

Chapter 5: MOSFET

3 terminal semiconductor devices: (2 types)

- 1) MOSFET
- 2) BJT

Enhancement-type MOSFET

4 terminals

- 1) gate terminal G
- 2) source terminal S
- 3) drain terminal D
- 4) body terminal B \rightarrow body has no effect

Three Terminal Device
(GSD)

- Voltage applied to gate controls current flow between source and drain. "Channel Region"

V_T = Threshold Voltage

(5.1) $V_{GS} - V_T = V_{OV}$: Interchangeable

$V_{GS} - V_T = V_{OV}$: effective Voltage or Overdrive Voltage
- quantity that determines charge in the channel

(5.2) $I_D = C_{ox}(V_{OV})^{3/2}$

C_{ox} = Oxide Capacitance

Voltage V_{DS} causes current I_D to flow through induced n channel.

n_n = mobility of electrons.

(5.4) : $\frac{q}{l} = C_{ox} V_{OV}$ (Charge per unit channel length)

(5.5) : $|E| = \frac{V_{DS}}{l}$ (Electric Field)

(5.6) : Electron drift velocity = $n_n |E| = n_n \frac{V_{DS}}{l}$

is found by multiplying Charge per unit length (5.4)
by electron drift velocity. (5.6)

$i_D = \Gamma (n_n C_{ox}) (V_{OV})^{3/2} l V_{DS} [(5.7)]$

5.1.4 $V_{Dg} = \text{small}$

or $i_D = [\mu_n C_{ox} \left(\frac{W}{L} \right) (V_{GS} - V_t)] V_{Dg}$

process transconductance: product $\mu_n C_{ox}$
Oxide Capacitance \times mobility of electrons

$$k'_n = \mu_n C_{ox} \quad (5.1.1)$$

(subscript n = n channel)

dimensions: A/V^2

w/L = transistor aspect ratio

* channel conductance proportional to channel width (w)
and inversely proportional to channel Length (L)

transconductance parameter k_{nT}

- product of process transconductance k'_n
- and aspect ratio w/L

$$k_n = k'_n (w/L) = (\mu_n C_{ox}) (w/L) \quad (5.1.2) \quad (\text{A/V}^2)$$

Units:

g_{Dg} = channel conductance

V_{Dg} small MOSFET behaves as resistor r_{Dg}
controlled by gate voltage V_{Gg}

$$r_{Dg} = 1/V_{Dg} = 1/(\mu_n C_{ox})(w/L) V_{Dg} = 1/(\mu_n C_{ox})(w/L)(V_{GS} - V_t)$$

$V_{Gg} > V_t$ "enhances channel"
thus enhancement type.

Ex 5.1

Given: $t_{ox} = 4 \text{ nm}$
 $M_n = 450 \text{ cm}^2/\text{V}\cdot\text{s}$

Find: $k'_n \propto W$

$$V_t = 0.5 \text{ V}$$

$$L = 0.18 \times 10^{-6}$$

$$r_{Df} = 1000 \Omega$$

$$V_{Df} = 1 \text{ V}$$

Overdrive Voltage:

$$V_{ov} = V_{Df} - V_t = 1 - 0.5 = 0.5 \text{ V}$$

Permittivity of SiO_2 :

$$\epsilon_{ox} = 3.45 \times 10^{-11} \text{ F/m}$$

Oxide Capacitance:

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.45 \times 10^{-11}}{4 \times 10^{-9}} = 0.8625 \times 10^{-2} \text{ F/m}^2$$

Transconductance:

$$k'_n = M_n C_{ox} = (450 \times 10^{-4})(0.8625 \times 10^{-2}) = 382.5 \times 10^{-4} \text{ A/V}^2$$

Linear resistance

$$r_{Df} = 1 / (M_n C_{ox}) \left(\frac{W}{L} \right) (V_{Df} - V_t)$$

$$1000 = 1 / (450 \times 10^{-4}) (0.8625 \times 10^{-2}) \left(\frac{W}{0.18 \times 10^{-6}} \right) (1 - 0.5)$$

$$W = 1 / (450 \times 10^{-4}) (0.8625 \times 10^{-2}) \left(1000 / (0.18 \times 10^{-6}) \right) (0.5)$$

$$W = 9.28 \times 10^{-4} \text{ m}$$

5.1.5 V_{Df} increased

V_{Df} increase channel becomes tapered.

$$i_D = k'_n \left(\frac{W}{L} \right) (V_{ov} V_{Df} - \frac{1}{2} V_{Df}^2) \quad (5.1.5)$$

$$i_D = k'_n \left(\frac{W}{L} \right) (V_{ov} - \frac{1}{2} V_{Df}) V_{Df} \quad (5.1.4)$$

$$I_D = k'_n \left(\frac{W}{L} \right) [V_{Df} - \frac{1}{2} V_{Df}^2] \quad (5.1.6)$$

5.1.6 $V_{Df} \geq V_{ov}$

Channel Pinch/ Current Saturation

Here $V_{GD} > V_T$

$V_{DS} = V_{OV} = \text{Saturation}$

$$I_D = \frac{1}{2} k'_n \left(\frac{W}{L}\right) V_{OV}^2 \quad (6.17)$$

Saturation Region

Example 6.1

Given: $L_{min} = 0.18 \mu m$

$t_{ox} = 4 nm$

$\mu_n = 450 \text{ cm}^2/\text{V}\cdot\text{s}$

$V_t = 0.5 \text{ V}$

a] Find $C_{ox} \& k'_n$

b] if $W/L = 1.8 \mu m/0.18 \mu m$

find $V_{OV}, V_{GS}, V_{GDS} @ i_D = 100 \mu A$

c] find $V_{OV} \& V_{GS}$ to achieve $r_{DS} = 1000 \Omega$
assume very small V_{AP}

$$a) C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.45 \times 10^{-11}}{4 \times 10^{-9}} = 8.63 \times 10^{-3} \text{ F/m}^2$$

$$k'_n = \mu_n C_{ox} = (450 \times 10^{-6})(8.63 \times 10^{-3}) = 3.88 \times 10^{-4} \text{ A/V}^2$$

b] Operation in saturation region

$$i_D = \frac{1}{2} k'_n \left(\frac{W}{L}\right) V_{OV}^2$$
$$100 \times 10^{-6} = \frac{1}{2} (3.88 \times 10^{-4}) \left(\frac{1.8 \times 10^{-6}}{0.18 \times 10^{-6}}\right) V_{OV}^2$$
$$V_{OV} = 0.227 \text{ V}$$

$$V_{GS} = V_{OV} + V_T = 0.227 + 0.5 = 0.727 \text{ V}$$

$$V_{GDS\min} = V_{OV} = 0.227 \text{ V}$$

$$c) r_{DS} = \left| \frac{1}{k'_n \left(\frac{W}{L}\right) V_{OV}} \right|$$
$$\frac{1}{1000} = \left| \frac{1}{(3.88 \times 10^{-4})(10)} V_{OV} \right|$$
$$V_{OV} = 0.257 \text{ V}$$
$$V_{GS} = V_{OV} + 0.5 = 0.757 \text{ V}$$

Ex 5.1.3

$$\frac{t_{ox}}{A_{ox}} = 1.4 \text{ nm}$$

$$= 6.5 \times 10^{-4}$$

$$m_n = 216 \text{ cm}^2/\text{V}\cdot\text{s}$$

$$V_t = 0.35 \text{ V}$$

$$W/L = 10 \text{ m}$$

$$L_D = 50 \times 10^{-6}$$

Find C_{ox} , k'_n , V_{ov} , V_{GP} , $V_{PS\min}$

$$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = \frac{3.45 \times 10^{-11}}{1.4 \times 10^{-9}} =$$

$$C_{ox} = 0.0244 \text{ F}$$

$$k'_n = m_n C_{ox} = (216 \times 10^{-4})(0.024) = 532 \times 10^{-4}$$

$$i_D = \frac{1}{2} k'_n \left(\frac{W}{L} \right) V_{ov}^2$$

$$C_{ox}/L = \frac{1}{2} \left(532 \times 10^{-4} \right) \left(10 \right) V_{ov}^2$$

$$V_{ov} = 0.137 \text{ V}$$

$$V_{GP} = 0.137 + 0.35 = 0.487 \text{ V}$$

$$V_{PS\min} = 0.137 \text{ V}$$

5.1.7 p channel MOSFET

- substrate is n type

- channel regions are p type

- polarity reversed.

To induce current (-) voltage is applied.

$$V_{GP} \leq V_t$$

$$|V_{DS}| \geq |V_{GP}|$$

Pmos originally dominated b/c NMOS was hard to make.
as NMOS tech difficulties solved NMOS began to dominate
the market.

NMOS > gains & operation speeds

$$m_p > m_n$$

PMOS low dominates; both NMOS & PMOS