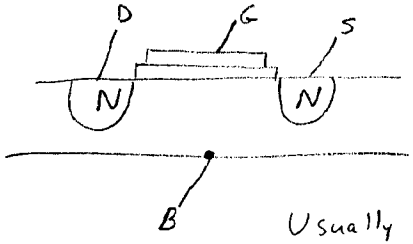
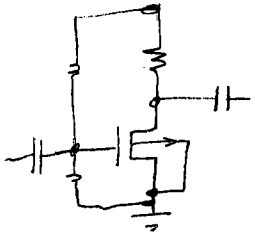
"Body" effect

The substrate has an influence on V_{TH}.



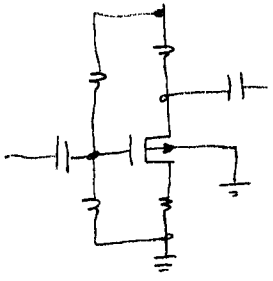
Homework —
4.1 — all "exercises" p.360: 1–7
4.2 — all "exercises" p.360: 8, 9, 10, 11, 12, 13, 14, 15, 17, 18

Usually the substrate is connected to the most negative voltage.
Sometimes it is the same as the source:



In this case, it works as we expect.

But when it isn't!

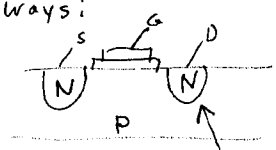


V_{TH} changes

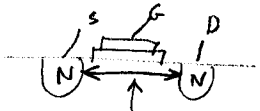
Formula is in the book — (4.2.5).
just be aware of it.

Breakdown

3 ways:

1. 

This junction — usually not destructive unless current is high

2. 

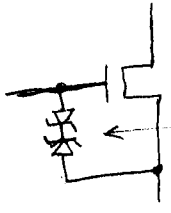
Punch through. — usually not destructive unless current is high.

3. Gate - source

Oxide breaks down. ≈30V. — Usually destructive

Static charge can destroy a device.

Protection:



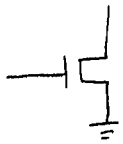
These diodes are often built-in for discrete devices.

The FET as a resistor

(IC 3)

When V_{DS} is low, triode region ----

$\downarrow R = ?$ (for V_{DS} small).



$V_{TH} = 1$

$K' = 2 \times 10^{-3}$ $\frac{\text{Amps}}{\text{Volt}^2}$

$W = L = 1\,\mu m.$

Triode region

$$I_D = K'\frac{W}{L}\Big(\underbrace{(V_{GS}-V_{TH})}_{\text{call this } V_{ov}.}V_{DS} - \tfrac{1}{2}V_{DS}^2\Big)$$

$$I_D = K'\frac{W}{L}\left(V_{ov}V_{DS} - \tfrac{1}{2}V_{DS}^2\right)$$

When V_{DS} is small, $V_{DS}^2 \approx 0$

$$I_D = K'\frac{W}{L}(V_{ov}V_{DS})$$

$R = \frac{V_{DS}}{I_D}$ so solve for $\frac{V_{DS}}{I_D}$ ...

$$\frac{1}{K'\frac{W}{L}V_{ov}} = \frac{V_{DS}}{I_D} = \frac{L}{W}\frac{1}{K'V_{ov}}$$

For this example: $R = \frac{1\mu}{1\mu}\frac{1}{(2\times10^{-3})(V_{ov})}$

$= \frac{1}{2\times10^{-3}}\frac{1}{V_{ov}}$

V_{ov}	R
0	∞
.5	1000
1	500
2	250
5	100

To change R...

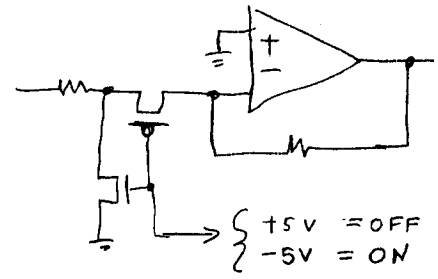
change L, W, V_{ov}.

$\uparrow$

voltage controlled resistor.

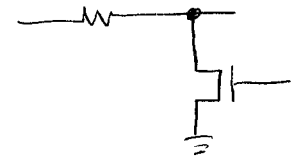
Circuits using FET's as voltage controlled resistors:

(IC 4)



Electronic switch -

(Very common circuit for selecting audio inputs)

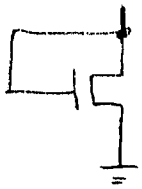


Variable attenuator.

(only for small signals!)

Uses: Automatic gain control.

"Diode connected" MOSFET



Example: $K' = 2\times10^{-3}\ \frac{\text{Amps}}{\text{volt}^2}$

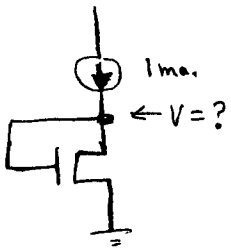
$W = L = 1\,\mu m.$

$V_{TH} = 1$ volt.

What region? $\longrightarrow$ saturation if $V_{TH} > 0$

$V_{DS} = V_{GS} > V_{GS} - V_{TH}.$

triode if $V_{TH} < 0$



$$I_D = \frac{1}{2} K' \frac{W}{L} (V_{GS} - V_{TH})^2$$

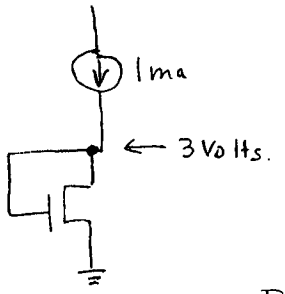
$$10^{-3} = \frac{1}{2}(2\times10^{-3})(1)(V_{GS} - 1)^2$$

$$\frac{10^{-3}}{\frac{1}{2}(2\times10^{-3})(1)} = (V_{GS} - 1)^2$$

$$(V_{GS} - 1)^2 = 1$$

$$V_{GS} = 2$$

Design for $V_{DS} = \underline{\underline{3}}$



$K' = 2\times10^{-3}\ \frac{A}{V^2}$, $V_{TH} = 1$ volt } Process parameters Given

$L \geq 1\,\mu m$, $W \geq 1\,\mu m$ } Determine actual L, W

$$I_D = \frac{1}{2} K' \frac{W}{L} (V_{GS} - V_{TH})^2$$

Substitute:

$$10^{-3} = \frac{1}{2}(2\times10^{-3})\frac{W}{L}\underbrace{(3-1)^2}_{2^2=4}$$

$$10^{-3} = 4\times10^{-3}\frac{W}{L}$$

$$\frac{10^{-3}}{4\times10^{-3}} = \boxed{\frac{W}{L} = \frac{1\,\mu m}{4\,\mu m}} \leftarrow \text{answer.}$$

$$r = \frac{1}{\frac{di}{dv}} = \frac{1}{K'\frac{W}{L}V_{ov}} = \frac{1}{g_m}.$$

```
Gnucap 2005.03.20 RCS 25.15
The Gnu Circuit Analysis Package
Never trust any version less than 1.0
Copyright 1982-2002, Albert Davis
Gnucap comes with ABSOLUTELY NO WARRANTY
This is free software, and you are welcome
to redistribute it under certain conditions
according to the GNU General Public License.
See the file "COPYING" for details.
gnucap> build

>m1 3 2 0 0 nn l=1u w=50u

>r1 4 2 9meg

>r2 2 0 1meg

>rd 4 3 1k

>cin 1 2 1u

>cout 3 5 1u

>vdd 4 0 dc 10

>vin 1 0 generator

>.model nn nmos level=1 vt=0 kp=2e-4

.model nn nmos level=1 vt=0 kp=2e-4
                        ^ ? what's this?
>.model nn nmos level=1 vth=0 kp=2e-4

.model nn nmos level=1 vth=0 kp=2e-4
                        ^ ? what's this?
>.model nn nmos level=1 vto=0 kp=2e-4

>

gnucap> pr op v nodes

gnucap> op

#          v(1)       v(2)       v(3)       v(4)       v(5)
 300.15    0.         1.         9.5        10.        0.
gnucap> pr op + id(m1)

gnucap> op

#          v(1)       v(2)       v(3)       v(4)       v(5)       id(M1)
 300.15    0.         1.         9.5        10.        0.         500.u
gnucap> l

M1 ( 3 2 0 0 )  nn  l= 1.u  w= 50.u
R1 ( 4 2 )  9.Meg
R2 ( 2 0 )  1.Meg
Rd ( 4 3 )  1.K
Cin ( 1 2 )  1.u
Cout ( 3 5 )  1.u
Vdd ( 4 0 )  DC  10.
Vin ( 1 0 ) GENERATOR
.model  nn  nmos  (level=1  tnom= 27.  fc= 0.5  pb= 0.8  cj= 0.  mj= 0.5  cjsw= 0.
 mjsw= 0.5  is= 10.f  rsh= 0.  cgso= 0.  cgdo= 0.  cgbo= 0.  vto= 0.  gamma= 0.  ph
i= 0.6  ld= 0.  uo= 600.  tpg=1  kp= 20.u)
*+(* cox= 0.)
.model  nn  nmos  (level=1  tnom= 27.  fc= 0.5  pb= 0.8  cj= 0.  mj= 0.5  cjsw= 0.
 mjsw= 0.5  is= 10.f  rsh= 0.  cgso= 0.  cgdo= 0.  cgbo= 0.  vto= 0.  gamma= 0.  ph
i= 0.6  ld= 0.  uo= 600.  tpg=1  kp= 20.u)
*+(* cox= 0.)
```

Manually enter a netlist.

I forgot the name.

Try again.

I give up — Look it up in the manual.

"print op v(nodes) print voltage at all nodes, for op analysis.

add this

wrong.

wrong.

Oh---- I have 3 copies of the model.

```
.model  nn  nmos  (level=1  tnom= 27.  fc= 0.5  pb= 0.8  cj= 0.  mj= 0.5  cjsw= 0.
 mjsw= 0.5  is= 10.f  rsh= 0.  cgso= 0.  cgdo= 0.  cgbo= 0.  vto= 0.  gamma= 0.  ph
i= 0.6  ld= 0.  uo= 600.  tpg=1  kp= 200.u)
*+(* cox= 0.)
gnucap> del nn

gnucap> del nn
gnucap> list

M1 ( 3 2 0 0 )  nn  l= 1.u  w= 50.u
R1 ( 4 2 )  9.Meg
R2 ( 2 0 )  1.Meg
Rd ( 4 3 )  1.K
Cin ( 1 2 )  1.u
Cout ( 3 5 )  1.u
Vdd ( 4 0 )  DC  10.
Vin ( 1 0 ) GENERATOR
gnucap> b

>.model nn nmos level=1 vto=0 kp=2e-4

>

gnucap> op

#          v(1)       v(2)       v(3)       v(4)       v(5)       id(M1)
 300.15    0.         1.         5.         10.        0.         0.005
gnucap> ac 1k

#Freq
 1.K
gnucap> pr ac v nodes

gnucap> ac

#Freq      v(1)       v(2)       v(3)       v(4)       v(5)
 1.K       1.         1.         10.        99.999n    10.
gnucap> del rd

gnucap> b

>Rd ( 4 3 )  1.K

gnucap> list

M1 ( 3 2 0 0 )  nn  l= 1.u  w= 50.u
R1 ( 4 2 )  9.Meg
R2 ( 2 0 )  1.Meg
Cin ( 1 2 )  1.u
Cout ( 3 5 )  1.u
Vdd ( 4 0 )  DC  10.
Vin ( 1 0 ) GENERATOR
.model  nn  nmos  (level=1  tnom= 27.  fc= 0.5  pb= 0.8  cj= 0.  mj= 0.5  cjsw= 0.
 mjsw= 0.5  is= 10.f  rsh= 0.  cgso= 0.  cgdo= 0.  cgbo= 0.  vto= 0.  gamma= 0.  ph
i= 0.6  ld= 0.  uo= 600.  tpg=1  kp= 200.u)
*+(* cox= 0.)
Rd ( 4 3 )  1.K
gnucap> op

#          v(1)       v(2)       v(3)       v(4)       v(5)       id(M1)
 300.15    0.         1.         5.         10.        0.         0.005
gnucap> ac

#Freq      v(1)       v(2)       v(3)       v(4)       v(5)
 1.K       1.         1.         10.        99.999n    10.
```

It took the first. (It's not a bug, it's a feature.)

ok---

Enter it again.

This is what I expected.

Gain is as expected.

see all of the parameters.

Same as above — I did it again. Don't know why.

```
gnucap> ls

ls
^ ? bad command
gnucap> list

M1 ( 3 2 0 0 )  nn  l= 1.u  w= 50.u
R1 ( 4 2 )  9.Meg
R2 ( 2 0 )  1.Meg
Cin ( 1 2 )  1.u
Cout ( 3 5 )  1.u
Vdd ( 4 0 )  DC  10.
Vin ( 1 0 ) GENERATOR
.model  nn  nmos  (level=1  tnom= 27.  fc= 0.5  pb= 0.8  cj= 0.  mj= 0.5  cjsw= 0.
 mjsw= 0.5  is= 10.f  rsh= 0.  cgso= 0.  cgdo= 0.  cgbo= 0.  vto= 0.  gamma= 0.  ph
i= 0.6  ld= 0.  uo= 600.  tpg=1  kp= 200.u)
*+(* cox= 0.)
Rd ( 4 3 )  1.K
gnucap> del nn
```

I wanted to see it — it scrolled off the screen.

← delete the model

```
gnucap> b

>.model nn nmos level=1 vto=0 kp=2e-4 lambda=.01

>

gnucap> l

M1 ( 3 2 0 0 )  nn  l= 1.u  w= 50.u
R1 ( 4 2 )  9.Meg
R2 ( 2 0 )  1.Meg
Cin ( 1 2 )  1.u
Cout ( 3 5 )  1.u
Vdd ( 4 0 )  DC  10.
Vin ( 1 0 ) GENERATOR
Rd ( 4 3 )  1.K
.model  nn  nmos  (level=1  tnom= 27.  fc= 0.5  pb= 0.8  cj= 0.  mj= 0.5  cjsw= 0.
 mjsw= 0.5  is= 10.f  rsh= 0.  cgso= 0.  cgdo= 0.  cgbo= 0.  vto= 0.  gamma= 0.  ph
i= 0.6  lambda= 0.01  ld= 0.  uo= 600.  tpg=1  kp= 200.u)
*+(* cox= 0.)
gnucap> op
```

← enter a new one — with λ.

OK — it changed a little.

```
#          v(1)       v(2)       v(3)       v(4)       v(5)       id(M1)
 300.15    0.         1.         4.7619     10.        0.         0.0052381
gnucap> ac

#Freq      v(1)       v(2)       v(3)       v(4)       v(5)
 1.K       1.         1.         9.9773     99.772n    9.9773
gnucap> pr op + ro m1

gnucap> op

#          v(1)       v(2)       v(3)       v(4)       v(5)       id(M1)     ro(M1
)
 300.15    0.         1.         4.7619     10.        0.         0.0052381  ??

gnucap> pr op - ro m1 + gds m1

gnucap> op

#          v(1)       v(2)       v(3)       v(4)       v(5)       id(M1)     gds(M
1)
 300.15    0.         1.         4.7619     10.        0.         0.0052381  50.u

gnucap> pr op + gm m1

gnucap> op

#          v(1)       v(2)       v(3)       v(4)       v(5)       id(M1)     gds(M
1)    gm(M1)
 300.15    0.         1.         4.7619     10.        0.         0.0052381  50.u
      0.010476
gnucap> !date

Thu Apr  7 23:47:25 EDT 2005
gnucap> del Rd
```

it dropped. But not as much as expected. Why?

$r_o = 20K$

← Remove the drain resistor

```
gnucap> b

>Id 4 3 dc .005

>

gnucap> op

#          v(1)       v(2)       v(3)       v(4)       v(5)       id(M1)     gds(M
1)    gm(M1)
 300.15    0.         1.         0.90529    10.        0.         0.005      0.001
0052  0.0091349
gnucap> b

>Id 4 3 dc .0053

replacing [Id]
>

gnucap> op

#          v(1)       v(2)       v(3)       v(4)       v(5)       id(M1)     gds(M
1)    gm(M1)
 300.15    0.         1.         6.0002     10.        0.         0.0053     50.u
      0.0106
gnucap> op

#          v(1)       v(2)       v(3)       v(4)       v(5)       id(M1)     gds(M
1)    gm(M1)
 300.15    0.         1.         6.0002     10.        0.         0.0053     50.u
      0.0106
gnucap> ac

#Freq      v(1)       v(2)       v(3)       v(4)       v(5)
 1.K       1.         1.         212.       1.1111p    212.
gnucap> b

>Id 4 3 dc .005

replacing [Id]
>

gnucap> op

#          v(1)       v(2)       v(3)       v(4)       v(5)       id(M1)     gds(M
1)    gm(M1)
 300.15    0.         1.         0.90529    10.        0.         0.005      0.001
0052  0.0091349
gnucap> ac

#Freq      v(1)       v(2)       v(3)       v(4)       v(5)
 1.K       1.         1.         9.0874     1.1111p    9.0874
gnucap> pr op + region(m1)

gnucap> op

#          v(1)       v(2)       v(3)       v(4)       v(5)       id(M1)     gds(M
1)    gm(M1)     region(M1)
 300.15    0.         1.         0.90529    10.        0.         0.005      0.001
0052  0.0091349  3.
gnucap>
```

← Make current a little higher. (.0052381 would be exact).

?? Too low.

← better.

← current source back to 5ma.

← gain OK higher than predicted. Why?

Confirm as before.

Region probe

← gain = 9 ??

← triode region. (7 = saturation, 0 = cutoff)