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第三章

3-2

一个NPN硅晶体管,具有下列参数: $x_B=2\mu m$, 在均匀掺杂基区 $N_a=5\times 10^{16}\,cm^{-3}$, $\tau_n=1\mu s$, $A=0.01cm^2$ 。 若集电结被反向偏置, $I_{nE}=1mA$,计算在发射结基区一边的过量电子浓度,发射结电压以及基区输运因子。

解:

$$egin{aligned} D_n &= V_T \mu_n = 26 m V imes 1350 cm^2 / V \cdot s = 35.1 cm^2 / s \ L_n &= \sqrt{D_n au_n} = \sqrt{35.1 cm^2 / s imes 1\mu s} = 5.9 imes 10^{-3} cm \ n_{p0} &= rac{n_i^2}{N_a} = rac{(1.5 imes 10^{10})^2}{5 imes 10^{16}} cm^{-3} = 4.5 imes 10^3 cm^{-3} \end{aligned}$$

当 $x_B \ll L_n$ 即 $x_B/L_n \ll 1$ 时,有

$$\coth(x_B/L_n) pprox rac{1}{\sinh(x_B/L_n)} pprox rac{L_n}{x_B}$$

且有集电结反偏即 $V_C < 0$,则

$$egin{aligned} I_{nE} &= -rac{qAD_n n_{p0}}{L_n}[(e^{V_E/V_T}-1)\coth(x_B/L_n) - (e^{V_C/V_T}-1)rac{1}{\sinh(x_B/L_n)}] \ &pprox -rac{qAD_n n_{p0}}{L_n}[(e^{V_E/V_T}-1)rac{L_n}{x_B} + rac{L_n}{x_B}] \ &= -rac{qAD_n n_{p0}e^{V_E/V_T}}{x_B} \end{aligned}$$

则有:

$$egin{align*} e^{V_E/V_T} &= -rac{x_B I_{nE}}{qAD_n n_{p0}} \ &= -rac{2\mu m imes 1mA}{-1.6 imes 10^{-19} C imes 0.01 cm^2 imes 35.1 cm^2/s imes 4.5 imes 10^3 cm^{-3}} \ &pprox 7.91 imes 10^8 \ \end{align*}$$

解得发射结电压

$$V_E = V_T \ln e^{V_E/V_T} = 0.026 V imes \ln \left(7.91 imes 10^8
ight) pprox 0.5327 V$$

电子浓度

$$n_p(0) = n_{p0} e^{V_E/V_T} = 4.5 imes 10^3 cm^{-3} imes 7.91 imes 10^8 = 3.56 imes 10^{12} cm^{-3}$$

基区输运因子

$$rac{x_B}{L_n} = rac{2 \mu m}{5.9 imes 10^{-3} cm} pprox 0.0339$$
 $eta_T = rac{I_{nC}}{I_{nE}} = rac{1}{\cosh{(x_B/L_n)}} = rac{1}{\cosh{0.0339}} pprox 0.9989$

3-3

在习题3-2的晶体管中,假设发射极的掺杂浓度为

 $10^{18}cm^{-3}$, $x_E=2\mu m$, $au_{pE}=10ns$, 发射结空间电荷区中 $au=0.1\mu s$ 。计算在 $I_{nE}=1mA$ 时的发射效率和 h_{FE} 。

解:

发射结内建电势差

$$\psi_0 = V_T \ln rac{N_a N_d}{n_i^2} = 0.026 V imes \ln rac{5 imes 10^{16} imes 10^{18}}{(1.5 imes 10^{10})^2} pprox 0.8598 V$$

发射结势垒区宽度

$$egin{align} W_E &= \sqrt{rac{2\epsilon(\psi_0 - V_E)}{qN_a}} \ &= \sqrt{rac{2 imes 1.053 imes 10^{-12} imes (0.8598 - 0.5327)}{1.6 imes 10^{-19} imes 5 imes 10^{16}}}cm \ &pprox 9.24 imes 10^{-6}cm \ \end{cases}$$

发射结反向电流

$$egin{align*} I_{RE} &= rac{qAn_iW}{2 au_0}e^{V_E/2V_T} \ &= rac{1.6 imes10^{-19} imes0.01 imes1.5 imes10^{10} imes9.24 imes10^{-6}}{2 imes10^{-7}} imes\sqrt{7.91 imes10^8} \ &pprox 3.12 imes10^{-6}A = 3.12 imes10^{-2}mA \end{split}$$

空穴扩散系数 $D_{pE} = V_T \mu_p = 0.026 V imes 480 cm^2/V \cdot s = 12.48 cm^2/s$

空穴浓度
$$p_{E0}=rac{n_i^2}{N_d}=rac{(1.5 imes 10^{10})^2}{10^{18}}cm^{-3}=225cm^{-3}$$

空穴电流

$$egin{align} I_{pE} &= -rac{qAD_{pE}p_{E0}}{x_E-W_E}(e^{V_E/V_T}-1) \ &= rac{1.6 imes 10^{-19} imes 0.01 imes 12.48 imes 225}{2 imes 10^{-4}-9.24 imes 10^{-6}} imes (7.91 imes 10^8-1)A \ &pprox 1.68 imes 10^{-5}A = 1.68 imes 10^{-2}mA \ \end{align}$$

发射效率

$$\gamma = rac{I_{nE}}{I_E} = rac{I_{nE}}{I_{nE} + I_{pE} + I_{RE}} = rac{1}{1 + 1.68 imes 10^{-2} + 3.12 imes 10^{-2}} pprox 0.954$$

共基极直流电流增益

$$lpha_0 = \gamma eta_T = 0.954 imes 0.9989 pprox 0.953$$

共发射极直流电流增益

$$h_{FE} = \frac{\alpha_0}{1 - \alpha_0} = \frac{0.953}{1 - 0.953} \approx 20.28$$

(1) 根据公式(3-3-5)或(3-3-6),证明对于任意的 x_B/L_n 值,公式(3-4-9)和(3-4-11)变成

$$egin{aligned} a_{11} &= -qAn_i^2 \left[rac{D_n}{N_a L_n} \coth rac{x_B}{L_n} + rac{D_{PE}}{N_{dE} x_E}
ight] \ a_{12} &= a_{21} = rac{qAD_n n_i^2}{N_a L_n} \mathrm{csc} \, h rac{x_B}{L_n} \ a_{22} &= -qAn_i^2 \left[rac{D_n}{N_a L_n} \coth rac{x_B}{L_n} + rac{D_{PC}}{N_{dC} L_{PC}}
ight] \end{aligned}$$

(2) 证明,若 $x_B/L_n << 1$,(1) 中的表达式约化为(3-4-9) 和(3-4-11)。

$$I_E = -I_{F0}(e^{V_E/V_T} - 1) + \alpha_R I_{R0}(e^{V_C/V_T} - 1)$$
 (3-4-5)

$$I_C = \alpha_F I_{F0} (e^{V_E/V_T} - 1) - I_{R0} (e^{V_C/V_T} - 1)$$
 (3-4-6)

$$a_{11} = -qAn_i^2\left(rac{D_n}{N_a x_B} + rac{D_{PE}}{N_{dE} x_E}
ight), \quad a_{12} = rac{qAD_n n_i^2}{N_a x_B} \hspace{0.5cm} (ext{3-4-9})$$

$$a_{21} = rac{qAD_n n_i^2}{N_a x_B}, \quad a_{22} = -qAn_i^2 \left(rac{D_n}{N_a x_B} + rac{D_{PC}}{N_{dC} L_{PC}}
ight) \ \ (ext{3-4-11})$$

解:

(1) 对于E-M方程,有 $I_E=I_{pE}+I_{nE}$,其中

$$egin{split} I_{nE} &= -rac{qAD_n n_{p0}}{L_n}[(e^{V_E/V_T}-1)\coth(x_B/L_n) - (e^{V_C/V_T}-1)rac{1}{\sinh(x_B/L_n)}] \ I_{pE} &= -qAn_i^2rac{D_{PE}}{N_{dE}x_E}(e^{V_E/V_T}-1) \end{split}$$

两项相加并对比E-M方程系数可得

$$egin{aligned} a_{11} &= -qAn_i^2\left[rac{D_n}{N_aL_n}\cothrac{x_B}{L_n} + rac{D_{PE}}{N_{dE}x_E}
ight] \ a_{12} &= rac{qAD_nn_i^2}{N_aL_n} \csc hrac{x_B}{L_n} \end{aligned}$$

同理可得

$$egin{align} a_{21} &= rac{qAD_n n_i^2}{N_a L_n} \mathrm{csc}\, h rac{x_B}{L_n} \ a_{22} &= -qAn_i^2 \left[rac{D_n}{N_a L_n} \mathrm{coth}\, rac{x_B}{L_n} + rac{D_{PC}}{N_{dC} L_{PC}}
ight] \end{aligned}$$

(2) 若
$$x_B/L_n << 1$$
,则有 $\coth rac{x_B}{L_n} pprox rac{L_n}{x_B}$ 代入可得

$$egin{aligned} a_{11} &= -qAn_i^2 \left(rac{D_n}{N_a x_B} + rac{D_{PE}}{N_{dE} x_E}
ight) \ a_{12} &= a_{21} = rac{qAD_n n_i^2}{N_a x_B} \ a_{22} &= -qAn_i^2 \left(rac{D_n}{N_a x_B} + rac{D_{PC}}{N_{dC} L_{PC}}
ight) \end{aligned}$$

证明在正向有源模式,晶体管发射极电流-电压特性可用下式表示

 $I_Epprox rac{I_{E0}}{1-lpha_Flpha_R}e^{V_E/V_T}+rac{qAn_iW_E}{2 au_0}e^{V_E/2V_T}$,其中 I_{E0} 为集电极开路时发射结反向饱和电流。

提示:首先由EM方程导出 $I_{F0}=rac{I_{E0}}{1-lpha_Flpha_R}$ 。

证明:有EM方程

$$\left\{egin{aligned} I_E = -I_{F0}(e^{V_E/V_T}-1) + lpha_R I_{R0}(e^{V_C/V_T}-1) \ I_C = lpha_F I_{F0}(e^{V_E/V_T}-1) - I_{R0}(e^{V_C/V_T}-1) \end{aligned}
ight.$$

当集电极开路,发射极反偏时, $I_C=0$, $e^{V_E/V_T}\ll 1$

$$\left\{egin{aligned} I_{E0} = I_{F0} + lpha_R I_{R0} (e^{V_C/V_T} - 1) \ 0 = -lpha_F I_{F0} - I_{R0} (e^{V_C/V_T} - 1) \end{aligned}
ight.$$

二式联立可得
$$I_{E0}=I_{F0}-lpha_Rlpha_FI_{F0}\implies I_{F0}=rac{I_{E0}}{1-lpha_Flpha_R}$$

正向有源模式下, $e^{V_C/V_T} \ll 1$, $e^{V_E/V_T} \gg 1$, 则有

$$egin{aligned} I_E &= -I_{F0}(e^{V_E/V_T}-1) + lpha_R I_{R0}(e^{V_C/V_T}-1) \ &pprox -I_{F0}e^{V_E/V_T} - lpha_R I_{R0} \ &pprox -I_{F0}e^{V_E/V_T} \end{aligned}$$

EM方程忽略了复合电流
$$I_{RE}=rac{qAn_{i}W_{E}}{2 au_{0}}e^{V_{E}/2V_{T}}$$

且EM方程中 I_E 方向与实际方向相反。代入可得

(1) 忽略空间电荷区的复合电流,证明晶体管共发射极输出特性的精确表达式为

$$V_{CE} = -V_T \ln rac{I_{R0}(1-lpha_Flpha_R) + lpha_FI_B - I_C(1-lpha_F)}{I_{F0}(1-lpha_Flpha_R) + I_B + I_C(1-lpha_R)} - V_T \ln rac{lpha_R}{lpha_F}$$

提示:首先求出用电流表示结电压的显式解。

(2) 若 $I_B \gg I_{E0}$ 且 $\alpha_F I_B \gg I_{R0} (1 - \alpha_F \alpha_R)$,证明上式化为:

$$V_{CE}=V_T\lnrac{1/lpha_R+I_C/I_Bh_{FER}}{1-I_C/I_Bh_{FEF}}$$
 其中 $h_{FEF}=rac{lpha_F}{1-lpha_F}, h_{FER}=rac{lpha_R}{1-lpha_R}$

证明:

(1) 有EM方程

$$\left\{egin{aligned} I_E = -I_{F0}(e^{V_E/V_T}-1) + lpha_R I_{R0}(e^{V_C/V_T}-1) \ I_C = lpha_F I_{F0}(e^{V_E/V_T}-1) - I_{R0}(e^{V_C/V_T}-1) \end{aligned}
ight.$$

两式联立可解得:

$$\left\{egin{aligned} V_E = V_T \lnrac{I_E + lpha_R I_C + I_{F0}(lpha_R lpha_F - 1)}{I_{F0}(lpha_R lpha_F - 1)} \ V_C = V_T \lnrac{I_C + lpha_F I_E + I_{R0}(lpha_R lpha_F - 1)}{I_{R0}(lpha_R lpha_F - 1)} \end{aligned}
ight.$$

在EM方程中有 $I_E + I_C + I_B = 0, \alpha_R I_{R0} = \alpha_F I_{F0}$, 代入则有:

$$\begin{split} V_{CE} &= V_E - V_C \\ &= V_T \ln \frac{[I_E + \alpha_R I_C + I_{F0}(\alpha_R \alpha_F - 1)]I_{R0}}{[I_C + \alpha_F I_E + I_{R0}(\alpha_R \alpha_F - 1)]I_{F0}} \\ &= V_T \ln \frac{-(I_C + I_B) + \alpha_R I_C + I_{F0}(\alpha_R \alpha_F - 1)}{I_C - \alpha_F (I_C + I_B) + I_{R0}(\alpha_R \alpha_F - 1)} + V_T \ln \frac{I_{R0}}{I_{F0}} \\ &= -V_T \ln \frac{I_{R0}(1 - \alpha_R \alpha_F) + \alpha_F I_B - I_C (1 - \alpha_F)}{I_{F0}(1 - \alpha_R \alpha_F) + I_B + I_C (1 - \alpha_R)} - V_T \ln \frac{\alpha_R}{\alpha_F} \end{split}$$

(2) 由3-5可得 $I_{E0}=I_{F0}-lpha_Rlpha_FI_{F0}=I_{F0}(1-lpha_Rlpha_F)\ll I_B$,代入 V_{CE}

$$egin{aligned} V_{CE} &= -V_T \ln rac{I_{R0}(1 - lpha_R lpha_F) + lpha_F I_B - I_C (1 - lpha_F)}{I_{F0}(1 - lpha_R lpha_F) + I_B + I_C (1 - lpha_R)} - V_T \ln rac{lpha_R}{lpha_F} \ &pprox V_T \ln rac{[I_B + I_C (1 - lpha_R)] lpha_F}{[lpha_F I_B - I_C (1 - lpha_F)] lpha_R} \ &= V_T \ln rac{1/lpha_R + I_C (1 - lpha_R) / (I_B lpha_R)}{1 - I_C (1 - lpha_F) / (I_B lpha_F)} \ &= V_T \ln rac{1/lpha_R + I_C / (I_B h_{FRR})}{1 - I_C / (I_B h_{FEF})} \end{aligned}$$

其中
$$h_{FEF}=rac{lpha_F}{1-lpha_F}, h_{FER}=rac{lpha_R}{1-lpha_R}$$

一个用离子注入制造的NPN晶体管,其中性区内浅杂质浓度为 $N_a(x)=N_0e^{-x/L}$,其中 $N_0=2\times 10^{18}cm^{-3}$, $L=0.3\mu m$ 。

- (1) 求宽度为 $0.8\mu m$ 的中性区内单位面积的杂质总量;
- (2) 求出中性区内的平均杂质浓度;
- (3) 若 $L_{pE}=1\mu m$, $N_{dE}=10^{19}cm^{-3}$, $D_{pE}=1cm^2/s$, 基区内少子平均寿命为 $10^{-6}s$, 基区的平均扩散系数和(2)中的杂质浓度相应 , 求共发射极电流增益。

解:

(1) 单位面积杂质总量:

$$egin{split} \int_0^{x_B} N_a(x) \, dx &= \int_0^{x_B} N_0 e^{-x/L} \, dx = L N_0 (1 - e^{-x_B/L}) \ &= 0.3 \mu m imes 2 imes 10^{18} cm^{-3} imes (1 - e^{-0.8/0.3}) \ &= 5.58 imes 10^{13} cm^{-2} \end{split}$$

(2) 中性区平均杂质浓度:

$$\overline{N_a} = rac{\int_0^{x_B} N_a(x) \, dx}{x_B} = rac{5.58 imes 10^{13} cm^{-2}}{0.8 \mu m} = 6.975 imes 10^{17} cm^{-3}$$

(3) 共发射极电流增益取倒数:

$$h_{FE}^{-1} = rac{N_a x_B D_{pE}}{N_{dE} x_E D_n} + rac{x_B^2}{2L_n^2} + rac{N_a x_B W_E}{2D_n n_i au_0} e^{-V_E/2V_T} \overset{V_E \gg V_T}{pprox} rac{N_a x_B D_{pE}}{N_{dE} x_E D_n} + rac{x_B^2}{2L_n^2}$$

其中:

$$D_n = \mu_n V_T = 700 cm^2 / V \cdot s \times 0.026 V = 18.2 cm^2 / s$$

 $L_n^2 = D_n \tau_n = 18.2 cm^2 / s \times 10^{-6} s = 1.82 \times 10^{-7} cm^2$

代入电流增益倒数方程:

$$egin{aligned} h_{FE}^{-1} &= rac{N_a x_B D_{pE}}{N_{dE} x_E D_n} + rac{x_B^2}{2 L_n^2} \ &= rac{6.975 imes 10^{17} imes 0.8 imes 10^{-4} imes 1}{10^{19} imes 10^{-4} imes 18.2} + rac{(0.8 imes 10^{-4})^2}{2 imes 1.82 imes 10^{-7}} \ &pprox 0.00318 \end{aligned}$$

则电流增益: $h_{FE} = \frac{1}{0.00318} pprox 314$

3-8

若在公式 $I_n=\frac{qAD_nn_i^2}{\int_0^{x_B}N_adx}e^{V_E/V_T}$ 中假设 $I_C=I_n$,则可在集电极电流 $I_C\sim V_E$ 曲线计算出根梅尔数。求出图 3-12 中晶体管中的根梅尔数。采用 $D_n=35cm^2/s,\ A=0.1cm^2$ 、以及 $n_i=1.5\times 10^{10}cm^{-3}$ 。

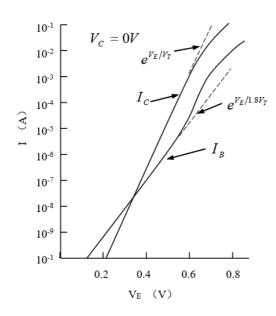


图 3-12 NPN 晶体管的静态电流—电压特性

解:令
$$G_M=\int_0^{x_B}N_adx$$
, $I_0=rac{qAD_nn_i^2}{G_M}$,则有 $I_n=I_0e^{V_E/V_T}\implies \lg I_n=rac{V_E}{V_T}\lg e+\lg I_0$

图像取两点 $(V_E, \lg I_n) = (0.22, -10)$ 和 $(V_E, \lg I_n) = (0.44, -6)$ 代入直线方程 $\lg I_n = KV_E + B$

$$\begin{cases} -10 &= 0.22K + B \\ -6 &= 0.44K + B \end{cases} \implies \begin{cases} K = 18.18 \\ B = -14 \end{cases}$$

即 $\lg I_0 = B = -14 \implies I_0 = 10^{-14} A$,代入 G_M 中:

$$egin{align} G_M &= rac{qAD_n n_i^2}{I_0} \ &= rac{1.6 imes 10^{-19} C imes 0.1 cm^2 imes 35 cm^2/s imes (1.5 imes 10^{10} cm^{-3})^2}{10^{-14} A} \ &= 1.26 imes 10^{16} cm^{-2} \ \end{align}$$

3-9

- (1) 证明对于均匀掺杂的基区,式 $eta_T=1-rac{1}{L_n^2}\int_0^{x_B}(rac{1}{N_a}\int_x^{x_B}N_adx)dx$ 简化为 $eta_T=1-rac{x_B^2}{2L_n^2}$;
- (2) 若基区杂质为指数分布,即 $N_a=N_0e^{-\alpha x/x_B}$,推导出基区输运因子的表示式。

解:

(1) 均匀掺杂即 N_a 与x无关,此时有

$$eta_T = 1 - rac{1}{L_n^2} \int_0^{x_B} (rac{1}{N_a} \int_x^{x_B} N_a dx) dx \ = 1 - rac{1}{L_n^2} \int_0^{x_B} \int_x^{x_B} dx dx \ = 1 - rac{1}{L_n^2} \int_0^{x_B} x_B - x dx \ = 1 - rac{1}{L_n^2} (x_B x - rac{1}{2} x^2) igg|_0^{x_B} \ = 1 - rac{x_B^2}{2L_n^2}$$

(2) 代入 $N_a = N_0 e^{-\alpha x/x_B}$

$$eta_T = 1 - rac{1}{L_n^2} \int_0^{x_B} (rac{1}{N_0 e^{-lpha x/x_B}} \int_x^{x_B} N_0 e^{-lpha x/x_B} dx) dx \ = 1 - rac{1}{L_n^2} \int_0^{x_B} \left[e^{lpha x/x_B} (-rac{x_B}{lpha} e^{-lpha x/x_B}) \Big|_x^{x_B} \right] dx \ = 1 - rac{1}{L_n^2} \int_0^{x_B} \left[e^{lpha x/x_B} (-rac{x_B}{lpha} e^{-lpha} + rac{x_B}{lpha} e^{-lpha x/x_B}) \right] dx \ = 1 - rac{1}{L_n^2} \int_0^{x_B} (rac{x_B}{lpha} - rac{x_B}{lpha} e^{lpha x/x_B - lpha}) dx \ = 1 - rac{1}{L_n^2} (rac{x_B}{lpha} x - rac{x_B^2}{lpha^2} e^{lpha x/x_B - lpha}) \Big|_0^{x_B} \ = 1 - rac{1}{L_n^2} (rac{x_B^2}{lpha} - rac{x_B^2}{lpha^2} + rac{x_B^2}{lpha^2} e^{-lpha}) \ = 1 - rac{x_B^2}{lpha^2 L_n^2} (lpha - 1 + e^{-lpha})$$

基区直流扩展电阻对集电极电流的影响可表示为 $I_C=I_0exp[(V_E-I_Br_{bb'})/V_T]$,用公式以及示于图3- 12的数据估算出 $r_{bb'}$ 。

解:由 $I_C=I_0e^{(V_E-I_Br_{bb'})/V_T}$ 可得

$$\left\{egin{aligned} I_{C1} &= I_0 exp[(V_{E1} - I_{B1} r_{bb'})/V_T] \ I_{C2} &= I_0 exp[(V_{E2} - I_{B2} r_{bb'})/V_T] \end{aligned}
ight.$$

两式相除:

$$egin{align} rac{I_{C2}}{I_{C1}} = exprac{(V_{E2}-V_{E1})-(I_{B2}-I_{B1})r_{bb'}}{V_T} \ \implies r_{bb'} = rac{1}{I_{B2}-I_{B1}}[(V_{E2}-V_{E1})-V_T\lnrac{I_{C2}}{I_{C1}}] \ \end{aligned}$$

取两点

$$\begin{cases} V_{E2} = 0.7V, I_{C2} = 10^{-2}A, I_{B2} = 5 \times 10^{-4}A \\ V_{E1} = 0.8V, I_{C1} = 10^{-1}A, I_{B1} = 6 \times 10^{-3}A \end{cases}$$

代入 $r_{bb'}$ 表达式

$$r_{bb'} = rac{1}{5 imes 10^{-4}A - 6 imes 10^{-3}A}[(0.7V - 0.8V) - 0.026V imes \lnrac{10^{-2}A}{10^{-1}A}] pprox 7.30\Omega$$

注:据老师说图不准确,取不同点结果相差很大

3-11

- (1) 推导出均匀掺杂基区晶体管的基区渡越时间表达式。假设 $x_B/L_n\ll 1$ 。
- (2) 若基区杂质分布为 $N_a=N_0e^{-ax/x_B}$, 重复 (1)。

解:

基区渡越时间

$$au_B = \int_0^{ au_B} \, \mathrm{d}t = \int_0^{x_B} rac{\mathrm{d}x}{v(x)} = rac{Aq}{I_n} \int_0^{x_B} n_p(x) \, \mathrm{d}x = \int_0^{x_B} rac{\mathrm{d}x}{D_n N_a(x)} \int_x^{x_B} N_a(x) \, \mathrm{d}x$$

(1) 当掺杂均匀, 即 $N_a =$ 常数时有

$$au_B = \int_0^{x_B} rac{\mathrm{d}x}{D_n N_a(x)} \int_x^{x_B} N_a(x) \, \mathrm{d}x = rac{1}{D_n} \int_0^{x_B} \int_x^{x_B} \, \mathrm{d}x = rac{x_B^2}{2D_n}$$

(2) 当杂质分布为 $N_a=N_0e^{-ax/x_B}$ 时,代入 au_B 公式

$$egin{aligned} au_B &= \int_0^{x_B} rac{\mathrm{d}x}{D_n N_a(x)} \int_x^{x_B} N_a(x) \, \mathrm{d}x \ &= \int_0^{x_B} rac{\mathrm{d}x}{D_n N_0 e^{-ax/x_B}} \int_x^{x_B} N_0 e^{-ax/x_B} \, \mathrm{d}x \ &= \int_0^{x_B} rac{e^{ax/x_B}}{D_n} \, \mathrm{d}x \left(-rac{x_B}{a} e^{-ax/x_B}
ight) \Big|_x^{x_B} \ &= \int_0^{x_B} rac{e^{ax/x_B}}{D_n} \left(-rac{x_B}{a} e^{-a} + rac{x_B}{a} e^{-ax/x_B}
ight) \, \mathrm{d}x \ &= \int_0^{x_B} -rac{x_B e^{-a} e^{ax/x_B}}{aD_n} + rac{x_B}{aD_n} \, \mathrm{d}x \ &= -rac{x_B^2 e^{-a} e^{ax/x_B}}{a^2 D_n} \Big|_0^{x_B} + rac{x_B}{aD_n} (x_B - 0) \ &= -rac{x_B^2}{a^2 D_n} + rac{x_B^2 e^{-a}}{a^2 D_n} + rac{x_B^2}{aD_n} \ &= rac{x_B^2}{a^2 D_n} (e^{-a} + a - 1) \end{aligned}$$

硅NPN晶体管在300K具有如下参数:

 $I_E=1mA, C_{TE}=1pF, x_B=0.5\mu m, D_n=25cm^2/s, x_m=2.4\mu m, r_{SC}=20\Omega, C_{TC}=0.1pE$ 。 求发射区—集电区渡越时间和截止频率。

解:

$$egin{aligned} au_E &= r_E C_{TE} = rac{V_T}{I_E} C_{TE} = rac{0.026V}{1mA} imes 1pF = 26ps \ au_B &= rac{x_B^2}{2D_n} = rac{(0.5 \mu m)^2}{2 imes 25 cm^2/s} = 50ps \ au_d &= rac{x_m}{v_s} = rac{2.4 \mu m}{10^7 cm/s} = 24ps \ au_C &= r_{SC} C_{TC} = 20\Omega imes 0.1pF = 2ps \end{aligned}$$

则总的渡越时间

$$au_{EC} = au_E + au_B + au_d + au_C = 26ps + 50ps + 24ps + 2ps = 102ps$$

截止频率:

$$f_{lpha} = rac{1}{2\pi au_{EC}} = rac{1}{2 imes 3.14 imes 102 ps} = 1.56 imes 10^9 Hz = 1.56 GHz$$

3-13

- (1) 求出图3-24中输出短路时 i_{out}/i_{in} 的表达式;
- (2) 求出 ω_{β} ,它相应于 i_{out}/i_{in} 的数值下降了3dB的情况;
- (3) 求出 ω_T 。

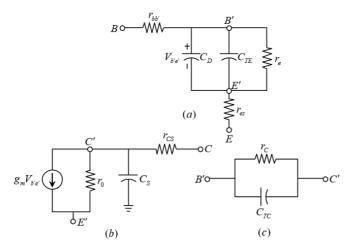


图 3-24 H-P 模型等效电路中的组成部分

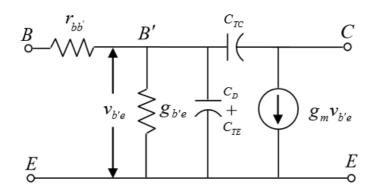


图 3-26 混接 和型等效电路

解:

(1) 当输出短路时,有

$$egin{aligned} i_{in} &= v_{b'e}[g_{b'e} + \jmath\omega(C_D + C_{TE} + C_{TC})] \ i_{out} &= g_m v_{b'e} + \jmath\omega C_{TC} v_{b'e} pprox g_m v_{b'e} ext{(低频)} \end{aligned}$$

可得:

$$rac{i_{in}}{i_{out}} = rac{g_m}{g_{b'e} + \jmath\omega(C_D + C_{TE} + C_{TC})}$$

(2) 下降3dB对应于原数值的 $\frac{1}{\sqrt{2}}$ 倍,有

$$|h_{fe}^2|_{\omega=\omega_eta} = rac{g_m^2}{g_{b'e}^2 + \omega_eta^2 (C_D + C_{TE} + C_{TC})^2} = rac{1}{2} h_{FE}^2$$

代入
$$g_{b'e}=rac{g_m}{h_{FE}}$$
可解得

$$\omega_{eta} = rac{g_m}{h_{FE}(C_D + C_{TE} + C_{TC})}$$

(3) 当 $C_D\gg C_{TE}+C_{TC}$ 时

$$\omega_T = h_{FE} \omega_eta = rac{g_m}{C_D + C_{TE} + C_{TC}} pprox rac{g_m}{C_D} = rac{1}{ au_B} = rac{2D_n}{x_B^2}$$

3-14

证明均匀基区BJT穿通击穿电压可表示为 $BV_{BC}=rac{qW_B^2}{2k\epsilon_0}rac{N_a(N_a+N_{dc})}{N_{dc}}$

证明:

当基极穿通击穿时,集电极空间电荷区的基极部分宽度应约等于基极的冶金学宽度。即有

$$W_Bpprox x_B=\sqrt{rac{2k\epsilon_0(\psi_0+V_R)}{q(N_a+N_{dc})}rac{N_{dc}}{N_a}}$$

此时反偏电压即为穿通击穿电压,且有 $V_R \gg \psi_0$,可得:

$$BV_{BC}pprox BV_{BC}+\psi_0=rac{qW_B^2}{2k\epsilon_0}rac{N_a(N_a+N_{dc})}{N_{dc}}$$

3-15

一均匀基区硅BJT,基区宽度为 $0.5\mu m$,基区杂质浓度 $N_a=10^{16}\,cm^{-3}$ 。若穿通电压期望值为 $BV_{BC}=25V$,集电区掺杂浓度为若干?如果不使集电区穿通,集电区宽度至少应大于多少?

解:

曲3-14可得
$$BV_{BC}=rac{qW_B^2}{2k\epsilon_0}rac{N_a(N_a+N_{dc})}{N_{dc}}$$
,则有
$$rac{N_a}{N_{dc}}=rac{2k\epsilon_0BV_{BC}}{qW_B^2N_a}-1=rac{2 imes11.8 imes8.85 imes10^{-14} imes25}{1.6 imes10^{-19} imes(0.5 imes10^{-4})^2 imes10^{16}}-1=12.05375$$

$$\implies N_{dc}=rac{N_a}{12.05375}=rac{10^{16}cm^{-3}}{12.05375}=8.30 imes10^{14}cm^{-3}$$

集电结空间电荷区的集电极区部分有:

$$x_C = rac{N_a W_B}{N_{dc}} = 12.05375 imes 0.5 \mu m pprox 6.03 \mu m$$

即当 $W_C > x_C = 6.03 \mu m$ 即可保证集电区不被穿通。