EE 116 Lecture 33

Introduction to Bipolar Junction Transistor (BJT)

- **Read:** Ch. 5.1, 5.2, 5.3.1
- Transistors have two main characteristics:

  1) Amplification: a small signal (I or V, terminal #1) can control a large signal (usually I, flowing between terminal #2-#3).

  - Think of a tiny faucet controlling the amount of water flow through a giant hose. How many terminals? ____________.
  - Why is the water faucet/hose analogy particularly useful for sub-100 nm transistors today? _________________.

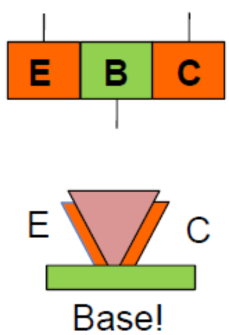
  2) Switching: the transistor can be turned on/off.

- Two main types of transistors:

  1) Bipolar junction transistor (BJT): small input <u>current</u> (faucet) controls large output current (hose)

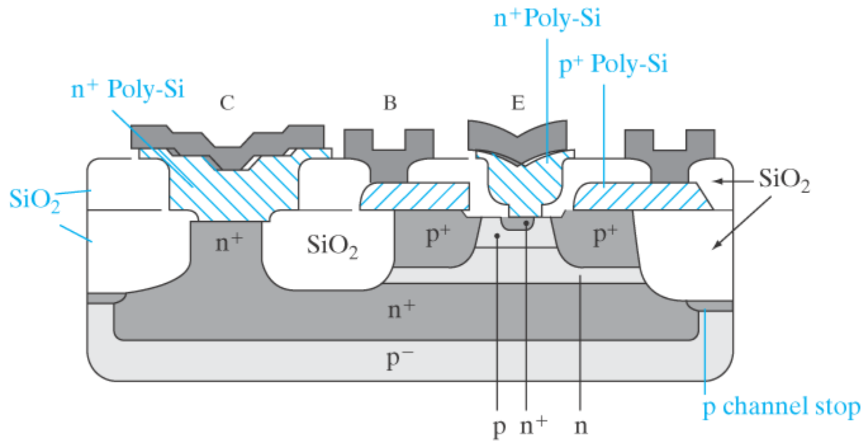
  2) Field effect transistors (FET): small input <u>voltage</u> (faucet) controls large output current (hose)

- Historical background of BJT

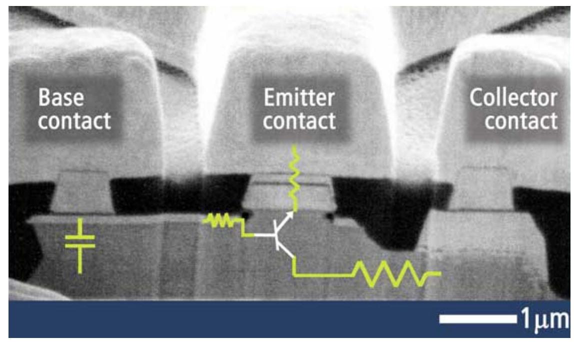


- First working solid-state transistor was BJT, not MOSFET
- It was actually a point-contact Ge-Au BJT (1947)
- BJT and later HBT work led to 2 Nobel prizes

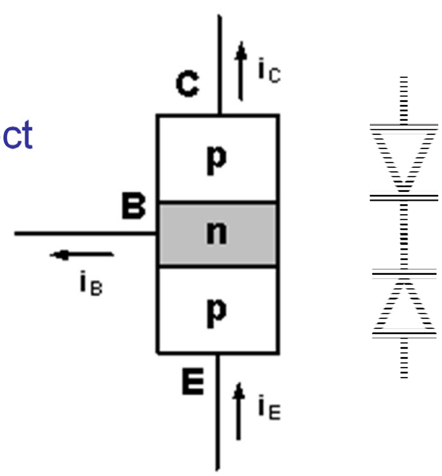
- This is what a modern BJT looks like:



- What kind of BJT?
- What is the cross-sectional area?
- What are the extra n+ and p+ regions?
- What's with all the SiO_2?

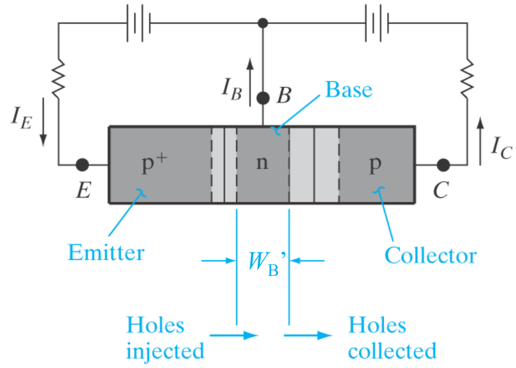


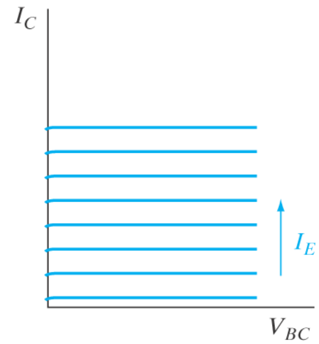
- Note, BJT = current-controlled current switch = always has some current flowing → power dissipation
- This is its Achilles' heel compared to the MOSFET, more power dissipation → limits integration levels per chip
  - BJTs gradually replaced with CMOS especially in high-density logic applications over past 30 yrs.
  - BJTs tend to be better for analog circuits → higher speed and gain.
- BJT has 2 back-to-back p-n diodes
- If one diode is forward-biased it can inject carriers into the other (reverse-biased) diode which "collects" them
- In a way, it is like a solar cell, except *instead of optically we inject carriers electrically* into a reverse-biased p-n



- Let's draw this with biases:

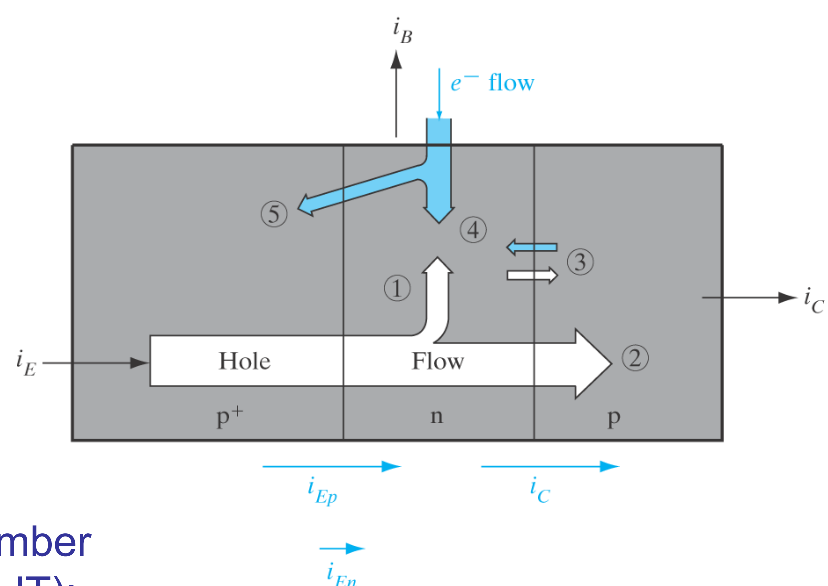
(Ch. 5.2 does this for an npn device)





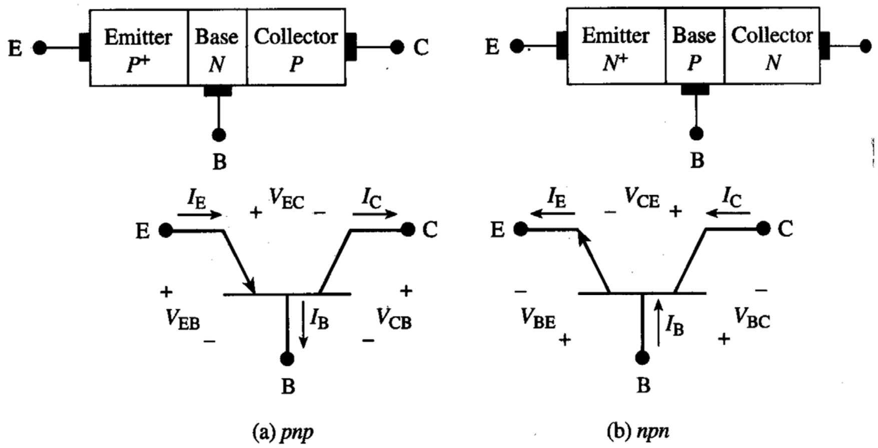
- Emitter (p+) injects holes into reverse-biased Base-Collector.
- For Collector to collect most holes we need Base $W_B' \ll L_p$.
  - Note book notation $W_B' = W_B - x_{n,BE} - x_{n,BC}$
  - If we omit primed notation, the understanding is that we refer to undepleted, quasi-neutral regions (so W_B' not W_B, W_E' not W_E, etc.)
- "Forward active" operation: EB junction forward and CB junction reverse biased (for pnp: $V_{EB} > 0$ and $V_{CB} < 0$, same as $V_{BC} > 0$).
- If so, then almost all injected holes are collected: $I_E \approx I_C$ are the "large" currents here (water passing through the hose).

- Is there a Base current I_B? What does it consist of?



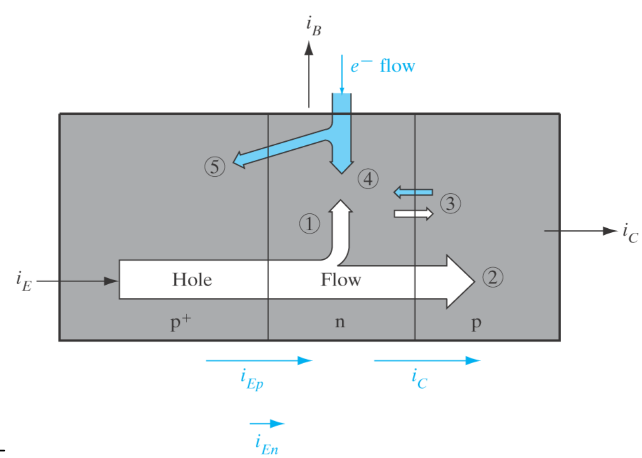
- Base current I_B (remember base is n-type for pnp BJT):
  - Some electrons recombining with injected holes.
  - Some electrons injected into p+ (forward biased EB).
  - Few electrons from thermal generation in reverse-biased CB junction
- Small but non-zero base current I_B (see Fig. 5.2.1 online for npn)

- In a well-designed BJT, $I_E \approx I_C \approx 100 I_B$
- We can write from current continuity: $I_E = I_C + I_B$



- There are both PNP and NPN bipolar transistors.
  - Easier to study PNP because current flows in direction of holes. But NPN is similar, replace holes w/ electrons and keep track of signs!
  - Intuitively (dimensions, doping being equal), which is faster?

- BJT performance parameters (here for the pnp)



- Emitter efficiency: $\gamma = \frac{I_{Ep}}{I_{Ep} + I_{En}}$
- Base transport factor: $\alpha_T = I_C / I_{Ep}$
- Current transfer factor: $\frac{I_C}{I_E} = B\gamma = \alpha$
- Current gain (amplification): $\frac{I_C}{I_B} = \frac{\alpha}{1-\alpha} = \beta$

in text online the α font sometimes shows up as "a"

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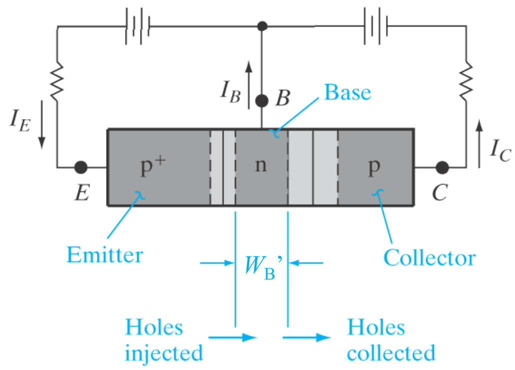
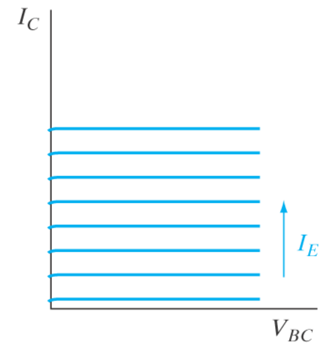
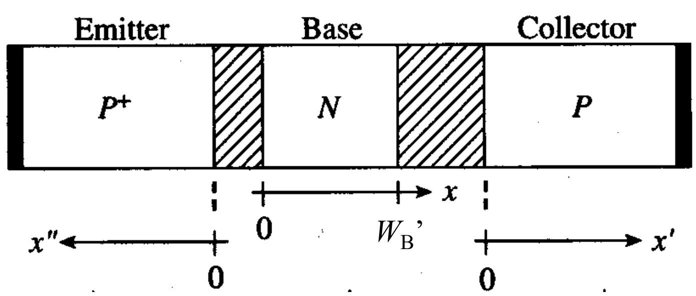
Short-Base BJT





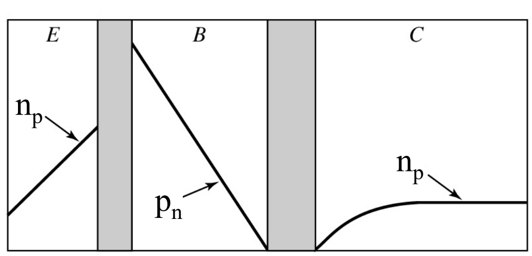
- What did we learn so far? What is special about the Base?
- Try to make things simple(r):
  - E → B current is all holes (p+ to n)
  - Holes diffuse across base, ignore *drift* (how come?)
  - Ignore any small reverse current at CB junction
  - Assume little recombination in quasi-neutral regions ("short" E and B)

- Back to our simplified analysis of the P+NP (V_{EB}>0, V_{CB}<0):



- We know all action is *minority carrier diffusion*, focus there:

note: "short" emitter and base, so $W_{E,B} << L_{n,p}$



- In fact, most action is *hole diffusion across base*, get δp there:

- Now we can *almost* calculate collector (hole) current…

$$I_C \approx -qAD_p \left.\frac{dp}{dx}\right|_{x=W_B}$$

- … because I get a nice (linear) slope from knowing $W_B' << L_p$

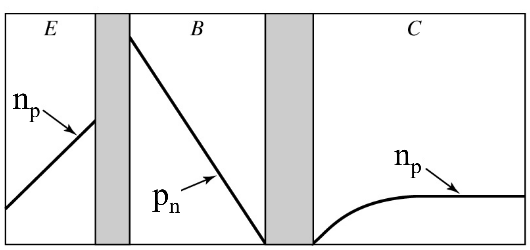
$$\frac{dp}{dx} \approx$$

- This is a short-base BJT, and we want it that way! Then:

$$I_C \approx$$

- Remember, only holes are "captured" by the Collector → this happens due to the direction of the E-field (from B to C in the reverse biased CB junction of the pnp device).

- To get Emitter current, don't forget there is a (small) electron injection component from the n-type Base
- Draw these injected (minority) electrons in Emitter:



- And remember the expressions from short diode:

$$I_{Ep} = qA\frac{D_p}{W_B}\frac{n_i^2}{N_B}\left(e^{qV_{EB}/kT}-1\right) \qquad I_{En} = qA\frac{D_{nE}}{W_E}\frac{n_i^2}{N_E}\left(e^{qV_{EB}/kT}-1\right)$$

- We can finally write the entire Emitter current:

$$I_E = I_{Ep} + I_{En} \approx$$

- Now we can calculate a lot of those "merit" parameters listed in the last lecture, like Emitter efficiency, $\gamma = I_{Ep}/I_E$

- Finally, what is the Base current?

$$I_B = I_B(\text{inj. to E}) + I_B(\text{recomb. with excess holes})$$
$$\approx I_{En} + Q_B(\text{stored})/\tau_p$$
$$\approx$$

- Often, we can ignore recombination in the base, so *gain* is:

$$\beta = \frac{I_C}{I_B} \cong \frac{I_{Ep}}{I_{En} + \cancel{I_{B,rec.}}} \approx \frac{D_{pB}}{D_{nE}} \frac{N_E}{N_B} \frac{W_E}{W_B}$$ (here for "short" pnp)

- Expression for *gain β* gives us most important design rules

$$\beta \approx \frac{D_{pB}}{D_{nE}} \frac{N_E}{N_B} \frac{W_E}{W_B}$$

- **Most important practical knobs for getting high gain are to set N_E >> N_B and make W_B as short as possible**

- Why not make W_E or W_C as long as possible?

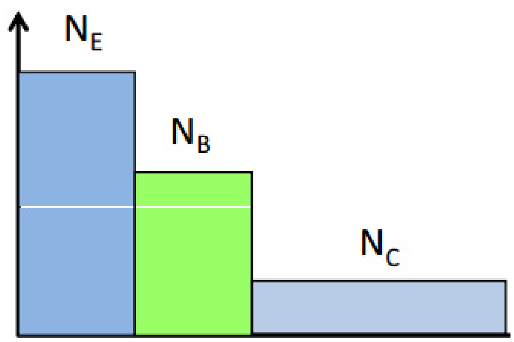
- BJT is <u>not</u> a symmetric device (the MOSFET is)

- If you are not given $D_{p,n}$ how do you calculate them?

- What if the E length is "long"?

Design of "Good" BJTs

$$\beta \approx \frac{D_{pB}}{D_{nE}} \frac{N_E}{N_B} \frac{W_E}{W_B}$$



Emitter doping:

- As high as possible

Base doping:

- *As low* as possible for high gain
- But *high* to avoid punch-through

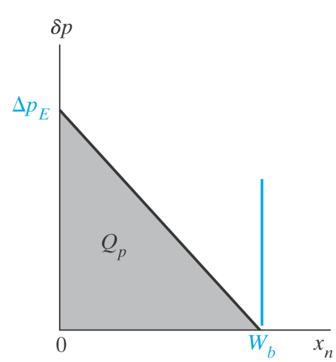
Collector doping:

- Lower than base

Base width:

- As thin as possible without punch-through

- Clearly (by construction) $\beta >> 1$ so we get CURRENT GAIN
- Why? (qualitatively). Draw excess charge in Base, think about what happens if I pull a small current from Base terminal (inject electrons).



- This is the tail wagging the dog!

Recap our simple models for P⁺NP bipolar operation:

1) Current continuity: $I_E = I_B + I_C$
2) When EB diode is forward biased ($V_{EB} > 0$), Emitter current I_E has two components:
   a) Holes it injects into the Base (I_{Ep})
   b) Electrons the n-type Base injects into it (I_{En})
3) Base current has two components:
   a) Electrons it draws from terminal to supply I_{En}
   b) Electrons it draws from terminal to recombine with injected holes (Q_B/τ_p)
4) Collector current is made up of holes it manages to sweep ("collect") from the ones injected by Emitter, minus those that have recombined in the Base, strictly speaking $I_C = I_{Ep} - Q_B/\tau_p$

- Is Collector current made up of any electrons?
- Does our current continuity assumption hold?
- When and what can we ignore to simplify our life?

- One more look at the equations for P⁺NP:

$$I_{Ep} = qA\frac{D_p}{W_B}\frac{n_i^2}{N_B}\left(e^{qV_{EB}/kT}-1\right)$$

$$I_{En} = qA\frac{D_{nE}}{W_E}\frac{n_i^2}{N_E}\left(e^{qV_{EB}/kT}-1\right)$$

$$I_{B,rec} = \frac{Q_{B,stored}}{\tau_p} = \frac{qAW_B}{2\tau_p}\frac{n_i^2}{N_B}\left(e^{qV_{EB}/kT}-1\right)$$

- Where, remember $L_p = (D_p\tau_p)^{1/2}$ for holes in the Base.
- How do we keep things straight?
  - Tip #1: Remember who is injecting what where (if it's into the Base, then use Base parameters like D_p, L_p W_B and N_B)
  - Tip #2: If the terminal is "short" use its width instead of the minority carrier diffusion length
  - Tip #3: $Q_{B,stored}$ is just the "area" under the stored charge "triangle" in the Base (1/2 * height * width…)
  - Tip #4: On notation, if it's unambiguous we don't need the extra E/B/C super/subscript (Base is the only n-type chunk here, so D_p must be for… minority holes in the Base!)
  - Tip #5: Remember the (e^x - 1) factor is what multiplies the equilibrium minority carrier concentration (e.g. n_i^2/N_B)

Practice problem: P+NP bipolar with $N_E=10^{18}$ cm^{-3} and $N_B=10^{17}$ cm^{-3}. The quasi-neutral region width in the emitter is 1 μm and 0.2 μm in the base. Use μ_n=1000 cm^2/Vs and μ_p=300 cm^2/Vs. The minority carrier lifetimes are 10 ns. Calculate the emitter efficiency, the base transport factor, and the current gain of this transistor biased in the forward active mode. Assume there is no recombination in the depletion regions. *(Note: are the emitter and base "short" or "long"?)*

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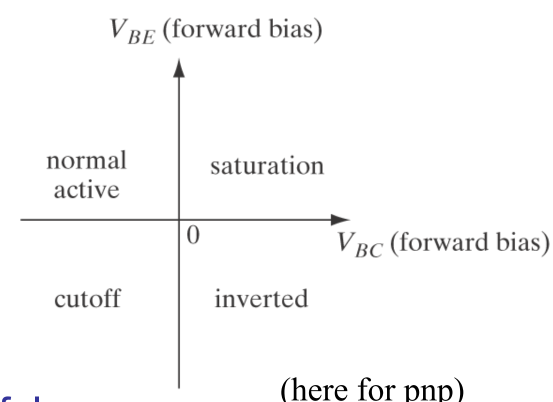
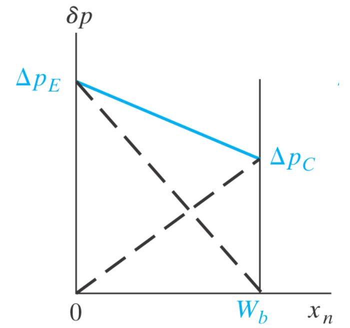
Other Modes of BJT Operation; Common-Emitter Gain

- **Read:** Online 5.3.2-5.3.4, skim Ch. 5.4 and 5.6
- So far we've studied BJT only in "forward active" mode (for PNP, V_{EB} >0 forward biased, V_{CB} < 0 reverse biased). Useful β = 50-300.
- **What about operation in other bias conditions?**



- "Inverted" mode: CB forward-biased, EB reverse-biased.
- "Cut-off" mode: both junctions reverse-biased. Negligible currents (~1 pA), nearly an open circuit → useful.

- "Saturation" mode: Both EB and CB junctions are forward-biased. Base is flooded with minority carriers, i.e. holes for a PNP.
  - No isolation, slow recovery, in practice → avoid.
  - But, interesting to study because it is a superposition of "forward" and "inverted" modes of operation



- Key observation: minority carrier diffusion equation is linear, so *all* BJT operation modes can be written as a *superposition* of the "normal active" and "inverted" modes → this is how SPICE models are put together

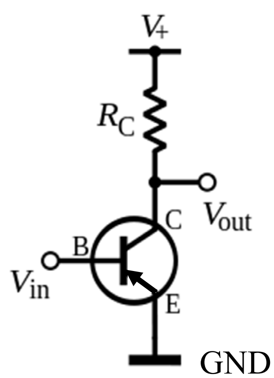
$$I_E = I_{Ep} + I_{En}$$

$$I_C = I_{Cp} + I_{Cn}$$

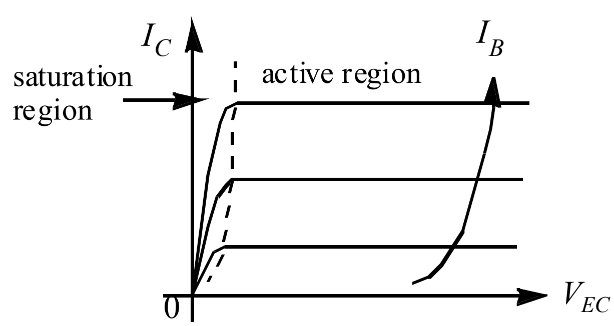
$$I_B = \frac{Q_p}{\tau_p} + (I_{En} - I_{Cn}) = I_{B,rec} + I_{B,inj}$$

(note that I_C and I_E can have either sign depending on voltages.)

- Ex: Common-Emitter configuration (voltage amplifier):

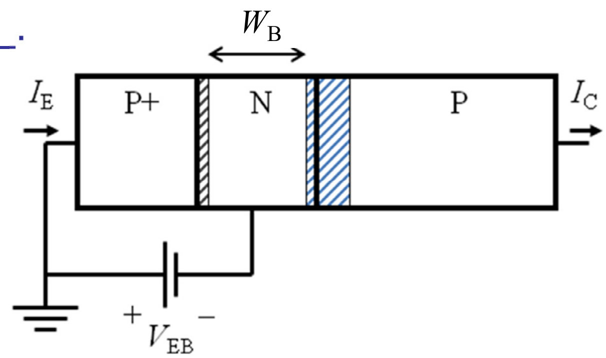


- Draw current-voltage diagram:

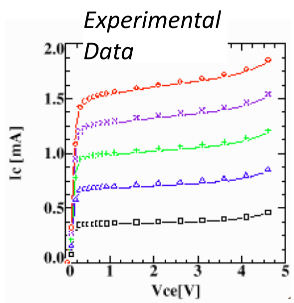


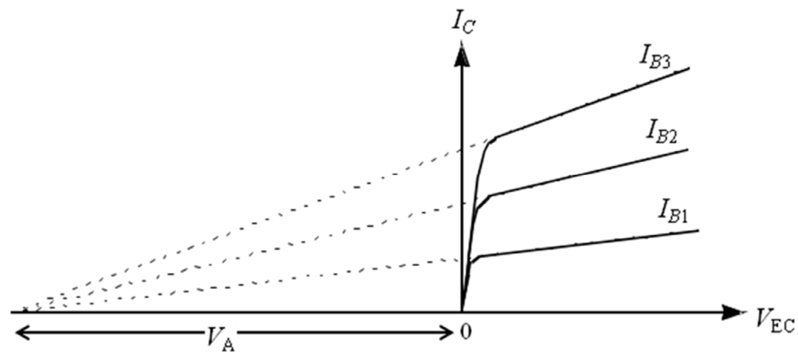
  - At low V_{EC} both CB and EB diodes are in ________________. Consequently the transistor is in ________________.
  - At higher V_{EC}, CB diode goes into deeper and deeper reverse bias, and EB stays forward-biased with roughly constant V_{EB} ~ _________.

- As the CB diode is pushed into deeper reverse bias, the CB depletion region ______________.



- This effectively modulates (decreases) the base width W_B
- Which also modulates (increases) the ______________.





- Ideally, we do not want the gain to change due to Base width modulation. During design, we have three options:
  1) Increase the Base width, W_B
  2) Increase the Base doping, N_B
  3) Decrease the Collector doping, N_C
- Which one is the most acceptable in practice?

- What if we really push V_{EC} until the transistor breaks?
  - Punch-through ($W_B \rightarrow 0$)
  - Avalanche breakdown