微电子器件物理
双极型晶体管3

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本节课提纲

1. 传统双极型晶体管的问题
2. 多晶硅发射极
3. 短基极输运
4. 高频响应

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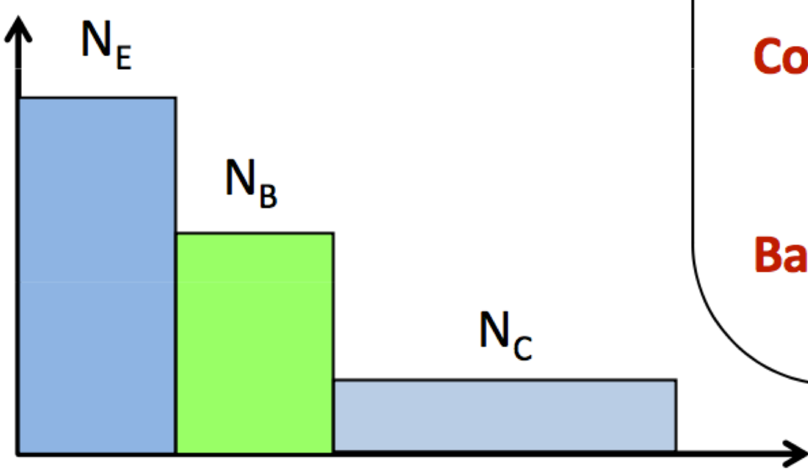
设计掺杂浓度

$$\beta_{dc} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$



Emitter doping: As high as possible without *band gap narrowing*

Base doping: As low as possible, without *current crowding, Early effect*

Collector doping: Lower than base doping *without Kirk Effect*

Base Width: As thin as possible without *punch through*

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如何设计一个更好的晶体管？

$$\beta \approx \frac{D_n}{W_B} \frac{W_E}{D_p} \frac{n_{i,B}^2}{n_{i,E}^2} \frac{N_E}{N_B}$$

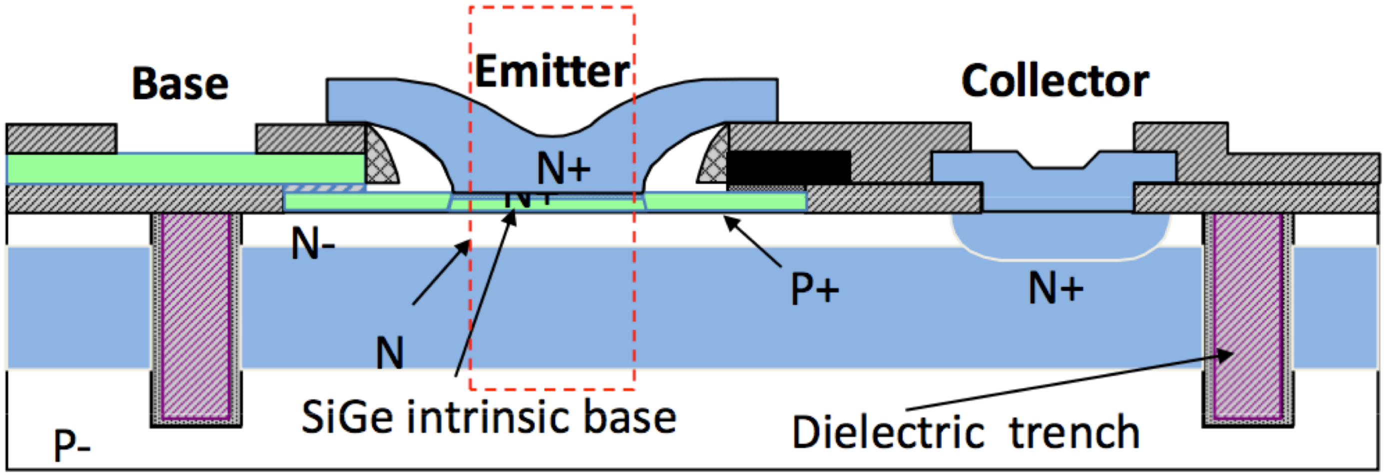
Graded Base transport

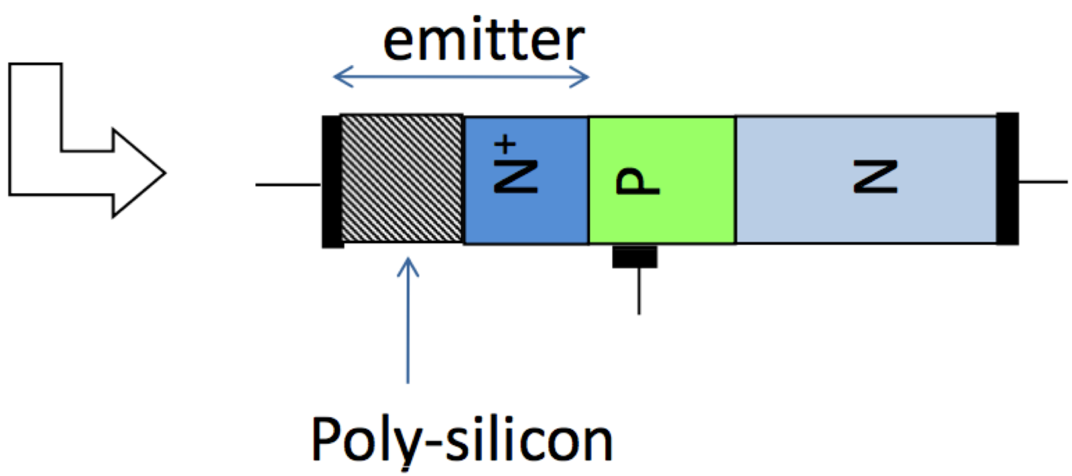
Polysilicon Emitter

Classical Shockley Transistor

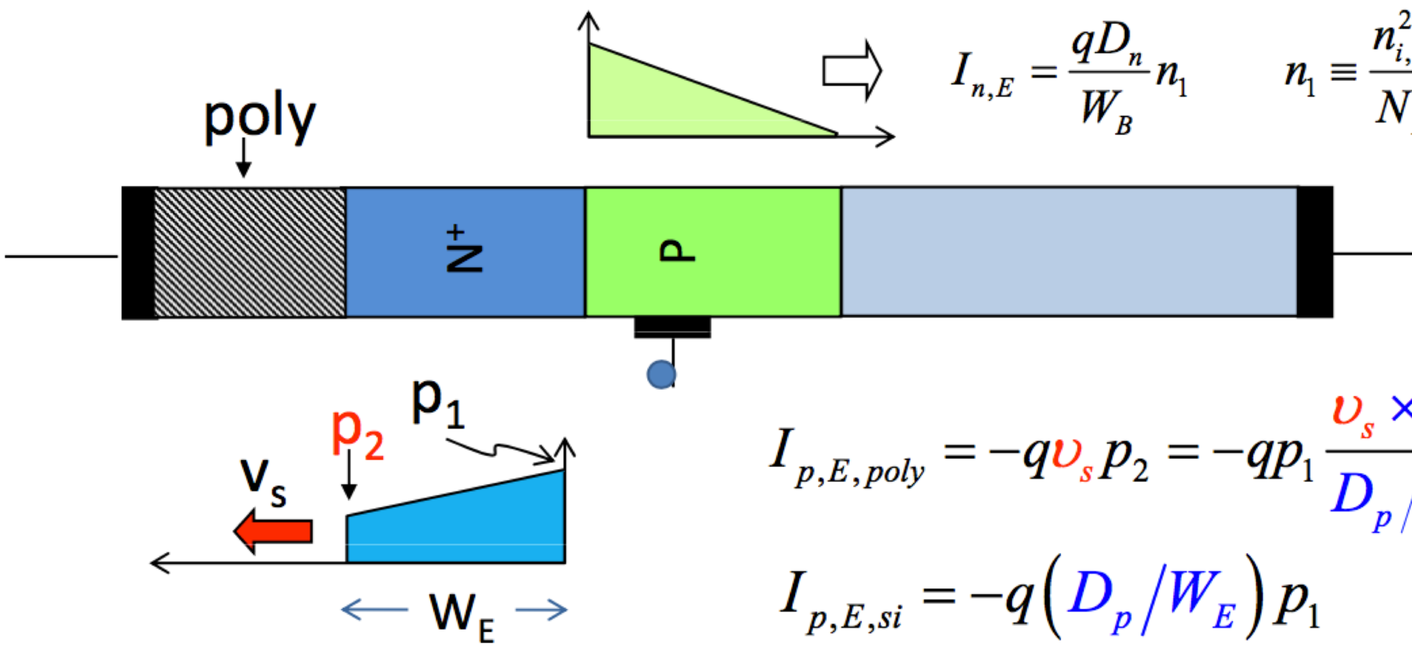
Heterojunction Bipolar Transistor

多晶硅发射极


Base
Emitter
Collector
N+
N-
N
P+
N+
SiGe intrinsic base
Dielectric trench
P-


emitter
N+
P
N
Poly-silicon

多晶硅发射极



$$I_{n,E} = \frac{qD_n}{W_B} n_1 \qquad n_1 \equiv \frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}\beta} - 1\right)$$

$$I_{p,E,poly} = -q\upsilon_s p_2 = -qp_1 \frac{\upsilon_s \times D_p / W_E}{D_p / W_E + \upsilon_s}$$

$$I_{p,E,si} = -q\left(D_p / W_E\right) p_1$$

$$\frac{I_{p,E,poly}}{I_{p,E,si}} = \frac{\upsilon_s}{D_p / W_E + \upsilon_s}$$

$$I_{p,E,poly} = -qD_p \frac{p_1 - p_2}{W_E} = -q\upsilon_s p_2$$

$$\frac{p_2}{p_1} = \frac{D_p / W_E}{D_p / W_E + \upsilon_s}$$

Question: Why does poly only suppress the hole current, not electron current?

多晶硅发射极晶体管的电流增益

$$I_{p,E,poly} = -qp_1 \frac{\upsilon_s \times D_p / W_E}{D_p / W_E + \upsilon_s} = I_{p,B,poly}$$

$$I_{p,E,si} = -q\left(D_p / W_E\right) p_1$$

$$\frac{I_{p,B,poly}}{I_{p,B,si}} = \frac{\upsilon_s}{D_p / W_E + \upsilon_s} \simeq \frac{I_{B,poly}}{I_{B,si}}$$

$$\beta_{poly} = \frac{I_C}{I_{B,poly}} = \left(\frac{I_C}{I_{B,si}}\right) \times \left[\frac{I_{B,si}}{I_{B,poly}}\right] \approx \left(\frac{D_n}{W_B} \frac{W_E}{D_p} \frac{n_{i,B}^2}{n_{i,E}^2} \frac{N_E}{N_B}\right) \times \left[\frac{D_p / W_E + \upsilon_s}{\upsilon_s}\right]$$

$$\rightarrow \frac{D_n}{W_B} \frac{n_{i,B}^2}{n_{i,E}^2} \frac{N_E}{N_B} \times \frac{1}{\upsilon_s} \quad (\because \upsilon_s << D_p / W_E)$$

Poly suppresses base current, increases gain ...

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$$\beta \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,E}^2}{n_{i,B}^2}\frac{N_E}{N_B} \rightarrow \frac{D_n}{W_B}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}\times\frac{1}{\upsilon_s}$$

Polysilicon Emitter

Graded Base transport

Classical Shockley transistor

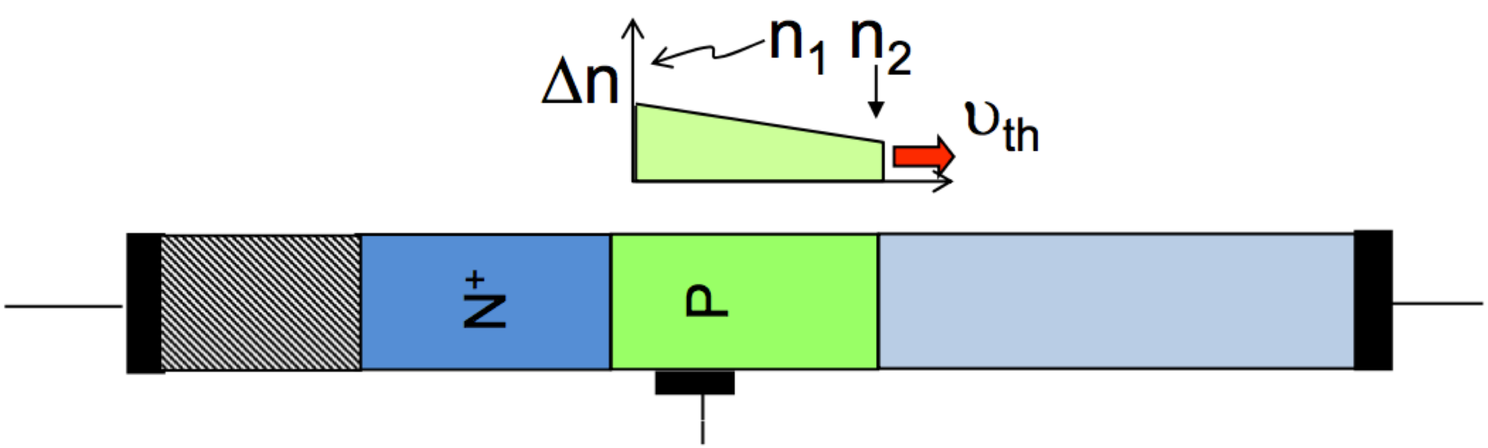
Heterojunction bipolar transistor

短基区准弹道输运晶体管

$$I_{n,E} = -qD_n \frac{n_1 - n_2}{W_B} = -q\upsilon_{th} n_2$$

$$\frac{n_2}{n_1} = \frac{D_n / W_B}{D_n / W_B + \upsilon_{th}}$$

$$\frac{I_{n,E,ballistic}}{I_{n,E,si}} = \frac{\upsilon_{th}}{D_n / W_B + \upsilon_{th}}$$



短基区准弹道输运晶体管的电流增益

$$\frac{I_{p,B,poly}}{I_{p,B,si}} = \frac{\upsilon_s}{D_p / W_E + \upsilon_s} \simeq \frac{I_{B,poly}}{I_{B,si}} \qquad \frac{I_{n,E,ballistic}}{I_{n,E,si}} = \frac{\upsilon_{th}}{D_n / W_B + \upsilon_{th}}$$

$$\beta_{poly,ballistic} = \frac{I_{C,ballistic}}{I_{B,poly}} = \left[\frac{I_{C,ballistic}}{I_{C,si}}\right] \times \left[\frac{I_{C,si}}{I_{B,si}}\right] \times \left[\frac{I_{B,si}}{I_{B,poly}}\right]$$

$$\approx \left[\frac{\upsilon_{th}}{D_n / W_B + \upsilon_{th}}\right] \times \left[\frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}\right] \times \left[\frac{D_p / W_E + \upsilon_s}{\upsilon_s}\right]$$

$$\rightarrow \frac{n_{i,B}^2}{n_{i,E}^2} \times \frac{N_E}{N_B} \times \frac{\upsilon_{th}}{\upsilon_s}$$

Quasi-Ballistic transport in very short base limits the gain ...

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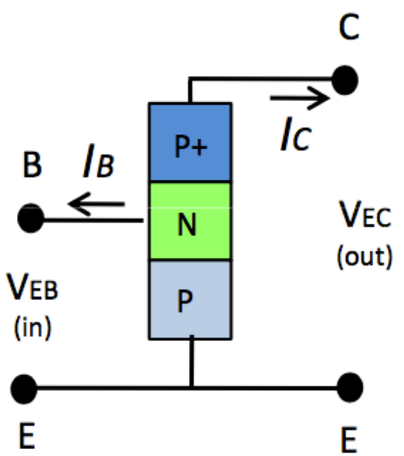
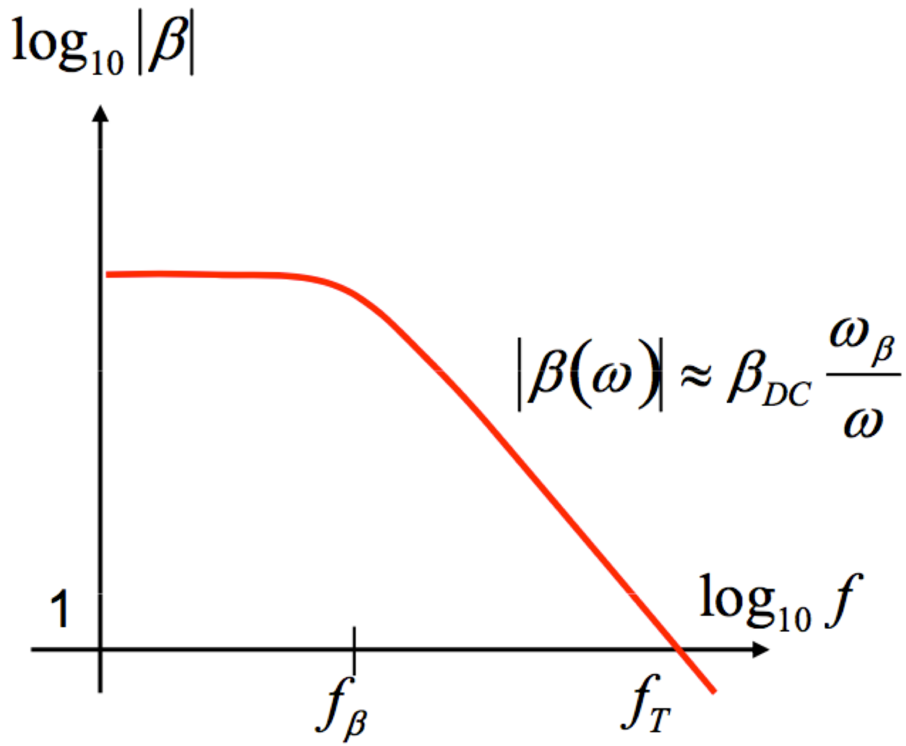
小信号响应

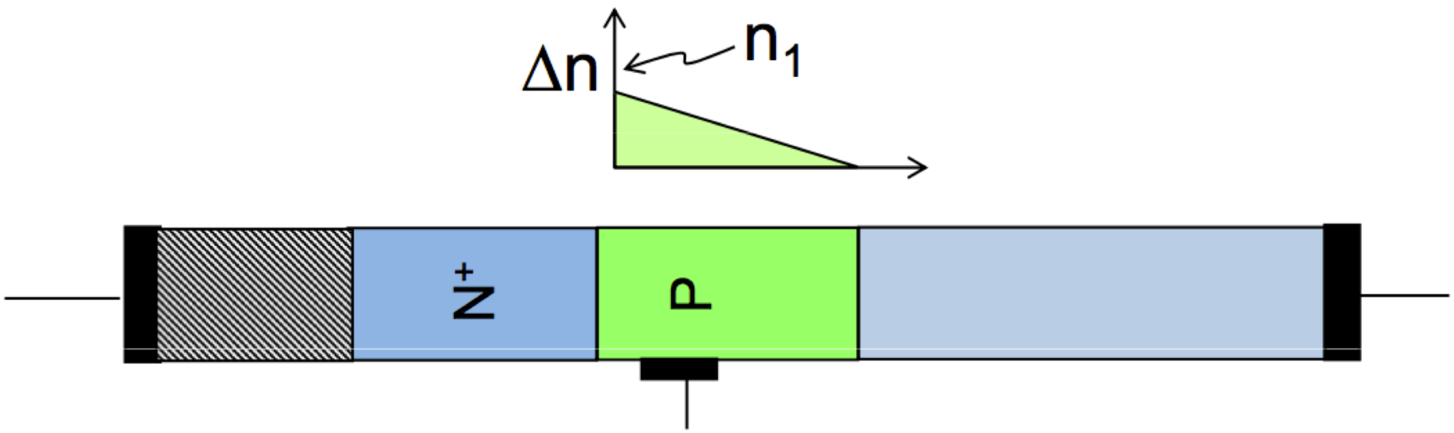




$$\frac{1}{2\pi f_T} = \left[\frac{W_B^2}{2D_n} + \frac{W_{BC}}{2\upsilon_{sat}}\right] + \frac{k_B T}{qI_C}\left[C_{j,BC} + C_{j,BE}\right]$$

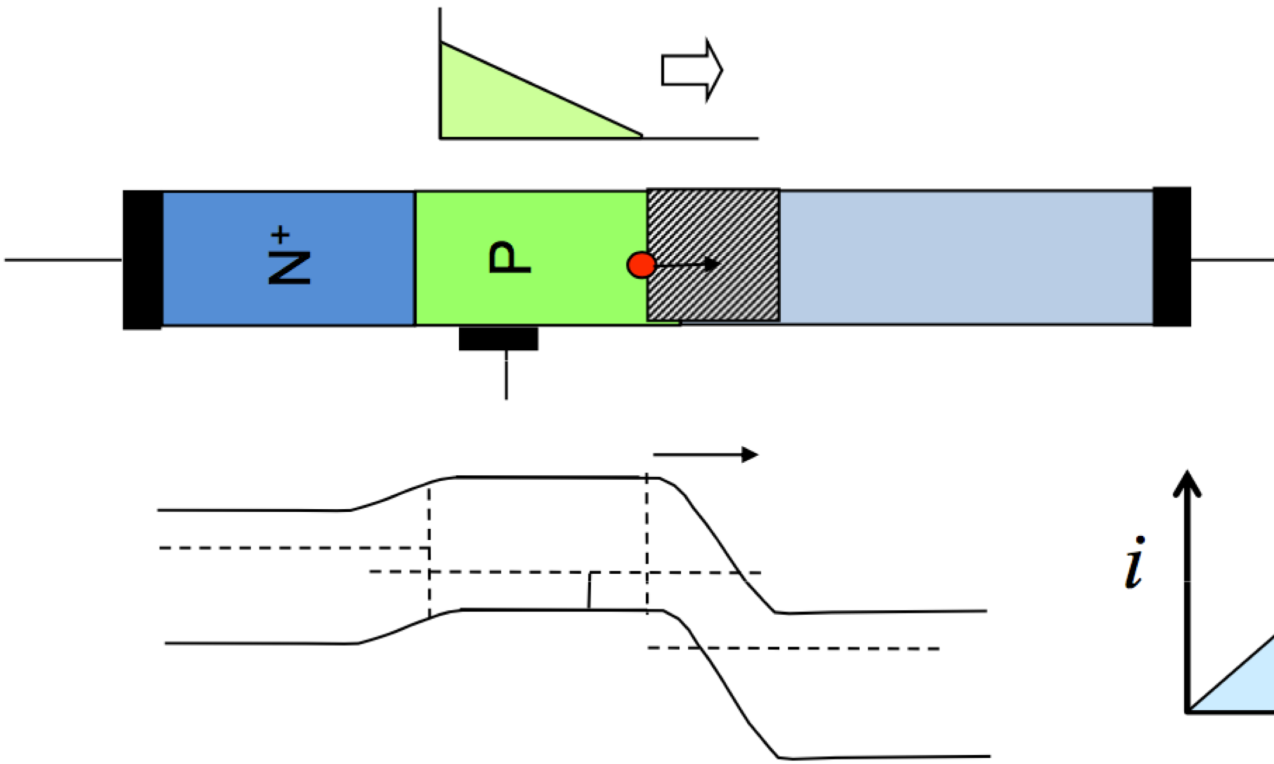
基区渡越时间

Ref. Charge control model

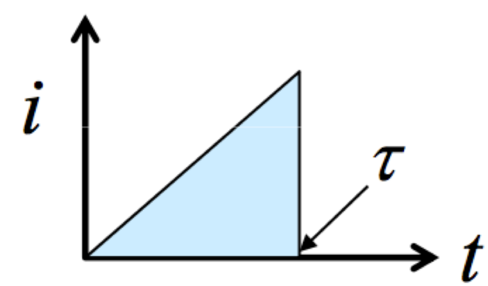


$$\frac{dQ_B}{dI_C}=\frac{Q_B}{I_C}=\frac{q\frac{1}{2}n_1W_B}{q\frac{n_1}{W_B}}=\frac{W_B^2}{2D_n}$$

收集区渡越时间



$$\tau = \frac{W_{BC}}{\upsilon_{sat}} ?$$



$$\tau_{eff,BC} = \frac{q}{i} = \frac{\tau}{2} = \frac{W_{BC}}{2\upsilon_{sat}}$$

$$\frac{1}{2} \times i \times \tau = q$$

Thanks!
Q&A