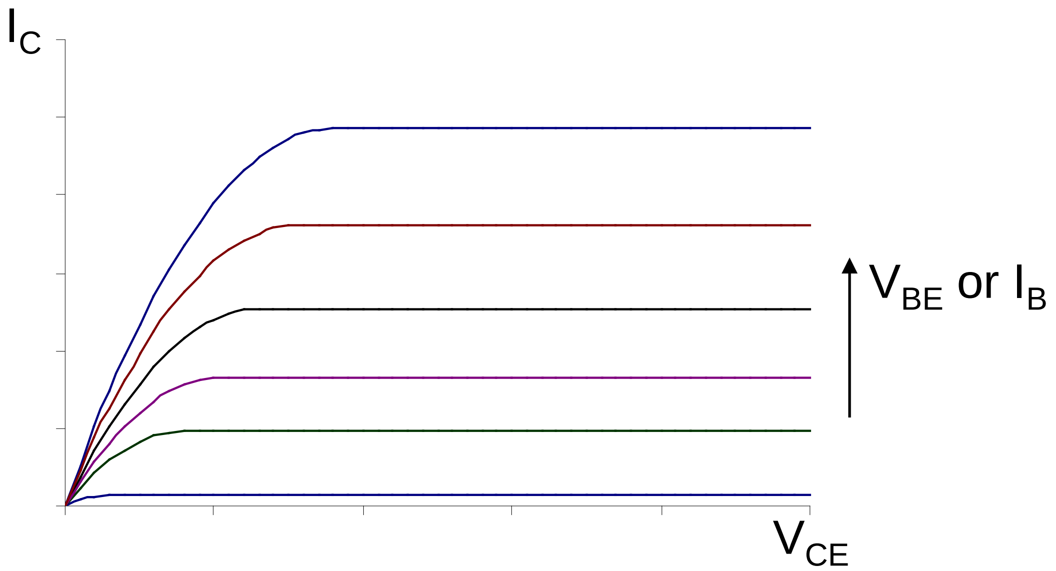
Output Characteristics



$$I_C = J_S A_E e^{\frac{V_{BE}}{V_t}}$$

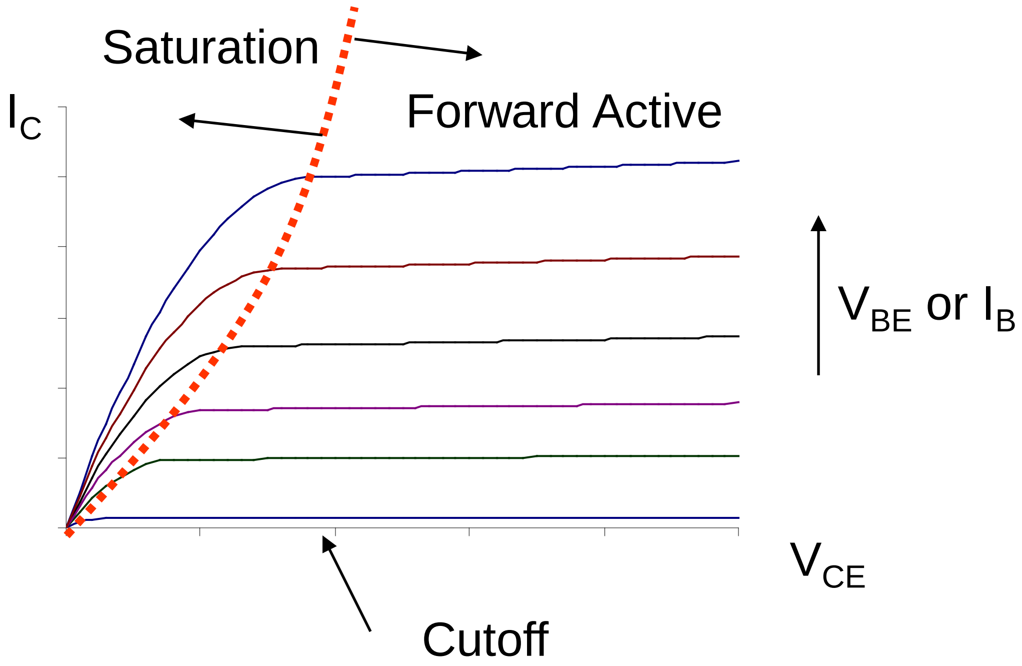
Simple dc model

Better Model of Output Characteristics



Simple dc model

Typical Output Characteristics



Forward Active region of BJT is analogous to Saturation region of MOSFET

Saturation region of BJT is analogous to Triode region of MOSFET

End of Lecture 18