IN3170/4170, Spring 2023

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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)

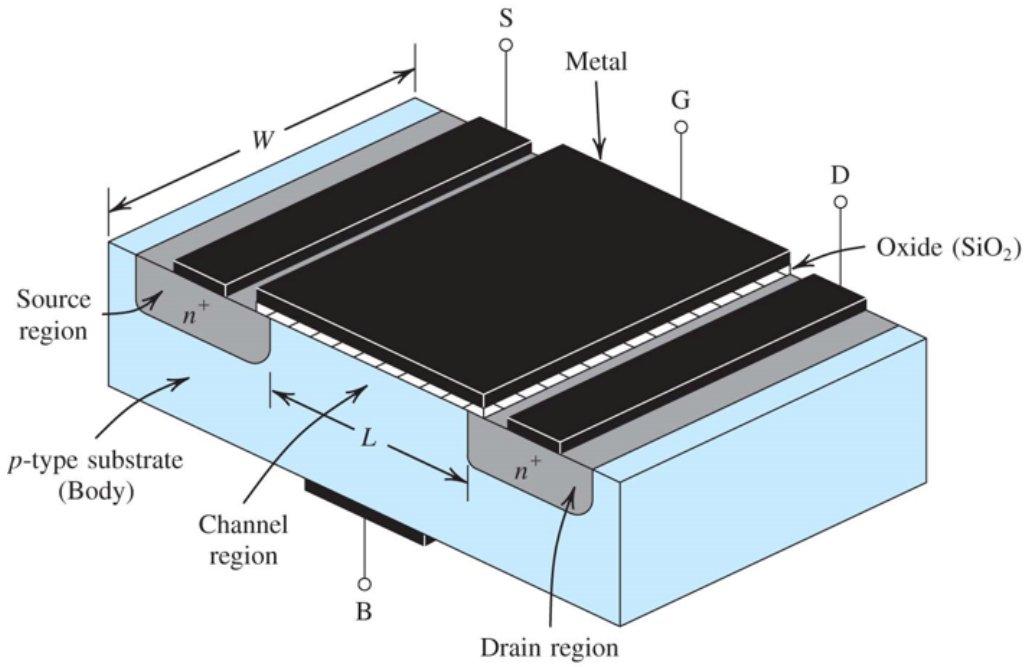
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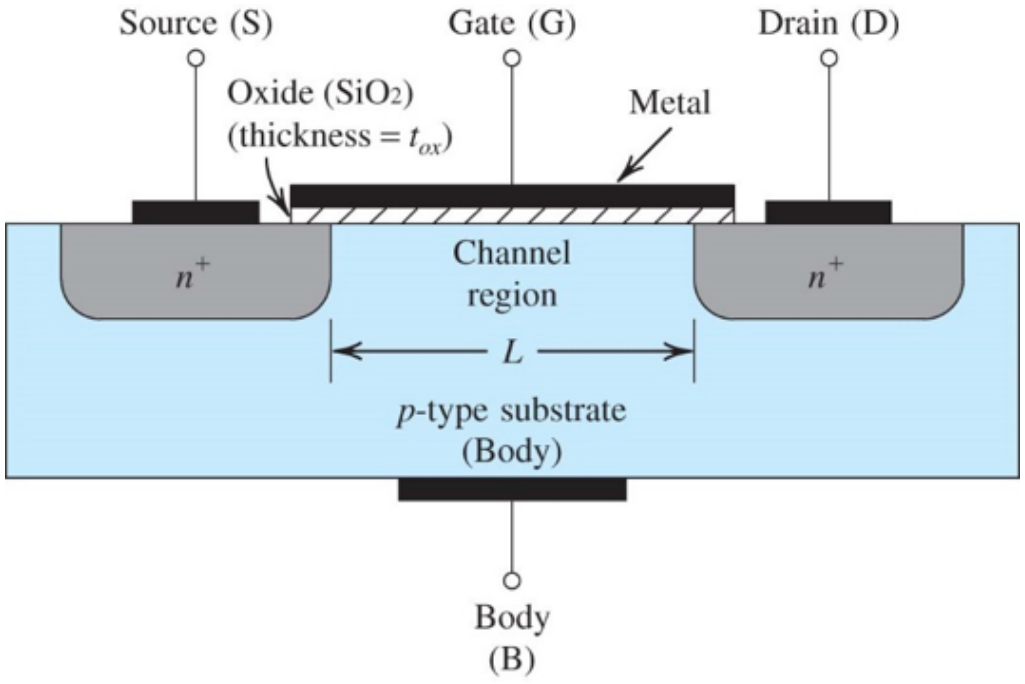
Further Model Refinements (book 5.4, will be discussed later)

Device Concept



(a)

Device Cross Section



(b)

Short Sidetrack: PN-junction

(from book: Carusone, Johns, Martin)

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

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

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

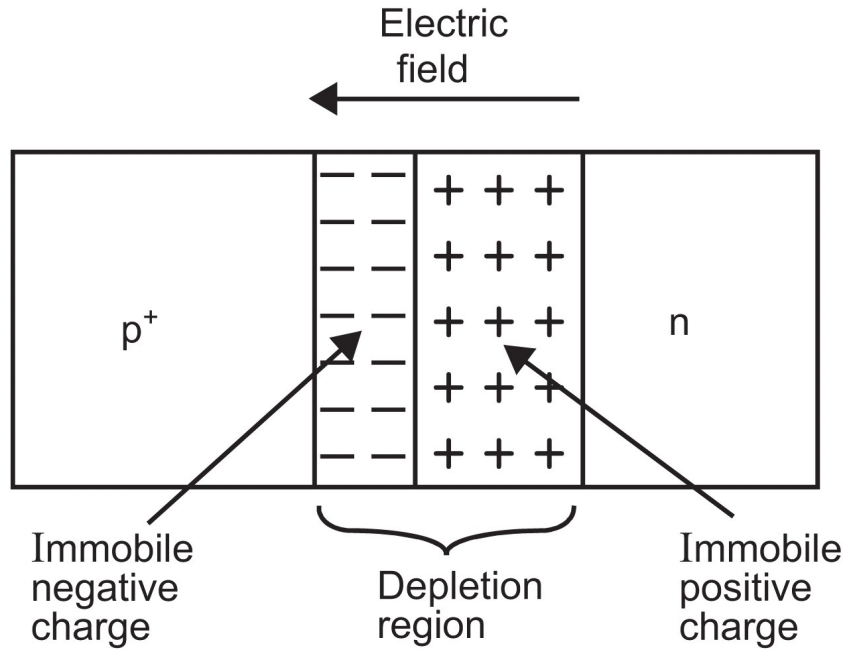
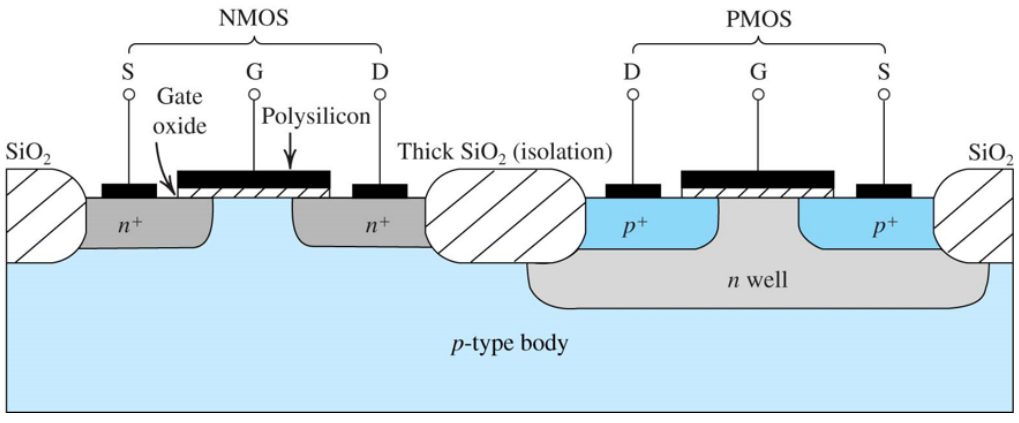
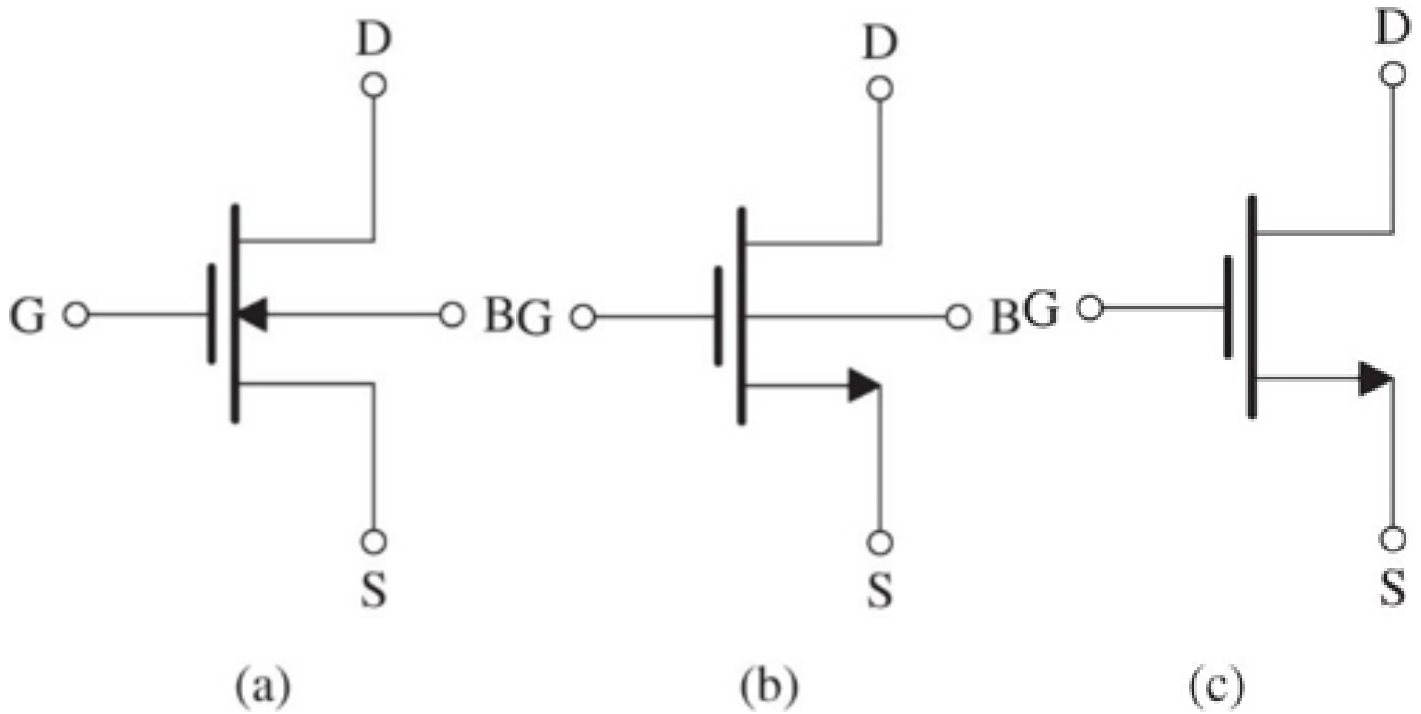


Figure 1.2
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nFET/NMOS and pFET/PMOS cross section

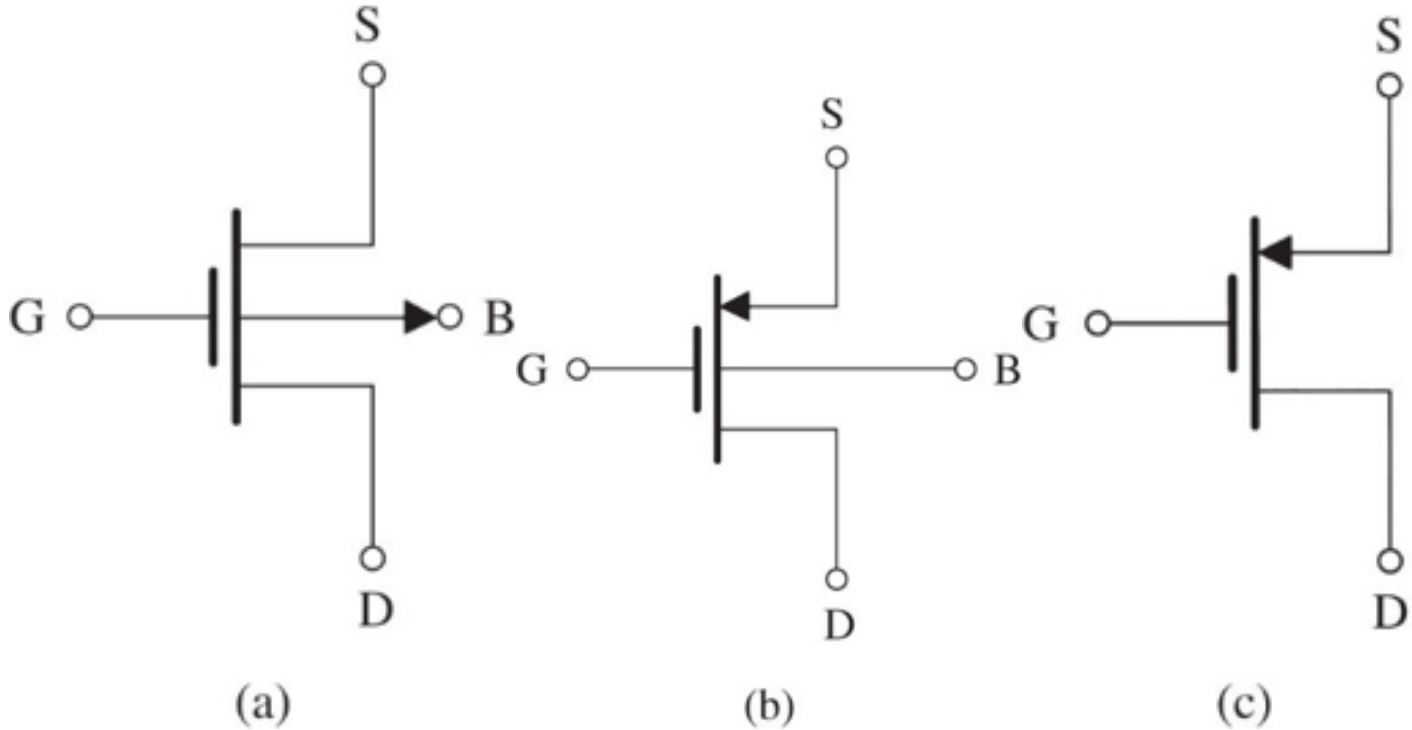


nMOSFET Device Symbols



Plus the 'digital' version preferred in Philipp's drawings: live.

pMOSFET Device Symbols



Plus the 'digital' version preferred in Philipp's drawings: live.

Large signal models of the MOSFET

Large signal models can be used when the variables are anywhere between the supply rails. Supply rails in the book denominated as Vdd and $-Vss$. Sometimes the signal zero reference Gnd is $Gnd = -Vss$ (mostly for discussion of digital circuits), but sometimes it is also somewhere between the supply rails!

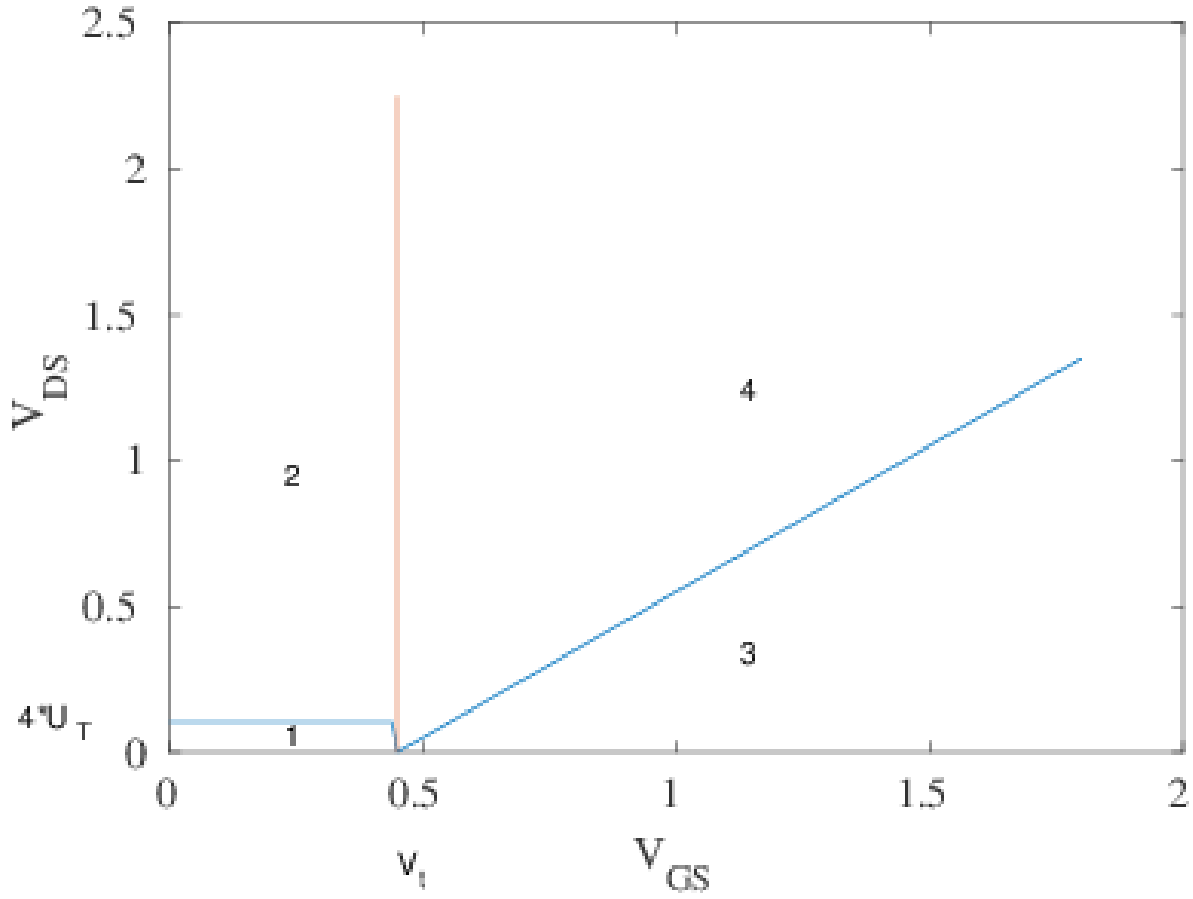
$$I_D = f(V_G - V_S, V_D - V_S) = f(V_{GS}, V_{DS})$$

Some 'hidden' parameters in those functions, either 'process parameters' or 'design parameters: $W, L, \mu, C_{ox}, V_t, \lambda, n$

Two large signal models in the course:

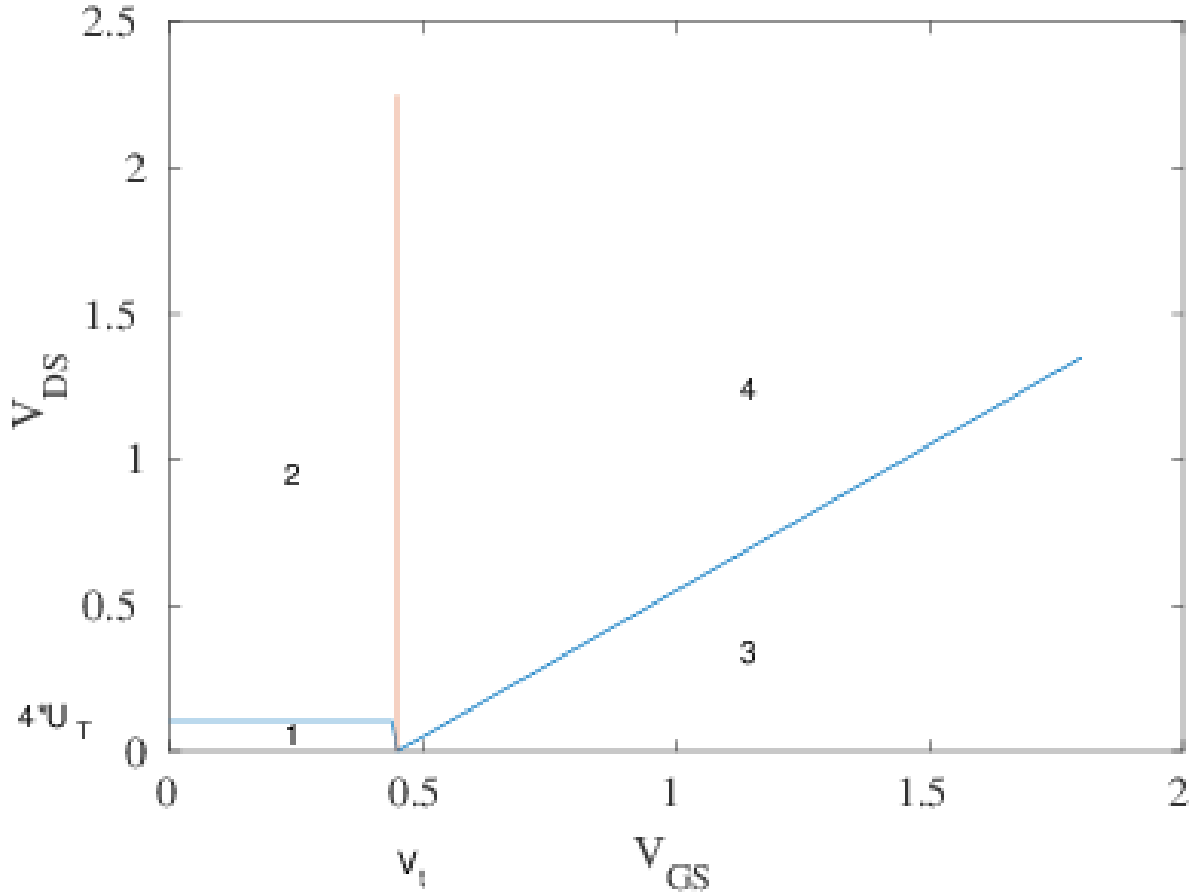
- Book model with 4 functions and regions of operation
- EKV unified model with one function and no division into regions of operation

Regions of operation (1/3)



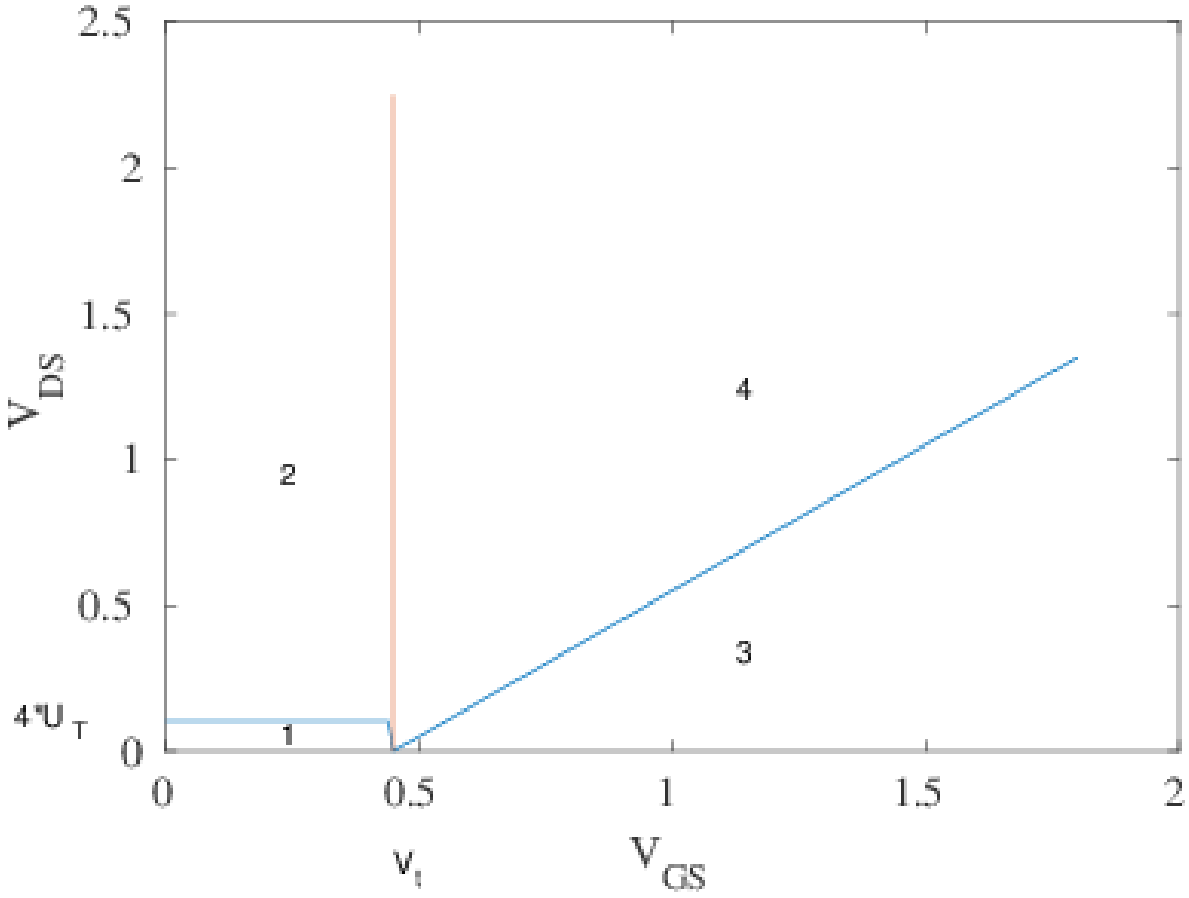
There are **4** differnt regions of operation usually modelled with their own formula for hand-calculations modelling the current i_{DS} in dependence of v_{GS} and v_{DS}.

Regions of operation (2/3)



The blue line separates the 'triode region' (below) from the 'active region' (above), and the red the 'weak inversion' (left) from the 'strong inversion'. This results in the 4 possible combinations: 1) weak inversion, triode region OR 2) weak inversion, active region OR 3) strong inversion, triode region OR 4) strong inversion, active

Regions of operation (3/3)



Note that different names for these regions are also used in literature:
linear-/saturation region for triode-/active region
above-/sub-threshold for strong-/weak inversion

The EKV model

(Check hand out paper by Vittoz, equations (1)-(12).)
Somewhat more complicated, there is also a 'unified' formula that is valid **in ALL of the 4 regions** and which 'automatically' simplifies to the region specific formulae when clearly within a region (i.e. far from the region separation lines).

$$I_D = I_F - I_R$$

$$I_{F(R)} = I_S \ln\left[1 + e^{\frac{V_G - V_{tn} - nV_{S(D)}}{nV_T}}\right]^2 (1 + \lambda V_{DS})$$

(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 $V_A = V'_A L$, where V'_A is a process parameter.)
The book only consider the region dependent simpler equations for hand calculations.

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 ($V_{sat} = V_{ov}$).

strong inversion, active region

$$I_D = \frac{1}{2n} k_n \left(V_G - V_{tn} - nV_S\right)^2 \left(1 + \lambda V_{DS}\right)$$

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

$$I_D = I_S e^{\frac{V_G - V_{tn} - nV_S}{nV_T}} (1 + \lambda V_{DS}) \quad (16.13)$$

Where $I_S = 2nk_n V_T^2$

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:

$$I_D = I_S e^{\frac{V_G - V_{tn}}{nV_T}} \left(e^{\frac{-V_S}{V_T}} - e^{\frac{-V_D}{V_T}} \right)$$

For $v_S = 0$:

$$I_D = I_S e^{\frac{V_{ov}}{nV_T}} \left(1 - e^{\frac{-V_D}{V_T}} \right)$$

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

$$I_D = I_S e^{\frac{V_{ov}}{nV_T}} \frac{V_D}{V_T} \Rightarrow g_{DS} = I_S e^{\frac{V_{ov}}{nV_T}} \frac{1}{V_T}$$

Illustration I_D vs V_{GS}

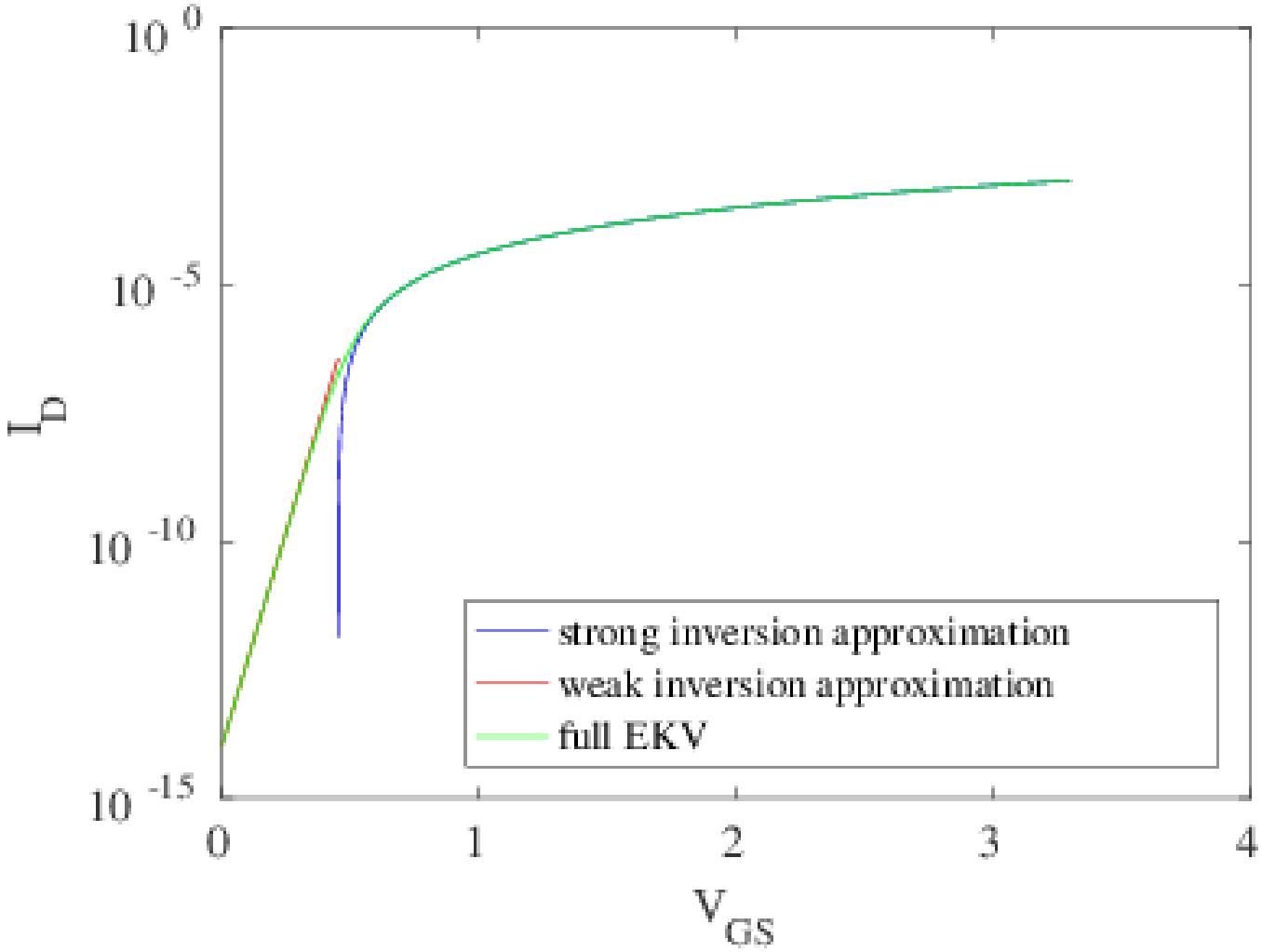
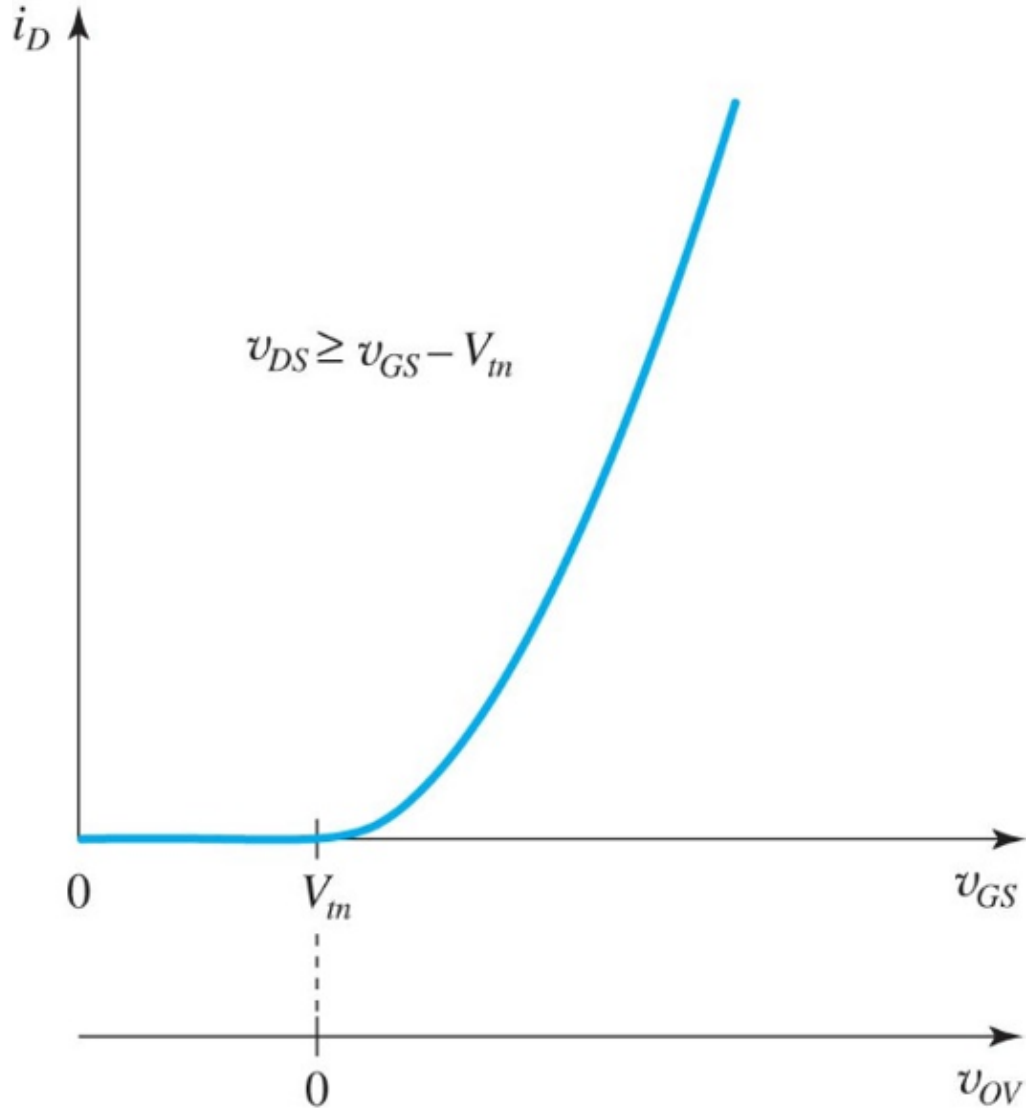


Illustration I_D vs V_{GS}

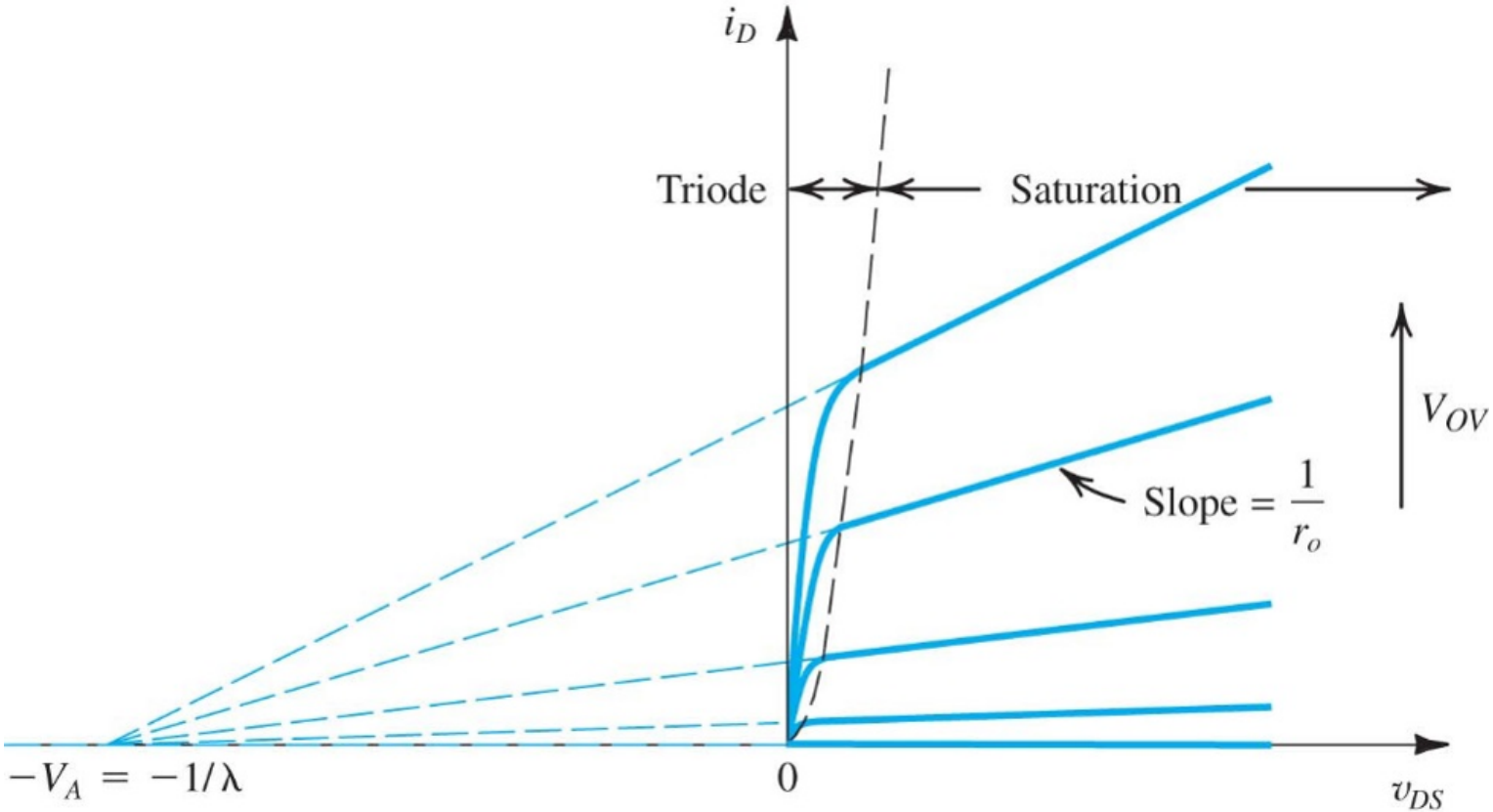
'old school' without considering weak inversion.



(fig. 5.14)

Illustration I_D vs V_{DS}, channel length modulation

Here in saturation, but this works in subthreshold too.

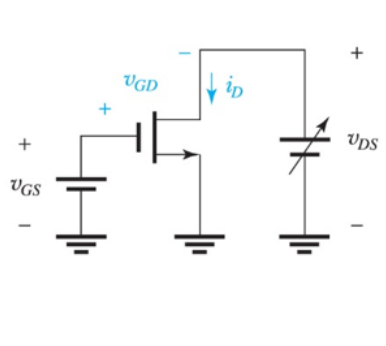


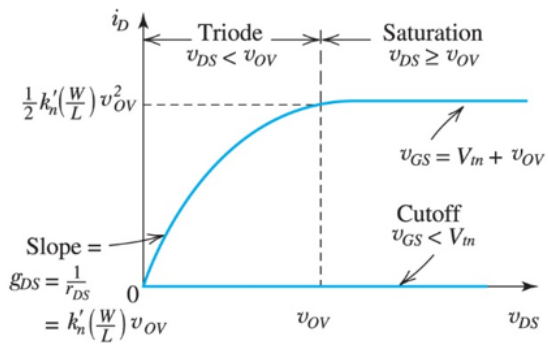
(fig. 5.17)

Chapter 5 NFET

Note! Chapter 5 only treats Above Threshold Regions of Operation
'Above Threshold' is also called 'Strong Inversion'

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

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

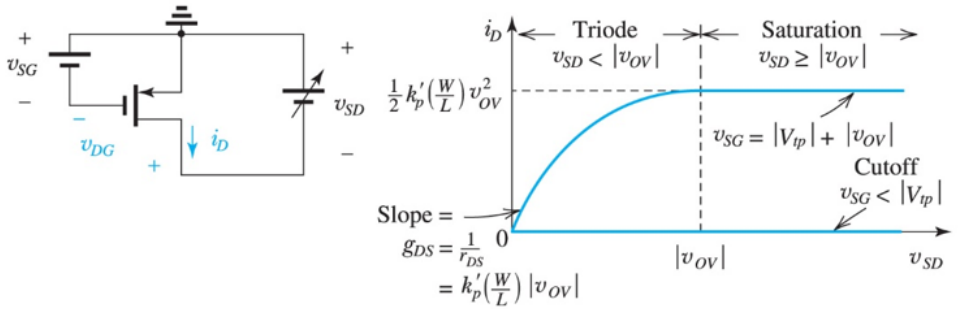
or equivalently,

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

Chapter 5 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

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

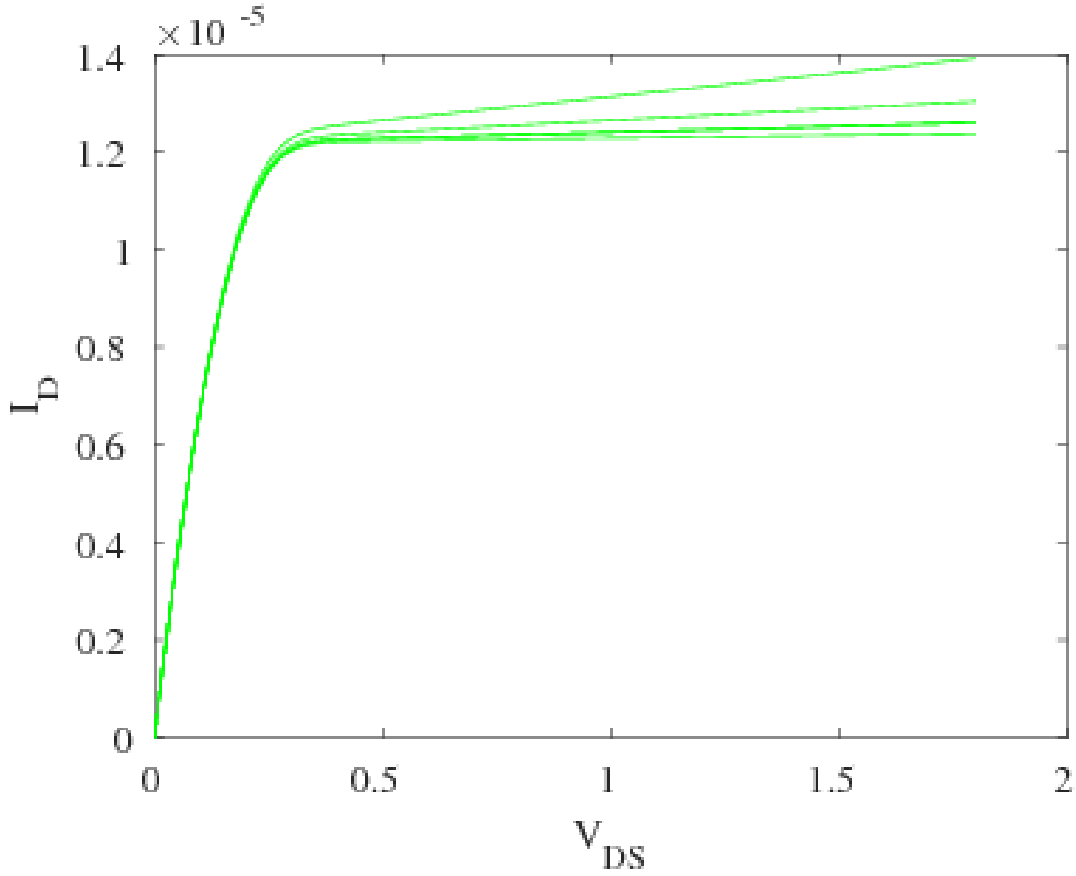
or equivalently

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

Subthreshold in book?

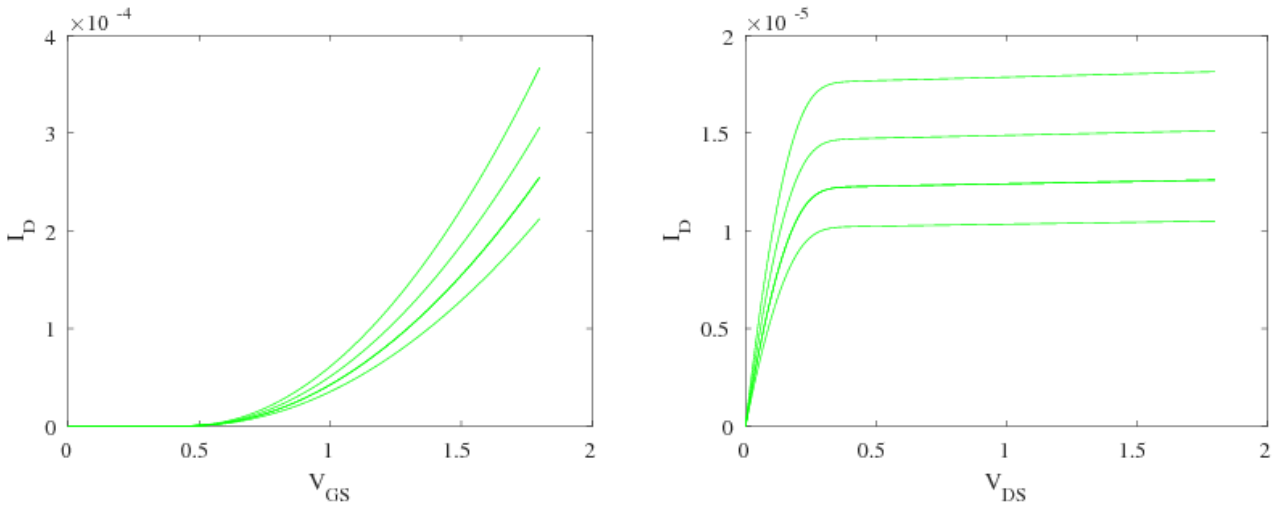
Mentioned in passing in chapter 5 and equation in chapter 16.1.4

Effects of Parameter Tweaking: λ



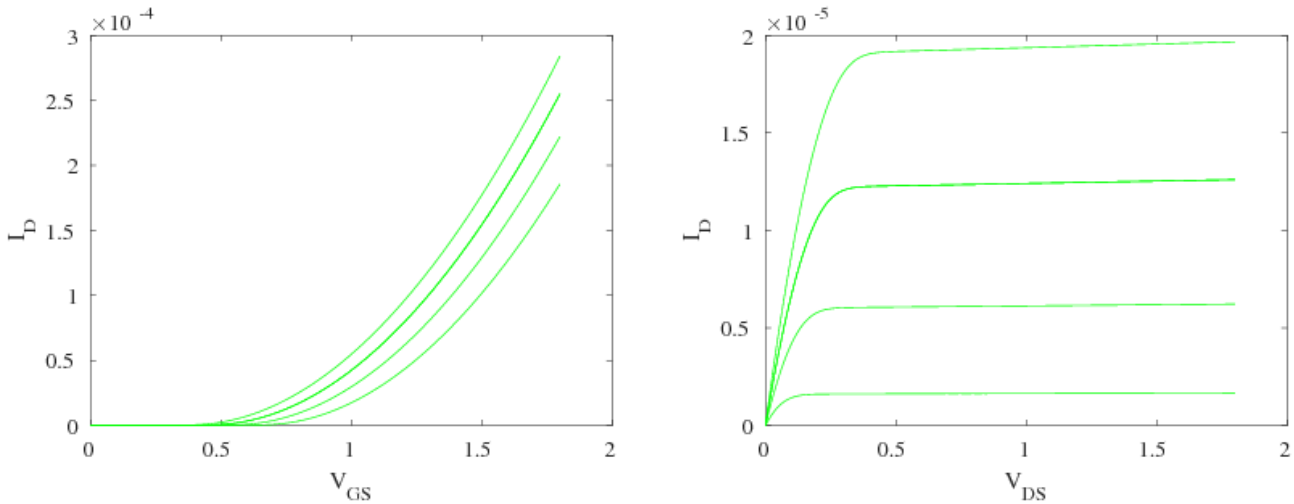
λ can be tweaked at design time by changing L: note that $\frac{1}{\lambda} = V_A = L * V'_A$ where V'_A is a process parameter.

Effects of Parameter Tweaking: k_n



k_n can be tweaked at design time by chaging W/L. Note that $k_n = \frac{W}{L}\mu C_{ox}$ where μC_{ox} is a process parameter.

Effects of Parameter Tweaking: v_{tn}, v_{tp}



v_{tn}, v_{tp} cannot be tweaked at design time. They are process parameters.

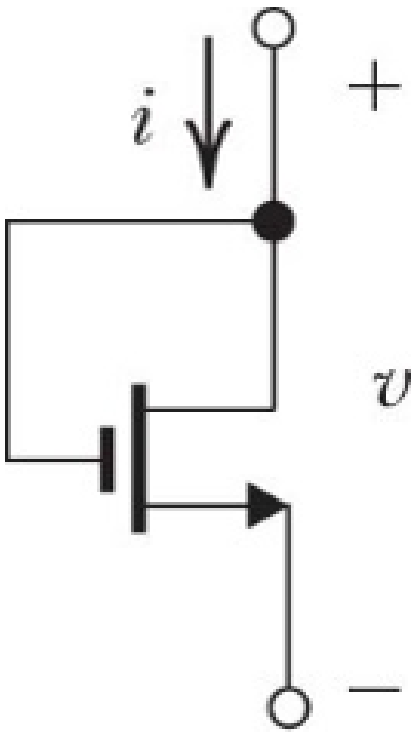
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Further Model Refinements (book 5.4, will be discussed later)

Diode Connected Transistor



In strong inversion:

$$I = \frac{1}{2} k_n (V - V_{tn})^2$$

Simple Current Mirror

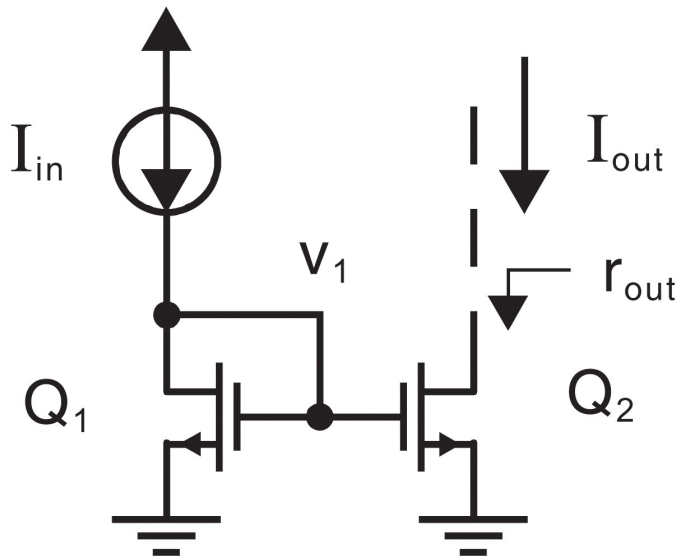


Figure 3.1
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When will $I_{out} = I_{in}$, $I_{out} \neq I_{in}$, $I_{out} \approx I_{in}$, $I_{out} \approx xI_{in}$?

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