EE 330
Lecture 16

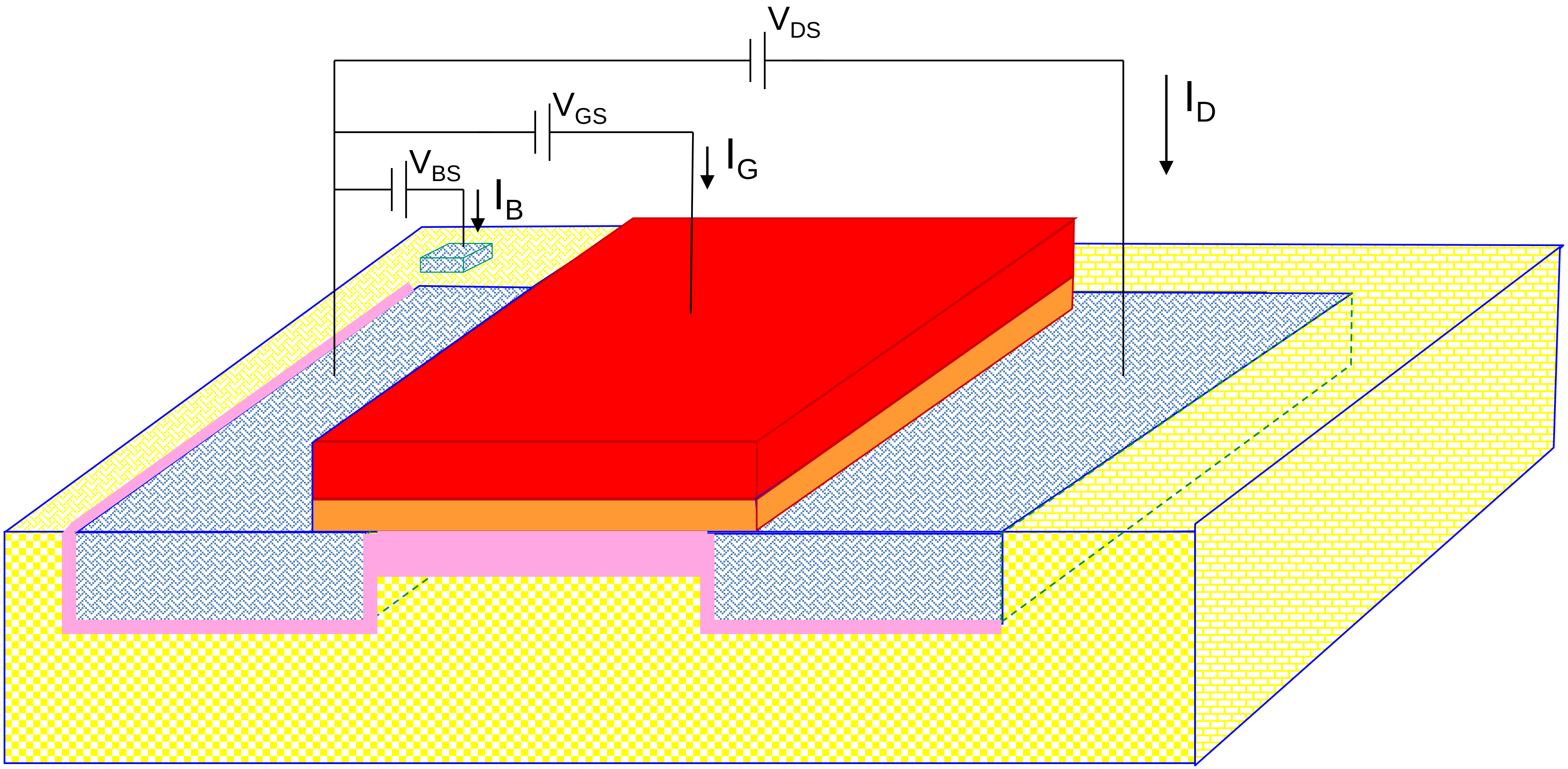
Devices in Semiconductor Processes

- MOSFETs

Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT

n-Channel MOSFET Operation and Model

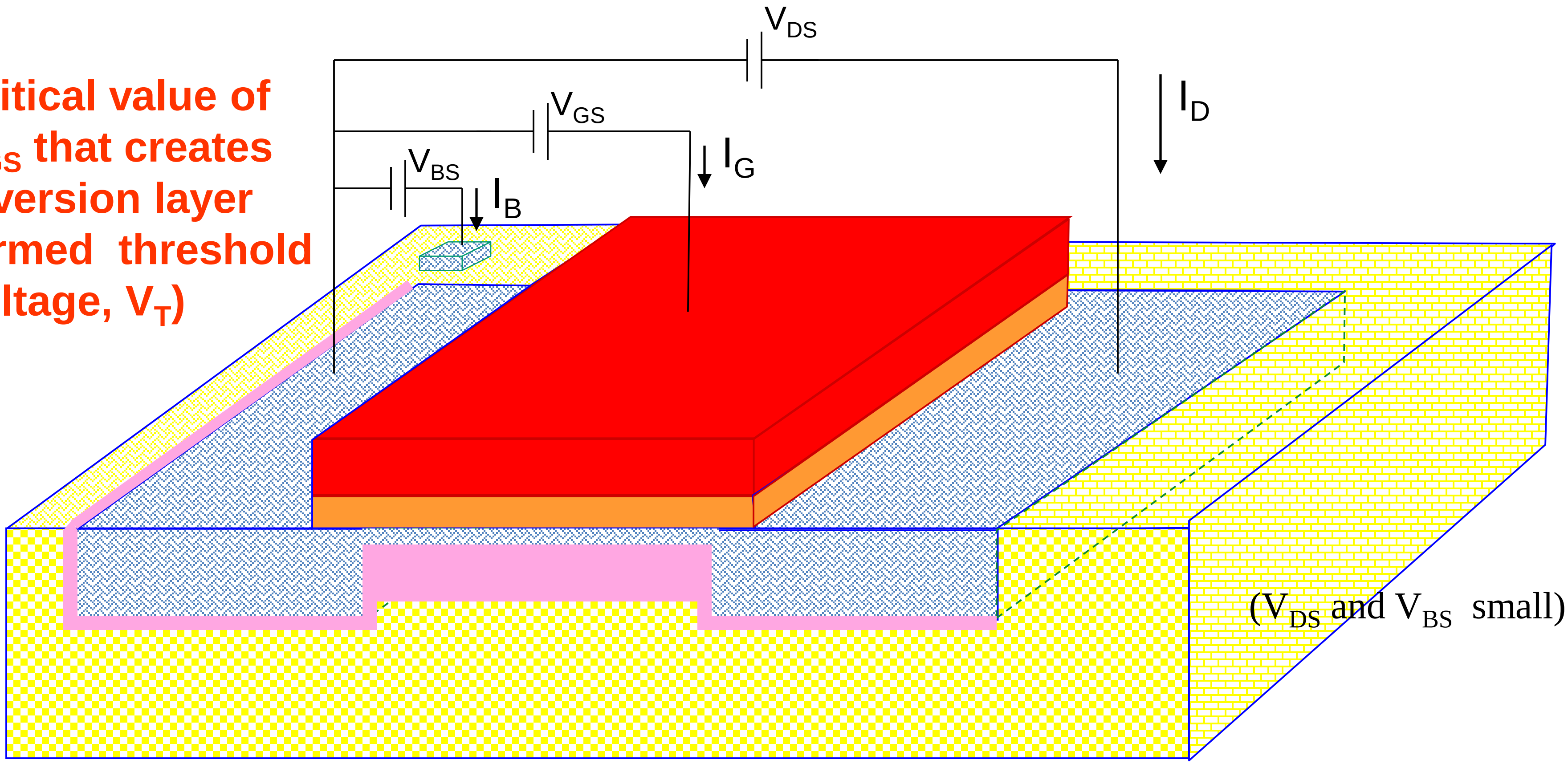


$I_D=0$
$I_G=0$
$I_B=0$

Model in Cutoff Region

n-Channel MOSFET Operation and Model

Critical value of V_{GS} that creates inversion layer termed threshold voltage, V_T)



Increase V_{GS} more

Inversion layer forms in channel

Inversion layer will support current flow from D to S

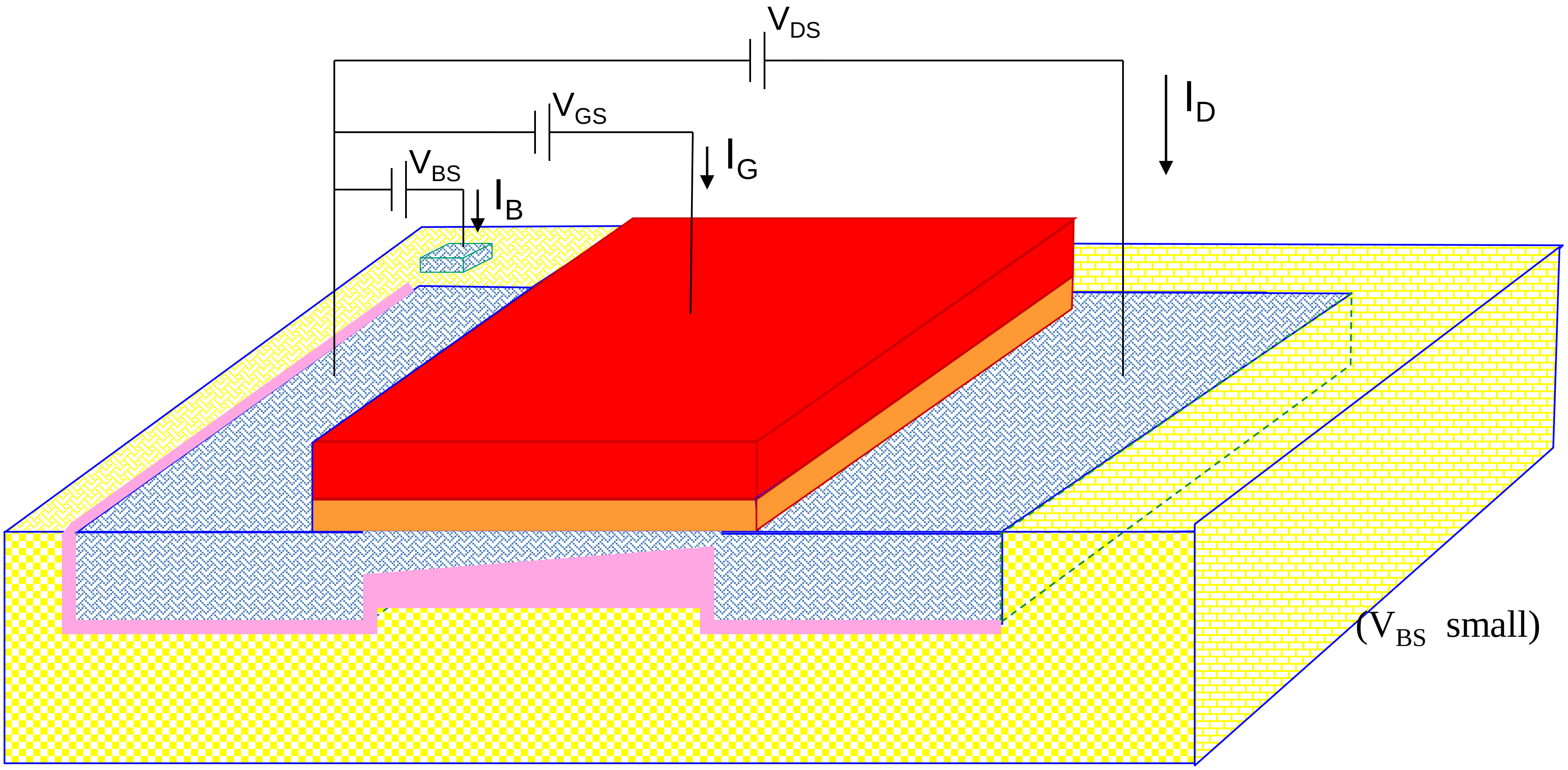
Channel behaves as thin-film resistor

$I_D R_{CH} = V_{DS}$

$I_G = 0$

$I_B = 0$

n-Channel MOSFET Operation and Model



Increase V_{DS}

Inversion layer thins near drain

I_D no longer linearly dependent upon V_{DS}

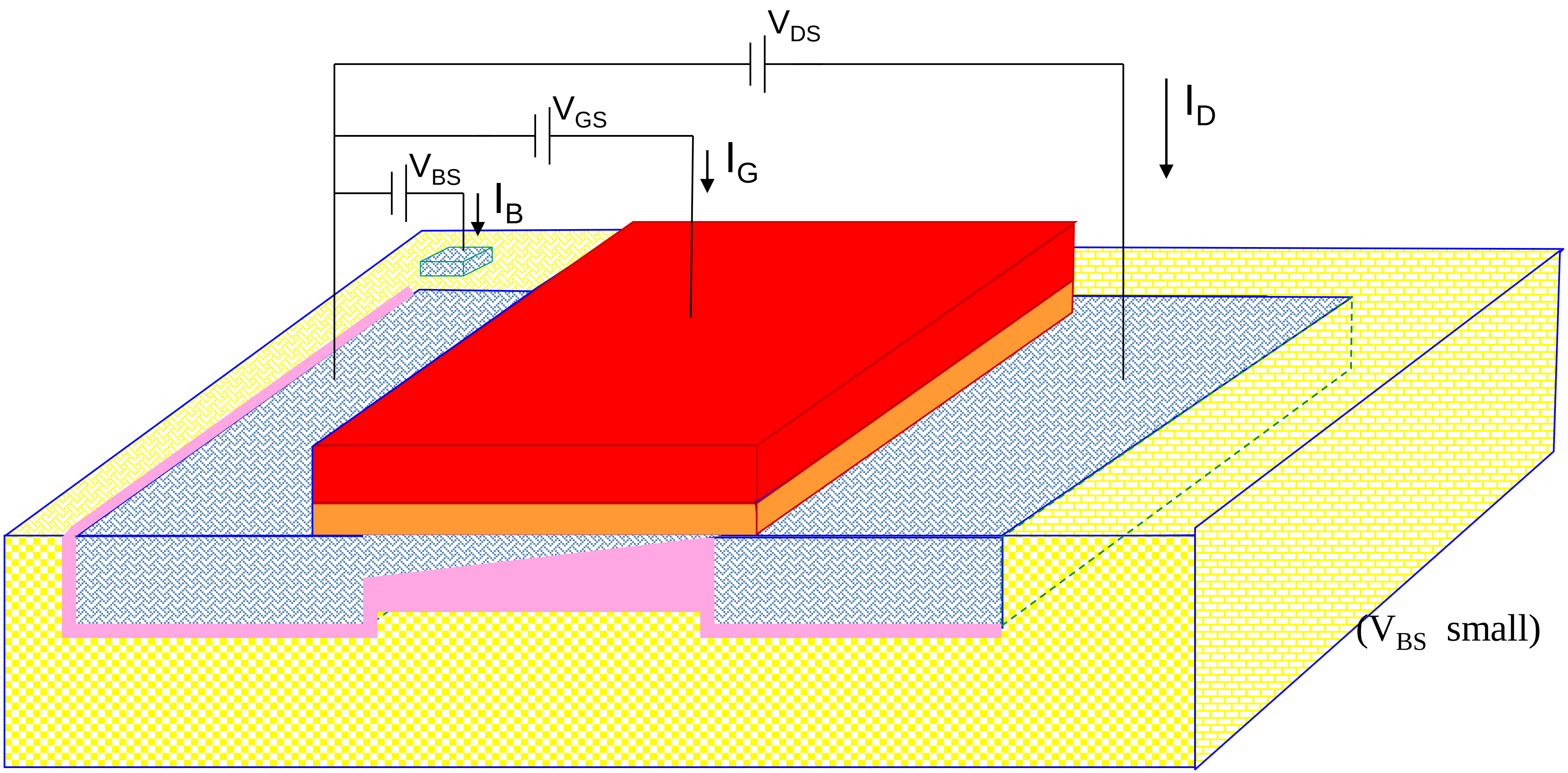
Still termed “ohmic” or “triode” region of operation

I_D=?

I_G=0

I_B=0

n-Channel MOSFET Operation and Model



Increase V_{DS} even more

Inversion layer disappears near drain

Termed “saturation”region of operation

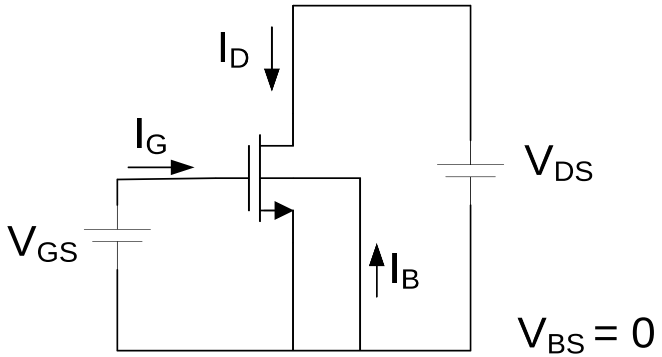
Saturation first occurs when $V_{DS}=V_{GS}-V_T$

I_D=?

I_G=0

I_B=0

Model Summary



$$I_D = \begin{cases} 0 & V_{GS} \le V_T \quad \text{Cutoff} \\ \mu C_{OX} \dfrac{W}{L}\left(V_{GS} - V_T - \dfrac{V_{DS}}{2}\right)V_{DS} & V_{GS} \ge V_T \quad V_{DS} < V_{GS} - V_T \quad \text{Triode} \\ \mu C_{OX} \dfrac{W}{2L}\left(V_{GS} - V_T\right)^2 & V_{GS} \ge V_T \quad V_{DS} \ge V_{GS} - V_T \quad \text{Saturation} \end{cases}$$

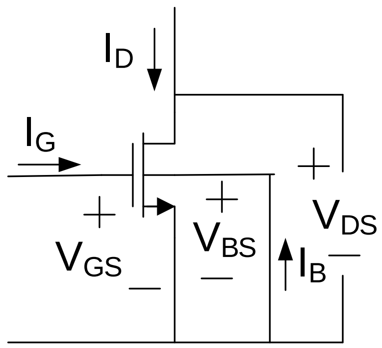
$$I_G = I_B = 0$$

This is a piecewise model (not piecewise linear though)

Note: This is the third model we have introduced for the MOSFET

(Deep triode special case of triode where V_{DS} is small $R_{CH} = \dfrac{L}{W}\dfrac{1}{(V_{GS} - V_T)\mu C_{OX}}$)

Model Summary



$V_{BS} = 0$

$$I_D = \begin{cases} 0 & V_{GS} \le V_T \\ \mu C_{OX} \frac{W}{L}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS} & V_{GS} \ge V_T \quad V_{DS} < V_{GS} - V_T \\ \mu C_{OX} \frac{W}{2L}\left(V_{GS} - V_T\right)^2 & V_{GS} \ge V_T \quad V_{DS} \ge V_{GS} - V_T \end{cases}$$

$$I_G = I_B = 0$$

Observations about this model (developed for V_{BS}=0):

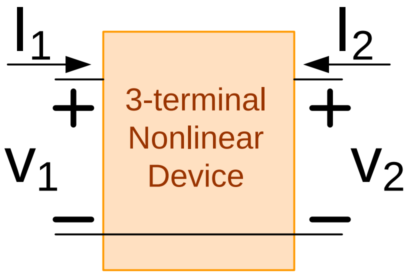
$$I_D = f_1\left(V_{GS}, V_{DS}\right)$$

$$I_G = f_2\left(V_{GS}, V_{DS}\right)$$

$$I_B = f_3\left(V_{GS}, V_{DS}\right)$$

This is a nonlinear model characterized by the functions f_1, f_2, and f_3 where we have assumed that the port voltages V_{GS} and V_{DS} are the independent variables and the drain currents are the dependent variables

General Nonlinear Model

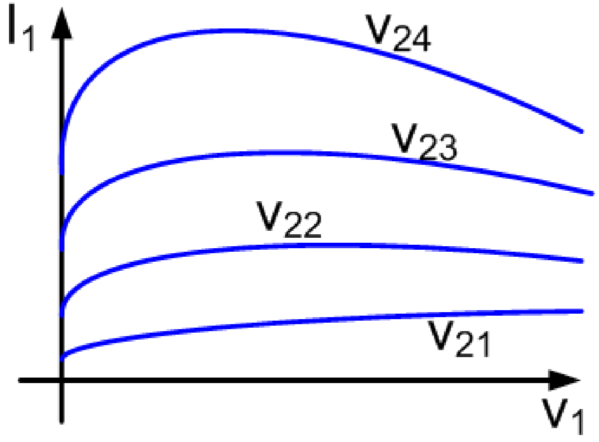


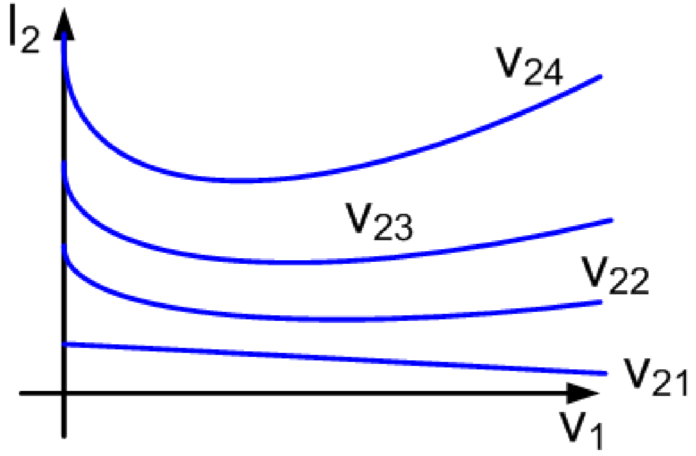
$$I_1 = f_1(V_1, V_2)$$

$$I_2 = f_2(V_1, V_2)$$

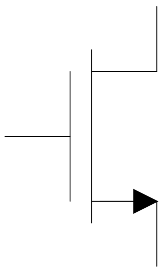
I_1 and I_2 are 3-dimensional relationships which are often difficult to visualize

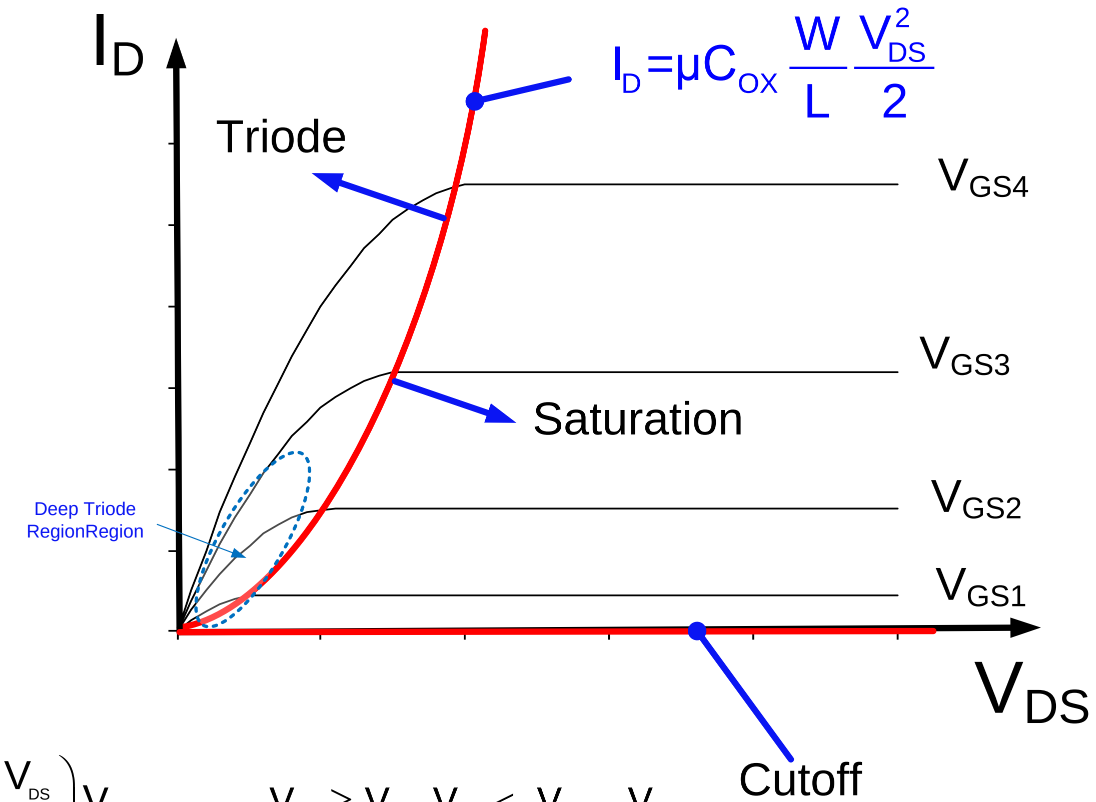
Two-dimensional representation of 3-dimensional relationships





Graphical Representation of MOS Model

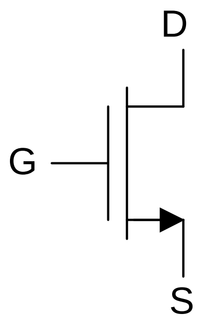


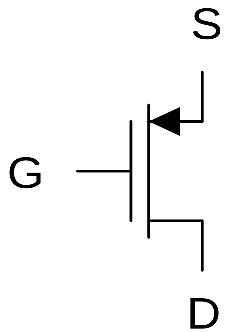


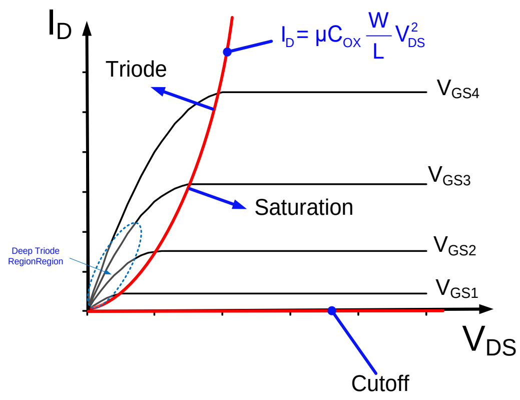
$$I_D = \begin{cases} 0 & \\ \mu C_{OX}\frac{W}{L}\left(V_{GS}-V_T-\frac{V_{DS}}{2}\right)V_{DS} & V_{GS}\geq V_T \quad V_{DS} < V_{GS}-V_T \\ \mu C_{OX}\frac{W}{2L}\left(V_{GS}-V_T\right)^2 & V_{GS}\geq V_T \quad V_{DS}\geq V_{GS}-V_T \end{cases}$$

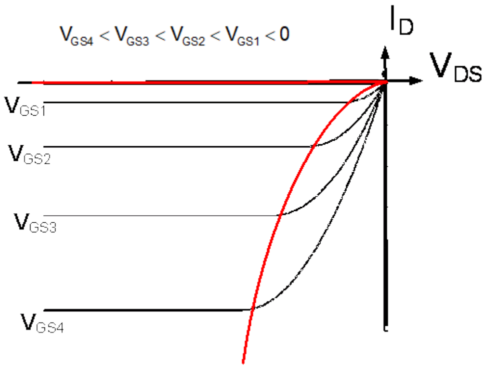
$$I_G = I_B = 0$$

PMOS and NMOS Models



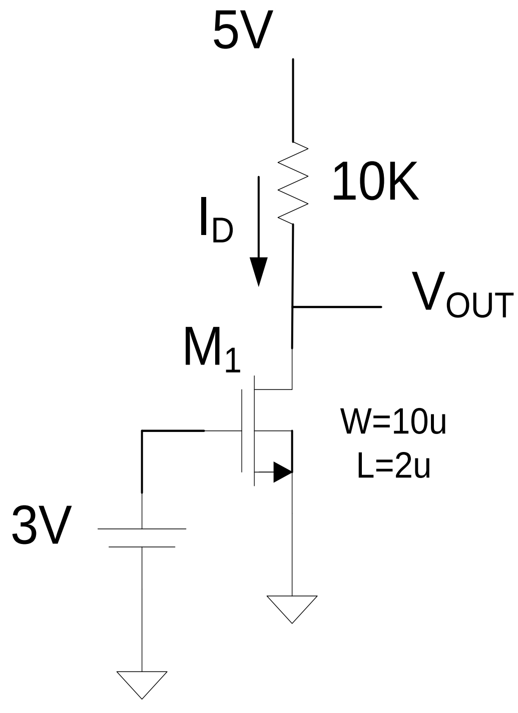






- Functional form identical, sign changes and parameter values different
- Will give details about p-channel model later

Example: Determine the output voltage for the following circuit using the square-law model of the MOSFET. Assume V_T=1V and μC_{OX}=100µAV^{-2}

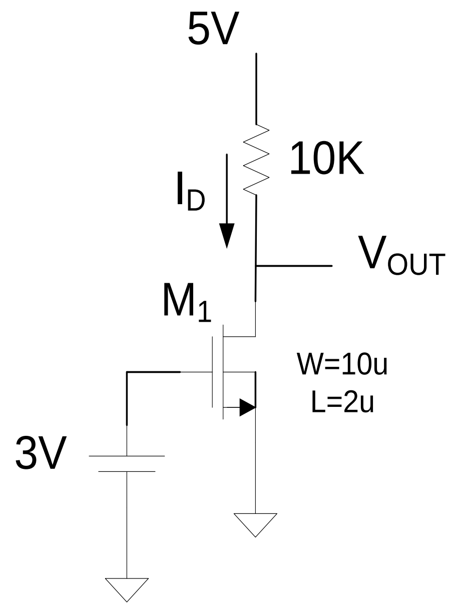


Solution:

Since $V_{GS}>V_T$, M_1 is operating in either saturation or triode region

Strategy will be to guess region of operation, solve, and then verify region

Example: Determine the output voltage for the following circuit using the square-law model of the MOSFET. Assume V_T=1V and μC_{OX}=100μAV^{-2}



Solution:

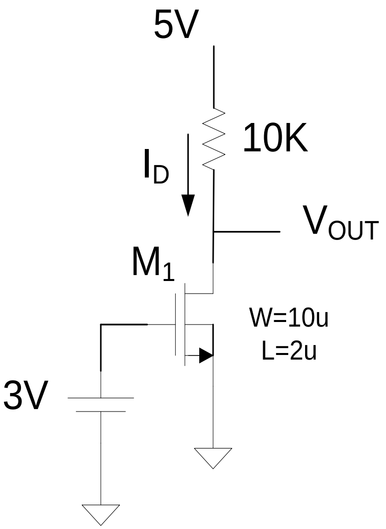
Guess M_1 in saturation

$$\left.\begin{aligned} 5V &= I_D 10K + V_{OUT} \\ I_D &= \frac{\mu C_{OX} W}{2L}(3-V_T)^2 \end{aligned}\right\}$$

Required verification: $V_{DS} > V_{GS} - V_T$

Can eliminate I_D between these 2 equations to obtain V_{OUT}

Example: Determine the output voltage for the following circuit using the square-law model of the MOSFET. Assume V_T=1V and μC_{OX}=100μAV^{-2}



Guess M_1 in saturation

Required verification: $V_{DS}>V_{GS}-V_T$

$$\left.\begin{aligned} 5V &= I_D 10K + V_{OUT} \\ I_D &= \frac{\mu C_{OX} W}{2L}(3-V_T)^2 \end{aligned}\right\}$$

$$V_{OUT} = 5V - 10K\left[\frac{100\mu AV^{-2}10\mu}{2 \bullet 2\mu}(2V)^2\right]$$

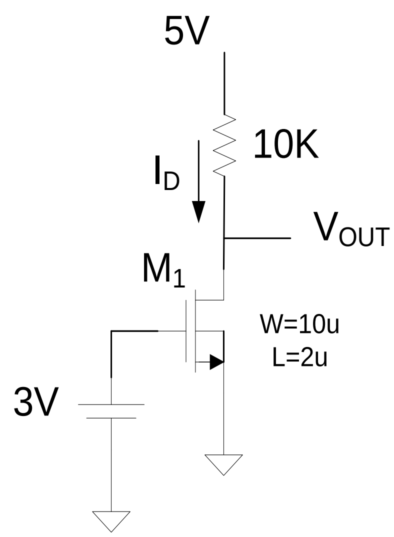
$$V_{OUT} = 5V - 10K\left[\frac{100\mu AV^{-2}10\mu}{2 \bullet 2\mu}(2V)^2\right]$$

$$V_{OUT} = -5V$$

Verification: $V_{DS}=V_{OUT}$

-5 >? 2V - - 0 No! So verification fails and Guess of region is invalid

Example: Determine the output voltage for the following circuit using the square-law model of the MOSFET. Assume V_T=1V and $\mu C_{OX}=100\mu AV^{-2}$



Guess M_1 in triode

Required verification: $V_{DS}<V_{GS}-V_T$

$$\left.\begin{aligned} &5V = I_D 10K + V_{OUT} \\ &I_D = \frac{\mu C_{OX} W}{L}\left(3\text{-}V_T - \frac{V_{DS}}{2}\right)V_{DS} \end{aligned}\right\}$$

$$V_{OUT} = 5V\text{-}10K\left[\frac{100\mu AV^{-2} 10\mu}{2\mu}\left(2V\text{-}\frac{V_{OUT}}{2}\right)V_{OUT}\right]$$

$$V_{OUT} = 5V\text{-}\left[5\left(2V\text{-}\frac{V_{OUT}}{2}\right)V_{OUT}\right]$$

Solving for V_{OUT}, obtain

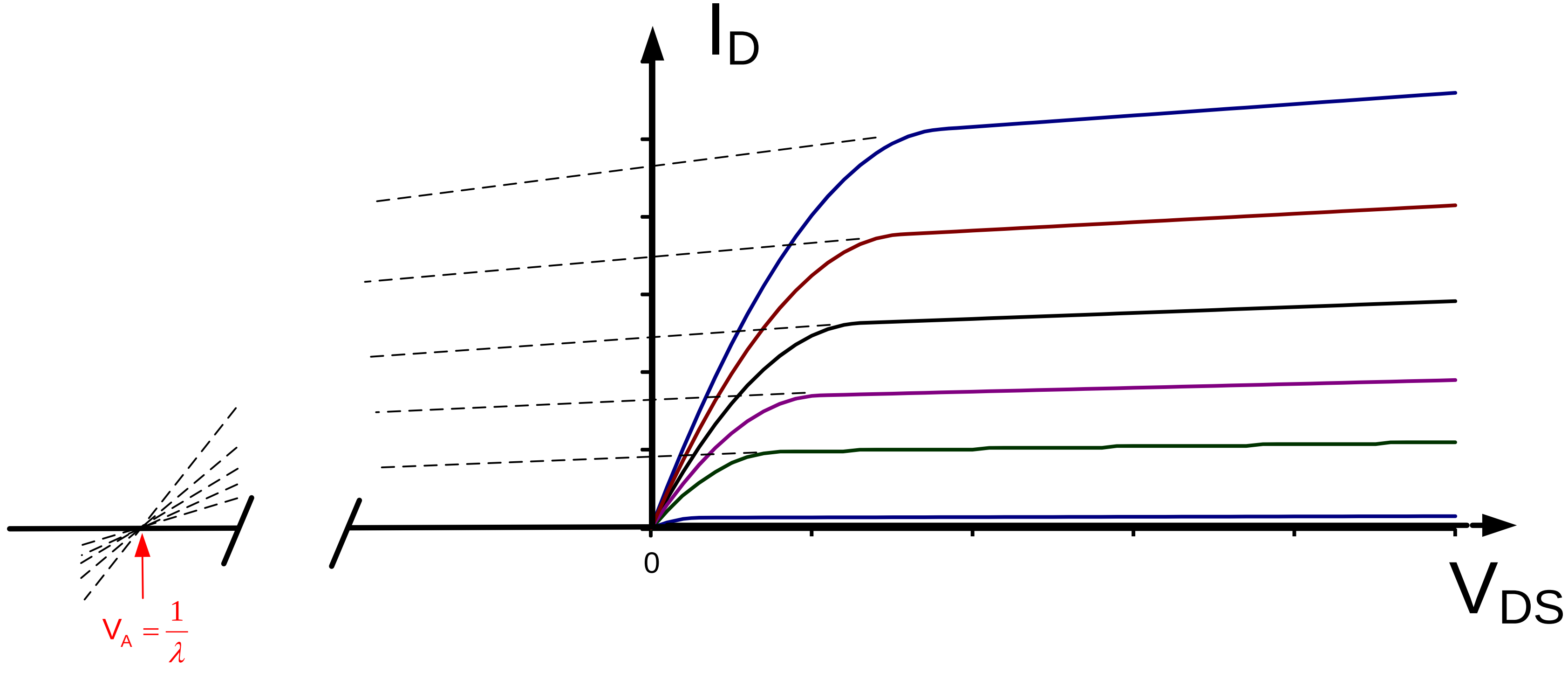
$$V_{OUT} = 0.515V$$

Verification: $V_{DS}=V_{OUT}$

0.515 <? 2V - - 0 Yes! So verification succeeds and triode region is valid

$$V_{OUT} = 0.515V$$

Model Extensions

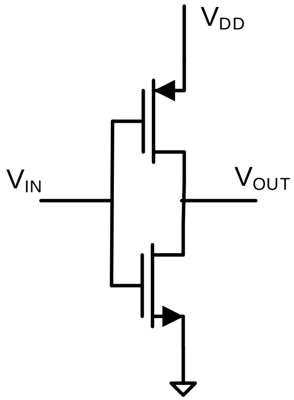


Projections intersect $-V_{DS}$ axis at same point, termed Early Voltage

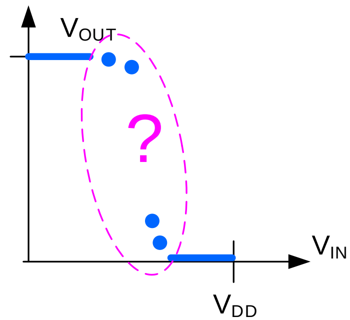
Typical values from -20V to -200V

Usually use parameter λ instead of V_A in MOS model

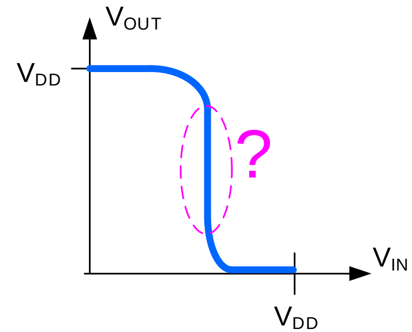
Limitations of Existing Models



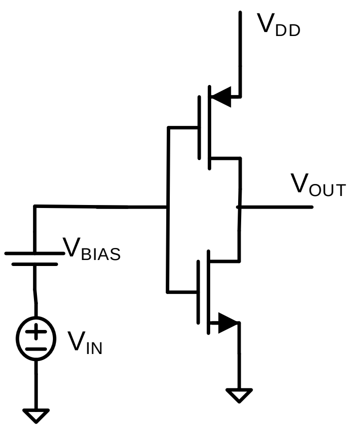
Logic Gate



Switch-Level Models



Simple square-law Model



Voltage Amplifier

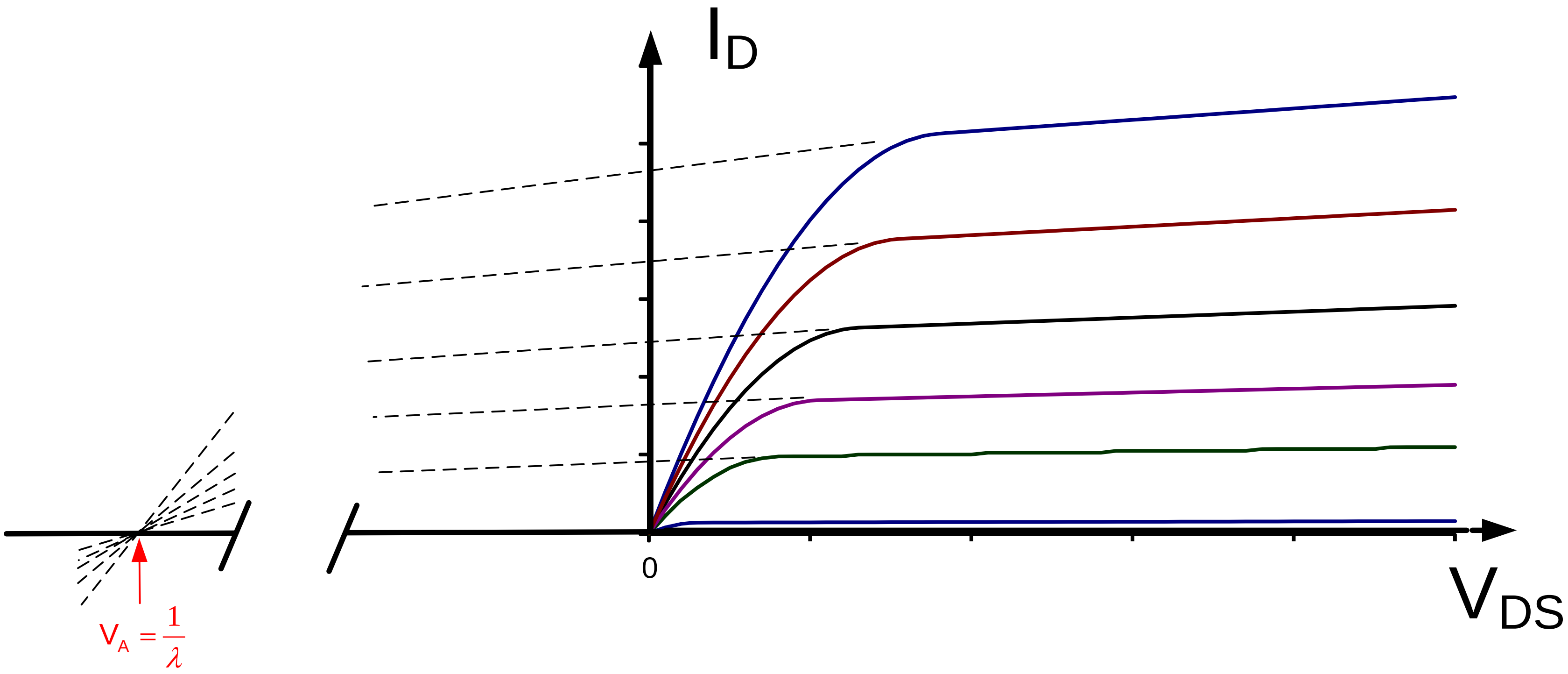
Switch-Level Models

Simple square-law Model }

Voltage Gain

Input/Output Relationship ?

Model Extensions



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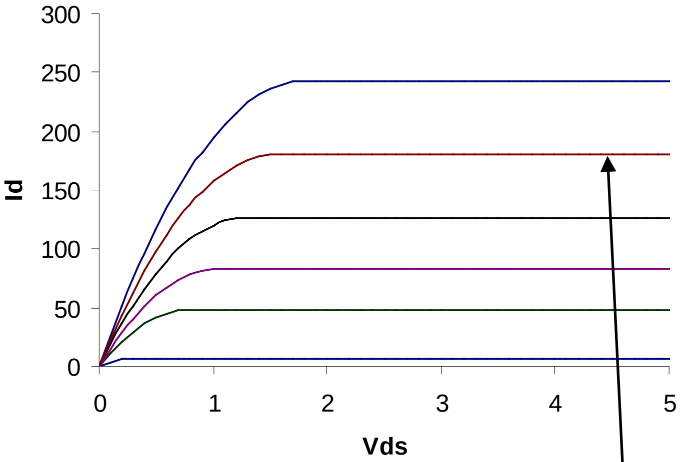
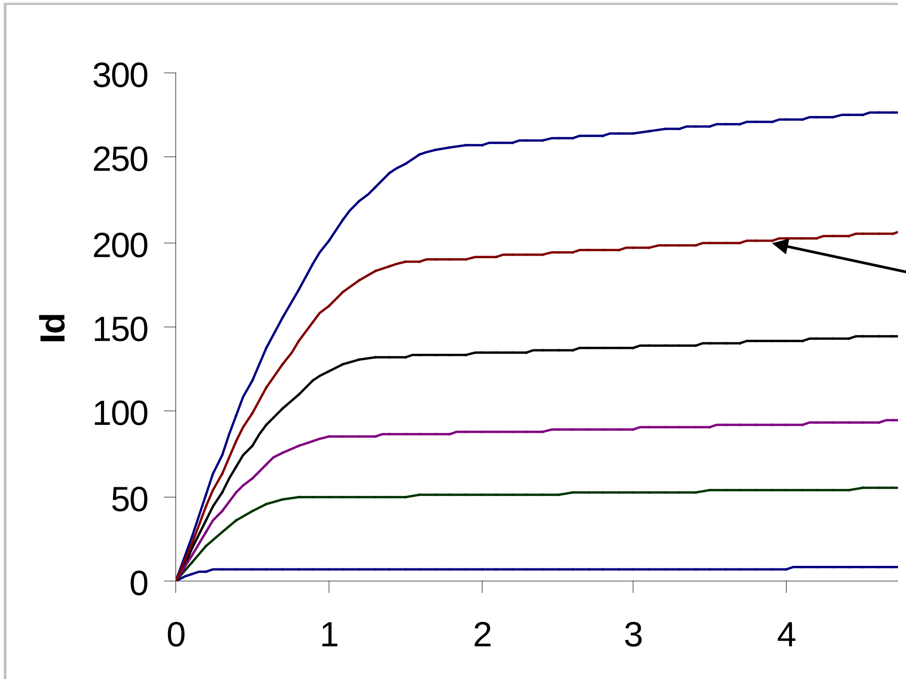
Model Extensions



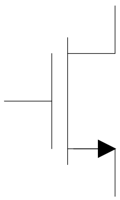
Existing Model

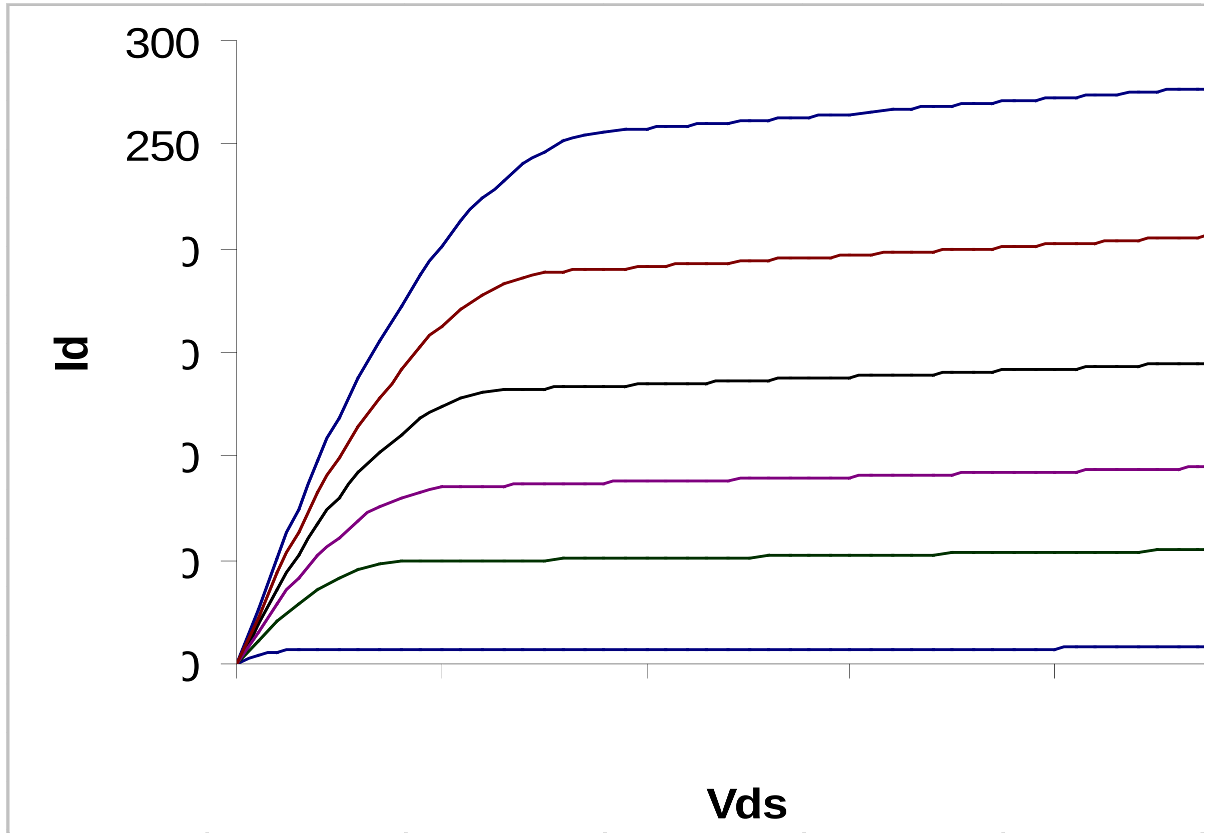


Actual Device

Slope is not 0

Model Extensions





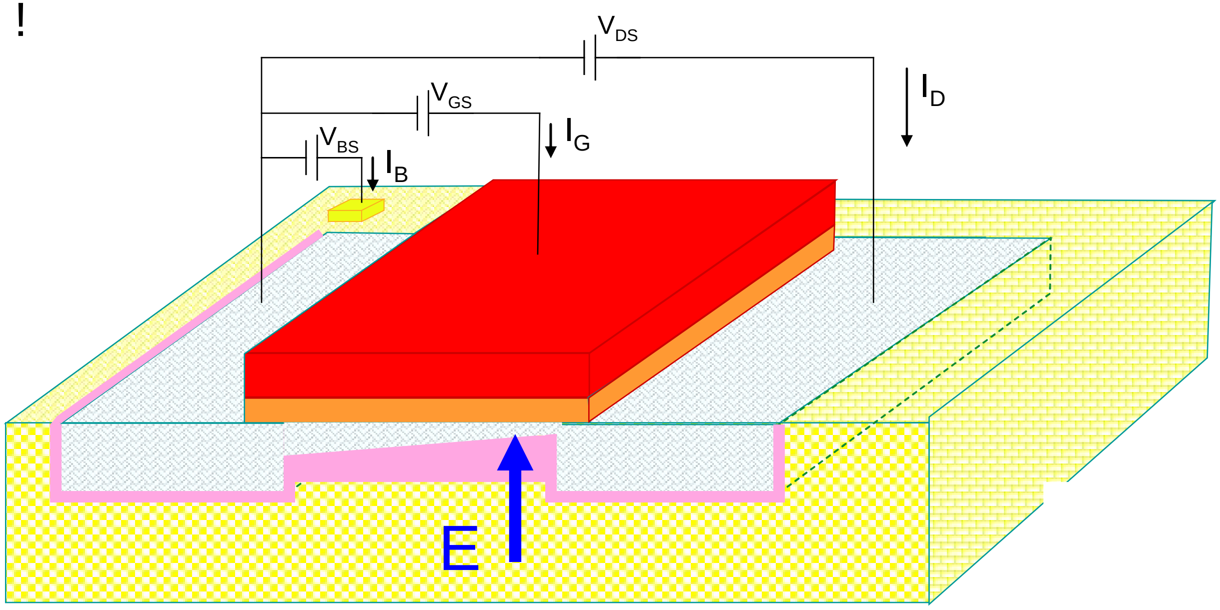
$$
I_D = \begin{cases} 0 & V_{GS} \le V_T \\ \mu C_{OX} \dfrac{W}{L}\left(V_{GS} - V_T - \dfrac{V_{DS}}{2}\right)V_{DS} & V_{GS} \ge V_T \quad V_{DS} < V_{GS} - V_T \\ \mu C_{OX} \dfrac{W}{2L}(V_{GS} - V_T)^2 \bullet (1 + \lambda V_{DS}) & V_{GS} \ge V_T \quad V_{DS} \ge V_{GS} - V_T \end{cases}
$$

Note: This introduces small discontinuity (not shown) in model at SAT/Triode transition

Further Model Extensions

Existing model does not depend upon the bulk voltage !

Observe that changing the bulk voltage will change the electric field in the channel region !



Further Model Extensions

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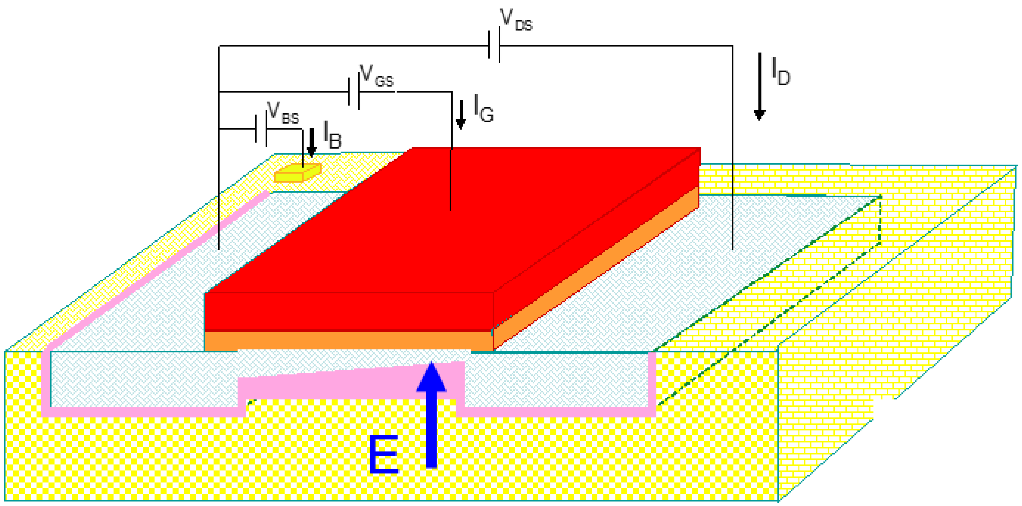
Observe that changing the bulk voltage will change the electric field in the channel region !



Changing the bulk voltage will change the thickness of the inversion layer

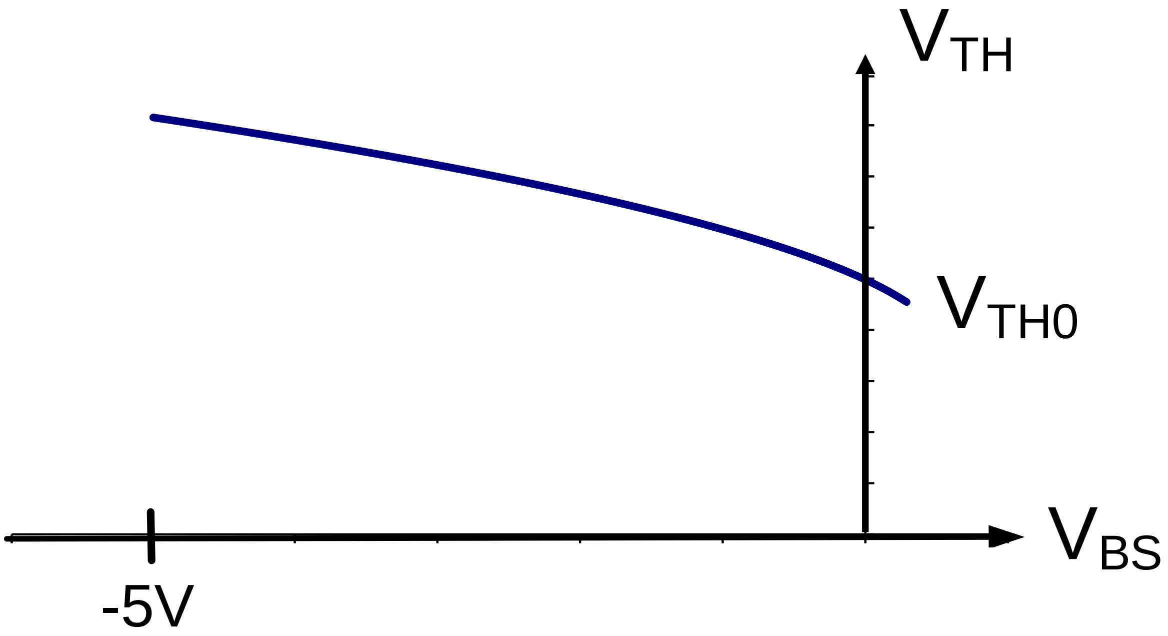
Changing the bulk voltage will change the threshold voltage of the device

$$V_T = V_{T0} + \gamma\left(\sqrt{\phi - V_{BS}} - \sqrt{\phi}\right)$$

Typical Bulk Effects on Threshold Voltage for n-channel Devices

$$V_{TH}=V_{TH0}+\gamma\left(\sqrt{\phi-V_{BS}}-\sqrt{\phi}\right)$$

$$\gamma \cong 0.4V^{1/2} \qquad \phi \cong 0.6V$$

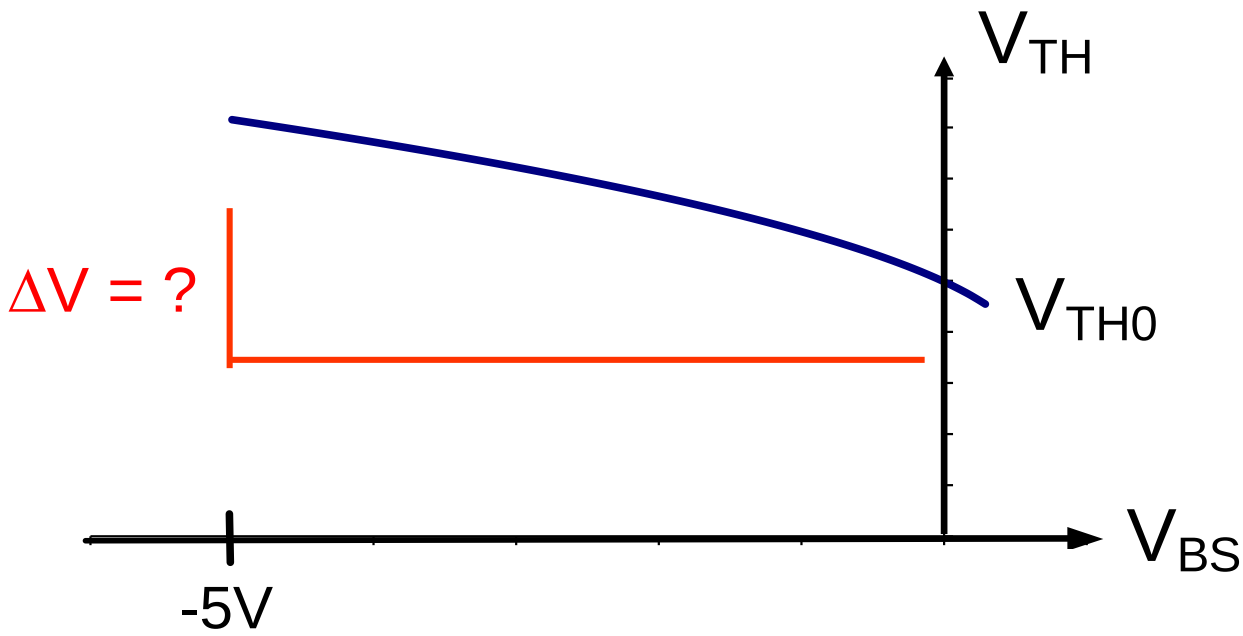


- Bulk-Diffusion Generally Reverse Biased (V_{BS}<0 or at least V_{BS}<0.3V) for n-channel
- Shift in threshold voltage with bulk voltage can be substantial
- Often $V_{BS}=0$

Typical Bulk Effects on Threshold Voltage for n-channel Devices

$$V_{TH}=V_{TH0}+\gamma\left(\sqrt{\phi-V_{BS}}-\sqrt{\phi}\right)$$

$$\gamma \cong 0.4V^{1/2} \qquad \phi \cong 0.6V$$



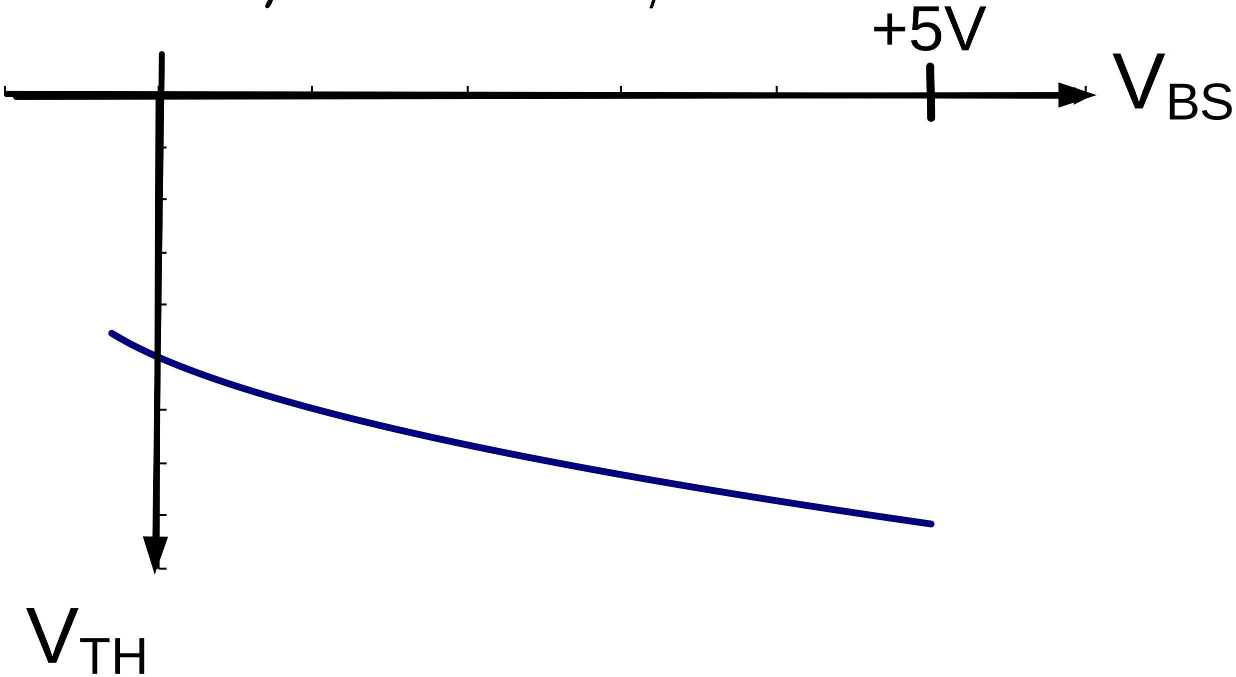
$$\Delta V=V_{TH}-V_{TH0}=\gamma\left(\sqrt{\phi-V_{BS}}-\sqrt{\phi}\right)$$

$$\Delta V \cong 0.4\left(\sqrt{0.6V--5V}-\sqrt{0.6}\right)\cong 0.64V$$

Typical Bulk Effects on Threshold Voltage for p-channel Devices

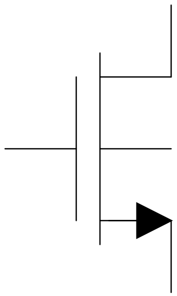
$$V_{TH}=V_{TH0}+\gamma\left(\sqrt{\phi-V_{BS}}-\sqrt{\phi}\right)$$

$$\gamma \cong 0.4V^{1/2} \qquad \phi \cong 0.6V$$



- Bulk-Diffusion Generally Reverse Biased (V_{BS}>0 or at least V_{BS}>-0.3V) for p-channel
- Same functional form as for n-channel but $V_{TH0}<0$
- Magnitude of threshold voltage increases with magnitude of reverse bias

Model Extension Summary



$$\mathbf{I_G = 0}$$

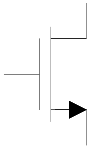
$$\mathbf{I_B = 0}$$

$$I_D = \begin{cases} 0 & V_{GS} \le V_T \\ \mu C_{OX} \dfrac{W}{L}\left(V_{GS} - V_T - \dfrac{V_{DS}}{2}\right)V_{DS} & V_{GS} \ge V_T \quad V_{DS} < V_{GS} - V_T \\ \mu C_{OX} \dfrac{W}{2L}\left(V_{GS} - V_T\right)^2 \bullet \left(1 + \lambda V_{DS}\right) & V_{GS} \ge V_T \quad V_{DS} \ge V_{GS} - V_T \end{cases}$$

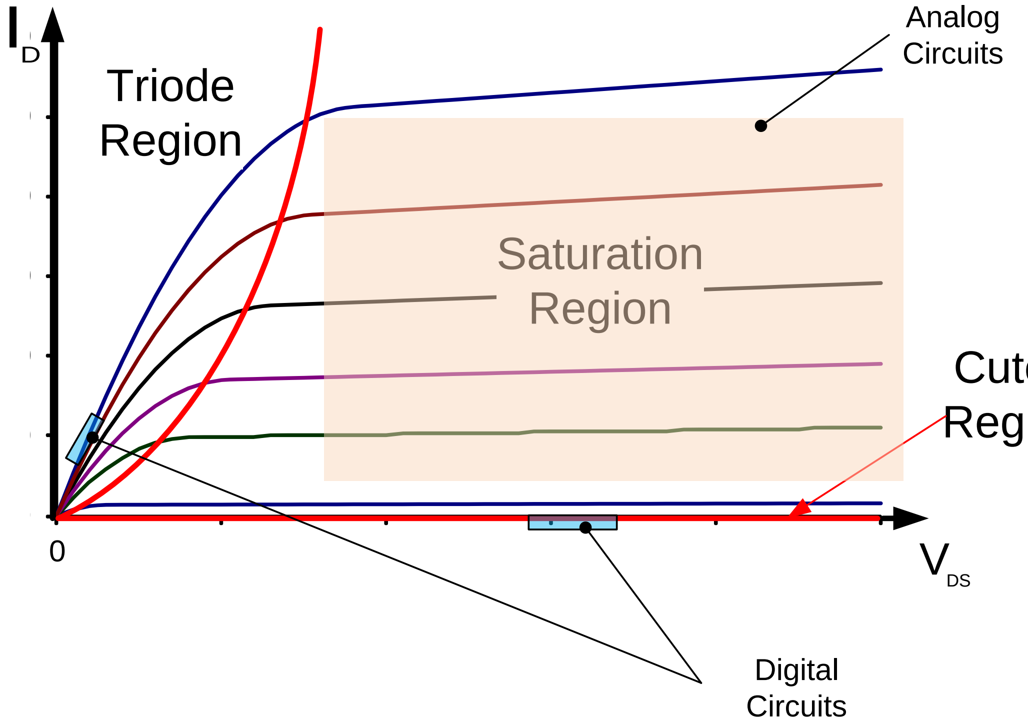
$$V_T = V_{T0} + \gamma\left(\sqrt{\phi - V_{BS}} - \sqrt{\phi}\right)$$

Model Parameters : $\{\mu, C_{OX}, V_{T0}, \varphi, \gamma, \lambda\}$

Design Parameters : $\{W,L\}$ but only one degree of freedom W/L



Operation Regions by Applications



Most analog circuits operate in the saturation region

(basic VVR operates in triode and is an exception)

Most digital circuits operate in triode and cutoff regions and switch between these two with Boolean inputs

Model Extension (short devices)

$$I_D = \begin{cases} 0 & V_{GS} \le V_T \\ \mu C_{OX} \dfrac{W}{L}\left(V_{GS} - V_T - \dfrac{V_{DS}}{2}\right)V_{DS} & V_{GS} \ge V_T \quad V_{DS} < V_{GS} - V_T \\ \mu C_{OX} \dfrac{W}{2L}\left(V_{GS} - V_T\right)^2 & V_{GS} \ge V_T \quad V_{DS} \ge V_{GS} - V_T \end{cases}$$

As the channel length becomes very short, velocity saturation will occur in the channel and this will occur with electric fields around 2V/u. So, if a gate length is around 1u, then voltages up to 2V can be applied without velocity saturation. But, if gate length decreases and voltages are kept high, velocity saturation will occur

$$I_D = \begin{cases} 0 & V_{GS} \le V_T \\ \dfrac{\theta_2}{\theta_1} \mu C_{OX} \dfrac{W}{L}\left(V_{GS} - V_T\right)^{\frac{\alpha}{2}} V_{DS} & V_{GS} \ge V_T \quad V_{DS} < \theta_1\left(V_{GS} - V_T\right)^{\frac{\alpha}{2}} \\ \theta_2 \mu C_{OX} \dfrac{W}{L}\left(V_{GS} - V_T\right)^{\alpha} & V_{GS} \ge V_T \quad V_{DS} \ge \theta_1\left(V_{GS} - V_T\right)^{\frac{\alpha}{2}} \end{cases}$$

α is the velocity saturation index, $2 \ge \alpha \ge 1$

Model Extension (short devices)

$$I_D = \begin{cases} 0 & V_{GS} \le V_T \\ \dfrac{\theta_2}{\theta_1} \mu C_{OX} \dfrac{W}{L} \left(V_{GS} - V_T\right)^{\frac{\alpha}{2}} V_{DS} & V_{GS} \ge V_T \quad V_{DS} < \theta_1 \left(V_{GS} - V_T\right)^{\frac{\alpha}{2}} \\ \theta_2 \mu C_{OX} \dfrac{W}{L} \left(V_{GS} - V_T\right)^{\alpha} & V_{GS} \ge V_T \quad V_{DS} \ge \theta_1 \left(V_{GS} - V_T\right)^{\frac{\alpha}{2}} \end{cases}$$

α is the velocity saturation index, $2 \ge \alpha \ge 1$

No longer a square-law model (some term it an α-power model)

For long devices, $\alpha=2$

Channel length modulation (λ) and bulk effects can be added to the velocity Saturation as well

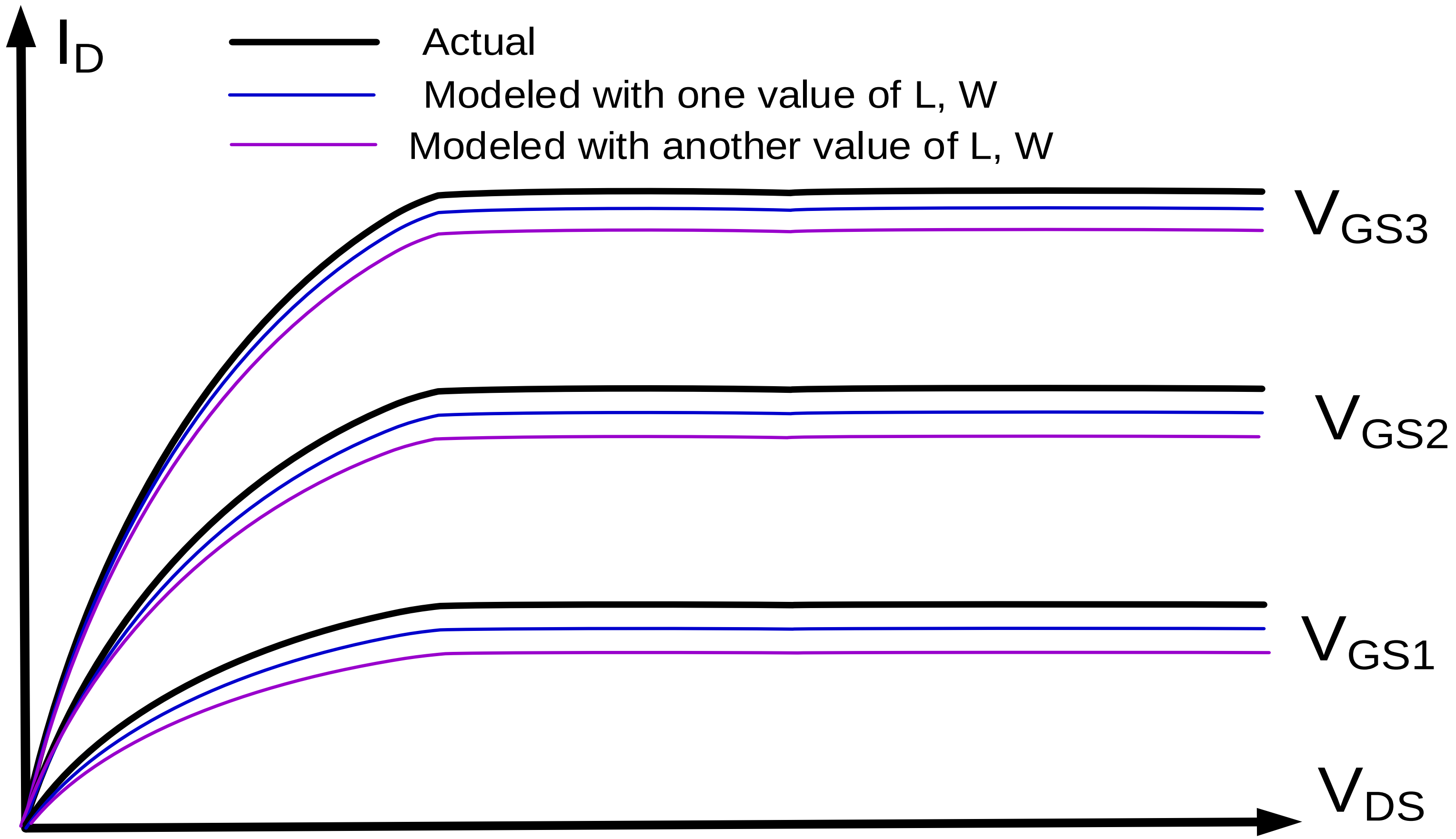
Degrading of α is not an attractive limitation of the MOSFET

Model Extension (BSIM model)

```
.MODEL CMOSN NMOS (                                LEVEL   = 49
+VERSION = 3.1            TNOM    = 27             TOX     = 1.42E-8
+XJ      = 1.5E-7         NCH     = 1.7E17         VTH0    = 0.629035
+K1      = 0.8976376      K2      = -0.09255       K3      = 24.0984767
+K3B     = -8.2369696     W0      = 1.041146E-8    NLX     = 1E-9
+DVT0W   = 0              DVT1W   = 0              DVT2W   = 0
+DVT0    = 2.7123969      DVT1    = 0.4232931      DVT2    = -0.1403765
+U0      = 451.2322004    UA      = 3.091785E-13   UB      = 1.702517E-18
+UC      = 1.22401E-11    VSAT    = 1.715884E5     A0      = 0.6580918
+AGS     = 0.130484       B0      = 2.446405E-6    B1      = 5E-6
+KETA    = -3.043349E-3   A1      = 8.18159E-7     A2      = 0.3363058
+RDSW    = 1.367055E3     PRWG    = 0.0328586      PRWB    = 0.0104806
+WR      = 1              WINT    = 2.443677E-7    LINT    = 6.999776E-8
+XL      = 1E-7           XW      = 0              DWG     = -1.256454E-8
+DWB     = 3.676235E-8    VOFF    = -1.493503E-4   NFACTOR = 1.0354201
+CIT     = 0              CDSC    = 2.4E-4         CDSCD   = 0
+CDSCB   = 0              ETA0    = 2.342963E-3    ETAB    = -1.5324E-4
+DSUB    = 0.0764123      PCLM    = 2.5941582      PDIBLC1 = 0.8187825
+PDIBLC2 = 2.366707E-3    PDIBLCB = -0.0431505     DROUT   = 0.9919348
+PSCBE1  = 6.611774E8     PSCBE2  = 3.238266E-4    PVAG    = 0

+PRT     = 0              UTE     = -1.5           KT1     = -0.11
+KT1L    = 0              KT2     = 0.022          UA1     = 4.31E-9
+UB1     = -7.61E-18      UC1     = -5.6E-11       AT      = 3.3E4
+WL      = 0              WLN     = 1              WW      = 0
+WWN     = 1              WWL     = 0              LL      = 0
+LLN     = 1              LW      = 0              LWN     = 1
+LWL     = 0              CAPMOD  = 2              XPART   = 0.5
+CGDO    = 2.32E-10       CGSO    = 2.32E-10       CGBO    = 1E-9
+CJ      = 4.282017E-4    PB      = 0.9317787      MJ      = 0.4495867
+CJSW    = 3.034055E-10   PBSW    = 0.8            MJSW    = 0.1713852
+CJSWG   = 1.64E-10       PBSWG   = 0.8            MJSWG   = 0.1713852
+CF      = 0              PVTH0   = 0.0520855      PRDSW   = 112.8875816
+PK2     = -0.0289036     WKETA   = -0.0237483     LKETA   = 1.728324E-3     )
*
```

Model Errors with Different W/L Values



Binning models can improve model accuracy

BSIM Binning Model

- Bin on device sizes
- multiple BSIM models !

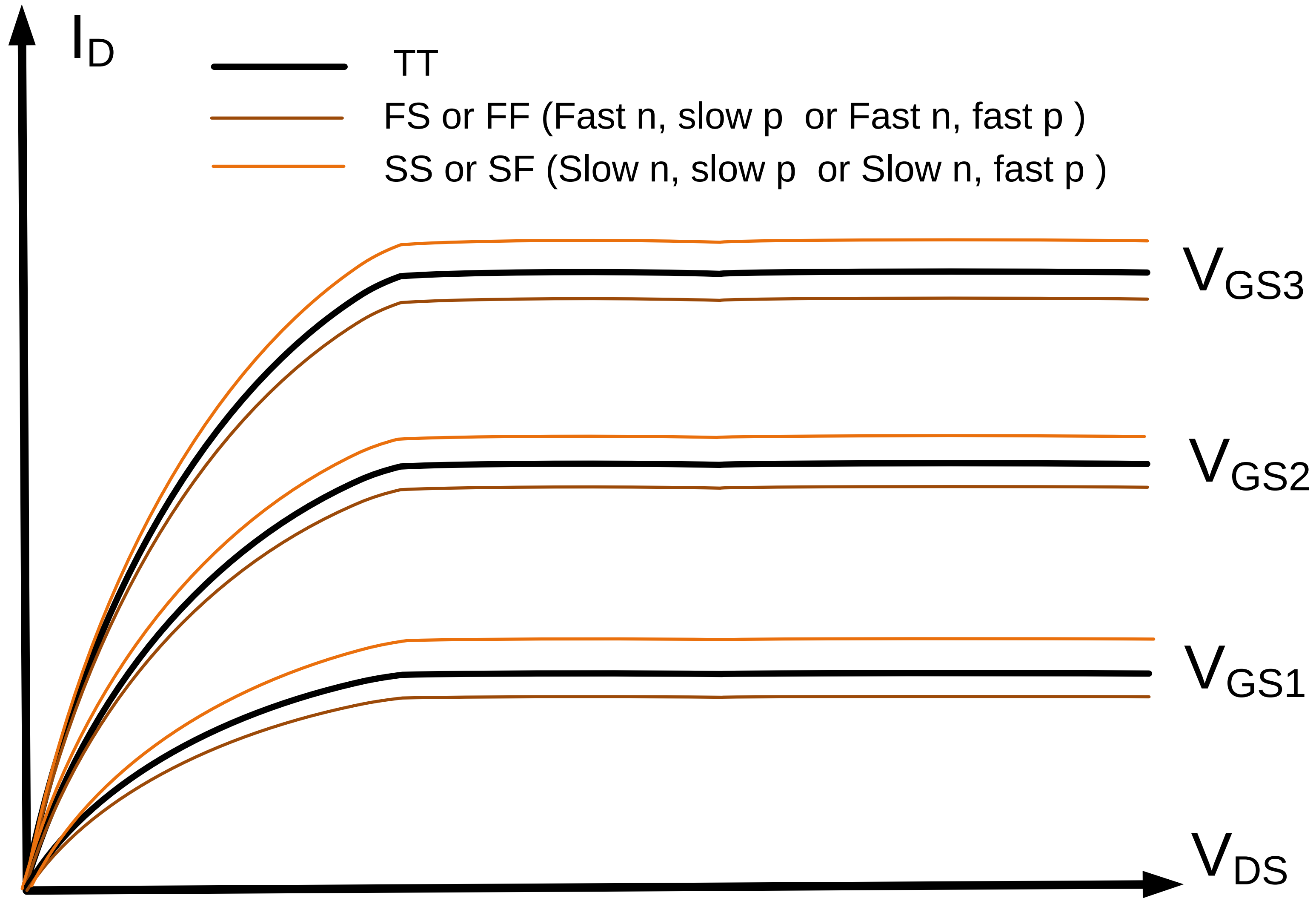
```
.MODEL CMOSN NMOS (                                     LEVEL   = 49
+VERSION = 3.1          TNOM    = 27                    TOX     = 1.42E-8
+XJ      = 1.5E-7       NCH     = 1.7E17                VTH0    = 0.629035
+K1      = 0.8976376    K2      = -0.09255              K3      = 24.0984767
+K3B     = -8.2369696   W0      = 1.041146E-8           NLX     = 1E-9
+DVT0W   = 0            DVT1W   = 0                     DVT2W   = 0
+DVT0    = 2.7123969    DVT1    = 0.4232931             DVT2    = -0.1403765
+U0      = 451.2322004  UA      = 3.091785E-13          UB      = 1.702517E-18
+UC      = 1.22401E-11  VSAT    = 1.715884E5            A0      = 0.6580918
+AGS     = 0.130484     B0      = 2.446405E-6           B1      = 5E-6
+KETA    = -3.043349E-3 A1      = 8.18159E-7            A2      = 0.3363058
+RDSW    = 1.367055E3   PRWG    = 0.0328586             PRWB    = 0.0104806
+WR      = 1            WINT    = 2.443677E-7           LINT    = 6.999776E-8
+XL      = 1E-7         XW      = 0                     DWG     = -1.256454E-8
+DWB     = 3.676235E-8  VOFF    = -1.493503E-4          NFACTOR = 1.0354201
+CIT     = 0            CDSC    = 2.4E-4                CDSCD   = 0
+CDSCB   = 0            ETA0    = 2.342963E-3           ETAB    = -1.5324E-4
+DSUB    = 0.0764123    PCLM    = 2.5941582             PDIBLC1 = 0.8187825
+PDIBLC2 = 2.366707E-3  PDIBLCB = -0.0431505            DROUT   = 0.9919348
+PSCBE1  = 6.611774E8   PSCBE2  = 3.238266E-4           PVAG    = 0

+PRT     = 0            UTE     = -1.5                  KT1     = -0.11
+KT1L    = 0            KT2     = 0.022                 UA1     = 4.31E-9
+UB1     = -7.61E-18    UC1     = -5.6E-11              AT      = 3.3E4
+WL      = 0            WLN     = 1                     WW      = 0
+WWN     = 1            WWL     = 0                     LL      = 0
+LLN     = 1            LW      = 0                     LWN     = 1
+LWL     = 0            CAPMOD  = 2                     XPART   = 0.5
+CGDO    = 2.32E-10     CGSO    = 2.32E-10              CGBO    = 1E-9
+CJ      = 4.282017E-4  PB      = 0.9317787             MJ      = 0.4495867
+CJSW    = 3.034055E-10 PBSW    = 0.8                   MJSW    = 0.1713852
+CJSWG   = 1.64E-10     PBSWG   = 0.8                   MJSWG   = 0.1713852
+CF      = 0            PVTH0   = 0.0520855             PRDSW   = 112.8875816
+PK2     = -0.0289036   WKETA   = -0.0237483            LKETA   = 1.728324E-3    )
*
```

With 32 bins, this model has 3040 model parameters !

Model Changes with Process Variations

(n-ch characteristics shown)



Corner models can improve model accuracy

BSIM Corner Models with Binning

- Often 4 corners in addition to nominal TT, FF, FS, SF, and SS

- bin on device sizes

```
.MODEL CMOSN NMOS (                                      LEVEL    = 49
+VERSION = 3.1          TNOM     = 27                    TOX      = 1.42E-8
+XJ      = 1.5E-7       NCH      = 1.7E17                VTH0     = 0.629035
+K1      = 0.8976376    K2       = -0.09255              K3       = 24.0984767
+K3B     = -8.2369696   W0       = 1.041146E-8           NLX      = 1E-9
+DVT0W   = 0            DVT1W    = 0                     DVT2W    = 0
+DVT0    = 2.7123969    DVT1     = 0.4232931             DVT2     = -0.1403765
+U0      = 451.2322004  UA       = 3.091785E-13          UB       = 1.702517E-18
+UC      = 1.22401E-11  VSAT     = 1.715884E5            A0       = 0.6580918
+AGS     = 0.130484     B0       = 2.446405E-6           B1       = 5E-6
+KETA    = -3.043349E-3 A1       = 8.18159E-7            A2       = 0.3363058
+RDSW    = 1.367055E3   PRWG     = 0.0328586             PRWB     = 0.0104806
+WR      = 1            WINT     = 2.443677E-7           LINT     = 6.999776E-8
+XL      = 1E-7         XW       = 0                     DWG      = -1.256454E-8
+DWB     = 3.676235E-8  VOFF     = -1.493503E-4          NFACTOR  = 1.0354201
+CIT     = 0            CDSC     = 2.4E-4                CDSCD    = 0
+CDSCB   = 0            ETA0     = 2.342963E-3           ETAB     = -1.5324E-4
+DSUB    = 0.0764123    PCLM     = 2.5941582             PDIBLC1  = 0.8187825
+PDIBLC2 = 2.366707E-3  PDIBLCB  = -0.0431505            DROUT    = 0.9919348
+PSCBE1  = 6.611774E8   PSCBE2   = 3.238266E-4           PVAG     = 0
+DELTA   = 0.01         RSH      = 83.5                  MOBMOD   = 1
+PRT     = 0            UTE      = -1.5                  KT1      = -0.11
+KT1L    = 0            KT2      = 0.022                 UA1      = 4.31E-9
+UB1     = -7.61E-18    UC1      = -5.6E-11              AT       = 3.3E4
+WL      = 0            WLN      = 1                     WW       = 0
+WWN     = 1            WWL      = 0                     LL       = 0
+LLN     = 1            LW       = 0                     LWN      = 1
+LWL     = 0            CAPMOD   = 2                     XPART    = 0.5
+CGDO    = 2.32E-10     CGSO     = 2.32E-10              CGBO     = 1E-9
+CJ      = 4.282017E-4  PB       = 0.9317787             MJ       = 0.4495867
+CJSW    = 3.034055E-10 PBSW     = 0.8                   MJSW     = 0.1713852
+CJSWG   = 1.64E-10     PBSWG    = 0.8                   MJSWG    = 0.1713852
+CF      = 0            PVTH0    = 0.0520855             PRDSW    = 112.8875816
+PK2     = -0.0289036   WKETA    = -0.0237483            LKETA    = 1.728324E-3     )
*
```

With 32 size bins and 4 corners, this model has 15,200 model parameters !

End of Lecture 16