微电子器件物理
MOSFET IV特性

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2020/10/20

本节课提纲

1. 亚阈值电流
2. 开态电流

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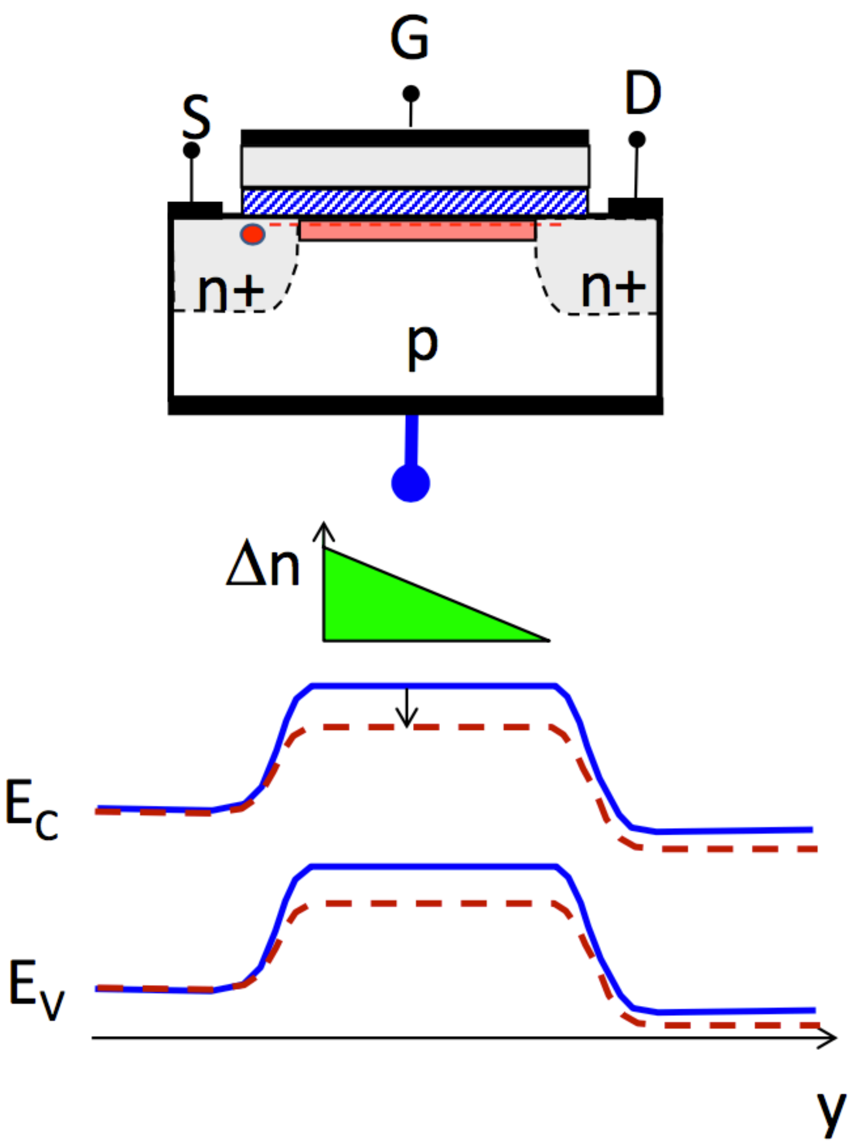
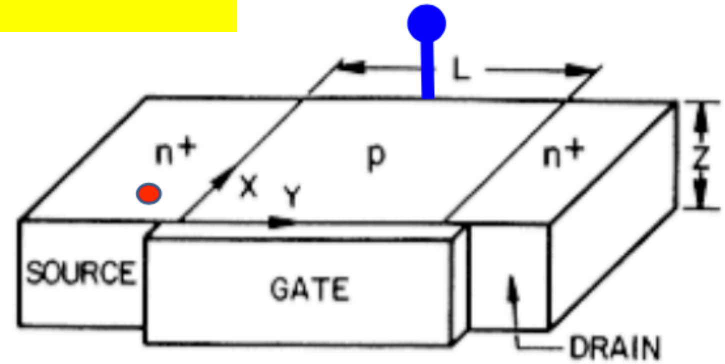
2. 开态电流

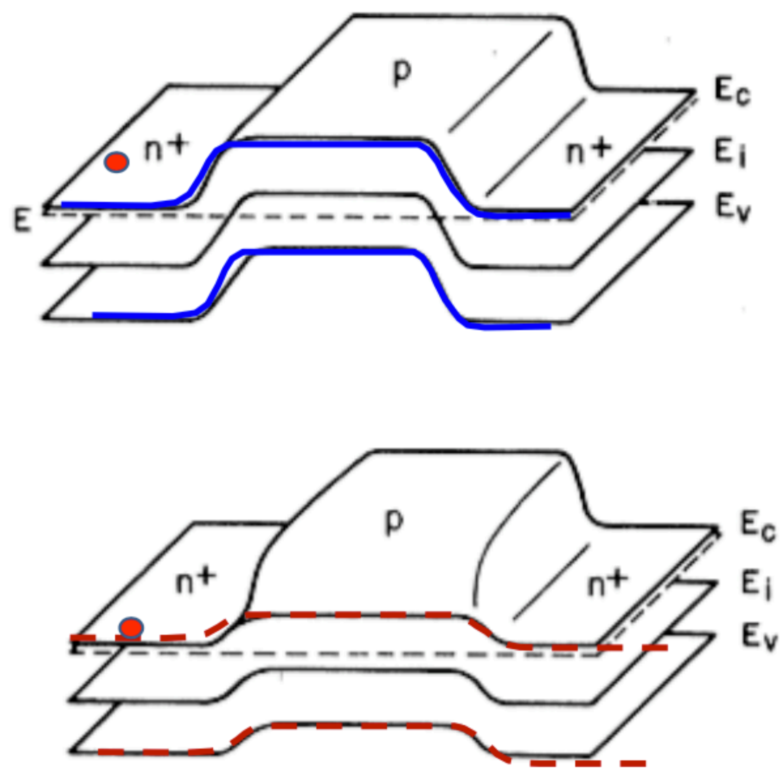
亚阈值区域



G
S
D
n+
n+
p
Δn
E_C
E_V
y

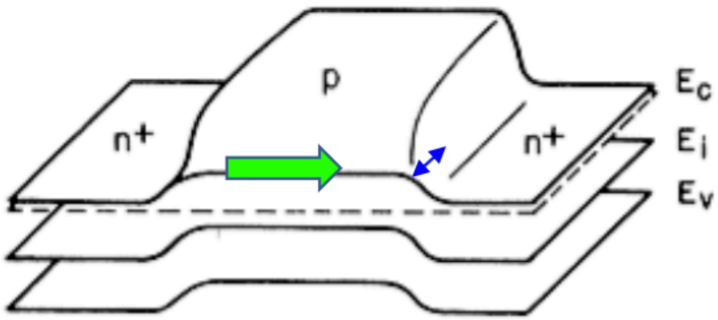


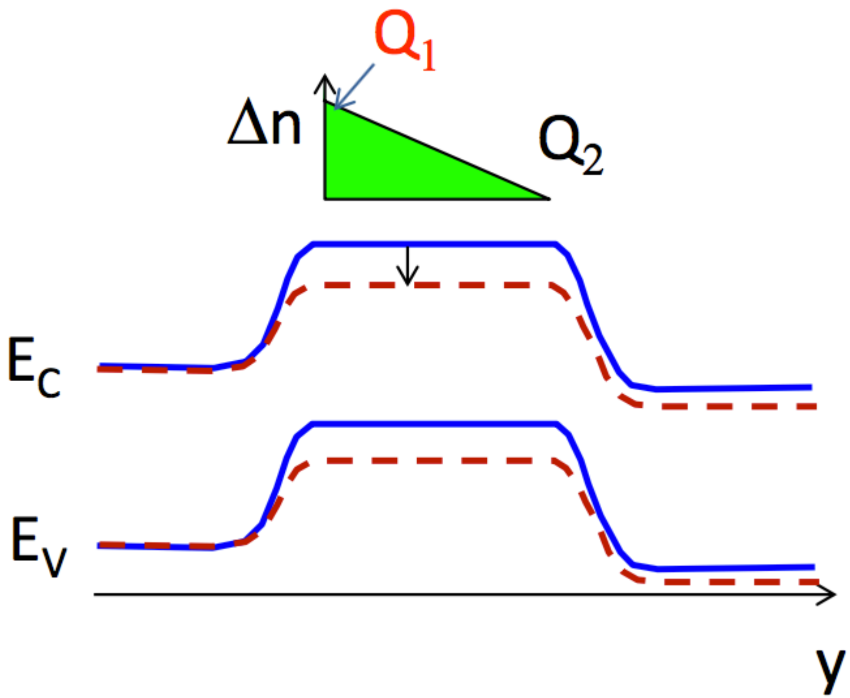
L
n+
p
n+
X
Y
Z
SOURCE
GATE
DRAIN

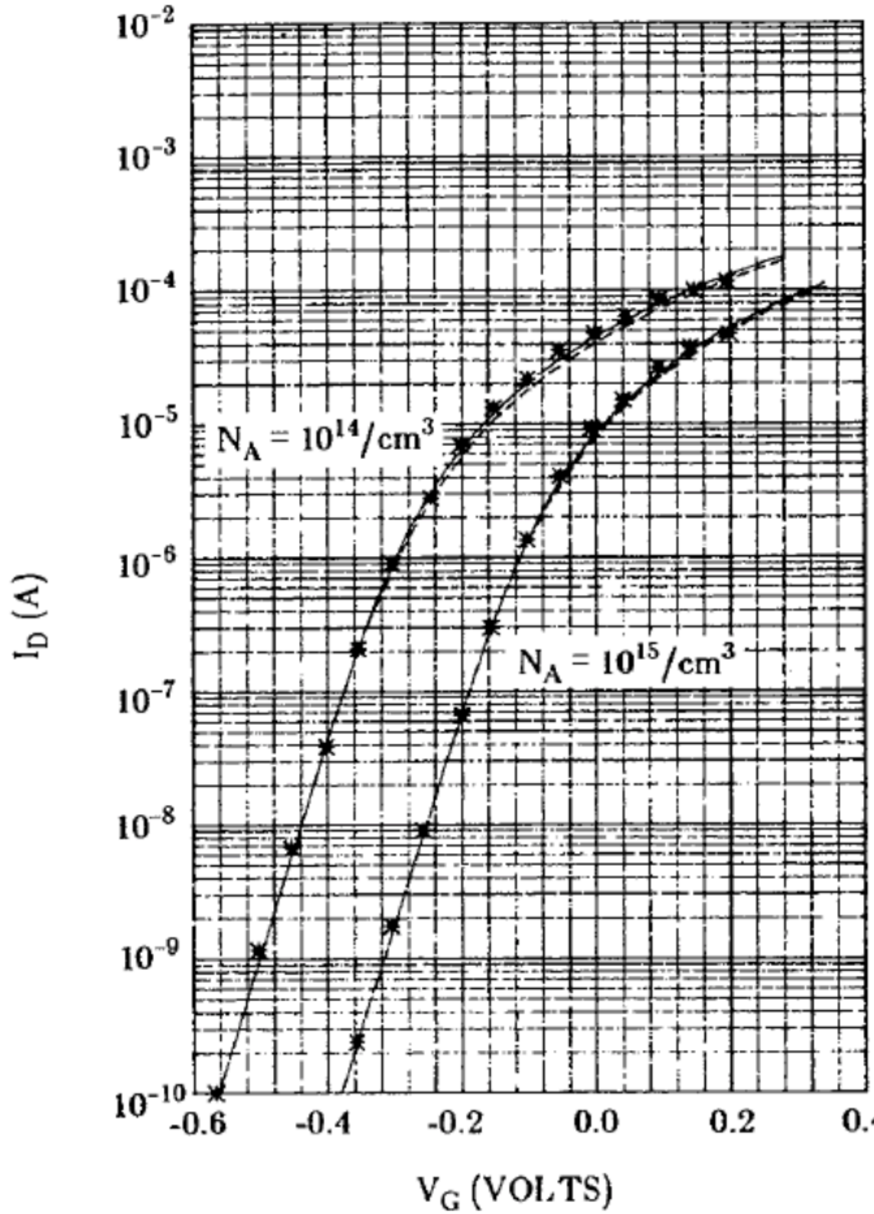


p
n+
n+
E
E_c
E_i
E_v
p
n+
n+
E_c
E_i
E_v

亚阈值区域


p
n+
n+
Ec
Ei
Ev


Q1
Δn
Q2
EC
EV
y


$N_A = 10^{14}/cm^3$
$N_A = 10^{15}/cm^3$
I_D (A)
V_G (VOLTS)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
-0.6
-0.4
-0.2
0.0
0.2
0.4

亚阈值区域

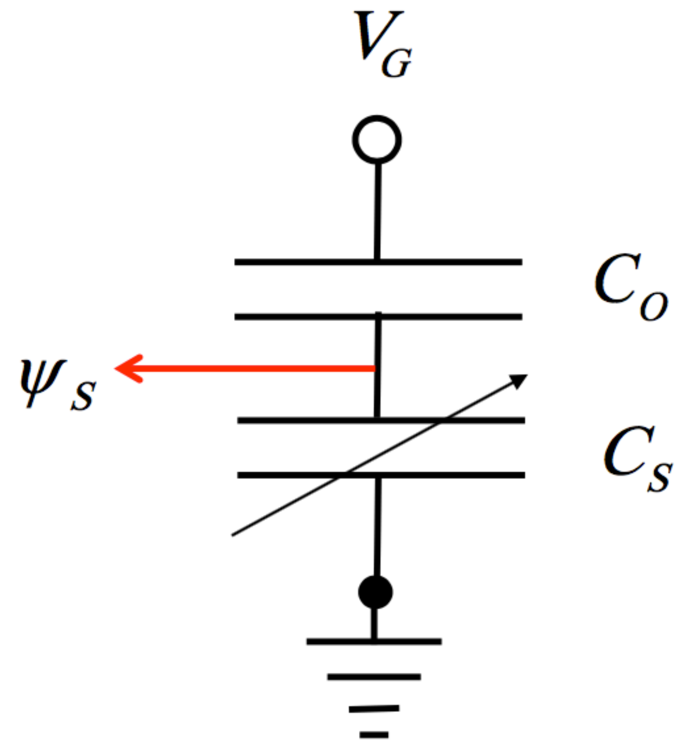
$$m=\left(1+C_S/C_O\right)$$

体效应因子

$$m=\left(1+\kappa_S x_O/\kappa_0 W_T\right)$$

通常

$$1.1\le m\le 1.4$$



$$\psi_S=\frac{C_O}{C_O+C_S}V_G\equiv\frac{V_G}{m}$$

本节课提纲

1. 亚阈值电流
2. 开态电流

开态电流

$$I_D = -\frac{W}{L_{ch}} \mu_{eff} \int_0^{V_{DS}} Q_i(V)\, dV$$

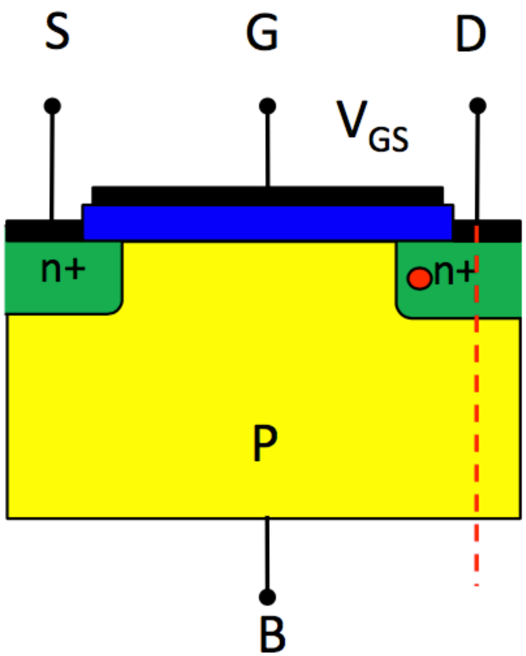
1) 平方律 $$Q_i(V) = -C_G\left[V_G - V_T - V\right]$$

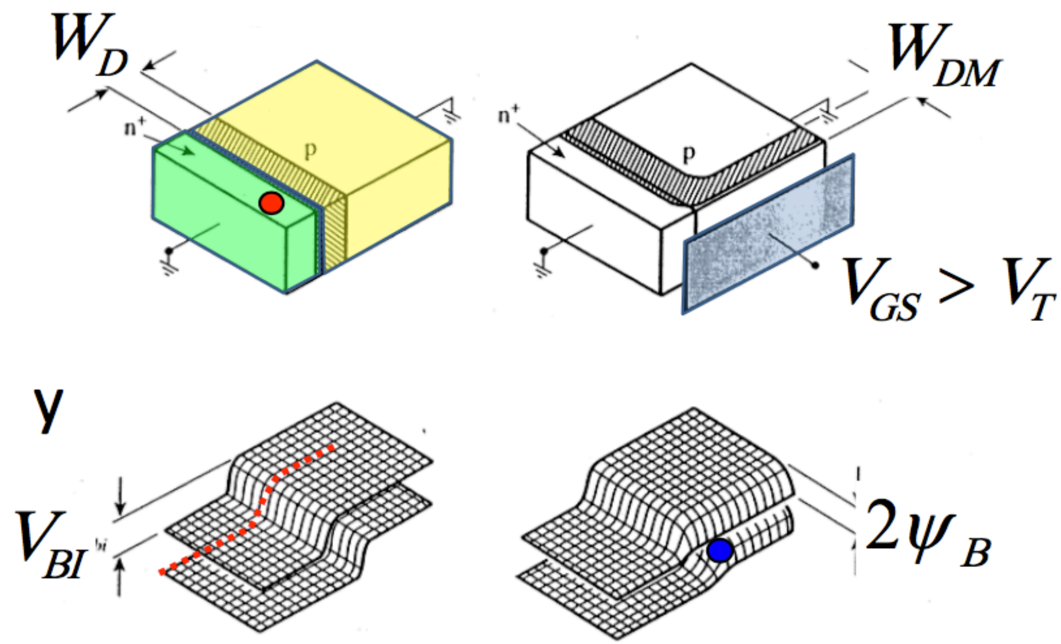
2) 体电荷模型 $$Q_i(V) = -C_G\left(V_G - V_{FB} - 2\psi_B - V - \frac{\sqrt{2q\varepsilon_{Si}N_A(2\phi_B + V)}}{C_O}\right)$$

3) 简化体电荷模型 $$Q_i(V) = -C_G\left[V_G - V_T - mV\right]$$

4) 精确解 (Pao-Sah or Pierret-Shields)

栅压的作用

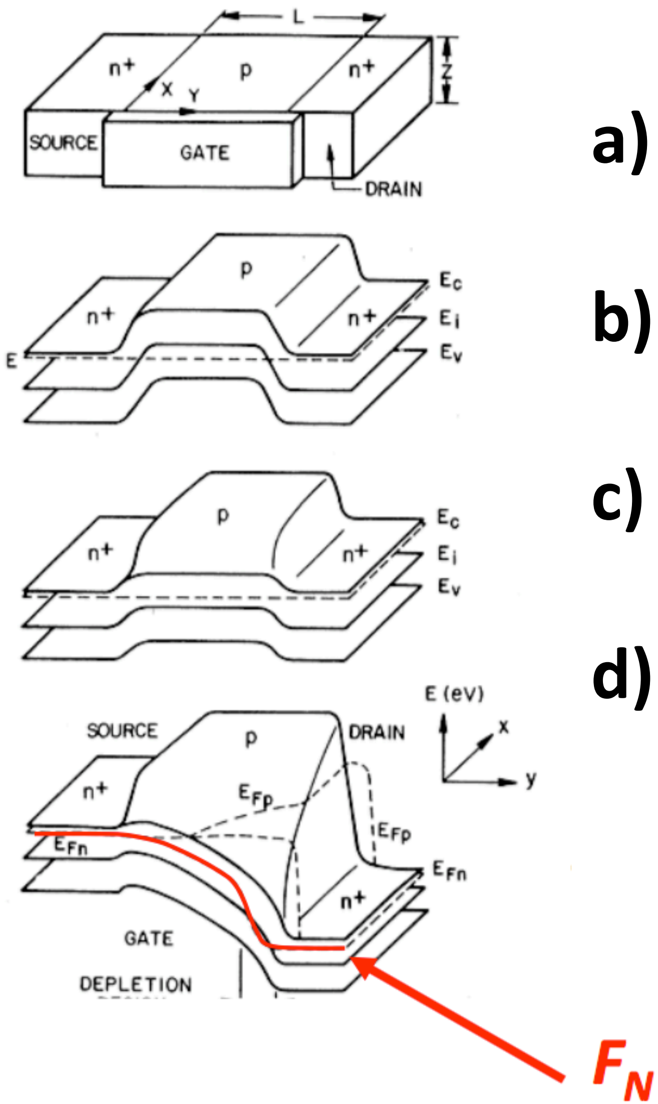




a) 平带
b) 反型

A. Grove, *Physics of Semiconductor Devices*, 1967.

漏压的作用



二维能带图

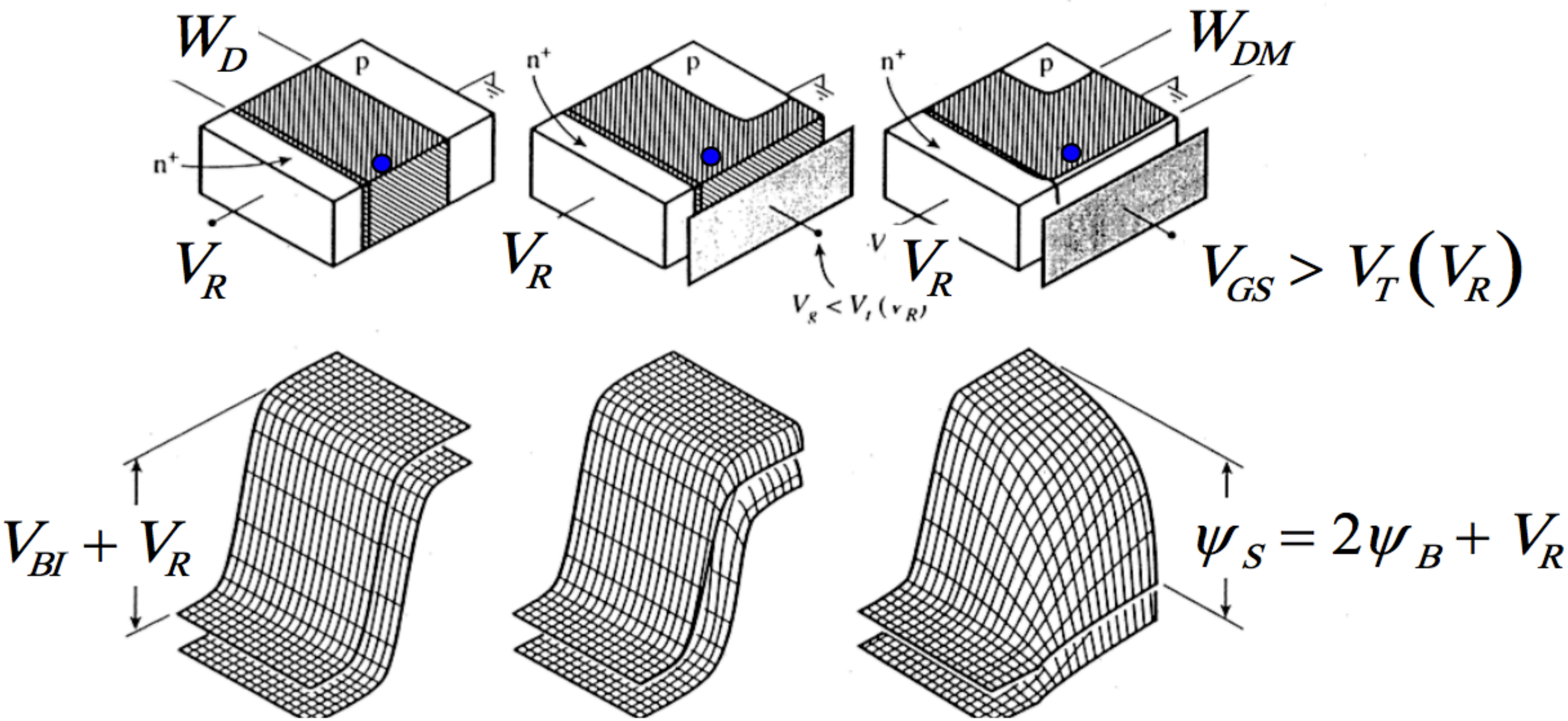
a) 器件示意图

b) 平带时候的能带图

c) 表面势为正（施加Vg）

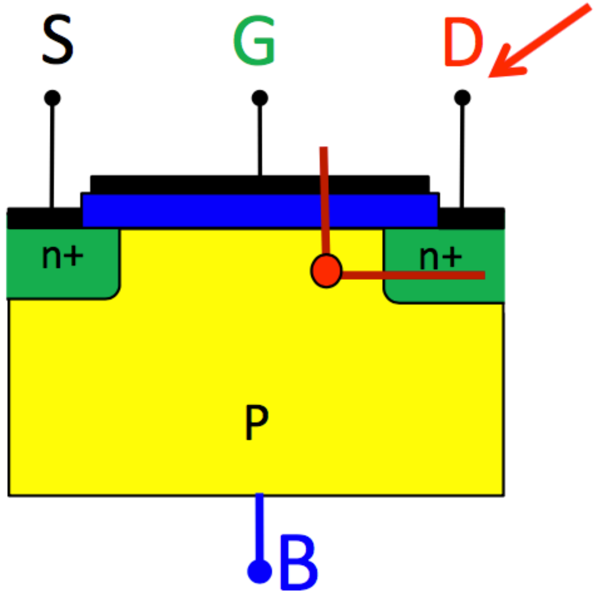
d) 同时施加Vg和Vd

漏压的作用



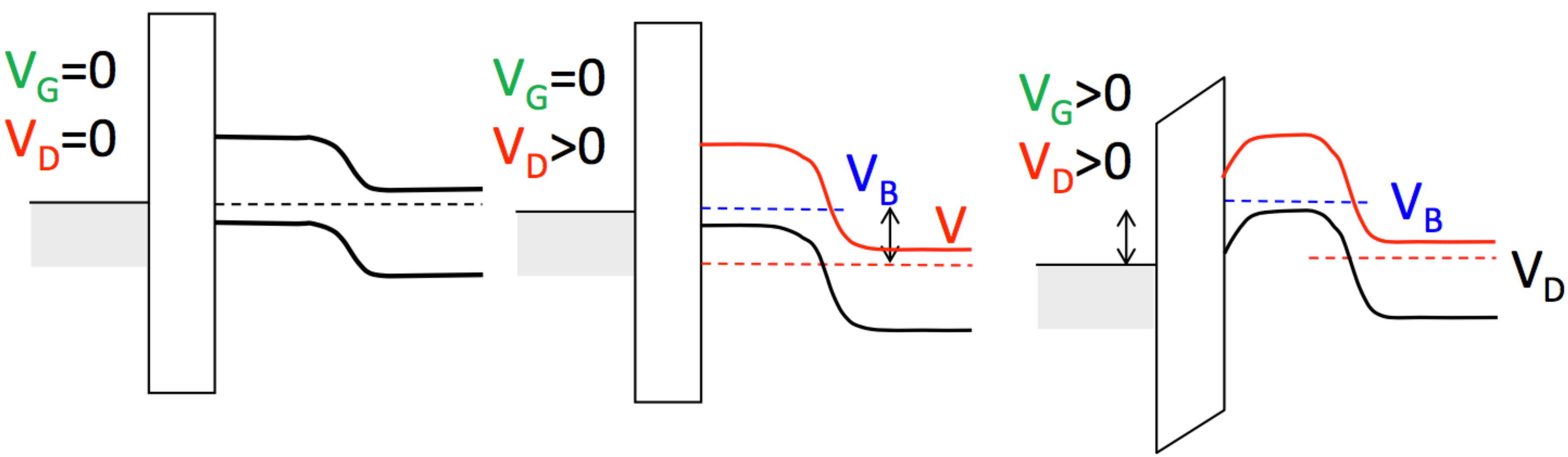
a) 平带
b) 耗尽
c) 反型

A. Grove, *Physics of Semiconductor Devices*, 1967.

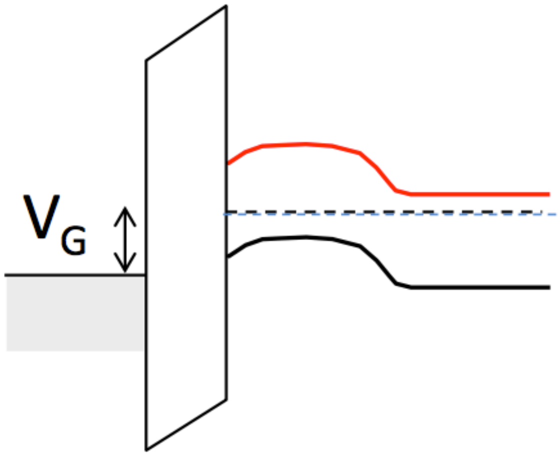


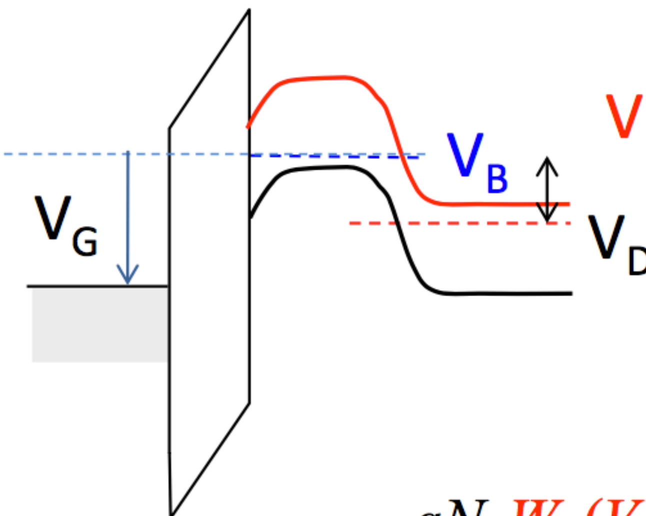
反型层电荷

$$Q_i = -C_{ox}(V_G - V_{th} - V) + qN_A(W_T(V) - W_T(V=0))$$



反型层电荷





$$V_{th} = 2\phi_F - \frac{qN_A W_T(V=0)}{C_{ox}}$$

$$V_{th}^{*} = \left(2\phi_F + V\right) - \frac{qN_A W_T(V)}{C_{ox}}$$

$$V_{th}^{*} = V_{th} + V - \frac{qN_A\left(W_T(V) - W_T(V=0)\right)}{C_{ox}}$$

$$Q_i = -C_{ox}(V_G - V_{th}^{*})$$

反型层电荷的简化公式

$$Q_i = -C_O(V_G - V_{th} - V) + qN_A\left(W_T(V) - W_T(V=0)\right)$$

$$= -C_O(V_G - V_{th} - V) + \left[\sqrt{2q\kappa_S\varepsilon_o N_A\left(2\phi_B + V\right)} - \sqrt{2q\kappa_S\varepsilon_o N_A\left(2\phi_B\right)}\right]$$

假设：

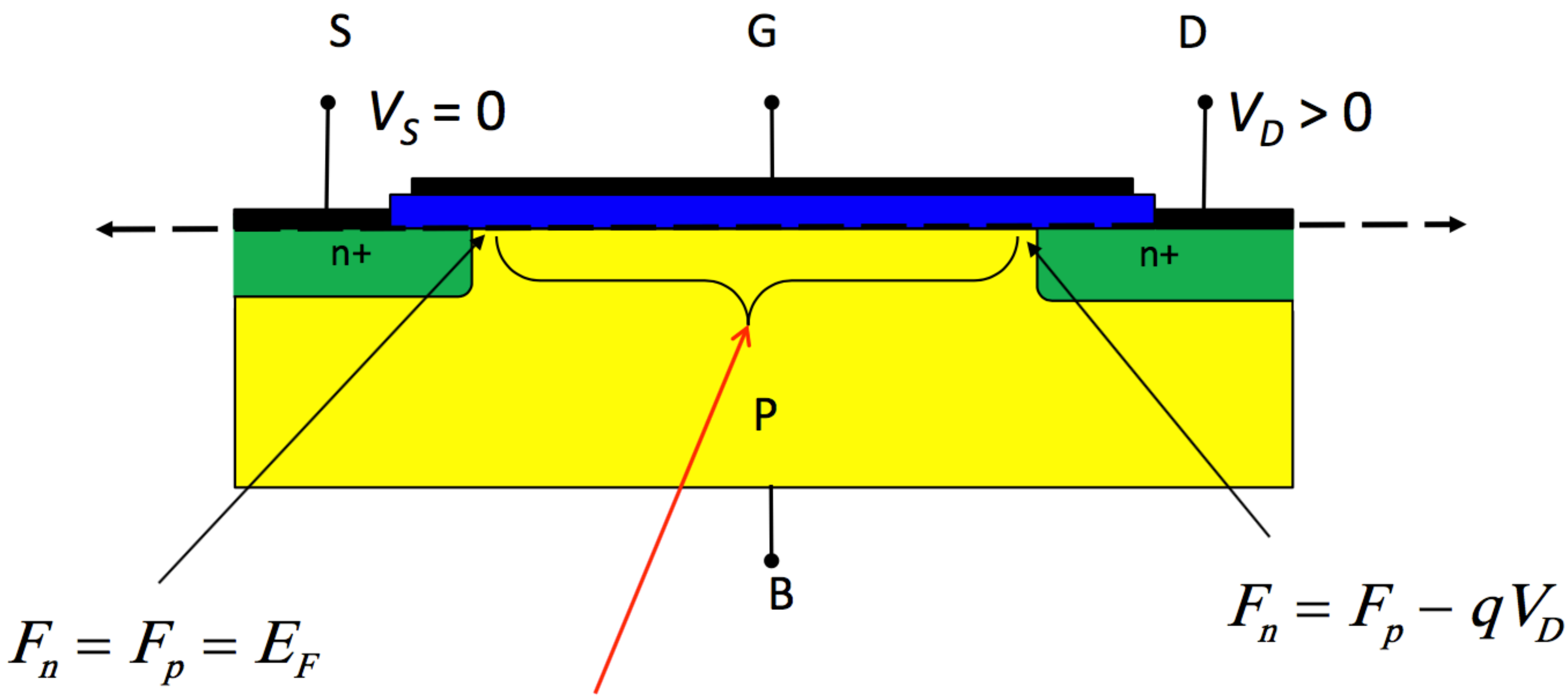
$$Q_i \approx -C_{ox}(V_G - V_{th} - V)$$

平方律

$$Q_i \approx -C_{ox}(V_G - V_{th} - mV)$$

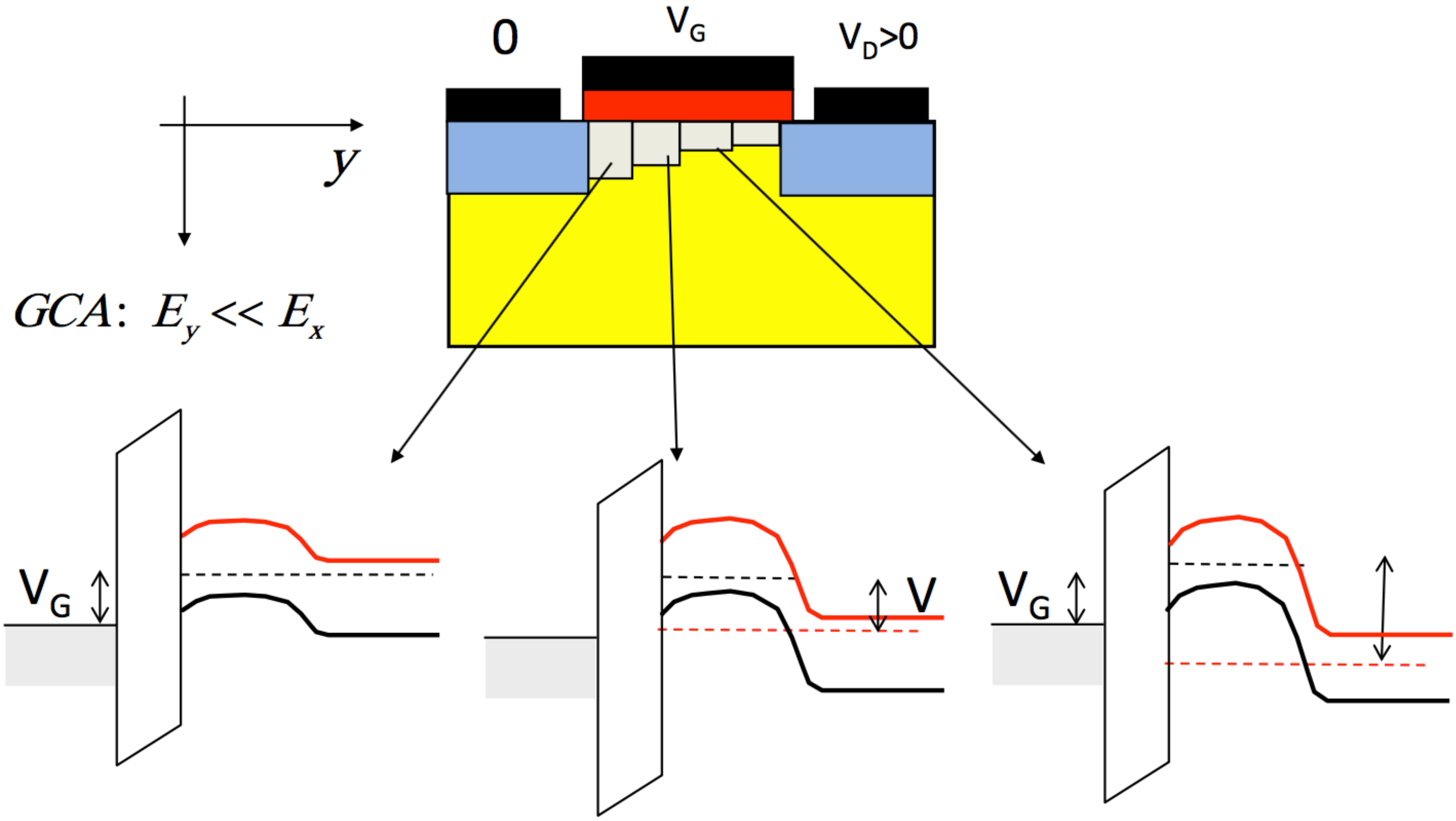
简化的体电荷

The MOSFET



F_n从源到漏逐渐减小

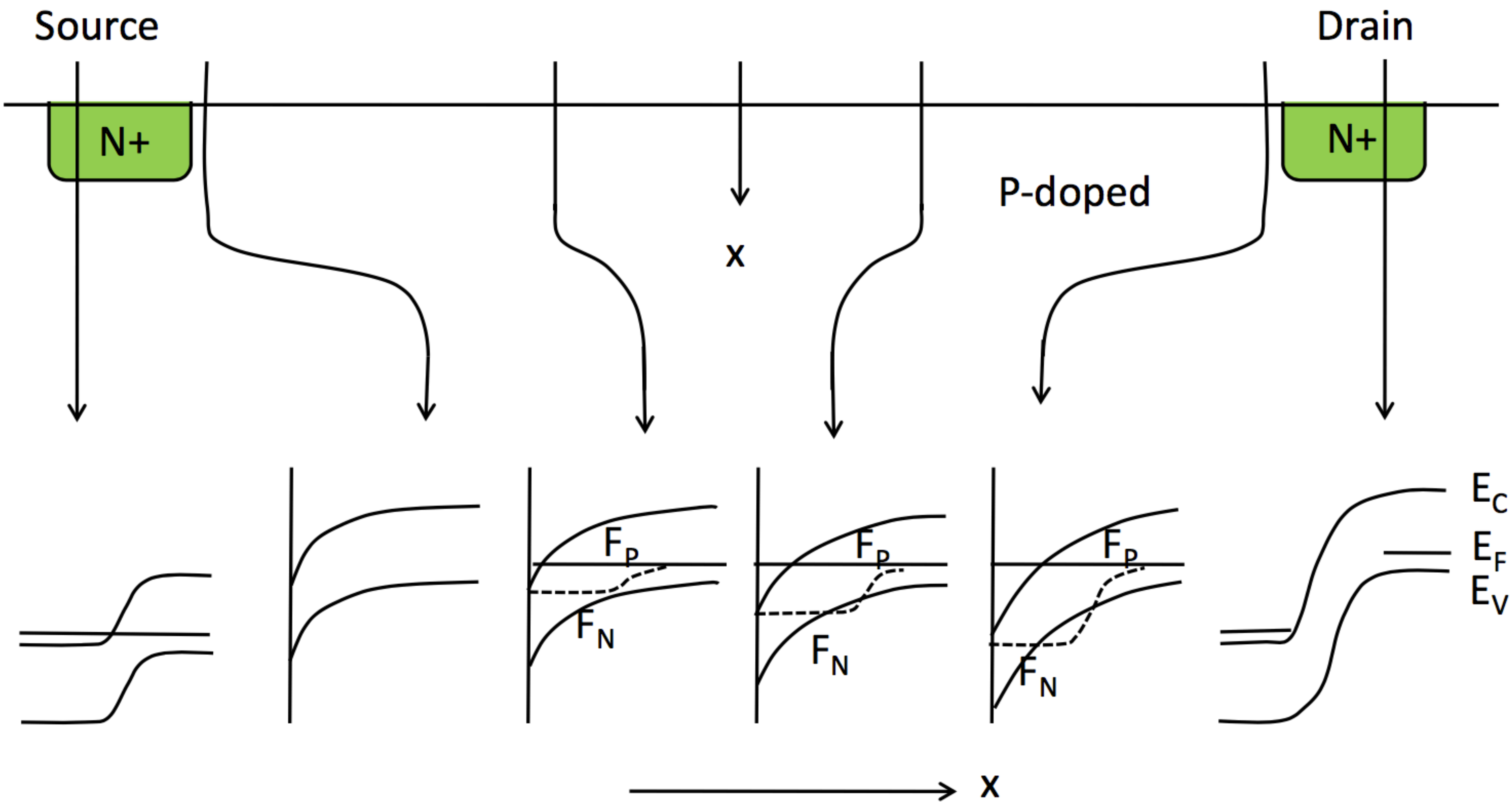
平方律理论



$GCA: E_y << E_x$

$$Q_i(y) = -C_{ox}\left[V_G - V_{th} - mV(y)\right]$$

沟道电势分布



平方律理论

$$J_1 = Q_1 \mu \mathcal{E}_1 = Q_1 \mu \left.\frac{dV}{dy}\right|_1$$

$$J_2 = Q_2 \mu \mathcal{E}_2 = Q_2 \mu \left.\frac{dV}{dy}\right|_2$$

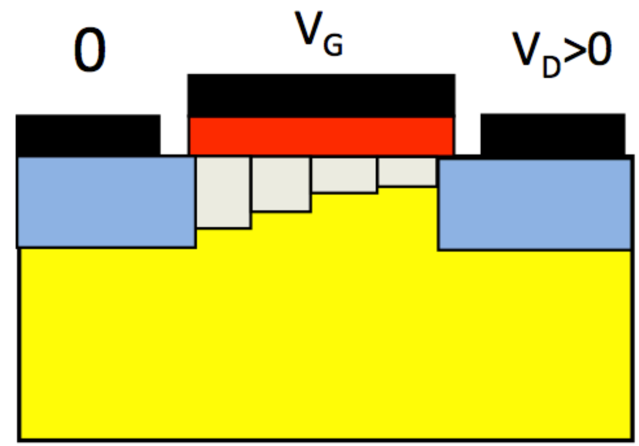
$$J_3 = Q_3 \mu \mathcal{E}_3 = Q_3 \mu \left.\frac{dV}{dy}\right|_3$$

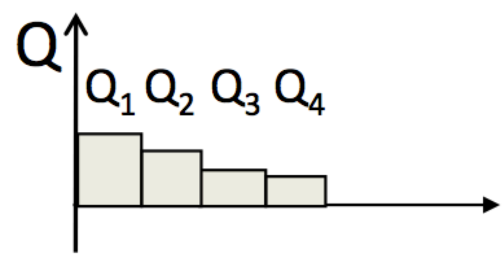
$$J_4 = Q_4 \mu \mathcal{E}_4 = Q_4 \mu \left.\frac{dV}{dy}\right|_4$$

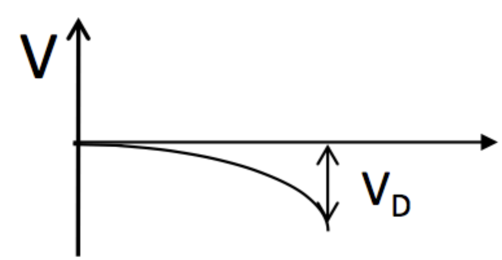
$$\sum_{i=1,N} \frac{J_i dy}{\mu} = \sum_{i=1,N} Q_i \, dV$$

$$\frac{J_D}{\mu} \sum_{i=1,N} dy = \int_0^{V_D} C_{ox}(V_G - V_{th} - mV)dV$$

$$J_D = \frac{\mu C_{ox}}{L_{ch}} \left[(V_G - V_{th})V_D - m\frac{V_D^{\,2}}{2} \right]$$



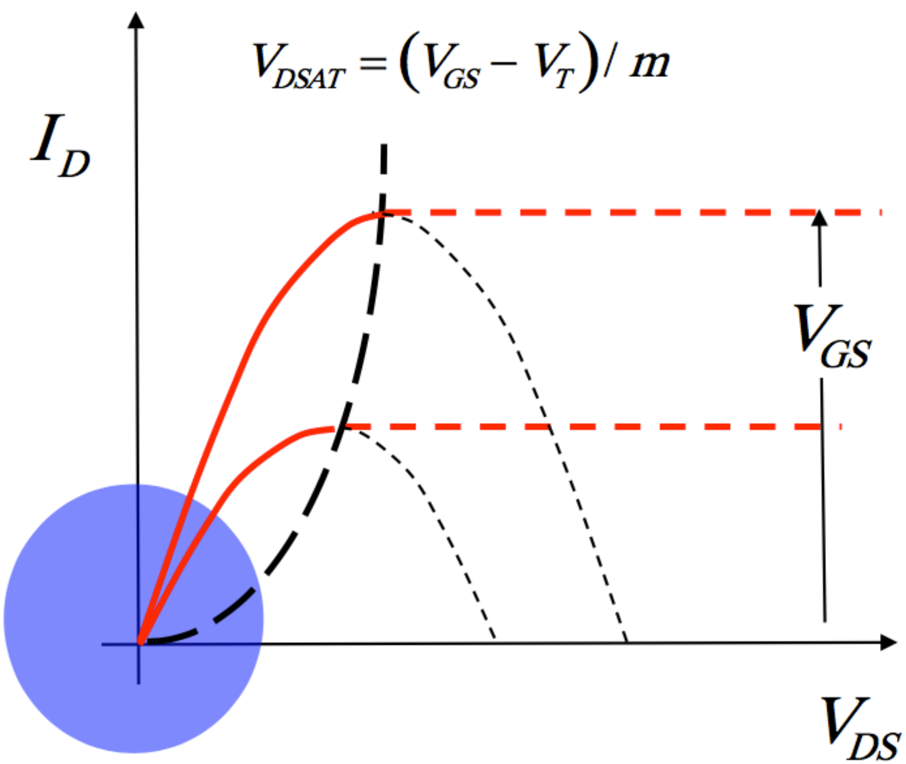




简化的体电荷模型

$$I_D = W\frac{\mu C_{ox}}{L_{ch}}\left[\left(V_G - V_{th}\right)V_D - m\frac{V_D{}^2}{2}\right]$$

$$\frac{dI_D}{dV} = 0 = \left(V_G - V_{th}\right) - mV_D \Rightarrow V_{D,sat} = \left(V_G{}^* - V_{th}\right)/m$$



$$I_D = \frac{W\mu C_o}{2mL_{ch}}\left(V_G - V_T\right)^2$$

$$J_D = \frac{\mu C_{ox}}{L_{ch}}\left[\left(V_G - V_{th}\right)V_D - m\frac{V_D{}^2}{2}\right]$$

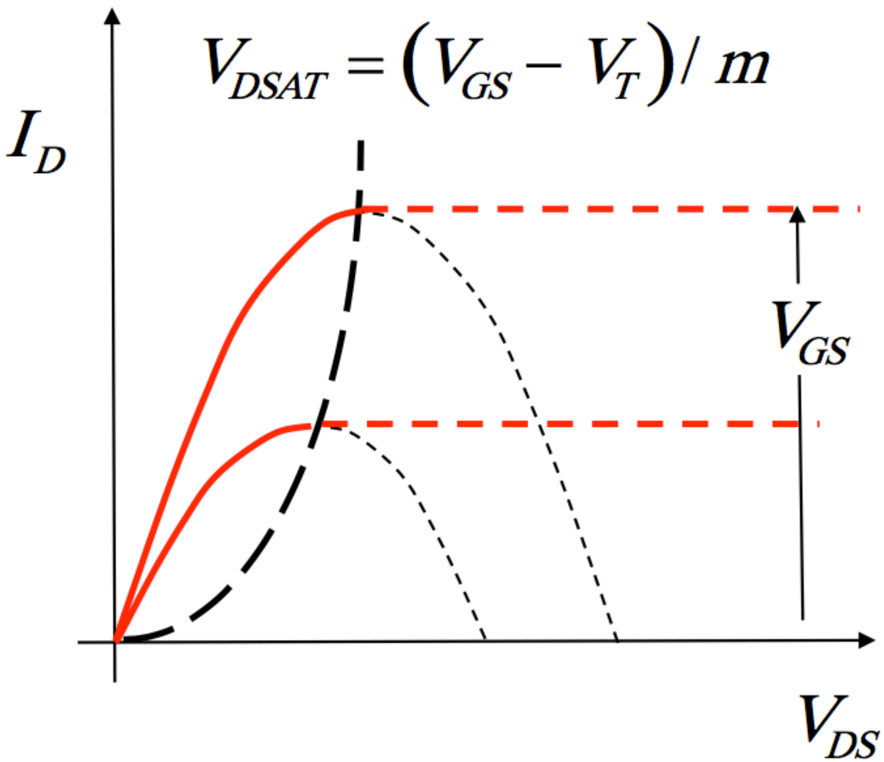
$$I_D = \mu\, C_o\frac{W}{L}\left(V_G - V_T\right)V_D$$

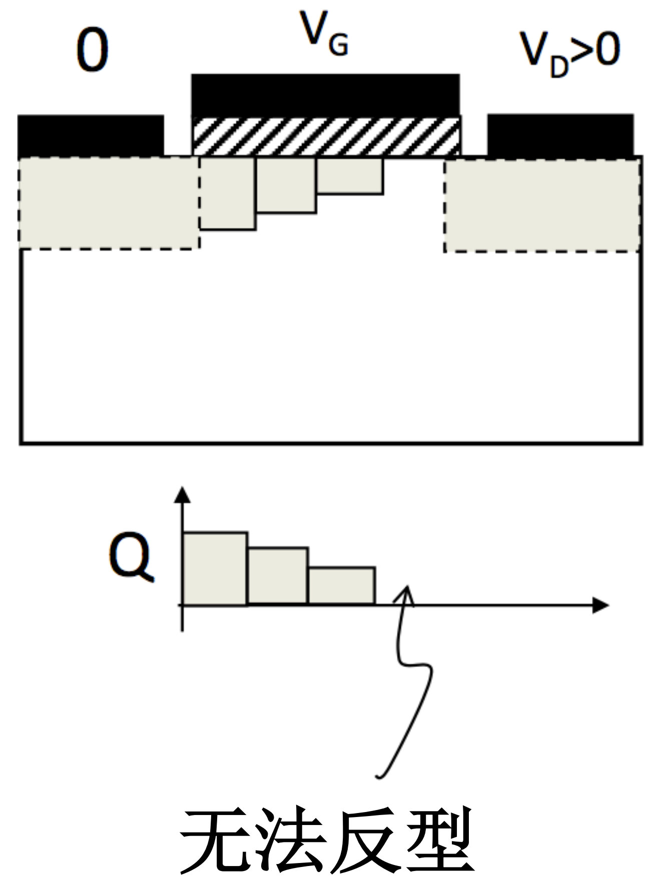
电流为什么饱和？

$$I_D = \frac{W \mu C_o}{2mL_{ch}}\left(V_G - V_T\right)^2$$

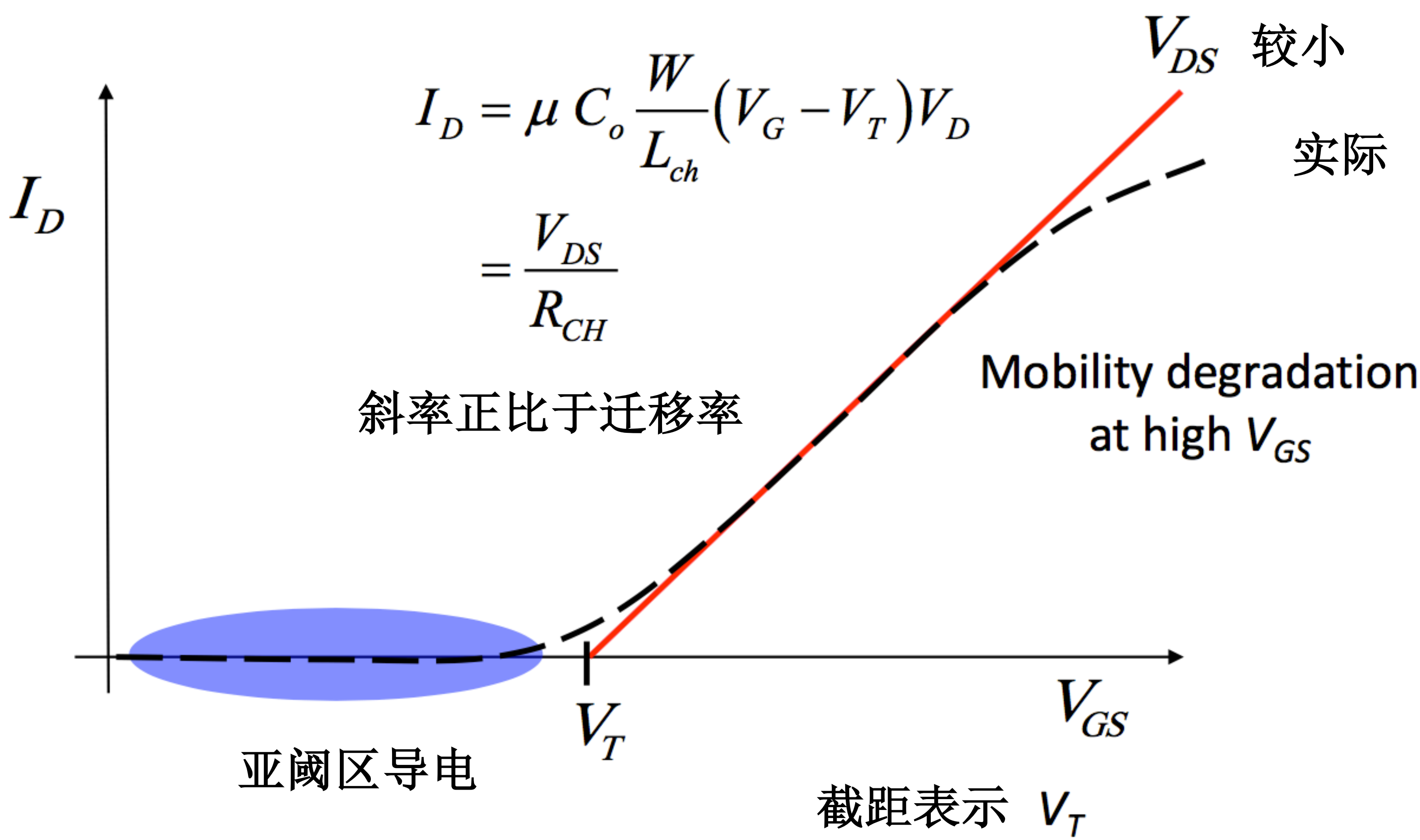
$$Q_i \approx -C_{ox}\left(V_G - V_{th} \ - mV\right)$$

$$V_{DSAT} = \left(V_{GS} - V_T\right)/\, m$$





线性区



V_{DS} 较小
$I_D = \mu C_o \frac{W}{L_{ch}}(V_G - V_T)V_D$
$= \frac{V_{DS}}{R_{CH}}$
实际
I_D
斜率正比于迁移率
Mobility degradation
at high V_{GS}
V_T
V_{GS}
亚阈区导电
截距表示 V_T

Thanks!
Q&A