ECE 340 Lecture 39
Semiconductor Electronics

Spring 2022
10:00-10:50am
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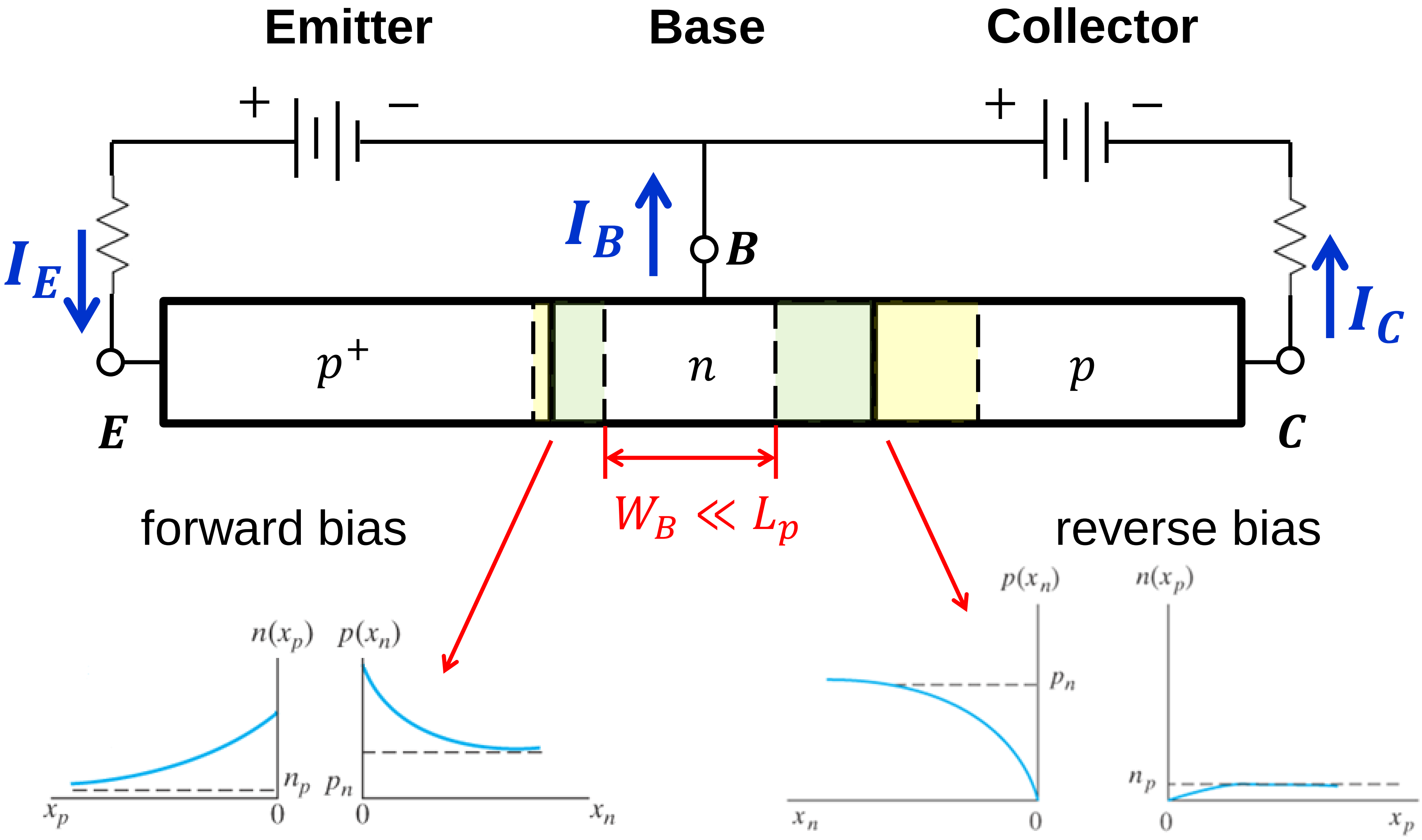
2062 ECE Building

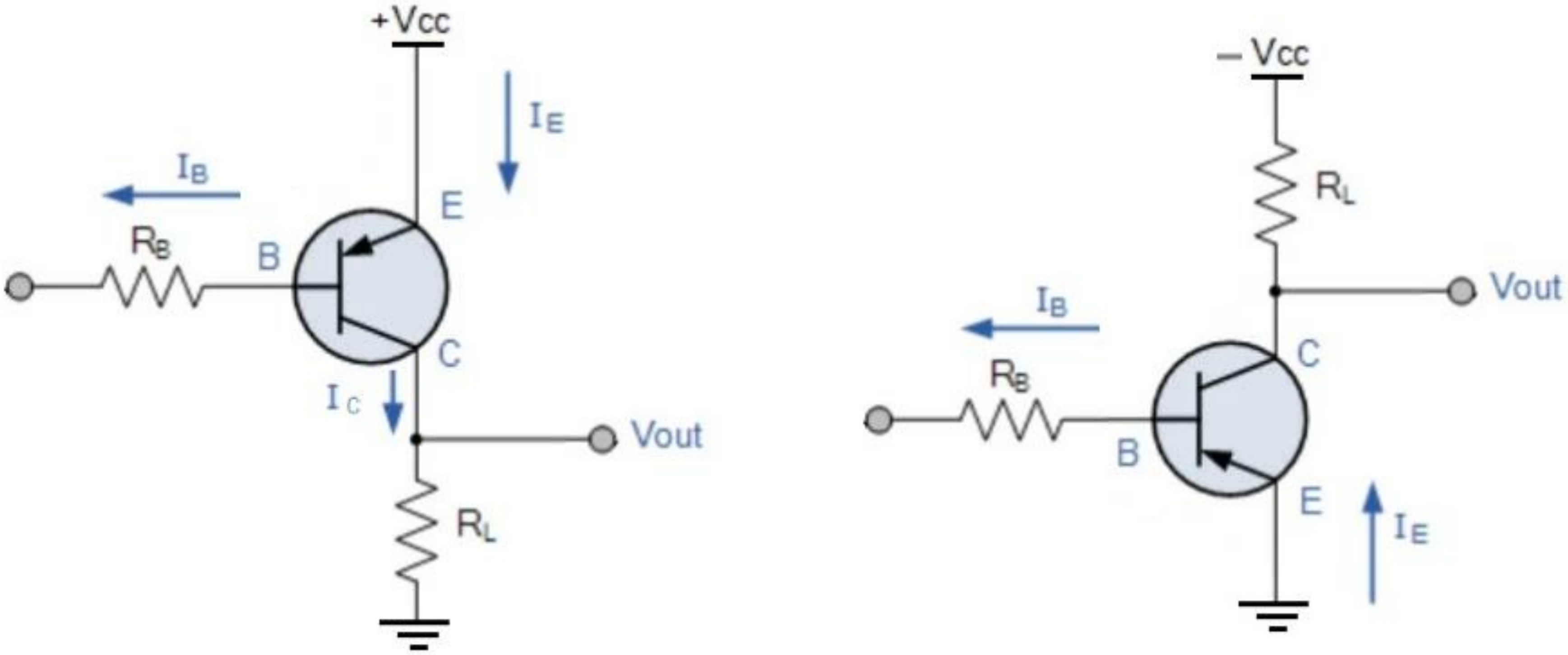
Today’s Discussion

- **Introduction to the Bipolar Junction Transistor (BJT)**

Normal mode operation-common emitter

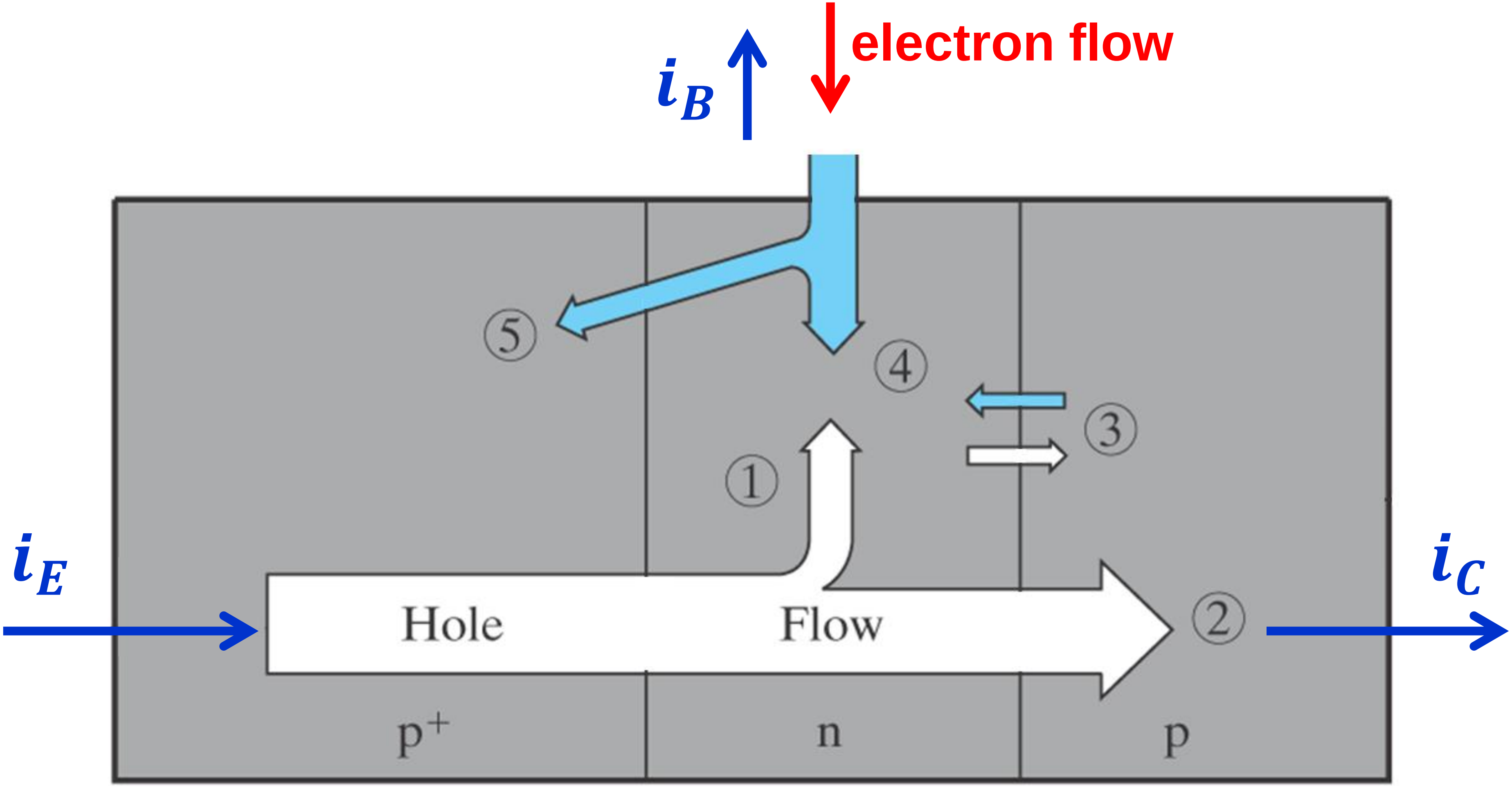


Normal mode operation-common emitter



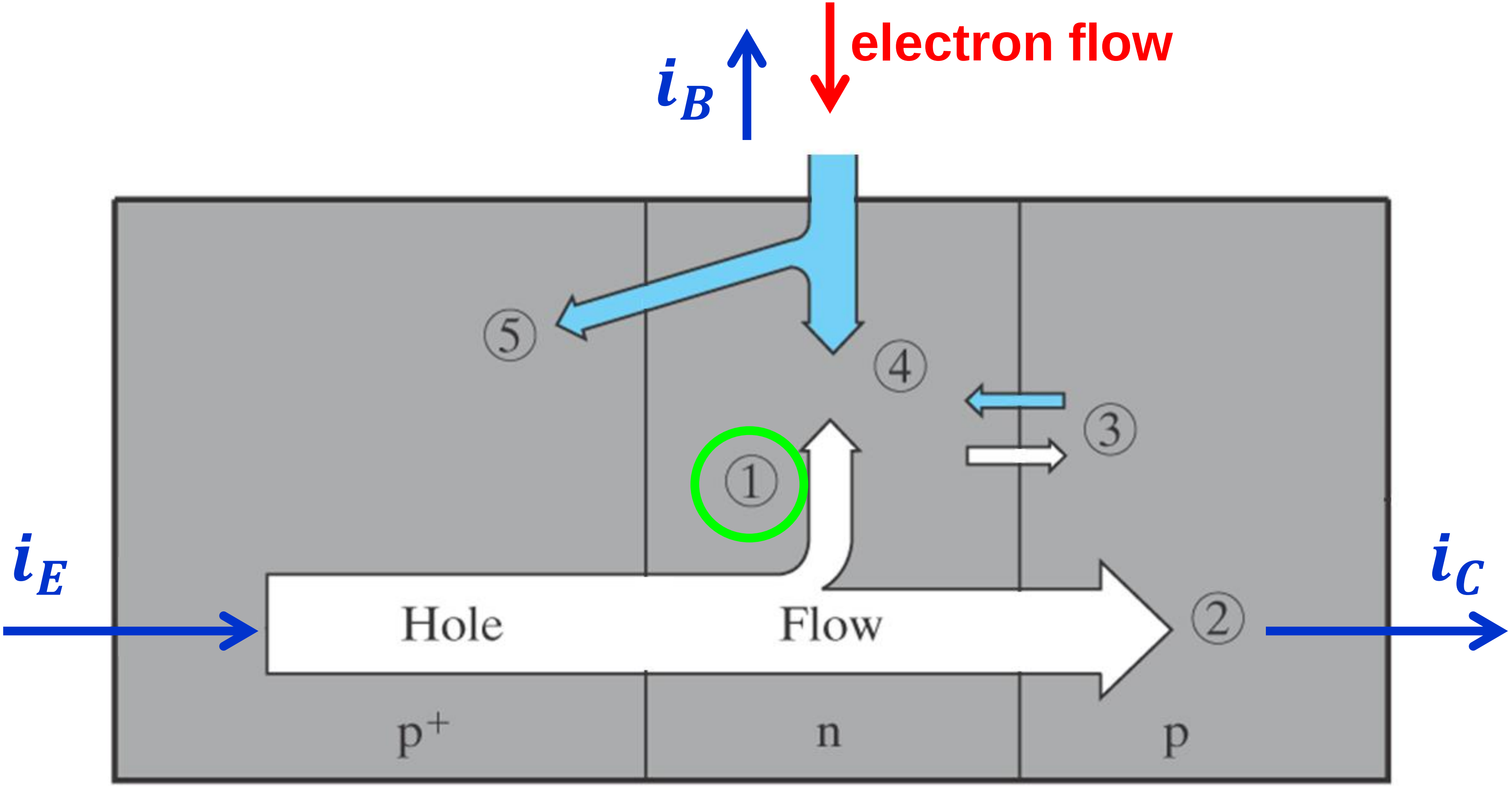
circuit schematics for p-n-p transistors

Let’s review again carrier flow in BJT



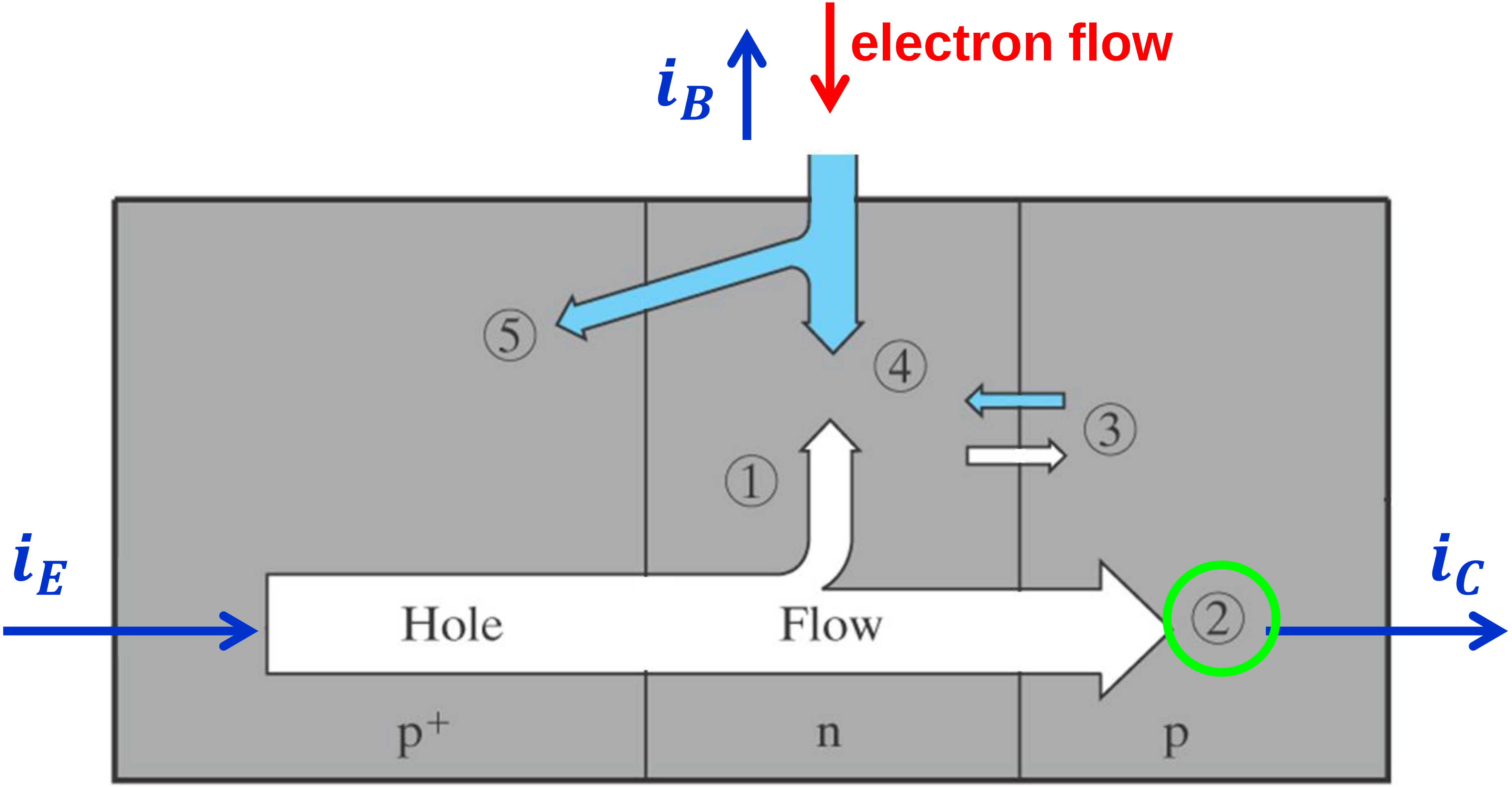
$$\xrightarrow{\;i_E\;} = \begin{cases} \longrightarrow i_{Ep} \\ \rightarrow i_{En} \end{cases} \qquad \xrightarrow{\;i_C\;}$$

Carrier flow



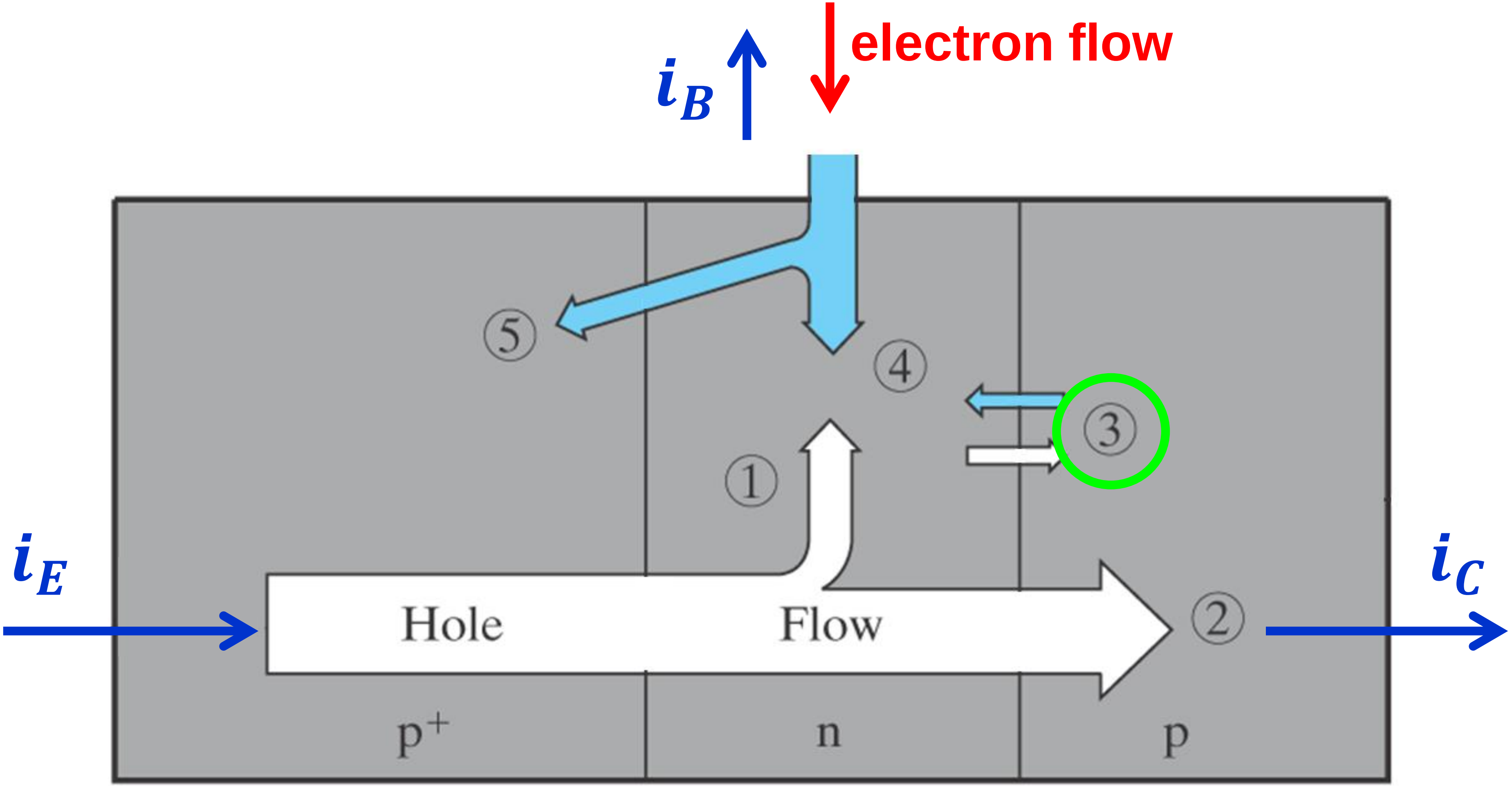
① injected holes lost to recombination in the base

Carrier flow



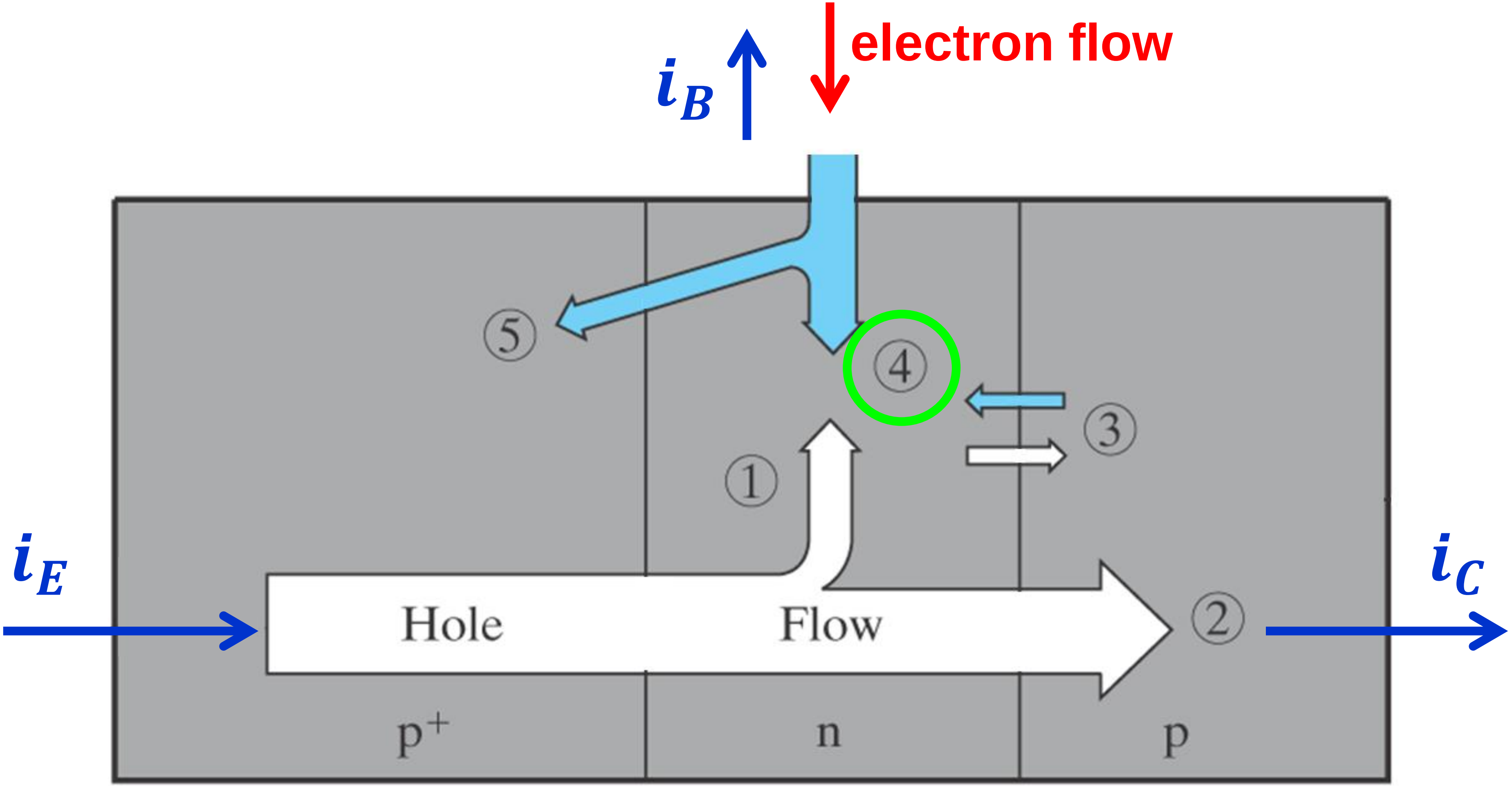
2 injected holes reaching reverse-biased collector junction

Carrier flow



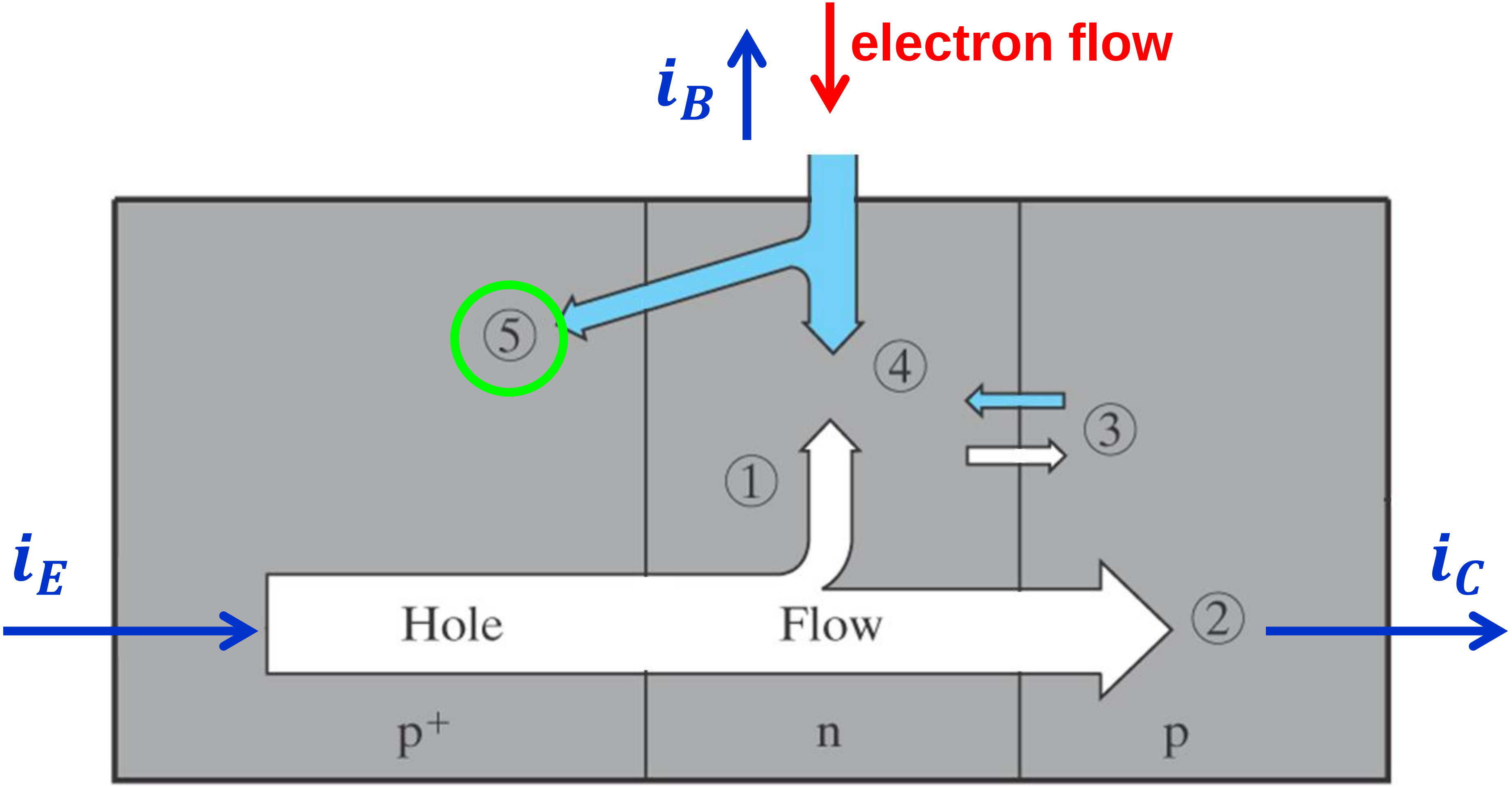
③ thermally generated electrons and holes (reverse saturation current of collector junction) which is part of the collector current

Carrier flow



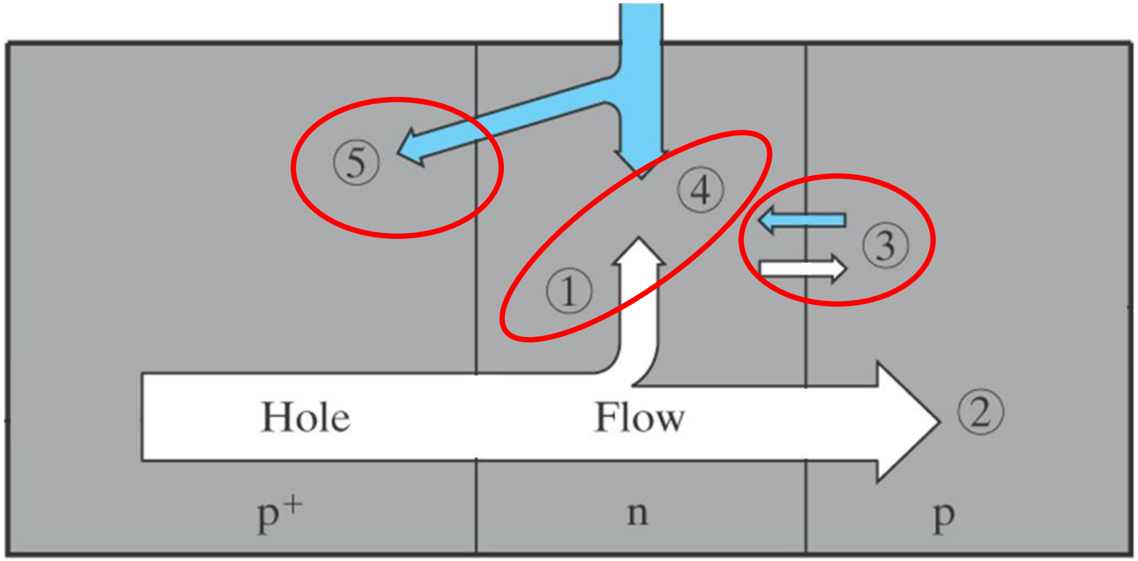
4 electrons supplied by the base contact which recombine with holes in the base neutral region

Carrier flow



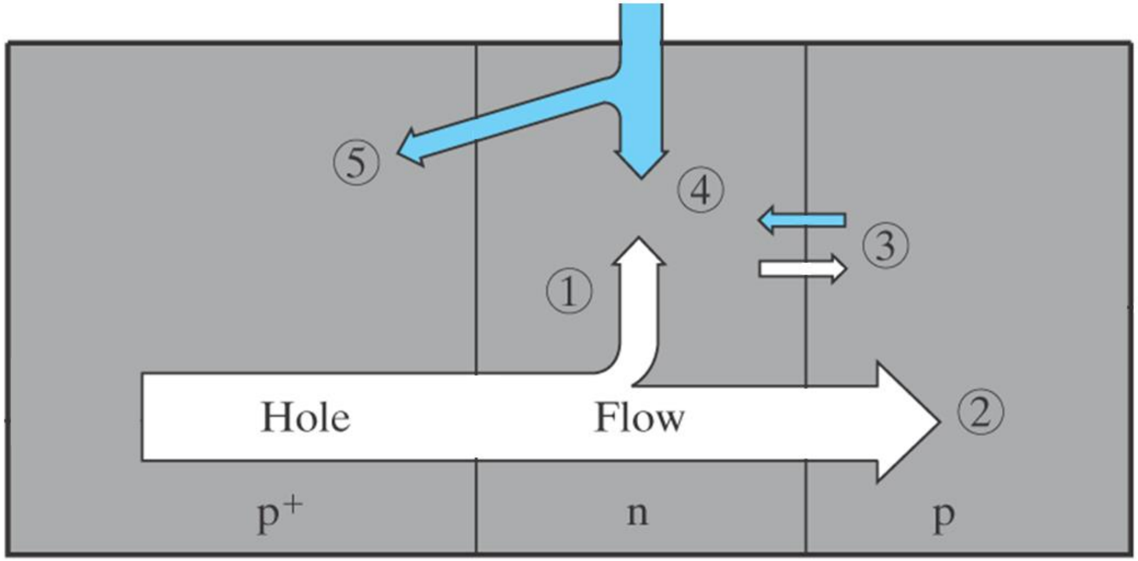
⑤ electrons supplied by the base contact which are injected across the forward biased junction and are part of the emitter current

Base current physical mechanisms



- recombination of injected holes even if $W_B \ll L_p$
- injection of electrons into the emitter
- thermally generated electrons in the reverse biased junction are swept into the base reducing the supply from the base contact

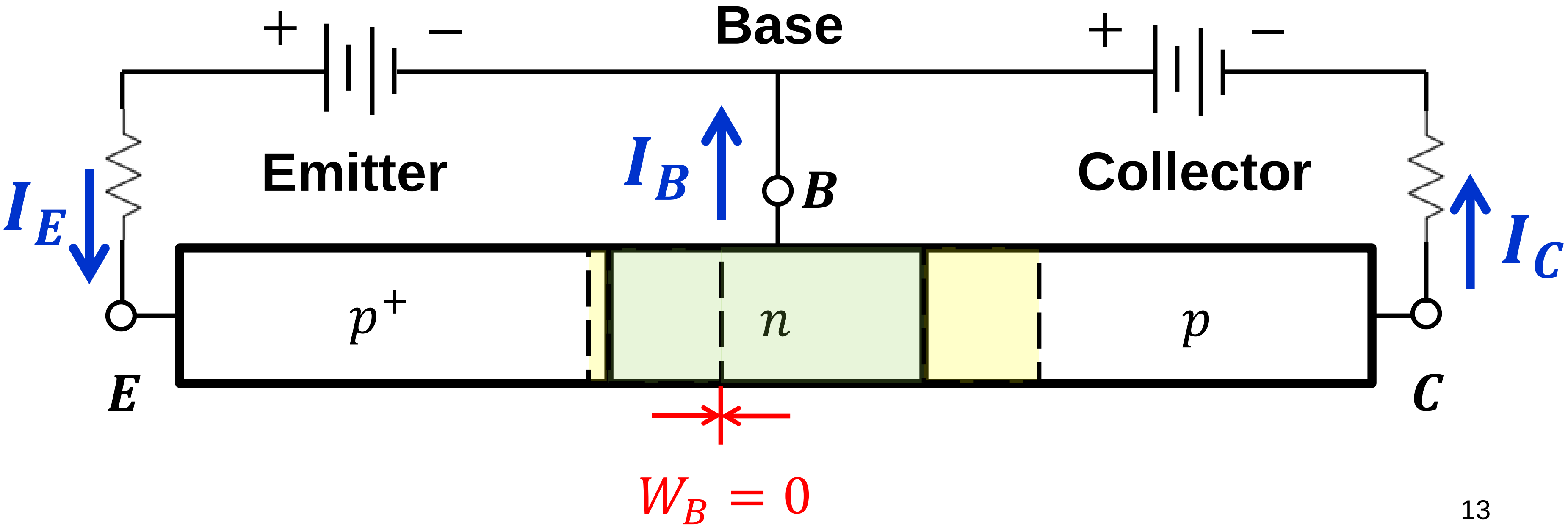
For a well-designed BJT



- Holes injected by the emitter into the base are collected as much as possible ($I_E - I_C$ very small) → we need base with narrow width and long hole lifetime so that $W_B \ll L_p = \sqrt{D_p \tau_p}$
- Current crossing the emitter should consist almost entirely of holes → we need high doping in emitter with respect to base doping (e.g., p^+-n emitter-base junction)

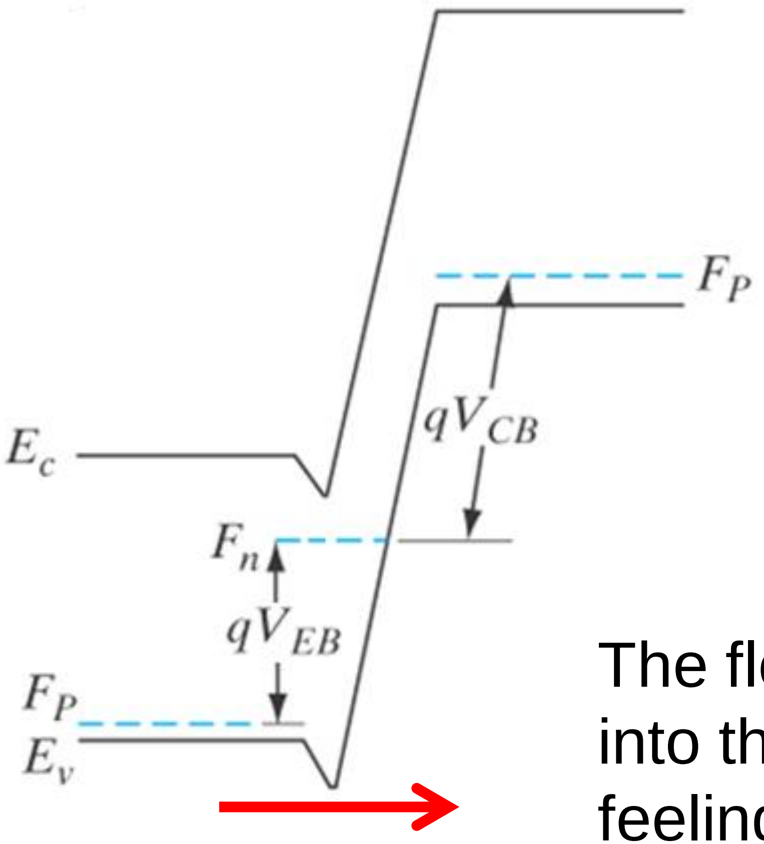
Base limitations: punch-through

- If the base region is too thin and if the base doping is too light, at the desired voltages the depletions from the two junctions may meet, resulting in "**punch-through**".
- In such conditions, the base current is no longer able to control the emitter current.



Base limitations: punch-through

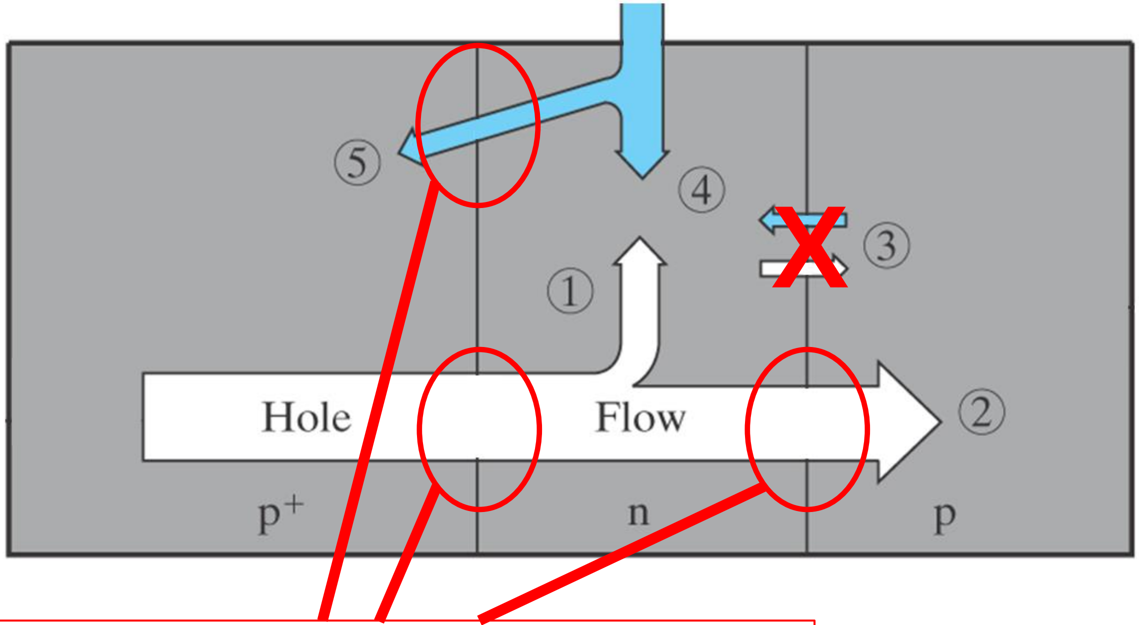
- The band diagram might look approximately like this:



The flow of holes goes directly into the collector region without feeling the influence of the base

Amplification with BJT

- The control input is the base current i_B



no current loss by recombination

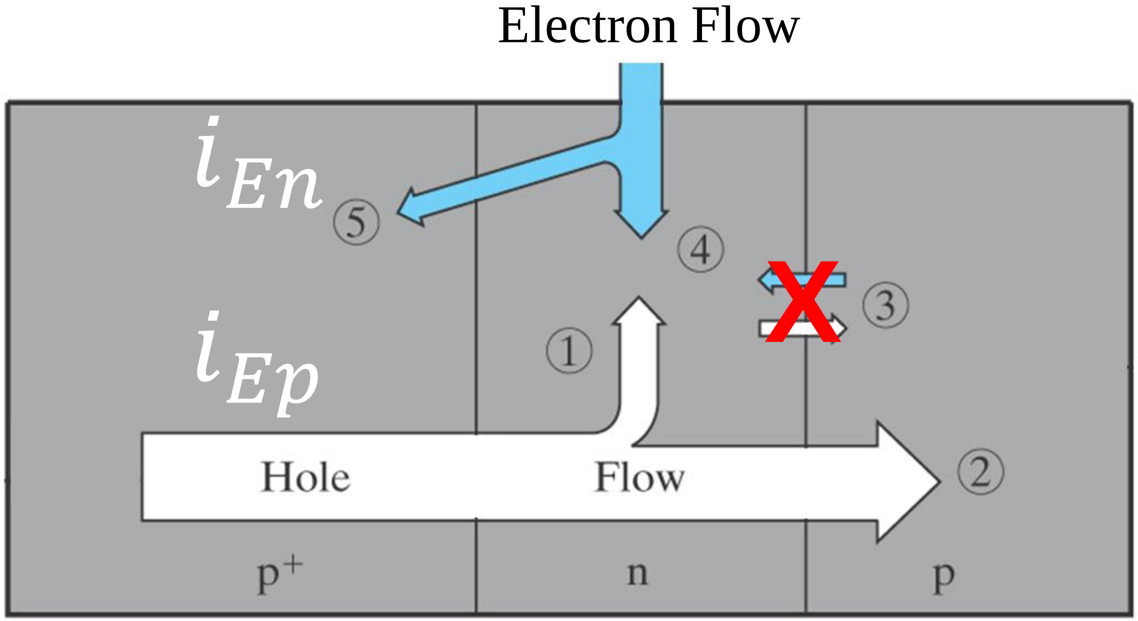
- Simplifying Assumptions:
  - Neglect reverse saturation current at collector
  - Neglect recombination in the depletion regions

Amplification with BJT – injection efficiency

$$i_E = i_{Ep} + i_{En}$$

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

emitter injection efficiency



Amplification with BJT – base transport factor

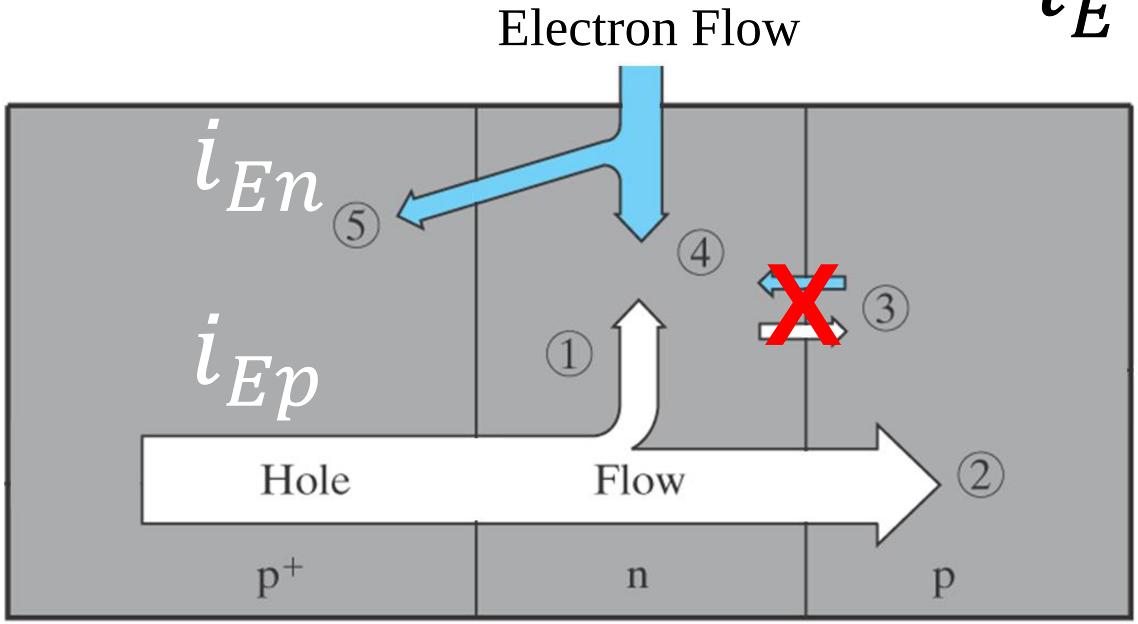
- Collector current

$$i_C = B\, \boldsymbol{i_{Ep}}$$

base transport factor

hole component
of emitter current

$$i_E = \boldsymbol{i_{Ep}} + i_{En}$$



For an efficient transistor – 1

- **Emitter injection efficiency → unity**

  emitter current is mostly holes

$$\gamma = \frac{i_{Ep}}{i_E} = \frac{i_{Ep}}{i_{Ep} + i_{En}} = \frac{1}{1 + \frac{i_{En}}{i_{Ep}}}$$

$$\gamma \to 1$$

$$\frac{i_{En}}{i_{Ep}} \to 0$$

We need

$$\boldsymbol{i_{En} \ll i_{Ep}}$$

For an efficient transistor – 2

- **Base transport factor → unity**

  most of the holes make it to the collector

Minimize recombination in the base so that

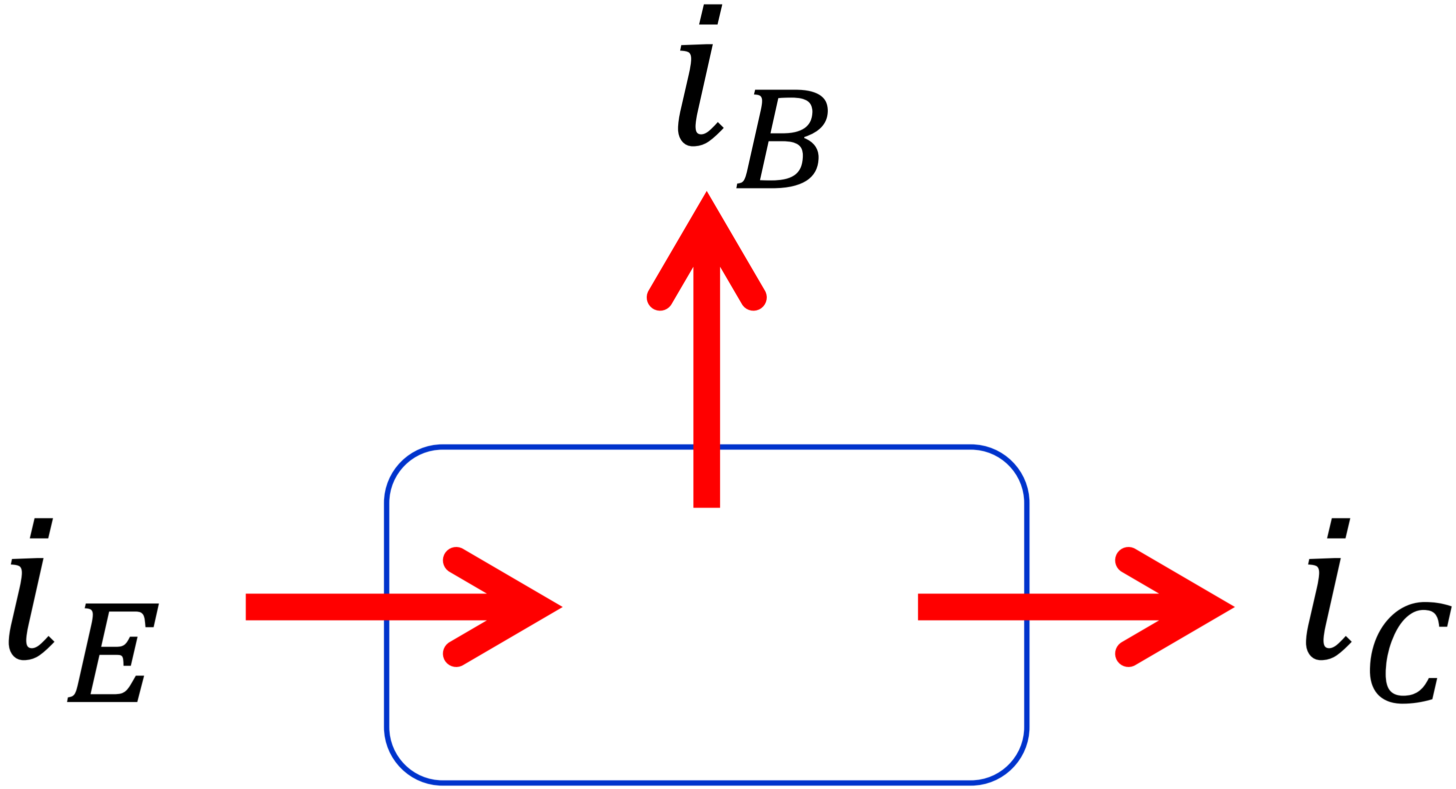
$$i_C \approx \boldsymbol{i_{Ep}}$$

Putting it all together

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

current transfer ratio

Base-to-Collector Amplification



$$i_E = i_B + i_C$$

Base-to-Collector Amplification

$$\frac{i_C}{i_B} = \boldsymbol{\beta}$$

base-to-collector
current amplification factor

$$i_B = i_E - i_C = i_{En} + i_{Ep} - B i_{Ep}$$

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

$\boldsymbol{B}$ = fraction of holes that make it across the base

$(\mathbf{1} - \boldsymbol{B})$ is the fraction of holes that recombine

Base-to-Collector Amplification

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

multyply by $\frac{(i_{En} + i_{Ep})}{(i_{En} + i_{Ep})} = 1$

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

$$= \frac{B\gamma}{\underbrace{\frac{i_{En}}{i_{En} + i_{Ep}} + \frac{i_{Ep}}{i_{En} + i_{Ep}}}_{= 1} - B \underbrace{\frac{i_{Ep}}{i_{En} + i_{Ep}}}_{= \gamma}} =$$

Base-to-Collector Amplification Factor β

$= \alpha$

current transfer ratio

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

Since α is close unity, β can be quite large

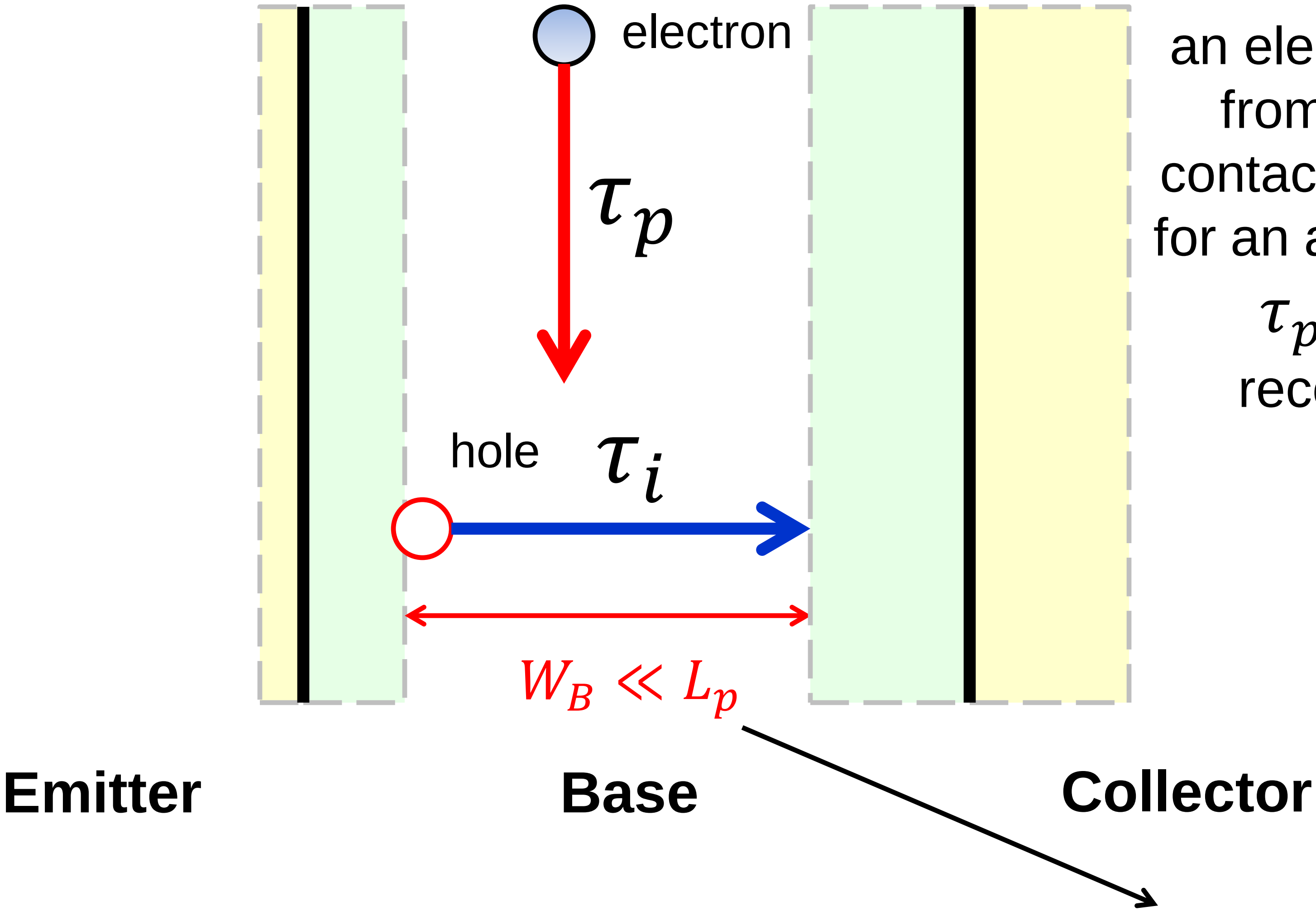
$$\alpha = 0.9 \quad \rightarrow \quad \beta = 9$$

$$\alpha = 0.95 \quad \rightarrow \quad \beta = 19$$

$$\alpha = 0.99 \quad \rightarrow \quad \beta = 99$$

$$\alpha = 0.999 \quad \rightarrow \quad \beta = 999$$

Hole transit time in the base



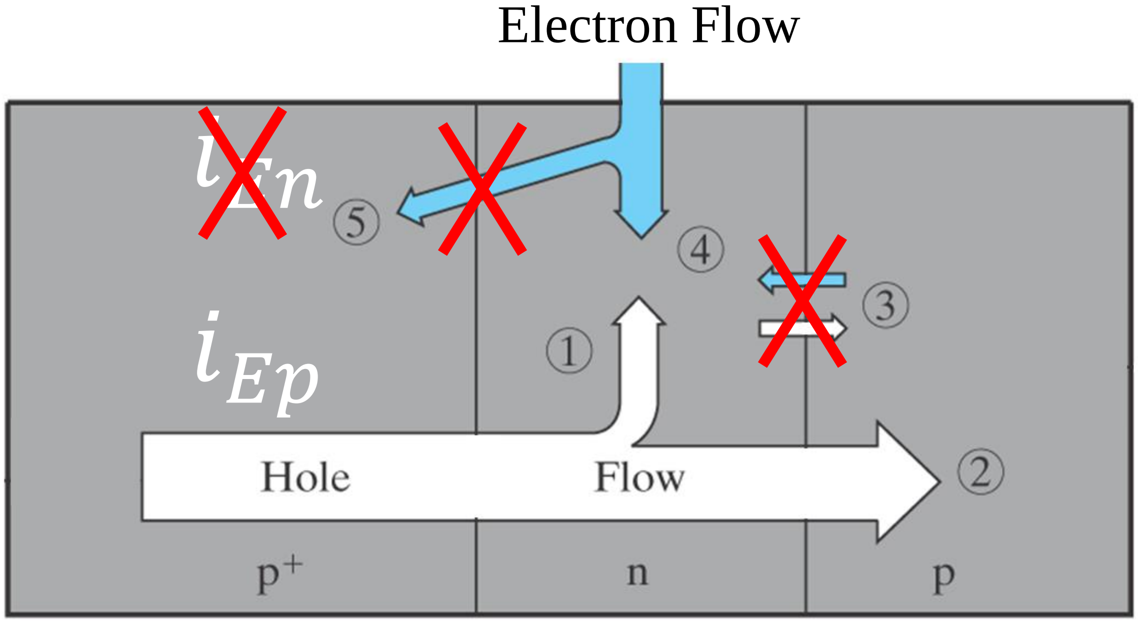
an electron enters from the base contact and lingers for an average time τ_p before recombining

Average time spent by hole in the narrow base $\tau_i \ll \tau_p$

Charge storage in the base

At steady-state there are excess electrons and holes in the base and for charge neutrality $Q_n = Q_p$

Assume $\tau_n = \tau_p$, perfect emitter injection efficiency $(\gamma = 1)$ and negligible saturation current



Charge storage in the base

$$\boxed{i_C = \frac{Q_p}{\tau_i}}$$

$$\boxed{i_B = \frac{Q_n}{\tau_n} = \frac{Q_n}{\tau_p}}$$

$$\boxed{Q_p = i_C \tau_i}$$

$$\boxed{Q_n = i_B \tau_p}$$

$$Q_n = Q_p$$

$$\boxed{i_C \tau_i = i_B \tau_n}$$

Amplification factor – physical interpretation

For each electron entering from the base contact, a number τ_p/τ_i of holes goes from emitter to collector maintaining charge neutrality

$$\boxed{\frac{i_C}{i_B} = \frac{\tau_p}{\tau_i} = \beta}$$

Mathematical analysis of the *p-n-p* BJT

- **Some simplifying assumptions are necessary in order to develop a manageable model which is general and valid for general bias conditions:**

1. **Negligible drift in the base region (holes move by diffusion)**
2. **Emitter injection efficiency $\gamma = 1$ (emitter is highly doped *p*+)**
3. **Reverse saturation current at the collector is negligible**
4. **Uniform cross-sectional area A (1-D model)**
5. **Steady-state conditions**

Posted handout:

We are going to focus on the significance of the results and on physical understanding of physical behavior.

Details of the analytical solution for the 1-D model BJT are outlined in the posted handout and are left as optional reading for the interested students.

Actual complete simulations of realistic devices are carried out by numerical solution of the coupled system of semiconductor equations consisting of:

- **continuity equations for electrons and holes based on the drift-diffusion current model**
- **Poisson equation to obtained self-consistent space dependent electric fields**

Results obtained from analytical solution

$$I_{Ep} = qA\frac{D_p}{L_p}\left[\Delta p_E \operatorname{ctnh}\frac{W_B}{L_P} - \Delta p_C \operatorname{csch}\frac{W_B}{L_P}\right]$$

$$I_C = qA\frac{D_p}{L_p}\left[\Delta p_E \operatorname{csch}\frac{W_B}{L_P} - \Delta p_C \operatorname{ctnh}\frac{W_B}{L_P}\right]$$

$$I_B = qA\frac{D_p}{L_p}\left[(\Delta p_E + \Delta p_C)\tanh\frac{W_B}{2L_P}\right]$$

For the narrow base diode

$$I_p(x_n = 0) = qA\frac{D_p}{L_p}\Delta p_n \operatorname{ctnh}\frac{\boldsymbol{\ell}}{L_P}$$

$$I_p(x_n = \boldsymbol{\ell}) = qA\frac{D_p}{L_p}\Delta p_n \operatorname{csch}\frac{\boldsymbol{\ell}}{L_P}$$

$$I_n(\mathrm{recomb}) = qA\frac{D_p}{L_p}\Delta p_n \tanh\frac{\boldsymbol{\ell}}{2L_P}$$

With $\Delta p_c \approx 0$ essentially the same result obtained for BJT

For the curious ones:

- Video by Bill Hammack on the first transistor invented by Bardeen and Brattain at Bell Labs (point-contact transistor)

https://www.youtube.com/watch?v=RdYHljZi7ys

The book by Shockley contains an extensive description of the point-contact transistor, based on metal-semiconductor junctions rather than p-n junctions

https://archive.org/details/ElectronsAndHolesInSemiconductors

- AT&T Archives video: Genesis of the Transistor:

https://www.youtube.com/watch?v=WiQvGRjrLnU