第一章

1.5

5. 证明：对于一个体心立方结构，其晶格常数 a 满足关系式 $a=\frac{4r}{\sqrt{3}}$ 其中，r 为原子半径.

5. 在体心立方结构对角线上，有 $4r=\sqrt{3}a$

故 $a=\frac{4r}{\sqrt{3}}$，得证.

1.8

8. 如果导带能级满足关系式：$E(1+\alpha E)=p^2/(2m_0)$，其中，α 为常数，m_0 为电子静质量，p 为动量，求其有效质量的表达式.

8. 方程左右两边同时对 p 求导，有：

$$(1+2\alpha E)\frac{dE}{dp}=\frac{p}{m_0} \quad ①$$

整理得：

$$\frac{dE}{dp}=\frac{p}{(1+2\alpha E)m_0} \quad ②$$

将①式对 p 再求导得：

$$(1+2\alpha E)\frac{d^2E}{dp^2}=\frac{1}{m_0}-\frac{2\alpha p^2}{(1+2\alpha E)^2m_0^2} \quad ③$$

将 $E(1+\alpha E)=\frac{p^2}{2m_0}$ 代入③中，整理得。

$$\frac{d^2E}{dp^2}=\frac{1}{m_0(1+2\alpha E)^3}$$

故有效质量 $m_n^*=\left(\frac{d^2E}{dp^2}\right)^{-1}=m_0(1+2\alpha E)^3$

1.13

13. (a) 求出一个速度为 10^7 cm/s 的自由电子的德布罗意(de Broglie)波长；

(b) 在砷化镓中，导带电子的有效质量为 $0.063m_0$. 假如它们有相同的速度，求其德布罗意波长.

13. (a) $\lambda = \frac{h}{p} = \frac{h}{mv} = \frac{6.626\times10^{-34}}{9.109\times10^{-31}\times10^{5}} = 7.27\times10^{-9}$ m

(b) $\lambda_n = \frac{m_0}{m_p}\lambda = \frac{1}{0.063}\times 72.7$ Å $= 1.154\times10^{-7}$ m

1.17

17. 已知一个硅样品的费米能级均匀地位于导带下方 0.2eV 处，计算：

(a) 电子和空穴密度；

(b) 掺杂浓度.

假设硅带隙宽度为 1.12eV，$T=300$K，导带有效态密度为 $2.86\times10^{19}\text{cm}^{-3}$.

解: (a) $n = N_c \exp\left(-\frac{E_c - E_F}{kT}\right) = 2.86\times10^{19}\exp\left(-\frac{0.2}{0.026}\right) = 1.305\times10^{16}\,\text{cm}^{-3}$

$n_i = 9.65\times10^{9}\,\text{cm}^{-3}$

$\therefore p = \frac{n_i^2}{n} = \frac{(9.65\times10^9)^2}{1.305\times10^{16}} = 7.136\times10^{3}\,\text{cm}^{-3}$

(b) 掺杂浓度 $N_D = n = 1.305\times10^{16}\,\text{cm}^{-3}$.

第二章

2.5

5. 对一未掺杂的半导体，$n_i=10^{10}/cc$，$T=300K$，$N_C=3\times10^{19}/cc$，$N_V=2.5\times10^{19}/cc$，$m_e=9.1\times10^{-32}kg$，求：

(a) 价带中空穴的有效质量；

(b) 半导体的禁带宽度；

(c) 费米能级相对导带的 eV 值；

(d) 空穴的热速度.

5. (a) $N_V = 2\left(\frac{2\pi m_p kT}{h^2}\right)^{\frac{3}{2}}$

$\Rightarrow m_p = \frac{\left(\frac{N_V}{2}\right)^{\frac{2}{3}} \cdot h^2}{2\pi kT} = 9.09\times10^{-31}\ kg$

(b) $\begin{cases} kT\ln\frac{n_i}{N_c} = E_F - E_c \\ kT\ln\frac{n_i}{N_v} = E_V - E_F \end{cases}$

$\Rightarrow kT\ln\frac{n_i^2}{N_c \cdot N_v} = E_V - E_c$

则禁带宽度 $E_c - E_V = -kT\ln\frac{n_i^2}{N_c\cdot N_v} = 1.13eV$

(c) ~~$E_F - E_c =$~~

~~$E_c - E_V$~~

(c) $E_F - E_c = kT\cdot\ln\frac{n_i}{N_c} = -0.567eV$

(d) $\frac{1}{2}m_p^* v^2 = \frac{3}{2}kT$

得热速度 $v = \sqrt{\frac{3kT}{m_p^*}} = 1.17\times10^5 m/s$

2.11

11. 一个本征硅样品从一端掺杂了施主，而使得 $N_D=N_0\exp(-ax)$.
(a) 在 $N_D \gg n_i$ 的范围中，求在平衡状态下内建电场 $E(x)$ 的表示法；
(b) 计算出当 $a=1\mu m^{-1}$ 时的 $E(x)$.

$$J_n = q\mu_n nE + qD_n \frac{dn}{dx}. \quad (31)$$

11. (a) From Eq. 31, $J_n = 0$ and

$$E(x) = -\frac{D_n}{\mu_n}\frac{dn/dx}{n} = -\frac{kT}{q}\frac{N_0(-a)e^{-ax}}{N_0 e^{-ax}} = +\frac{kT}{q}a$$

(b) $\mathscr{E}(x) = 0.0259\ (10^4) = 259$ V/cm.

2.16

16. 假定一 n 型半导体均匀地照光，而造成一均匀的过剩产生速率 G. 证明在稳态下，半导体电导率的改变为

$$\Delta\sigma = q(\mu_n + \mu_p)\tau_p G$$

16.

$$\sigma = qn\mu_n + qp\mu_p$$

Before illumination

$$n_n = n_{no},\ p_n = p_{no}$$

After illumination

$$n_n = n_{no} + \Delta n = n_{no} + \tau_p G,$$

$$p_n = p_{no} + \Delta p = p_{no} + \tau_p G$$

$$\Delta\sigma = [q\mu_n(n_{no} + \Delta n) + q\mu_p(p_{no} + \Delta p)] - (q\mu_n n_{no} + q\mu_p p_{no})$$
$$= q(\mu_n + \mu_p)\tau_p G.$$

第三章

3.6

6．一突变硅 p-n 结（$n_i=10^{10}\,\mathrm{cm}^{-3}$），p 区的受主掺杂浓度为 $N_A=10^{16}\,\mathrm{cm}^{-3}$，n 区的施主掺杂浓度为 $N_D=5\times10^{16}\,\mathrm{cm}^{-3}$．

(a) 计算此 p-n 结的内建电势；

(b) 当 V_a 为 0、0.5 以及 −2.5V 时，分别计算整个耗尽区的宽度；

(c) 当 V_a 为 0、0.5 以及 −2.5V 时，分别计算耗尽区内的最大电场；

(d) 当 V_a 为 0、0.5 以及 −2.5V 时，分别计算降落在 n 区一侧的电势．

(a) $V_{bi}=\frac{kT}{q}\ln\left(\frac{N_AN_D}{n_i^2}\right)=0.026\times\ln\left(\frac{10^{16}\times5\times10^{16}}{10^{20}}\right)=0.76\,V$

(b) $W=\sqrt{\frac{2\varepsilon_s}{q}\left(\frac{N_A+N_D}{N_AN_D}\right)(V_{bi}-V_a)}=\sqrt{\frac{2\times1.05\times10^{-12}}{1.6\times10^{-19}}\times\frac{6\times10^{16}}{5\times10^{32}}\times(0.76-V_a)}=\sqrt{1.58\times10^{-9}\times(0.76-V_a)}$

$V_a=0$时　$W=\sqrt{1.58\times10^{-9}\times0.76}=3.47\times10^{-5}\,cm$

$V_a=0.5V$时，$W=\sqrt{1.58\times10^{-9}\times0.26}=2.03\times10^{-5}\,cm$

$V_a=-2.5V$时，$W=\sqrt{1.58\times10^{-9}\times3.26}=7.18\times10^{-5}\,cm$

(c) $V_{bi}=\frac{1}{2}E_m\cdot W\Rightarrow E_m=\frac{2V_{bi}}{W}$

$V_a=0$时　$E_m=\frac{2\times0.76}{3.47\times10^{-5}}=4.38\times10^{4}\,V/cm$

$V_a=0.5V$时　$E_m=\frac{2\times0.76}{2.03\times10^{-5}}=7.49\times10^{4}\,V/cm$

$V_a=-2.5V$时　$E_m=\frac{2\times0.76}{7.18\times10^{-5}}=2.12\times10^{4}\,V/cm$

(d) $N_Ax_p=N_Dx_n$，$V_n=\frac{x_n}{W}\cdot(V_{bi}-V)=\frac{1}{6}(V_{bi}-V)$

$V_a=0$时　$V_n=0.127\,V$

$V_a=0.5V$时　$V_n=\frac{1}{6}\times0.26=0.043\,V$

$V_a=-2.5V$时　$V_n=\frac{1}{6}\times3.26=0.543\,V$

(c)

$$V_{bi}-V_a=\frac{E_m\times W}{2}$$

$$E_m=\frac{2(V_{bi}-V_a)}{w}$$

$$V_a=(0,0.5,-2.5),\qquad E_m=(4.38e6,\qquad 2.55e6,\qquad 9.08e6\ )V/m$$

3.7

*7. 一突变 p-n 结在轻掺杂质 n 侧的掺杂浓度为 $10^{15}cm^{-3}$、$10^{16}cm^{-3}$或 $10^{17}cm^{-3}$而重掺杂质 p 侧为 $10^{19}cm^{-3}$. 求出一系列的 $1/C^2$ 对 V 的曲线，其中 V 的范围从 −4V 到 0，以 0.5V 为间距. 对于这些曲线的斜率及电压轴的交点提出注释.

7. From Eq. 12 and Eq. 35, we can obtain the $1/C^2$ versus V relationship for doping concentration of 10^{15}, 10^{16}, or 10^{17} cm^{-3}, respectively.

For $N_D=10^{15}$ cm^{-3},

$$\frac{1}{C_j^{\,2}}=\frac{2(V_{bi}-V)}{q\varepsilon_s N_B}=\frac{2\times(0.837-V)}{1.6\times10^{-19}\times11.9\times8.85\times10^{-14}\times10^{15}}=1.187\times10^{16}(0.837-V)$$

For $N_D=10^{16}$ cm^{-3},

$$\frac{1}{C_j^{\,2}}=\frac{2(V_{bi}-V)}{q\varepsilon_s N_B}=\frac{2\times(0.896-V)}{1.6\times10^{-19}\times11.9\times8.85\times10^{-14}\times10^{16}}=1.187\times10^{15}(0.896-V)$$

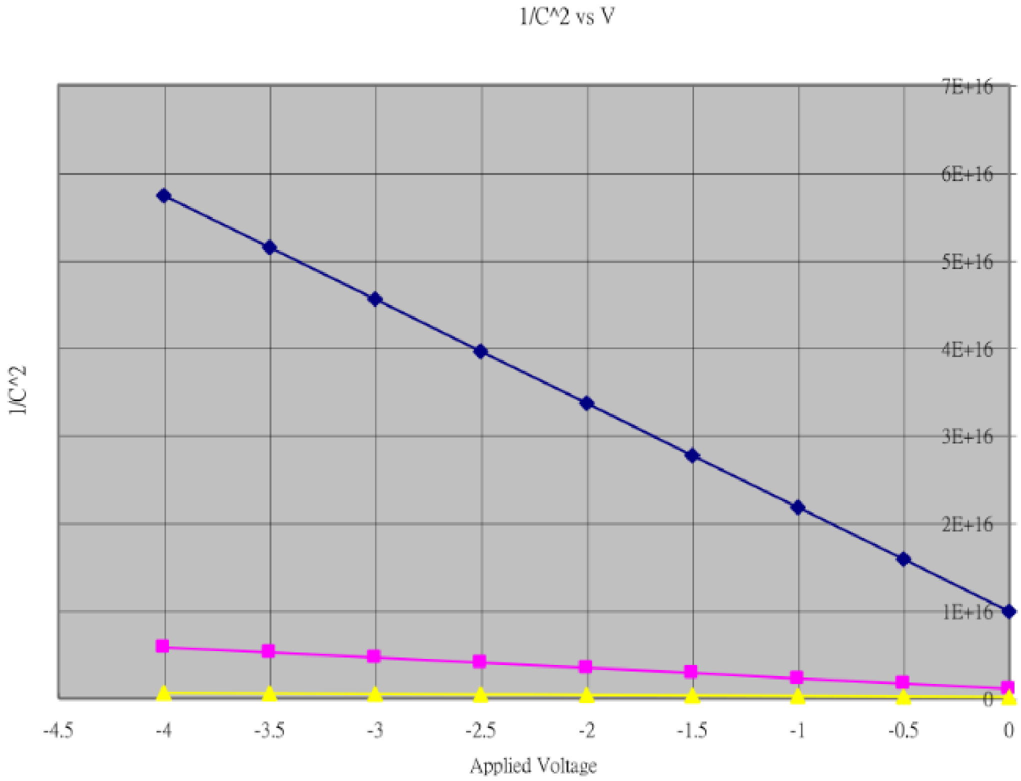
For $N_D=10^{17}$ cm^{-3},

$$\frac{1}{C_j^{\,2}}=\frac{2(V_{bi}-V)}{q\varepsilon_s N_B}=\frac{2\times(0.956-V)}{1.6\times10^{-19}\times11.9\times8.85\times10^{-14}\times10^{17}}=1.187\times10^{14}(0.956-V)$$

When the reversed bias is applied, we summarize a table of $1/C_j^2$ vs V for various N_D values as following,

V	N_D=1E15	N_D=1E16	N_D=1E17
-4	5.741E+16	5.812E+15	5.883E+14
-3.5	5.148E+16	5.218E+15	5.289E+14
-3	4.555E+16	4.625E+15	4.696E+14
-2.5	3.961E+16	4.031E+15	4.102E+14
-2	3.368E+16	3.438E+15	3.509E+14
-1.5	2.774E+16	2.844E+15	2.915E+14
-1	2.181E+16	2.251E+15	2.322E+14
-0.5	1.587E+16	1.657E+15	1.728E+14
0	9.935E+15	1.064E+15	1.134E+14

Hence, we obtain a series of curves of $1/C^2$ versus V as following,



The slopes of the curves is positive proportional to the values of the doping concentration.

The interceptions give the built-in potential of the *p-n* junctions.

3.13

13. 一理想硅 p-n 二极管，$N_D=10^{18}\,cm^{-3}$，$N_A=10^{16}\,cm^{-3}$，$\tau_p=\tau_n=10^{-6}\,s$，且器件面积为 $1.2\times10^{-5}\,cm^2$.

(a) 计算在 300K 时饱和电流理论值；

(b) 计算在±0.7V 时的正向和反向电流.

13. Assume $\tau_g=\tau_p=\tau_n=10^{-6}$ s, $D_n=21$ cm²/sec, and $D_p=10$ cm²/sec

(a) The saturation current calculation.

From Eq. 55a and $L_p=\sqrt{D_p\tau_p}$, we can obtain

$$J_s=\frac{qD_p p_{n0}}{L_p}+\frac{qD_n n_{p0}}{L_n}=qn_i^2\left(\frac{1}{N_D}\sqrt{\frac{D_p}{\tau_{p0}}}+\frac{1}{N_A}\sqrt{\frac{D_n}{\tau_{n0}}}\right)$$

$$=1.6\times10^{-19}\times\left(9.65\times10^{9}\right)^2\left(\frac{1}{10^{18}}\sqrt{\frac{10}{10^{-6}}}+\frac{1}{10^{16}}\sqrt{\frac{21}{10^{-6}}}\right)$$

$$=6.87\times10^{-12}\,\text{A/cm}^2$$

And from the cross-sectional area A = 1.2×10^{-5} cm², we obtain

$$I_s=A\times J_s=1.2\times10^{-5}\times6.87\times10^{-12}=8.244\times10^{-17}\,\text{A}.$$

(b) The total current density is

$$J=J_s\left(e^{\frac{qV}{kt}}-1\right)$$

Thus

$$I_{0.7V}=8.244\times10^{-17}\left(e^{\frac{0.7}{0.0259}}-1\right)=8.244\times10^{-17}\times5.47\times10^{11}=4.51\times10^{-5}\,\text{A}$$

$$I_{-0.7V}=8.244\times10^{-17}\left(e^{\frac{-0.7}{0.0259}}-1\right)=-8.24\times10^{-17}A$$

3.17

17. 对一理想突变 p^+-n 硅结，其 $N_D = 10^{16}\,\text{cm}^{-3}$，当外加正向电压为 1V 时，找出中性 n 区每单位面积储存的少数载流子. 中性区的长度为 1μm，且空穴扩散长度为 5μm.

17. From Eq. 39,

$$Q_p = q\int_{x_n}^{\infty}(p_n - p_{no})\ dx$$

$$= q\int_{x_n}^{\infty} p_{no}\left(e^{qV/kT} - 1\right)\ e^{-(x-x_n)/L_p}\,dx$$

The hole diffusion length is larger than the length of neutral region.

$$Q_p = q\int_{x_n}^{x_n'}(p_n - p_{no})\ dx$$

$$= q\int_{x_n}^{x_n'} p_{no}\left(e^{qV/kT} - 1\right)\ e^{-(x-x_n)/L_p}\,dx$$

$$= qp_{no}(-L_p)\left(e^{\frac{qV}{kT}} - 1\right)\left(e^{-\frac{x_n'-x_n}{L_p}} - e^{-\frac{x_n-x_n}{L_p}}\right)$$

$$= 1.6\times10^{-19}\times\frac{(9.65\times10^9)^2}{10^{16}}(-5\times10^{-4})\left(e^{\frac{1}{0.0259}} - 1\right)\left(e^{-\frac{1}{5}} - e^{-\frac{0}{5}}\right)$$

$$= 8.784\times10^{-3}\,\text{C/cm}^2.$$

3.21

21. 假如砷化镓 $\alpha_n=\alpha_p=10^4\left(\frac{E}{4}\times10^5\right)^6\ \mathrm{cm^{-1}}$，其中 E 的单位为 V/cm，求下列情况下的击穿电压.

(a) p-i-n 二极管，其本征层宽度为 10μm；

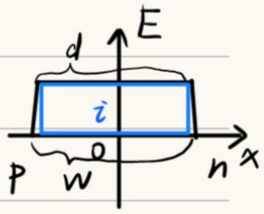
(b) p^+-n 结，其轻掺杂端杂质浓度为 $2\times10^{16}\ \mathrm{cm^{-3}}$.

(1) 若认为本征层宽度 $d\approx W$ 则 $W=10\ \mu m$

令 $\int_0^W \alpha\, dx=1$ 有 $\int_0^W 10^4\left(\frac{E}{4}\times10^{-5}\right)^6 dx=1$

则 $E=\frac{4}{\sqrt[6]{10}}\times10^5$ cm/V $=2.73\times10^5$ cm/V

$V_B\approx E\cdot W=273$ V



(b) From Fig. 26, the critical field is 5×10^5 V/cm.

$$V_B(\text{breakdown voltage})=\frac{E_c W}{2}=\frac{\varepsilon_s E_c^2}{2q}(N_B)^{-1}$$

$$=\frac{12.4\times8.85\times10^{-14}\times(5\times10^5)^2}{2\times1.6\times10^{-19}}(2\times10^{16})^{-1}$$

$$=42.8\ \text{V.}$$

第四章

4.4

4. 一个硅 p-n-p 晶体管的发射区、基区、集电区掺杂浓度分别为 $5\times10^{18}\ \text{cm}^{-3}$，$2\times10^{17}\ \text{cm}^{-3}$ 和 $10^{16}\ \text{cm}^{-3}$，基区宽度为 $1.0\mu\text{m}$，器件截面积为 0.2mm^2. 当射基结正向偏置在 0.5V 且集基结反向偏置在 5V 时，计算：

(a) 中性基区宽度；

(b) 射基结处的少数载流子浓度.

(a) The emitter-base junction is forward biased. From Chapter 3 we obtain

$$V_{bi} = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.0259\ln\left[\frac{5\times10^{18}\cdot 2\times10^{17}}{\left(9.65\times10^{9}\right)^2}\right] = 0.956\text{V} .$$

The depletion-layer width in the base is

$$W_1 = \left(\frac{N_A}{N_A+N_D}\right)(\text{Total depletion-layer width of the emitter-base junction})$$

$$= \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{N_A}{N_D}\right)\left(\frac{1}{N_A+N_D}\right)(V_{bi}-V)}$$

$$= \sqrt{\frac{2\cdot1.05\times10^{-12}}{1.6\times10^{-19}}\left(\frac{5\times10^{18}}{2\times10^{17}}\right)\left(\frac{1}{5\times10^{18}+2\times10^{17}}\right)(0.956-0.5)}$$

$$= 5.364\times10^{-6}\ \text{cm} = 5.364\times10^{-2}\ \mu\text{m} .$$

Similarly we obtain for the base-collector function

$$V_{bi} = 0.0259\ln\left[\frac{2\times10^{17}\cdot10^{16}}{\left(9.65\times10^{9}\right)^2}\right] = 0.795\text{V} .$$

and

$$W_2 = \sqrt{\frac{2\cdot1.05\times10^{-12}}{1.6\times10^{-19}}\left(\frac{10^{16}}{2\times10^{17}}\right)\left(\frac{1}{10^{16}+2\times10^{17}}\right)(0.795+5)}$$

$$= 4.254\times10^{-6}\ \text{cm} = 4.254\times10^{-2}\ \mu\text{m} .$$

Therefore the neutral base width is

$$W = W_B - W_1 - W_2 = 1 - 5.364\times10^{-2} - 4.254\times10^{-2} = 0.904\mu\text{m} .$$

(b) Using Eq. 13*a*

$$p_n(0) = p_{no}e^{qV_{EB}/kT} = \frac{n_i^2}{N_D}e^{qV_{EB}/kT} = \frac{\left(9.65\times10^{9}\right)^2}{2\times10^{17}}e^{0.5/0.0259} = 1.13\times10^{11}\ \text{cm}^{-3} .$$

4.5

5. 对习题 4 中的晶体管，其发射区、基区、集电区中少数载流子的扩散系数分别为 $52\text{cm}^2/\text{s}$、$40\text{cm}^2/\text{s}$ 和 $115\text{cm}^2/\text{s}$，对应各区寿命分别为 10^{-8}s、10^{-7}s 和 10^{-6}s. 求出图 4.5 中的各电流分量（I_{Ep}、I_{Cp}、I_{En}、I_{Cn}和 I_{BB}）.

5. In the emitter region

$$D_E = 52 \text{ cm/s} \quad L_E = \sqrt{52 \cdot 10^{-8}} = 0.721 \times 10^{-3} \text{ cm}$$
$$n_{EO} = \frac{(9.65 \times 10^9)^2}{5 \times 10^{18}} = 18.625 \ .$$

In the base region

$$D_p = 40 \text{cm/s} \quad L_p = \sqrt{D_p \tau_p} = \sqrt{40 \cdot 10^{-7}} = 2 \times 10^{-3} \text{ cm}$$
$$p_{no} = \frac{n_i^{\ 2}}{N_D} = \frac{(9.65 \times 10^9)^2}{2 \times 10^{17}} = 465.613.$$

In the collector region

$$D_C = 115 \text{ cm/s} \quad L_C = \sqrt{115 \cdot 10^{-6}} = 10.724 \times 10^{-3} \text{ cm}$$
$$n_{CO} = \frac{(9.65 \times 10^9)^2}{10^{16}} = 9.312 \times 10^3 \ .$$

The current components are given by Eqs. 20, 21, 22, and 23:

$$I_{Ep} = \frac{1.6 \times 10^{-19} \cdot 0.2 \times 10^{-2} \cdot 40 \cdot 465.613}{0.904 \times 10^{-4}} e^{0.5/0.0259} = 1.596 \times 10^{-5} \text{ A}$$
$$I_{Cp} \cong I_{Ep} = 1.596 \times 10^{-5} \text{ A}$$
$$I_{En} = \frac{1.6 \times 10^{-19} \cdot 0.2 \times 10^{-2} \cdot 52 \cdot 18.625}{0.721 \times 10^{-3}} \left(e^{0.5/0.0259} - 1\right) = 1.041 \times 10^{-7} \text{ A}$$
$$I_{Cn} = \frac{1.6 \times 10^{-19} \cdot 0.2 \times 10^{-2} \cdot 115 \cdot 9.312 \times 10^3}{10.724 \times 10^{-3}} = 3.196 \times 10^{-14} \text{ A}$$
$$I_{BB} = I_{Ep} - I_{Cp} = 0 \ .$$

4.6

6. 利用习题 4 和习题 5 所得到的结果，
(a) 求出晶体管的端电流 I_E、I_C 和 I_B；
(b) 计算发射极效率、基区输运系数、共基电流增益和共射电流增益；
(c) 讨论如何改善发射极效率以及基区输运系数.

6. (a) The emitter, collector, and base currents are given by

$$I_E = I_{Ep} + I_{En} = 1.606\times10^{-5}\ \text{A}$$
$$I_C = I_{Cp} + I_{Cn} = 1.596\times10^{-5}\ \text{A}$$
$$I_B = I_{En} + I_{BB} - I_{Cn} = 1.041\times10^{-7}\ \text{A}\ .$$

(b) We can obtain the emitter efficiency and the base transport factor:

$$\gamma = \frac{I_{Ep}}{I_E} = \frac{1.596\times10^{-5}}{1.606\times10^{-5}} = 0.9938$$

$$\alpha_T = \frac{I_{Cp}}{I_{Ep}} = \frac{1.596\times10^{-5}}{1.596\times10^{-5}} = 1\ .$$

Hence, the common-base and common-emitter current gains are

$$\alpha_0 = \gamma\alpha_T = 0.9938$$
$$\beta_0 = \frac{\alpha_0}{1-\alpha_0} = 160.3\ .$$

(c) To improve γ, the emitter has to be doped much heavier than the base.

To improve α_T, we can make the base width narrower.

4.9

9. 假设晶体管工作在放大模式且 $p_n(0) \gg p_{n0}$，推导总的过剩少数载流子电荷 Q_B 的表达式. 请解释为何电荷量可以近似于图 4.6 中所示基极中的三角形面积，此外请利用习题 4 的参数求出 Q_B.

9. The total excess minority carrier charge can be expressed by

$$
\begin{aligned}
Q_B &= qA\int_0^W [p_n(x) - p_{no}]dx \\
&= qA\int_0^W \left[p_{no}e^{qV_{EB}/kT}(1-\frac{x}{W}) \right] dx \\
&= qAp_{no}e^{qV_{EB}/kT}(x-\frac{x^2}{2W})\Big|_0^W \\
&= \frac{qAWp_{no}e^{qV_{EB}/kT}}{2} \\
&= \frac{qAWp_n(0)}{2} .
\end{aligned}
$$

From Fig. 6, the triangular area in the base region is $\frac{Wp_n(0)}{2}$. By multiplying this value by q and the cross-sectional area A, we can obtain the same expression as Q_B.

In Problem 3,

$$
\begin{aligned}
Q_B &= \frac{1.6\times10^{-19}\cdot 0.2\times10^{-2}\cdot 0.904\times10^{-4}\cdot 2.543\times10^{11}}{2} \\
&= 3.678\times10^{-15}\ \text{C} .
\end{aligned}
$$

4.10

10. 利用习题 9 所推导出的 Q_B 的表达式，证明式(27)的集电极电流可以近似为 $I_C \approx \left(\frac{2D_p}{W^2}\right)Q_B$.

10. In Eq. 27,

$$
\begin{aligned}
I_C &= a_{21}\left(e^{qV_{EB}/kT}-1\right)+a_{22} \\
&\cong \frac{qAD_p\,p_n(0)}{W} \\
&= \frac{2D_p}{W^2}\frac{qAQp_n(0)}{2} \\
&= \frac{2D_p}{W^2}Q_B\ .
\end{aligned}
$$

Therefore, the collector current is directly proportional to the minority carrier charge stored in the base.

11. 证明基区输运系数 α_T 可以简化为 $1-\left(\frac{W^2}{2L_p{}^2}\right)$.

4.11

11. The base transport factor is

$$
\alpha_T \cong \frac{I_{Cp}}{I_{Ep}} = \frac{\dfrac{1}{\sinh\left(\dfrac{W}{L_p}\right)}\left[\left(e^{qV_{EB}/kT}-1\right)+\cosh\left(\dfrac{W}{L_p}\right)\right]}{\coth\left(\dfrac{W}{L_p}\right)\left[\left(e^{qV_{EB}/kT}-1\right)+\dfrac{1}{\cosh\left(\dfrac{W}{L_p}\right)}\right]}\ .
$$

For $W/L_p \ll 1$, $\cosh(W/L_p) \cong 1$. Thus,

$$
\begin{aligned}
\alpha_T &= \frac{1}{\sinh\left(\dfrac{W}{L_p}\right)\cdot\coth\left(\dfrac{W}{L_p}\right)} \\
&= \operatorname{sech}\left(\frac{W}{L_p}\right) \\
&= 1-\frac{1}{2}\left(\frac{W}{L_p}\right)^2 \\
&= 1-\left(W^2/2L_p{}^2\right).
\end{aligned}
$$

4.12

12. 一 p-n-p 晶体管有如下特性. 掺杂：$N_E = 10N_B$，$N_B = 10N_C$，$N_C = 10^{16}\,cm^{-3}$；中性区宽度：$W_E = W_B = 0.1L_B = 5\times10^{-5}\,cm$，$W_C = 500W_B$；少子扩散系数：$D_E = D_B = 0.25D_C = 50cm^2/s$；少子扩散长度：$L_E = 0.5L_B = 10L_C$. 基于以上数据，计算：

(a) 发射效率；

(b) 基区输运系数；

(c) 截止频率 f_T.

(b) 基区输运系数；

(c) 截止频率 f_T.

$= 0.5\times5\times10^{-5}$

$$(a)\ \alpha = \frac{I_{Ep}}{I_E} = \frac{\frac{qAD_Bp_{n0}}{W}\exp\left(\frac{qV_{EB}}{kT}\right)}{\frac{qAD_Bp_{n0}}{W}\exp\left(\frac{qV_{EB}}{kT}\right) + \frac{qAD_En_{E0}}{L_E}\left(e^{\frac{qV_{EB}}{kT}}-1\right)}$$

$n_{E0} = \frac{n_i^2}{N_E}$, $p_{n0} = p_{B0} = \frac{n_i^2}{N_B}$ $\Rightarrow \frac{p_{n0}}{n_{E0}} = \frac{N_E}{N_B} = 10$, $W_B = 0.1L_B = 0.2L_E$

$\frac{D_Bp_{n0}}{W} = \frac{10D_En_{E0}}{0.2L_E} = 50\frac{D_En_{E0}}{L_E}$

$$\therefore \alpha = \frac{50\exp\left(\frac{qV_{EB}}{kT}\right)}{51\exp\left(\frac{qV_{EB}}{kT}\right)-1} \approx \frac{50}{51} = 0.98$$

$$(b)\ \alpha_T = \frac{I_{Cp}}{I_{Ep}} \doteq 1 - \frac{W^2}{2L_p^2} = 1 - \frac{1}{2}\times0.1^2 = 0.995$$

$(c)\ f_T = (2\pi\tau_T)^{-1}$ $\qquad \tau_T = \tau_E + \tau_C + \tau_B$

$I_p = qv(x)p(x)A$ $\qquad \tau_B = \int_0^W \frac{dx}{v(x)} = \int_0^W \frac{qp(x)A}{I_p}dx = \int_0^W \frac{qp(x)}{J}dx$

$\because J = qD_p\frac{dp}{dx}$ $\qquad = \int_0^W \frac{p(x)}{D_p\,dp}dx = \frac{W^2}{2D_p} = \frac{(5\times10^{-5})^2}{2\times50} = 2.5\times10^{-11}s$

$\tau_T \approx \tau_B = 2.5\times10^{-11}s$.

$$f_T \approx (2\pi\tau_B)^{-1} = \frac{1}{2\pi\times2.5\times10^{-11}} = 6.37\times10^9 Hz$$

4.13

13. 若发射极效率非常接近 1，请证明共射电流增益 β_0 可表示为 $\frac{2L_p^2}{W^2}$.（提示：利用习题 11 的 α_T）

13. The common-emitter current gain is given by

$$\beta_0 \equiv \frac{\alpha_0}{1-\alpha_0} = \frac{\gamma\alpha_T}{1-\gamma\alpha_T} \ .$$

Since $\gamma \cong 1$,

$$\begin{aligned}\beta_0 &\cong \frac{\alpha_T}{1-\alpha_T} \\ &= \frac{1-\left(W^2/2L_p^{\ 2}\right)}{1-\left[1-\left(W^2/2L_p^{\ 2}\right)\right]} \\ &= \left(2L_p^{\ 2}/W^2\right)-1 \ .\end{aligned}$$

If $W/L_p << 1$, then $\beta_0 \cong 2L_p^{\ 2}/W^2$.

4.16

16. 一利用离子注入形成的 n-p-n 晶体管，其中性基区的净掺杂浓度为 $N(x)=N_{AO}e^{-\frac{x}{l}}$，其中 $N_{AO}=2\times10^{18}\,\text{cm}^{-3}$，$l=0.3\mu\text{m}$.

(a) 求出中性基区单位面积上的杂质；

(b) 若中性基区宽度为 0.8μm，求出中性基区的平均掺杂浓度.

16. (a) The total number of impurities in the neutral base region is

$$Q_G=\int_0^W N_{AO}e^{-x/l}dx=N_{AO}l\left(1-e^{-W/l}\right)$$
$$=2\times10^{18}\cdot3\times10^{-5}\left(1-e^{-8\times10^{-5}/3\times10^{-5}}\right)=5.583\times10^{13}\ \text{cm}^{-2}\ .$$

(b) Average impurity concentration is

$$\frac{Q_G}{W}=\frac{5.583\times10^{13}}{8\times10^{-5}}$$
$$=6.979\times10^{17}\ \text{cm}^{-3}\ .$$

4.17

17. 参考习题 16，若 $L_E=1\mu\text{m}$，$N_E=10^{19}\,\text{cm}^{-3}$，$D_E=1\text{cm}^2/\text{s}$，基区中的平均寿命为 10^{-6}s，基区中的平均扩散系数由习题 16 中的掺杂浓度决定，求出共射电流增益.

17. For $N_A=6.979\times10^{17}\ \text{cm}^{-3}$, $D_n=7.77\,\text{cm}^3/\text{s}$, and

$$L_n=\sqrt{D_n\tau_n}=\sqrt{7.77\cdot10^{-6}}=2.787\times10^{-3}\ \text{cm}$$

$$\alpha_T\cong1-\frac{W^2}{2L_n{}^2}=1-\frac{\left(8\times10^{-5}\right)^2}{2\left(2.787\times10^{-3}\right)^2}=0.999588$$

$$\gamma=\frac{1}{1+\frac{D_E}{D_n}\frac{Q_G}{N_EL_E}}=\frac{1}{1+\frac{1}{7.77}\cdot\frac{5.583\times10^{13}}{10^{19}\cdot10^{-4}}}=0.99287\ .$$

Therefore,

$$\alpha_0=\gamma\alpha_T=0.99246$$

$$\beta_0=\frac{\alpha_0}{1-\alpha_0}=131.6\ .$$

4.20

20. 根据基本的埃伯斯-摩尔模型(Ebers-Moll model) [J. J. Ebers and J. L. Moll, "Large-Single Behavior of Junction Transistors," *Proc. IRE.*, 42, 1761, 1954],发射极和集电极电流的一般性方程为

$$I_E = I_{FO}\left(e^{\frac{qV_{EB}}{kT}} - 1\right) - \alpha_R I_{RO}\left(e^{\frac{qV_{CB}}{kT}} - 1\right),$$

$$I_C = \alpha_F I_{FO}\left(e^{\frac{qV_{EB}}{kT}} - 1\right) - I_{RO}\left(e^{\frac{qV_{CB}}{kT}} - 1\right).$$

其中 α_F 和 α_R 分别为正向共基电流增益(forward common-base current gain)和反向共基电流增益(reverse common-base current gain),I_{FO}和 I_{RO}分别为正常正向和反向偏压二极管饱和电流.请以式(25)、式(26)、式(28)、式(29)中的常数来表示 α_F和 α_R.

20. Comparing the equations with Eq. 32 gives

$$I_{FO} = a_{11},\quad \alpha_R I_{RO} = a_{12}$$

$$\alpha_F I_{FO} = a_{21}, \text{ and } \quad I_{RO} = a_{22}\ .$$

Hence,

$$\alpha_F = \frac{a_{21}}{a_{11}} = \frac{1}{1 + \frac{W}{L_E}\cdot\frac{D_E}{D_p}\cdot\frac{n_{EO}}{p_{no}}}$$

$$\alpha_R = \frac{a_{12}}{a_{22}} = \frac{1}{1 + \frac{W}{L_C}\cdot\frac{D_C}{D_p}\cdot\frac{n_{CO}}{p_{no}}}\ .$$

4.24

24. 一硅晶体管,其 $D_p = 10\text{cm}^2/\text{s}$,$W = 0.5\mu\text{m}$,共基电流增益 α_0 为 0.998,试求出其截止频率.可忽略发射极和集电极延迟.

解: $\tau_B = \frac{W^2}{2D_p} = \frac{(0.5\times10^{-4})^2}{2\times10} = 1.25\times10^{-10}\text{s}$

截止频率 $f_T = \frac{1}{2\pi\tau_B} = 1.27\times10^{9}\text{Hz} = 1.27\text{GHz}$

共基截止频率 $f_\alpha = \frac{f_T}{\alpha_0} = \frac{1.27\times10^9}{0.998} = 1.275\text{GHz}$

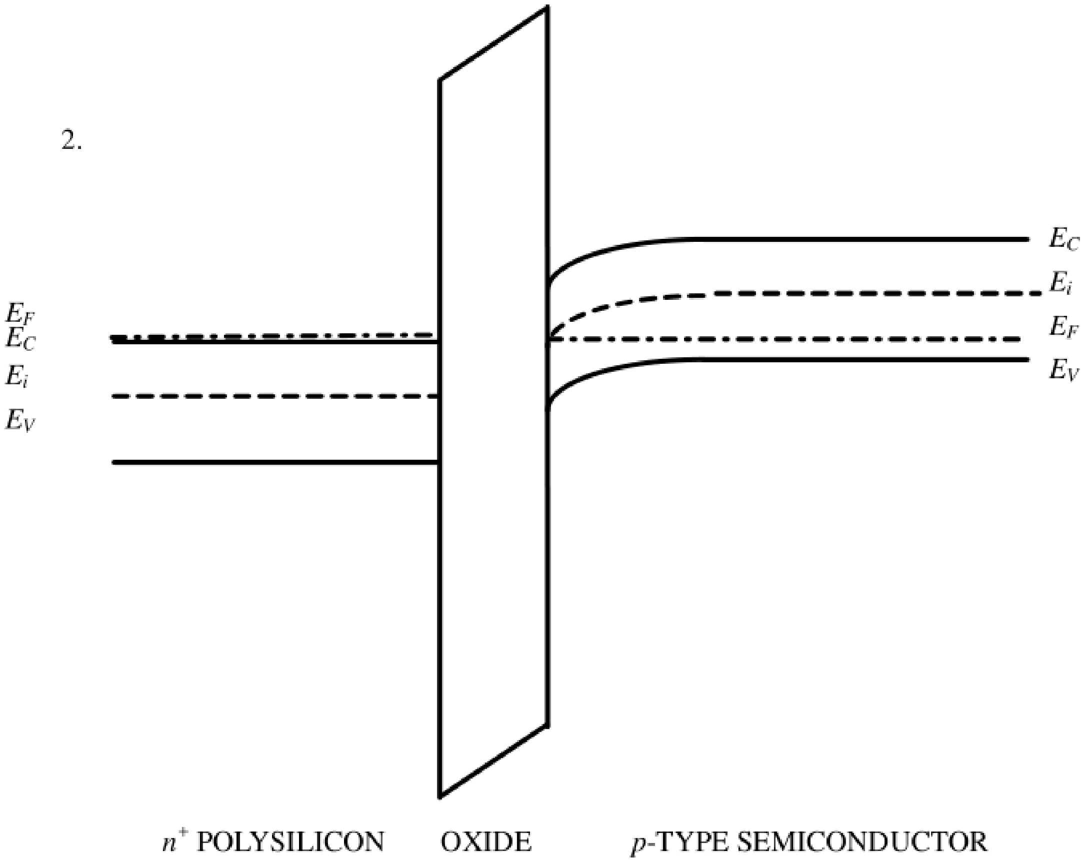
共射截止频率 $f_\beta = (1-\alpha_0)f_\alpha = (1-0.998)\times1.275\times10^9 = 2.55\text{MHz}$

第五章

5.2

2. 试画出 $V_G=0$ 时，由 p 型衬底和 n^+ 多晶硅栅极构成的 MOS 电容器的能带图.

2.



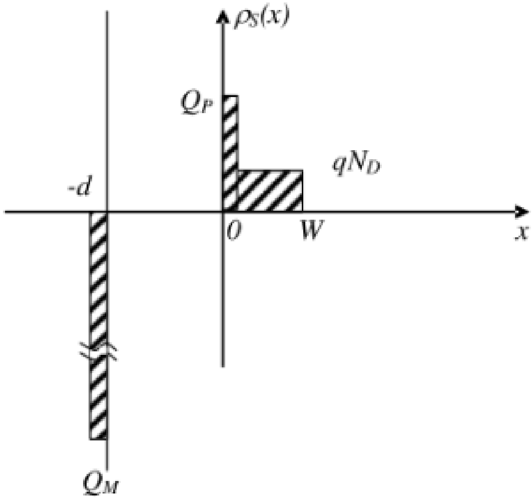
5.4

4. 考虑一 n 型衬底理想 MOS 电容器在反型状态下，请画出：

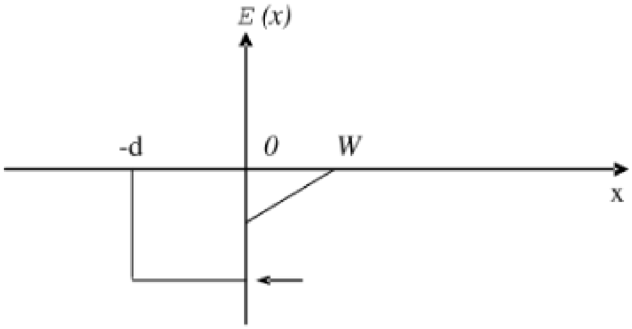
（a）电荷分布；

（b）电场分布；

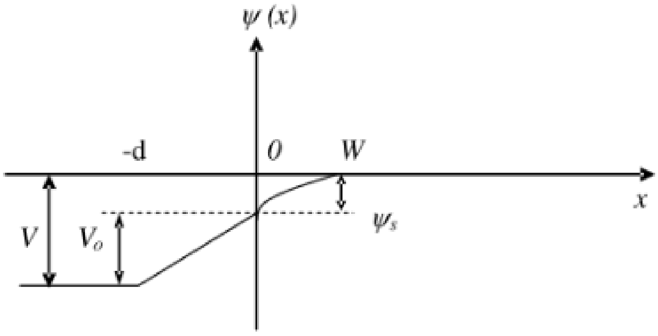
（c）电势分布.



(a)



(b)



(c)

5.6

6. 一理想 Si-SiO_2 MOS 电容器参数如下：$d=30\text{nm}$，$n_i=1.45\times10^{10}\text{cm}^{-3}$，$\varepsilon_{si}=11.9\ \varepsilon_0$，$\varepsilon_{ox}=3.9\ \varepsilon_0$，$N_A=5\times10^{15}\text{cm}^{-3}$，求在 $T=300\text{K}$ 时，发生强反型时界面处所需要的电场.

$$\psi_B=\frac{kT}{q}\ln\frac{N_A}{n_i}=0.026\ln\frac{5\times10^{15}}{1.45\times10^{10}}=0.332V. \qquad \psi_s=2\psi_B=0.663V.$$

$$C_0=\frac{\varepsilon_{ox}}{d}=\frac{3.9\times8.85\times10^{-14}}{3\times10^{-6}}=1.1505\times10^{-7}F/cm^2.$$

$$V_T=\frac{\sqrt{2\varepsilon_{si}qN_A(2\psi_B)}}{C_0}+2\psi_B=\frac{\sqrt{2\times11.9\times8.85\times10^{-14}\times1.6\times10^{-19}\times5\times10^{15}\times0.663}}{1.1505\times10^{-7}}+0.663=0.954V.$$

$$E_0=\frac{V_0}{d}=\frac{V_T-\psi_s}{d}=\frac{0.954-0.663}{3\times10^{-6}}=9.684\times10^4\ V/cm$$

$$E_s=\frac{\varepsilon_{ox}}{\varepsilon_{si}}E_0=\frac{3.9}{11.9}\times9.684\times10^4=3.174\times10^4\ V/cm.$$

5.9

9. 考虑两个 MOS 器件，除了氧化层厚度以外，其余均相同. 高频 C-V 测量产生的 C_{max}/C_{min} 比分别为 3 和 2. 基于这个数据，若 $\varepsilon_{si}=11.9\varepsilon_0$，$\varepsilon_{ox}=3.9\varepsilon_0$，求这两种器件的氧化层厚度的比值.

$$C_0=\frac{\varepsilon_{ox}}{d}.$$

$$\frac{C_{min1}}{C_{max}}=\frac{C_{min1}}{C_0}=\frac{1}{3}=\frac{d_1}{d_1+\frac{3.9}{11.9}W_m}. \qquad d_1+\frac{3.9}{11.9}W_m=3d_1. \qquad d_1=\frac{39}{238}W_m$$

$$\frac{C_{min2}}{C_{max}}=\frac{C_{min2}}{C_0}=\frac{1}{2}=\frac{d_2}{d_2+\frac{3.9}{11.9}W_m}. \qquad d_2+\frac{3.9}{11.9}W_m=2d_2. \qquad d_2=\frac{39}{119}W_m$$

$$\frac{d_1}{d_2}=\frac{\frac{39}{238}W_m}{\frac{39}{119}W_m}=\frac{1}{2}.$$

5.13

13. 假设氧化层中的陷阱电荷呈三角形分布，$\rho_{ot}(y)=q\times(5\times10^{23}\times y)\mathrm{cm}^{-3}$，氧化层的厚度为 10nm. 试计算因 Q_{ot} 所导致的平带电压变化.

13. $$Q_{ot}=\frac{1}{d}\int_0^{10^{-6}} y(q\times5\times10^{23}\times y)dy$$

$$=2.67\times10^{-8}\ \mathrm{C/cm^2}$$

$$\therefore \Delta V_{FB}=\frac{Q_{ot}}{C_o}=\frac{2.67\times10^{-8}}{3.45\times10^{-7}}=7.74\times10^{-2}\ \ \mathrm{V}.$$

5.14

14. 假设 $V_D \ll V_G - V_T$，试根据课本中公式(35)推导公式(36).

14. Since $V_D << (V_G - V_T)$, the first term in Eq. 35 can be approximated as

$$\frac{Z}{L}\mu_n C_o (V_G - 2\psi_B - \frac{V_D}{2})V_D.$$

Performing Taylor's expansion on the 2nd term in Eq. 35, we obtain

$$(V_D+2\psi_B)^{3/2}-(2\psi_B)^{3/2}\cong(2\psi_B)^{3/2}+\frac{3}{2}(2\psi_B)^{1/2}V_D-(2\psi_B)^{3/2}=\frac{3}{2}(2\psi_B)^{1/2}V_D$$

Equation 33 can now be re-written as

$$I_D\cong\frac{Z}{L}\mu_n C_o\left[(V_G-2\psi_B-\frac{V_D}{2})V_D-\frac{2}{3}\frac{\sqrt{2\varepsilon_s qN_A}}{C_o}\times\frac{3}{2}\sqrt{2\psi_B}V_D\right]$$

$$\cong\frac{Z}{L}\mu_n C_o\left\{V_G-\left[2\psi_B+\frac{\sqrt{2\varepsilon_s qN_A(2\psi_B)}}{C_o}\right]-\frac{V_D}{2}\right\}V_D$$

$$\cong(\frac{Z}{L})\mu_n C_o(V_G-V_T-\frac{V_D}{2})V_D$$

where $V_T=2\psi_B+\dfrac{\sqrt{2\varepsilon_s qN_A(2\psi_B)}}{C_o}$.

5.17

17. 对于一亚微米 MOSFET，$L=0.25\mu m$，$Z=5\mu m$，$N_A=10^{17} cm^{-3}$，$\mu_n=500cm^2/(V\cdot s)$，$C_o=3.45\times10^{-7}F/cm^2$ 且 $V_T=0.5V$，计算 $V_G=1V$ 与 $V_D=0.1V$ 时的沟道电导.

The device is operated in linear region, since $V_D=0.1$ V < $(V_G-V_T)=0.5$ V

$$g_d=\frac{\partial I_D}{\partial V_G}=\frac{Z}{L}\mu_n C_o(V_G-V_T-V_D)=1.38\times10^{-3}S$$

5.18

18. 对习题 17 中的器件，计算其跨导.

$$g_m=\left.\frac{\partial I_D}{\partial V_G}\right|_{V_D=const}=\frac{Z}{L}\mu_n C_o V_D$$

$$=\frac{5}{0.25}\times500\times3.45\times10^{-7}\times0.1$$

$$=3.45\times10^{-4}\ S.$$

5.22

22. 一 p 沟道的 n^+ 多晶硅-SiO_2-Si MOSFET，其中 $N_D=10^{17}cm^{-3}$，$Q_f/q=5\times10^{10}cm^{-2}$ 且 $d=10nm$，计算其阈值电压.

22. $$\phi_{ms} = -\frac{E_g}{2} + \psi_B = -0.56 + 0.42 = -0.14 \text{ V}$$

$$V_T = \phi_{ms} - \frac{Q_f}{C_o} - 2\psi_B - \frac{2\sqrt{\varepsilon_s q N_D \psi_B}}{C_o}$$

$$= -0.14 - 0.02 - 0.84 - \frac{2\sqrt{11.9\times8.85\times10^{-14}\times1.6\times10^{-19}\times10^{17}\times0.42}}{3.45\times10^{-7}}$$

$$= -1.49 \text{ V.}$$

5.23

23. 对习题 22 中的器件，注入硼离子使阈值电压减少至$-0.7V$，假设注入的离子在 Si-SiO_2 的界面处形成一薄层负电荷，计算注入的硼离子剂量.

23. $$-0.7 = -1.49 + \frac{qF_B}{3.45\times10^{-7}}$$

$$F_B = \frac{0.79\times3.45\times10^{-7}}{1.6\times10^{-19}} = 1.7\times10^{12} \text{ cm}^{-2}.$$

5.26

26. 一 MOSFET 的阈值电压 $V_T=0.5V$，亚阈值摆幅为 100mV/decade，且在栅极偏压为 V_T 时漏极电流为 $0.1\mu A$. 请问在 $V_G=0$ 时的亚阈值漏电流为多少？

26. $$V_T = 0.5 \text{ V at } I_d = 0.1\mu \text{ A}$$

$$\text{Subthreshold swing} = \left(\frac{\log I_D|_{V_G=V_T} - \log I_D|_{V_G=0}}{V_T - 0} \right)^{-1}$$

$$0.1 = \frac{0.5}{-7 - \log I_D|_{V_G=0}}$$

$$\log I_D|_{V_G=0} = -12 \qquad \therefore I_D|_{V_G=0} = 1\times10^{-12} \text{ A}.$$

第六章

6.2

2. 在一 n 沟道 MOSFET 中，$N_A=3\times10^{16}\,cm^{-3}$，$L=1\mu m$，$r_j=0.3\mu m$，栅氧厚度 $t_{ox}=2nm$，$\varepsilon_{ox}=3.9\varepsilon_0$，$T=300K$. 假设 $W_m=0.18\mu m$，计算由于短沟道效应引起的阈值电压漂移.

2. From Fig. 2 we have

$$(r_j+\Delta)^2=(r_j+W_m)^2-W_m^{\ 2}$$

$$\therefore \Delta^2+2\Delta r_j-2W_m r_j=0$$

$$\Delta=-r_j+\sqrt{r_j+2W_m r_j}$$

$$L'=L-2\Delta$$

$$\frac{L+L'}{2L}=\frac{2L-2\Delta}{2L}=1-\frac{\Delta}{L}=1-\frac{r_j}{L}\left(\sqrt{1+\frac{2W_m}{r_j}}-1\right)$$

From Eq. 17, Ch. 5 we have

$$\Delta V_T=\frac{\text{(space charge in the trapezaidal region } - \text{ space charge in the rectangular region)}}{C_o}$$

$$=\frac{qN_AW_m}{C_o}\left(\frac{L+L'}{2L}\right)-\frac{qN_AW_m}{C_o}=-\frac{qN_AW_mr_j}{C_oL}\left(\sqrt{1+\frac{2W_m}{r_j}}-1\right).$$

$$\Delta V_T=-\frac{qN_AW_mr_jt_{ox}}{\varepsilon_{ox}L}\left(\sqrt{1+\frac{2W_m}{r_j}}-1\right)=-\frac{1.6\times10^{-19}\times3\times10^{16}\times1.8\times10^{-5}\times3\times10^{-5}\times2\times10^{-7}}{3.9\times8.85\times10^{-14}\times10^{-4}}$$

$$\times\left(\sqrt{1+\frac{2\times1.8}{3}}-1\right)=-7.258\,mV$$

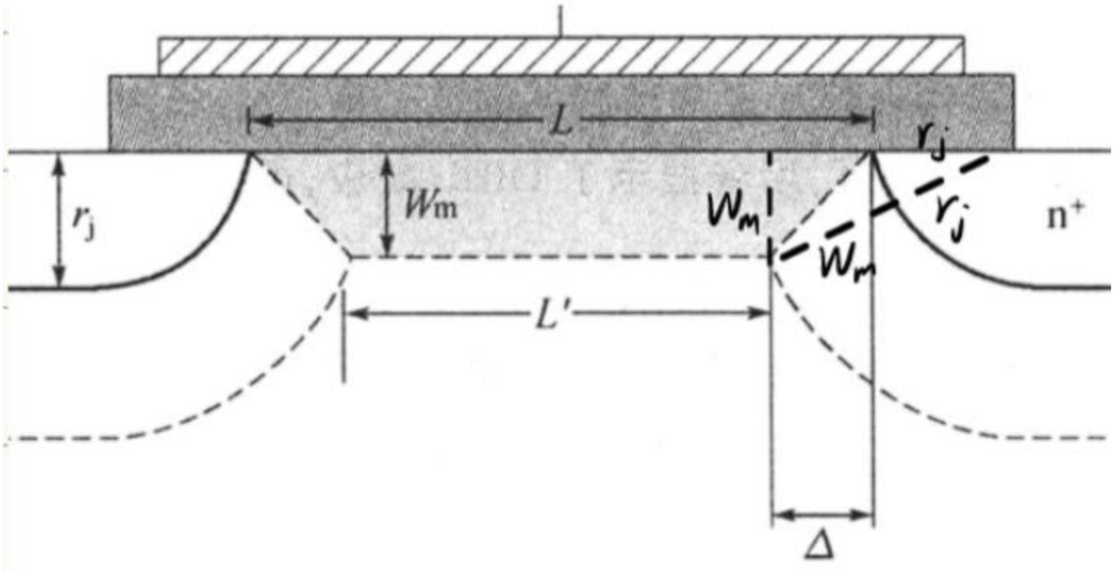


Fig. 2

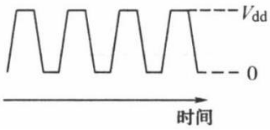
6.8

8. 如图 6.14 所示的 CMOS 反相器. 如果一个电压波形(V_{in})被施加到 CMOS 反相器的输入端上:

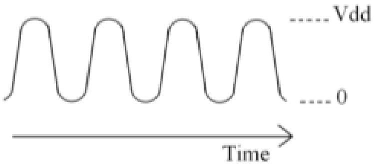
(a) 画出相应输出电压(V_{out})的示意图;

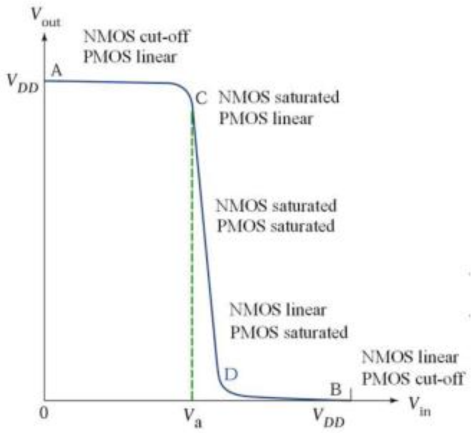
(b) NMOS 和 PMOS 在相应的标记点 A、B、C、D 以及 C 和 D 之间各是什么状态?

(c) 如果 n 沟道 MOSFET 和 p 沟道 MOSFET 的阈值电压分别是 V_{tn} 和 V_{tp},指出在下面参数下 NMOS 从线性区到达饱和区的临界点:对于 n 沟道 MOSFET:$\mu_{ns}C_0(Z/L)=20\text{mA/V}^{-2}$ 且 $V_{tn}=2\text{V}$;对于 p 沟道 MOSFET:$\mu_{ps}C_0(Z/L)=20\text{mA/V}^{-2}$ 且 $V_{tp}=1\text{V}$.



8. (a)





(c)

At point C, the voltage Va= Vin (input voltage) , the NMOS is just becoming saturated from the linear region. Since NMOS is in the linear region and PMOS in the saturation region, the drain current of NMOS is equal to the drain current of the PMOS, that is $I_{DN}= I_{DP}$

Therefore,

$$20\left[(V_a-2)^2-\frac{(V_a-2)^2}{2}\right]=\frac{20}{2}(5-V_a-1)^2$$

$$20(V_a-2)^2=20(4-V_a)^2 \Rightarrow V_a=3\text{V}$$

6.18

18. 在下表中简单描述器件的各种特性.

18.

	Cell size	Write one byte rate	Rewrite cycle	Keep data without power	Applications
SRAM	Large	Fast	unlimited	No	Embedded in ligic chips
DRAM	Mid	Fast	unlimited	No	Stand-alone chips and enbeded
Flash	small	Slow	limited	Yes	Nonvoltatile storage stand-alone

第七章

7.1

1. 假设金属的功函数为 4.55eV，半导体的电子亲和能为 4.01eV，$N_D=2\times10^{16}\,cm^{-3}$，温度为 300K. 计算零偏压时金属-半导体二极管的势垒高度和内建电势的理论值.

1. From Eq.1, the theoretical barrier height is

$$\phi_{Bn}=\phi_m-\chi=4.55-4.01=0.54\,\text{eV}$$

We can calculate V_n as

$$V_n=\frac{kT}{q}\ln\frac{N_C}{N_D}=0.0259\ln(\frac{2.86\times10^{19}}{2\times10^{16}})=0.188\,\text{V}$$

Therefore, the built-in potential is

$$V_{bi}=\phi_{Bn}-V_n=0.54-0.188=0.352\,\text{V}.$$

7.4

4. 将铜淀积于精心准备的 n 型硅衬底上，形成理想的肖特基二极管. $\varphi_m=4.65\text{eV}$，电子亲和能为 4.05eV，$N_D=3\times10^{16}\,cm^{-3}$，$T=300\text{K}$. 计算零偏压时的势垒高度、内建电势、耗尽层宽度以及最大电场.

解 势垒高度 $\phi_{Bn}=\phi_m-\chi=4.65-4.05=0.6V$

$V_n=\frac{kT}{q}\ln\frac{N_c}{N_D}=0.0259\ln\frac{2.86\times10^{19}}{3\times10^{16}}=0.178V$

内建电势 $V_{bi}=\phi_{Bn}-V_n=0.6-0.178=0.422V$

耗尽层宽度 $W=\sqrt{\frac{2\varepsilon_s(V_{bi}-V)}{qN_D}}=\sqrt{\frac{2\times11.9\times8.85\times10^{-14}\times0.422}{1.6\times10^{-19}\times3\times10^{16}}}=1.36\times10^{-5}cm$

$=0.136\mu m$

最大电场 $|E_m|=|E|_{x=0}|=\frac{qN_D}{\varepsilon_s}W=\frac{1.6\times10^{-19}\times3\times10^{16}\times1.36\times10^{-5}}{11.9\times8.85\times10^{-14}}=6.2\times10^{4}\,V/cm$

7.5

*5. 已知一个由金(Au)和 n-型砷化镓构成的肖特基势垒二极管的电容满足关系式 $1/C^2 = 1.57\times10^5 - 2.12\times10^5 V_a$. 其中, C 的单位为 μF, V_a 的单位为 V. 若二极管面积为 10^{-1} cm^2, 计算内建电势、势垒高度、砷化镓的掺杂浓度及其功函数.

解 将C的单位从 μF 转换为 F/cm^2. 由二极管面积为 10^{-1}cm^2 得

$1/C^2 = 1.57\times10^{15} - 2.12\times10^{15} V_a \quad (\mathrm{cm^2/F})^2$

在 $1/C^2=0$ 时, 有内建电势 $V_{bi} = \dfrac{1.57\times10^{15}}{2.12\times10^{15}} = 0.74\,V$

$(\varepsilon_s = 12.4\varepsilon_0)$

$(N_c = 4.5\times10^{17}\,\mathrm{cm^{-3}})$

$\dfrac{d(1/C^2)}{dV_a} = -2.12\times10^{15}\,(\mathrm{cm^2/F})^2/V$

∴掺杂浓度 $N_D = \dfrac{2}{q\varepsilon_s}\left[\dfrac{-1}{d(1/C^2)/dV_a}\right] = \dfrac{2}{1.6\times10^{-19}\times12.4\times8.85\times10^{-14}}\times\dfrac{1}{2.12\times10^{15}}$

$= 5.37\times10^{15}\,\mathrm{cm^{-3}}$

$V_n = \dfrac{kT}{q}\ln\dfrac{N_c}{N_D} = 0.0259\ln\dfrac{4.5\times10^{17}}{5.37\times10^{15}} = 0.115\,V$

势垒高度 $\phi_{Bn} = V_{bi} + V_n = 0.74 + 0.115 = 0.855\,V$

功函数 $q\varphi_s = q(\chi + V_n) = 4.07 + 0.115 = 4.185\,eV$

7.11

11. 已知一 n 沟道砷化镓 MESFET：$\varphi_{Bn}=0.9\text{V}$，$N_D=10^{17}\text{cm}^{-3}$，$N_C=4\times10^{17}\text{cm}^{-3}$，$a=0.2\mu\text{m}$，$\varepsilon_s=12.4\varepsilon_0$，$\mu_0=5000\text{cm}^2/(\text{V}\cdot\text{s})$，$L=1.0\mu\text{m}$，$Z=10\mu\text{m}$，$T=300\text{K}$.

(a) 这个器件是增强型还是耗尽型?

(b) 计算其在 $V_G=0\text{V}$ 时的饱和电流；

(c) 计算其截止频率.

(a) The built-in voltage is

$$V_{bi}=\phi_{Bn}-V_n=0.9-0.025\ln\left(\frac{4.7\times10^{17}}{10^{17}}\right)=0.86\text{ V}$$

At zero bias, the width of the depletion layer is

$$W=\sqrt{\frac{2\varepsilon_s V_{bi}}{qN_D}}=\sqrt{\frac{2\times1.09\times10^{-12}\times0.86}{1.6\times10^{-19}\times10^{17}}}$$

$$=1.07\times10^{-5}\text{ cm}$$

$$=0.107\ \mu\text{m}$$

Since W is smaller than 0.2 μm, it is a depletion-mode device.

(b) $V_P=\dfrac{qN_Da^2}{2\varepsilon_s}=2.919\text{ V}$

$I_P=\dfrac{Z\mu_n q^2N_D^2a^3}{2\varepsilon_s L}=46.8\text{ mA}$

$\therefore I_{Dsat}=I_P\left[\frac{1}{3}-\left(\frac{V_G+V_{bi}}{V_P}\right)+\frac{2}{3}\left(\frac{V_G+V_{bi}}{V_P}\right)^{\frac{3}{2}}\right]=6.77\text{ mA}$

(c) $f_T=\dfrac{g_m}{2\pi C_G}$ 其中 $\begin{cases} g_m=\dfrac{\partial I_{Dsat}}{\partial V_G}=\dfrac{I_P}{V_P}\left(1-\sqrt{\dfrac{V_G+V_{bi}}{V_P}}\right) \\ C_G\approx\dfrac{ZL\varepsilon_s}{a}\end{cases}$

7.12

12. 已知一个 n 沟道砷化镓 MESFET 的沟道掺杂为 $N_D = 2\times10^{15}\,\mathrm{cm}^{-3}$，$\varphi_{Bn} = 0.8\,\mathrm{V}$，$a = 0.5\,\mu\mathrm{m}$，$L = 1\,\mu\mathrm{m}$，$Z = 50\,\mu\mathrm{m}$，$\mu_n = 4500\,\mathrm{cm}^2/(\mathrm{V\cdot s})$. 求出其夹断电压、阈值电压以及当 $V_G = 0$ 时的饱和电流.

12 解: $V_P = \dfrac{qN_D a^2}{2\varepsilon_s} = 0.365\ \mathrm{V}$ 为夹断电压

$V_n = \dfrac{kT}{q}\ln\dfrac{N_c}{N_D} = 0.141\ \mathrm{V}$

$\therefore V_{bi} = \varphi_{Bn} - V_n = 0.659\ \mathrm{V}$

$\therefore V_T = V_P - V_{bi} = 0.294\ \mathrm{V}$ 为阈值电压

$\because I_{Dsat}\big|_{V_G=0} = I_P\left[\dfrac{1}{3} - \left(\dfrac{V_G+V_{bi}}{V_P}\right) + \dfrac{2}{3}\left(\dfrac{V_G+V_{bi}}{V_P}\right)^{\frac{3}{2}}\right]$ $I_P = \dfrac{Z\mu_n q^2 N_D^2 a^3}{2\varepsilon_s L}$

$\therefore I_{Dsat} = \dfrac{Z\mu_n q^2 N_D^2 a^3}{2\varepsilon_s L}\left[\dfrac{1}{3} - \dfrac{V_{bi}}{V_P} + \dfrac{2}{3}\left(\dfrac{V_{bi}}{V_P}\right)^{\frac{3}{2}}\right] = 1.91\times10^{-4}\ \mathrm{A}$

7.13

13. 已知两个砷化镓 n 沟道 MESFET 的势垒高度 φ_{Bn} 都是 0.85V，器件 1 的沟道掺杂浓度为 $N_D = 4.7\times10^{16}\,\mathrm{cm}^{-3}$，而器件 2 为 $N_D = 4.7\times10^{17}\,\mathrm{cm}^{-3}$. 若每个器件阈值电压均为 0V，计算两个器件的沟道厚度分别需要为多少.

解:

13. $$0.85 - 0.0259\ln\left(\frac{4.7\times10^{17}}{N_D}\right) - \frac{1.6\times10^{-19}\times N_D}{2\times12.4\times8.85\times10^{-14}}a^2 = 0$$

For $N_D = 4.7\times10^{16}\ \mathrm{cm}^{-3}$

$$a = \left(0.85 - 0.0259\ln\frac{4.7\times10^{17}}{N_D}\right)^{1/2}\frac{(3.7\times10^3)}{\sqrt{N_D}}$$

$= 1.52\times10^{-5}\ \mathrm{cm} = 0.152\ \mu\mathrm{m}$

For $N_D = 4.7\times10^{17}\ \mathrm{cm}^{-3}$

$a = 0.496\times10^{-5}\ \mathrm{cm} = 0.0496\ \mu\mathrm{m}.$