Columbia Engineering — The Fu Foundation School of Engineering and Applied Science

ELEN E3106/4106 Lecture 15

Introduction to BJTs

Outline

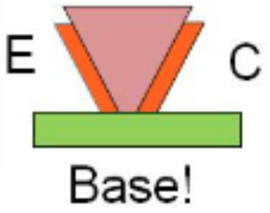
- Qualitative overview
- Theory of operation
- Energy band diagrams
- Electrostatics in Equilibrium

Assignments:
Reading: Streetman and Banerjee §7.1-7.2
Exam 2 this Tuesday Oct. 28th during class

BJT Intro

- B ipolar J unction T ransistor
  - Bipolar: both e^- and h^+ involved
  - Junction: p-n junctions are critical to its operation!





1947
Invention of the 1st transistor (Ge point contact)
Shockley, Bardeen, Brattain
Bell Labs

What do transistors do?

1. **Amplification:** a small signal (I or V, terminal #~~2~~ 3) can control large signal (usually I, flowing between terminal #1 and #~~3~~ 2)
   - Think of a tiny faucet controlling the amount of water flow through a giant hose!
2. **Switching:** the transistor can be turned on/off (memory, logic, other circuits)

- Two main types of transistors studied in E3106/4106:

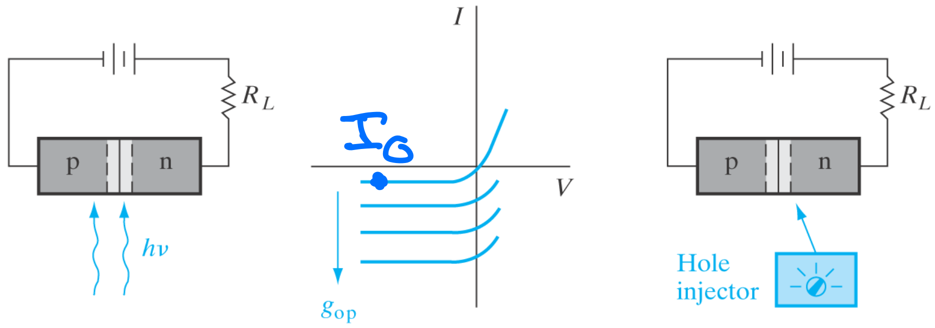
  1) BJT: small input current (faucet) controls large output current (hose) e.g. current-controlled current source

  2) Next unit: Field effect transistors (FET): small input voltage (faucet) controls large output current (hose) e.g. voltage-controlled current source

Sources: E. Pop ECE 340 Slides

BJT Advantages and Recap of p-n Diode

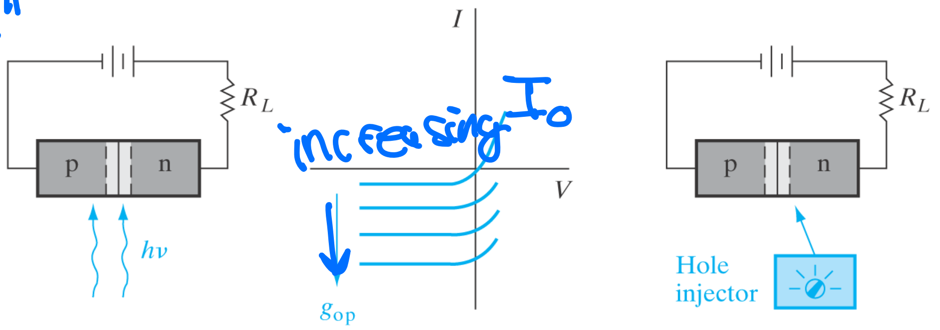
- Disadvantage: Current-controlled current sources always have some current flowing (power dissipation in the off-state)
  - Limits integration levels per chip
  - This is where FETs have an advantage
- BJTs have gradually been replaced by CMOS (FETs) in the past 30 years, especially for high-speed logic
- But, BJTs are better for have higher speed and gain
  - Better for analog circuits
- p-n diode with the lights on
  - Recall: In RB, the current with the lights off was *small* (I_0)
- When light is on, it creates EHPs in the SCR(W). Assuming L.L. injection, minority carriers are easily swept across by the E-field and injected into the other side, modulating the current.



Sources: ECE 340 Slides, Textbook

BJT Principle of Operation

- Takeaway of RB p-n diode under illumination: we can __increase__ the reverse current through the diode by __increasing__ the rate of EHP generation! (optically)
- Question: Is it possible to inject __minority carriers__ into the neighborhood of the junction electrically instead of optically?
- __Yes__! Consider a "hole injection device"
- If we can inject __carriers (holes)__ into n side, current will resemble optical generation effects
  - Current from n to p will depend on rate of injection and **not** __bias__



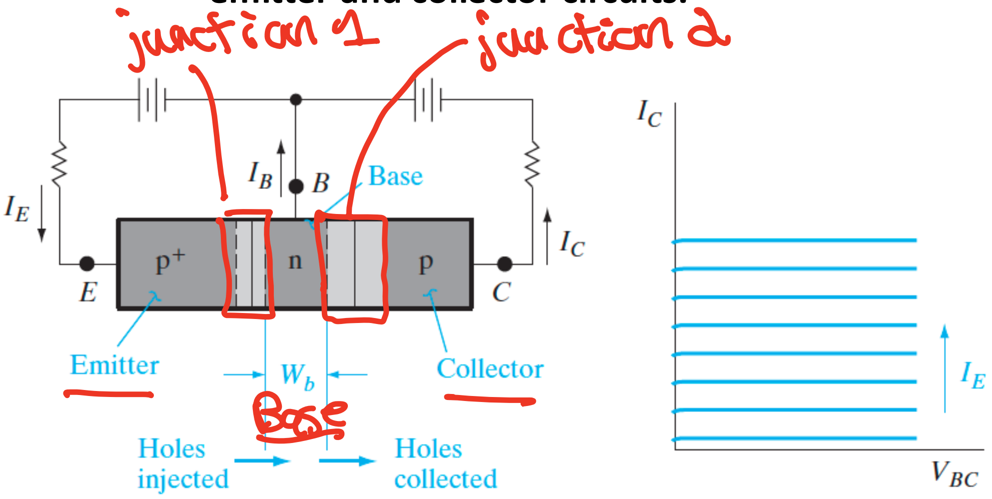
- What happens to the current if we increase the external load, R_L?

Sources: ECE 340 Slides, Textbook

BJT Principle of Operation

- What would be a convenient hole injection device?
  - A __FB__ p^+-n junction!
  - Recall: current due primarily to __h^+__ injected from p+ side into the n material
- If we make the __n-side__ of the RB p-n junction the same as the n-side of the FB p^+-n junction, we have a __p^+np__ BJT!
  - A BJT is basically __a back-to-back__ p-n junctions

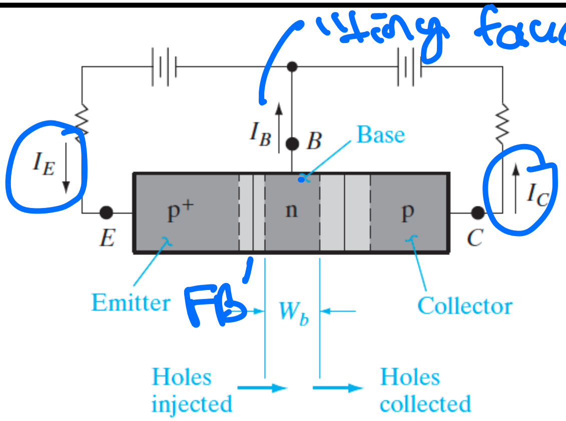
Common base **configuration: base electrode B is common to the emitter and collector circuits.**

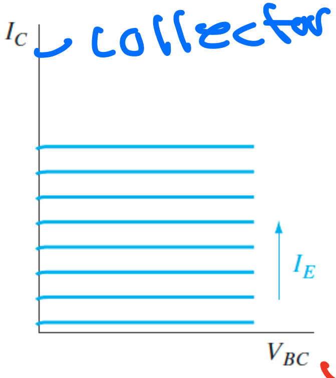


pnp BJT with FB emitter and RB collector and the I-V characteristics of the RB n-p junction (collector) as a function of emitter current.

Sources: ECE 340 Slides, Textbook

BJT Requirements for Efficient Hole Collection





- Emitter (FB junction) injects h+ into RB base-collector
- Requirement: For collect to collect most holes, the n base region W_b must be short compared to the hole diffusion length so carriers don't recombine before reaching collector! $W_b \ll$ L_p (we called this a narrow base diode!)
  - Recall: $L_p = \sqrt{D_p \tau_p}$

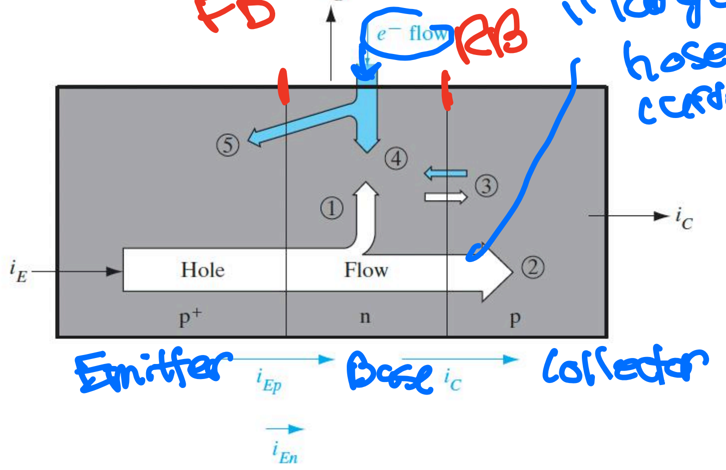
* W_b is l in Lecture 14

this junction RB so I_C independent of V_{BC}

- If so, when BJT is biased "on" then almost all injected holes are collected:
- $I_E \approx$ I_C are the "large" currents here (water passing through the hose)

Sources: ECE 340 Slides, Textbook

BJT Base Current

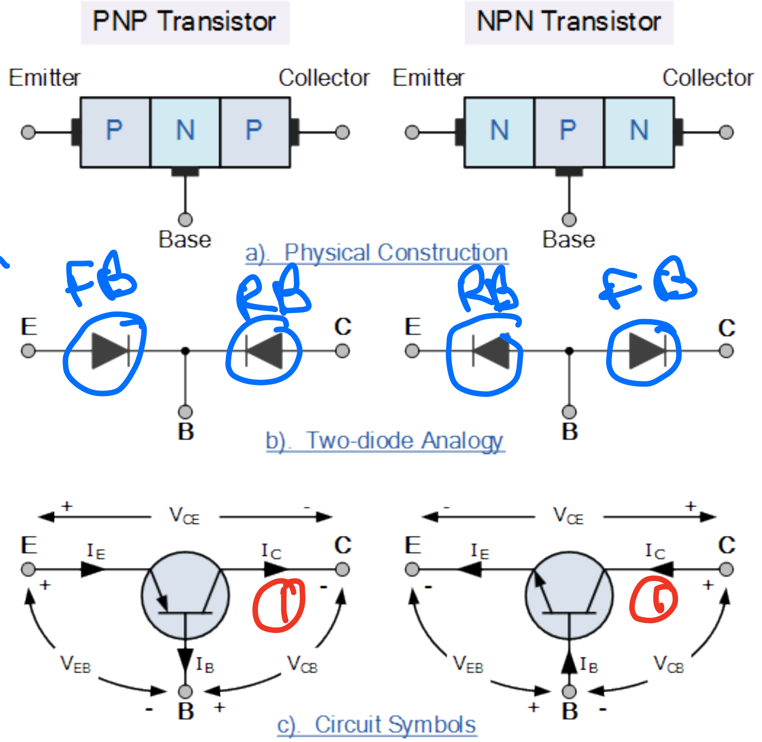


- But is there a base current __I_B__? Why? Yes!
- Recall: base is __n__-type in pnp
  - Some e- in the base will __recombine__ with injected holes
  - Some e- will be __injected__ from n to p+ in the FB emitter junction
  - Some __thermally generated__ e- from collector are swept into base at the RB collector junction (reduces I_B)
- Ideally, I_B is very __small__ so $I_E \approx I_C$
- In properly designed BJT, $I_C = IE - I_B$ $where$ $I_E \approx$ __100__ I_B

Sources: ECE 340 Slides, Textbook

BJT Symbols and Conventions

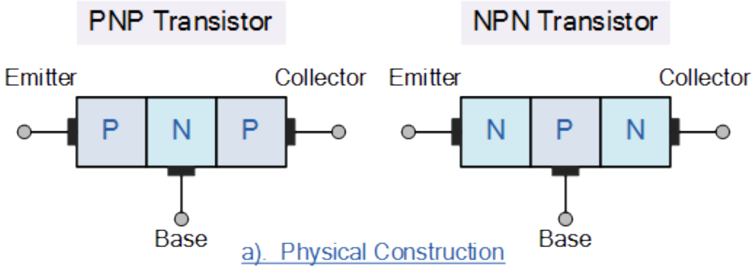
- Why does direction of arrow in symbol note? direction of current flow
- In pnp, current flows ______ from the emitter to the collector
- In npn, current flows ______ from the ~~emitter~~ collector to the emitter
- Easier to study pnp because current flows in direction of ______ hole movement
- But npn is similar, we can just reverse the roles of e- and h+ from our pnp discussion
- Which is faster? Why? npn, $\mu_n >> \mu_p$



Sources: https://www.electronics-tutorials.ws/transistor/tran_1.html

Transistor Terminals

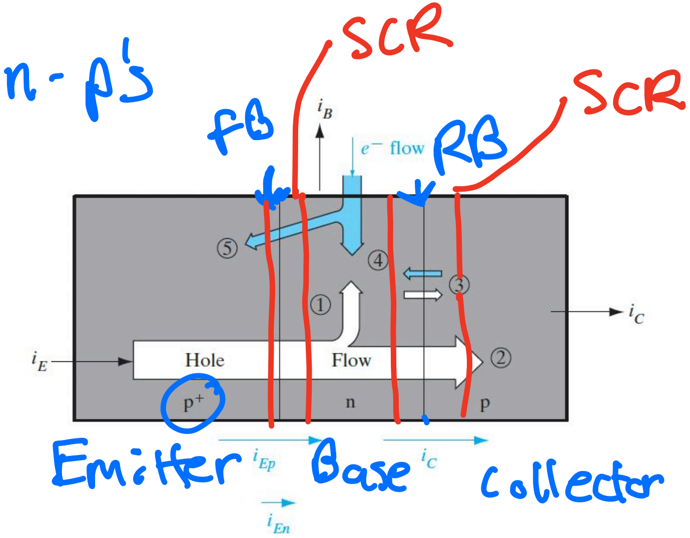
- Terminal: Any externally available point of connection (M-S contact)
- Recall: M-S contacts can be thought of as infinite carrier sources/sinks
- How many terminals does a transistor have? 3
- Terminal 1: brings current into the transistor
  - BJT: emitter, MOSFET: source
- Terminal 2: carriers current out
  - BJT: Collector, MOSFET: drain
- Terminal 3: acts as a handle to control the current flow (input terminal)
  - BJT: Base, MOSFET: gate



Sources: https://www.electronics-tutorials.ws/transistor/tran_1.html, Amazon

BJT Simple Analysis: Performance Parameters

*ex: for p-n-p's



- Base transport factor: $B = I_C / I_{E,majority}$
  - Fraction of h+ which make it across the base to collector
- Emitter injection efficiency: $\gamma = \frac{I_{E,majority}}{I_{E,majority}+I_{E,minority}}$
  - Ratio of current due to h+ to total current
- Current transfer ratio: $\alpha = B\gamma = \frac{BI_{E,majority}}{I_{E,majority}+I_{E,minority}} = \frac{I_C}{I_E} = \frac{B}{1+B}$
  - Represents the emitter-to-collector current amplification
- Base-to-collector current amplification factor: $\beta = \frac{I_C}{I_B} = \frac{B\gamma}{1-B\gamma} = \frac{\alpha}{1-\alpha}$ → $I_C = \beta I_B$
- Applies to DC and small-signal AC (low-frequency) operation
- We are assuming no recombination in the SCRs
- What have we found? I_C is controlled by I_B!
- A small increase in I_B results in a much larger increase in I_C. The transistor amplifies the small base current into a much larger collector current, which is why BJTs are used as current amplifiers!
- I_E is related to both the base current and the collector current but is not the controlling factor in BJT behavior. Instead, it is the sum of the two currents and is slightly larger than I_C!

*i - typical AC signal (time-varying)

*I - DC or steady-state

Sources: ECE 340 Slides, Textbook

BJT Band Diagram

pnp:

- In equilibrium:

- In "normal" mode:
  - E-B junction: *Forward biased*
    - Recall, rate of injection $\alpha = \frac{I_C}{I_E}$
  - C-B junction: *Reverse biased*

exponential increase in FB

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

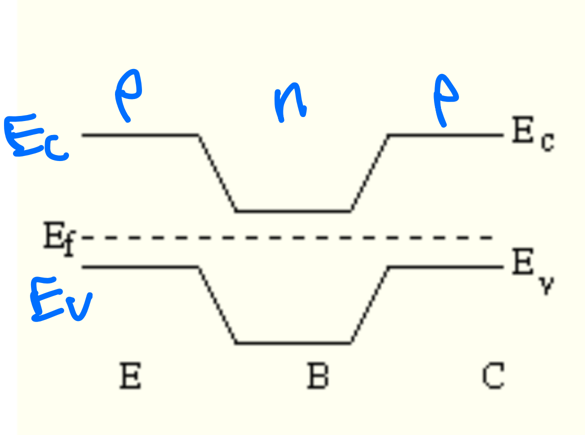


Figure A

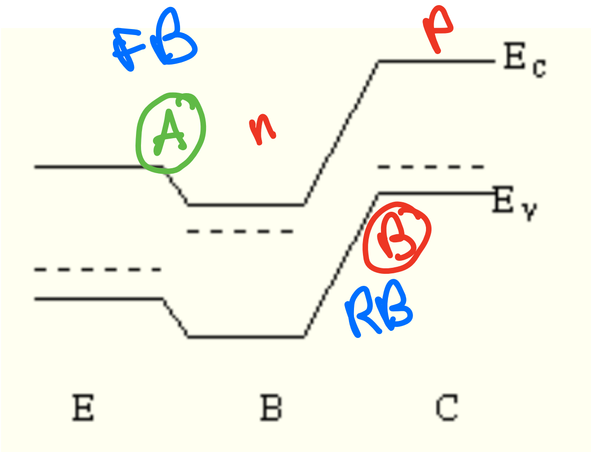
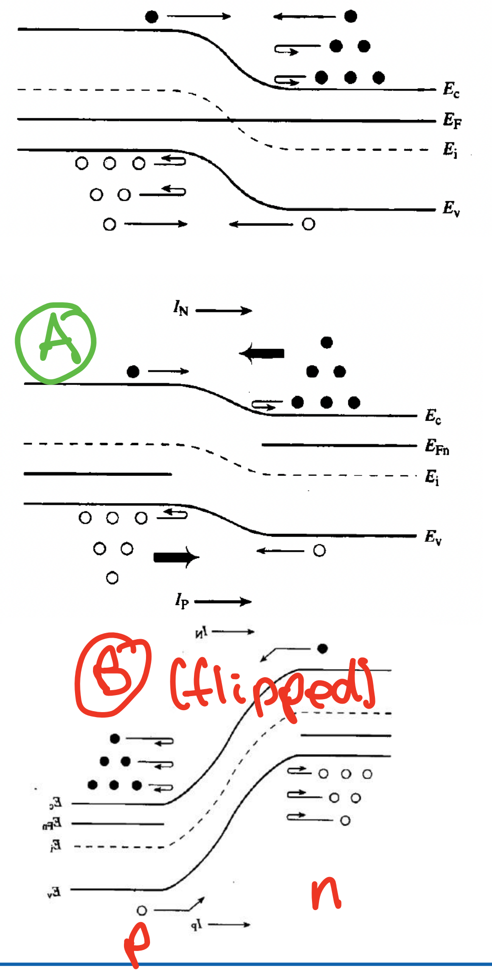


Figure B

Recall our equilibrium, FB, and RB diagrams for a single p-n junction:

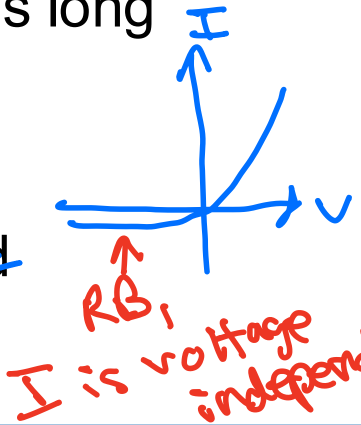


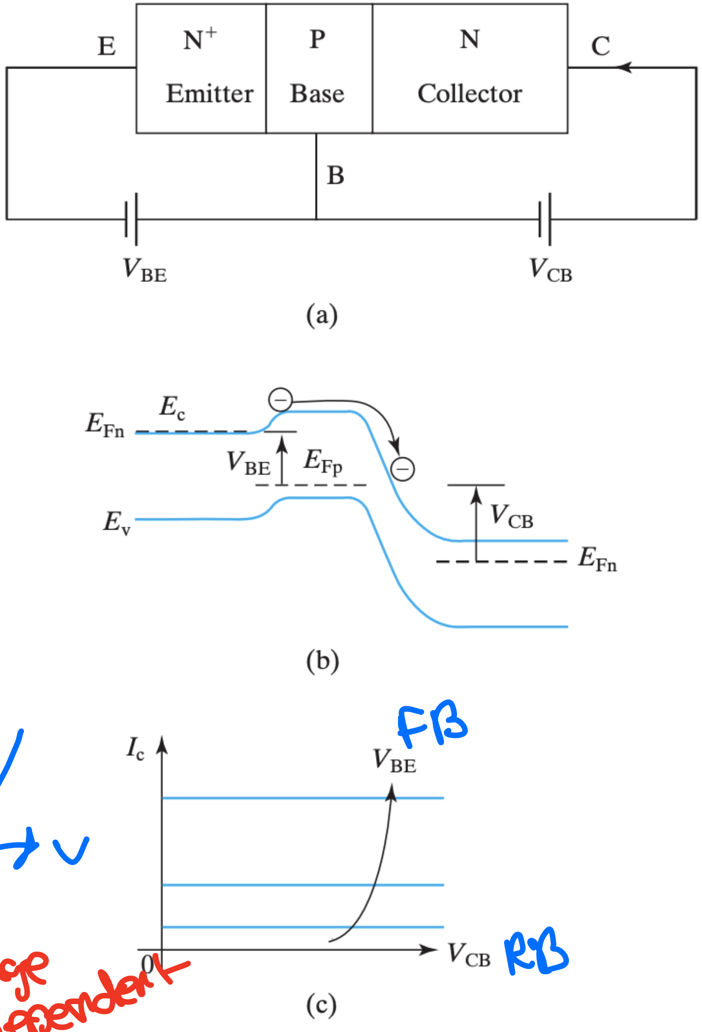
Sources: The Ohio State University

BJT Band Diagram

npn in "normal" mode:

- When the base–emitter junction is FB, e- are injected into the <u>lightly doped</u> base
- e- <u>diffuse</u> across the narrow base to RB base–collector junction, reach edge of the <u>W</u>, and get swept into the collector
- I_C is essentially independent of V_{CB}, as long as V_{CB} is <u>RB</u> (or small FB)
- I_C is instead determined by rate of e- injection from the <u>emitter</u> (e.g. V_{BE} ~~and~~ + <u>FB</u>)

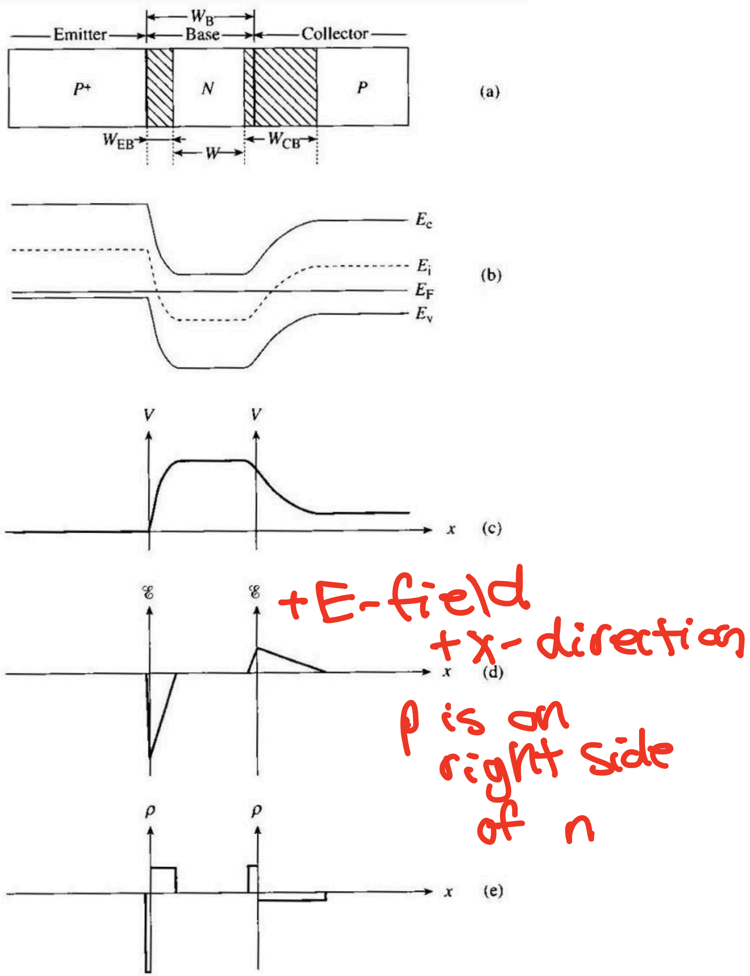




Sources: ECE 340 Slides, Textbook

BJT "Big Three"

- Let's again consider the BJT as two independent p-n junctions
- In equilibrium
  - Electrostatic potential:
  - Electric field:
  - Charge density:
- In this example, $N_{a,E} \gg N_{d,B} > N_{a,C}$



Sources: E. Pop ECE 340 Slides, Korea University Photonics Laboratory: http://contents.kocw.or.kr/KOCW/document/2015/korea_sejong/youjonghoon1/04.pdf