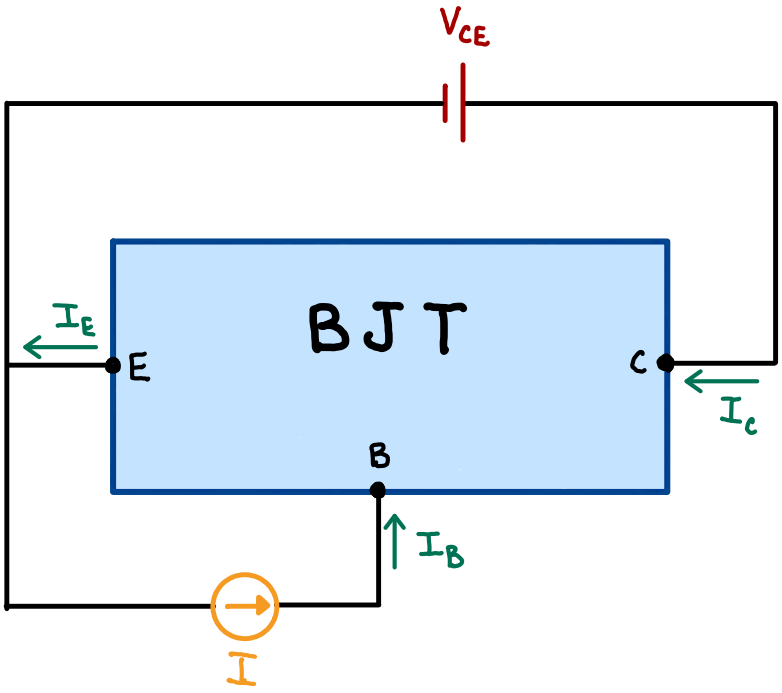
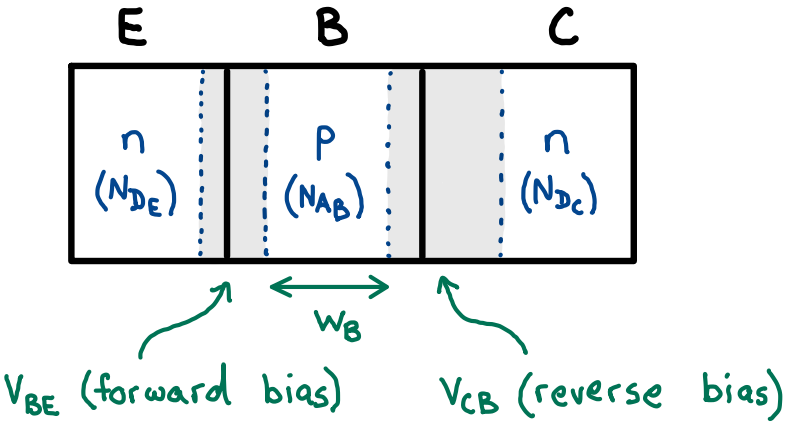
# Bipolar Junction Transistors (BJTs)



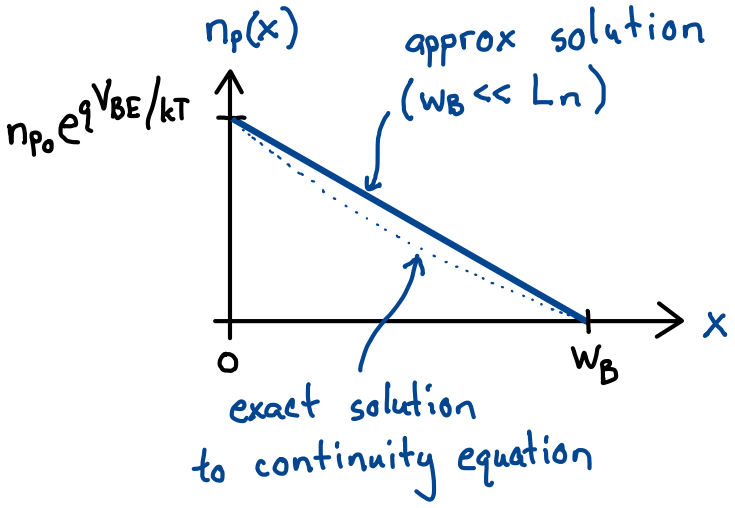

- $I_E = I_B + I_C$
- $I_C = \beta I_B$

$\beta$: DC current gain

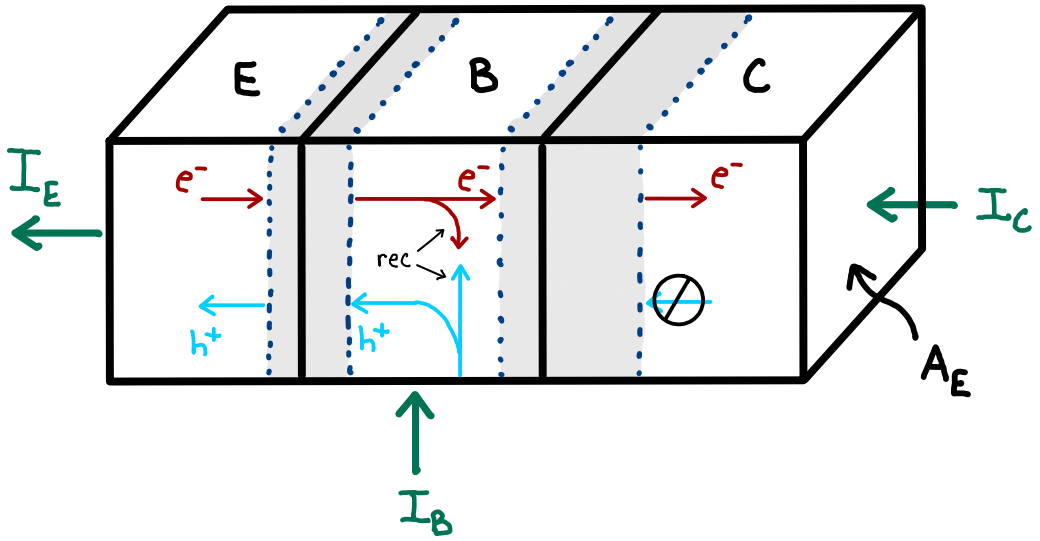



- $V_{BE} + V_{CB} = V_{CE}$
- $V_{BE}$ = diode on-voltage
- $W_B$ = neutral base length
- $W_B \ll L_n$

Minority charge distribution in the base:




- electron current $J_n(x) = qD_{n_B}\frac{dn_p}{dx}$
- $n_{p_0} = \frac{n_i^2}{N_{A_B}}$
- $J_{n_B}(0) \simeq \frac{qD_{n_B} n_{p_0}}{w_B} e^{qV_{BE}/kT}$




$$I_E = I_{n_E} + I_{p_E} = A_E\left[J_{n_B}(0) + \frac{qD_{p_E} n_i^2}{N_{D_E} L_{p_E}} e^{qV_{BE}/kT}\right]$$

$$I_B = I_{p_E} + I_{rec}$$

$$I_C = I_{n_E} - I_{rec}$$

stored charge in base

$$I_{rec} = \frac{Q_B}{\tau_{n_B}} = \frac{\frac{1}{2}\left(qn_{p_0} e^{qV_{BE}/kT} w_B\right) A_E}{\tau_{n_B}}$$

minority carrier lifetime

$$= \boxed{\frac{qn_i^2 w_B A_E}{2N_{A_B}\tau_{n_B}} e^{qV_{BE}/kT}}$$

Figures of merit:

Emitter efficiency: $\gamma = \frac{I_{nE}}{I_{nE} + I_{pE}} = \frac{1}{1 + I_{pE}/I_{nE}}$

$$\gamma = \frac{1}{1 + \frac{W_B N_{A_B} D_{pE}}{L_{pE} N_{D_E} D_{n_B}}}$$

What would this term be if emitter width was very small?

- To make $\gamma$ close to 1, make $W_B$ small and $N_{A_B} < N_{D_E}$

Base transport factor $\alpha_T$:

$$\alpha_T = \frac{I_{nE} - I_{rec}}{I_{nE}} = 1 - \frac{I_{rec}}{I_{nE}}$$

$$\alpha_T = 1 - \frac{W_B^2}{2L_{n_B}^2}$$

- To make $\alpha_T$ close to 1, make $W_B$ small

## Current gain $\beta$:

$$\beta = \frac{I_C}{I_B}$$

$$I_E = I_C + I_B \quad (1)$$

$$I_{nE} = \gamma I_E \quad (2)$$

$$I_C = \alpha_T I_{nE} = \gamma \alpha_T I_E \rightarrow I_E = \frac{I_C}{\gamma \alpha_T} \quad (3)$$

plug in (2)

Plug (3) into (1):

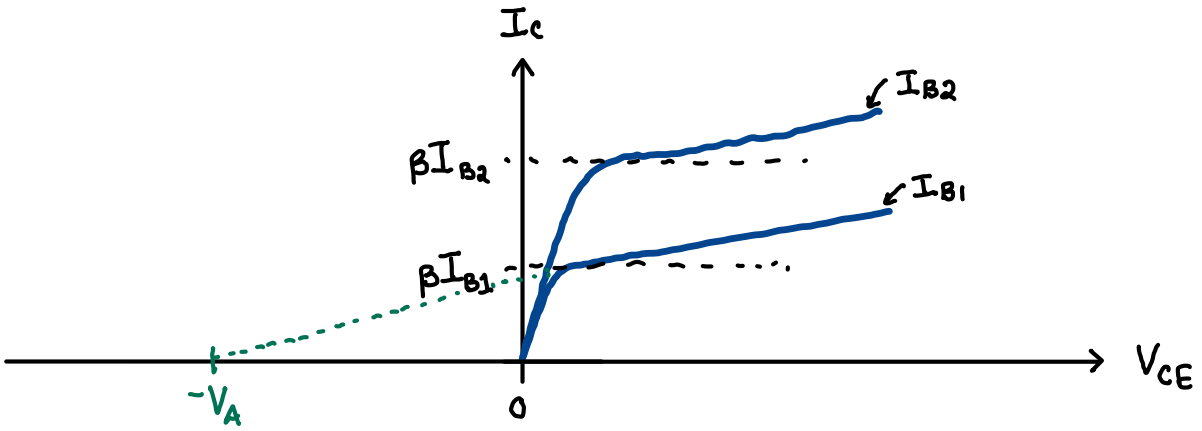
$$\frac{I_C}{\gamma \alpha_T} = I_C + I_B \quad \text{(divide both sides by } I_B\text{)}$$

$$\frac{\beta}{\gamma \alpha_T} = \beta + 1 \rightarrow \beta\left(\frac{1}{\gamma \alpha_T} - 1\right) = 1$$

$$\boxed{\beta = \frac{\gamma \alpha_T}{1 - \gamma \alpha_T}}$$

- To make $\beta$ large, make $\gamma$ and $\alpha_T$ close to 1 by making $W_B$ small and $N_{A_B} << N_{D_E}$

## Early Effect: base narrowing with increasing $V_{CE}$




$V_A \equiv$ Early Voltage

- To mitigate Early effect, make collector $n^-$ and add $n^+$ sub-collector for collector contact (note: this will also increase $V_{br}$)

## Summary of BJT design parameters:

→ To maximize $\beta$:

- make $W_B$ small
- make $N_{A_B} << N_{DE}$

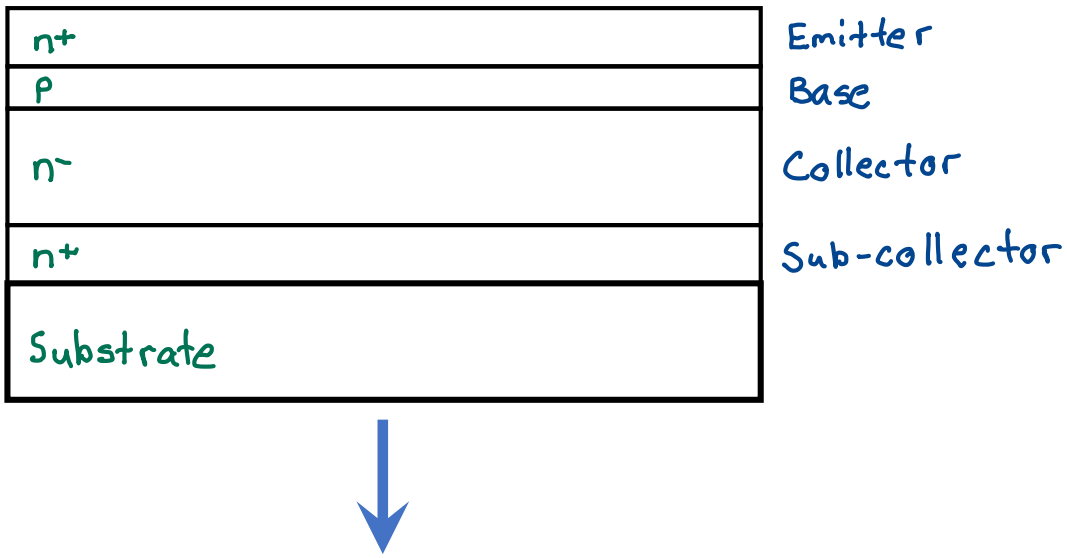
→ To mitigate Early effect and increase $V_{br}$:

- make collector $n^-$

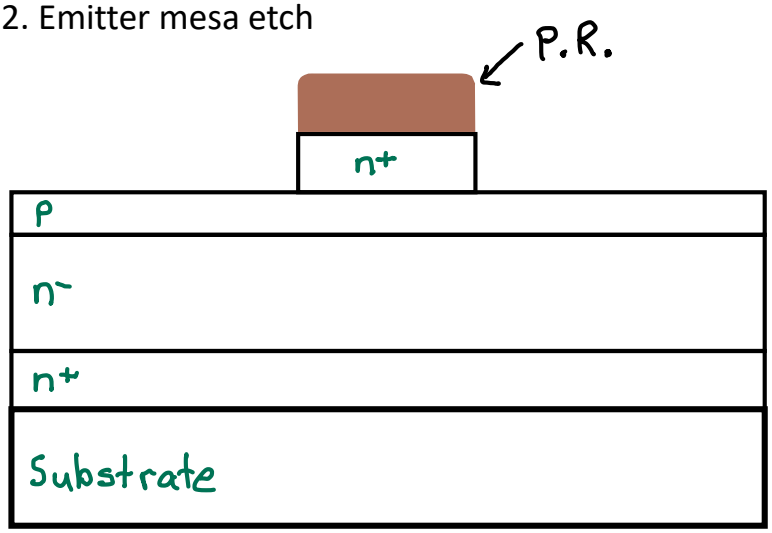
# Fabrication of BJTs

III-V Material Systems (e.g., GaAs, InP, GaN):

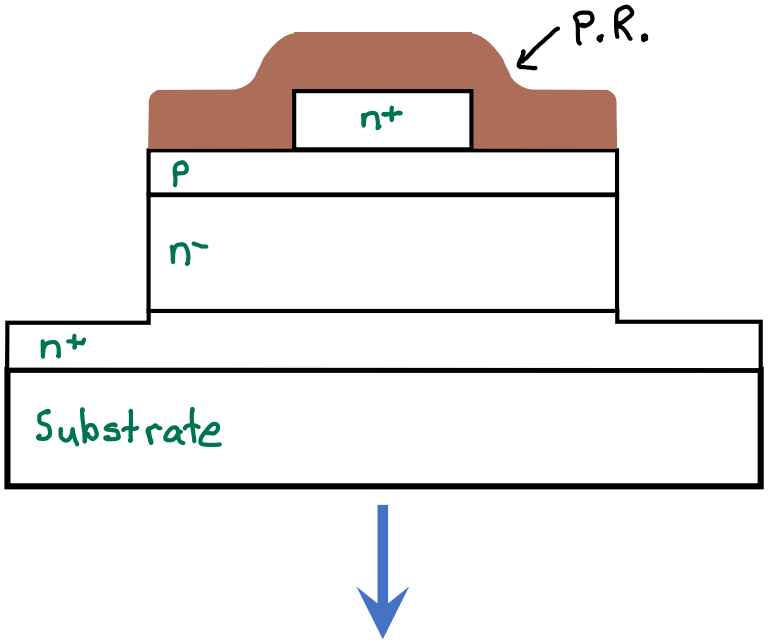
1. Epitaxial growth of material layers



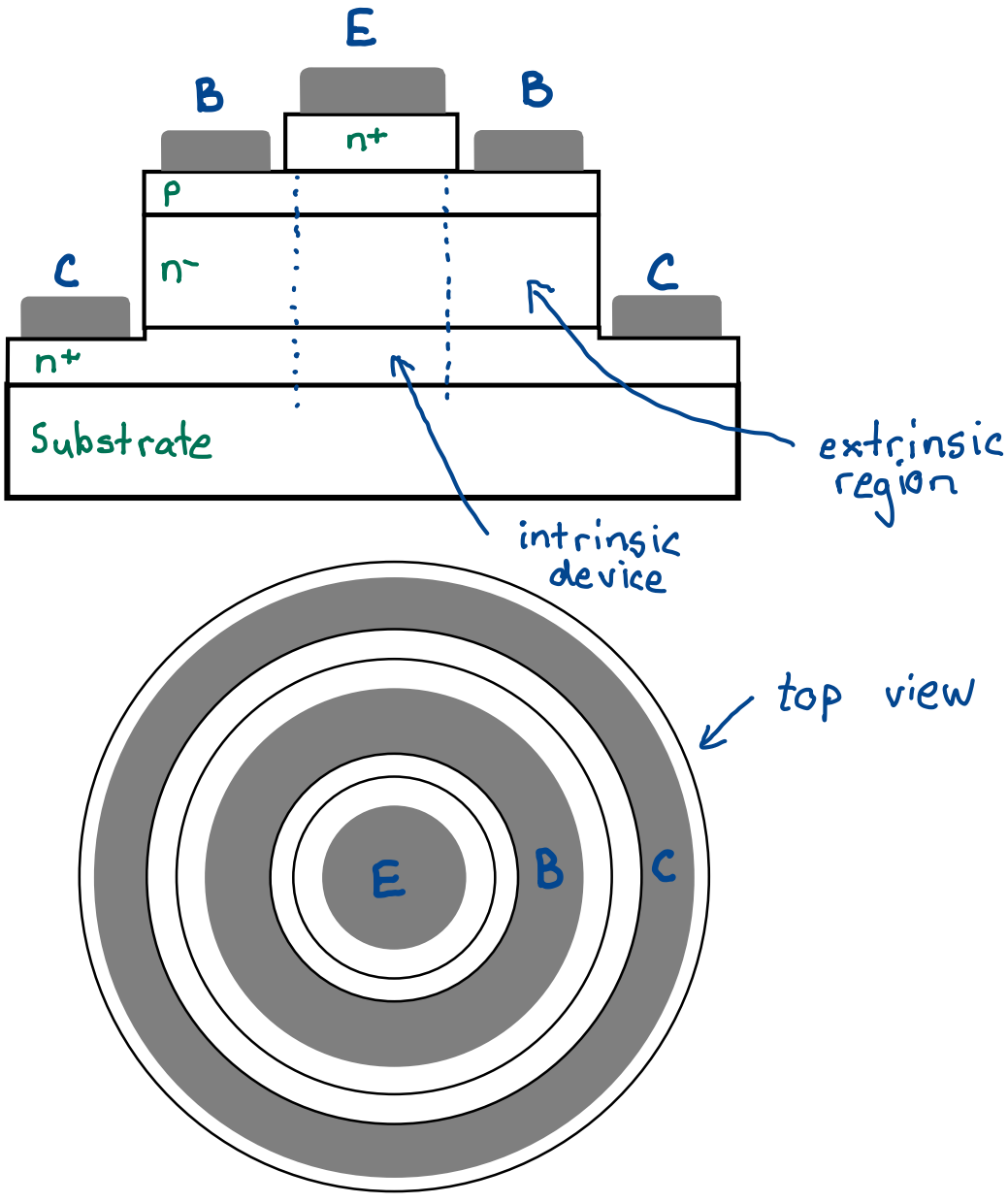

2. Emitter mesa etch



3. Base mesa etch

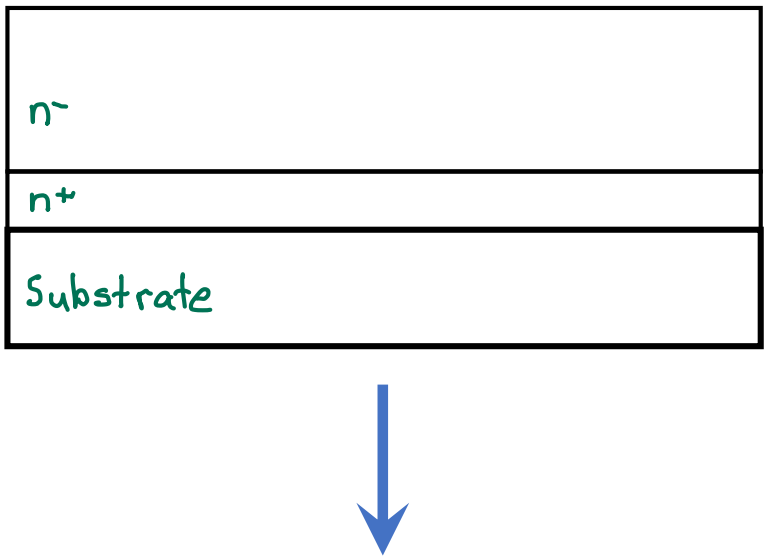



4. Deposit contacts

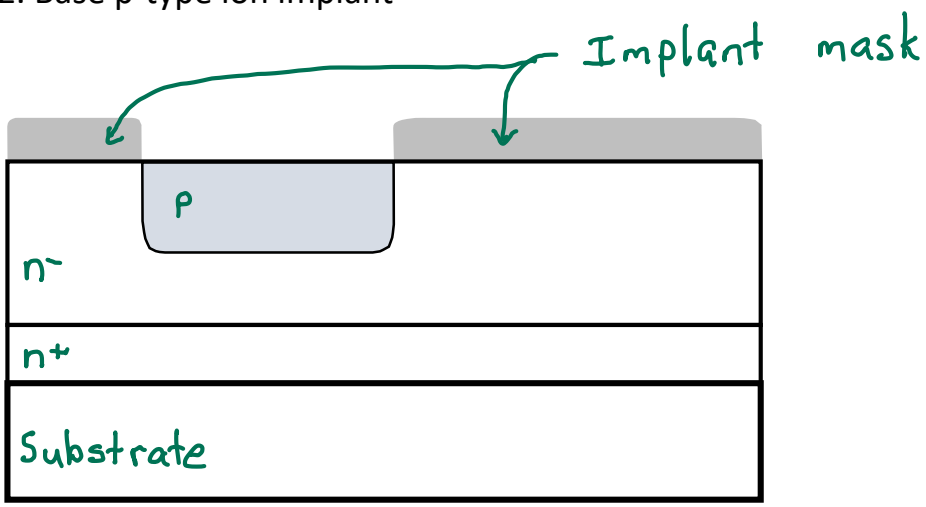


Si IC Process (old):

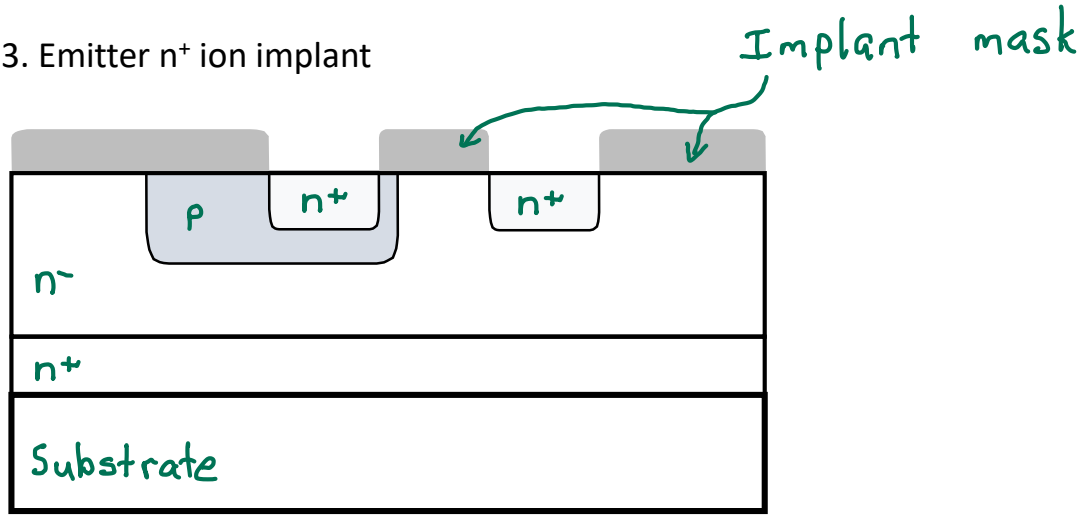
1. Epitaxial growth of material layers



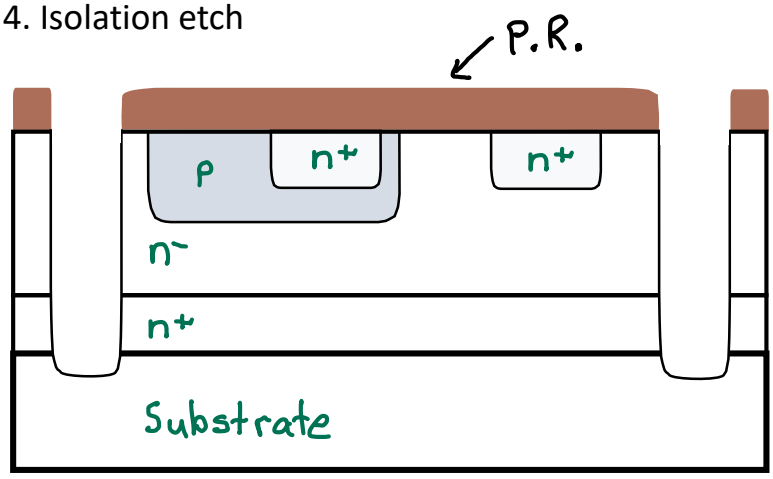

2. Base p-type ion implant



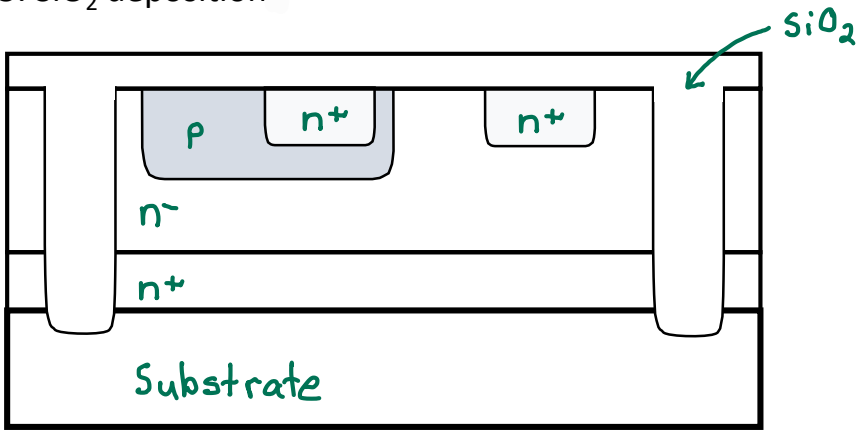
3. Emitter $n^+$ ion implant



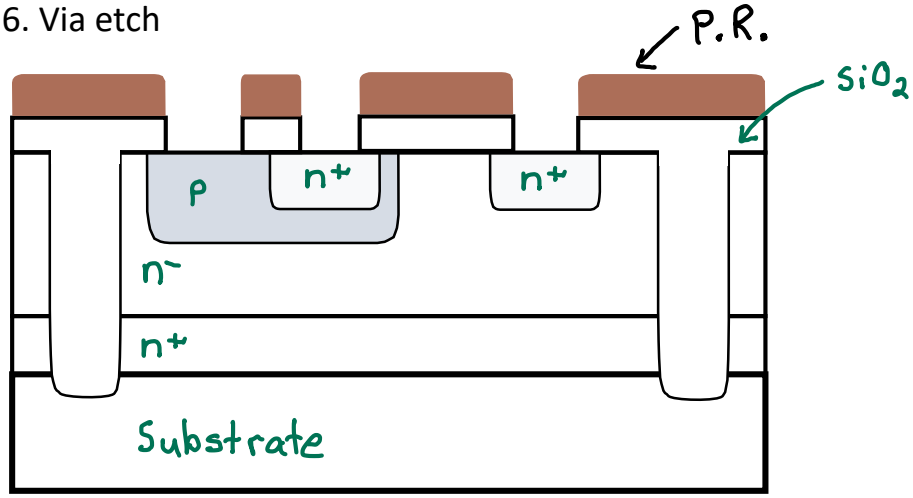

4. Isolation etch



5. $SiO_2$ deposition




6. Via etch




7. Contact Deposition