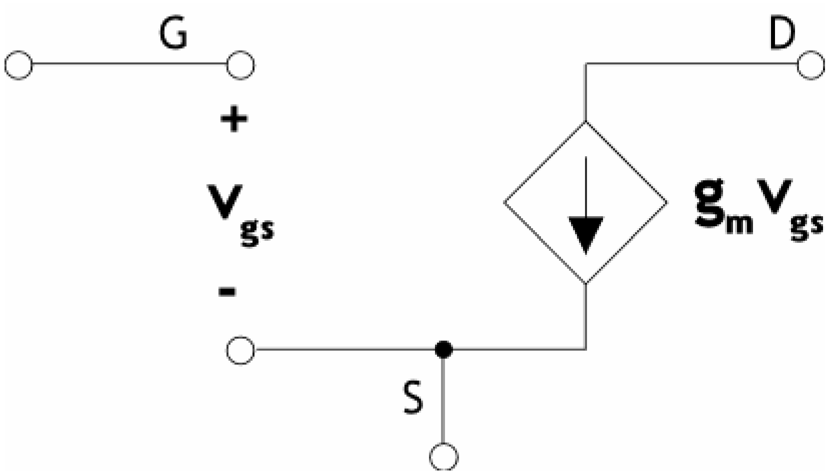
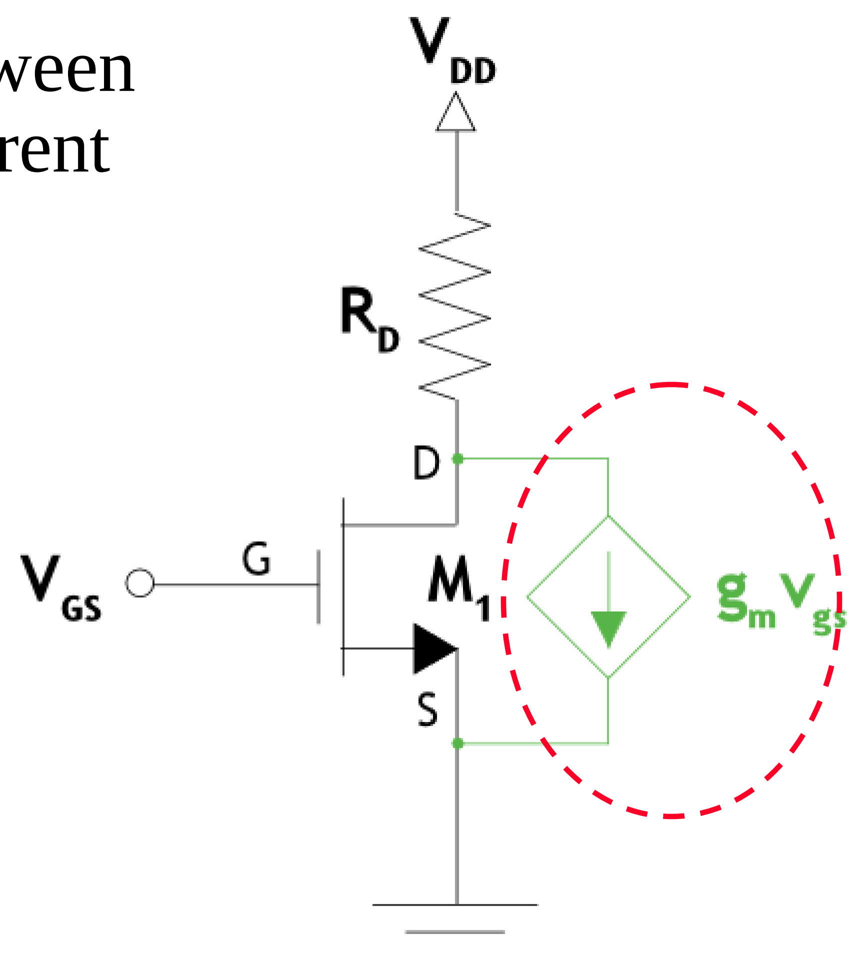
Outline of Chapter 4

- *1- Intro to MOS Field Effect Transistor (MOSFET)*
- 2- NMOS FET
- 3- PMOS FET
- 4- DC Analysis of MOSFET Circuits
- 5- MOSFET Amplifier
- <u>6- MOSFET Small Signal Model</u>
- 7- MOSFET Integrated Circuits
- 8- CSA, CGA, CDA
- 9- CMOS Inverter & MOS Digital Logic

Small Signal Modeling

- In response to signal input between gate and source, v_{gs}, signal current flows in drain, i_d

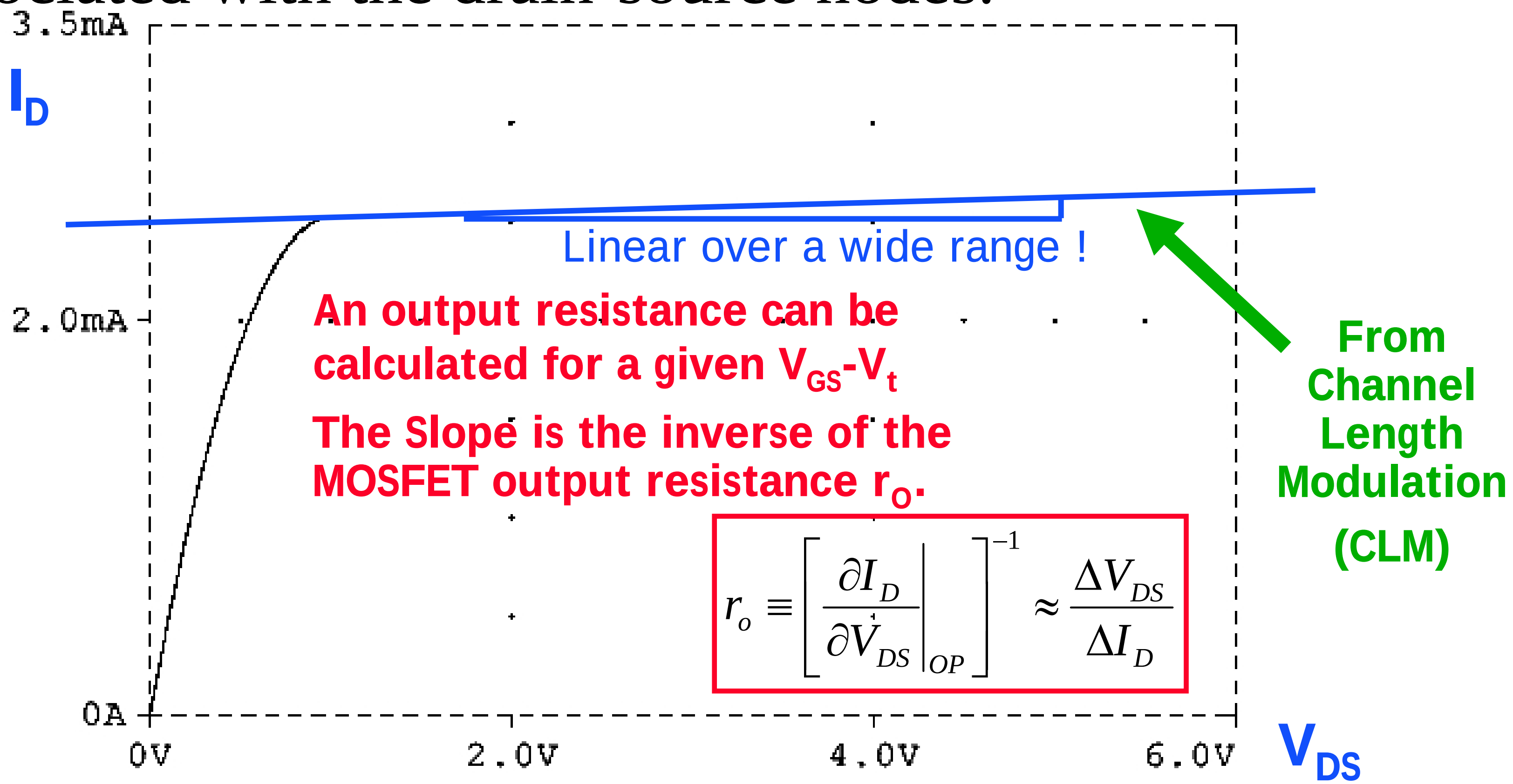




Still to be determined:
- output resistance (r_o)
- input resistance
- body terminal

Small Signal Output Resistance

- Since the characteristic curve for I_D-V_{DS} indicates a slope when in saturation, there is an output resistance associated with the drain-source nodes.



An output resistance can be calculated for a given V_{GS}-V_t

The Slope is the inverse of the MOSFET output resistance r_o.

$$r_o \equiv \left[\left. \frac{\partial I_D}{\partial V_{DS}} \right|_{OP} \right]^{-1} \approx \frac{\Delta V_{DS}}{\Delta I_D}$$

Output Resistance – r_o

- To derive an expression for r_o:

$$r_o \equiv \left[\left. \frac{\partial i_D}{\partial v_{DS}} \right|_{OP} \right]^{-1}$$

- Start with full I_D equation

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

- Take derivative and simplify

$$\frac{\partial i_D}{\partial v_{DS}} = \tfrac{1}{2} k_n' \frac{W}{L} \left(v_{GS} - V_t \right)^2 \cdot \lambda$$

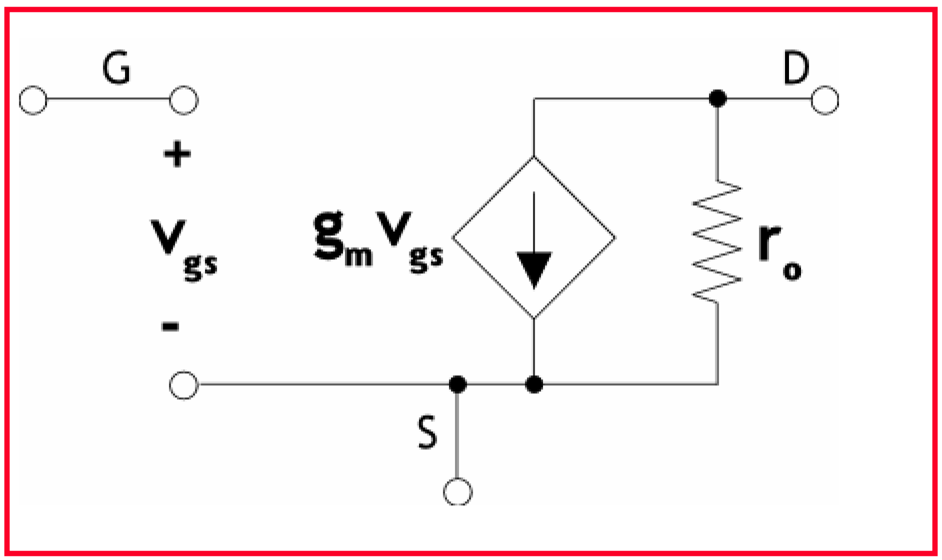
- Plug in the operating point

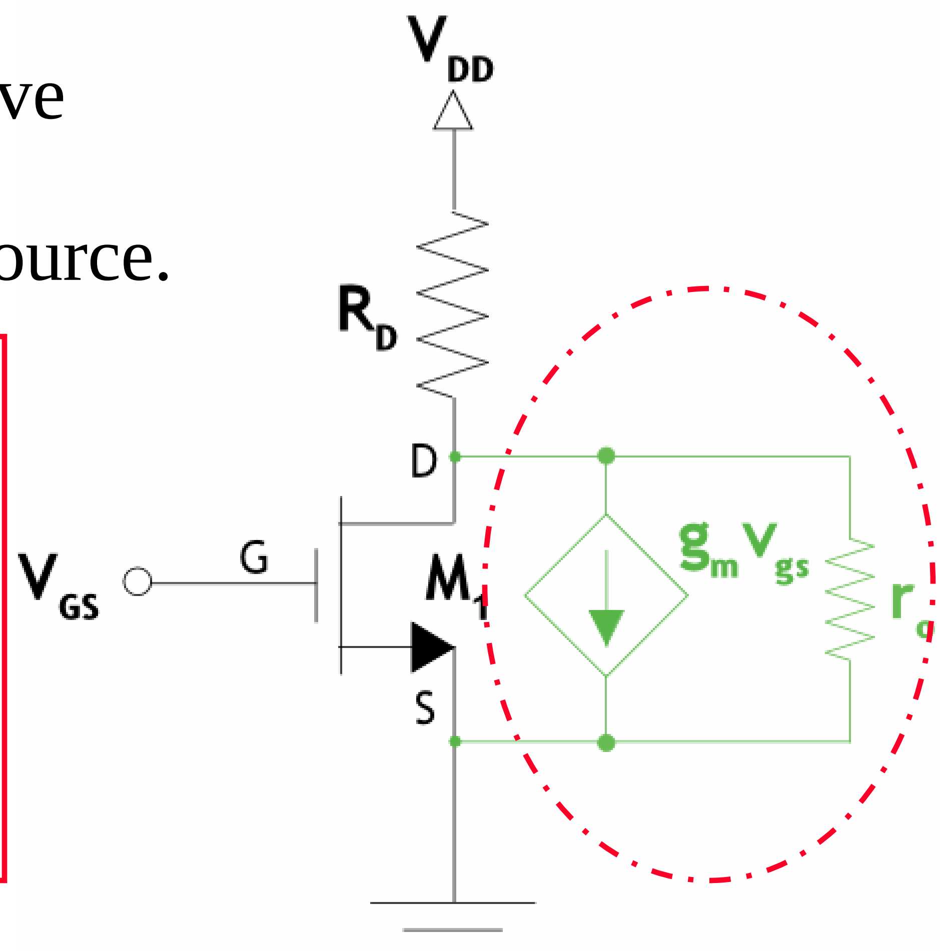
$$\left. \frac{\partial i_D}{\partial v_{DS}} \right|_{OP} = \frac{\lambda \cdot I_D}{1 + \lambda \cdot V_{DS}} = \frac{I_D}{\frac{1}{\lambda} + V_{DS}} = \frac{I_D}{V_A + V_{DS}} \approx \lambda \cdot I_D$$

$$\boxed{r_o \approx \frac{1}{\lambda \cdot I_D}}$$

Small Signal Modeling

- The slope of the I_D-V_{DS} curve indicates a finite resistance between the drain and the source.





The MOSFET T-Model

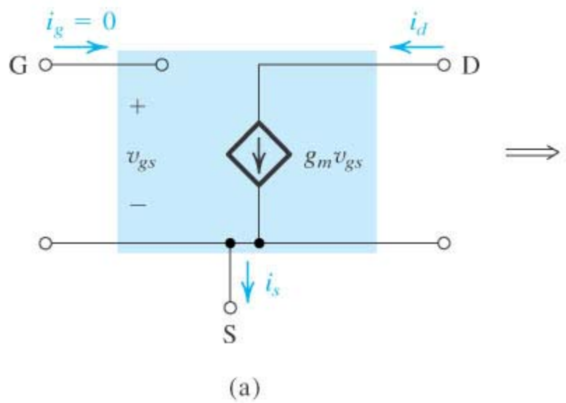
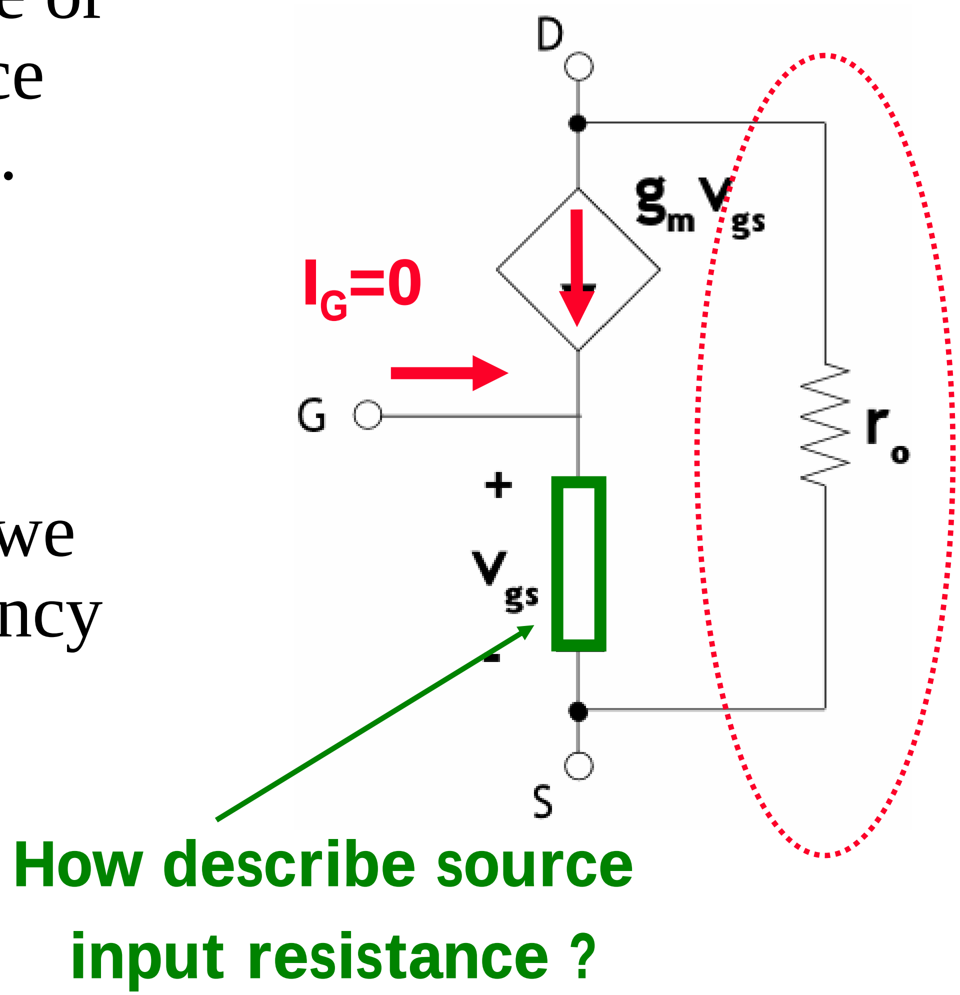


Figure 4.39 Development of the T equivalent-circuit model for the MOSFET. For simplicity, r_o has been omitted but can be added between D and S in the T model of **(d)**.

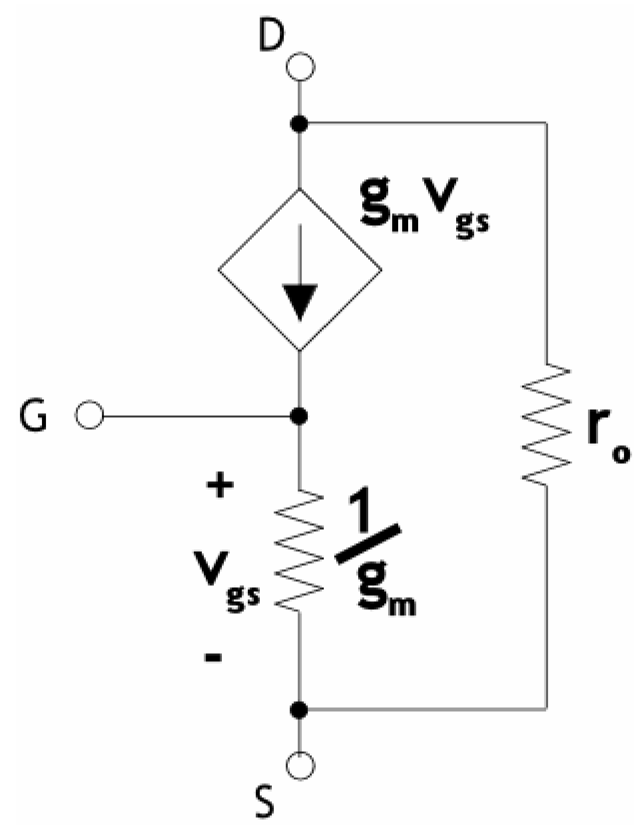
The MOSFET T-Model

- When input signal (voltage or current) is applied at source terminal, use the **T-model**.
- Non-zero signal current flows in source
- Input resistance looking into source is finite when we do not consider the frequency response
- Need to determine source resistance parameter



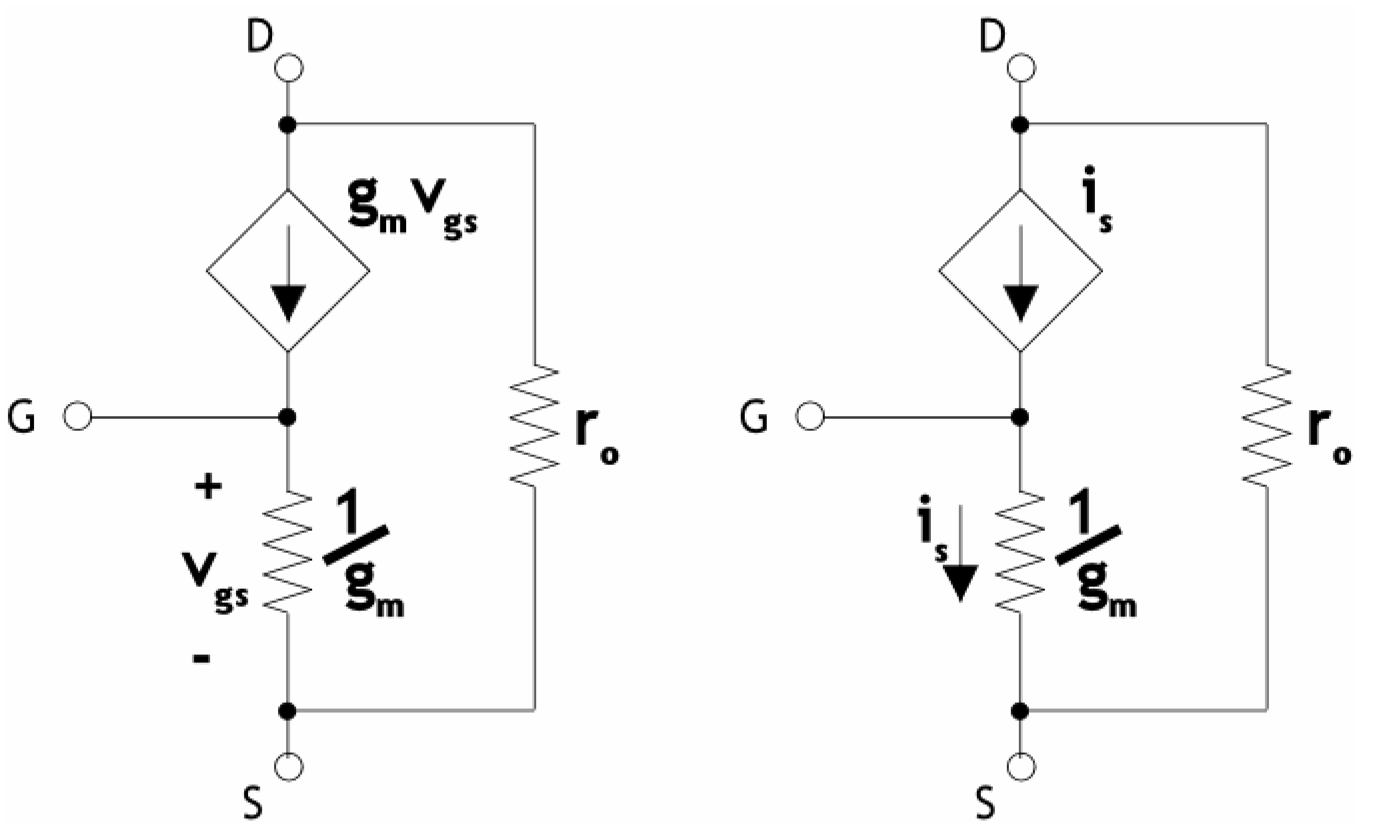
Source Resistance for T-model

- Find the relationship between source current and gate-source voltage. We can identify a V=IR relationship
- Define r_s as the input resistance looking into the source
- Can compute: $r_s = v_{gs}/i_s$
- Since $i_s = i_d$, and $i_d = g_m v_{gs}$, recognize that $r_s = 1/g_m = v_{gs}/i_s$



Source Absorption Theorem

The MOSFET T Small Signal Model



The Body Effect – Small Signal

- Recall that DC Body effect occurs because Body and Source not always maintained at same potential
- The same thing can apply to AC analysis
  - The body terminal always connected to the most negative DC power supply;
  - Body terminal will always be at signal (AC) ground.
  - The small signal body effect occurs when the source is not at signal ground.
  - Result: the body behaves like a second – albeit weaker – gate

Modeling the Small Signal Body Effect

- Consider effect of small changes in V_{BS} on I_D:
- V_{BS} dependence is in V_t:
- Start with full I_D expression
- Take derivative and simplify

$$\left.\frac{\partial i_D}{\partial v_{BS}}\right|_{OP}$$

$$V_t = V_{t0} + \gamma\left(\sqrt{2\phi_f + V_{SB}} - \sqrt{2\phi_f}\right)$$

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

$$\frac{\partial i_D}{\partial v_{BS}} = \frac{\partial i_D}{\partial v_t} \cdot \frac{\partial v_t}{\partial v_{BS}} = \left[2 \cdot \tfrac{1}{2} k_n' \frac{W}{L} (V_{GS} - v_t)(1 + \lambda \cdot V_{DS})(-1)\right] \cdot \left[\tfrac{1}{2} \cdot \gamma (2\phi_f + v_{SB})^{-1/2} (-1)\right]$$

Insert the operating point

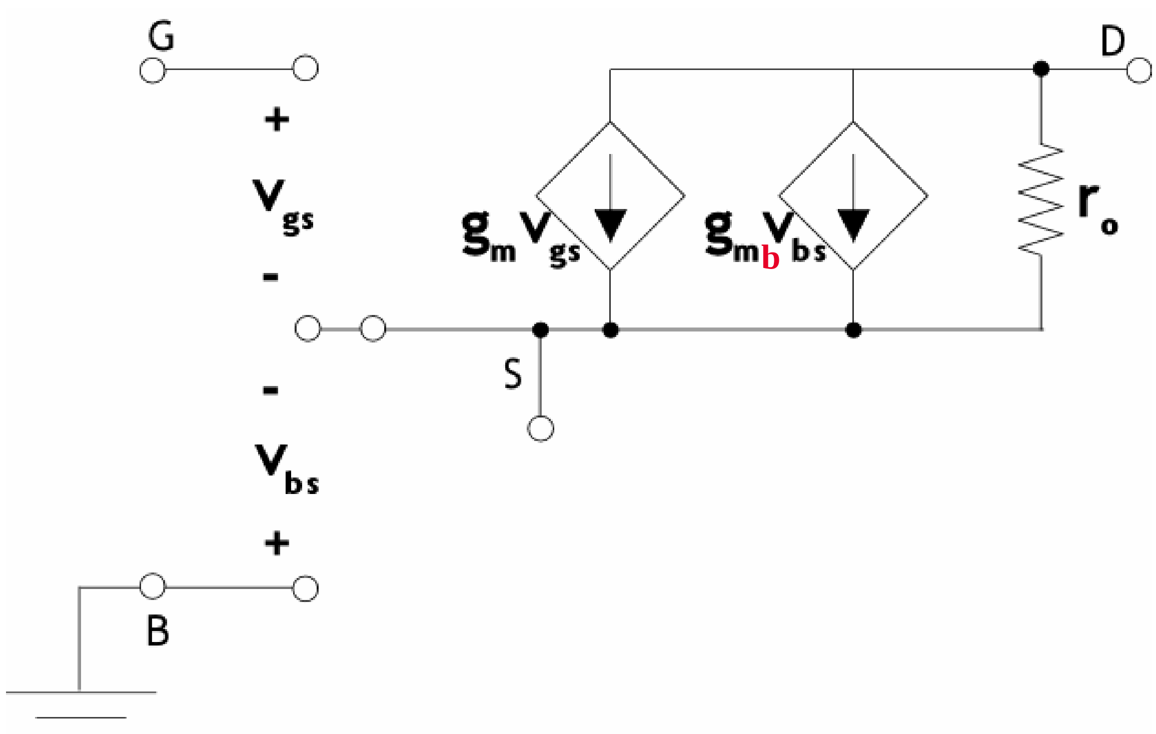
$$= \left[\frac{\gamma}{2} \frac{1}{\sqrt{2\phi_f + V_{SB}}}\right] \cdot g_m = \chi \cdot g_m$$

Body transconductance

$$g_{mb} = \chi \cdot g_m$$

$$\chi = \frac{\gamma}{2} \cdot \frac{1}{\sqrt{2\phi_f + V_{SB}}}$$

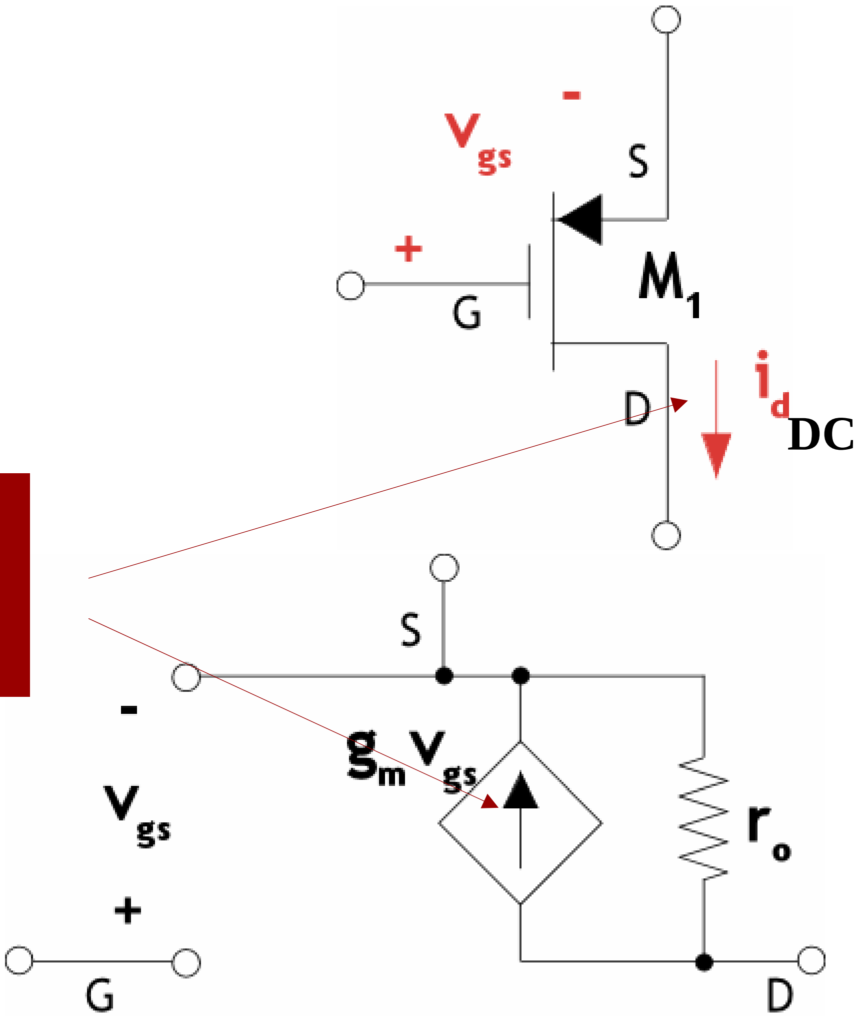
Hybrid-π Small Signal Model



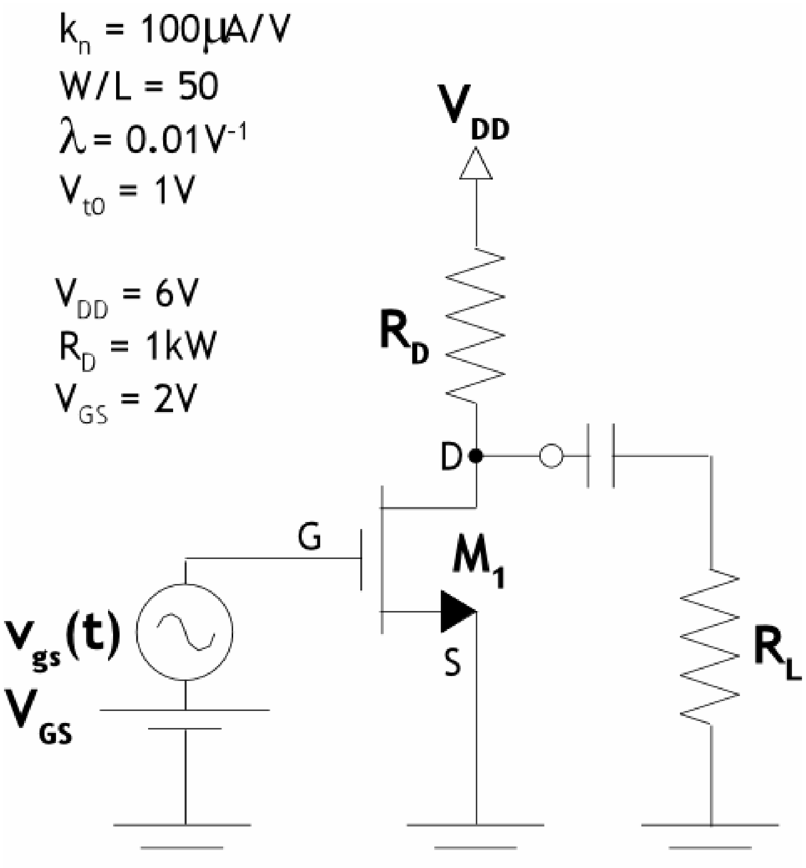
- AC Body effect: another VCCS (dependent on g_{mb}) in parallel with the one dependent on g_m
- T model generally not used when modeling Body effect, regardless of circuit topology

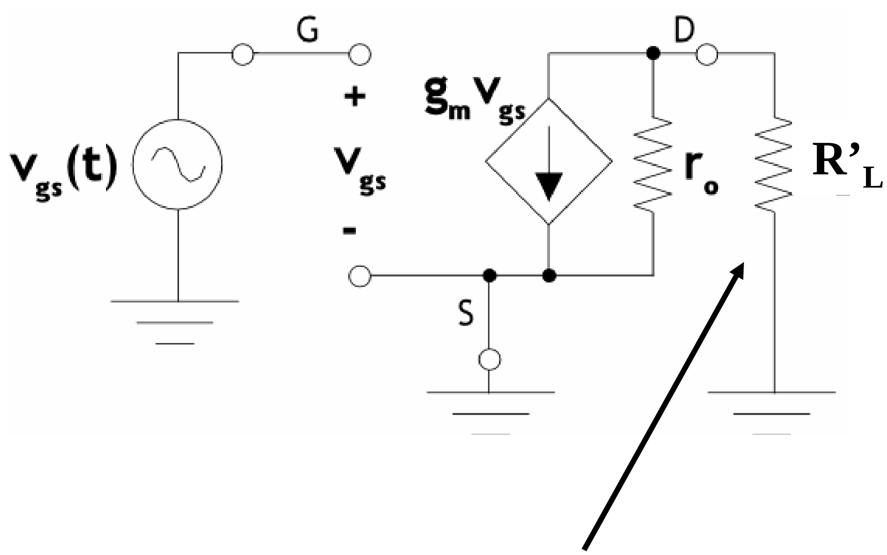
pMOS Small Signal Model

- Small signal model for PMOS is identical to that for NMOS
- Be careful of location of G, D, and S terminals
  - DC current flows one way, signal current flows the other way



Common Source MOSFET Amplifier





$$R_L^{'} = R_D \| R_L$$

Small Signal Operation

- Small signal analysis requires the use of “small” signals to be valid
- Start with expression for drain current:

$$i_D = \tfrac{1}{2} k_n' \frac{W}{L} \left(v_{GS} - V_t\right)^2 \left(1 + \lambda V_{DS}\right)$$

- Substitute $v_{GS} = V_{GS} + v_{gs}$, $i_D = I_D + i_d$
- Expand quadratic term:

$$I_D + i_d = \tfrac{1}{2} k_n' \frac{W}{L} \left(V_{GS} + v_{gs} - V_t\right)^2 \left(1 + \lambda V_{DS}\right)$$

$$\left(V_{GS} + v_{gs} - V_t\right)^2 = \left[\left(V_{GS} - V_t\right) + v_{gs}\right]^2$$

$$= \left(V_{GS} - V_t\right)^2 + 2 v_{gs}\left(V_{GS} - V_t\right) + v_{gs}^2$$

$$v_{gs}^2 << 2 v_{gs}\left(V_{GS} - V_t\right) \qquad v_{gs} << 2\left(V_{GS} - V_t\right)$$