7.3 复合理论11

7.3.3 间接复合

—τ 与 E_t 能级位置的关系

净复合率 $U=\dfrac{N_t r_n r_p\left(np-n_i^2\right)}{r_n\left(n+n_1\right)+r_p\left(p+p_1\right)}$

$$n_1 = N_C \exp\left(-\frac{E_C - E_t}{kT}\right)$$

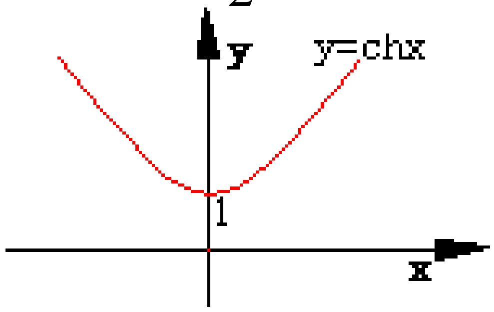
$$p_1 = N_V \exp\left(-\frac{E_t - E_V}{kT}\right)$$

简单假设 $r_n = r_p = r$，则

$$U = \frac{N_t r\left(np-n_i^2\right)}{\left(n+n_1\right)+\left(p+p_1\right)}$$

$$= \frac{N_t r\left(np-n_i^2\right)}{\left(n+p\right)+2n_i ch\left(\dfrac{E_t-E_i}{kT}\right)}$$

双曲余弦 $ch(x) = \dfrac{e^x + e^{-x}}{2}$



当 $E_t = E_i$ 时，U 极大

当 $|E_t - E_i| >> kT$ 时，$U \to 0$

深能级 —— 有效的复合中心

7.3 复合理论12

7.3.3 间接复合

—τ 与温度 T 的关系（设 n 型半导体，且 E_t 位于禁带上半部）

1° 低温 $E_F > E_t$ $\quad \tau = \dfrac{1}{N_t\, r_p}$

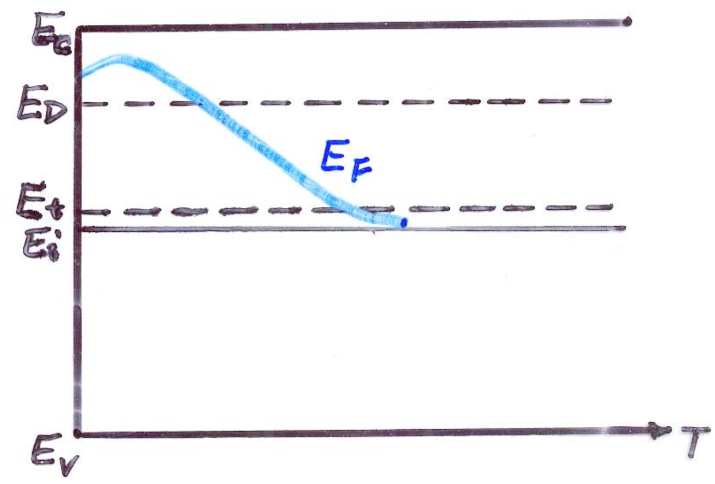
$$r_p = \sigma_+ \bar{v}_T \qquad \bar{v}_T \propto T^{1/2} \qquad \sigma_+ \propto T^{-n}\quad n = 2 \sim 4$$

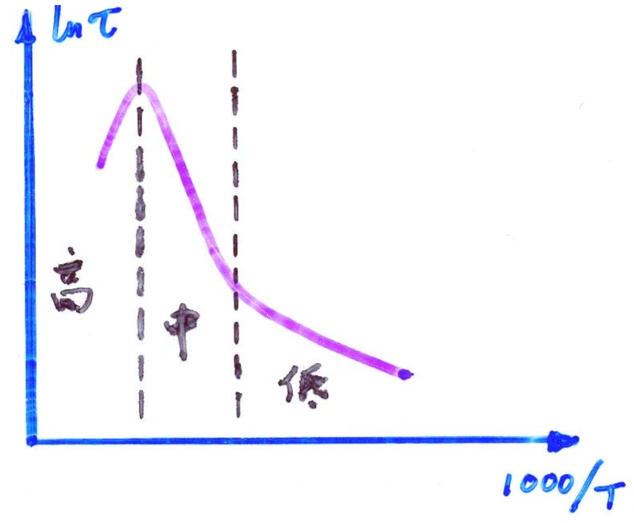
2° 中温 $E_F < E_t$ $\quad \tau = \dfrac{1}{N_t r_p}\dfrac{n_1}{n_0}$

$$n_1 = N_C \exp\left(-\frac{E_C - E_t}{kT}\right) \qquad n_0 = N_D$$

3° 高温 $E_F \approx E_i$ $\quad \tau = \dfrac{1}{N_t r_p}\dfrac{n_1}{n_0}$

$$n_1 = n_i \exp\left(\frac{E_t - E_i}{kT}\right) \qquad n_0 = n_i$$

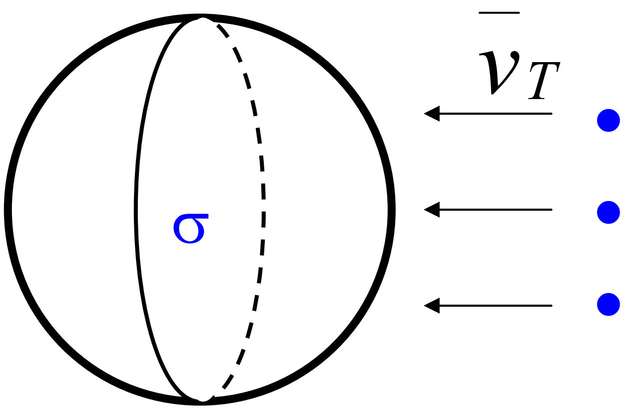




7.3 复合理论13

7.3.3 间接复合

—俘获截面



单位时间内某个复合中心俘获电子（或空穴）的数目

$$n \cdot r_n = \sigma_- \bar{v}_T \cdot n$$

$$\boxed{r_n = \sigma_- \bar{v}_T}$$

$$\boxed{r_p = \sigma_+ \bar{v}_T}$$

[cm^2]

[cm^{3}s^{-1}]

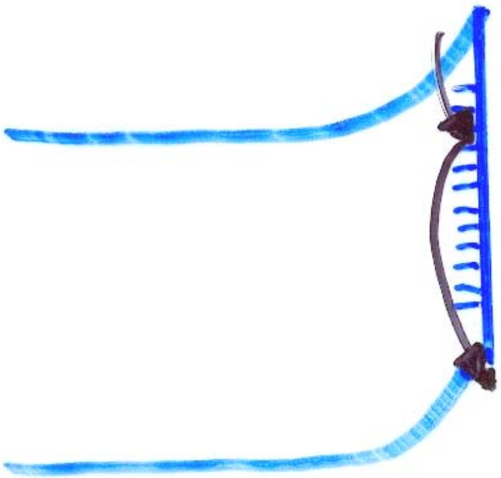
r_n、 r_p 均可用 σ_-、σ_+ 来替换， $\sigma_\pm = 10^{-13} \sim 10^{-17}$ cm^2

7.3 复合理论14

7.3.4 表面复合

表面态，通常都是深能级

——有效的复合中心



表面复合率

$$U_s = \frac{\text{复合数目}}{\text{单位时间}\cdot\text{单位表面积}} = s_p \cdot (\Delta p)_s$$

[cm^{-2}s^{-1}]　　[cm/s][cm^{-3}]

$$U_s = \sigma_+ \bar{v}_T N_{st} \cdot (\Delta p)_s = s_p \cdot (\Delta p)_s$$

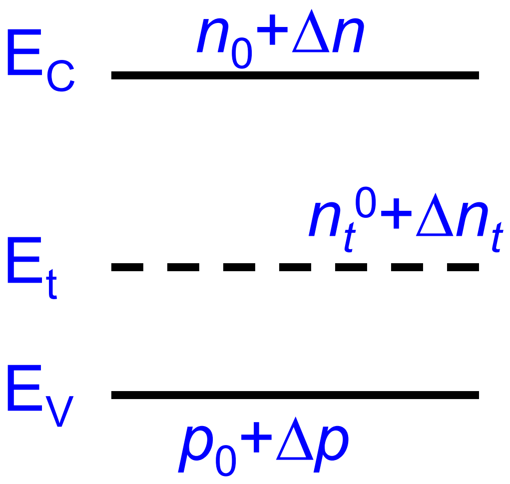
复合中心面密度

表面复合速度 $s_p = \sigma_+ \bar{v}_T N_{st}$

第七章 非平衡载流子

7.4 陷阱效应1

7.4.1 陷阱现象



$\Delta p \neq \Delta n$

$\Delta p = \Delta n + \Delta n_t$

若 $\Delta n_t > 0$，电子陷阱作用

若 $\Delta n_t < 0$，空穴陷阱作用

有效的陷阱：在 N_t 较低的条件下，

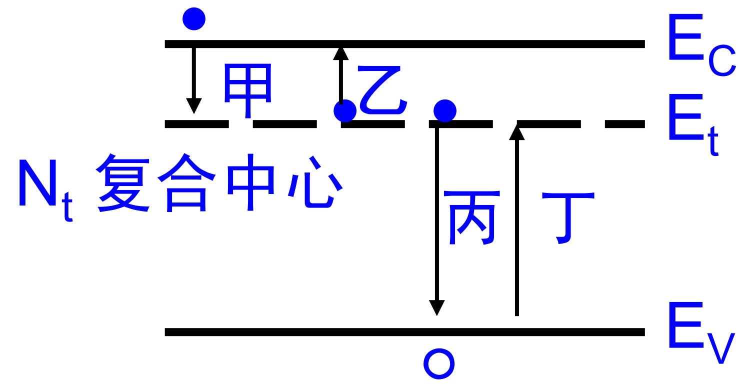
$\Delta n_t >> \Delta n$（Δp）.

杂质能级积累非平衡载流子的作用称为陷阱效应

7.4 陷阱效应2

7.4.2 成为陷阱的条件

杂质能级上的电子数



$$n_t = N_t \frac{r_n n + r_p p_1}{r_n(n+n_1)+r_p(p+p_1)}$$

$$\Delta n_t = \left(\frac{\partial n_t}{\partial n}\right)_0 \Delta n + \left(\frac{\partial n_t}{\partial p}\right)_0 \Delta p \qquad n_t^0 = N_t \frac{r_n n_0 + r_p p_1}{r_n(n_0+n_1)+r_p(p_0+p_1)}$$

$$\left(\frac{\partial n_t}{\partial n}\right)_0 = N_t \frac{r_n\left[r_n(n_0+n_1)+r_p(p_0+p_1)\right]-r_n(r_n n_0+r_p p_1)}{\left[r_n(n_0+n_1)+r_p(p_0+p_1)\right]^2}$$

$$= \boxed{N_t \frac{r_n(r_n n_1+r_p p_0)}{\left[r_n(n_0+n_1)+r_p(p_0+p_1)\right]^2}}$$

$$\left(\frac{\partial n_t}{\partial p}\right)_0 = -\boxed{N_t \frac{r_p(r_n n_0+r_p p_1)}{\left[r_n(n_0+n_1)+r_p(p_0+p_1)\right]^2}}$$

A

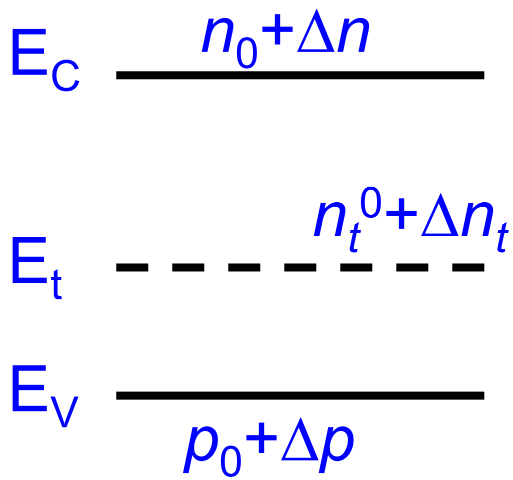
7.4 陷阱效应3

7.4.2 成为陷阱的条件

$$\boxed{\Delta n_t = \left(\frac{\partial n_t}{\partial n}\right)_0 \Delta n + \left(\frac{\partial n_t}{\partial p}\right)_0 \Delta p}$$

$$\boxed{\left(\frac{\partial n_t}{\partial n}\right)_0 = Ar_n\left(r_n n_1 + r_p p_0\right)}$$

$$\boxed{\left(\frac{\partial n_t}{\partial p}\right)_0 = -Ar_p\left(r_n n_0 + r_p p_1\right)}$$



$\Delta p \neq \Delta n$

$\Delta p = \Delta n + \Delta n_t$

若 $\Delta n_t > 0$，电子陷阱作用

若 $\Delta n_t < 0$，空穴陷阱作用

$$\begin{cases} \Delta n_t = Ar_n\left(r_n n_1 + r_p p_0\right)\Delta n - Ar_p\left(r_n n_0 + r_p p_1\right)\Delta p \\ \Delta n_t = \Delta p - \Delta n \end{cases}$$

$$\Rightarrow \frac{\Delta n_t}{\Delta n} = \frac{Ar_n\left(r_n n_1 + r_p p_0\right) - Ar_p\left(r_n n_0 + r_p p_1\right)}{1 + Ar_p\left(r_n n_0 + r_p p_1\right)} = \frac{1 + Ar_n\left(r_n n_1 + r_p p_0\right)}{1 + Ar_p\left(r_n n_0 + r_p p_1\right)} - 1$$

$\dfrac{\Delta n_t}{\Delta n} > 0$ —— 电子陷阱

7.4 陷阱效应4

7.4.2 成为陷阱的条件

$$\frac{\Delta n_t}{\Delta n}=\frac{Ar_n\left(r_n n_1+r_p p_0\right)-Ar_p\left(r_n n_0+r_p p_1\right)}{1+Ar_p\left(r_n n_0+r_p p_1\right)}=\frac{1+Ar_n\left(r_n n_1+r_p p_0\right)}{1+Ar_p\left(r_n n_0+r_p p_1\right)}-1$$

成为有效电子陷阱的条件： $\boxed{\dfrac{\Delta n_t}{\Delta n}>>1}$

则要求 $Ar_n\left(r_n n_1+r_p p_0\right)>>Ar_p\left(r_n n_0+r_p p_1\right)>>1$

或 $Ar_n\left(r_n n_1+r_p p_0\right)>>1>>Ar_p\left(r_n n_0+r_p p_1\right)$

简单地 $r_n>>r_p$

$$\Delta n_t=Ar_n\left(r_n n_1+r_p p_0\right)\Delta n-Ar_p\left(r_n n_0+r_p p_1\right)\Delta p$$

$$\boxed{\Delta n_t\approx\left(\frac{\partial n_t}{\partial n}\right)_0\Delta n\approx N_t\frac{r_n\left(r_n n_1+0\right)}{\left[r_n\left(n_0+n_1\right)\right]^2}\Delta n=N_t\frac{n_1}{\left(n_0+n_1\right)^2}\Delta n}$$

7.4 陷阱效应5

7.4.2 成为陷阱的条件

$r_n >> r_p$

$$\boxed{\Delta n_t = N_t \frac{n_1}{(n_0 + n_1)^2} \Delta n}$$

1° 当 $n_1 = n_0$（即 $E_t = E_F$）时 $(\Delta n_t)_{\max} = \dfrac{N_t}{4n_0}\Delta n$

2° 要使 Δn_t 大，n_0 最好为少子，即 p 型半导体.

$r_n >> r_p$ 陷阱俘获电子后，很难俘获空穴，因而被俘获的电子往往在复合前受到热激发又被重新释放回导带。

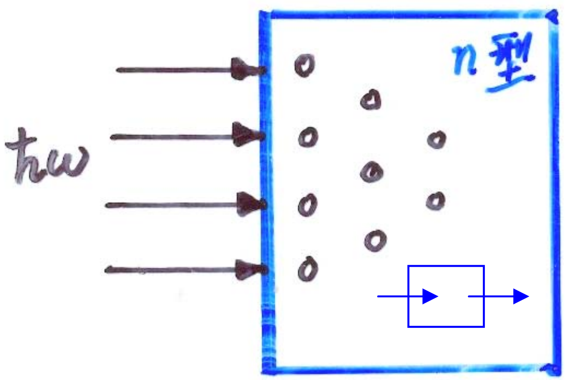
陷阱的作用 —— 增加少子寿命

第七章 非平衡载流子

7.1 非平衡载流子的注入与复合
7.2 准费米能级
7.3 复合理论
7.4 陷阱效应
7.5 载流子的扩散运动
7.6 载流子的漂移运动、双极扩散
7.7 连续性方程

7.5 载流子的扩散运动1

7.5.1 一维扩散方程



空穴 —— 非平衡少子 $\Delta p(x)$

扩散流密度 $s_p = -D_p \dfrac{d\Delta p(x)}{dx}$

空穴扩散系数 $[cm^2/s]$

在 $x \to x+dx$ 范围内，单位时间内增加的空穴数 $\left[s_p(x) - s_p(x+dx)\right]A$

增加的空穴浓度

$$\left(\frac{d\Delta p}{dt}\right)_{扩散} = \frac{\left[s_p(x) - s_p(x+dx)\right]A}{Adx} = -\frac{ds_p(x)}{dx} = D_p \frac{d^2\Delta p(x)}{dx^2}$$

一维扩散方程

而 $\left(\dfrac{d\Delta p}{dt}\right)_{复合} = -\dfrac{\Delta p(x)}{\tau}$

$$\boxed{\frac{\partial \Delta p(x,t)}{\partial t} = D_p \frac{\partial^2 \Delta p(x,t)}{\partial x^2} - \frac{\Delta p(x,t)}{\tau}}$$