微电子器件物理
双极型晶体管2

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本节课提纲

1. 三极管的电流增益
2. 基极的掺杂设计
3. 集电极的掺杂设计

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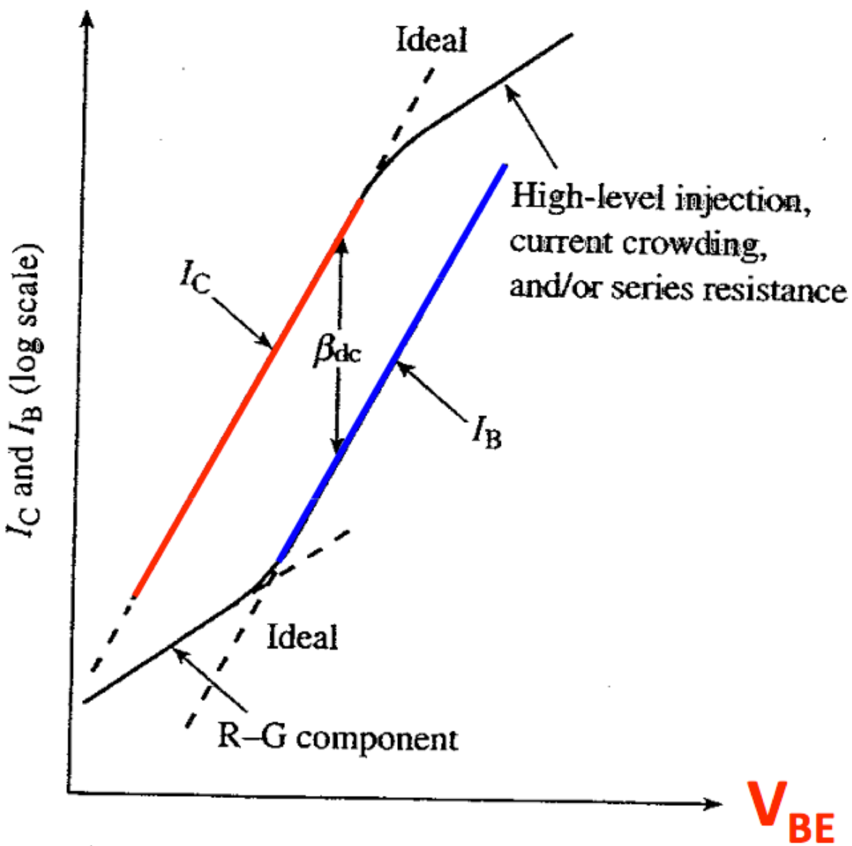
输出特性曲线

$$\frac{I_C}{A} \simeq -\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BE}/kT}-1\right) + \cancel{\frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV_{BC}/kT}-1\right)}$$



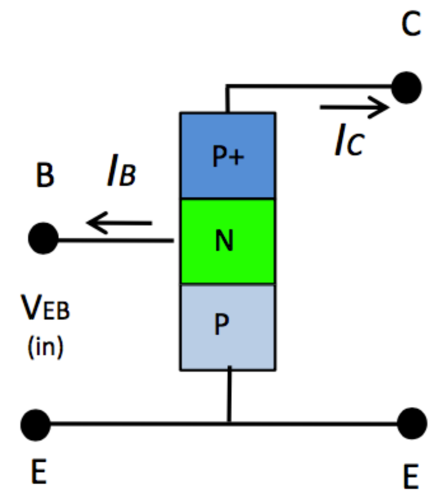
$$\frac{I_B}{A} = \frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}\left(e^{qV_{BE}/kT}-1\right)$$

$$\beta_{DC} = \frac{I_C}{I_B}$$

$\beta_{DC} \longrightarrow$ 共射级增益

电流增益

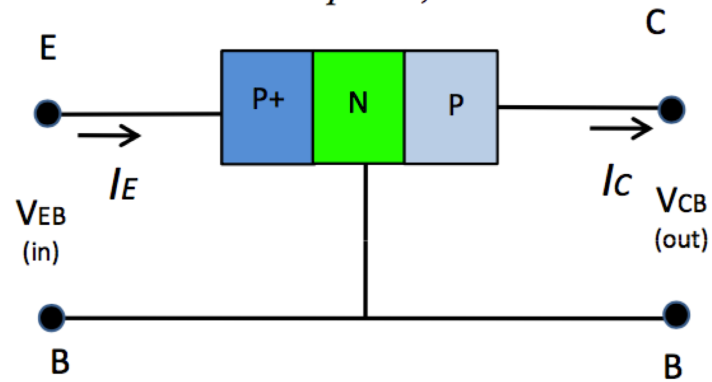
共射极电流增益



$$\beta_{DC} = \frac{I_C}{I_B}$$

$$= \frac{\dfrac{qD_n}{W_B}\dfrac{n_{i,B}^2}{N_B}(e^{qV_{BE}/kT}-1) + \dfrac{qD_n}{W_B}\dfrac{n_{i,B}^2}{N_B}(e^{(qV_{BC}/kT)}-1)}{\dfrac{qD_n}{W_E}\dfrac{n_{i,E}^2}{N_E}(e^{qV_{BE}/kT}-1)} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$

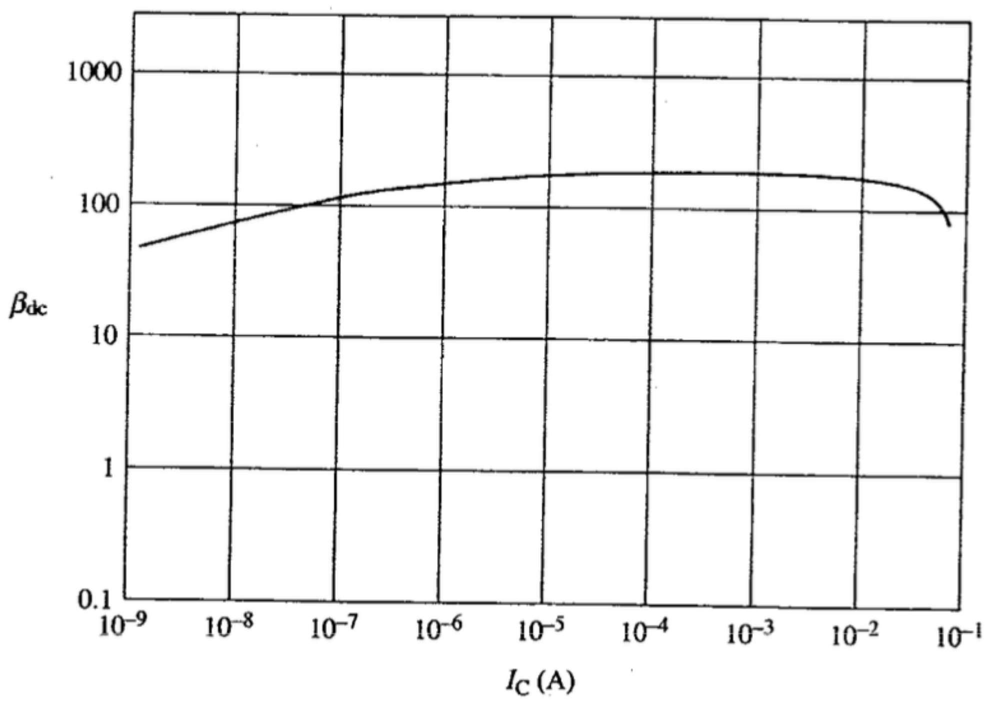
共基极电流增益



$$\alpha_{DC} = \frac{I_C}{I_E} \Rightarrow \beta_{DC} = \frac{I_C}{I_B} = \frac{I_C}{I_E - I_C} = \frac{\alpha_{DC}}{1-\alpha_{DC}}$$

电流增益

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



如何设计一个好的三极管

For a given Emitter length

~1, same material

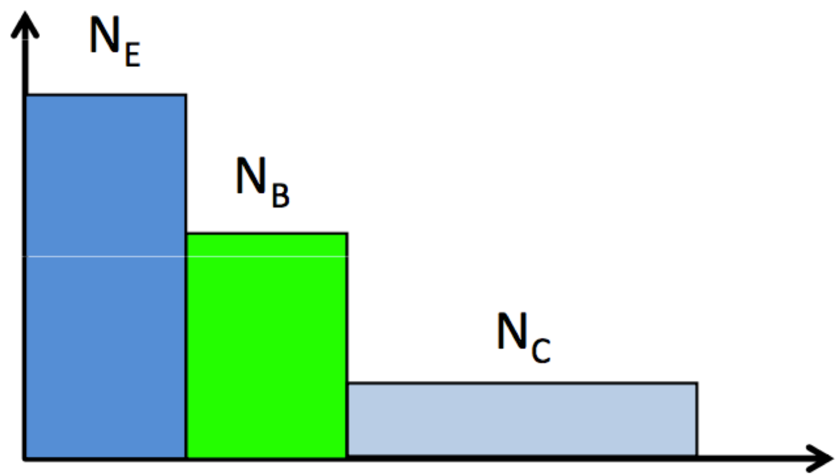
$$\beta_{DC} \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B}$$

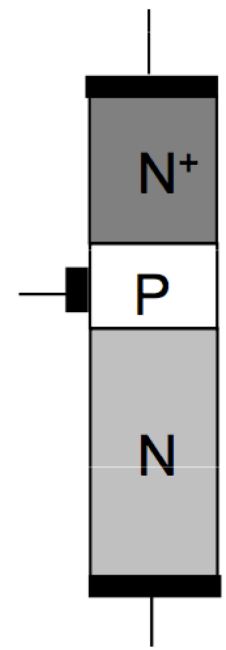
Make-Base short …
(few mm in 1950s, 200 A now)

Emitter doping higher
than Base doping

修改掺杂浓度

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





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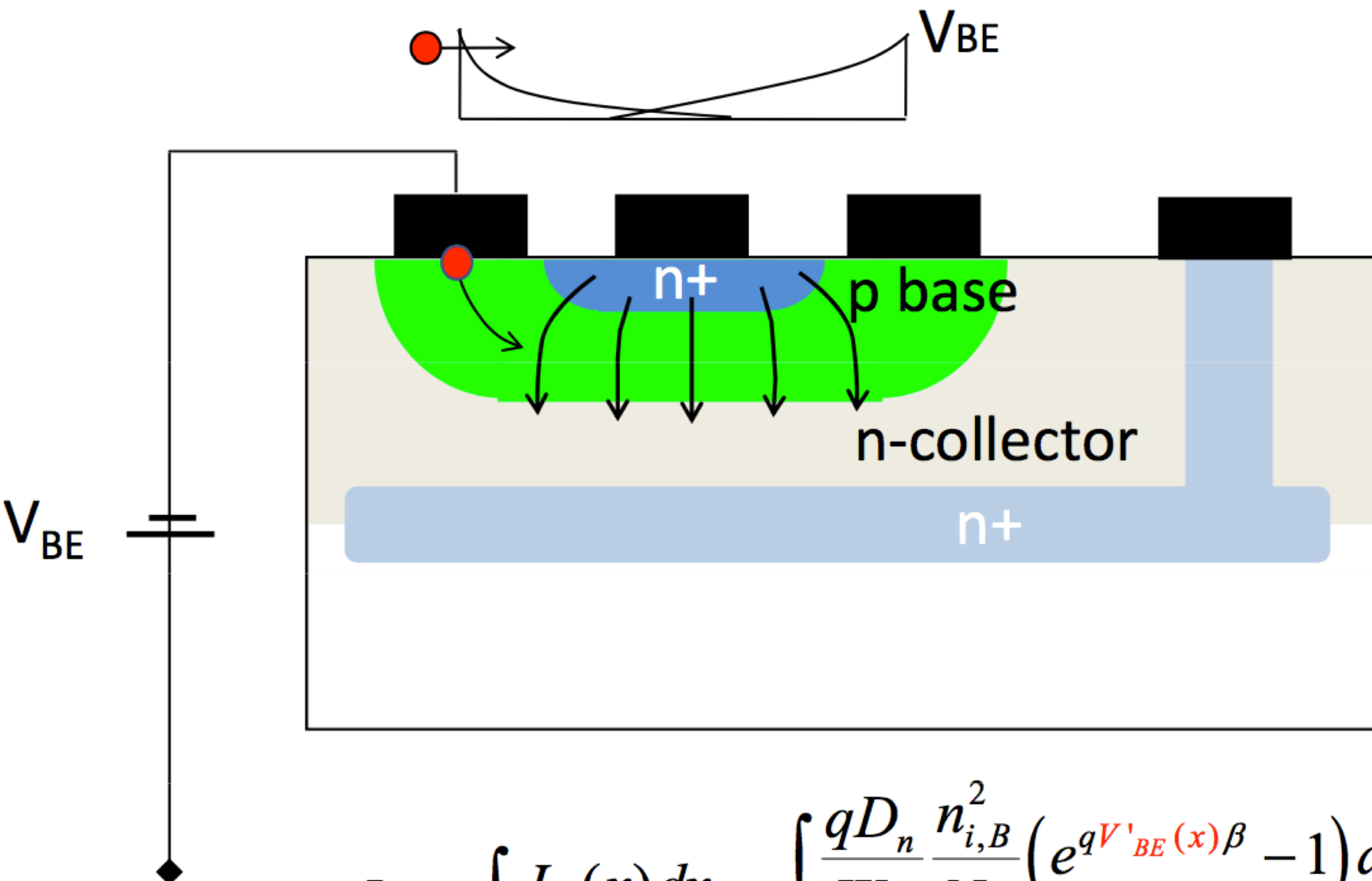
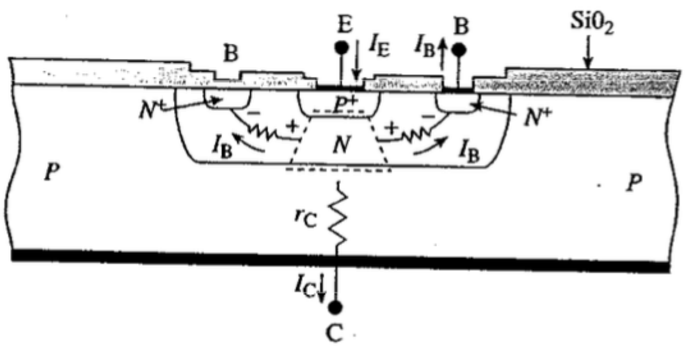
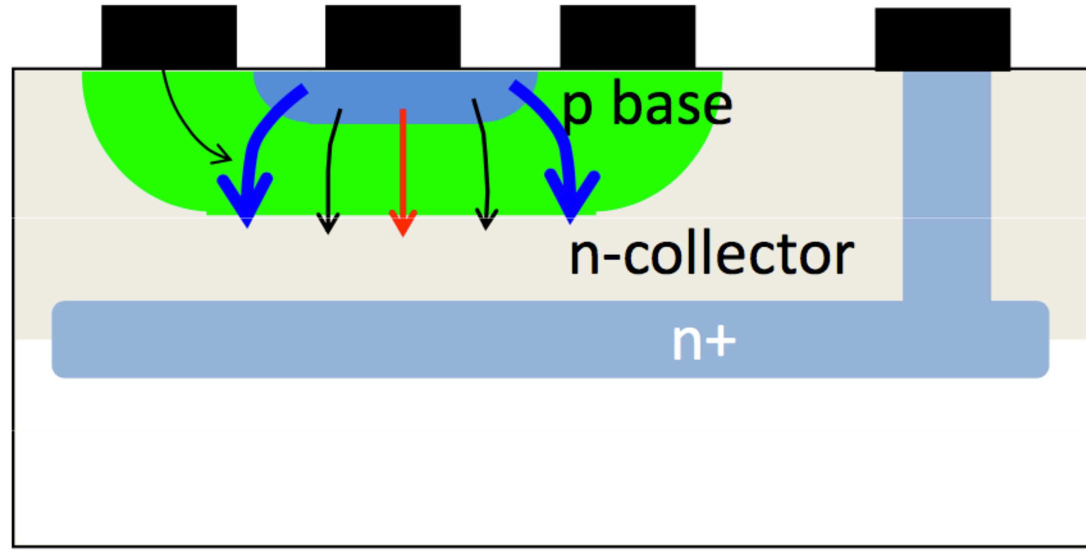
基极低掺杂浓度引入的问题1

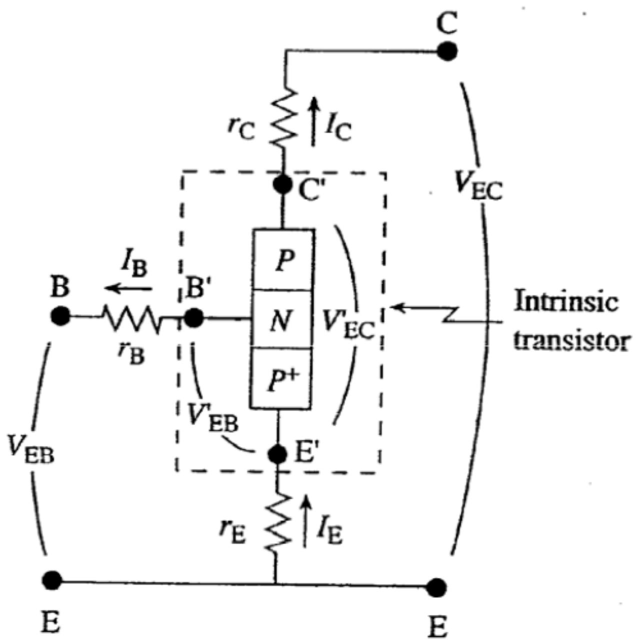


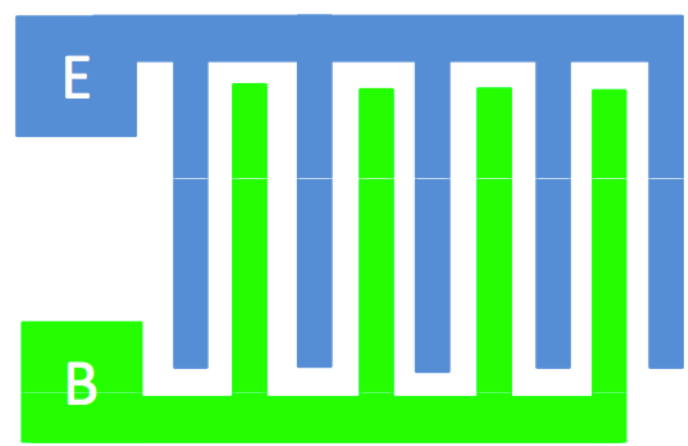
$$\beta = \frac{I_C}{I_B} = \frac{\int J_C(x)dx}{\int J_B(x)dx} = \frac{\int \frac{qD_n}{W_B}\frac{n_{i,B}^2}{N_B}\left(e^{qV'_{BE}(x)\beta}-1\right)dx}{\int \frac{qD_p}{W_E}\frac{n_{i,E}^2}{N_E}\left(e^{qV'_{BE}(x)\beta}-1\right)dx}$$

基极低掺杂浓度引入的问题2

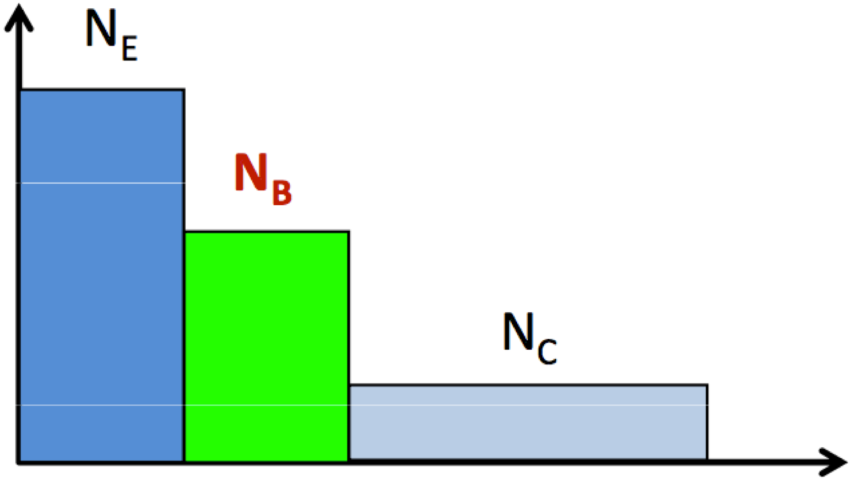


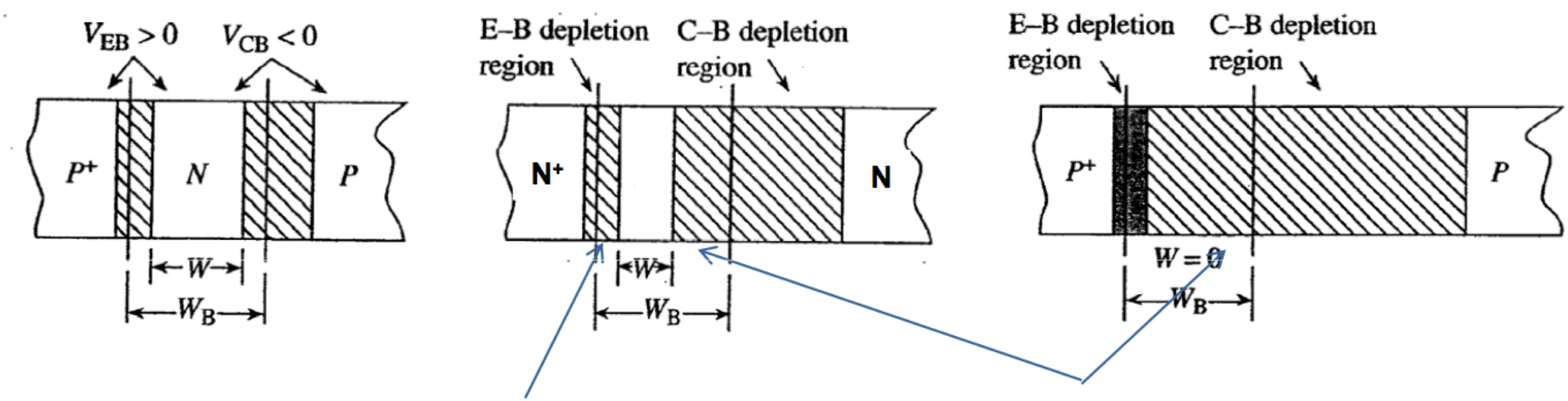






基极低掺杂浓度引入的问题3



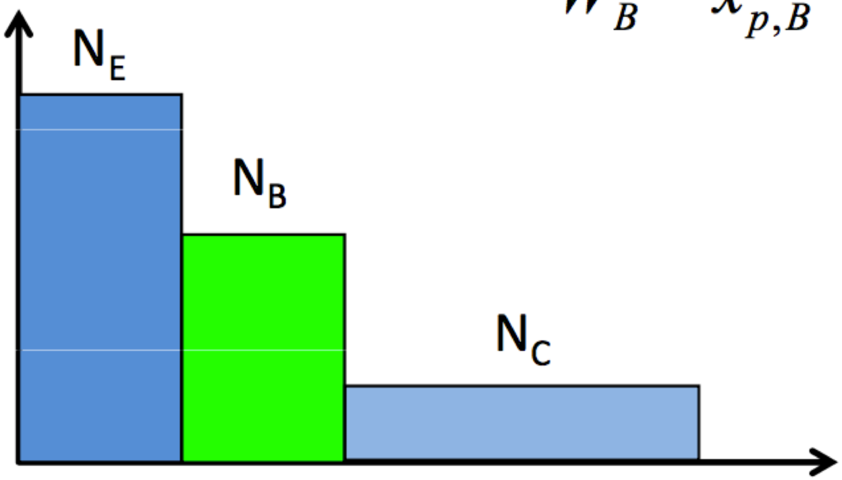


$$x_{p,BE}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_E}{N_B\left(N_E+N_B\right)}\left(V_{bi}-V_{BE}\right)}$$

$$x_{p,BC}=\sqrt{\frac{2k_s\varepsilon_0}{q}\frac{N_C}{N_B\left(N_C+N_B\right)}\left(V_{bi}-V_{BC}\right)}$$

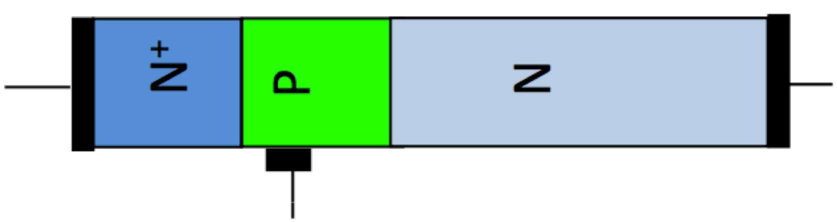
基极低掺杂浓度引入的问题4

$$\beta_{DC} \approx \frac{D_n}{W_B - x_{p,B} - x_{p,c}} \frac{W_E \cancel{n^2_{i,B}}}{D_p \cancel{n^2_{i,E}}} \frac{N_E}{N_B}$$



$$x_{p,BE} = \sqrt{\frac{2k_s\varepsilon_0}{q} \frac{N_E}{N_B(N_E + N_B)} (V_{bi} - V_{BE})}$$

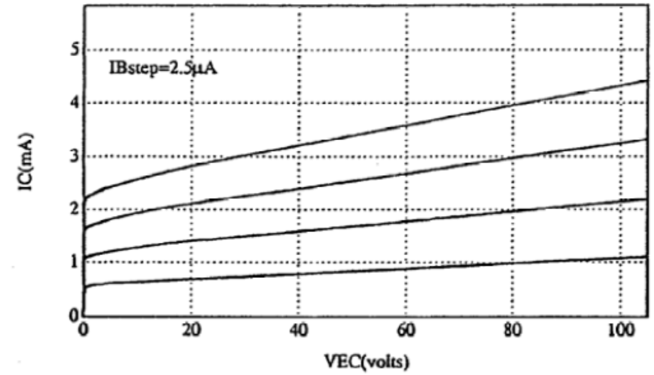
$$x_{p,BC} = \sqrt{\frac{2k_s\varepsilon_0}{q} \frac{N_C}{N_B(N_C + N_B)} (V_{bi} - V_{BC})}$$



Gain depends on collector voltage (bad) ...

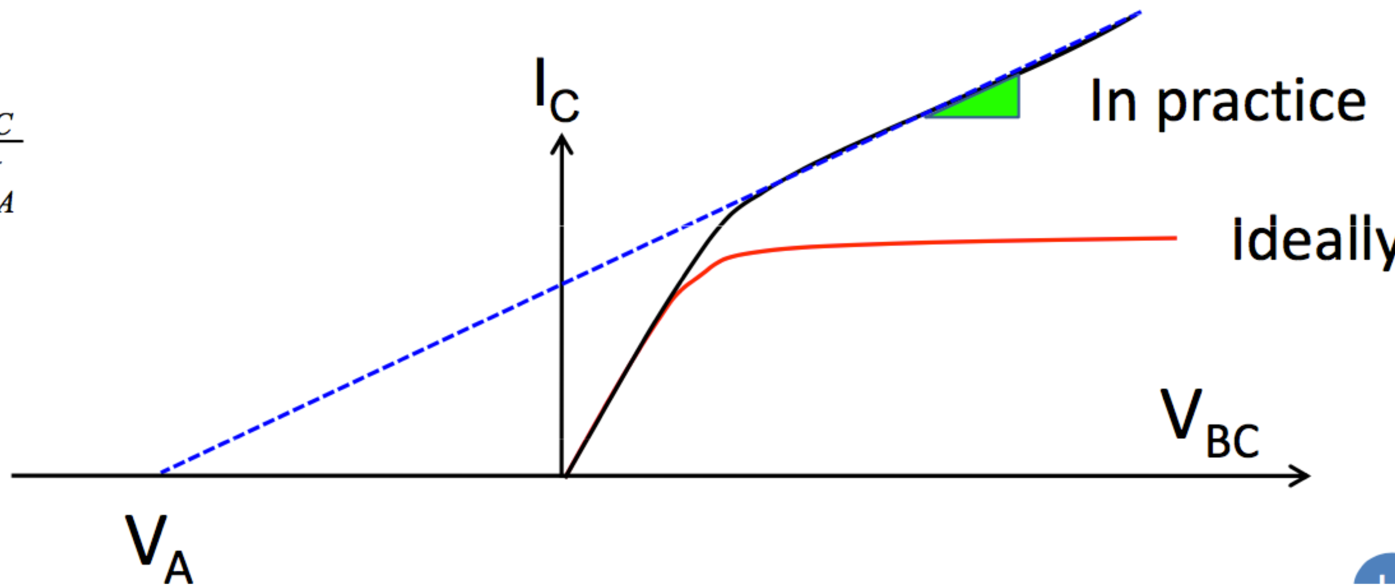
Early电压

$$\beta_{DC} \approx \frac{D_n}{W_B - x_{p.B} - x_{p.C}} \frac{W_E}{D_p} \cancel{\frac{n^2_{i,B}}{n^2_{i,E}}} \frac{N_E}{N_B}$$



$$I_{n,C} = -\frac{qD_n}{W_B'} \frac{n^2_{i,B}}{N_B}\left(e^{(qV_{BE}/kT)} - 1\right) + \frac{qD_n}{W_B'} \frac{n^2_{i,B}}{N_B}\left(e^{(qV_{BC}/kT)} - 1\right)$$

$$\frac{dI_C}{dV_{BC}} = \frac{I_C}{V_{BC} + V_A} \approx \frac{I_C}{V_A}$$



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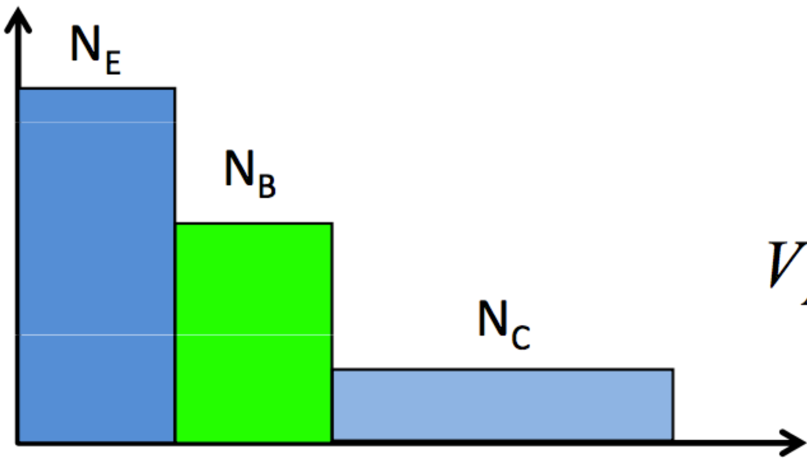
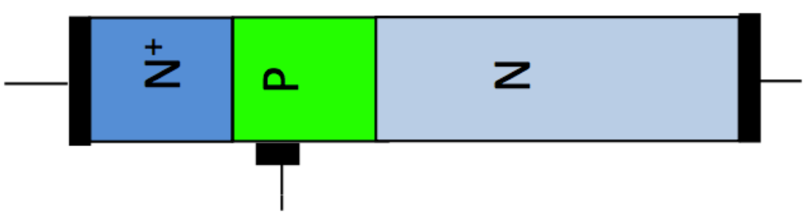
集电极掺杂

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

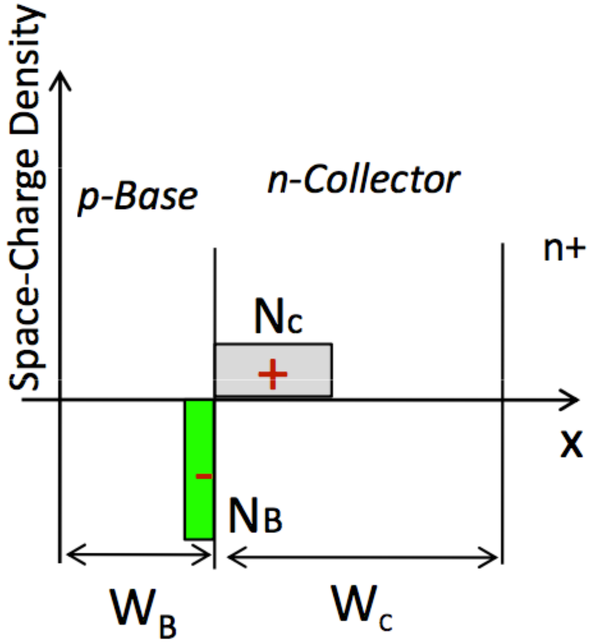


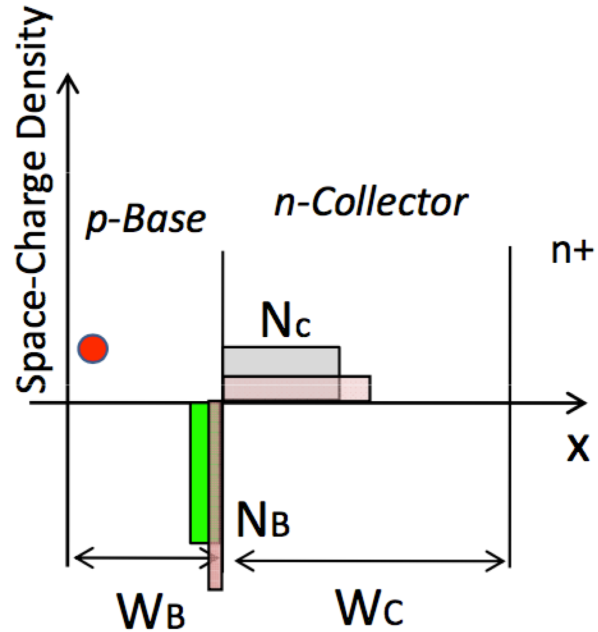
$$V_A = -\frac{q N_B W_B}{C_{CB}} \qquad C_{CB} = \frac{\kappa_s \varepsilon_0}{x_{n,C} + x_{p,B}}$$



If you want low base doping then reduce collector doping even more to increase Collector depletion.....

Kirk效应与基区扩展效应





$$N_B x_B = N_C x_C$$

$$V_{bi} - V_{BC} = \frac{q}{2\kappa_s \varepsilon_0}\left[N_B x_B^2 + N_C x_C^2\right]$$

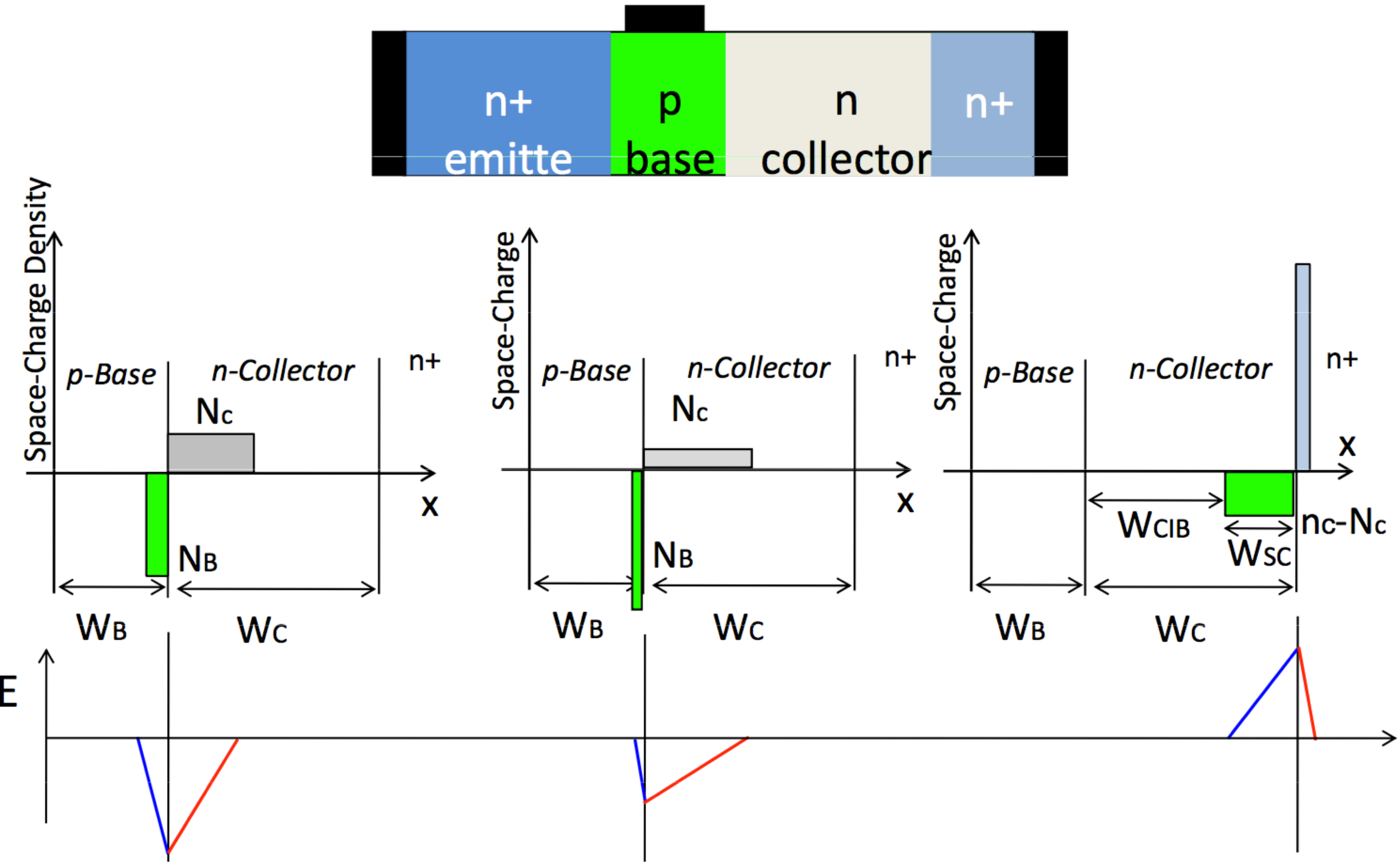
$$J_C = q\upsilon_{sat} n$$

$$\left(N_B + n\right) x_B' = \left(N_C - n\right) x_C'$$

$$V_{bi} - V_{BC} = \frac{q}{2\kappa_s \varepsilon_0}\left[\left(N_B + n\right) x_B^2{}' + \left(N_C - n\right) x_C^2{}'\right.$$

$$x_C' = x_C \sqrt{\frac{1 + \frac{n}{N_B}}{1 - \frac{n}{N_C}}} = x_C \sqrt{\frac{1 + \frac{J_C}{q\upsilon_{sat} N_B}}{1 - \frac{J_C}{q\upsilon_{sat} N_C}}}$$

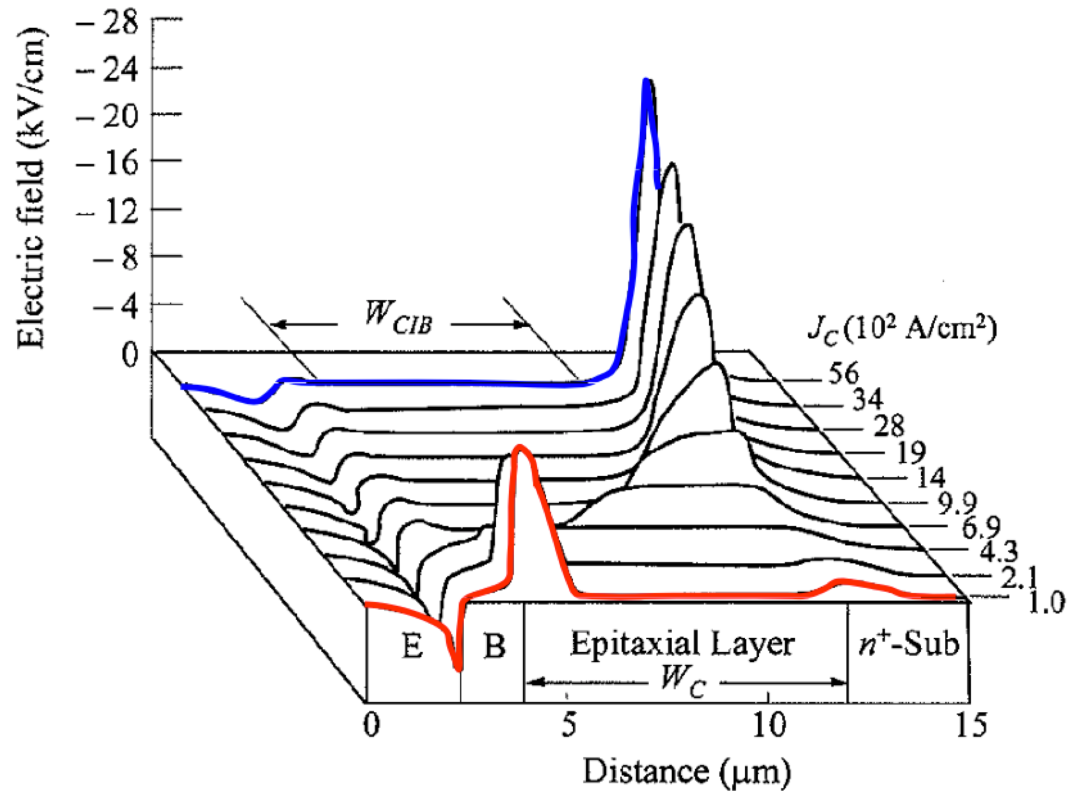
Kirk效应与基区扩展效应



Kirk效应与基区扩展效应

$$x_C' = x_C \sqrt{\frac{1+\dfrac{J_C}{q\upsilon_{sat}N_B}}{1-\dfrac{J_C}{q\upsilon_{sat}N_C}}}$$

$$J_{C,crit} = q\upsilon_{sat}N_C \equiv J_K$$



Can not reduce collector doping arbitrarily without causing base pushout

增加发射区掺杂浓度?

禁带变窄导致电流增益急剧降低

$$\beta \approx \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{n_{i,B}^2}{n_{i,E}^2}\frac{N_E}{N_B} = \frac{D_n}{W_B}\frac{W_E}{D_p}\frac{N_C N_V e^{-E_{g,B}/kT}}{N_C N_V e^{-E_{g,E}/kT}}\frac{N_E}{N_B} \approx e^{-\Delta E_g/kT}\frac{N_E}{N_B}$$

量子隧穿效应导致基极无法完全控制电流

Thanks!
Q&A