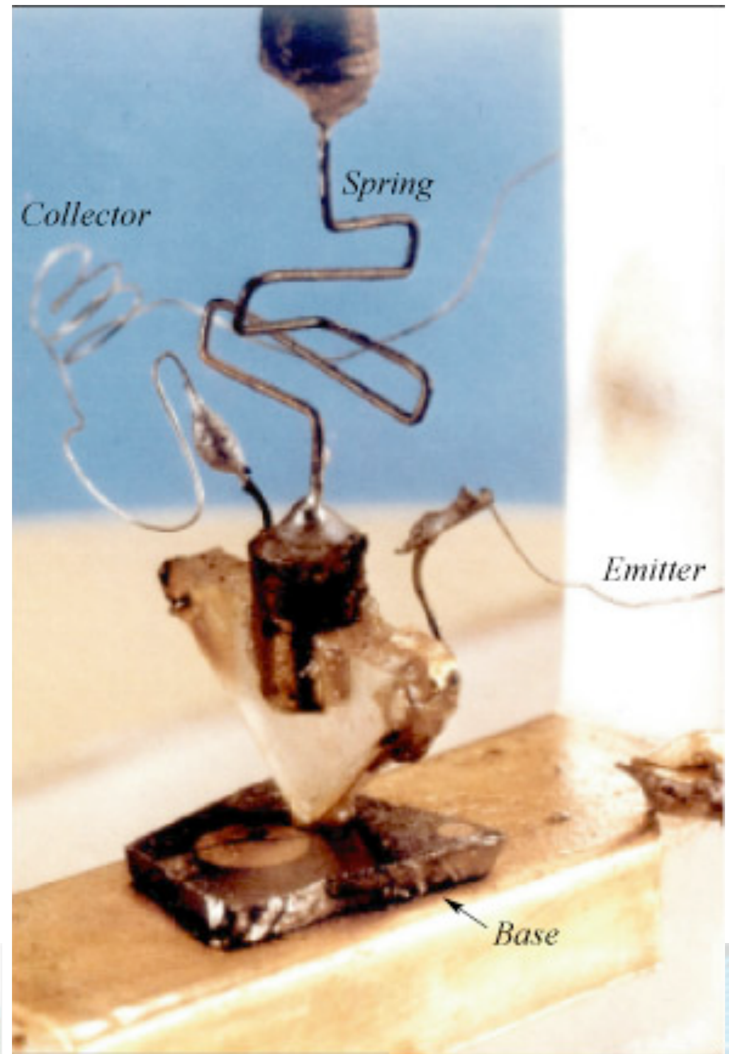
7.1, 7.2 – BJT Fundamentals
7.6 - BJT Switching

The first transistor (point contact) was invented at Bell Laboratories on December 16, 1947 by William Shockley, John Bardeen, and Walter Brattain.



Note:

☆ = potential quiz question

COVER SHEET FOR TECHNICAL MEMORANDA

SUBJECT: Terminology for Semiconductor Triodes - Committee Recommendations - Case 38139-8

MM- 48-130-10
DATE May 28, 1948
AUTHOR L.A.Meacham
C.O.Mallinckoodt
H.L.Barney

Surface States - Terminology

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ABSTRACT

Recommendations are made for an equivalent circuit representation, and terminology relating to semiconductor triodes.

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ABSTRACT

Recommendations are made f
cuit representation, and terminology
conductor triodes.

Designate by the numbers 1, 2 and 3, the order of your preference for the names listed below:

____ Semiconductor Triode

____ Surface States Triode

____ Crystal Triode

____ Solid Triode

____ Iotatron

____ Transistor

____ ____________________ (Other suggestion)

Comments: ______________________________

Signed ______________

Please return this ballot to Miss G. R. Callender in 1A-323 at Murray Hill.

- This is a PNP BJT…

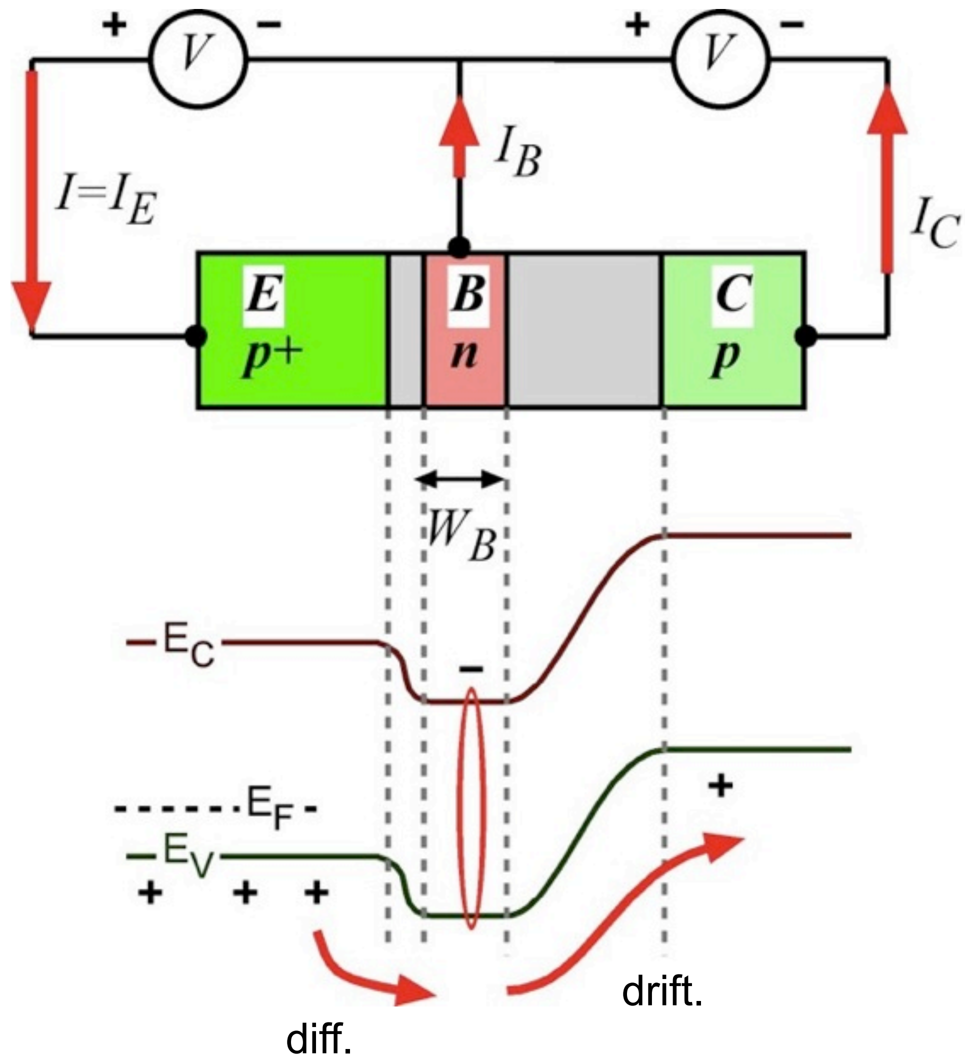
… it is two diodes, one reverse biased, one forward biased… So we need to review diodes first!

Emitter
Base
Collector
$I=I_E=I_B+I_C$

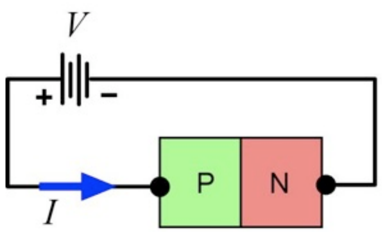
- Lets first look at the reverse biased diode, the COLLECTOR (C).

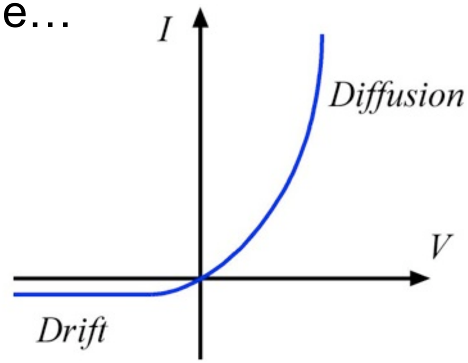
- Then look at the forward biased diode, the EMITTER (E).

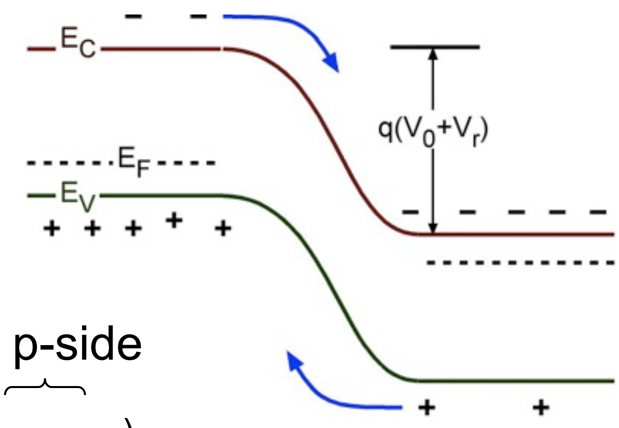
- The, lastly, try to figure out what the BASE (B) does!



- Reverse biased diode…



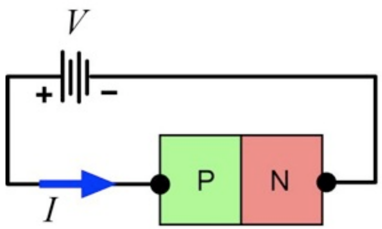


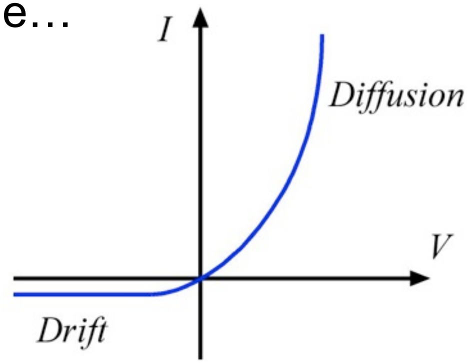


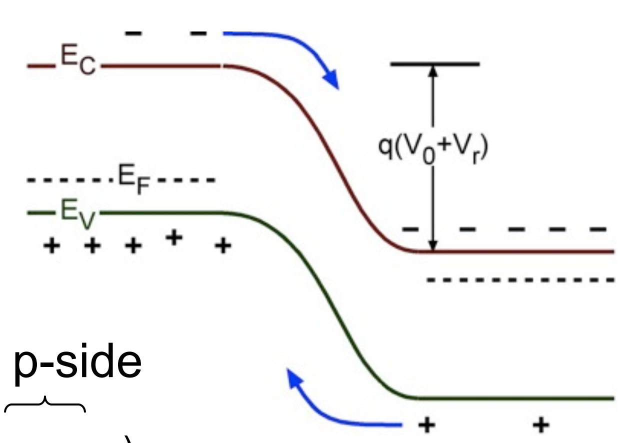
$$I = I_0\left(e^{qV/kT} - 1\right)$$

$$I_0 = qA\left(\overbrace{\frac{D_p}{L_p}p_n}^{\text{n-side}} - \overbrace{\frac{D_n}{L_n}n_p}^{\text{p-side}}\right)$$

- Reverse biased diode…







$$I = I_0(e^{qV/kT} - 1)$$

$$I_0 = qA\left(\overbrace{\frac{D_p}{L_p} p_n}^{\text{n-side}} - \overbrace{\frac{D_n}{L_n} n_p}^{\text{p-side}}\right)$$

- The COLLECTOR of a BJT is a reversed biased diode *that collects **minority*** carriers <u>brought to it…</u>

… but how how do we bring those minority carriers in a BJT?

- That is where the EMITTER comes into play… it EMITS carriers that can the be COLLECTED by the COLLECTOR.
- The EMITTER is a special forward biased p+n diode, lets review it now…

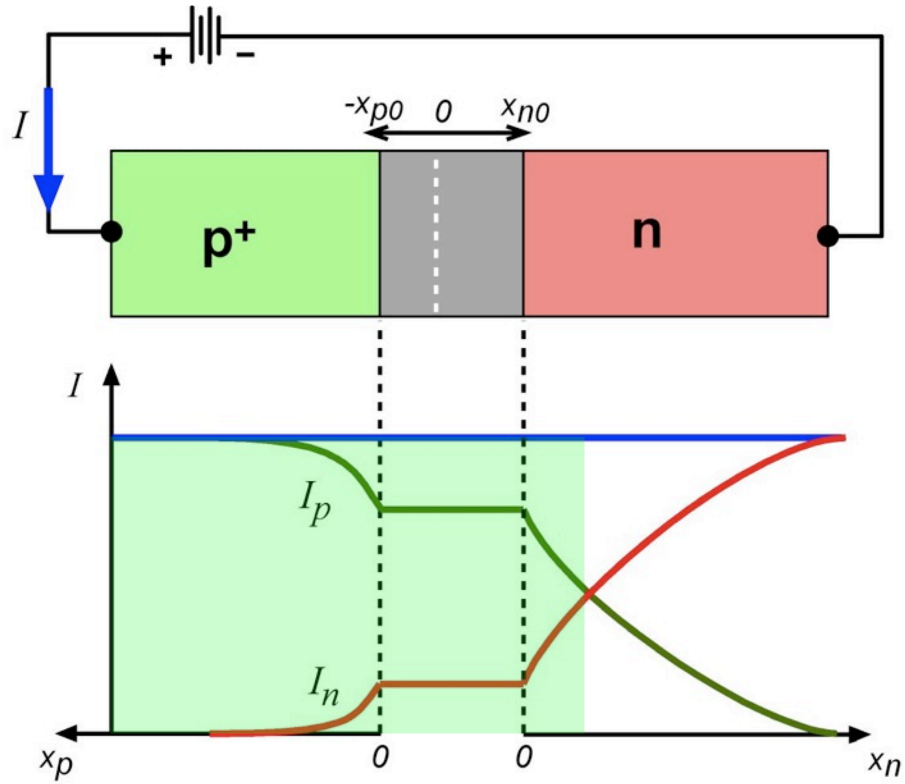
- Forward bias: I_{diff}

- p+ side has more carriers ready to diffuse so hole current dominates ***across and near*** *the junction…*

- Deeper in the n-side electron current dominates only because we need to bring in electrons to recombine with all the holes that are we are diffusing over…

- KEY POINT: p+n… hole current dominates across junction… and importantly ***dominates over a certain distance into the n-type material!***

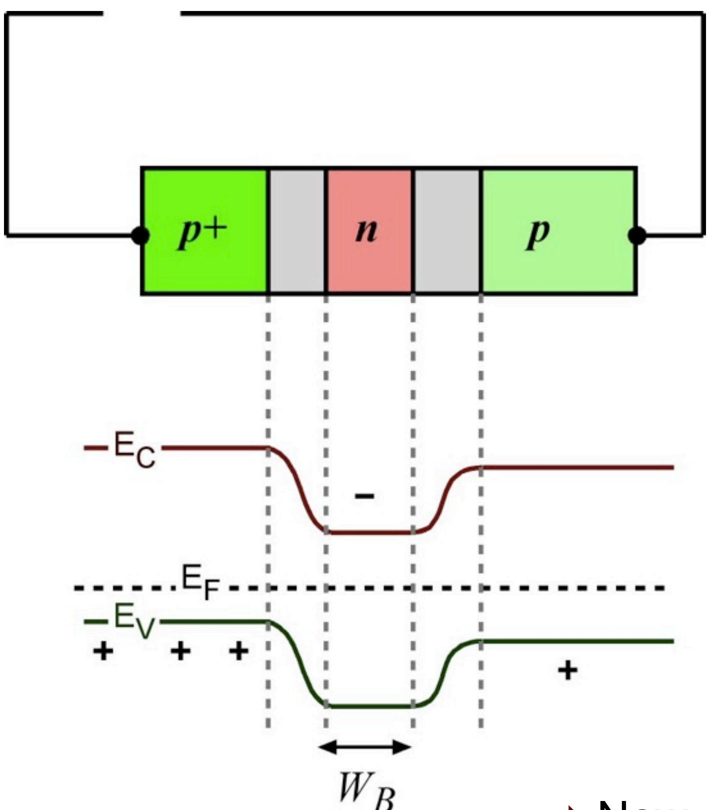
Okay, now we are ready to make and understand a p+np BJT!



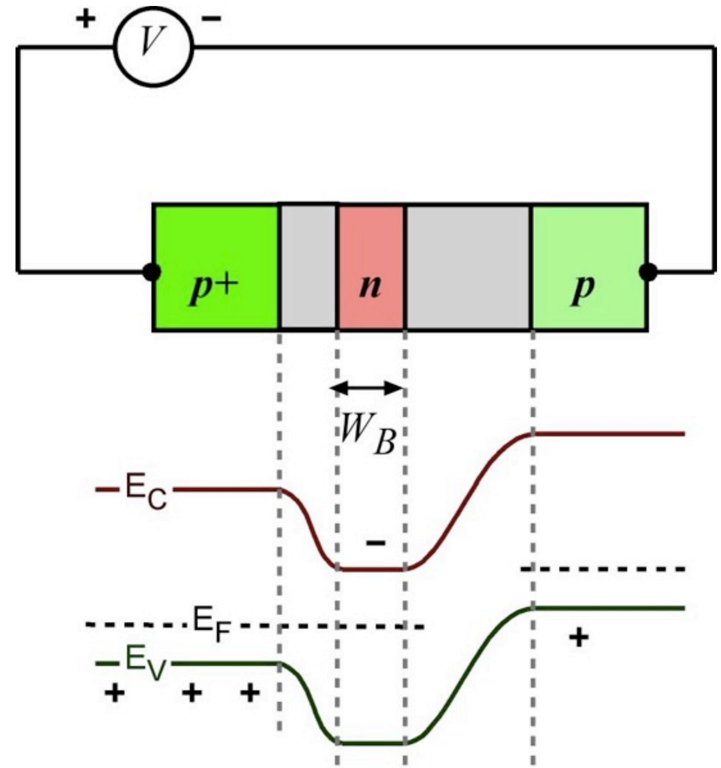
$$n_p << p_n$$

$$I = I_0(e^{qV/kT} - 1) \qquad I_0 = qA\left(\frac{D_p}{L_p}p_n - \cancel{\frac{D_n}{L_n}n_p}\right)$$

- Join p+, n, p Si
- Let's keep the n thin (W_B)



- Apply voltage, what happens? where is the voltage drop? ☆



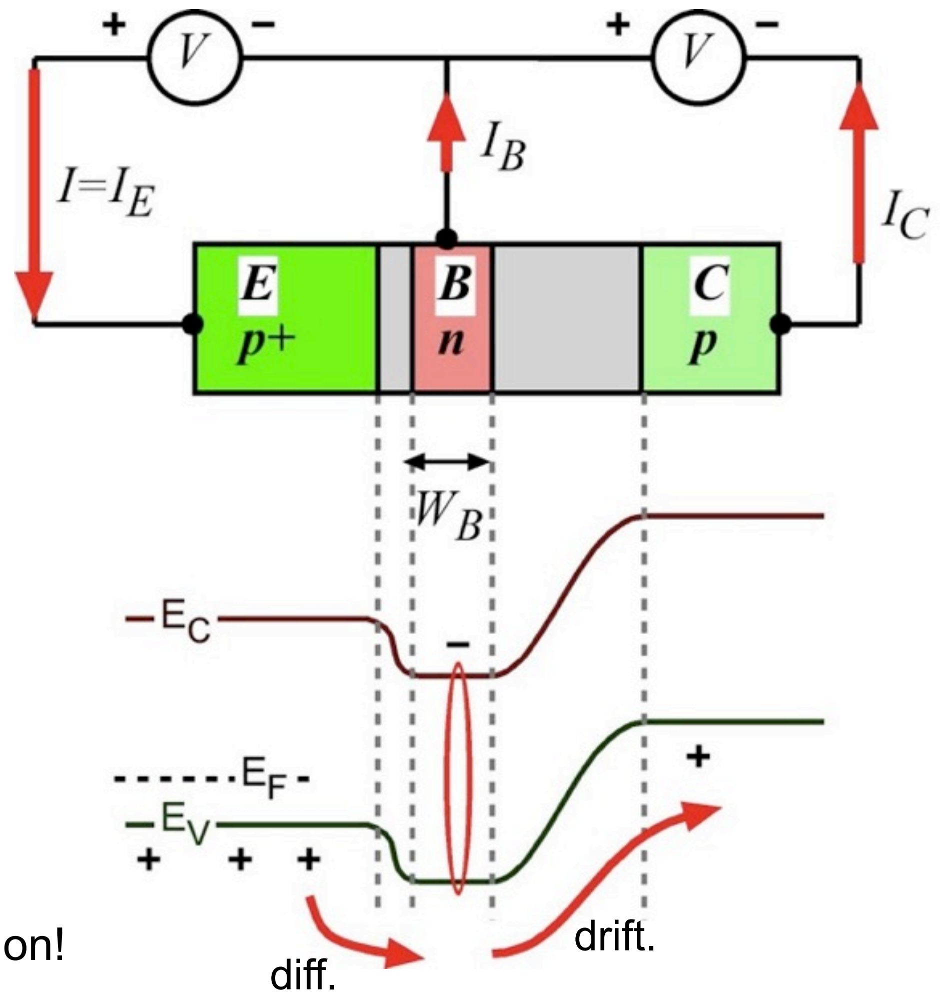
- Now, if we could inject some more holes from p+ to n, what could happen???
- But all voltage is across np, what else could we do?

- We add a 2nd voltage source to forward bias the p+n junction

  - the EB diffusion barrier decreases, current magnitudes for h's vs. e's?

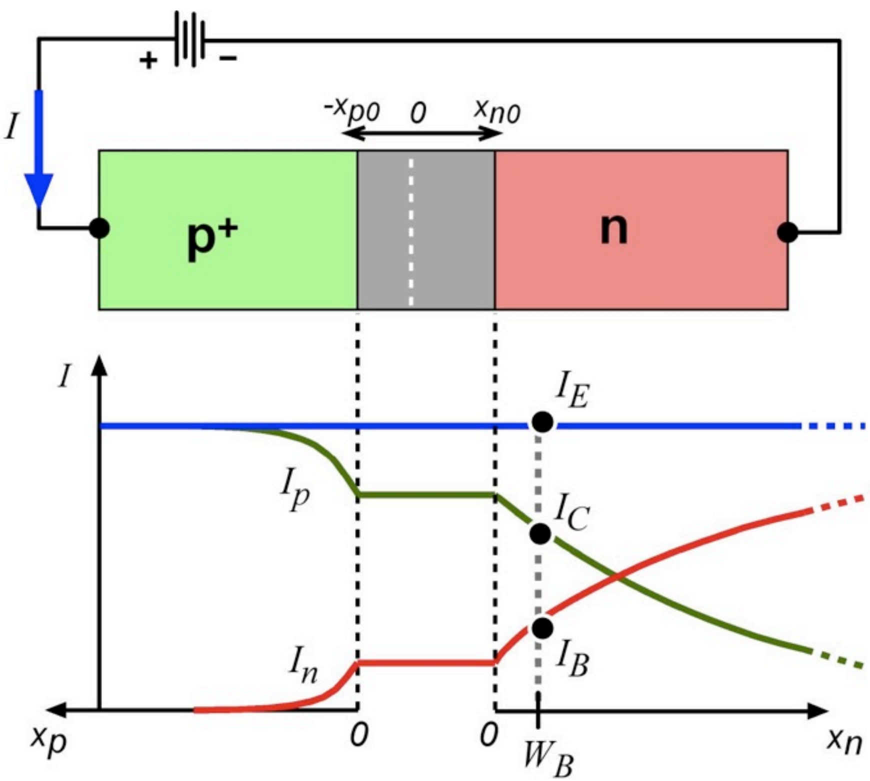
  - W_B is small, so will h's recombine *or end up where instead?*

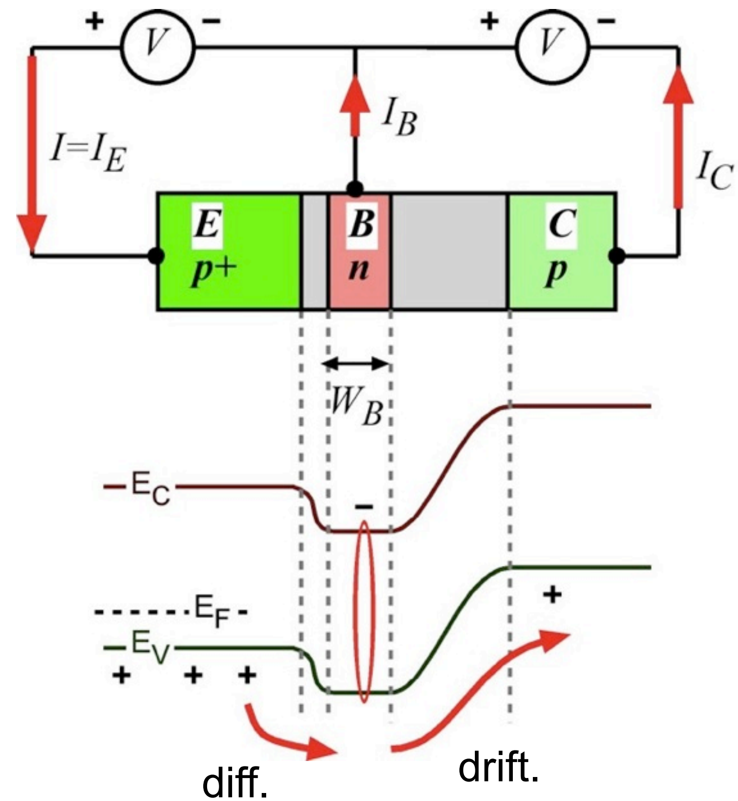
  - *if* W_B was large, how would this change the current due to e's (I_B)?



- Note the magnitudes of currents, amplification!

- ☆ Key! At EB side of n we get an <u>excess</u> of holes (forward biased diode), and the BC side of n is a reverse biased diode so what is the hole concentration at that depletion edge? Therefore what drives the holes across the base?





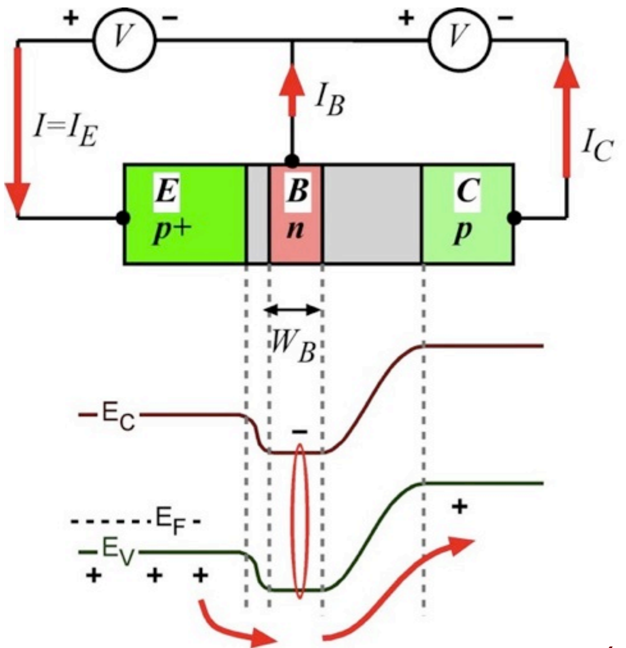
- Again, recall we have a **p+n** junction with low N_D for long L_P, so that excess of holes is preserved over a distance: *example: $N_D=10^{15}$/cc, L_P~100 μm*

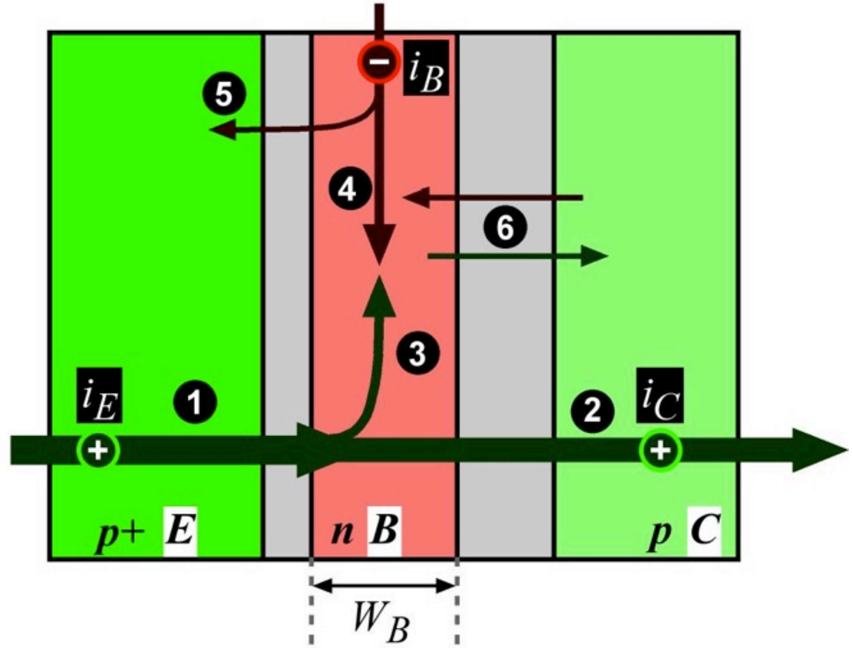
$$L_p = \sqrt{D_p \tau_p}$$

$$D_p = \frac{kT}{q}\mu_p \qquad \tau_p = \frac{1}{\alpha_r(n_0 + p_0)}$$

- Therefore, the shorter W_b gets, the smaller I_B gets… for typical W_b a very small change in I_B causes a large change in I_C, I_B … typically W_b~1μm!

lets look at it another way…





Emitter (inject holes)
Base (historical, Ge slab)
Collector (collect holes)
$I=I_E=I_B+I_C$

(1) Holes injected do what? **diffuse** across EB
(2) Holes reach BC and do what? **drift** to C
(3) Holes injected do what? **recombine** with B electrons
(4) Electrons injected do what? **recombine** with B holes
(5) Electrons injected do what? **diffuse** across EB
(6) Reverse bias e or h do what? **drift** across BC (small)

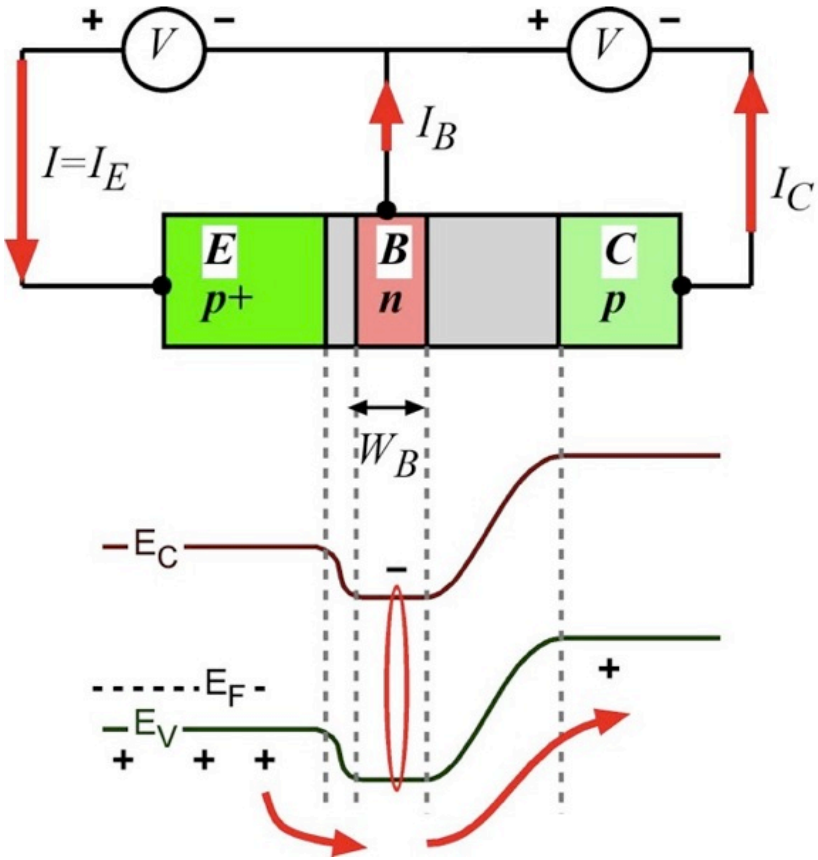
Remember: *p+n for EB so (1) >> (5),* $W_b << L_p$ *so (2) >> (3), but (3)≠0*

- Make sure you are solid on the starred items (☆), and if you paid attention, you should be able to answer these questions:

(1) The emitter 'emits' by being Forward or reverse biased? Drift or diffusion?

(2) The collector 'collects' by being Forward or reverse biased? Drift or diffusion?

(3) We get amplification because the a small base current results in large emitter and collector currents. The base current is small and we get strong current amplification because of what? See slide 11.



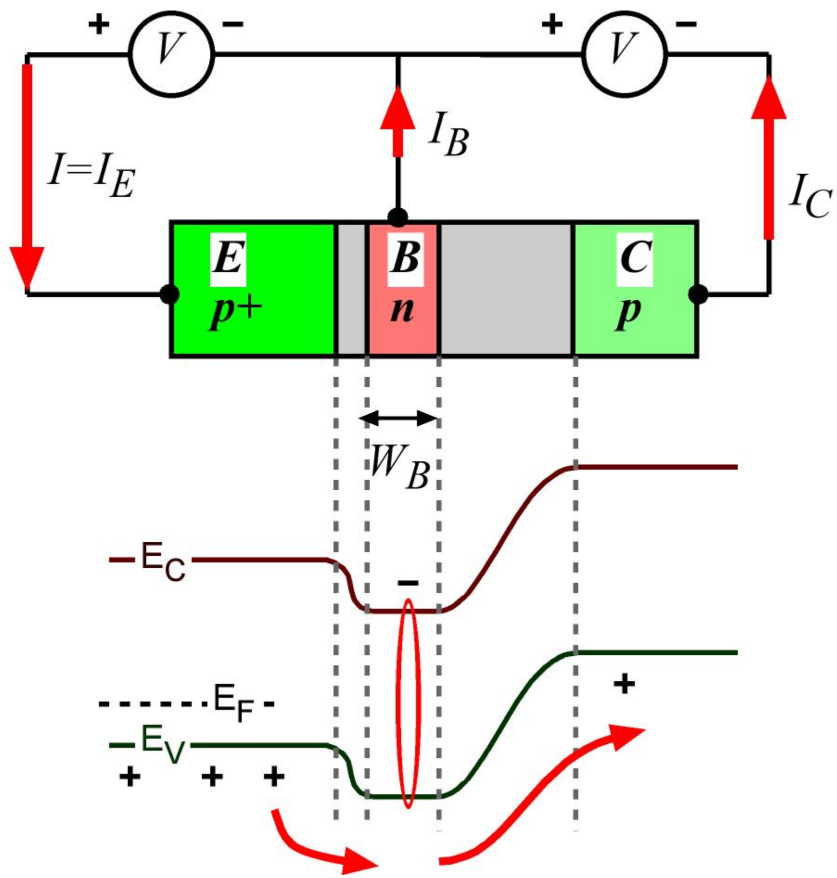
- Quick note to start… we figured out the model for pnp BJT, what about npn?

all currents reversed…!

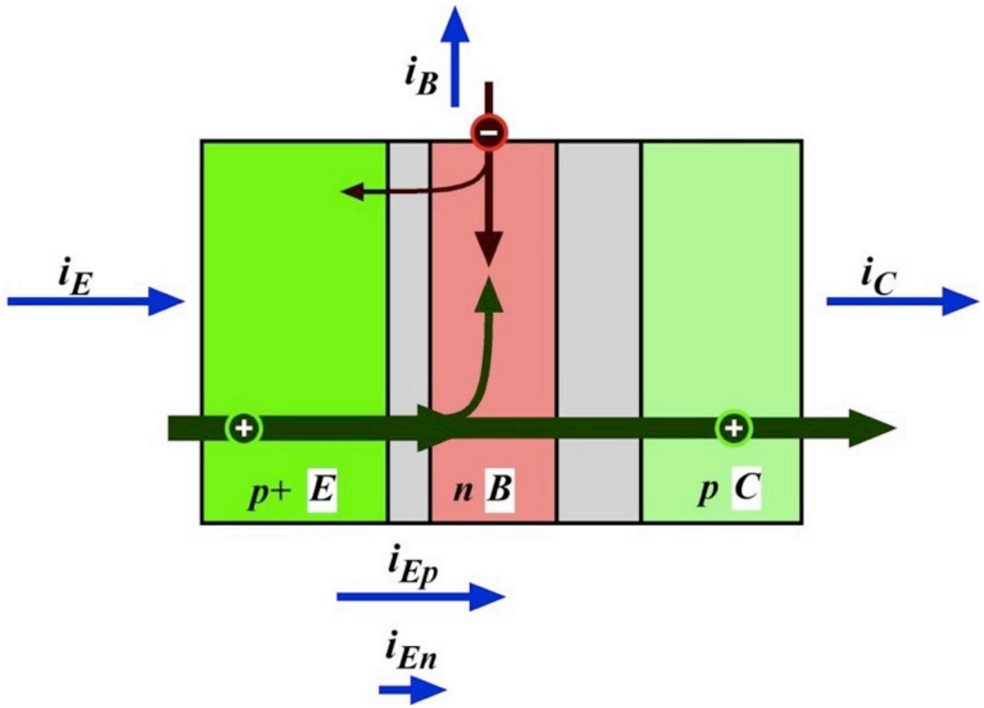
- BJTs great for **high power** / high frequency amplifiers (small change in I_B leads to large change in I_C)

- To understand amplification lets look a idealized (simple) model that assumes:

(1) No rev. saturation current in I_C
(2) DC & low frequency AC
(3) Neglect recombination in *depletion* regions (but not in base!)



- First note current directions (e,h movement vs. current)



- Next, relate i_{Ep} (not i_E) to i_C using a proportionality constant B

$$i_c = Bi_{Ep}$$

B = base transport factor

- Ideally want h injection (diffusion) ***not* e** across EB (small i_{En}, large i_{Ep}):

$$i_E = i_{En} + i_{Ep} \qquad \gamma = \frac{i_{Ep}}{i_{En} + i_{Ep}}$$

Υ = emitter injection efficiency

- We can further define *current transfer ratio* (α) as:

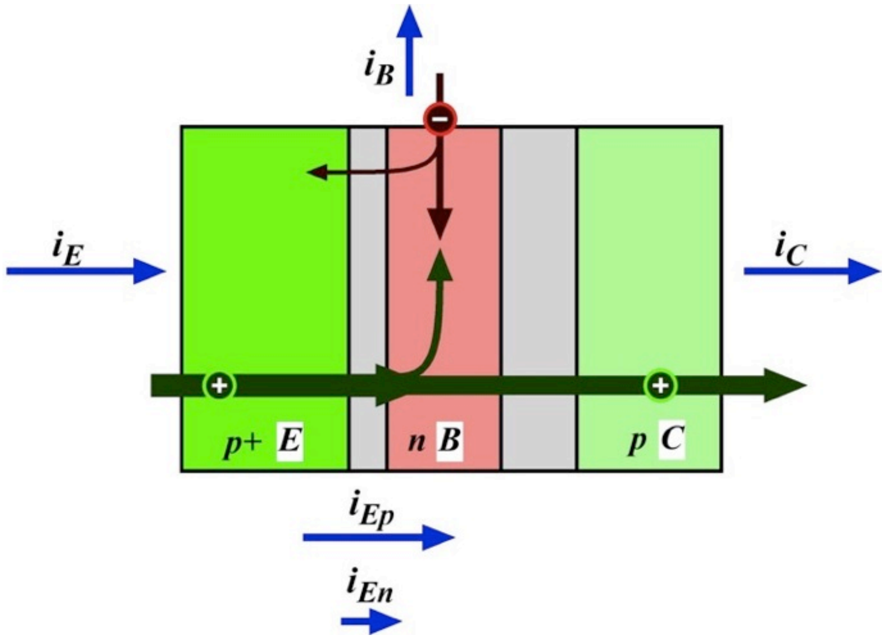
$$\alpha = \frac{i_C}{i_E} = \frac{Bi_{Ep}}{i_{En} + i_{Ep}} = B\gamma$$

- In an ideal world, what value should we want for B, *Υ,α ?*

Good thing that base is lightly doped, and p+n! and W_b is thin!

- We would like our *current transfer ratio* (α) to be close to unity… but this says nothing about gain

$$i_c = Bi_{Ep} \qquad \gamma = \frac{i_{Ep}}{i_{En} + i_{Ep}} \qquad \alpha = \frac{i_C}{i_E} = \frac{Bi_{Ep}}{i_{En} + i_{Ep}} = B\gamma$$



- Let's turn our attention to i_B…

$$i_B = i_{En} + (1 - B)i_{Ep}$$

e's diff. across EB junction

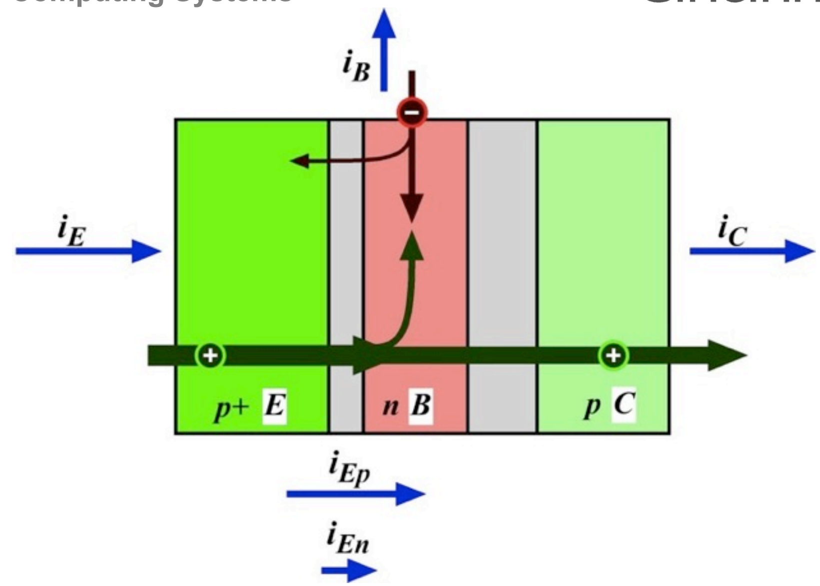
e's needed to recombine with some of the holes injected from EB *(holes that do not make it across base)*

- *right away we notice that neither of these components helps us increase i_C, so ideally we want these components to be?*

- What we know so far

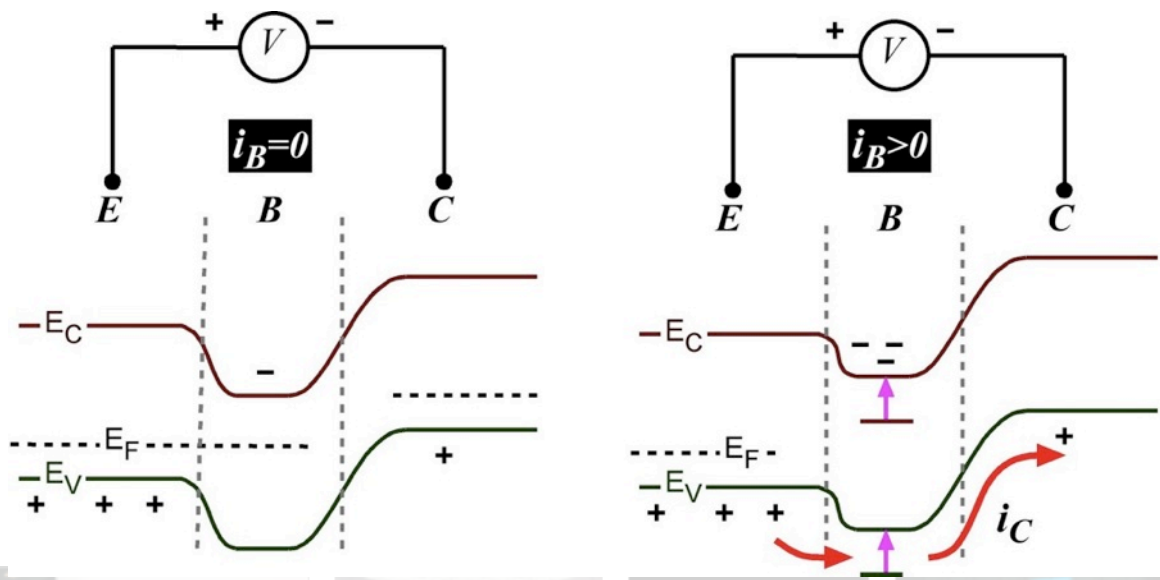
$$i_c = Bi_{Ep} \qquad \alpha = \frac{i_C}{i_E} = \frac{Bi_{Ep}}{i_{En} + i_{Ep}} = B\gamma$$

$$\gamma = \frac{i_{Ep}}{i_{En} + i_{Ep}} \qquad i_B = i_{En} + (1 - B)i_{Ep}$$



- So for maximum amplification, we desire a large change in i_C to a small change in i_B….

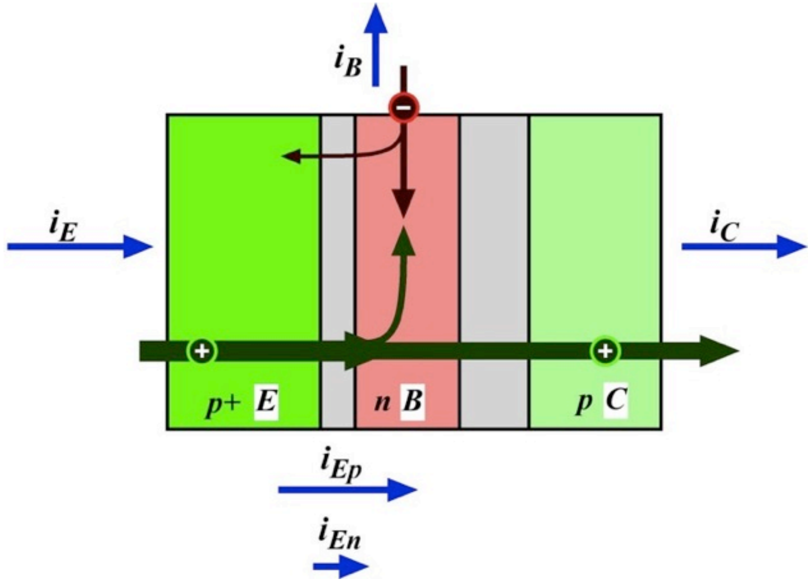
How can we calculate this?



- What we know so far

$$i_c = Bi_{Ep} \qquad \alpha = \frac{i_C}{i_E} = \frac{Bi_{Ep}}{i_{En} + i_{Ep}} = B\gamma$$

$$\gamma = \frac{i_{Ep}}{i_{En} + i_{Ep}} \qquad i_B = i_{En} + (1 - B)i_{Ep}$$



- We can express our base-to-collector <u>*amplification factor (β)*</u> as:

$$\frac{i_C}{i_B} = \frac{Bi_{Ep}}{i_{En} + (1 - B)i_{Ep}}$$

$$= \frac{B\left[i_{Ep}/(i_{En} + i_{Ep})\right]}{i_{En}/(i_{En} + i_{Ep}) + (1 - B)\left[i_{Ep}/(i_{En} + i_{Ep})\right]} = \frac{B\left[i_{Ep}/(i_{En} + i_{Ep})\right]}{\underbrace{i_{En}/(i_{En} + i_{Ep}) + i_{Ep}/(i_{En} + i_{Ep})}_{1} - B\left[i_{Ep}/(i_{En} + i_{Ep})\right]}$$

$$\frac{i_C}{i_B} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1 - \alpha} \equiv \beta$$

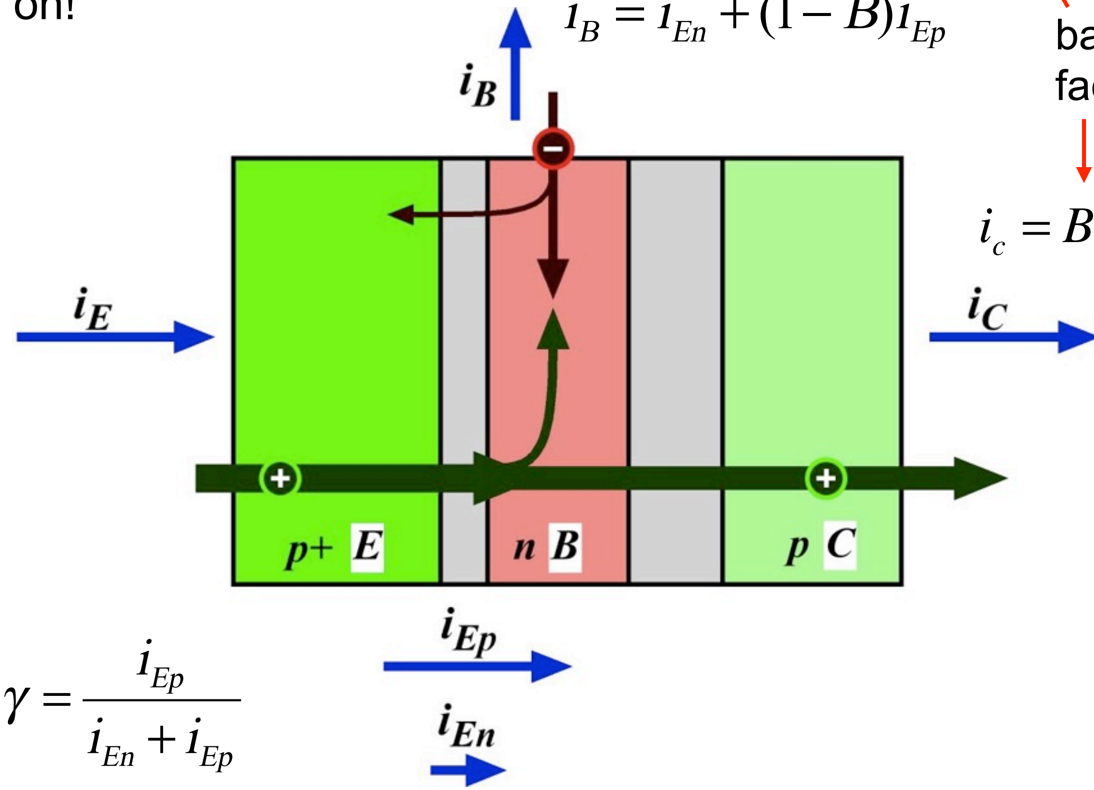
α can be close to unity in real devices so β can be very large

- Make sure these make sense before you move on!

$$i_B = i_{En} + (1 - B)i_{Ep}$$

base transport factor

$$i_c = Bi_{Ep}$$



emitter injection efficiency

$$\gamma = \frac{i_{Ep}}{i_{En} + i_{Ep}}$$

amplification factor

$$\frac{i_C}{i_B} = \frac{B\gamma}{1 - B\gamma} = \frac{\alpha}{1 - \alpha} \equiv \beta$$

current transfer ratio

$$\alpha = \frac{i_C}{i_E} = \frac{Bi_{Ep}}{i_{En} + i_{Ep}} = B\gamma$$

- Let look at amplification another way as well… assume unity injector efficiency (all injected e's stay in base)

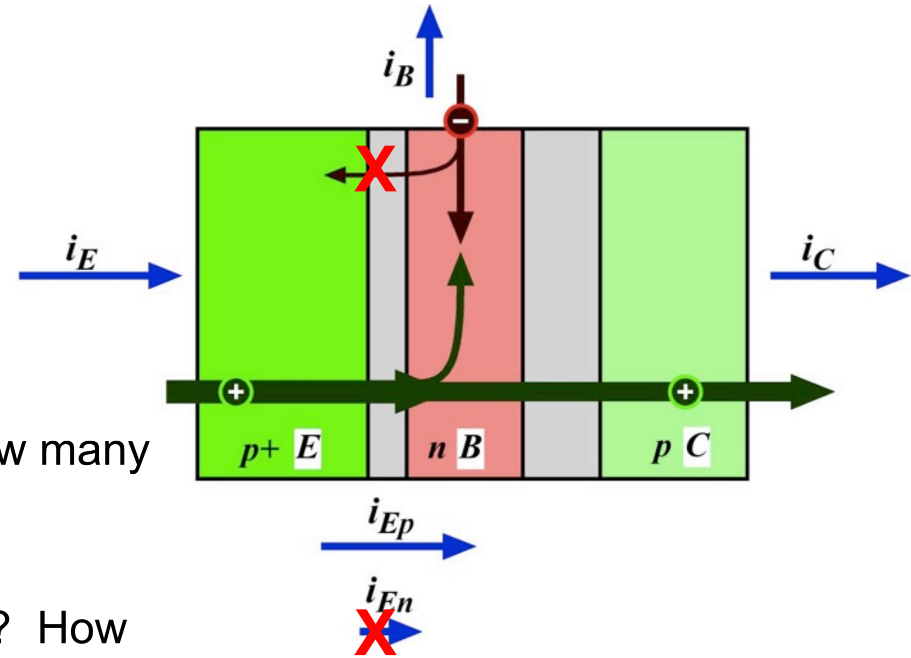
- We know we always must have charge neutrality in the base.

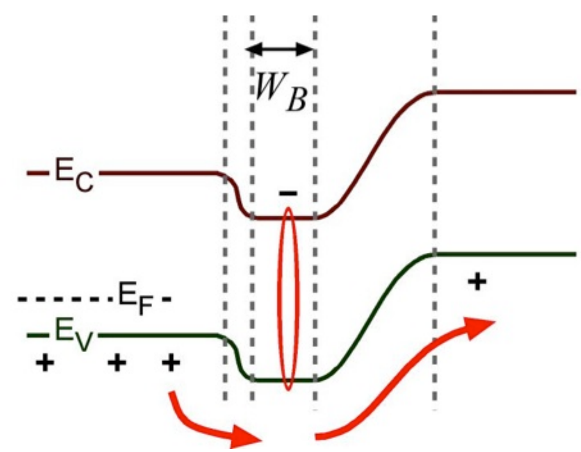
- So, if we add 5 extra electrons to the base, how many extra holes will be in the base at any given time?

- The electrons we added, do they just sit there? How do they sit there, and how long until, they disappear?

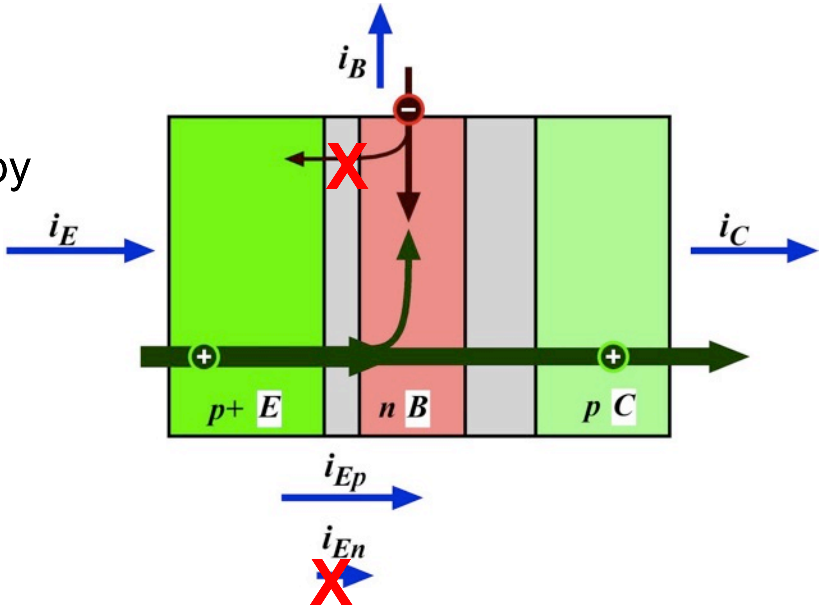
- During the time it takes for the electrons to disappear what were the holes doing? Relatively, how long does a hole spend in the base, longer or shorter than time for an electron?

- How can we use this to calculate amplification factor?





- Thus, for each e entering the base through the base contact, t_p/t_t h's can pass through the base region with out upsetting the balance maintained by charge neutrality. (t_t is the h transit time)



- This implies that:

$$\frac{i_C}{i_B} = \beta = \frac{\tau_p}{\tau_t}$$

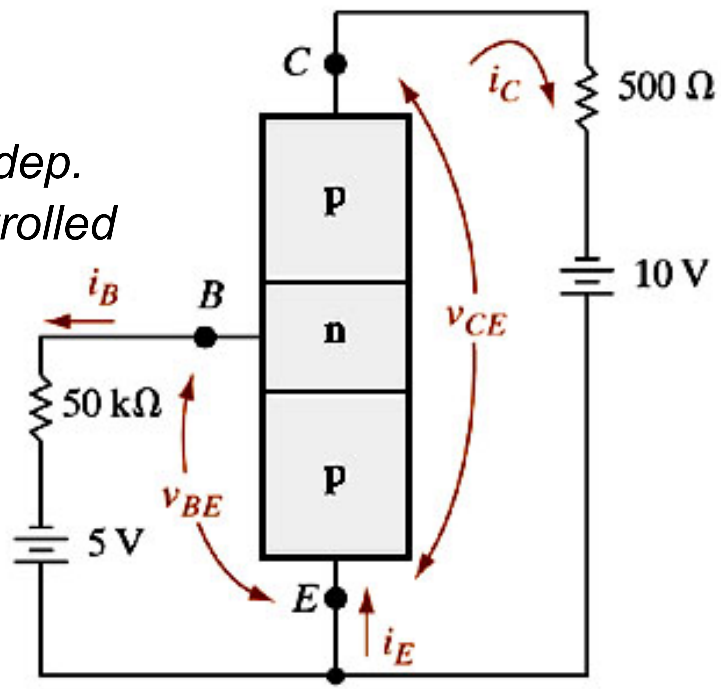
another reason why we want a thin base!

- What happens if we restrict or increase the flow of e's coming from the base contact?

(1) We must maintain charge neutrality (same # of e's and h's in base). ☆
(2) Any change in e's in the base requires a much larger change in h's flowing through the base since most h's go through without recombining… *amplification.*

- An example circuit: *'common emitter' where emitter is common (ground) to B and C*

i_B indep. controlled



note Ic indep. of load!

$$\tau_p = 10\ \mu s$$

$$\tau_t = 0.1\ \mu s$$

$$\frac{i_C}{i_B} = \beta = \frac{\tau_p}{\tau_t} = 100$$

Neglecting v_{BE}

$$I_B = \frac{5\ \text{V}}{50\ \text{k}\Omega} = 0.1\ \text{mA}$$

$$I_C = \beta I_B = 10\ \text{mA}$$

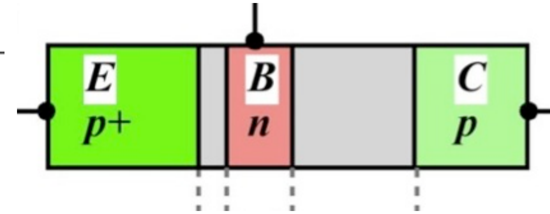
- What is the amplification factor (two ways to get it)… ☆
- Why is I_C so beautifully linear to I_B? ☆
- What does I_C vs. V_{BE} look like, and why? ☆
- Why does I_C saturate with increasing V_{CE}? Hmm… lets look at the final part for this lecture…
- Why does I_C saturation have a slope to it? Wait till next lectures…

TOSHIBA

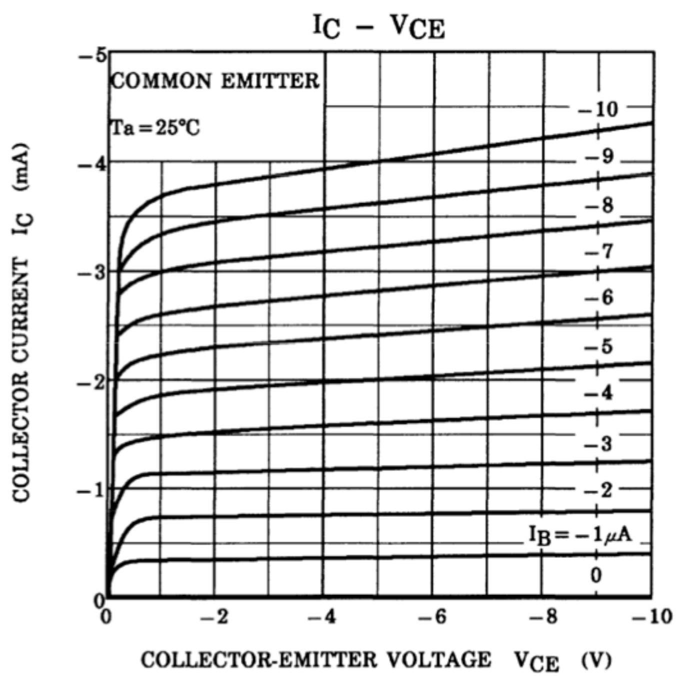
TOSHIBA Transistor Silicon PNP Epitaxial Type (PCT process)

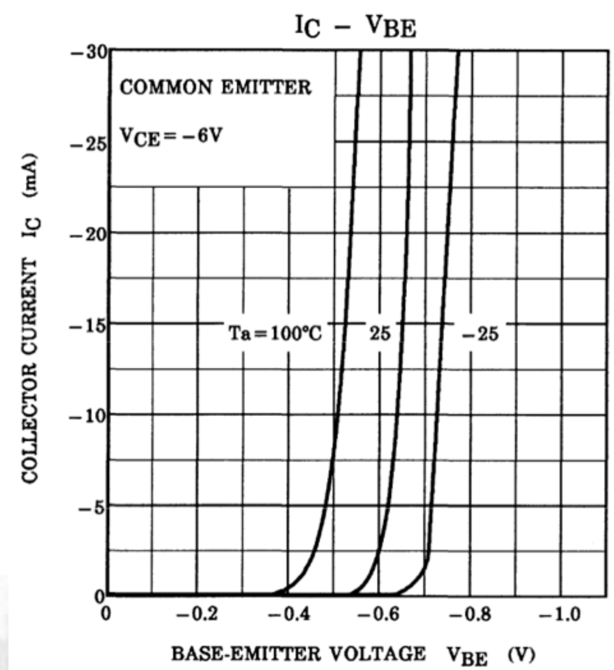
2SA1163

Audio Frequency General Purpose Amplifier Applications

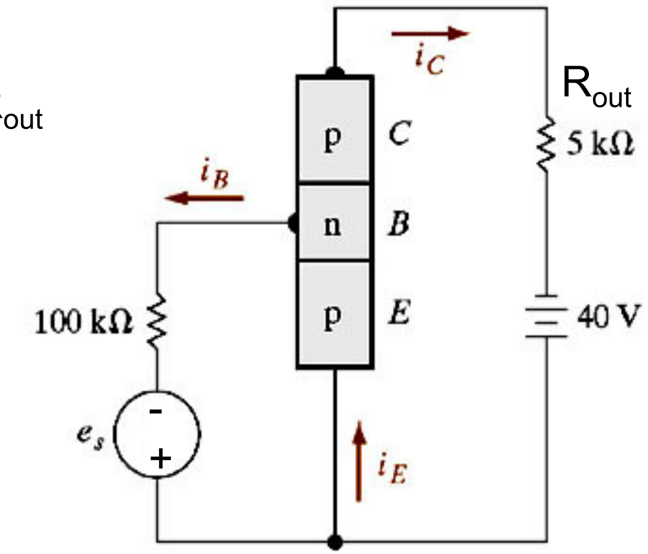


Characteristics	Symbol	Test Condition	Min	Typ.	Max	Unit
Collector cut-off current	I_{CBO}	$V_{CB} = -120$ V, $I_E = 0$	—	—	−0.1	μA
Emitter cut-off current	I_{EBO}	$V_{EB} = -5$ V, $I_C = 0$	—	—	−0.1	μA
DC current gain	h_{FE} (Note)	$V_{CE} = -6$ V, $I_C = -2$ mA	200	—	700	
Collector-emitter saturation voltage	$V_{CE\ (sat)}$	$I_C = -10$ mA, $I_B = -1$ mA	—	—	−0.3	V
Transition frequency	f_T	$V_{CE} = -6$ V, $I_C = -1$ mA	—	100	—	MHz





- Normal forward mode operation with R… R could be internal, contact, or external! A load is always there and often listed as R_{out}



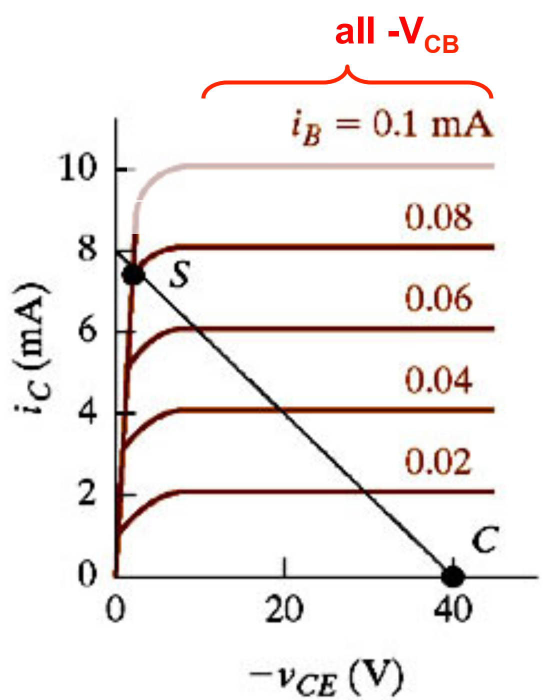
- 40V supply is fixed, R_{out}=5 kΩ: $\therefore I_C \leq \frac{-V_{CE}}{R} \leq 8\,mA$

- If I_B small or negative then how much current flows through the R_{out}? Where is the voltage drop then?

  - *this is referred to as BJT **C**utoff (min current!)*

- If we increase I_B by just a bit we get an increase in I_C

  - *each increase in I_B shown as new curve (typical for BJT)*
  - *what is our value for β ?*



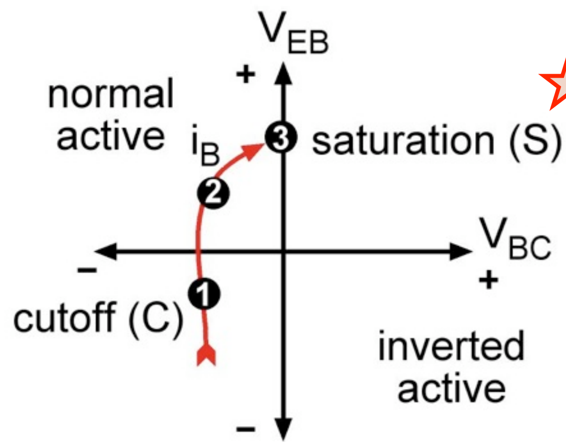
- Lets say we keep increasing I_B, and more current flows ☆ through R_{out}… Where is the voltage drop then? So if we keep increasing I_B will I_C keep increasing as well?

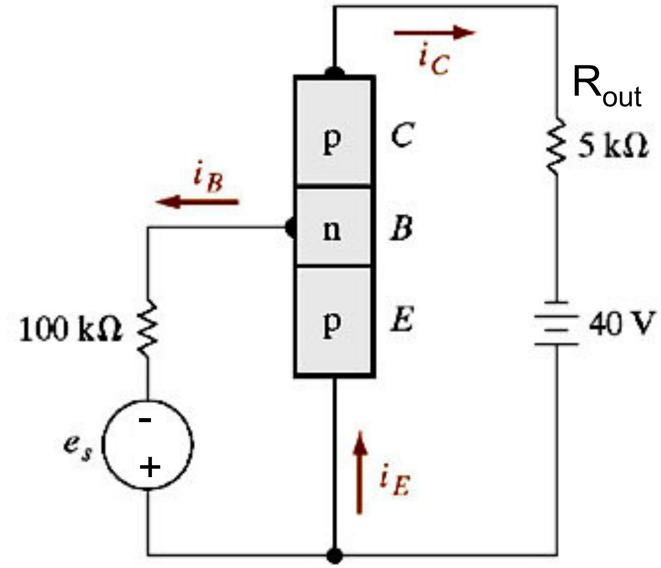
  - *this is referred to as BJT **S**aturation!*
  - *look at how it nicely follows the load line!*

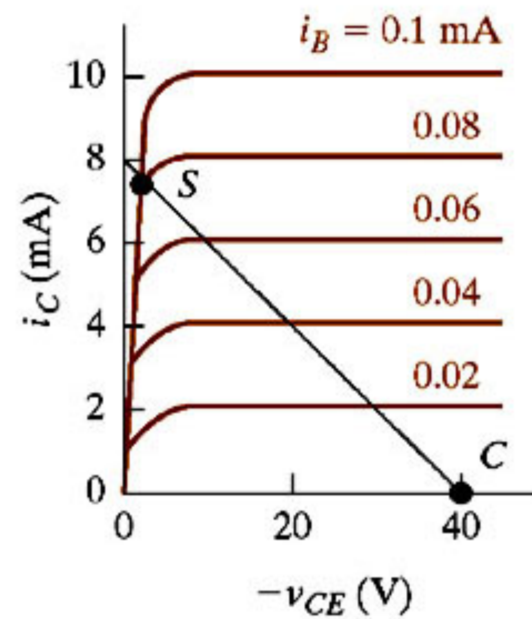
- As we increase V_{CE} the current saturates, why? Hint - where does the applied V_{CE} appear… does more help at all?

- Four regions of operation:
  - **C**utoff: EB at 0V or reverse biased
  - Normal Active: EB forward and BC reverse
  - **S**aturation: EB strong forward, BC ~ 0V
  - Inverted Active: what is it?

i_B (mA)	I_C (mA)	v_{CE}
❶, <0	0	40 V
❷, >0	…	…
❸, >0.08	8	0 V







- Ways to use a BJT:

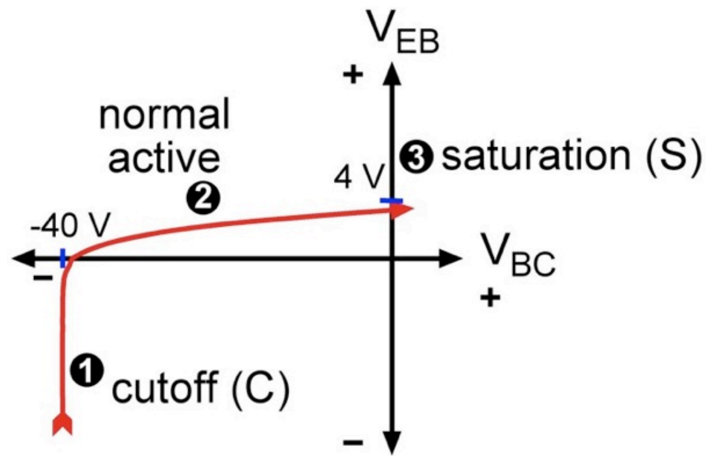
  * as a logic switch between (1) and (3) … *not so popular!*

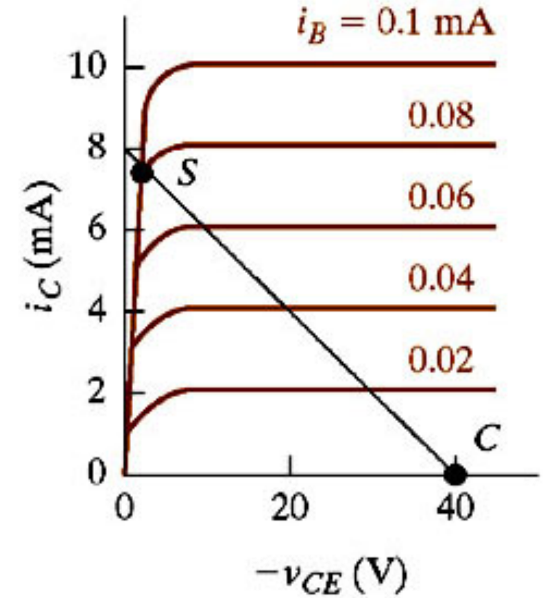
  * as an amplifier (2) … *used in many applications*

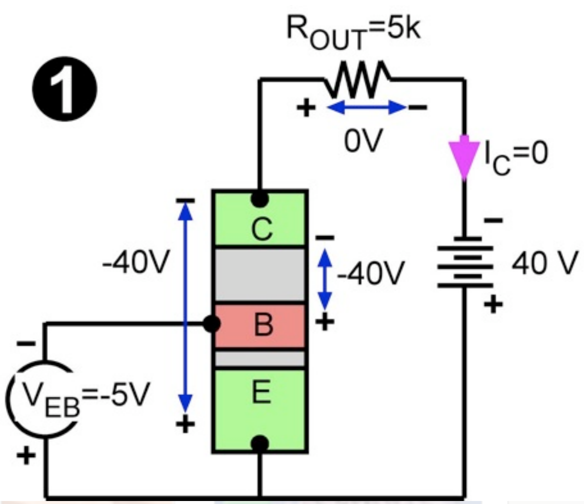
  … BJT's are attractive because so linear and you are only limited to R_{OUT} which can be small

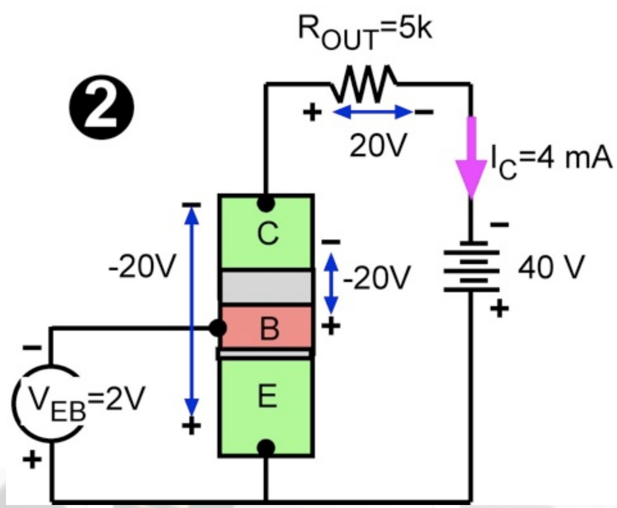
- Remember, we always have an R_{out} for every type of device in this course…

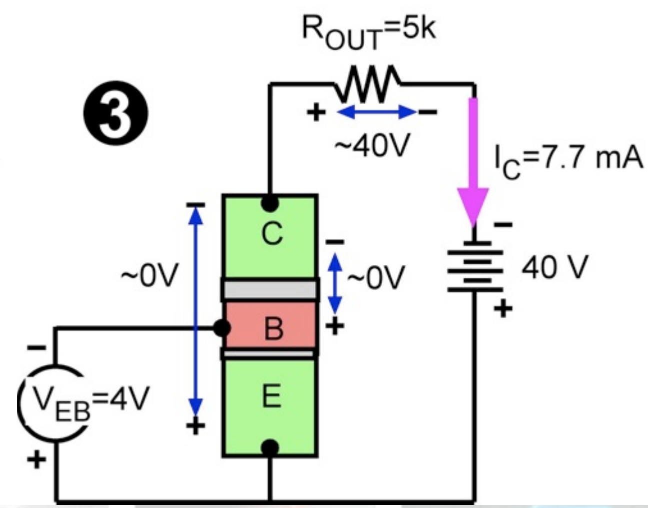
… in this case it is the lightly-doped (resistive) collector. The collector is lightly doped because of how we fabricate the device (more info later…).









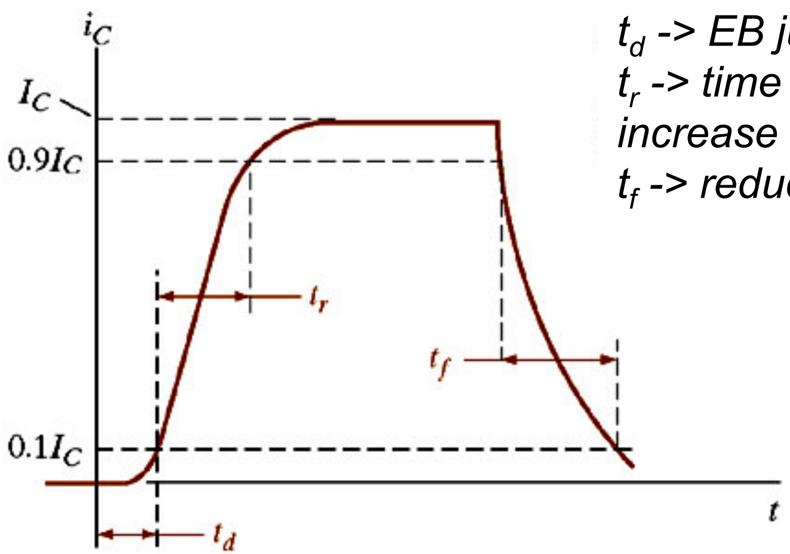


- Remaining sections in 7.6 (Cuttoff/Saturation/Switching Cycle/Specifications) present further detail on BJTs as switches…

- We will skip these sections (since BJTs are mainly used as amplifiers these days)

- However, if you read-through them it will only enhance your understanding of BJTs (and BJT switches are still used)

- Basically, one thing that is shown in the remainder of 7.6 is that switching time for the BJT is derived and related to the same effects we derived for the PN junction switching time

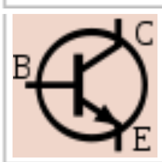
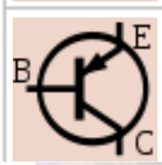


t_d -> EB junction cap (rev. to forward)
t_r -> time for excess hole conc. in base to increase to saturation level
t_f -> reduction of hole conc. in base

- How to tell different transistors apart… (but you will find not everyone follows this!).

Look at diagrams… Why 'B' and 'C' lines connect so close to one another at 'B'? *Two reasons, one could be due to the fabrication method for the point-contact transistor…*

Why E current direction different for PNP vs NPN? *Think of just the PN part of each device…*

	JFET-N Transistor	N-channel field effect transistor
	JFET-P Transistor	P-channel field effect transistor
	NMOS Transistor	N-channel MOSFET transistor
	PMOS Transistor	P-channel MOSFET transistor
	NPN Bipolar Transistor	Allows current flow when high potential at base (middle)
	PNP Bipolar Transistor	Allows current flow when low potential at base (middle)

- To make a BJT we have to take two back-to-back PN junctions but make two key modifications…. <u>Small or wide base width? Heavy or light base doping?</u> ☆

- These two modifications increase amplification, and … <u>increase base current or decrease required base current?</u> ☆

- Assume an amplification factor of 100. I use the base wire to add 4 electrons to the base, on average how many additional holes will be in the base at any given time? <u>Zero, four, or four-hundred holes?</u> ☆

- Lets say I cut the base terminal wire and using my 'electron gun' I again add 4 electrons to the base, and assume my amplification factor is 100. How many holes will I collect? <u>Zero, four, or four-hundred holes?</u> ☆

- Bit tougher question, how many holes did I <u>emit</u> from the emitter? Here is your hint… you will need the holes collected, plus enough holes to eventually cause the electrons to recombine… <u>Zero, four, four-hundred, or four-hundred and four?</u> ☆

- If I keep increasing I_B, I_C will… <u>Not change, keep increasing forever, or saturate as all voltage drop appears across R_{out} (the output resistance)?</u> ☆