EE 330
Lecture 16

Devices in Semiconductor Processes

- Diodes (continued)
- Capacitors
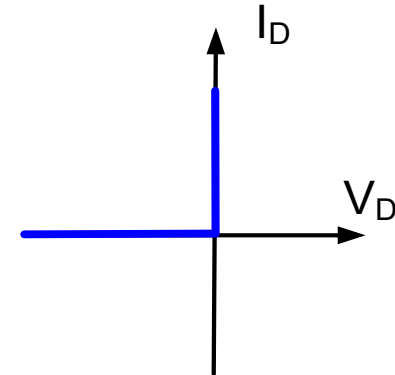- MOSFETs

Exam Schedule for Fall 2022
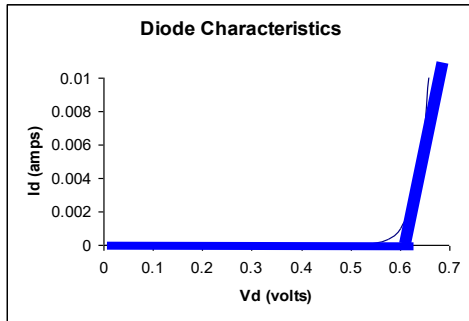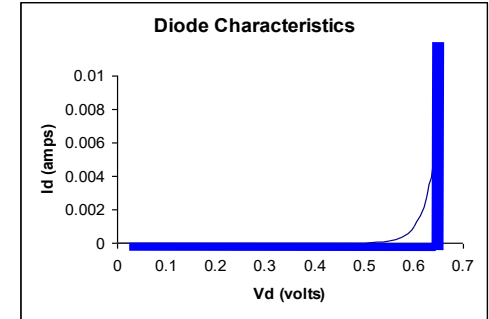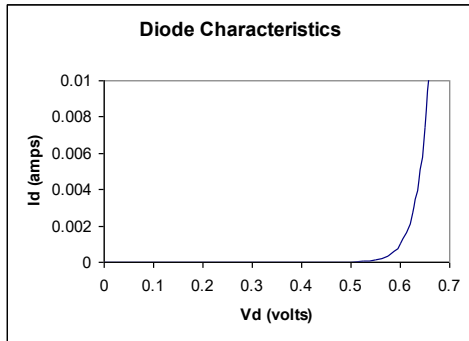
Exam 1   Friday Sept 23

Exam 2   Friday Oct 21

Exam 3   Friday Nov 13

Final   Tuesday Dec 13   12:00 – 2:00 p.m.

Diode Models

Which model should be used?

The simplest model that will give acceptable results in the analysis of a circuit

Use of Piecewise Models for Nonlinear Devices when Analyzing Electronic Circuits

Process:

1. Guess state of the device
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify model (if necessary)

Observations:

o Analysis generally simplified dramatically (particularly if piecewise model is linear)

o Approach applicable to wide variety of nonlinear devices

o Closed-form solutions give insight into performance of circuit

o Usually much faster than solving the nonlinear circuit directly

o Wrong guesses in the state of the device do not compromise solution (verification will fail)

o Helps to guess right the first time

o Detailed model is often not necessary with most nonlinear devices

o Particularly useful if piecewise model is PWL (but not necessary)

o For practical circuits, the simplified approach usually applies

Key Concept For Analyzing Circuits with Nonlinear Devices

A Diode Application
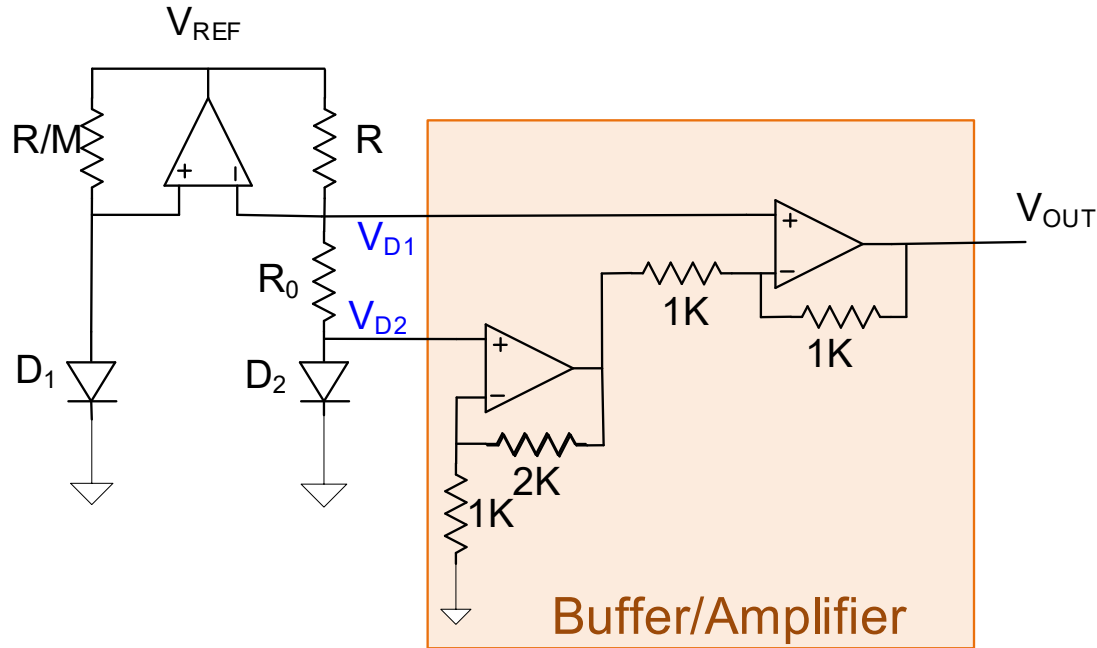
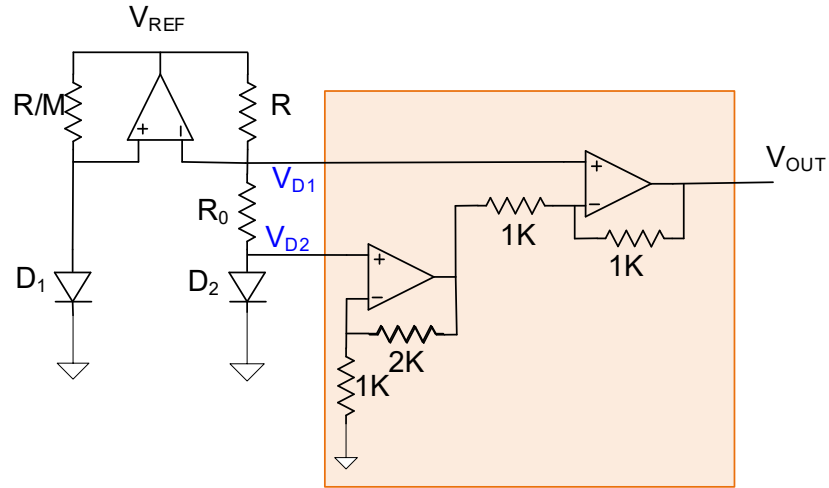If buffer/amplifier added, serves as temperature sensor at V_{OUT}

$$V_{OUT} = 2(V_{D1} - V_{D2})$$

May need compensation and startup circuits

For appropriate R_0, serves as bandgap voltage reference (buffer/amplifier excluded)

$$V_{REF} = V_{D1} + \frac{R}{R_0}(V_{D1} - V_{D2})$$

A Diode Application

$$V_{OUT} = 2(V_{D1} - V_{D2})$$

Analysis of temperature sensor (assume D_1 and D_2 matched)

$$I_{D2}(T) = \left(J_{SX}\left[T^m e^{\frac{-V_{G0}}{V_t}}\right]\right)A e^{\frac{V_{D2}}{V_t}}$$

$$I_{D1}(T) = \left(J_{SX}\left[T^m e^{\frac{-V_{G0}}{V_t}}\right]\right)A e^{\frac{V_{D1}}{V_t}}$$

$$I_{D1}(T) = M I_{D2}(T)$$

$$V_t = \frac{k}{q}T$$

$$\left(J_{SX}\left[T^m e^{\frac{-V_{G0}}{V_t}}\right]\right)A e^{\frac{V_{D1}}{V_t}} = M\left(J_{SX}\left[T^m e^{\frac{-V_{G0}}{V_t}}\right]\right)A e^{\frac{V_{D2}}{V_t}}$$
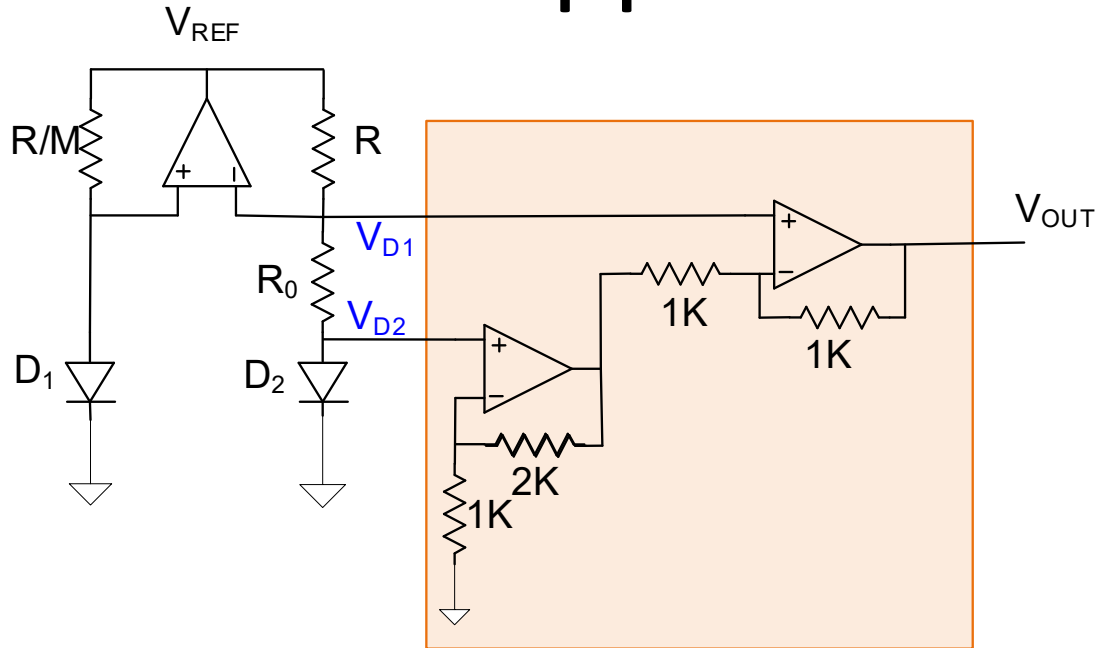
Cancelling terms and taking ln we obtain

$$V_{D1} - V_{D2} = V_t \ln M$$

Thus

$$V_{OUT} = 2(V_{D1} - V_{D2}) = 2\ln M \bullet \frac{k}{q}T$$

$$T = V_{OUT}\frac{q}{2k \ln M}$$

A Diode Application

May need compensation and startup circuits

If buffer/amplifier added, serves as temperature sensor at V_{OUT}

$$V_{OUT} = 2(V_{D1} - V_{D2})$$ ➡ $T = V_{OUT} \dfrac{q}{2k \ln M}$

For appropriate R_0, serves as bandgap voltage reference

$$V_{REF} = V_{D1} + \frac{R}{R_0}(V_{D1} - V_{D2})$$ ➡ **?**

Analysis of V_{REF} to show output is nearly independent of T and V_{DD} is more tedious

Use of <u>Piecewise</u> Models for Nonlinear Devices when Analyzing Electronic Circuits

Process:

1. Guess state of the device
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
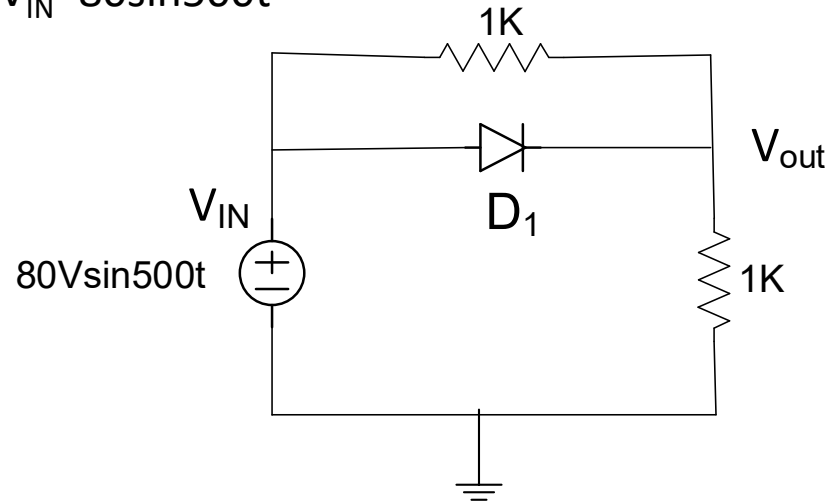5. Verify model (if necessary)

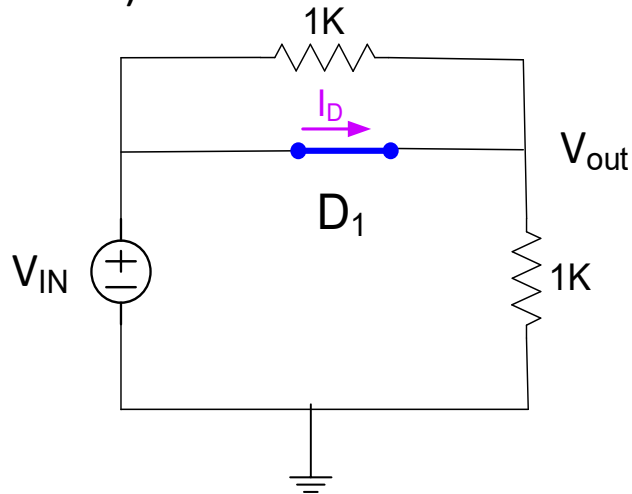What about nonlinear circuits (using piecewise models) with time-varying inputs?
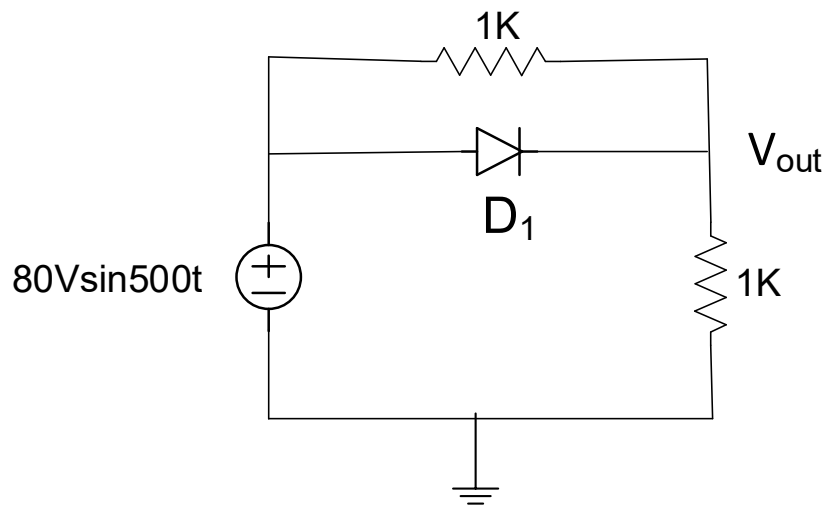
Same process except state verification (step 3) may include a range where solution is valid

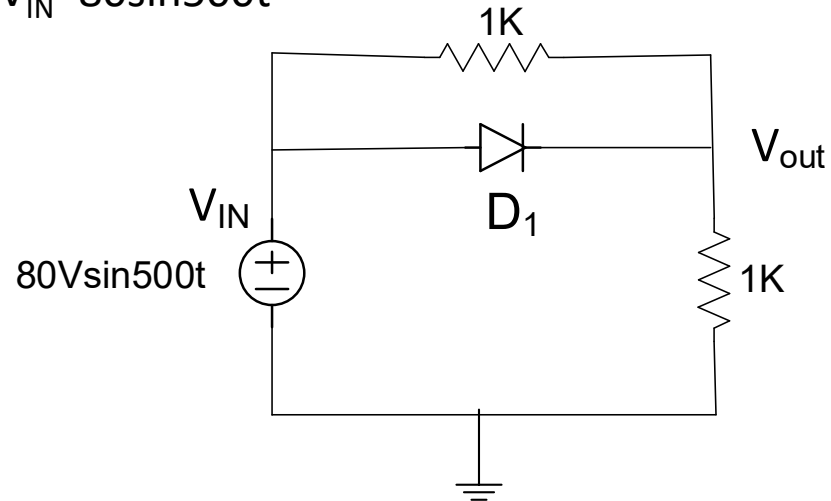Example: Determine V_{OUT} for $V_{IN}=80\sin500t$

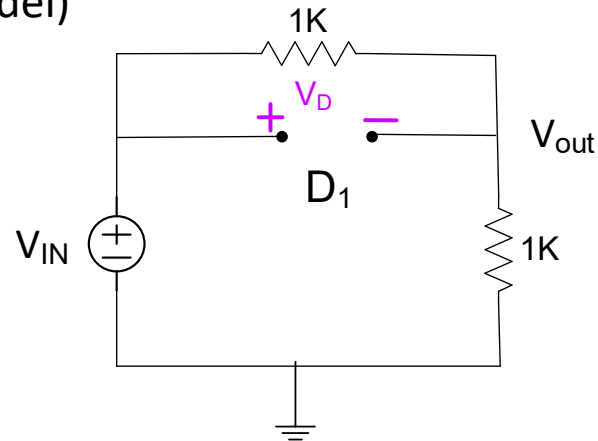Guess D_1 ON (will use ideal diode model)

$V_{OUT}=V_{IN}=80\sin(500t)$

Valid for $I_D>0$ $\qquad I_D = \dfrac{V_{IN}}{1K}$

Thus valid for $V_{IN} > 0$

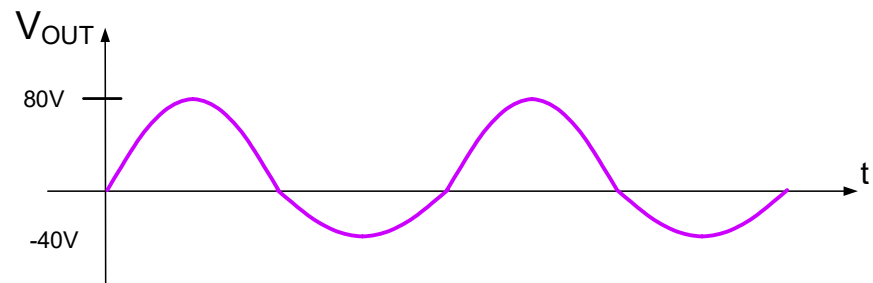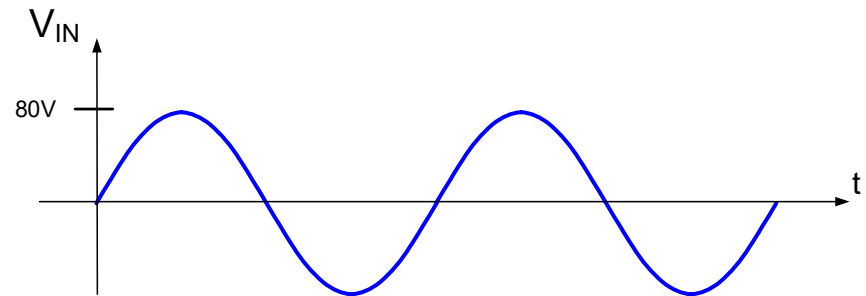Example: Determine V_{OUT} for $V_{IN}=80\sin500t$

1K

D_1

V_{IN}

V_{out}

80Vsin500t

1K

Guess D_1 OFF (will use ideal diode model)

1K

$+$ V_D $-$

V_{out}

D_1

V_{IN}

1K

$V_{OUT}=V_{IN}/2=40\sin(500t)$

Valid for $V_D<0$ $\qquad V_D = \dfrac{V_{IN}}{2}$

Thus valid for $V_{IN}<0$

Example: Determine V_{OUT} for V_{IN}=80sin500t

1K

V_{IN}

D_1

V_{out}

80Vsin500t

1K
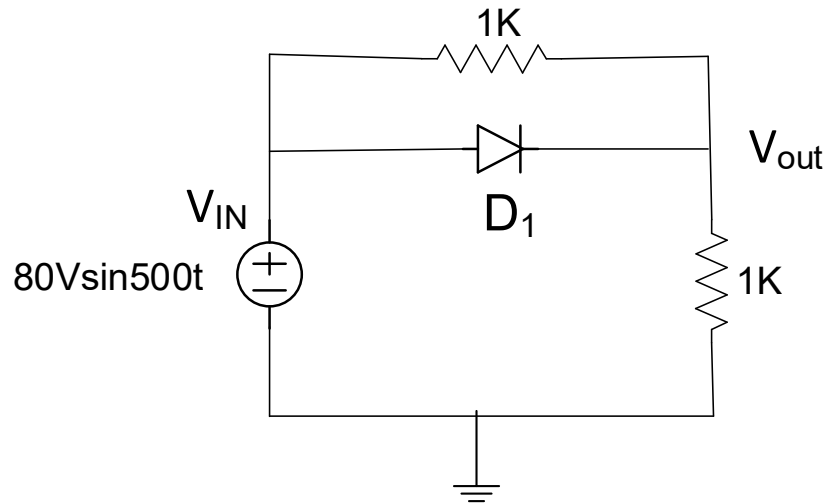
Thus overall solution

$$V_{OUT} = \begin{cases} 80\sin 500t & for\ V_{IN} > 0 \\ 40\sin 500t & for\ V_{IN} < 0 \end{cases}$$

V_{IN}

80V

t

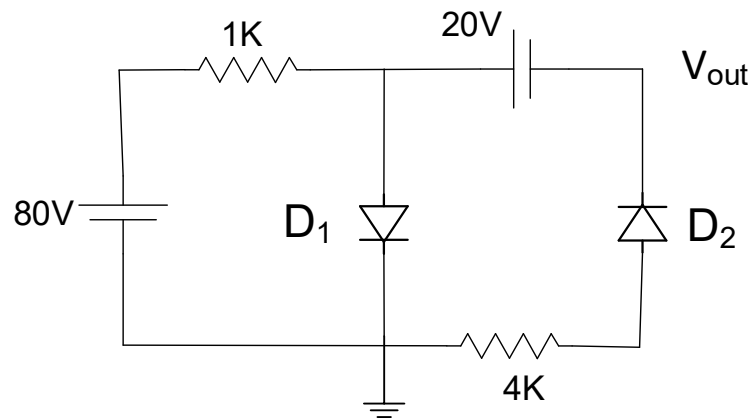V_{OUT}

80V

-40V

t

# Use of <u>Piecewise</u> Models for Nonlinear Devices when Analyzing Electronic Circuits

Process:

1. Guess state of the device
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify model (if necessary)

What about circuits (using piecewise models) with multiple nonlinear devices?
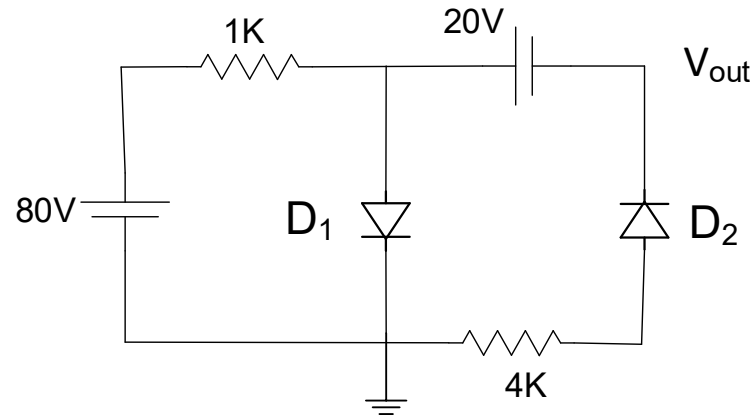

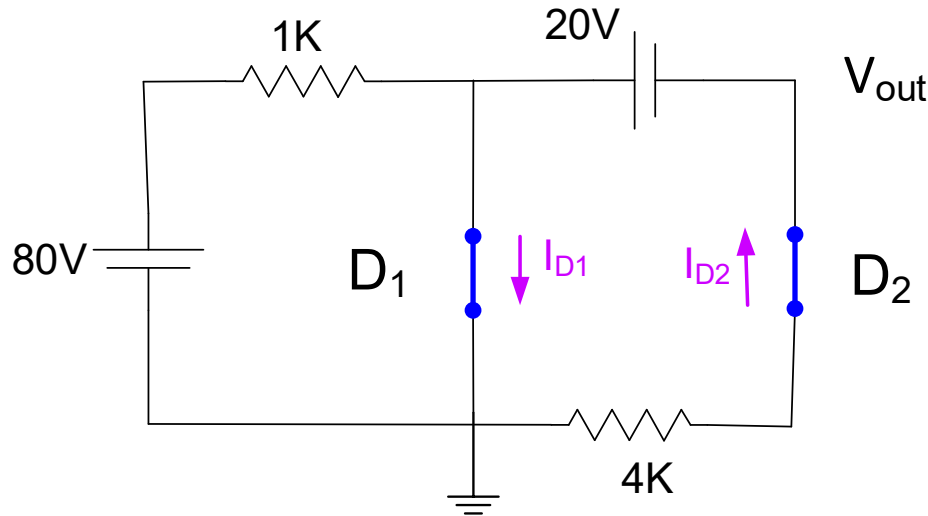Guess state for each device (multiple combinations possible)

Example: Obtain V_{OUT}
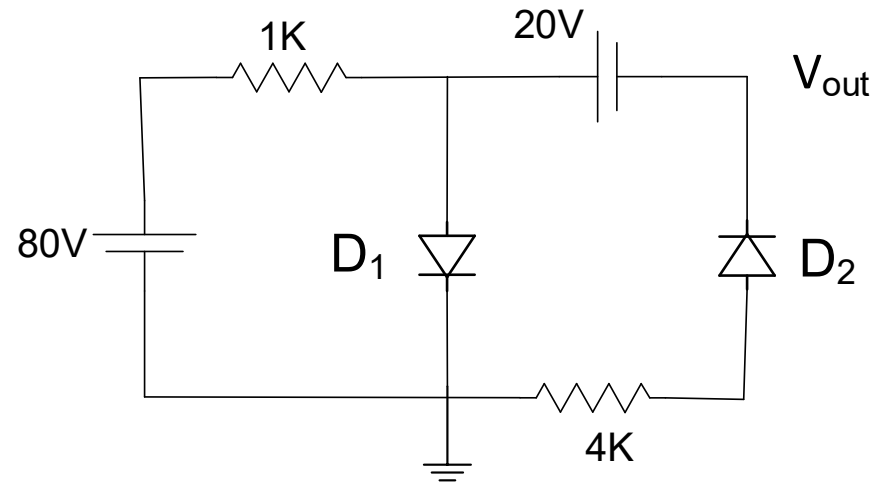
Example: Obtain V_{OUT}

Guess D_1 and D_2 on

V_{OUT}=-20V

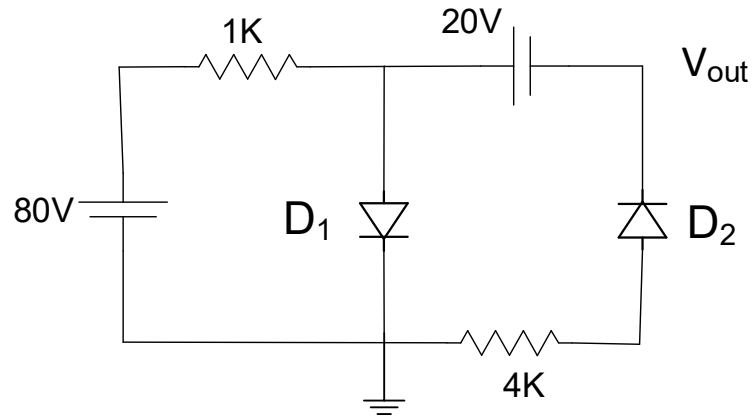Valid for I_{D2}>0   and I_{D1}>0

$$I_{D2} = \frac{20V}{4K} = 5mA > 0 \qquad I_{D1} = \frac{80V}{1K} + I_{D2} = 85mA > 0$$
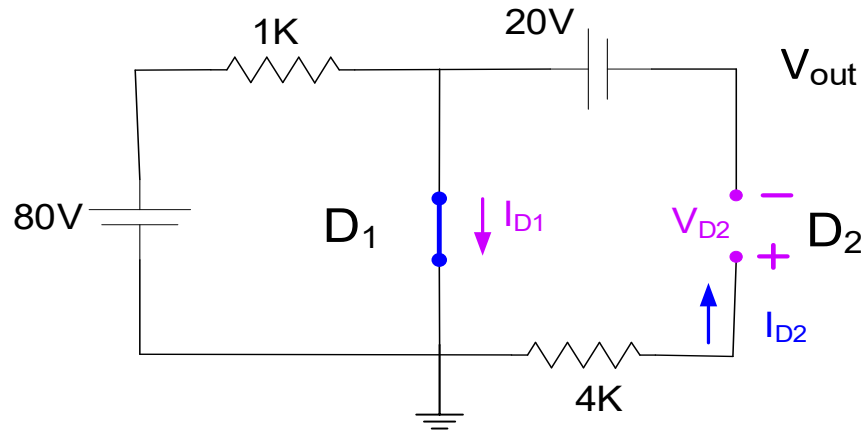
Validates

Validates

Since validates, solution is valid

Example: Obtain V_{OUT}

If we had guessed wrong
 Guess D_1 ON and D_2 OFF

V_{OUT}=-20V

 Valid for $I_{D1}>0$ and $V_{D2}<0$

$$I_{D1} = \frac{80V}{1K} + I_{D2} = 80mA > 0$$ V_{D2}=+20

Validates   Fails
                                 Validation

Since fails to validate, solution is not
valid so guess is wrong !

Use of <u>Piecewise</u> Models for Nonlinear Devices when Analyzing Electronic Circuits

Single Nonlinear Device

Process:

1. Guess state of the device
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify model (if necessary)

Multiple Nonlinear Devices

Process:

1. Guess state of each device (may be multiple combinations)
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify models (if necessary)

Analytical solutions of circuits with multiple nonlinear devices are often impossible to obtain if detailed non-piecewise nonlinear models are used
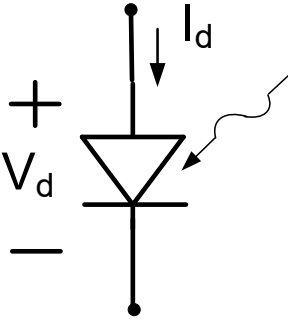
Diode Breakdown
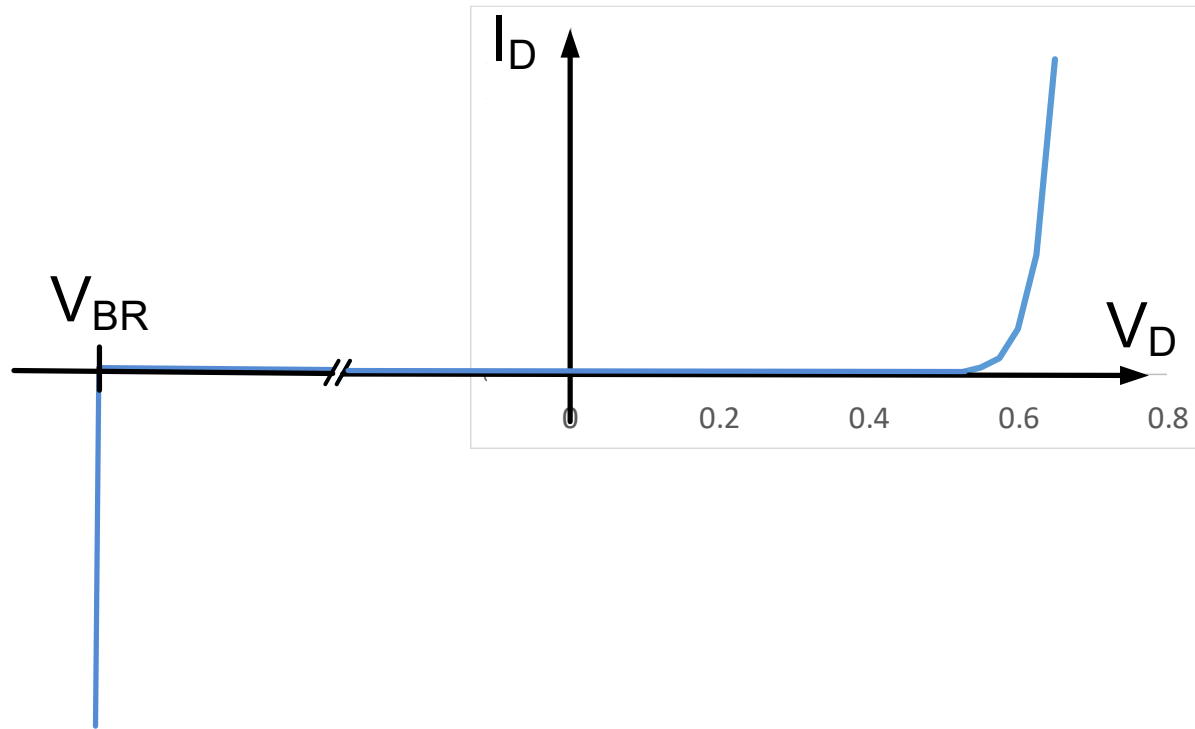
- Diodes will "break down" if a large reverse bias is applied
- Unless current is limited, reverse breakdown is destructive
- Breakdown is very sharp
- For many signal diodes, V_{BR} is in the -100V to -1000V range
- Relatively easy to design circuits so that with correct diodes, breakdown will not occur
- Zener diodes have a relatively small breakdown and current is intentionally limited to use this breakdown to build voltage references
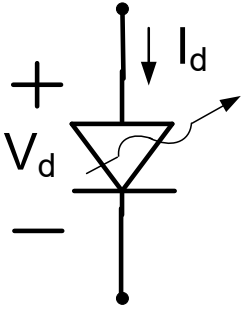
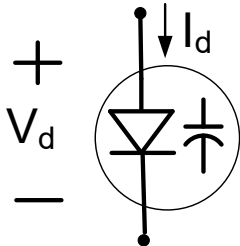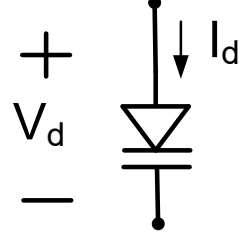# Types of Diodes

pn junction diodes
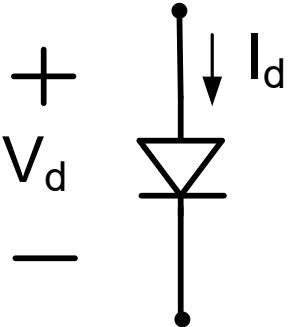
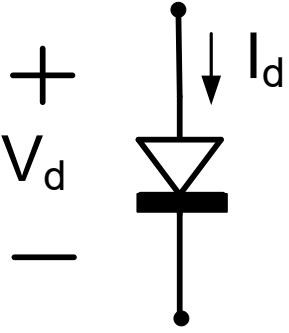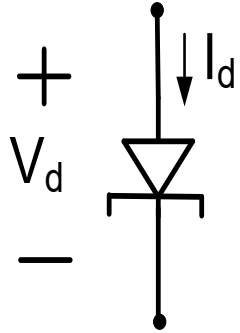| Signal or Rectifier	Pin or Photo	Light Emitting LED Laser Diode	Zener	Varactor or Varicap
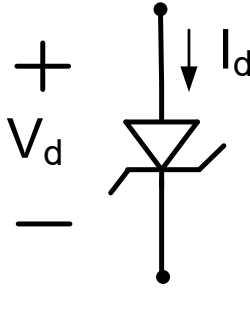
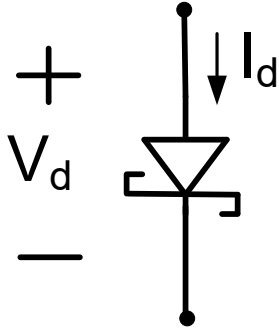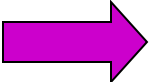**Metal-semiconductor junction diodes**
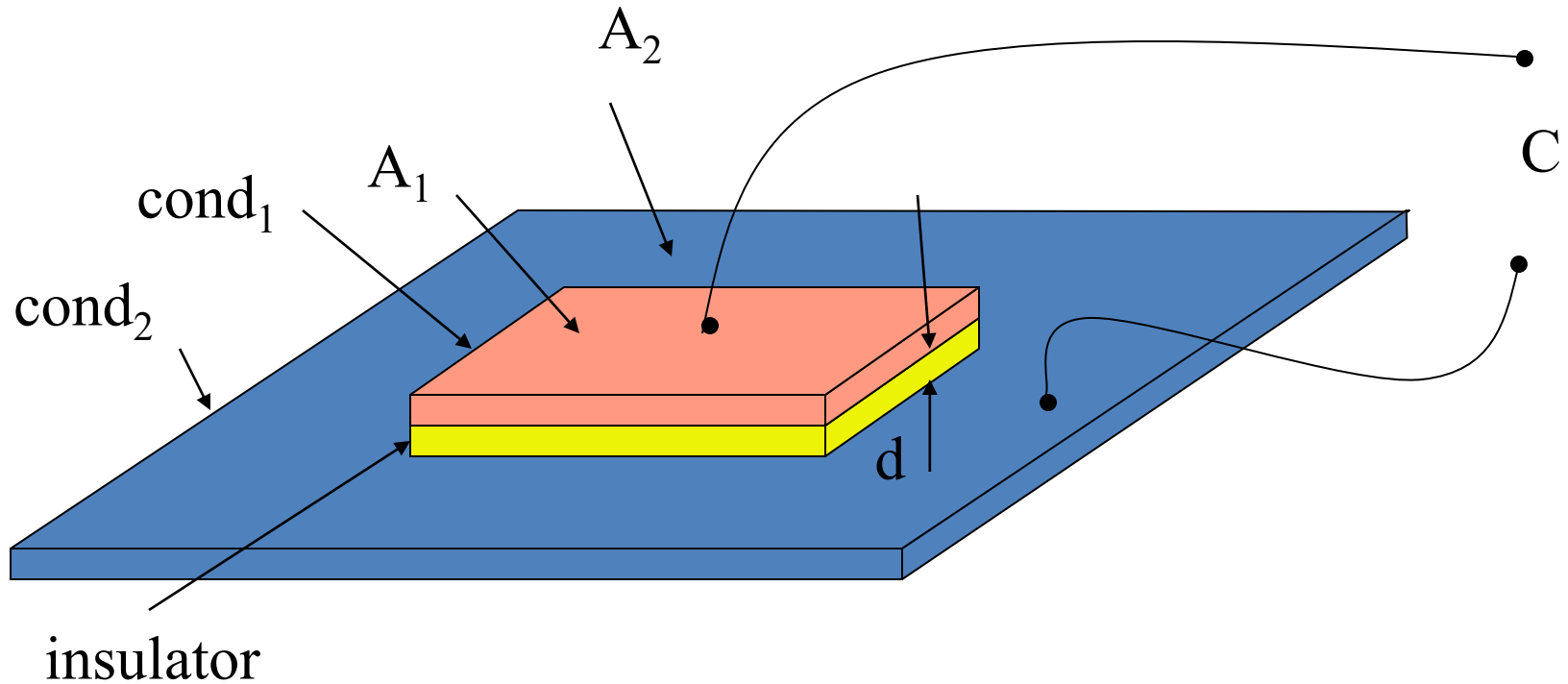

Schottky Barrier

Basic Devices and Device Models

- Resistor
- Diode
- → Capacitor
- MOSFET
- BJT

Capacitors

- Types
  - Parallel Plate
  - Fringe
  - Junction

Parallel Plate Capacitors

$A = $ area of intersection of A_1 & A_2

One (top) plate intentionally sized smaller to determine C

$$C = \frac{\in A}{d}$$

Parallel Plate Capacitors
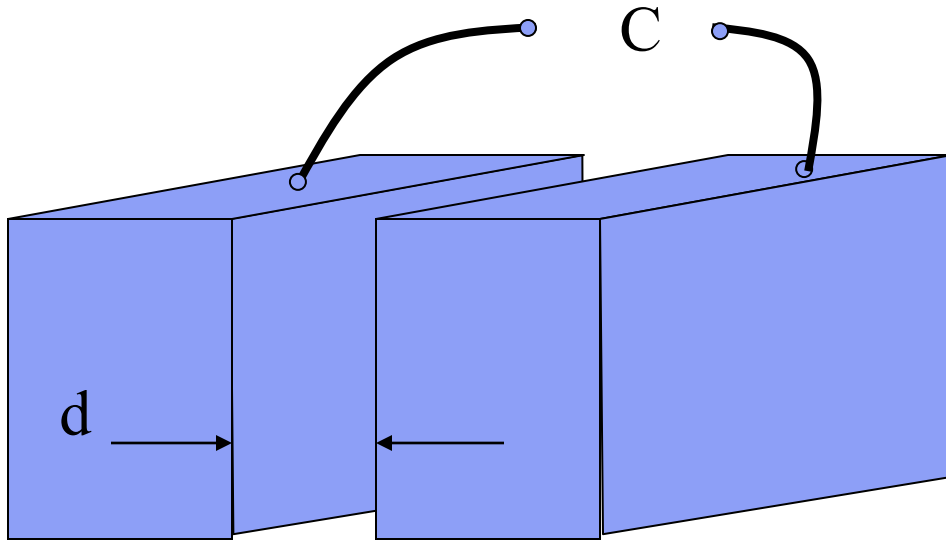
$$\text{If } C_d = \frac{\text{Cap}}{\text{unit area}}$$

$$C = \frac{\varepsilon\, A}{d}$$

$$C = C_d A$$

where

$$C_d = \frac{\varepsilon}{d}$$
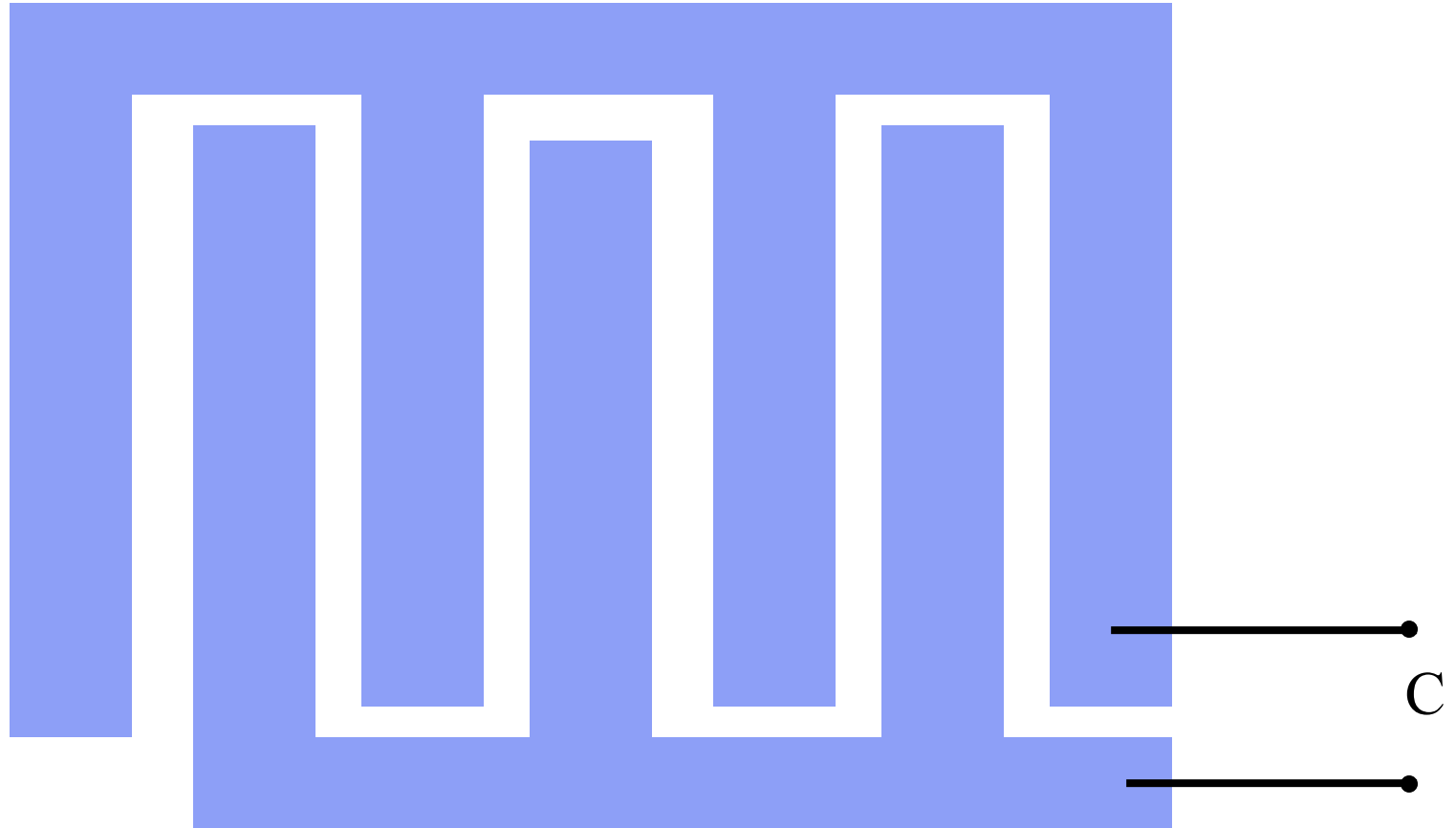
Fringe Capacitors

$$C = \frac{\varepsilon A}{d}$$

A is the area where the two plates are parallel

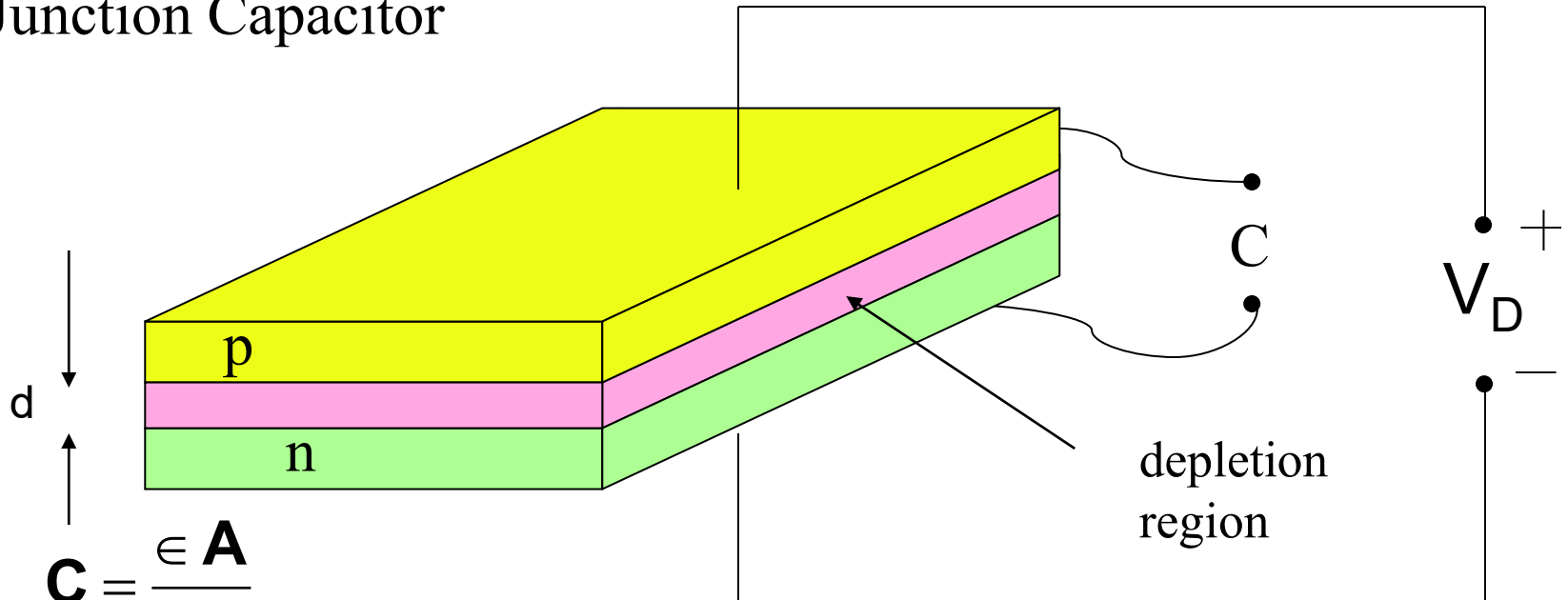**Only a single layer is needed to make fringe capacitors**

Fringe Capacitors

C

Capacitance

Junction Capacitor

$$C = \frac{\in A}{d}$$

$\in$ is dielectric constant

$$C = \frac{C_{jo}A}{\left(1 - \dfrac{V_D}{\varphi_B}\right)^n} \quad for \quad V_{FB} < \frac{\varphi_B}{2}$$

depletion region

Note: d is voltage dependent
-capacitance is voltage dependent
-usually parasitic caps
-varicaps or varactor diodes exploit
  voltage dep. of C

C_{j0} is the zero—bias junction capacitance density

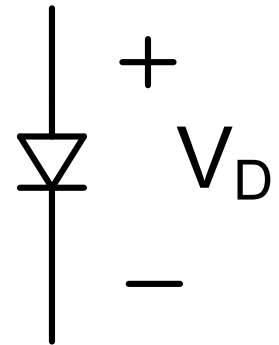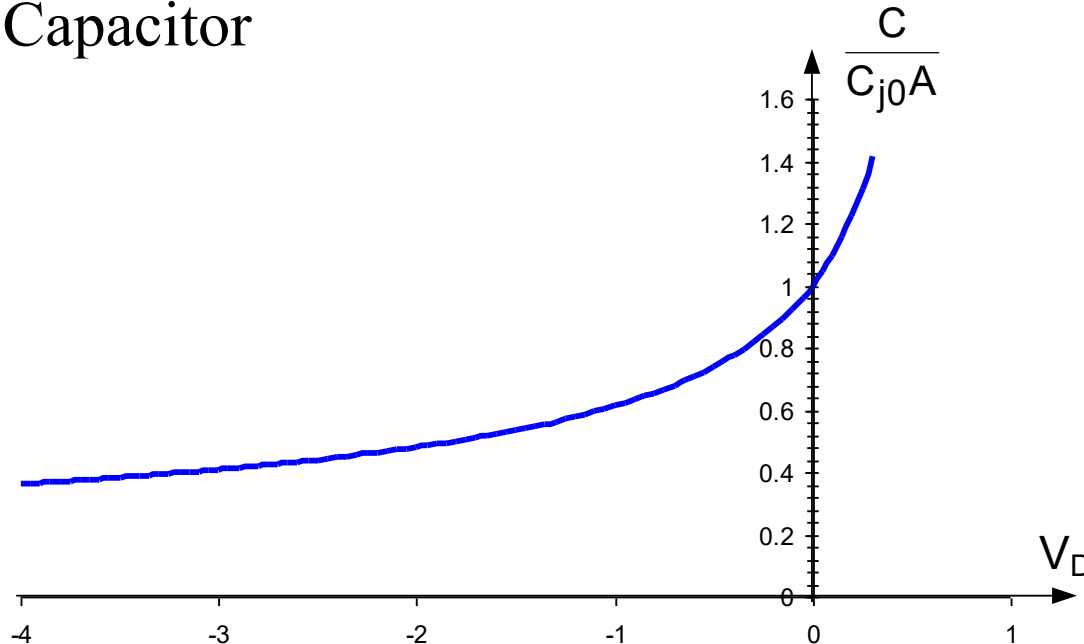Model parameters $\{C_{jo}, n, \varphi_B\}$ Design parameters $\{A\}$

$\varphi_B \cong 0.6V$ $n \simeq 0.5$ C_{jo} highly process dependent around 500aF/μm^2

Capacitance

Junction Capacitor

$$C = \frac{C_{jo}A}{\left(1 - \dfrac{V_D}{\varphi_B}\right)^n} \quad for \ \ V_{FB} < \frac{\varphi_B}{2}$$
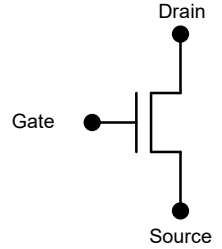
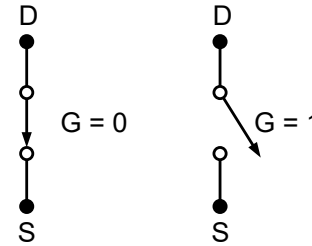Voltage dependence is substantial

$$\varphi_B \cong 0.6V \quad n \simeq 0.5$$

Basic Devices and Device Models

- Resistor
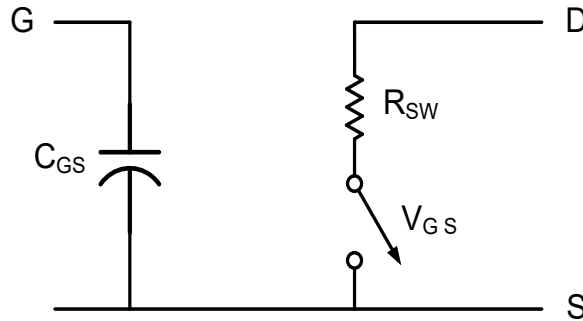- Diode
- Capacitor

→ MOSFET
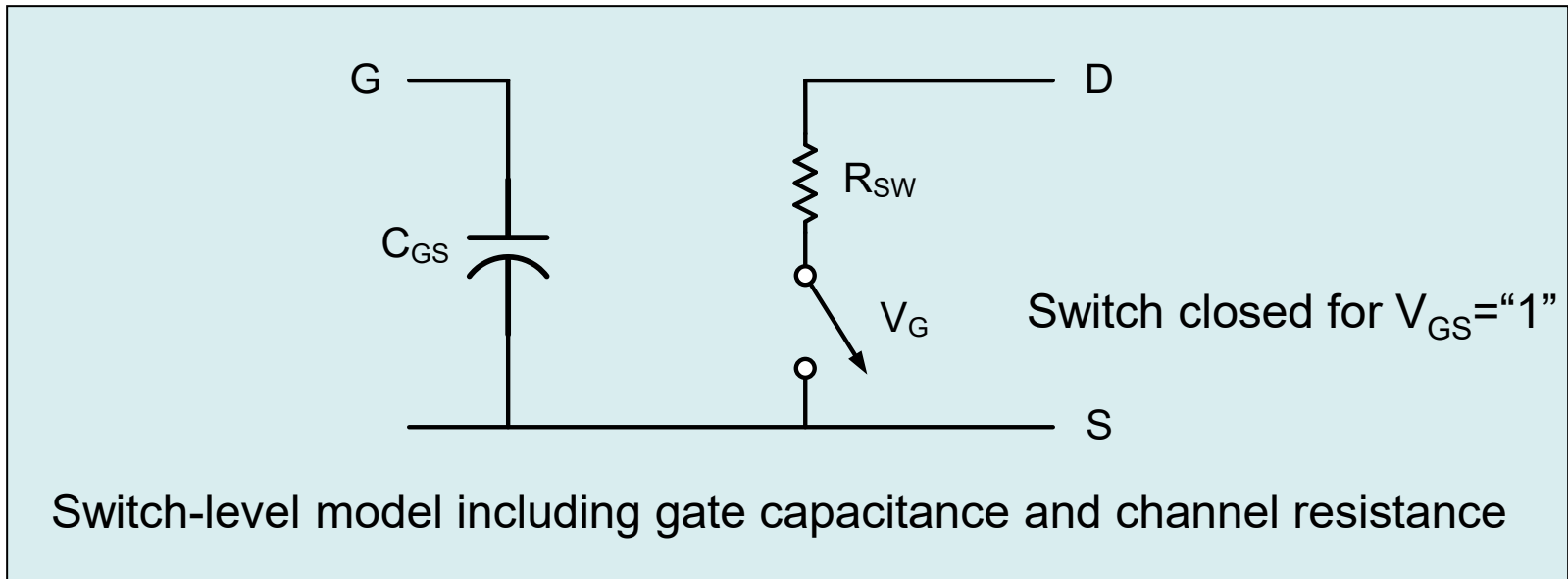
- BJT

Summary of Existing Models (for n-channel)

Drain

Gate

Source

1.   Switch-Level model

D   D

G = 0   G = 1

S   S

2.   Improved switch-level model

G ———————————————— D

R_{SW}

C_{GS}

V_{GS}

S

Switch closed for $|V_{GS}|$ = large
Switch open   for $|V_{GS}|$ = small

Improved Switch-Level Model

Switch-level model including gate capacitance and channel resistance
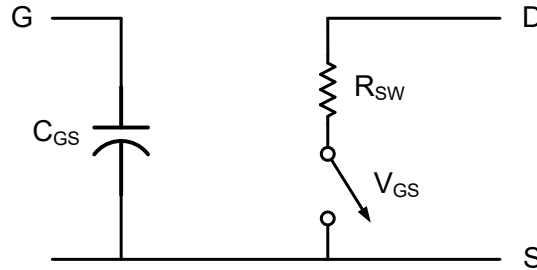
Switch closed for $V_{GS}=$"1"

- Connect the gate capacitance to the source to create lumped model
- Still neglect bulk connection

Limitations of Existing MOSFET Models
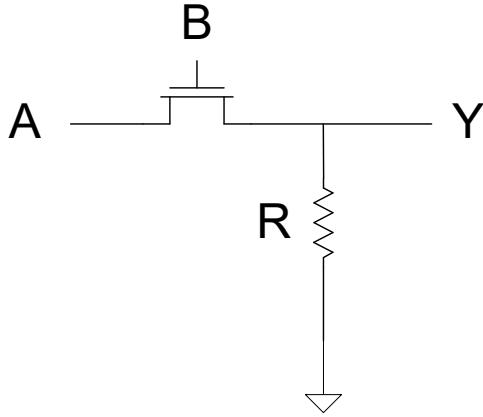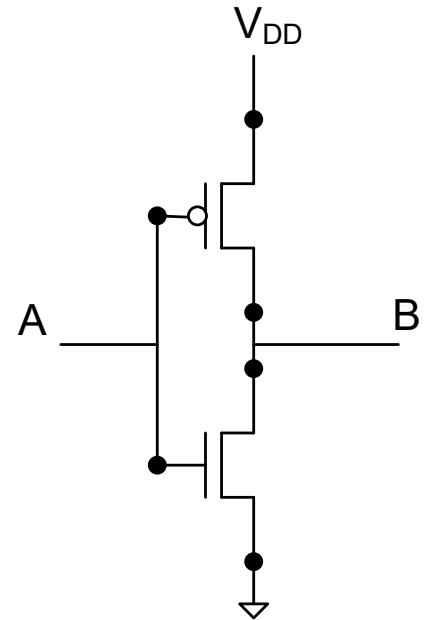

For minimum-sized devices in a 0.5u process with V_{DD}=5V

$$C_{GS} \cong 1.5fF$$

$$R_{sw} \cong \left. \begin{array}{l} 2K\Omega \;\; n-channel \\ 6K\Omega \;\; p-channel \end{array} \right\}$$

What is Y when A=B=VDD

What is R_{SW} if MOSFET is not minimum sized?

What is power dissipation if A is stuck at an intermediate voltage?

Better Model of MOSFET is Needed!

Stay Safe and Stay Healthy !

End of Lecture 16