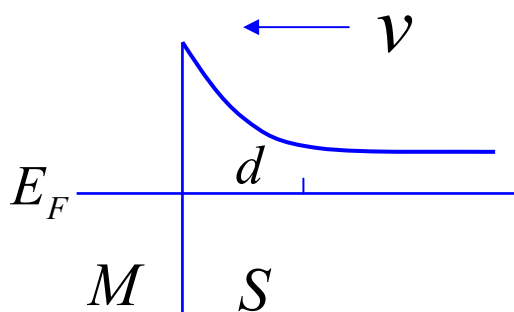


9.2 金半接触的整流输运理论⁵

9.2.2 热电子发射理论



—适用于势垒宽度 \ll 电子平均自由程 $l_n \gg d$

$$E - E_C = \frac{m_n^*}{2} (v_x^2 + v_y^2 + v_z^2) = \frac{1}{2m_n^*} (P_x^2 + P_y^2 + P_z^2)$$

单位动量空间 $dP_x dP_y dP_z$ 中的状态数

$$2 \frac{V}{(2\pi)^3} dk_x dk_y dk_z = \frac{2V}{\hbar^3 (2\pi)^3} dP_x dP_y dP_z = \frac{2V}{h^3} dP_x dP_y dP_z$$

实空间单位体积中，动量空间单位体积 $dP_x dP_y dP_z$ 中的电子数

$$\begin{aligned} dn' &= \frac{2dP_x dP_y dP_z}{h^3} \exp\left(-\frac{E - E_F}{kT}\right) = \frac{2dP_x dP_y dP_z}{h^3} \exp\left[-\frac{m_n^* (v_x^2 + v_y^2 + v_z^2)}{2kT}\right] \exp\left(-\frac{E_C - E_F}{kT}\right) \\ &= \frac{2m_n^{*3}}{h^3} \exp\left(-\frac{E_C - E_F}{kT}\right) \exp\left[-\frac{m_n^* (v_x^2 + v_y^2 + v_z^2)}{2kT}\right] dv_x dv_y dv_z \\ &= n_0 \left(\frac{m_n^*}{2\pi kT}\right)^{3/2} \exp\left[-\frac{m_n^* (v_x^2 + v_y^2 + v_z^2)}{2kT}\right] dv_x dv_y dv_z \end{aligned}$$

$$n_0 = 2 \frac{(2\pi m_n^* kT)^{3/2}}{h^3} \exp\left(-\frac{E_C - E_F}{kT}\right)$$

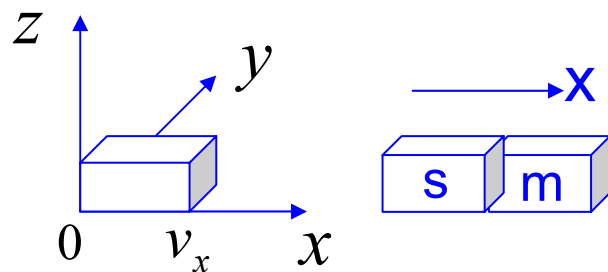
速度空间单位体积中的电子数₁₃₂₃

9.2 金半接触的整流输运理论⁶

9.2.2 热电子发射理论

实空间单位体积，速度空间电子的分布

$$dn' = n_0 \left(\frac{m_n^*}{2\pi kT} \right)^{3/2} \exp \left[-\frac{m_n^* (v_x^2 + v_y^2 + v_z^2)}{2kT} \right] dv_x dv_y dv_z$$



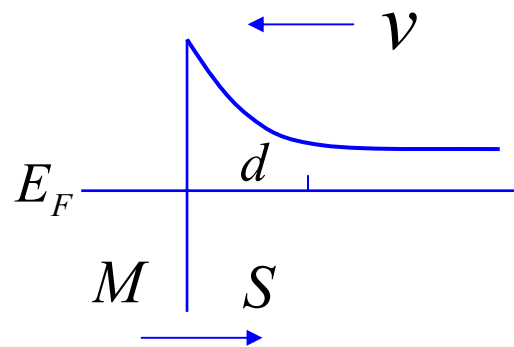
$$l_n \gg d$$

实空间单位面积，单位时间，速度 $v_x(>0)$ 的电子都可以到达金半界面，其数目为

$$dN = n_0 \left(\frac{m_n^*}{2\pi kT} \right)^{3/2} \exp \left[-\frac{m_n^* (v_x^2 + v_y^2 + v_z^2)}{2kT} \right] v_x dv_x dv_y dv_z$$

可以越过势垒电子的能量要求

$$\frac{1}{2} m_n^* v_{x0}^2 = q(V_D - V)$$



v_x 积分限: $v_{x0} \rightarrow +\infty$ → 电流密度

v_y 积分限: $-\infty \rightarrow +\infty$

$$v_z \text{ 积分限: } -\infty \rightarrow +\infty \quad J_{s \rightarrow m} = \iiint n_0 \left(\frac{m_n^*}{2\pi kT} \right)^{3/2} \exp \left[-\frac{m_n^* (v_x^2 + v_y^2 + v_z^2)}{2kT} \right] \cdot q v_x dv_x dv_y dv_z$$

9.2 金半接触的整流输运理论

9.2.2 热电子发射理论

$$J_{s \rightarrow m} = \iiint n_0 \left(\frac{m_n^*}{2\pi kT} \right)^{3/2} \exp \left[-\frac{m_n^* (v_x^2 + v_y^2 + v_z^2)}{2kT} \right] \cdot q v_x dv_x dv_y dv_z$$

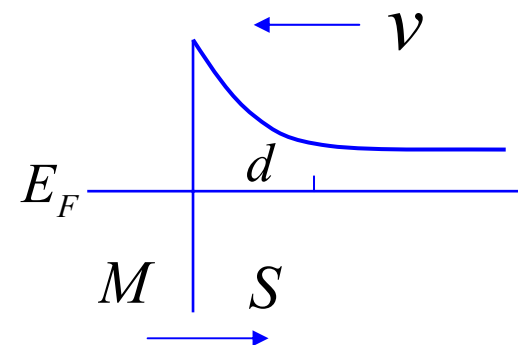
$V_x: V_{x0} \rightarrow +\infty; V_y: -\infty \rightarrow +\infty; V_z: -\infty \rightarrow +\infty$

$$= q n_0 \left(\frac{kT}{2\pi m_n^*} \right)^{1/2} \exp(-m_n^* v_{x0}^2 / 2kT)$$

$$= \frac{4\pi q m_n^* k^2}{h^3} T^2 \exp(-q\phi_{ns}/kT) \exp(qV/kT)$$

$$= A^* T^2 \exp(-q\phi_{ns}/kT) \exp(qV/kT)$$

$$A^* = 120 (m_n^*/m_0) [\text{Acm}^{-2}\text{K}^{-2}]$$



$$\frac{1}{2} m_n^* v_{x0}^2 = q(V_D - V)$$

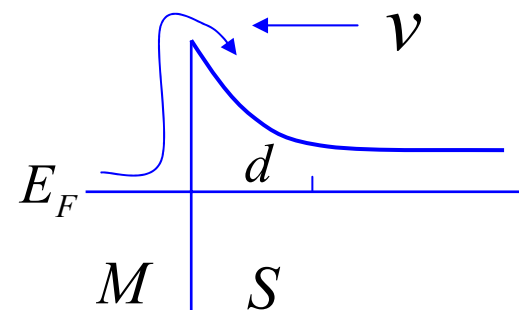
— 半导体到金属的电子流
依赖于电压

9.2 金半接触的整流输运理论₈

9.2.2 热电子发射理论

— 金属到半导体的电子流基本不依赖于电压

$J_{m \rightarrow s}$: 常数

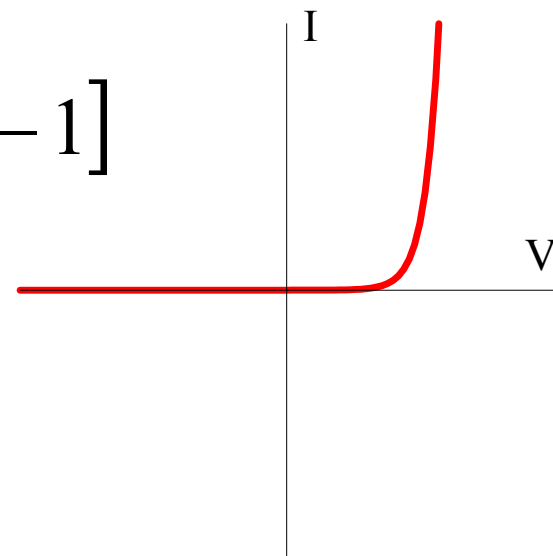


$$V=0, J=0 \longrightarrow J_{m \rightarrow s} \big|_{V=0} = -J_{s \rightarrow m} \big|_{V=0} = -A^* T^2 \exp(-q\phi_{ns}/kT)$$

$$J(V) = J_{s \rightarrow m}(V) + J_{m \rightarrow s}(0)$$

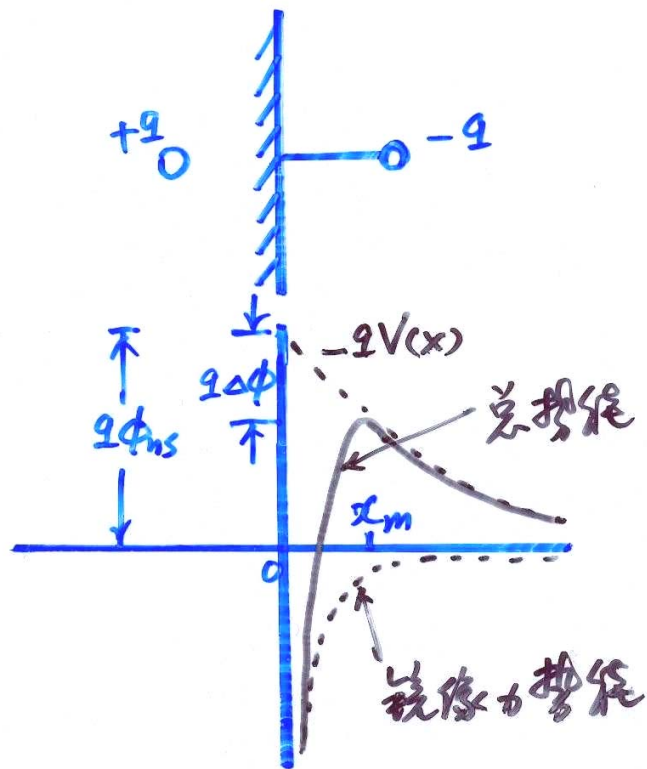
$$= A^* T^2 \exp(-q\phi_{ns}/kT) [\exp(qV/kT) - 1]$$

$$= J_{ST} [\exp(qV/kT) - 1]$$



9.2 金半接触的整流输运理论⁹

9.2.3 镜像力影响



$$f_{im} = -\frac{q^2}{4\pi\epsilon_0\epsilon_r(2x)^2}$$

$$U_{im}(x) = \int_x^\infty f_{im} dx = -\frac{q^2}{16\pi\epsilon_0\epsilon_r x}$$

$$V(x) = -\frac{qN_D}{2\epsilon_0\epsilon_r}(x^2 - 2xd) - \phi_{ns}$$

电子总电势能

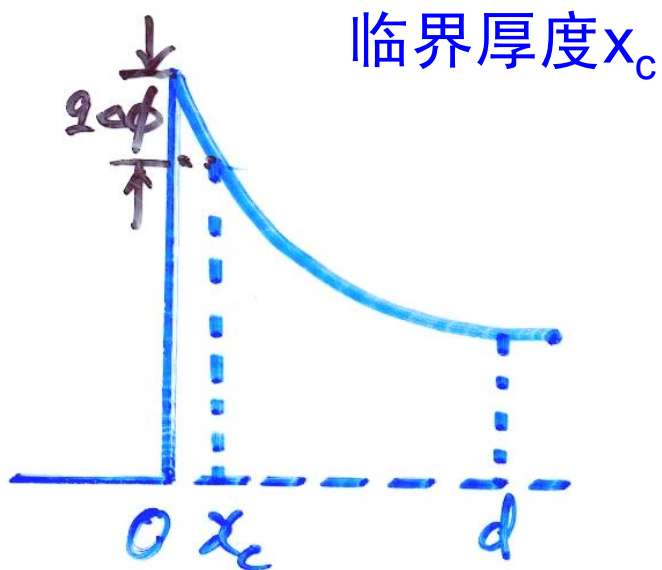
$$U(x) = -\frac{q^2}{16\pi\epsilon_0\epsilon_r x} - qV(x)$$

$$\left. \frac{dU(x)}{dx} \right|_{x=x_m} = 0 \quad \xrightarrow{x_m \ll d} x_m = (4\pi N_D d)^{-1/2}$$

$$q\Delta\phi = \frac{q^2 N_D}{\epsilon_0 \epsilon_r} x_m d = \frac{1}{4} \left[\frac{2q^7 N_D}{\pi^2 \epsilon_0^3 \epsilon_r^3} (V_D - V) \right]^{1/4} \quad \leftarrow -qV(x_m) = q\phi_{ns} - \frac{q^2 N_D}{\epsilon_0 \epsilon_r} x_m d$$

9.2 金半接触的整流输运理论¹⁰

9.2.4 隧道效应影响



$$-qV(x_c) = -q \left[\frac{qN_D}{\epsilon_0 \epsilon_r} \left(x_c d - \frac{x_c^2}{2} \right) - \phi_{ns} \right]$$

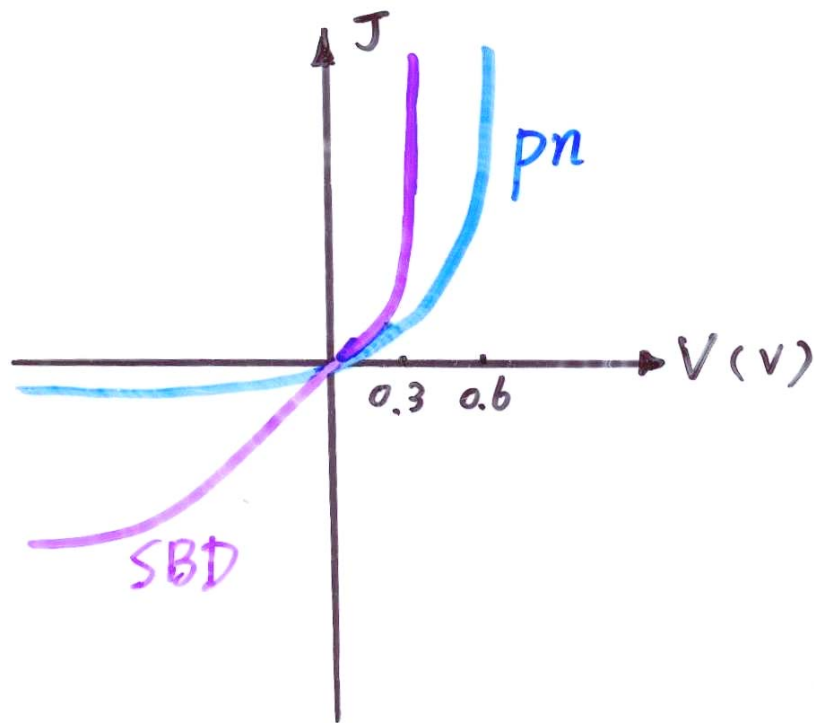
$$x_c \ll d$$

$$-qV(x_c) \approx q\phi_{ns} - \left[\frac{2q^3 N_D}{\epsilon_0 \epsilon_r} (V_D - V) \right]^{1/2} x_c$$

$$q\Delta\phi = \left[\frac{2q^3 N_D}{\epsilon_0 \epsilon_r} (V_D - V) \right]^{1/2} x_c$$

9.2 金半接触的整流输运理论¹¹

9.2.5 pn结和肖特基势垒二极管



pn	SBD
少子器件, 电荷存贮效应	多子器件, 载流子无存贮
低频	高频
导通电压 ~ 0.6 V	导通电压 ~ 0.3 V

第九章 金半接触

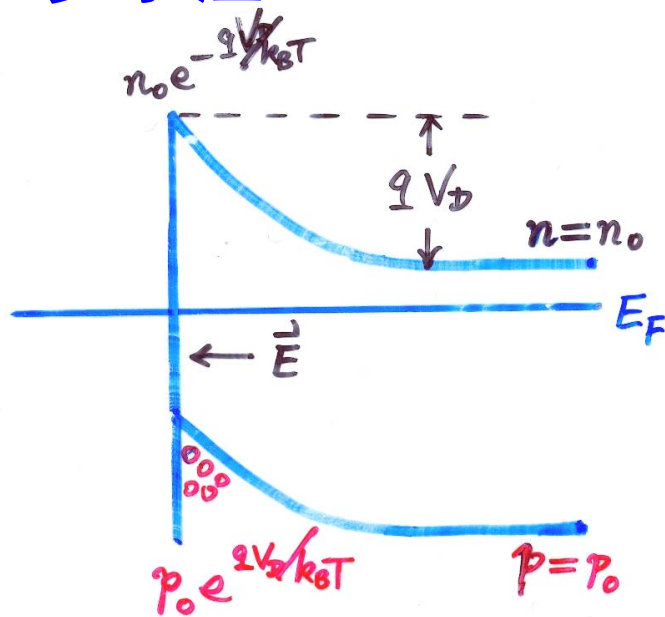
9.1 金半接触的能带图

9.2 金半接触的整流输运理论

9.3 少子注入和欧姆接触

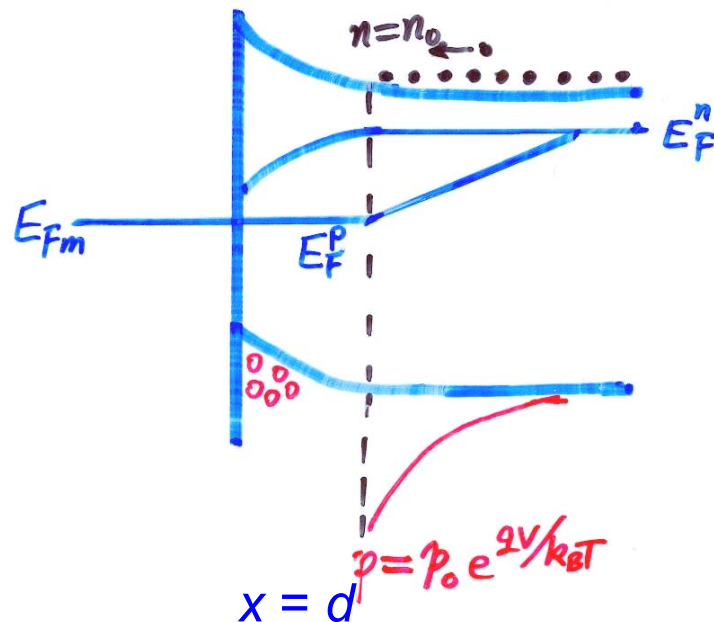
9.3 少子注入和欧姆接触₁

9.3.1 少子注入



$V = 0$ (平衡态)

空穴扩散与电场抵消



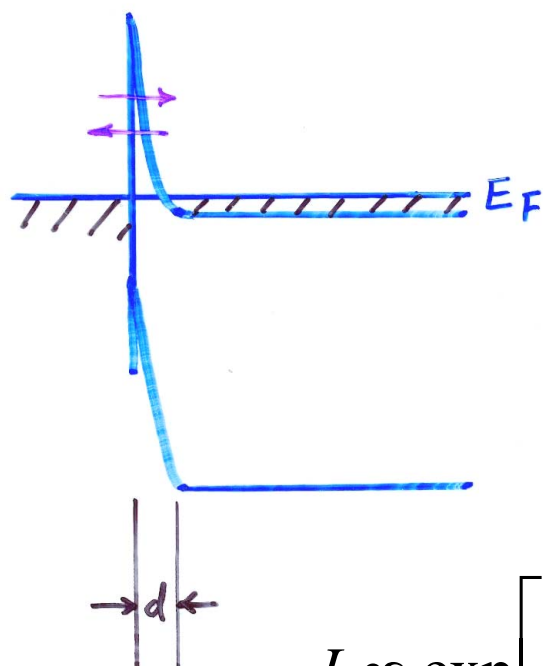
$V > 0$ (正偏) 空穴扩散主导

少子注入比

$$\gamma = \frac{J_p}{J} = \frac{J_p}{J_n + J_p}$$

9.3 少子注入和欧姆接触₂

9.3.2 欧姆接触



金属—重掺杂半导体接触

$$N_D = 10^{19} \text{ cm}^{-3} \quad d \sim 10^2 \text{ \AA}$$

电子隧穿通过势垒区

$$J_{s \rightarrow m} \propto \exp \left[-\frac{4\pi}{h} \left(\frac{m_n^* \varepsilon_0 \varepsilon_r}{N_D} \right)^{1/2} (V_D - V) \right]$$

$$J_{m \rightarrow s} = C \equiv J_{m \rightarrow s}|_{V=0} = J_{s \rightarrow m}|_{V=0}$$

$$J \propto \exp \left[-\frac{4\pi}{h} \left(\frac{m_n^* \varepsilon_0 \varepsilon_r}{N_D} \right)^{1/2} V_D \right] \left\{ \exp \left[\frac{4\pi}{h} \left(\frac{m_n^* \varepsilon_0 \varepsilon_r}{N_D} \right)^{1/2} V \right] - 1 \right\}$$

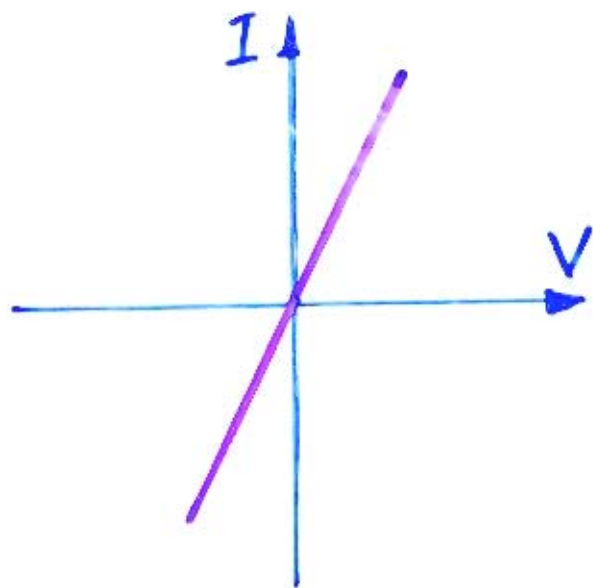
$$N_D \gg 1 \rightarrow J \propto \frac{4\pi}{h} \left(\frac{m_n^* \varepsilon_0 \varepsilon_r}{N_D} \right)^{1/2} \exp \left[-\frac{4\pi}{h} \left(\frac{m_n^* \varepsilon_0 \varepsilon_r}{N_D} \right)^{1/2} V_D \right] \cdot V$$

$$\propto V$$

9.3 少子注入和欧姆接触₃

9.3.2 欧姆接触

$$J \propto \frac{4\pi}{h} \left(\frac{m_n^* \epsilon_0 \epsilon_r}{N_D} \right)^{1/2} \exp \left[- \frac{4\pi}{h} \left(\frac{m_n^* \epsilon_0 \epsilon_r}{N_D} \right)^{1/2} V_D \right] \cdot V \quad \boxed{\propto V}$$



1° 线性 I - V , 正反向对称

2° $R = \left(\frac{dI}{dV} \right)^{-1}$ 接触电阻很小