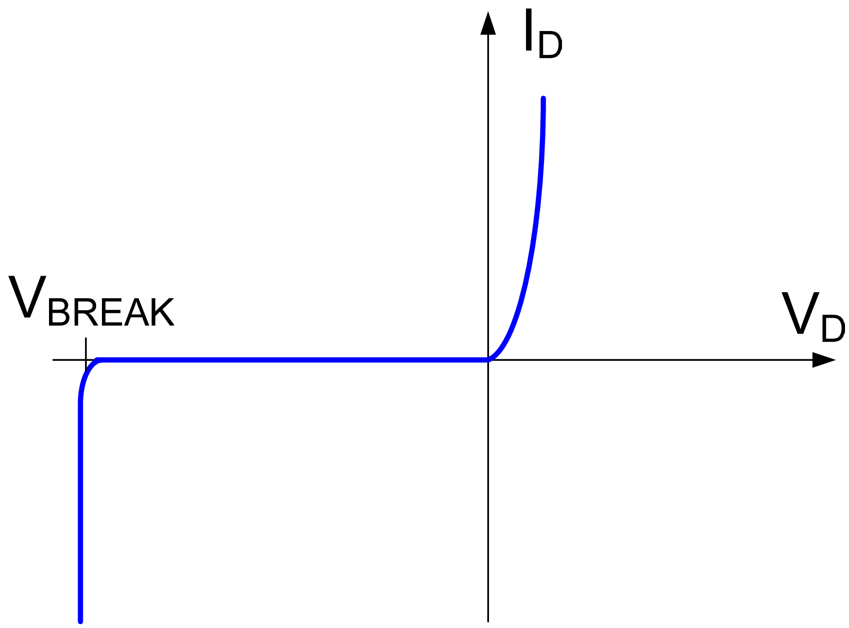
EE 230
Lecture 30

The MOS Transistor

Quiz 30

Under reverse bias, all diodes will break down. Why is the break down often destructive?



And the number is ?

1 3 8

5 4

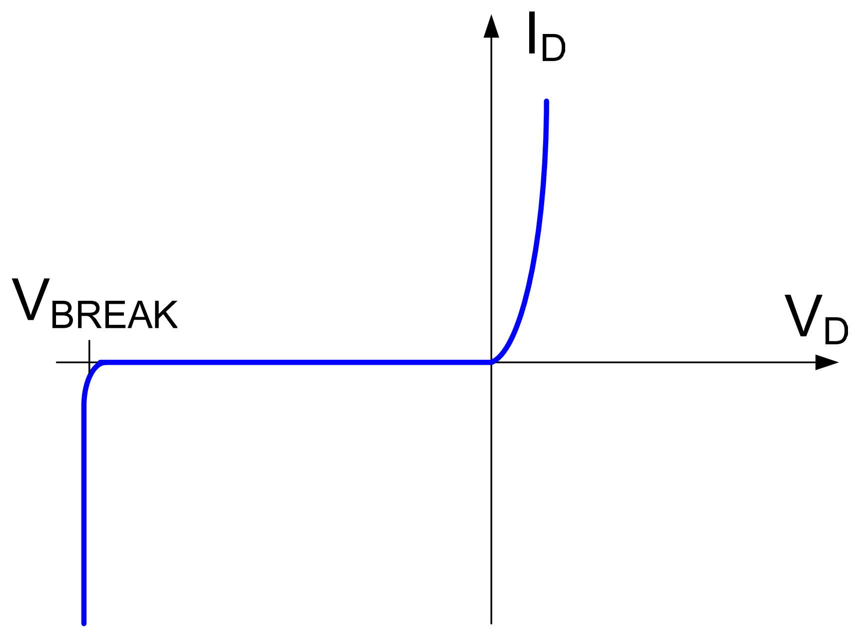
?

2 6

9 7

Quiz 30

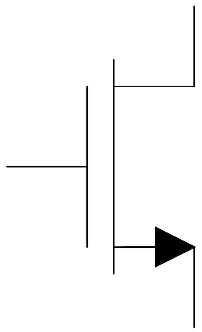
Under reverse bias, all diodes will break down. Why is the break down often destructive?



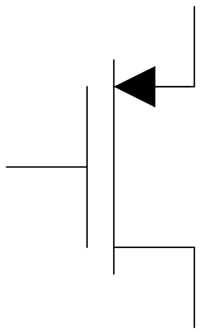
Solution: Because the power dissipation becomes too large.

Review from Last Time:

MOS Transistors



n-channel

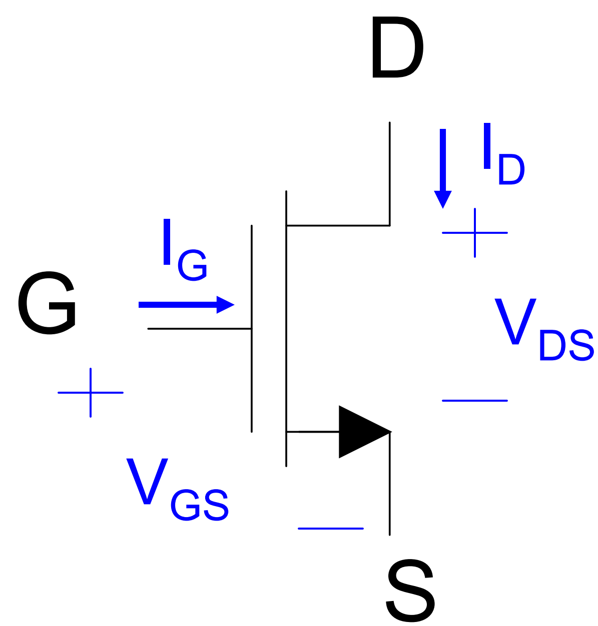


p-channel

- Operation very similar
- Model parameters differ modestly
- Direction of current flow differs

Review from Last Time:

MOS Transistors



Model:

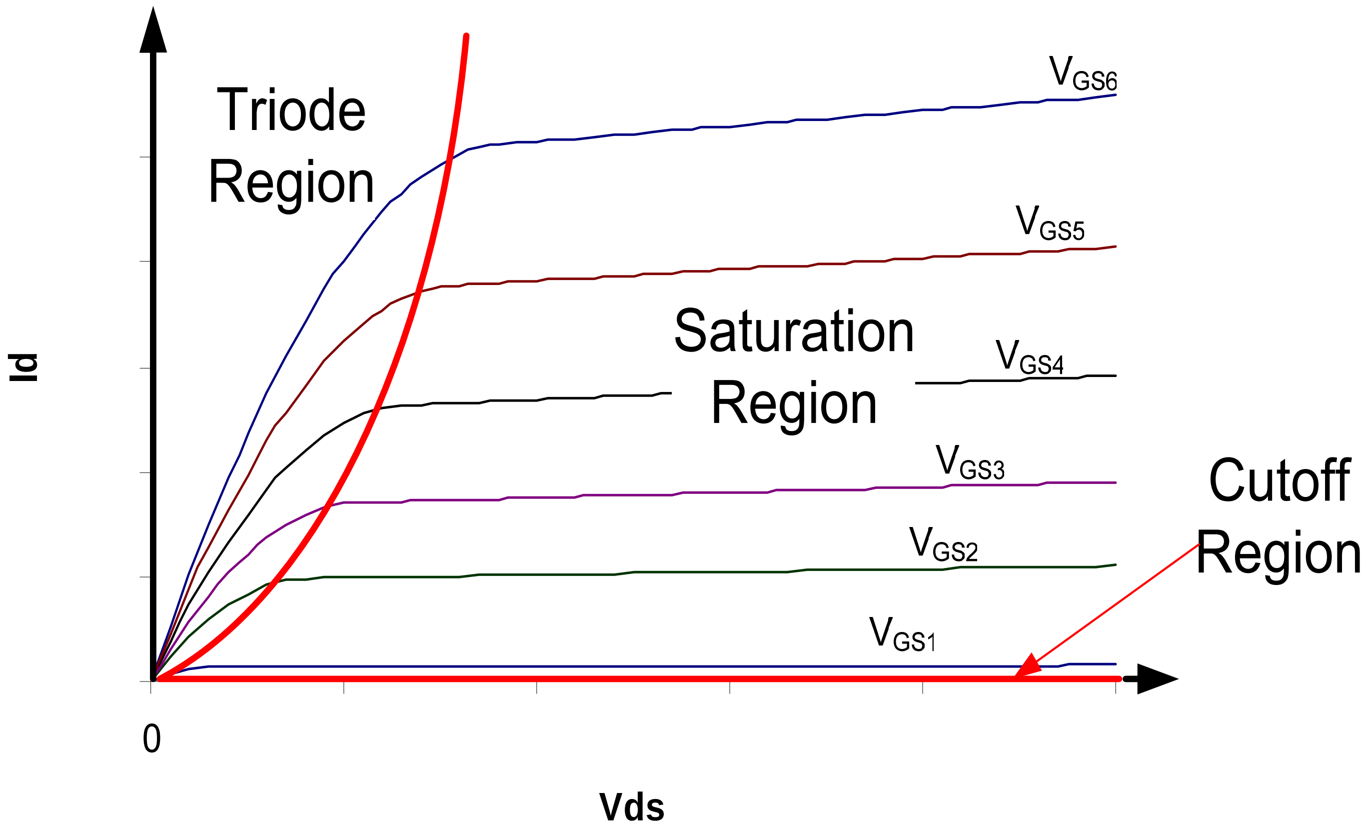
$$I_G = 0$$

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

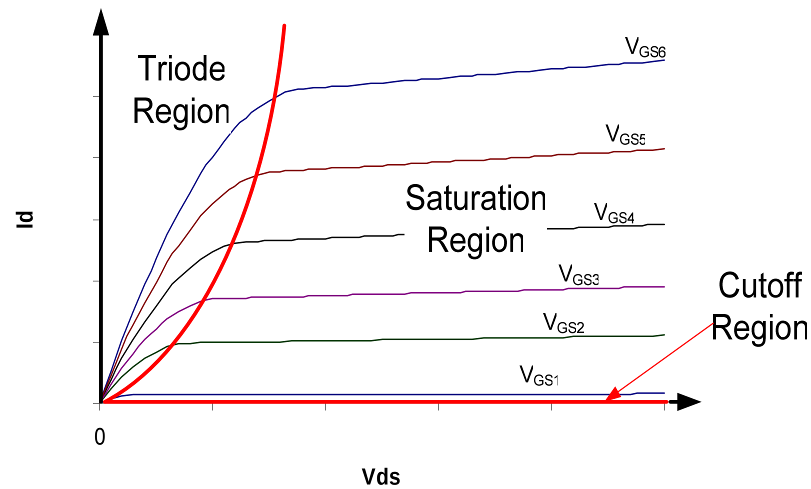
the two-variable function f_1 is quite nonlinear

D: Drain
G: Gate
S: Source

MOS Transistors



MOS Transistors



Popular square-law model for the transistor

$$I_G = 0$$

$$I_D = \begin{cases} 0 & V_{GS} \le V_T \\ \mu C_{OX} \frac{W}{L}\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS} & V_{GS} \ge V_T \quad V_{DS} < V_{GS} - V_T \\ \mu C_{OX} \frac{W}{2L}(V_{GS} - V_T)^2 \bullet (1+\lambda V_{DS}) & V_{GS} \ge V_T \quad V_{DS} \ge V_{GS} - V_T \end{cases}$$

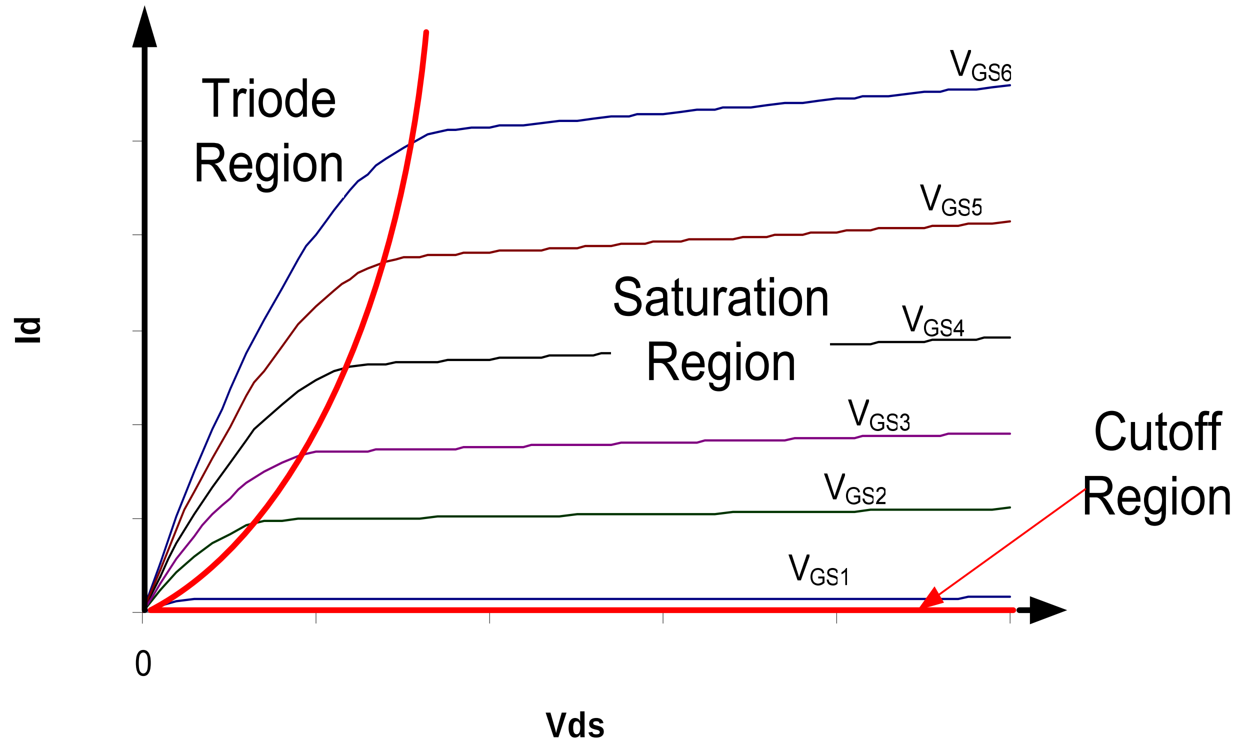
← Cutoff

← Triode

← Saturation

$\{\mu, C_{OX}, V_T, \lambda, W, L\}$ are model parameters

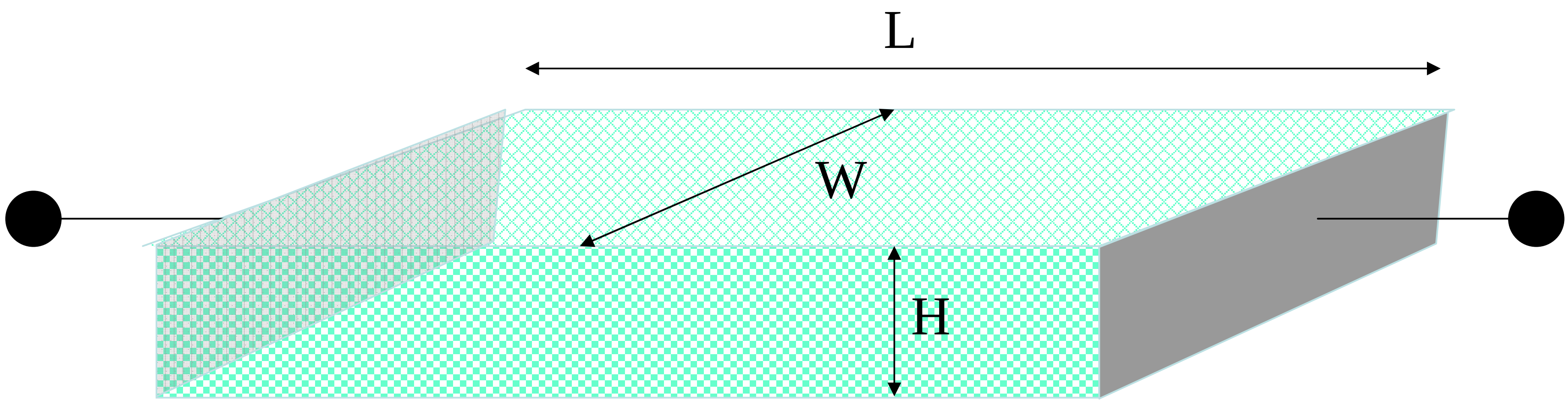
MOS Transistors



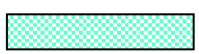
In <u>most</u> analog applications, the MOSFET is operated in the saturation region

In <u>most</u> digital applications, the MOSFET is operated in either the cutoff or triode regions and changes between these two regions as the boolean variables change from a "0" to a "1"

n-type resistor

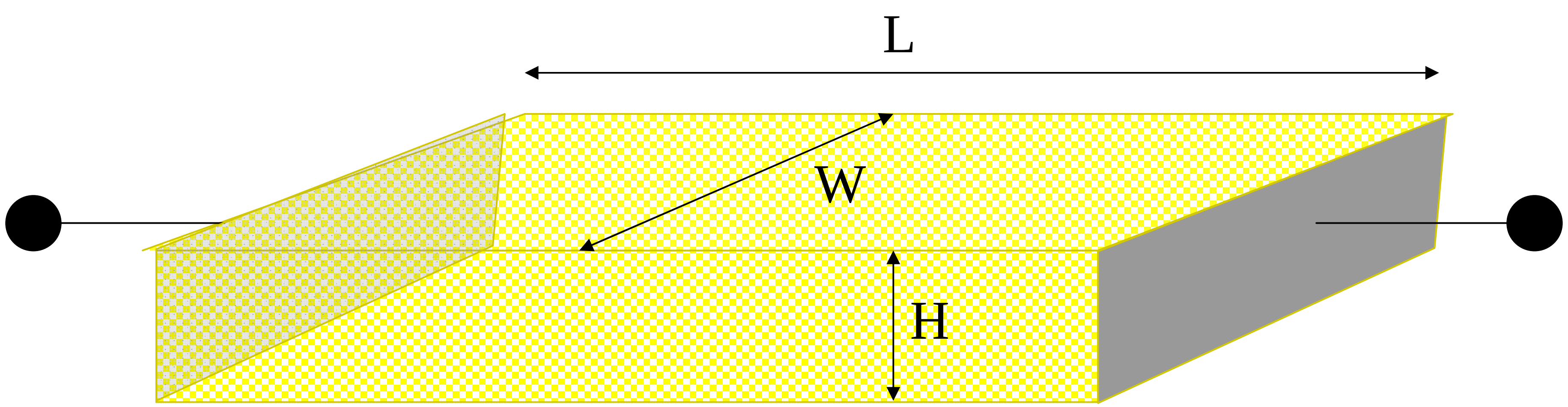


$$R = \rho \frac{L}{WH}$$

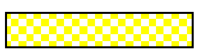


If H is small compared to L and W, termed a thin-film resistor

p-type resistor



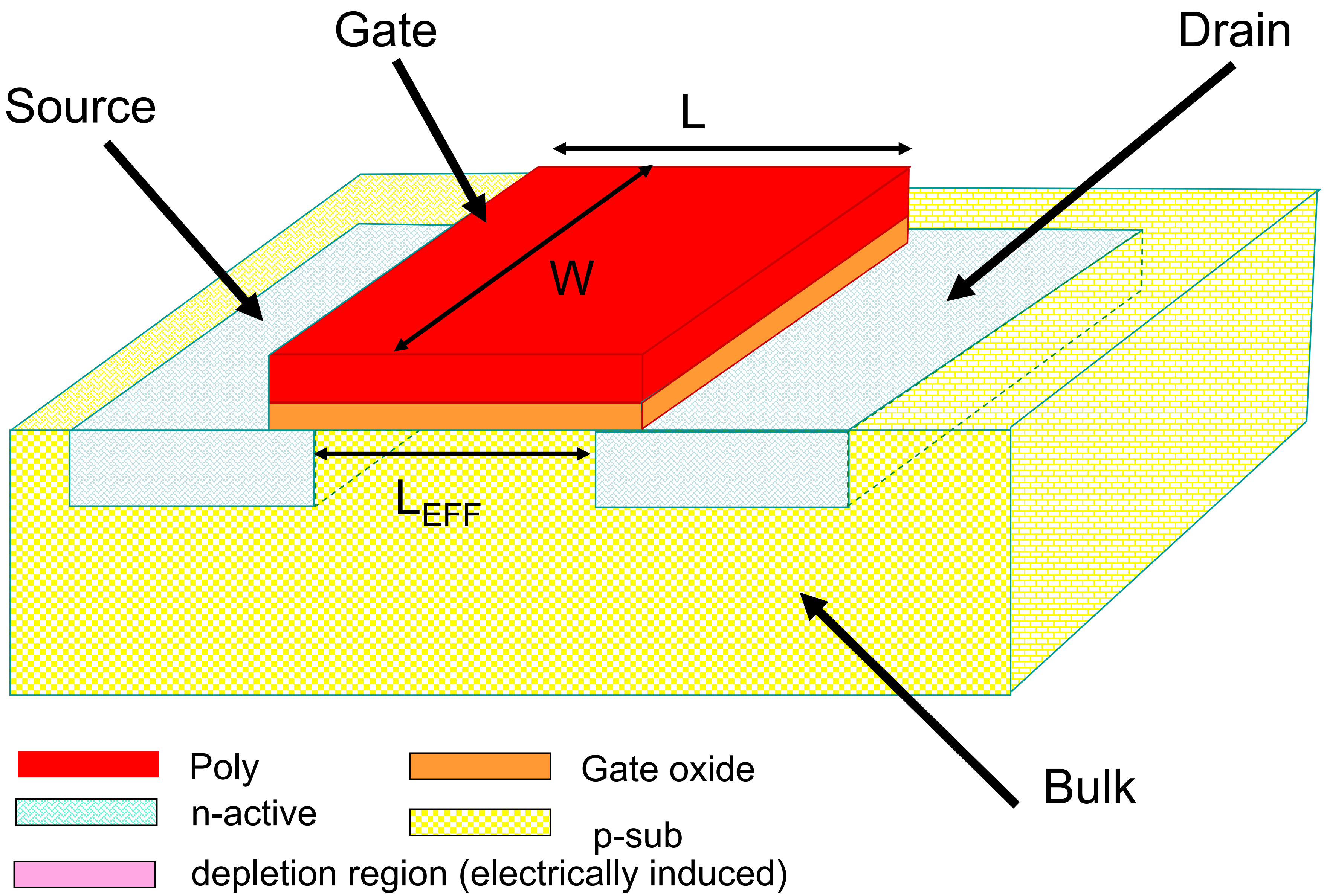
$$R = \rho \frac{L}{WH}$$



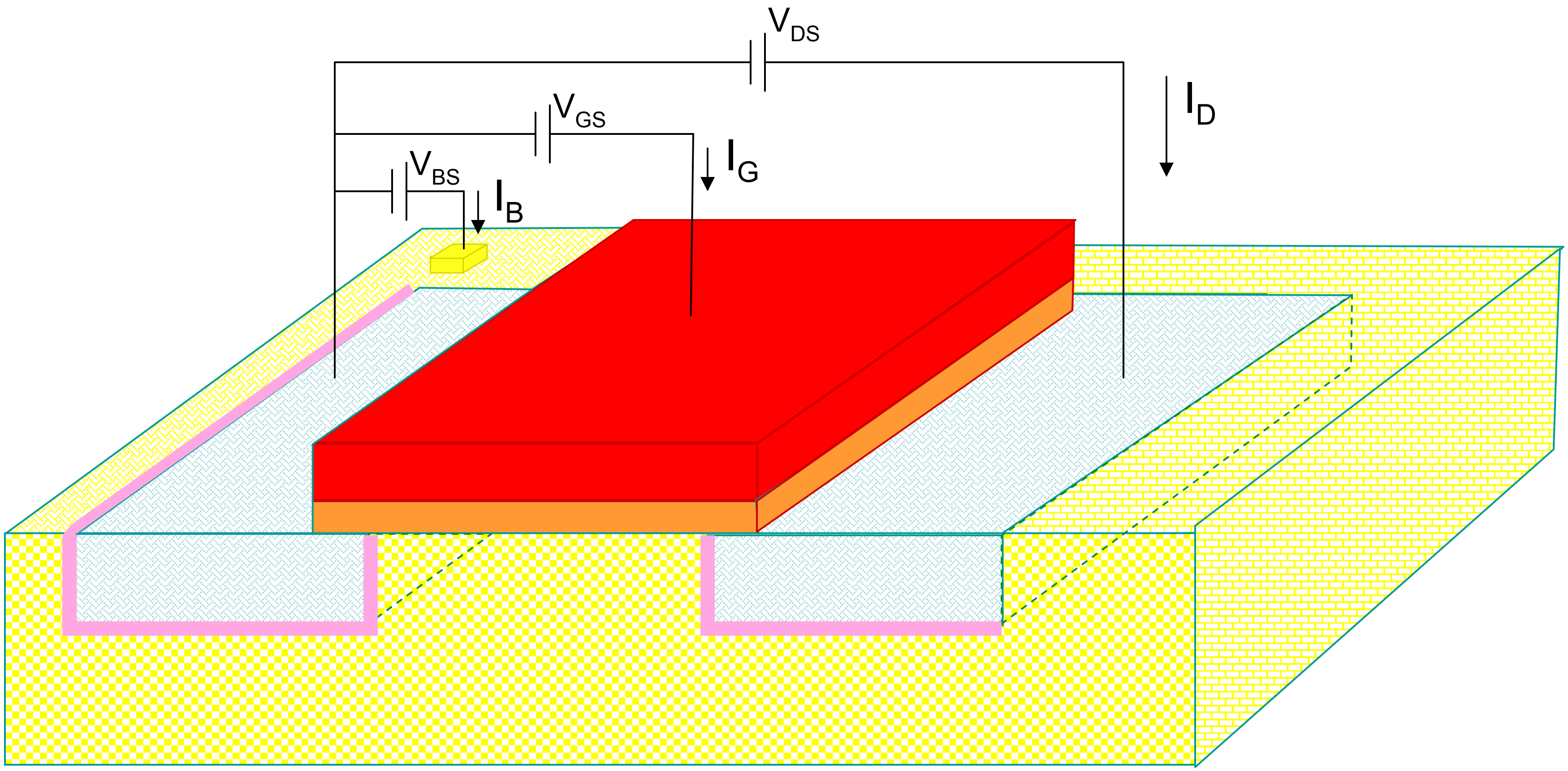
p-type semiconductor

If H is small compared to L and W, termed a thin-film resistor

n-Channel MOSFET



n-Channel MOSFET Operation and Model

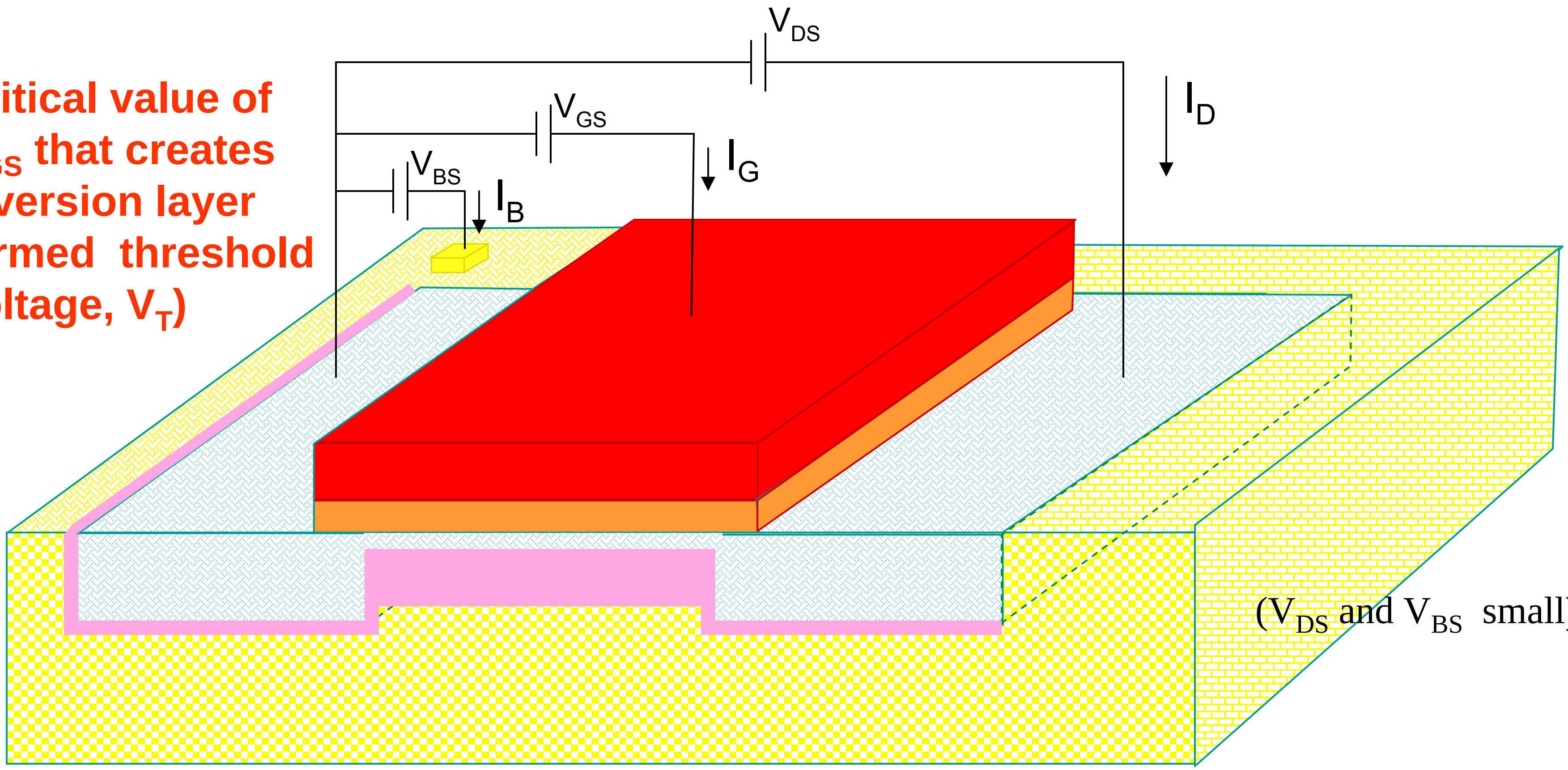


“Cutoff” region of operation

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

n-Channel MOSFET Operation and Model

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



"Triode" region of operation

Inversion layer forms in channel

Inversion layer will support current flow from D to S

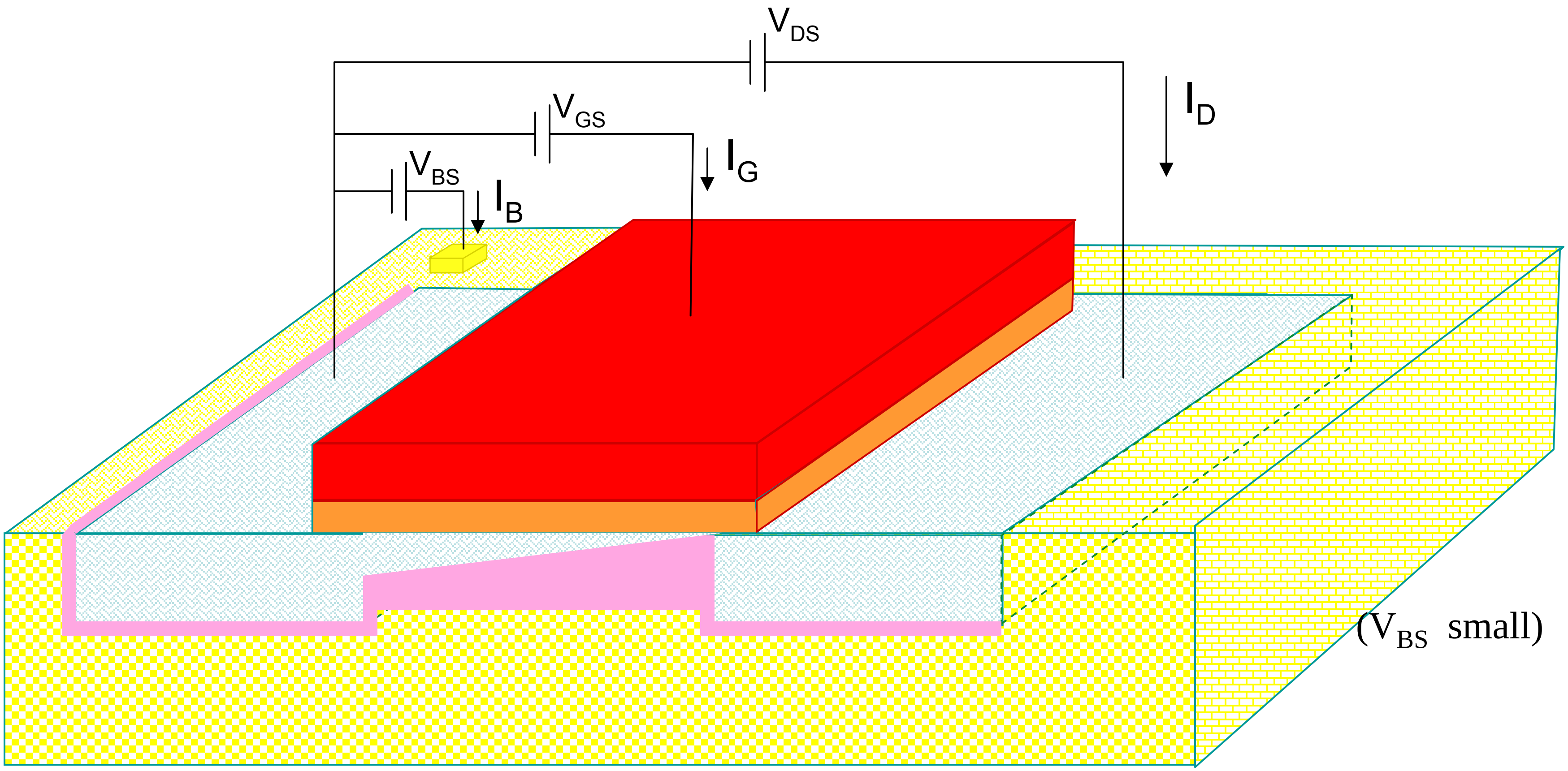
Channel behaves as thin-film resistor

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

$I_G = 0$

$I_B = 0$

n-Channel MOSFET Operation and Model



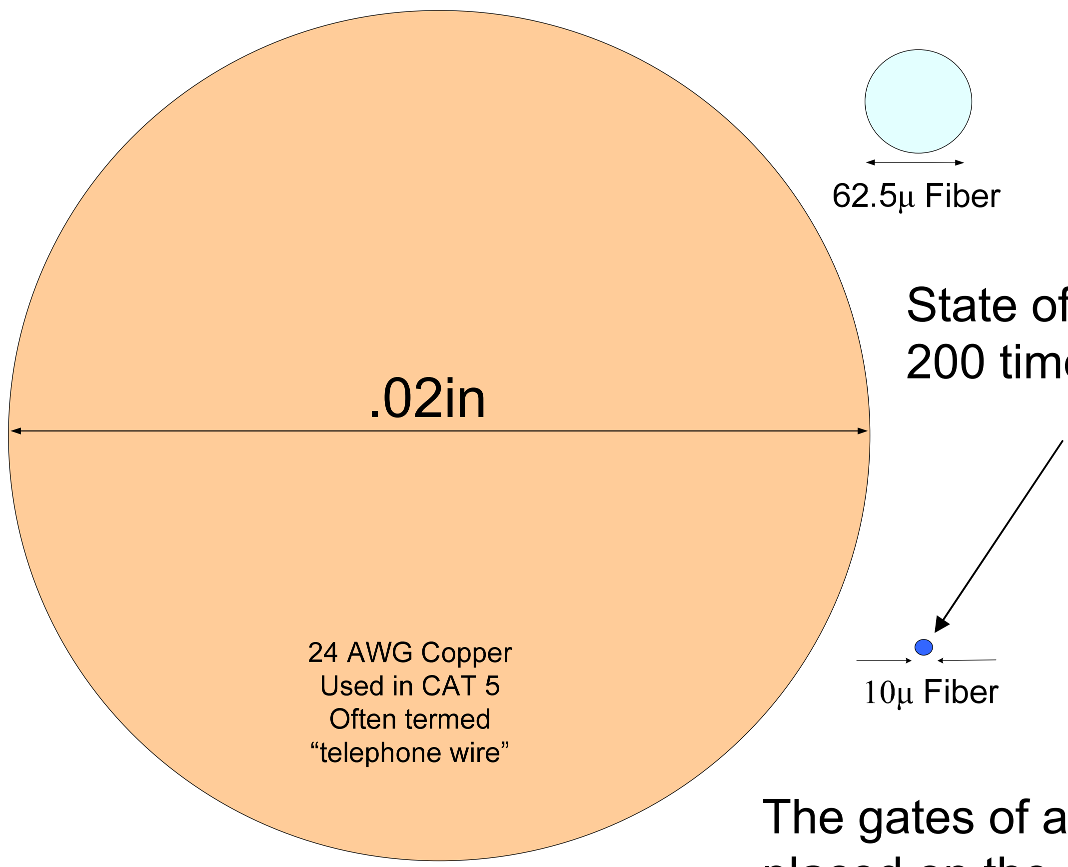
"Saturation" region of operation

I_D=?
I_G=0
I_B=0

Inversion layer disappears near drain

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

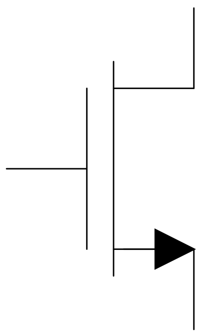
Transistor Size Comparison with 24AWG Copper Cable
(Drawn to scale)

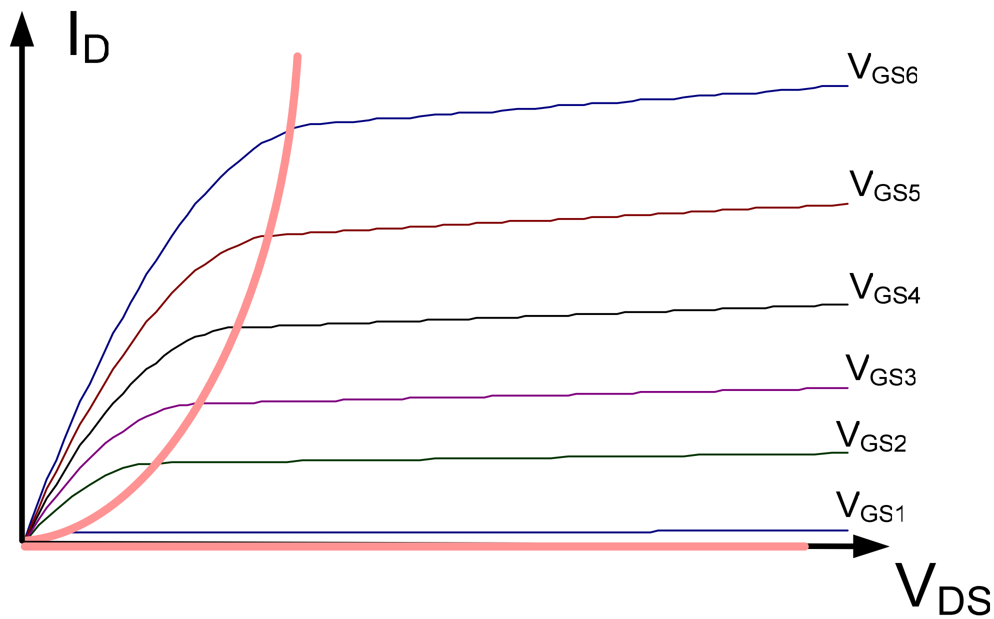


State of Art transistor dimensions about 200 times smaller (lateral) than 10μ fiber

The gates of about 40000 transistors can be placed on the cross-section of this fiber (maybe only 4000 transistors)

MOS Transistors





Standard square-law model

$I_G = 0$

$$I_D = \begin{cases} 0 & V_{GS} < V_T & \text{Cutoff} \\ \left(\frac{\mu C_{OX} W}{L}\right)\left(V_{GS} - V_T - \frac{V_{DS}}{2}\right)V_{DS} & V_{GS} \geq V_T \quad V_{DS} \leq V_{GS} - V_T & \text{Triode} \\ \left(\frac{\mu C_{OX} W}{2L}\right)(V_{GS} - V_T)^2 (1 + \lambda V_{DS}) & V_{GS} \geq V_T \quad V_{DS} > V_{GS} - V_T & \text{Saturation} \end{cases}$$

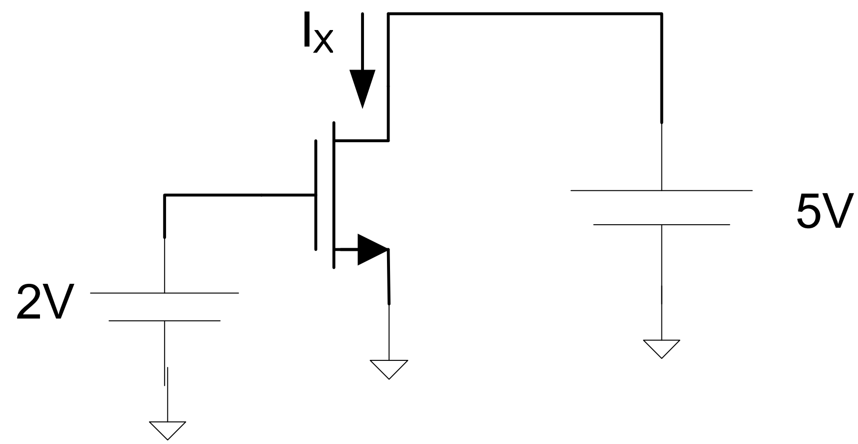
$\mu C_{OX} \approx 10^{-4}\, A/V^2$

$\lambda \approx .01 V^{-1}$

$V_T \approx 0.5V$ to $3V$

W/L varies by design

Example:



Determine I_X. Assume W=10u, L=2u, V_T=1V, $uC_{OX}=10^{-4}A/V^2$, λ=0

$I_G = 0$

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← Cutoff

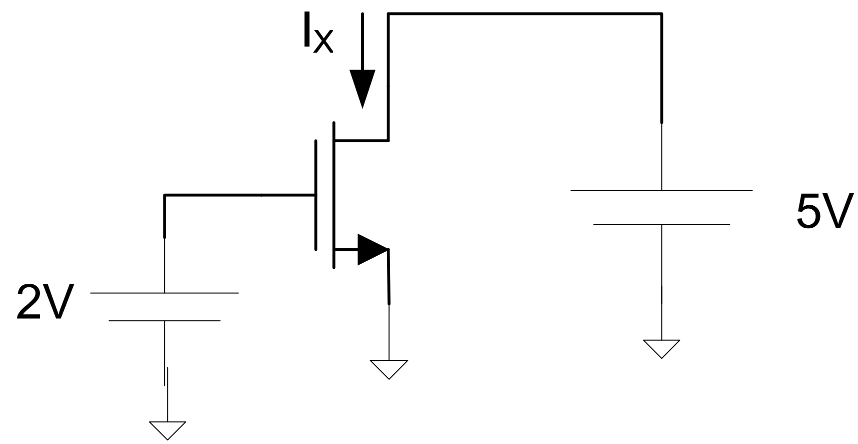
← Triode

← Saturation

Guess Saturation:

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

Example:



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Guess Saturation:

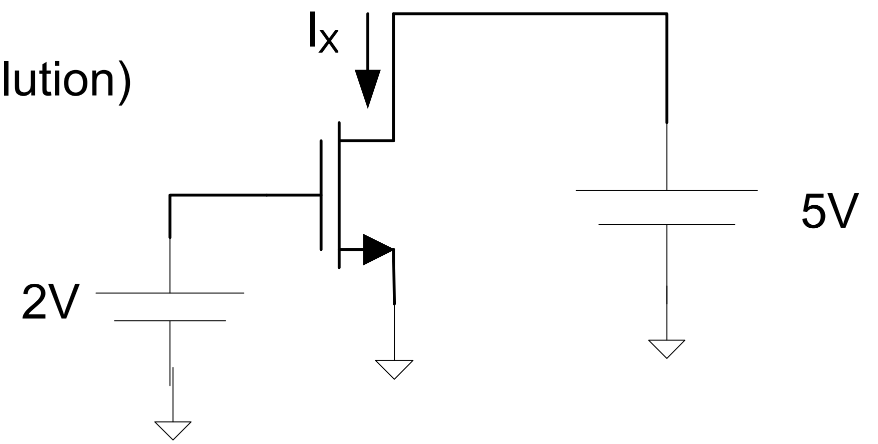
$$I_D = \mu C_{OX}\frac{W}{2L}(V_{GS}-V_T)^2 \qquad V_{GS} \geq V_T \qquad V_{DS} > V_{GS}-V_T$$

$$I_D = 10^{-4}\frac{10u}{2\bullet 2u}(2-1)^2 \qquad 2V \geq 1V \qquad 5V > 2V-1V$$

$$I_D = 0.25mA$$

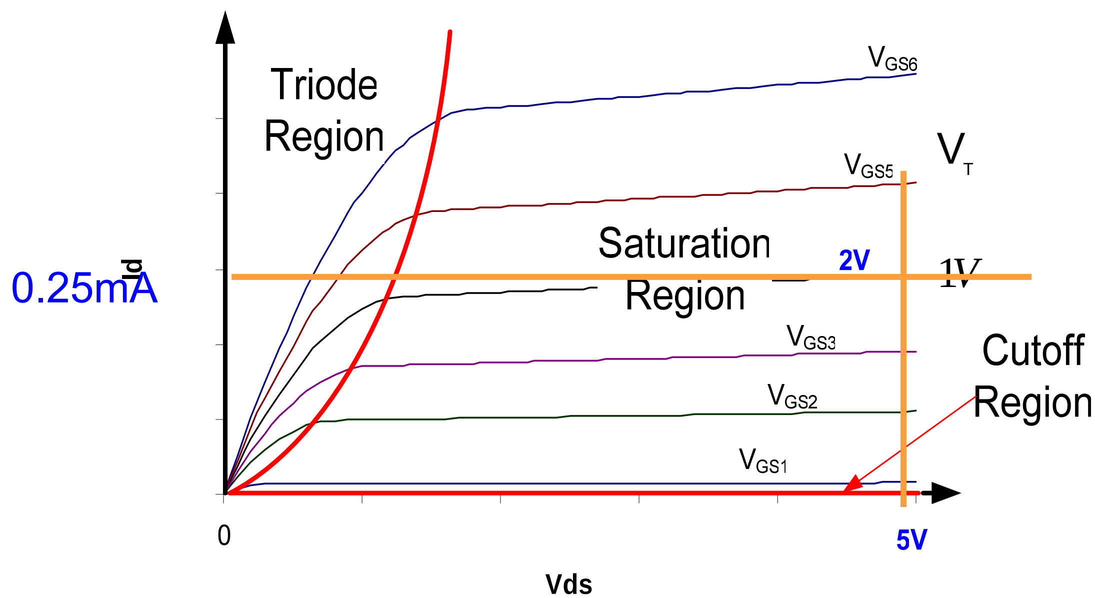
Example:

(alternative graphical solution)

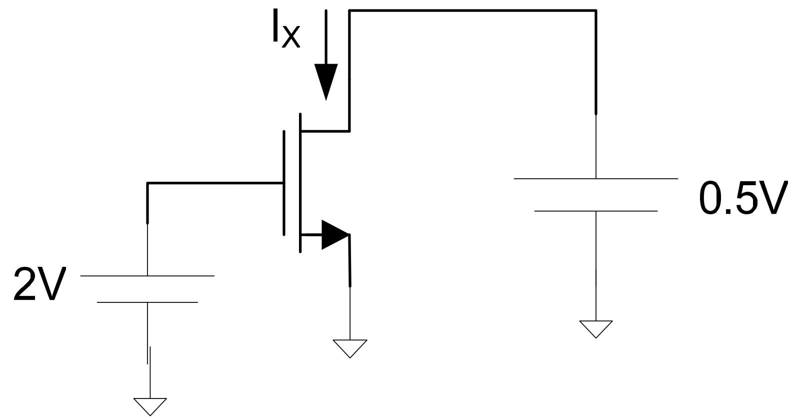


Determine I_X. Assume W=10u, L=2u, V_T=1V, $uC_{OX}=10^{-4}A/V^2$, $\lambda=0$

Consider model for THIS device:



Example:



Determine I_X. Assume W=10u, L=2u, V_T=1V, $uC_{OX}=10^{-4}A/V^2$, $\lambda=0$

$$I_G = 0$$

$$I_D = \begin{cases} 0 & V_{GS} \le V_T \\ \mu C_{OX}\frac{W}{L}\left(V_{GS}-V_T-\frac{V_{DS}}{2}\right)V_{DS} & V_{GS} \ge V_T \quad V_{DS} < V_{GS}-V_T \\ \mu C_{OX}\frac{W}{2L}\left(V_{GS}-V_T\right)^2 \bullet \left(1+\lambda V_{DS}\right) & V_{GS} \ge V_T \quad V_{DS} \ge V_{GS}-V_T \end{cases}$$

← Cutoff

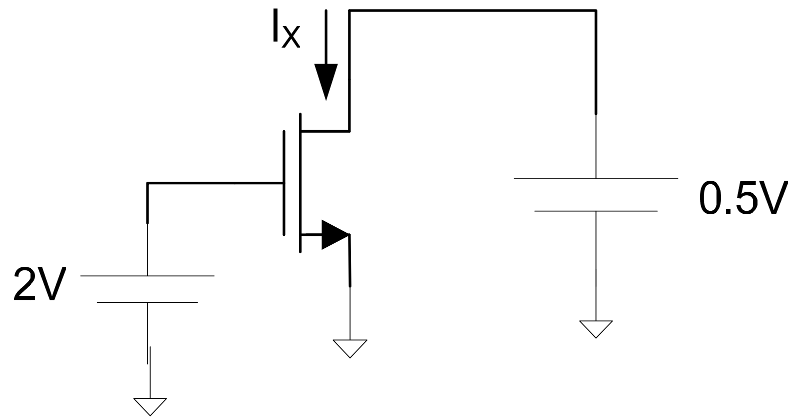
← Triode

← Saturation

Guess Saturation:

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

Example:



Determine I_X. Assume W=10u, L=2u, V_T=1V, $uC_{OX}=10^{-4}A/V^2$, $\lambda=0$

Guess Saturation:

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

$$V_{GS} \geq V_T \qquad V_{DS} > V_{GS} - V_T$$

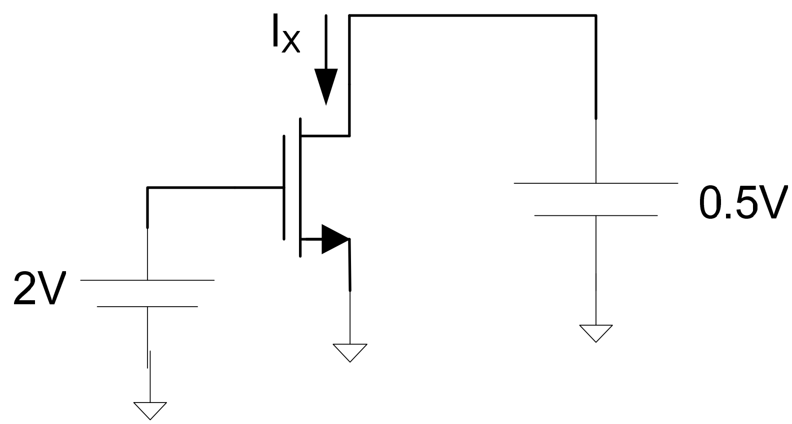
$$I_D = 10^{-4}\frac{10u}{2 \bullet 2u}(2-1)^2$$

$$2V \geq 1V \qquad 0.5V > 2V - 1V$$

$$I_D = 0.25mA$$

Verification Fails

Example:



Determine I_X. Assume W=10u, L=2u, V_T=1V, $uC_{OX}=10^{-4}A/V^2$, $\lambda=0$

Guess Triode:

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

$$V_{GS} \geq V_T \qquad V_{DS} < V_{GS}-V_T$$

$$I_D = 10^{-4}\frac{10u}{2u}(2-1-0.25)0.25$$

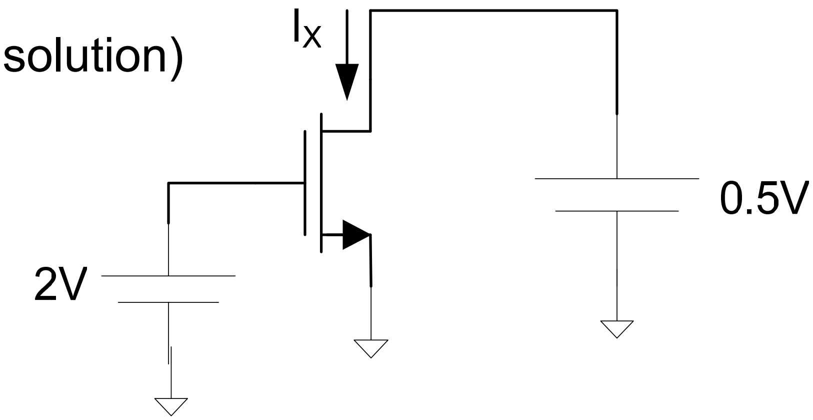
$$2V \geq 1V \qquad 0.5V < 2V - 1V$$

$$I_D = 94\mu A$$

Verification Passes

Example:

(alternative graphical solution)



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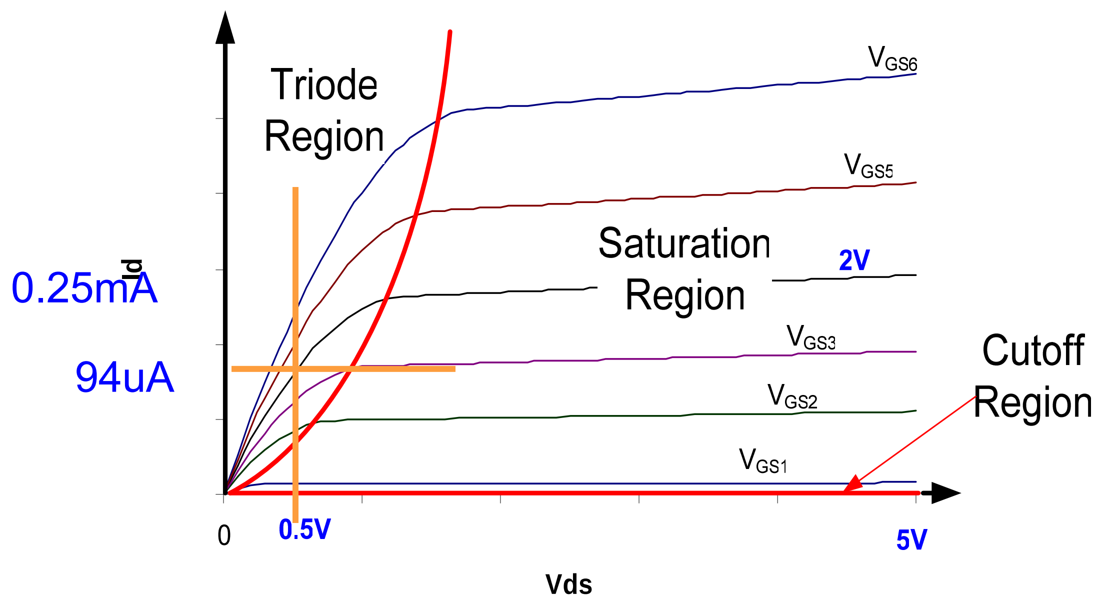
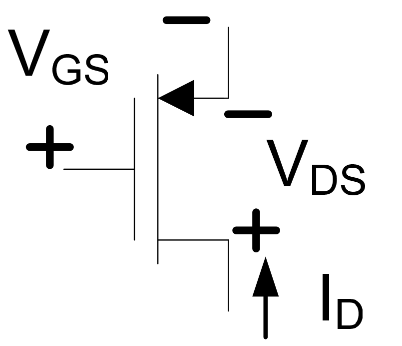
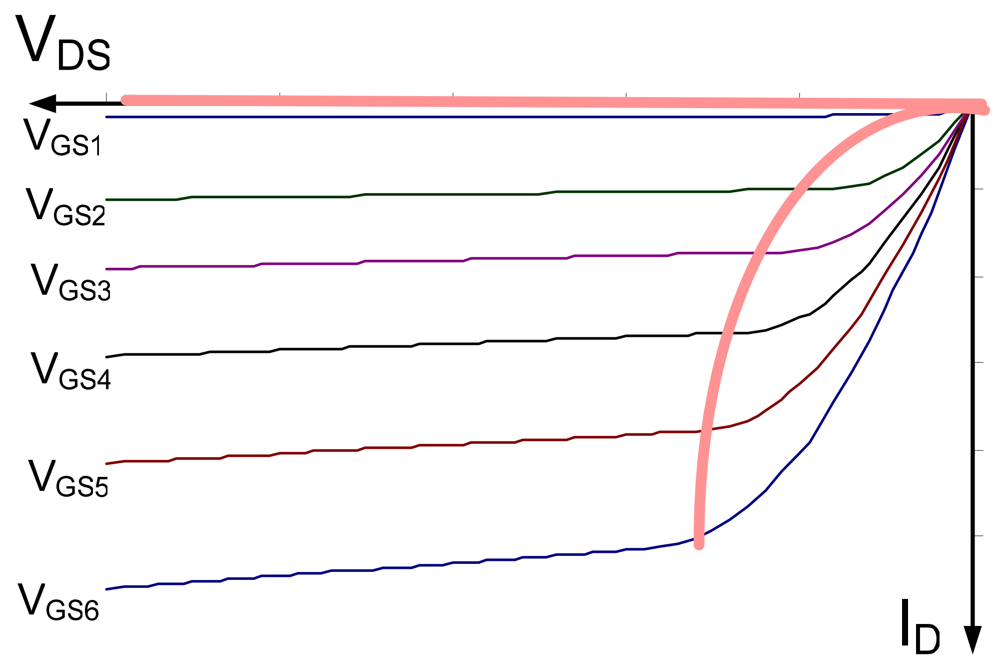


MOS Transistors



p-channel MOSFET



Standard square-law model

$I_G=0$

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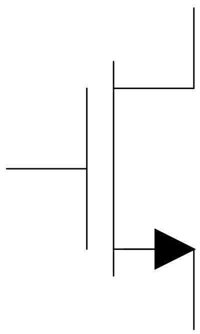
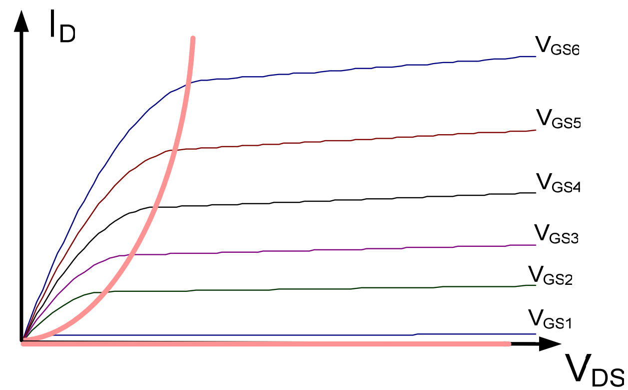
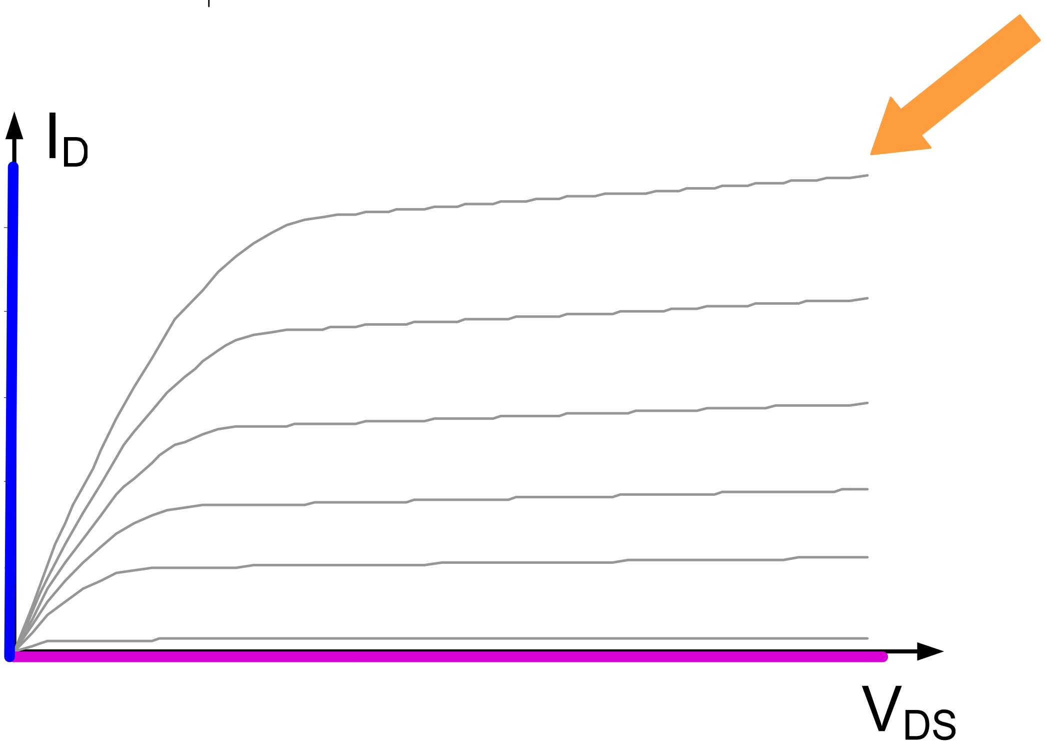
$V_T < 0$
$I_D \le 0$
$V_{DS} \le 0$

MOS Transistor Models

simplifications







$I_G=0$

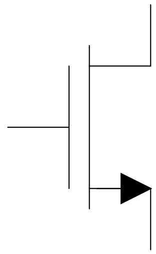
$I_D=0$ $V_{GS}<V_T$ Cutoff

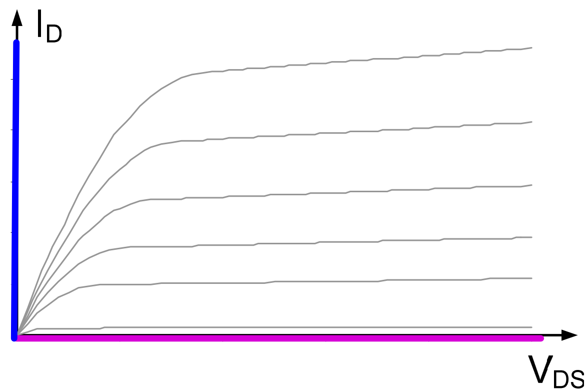
$V_{DS}=0$ $V_{GS} \geq V_T$ Triode

Switch-level dc model – *good enough for predicting basic operation of many digital circuits*

MOS Transistor Models

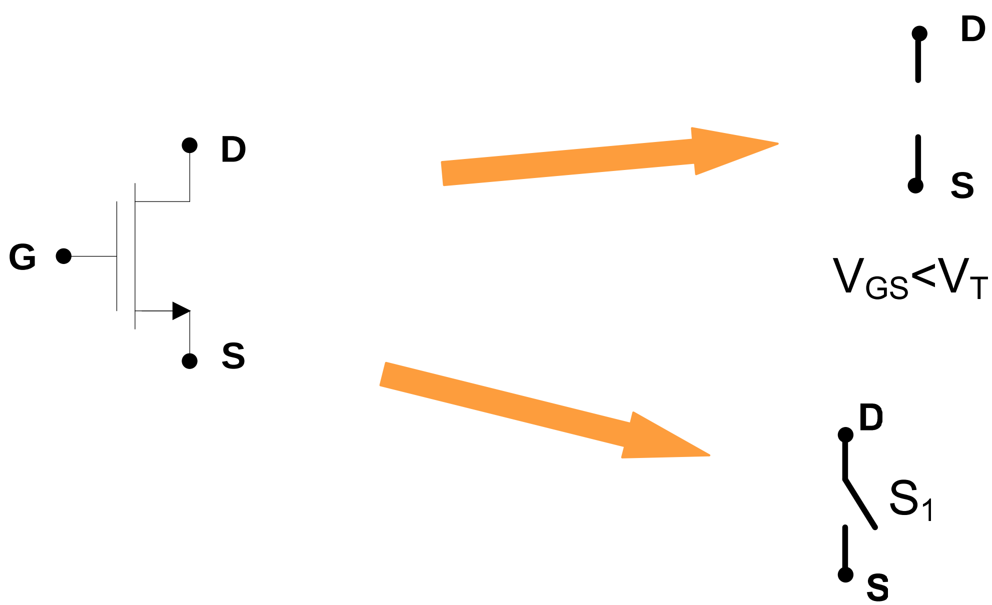
simplifications





$I_G=0$		
$I_D=0$	$V_{GS}<V_T$	Cutoff
$V_{DS}=0$	$V_{GS} \geq V_T$	Triode

Equivalent Circuit Models

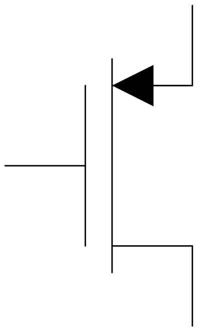


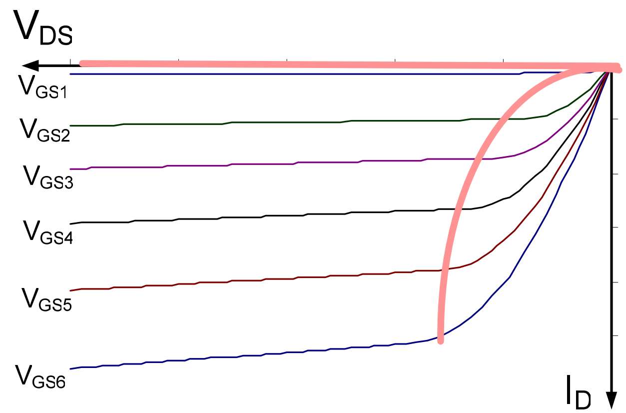
S_1 open for $V_{GS}<V_T$

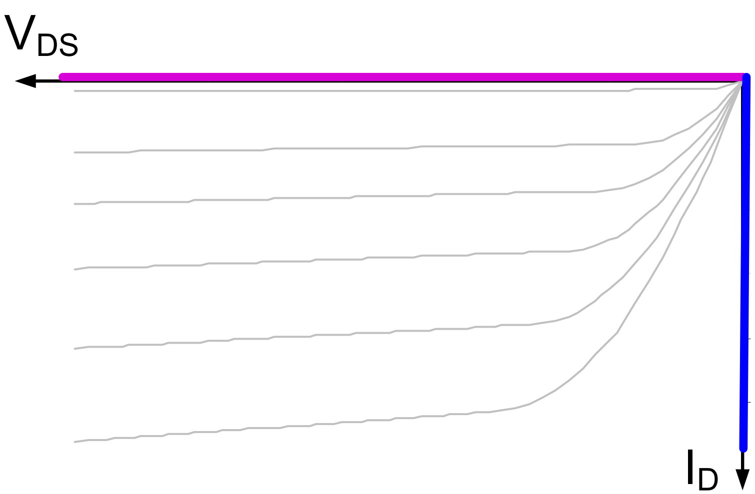
S_1 closed for $V_{GS}>V_T$

MOS Transistor Models

simplifications





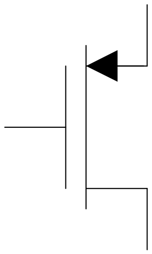


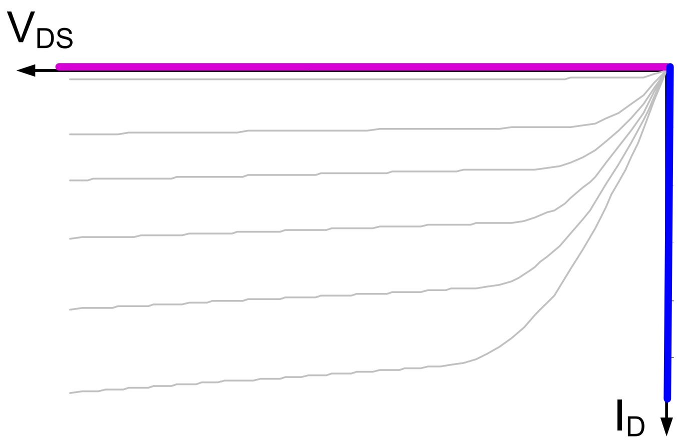
$I_G=0$		
$I_D=0$	$V_{GS} > V_T$	Cutoff
$V_{DS}=0$	$V_{GS} \leq V_T$	Triode

Switch-level dc model – *good enough for predicting basic operation of many digital circuits*

MOS Transistor Models

simplifications





$I_G=0$		
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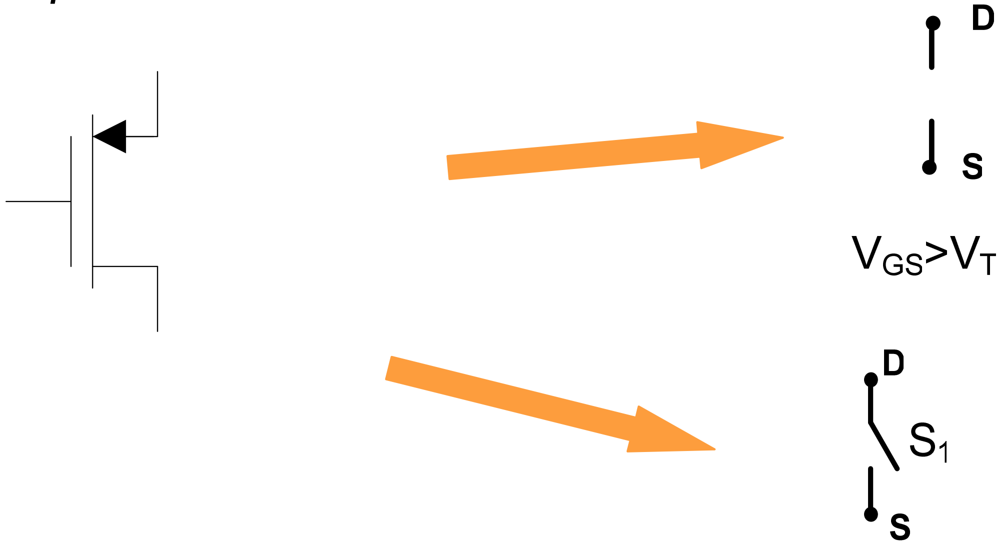
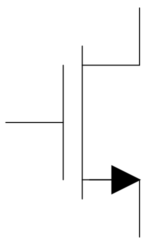
Equivalent Circuit Models

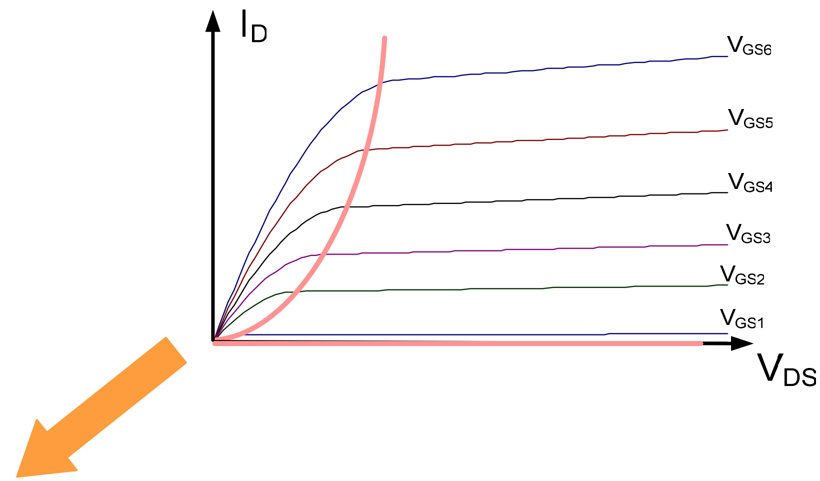


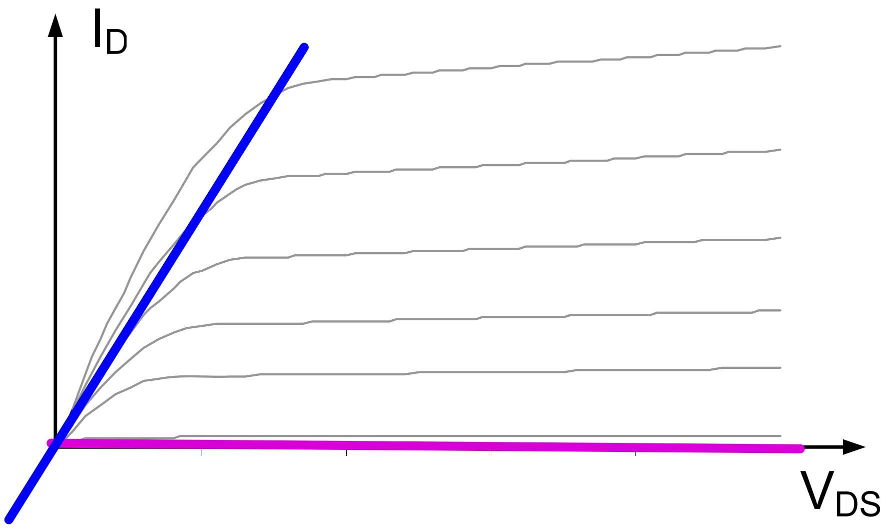
S_1 open for $V_{GS}>V_T$

S_1 closed for $V_{GS}<V_T$

MOS Transistor Models
simplifications







$$I_G = 0$$

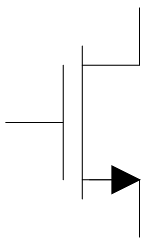
$$I_D = \begin{cases} 0 & V_{GS} < V_T \quad \text{Cutoff} \\ V_{DS}/R_{FET} & V_{GS} \geq V_T \quad \text{Triode} \end{cases}$$

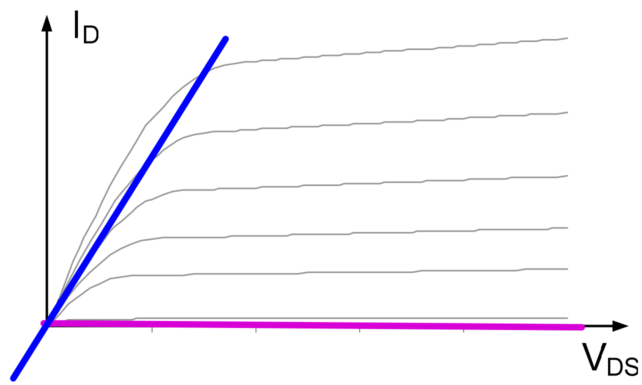
$$R_{FET} \cong \frac{1}{V_{GS} - V_T}\left(\frac{L}{\mu C_{ox} W}\right)$$

Better Switch-level dc model – *good enough for predicting basic operation of many digital circuits and can be used to predict speed performance if parasitic capacitances are added*

MOS Transistor Models

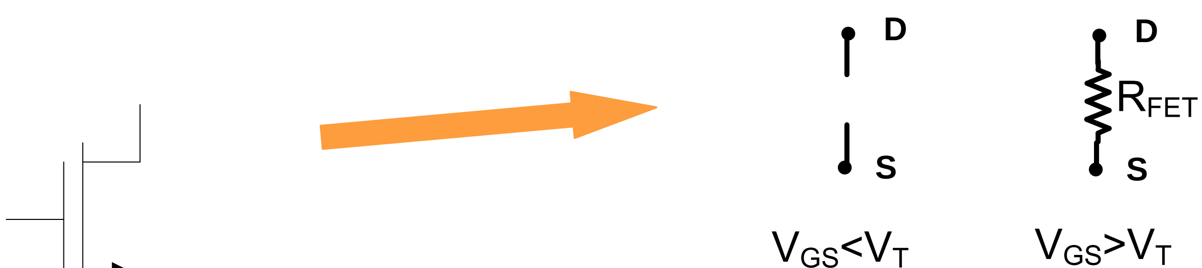
simplifications



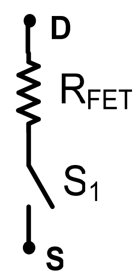


$I_G = 0$

$$I_D = \begin{cases} 0 & V_{GS} < V_T \quad \text{Cutoff} \\ V_{DS}/R_{FET} & V_{GS} \geq V_T \quad \text{Triode} \end{cases}$$



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

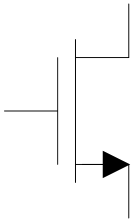


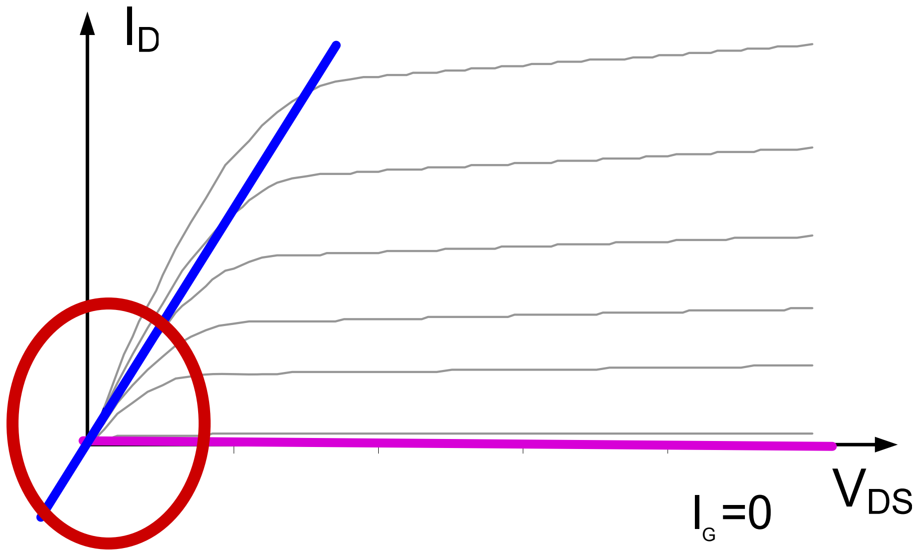
S_1 closed for $V_{GS}>V_T$

S_1 open $V_{GS}<V_T$

MOS Transistor Models

Voltage Variable Resistor (VVR) operation





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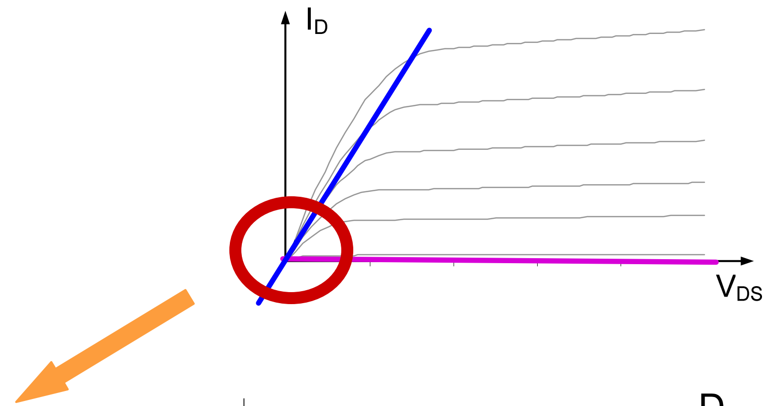
$$R_{FET} \cong \frac{1}{V_{GS}-V_T}\left(\frac{L}{\mu C_{OX} W}\right)$$

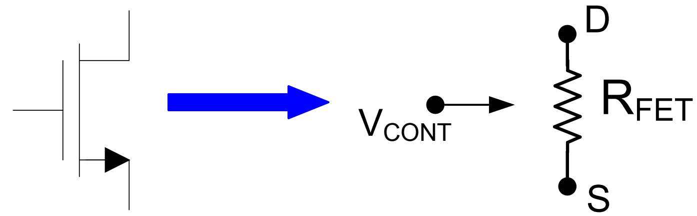
VVR Application – *dc gate to source voltage can be used to control the resistance*

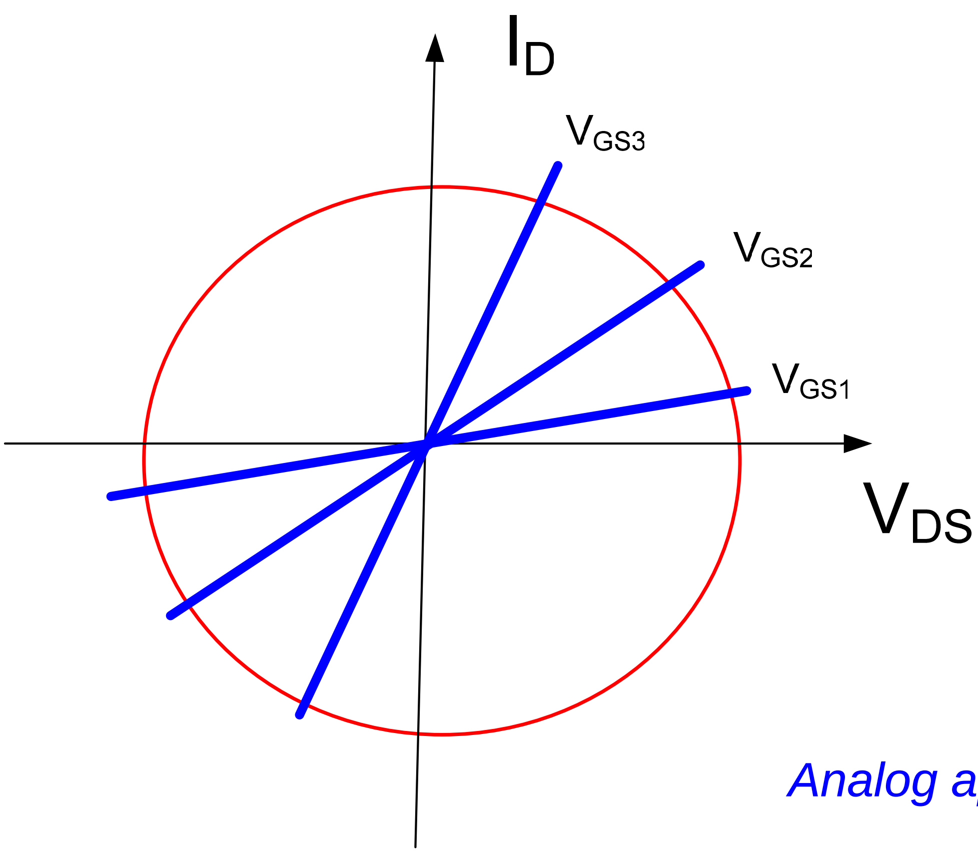
Widespread applications in analog circuits and computer-control of electronic circuits

MOS Transistor Models

Voltage Variable Resistor (VVR) operation



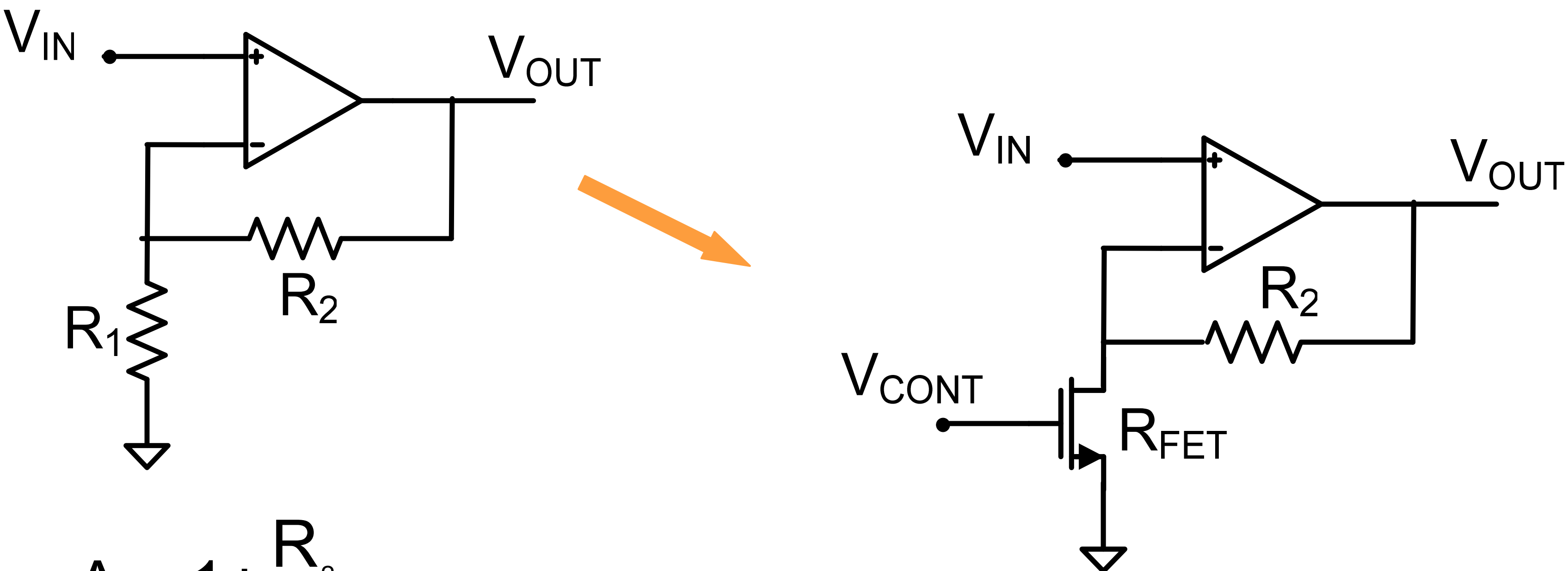




$$R_{FET} \cong \frac{1}{V_{GS} - V_T} \left(\frac{L}{\mu C_{OX} W} \right)$$

Analog application of MOSFET in triode region

Voltage Variable Resistor



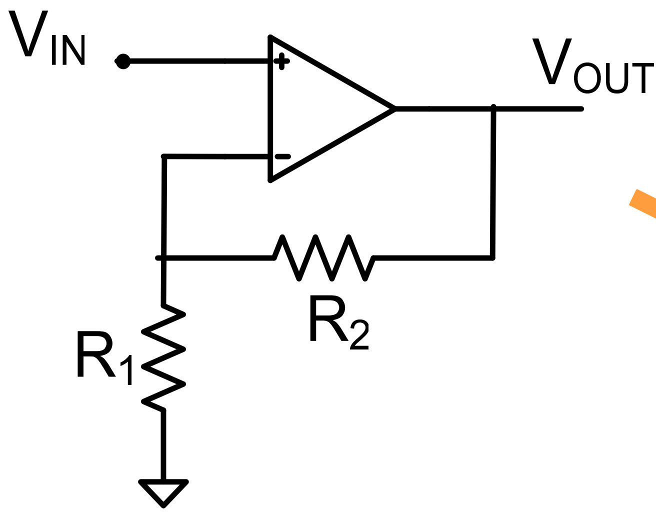
$$A_V = 1 + \frac{R_2}{R_1}$$

$$A_V = 1 + \frac{R_2}{R_{FET}}$$

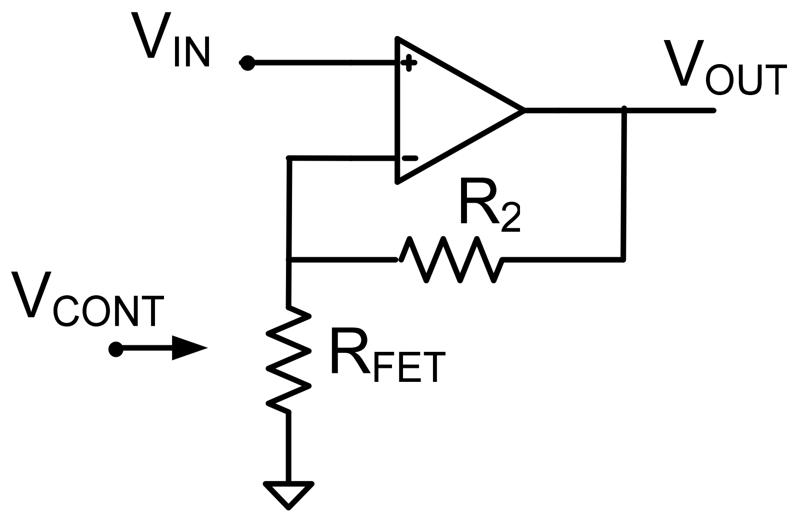
$$R_{FET} \cong \frac{1}{V_{GS} - V_T}\left(\frac{L}{\mu C_{ox} W}\right)$$

Applications include Automatic Gain Control (AGC)

Voltage Variable Resistor



$$A_V = 1 + \frac{R_2}{R_1}$$



$$A_V = 1 + \frac{R_2}{R_{FET}}$$

$$R_{FET} \cong \frac{1}{V_{GS} - V_T}\left(\frac{L}{\mu C_{ox} W}\right)$$

Applications include Automatic Gain Control (AGC)

End of Lecture 30