2023春半导体物理习题课

第五章　PN结

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Ge突变pn结

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

Ge突变pn结

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

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

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Si突变pn结: PART I

现有一Si突变pn结，其N区的$\rho_n = 5\Omega \cdot \mathrm{cm}, \tau_p = 1\mu \mathrm{s}$, P区的$\rho_p = 0.1\Omega \cdot \mathrm{cm}, \tau_n = 5\mu \mathrm{s}$. 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

$$\begin{aligned} N_D &= 9 \times 10^{14}\mathrm{cm}^{-3} \\ N_A &= 3 \times 10^{17}\mathrm{cm}^{-3} \end{aligned} \tag{2.1}$$

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

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

借助Einstein关系即有

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

Si突变pn结: PART I(1)

另一方面，两边少子浓度分别为

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

且由于空穴电流和电子电流

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

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

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

Si突变pn结: PART I(2)(3)

总的饱和电流密度则为

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

在正向偏压$V = 0.3\mathrm{V}$时,

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

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.

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

Si突变pn结: PART II

首先计算内建电势

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

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:

偏压V(V) / 物理量	-10	0	0.3
$X_D = \sqrt{\frac{2\varepsilon_r\varepsilon_0}{qN_D}}(V_D - V)\ (\mu\text{m})$	3.964	1.040	0.802
$C_T' = \sqrt{\frac{\varepsilon_r\varepsilon_0 q N_D}{2(V_D - V)}}\ (\text{F}/\text{m}^2)$	2.657×10^{-5}	1.010×10^{-4}	*

特别地, *处的势垒电容应按正向偏压下的式6-105计算:

$$C_T' = 4C_T'(0) = 4.040 \times 10^{-4}\ (\text{F}/\text{m}^2) \tag{3.2}$$

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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$D/\tau \propto T^{\gamma}$，

$$\begin{aligned} J_s &= \frac{qD_p p_{n0}}{L_p} + \frac{qD_n n_{p0}}{L_n} = qn_i^2 \left(\sqrt{\frac{D_p}{\tau_p}} \frac{1}{N_D} + \sqrt{\frac{D_n}{\tau_n}} \frac{1}{N_A} \right) \\ &\propto n_i^2 T^{\gamma/2} \propto T^{3+\gamma/2} \exp\left(-\frac{E_g}{k_B T} \right) \end{aligned} \tag{4.1}$$

不妨设$\gamma = 1$，并忽略$E_g \sim T$变化，则

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

Tips：指数项占主导地位，可认为γ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.

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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$\mathscr{E}(x), V(x)$关系图.

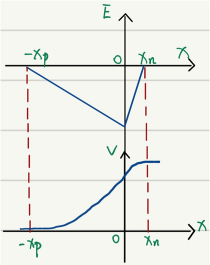
单边突变结(1)(2)

结材料设为Si, 则该单边结的势垒高度

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

宽度

$$X_D = \sqrt{\frac{2\varepsilon_r \varepsilon_0}{q N_A} V_D} \approx 0.355\mu\mathrm{m} \tag{5.2}$$



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Si-n$^+$p结

分别计算Si-n$^+$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$N_A = 5 \times 10^{17}\mathrm{cm}^{-3}, V_D = 0.8\mathrm{V}$.

Si-n$^+$p结

如法炮制,

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

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Si-p$^+$n结

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

Si-p$^+$n结

由式6-79,

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

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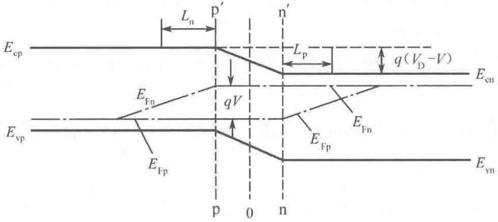
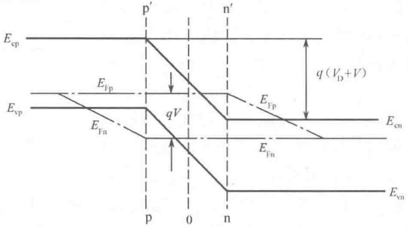
pn结能带绘图

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