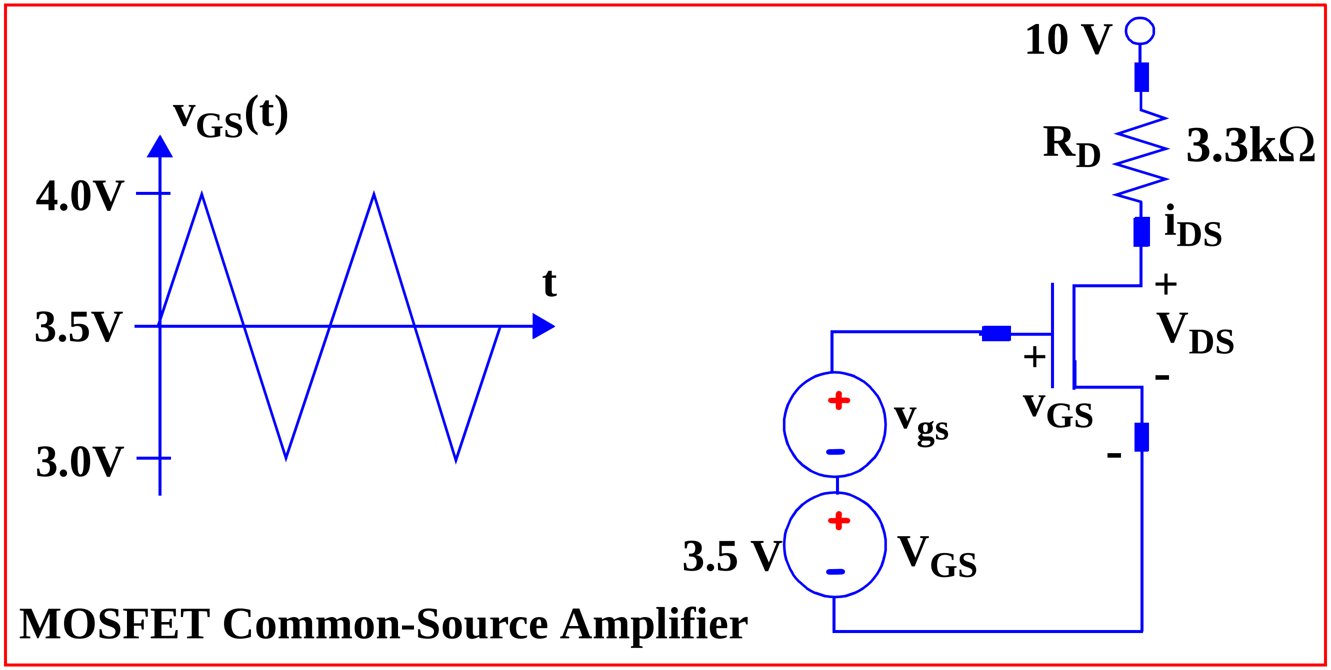
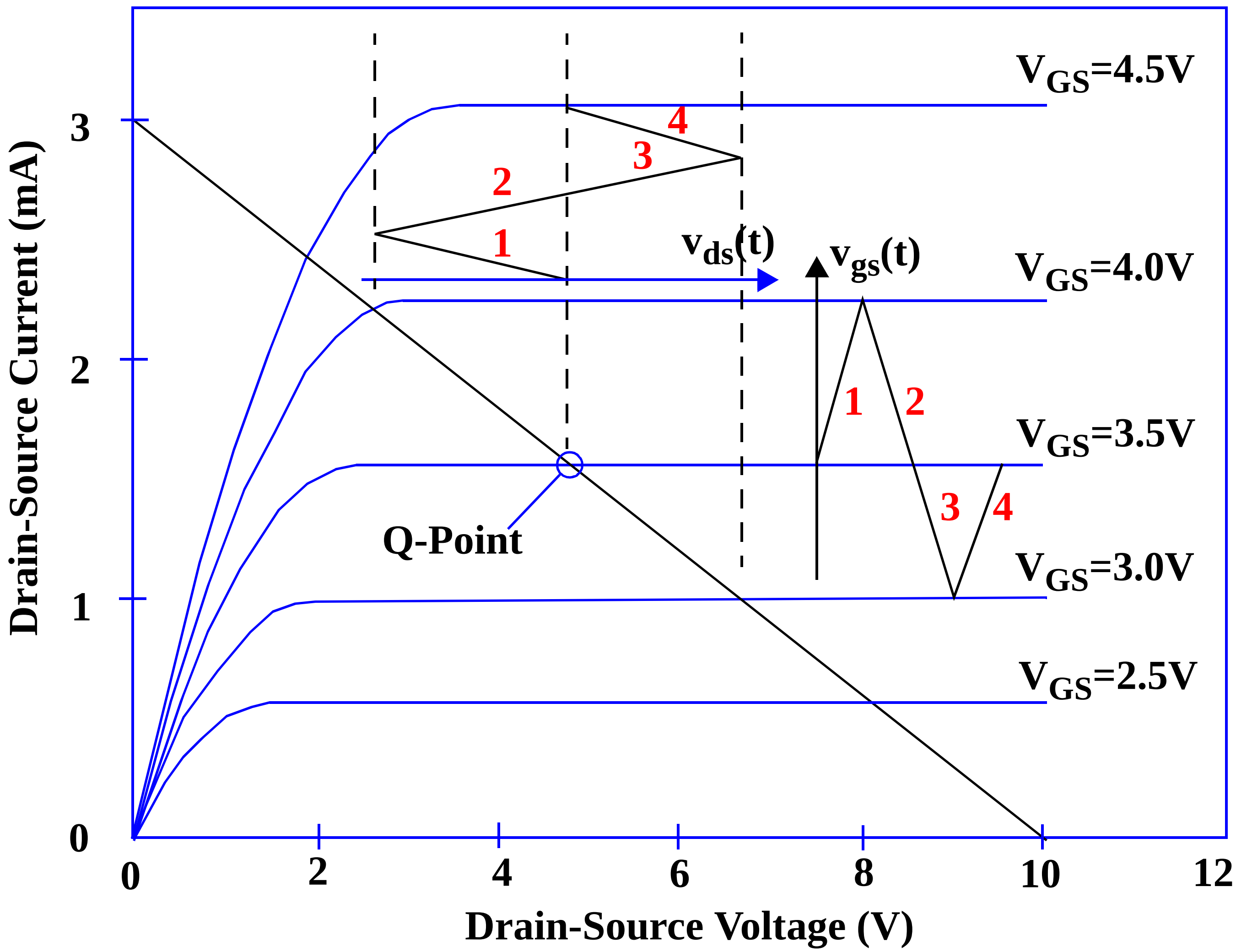
Lecture #20

Small-Signal Modeling & Linear Amplification - FETs

Outline/Learning Objectives:

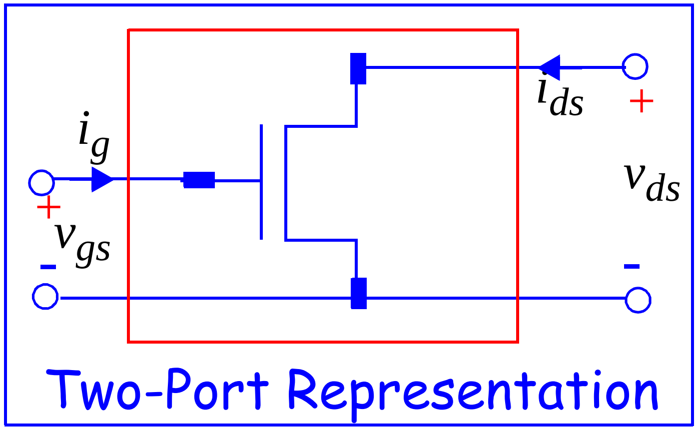
- Describe the FET as an amplifier
- Define and describe the use of coupling and bypass capacitors
- Define and describe the small-signal model for the pn junction diode.
- Analyze FET amplifiers using a two-part process:
- (1) dc Analysis:
- (a) construct the dc equivalent circuit;
- (b) solve for the Q-point.
- (2) ac Analysis:
- (3) construct the ac equivalent circuit;
- (4) replace the FET by its small-signal model;
- (5) solve the ac circuit.
- Define and describe the small-signal-model of the FET.
- Analyze the FET common-source (C-S) amplifier.
- Use the electronics laboratory to investigate the electrical behavior of simple circuits and devices.


vGS(t)
4.0V
3.5V
3.0V
t
10 V
RD
3.3kΩ
iDS
+
VDS
-
+
vGS
-
vgs
3.5 V
VGS
MOSFET Common-Source Amplifier



Q-Point and Load-Line Signals for Circuit Above

Small Signal Model of MOSFET



$$i_g = y_{11}v_{gs} + y_{12}v_{ds}$$

$$i_{ds} = y_{21}v_{gs} + y_{22}v_{ds}$$

$$v_{DS} = V_{DS} + v_{ds};\ v_{GS} = V_{GS} + v_{gs}$$

$$i_G = I_G + i_g;\ i_{DS} = I_{DS} + i_{ds};$$

$v_{gs} = \Delta v_{GS}$, $v_{ds} = \Delta v_{DS}$, $i_g = \Delta i_G$ and $i_{ds} = \Delta i_{DS}$.

$$y_{11} = \left.\frac{i_g}{v_{gs}}\right|_{v_{ds}=0} = \left.\frac{\partial i_G}{\partial v_{GS}}\right|_{Q-Point};\quad y_{12} = \left.\frac{i_g}{v_{ds}}\right|_{v_{gs}=0} = \left.\frac{\partial i_G}{\partial v_{DS}}\right|_{Q-Point}$$

$$y_{21} = \left.\frac{i_{ds}}{v_{gs}}\right|_{v_{ds}=0} = \left.\frac{\partial i_{DS}}{\partial v_{GS}}\right|_{Q-Point};\quad y_{22} = \left.\frac{i_{ds}}{v_{ds}}\right|_{v_{gs}=0} = \left.\frac{\partial i_{DS}}{\partial v_{DS}}\right|_{Q-Point}$$

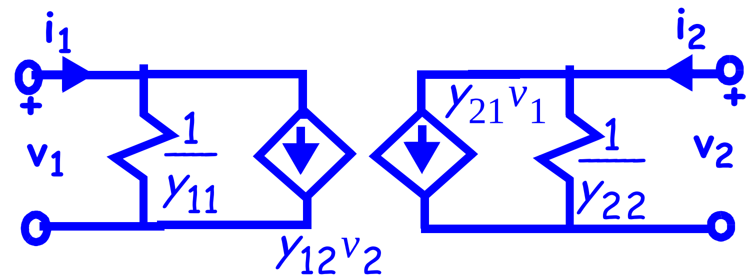
$$i_{DS} = \frac{K_n}{2}(v_{GS} - V_{TN})^2(1 + \lambda v_{DS})$$

with $K_n = \mu C_{ox}\frac{W}{L}$, $v_{DS} \geq (v_{GS} - V_{TN}) \geq 0$ and $i_G = 0$.

$y_{11} = 0$ and $y_{12} = 0$

$$y_{21} = K_n(V_{GS} - V_{TN})(1 + \lambda V_{DS}) = \frac{2I_{DS}}{V_{GS} - V_{TN}} = g_m$$

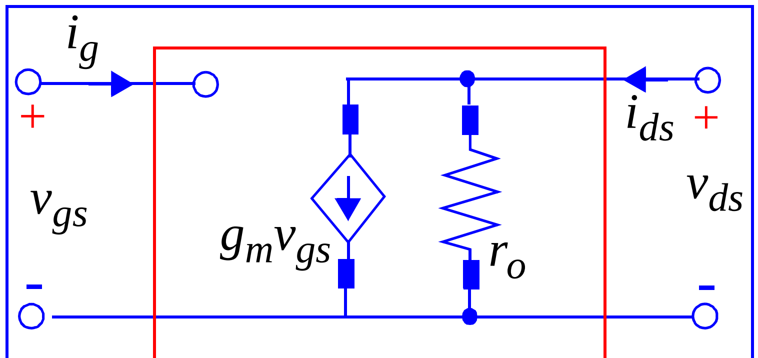
$$y_{22} = \frac{\lambda K_n}{2}(V_{GS} - V_{TN})^2 = \frac{\lambda I_{DS}}{1 + \lambda V_{DS}} = \frac{1}{r_o}$$



$$g_m = K_n(V_{GS} - V_{TN})(1 + \lambda V_{DS})$$

$$g_m = \sqrt{2K_n I_{DS}(1 + \lambda V_{DS})} \, .$$

$$g_m = \frac{2I_{DS}}{V_{GS} - V_{TN}} \, .$$



For $\lambda V_{DS} \ll 1$,

$g_m = K_n(V_{GS} - V_{TN})$ or $g_m = \sqrt{2K_n I_{DS}}$

Amplification Factor (μ_f)

$$\mu_f = g_m r_o = \frac{2I_{DS}}{V_{GS} - V_{TN}} \cdot \frac{1 + \lambda V_{DS}}{\lambda I_{DS}} = \frac{2(1 + \lambda V_{DS})}{\lambda (V_{GS} - V_{TN})}$$

$$\mu_f = g_m r_o = \sqrt{2K_n I_{DS}(1 + \lambda V_{DS})} \cdot \frac{1 + \lambda V_{DS}}{\lambda I_{DS}}$$

$$\mu_f = g_m r_o = \left(\frac{1}{\lambda} + V_{DS}\right) \cdot \sqrt{\frac{2K_n}{I_{DS}}(1 + \lambda V_{DS})}$$

For $\lambda V_{DS} \ll 1$, $\mu_f \approx \frac{1}{\lambda} \cdot \sqrt{\frac{2K_n}{I_{DS}}} \approx \frac{2}{\lambda (V_{GS} - V_{TN})}$

I_D	g_m	r_o	μ_f
1 μA	4.76×10^{-5} S	85.20 MΩ	4060
10 μA	1.51×10^{-4} S	8.52 MΩ	1280
100 μA	4.76×10^{-4} S	852 kΩ	406
1 mA	1.51×10^{-3} S	85.2 kΩ	128
10 mA	4.76×10^{-3} S	8.52 kΩ	40

Definition of Small-Signal Operation of MOSFET

$$i_{DS} = \frac{K_n}{2}(v_{GS} - V_{TN})^2$$ for $v_{DS} \geq (v_{GS} - V_{TN}) \geq 0$.

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

$$I_{DS} + i_{ds} = \frac{K_n}{2}(V_{GS} + v_{gs} - V_{TN})^2$$

$$I_{DS} + i_{ds} = \frac{K_n}{2}\{(V_{GS} - V_{TN})^2 + 2v_{gs}(V_{GS} - V_{TN}) + v_{gs}^2\}$$

DC drain current is $$I_{DS} = \frac{K_n}{2}(V_{GS} - V_{TN})^2$$

$$i_{ds} = \frac{K_n}{2}\{v_{gs}[2(V_{GS} - V_{TN}) + v_{gs}]\}$$

For i_{ds} to be linearly proportional to v_{gs}, we need $v_{gs} \ll 2(V_{GS} - V_{TN})$.

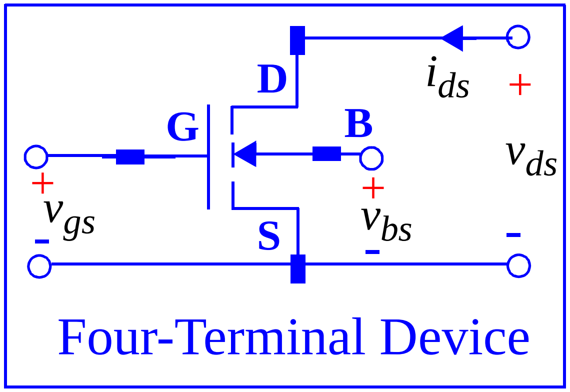
We can use a factor of 10 to satisfy the inequality, so we get, $v_{gs} = 0.2(V_{GS} - V_{TN})$.

Also, $\boxed{\frac{i_{ds}}{I_{DS}} = \frac{g_m v_{gs}}{I_{DS}} = \frac{I_{DS}}{(V_{GS} - V_{TN})/2} \cdot 0.2(V_{GS} - V_{TN}) \cdot \frac{1}{I_{DS}}}$.

Therefore, a change of $0.2(V_{GS} - V_{TN})$ causes a 40% change in drain and source currents from their quiescent values.

Body-Effect in Four-Terminal MOSFET

please read the body effect part

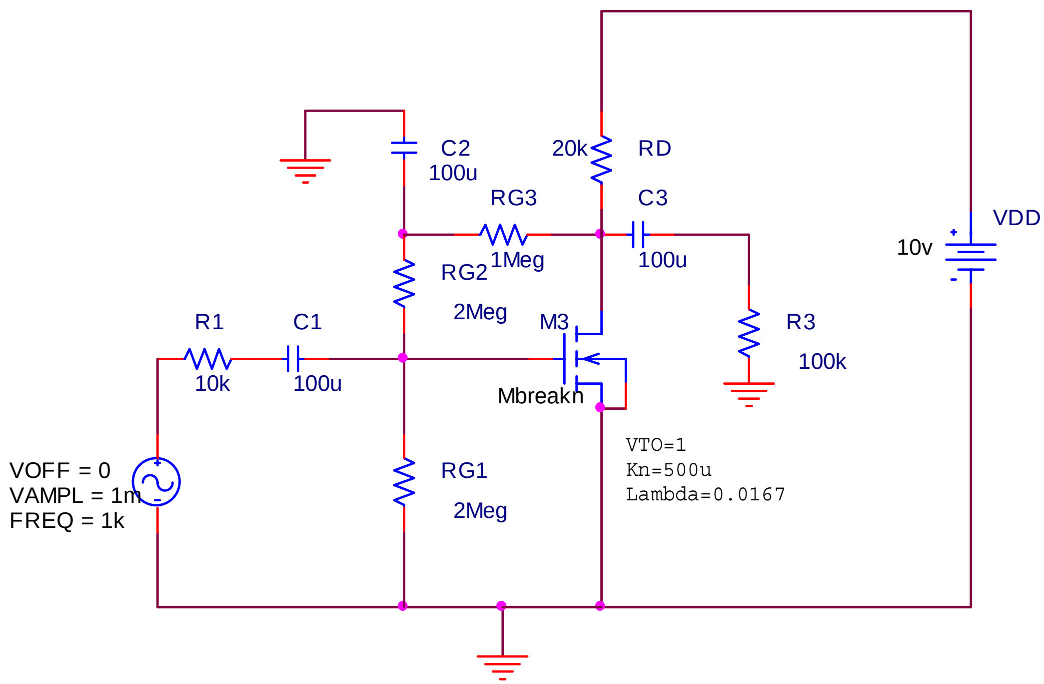


Summary of MOSFET Small-Signal Parameters

Parameter	MOSFET
Transconductance g_m	$\frac{I_{DS}}{(V_{GS}-V_{TN})/2}$ $K_n(V_{GS}-V_{TN})(1+\lambda V_{DS})$ $\sqrt{2K_n I_{DS}(1+\lambda V_{DS})}$
Input Resistance	∞
Output Resistance r_o	$\frac{(1/\lambda)+V_{DS}}{I_{DS}}$
Amplification Factor μ_f $\mu_f = g_m r_o$	$\left\{\frac{1}{\lambda}+V_{DS}\right\} \Big/ \left(\frac{V_{GS}-V_{TN}}{2}\right)$ $\approx \frac{1}{\lambda}\cdot\sqrt{\frac{2K_n}{I_{DS}}} = \frac{2}{\lambda(V_{GS}-V_{TN})}$
Small-Signal Requirement	$v_{gs} \le 0.2(V_{GS}-V_{TN})$

The small signal model of the PMOS transistor is identical to that of the NMOS transistor.

PSPICE EXAMPLE



*Libraries:

* Local Libraries :

.LIB ".\example8.lib"

* From [PSPICE NETLIST] section of C:\Program Files\OrcadLite\PSpice\PSpice.ini file:

.lib "nom.lib"

*Analysis directives:

.TRAN 0 20ms 0 10u

.PROBE V(*) I(*) W(*) D(*) NOISE(*)

PSPICE EXAMPLE (Cont'd)

```
.INC ".\example8-SCHEMATIC1.net"
**** INCLUDING example8-SCHEMATIC1.net ****
* source EXAMPLE8
R_RG1        0 N00114  2Meg
R_R3         0 N00510  100k
M_M3         N00072 N00114 0 0 Mbreakn
C_C2         N00186 0  100u
R_RD         N00072 N00350  20k
V_VDD        N00350 0 10v
R_RG3        N00186 N00072  1Meg
C_C1         N006390 N00114  100u
R_R1         N00748 N006390  10k
R_RG2        N00114 N00186  2Meg
C_C3         N00072 N00510  100u
V_Vin        N00748 0
+SIN 0 1m 1k 0 0 0
**** RESUMING example8-SCHEMATIC1-Example7Profile.sim.cir ****
.END
```

PSPICE EXAMPLE (Cont'd)

**** MOSFET MODEL PARAMETERS

****

Mbreakn

NMOS

LEVEL 1

L 100.000000E-06

W 100.000000E-06

VTO 1

KP 500.000000E-06

GAMMA 0

PHI .6

LAMBDA .0167

**** INITIAL TRANSIENT SOLUTION TEMPERATURE = 27.000 DEG C

****

NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE	NODE	VOLTAGE
(N00072)	4.9182	(N00114)	1.9673	(N00186)	3.9345	(N00350)	10.0000
(N00510)	0.0000	(N00748)	0.0000	(N006390)	0.0000		

PSPICE EXAMPLE (Cont'd)

VOLTAGE SOURCE CURRENTS

NAME	CURRENT
V_VDD	-2.541E-04
V_Vin	0.000E+00

TOTAL POWER DISSIPATION 2.54E-03 WATTS

JOB CONCLUDED

TOTAL JOB TIME .39