

# 2023春半导体物理习题课

## 第五章 PN结

宋冰睿 王民泽

2023 年 6 月 12 日

# Contents

- 1 题6.1
- 2 题6.5
- 3 题6.6
- 4 题6.7
- 5 题6.9
- 6 题6.11
- 7 题6.12
- 8 补充题

# Ge突变pn结

若一Ge突变pn结的  $N_D = 5 \times 10^{15} \text{cm}^{-3}$ ,  $N_A = 10^{17} \text{cm}^{-3}$ , 求室温下该结的  $V_D$ .

# Ge突变pn结

查P66表3-2知Ge的 $n_i = 2.33 \times 10^{13} \text{cm}^{-3}$ , 故

$$\begin{aligned} V_D &= \frac{k_B T}{q} \ln \left( \frac{N_D N_A}{n_i^2} \right) \\ &\approx 0.02585 \times \ln \left( \frac{5 \times 10^{32}}{2.33^2 \times 10^{26}} \right) \\ &\approx 0.355(\text{V}) \end{aligned} \quad (1.1)$$

# Contents

- 1 题6.1
- 2 题6.5
- 3 题6.6
- 4 题6.7
- 5 题6.9
- 6 题6.11
- 7 题6.12
- 8 补充题

# Si突变pn结: PART I

现有一Si突变pn结, 其N区的 $\rho_n = 5\Omega \cdot \text{cm}$ ,  $\tau_p = 1\mu\text{s}$ , P区的 $\rho_p = 0.1\Omega \cdot \text{cm}$ ,  $\tau_n = 5\mu\text{s}$ . 试计算室温下该结:

- ① 空穴电流与电子电流之比;
- ② 饱和电流密度;
- ③ 正向偏压为0.3V时流过的电流密度.

## Si突变pn结: PART I

由给出的电阻率值查P109图4-15(b)知

$$\begin{aligned} N_D &= 9 \times 10^{14} \text{cm}^{-3} \\ N_A &= 3 \times 10^{17} \text{cm}^{-3} \end{aligned} \quad (2.1)$$

进而根据P107图4-14(a), 得到N区少子空穴迁移率和P区少子电子迁移率分别为

$$\begin{aligned} \mu_p(\text{N}) &= 500 \text{cm}^2/(\text{V} \cdot \text{s}) \\ \mu_n(\text{P}) &= 550 \text{cm}^2/(\text{V} \cdot \text{s}) \end{aligned} \quad (2.2)$$

借助Einstein关系即有

$$\begin{aligned} D_p &= \frac{k_B T}{q} \mu_p \approx 12.9 \text{cm}^2/\text{s} \\ D_n &= \frac{k_B T}{q} \mu_n \approx 14.2 \text{cm}^2/\text{s} \end{aligned} \quad (2.3)$$

## Si突变pn结: PART I(1)

另一方面, 两边少子浓度分别为

$$\begin{aligned} p_{n0} &= \frac{n_i^2}{N_D} = \frac{1.02^2 \times 10^{20}}{9 \times 10^{14}} \approx 1.156 \times 10^5 \text{ (cm}^{-3}\text{)} \\ n_{p0} &= \frac{n_i^2}{N_A} = \frac{1.02^2 \times 10^{20}}{3 \times 10^{17}} \approx 3.468 \times 10^2 \text{ (cm}^{-3}\text{)} \end{aligned} \quad (2.4)$$

且由于空穴电流和电子电流

$$\begin{aligned} J_{sp} &= J_p(x_n) = \frac{qD_p p_{n0}}{L_p} \left[ \exp\left(\frac{qV}{k_B T}\right) - 1 \right] \\ J_{sn} &= J_n(-x_p) = \frac{qD_n n_{p0}}{L_n} \left[ \exp\left(\frac{qV}{k_B T}\right) - 1 \right] \end{aligned} \quad (2.5)$$

故根据  $L_{\square} = \sqrt{D_{\square}\tau_{\square}}$  可计算二者之比

$$\frac{J_{sp}}{J_{sn}} = \frac{D_p}{D_n} \frac{L_n}{L_p} \frac{p_{n0}}{n_{p0}} = \sqrt{\frac{D_p \tau_n}{D_n \tau_p}} \frac{N_A}{N_D} = \sqrt{\frac{12.9 \times 5}{14.2}} \cdot \frac{3 \times 10^{17}}{9 \times 10^{14}} \approx 711 \quad (2.6)$$



## Si突变pn结: PART I(2)(3)

总的饱和电流密度则为

$$\begin{aligned}
 J_s &= J_{sp} + J_{sn} = \frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} \\
 &= q \left( p_{n0} \sqrt{\frac{D_p}{\tau_p}} + n_{p0} \sqrt{\frac{D_n}{\tau_n}} \right) \approx 6.652 \times 10^{-11} \text{ (A/cm}^2\text{)}
 \end{aligned} \tag{2.7}$$

在正向偏压  $V = 0.3\text{V}$  时,

$$\begin{aligned}
 J &= J_s \left[ \exp \left( \frac{qV}{k_B T} \right) - 1 \right] \approx 6.652 \times 10^{-11} \times \left[ \exp \left( \frac{0.3}{0.02585} \right) - 1 \right] \\
 &\approx 7.297 \times 10^{-6} \text{ (A/cm}^2\text{)}
 \end{aligned} \tag{2.8}$$

Tips: 查P107图4-14(a)写出式2.2时, 需注意横轴数值 “ $N_D + N_A$ ” 在不同结区的物理意义.

# Contents

- 1 题6.1
- 2 题6.5
- 3 题6.6**
- 4 题6.7
- 5 题6.9
- 6 题6.11
- 7 题6.12
- 8 补充题

## Si突变pn结: PART II

对于一各条件与上题相同的pn结, 试计算下列偏压时其势垒区宽度和单位面积电容:

- ①  $-10\text{V}$ ;
- ②  $0\text{V}$ ;
- ③  $0.3\text{V}$ .

## Si突变pn结: PART II

首先计算内建电势

$$V_D = \frac{k_B T}{q} \ln \left( \frac{N_D N_A}{n_i^2} \right) \approx 0.739V \quad (3.1)$$

由于  $N_A \gg N_D$ , 故势垒区宽度和单位面积电容可简化计算如下:

物理量 \ 偏压 $V(V)$	-10	0	0.3
$X_D = \sqrt{\frac{2\epsilon_r \epsilon_0}{q N_D} (V_D - V)} (\mu m)$	3.964	1.040	0.802
$C'_T = \sqrt{\frac{\epsilon_r \epsilon_0 q N_D}{2(V_D - V)}} (F/m^2)$	$2.657 \times 10^{-5}$	$1.010 \times 10^{-4}$	*

特别地, \*处的势垒电容应按正向偏压下的式6-105计算:

$$C'_T = 4C'_T(0) = 4.040 \times 10^{-4} (F/m^2) \quad (3.2)$$

# Contents

- 1 题6.1
- 2 题6.5
- 3 题6.6
- 4 题6.7**
- 5 题6.9
- 6 题6.11
- 7 题6.12
- 8 补充题

## Si-pn结的反向电流

试计算当温度从300K增加至400K时, Si-pn结反向电流增加的倍数.

## Si-pn结的反向电流

因扩散系数等物理量依赖于温度, 根据P167叙述可设 $D/\tau \propto T^\gamma$ ,

$$J_s = \frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} = qn_i^2 \left( \sqrt{\frac{D_p}{\tau_p}} \frac{1}{N_D} + \sqrt{\frac{D_n}{\tau_n}} \frac{1}{N_A} \right) \quad (4.1)$$

$$\propto n_i^2 T^{\gamma/2} \propto T^{3+\gamma/2} \exp\left(-\frac{E_g}{k_B T}\right)$$

不妨设 $\gamma = 1$ , 并忽略 $E_g \sim T$ 变化, 则

$$\frac{J_s(400\text{K})}{J_s(300\text{K})} = \left(\frac{400}{300}\right)^{3.5} \times \exp\left(\frac{1.12}{0.02585 \times 4}\right) \approx 1.385 \times 10^5 \quad (4.2)$$

**Tips:** 指数项占主导地位, 可认为 $\gamma$ 值的选取无关紧要.

该结果同时表明, 热效应在pn结中具有十分重要的影响.

# Contents

- 1 题6.1
- 2 题6.5
- 3 题6.6
- 4 题6.7
- 5 题6.9**
- 6 题6.11
- 7 题6.12
- 8 补充题



# 单边突变结

设一突变结两边的杂质浓度  $N_A = 10^{16}\text{cm}^{-3}$ ,  $N_D = 10^{20}\text{cm}^{-3}$ .

- ① 求势垒的高度和宽度;
- ② 画出  $\mathcal{E}(x)$ ,  $V(x)$  关系图.

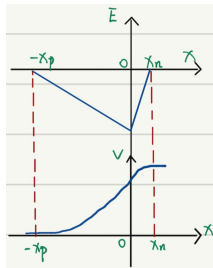
## 单边突变结(1)(2)

结材料设为Si, 则该单边结的势垒高度

$$V_D = \frac{k_B T}{q} \ln \left( \frac{N_D N_A}{n_i^2} \right) \approx 0.95 \text{V} \quad (5.1)$$

宽度

$$X_D = \sqrt{\frac{2\epsilon_r \epsilon_0}{q N_A} V_D} \approx 0.355 \mu\text{m} \quad (5.2)$$



# Contents

- 1 题6.1
- 2 题6.5
- 3 题6.6
- 4 题6.7
- 5 题6.9
- 6 题6.11**
- 7 题6.12
- 8 补充题

# Si-n<sup>+</sup>p结

分别计算Si-n<sup>+</sup>p结在正向偏压0.6V和反向偏压40V时的势垒区宽度. 设已知 $N_A = 5 \times 10^{17} \text{cm}^{-3}$ ,  $V_D = 0.8\text{V}$ .

Si-n<sup>+</sup>p结

如法炮制,

$$X_D = \sqrt{\frac{2\varepsilon_r\varepsilon_0}{qN_A} (V_D - V)} \approx \begin{cases} 22.95\text{nm} & , 0.6\text{V} \\ 327.8\text{nm} & , -40\text{V} \end{cases} \quad (6.1)$$

# Contents

- 1 题6.1
- 2 题6.5
- 3 题6.6
- 4 题6.7
- 5 题6.9
- 6 题6.11
- 7 题6.12**
- 8 补充题

# Si-p<sup>+</sup>n结

分别计算Si-p<sup>+</sup>n结在平衡和反向偏压45V时的最大电场强度. 设已知 $N_D = 5 \times 10^{15} \text{cm}^{-3}$ ,  $V_D = 0.7\text{V}$ .

Si-p<sup>+</sup>n结

由式6-79,

$$\begin{aligned} \mathcal{E}_m &= \frac{qN_D}{\varepsilon_r \varepsilon_0} X_D = \sqrt{\frac{2qN_D}{\varepsilon_r \varepsilon_0} (V_D - V)} \\ &\approx \begin{cases} 3.26 \times 10^4 \text{V/cm} & , 0\text{V} \\ 2.63 \times 10^5 \text{V/cm} & , -45\text{V} \end{cases} \end{aligned} \quad (7.1)$$



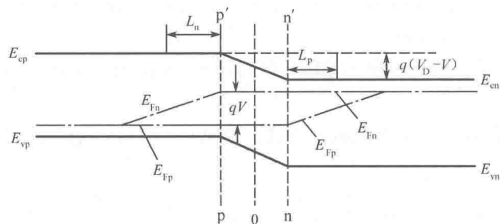
# Contents

- 1 题6.1
- 2 题6.5
- 3 题6.6
- 4 题6.7
- 5 题6.9
- 6 题6.11
- 7 题6.12
- 8 补充题**

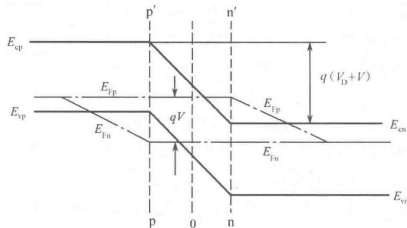
# pn结能带绘图

分别画出小注入条件下正偏及反偏pn结的能带示意图. (用准Fermi能级表示)

参见P163图6-13 (正偏) & P164图6-14 (反偏).



(a) 正偏



(b) 反偏