# Lecture 4:
# Heterojunction Bipolar Transistors (HBTs)

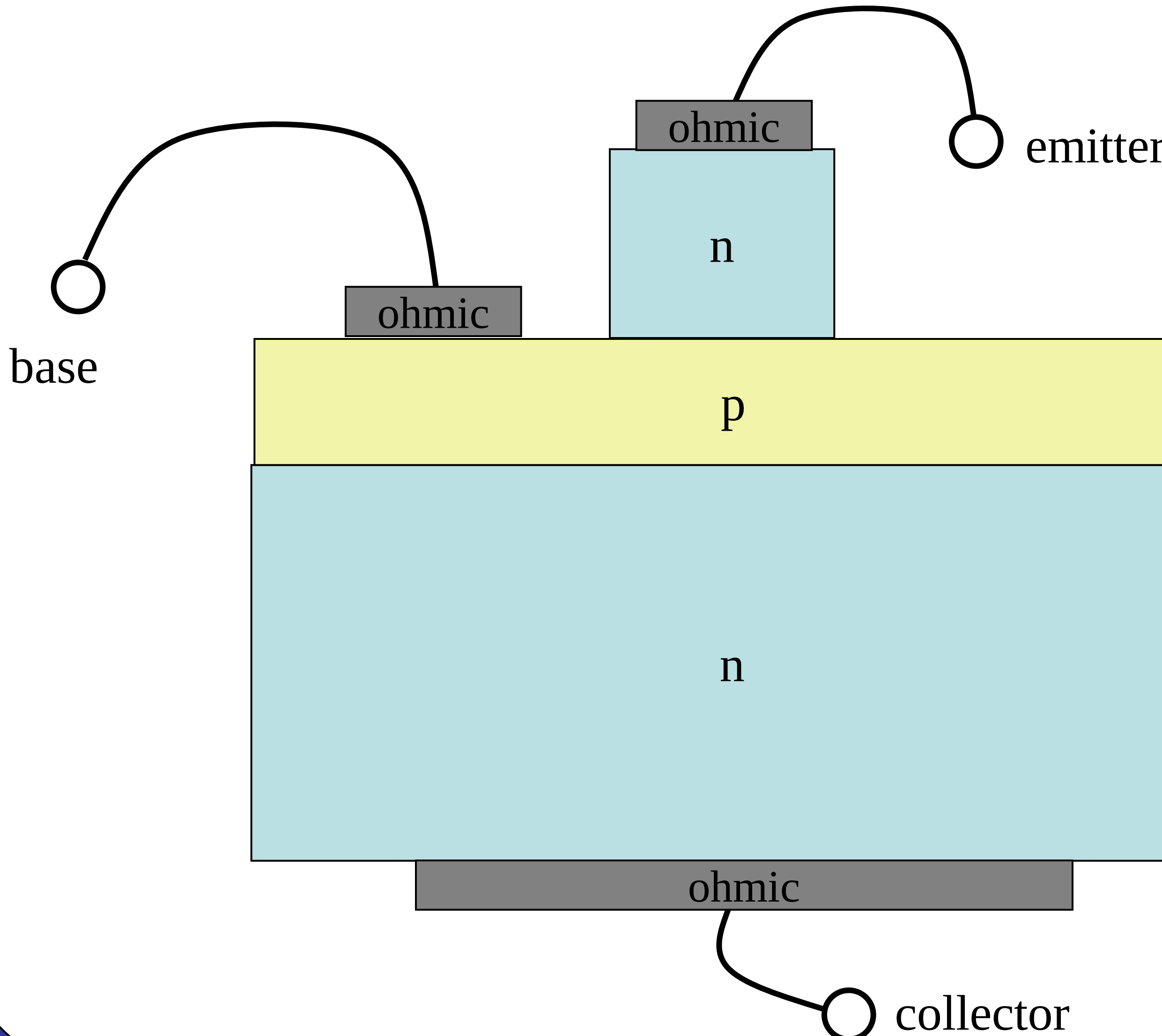
Bipolar means both electrons, holes participate in the device.

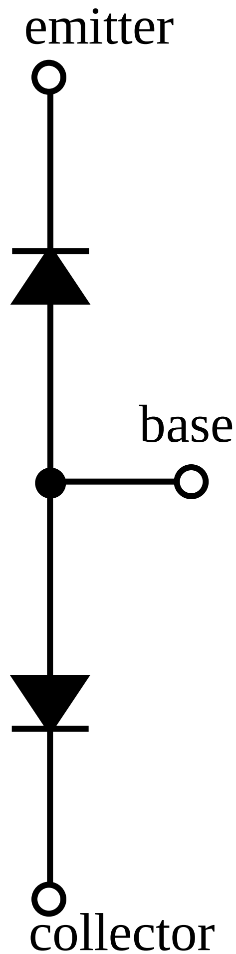
(In contrast, FET is unipolar.)

# Outline for today

- n-p-n homojunction band diagrams
- n-p-n DC I-V curves, etc.
- DC circuit models
- Why are we doing this? YOU, the designer will need to know how different transistor geometries translate into different effective circuit elements.

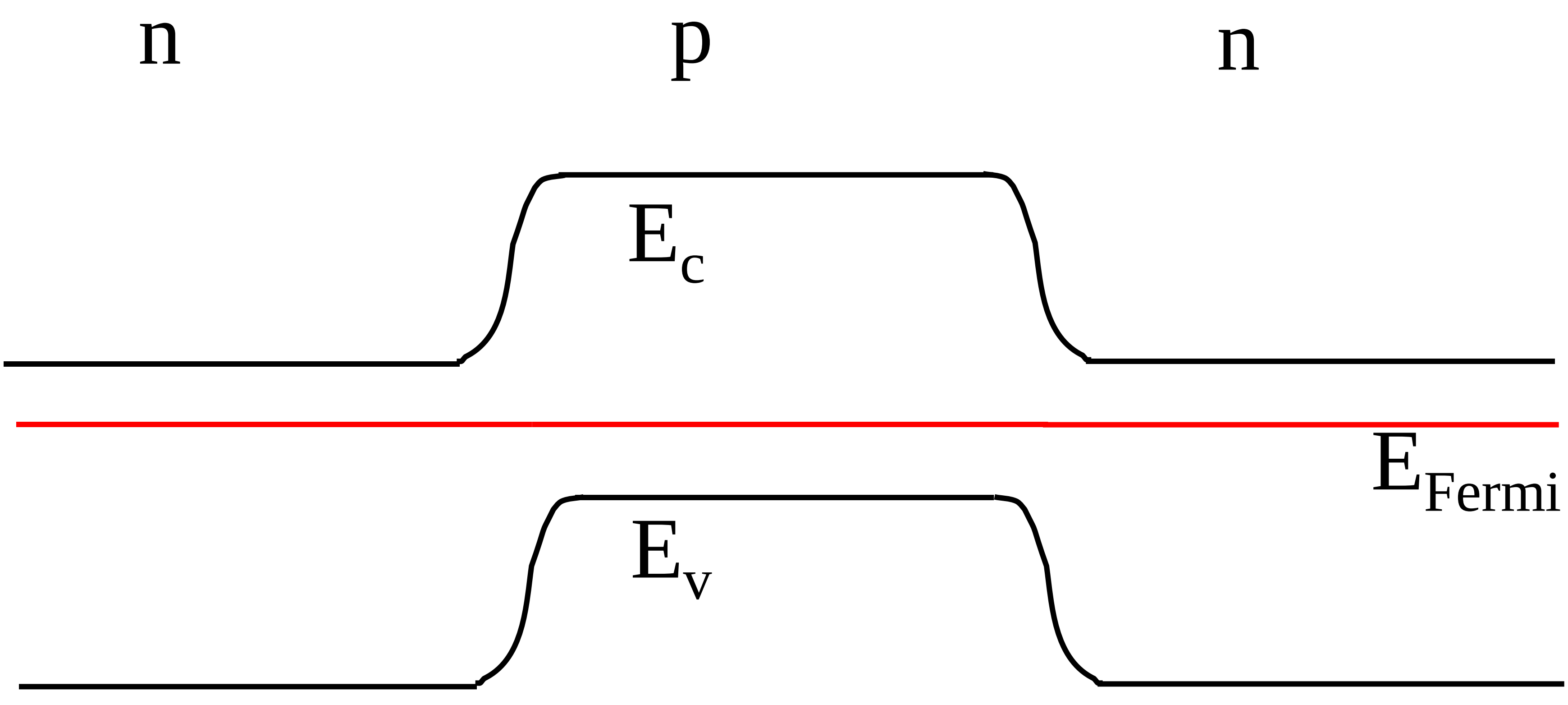
# n-p-n geometry




circuit only
if base LONG

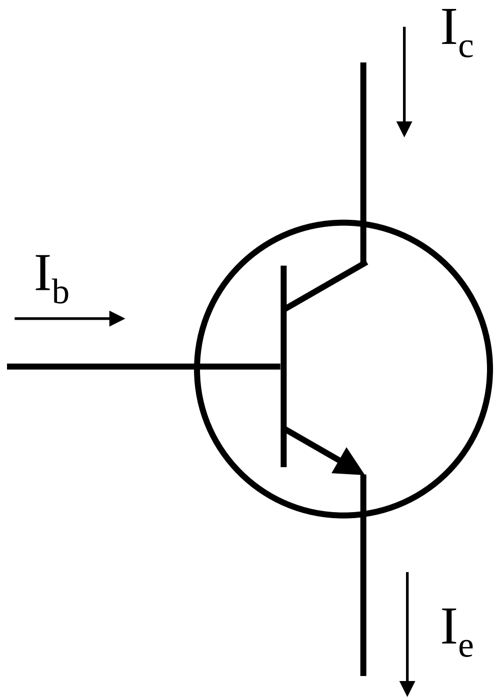
# n-p-n junction at zero bias



# Bias conditions

| Mode | E-B | C-B |
|---|---|---|
| Normal active | forward | reverse |
| saturation | forward | forward |
| cutoff | reverse | reverse |

# "Normal active" bias




- E-B forward bias ($V_b$>$V_e$)
- C-B reverse bias ($V_c$>$V_b$)
- $I_{ce}$ = 100 $I_{be}$=$\beta I_{be}$

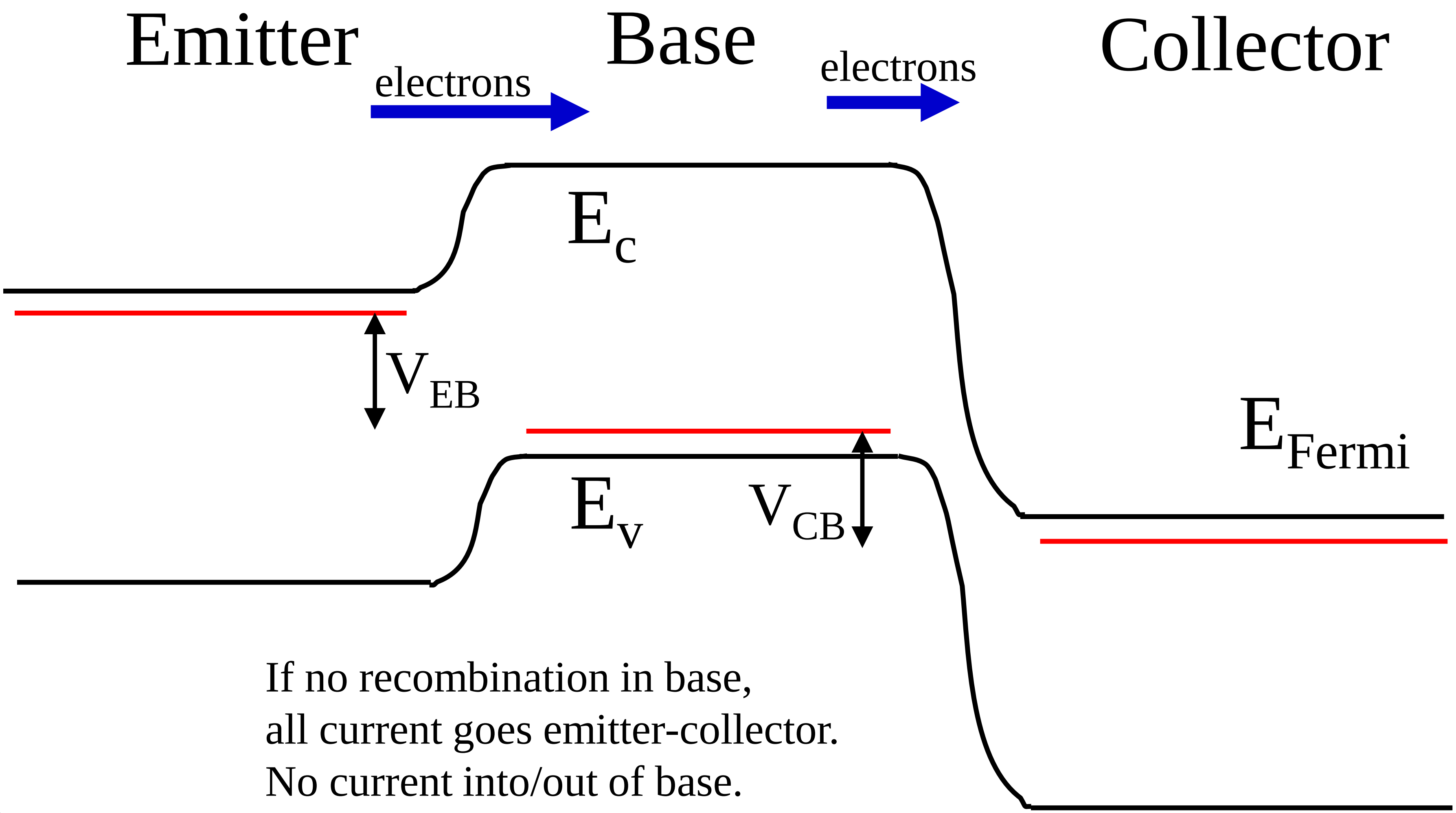
All of chapter 3 is about calculating β.

# Many current components

- Electron drift E-B
- Electron diffusion E-B
- Hole drift E-B
- Hole diffusion E-B
- Electron drift C-B
- Electron diffusion C-B
- Hole drift C-B
- Hole diffusion C-B

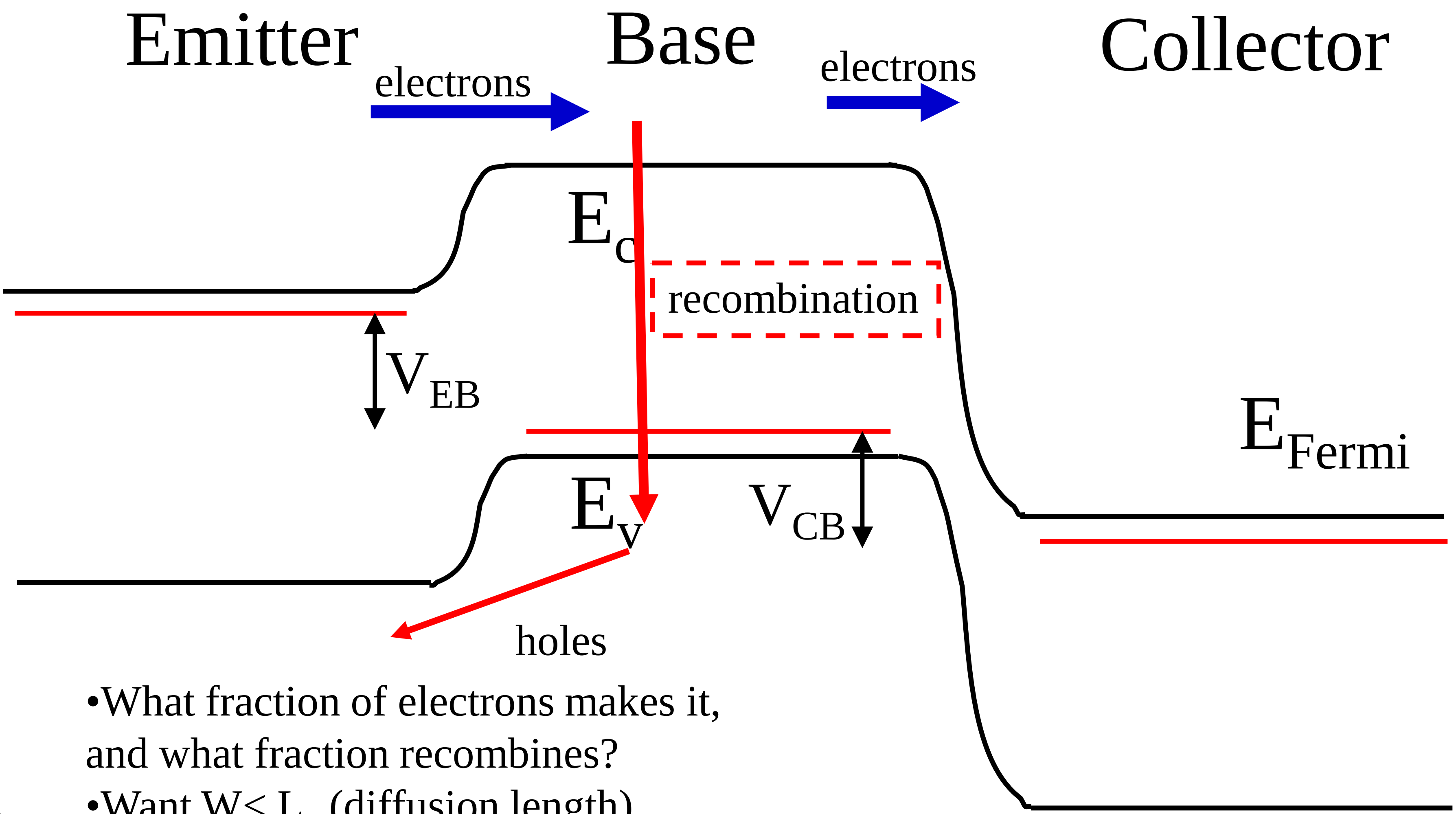
concentrate on these components, since they are the largest (Discuss why others small.)

# “Normal active” band diagram



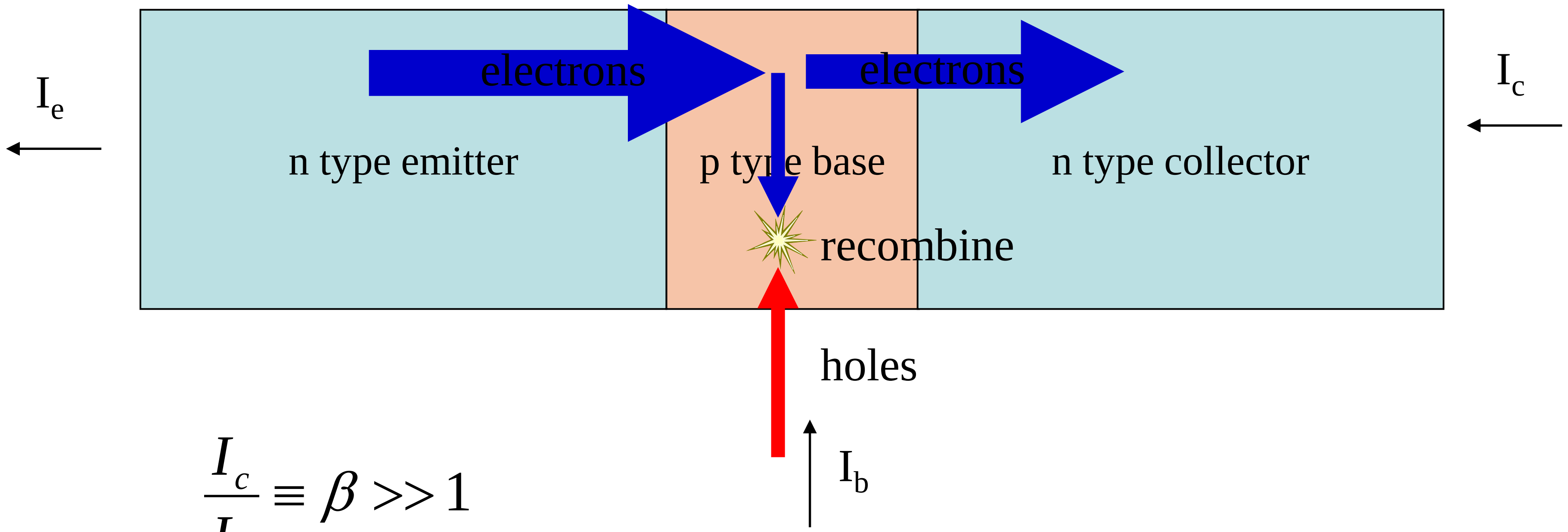

If no recombination in base,
all current goes emitter-collector.
No current into/out of base.

# "Normal active" band diagram




- What fraction of electrons makes it, and what fraction recombines?
- Want W< $L_n$ (diffusion length)
- Holes from B-E cause base current.

# “Normal active” schematic

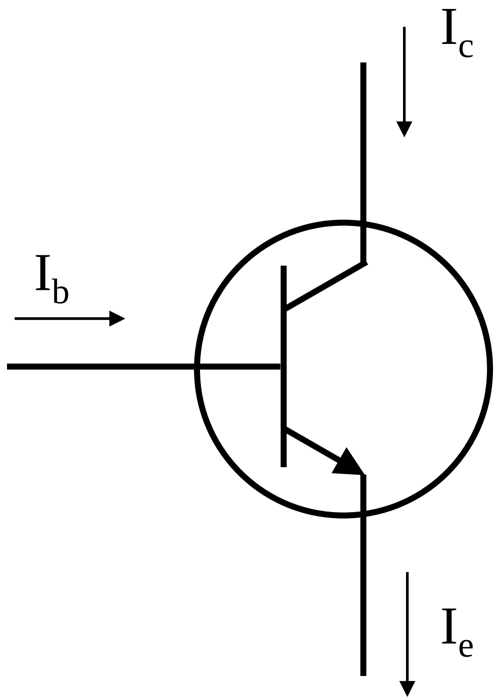



$$\frac{I_c}{I_b} \equiv \beta >> 1$$

$$\frac{I_c}{I_b} \approx \frac{\tau_n}{\tau_t}$$

$\tau_t \equiv$ transit time (discuss druken man analogy)

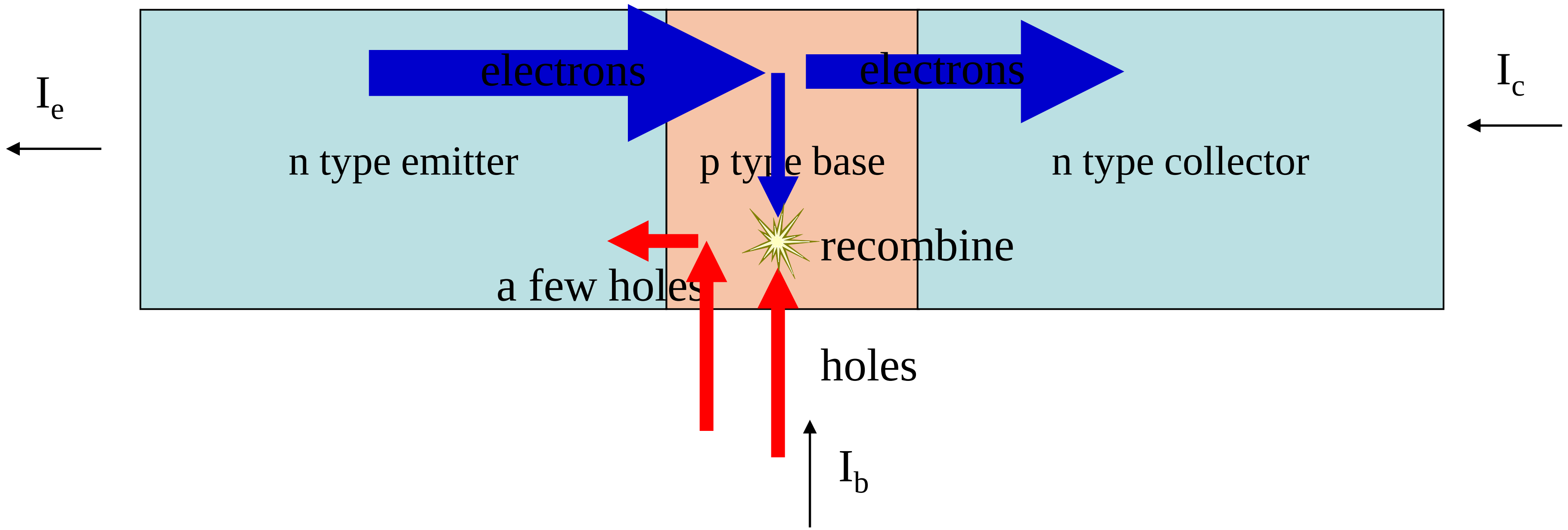
# “Normal active” current gain




$$\frac{I_c}{I_b} \equiv \beta >> 1$$

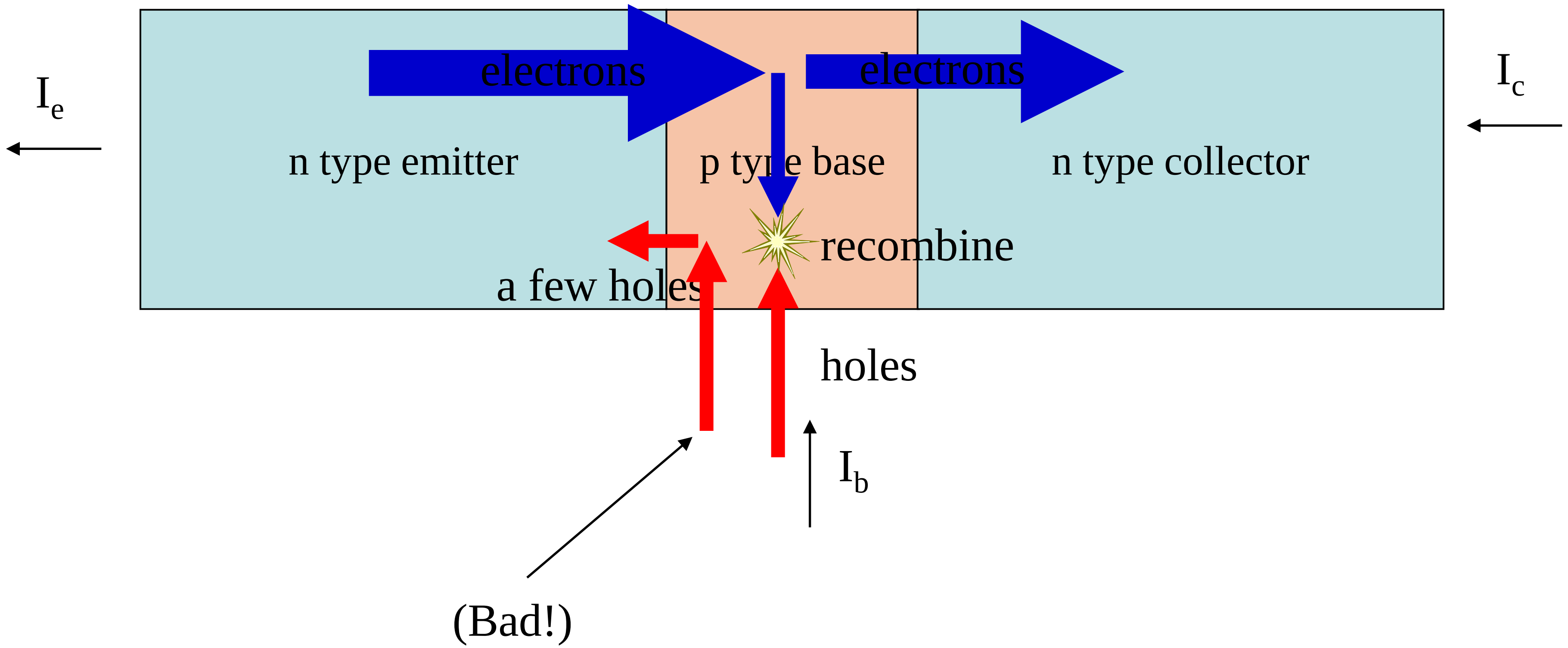
That is simplest circuit model. It just gets more complicated from here!

# “Normal active” schematic



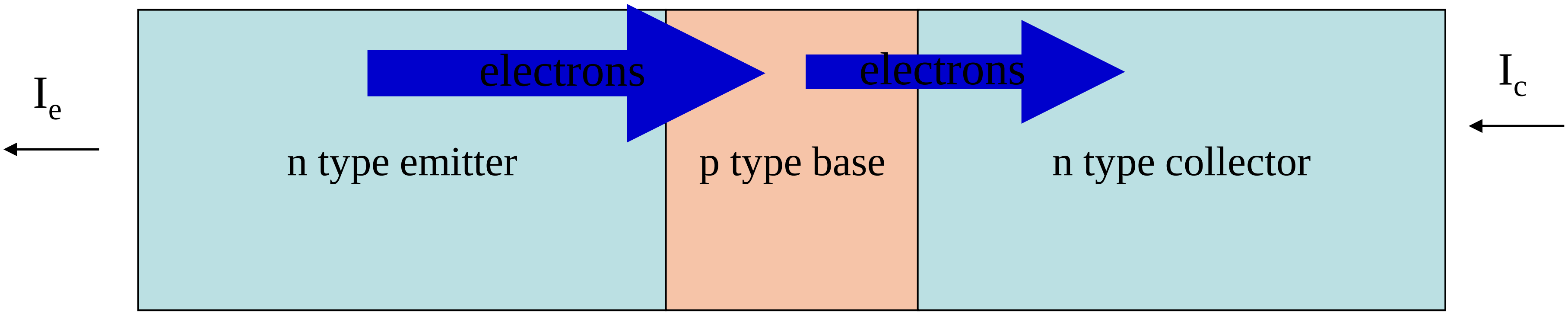

Goal: Find relationship between $I_b$, $I_c$

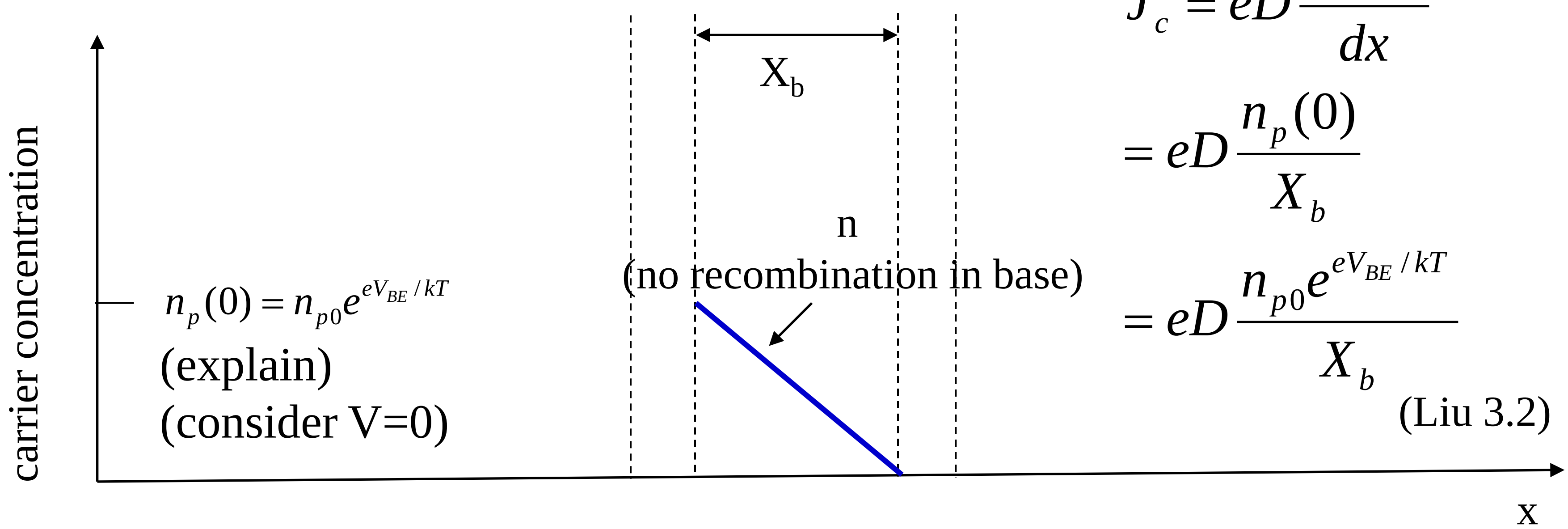
# “Normal active” schematic




- Want low p-type doping.
- Can show need n>p
- But n>p bad for base resistance (speed)
- Solution later: heterojunctions block p injection into emitter
- HBTs can have p>n good for speed

# "Normal active" schematic




$n_p(0) = n_{p0} e^{eV_{BE}/kT}$
(explain)
(consider V=0)

$$J_c = eD \frac{dn(x)}{dx}$$

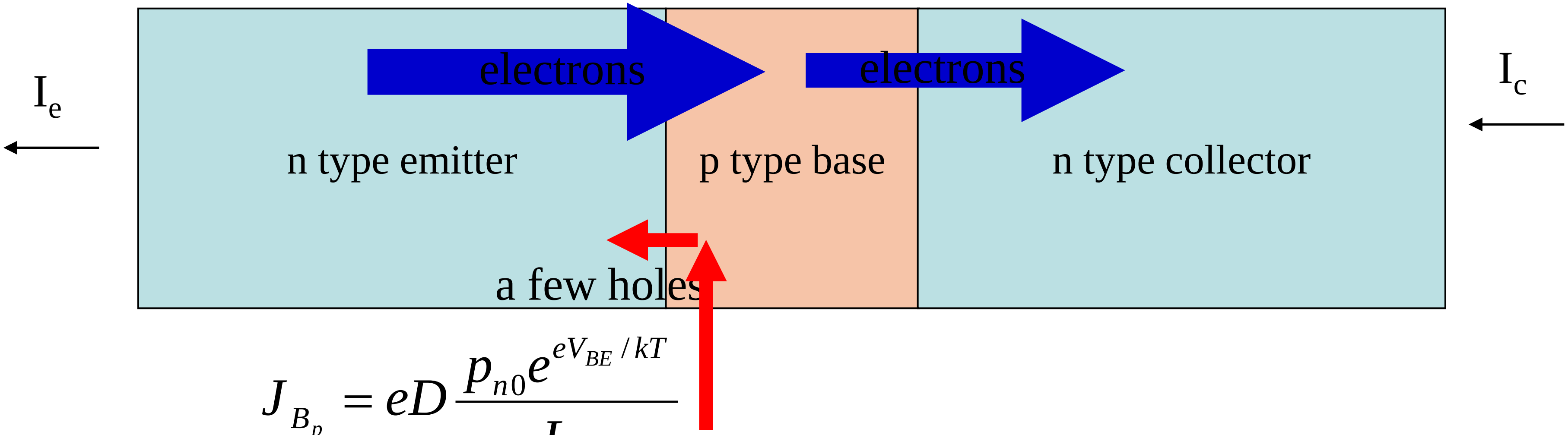
$$= eD \frac{n_p(0)}{X_b}$$

$$= eD \frac{n_{p0} e^{eV_{BE}/kT}}{X_b}$$

(Liu 3.2)

Discuss J vs. I. Discuss line vs. tanh.

# “Normal active” schematic



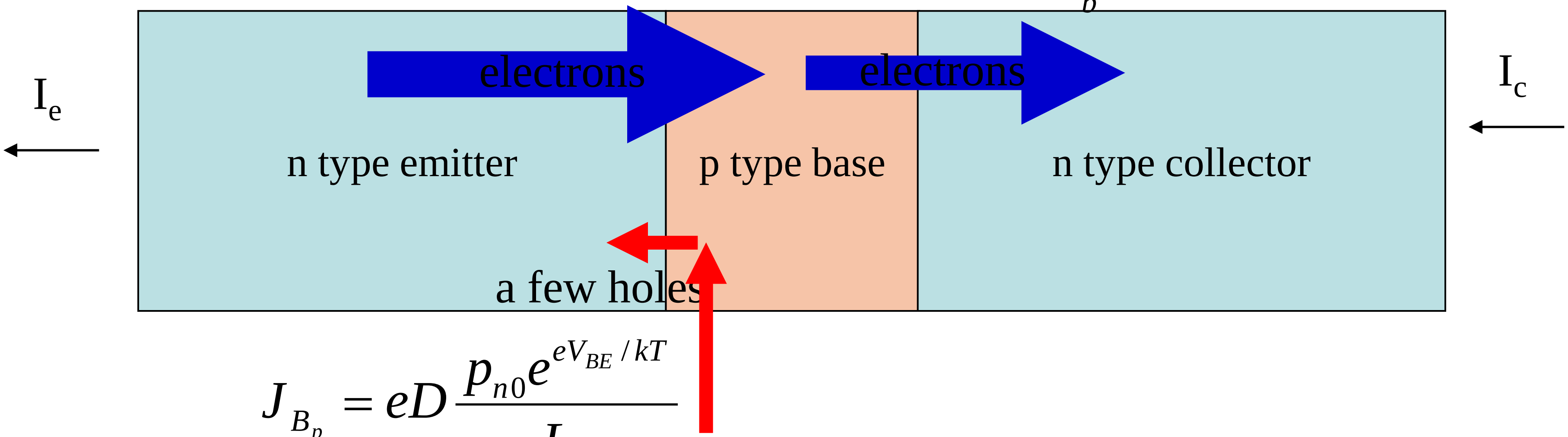

$$J_{B_p} = eD\frac{p_{n0}e^{eV_{BE}/kT}}{L_p}$$

(explain like HW#1)

Liu equation 3.1

# "Normal active" schematic

$$J_c = eD\frac{n_{p0}e^{eV_{BE}/kT}}{X_b}$$




$$J_{B_p} = eD\frac{p_{n0}e^{eV_{BE}/kT}}{L_p}$$

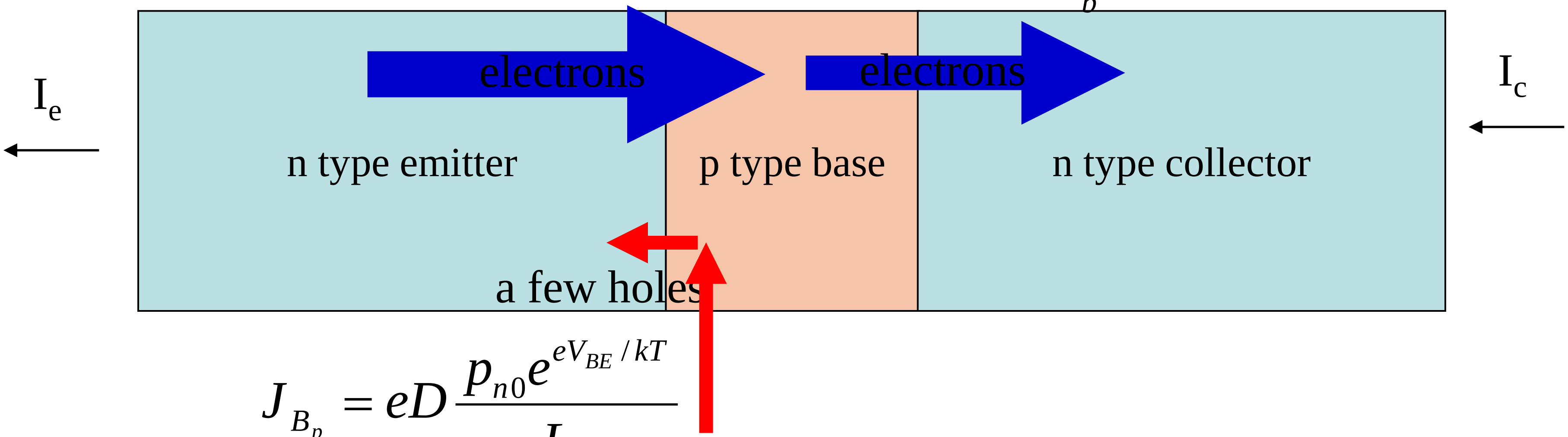
$$\frac{I_c}{I_b} \equiv \beta = \frac{eD\frac{n_{p0}e^{eV_{BE}/kT}}{X_b}}{eD\frac{p_{n0}e^{eV_{BE}/kT}}{L_p}} = \frac{\frac{n_{p0}}{X_b}}{\frac{p_{n0}}{L_p}} = \frac{n_{p0}}{p_{n0}}\frac{L_p}{X_b} ??? >> 1$$

$$Need \;\; n_{p0} >> p_{n0}$$

Bad for base resistance. Bad for E-B capacitance. So bad for speed.

# “Normal active” HBT

$$J_c = eD\frac{n_{p0}e^{eV_{BE}/kT}}{X_b}$$




$$J_{B_p} = eD\frac{p_{n0}e^{eV_{BE}/kT}}{L_p}$$

Holes exponentially suppressed if emitter is wider gap. (Graded.)

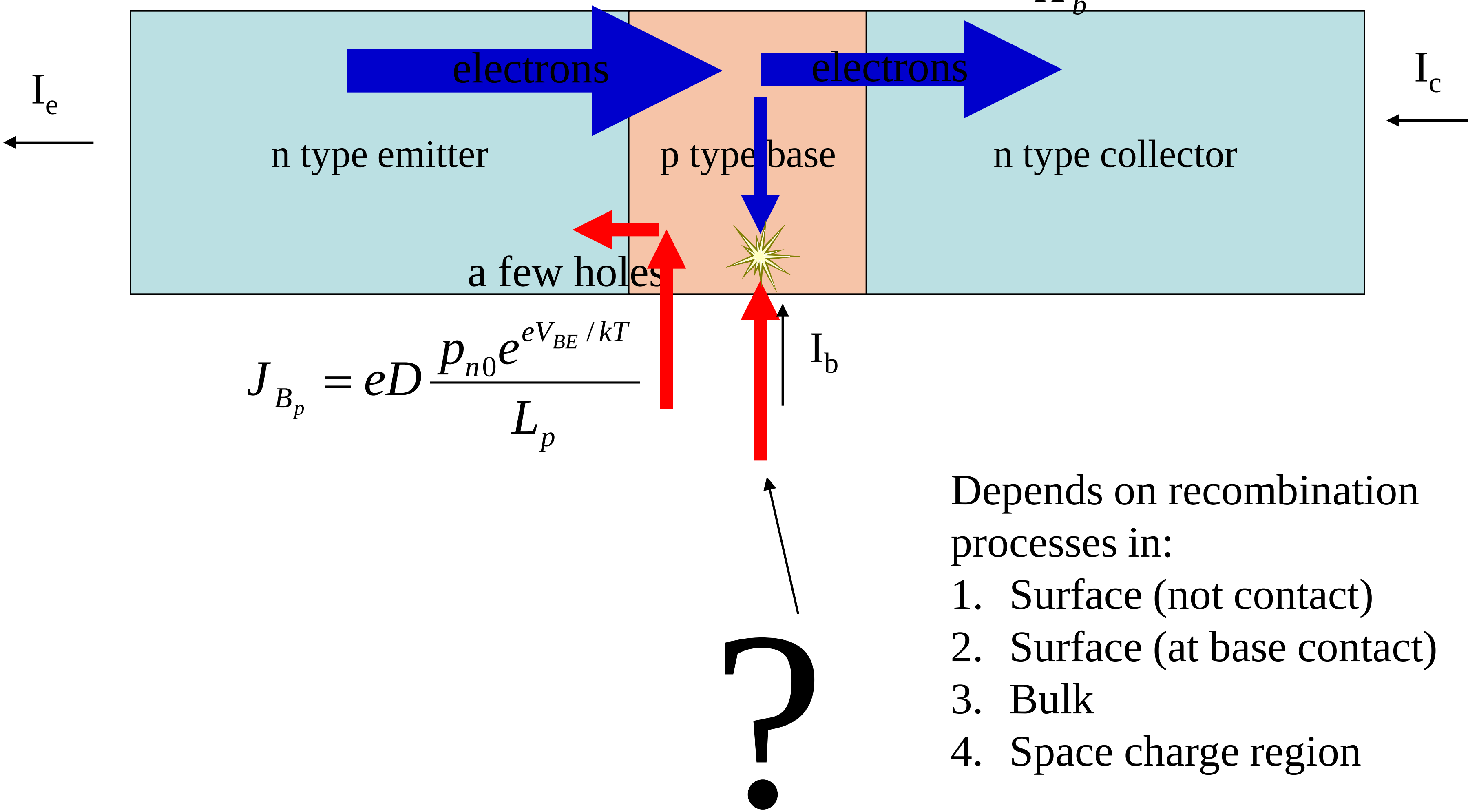
$$\frac{I_c}{I_b} \equiv \frac{n_{p0}}{p_{n0}}\frac{L_p}{X_b}e^{\Delta E_g/kT} >> 1$$

$$Don't\ \text{need}\ \ n_{p0} >> p_{n0}$$

Good for speed. Claims of 1 THz $f_T$ in literature.

# “Normal active” schematic

$$J_c = eD\frac{n_{p0}e^{eV_{BE}/kT}}{X_b}$$




$$J_{B_p} = eD\frac{p_{n0}e^{eV_{BE}/kT}}{L_p}$$

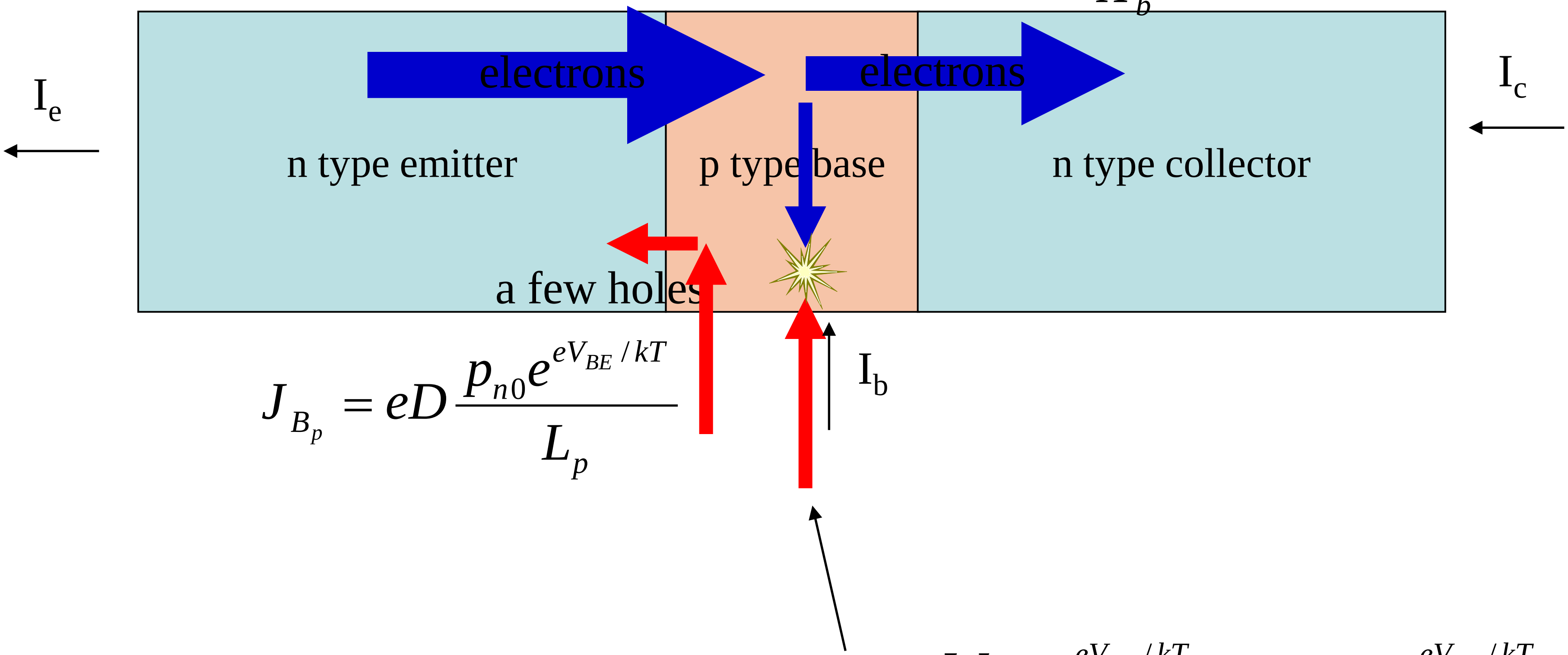
Depends on recombination processes in:

1. Surface (not contact)
2. Surface (at base contact)
3. Bulk
4. Space charge region

Try to minimize 1,2,4.

# "Normal active" schematic

$$J_c = eD\frac{n_{p0}e^{eV_{BE}/kT}}{X_b}$$

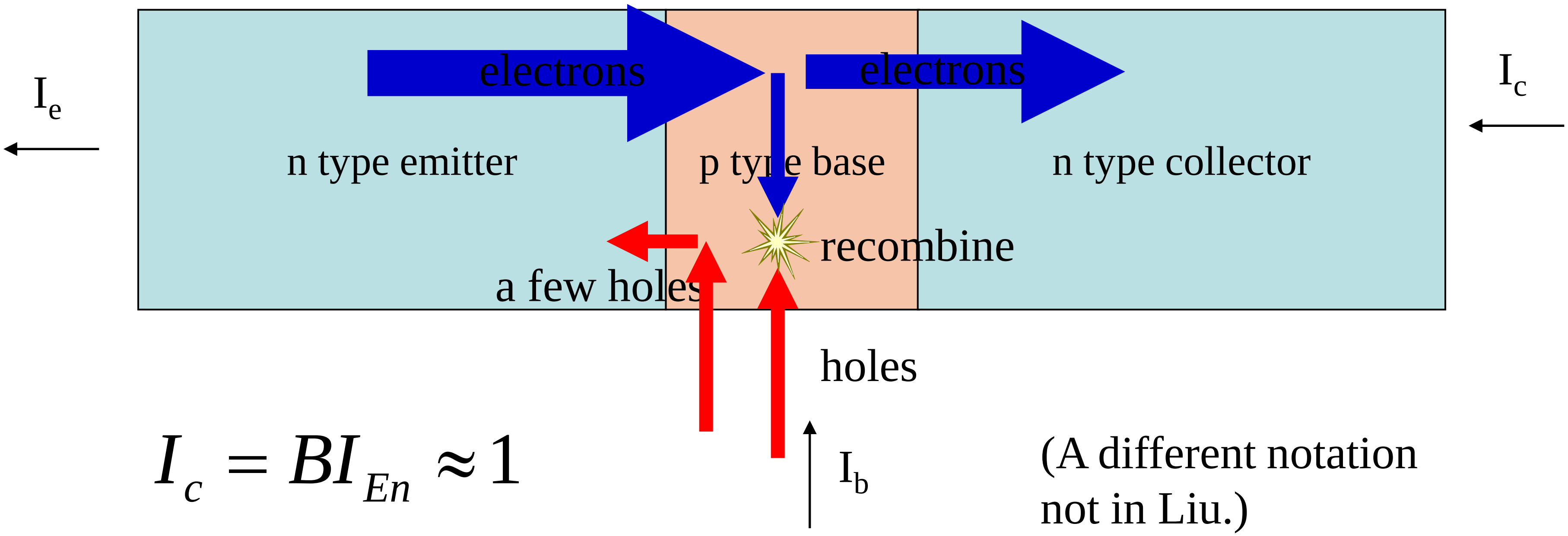



$$J_{B_p} = eD\frac{p_{n0}e^{eV_{BE}/kT}}{L_p}$$

$$J_{Brec.} = e\frac{Wn_{p0}e^{eV_{BE}/kT}}{2\tau_B} = eD\frac{n_{p0}e^{eV_{BE}/kT}}{X_B}$$

How to calculate:
Don't use line for n(x) but tanh.
dn/dx em. – dn/dx coll = base curr.
Explain on board. Will be HW#3.

# “Normal active” schematic




$$I_c = BI_{En} \approx 1$$

(A different notation not in Liu.)

$$\gamma \equiv \frac{I_{En}}{I_{Ep} + I_{En}} \approx 1$$

$$\frac{I_c}{I_E} = \frac{I_c}{I_{Ep} + I_{En}} = \frac{BI_{En}}{I_{Ep} + I_{En}} = \gamma B \equiv \alpha \approx 1$$

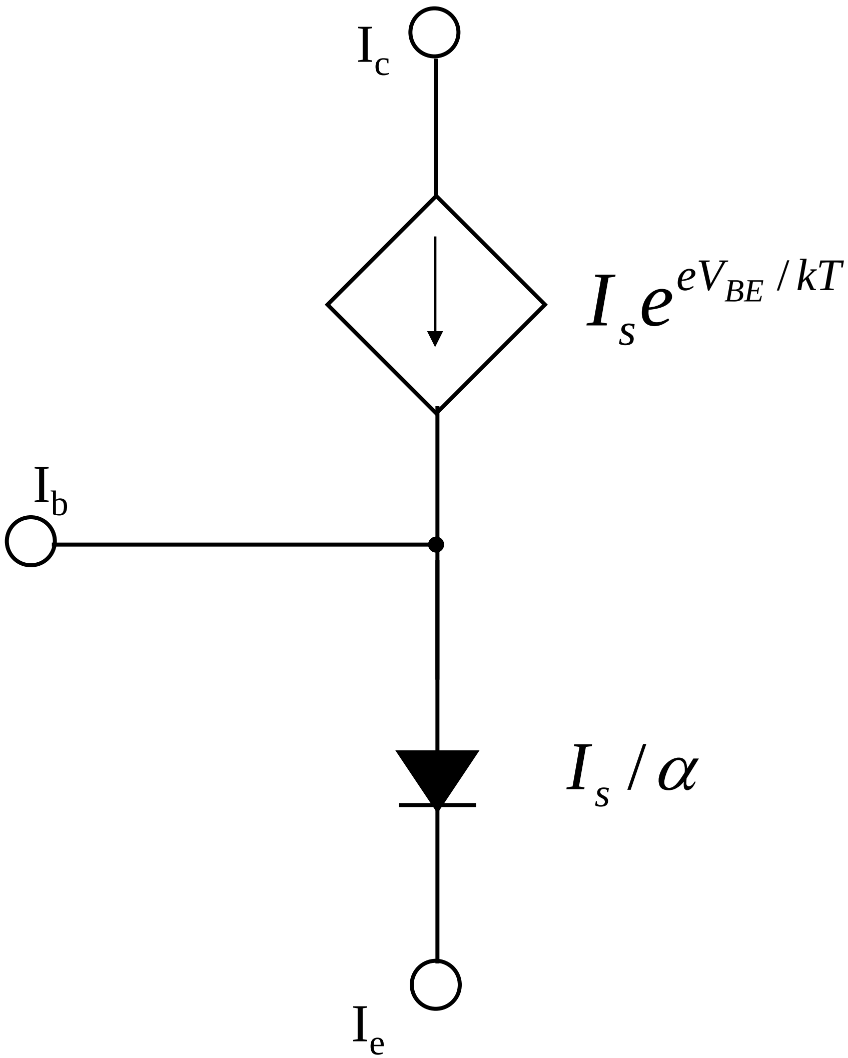
$$I_b = I_{Ep} + (1 - B) I_{En}$$

$$\frac{I_c}{I_b} = \frac{BI_{En}}{I_{Ep} + (1 - B) I_{En}} = \frac{\alpha}{1 - \alpha} \equiv \beta >> 1$$

# Complications

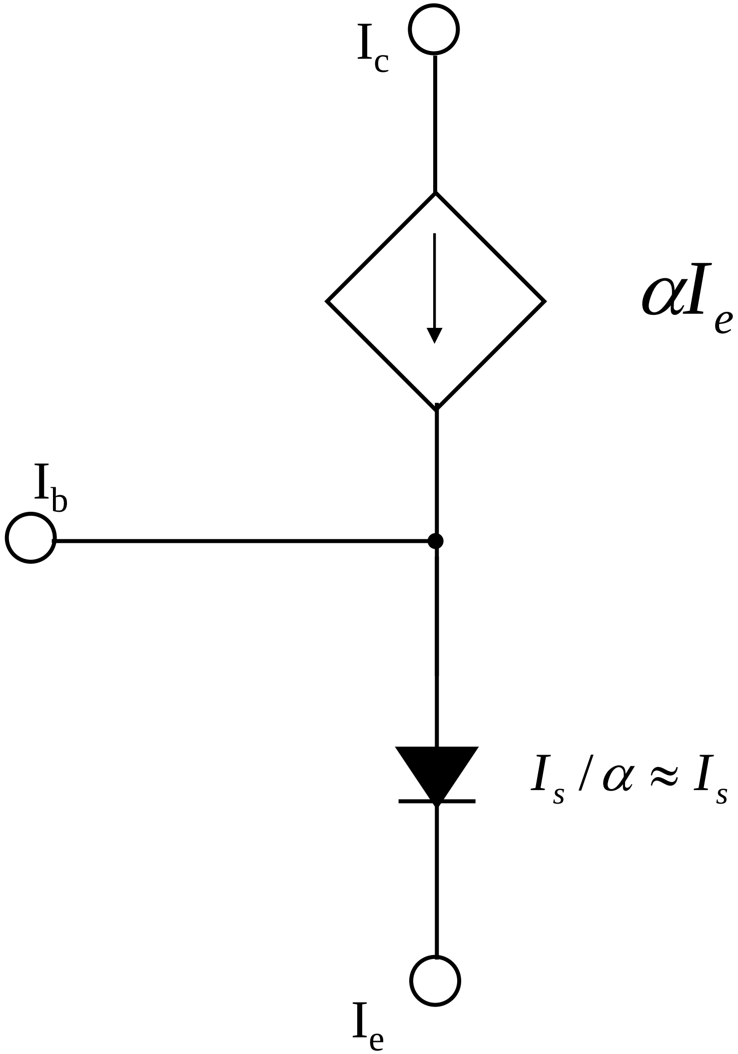
- High power
- Spreading resistance

# Equivalent circuit 1



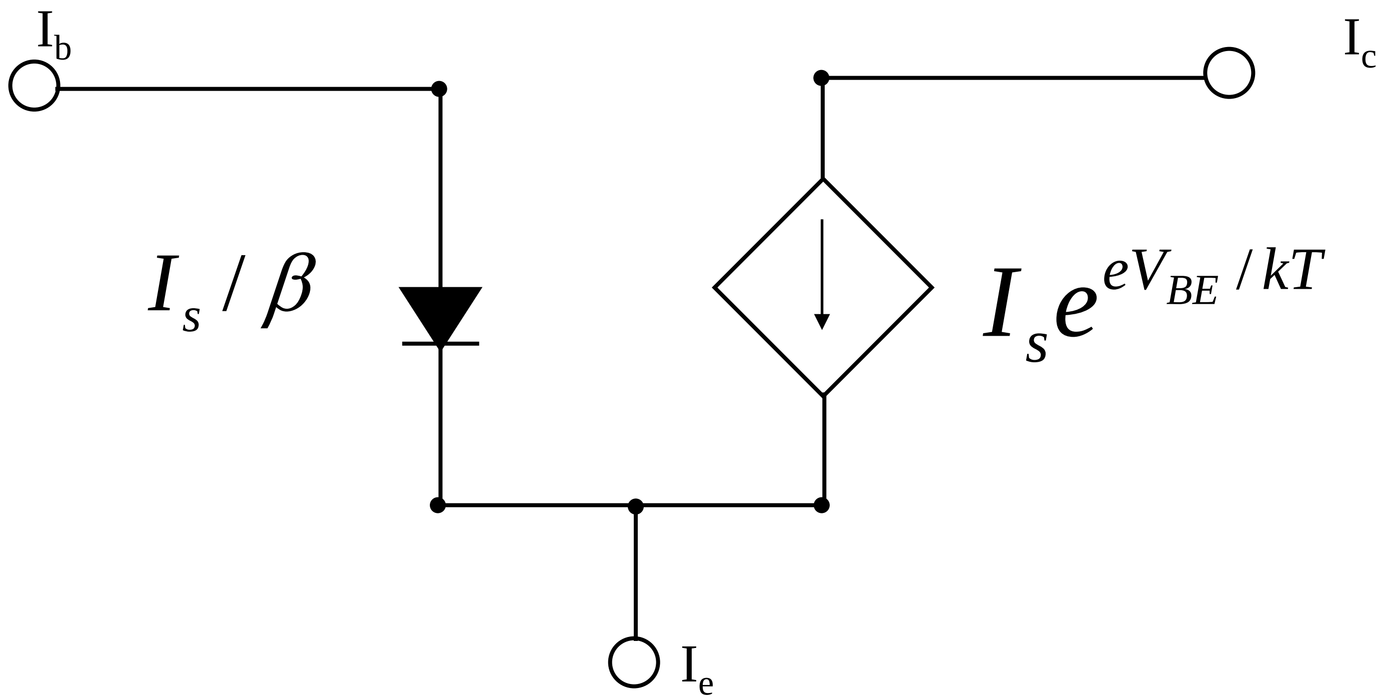

$$I_s \equiv \frac{AeDn_{po}}{X_B}$$

# Equivalent circuit 2

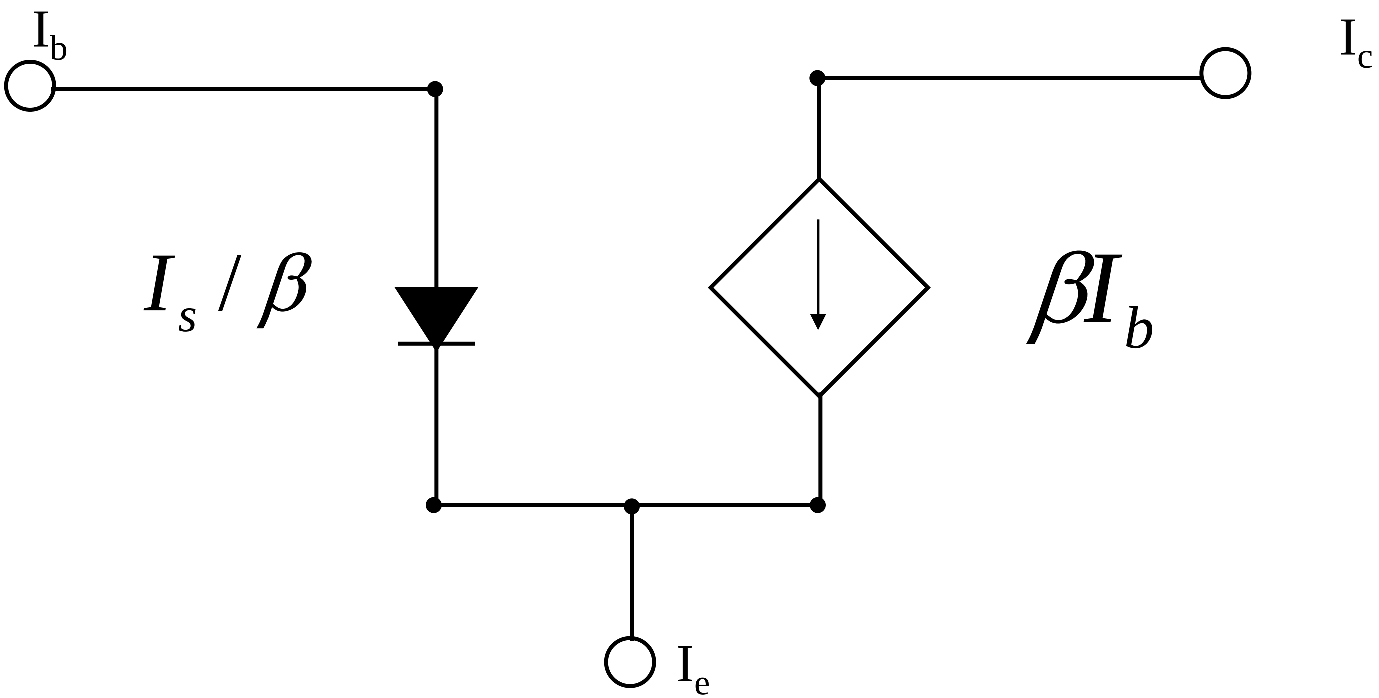



$$I_s \equiv \frac{AeDn_{po}}{X_B}$$

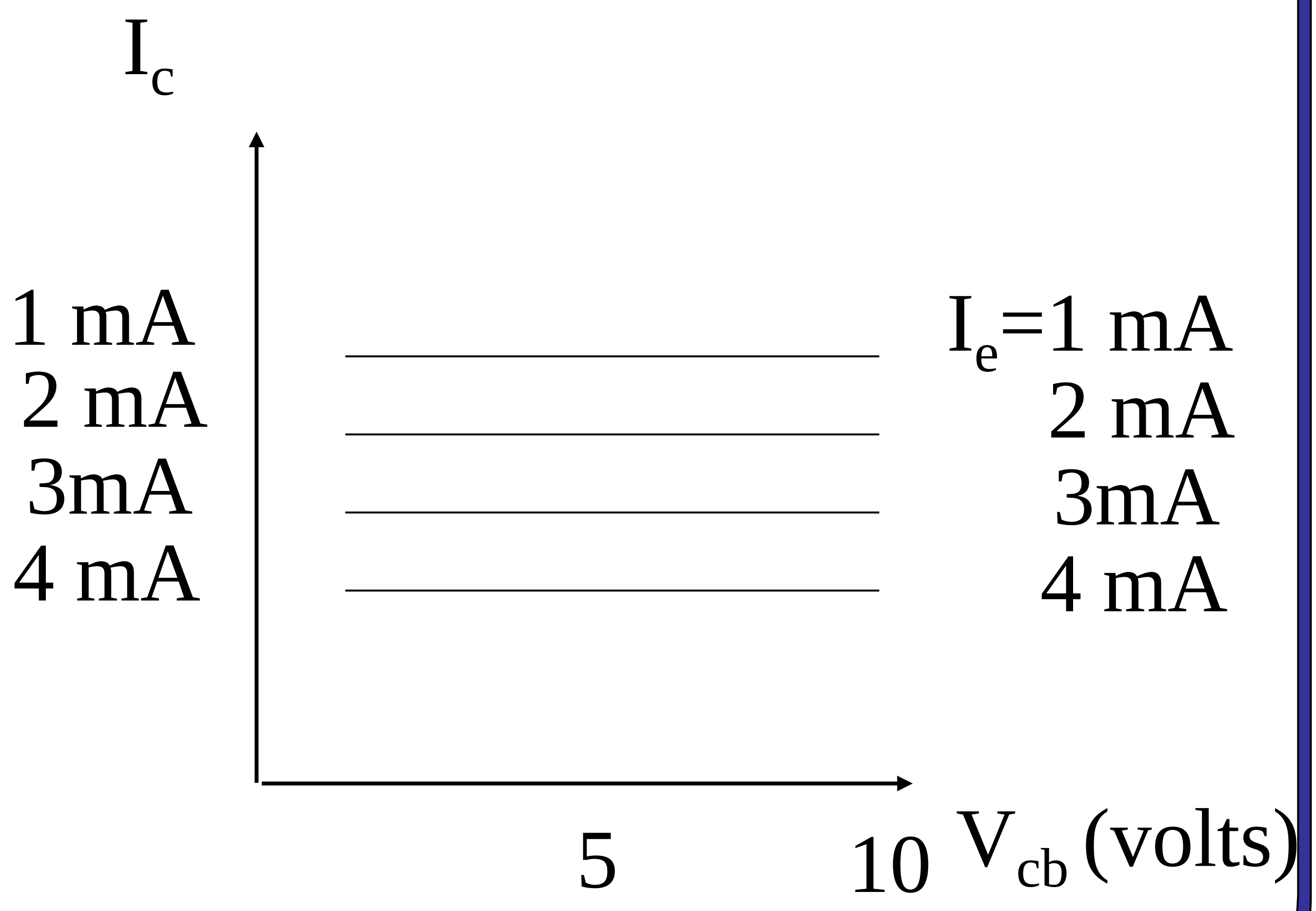
# Equivalent circuit 3



# Equivalent circuit 4



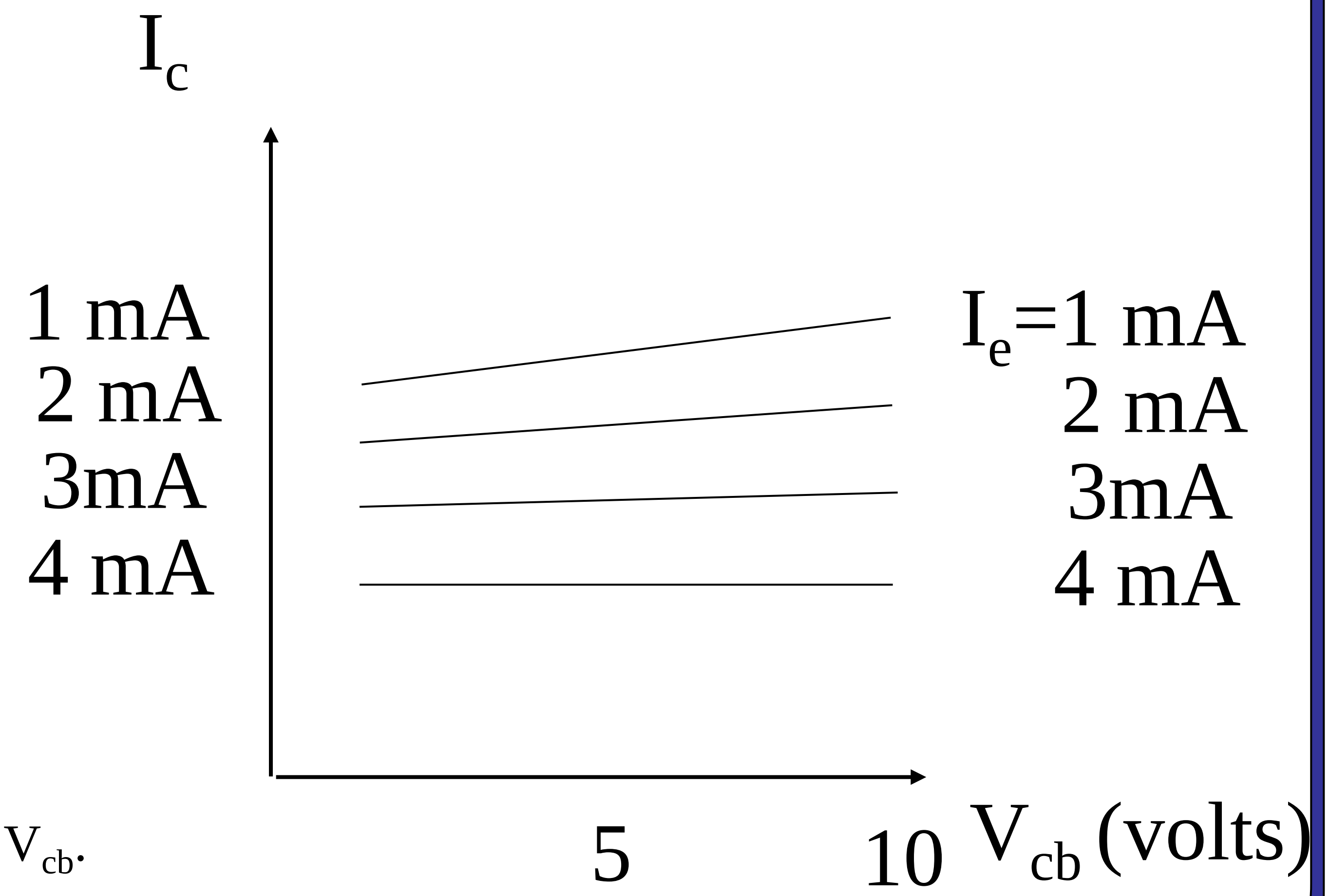
# Early effect



# Early effect

$$\frac{I_c}{I_b} \equiv \beta >> 1$$

$$\frac{I_c}{I_b} \approx \frac{\tau_n}{\tau_t}$$




W changes with $V_{cb}$.

# Bipolar advantages

- Speed set by base width, which is easy to control
- Large area contributes to current, good for power

# Bipolar dis-advantages

- Need base current at dc
- No easy complementary digital logic