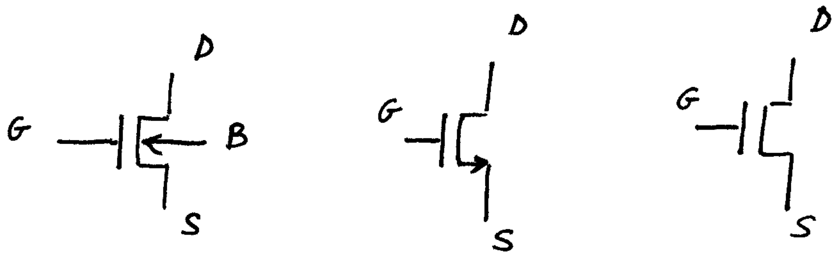
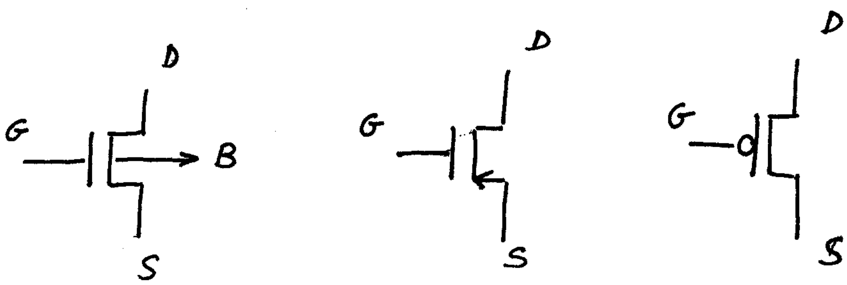
MOS Transistor

The MOS transistor is a device in which the current flowing in a conducting channel between source and drain is controlled by the voltage applied to the gate.



n-channel MOSFET



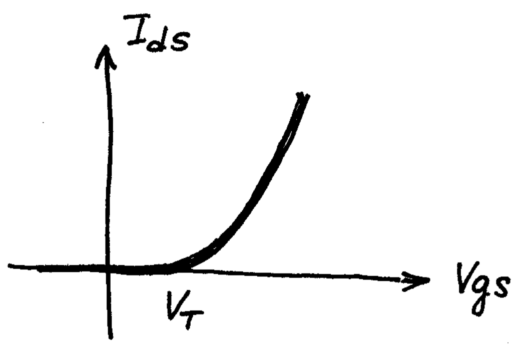
p-channel MOSFET

In an n-channel MOSFET the majority carriers are electrons.
If we apply a positive voltage between the gate and the substrate (also called bulk) the number of electrons in the channel (zone under the gate) is increased.
For gate voltages smaller than a threshold V_T the channel is "cut off".
The threshold voltage is therefore

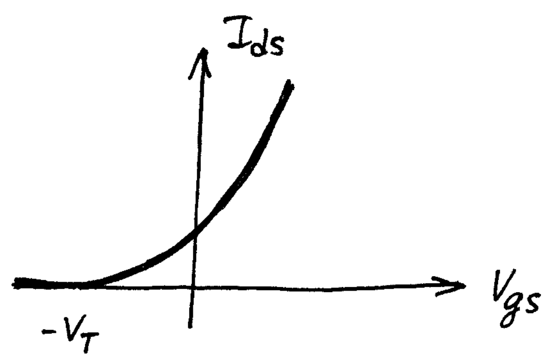
the voltage at which the transistor begins to conduct (the transistor is turned on).

The p-channel MOSFET works analogously. The difference is that the majority carriers are now holes and that we need to apply a negative voltage between gate and substrate to enhance the number of carriers in the channel.

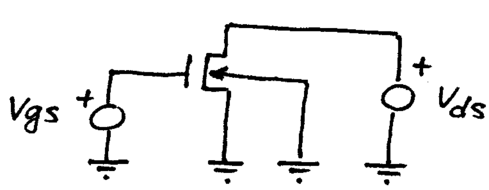
It is possible to build devices that conduct when the gate voltage is zero. The devices that are normally turned off (non conducting) with zero gate voltage are called "enhancement", while those devices that are turned on (conducting) with zero gate voltage are called "depletion-mode".

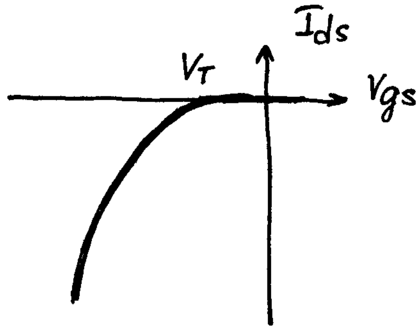


n-channel enhancement

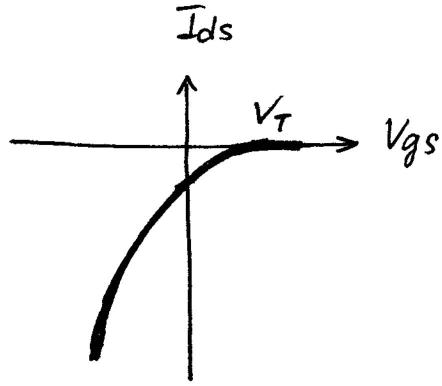


n-channel depletion

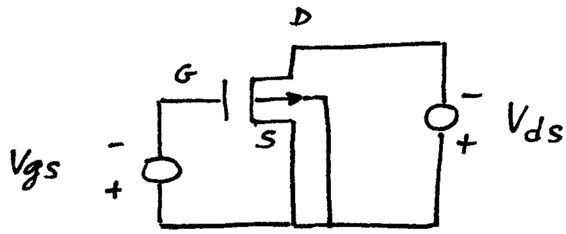




p-channel enhancement



p-channel depletion



n-type enhancement MOS

The MOS transistor can operate in 3 different ways depending on the control voltage we apply to it.

1. cut-off region (or subthreshold region)

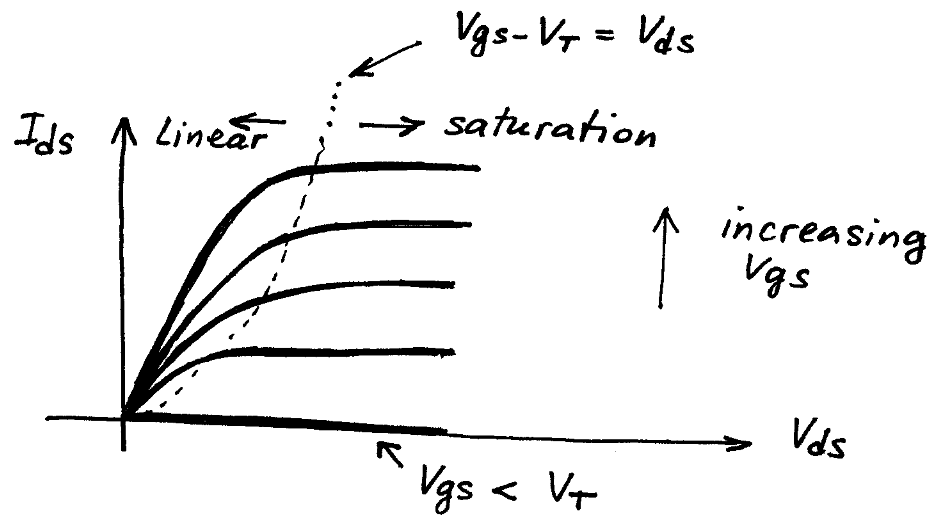
$$V_{gs} - V_T \leq 0$$

2. Linear region

$$0 < V_{ds} < V_{gs} - V_T$$

3. saturation region

$$0 < V_{gs} - V_T \leq V_{ds}$$



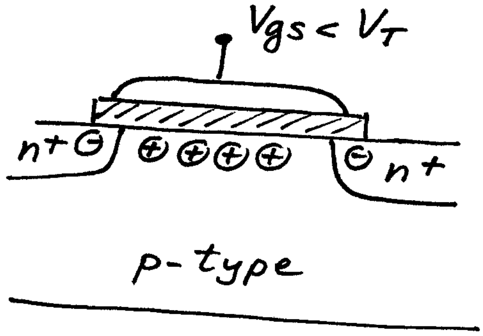
Let's try to find out equations describing the behavior of an n-MOS device

<u>cut off region</u>

$V_{gs} \leq V_T$

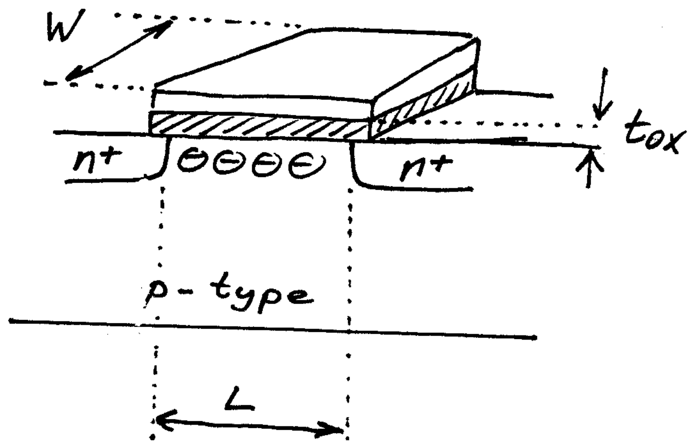
The control voltage applied V_{gs} is not sufficient to create a conducting channel between source and drain

$$I_{ds} = 0$$



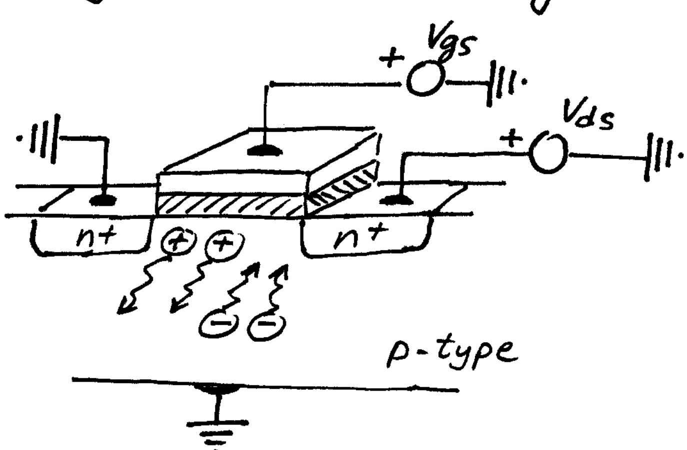
Linear region (non-saturation region)

$V_{gs} > V_T$ and $V_{ds} < V_{gs} - V_T$

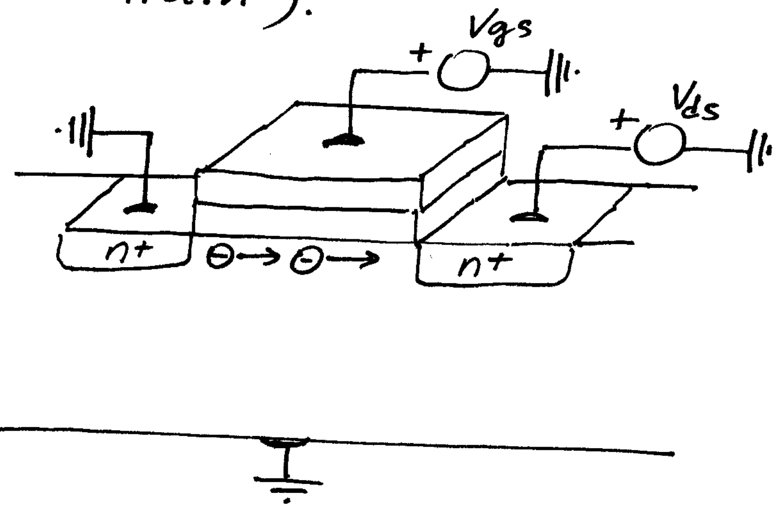


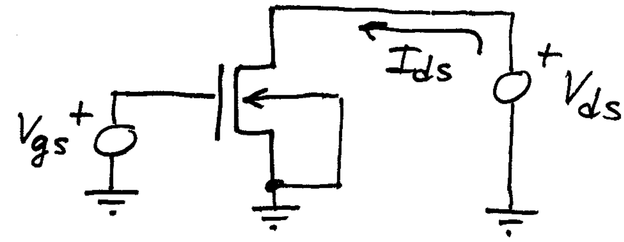
L = channel length
W = width
t_{ox} = oxide thickness

If we apply on the gate a positive voltage bigger than a threshold value V_T, the nature of the charge in the region below the gate is inverted



The inversion of charge forms a conducting channel (in the region below the gate) between source and drain.
Applying a voltage between drain and source we can drift the charge in the channel and therefore produce a current flow between drain and source (movement of electrons from source to drain).





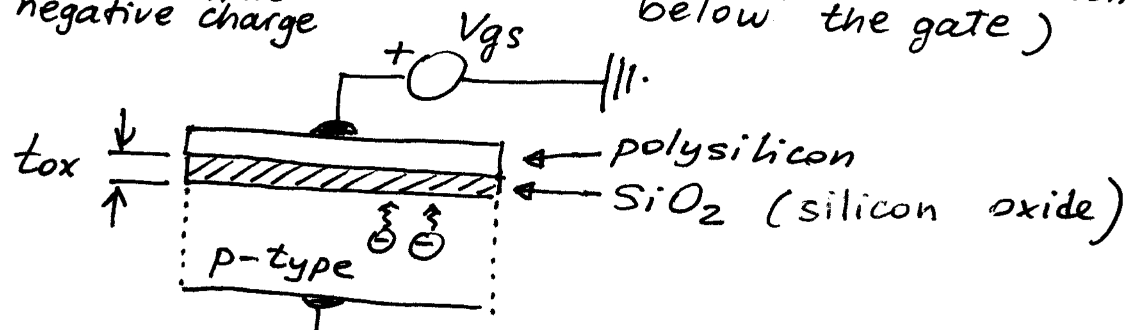
Let's try now to find out an equation for the current I_{ds}. We'll do it in an intuitive way first and in a more rigorous way later.

We can see the central part of the MOS, (roughly) as a simple capacitor. The charge accumulated by this capacitor is approximately:

$$Q \simeq -C_{ox}\,(V_{gs} - V_T)$$

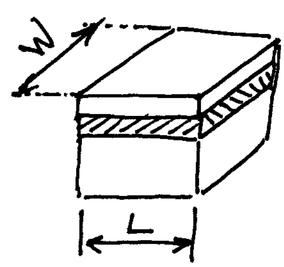
electrons have negative charge

We need to apply a voltage bigger than V_T before we have the inversion layer (enough electrons below the gate)



$$C_{ox} = \varepsilon_{ox} \cdot \frac{AREA}{t_{ox}} = \varepsilon_{ox} \cdot \frac{W \cdot L}{t_{ox}}$$

capacitance of a linear capacitor



The current flow I_{ds} is given by the amount of charge (electrons) we are able to drift (move) from source to drain in the unit of time

$$I_{ds} = \frac{Q}{\tau}$$

τ = transit time = time taken by the electrons to go from source to drain

$$\tau = \frac{\text{distance between source and drain}}{\text{velocity of the electrons}}$$

The drift velocity we impose on the electrons depends on the electrons' mobility μ (physical characteristic of the matter) and on the voltage we apply between source and drain (more precisely the electric field)

$$\text{velocity} = \mu E = -\mu \frac{V_{ds}}{L}$$

The distance between source and drain is L (channel length)

$$I_{ds} \simeq \frac{Q}{\tau} = \frac{\varepsilon_{ox} \cdot \frac{W \cdot L}{t_{ox}} \cdot (V_{gs} - V_T)}{\frac{L}{\mu \frac{V_{ds}}{L}}} =$$

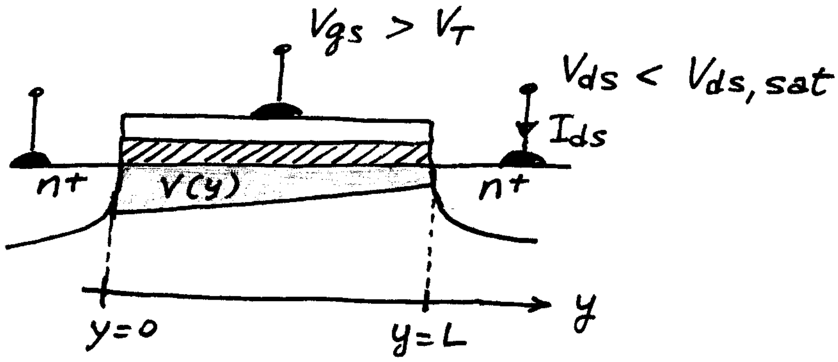
$$\cong \underbrace{\left\{ \mu \frac{\varepsilon_{ox}}{t_{ox}} \cdot \frac{W}{L} \right\}}_{= \beta} \cdot (V_{gs} - V_T) V_{ds}$$

β ← gain factor

$$\approx \beta \cdot (V_{gs} - V_T) V_{ds}$$

In the gain factor there is a part that depends on the geometry : $\frac{W}{L}$ and a part that depends on the "process" : $\mu \frac{\varepsilon_{ox}}{t_{ox}}$

The analysis done has the advantage to be very intuitive, but it is not very accurate. In computing the channel charge we should consider the effect of the voltage across the channel when a voltage is applied between drain and source.



Taking into account that the voltage across the channel change along the y direction the electron inversion charge in the channel is given by

$$Q(y) = -C_{ox}\left(V_{gs} - V_T - V(y)\right)$$

the sign is due to the fact that electrons have negative charge

voltage in the channel due to V_{ds}

The voltage across a differential segment dy is given by dV.

$$I_{ds} = \frac{Q(y)}{\tau}$$

$$\text{velocity} = \mu E = -\mu \frac{dV}{dy}$$

$$\tau = \frac{L}{\text{velocity}} = \frac{L}{-\mu \frac{dV}{dy}}$$

$$I_{ds} \cdot dy = + \frac{\mu C_{ox}}{L} \left(V_{gs} - V_T - V(y) \right) dV$$

$$I_{ds} \cdot dy = + \frac{\mu \varepsilon_{ox} W}{t_{ox}} \left(V_{gs} - V_T - V(y) \right) dV$$

$$C_{ox} = \varepsilon_{ox} \cdot \frac{W \cdot L}{t_{ox}}$$

$$\int_0^L I_{ds} \cdot dy = + \frac{\mu \varepsilon_{ox} W}{t_{ox}} \int_{V(0)}^{V(L)} [V_{gs} - V_T - V(y)] dV$$

$$I_{ds} \cdot L = + \frac{\mu \varepsilon_{ox} \cdot W}{t_{ox}} \int_0^{V_{ds}} \left[V_{gs} - V_T - V(y) \right] dV$$

$$I_{ds} = + \frac{\mu \varepsilon_{ox}}{t_{ox}} \cdot \frac{W}{L} \int_0^{V_{ds}} \left[V_{gs} - V_T - V(y) \right] dV$$

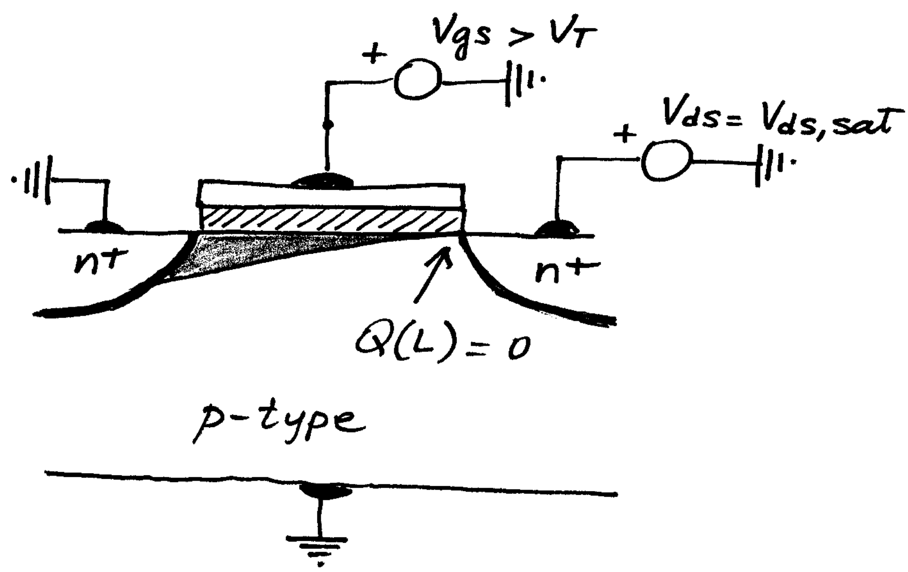
$$I_{ds} = + \beta \int_0^{V_{ds}} [V_{gs} - V_T] dV - \beta \int_0^{V_{ds}} V dV$$

$$I_{ds} = \beta \left[(V_{gs} - V_T) V_{ds} - \frac{V_{ds}^2}{2} \right]$$

saturation region

$V_{gs} > V_T$ and $V_{ds} \geq V_{gs} - V_T$

As the drain voltage is increased, the inversion layer region charge and the channel depth at the drain end start to decrease. For $V_{ds} = V_{ds,sat}$ the inversion charge at the drain is reduced to 0 (pinch-off point).



The saturation condition corresponds to a channel voltage of $V(y=L) = V_{ds,sat}$ so that the inversion charge is

$$Q(y=L) = 0$$

(In the reality the charge does not become exaclty equal to zero, it is just an approximation) which substituting in the equation of the inversion charge in the channel:

$$Q(y) = -C_{ox}\left[V_{gs} - V_T - V(y)\right]$$

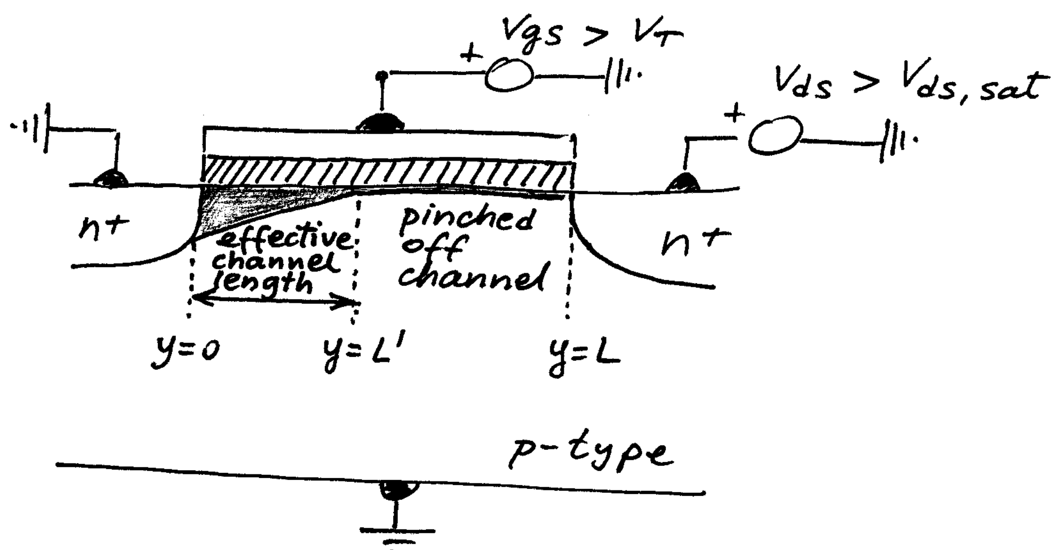
gives that the saturation voltage is:

$$Q(y=L) = -C_{ox}\left[V_{gs} - V_T - V_{ds,sat}\right]$$

$$0 = V_{gs} - V_T - V_{ds,sat}$$

$$V_{ds,sat} = V_{gs} - V_T$$

The channel is reduced to its minimum thickness.
As V_{ds} increase, the effective length of the channel decrease.



The effective channel length is reduced to:

$$L' = L - \Delta L$$

The pinch-off point moves from the drain end toward the source increasing V_{ds}.

The portion of channel between the pinch-off point and the drain will be in the depletion mode.

The current at the saturation will be given by:

$$I_{ds} \underset{\substack{\uparrow \\ V_{ds} = V_{ds,sat} = V_{gs} - V_T}}{=} \beta \left[(V_{gs} - V_T) V_{ds} - \frac{V_{ds}^2}{2} \right] =$$

$$= \beta \left[\frac{1}{2} (V_{gs} - V_T)^2 \right]$$

The current beyond saturation will be given by:

the voltage at the pinch-off point remains equal to $V_{ds,sat}$

$$I_{ds} = \frac{\mu \varepsilon_{ox}}{t_{ox}} \cdot \frac{W}{L'} \left[(V_{gs} - V_T) V_{ds} - \frac{V_{ds}^2}{2} \right] =$$

$V_{ds} = V_{ds,sat} = V_{gs} - V_T$

L': effective channel length

$$= \frac{\mu \varepsilon_{ox}}{t_{ox}} \cdot \frac{W}{L'} \left[\frac{1}{2} (V_{gs} - V_T)^2 \right]$$

We can combine the two equations:

$$I_{ds} = \frac{1}{1-\frac{\Delta L}{L}} \cdot \frac{\mu \varepsilon_{ox}}{t_{ox}} \cdot \frac{W}{L} \cdot \frac{1}{2} \cdot \left(V_{gs} - V_T\right)^2$$

p-type enhancement MOS

1. cut-off region

$V_{gs} \geq V_T$

$I_{ds} = 0$

2. Linear region

$V_{gs} \leq V_T$ and $V_{ds} > V_{gs} - V_T$

$$I_{ds} = \frac{\mu \varepsilon_{ox}}{t_{ox}} \cdot \frac{W}{L} \left[\left(V_{gs} - V_T\right) V_{ds} - \frac{V_{ds}^2}{2} \right]$$

3. saturation region

$V_{gs} < V_T$ and $V_{ds} \leq V_{gs} - V_T$

$$I_{ds} = \frac{1}{1-\frac{\Delta L}{L}} \cdot \frac{\mu \varepsilon_{ox}}{t_{ox}} \cdot \frac{W}{L} \left(V_{gs} - V_T\right)^2 \frac{1}{2}$$