BASIC SEMICONDUCTOR ELECTRONIC CIRCUITS

Introduction of two basic electronic elements: diode and transistor

LEARNING GOALS

Diodes
- structure and four modeling techniques

Transistors
- MOSFETs and BJTs.
- MOSFETs in switching and amplification

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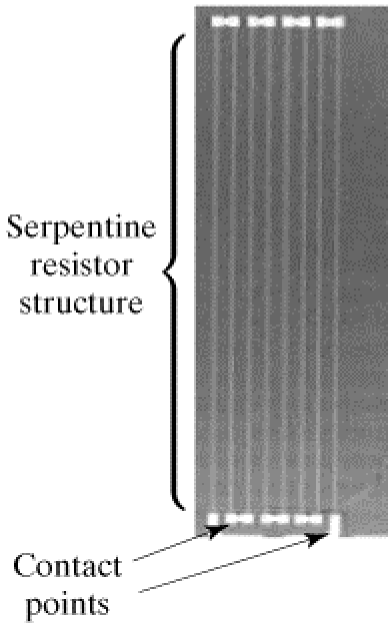
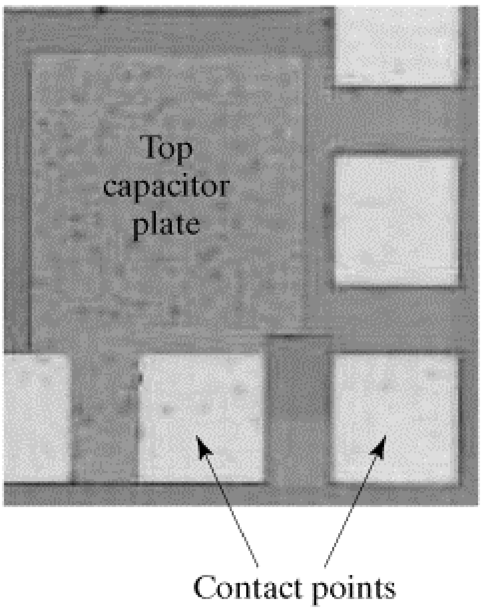
PASSIVE DEVICES IN INTEGRATED CIRCUITS

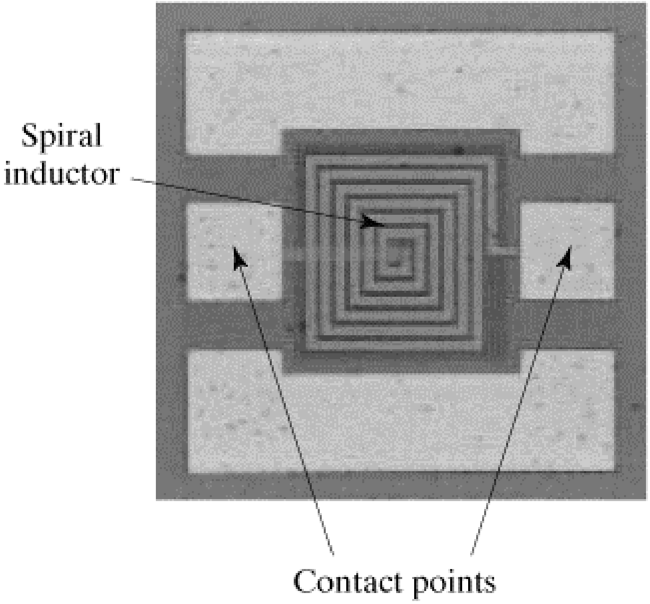


Resistor

Silicon is the bottom plate!



Capacitor



Inductor

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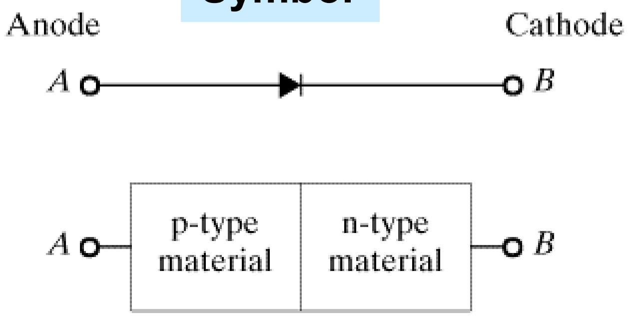
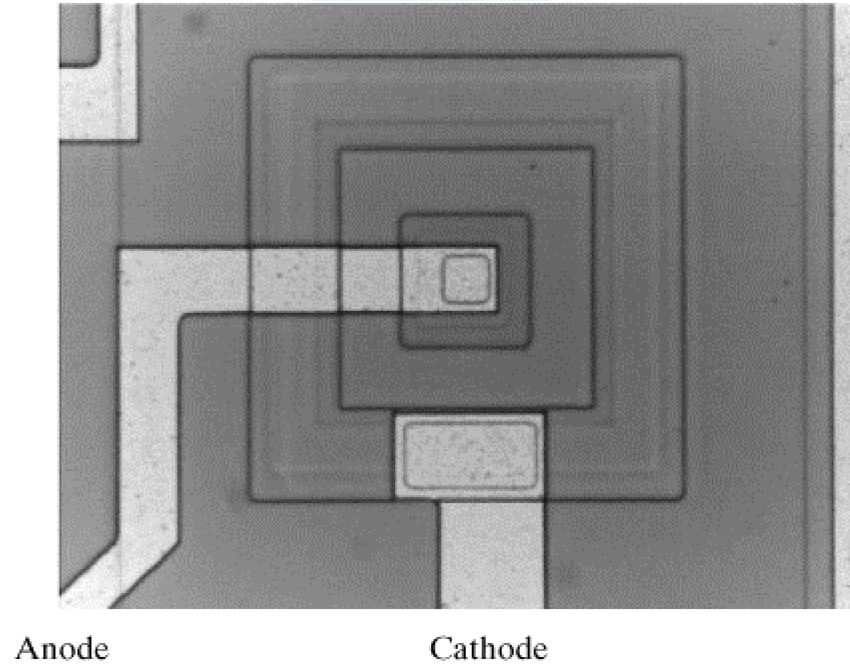
DIODES

Symbol

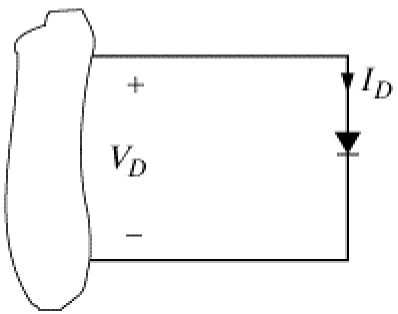


(a)

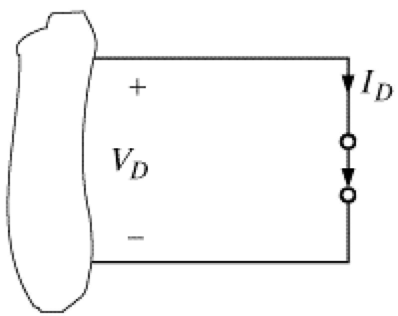
Structure



(b)

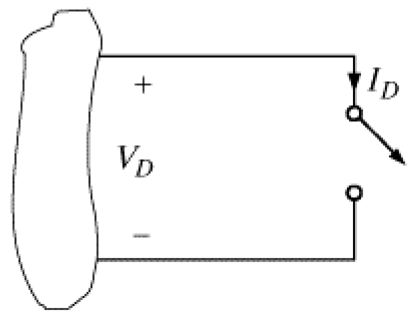


I-V convention



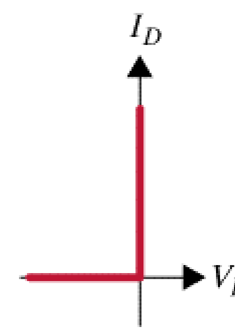
$V_D = 0$
$I_D > 0$

Ideal diode Forward bias



$V_D < 0$
$I_D = 0$

Ideal diode Reverse bias



Ideal diode I - V curve

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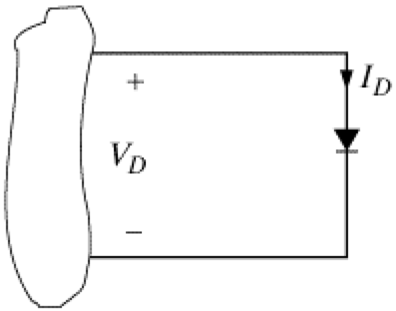
Actual diode I - V characteristic



$$I_D = I_S\left[e^{\frac{qV_D}{nkT}} - 1\right]$$

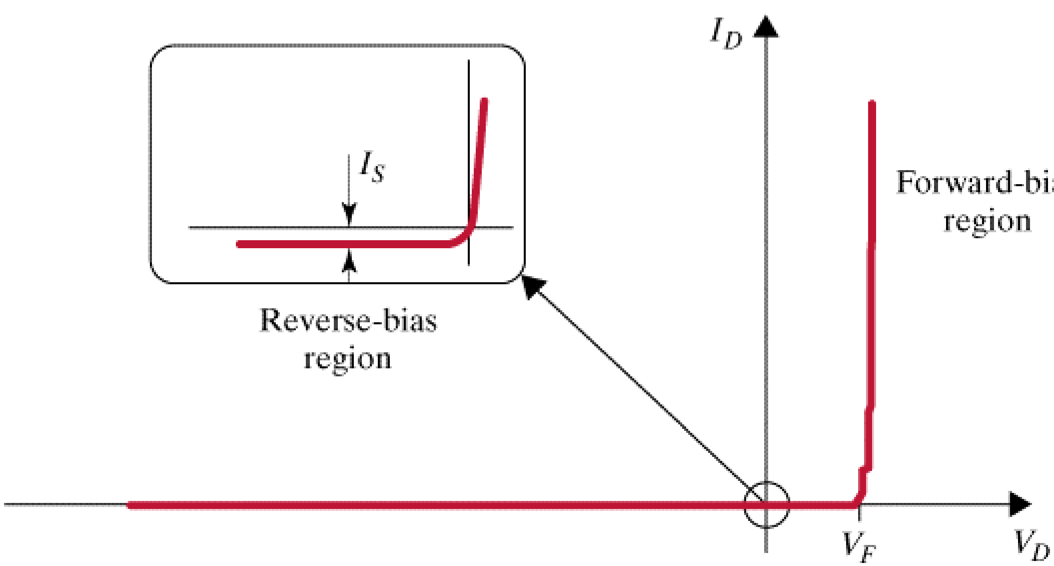
I_S = reverse saturation current
q = charge of electron
k = Boltzmann's constant
T = Temperature in degrees Kelvin
n = 'ideality' factor

Typically : $I_S \approx 10^{-14} A, n = 1$

For high power diodes : $I_S \approx 10^{-10} A, n = 2$

$\frac{q}{kT} \approx 39$ at room temperature

I - V curve of an actual diode



Next we develop two approximations to the actual I - V curve

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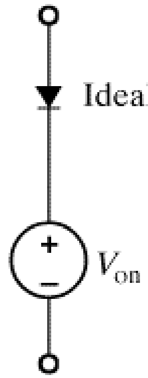
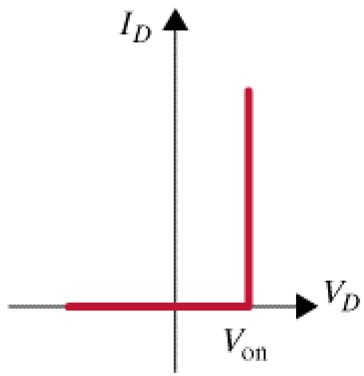
Constant voltage model

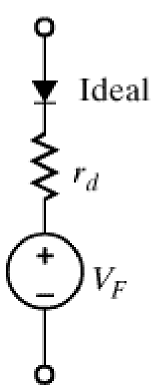


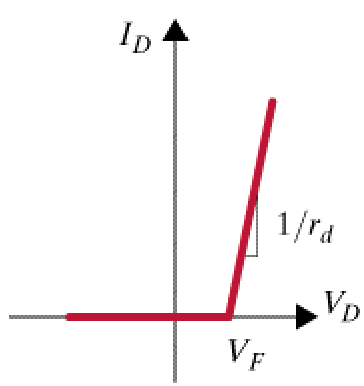


Circuit equivalent

I - V curve

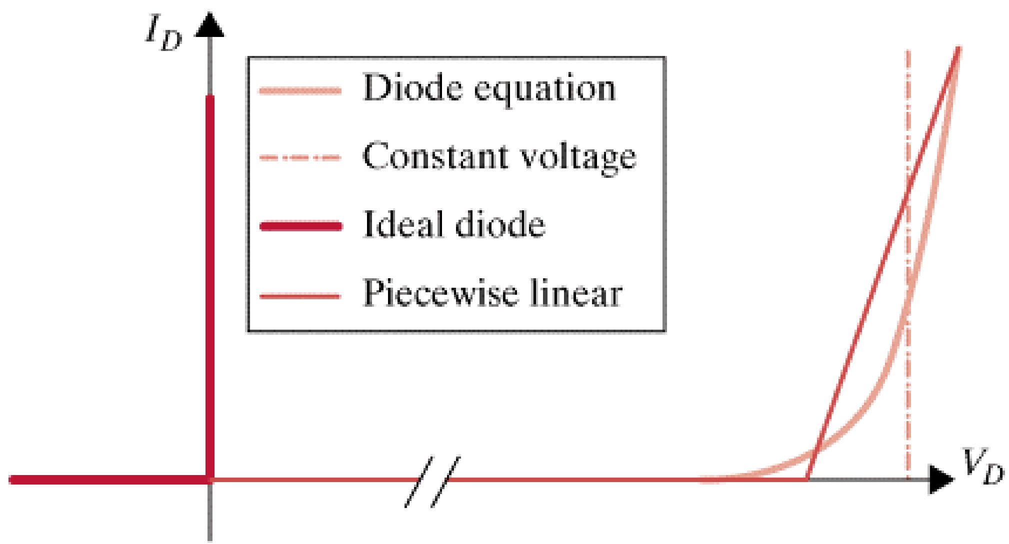
Piecewise linear model





Circuit equivalent

I - V curve



Comparison of models

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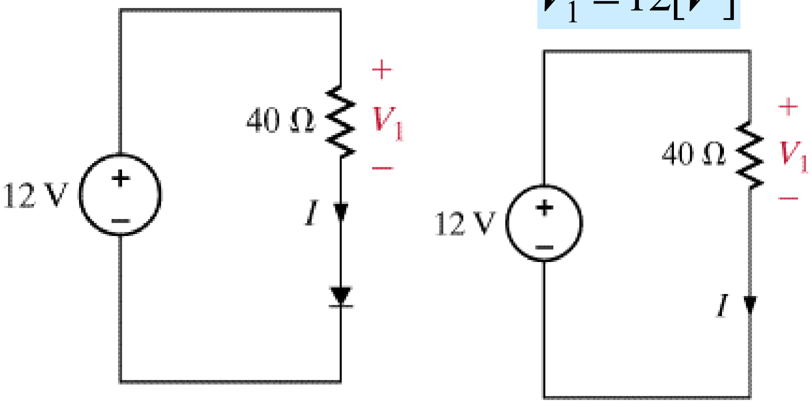
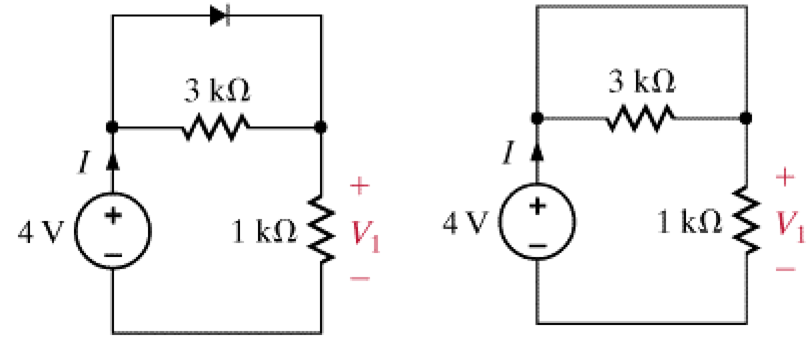
LEARNING EXAMPLE Using the ideal model, find the voltage V_1

$V_1 = 12[V]$

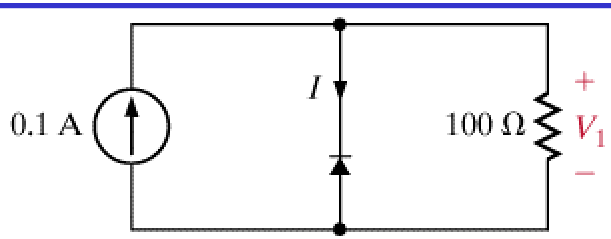


Diode is forward biased by the source

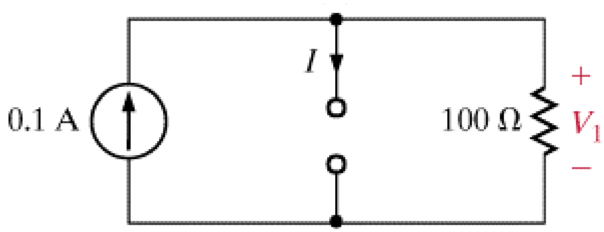


Forward bias

$V_1 = 4[V]$

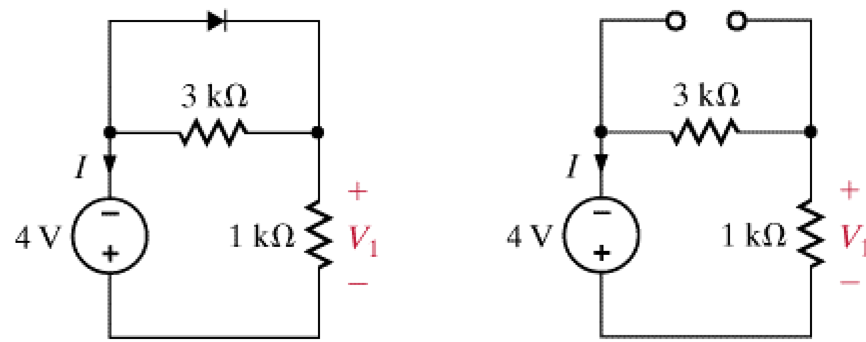


Diode is reverse biased



$V_1 = 10[V]$

(b)



Reverse bias

$V_1 = 1[V]$

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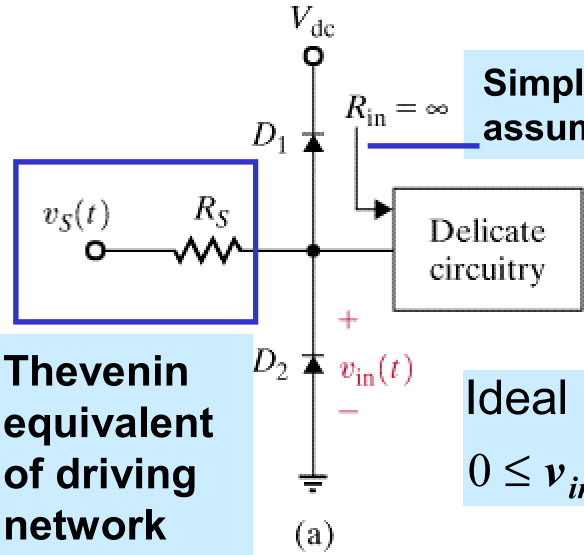
LEARNING EXAMPLE

Analyze the protection circuit using diode models



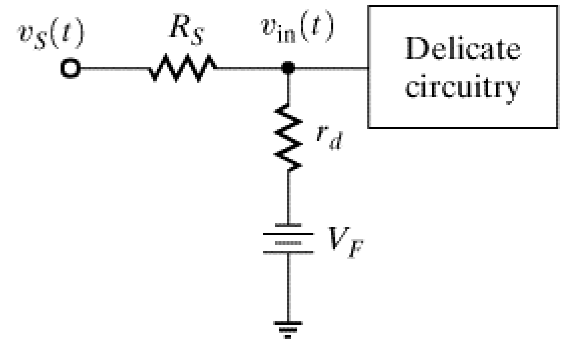
Thevenin equivalent of driving network

Simplifying assumption $v_{in} = v_s$

When diodes are reverse biased

Ideal diode model

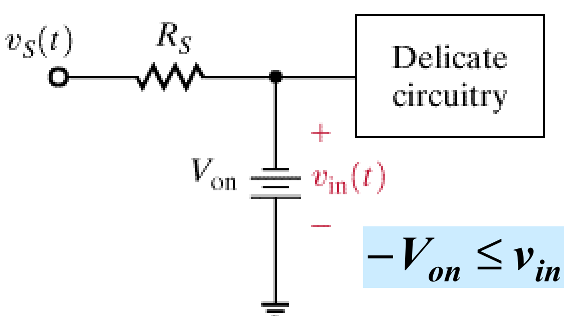
$$0 \le v_{in} \le V_{dc}$$



Under-voltage with piecewise linear model

Using source superposition

$$v_{inu} = \frac{r_d}{r_d + R_s} v_s - \frac{R_s}{R_s + r_d} V_F$$



$$-V_{on} \le v_{in} \le V_{dc} + V_{on}$$

Under-voltage protection model using diode constant voltage model

Using a similar way for over-voltage

$$v_{ino} = \frac{r_d}{r_d + R_s} v_S + \frac{R_S}{r_d + R_s} (V_{dc} + V_F)$$

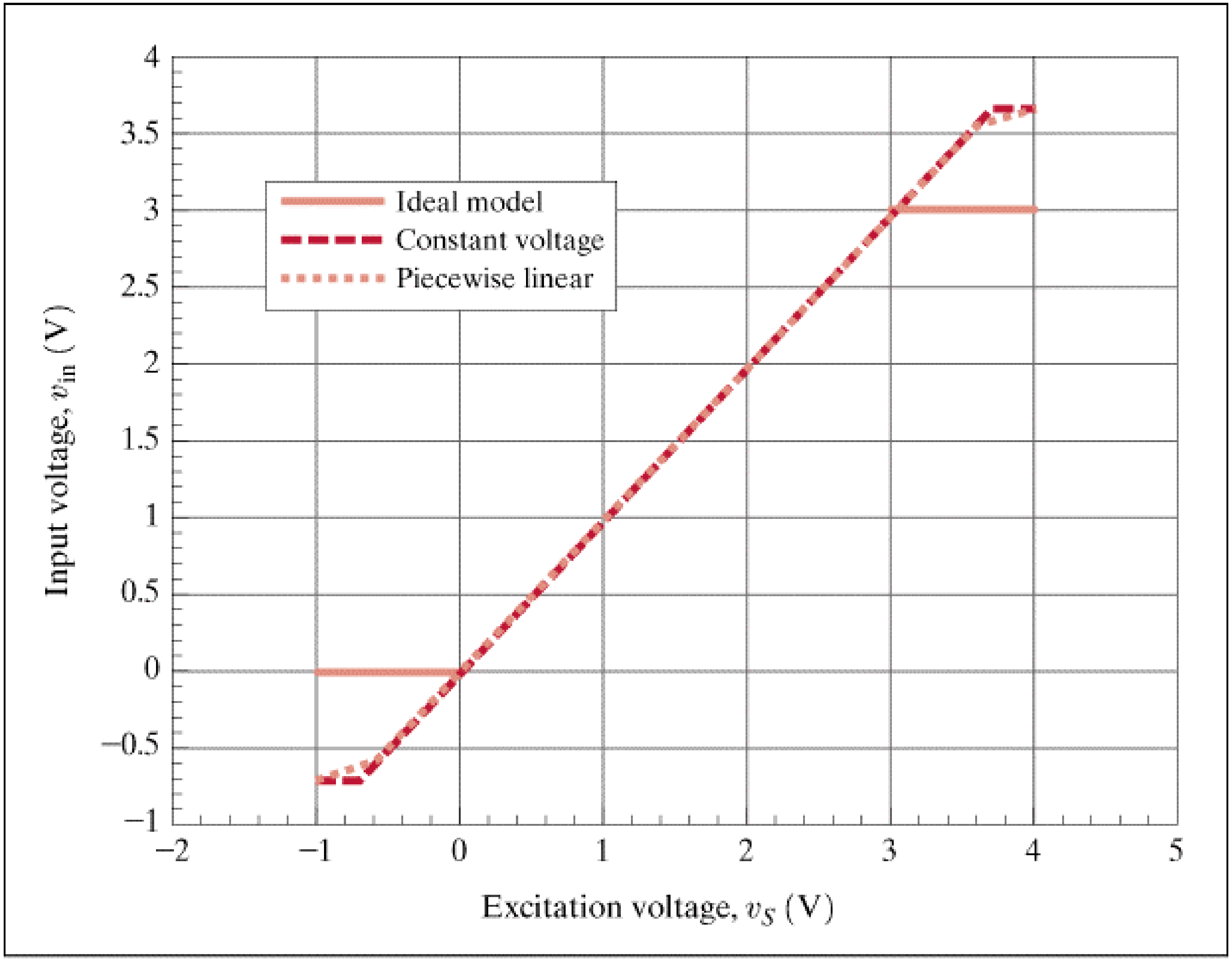
The figure in the next slide compares the three models

$V_{dc} = 3V$

$V_{on} = 0.7V$ (constant voltage model)

$\left.\begin{aligned} V_F &= 0.6V \\ r_d &= 10\Omega \end{aligned}\right\}$ (piecewise linear model)

$R_S = 40\Omega$



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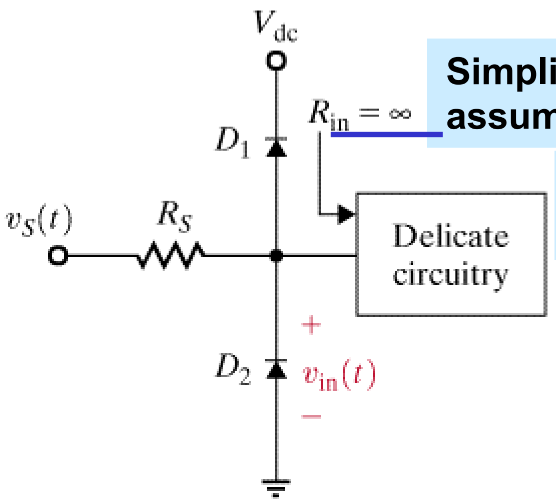
Analysis using non linear diode model



Simplifying assumption $v_{in} = v_s$

When diodes are reverse biased

Under-voltage scenario. Top diode open

$$\frac{v_S - v_{in}}{R_S} + i_D = 0$$

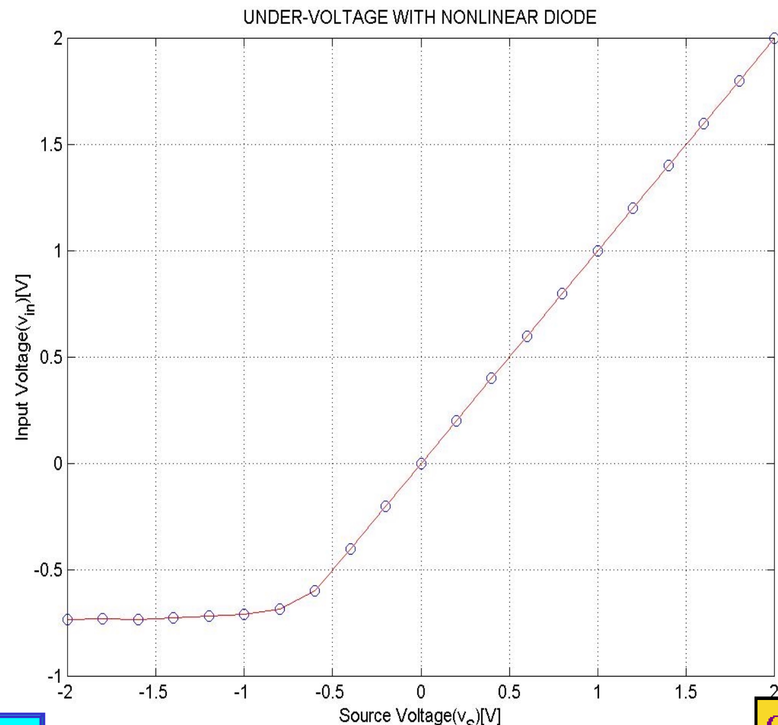
$$i_D = I_S\left[e^{39 v_D} - 1\right] = I_S\left[e^{-39 v_{in}} - 1\right] = \frac{v_{in} - v_S}{R_S}$$

$$v_D = -v_{in}$$

$$v_{in} = \frac{1}{39}\ln\left[\frac{v_{in} - v_S}{R_s I_s} + 1\right]$$

Implicit function. Must be evaluated numerically

```
Is=1e-14;% MATLAB SCRIPT TO ANALYZE
n=1;      % UNDER-VOLTAGE
Rs=40;
vs=[-2:.2:2]';
vin=[];
for k=1:length(vs)
   x0=[vs(k);vs(k);Rs;Is];
   kcl=inline('((x(2)-
x(1))/x(3)+x(4)*(exp(-39*x(1))-1))^2');
   x=fminsearch(kcl,x0);
   vin=[vin;x(1)];
end
plot(vs,vin,'bo',vs,vin,'r'),
title('UNDER-VOLTAGE WITH NONLINEAR
DIODE')
xlabel('Source Voltage(v_S)[V]'),
ylabel('Input Voltage(v_{in})[V]'),grid
```



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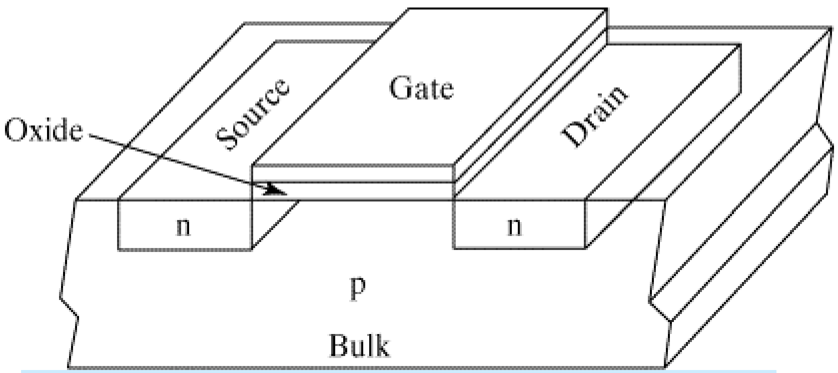
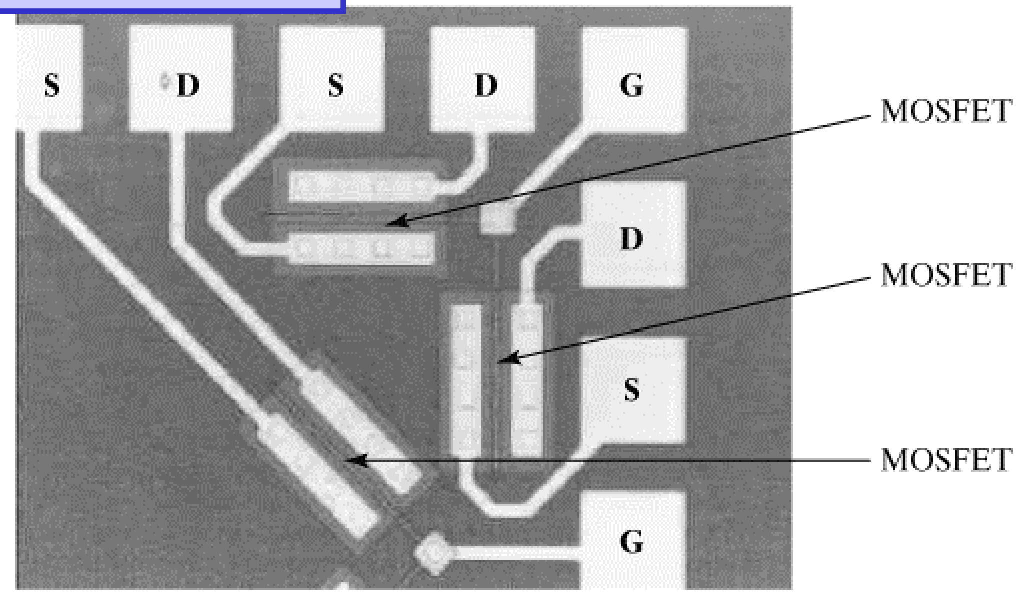
TRANSISTORS

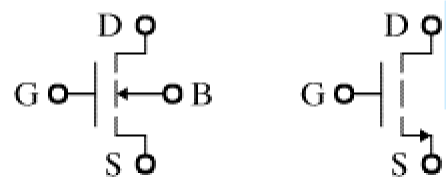
STRUCTURE OF MOSFETs

The oxide is an insulator allowing zero current into the gate

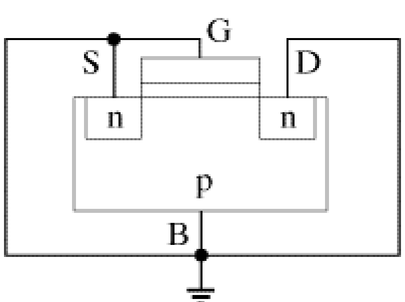


The gate voltage controls resistance from source to drain (in linear range)

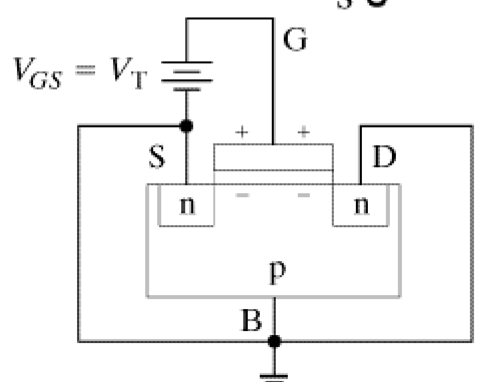




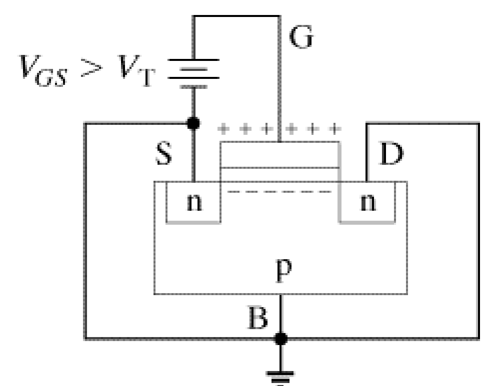
Bulk internally connected to source



Cutoff state



threshold



conducting

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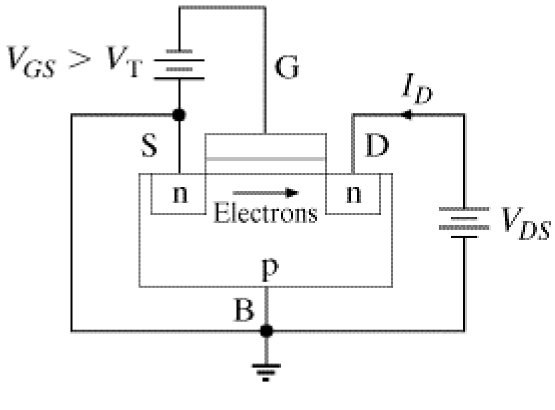
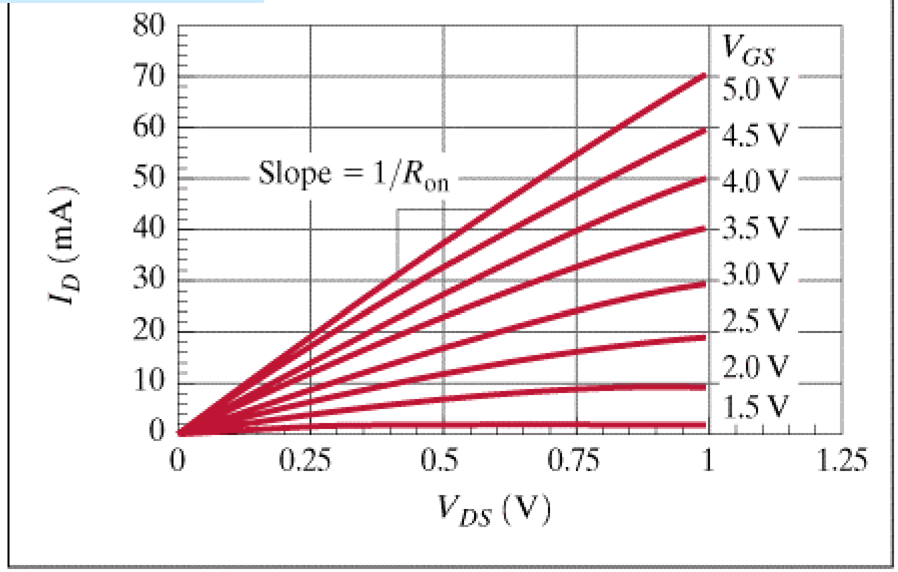
N - channel MOSFET in the linear range



(a)

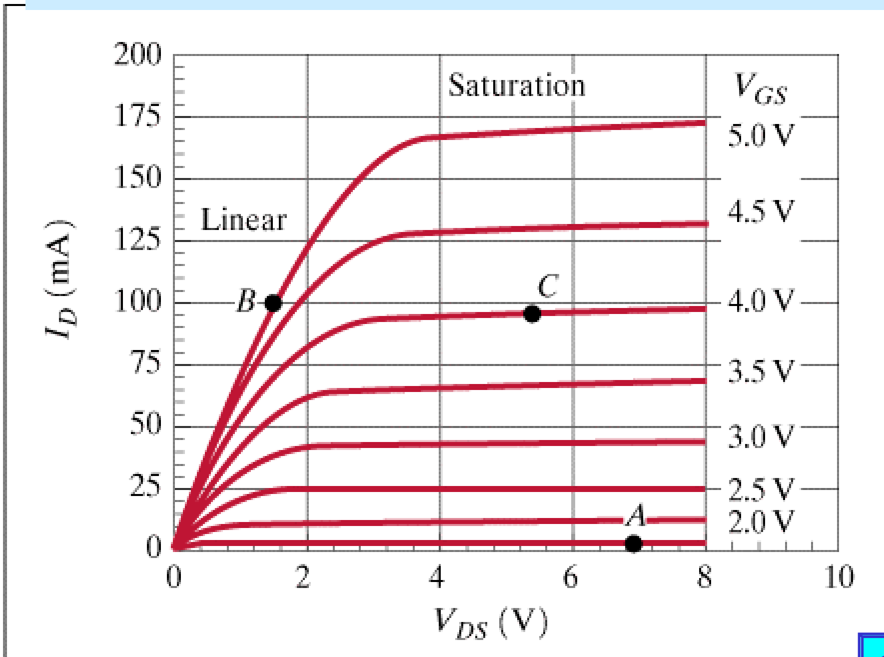
$$V_{DS} = R_{on} I_D$$



Linear characteristic

Threshold voltage $V_T = 1V$

Complete characteristics of n-channel MOSFET



A cutoff region

B linear region

C saturation region

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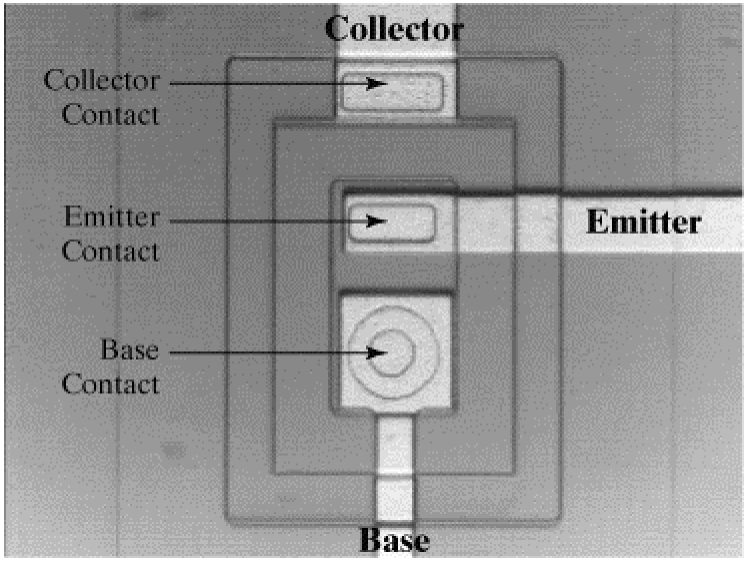
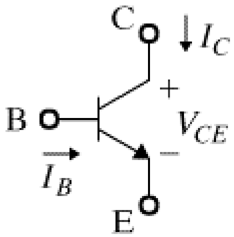
STRUCTURE OF BJTs (Bipolar Junction Tansistors)



(a)



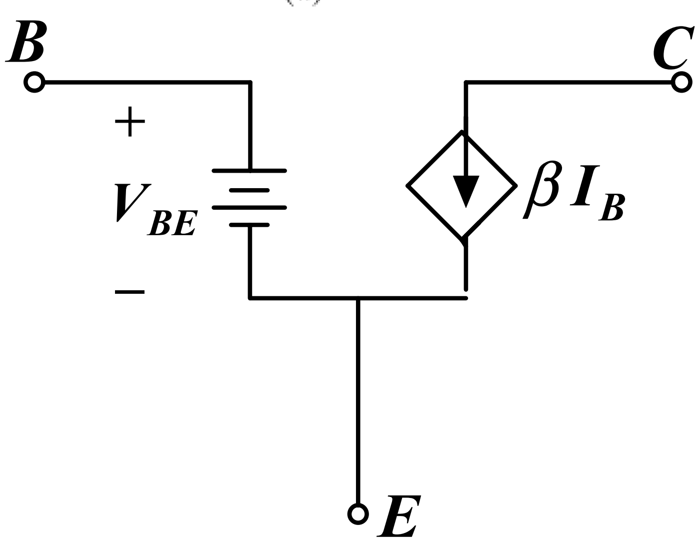
NPN transistor

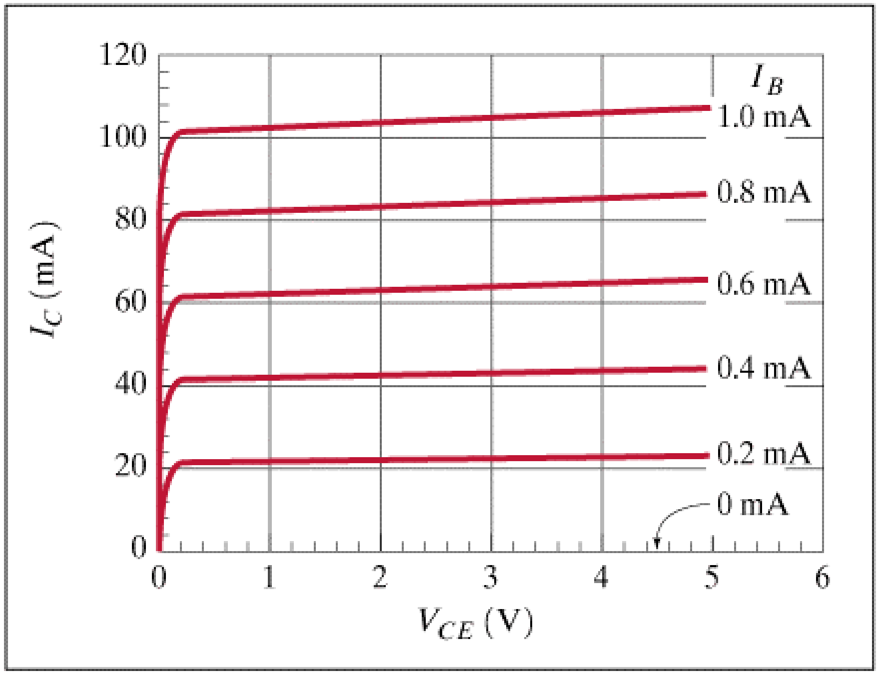
$V_{BE} \approx$ constant

Active mode : $I_C = \alpha I_E, I_C = \beta I_B \Rightarrow \beta = \dfrac{\alpha}{1-\alpha}$

$\beta =$ common emitter current gain (>> 1)

$\alpha =$ common base current gain





Linear model for BJT in active mode

(b)

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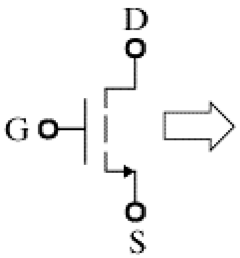
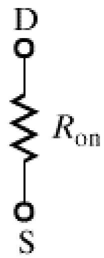
MODELING MOSFET SWITCHING APPLICATIONS



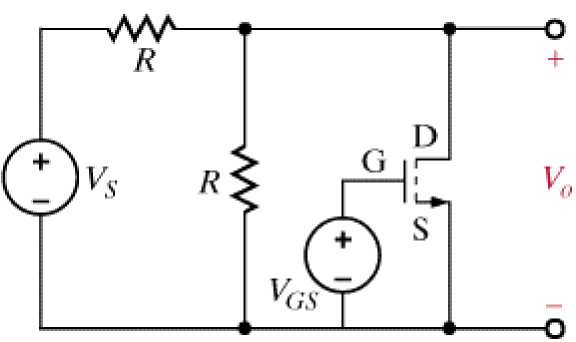
Cutoff



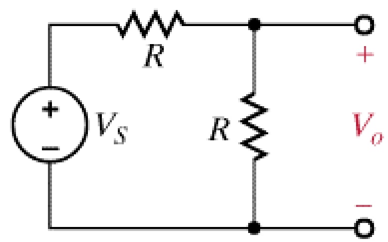
Linear Region

R_{on} depends on gate voltage.

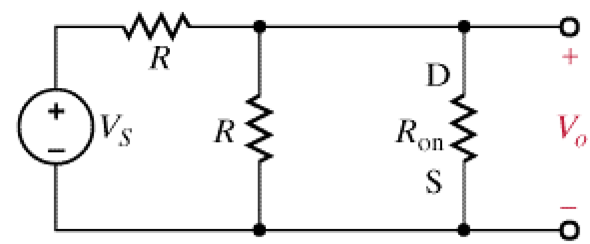
Typical values range from a few hundred Ohms for low-current applications to milli-ohms for currents in the tens of Amperes



Basic switching circuit



Cutoff (switch open)



'Switch closed'

$$V_o = \frac{V_S}{2 + \frac{R}{R_{on}}}$$

Ideally, $V_o = 0$

In the next slide we quantify this non-ideal behavior

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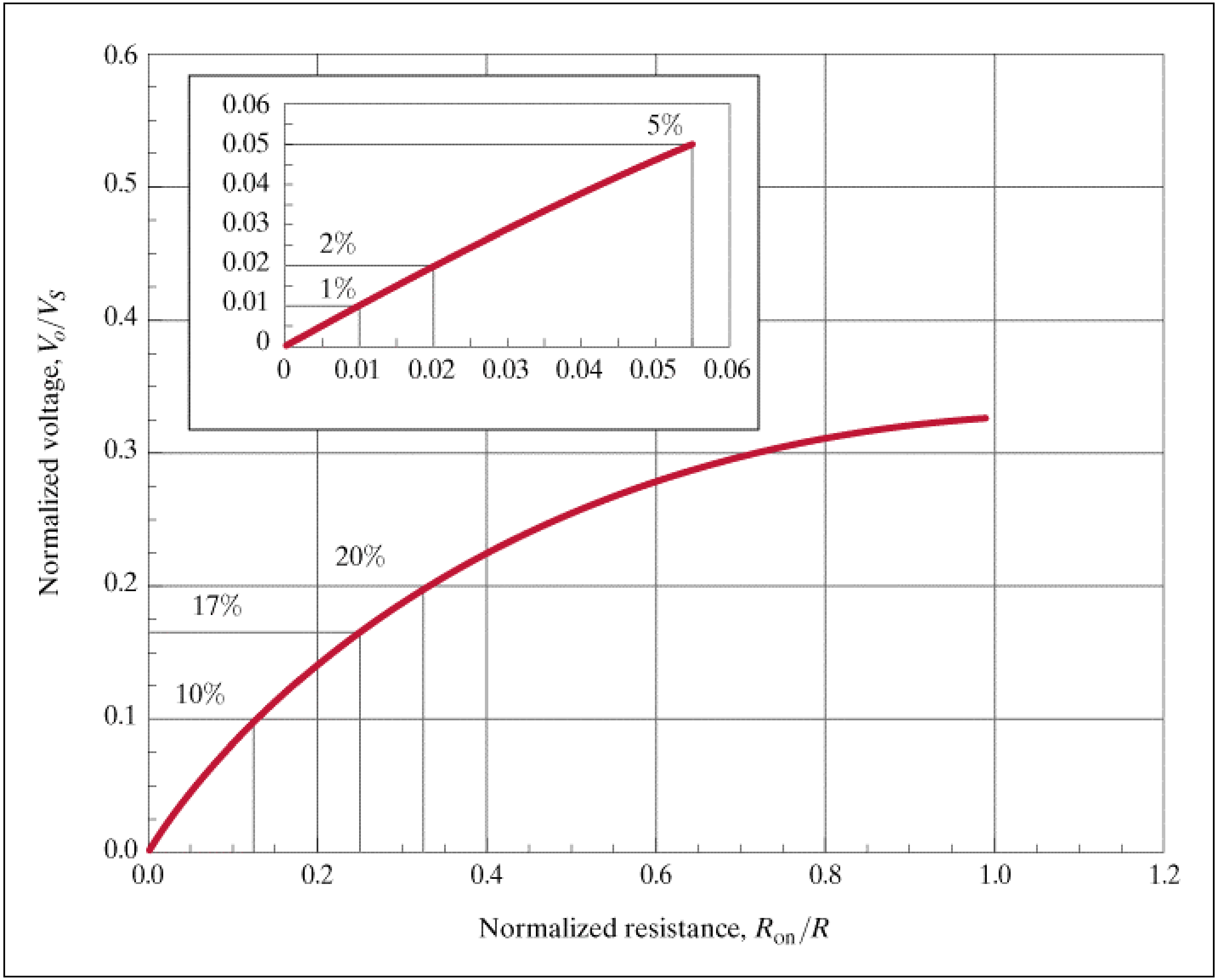
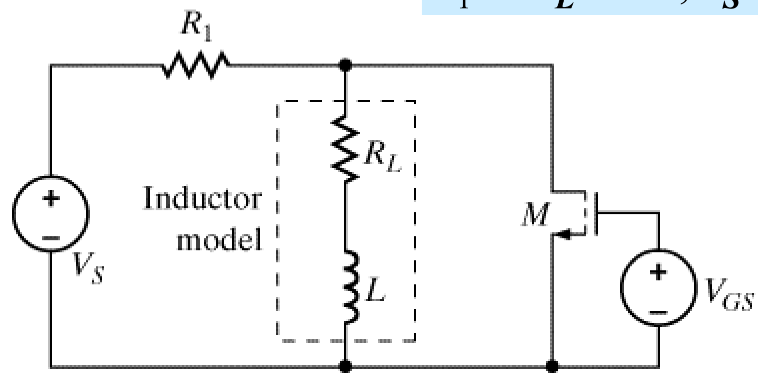
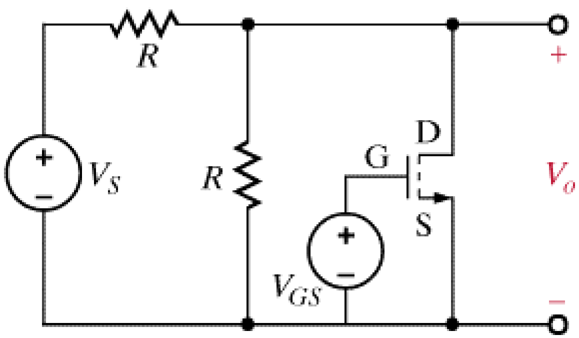


The ratio, $\frac{R_{on}}{R}$, is more important than the actual value of R_{on}

LEARNING EXAMPLE The MOSFET is used as switch to energize and de-energize an inductor. Determine the output voltage with the “switch closed”

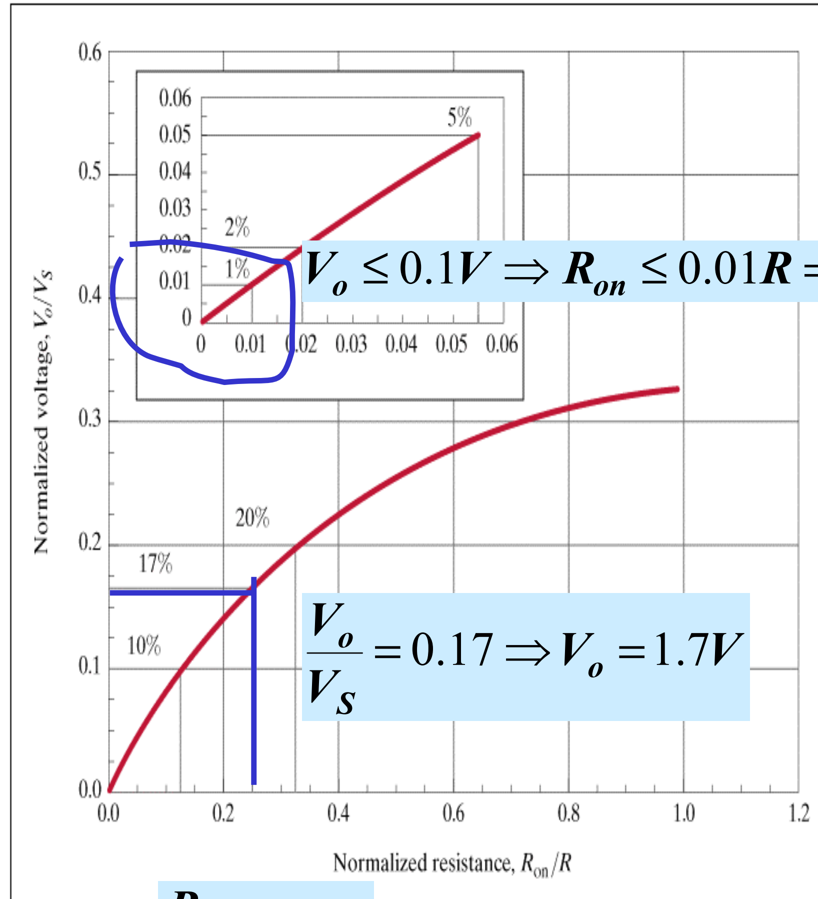
$$R_1 = R_L = 1\Omega, V_S = 10V, R_{on} = 0.25\Omega$$





Circuit after all transients have subsided (R=1 Ohm)

$$V_{on} = \frac{V_S}{2 + \frac{R}{R_{on}}}$$



$$V_o \le 0.1V \Rightarrow R_{on} \le 0.01R = 10m\Omega$$

$$\frac{V_o}{V_S} = 0.17 \Rightarrow V_o = 1.7V$$

$$\frac{R_{on}}{R} = 0.25$$

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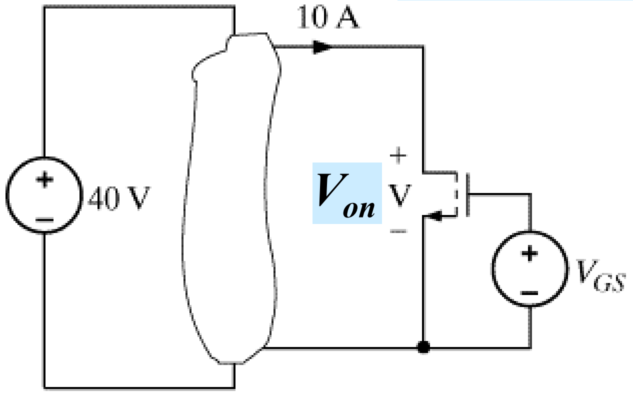
LEARNING EXAMPLE **The MOSFET is used to switch 10A of current. The voltage drop across the FET in the on state must be less than 4% of the supply voltage. Find the maximum value of *R_on***



$$V_{on} = 10\,A \times R_{on} \le 0.04 \times 40$$

$$R_{on} \le 0.16\Omega$$

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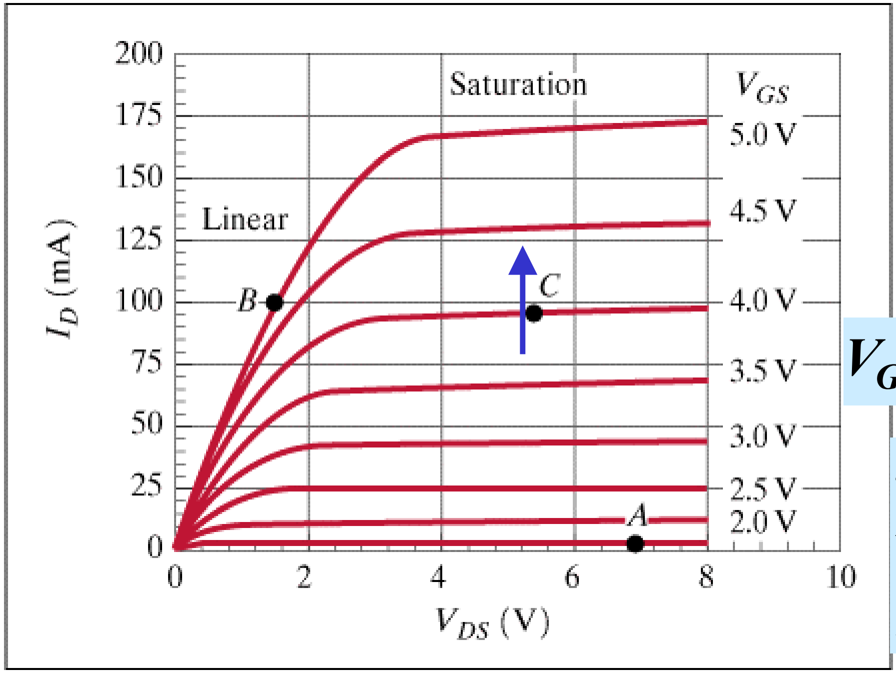
MODELING AMPLIFIER APPLICATIONS

MOSFET in saturation



Linear model : $i_d = g_m v_{gs}$

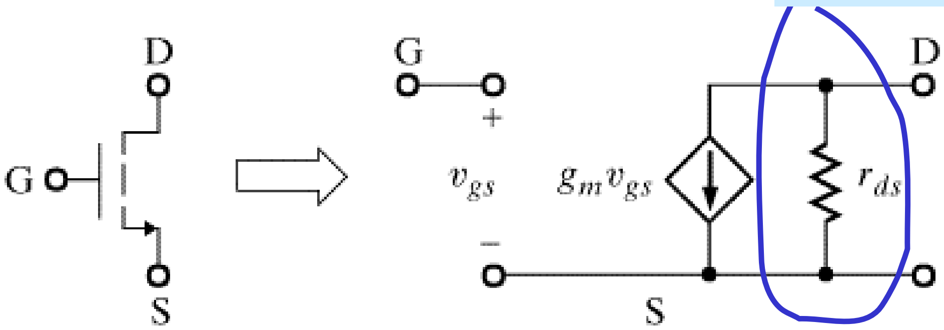
$V_{GS} \uparrow$ (by v_{gs}) $\Rightarrow I_D \uparrow$ (by $i_d e$)

i_d applied to a resistor, R, will generate

$v_o = (R g_m) v_{gs}$

$R g_m > 1 \Rightarrow$ amplificat ion

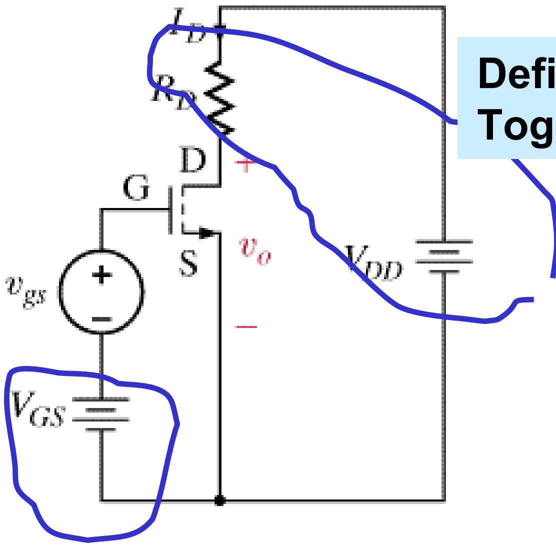
Due to non-zero slope of I - V curves in saturation



Linear (small signals) model for MOSFET

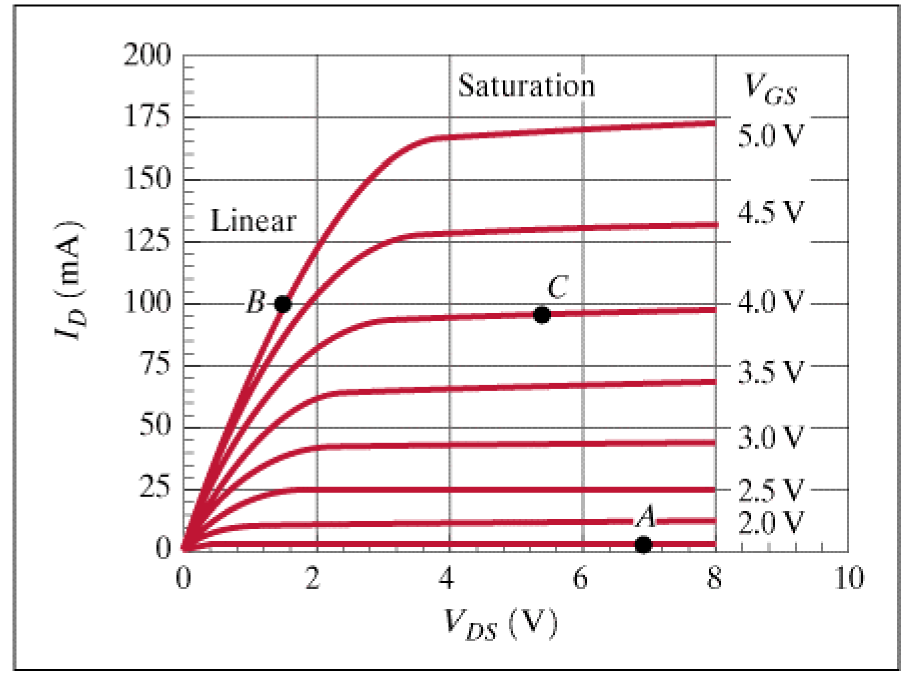
Common Source Amplifier

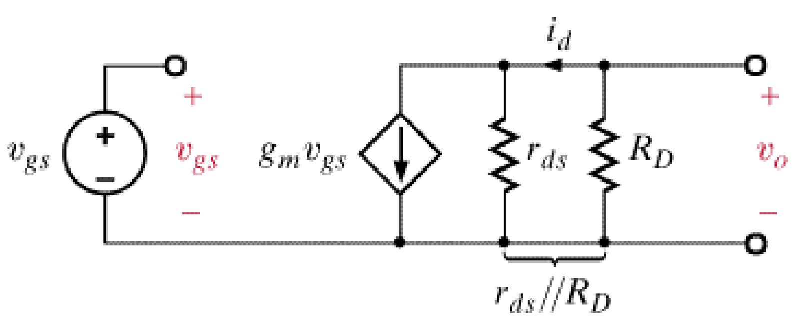
MOSFET in saturation range



Define drain-source current.
Together with bias voltage they define operating point

Bias voltage.
Helps to define location on I - V curve.





The operating point determines the values of the parameters g_m, r_{ds} **in the linear model**

Linear model relating *changes* in gate voltage to *changes* in output voltage

R_D also helps to determine gain

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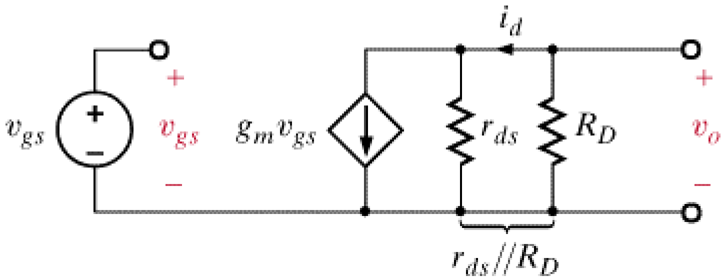
LEARNING EXAMPLE

Given : $g_m = 50mA/V$, $r_{ds} = 2k\Omega$.

Determine R_D to produce a gain of -50



(b)

$$v_o = -(r_{ds} \| R_D) g_m v_{gs} \Rightarrow A = -(r_{ds} \| R_D) g_m$$

$$\therefore 0.05[V/V] \frac{2k\Omega \times R_D}{2k\Omega + R_D} = -50 \Rightarrow R_D = 2k\Omega$$

LEARNING EXAMPLE

If $r_{ds} = 2k \pm 25\%$, what are the expected minimum and maximum gains

$$r_{ds\,\min} = 2k(1-0.25) = 1.5k\Omega \Rightarrow A_{\min} = -0.05(1.5k \| 2k) = -42.9$$

$$r_{ds\,\max} = 2k(1+0.25) = 2.5k\Omega \Rightarrow A_{\max} = -0.05(2.5k \| 2k) = -55.5$$

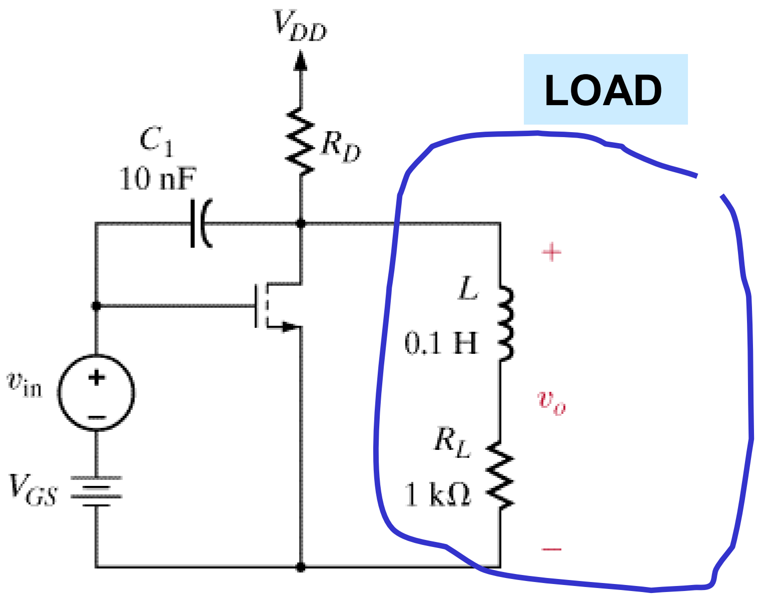
PROBLEM

If one must assure a gain of at least 50 in absolute value what should be the value for Rd?

LEARNING EXAMPLE

Find the value of R_d such that maximum average power is transferred to the load at 30krad/s $\Rightarrow \omega = 3\times 10^4$

$$\therefore Z_{TH} = R - j\omega L = 1 - j3\,k\Omega$$



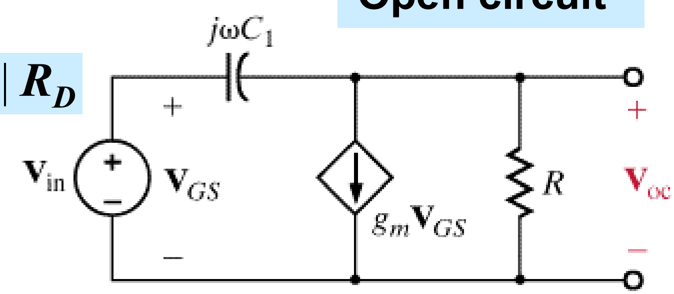
$$g_m = 1.5mS,\ r_{ds} = 110k\Omega$$

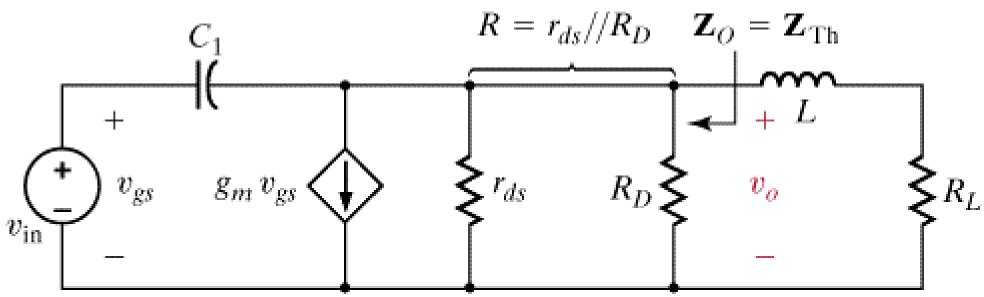
Because there are dependent sources we must determine open-circuit voltage and short-circuit current

$$Z_{TH} = \frac{V_{OC}}{I_{SC}}$$

Open circuit

$$R = r_{ds} \,||\, R_D$$





Small signals model

$$\text{KCL:}\ \frac{V_{OC}}{R} - g_m V_{gs} + \frac{V_{OC} - V_{gs}}{\frac{1}{j\omega C_1}} = 0$$

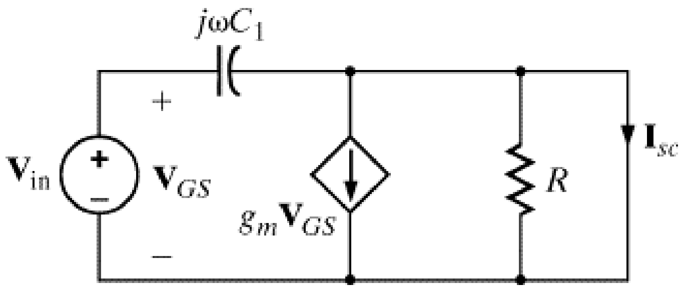
$$V_{OC} = V_{gs}\frac{(j\omega C_1 - g_m)R}{j\omega C_1 R + 1}$$

For maximum power transfer the Thevenin impedance of the amplifier must be the complex conjugate of the load

GEAUX

EXAMPLE (continued)

Determination of short-circuit current



$$I_{SC} = -g_m V_{gs} + j\omega C_1 V_{gs} = (j\omega C_1 - g_m) V_{gs}$$

$$V_{OC} = V_{gs} \frac{(j\omega C_1 - g_m) R}{j\omega C_1 R + 1}$$

$$Z_{TH} = \frac{V_{OC}}{I_{SC}} = \frac{R}{j\omega C_1 R + 1} \times \frac{1 - j\omega C_1 R}{1 - j\omega C_1 R}$$

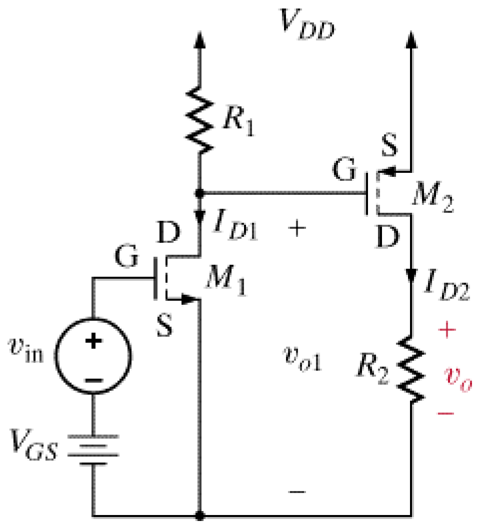
$$Z_{TH} = \frac{R}{1 + (\omega C_1)^2} - j \frac{\omega C_1 R^2}{1 + (\omega C_1)^2} = 1000 - j3000\ \Omega$$

$$\therefore \omega C_1 R = 3 \Rightarrow R = \frac{3}{3 \times 10^4 \times 10^{-9}} = 10k\Omega$$

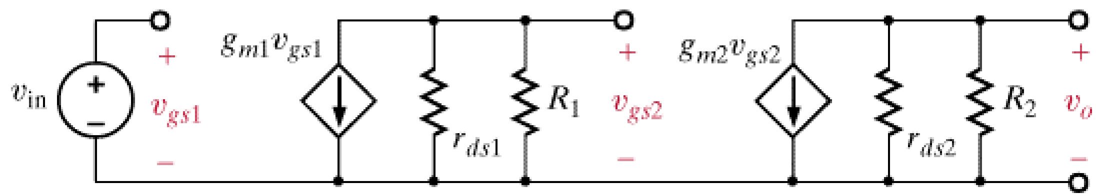
$$10k\Omega = r_{ds} \parallel R_D = 110k\Omega \parallel R_D \qquad R_D = 11k\Omega$$

GEAUX

CASCADING COMMON SOURCE AMPLIFIERS



(a)



$g_{m1} = 2.5$ mS $\quad g_{m2} = 1.5$ mS

$r_{ds1} = 80$ kΩ $\quad r_{ds2} = 80$ kΩ

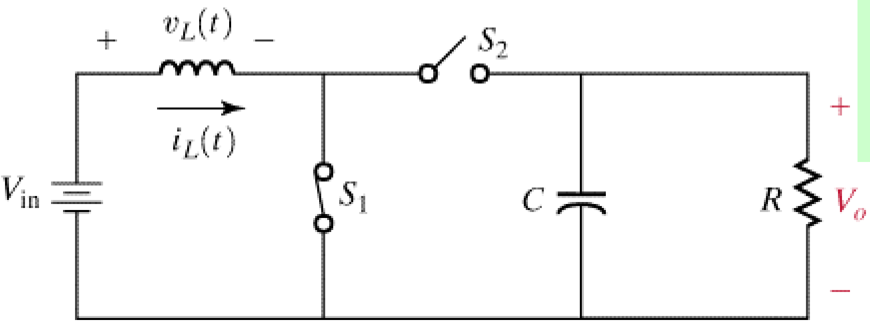
$R_1 = 8$ kΩ $\quad R_2 = 40$ kΩ

$$v_{gs2} = -(r_{ds1} \parallel R_1) g_{m1} v_{gs1} = -A_1 v_{gs1}$$

$$v_o = -(r_{ds2} \parallel R_2) g_{m2} v_{gs2} = -A_2 v_{gs2}$$

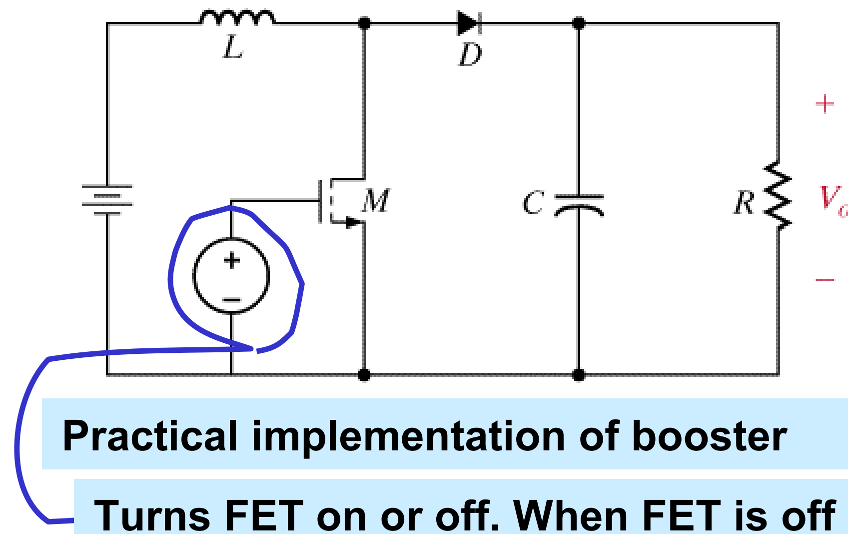
$$v_o = A_1 A_2 v_{gs1}$$

ANALYSIS OF A DC-DC CONVERTER



Idealized circuit

When S2 is open and S1 closed, the inductor stores energy. A large capacitor helps to keep output voltage constant
When S2 is closed and S1 open, the inductor transfers energy to capacitor



Practical implementation of booster

Turns FET on or off. When FET is off diode becomes direct biased

$$W_L = \frac{1}{2}LI_p^2;\ I_p = \frac{V_{in}t_{on}}{L}$$

D = duty cycle

T_s = switching period

$$t_{on} = DT_s \Rightarrow W_L = \frac{V_{in}^2 D^2 T_s^2}{2L}$$

$$f_s = \frac{1}{T_s}$$

$$W_C = \frac{1}{2}C(V_o^2 - V_{o-}^2) = \text{energy transferred to capacitor}$$

V_o = voltage at end of cycle

V_{o-} = voltage at beginning of cycle

Energy transferred to load

$$W_{load} = \frac{V_{o-}^2}{R_{load}}T_s$$

Assuming $W_L = W_C + W_{load}$ and solving for V_o

$$V_o = \sqrt{\frac{2W_L}{C} - \frac{2V_{o-}^2}{R_{load}Cf_s} + V_{o-}^2}$$

USING EXCEL TO COMPUTE OUTPUT OF DC-DC CONVERTER

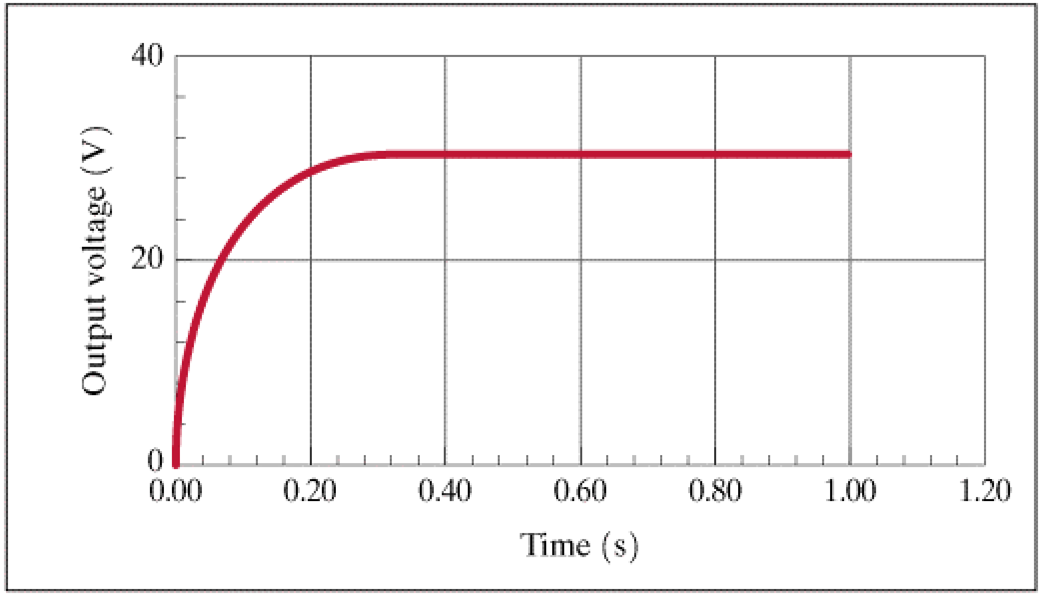
Vin[V]	5		
L[H]	1.00E-05		
C[F]	1.00E-06		
D	0.6		
fs	1.00E+05		
Rload	200		
n	Time(ms)	Wl	Vo
0	0.00E+00	4.50E-05	0
1	1.00E-02	4.50E-05	9.486833
2	2.00E-02	4.50E-05	13.0767
3	3.00E-02	4.50E-05	15.6173
4	4.00E-02	4.50E-05	17.5929
5	5.00E-02	4.50E-05	19.19789
6	6.00E-02	4.50E-05	20.53541
7	7.00E-02	4.50E-05	21.66871
8	8.00E-02	4.50E-05	22.64022
9	9.00E-02	4.50E-05	23.48024
10	1.00E-01	4.50E-05	24.21135
11	1.10E-01	4.50E-05	24.85097
12	1.20E-01	4.50E-05	25.41286
13	1.30E-01	4.50E-05	25.90815
14	1.40E-01	4.50E-05	26.34595
15	1.50E-01	4.50E-05	26.73384
16	1.60E-01	4.50E-05	27.07819
17	1.70E-01	4.50E-05	27.3844
18	1.80E-01	4.50E-05	27.65709
19	1.90E-01	4.50E-05	27.90024
20	2.00E-01	4.50E-05	28.11727

Excel formula to compute W_L

=$B$1^2*($B$4)^2/(2*($B$2)*($B$5)^2)

Excel formula to compute Vo (cellD10)

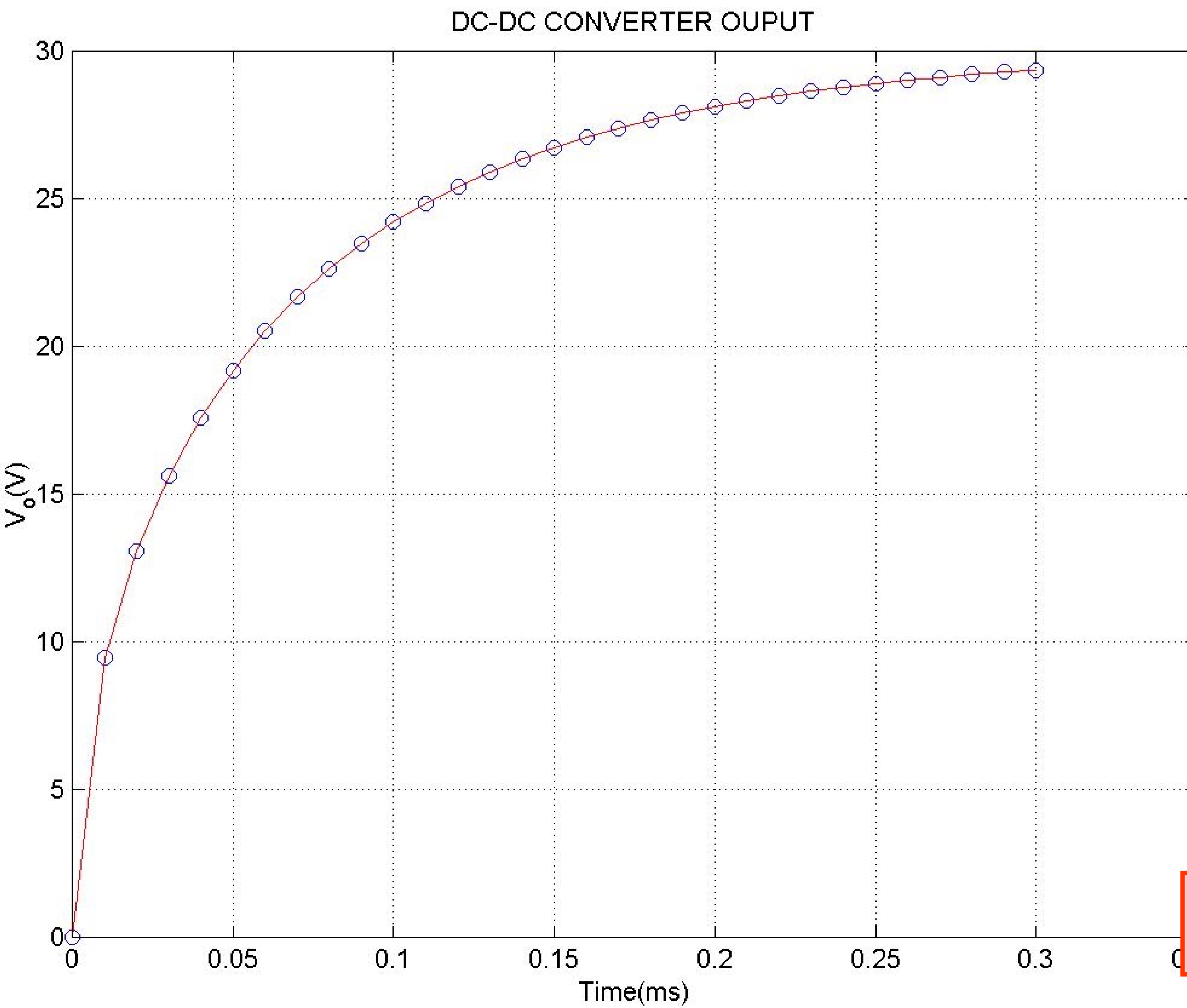
=SQRT(2*C10/$B$3-2*D9^2/($B$6*$B$3*$B$5)+D9^2)



Plot of DC-DC converter output voltage

MATLAB SCRIPT TO COMPUTE AND PLOT THE BOOSTER OUTPUT

```
%booster.m
%Solves the booster circuit in BECA 7th Ed, page648
%%%%%%%%% define circuit parameters
Vin=5;
L=1e-5;
C=1e-6;
D=0.6;
fs=1e5;
Rload=200;
%%%%%%%%% define iteration array
n=[0:30];
tms=1e3*n/fs; %time in msec
%%%%%%%%% initialize vectors and do one-time computations
Wl=Vin^2*D^2/(2*L*fs^2);
t1=2*Wl/C;
kt2=1-2/(Rload*C*fs);
vo=zeros(size(n)); %initialize output array
%%%%%%%%% do the iterations
for k=2:length(n)
   vo(k)=sqrt(t1+kt2*(vo(k-1))^2);
end
%%%%%%%%% display results
plot(tms,vo,'bo',tms,vo,'r'),title('DC-DC CONVERTER OUPUT')
xlabel('Time(ms)'),ylabel('V_o(V)'), grid
```



DIODES
MOSFETs

STOP