INF3410/4411, Fall 2018

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Excerpt of Sedra/Smith Chapter 5: CMOS Field Effect Transistors (FETs)

Content

CMOS FET Large Signal Models (book 5.1-5.2)

MOSFET circuits at DC (book 5.3)

Further Model Refinements (book 5.4, will be discussed later)

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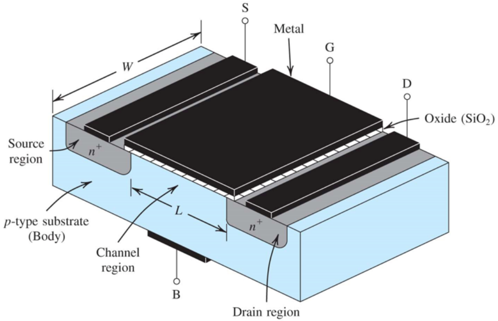
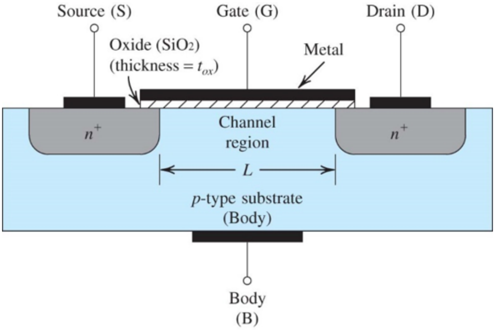
Device Concept



(a)

Device Cross Section



(b)

Short Sidetrack: PN-junction

(from book: Carusone, Johns, Martin)

$$C_j = \frac{C_{j0}}{\sqrt{1 + \frac{V_R}{\Phi_0}}} \quad (1.17)$$

$$C_{j0} = \sqrt{\frac{qK_S\varepsilon_0}{2\Phi_0} \frac{N_A N_D}{N_A + N_D}} \quad (1.18)$$

$$\Phi_0 = U_T \ln\left(\frac{N_A N_D}{n_i^2}\right) \quad (1.6)$$

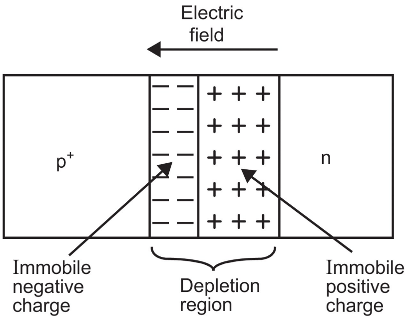
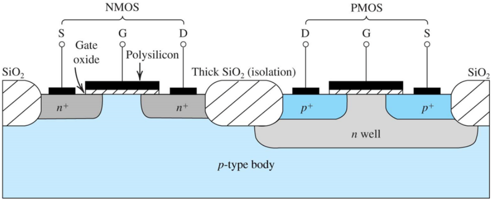


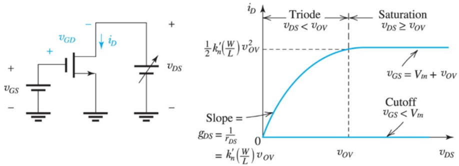
Figure 1.2

nFET/NMOS and pFET/PMOS cross section



Above Threshold Regions of Operation NFET

Table 5.1 Regions of Operation of the Enhancement NMOS Transistor



- $v_{GS} < V_{tn}$: no channel; transistor in cutoff; $i_D = 0$
- $v_{GS} = V_{tn} + v_{OV}$: a channel is induced; transistor operates in the triode region or the saturation region depending on whether the channel is continuous or pinched off at the drain end;

Triode Region

Continuous channel, obtained by:

$$v_{GD} > V_{tn}$$

or equivalently:

$$v_{DS} < v_{OV}$$

Then,

$$i_D = k_n'\left(\frac{W}{L}\right)\left[(v_{GS} - V_{tn})v_{DS} - \frac{1}{2}v_{DS}^2\right]$$

or equivalently,

$$i_D = k_n'\left(\frac{W}{L}\right)\left(v_{OV} - \frac{1}{2}v_{DS}\right)v_{DS}$$

Saturation Region

Pinched-off channel, obtained by:

$$v_{GD} \leq V_{tn}$$

or equivalently:

$$v_{DS} \geq v_{OV}$$

Then

$$i_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)(v_{GS} - V_{tn})^2$$

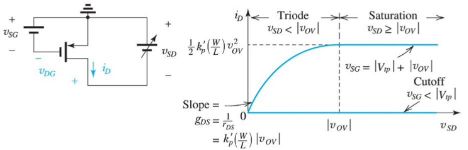
or equivalently,

$$i_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)v_{OV}^2$$

Above Threshold Regions of Operation PFET

'Above Threshold' is also called 'Strong Inversion'

Table 5.2 Regions of Operation of the Enhancement PMOS Transistor



- $v_{SG} < |V_{tp}|$: no channel; transistor in cutoff; $i_D = 0$
- $v_{SG} = |V_{tp}| + |v_{OV}|$: a channel is induced; transistor operates in the triode region or in the saturation region depending on whether the channel is continuous or pinched off at the drain end;

Triode Region

Continuous channel, obtained by:

$$v_{DG} > |V_{tp}|$$

or equivalently

$$v_{SD} < |v_{OV}|$$

Then

$$i_D = k_p'\left(\frac{W}{L}\right)\left[(v_{SG} - |V_{tp}|)v_{SD} - \frac{1}{2}v_{SD}^2\right]$$

or equivalently

$$i_D = k_p'\left(\frac{W}{L}\right)\left(|v_{OV}| - \frac{1}{2}v_{SD}\right)v_{SD}$$

Saturation Region

Pinched-off channel, obtained by:

$$v_{DG} \leq |V_{tp}|$$

or equivalently

$$v_{SD} \geq |v_{OV}|$$

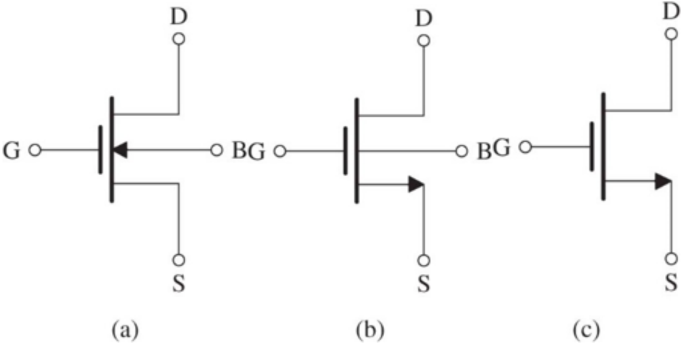
Then

$$i_D = \frac{1}{2}k_p'\left(\frac{W}{L}\right)(v_{SG} - |V_{tp}|)^2$$

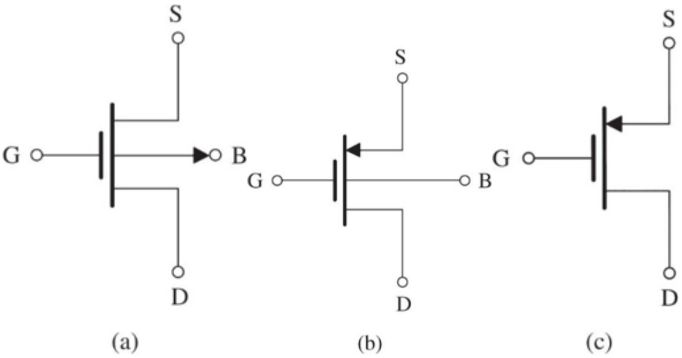
or equivalently

$$i_D = \frac{1}{2}k_p'\left(\frac{W}{L}\right)v_{OV}^2$$

nMOSFET Device Symbols



pMOSFET Device Symbols



The EKV model

$$i_D = i_F - i_R$$

$$i_{F(R)} = I_S \ln\left[1 + e^{\frac{v_G - V_{tn} - n v_{S(D)}}{n V_T}}\right]^2 (1 + \lambda v_{DS})$$

(Note that parameter λ is also expressed as the Early Voltage $V_A = \frac{1}{\lambda}$ and V_A is proportional to the transistor length L and thus sometimes expressed as $V_A = V_A' L$.)

Regions of operation: strong- vs weak inversion

This two regions of operation are dependent on v_{GS}!!!
INDEPENDENT of the active- and triode region of operation (see next slide) the transistor can operate in either:
weak inversion = subthreshold vs. strong inversion = above threshold
These are dependent on $v_{GS} \geq V_{tn}$ for strong inversion and $v_{GS} < V_{tn}$ for weak inversion. The transition between the two is not really aprupt and refered to as moderate inversion.

Regions of operation: triode- vs active region

This two regions of operation are dependent on v_{DS}!!!
INDEPENDENT of weak- and strong inversion the transistor can operate in either:
Triode region = 'linear' region vs. saturation = active region
These are dependent on $v_{DS} \geq V_{sat}$ for active region and $v_{DS} < V_{sat}$ for triode region, where the definition of V_{sat} is different dependent on if the transistor is in weak ($V_{sat} \approx 4V_T$)or strong inversion ($V_{sat} = V_{OV}$).

Regions of operation summary

So there are **4** differnt combinations possible:
weak inversion, triode region OR weak inversion, active region OR strong inversion, triode region OR strong inversion, active region!

strong inversion, active region

$$i_D = \frac{1}{2n} k_n \left(v_G - V_{tn} - n v_S\right)^2 (1 + \lambda v_{DS})$$

Different name in the EKV model: $\beta := k_n$ and $1 \leq n \leq 2$ and often $n \approx 1$ and is neglected

weak inversion, active region

$$i_D = I_S e^{\frac{v_G - V_{tn} - n v_S}{n V_T}} (1 + \lambda v_{DS}) \quad (16.13)$$

Where $I_S = 2 n k_n V_T^2$

strong inversion, triode region

(Note: term $*(1 + \lambda v_{DS})$ neglected here
... not so influential for small v_{DS})
EKV:

$$i_D = k_n v_{DS} \left[v_G - V_{tn} - \frac{n}{2}(v_D + v_S) \right]$$

Sedra & Smith:

$$i_D = k_n v_{DS} \left[v_{OV} - \frac{1}{2} v_{DS} \right]$$

Which is the same for $v_S = 0$ and $n = 1$
For $v_{DS} << V_{OV}$ (1st order Taylor expansion around $v_{DS} = 0$):

$$i_D = k_n v_{OV} v_{DS} \Rightarrow g_{DS} = k_n v_{OV}$$

weak inversion, triode region

EKV:

$$i_D = e^{\frac{v_G - V_{tn}}{nV_T}} \left(e^{\frac{-v_S}{V_T}} - e^{\frac{-v_D}{V_T}} \right)$$

For $v_S = 0$:

$$i_D = e^{\frac{v_{OV}}{nV_T}} \left(1 - e^{\frac{-v_D}{V_T}} \right)$$

For $v_{DS} << V_{OV}$ (1st order Taylor expansion around $v_{DS} = 0$):

$$i_D = e^{\frac{v_{OV}}{nV_T}} \frac{V_D}{V_T} \Rightarrow g_{DS} = e^{\frac{v_{OV}}{nV_T}} \frac{1}{V_T}$$

Illustration I_D vs V_{GS}

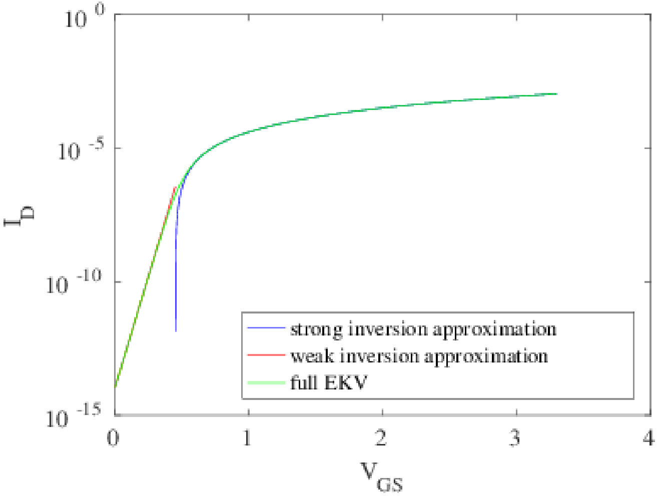


Illustration I_D vs V_{GS}, old school

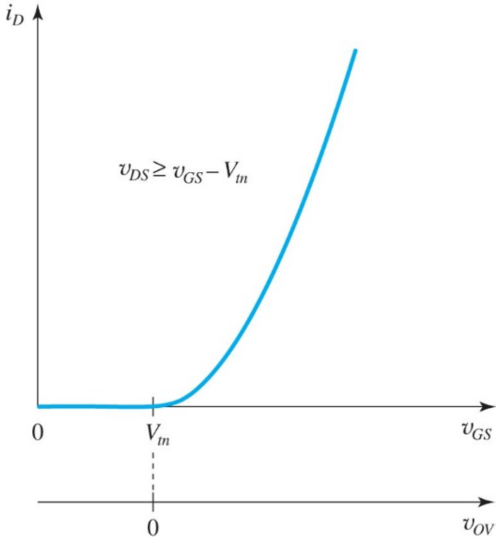
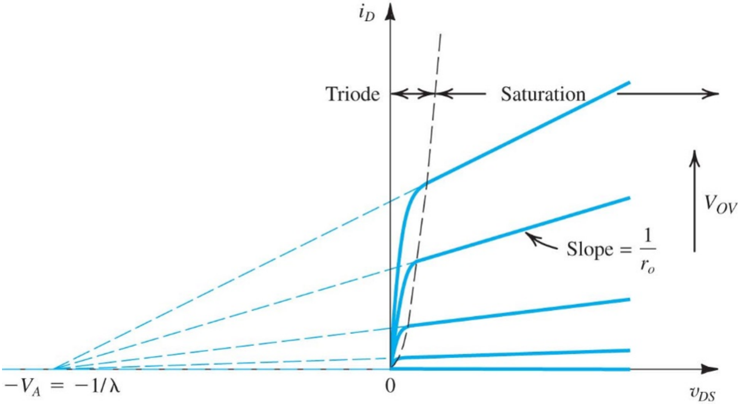


Illustration I_D vs V_{DS}, channel length modulation

Here in saturation, but this works in sunthreshold too.



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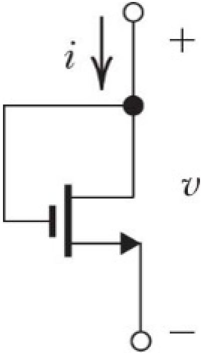
Diode Connected Transistor



In strong inversion:

$$i = \frac{1}{2} k_n (v - V_{tn})^2$$

Simple Current Mirror

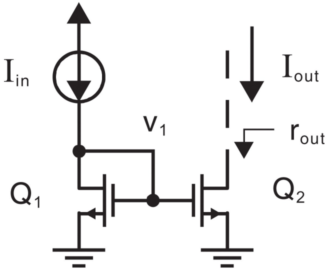


Figure 3.1

When will $I_{out} = I_{in}$, $I_{out} \neq I_{in}$, $I_{out} \approx I_{in}$, $I_{out} \approx xI_{in}$?

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