EE 330
Lecture 16

Devices in Semiconductor Processes

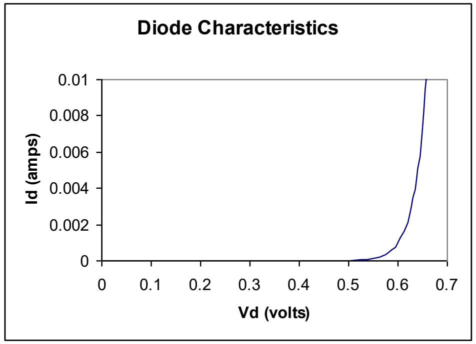
- Diodes (continued)
- Capacitors
- MOSFETs

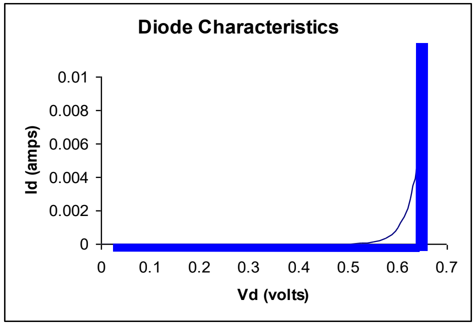
Fall 2024 Exam Schedule

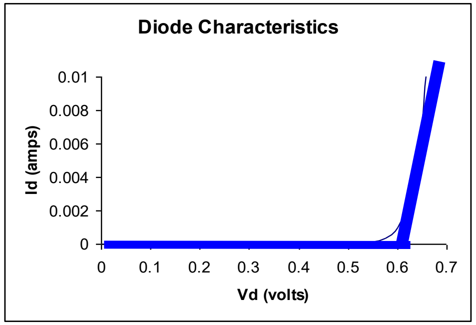
Exam 1	Friday	Sept 27
Exam 2	Friday	October 25
Exam 3	Friday	Nov 22
Final Exam	Monday	Dec 16 12:00 - 2:00 PM

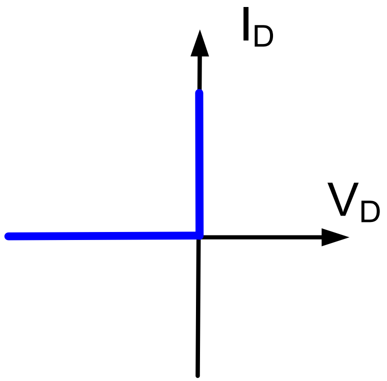
Review from Last Lecture

Diode Models









Which model should be used?

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

Review from Last Lecture

Analysis of Nonlinear Circuits

(Circuits with one or more nonlinear devices)

What analysis tools or methods can be used?

KCL ?

KVL?

~~Superposition?~~

~~Voltage Divider ?~~

~~Current Divider?~~

~~Thevenin and Norton Equivalent Circuits?~~

Nodal Analysis ?

Mesh Analysis ?

Two-Port Subcircuits ?

~~Passing Current ?~~

~~Blocking Current ?~~

- How are piecewise models accommodated?
- Will address the issue of how to rigorously analyze nonlinear circuits with piecewise models later

Review from Last Lecture

Use of Piecewise Models for Nonlinear Devices when Analyzing Electronic Circuits

Process:

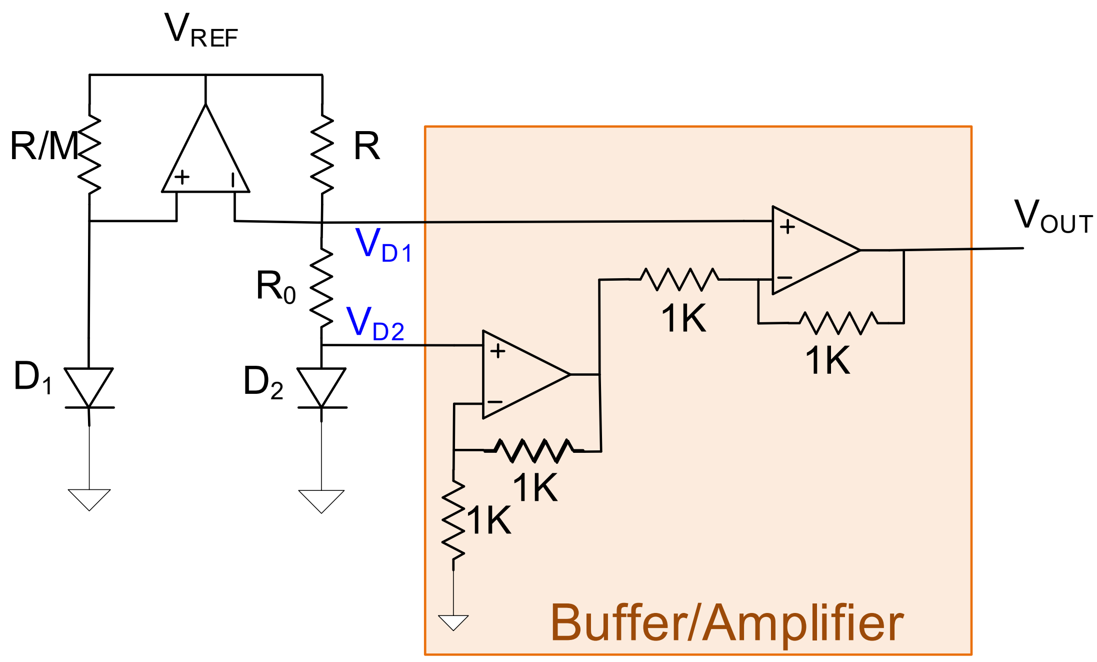
1. Guess state of the device
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify model (if necessary)

Observations:

- Analysis generally simplified dramatically (particularly if piecewise model is linear)
- Approach applicable to wide variety of nonlinear devices
- Closed-form solutions give insight into performance of circuit
- Usually much faster than solving the nonlinear circuit directly
- Wrong guesses in the state of the device do not compromise solution (verification will fail)
- Helps to guess right the first time
- Detailed model is often not necessary with most nonlinear devices
- Particularly useful if piecewise model is PWL (but not necessary)
- 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}

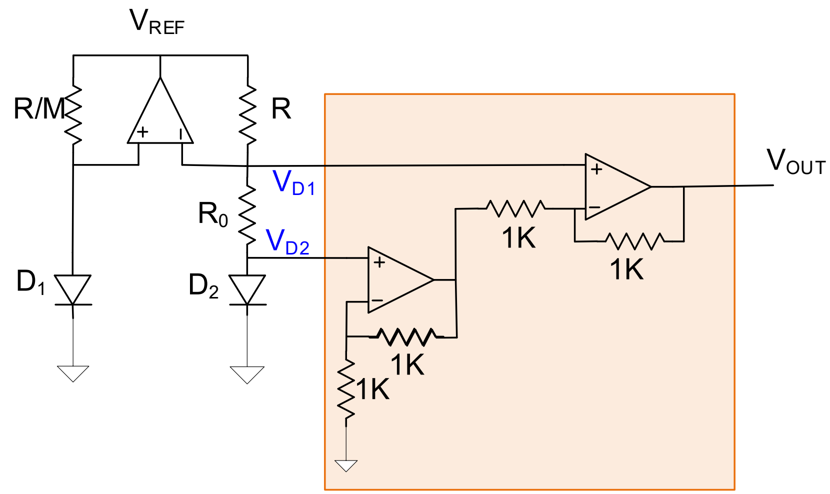
$$V_{OUT} = 2(V_{D1} - V_{D2})$$

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



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

Analysis of temperature sensor (assume D_1 and D_2 matched)

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

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

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

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

$$\Rightarrow \left(J_{SX}\left[T^m e^{\frac{-V_{G0}}{V_t}}\right]\right) A e^{\frac{V_{D1}}{V_t}} = M\left(J_{SX}\left[T^m e^{\frac{-V_{G0}}{V_t}}\right]\right) A e^{\frac{V_{D2}}{V_t}}$$

Cancelling terms and taking ln we obtain

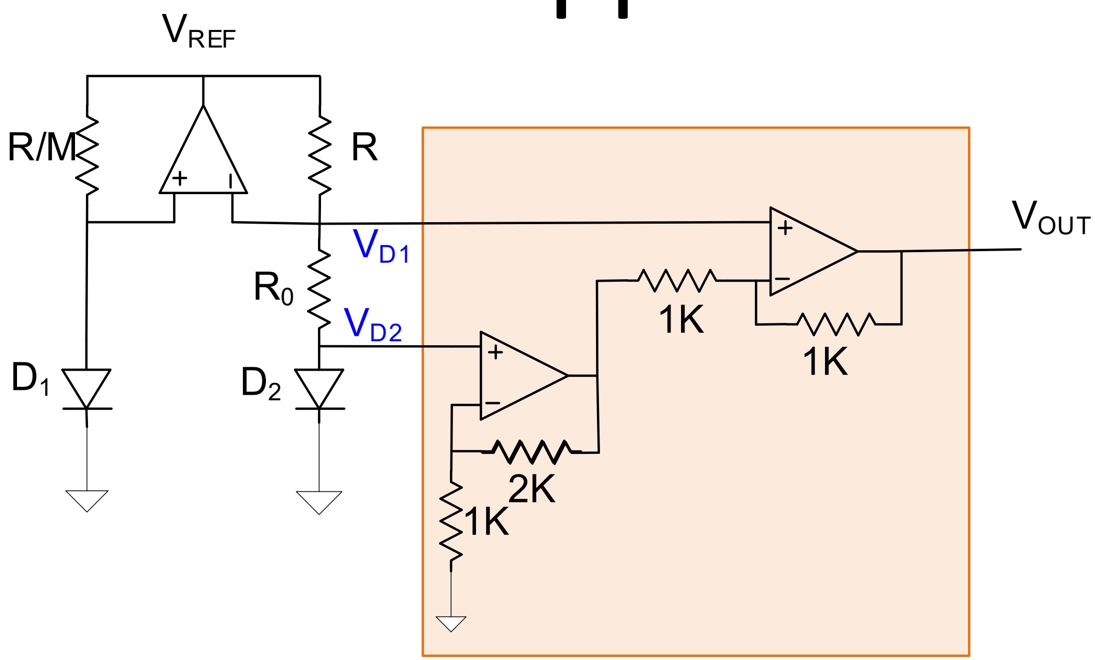
$$V_{D1} - V_{D2} = V_t \ln M$$

Thus

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

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

A Diode Application



May need compensation and startup circuits

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

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

For appropriate R_0, serves as bandgap voltage reference

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

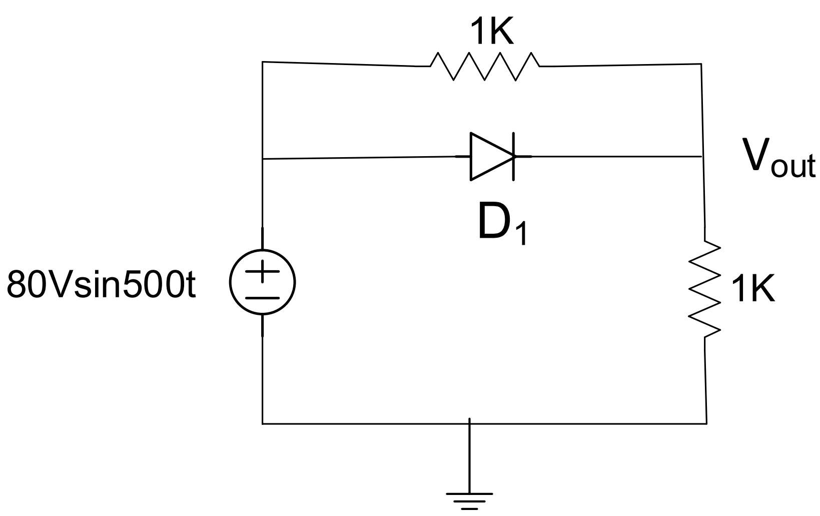
Analysis of V_{REF} to show output is nearly independent of T and V_{DD} is more tedious

Use of Piecewise Models for Nonlinear Devices when Analyzing Electronic Circuits

Process:

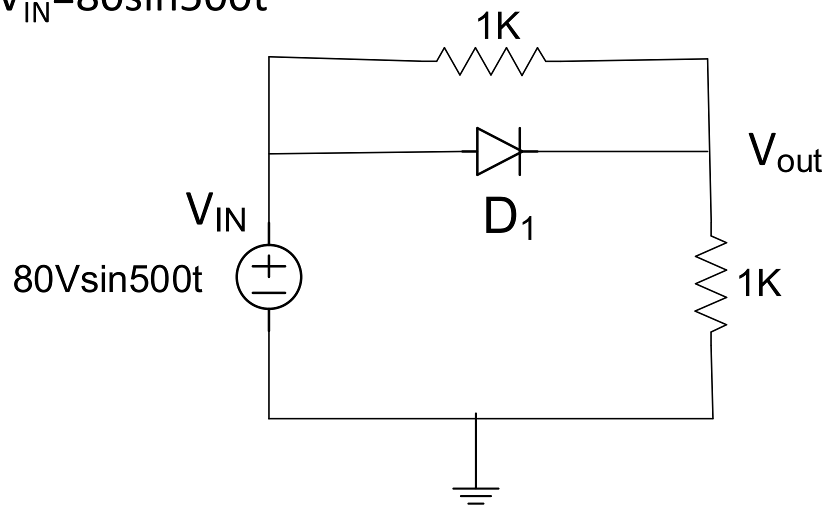
1. Guess state of the device
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify model (if necessary)

What about nonlinear circuits (using piecewise models) with time-varying inputs?

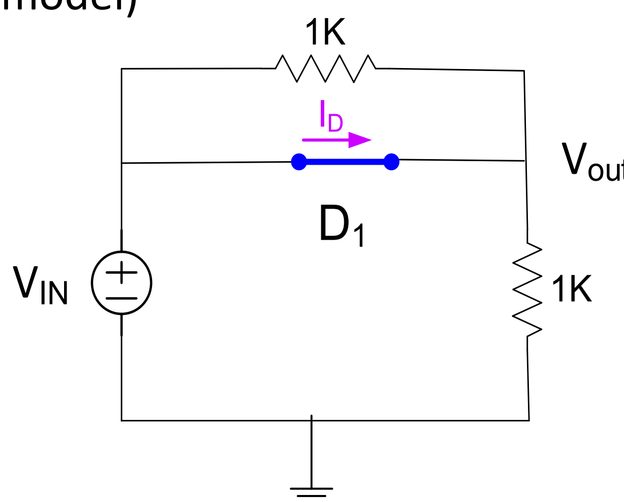


Same process except state verification (step 3) may include a range where solution is valid

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



Guess D_1 ON (will use ideal diode model)

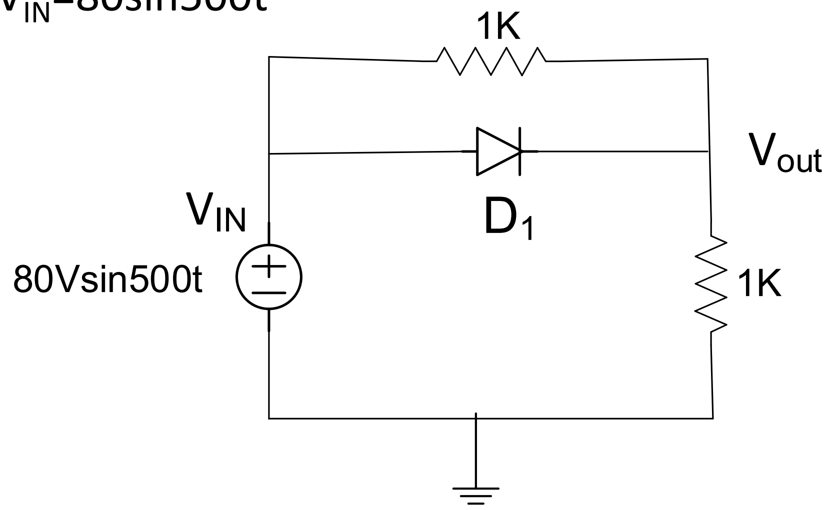


$V_{OUT}=V_{IN}=80\sin(500t)$

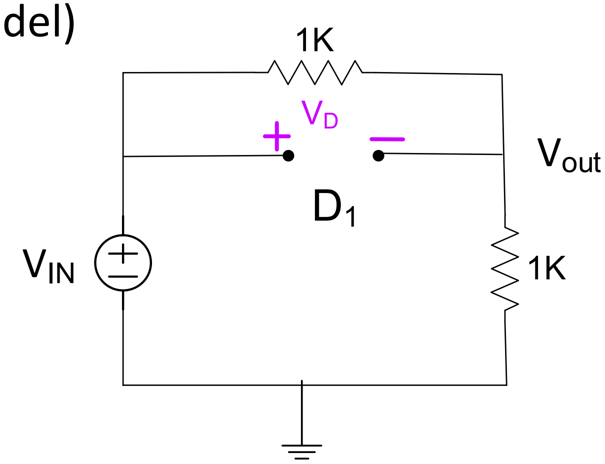
Valid for $I_D>0$ $$I_D = \frac{V_{IN}}{1K}$$

Thus valid for $V_{IN} > 0$

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



Guess D_1 OFF (will use ideal diode model)

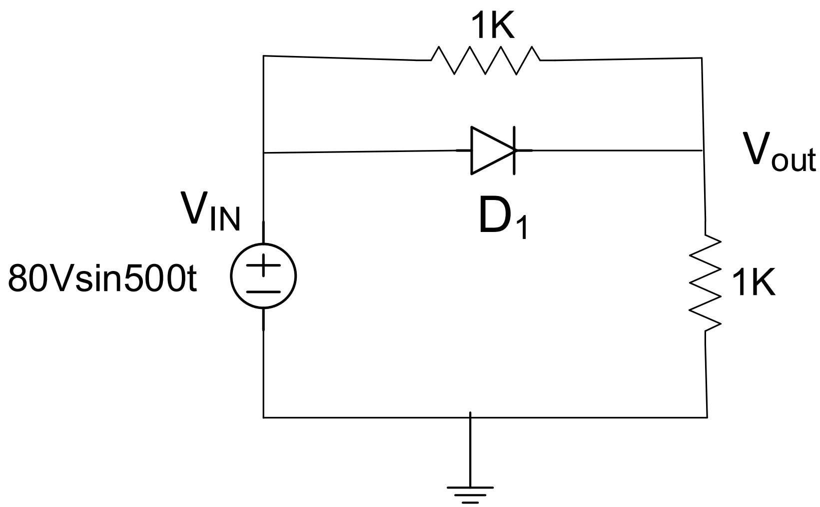


$V_{OUT}=V_{IN}/2=40\sin(500t)$

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

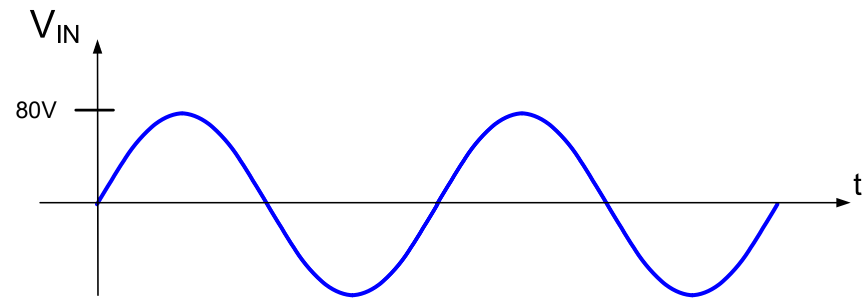
Thus valid for $V_{IN} < 0$

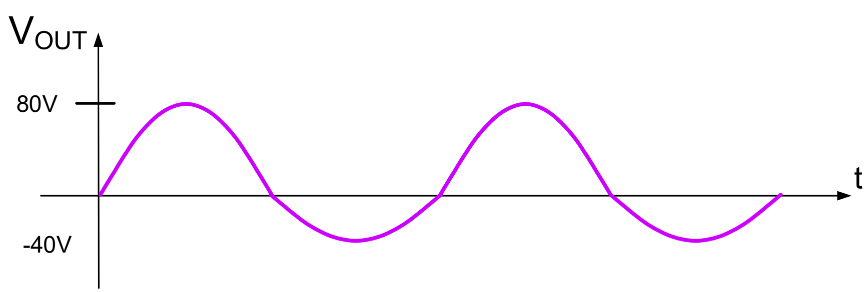
Example: Determine V_{OUT} for V_{IN}=80sin500t



Thus overall solution

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



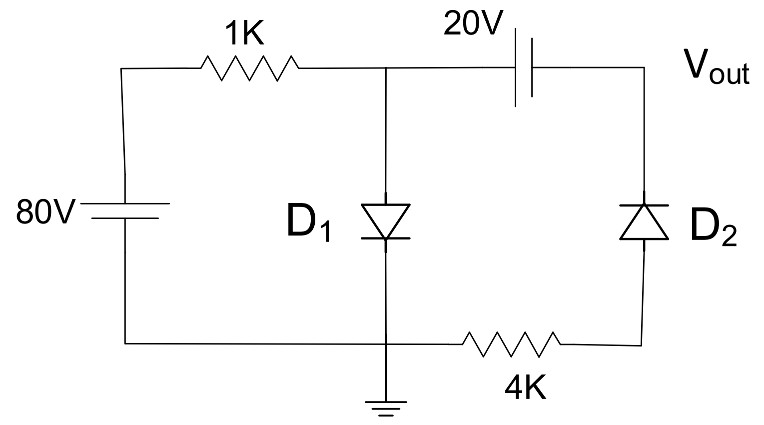


Use of Piecewise Models for Nonlinear Devices when Analyzing Electronic Circuits

Process:

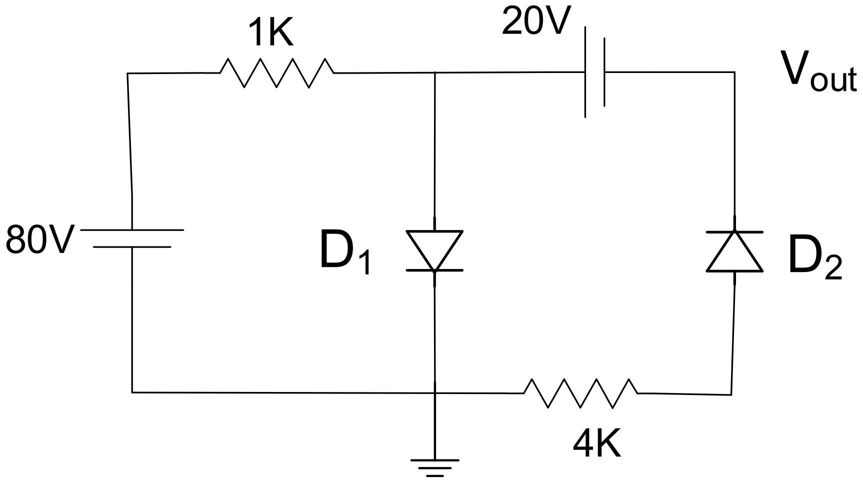
1. Guess state of the device
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify model (if necessary)

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

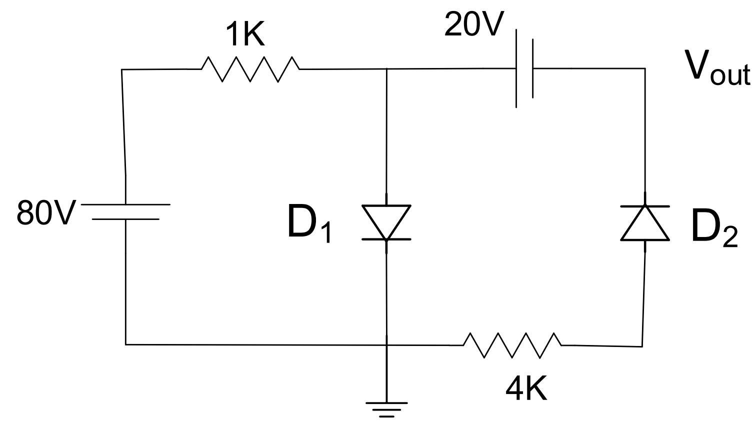


Guess state for each device (multiple combinations possible)

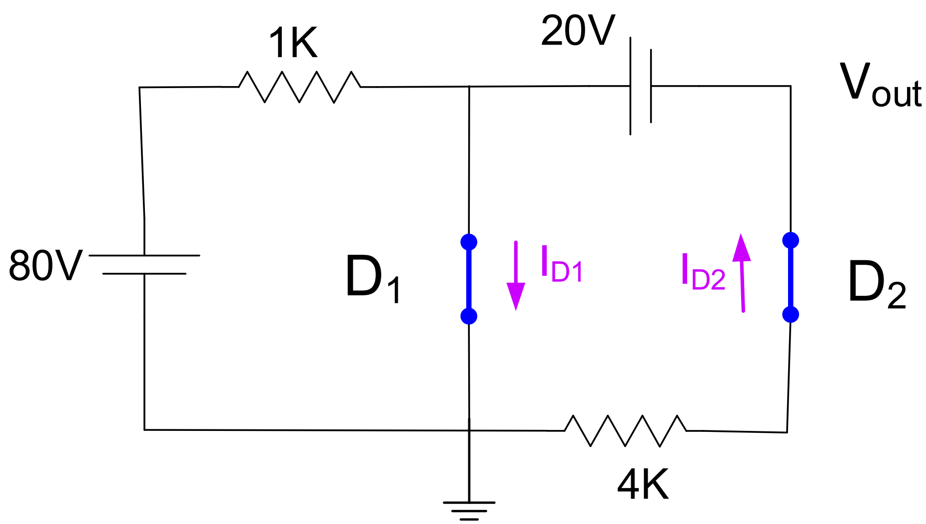
Example: Obtain V_{OUT}



Example: Obtain V_{OUT}



Guess D_1 and D_2 on



V_{OUT}=-20V

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

$$I_{D2} = \frac{20V}{4K} = 5mA > 0$$

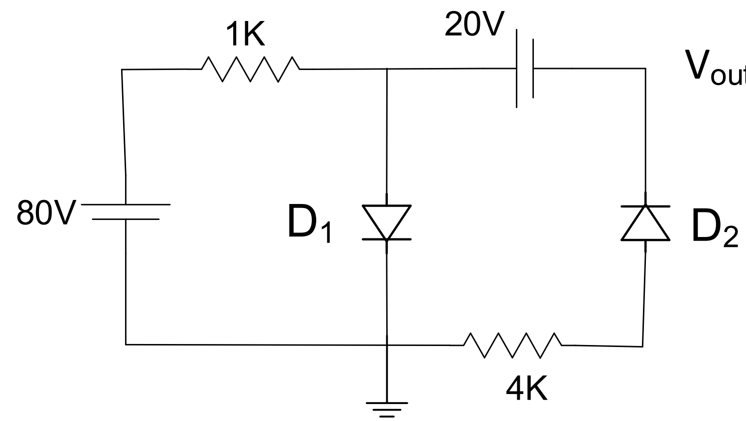
Validates

$$I_{D1} = \frac{80V}{1K} + I_{D2} = 85mA > 0$$

Validates

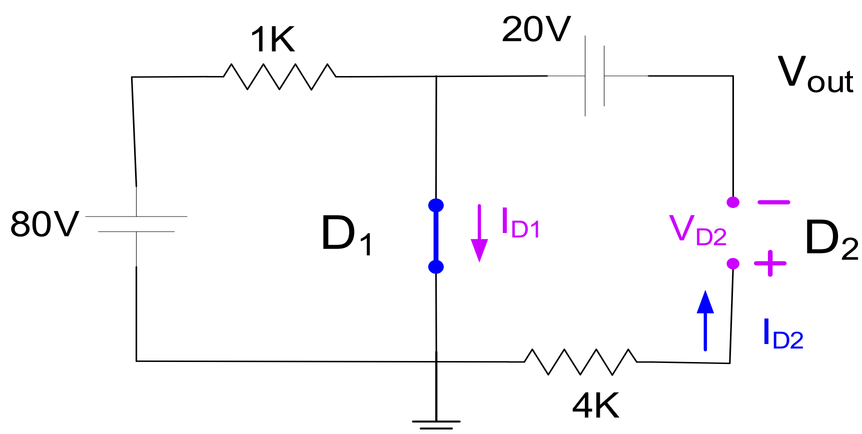
Since validates, solution is valid

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 $V_{D2}<0$

$$I_{D1} = \frac{80V}{1K} = 80mA > 0$$

Validates

V_{D2}=+20

Fails Validation

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

Use of Piecewise 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)

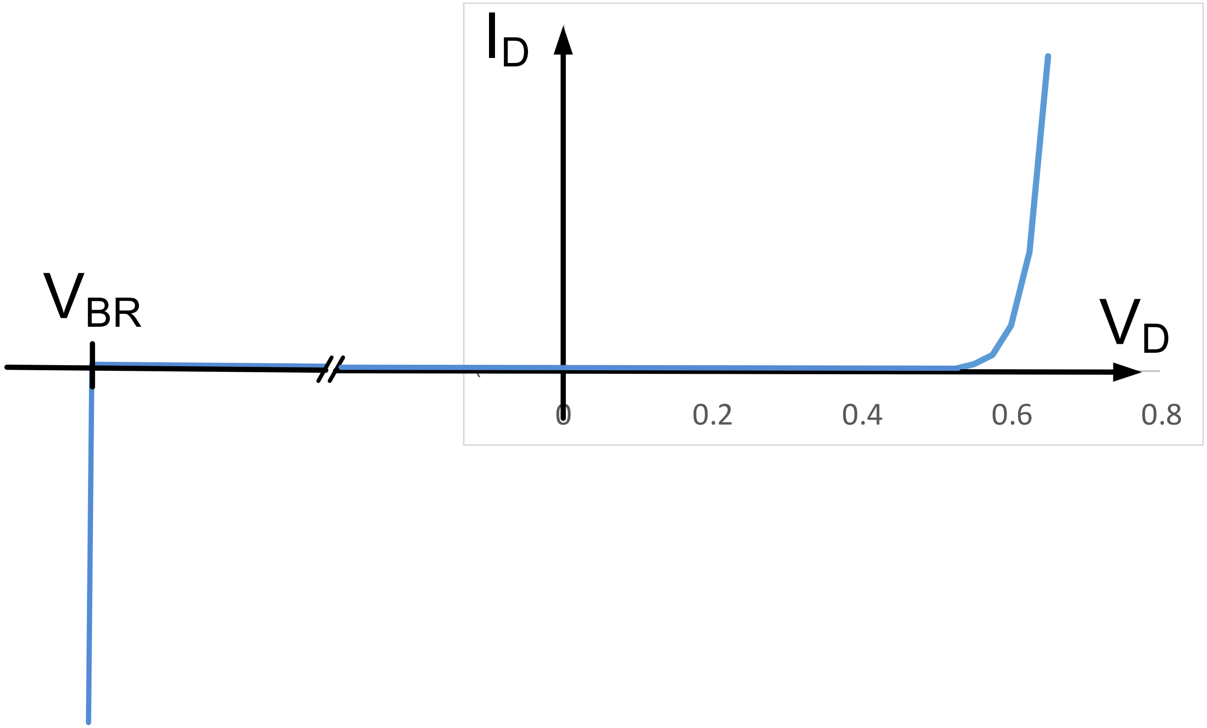
Multiple Nonlinear Devices

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

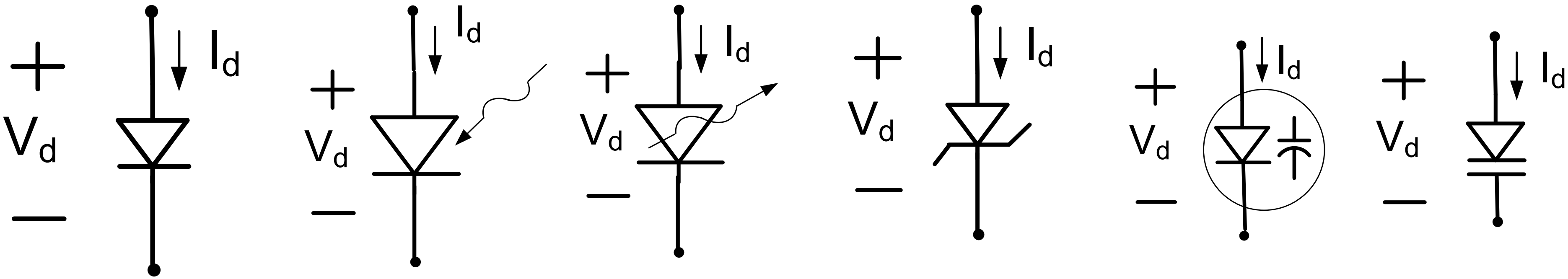
Diode Breakdown



- 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

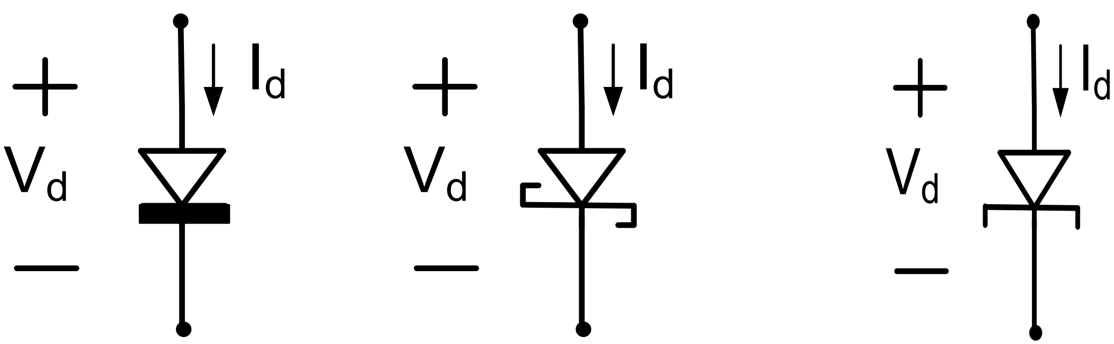
Pin or Photo

Light Emitting LED Laser Diode

Zener

Varactor or Varicap

Metal-semiconductor junction diodes



Schottky Barrier

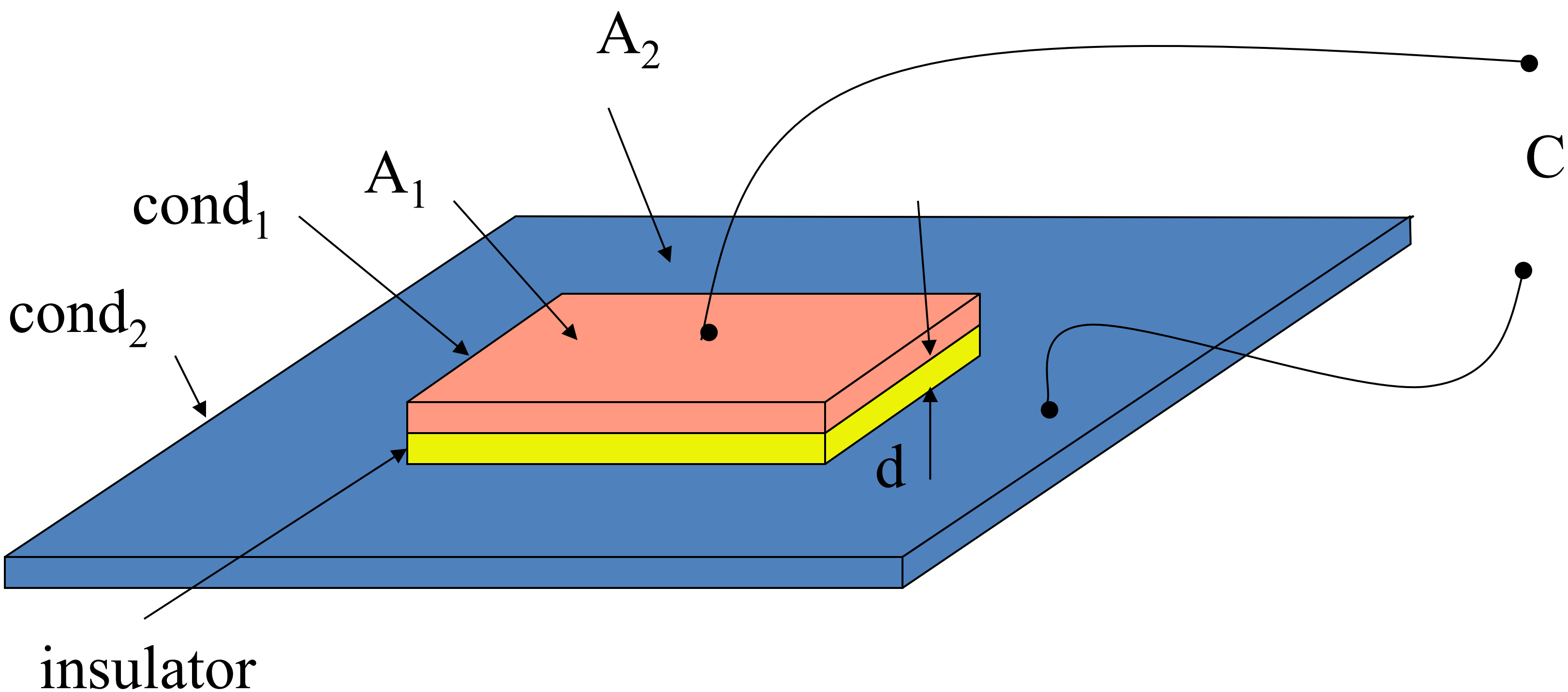
Basic Devices and Device Models

- 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

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

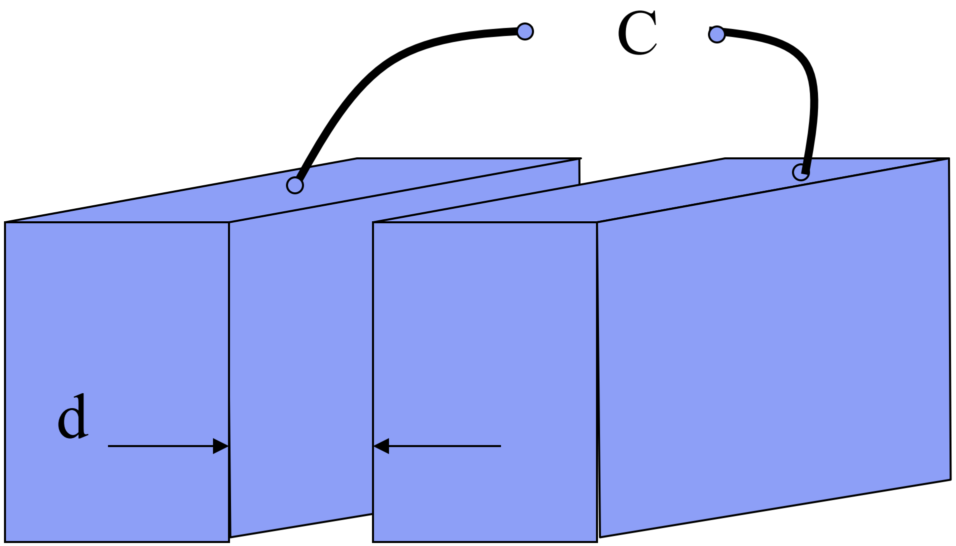
$$C = \frac{\varepsilon A}{d}$$

$$C = C_d A$$

where

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

Fringe Capacitors

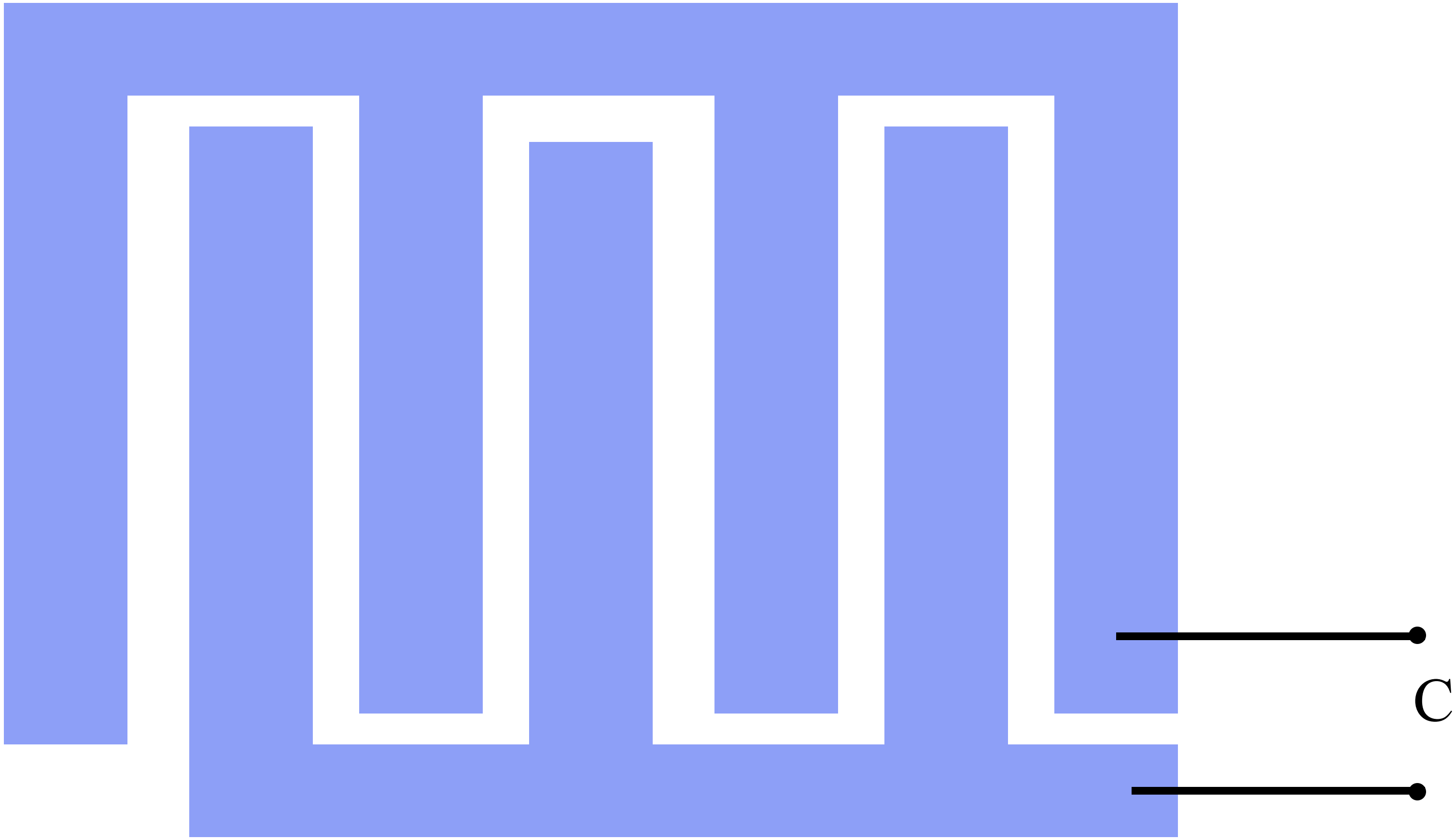


$$C = \frac{\varepsilon A}{d}$$

A is the area where the two plates are parallel

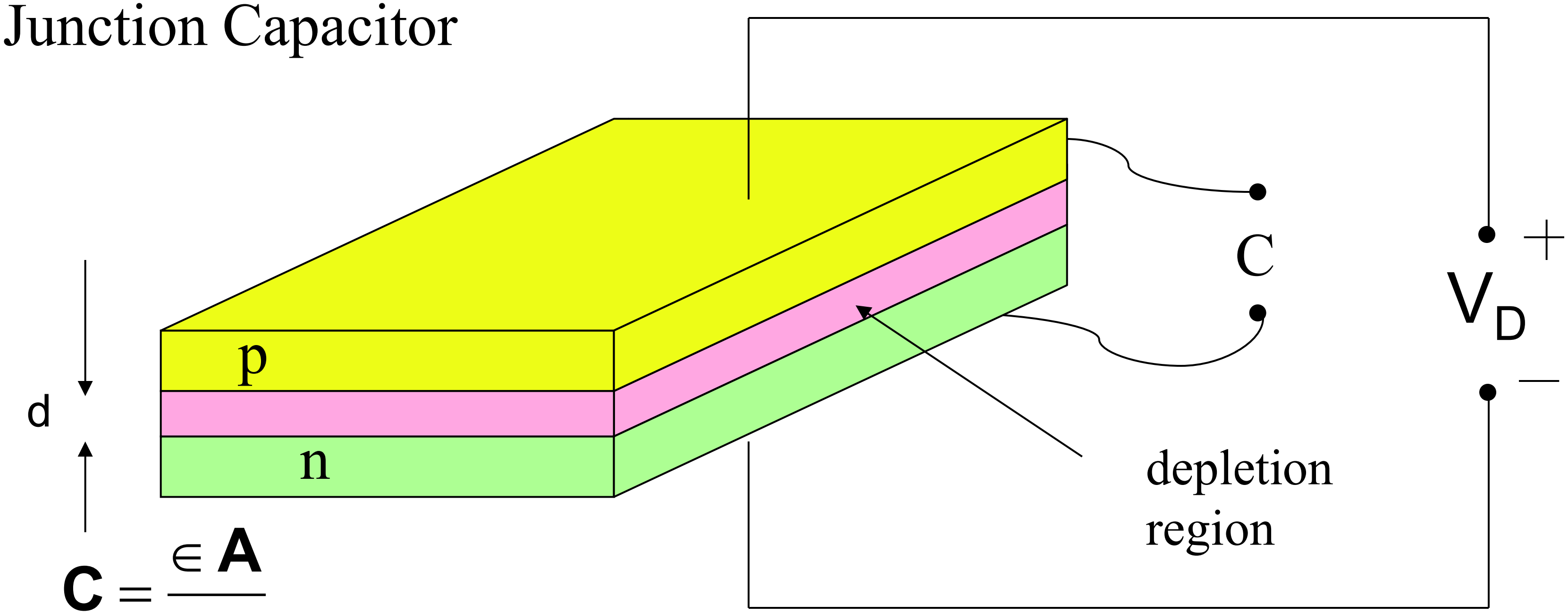
Only a single layer is needed to make fringe capacitors

Fringe Capacitors



Capacitance

Junction Capacitor



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

$\in$ is dielectric constant

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

Note: d is voltage dependent

-capacitance is voltage dependent

-usually parasitic caps

-varicaps or varactor diodes exploit voltage dep. of C

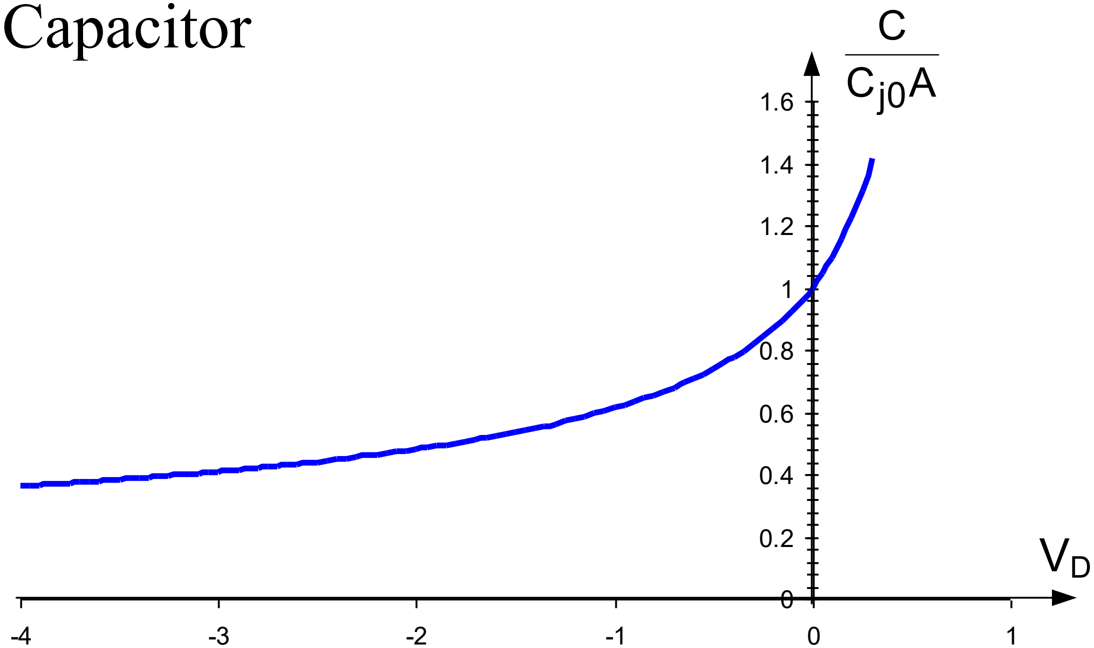
C_{j0} is the zero—bias junction capacitance density

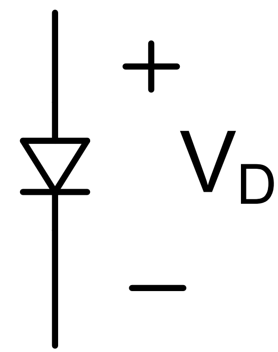
Model parameters $\{C_{jo}, n, \varphi_B\}$ Design parameters {A}

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

Capacitance

Junction Capacitor





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

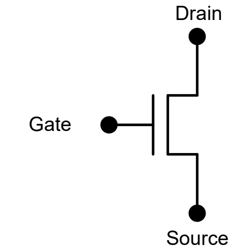
Voltage dependence is substantial

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

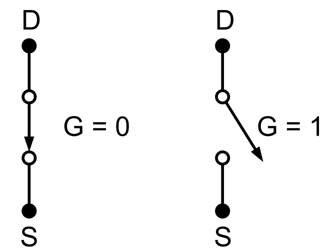
Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT

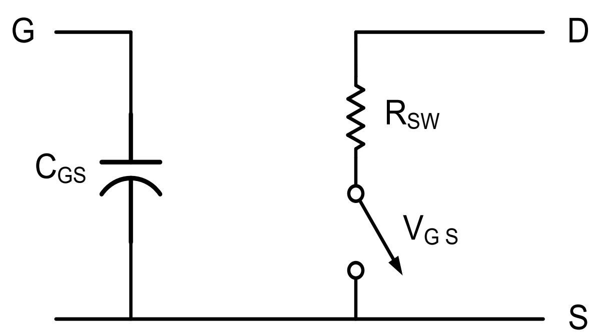
Summary of Existing Models (for n-channel)



1. Switch-Level model



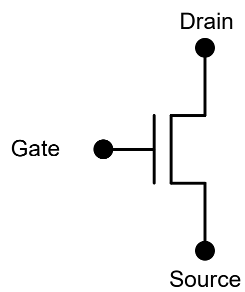
2. Improved switch-level model

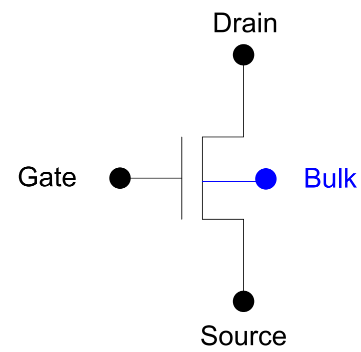


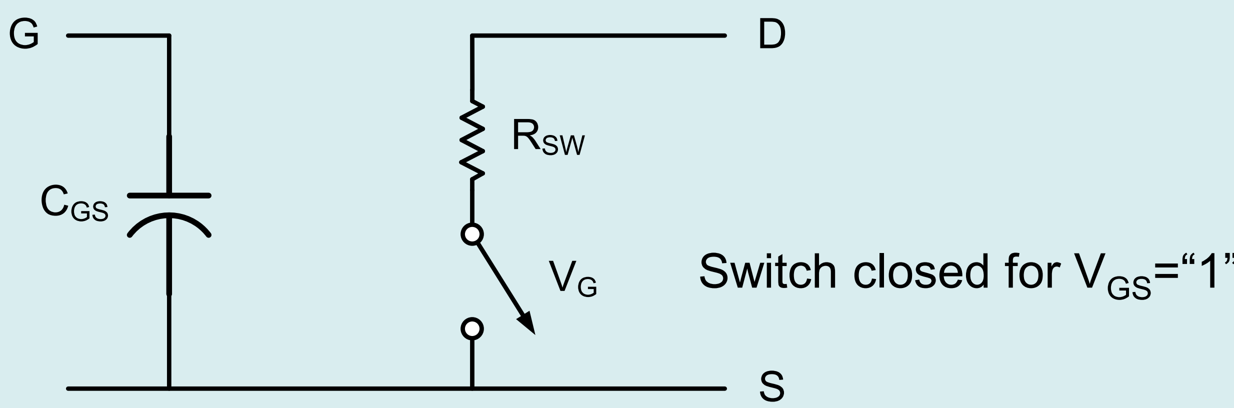
Switch closed for $|V_{GS}|$= *large*

Switch open for $|V_{GS}|$= *small*

Improved Switch-Level Model



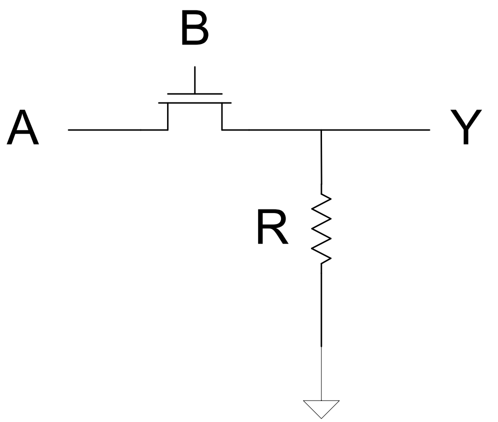




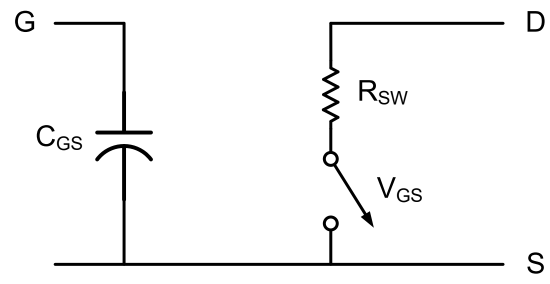
Switch-level model including gate capacitance and channel resistance

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

Limitations of Existing MOSFET Models



What is Y when A=B=VDD

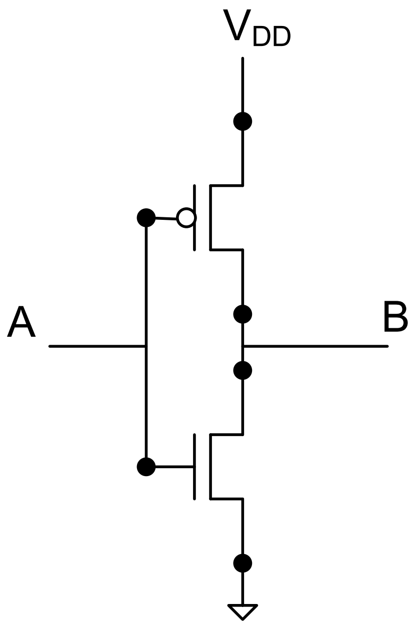


For minimum-sized devices in a 0.5u process with V_{DD}=5V

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

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

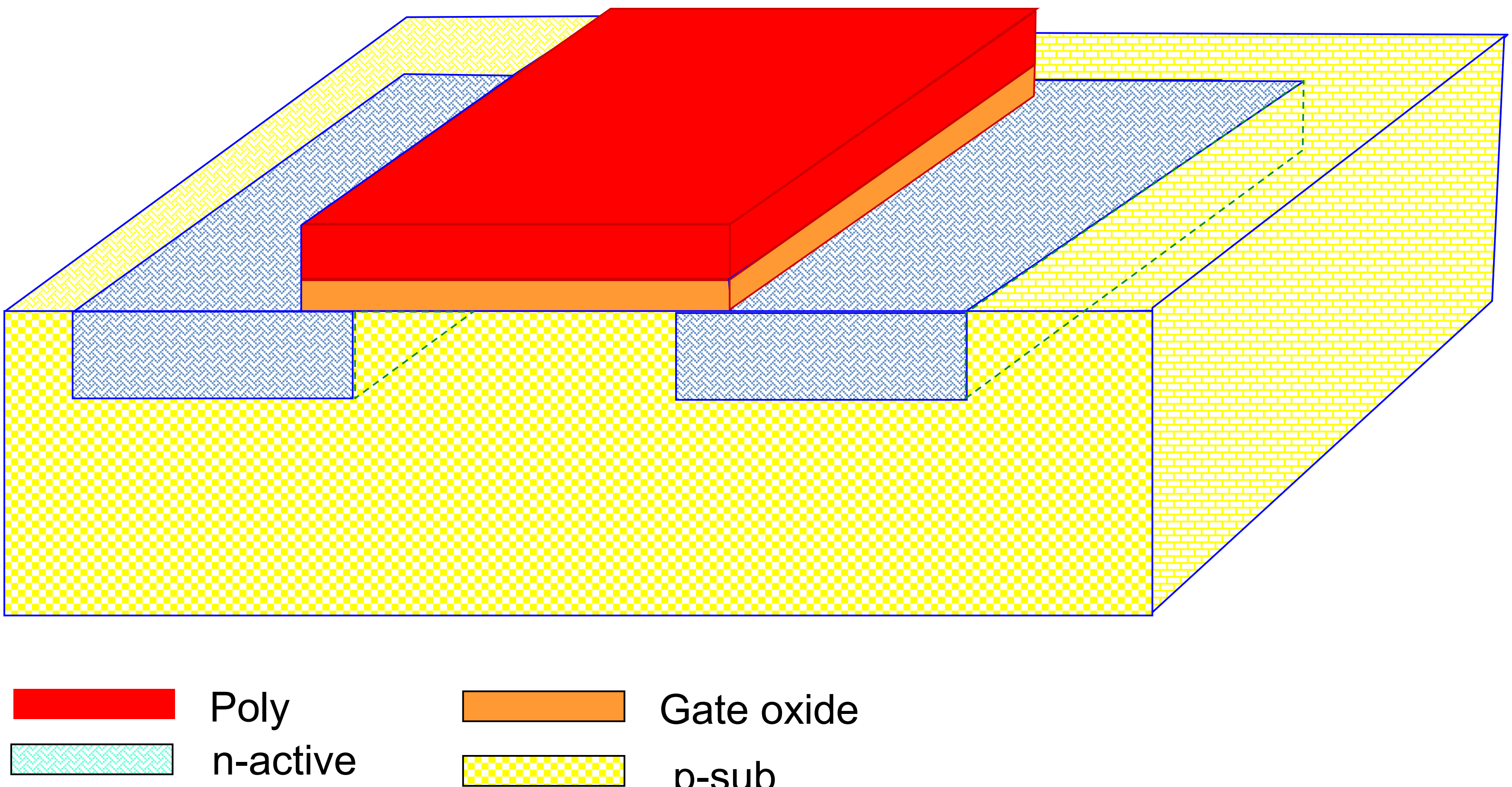
What is R_{SW} if MOSFET is not minimum sized?



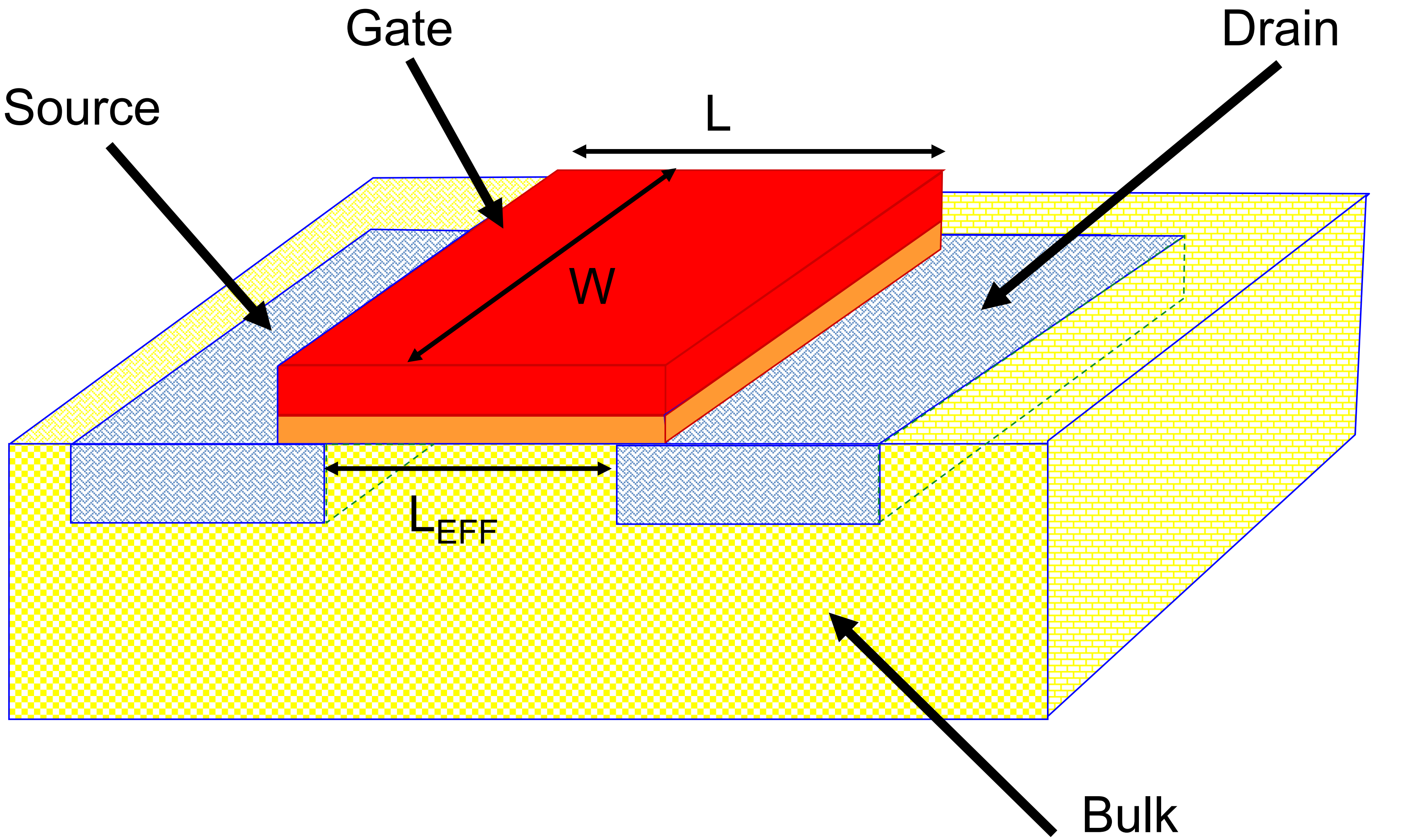
What is power dissipation if A is stuck at an intermediate voltage?

Better Model of MOSFET is Needed!

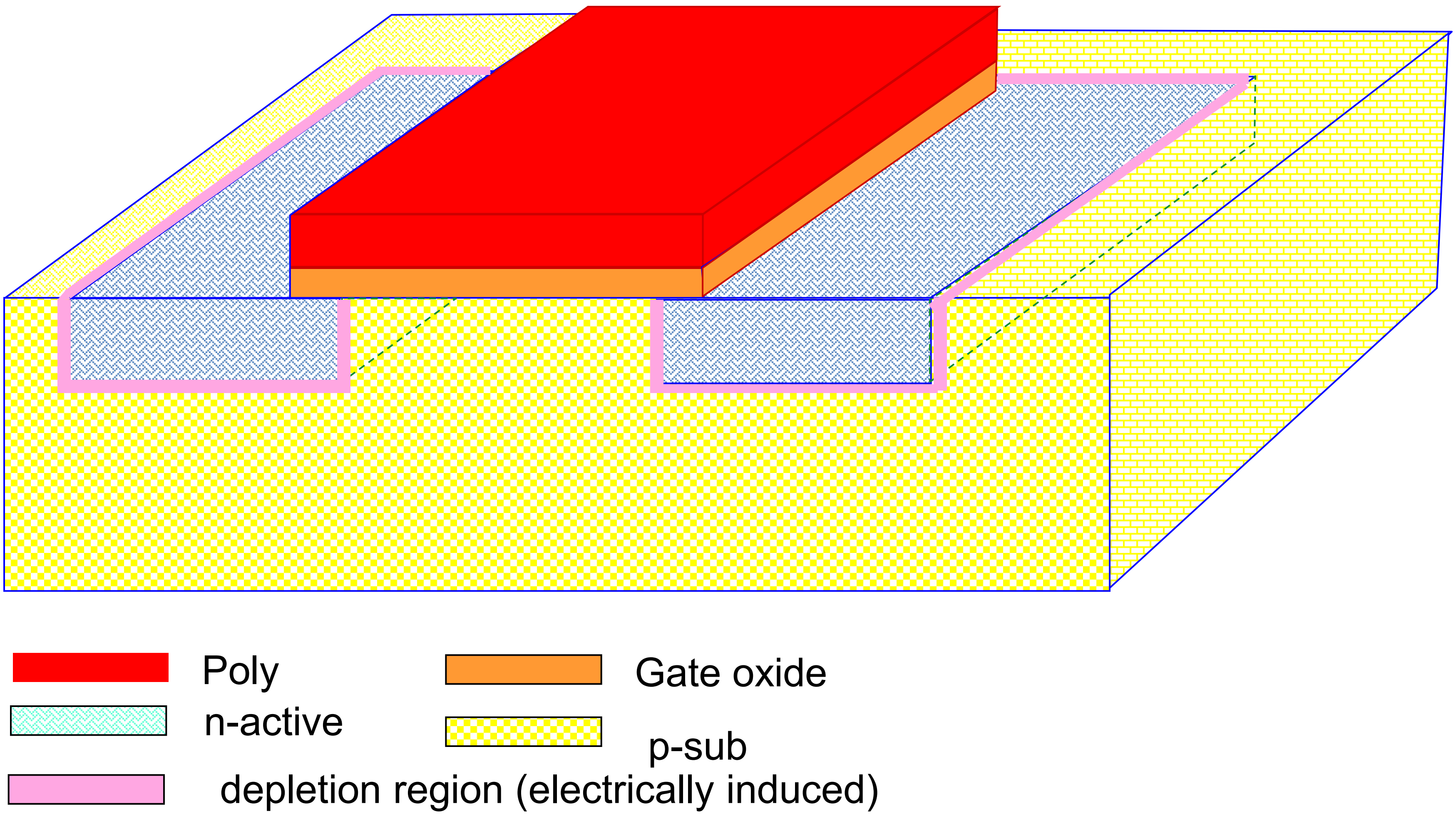
n-Channel MOSFET



n-Channel MOSFET

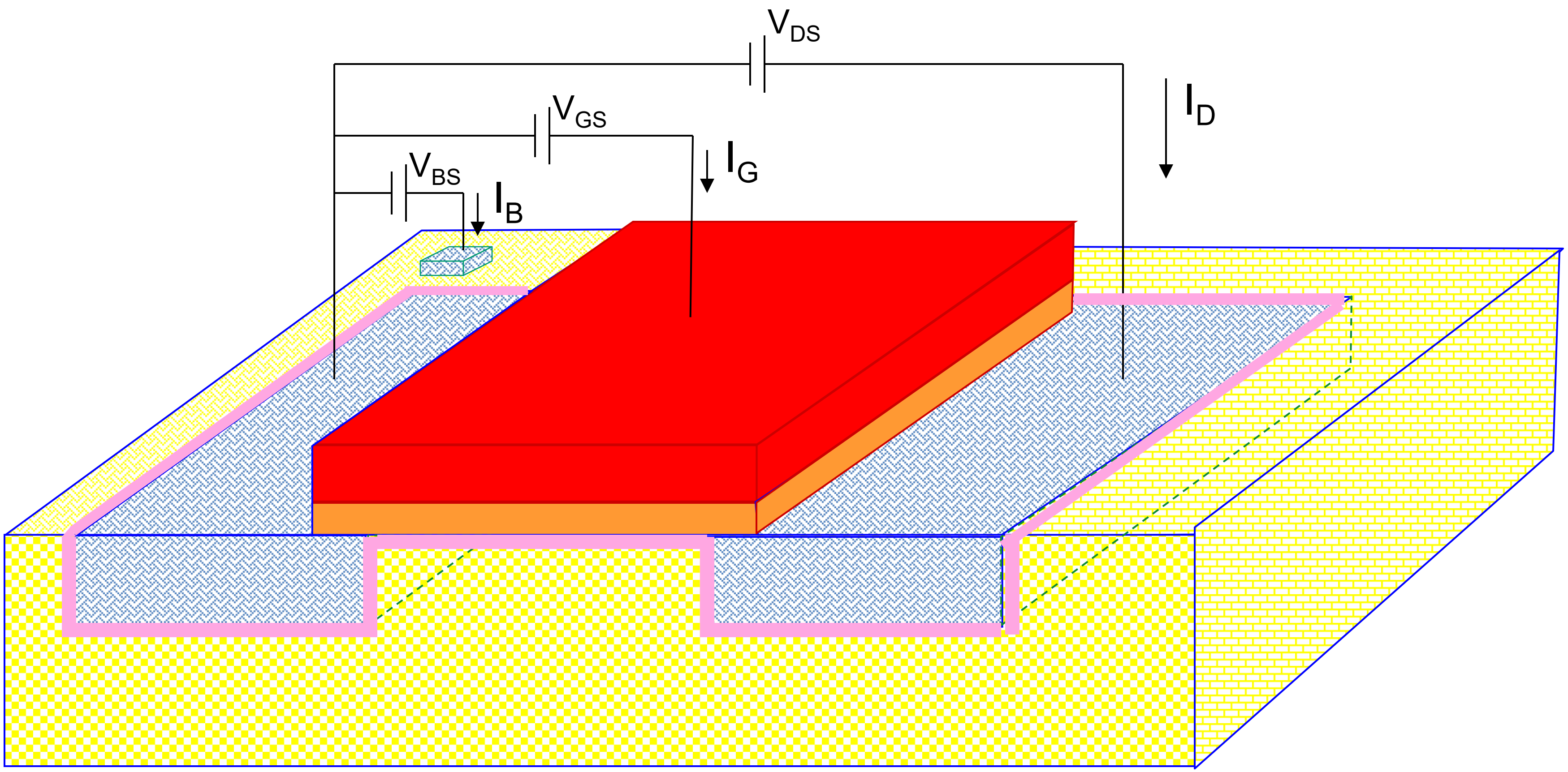


n-Channel MOSFET



- In what follows assume all pn junctions reverse biased (almost always used this way)
- Extremely small reverse bias pn junction current can be neglected in most applications

n-Channel MOSFET Operation and Model



Apply small V_{GS}

(V_{DS} and V_{BS} assumed to be small)

Depletion region electrically induced in channel

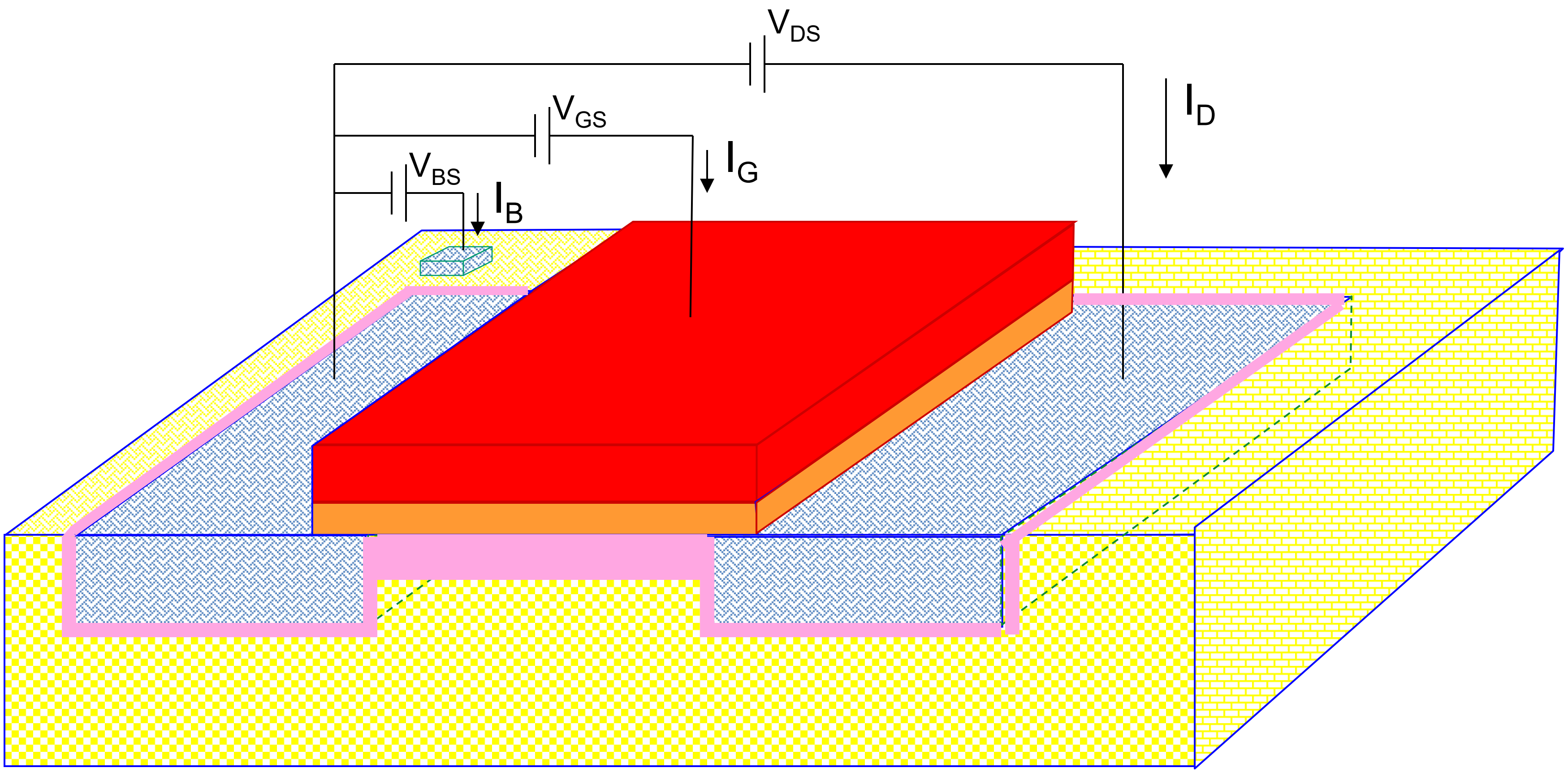
Termed "cutoff" region of operation

$I_D=0$

$I_G=0$

$I_B=0$

n-Channel MOSFET Operation and Model

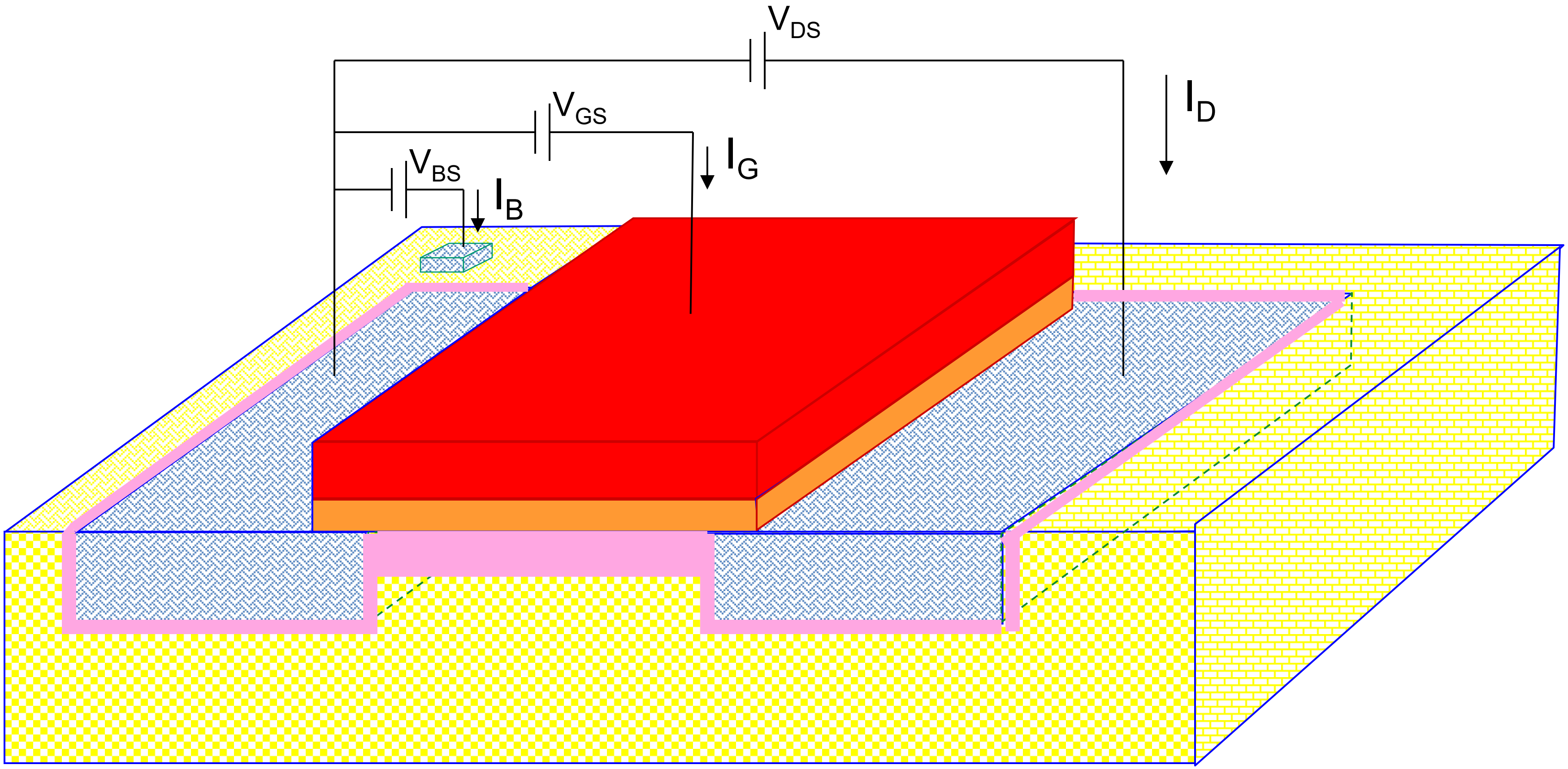


Increase V_{GS}
(V_{DS} and V_{BS} assumed to be small)

Depletion region in channel becomes larger

$I_D=0$
$I_G=0$
$I_B=0$

n-Channel MOSFET Operation and Model

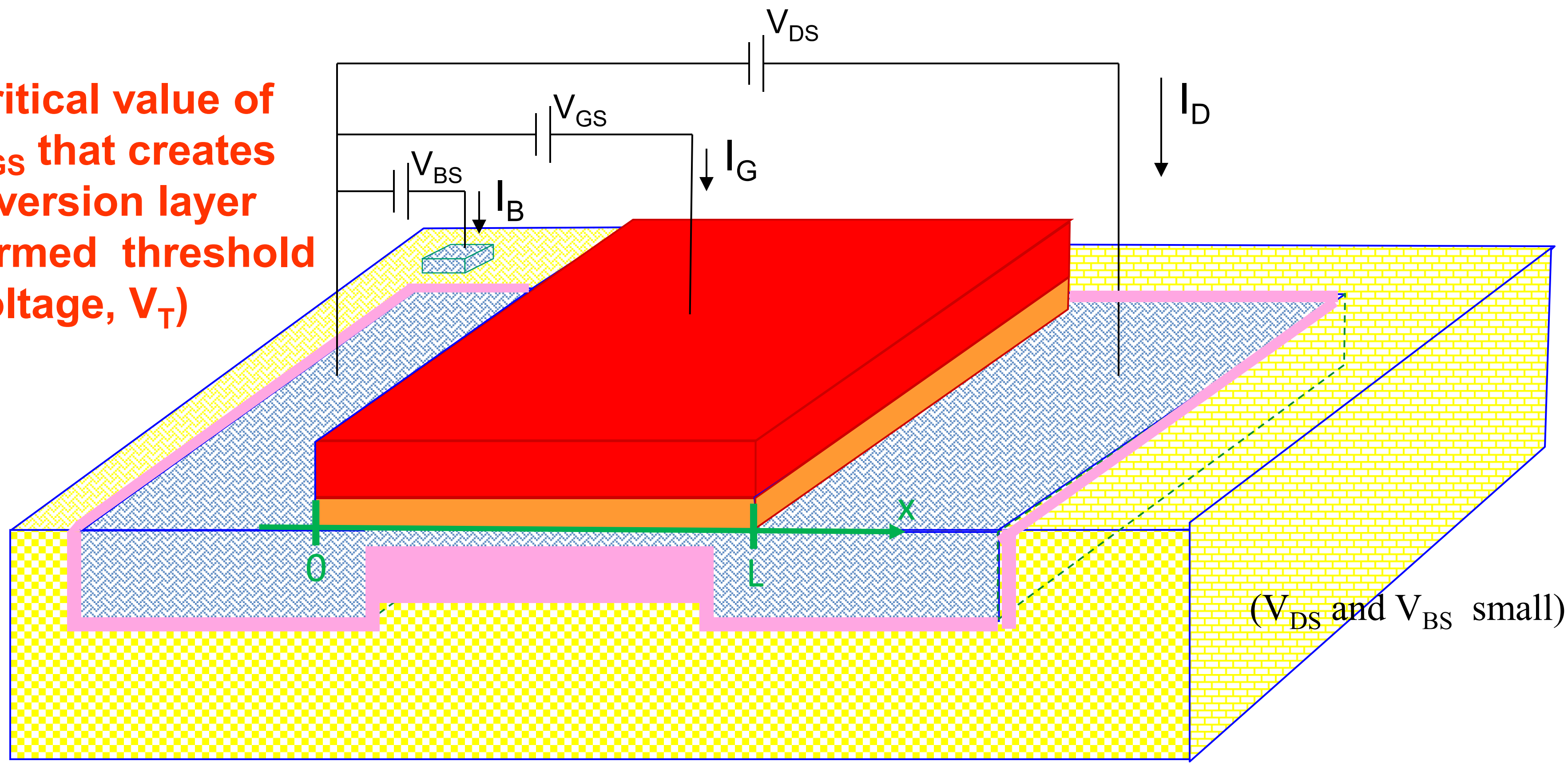


$I_D=0$
$I_G=0$
$I_B=0$

Model in Cutoff Region

n-Channel MOSFET Operation and Model

Critical value of V_{GS} that creates inversion layer termed threshold voltage, V_T)



Increase V_{GS} more

Inversion layer forms in channel

Inversion layer will support current flow from D to S

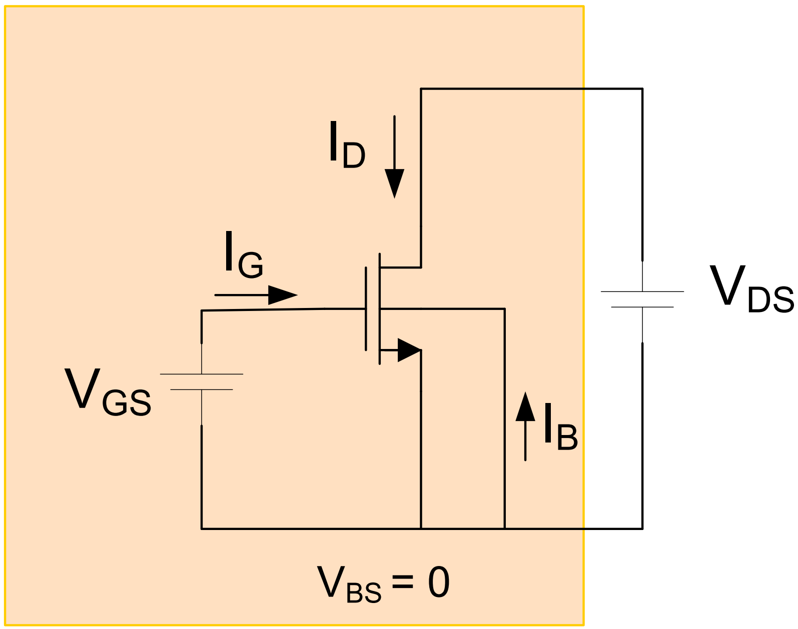
Channel behaves as thin-film resistor

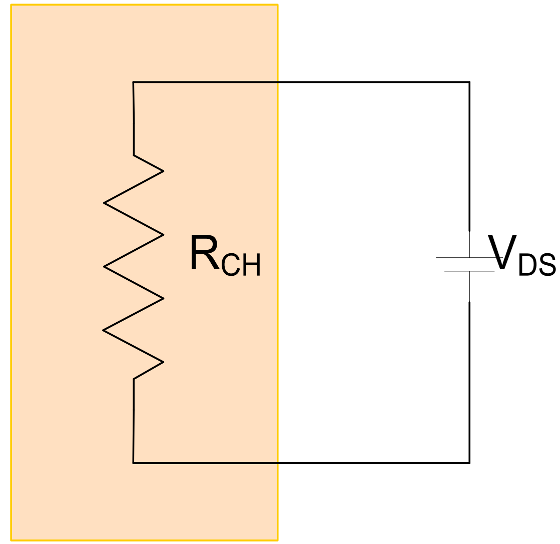
$I_D R_{CH} = V_{DS}$

$I_G = 0$

$I_B = 0$

Triode Region of Operation





For V_{DS} small

$$R_{CH} = \frac{L}{W} \frac{1}{(V_{GS} - V_{TH}) \mu C_{OX}}$$

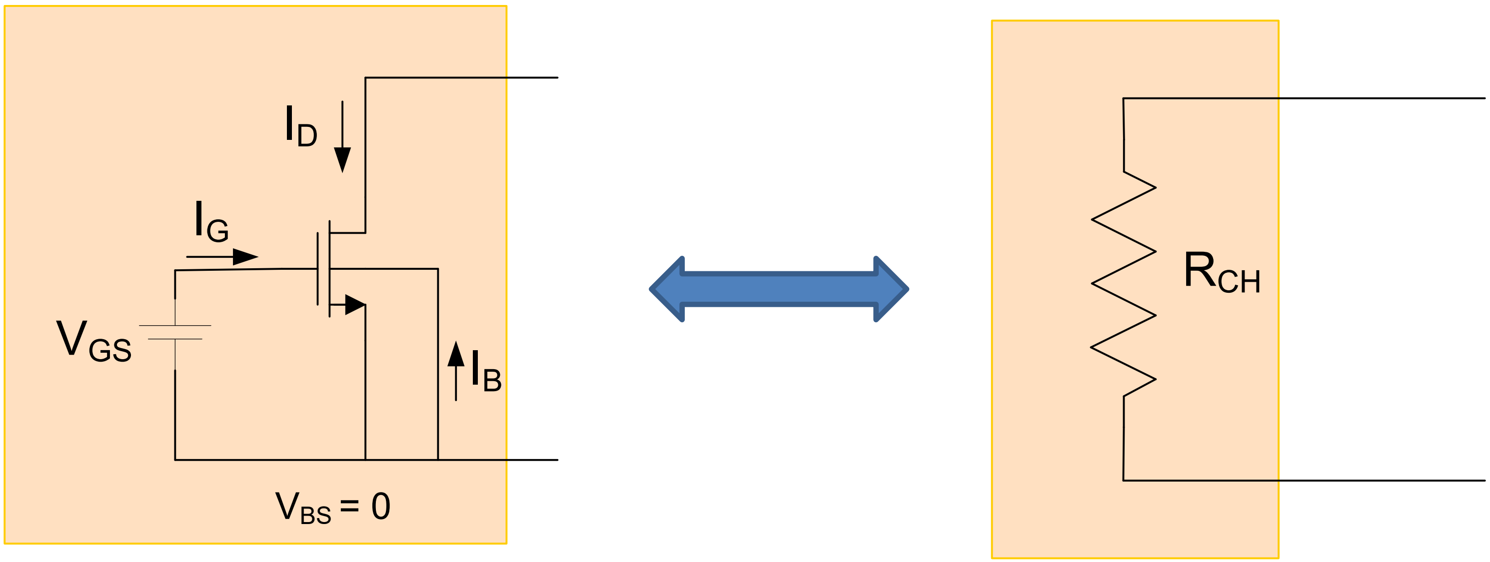
Behaves as a resistor between drain and source

$$I_D = \mu C_{OX} \frac{W}{L} (V_{GS} - V_{TH}) V_{DS}$$

$$I_G = I_B = 0$$

Model in Deep Triode Region

Triode Region of Operation

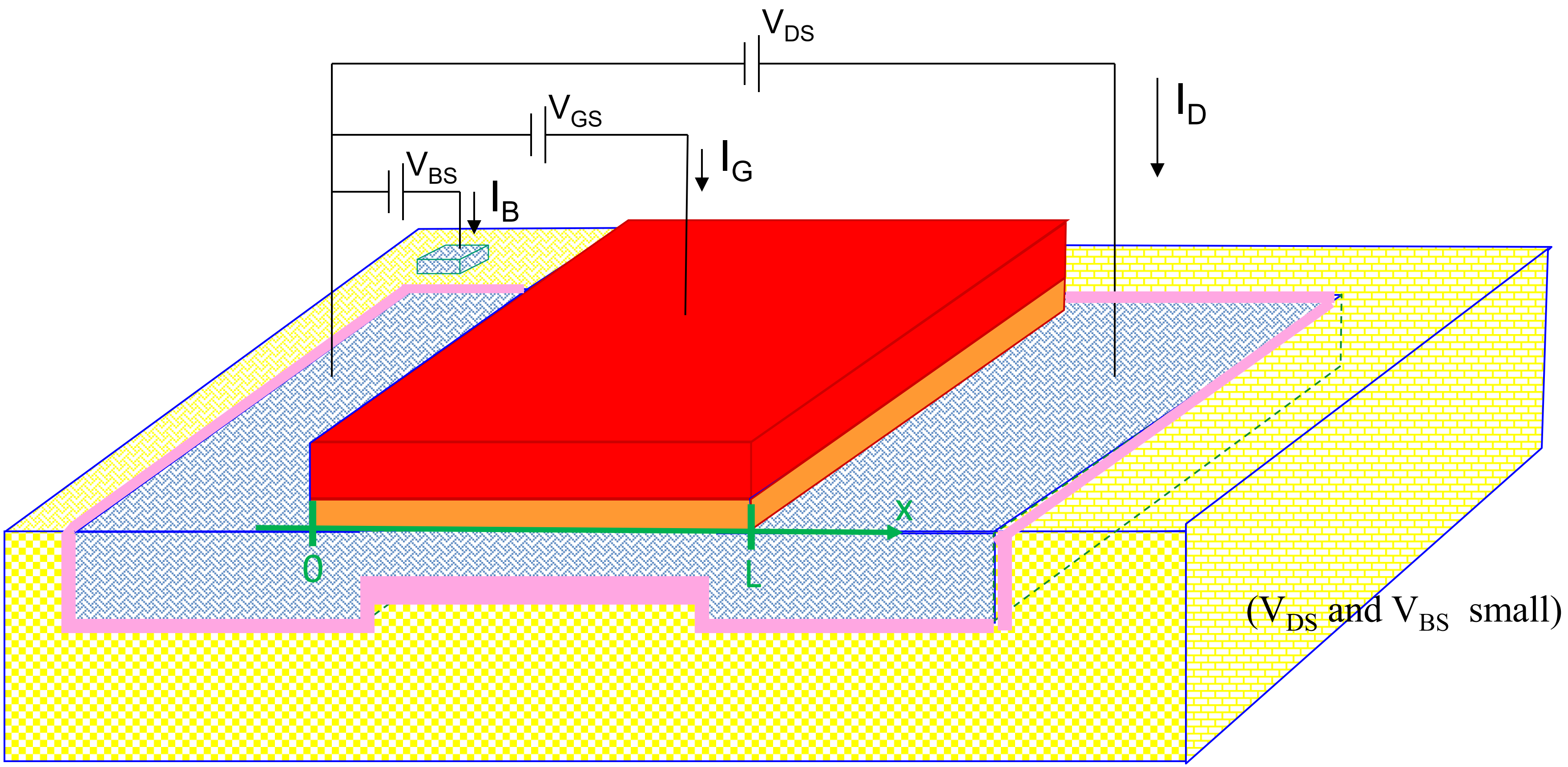


For V_{DS} small

$$R_{CH} = \frac{L}{W} \frac{1}{\left(V_{GS} - V_{TH}\right)\mu C_{OX}}$$

Resistor is controlled by the voltage V_{GS}
Termed a "Voltage Controlled Resistor" (VCR)

n-Channel MOSFET Operation and Model



$V_{GC}(x)$ approx. constant for small V_{DS}

Increase V_{GS} more (with V_{DS} and V_{BS} still small)

Inversion layer in channel thickens

R_{CH} will decrease

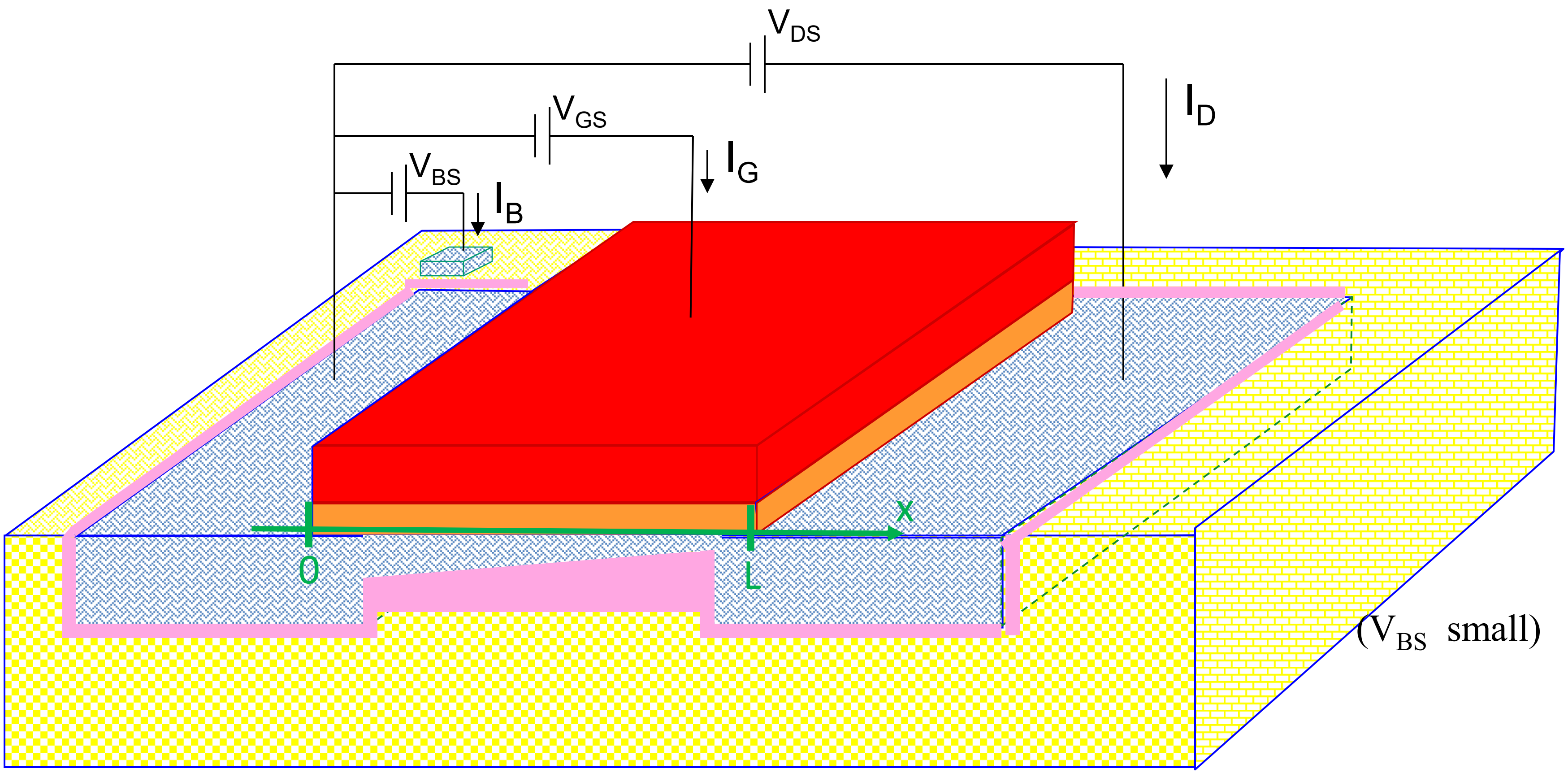
Termed "ohmic" or "triode" region of operation

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

$I_G = 0$

$I_B = 0$

n-Channel MOSFET Operation and Model



$V_{GC}(x)$ changes with x for larger V_{DS}

Increase V_{DS}

Inversion layer thins near drain

I_D no longer linearly dependent upon V_{DS}

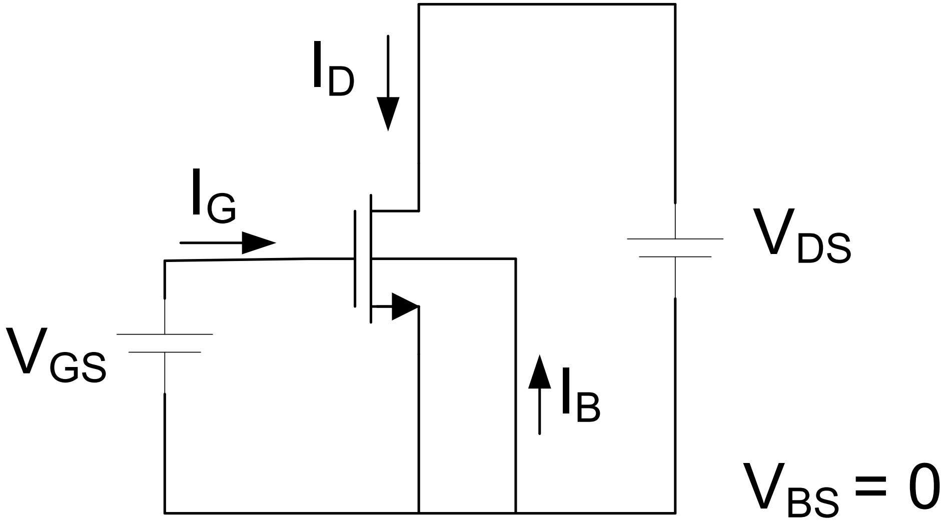
Still termed "ohmic" or "triode" region of operation

I_D=?

I_G=0

I_B=0

Triode Region of Operation



For V_{DS} larger

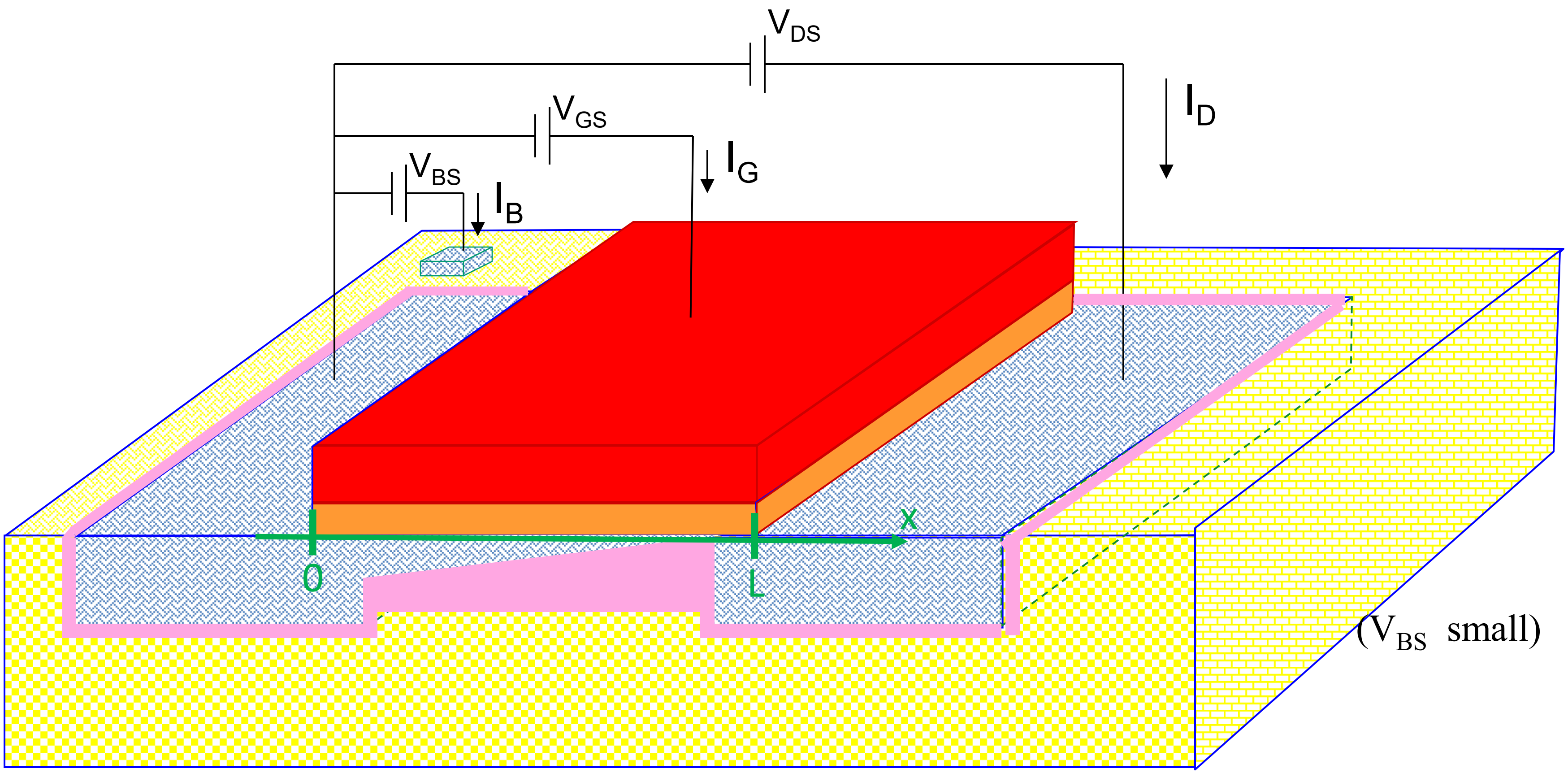
$$R_{CH} = \frac{L}{W}\frac{1}{\left(V_{GS} - V_{TH}\right)\mu C_{OX}}$$

$$I_D = \mu C_{OX}\frac{W}{L}\left(V_{GS} - V_{TH} - \frac{V_{DS}}{2}\right)V_{DS}$$

$$I_G = I_B = 0$$

Model in Triode Region

n-Channel MOSFET Operation and Model



Increase V_{DS} even more

$V_{GC}(L) = V_{TH}$ when channel saturates

Inversion layer disappears near drain

Termed “saturation”region of operation

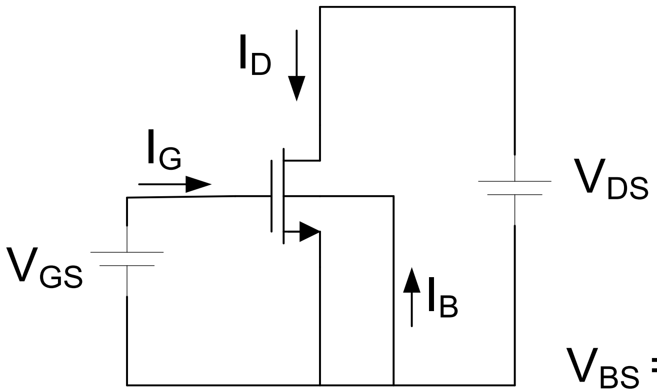
Saturation first occurs when $V_{DS}=V_{GS}-V_{TH}$

$I_D=?$

$I_G=0$

$I_B=0$

Saturation Region of Operation



$V_{BS} = 0$

$$I_D = \mu C_{OX} \frac{W}{L}\left(V_{GS} - V_{TH} - \frac{V_{DS}}{2}\right)V_{DS}$$

or equivalently

For V_{DS} at onset of saturation

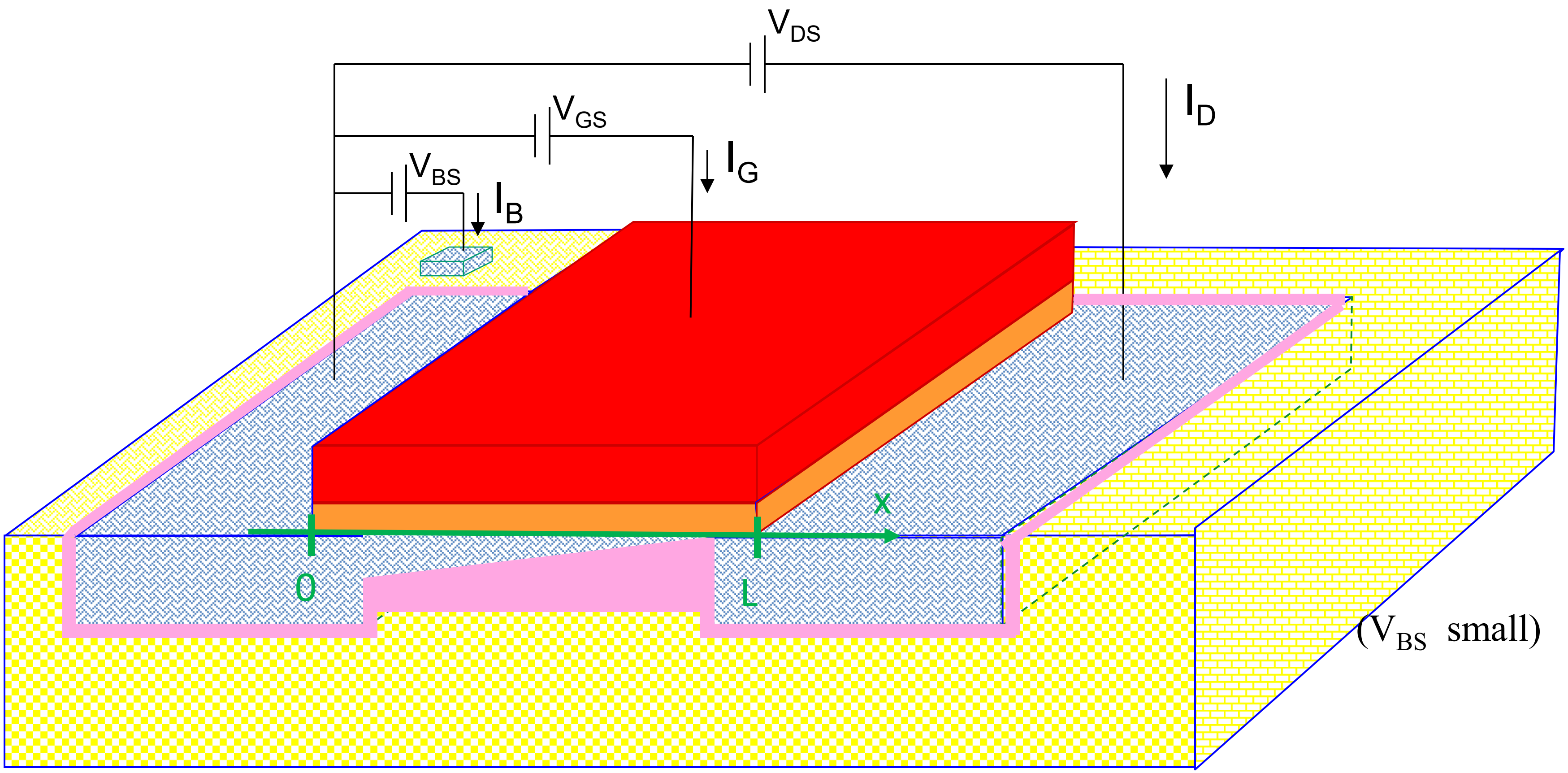
$$I_D = \mu C_{OX} \frac{W}{L}\left(V_{GS} - V_{TH} - \frac{V_{GS} - V_{TH}}{2}\right)\left(V_{GS} - V_{TH}\right)$$

or equivalently

$$I_D = \frac{\mu C_{OX} W}{2L}\left(V_{GS} - V_{TH}\right)^2$$

$$I_G = I_B = 0$$

n-Channel MOSFET Operation and Model



Increase V_{DS} even more (beyond V_{GS}-V_{TH})

Nothing much changes !!

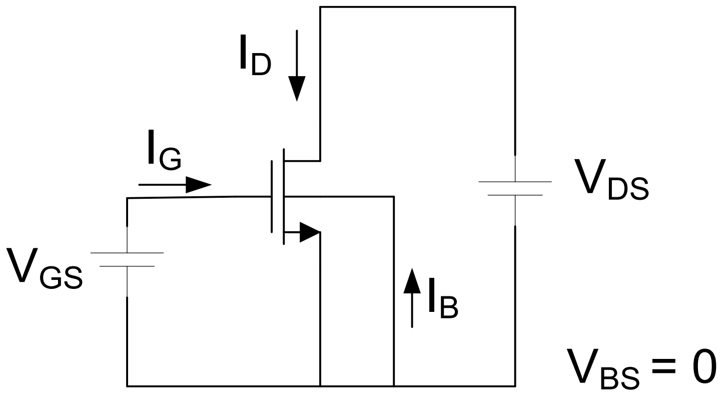
Termed "saturation" region of operation

I_D=?

I_G=0

I_B=0

Saturation Region of Operation



For V_{DS} in Saturation

$$I_D = \frac{\mu C_{OX} W}{2L}\left(V_{GS} - V_{TH}\right)^2$$

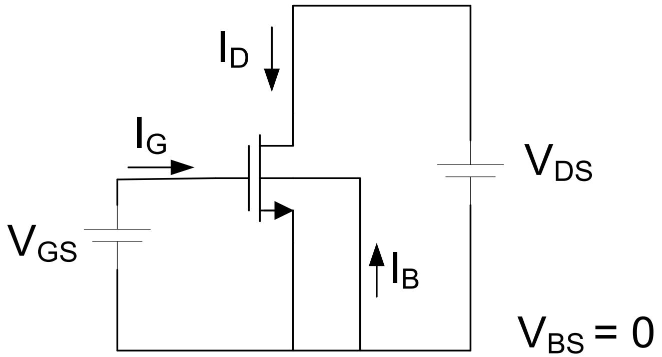
$$I_G = I_B = 0$$

Model in Saturation Region

Model Summary

n-channel MOSFET

Notation change: $V_T = V_{TH}$, don't confuse V_T with $V_t = kT/q$



$$I_D = \begin{cases} 0 & V_{GS} \le V_{TH} & \text{Cutoff} \\ \mu C_{OX} \dfrac{W}{L}\left(V_{GS} - V_{TH} - \dfrac{V_{DS}}{2}\right)V_{DS} & V_{GS} \ge V_{TH} \quad V_{DS} < V_{GS} - V_{TH} & \text{Triode} \\ \mu C_{OX} \dfrac{W}{2L}\left(V_{GS} - V_{TH}\right)^2 & V_{GS} \ge V_{TH} \quad V_{DS} \ge V_{GS} - V_{TH} & \text{Saturation} \end{cases}$$

$$I_G = I_B = 0$$

Model Parameters: $\{\mu, V_{TH}, C_{OX}\}$ Design Parameters : {W, L}

This is a piecewise model (not piecewise linear though)

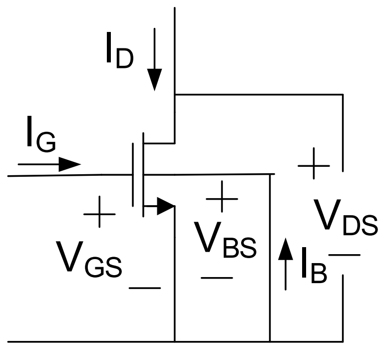
Piecewise model is continuous at transition between regions

(Deep triode special case of triode where V_{DS} is small $R_{CH} = \dfrac{L}{W}\dfrac{1}{(V_{GS} - V_{TH})\mu C_{OX}}$)

Note: This is the third model we have introduced for the MOSFET

Model Summary

n-channel MOSFET



$V_{BS} = 0$

$$I_D = \begin{cases} 0 & V_{GS} \le V_{TH} \\ \mu C_{OX} \frac{W}{L}\left(V_{GS} - V_{TH} - \frac{V_{DS}}{2}\right)V_{DS} & V_{GS} \ge V_{TH} \quad V_{DS} < V_{GS} - V_{TH} \\ \mu C_{OX} \frac{W}{2L}\left(V_{GS} - V_{TH}\right)^2 & V_{GS} \ge V_{TH} \quad V_{DS} \ge V_{GS} - V_{TH} \end{cases}$$

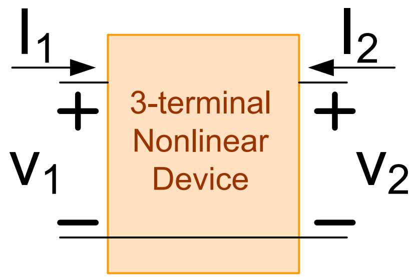
$$I_G = I_B = 0$$

Observations about this model (developed for $V_{BS}=0$):

$$I_D = f_1(V_{GS}, V_{DS})$$
$$I_G = f_2(V_{GS}, V_{DS})$$
$$I_B = f_3(V_{GS}, V_{DS})$$

This is a nonlinear model characterized by the functions f_1, f_2, and f_3 where we have assumed that the port voltages V_{GS} and V_{DS} are the independent variables and the drain currents are the dependent variables

General Nonlinear Models

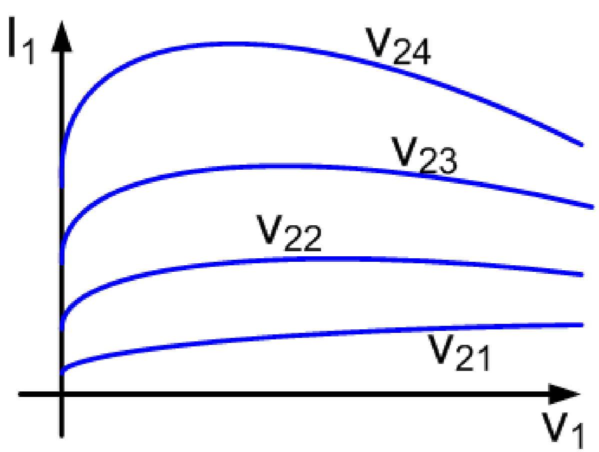


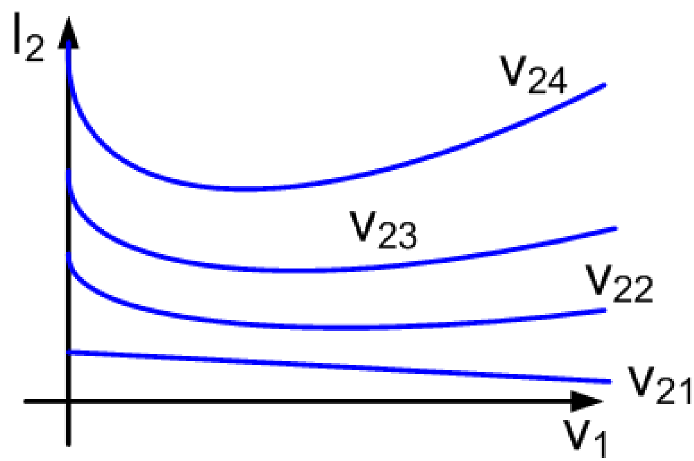
$$I_1 = f_1(V_1, V_2)$$

$$I_2 = f_2(V_1, V_2)$$

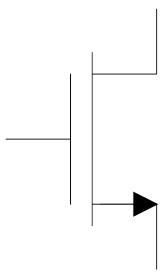
I_1 and I_2 are 3-dimensional relationships which are often difficult to visualize

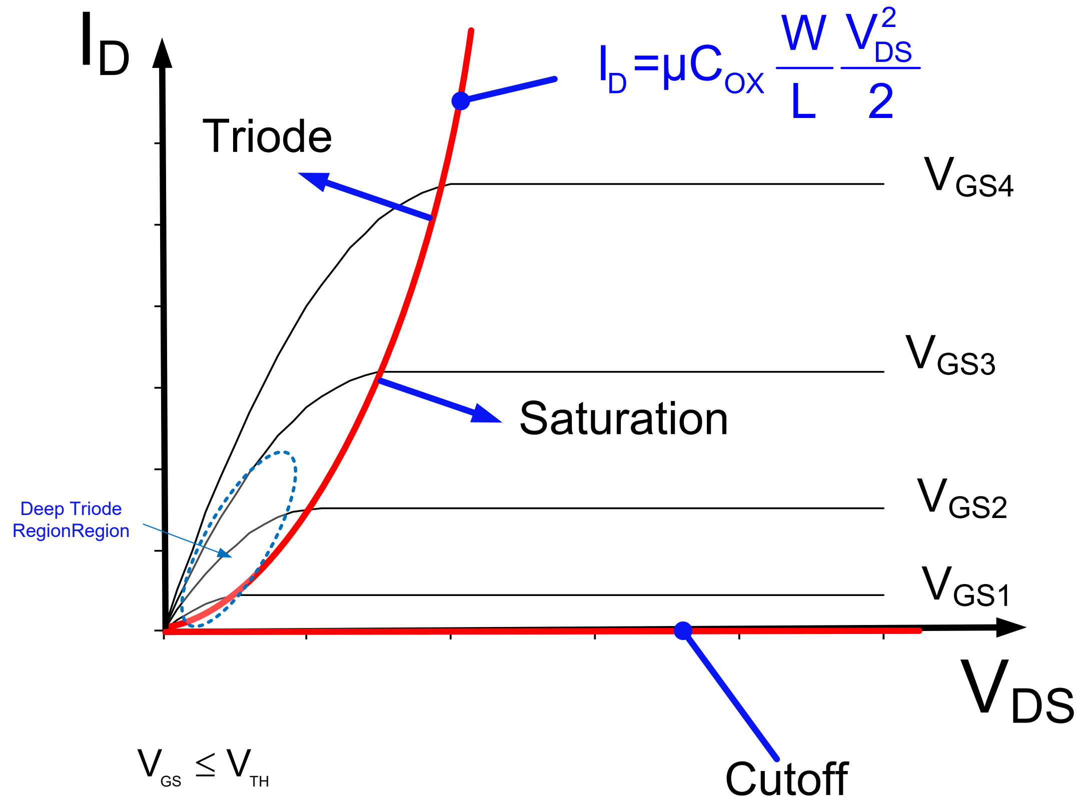
Two-dimensional representation of 3-dimensional relationships





Graphical Representation of MOS Model





$$I_D = \begin{cases} 0 & V_{GS} \le V_{TH} \\ \mu C_{OX} \frac{W}{L}\left(V_{GS} - V_{TH} - \frac{V_{DS}}{2}\right) V_{DS} & V_{GS} \ge V_{TH} \quad V_{DS} < V_{GS} - V_{TH} \\ \mu C_{OX} \frac{W}{2L}(V_{GS} - V_{TH})^2 & V_{GS} \ge V_{TH} \quad V_{DS} \ge V_{GS} - V_{TH} \end{cases}$$

$$I_G = I_B = 0$$

Parabola separated triode and saturation regions and corresponds to $V_{DS}=V_{GS}-V_{TH}$

Stay Safe and Stay Healthy !

End of Lecture 16