EE 330
Lecture 16

Devices in Semiconductor Processes

- Capacitors
- MOSFETs

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)

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 <u>practical</u> circuits, the simplified approach usually applies

Key Concept For Analyzing Circuits with Nonlinear Devices

Review from Last Lecture

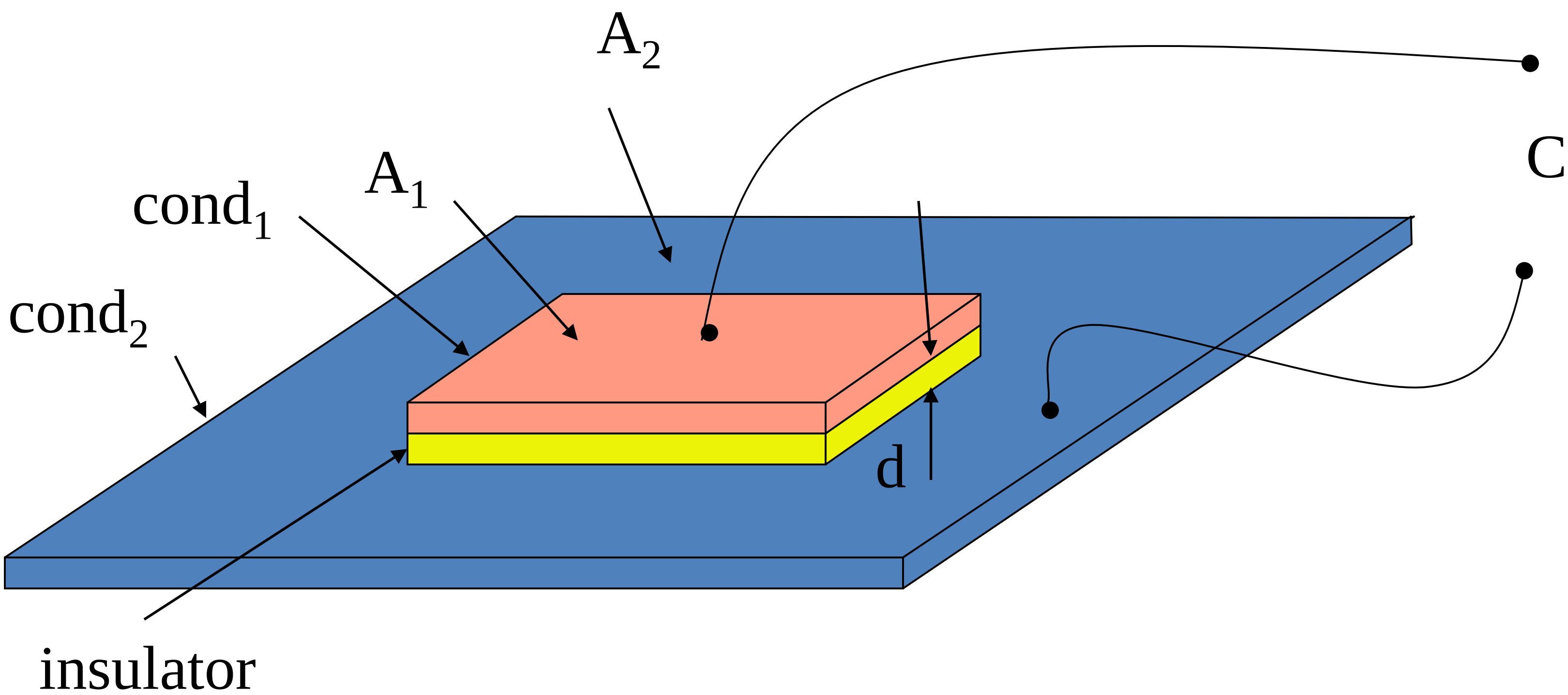
Basic Devices and Device Models

- 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

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

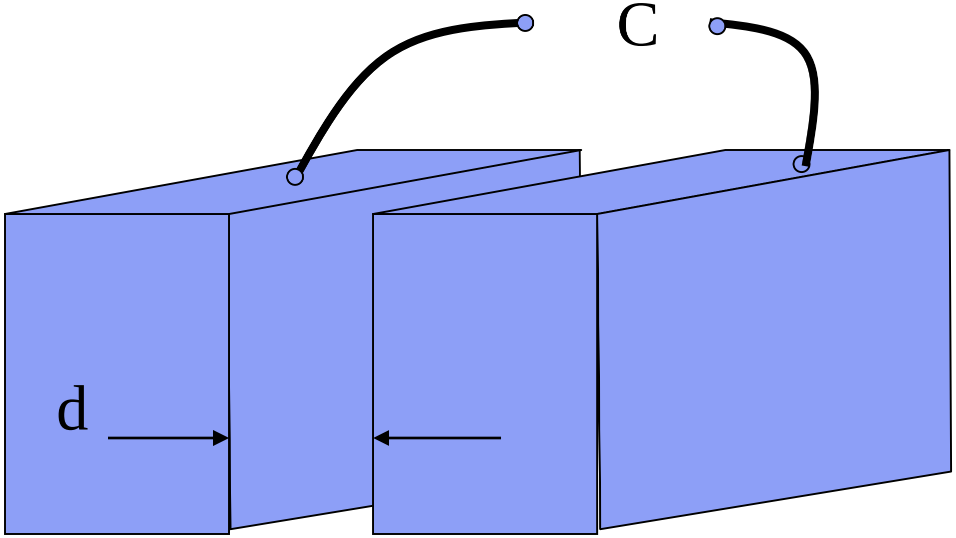
$$C = \frac{\varepsilon A}{d}$$

$$C = C_d A$$

where

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

Fringe Capacitors

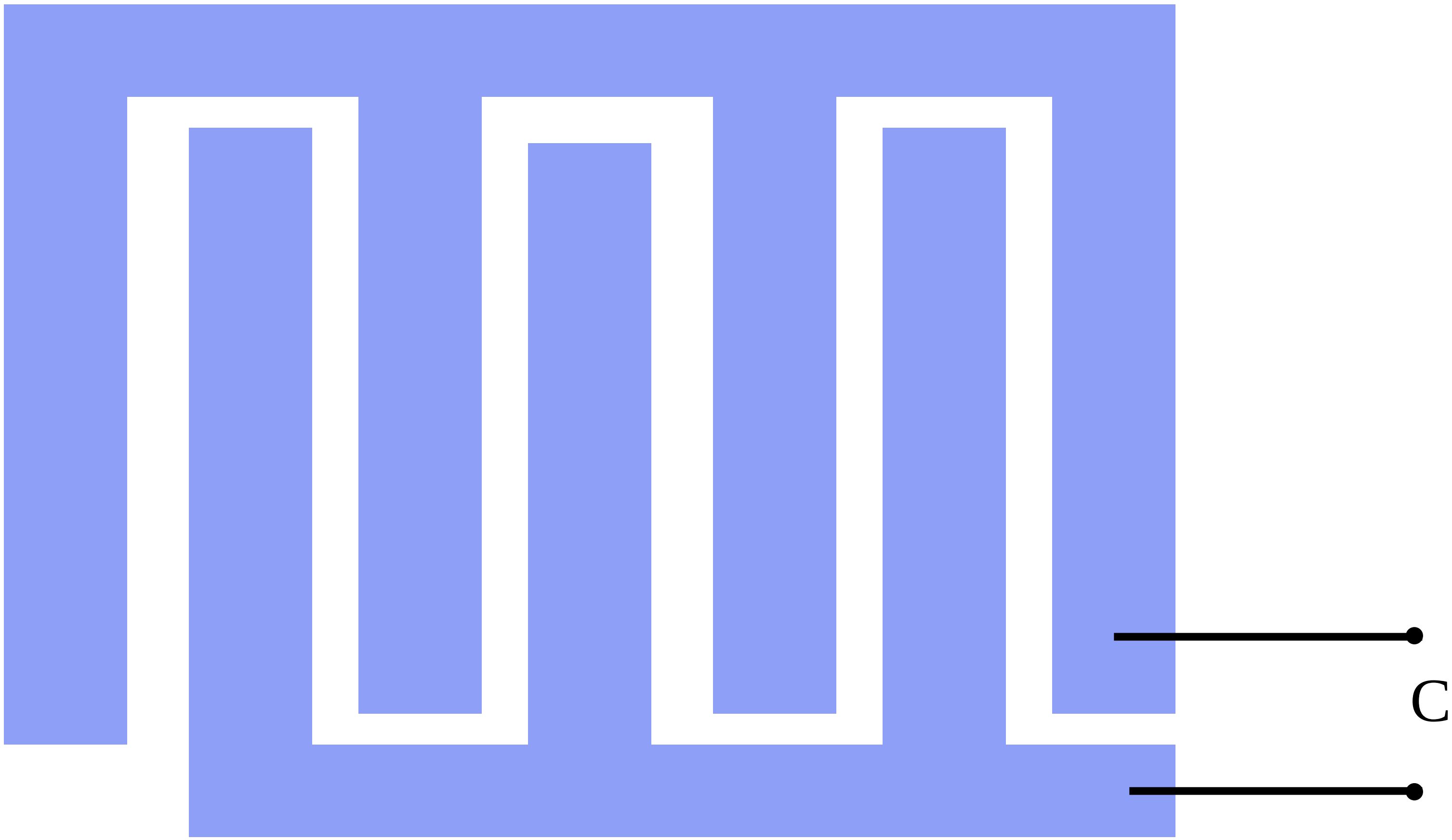


$$C = \frac{\varepsilon A}{d}$$

A is the area where the two plates are parallel

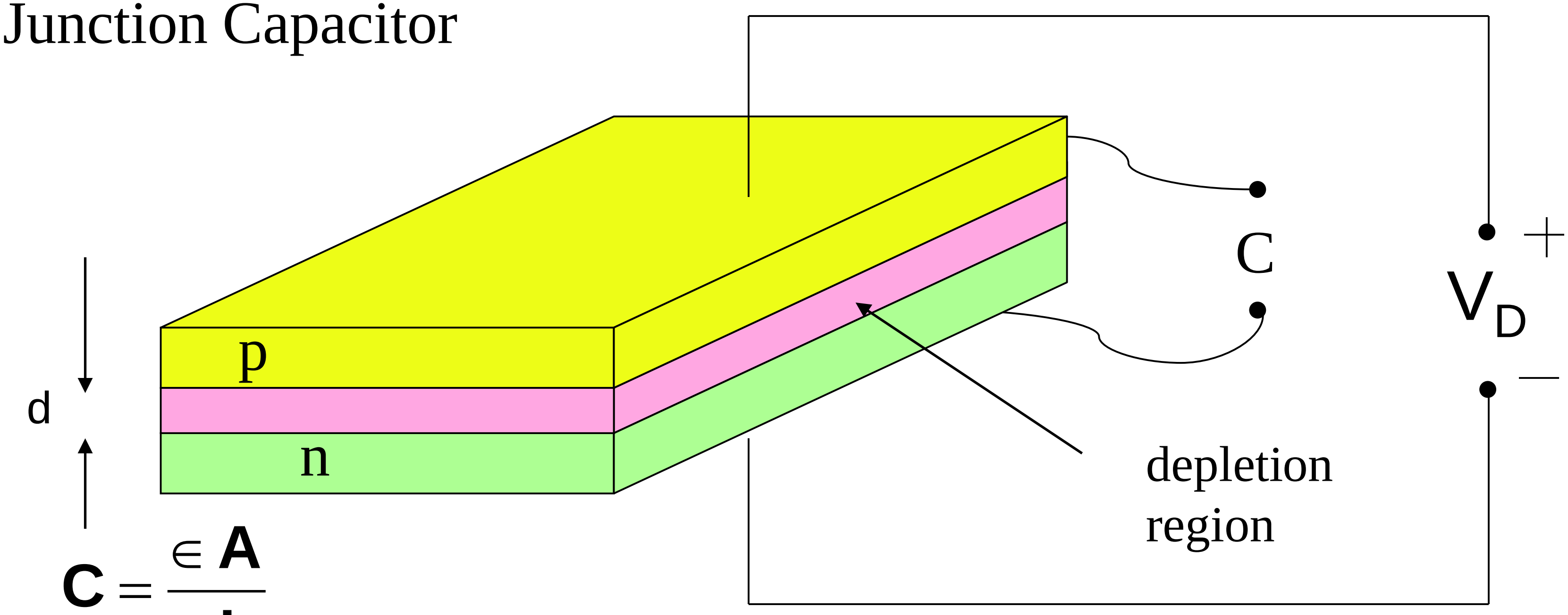
Only a single layer is needed to make fringe capacitors

Fringe Capacitors



Capacitance

Junction Capacitor



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

$\in$ is dielectric constant

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

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

Note: d is voltage dependent

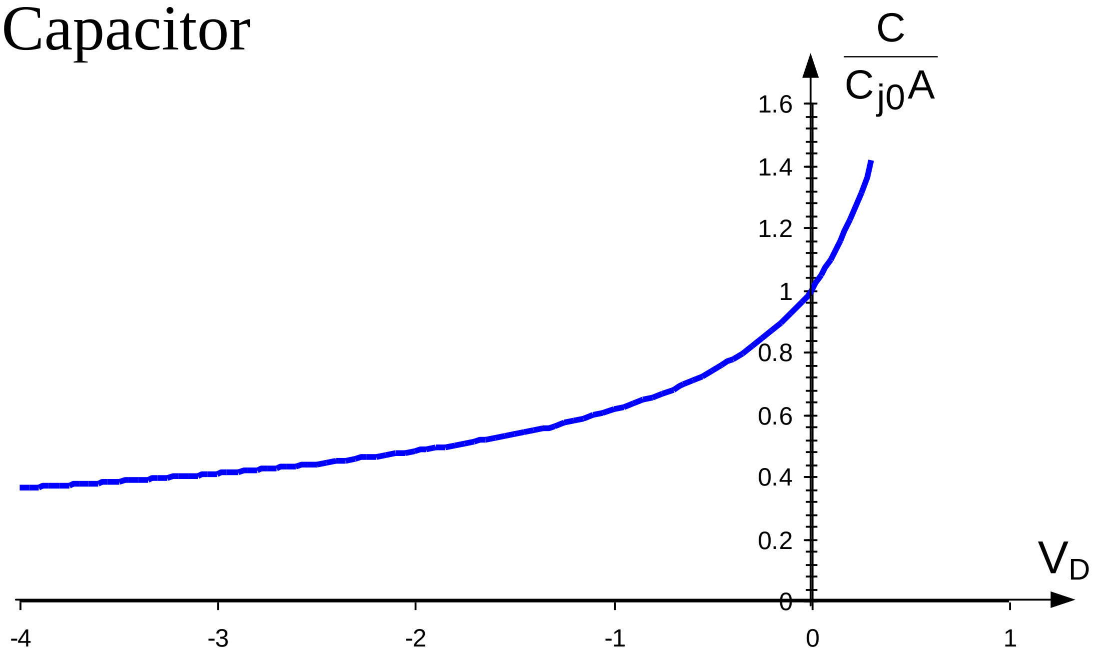
-capacitance is voltage dependent

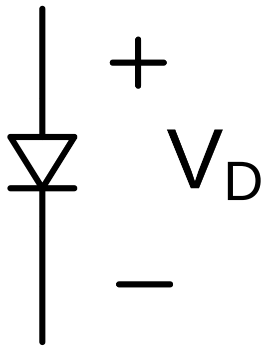
-usually parasitic caps

-varicaps or varactor diodes exploit voltage dep. of C

Capacitance

Junction Capacitor





$$\mathbf{C} = \frac{\mathbf{C_{jo}A}}{\left(\mathbf{1} - \frac{\mathbf{V_D}}{\boldsymbol{\varphi}_\mathbf{B}}\right)^{\mathbf{n}}} \qquad \textit{for} \quad \mathbf{V_{FB}} < \frac{\boldsymbol{\varphi}_\mathbf{B}}{\mathbf{2}}$$

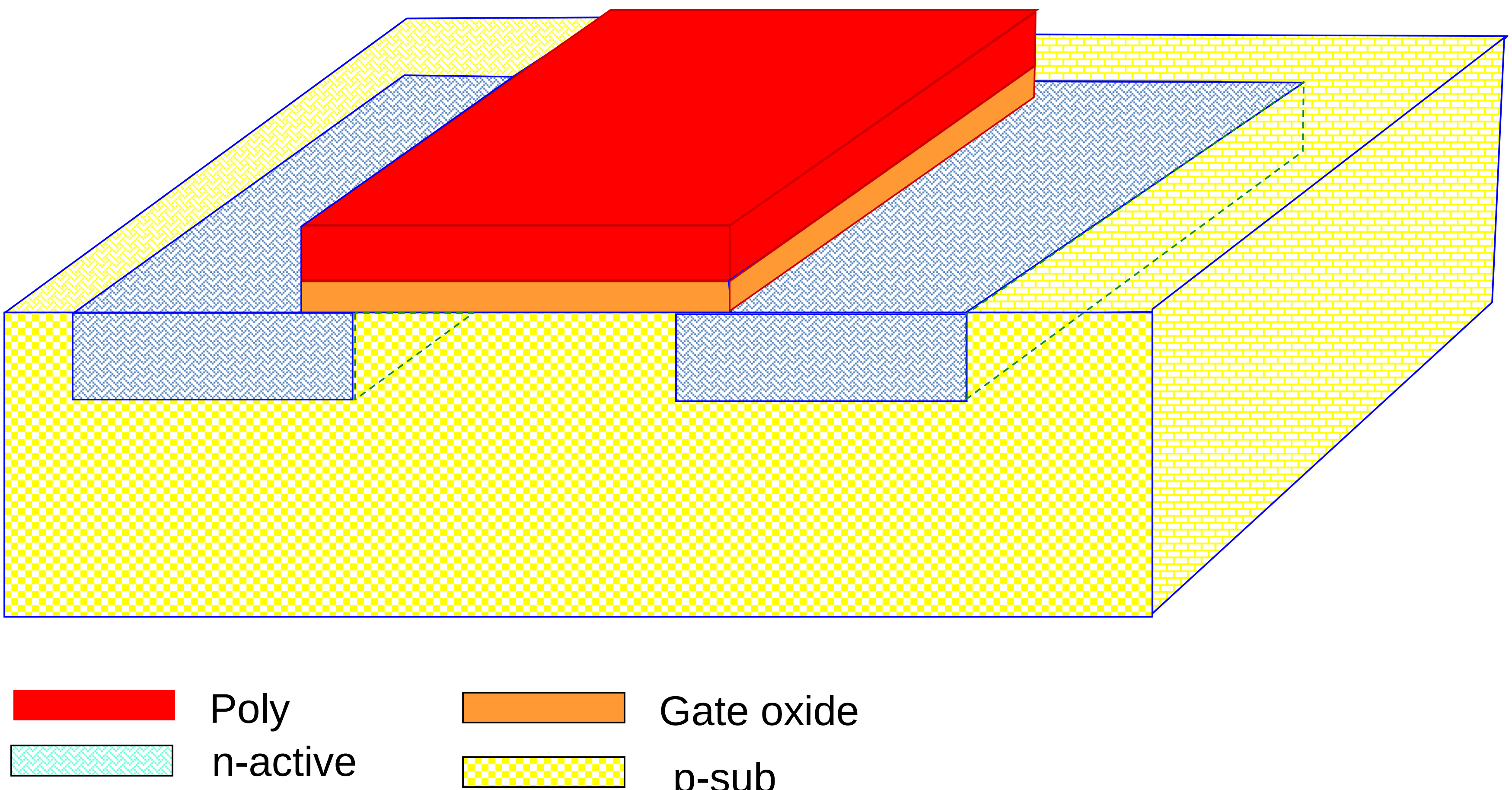
Voltage dependence is substantial

$$\boldsymbol{\varphi}_\mathbf{B} \cong \mathbf{0.6V} \qquad \mathbf{n} \simeq \mathbf{0.5}$$

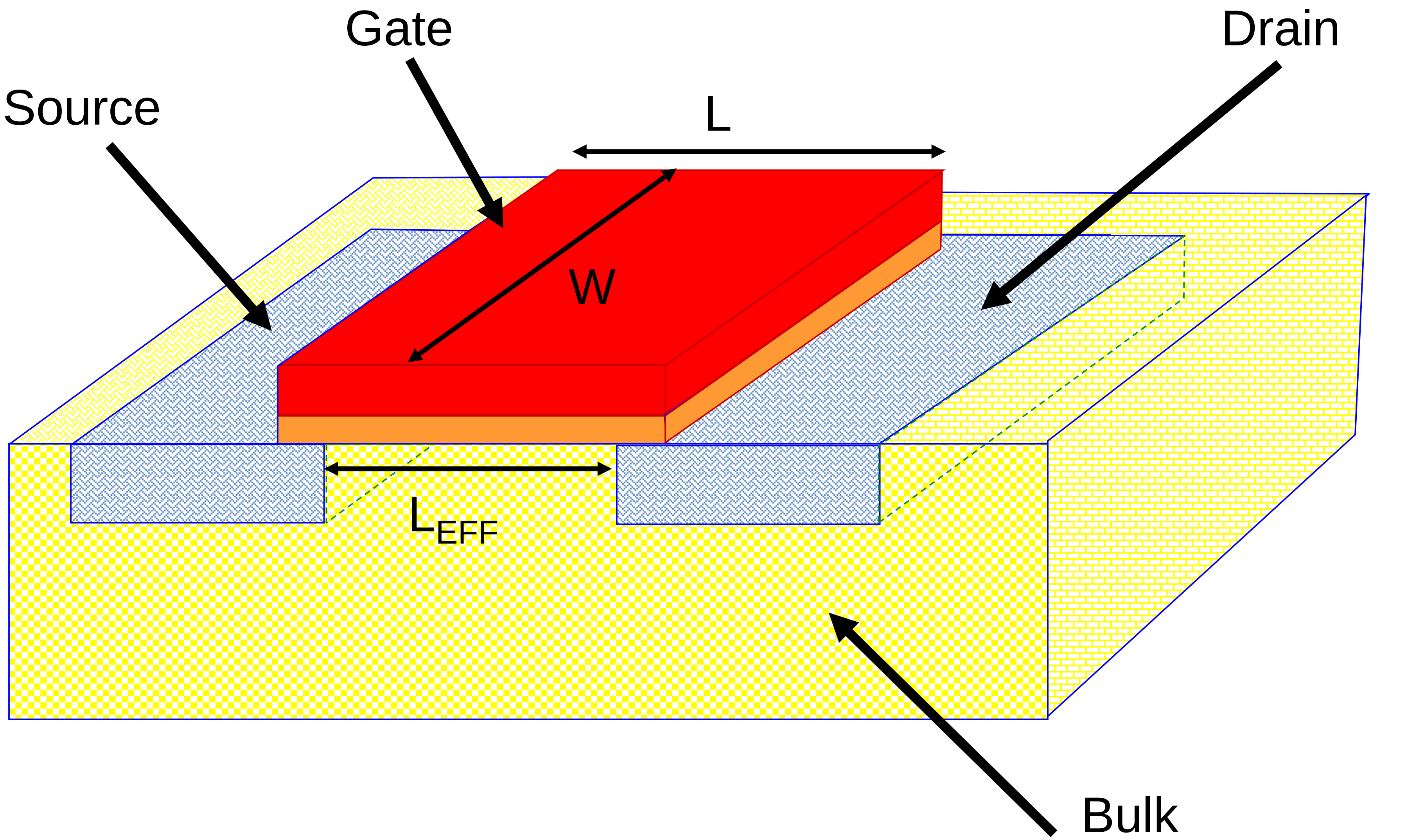
Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT

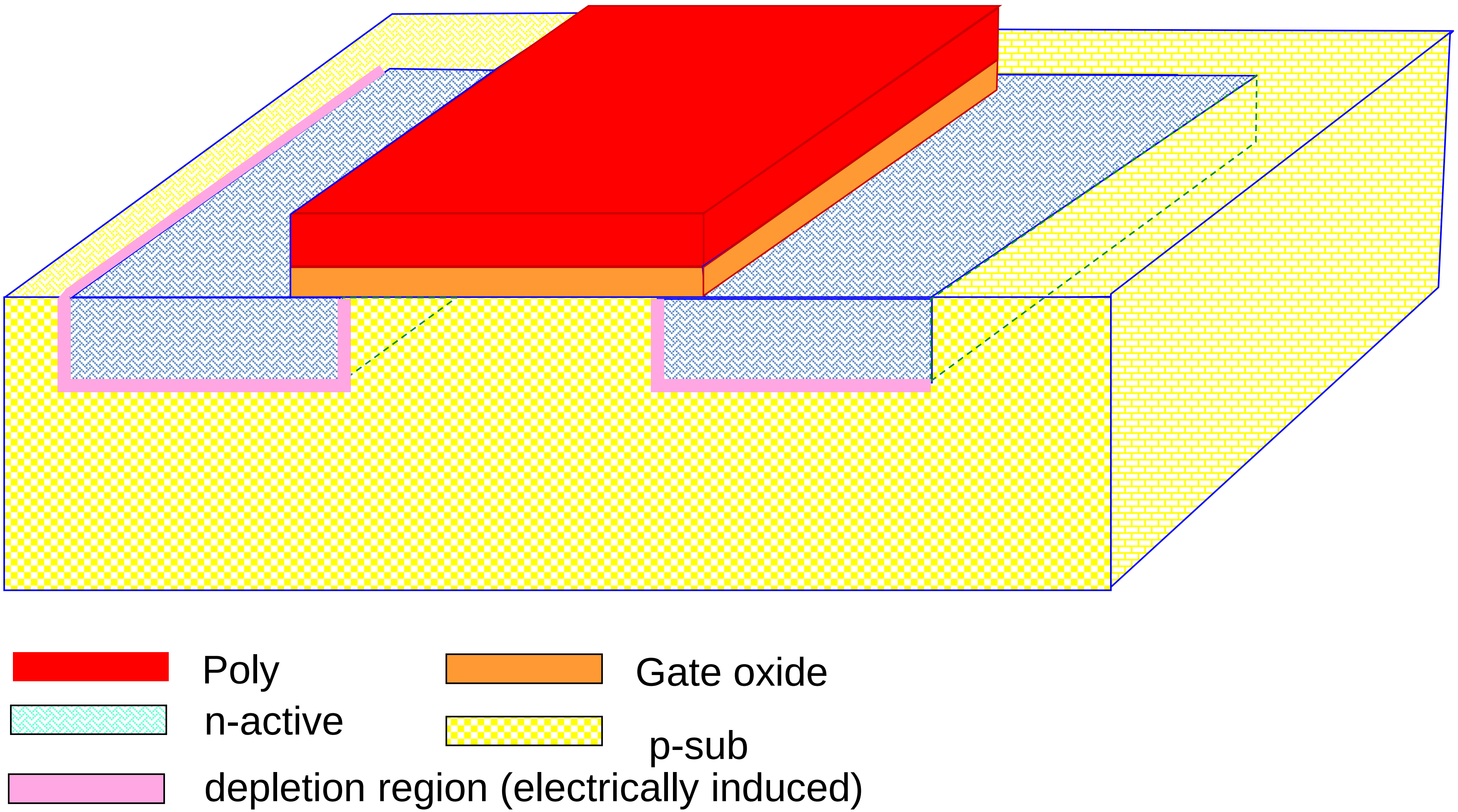
n-Channel MOSFET



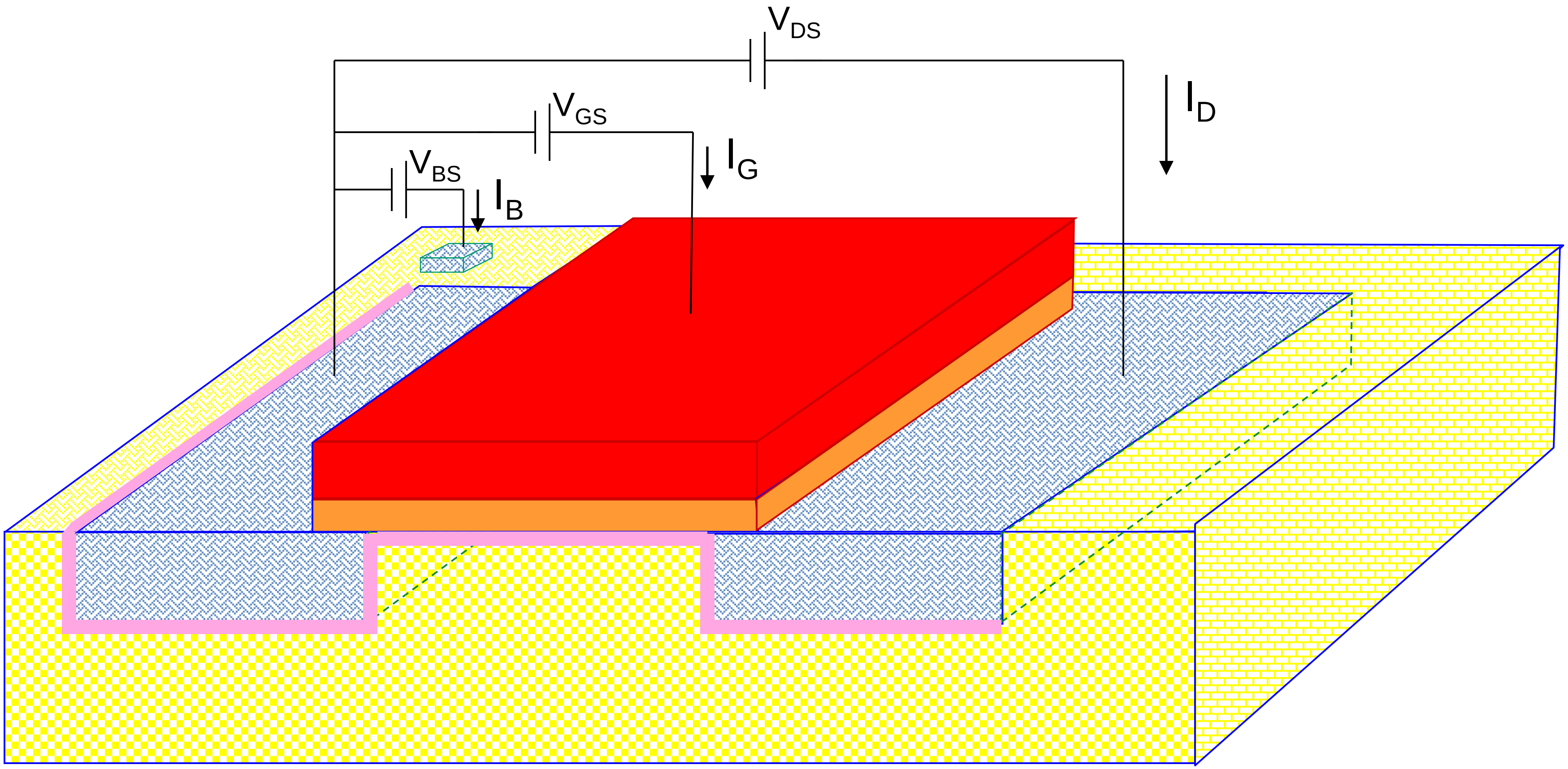
n-Channel MOSFET



n-Channel MOSFET



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

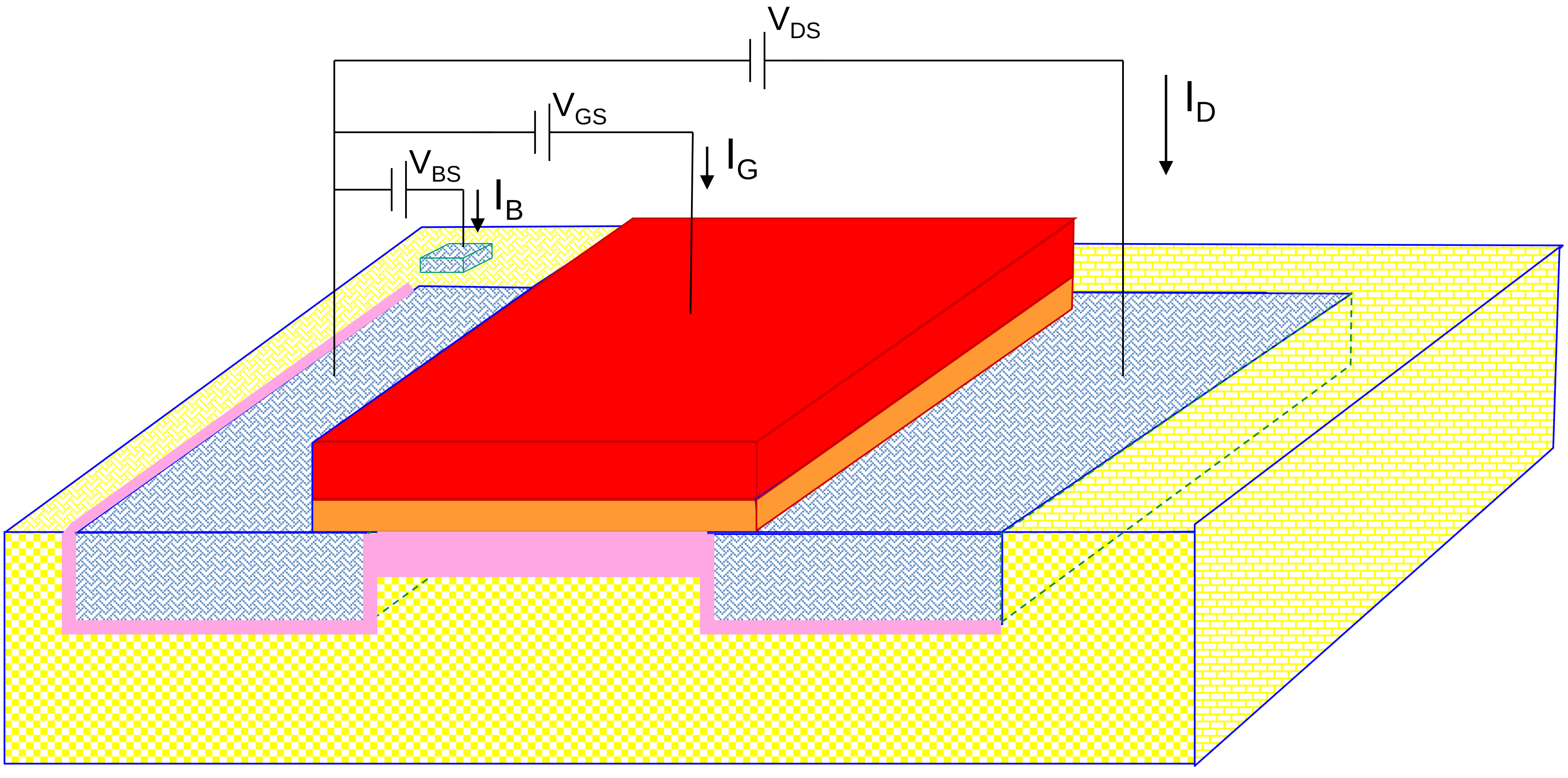
Termed "cutoff" region of operation

$I_D=0$

$I_G=0$

$I_B=0$

n-Channel MOSFET Operation and Model

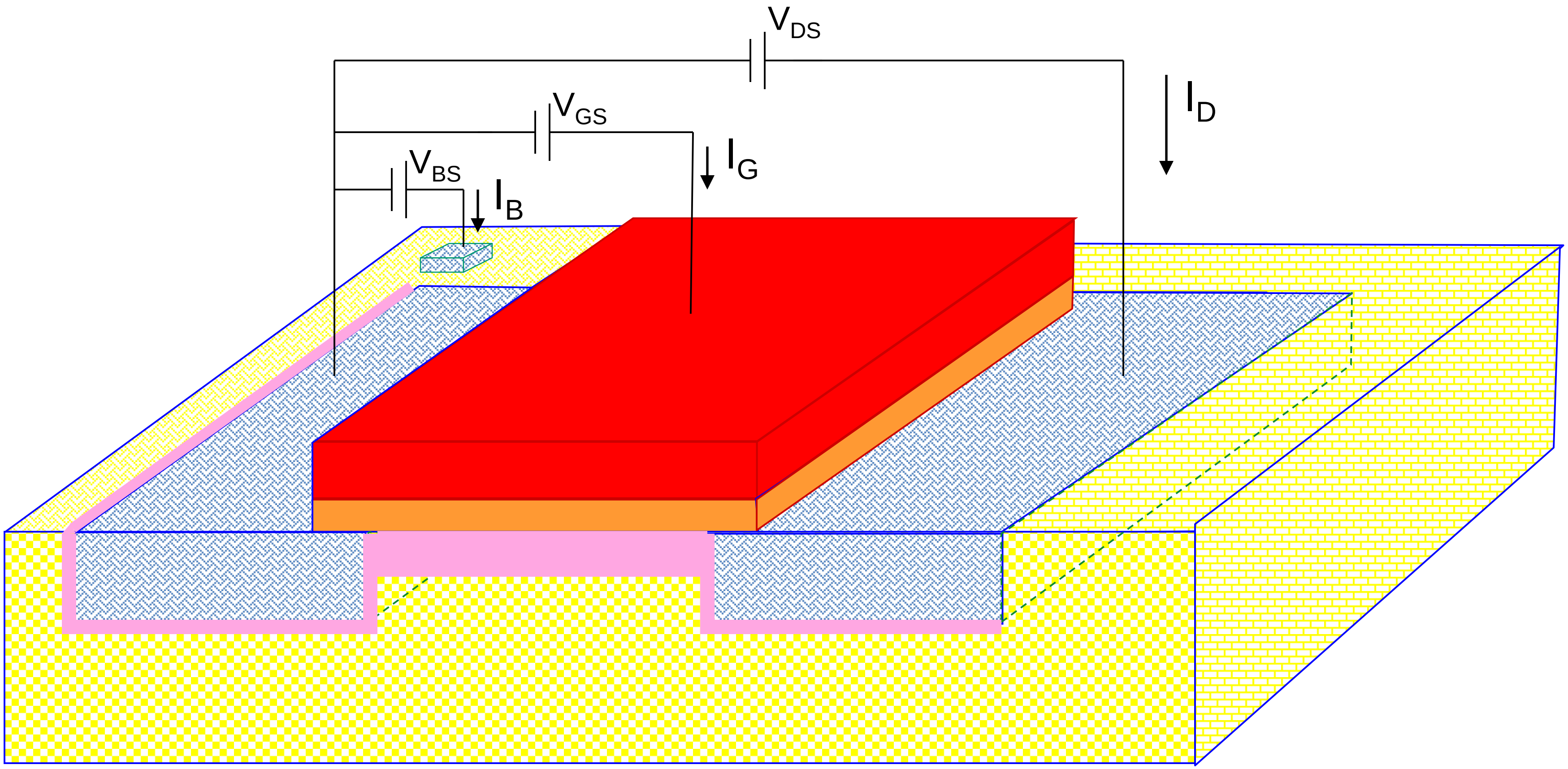


Increase V_{GS}
(V_{DS} and V_{BS} assumed to be small)

Depletion region in channel becomes larger

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

n-Channel MOSFET Operation and Model

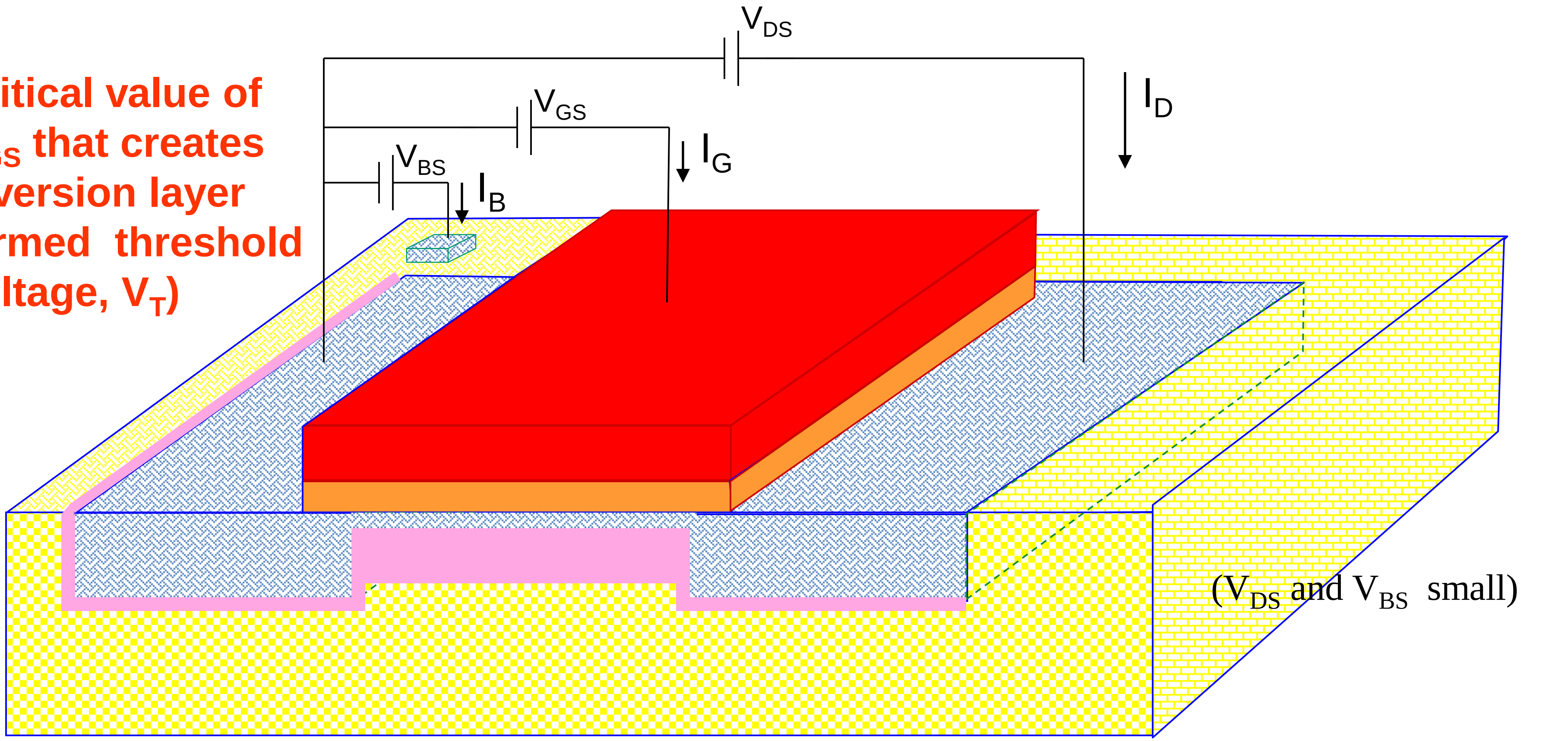


$I_D=0$
$I_G=0$
$I_B=0$

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

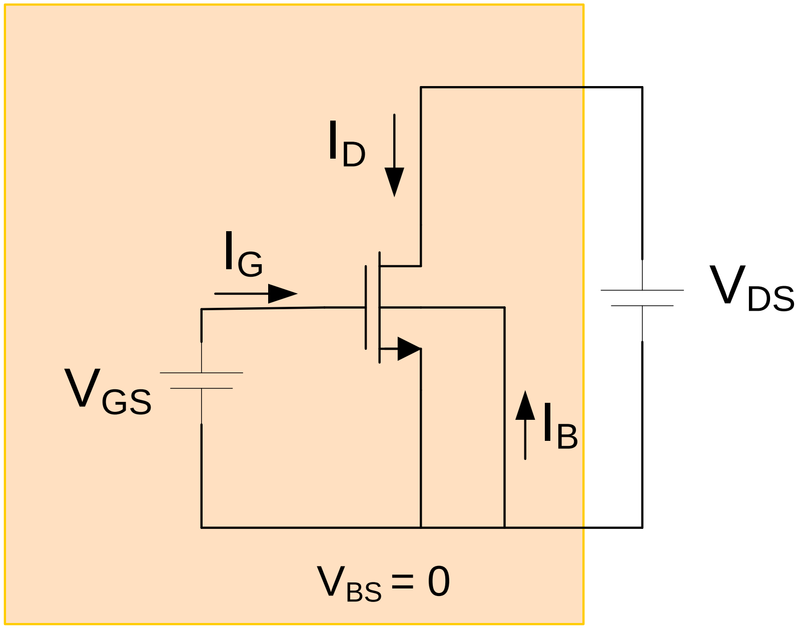
Channel behaves as thin-film resistor

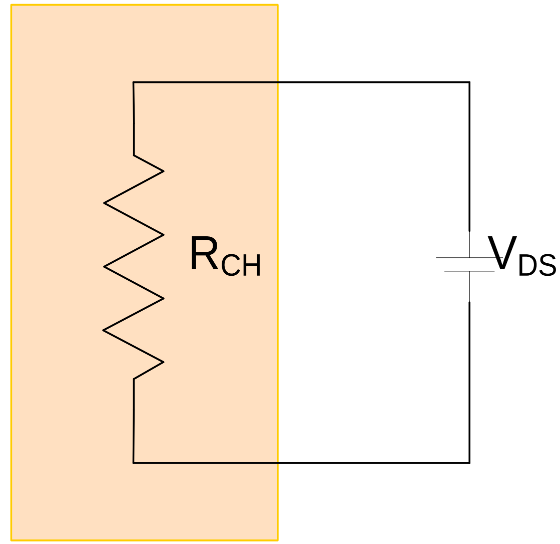
$I_D R_{CH} = V_{DS}$

$I_G = 0$

$I_B = 0$

Triode Region of Operation





For V_{DS} small

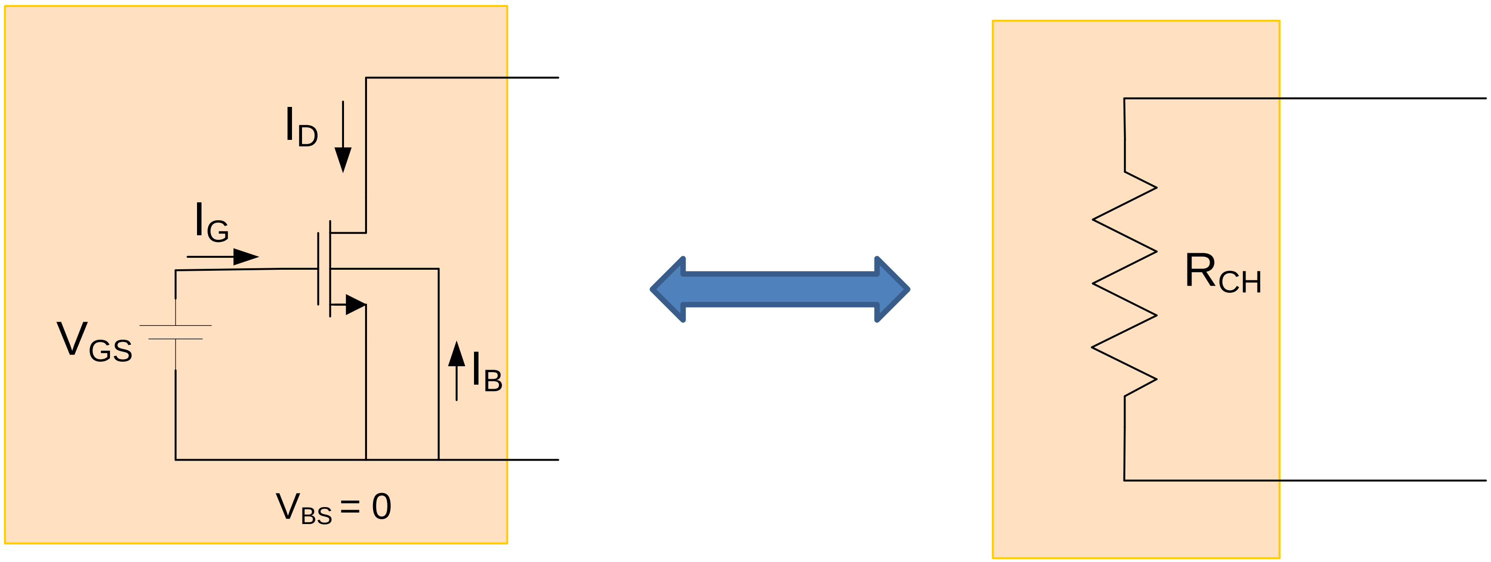
$$R_{CH} = \frac{L}{W}\frac{1}{(V_{GS} - V_T)\mu C_{OX}}$$

Behaves as a resistor between drain and source

$$\boxed{\begin{aligned} I_D &= \mu C_{OX}\frac{W}{L}(V_{GS} - V_T)V_{DS} \\ I_G &= I_B = 0 \end{aligned}}$$

Model in Deep Triode Region

Triode Region of Operation

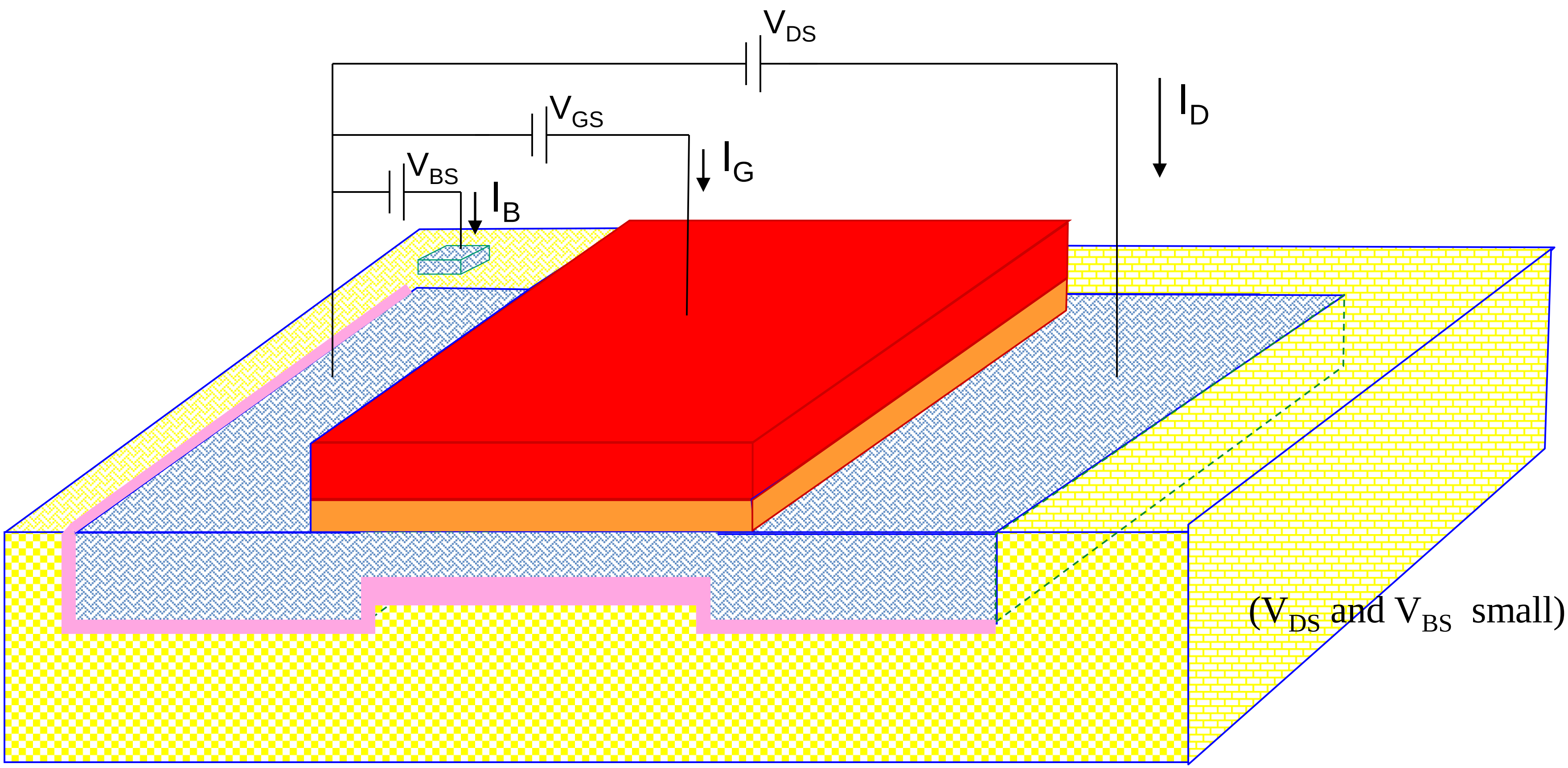


For V_{DS} small

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

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

n-Channel MOSFET Operation and Model



Increase V_{GS} more

Inversion layer in channel thickens

R_{CH} will decrease

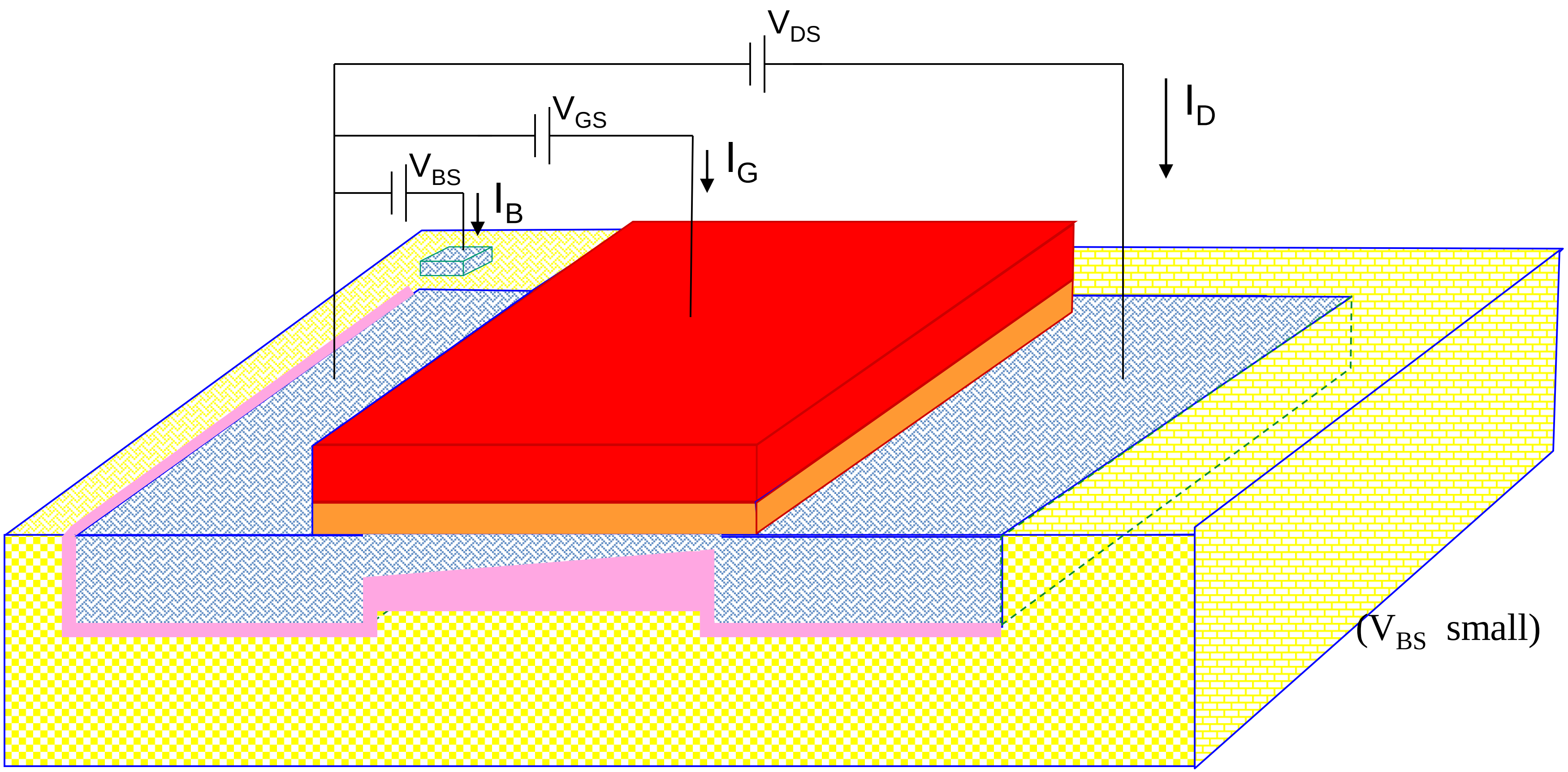
Termed "ohmic" or "triode" region of operation

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

$I_G = 0$

$I_B = 0$

n-Channel MOSFET Operation and Model



Increase V_{DS}

Inversion layer thins near drain

I_D no longer linearly dependent upon V_{DS}

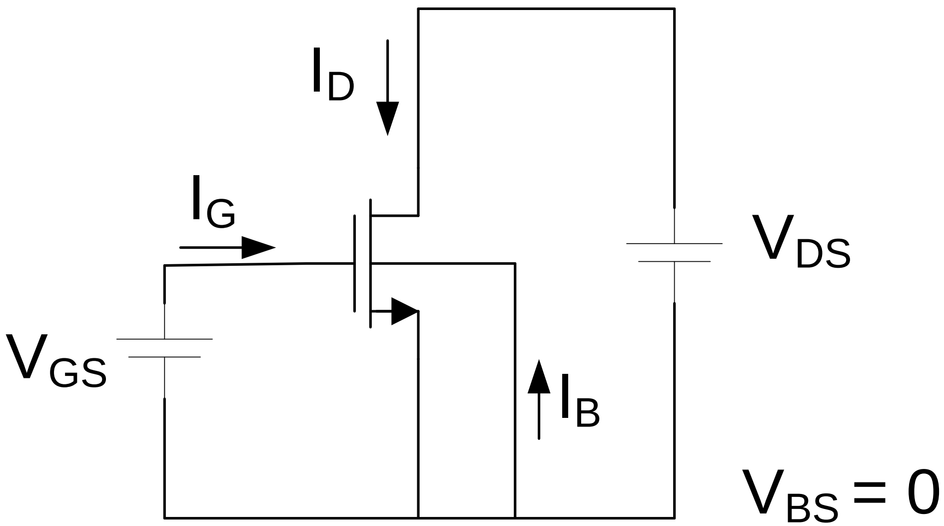
Still termed “ohmic” or “triode” region of operation

I_D=?

I_G=0

I_B=0

Triode Region of Operation



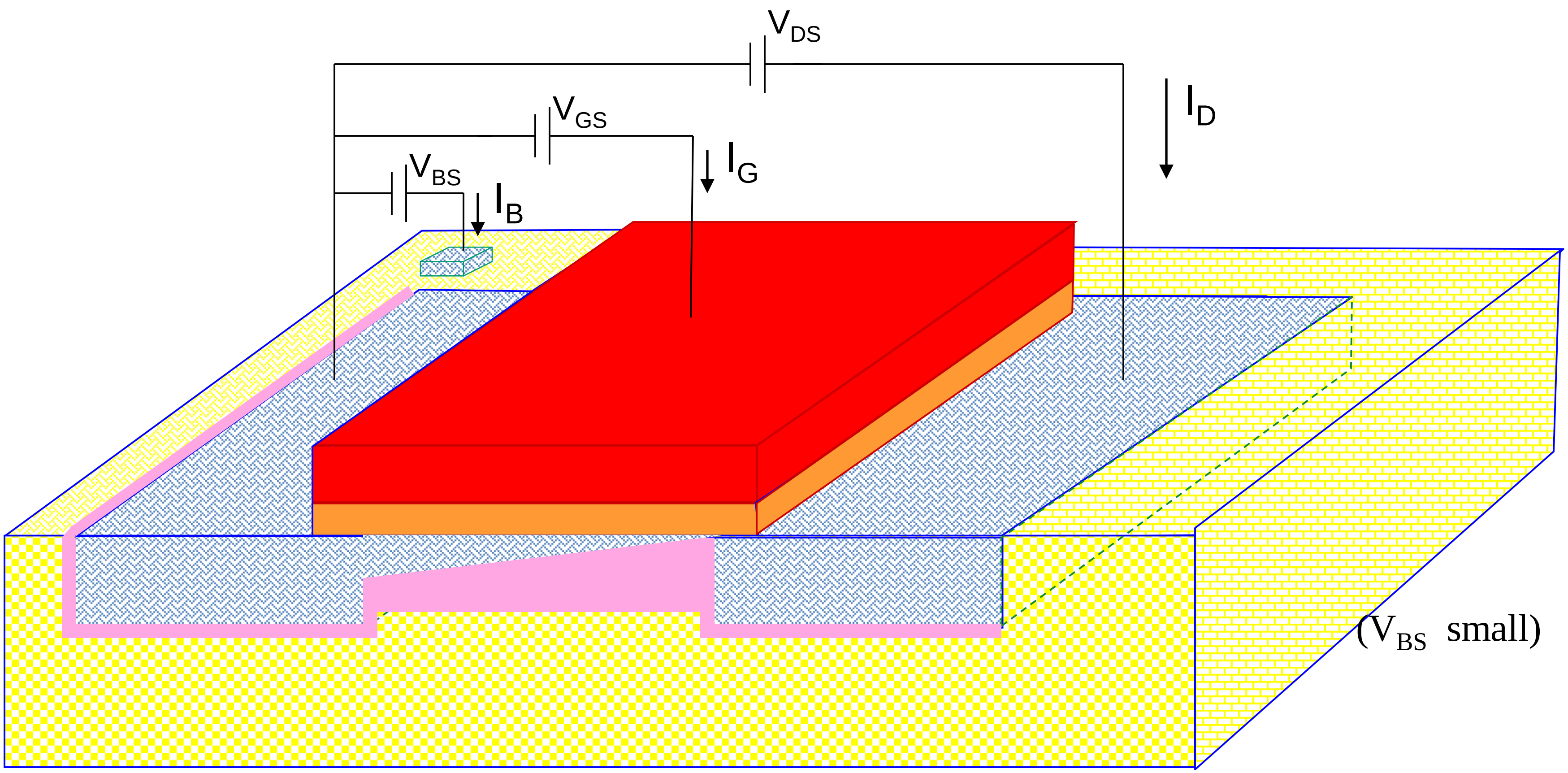
For V_{DS} larger

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

$$\boxed{\begin{array}{l} \mathbf{I_D = \mu C_{OX} \frac{W}{L}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS}} \\ \mathbf{I_G = I_B = 0} \end{array}}$$

Model in Triode Region

n-Channel MOSFET Operation and Model



Increase V_{DS} even more

Inversion layer disappears near drain

Termed "saturation" region of operation

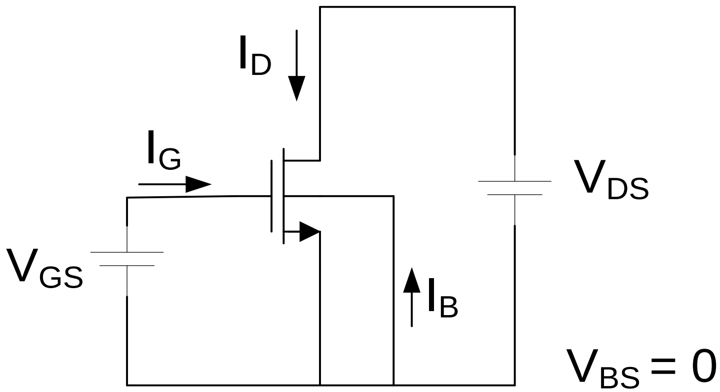
Saturation first occurs when $V_{DS}=V_{GS}-V_T$

$I_D=?$

$I_G=0$

$I_B=0$

Saturation Region of Operation



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

or equivalently

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

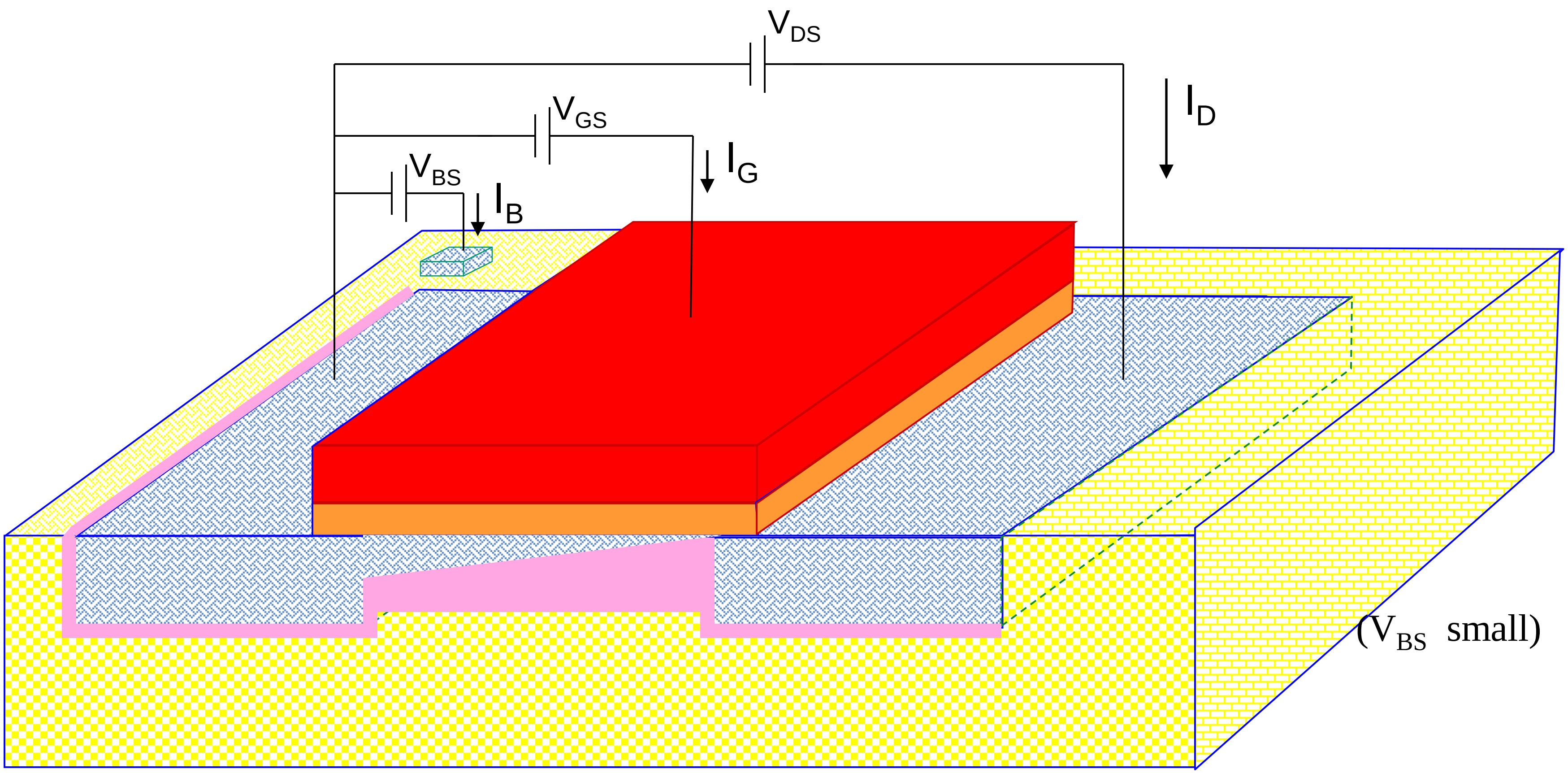
or equivalently

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

$$I_G = I_B = 0$$

For V_{DS} at onset of saturation

n-Channel MOSFET Operation and Model



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

Nothing much changes !!

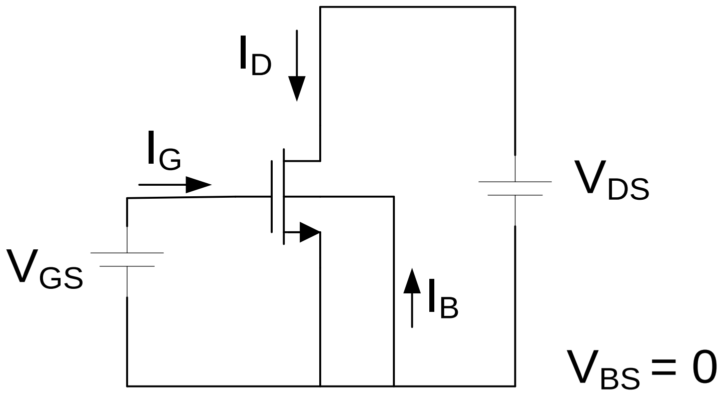
Termed "saturation"region of operation

I_D=?

I_G=0

I_B=0

Saturation Region of Operation



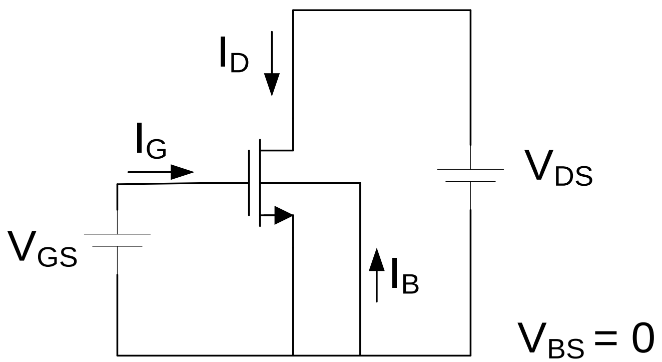
For V_{DS} in Saturation

$$\boxed{\begin{aligned} I_D &= \frac{\mu C_{OX} W}{2L}\left(V_{GS} - V_T\right)^2 \\ I_G &= I_B = 0 \end{aligned}}$$

Model in Saturation Region

Model Summary

n-channel MOSFET



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

$$I_G = I_B = 0$$

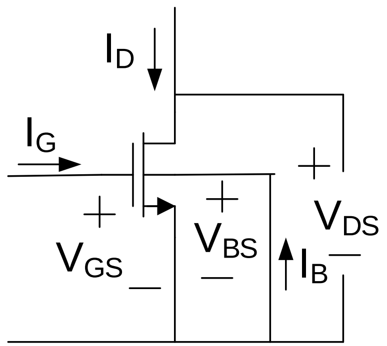
This is a piecewise model (not piecewise linear though)

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

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

Model Summary

n-channel MOSFET



$V_{BS} = 0$

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

$$I_G = I_B = 0$$

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

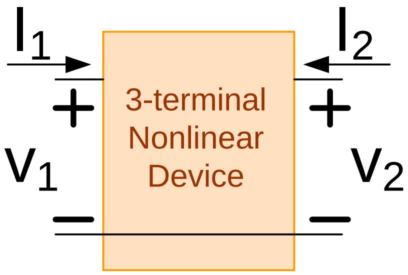
$$I_D = f_1\left(V_{GS}, V_{DS}\right)$$

$$I_G = f_2\left(V_{GS}, V_{DS}\right)$$

$$I_B = f_3\left(V_{GS}, V_{DS}\right)$$

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

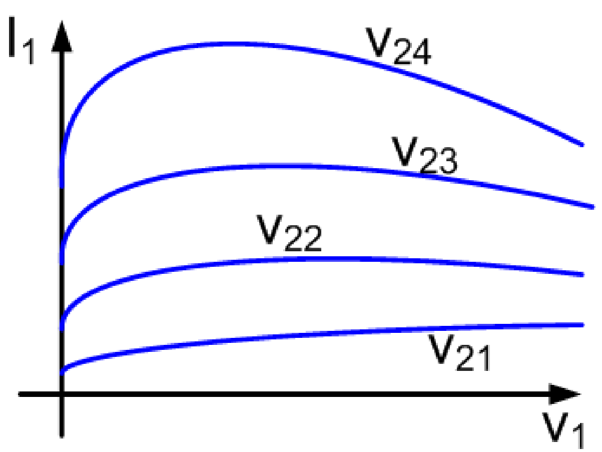
General Nonlinear Models

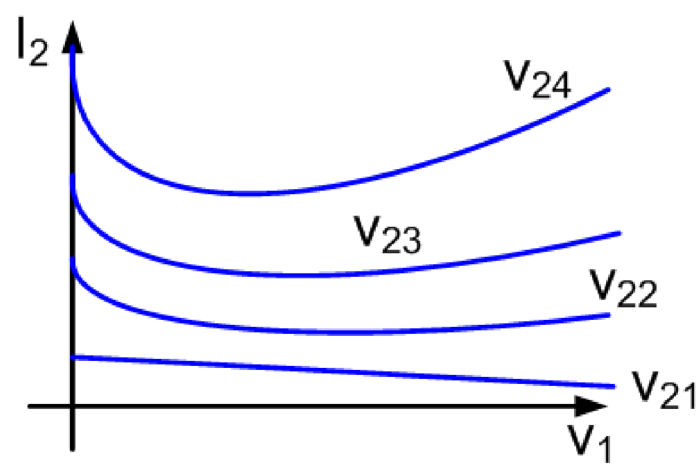


$$I_1 = f_1(V_1, V_2)$$
$$I_2 = f_2(V_1, V_2)$$

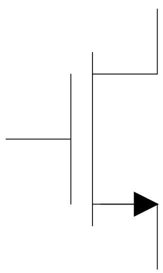
I_1 and I_2 are 3-dimensional relationships which are often difficult to visualize

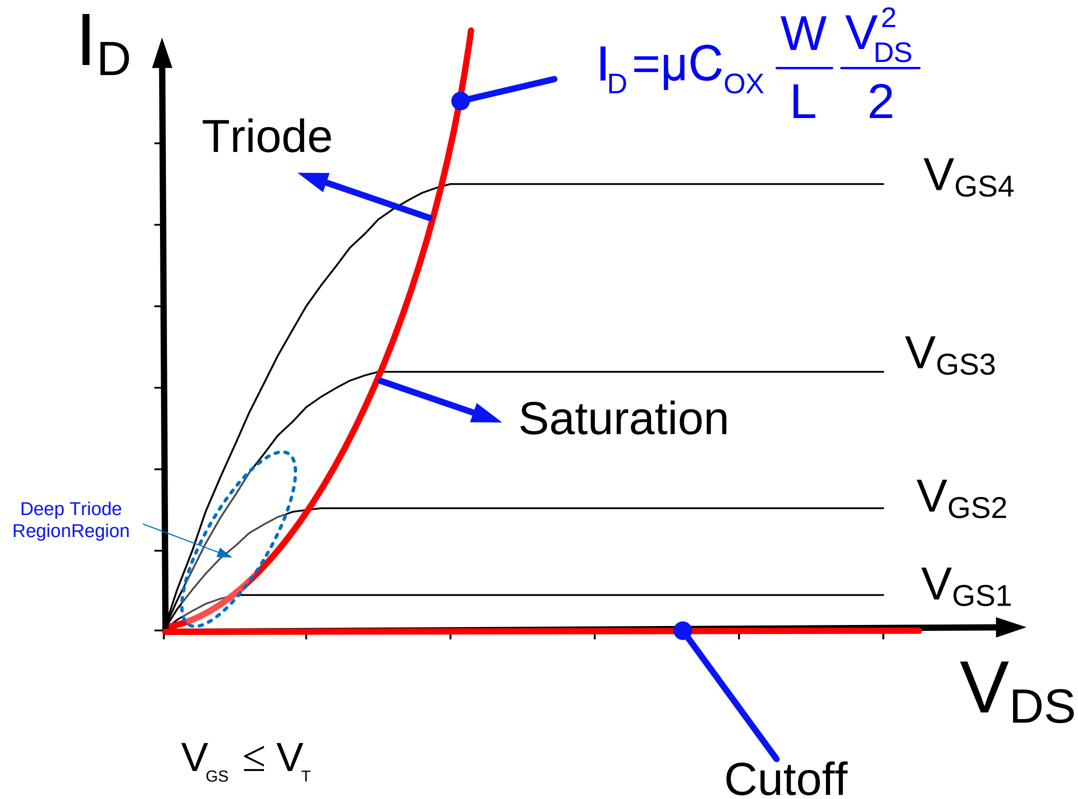
Two-dimensional representation of 3-dimensional relationships





Graphical Representation of MOS Model



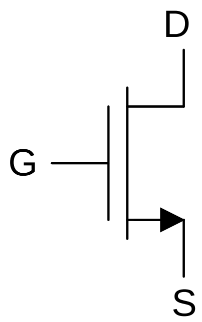


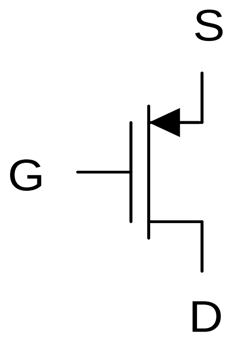
$$I_D = \begin{cases} 0 & V_{GS} \le V_T \\ \mu C_{OX} \frac{W}{L}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS} & V_{GS} \ge V_T \quad V_{DS} < V_{GS} - V_T \\ \mu C_{OX} \frac{W}{2L}\left(V_{GS} - V_T\right)^2 & V_{GS} \ge V_T \quad V_{DS} \ge V_{GS} - V_T \end{cases}$$

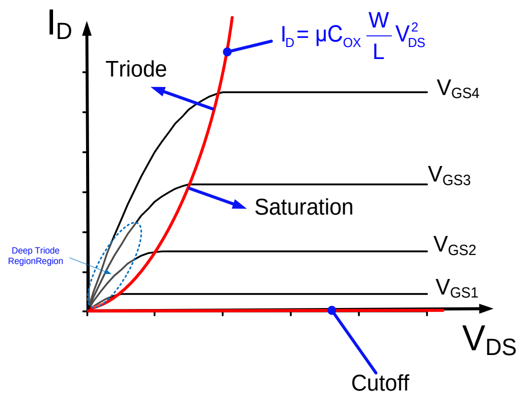
$$I_G = I_B = 0$$

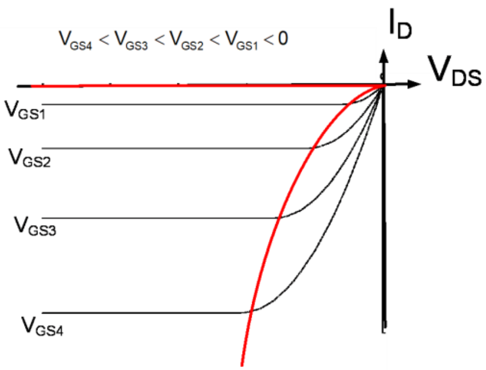
Parabola separated triode and saturation regions and corresponds to $V_{DS}=V_{GS}-V_T$

PMOS and NMOS Models









- Functional form identical, sign changes and parameter values different
- Will give details about p-channel model later

End of Lecture 16