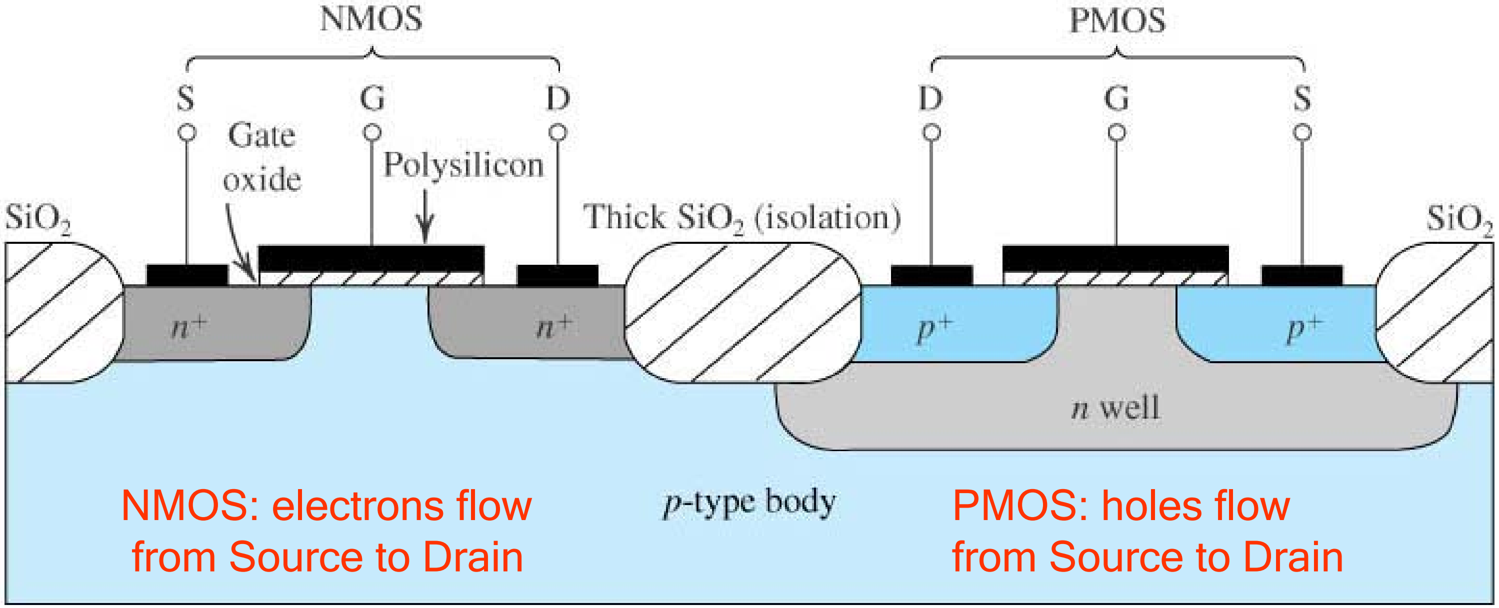
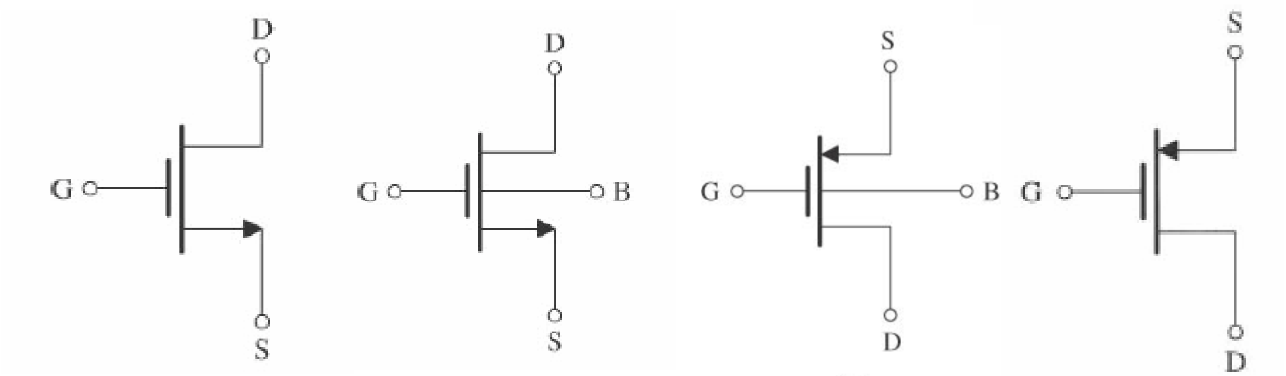
Lect. 3: MOSFET (S&S 4.1 – 4.3)



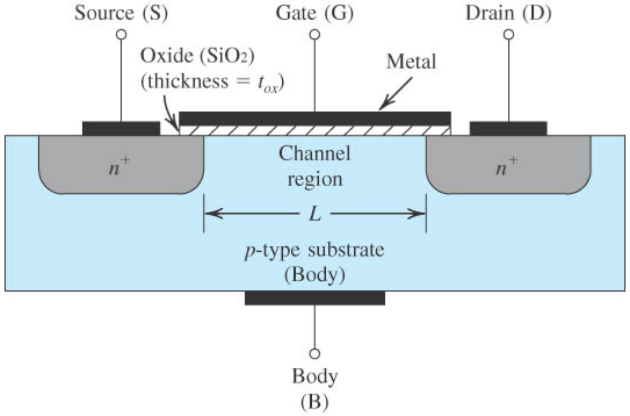
NMOS: electrons flow from Source to Drain

PMOS: holes flow from Source to Drain

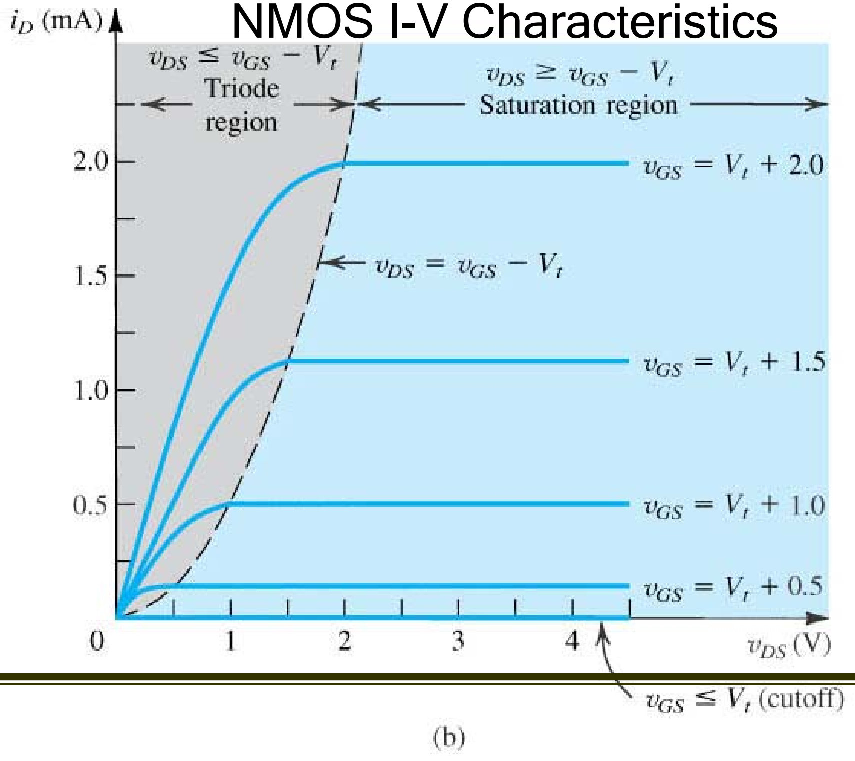


(b)

Lect. 3: MOSFET



NMOS I-V Characteristics



In cut-off $(v_{GS} < V_t),\ i_D = 0$

In triode, $(v_{GS} > V_t$ but $v_{DS} \le v_{GS} - v_T)$

$$i_D = k'\frac{W}{L}\left[(v_{GS} - V_t)\cdot v_{DS} - \frac{1}{2}{v_{DS}}^2\right]$$

In saturation $(v_{GS} > V_t$ and $v_{DS} \ge v_{GS} - v_T)$

$$i_D = \frac{1}{2}k'\frac{W}{L}(v_{GS} - V_t)^2$$

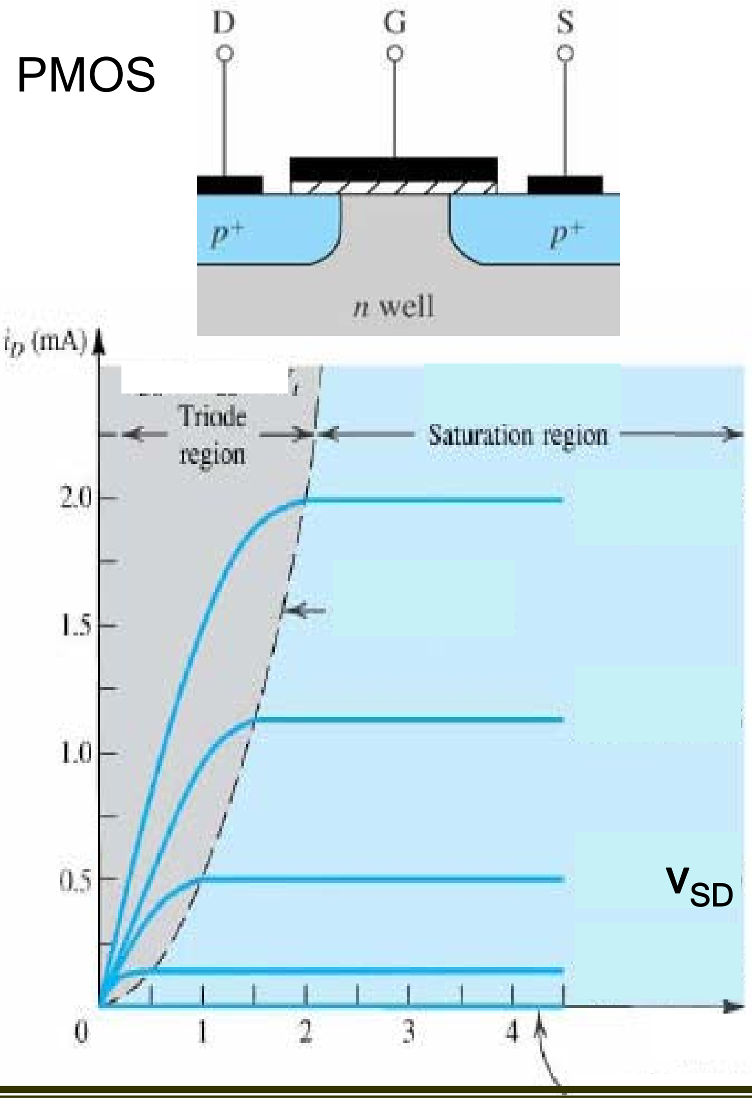
$k' = \mu_n C_{ox}$

μ_n : electron mobility

C_{ox} : oxide capacitance

V_t : threshold voltage

Lect. 3: MOSFET



$$v_{SG} < |V_t| : \ i_D = 0$$

$$v_{SG} > |V_t| \text{ and } v_{SD} < v_{SG} - |V_t| \text{ (triode)}:$$

$$i_D = \mu_p C_{ox} \frac{W}{L} \left[(v_{SG} - |V_t|) \cdot v_{SD} - \frac{1}{2} v_{SD}{}^2 \right]$$

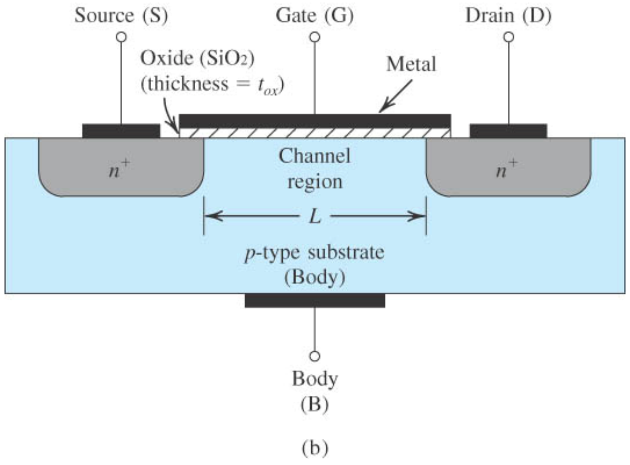
$$v_{SG} > |V_t| \text{ and } v_{SD} > v_{SG} - |V_t| \text{ (saturation)}:$$

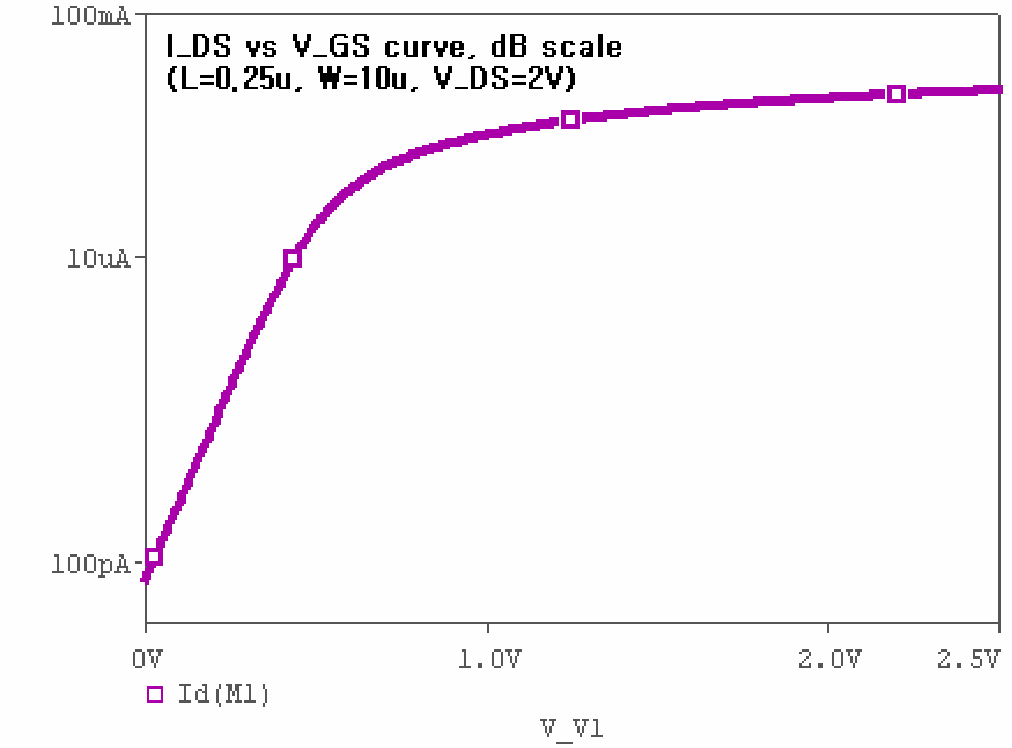
$$i_D = \frac{1}{2} \mu_p C_{ox} \frac{W}{L} (v_{SG} - |V_t|)^2$$

Lect. 3: MOSFET

Deviation from the ideal model

1) $I_D = 0$ in Cut-Off ?



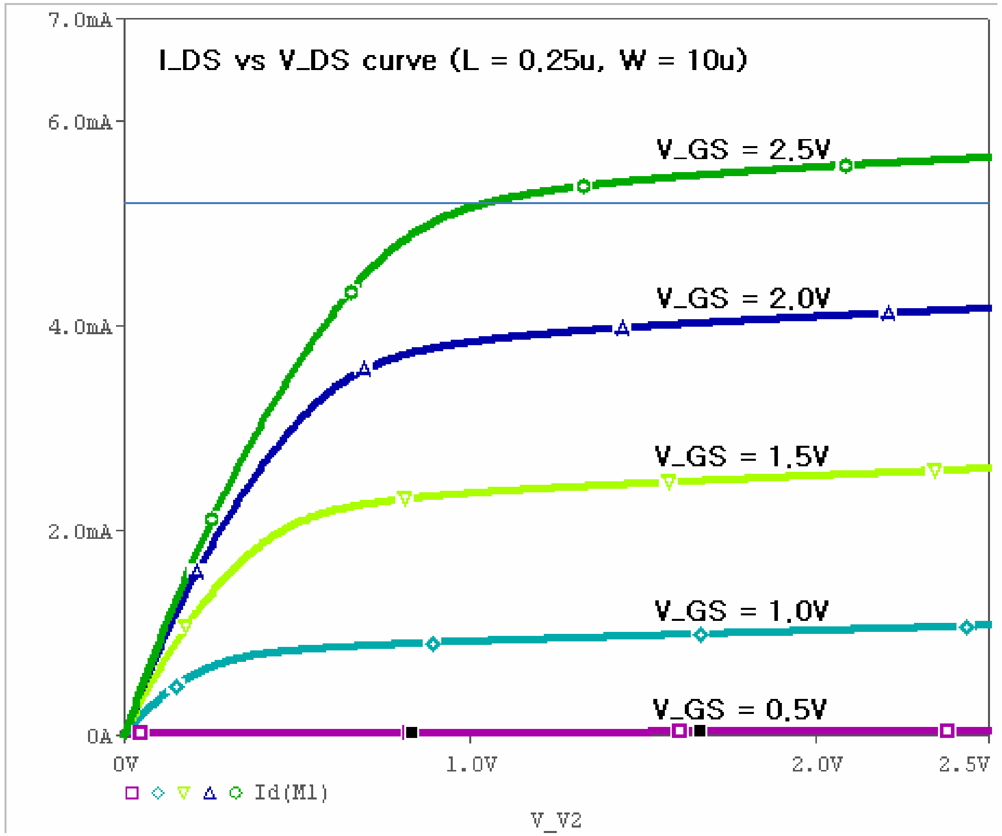


Leakage through the oxide: more significant for thinner oxide (smaller MOSFET)

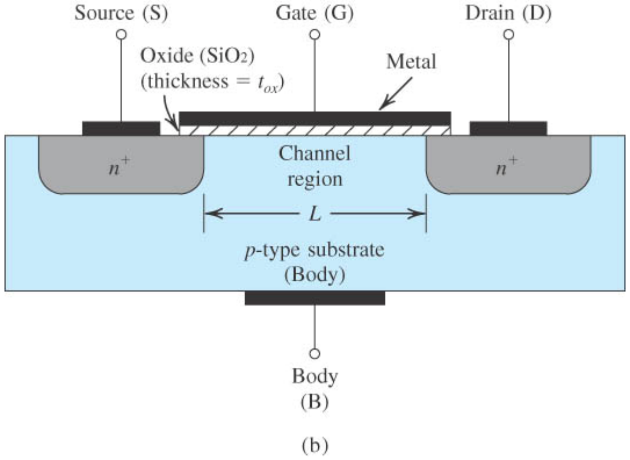
➔ Significant problem in modern digital circuits

Lect. 3: MOSFET

2) In saturation, $i_D = \frac{1}{2} k' \frac{W}{L} (v_{GS} - V_t)^2$



But I_D increases with v_{DS} even in saturation



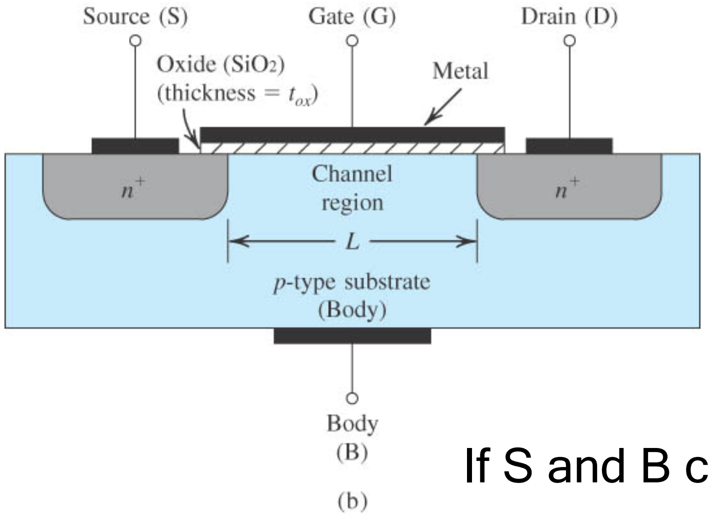
v_{DS} increase causes reduction in actual channel length.

➔ Channel length modulation.

$$i_D = \frac{1}{2} k' \frac{W}{L} (1 + \lambda \cdot v_{DS})(v_{GS} - V_t)^2$$

Lect. 3: MOSFET

3) Body effect: Voltage applied to B causes a change in threshold voltage



$$\mathbf{V}_t = \mathbf{V}_{tO} + \gamma[\sqrt{2\phi_f + \mathbf{V}_{SB}} - \sqrt{2\phi_f}]$$

$$\mathbf{V}_t = \mathbf{V}_{tO} \ \textbf{when} \ \mathbf{V}_{SB} = 0$$

ϕ_f **and** γ **process-dependent parameters**

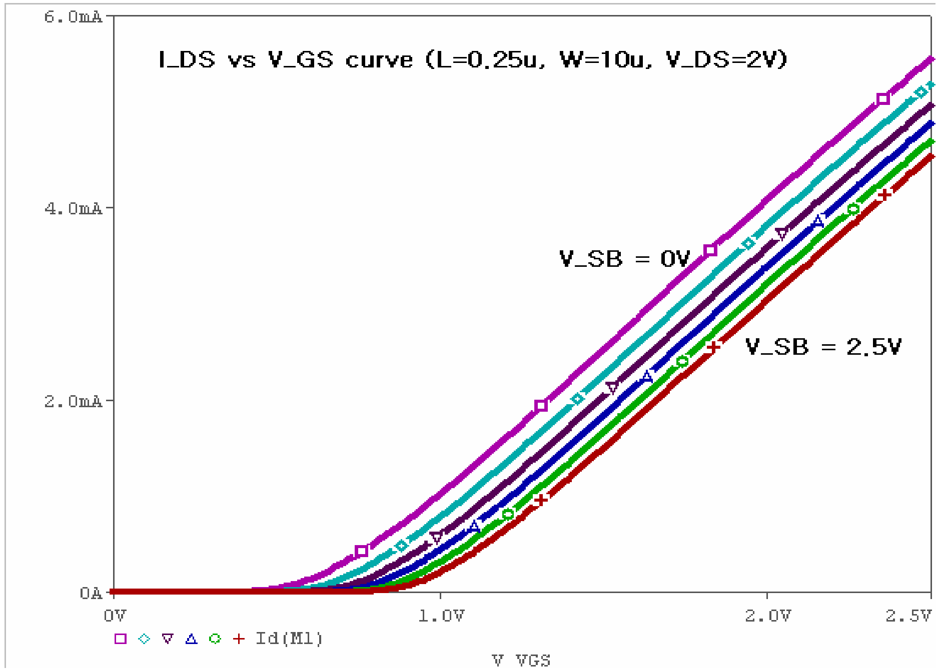
If S and B can be tied, no body effect.

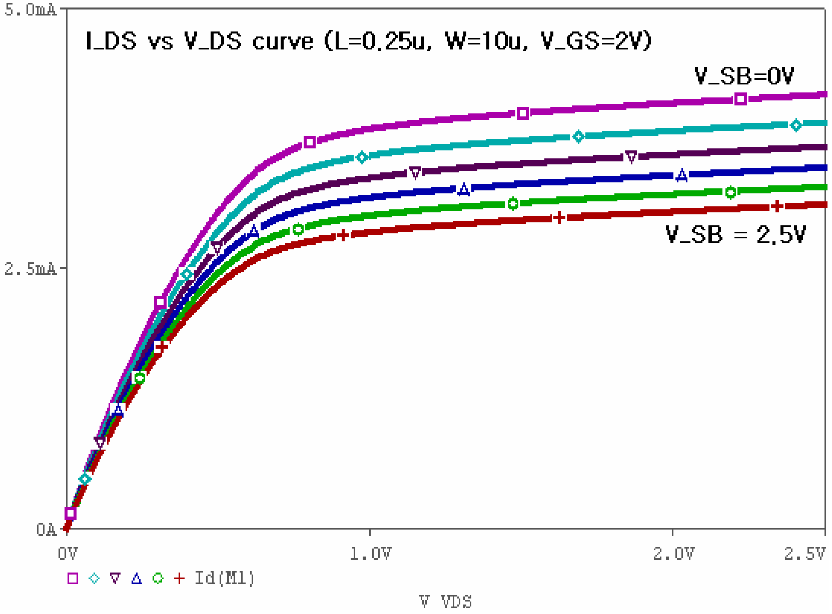
In IC, B is connected to
- the most negative supply voltage (NMOS)
- the most positive supply voltage (PMOS)

➔ V_t depends on V_S

Lect. 3: MOSFET

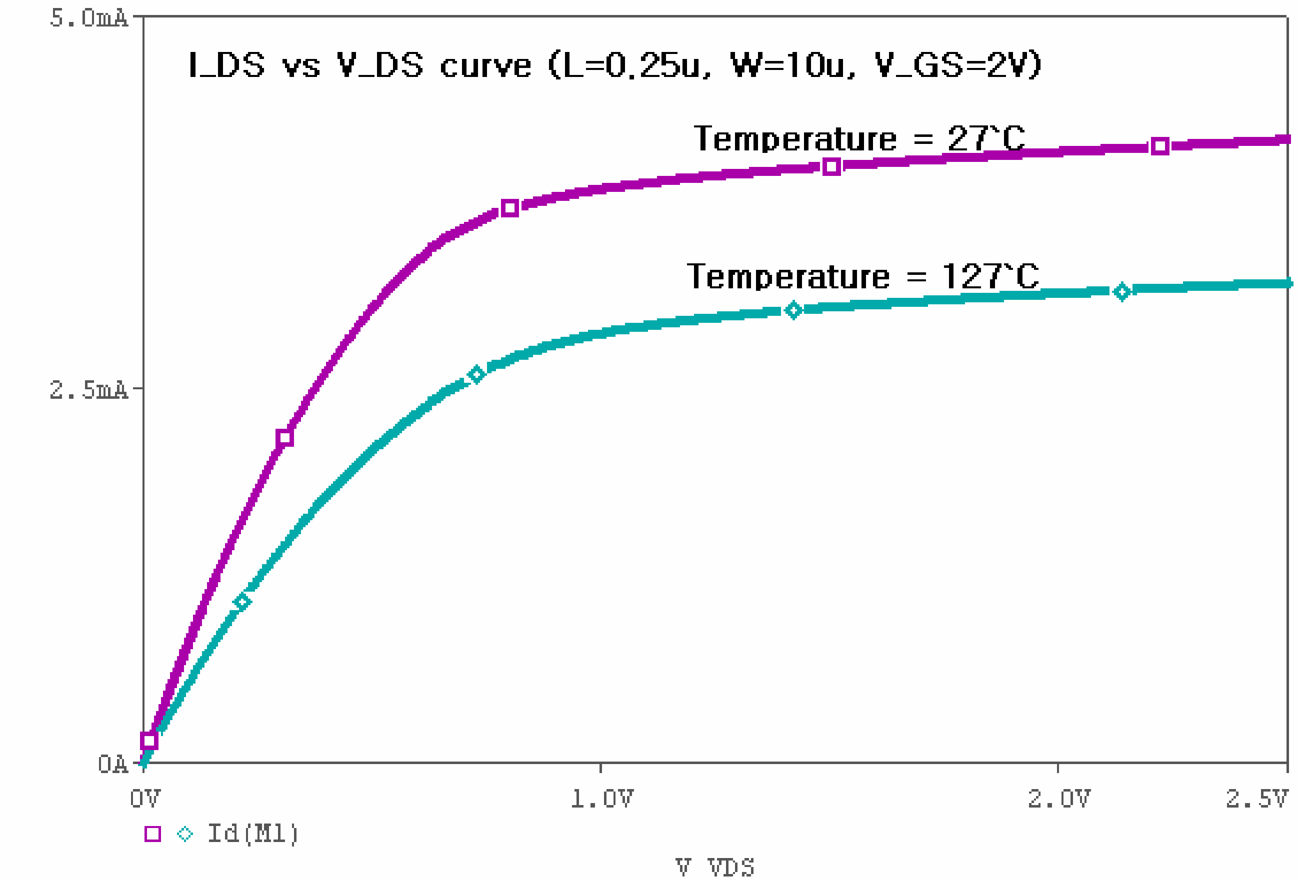
Body effect: Voltage applied to B causes a change in threshold voltage.





Lect. 3: MOSFET

4) Temperature effect: Many MOSFET parameters are temperature dependent



Higher temperature causes reduction in I_D

Lect. 3: MOSFET

- Modern transistors are very complicated in their structure.

- Many parameters are needed to model their characteristics accurately in SPICE

- SPICE parameters for 0.25μm NMOS are shown

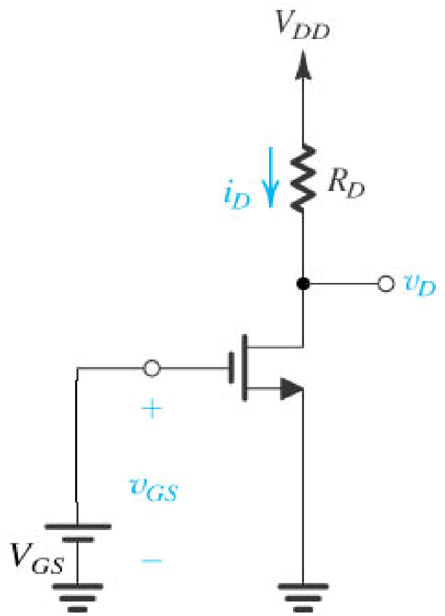
- For detailed explanations, See *MOSFET Users' Manual* at *www-device.eecs.berkeley.edu/~bsim3/get.html*

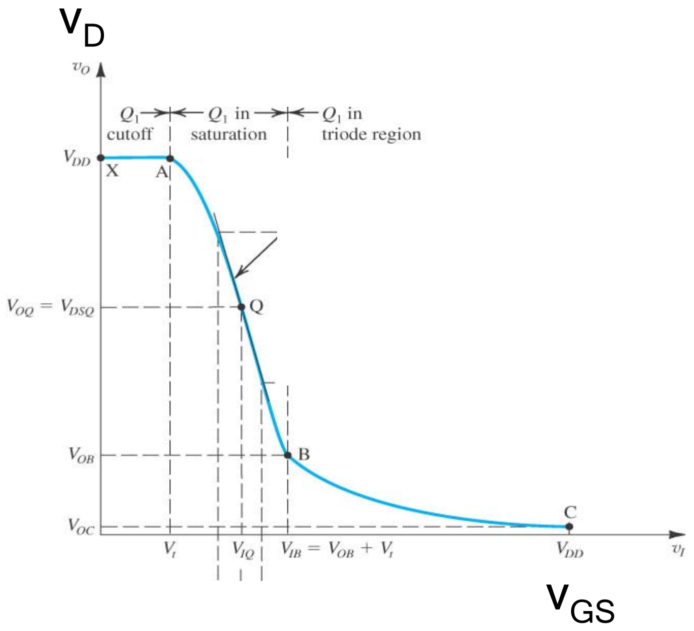
➔ Although complicated, they can precisely model the transistor characteristics and accurate circuit design is possible

```
MODEL orbit2L2N NMOS (                         LEVEL   = 7
+TNOM    = 27             TOX     = 5.6E-9
+XJ      = 1E-7          NCH     = 2.3549E17     VTH0    = 0.3654765
+K1      = 0.4732214      K2      = 7.994532E-4   K3      = 1E-3
+K3B     = 3.0713494      W0      = 1E-7          NLX     = 1.617898E-7
+DVT0W   = 0             DVT1W   = 0            DVT2W   = 0
+DVT0    = 0.455178       DVT1    = 0.6258687     DVT2    = -0.5
+U0      = 280.4589023   UA      = -1.607126E-9  UB      = 2.806549E-18
+UC      = 3.290051E-11  VSAT    = 1.07496E5     A0      = 1.8770435
+AGS     = 0.3310181      B0      = -3.173524E-8  B1      = -1E-7
+KETA    = -8.69841E-3    A1      = 8.317145E-5   A2      = 0.6592347
+RDSW    = 200           PRWG    = 0.4477477     PRWB    = 0.0208175
+WR      = 1             WINT    = 0            LINT    = 1.392558E-10
+DWG     = -2.28419E-8
+DWB     = -6.95781E-10  VOFF    = -0.0910963    NFACTOR = 1.202941
+CIT     = 0             CDSC    = 2.4E-4        CDSCD   = 0
+CDSCB   = 0             ETA0    = 5.0732E-3     ETAB    = 6.262008E-5
+DSUB    = 0.0310034      PCLM    = 1.5101091     PDIBLC1 = 0.897659
+PDIBLC2 = 2.924029E-3   PDIBLCB = 0.0651312     DROUT   = 1
+PSCBE1  = 7.017738E8    PSCBE2  = 2.271109E-4   PVAG    = 8.531511E-3
+DELTA   = 0.01          RSH     = 4.6           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    = 4.59E-10       CGSO    = 4.59E-10      CGBO    = 5E-10
+CJ      = 1.78338E-3     PB      = 0.99          MJ      = 0.4661295
+CJSW    = 4.154041E-10  PBSW    = 0.9563049     MJSW    = 0.3162462
+CF      = 0             PVTH0   = -9.648921E-3  PRDSW   = -10
+PK2     = 3.534961E-3   WKETA   = 0.0120981     LKETA   = -3.31688E-3    )
```

Lect. 3: MOSFET

Linearization of MOSFET: ➔ Small-signal circuit





(c)

Lect. 3: MOSFET

Small signal model for NMOS

$v_{GS}=V_{GS} + v_{gs}$, $v_{DS}=V_{DS} + v_{ds}$

$i_G = I_G + i_g$, $i_D=I_D + i_d$

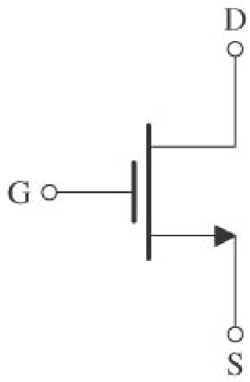
➔i_g, i_d as functions of v_{gs}, d_{vs}

$$i_g = 0$$

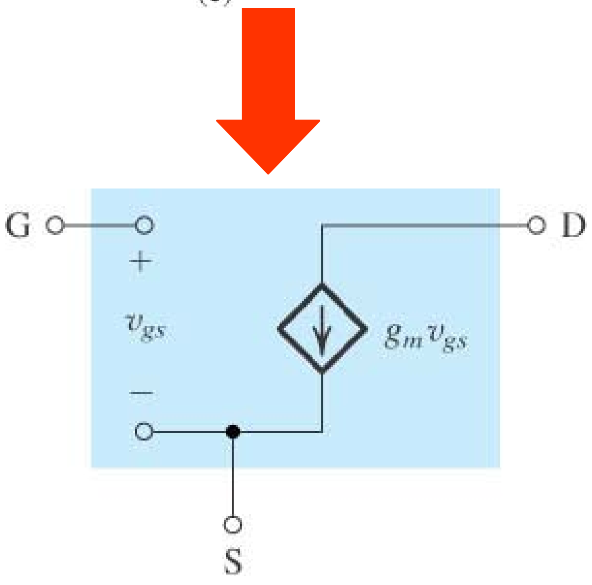
$$\text{From } i_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(v_{GS}-V_T)^2 \text{ with } v_{GS} = V_{GS} + v_{gs}$$

$$i_D \simeq \left[\frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_T)\right]^2 + \frac{di_D}{dv_{GS}}\Big|_{V_{GS}} \cdot v_{gs}$$

$$\therefore i_d = \mu_n C_{ox}\frac{W}{L}(V_{GS}-V_T)\cdot v_{gs} = g_m \cdot v_{gs}$$

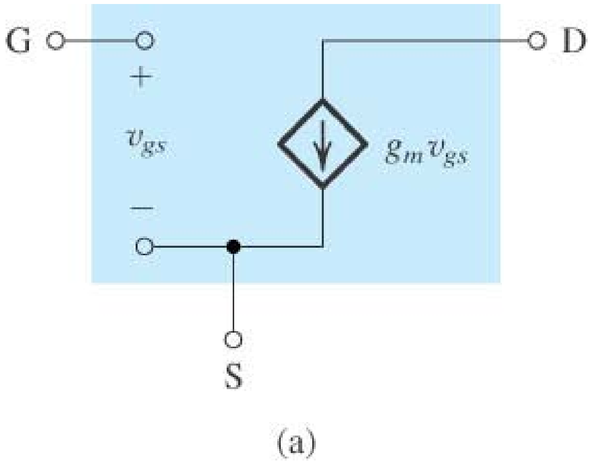


(c)



(a)

Lect. 3: MOSFET



Various expressions for g_m

$$\text{From } i_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(v_{GS} - V_T)^2$$

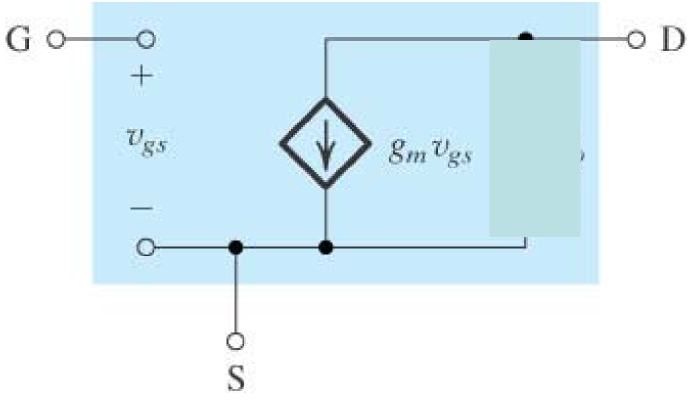
$$g_m = \frac{di_D}{dv_{GS}}\Big|_{V_{GS}} = \mu_n C_{ox}\frac{W}{L}(V_{GS} - V_T)$$

$$= \frac{2I_D}{V_{GS} - V_T}$$

$$= \sqrt{2\mu_n C_{ox}\cdot\frac{W}{L}\cdot I_D}$$

Lect. 3: MOSFET

Small-signal model including channel-length modulation



(b)

$$i_D = \frac{1}{2} k' \frac{W}{L} (1 + \lambda \cdot v_{DS})(v_{GS} - V_t)^2$$

$$\Delta i_D = \frac{\partial i_D}{\partial v_{GS}} \cdot \Delta v_{GS} + \frac{\partial i_D}{\partial v_{DS}} \cdot \Delta v_{DS}$$

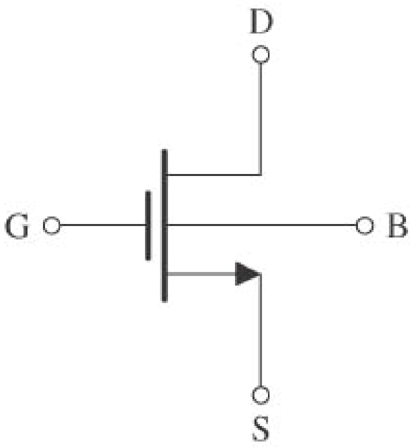
$$\frac{\partial i_D}{\partial v_{GS}} = g_m$$

$$i_d = g_m \cdot v_{gs} + \frac{v_{ds}}{r_0}$$

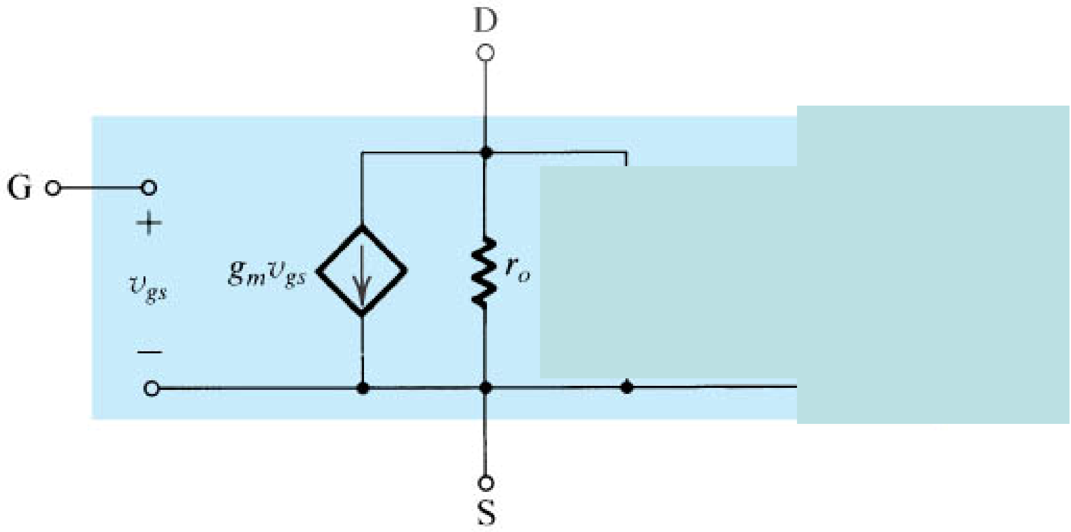
$$\frac{\partial i_D}{\partial v_{DS}} = \frac{1}{2} k' \frac{W}{L} \lambda (v_{GS} - V_t)^2 = \frac{1}{r_0} \quad \text{Often, } r_0 = \frac{V_A}{I_D}$$

Lect. 3: MOSFET

Small-signal model including Body effect



(a)



Practically, Body Effect
Is not easy to model analytically.

➔ Simulation

$$g_{mb} \equiv \left.\frac{\partial i_D}{\partial \upsilon_{BS}}\right|_{\substack{\upsilon_{GS} = \text{constant} \\ \upsilon_{DS} = \text{constant}}}$$

$$g_{mb} \equiv \chi g_m \qquad (\chi : 0.1 - 0.3)$$