微电子器件物理
MOSFET IV特性

曾琅

2020/10/20

本节课提纲

1. 亚阈值电流
2. 开态电流

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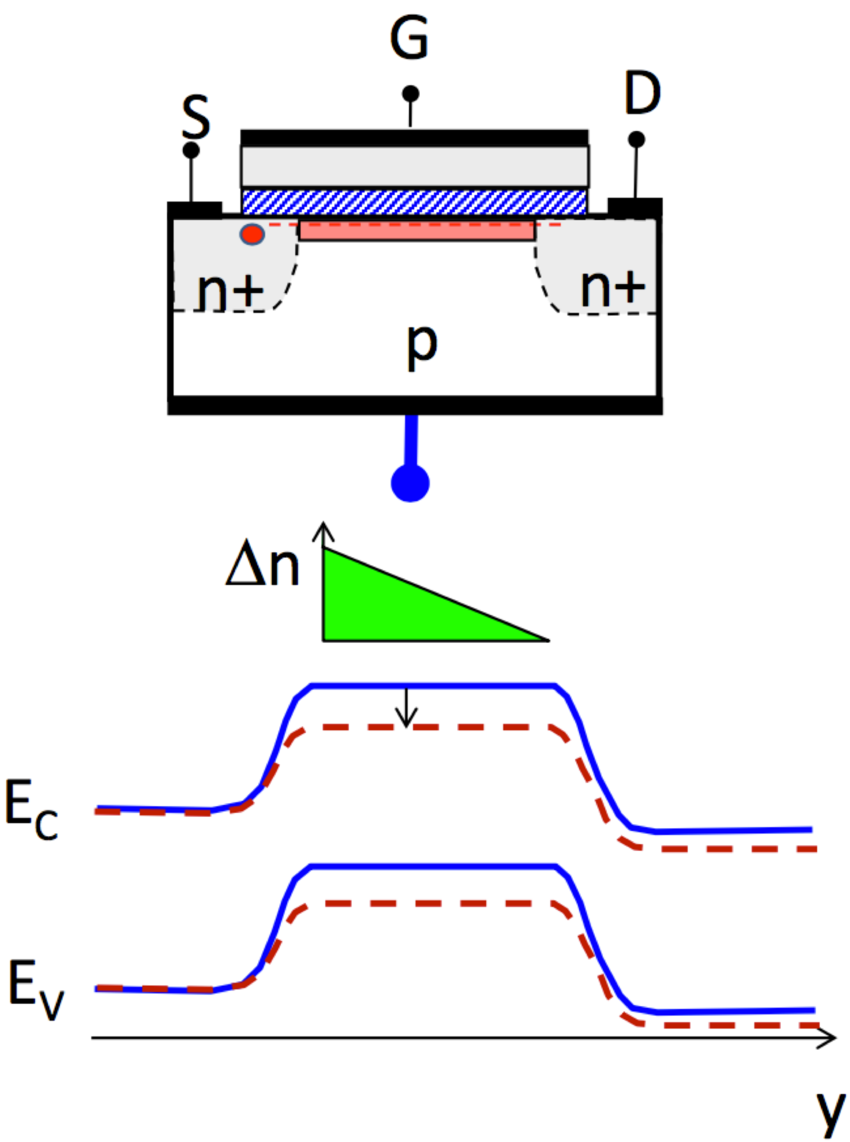
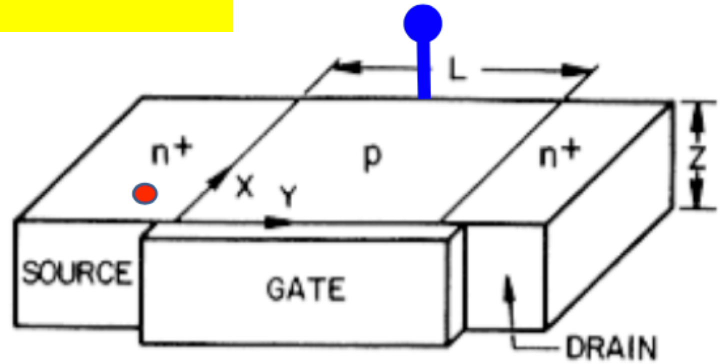
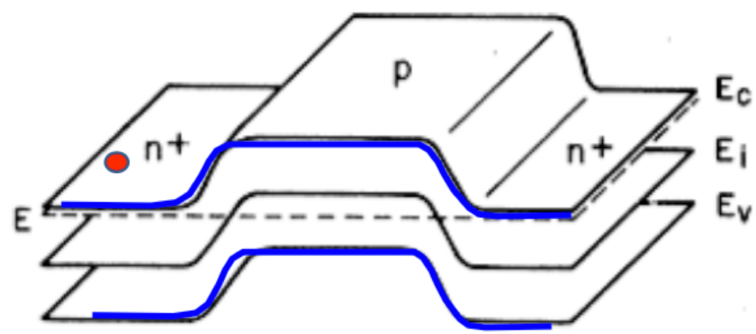
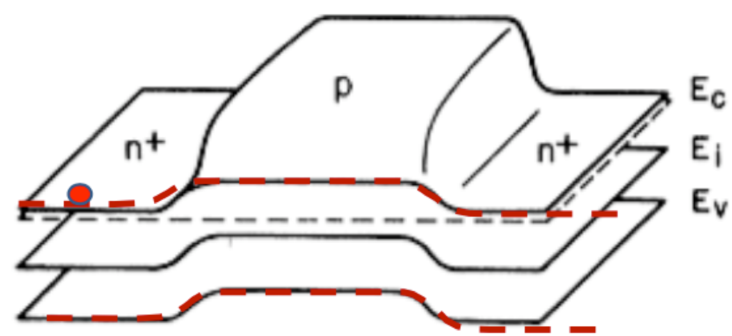
2. 开态电流

亚阈值区域

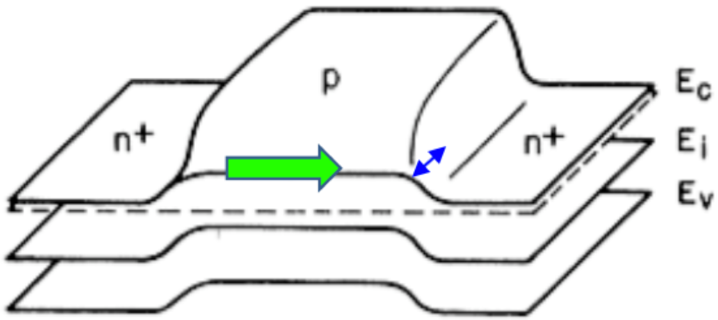

G
S
D
n+
n+
p
Δn
E_C
E_V
y


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

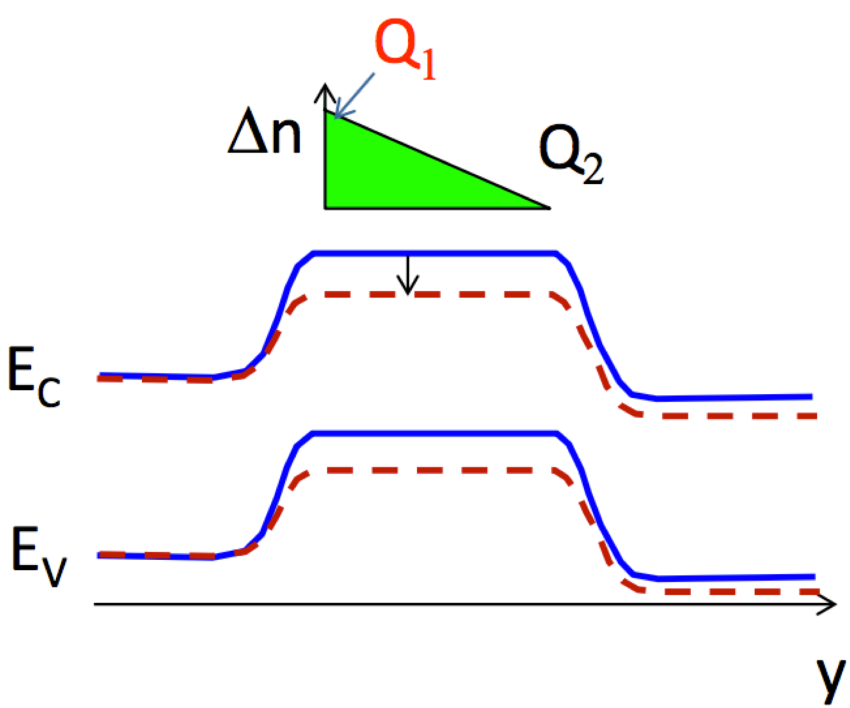

p
n+
n+
E
E_c
E_i
E_v


p
n+
n+
E_c
E_i
E_v

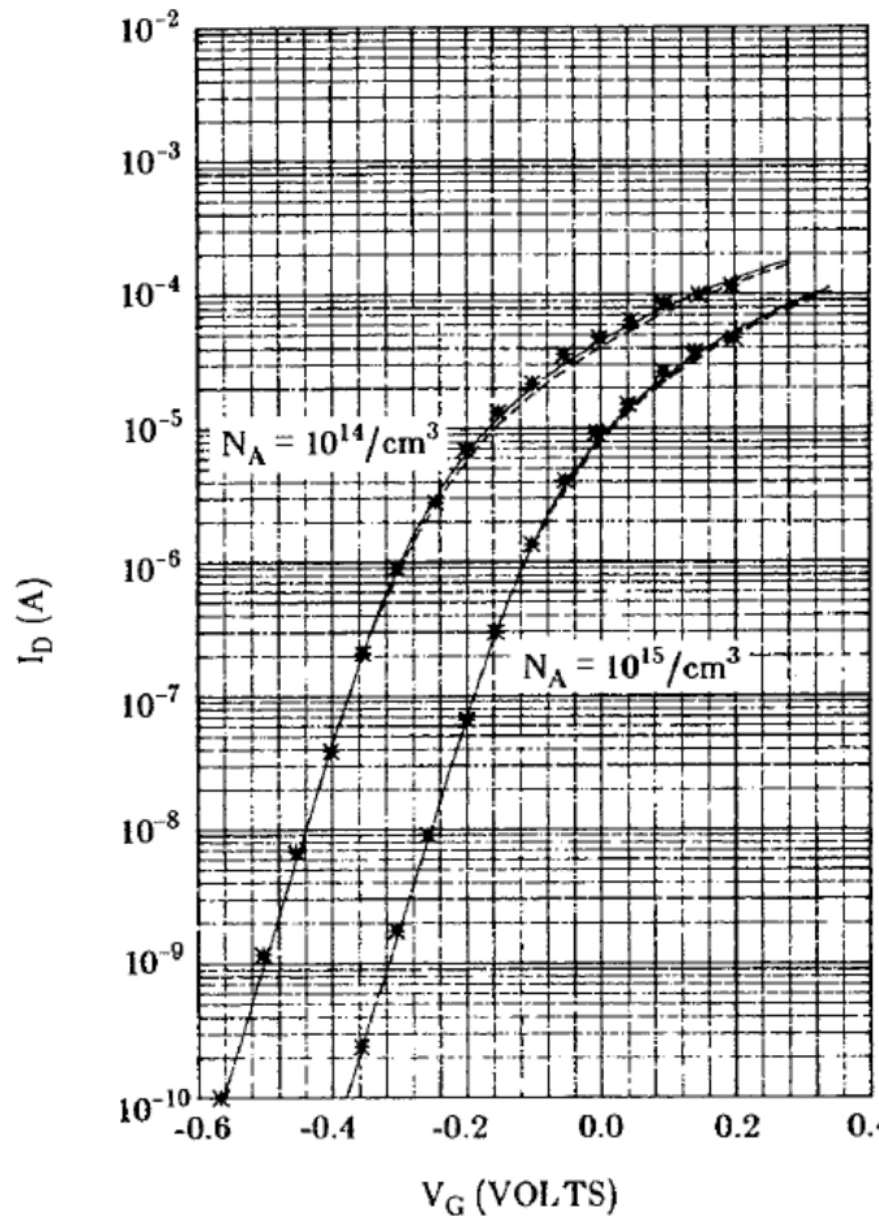
亚阈值区域



p
n+
n+
E_c
E_i
E_v



Q_1
Δn
Q_2
E_C
E_V
y



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

亚阈值区域

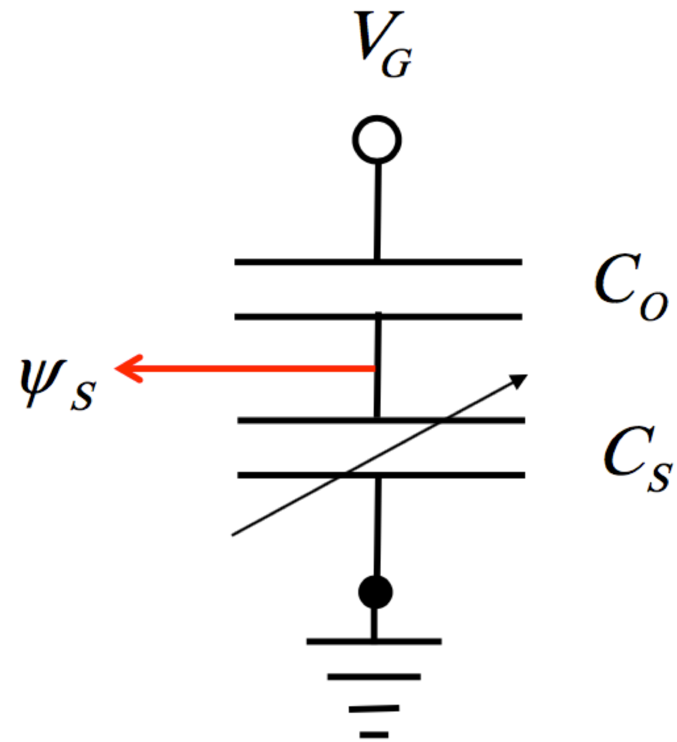
$$m = \left(1 + C_S / C_O\right)$$

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

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

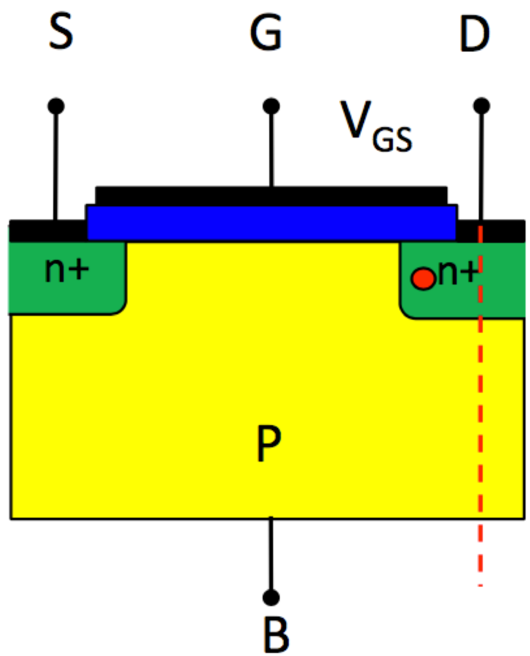
1) 平方律 $Q_i(V) = -C_G\left[V_G - V_T - V\right]$

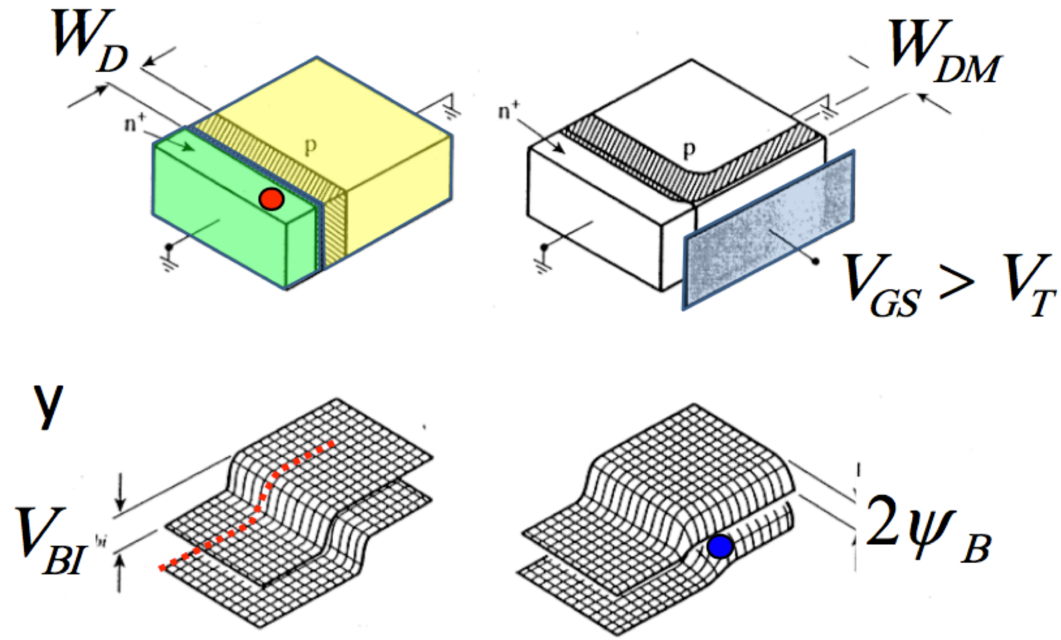
2) 体电荷模型 $Q_i(V) = -C_G\left(V_G - V_{FB} - 2\psi_B - V - \frac{\sqrt{2q\varepsilon_{Si}N_A(2\phi_B + V)}}{C_O}\right)$

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



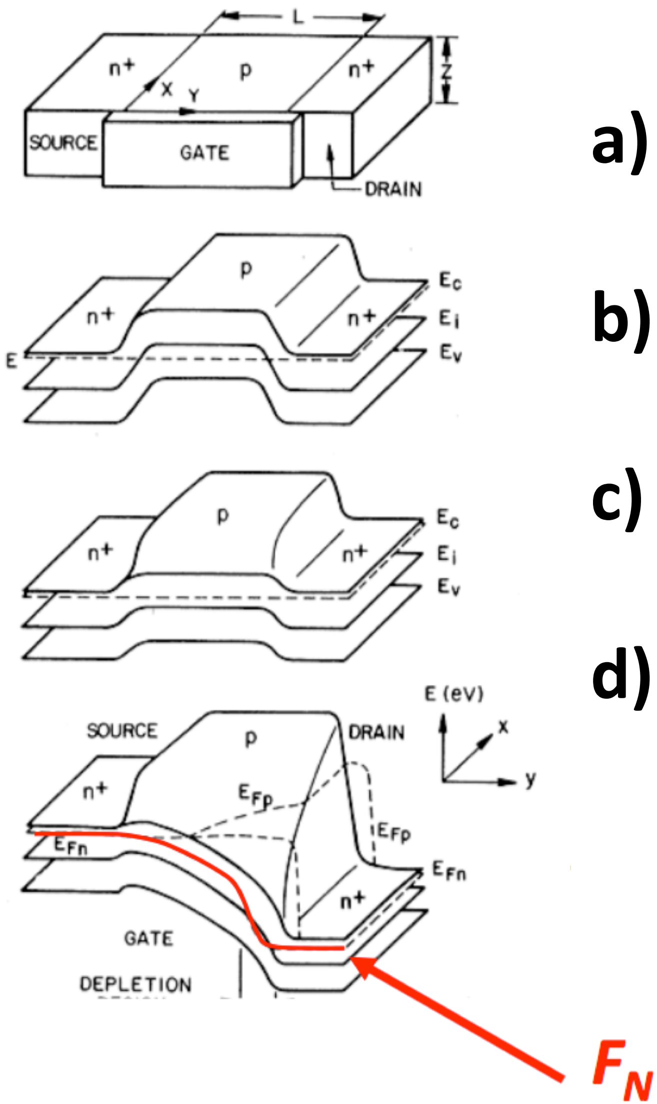


a) 平带
b) 反型

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

漏压的作用

二维能带图



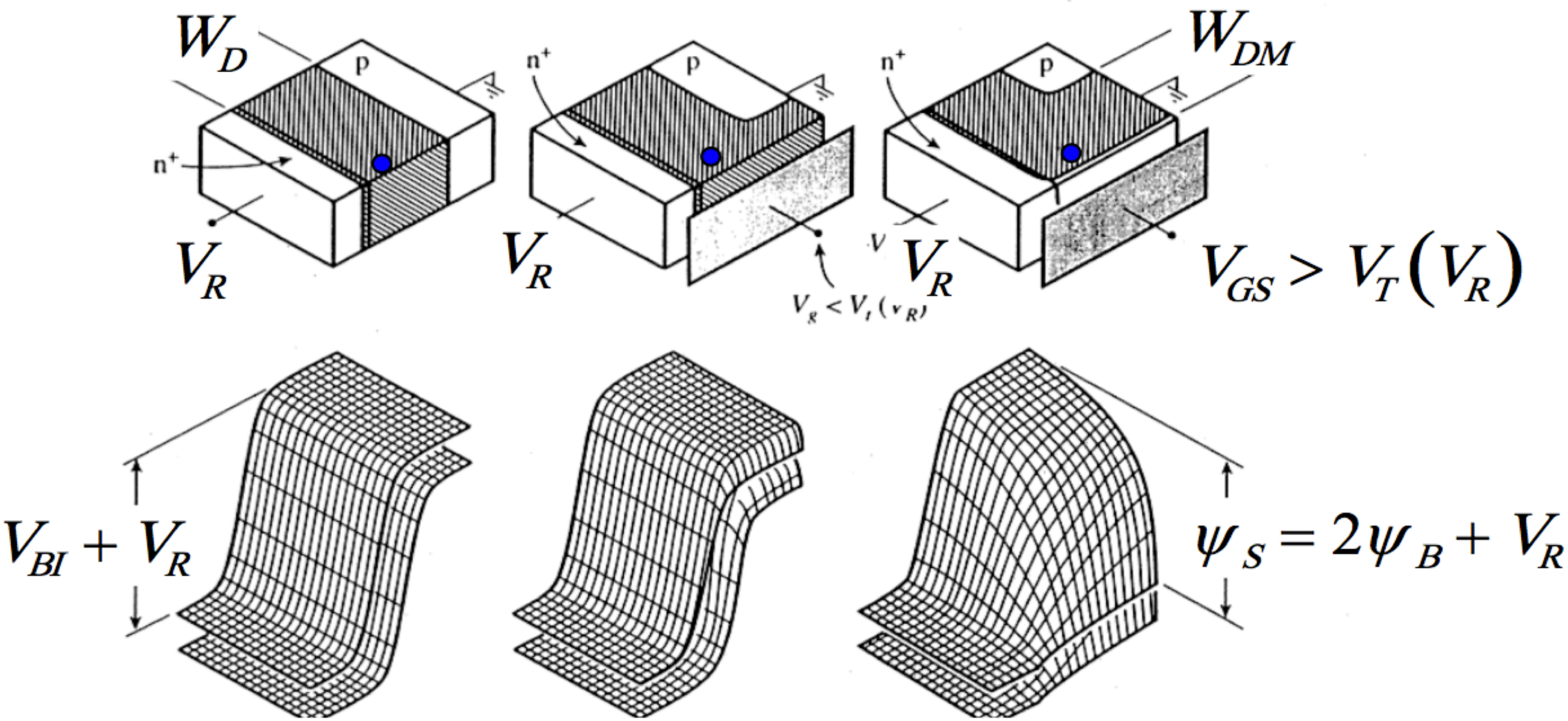
a) 器件示意图

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

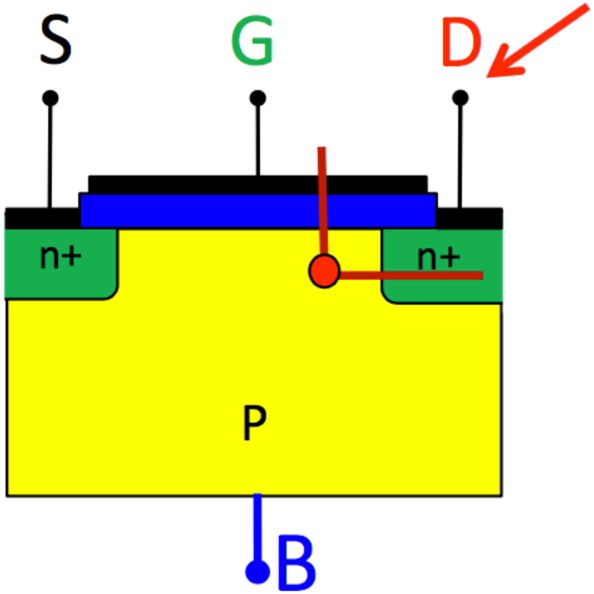
漏压的作用



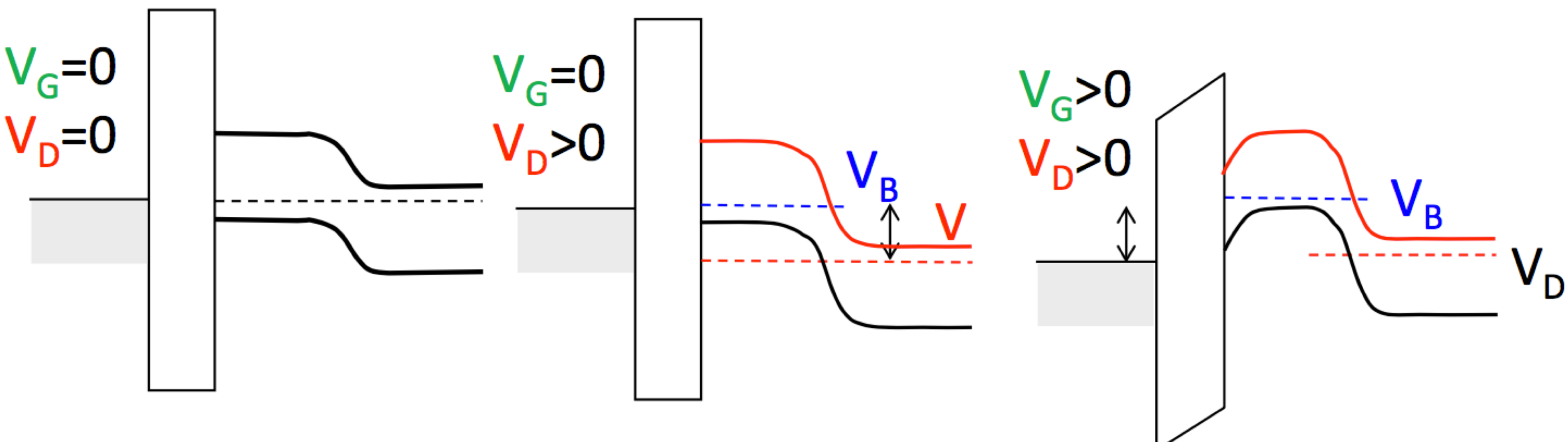
a) 平带
b) 耗尽
c) 反型

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

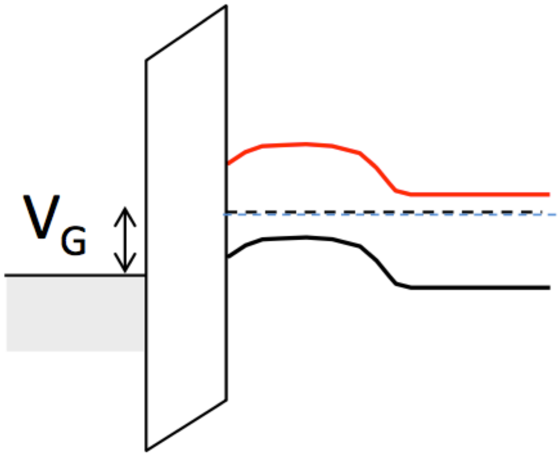
反型层电荷

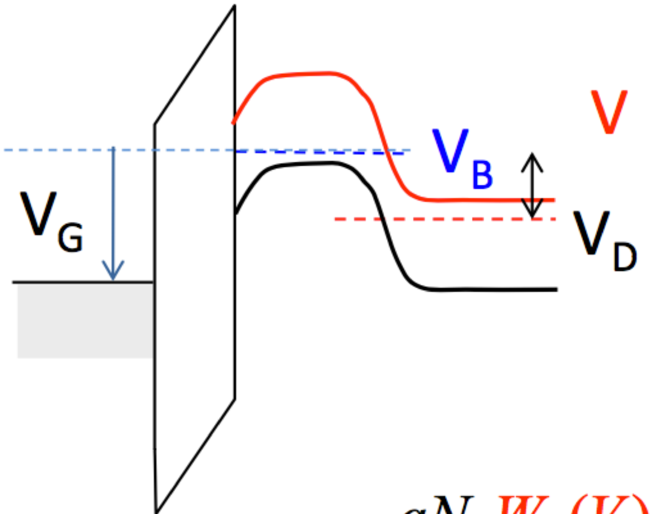


$$Q_i = -C_{ox}(V_G - V_{th} - V) + qN_A(W_T(V) - W_T(V=0))$$



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：

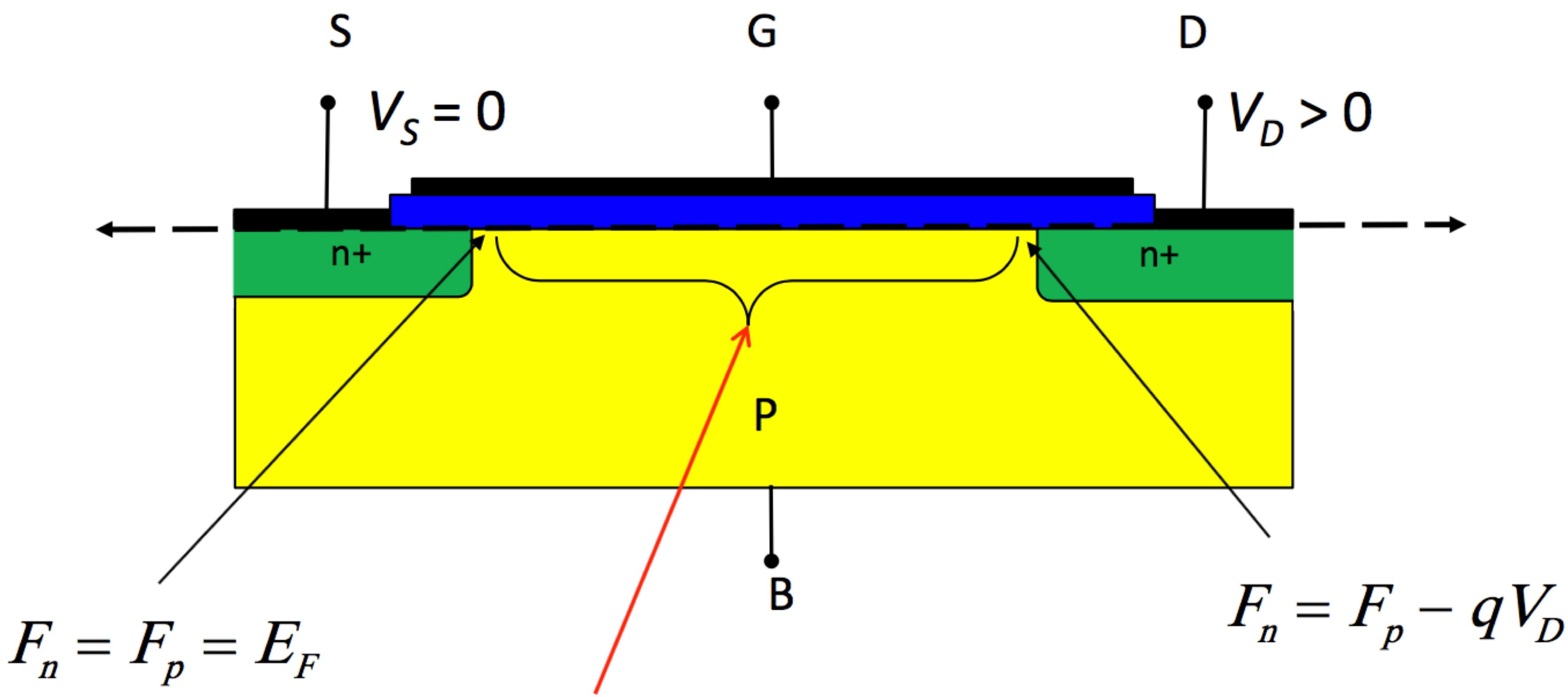
$$Q_i \approx -C_{ox}(V_G - V_{th} - V)$$

平方律

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

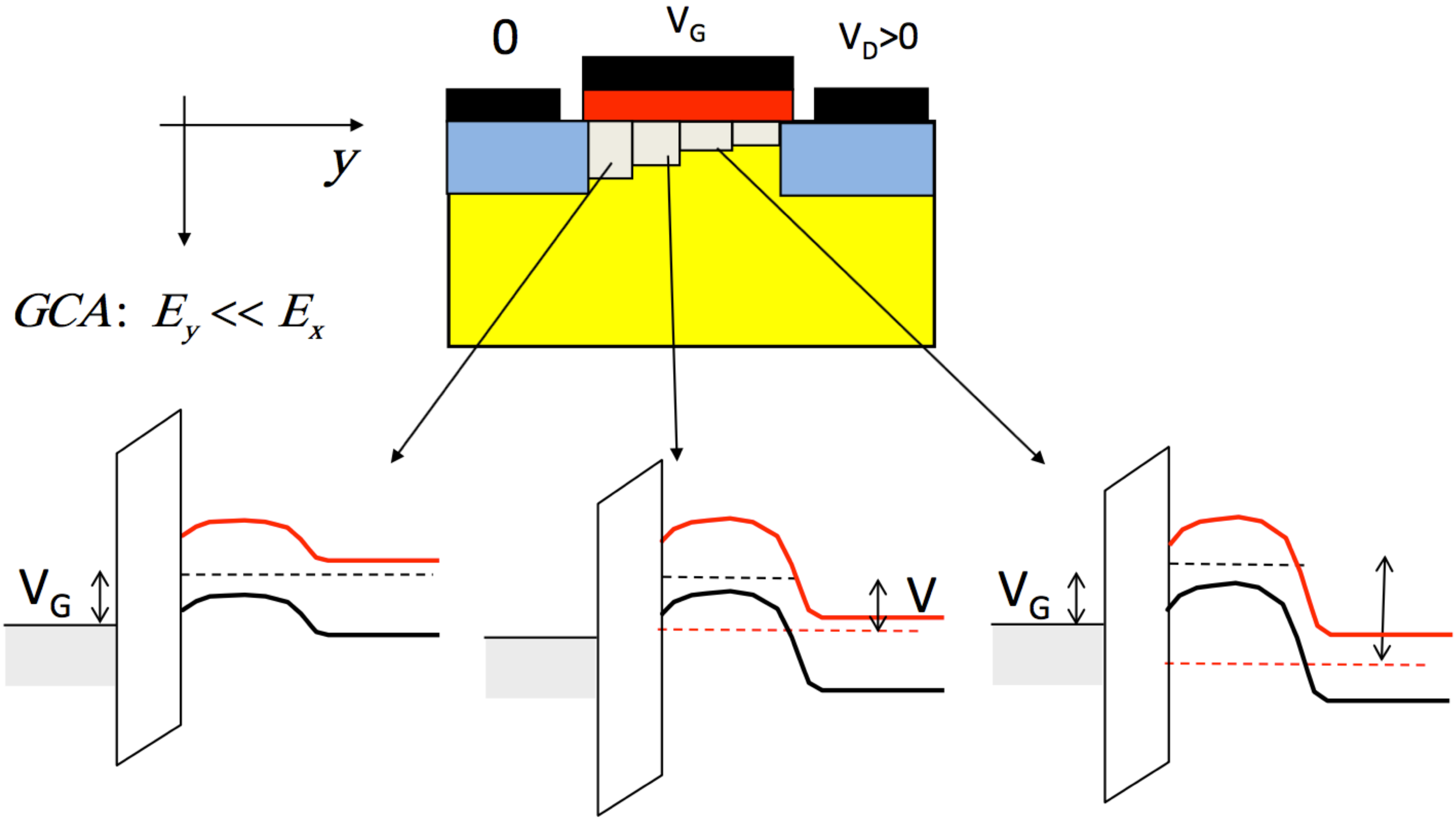
简化的体电荷

The MOSFET



F_n从源到漏逐渐减小

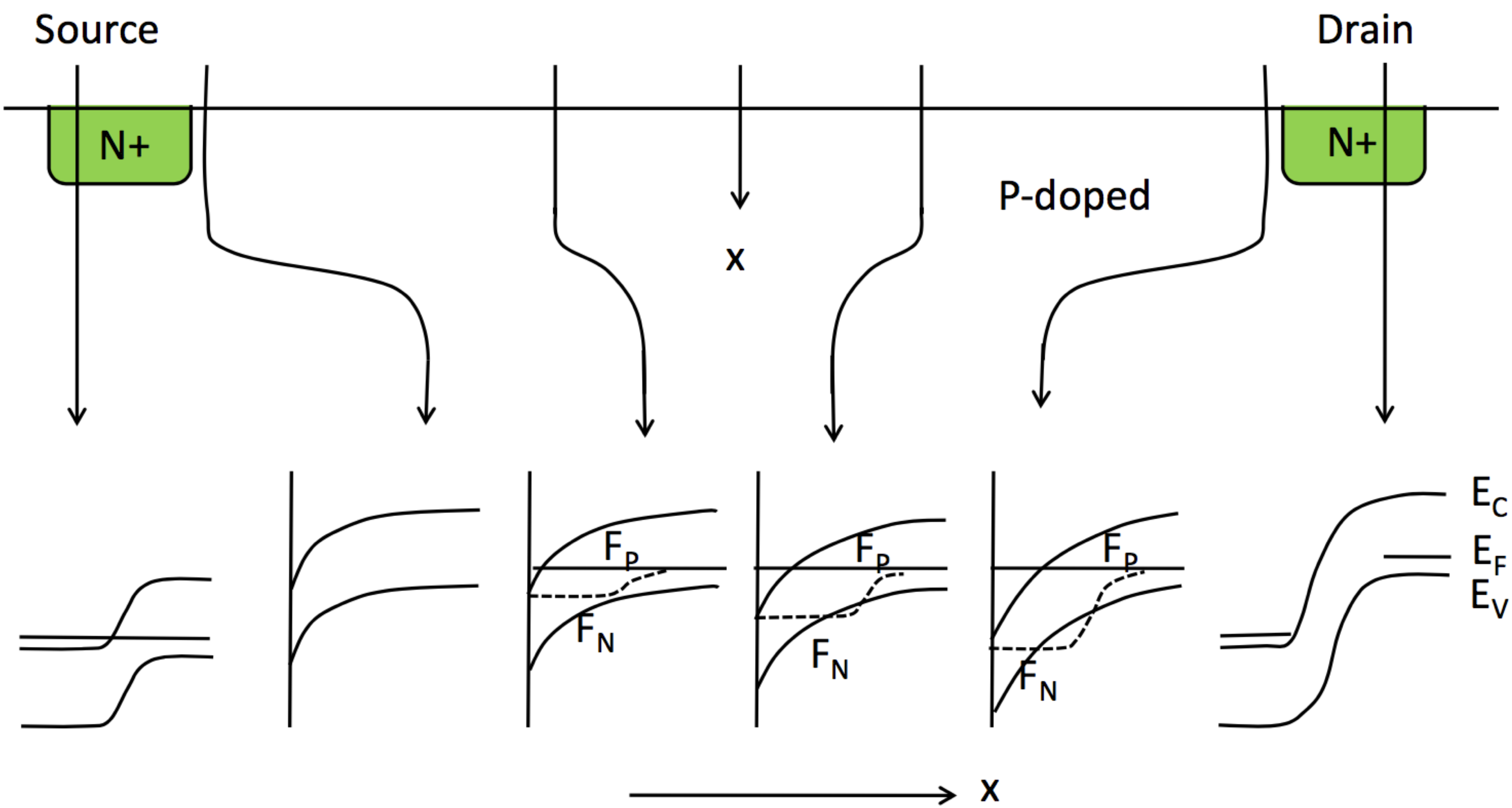
平方律理论



$$GCA:\ E_y \ll E_x$$

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

沟道电势分布



平方律理论

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

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

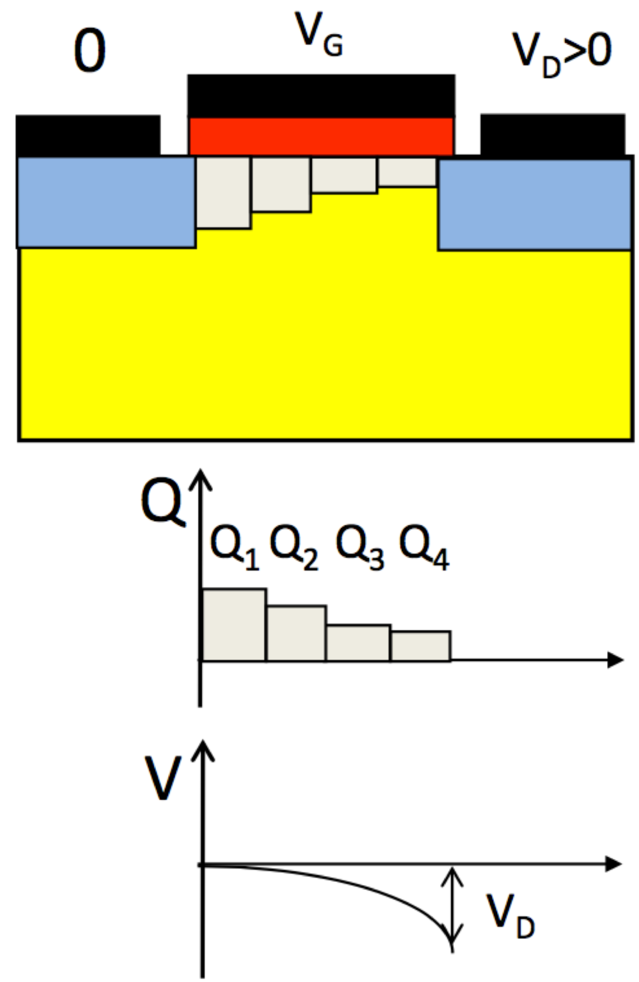
$$J_3 = Q_3 \mu \mathcal{E}_3 = Q_3 \mu \left.\frac{dV}{dy}\right|_3$$

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

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

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

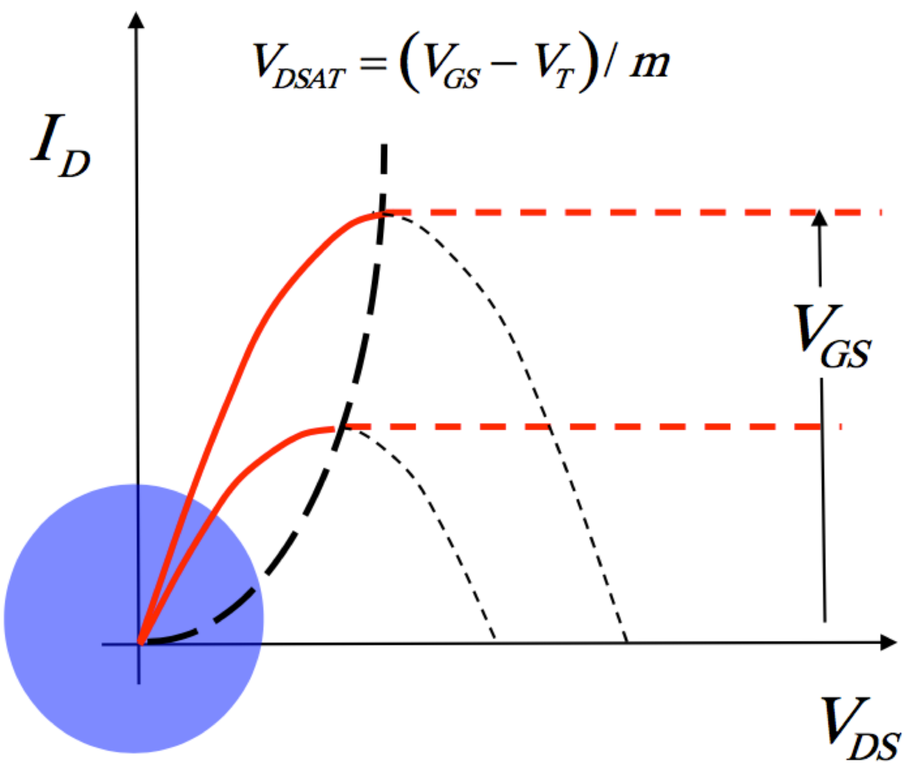
$$J_D = \frac{\mu C_{ox}}{L_{ch}} \left[(V_G - V_{th}) V_D - m \frac{V_D^{\ 2}}{2} \right]$$



简化的体电荷模型

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

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



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

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

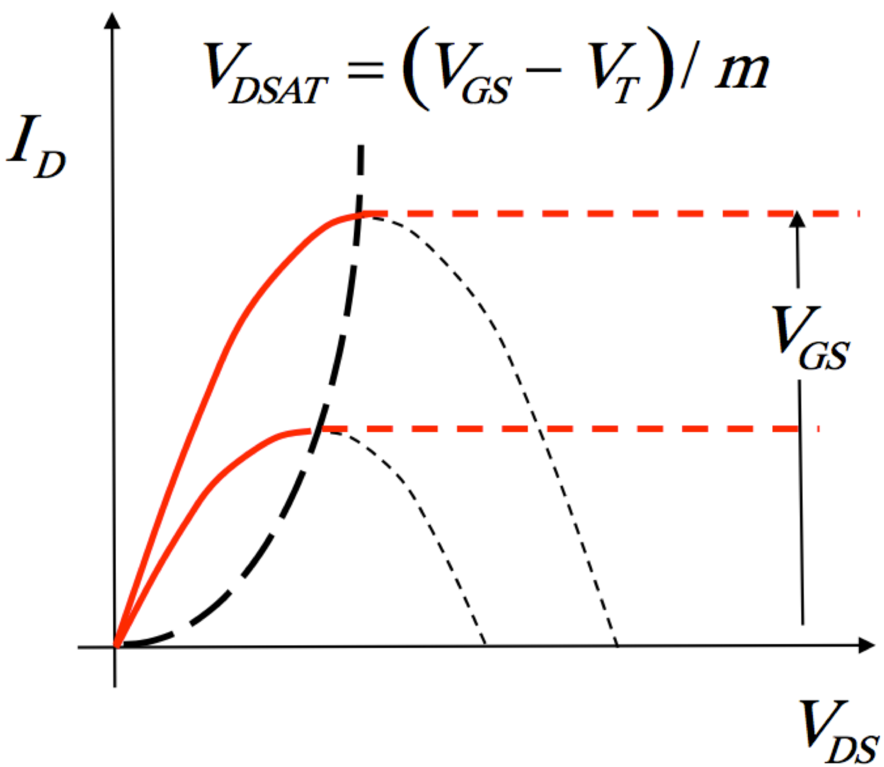
$$I_D = \mu\, C_o\frac{W}{L}(V_G - V_T)V_D$$

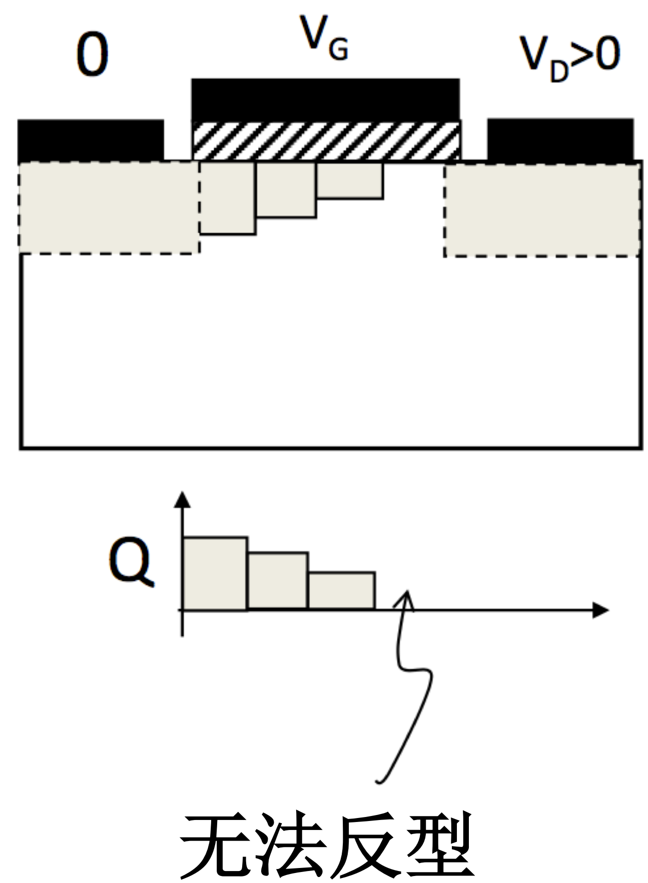
电流为什么饱和？

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

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

$$V_{DSAT} = (V_{GS} - V_T)/m$$

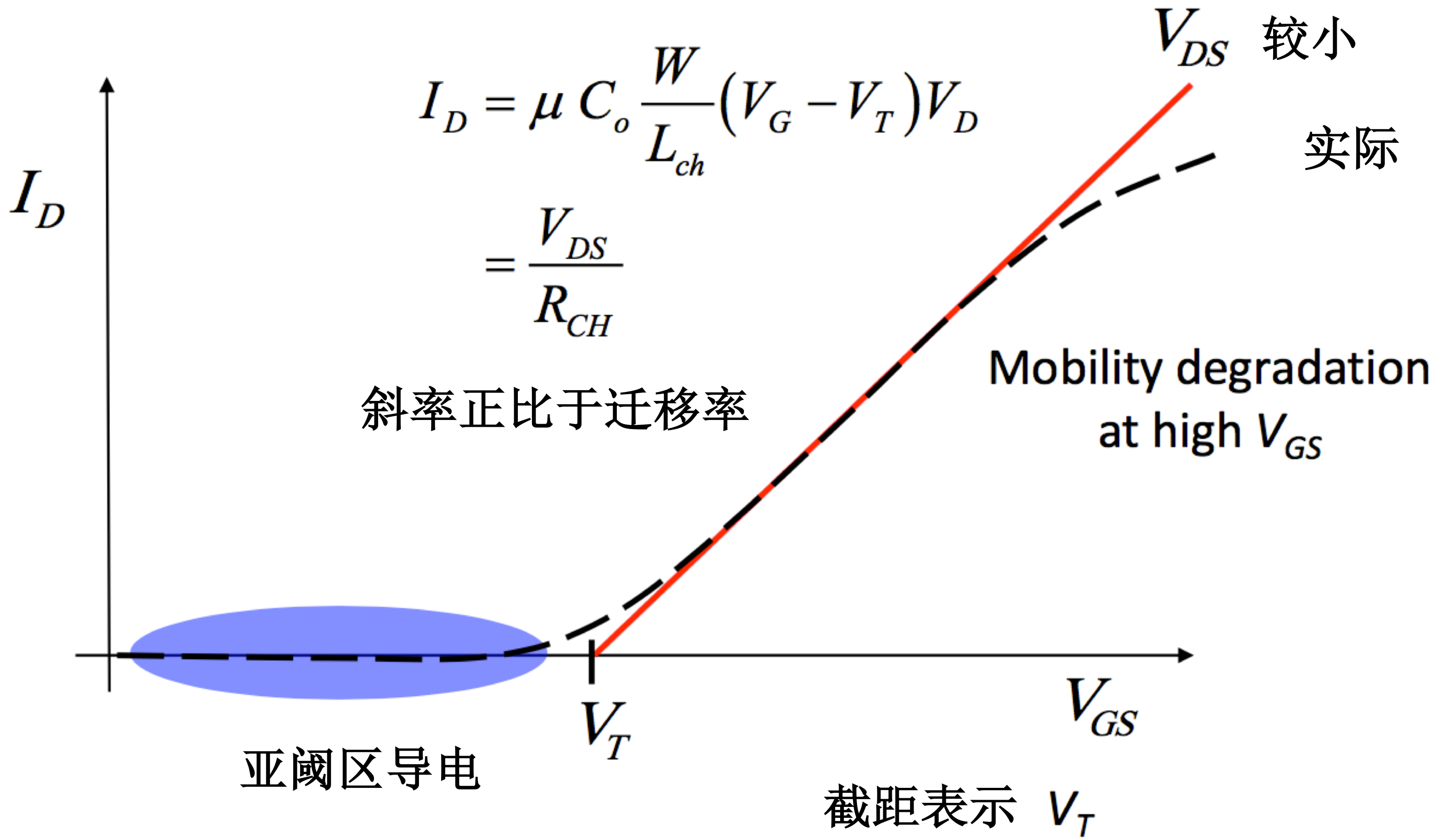




线性区

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

$$= \frac{V_{DS}}{R_{CH}}$$



Thanks!
Q&A