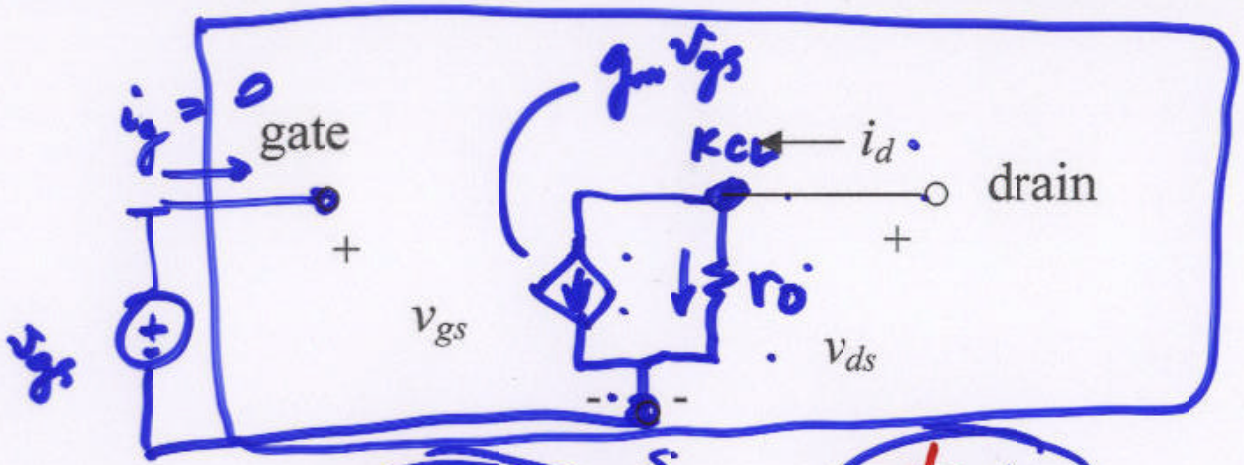
Lecture 16

- Last time:
  - MOSFET small-signal model (g_m, r_o)
- Today :
  - Complete small-signal model: add capacitors
  - P-channel MOSFET
  - MOSFET Spice Model

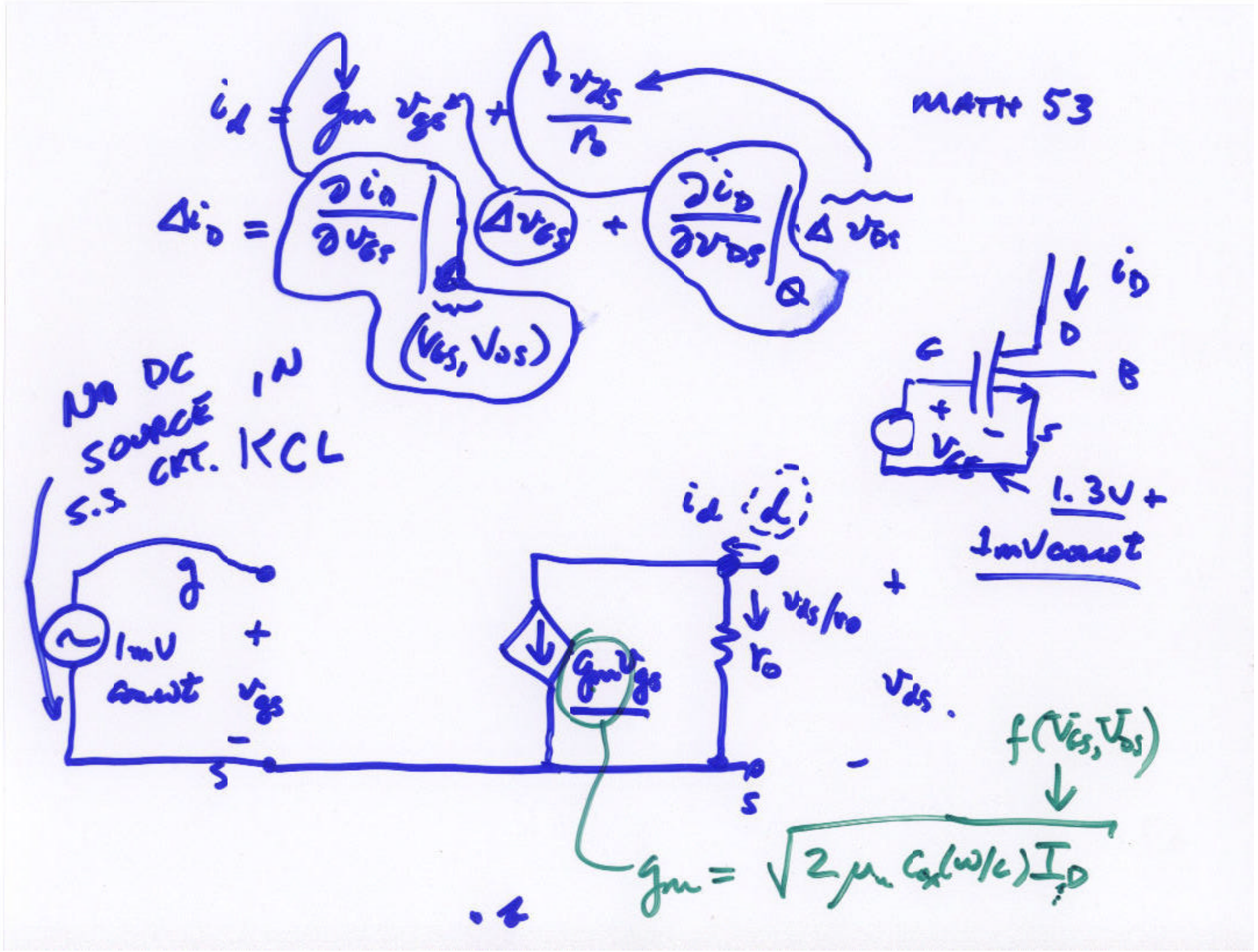
HARD.

Putting Together a Circuit Model



$$i_d = dI_D = \frac{\partial i_D}{\partial v_{GS}}\Delta v_{GS} + \frac{\partial i_D}{\partial v_{DS}}\Delta v_{DS} + (\ldots \text{LOTS OF STUFF})$$

$$r_o = \left.\frac{\Delta v_{DS}}{\Delta i_D}\right|_Q = \frac{v_{ds}}{i_d}$$ YES!!


MATH 53
$i_d = g_m v_{gs} + \frac{v_{ds}}{r_o}$
$\Delta i_D = \frac{\partial i_D}{\partial v_{GS}}\Big|_Q \Delta v_{GS} + \frac{\partial i_D}{\partial v_{DS}}\Big|_Q \Delta v_{DS}$
(V_{GS}, V_{DS})
No DC source ckt. KCL
5.3
1mV const
v_{gs}
$g_m v_{gs}$
r_o
v_{ds}/r_o
v_{ds}
i_d
i_D
D
G
B
S
+ V_{GS} -
1.3V +
1mV const
$f(V_{GS}, V_{DS})$
$g_m = \sqrt{2\mu_n C_{ox}(W/L) I_D}$

4th TERMINAL.

Role of the Substrate Potential

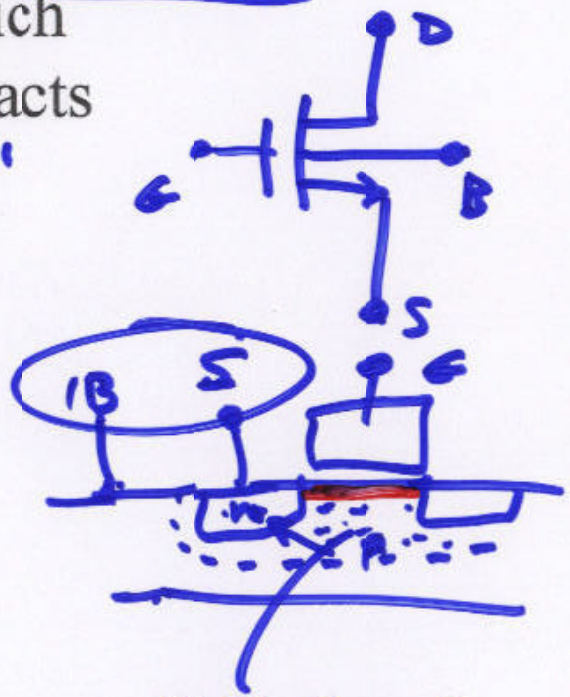
- Need not be the source potential, but $V_B < V_S$

$V_{BS} = \phi$ $V_B = V_S$ (COMMON).

Effect: changes threshold voltage, which changes the drain current … substrate acts like a "backgate" → "BOTTOM GATE" LOWER

$$g_{mb} = \left.\frac{\Delta i_D}{\Delta v_{BS}}\right|_Q = \left.\frac{\partial i_D}{\partial v_{BS}}\right|_Q$$

$$Q = (V_{GS}, V_{DS}, V_{BS})$$



DEPLETION CAPACITANCE BETWEEN B AND CHANNEL

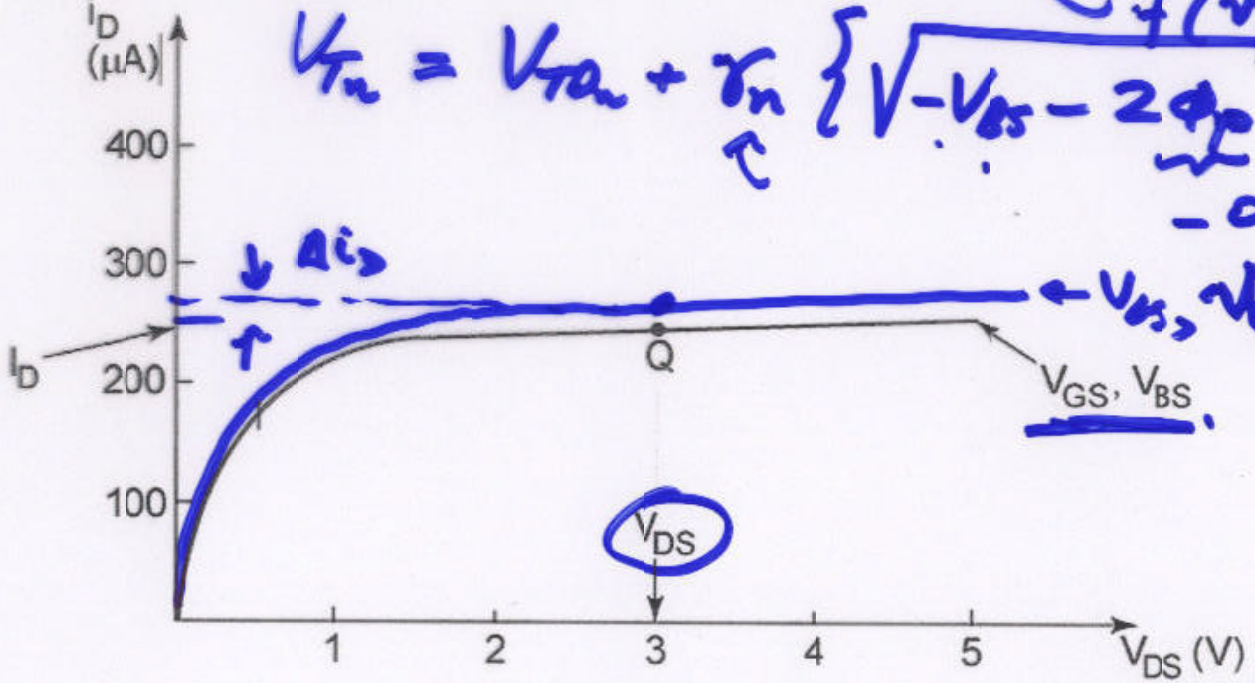
$I_D = \mu_n C_{ox} (W/2L)(v_{GS} - V_{Tn})^2 (1 + \lambda_n v_{DS})$

Backgate Transconductance

$V_{Tn} = V_{T0n} + \gamma_n \left\{ \sqrt{-V_{BS} - 2\phi_p} - \sqrt{-2\phi_p} \right\}$

$f(v_{BS})$

$-0.3 \ldots -0.4$



Δi_D

V_{GS}, V_{BS} ← $v_{GS} = V_{GS} + v_{gs}$

Result: $g_{mb} = \left.\frac{\partial i_D}{\partial v_{BS}}\right|_Q = \left.\frac{\partial i_D}{\partial V_{Tn}}\right|_Q \left.\frac{\partial V_{Tn}}{\partial v_{BS}}\right|_Q = \frac{\gamma_n g_m}{2\sqrt{-2\phi_n - V_{BS}}}$

$-g_m$

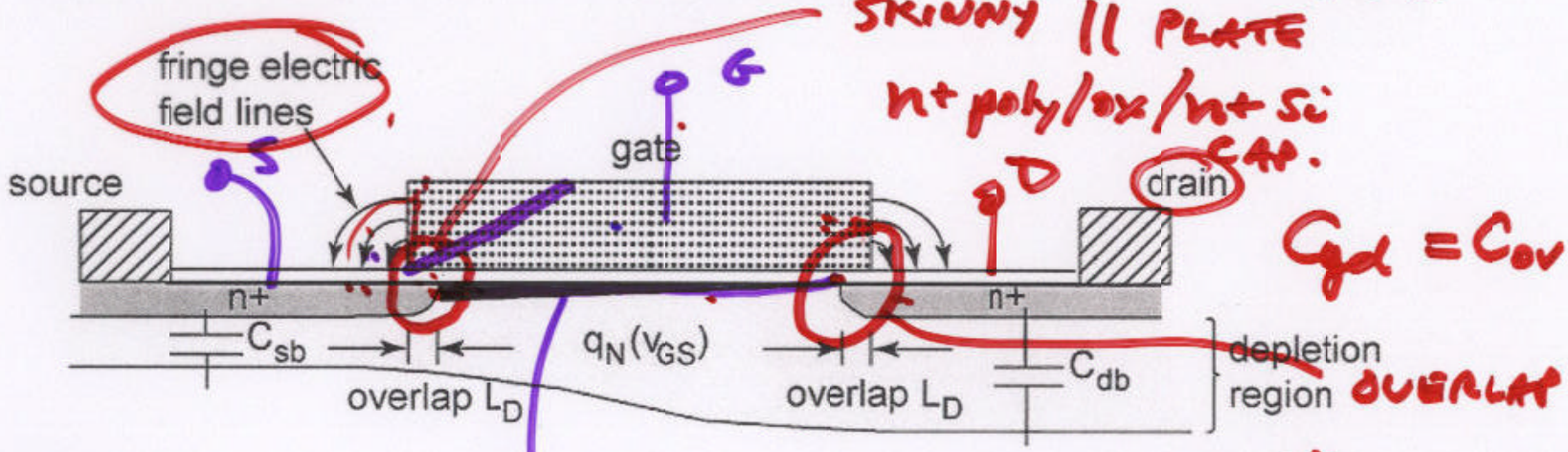
$\frac{-\gamma_n}{2\sqrt{-2\phi_n - V_{BS}}}$

MOSFET Capacitances in Saturation

C_{gs}

Gate-source capacitance: channel charge is not controlled by drain in saturation.

$\epsilon_{ox} A / t_{ox}$



SKINNY || PLATE n+ poly/ox/n+ Si CAP.

$C_{gd} = C_{ov}$

OVERLAP

$$\frac{\partial q_N}{\partial V_{GS}} = C_{ox}$$

$$q_N(V_{GS}) = C_{ox}(V_{GS} - V_{TH})$$

← no V_{DS}.

(FOR V_{DS} SMALL....

FOR SATURATION, IT'S A WEDGE)

Gate-Source Capacitance C_{gs}

Wedge-shaped charge in saturation → effective area is (2/3)WL
(see H&S 4.5.4 for details)

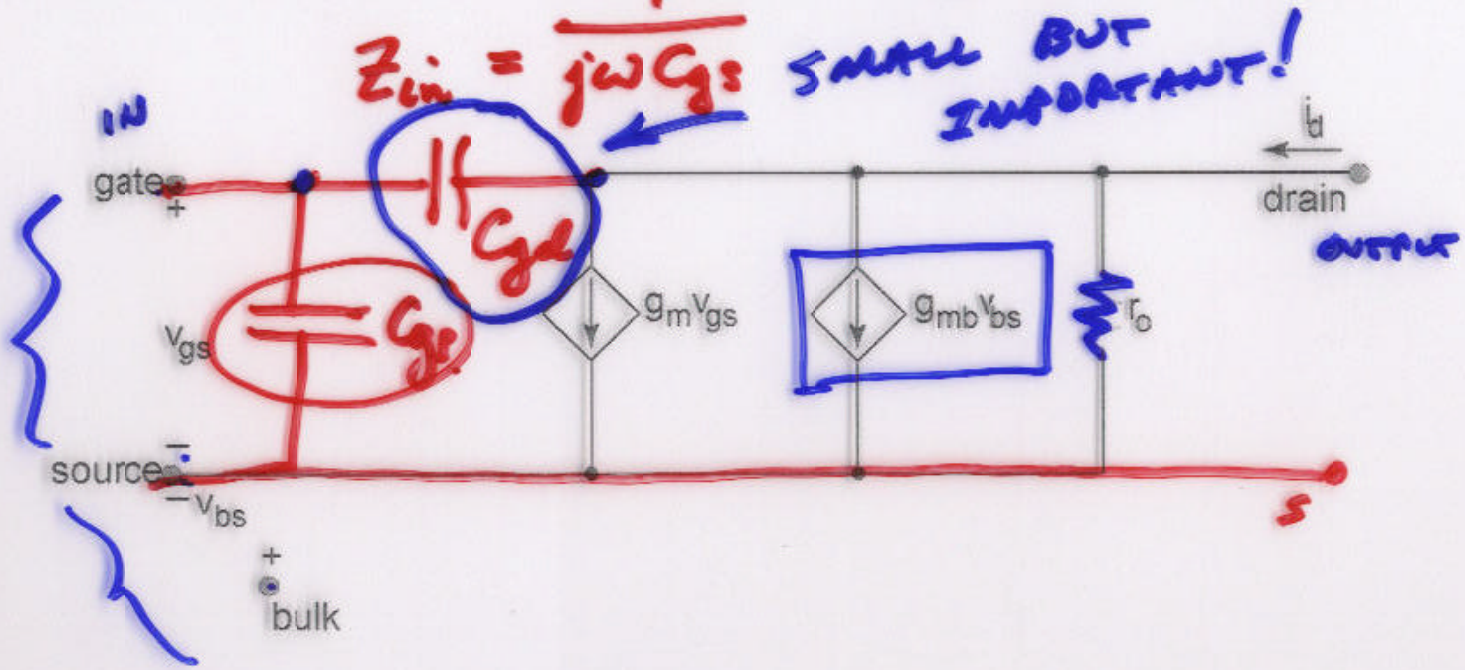
$$C_{gs} = (2/3)WLC_{ox} + C_{ov}$$

Overlap capacitance along source edge of gate →

$$C_{ov} = L_D W C_{ox}$$

(Underestimate due to fringing fields)

Four-Terminal Small-Signal Model



$Z_{in} = \frac{1}{j\omega C_{gs}}$ SMALL BUT IMPORTANT!

OUTPUT

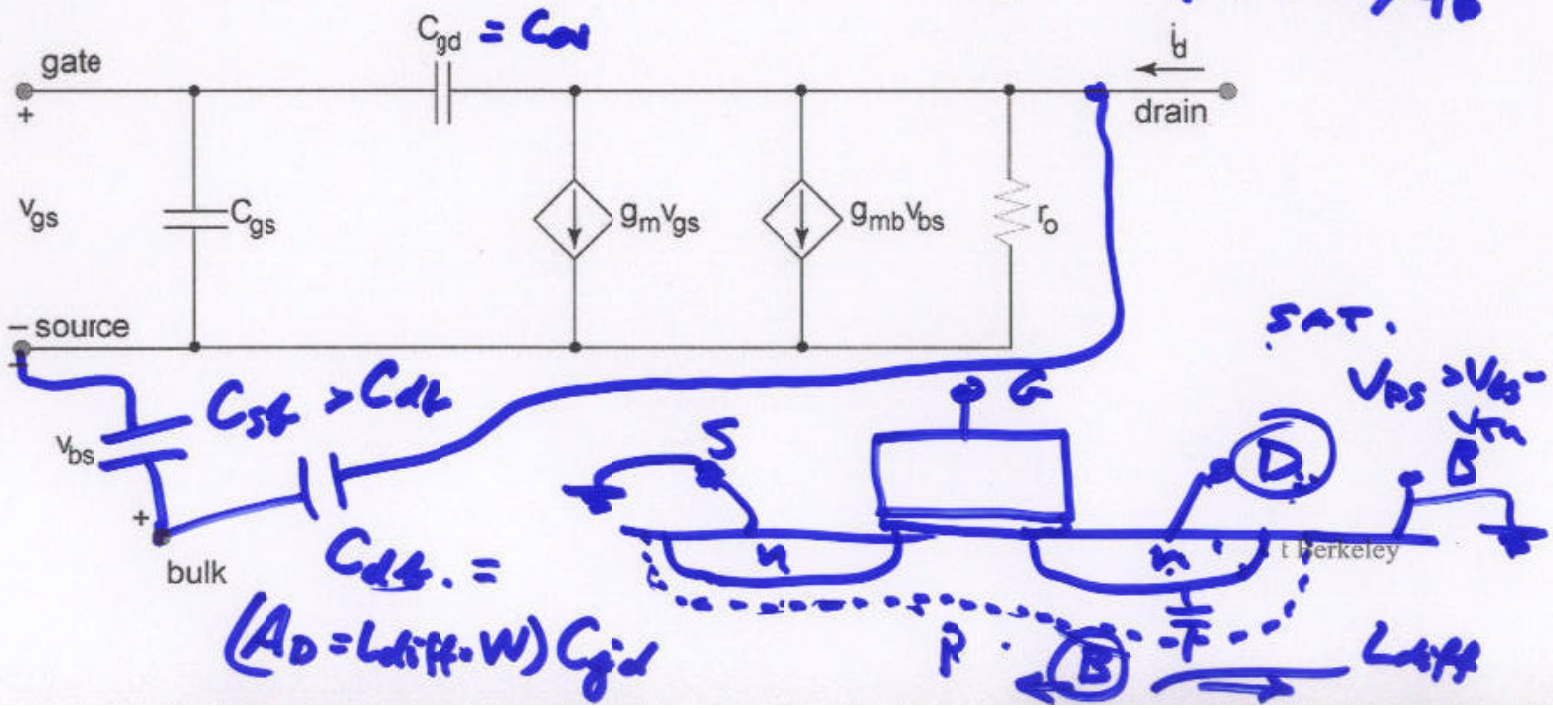
CHARGE = f(VOLTAGE)

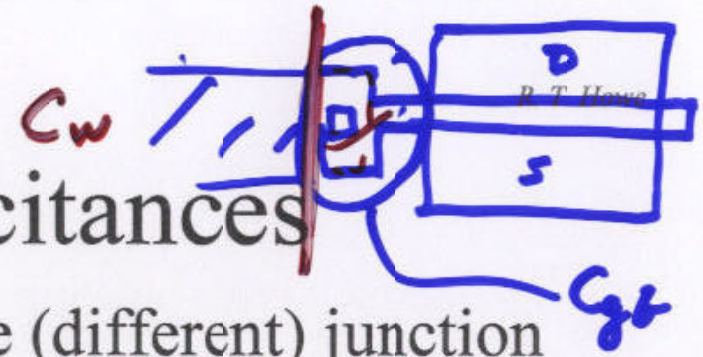
- G-S
- G-D
- D-B
- S-B

Gate-Drain Capacitance C_{gd}

Not due to change in inversion charge in channel

Overlap capacitance C_{ov} between drain and source is C_{gd}

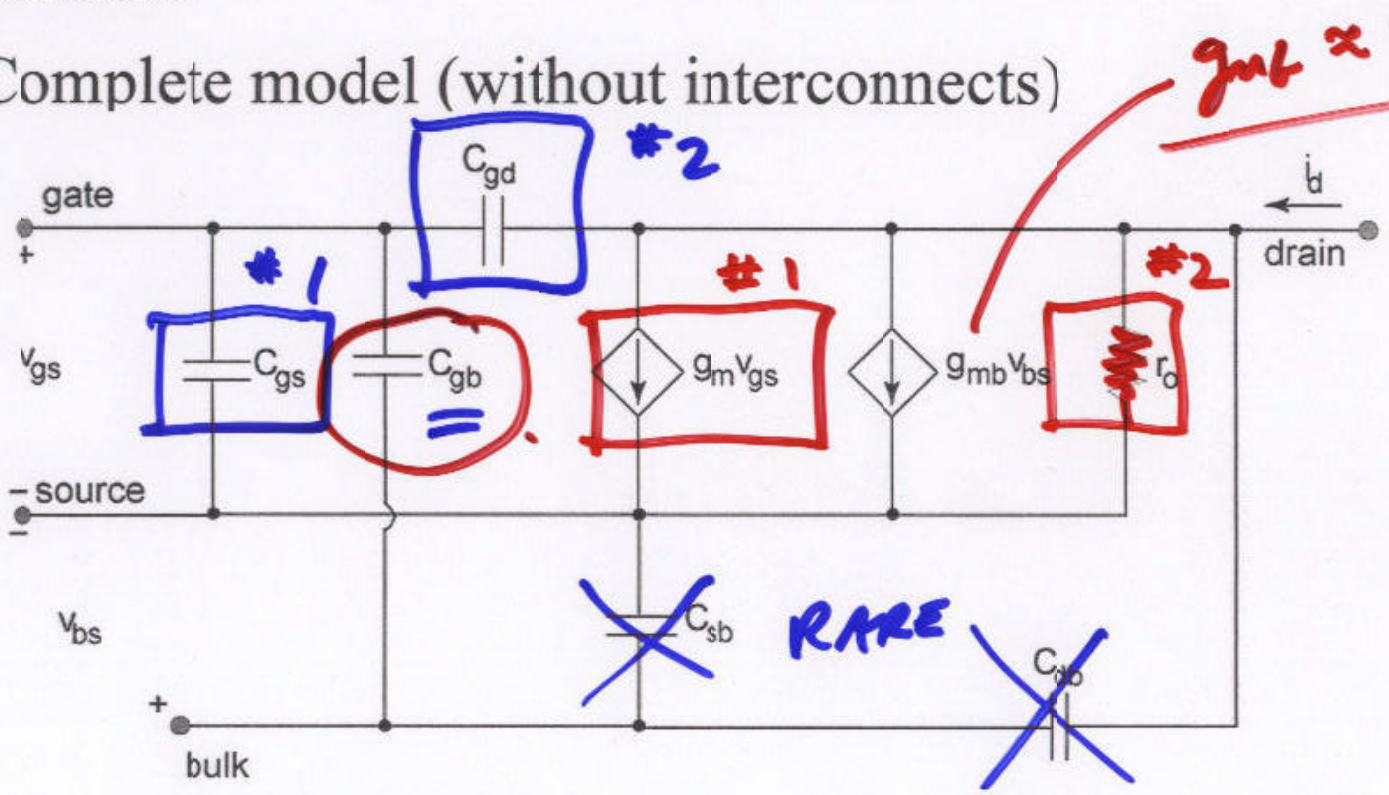




Junction Capacitances

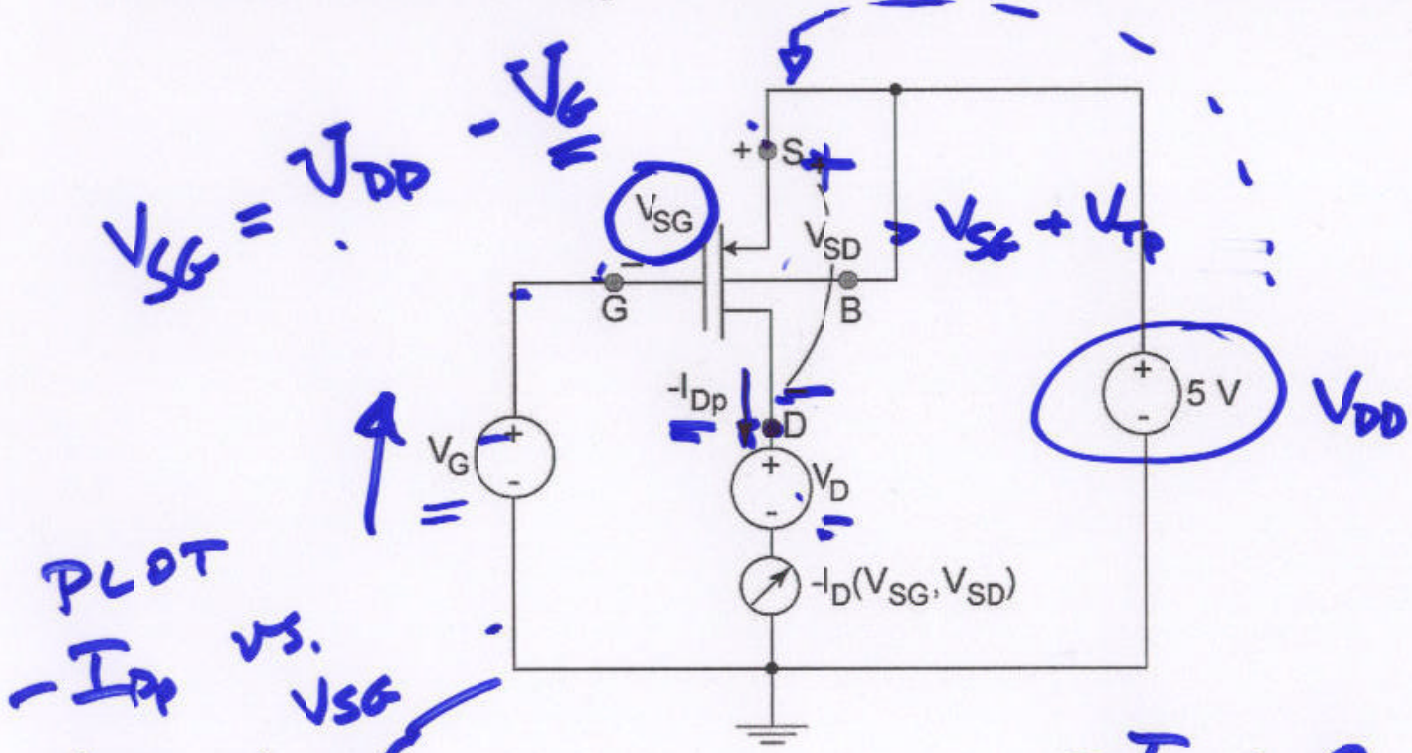
Drain and source diffusions have (different) junction capacitances since V_{SB} and $V_{DB} = V_{SB} + V_{DS}$ aren't the same

Complete model (without interconnects)

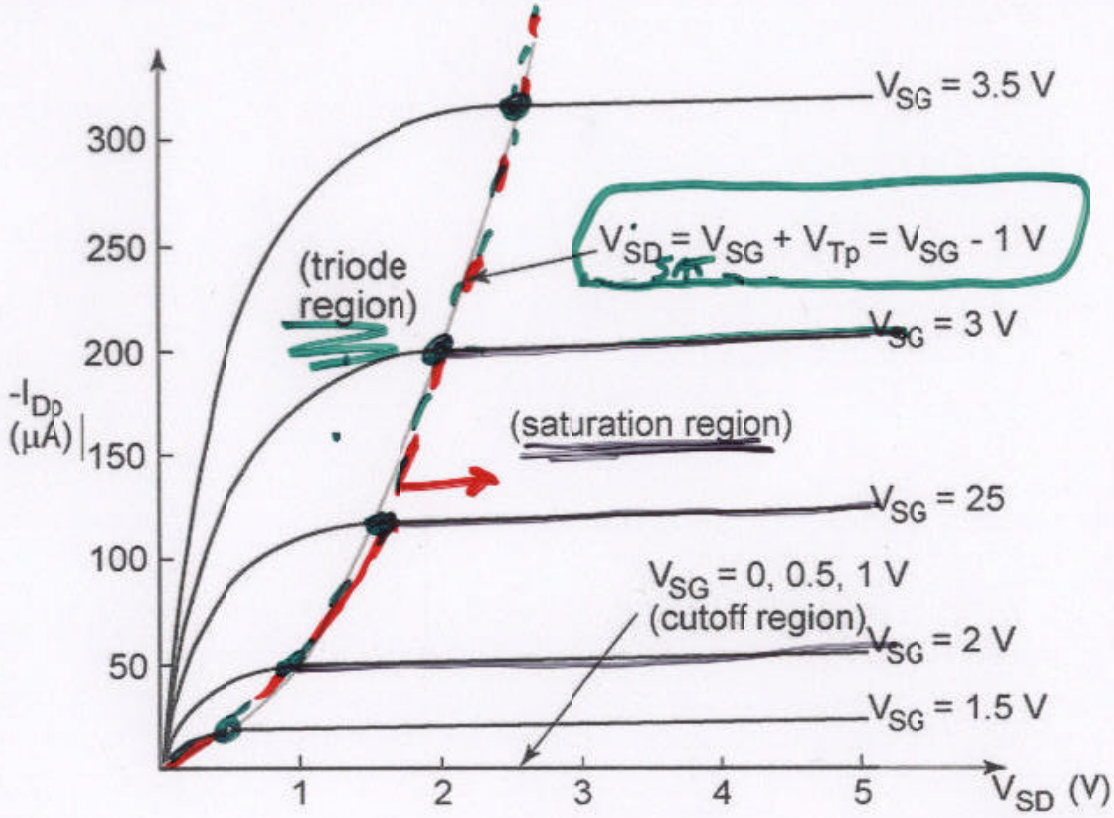


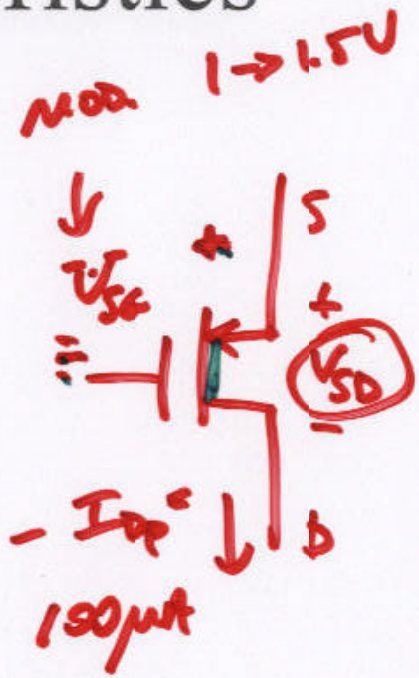
P-Channel MOSFET

Measurement of $-I_{Dp}$ versus V_{SD}, with V_{SG} as a parameter:



Square-Law PMOS Characteristics

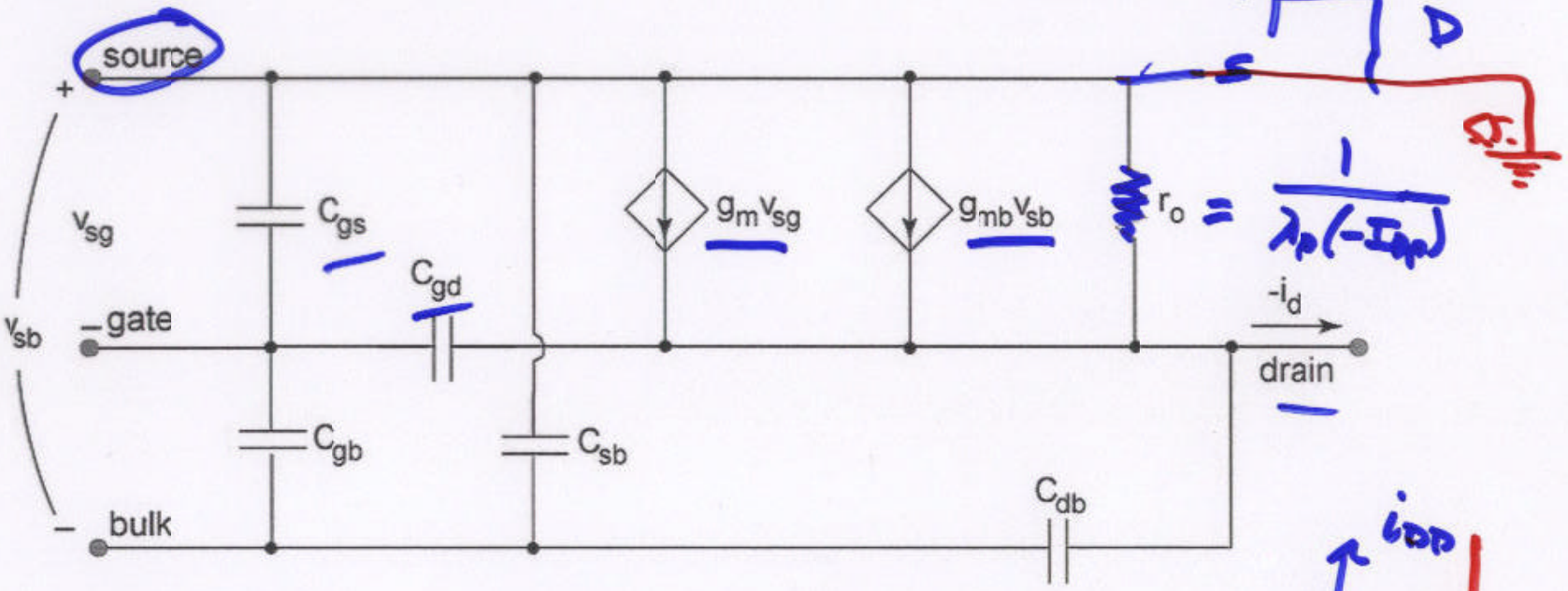


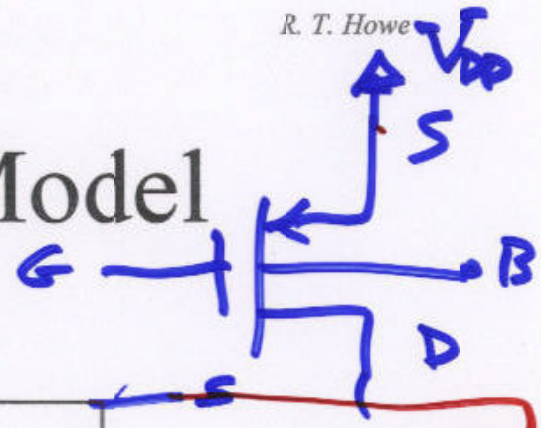


$$-I_{D_{PSAT}} = \frac{\mu_p C_{ox}}{2}\left(\frac{W}{L}\right)(V_{SG} + V_{Tp})^2(1 + \lambda_p V_{SD})$$

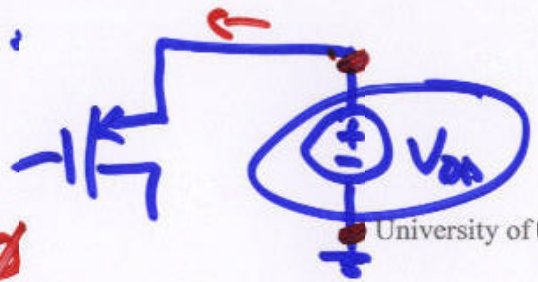
$V_{SD} \geq V_{SG} + V_{Tp}$; $V_{SG} \geq -V_{Tp} < 0$

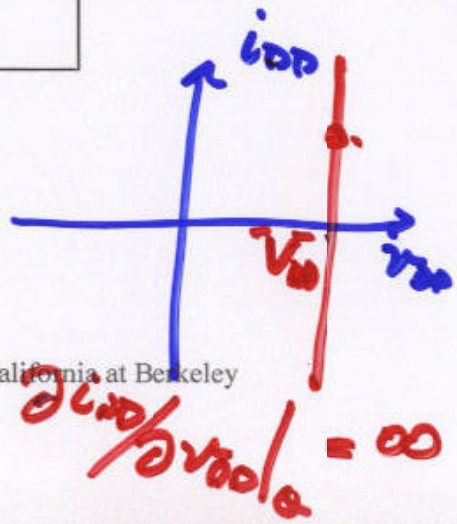
Small-Signal PMOS Model





SMALL-SIGNAL MODEL:





$r_{out} = \left(\frac{\partial i_{out}}{\partial v_{out}}\right)_Q = 0$

$\partial i_{out}/\partial v_{out}|_Q = \infty$

MOSFET SPICE Model

- Many "levels" … we will use the square-law "Level 1" model
  See H&S 4.6 + Spice refs. on reserve for details.

```
.MODEL MODN NMOS LEVEL=1 VTO = 1 KP = 50U LAMBDA = .033 GAMMA = .6
+ PHI = 0.8 TOX = 1.5E-10 CGDO = 5E-10 CGSO = 5E-10 CJ = 1E-4 CJSW = 5E-10
+ MJ = 0.5 PB = 0.95
.MODEL MODP PMOS LEVEL = 1 VTO = -1 KP = 25U LAMBDA = .033 GAMMA = .6
+ PHI = 0.8 TOX = 1.5E-10 CGDO = 5E-10 CGSO = 5E-10 CJ = 3E-4 CJSW = 3.5E-10
+ MJ = 0.5 PB = 0.95
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