1st晶体管: Willan Shonley, John Baddeny, Walter Brattan 1949

1st集成电路. Jack Killby. 1958.

$1\mu m = 10^{-4} cm \quad \mu_n = 1450\, cm^2/V\cdot S$

注意长度单位通常是cm!!

$\frac{kT}{q} = U_T = 25.9mV$

$q = 1.6\times10^{-19}$

$\varepsilon_{si} = 11.9 \times 8.854\times10^{-14}\ F/cm$

中国科学技术大学

(空间电荷)

中性 | 扩散 | 耗尽 | 扩散 | 中性

零偏　　正偏: V_F正偏

$V_{total} = V_{bi} + V_R$

PN结: $V_{bi} = U_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$　$= V_{bi} - V_f$

$X_D = x_n + x_p = \sqrt{\frac{2\varepsilon_{si} V_{total}}{q(N_A // N_D)}}$

$E_{max} = -\frac{q}{\varepsilon_{si}} N_A x_p$ 或 $-\frac{q}{\varepsilon_{si}} N_D x_n$ 或 $-\frac{2V_{total}}{X_D}$

能带: n: $E_F = E_c + kT \ln\left(\frac{N_D}{N_C}\right)$

$= E_{Fi} + kT \ln\left(\frac{N_D}{n_i}\right)$

p: $E_F = E_v - kT \ln\left(\frac{N_A}{N_V}\right)$

$= E_{Fi} + kT \ln\left(\frac{N_A}{n_i}\right)$

E_c, E_D, E_i, E_A, E_v, E_g

泊松方程: $\frac{d^2\varphi}{dx^2} = -\frac{\rho}{\varepsilon_{si}} = -\frac{dE}{dx}$　$\rho = q(N_A - N_D)$

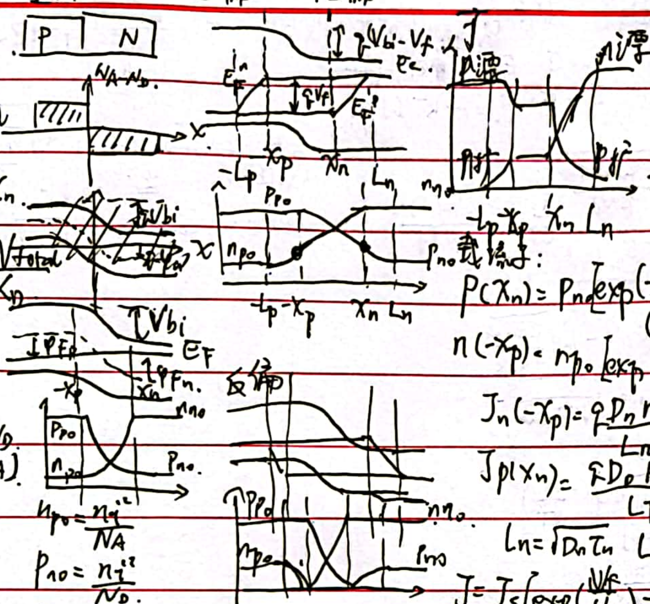
势垒电容: $C = Area \cdot \frac{\varepsilon_{si}}{X_D} = AC'$　$C' = \frac{\varepsilon_{si}}{X_D}$

$\left(\frac{1}{C'}\right)^2 = f(V_R) = \frac{2(V_D+V_R)}{q\varepsilon N_d}$ (低掺杂浓度)

扩散电容: $C = Aq^2 \left(\frac{p_{p0}L_n + p_{n0}L_p}{kT\ U_T}\right)\exp\left(\frac{V_F}{U_T}\right)$

雪崩击穿: $V_B = 60(E_g/1.1)^{3/2}(N_B/10^{16})^{-3/4}$

$V_B = V_R$.



$n_{p0} = \frac{n_i^2}{N_A}$

$p_{n0} = \frac{n_i^2}{N_D}$

$n_{n0} = N_A$

$p_{p0} = N_D$

p$_{n0}$载流子:

$p(x_n) = p_{n0}\left[\exp\left(\frac{V_F}{U_T}\right) - 1\right]$

$n(-x_p) = n_{p0}\left[\exp\left(\frac{V_F}{U_T}\right) - 1\right]$

$J_n(-x_p) = \frac{qD_n n_{p0}}{L_n}\left(e^{\frac{V}{U_T}} - 1\right)$

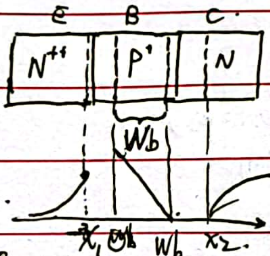
$J_p(x_n) = \frac{qD_p p_{n0}}{L_p}\left(e^{\frac{V}{U_T}} - 1\right)$

$L_n = \sqrt{D_n \tau_n} \quad L_p = \sqrt{D_p \tau_p}$

$J = J_s\left[\exp\left(\frac{V_F}{U_T}\right) - 1\right]$

$J_s = q n_i^2 \left(\sqrt{\frac{D_p}{\tau_p}}\frac{1}{N_D} + \sqrt{\frac{D_n}{\tau_n}}\frac{1}{N_A}\right)$

BJT: B-C 反偏 $V_R\uparrow$ 空间电荷区$\uparrow$. B-E 正偏 基区宽度 $\downarrow$ → 击穿.



以NPN为例. $\alpha_T = 1 - \frac{W_b^2}{2L_b^2}$　$L_b = \sqrt{D_b \tau_b}$　W_b: 基区宽度

$\gamma = \left(1 + \frac{D_{pe}}{D_{pb}}\frac{p_{ne0}}{n_{pb0}}\frac{W_b}{L_{pe}}\right)^{-1}$

$n_{pe0} = \frac{n_i^2}{N_E}$. $n_{pb0} = \frac{n_i^2}{N_B}$.

$\alpha_0 = \alpha_T \gamma$.

$\beta_0 = \frac{\alpha_0}{1-\alpha_0}$　$|\beta| = \frac{\beta_0}{\sqrt{1+(f/f_\beta)^2}}$

$p_{ne}(x_1) = p_{ne0}\exp(U_{be}/U_T)$.

$n_{pb}(0) = n_{pb0}\exp(U_{be}/U_T)$.

$n_{pb}(x) = n_{pb}(0)\left(1 - \frac{x}{W_b}\right)$.

$p_{nc}(x_2) = p_{nc}(0)\exp(U_{be}/U_T)$

$g_m = \frac{I_c}{U_T}$　$g_{be} = \frac{g_m}{\beta_0}$

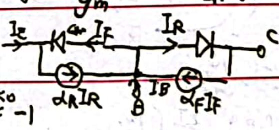
$f_T = \beta_0 f_\beta = \frac{1}{2\pi\left(\tau_F + \frac{C_{je} + C_{jc}}{g_m} + \frac{C_{jc}}{g_m}\right)}$

$= \frac{1}{2\pi(\tau_F + \tau_E + \tau_C)}$

$\tau_F = \tau_B = \frac{W_B^2}{2D_n} = \frac{C_{jE}}{g_m}$　$I_F = $

$\tau_C = r_C C_{jc} + \frac{C_{jc}}{g_m}$　$I_R = J_{SR}\left[\exp\left(\frac{V_{BC}}{V_T}\right) - 1\right]$

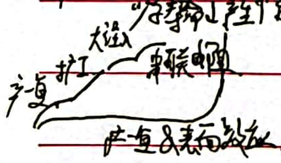
E-M模型:



近似: $e^x - 1 \overset{x<0}{\approx} -1$

非理想: 产生复合 $E_g \downarrow$ $n_i\uparrow$ 反向 $I\uparrow$.

少子寿命$\downarrow$ 产生$\uparrow$ 反$I\uparrow$.



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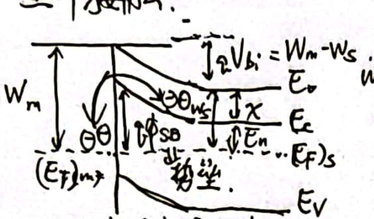
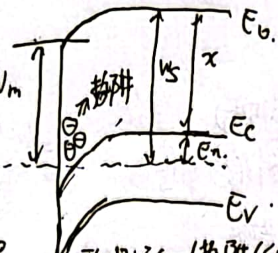
金半接触：





肖特基接触/势垒/阻挡层　　欧姆接触/势阱/反阻挡层

	$W_m>W_s$	$W_m<W_s$
n	肖特基	欧姆
p	欧姆	肖特基

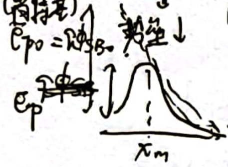
$E_n=E_c-E_F=-kT\ln\left(\frac{N_D}{N_C}\right)$

$E_p=E_F-E_V=-kT\ln\left(\frac{N_A}{N_V}\right)$

肖特基：耗尽区宽度 $W=x_n=\sqrt{\frac{2\varepsilon_s V_{total}}{qN_d}}$　　$\frac{1}{C^2}=\frac{2(V_{bi}+V_R)}{qN_d\varepsilon}$

镜像力效应：感应电荷　$C'=\frac{\varepsilon_s}{W}$
(肖特基)

$E_{max}=\frac{qN_dW}{\varepsilon}$　　ϕ_{Bn}



$\Delta E_p=-q\sqrt{\frac{qE_{max}}{4\pi\varepsilon_s}}$

$x_m=\sqrt{\frac{q}{16\pi\varepsilon_s E_{max}}}$

扩散理论：$J=J_{SD}\left[\exp\left(\frac{V_F}{V_T}\right)-1\right]$

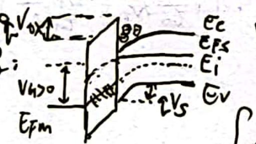
$J_{SD}=\sigma\sqrt{\frac{2qN_d}{\varepsilon_s}V_{total}}\exp\left(-\frac{V_{bi}}{V_T}\right)$

热电子发射理论：$J=J_{ST}\left[\exp\left(\frac{V_F}{V_T}\right)-1\right]$

$J_{ST}=R^*T^2\exp\left(-\frac{\phi_{Bn}}{V_T}\right)$

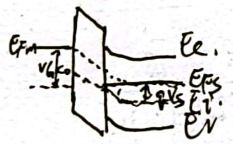
$R^*=120\frac{m^*}{m_0}$

MOSFET：
MOS电容：积累：



$V_{GS}-V_{TH}<V_{DS}$ 饱和
$V_{GS}-V_{TH}>V_{DS}$ 线

耗尽：

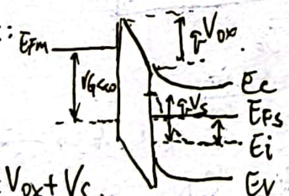


$$\begin{cases}\beta=\mu_n C_{ox}\frac{W}{L}\\ C_{ox}=\frac{\varepsilon_{ox}}{t_{ox}}\\ \text{饱：}I_D=\frac{1}{2}\beta(V_{GS}-V_{TH})^2\\ \text{线：}I_D=\beta\left[(V_{GS}-V_{TH})V_{DS}-\frac{1}{2}V_{DS}^2\right]\end{cases}$$

$g_D=\frac{\partial I_D}{\partial V_{DS}}=\beta(V_{GS}-V_{TH})$

$Q_{(x)}=-\frac{\varepsilon_{ox}}{t_{ox}}V_{(x)}$

反型：



$V_G=V_{ox}+V_S$

$E_{FS}-E_i=qV_B=kT\ln\left(\frac{N_D}{n_i}\right)$

$$\begin{cases}V_B=\frac{kT}{q}\ln\left(\frac{N_D}{n_i}\right)=\frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right)\\ Q_B=qN_Ad_{max}=\sqrt{2\varepsilon_s(2V_B)qN_A}\\ V_{Tn}=2V_B+\frac{Q_B}{C_{ox}}\ (+V_{FB})\qquad V_{Tp}=-2V_B-\frac{Q_B}{C_{ox}}\\ C_{ox}=\frac{\varepsilon_{ox}}{t_{ox}}\\ V_{FB}=\phi_{ms}-\frac{Q_{ss}}{C_{ox}}\\ \phi_{ms}=\frac{W_m-W_s}{q}\\ W_s=\chi+\frac{E_g}{2}+qV_B\\ C_{FB}=\frac{\varepsilon_{ox}S}{t_{ox}+\frac{\varepsilon_{ox}}{\varepsilon_s}\sqrt{U_T\frac{\varepsilon_s}{qN_D}}}\end{cases}$$

JFET：内夹断电压 $V_{p0}=\frac{qa^2N_d}{2\varepsilon_s}$

$V_p=V_{p0}-V_{bi}$

沟道电导 $G_0=\frac{2aqN_d\mu_n Z}{L}$　　MESFET：$W<a$ 耗尽型，$W>a$ 增强型

$W=\sqrt{\frac{2\varepsilon_s V_{bi}}{qN_d}}$

$G=\frac{a-W}{a}G_0$

$f_{c0}=\frac{G_0}{2\pi C_G}=\frac{V_{p0}\mu_n}{2\pi L^2}$　　$C_G=4ZL\frac{\varepsilon_s}{a}$

夹断前 I-V：$I_D=G_0\left[V_D-\frac{2}{3}\sqrt{\frac{1}{V_{p0}}}\left[(V_D+V_{bi}-V_G)^{3/2}-(V_{bi}-V_G)^{3/2}\right]\right]$　$V_D\ll V_{bi}-V_G$
(线性区)　$\overset{V_D=0}{=}G_0\left(1-\sqrt{\frac{V_{bi}-V_G}{V_{p0}}}\right)V_D$

饱和区：$I_{DS}=G_0\left(\frac{2}{3}\sqrt{\frac{V_{bi}-V_G}{V_{p0}}}-1\right)(V_{bi}-V_G)+\frac{1}{3}G_0V_{p0}$　$V_D>V_p+V_G$