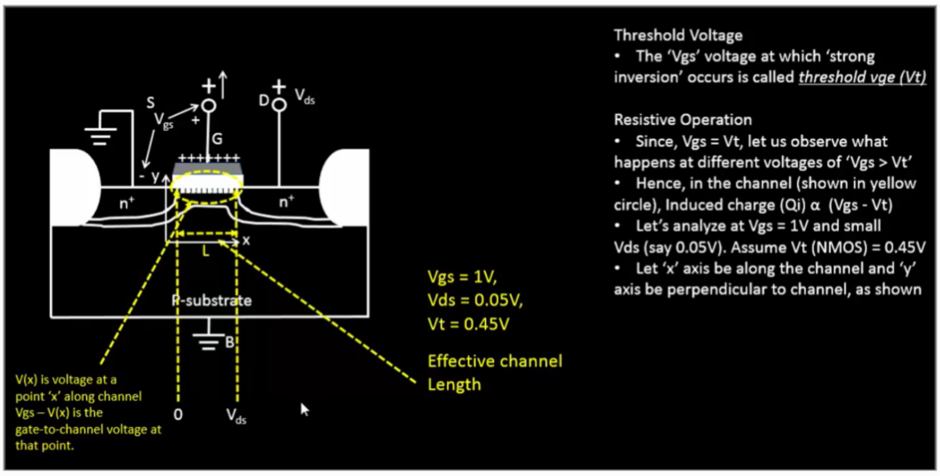
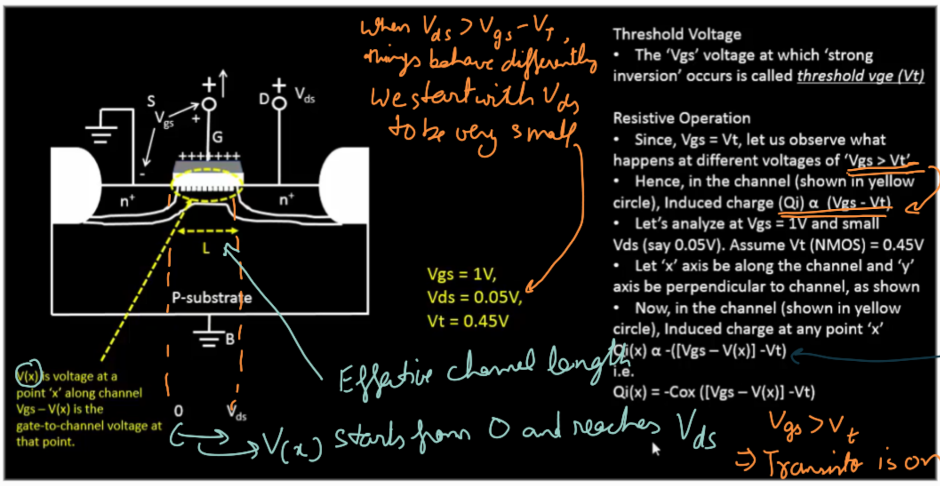


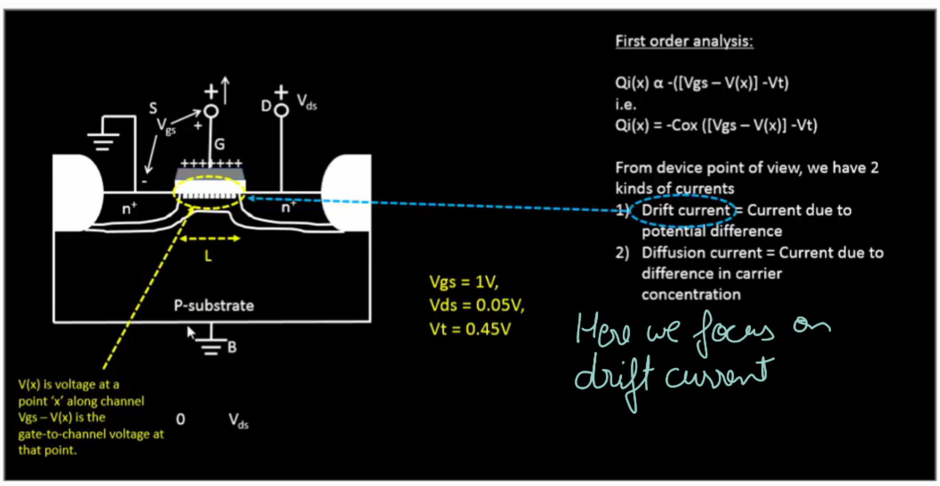


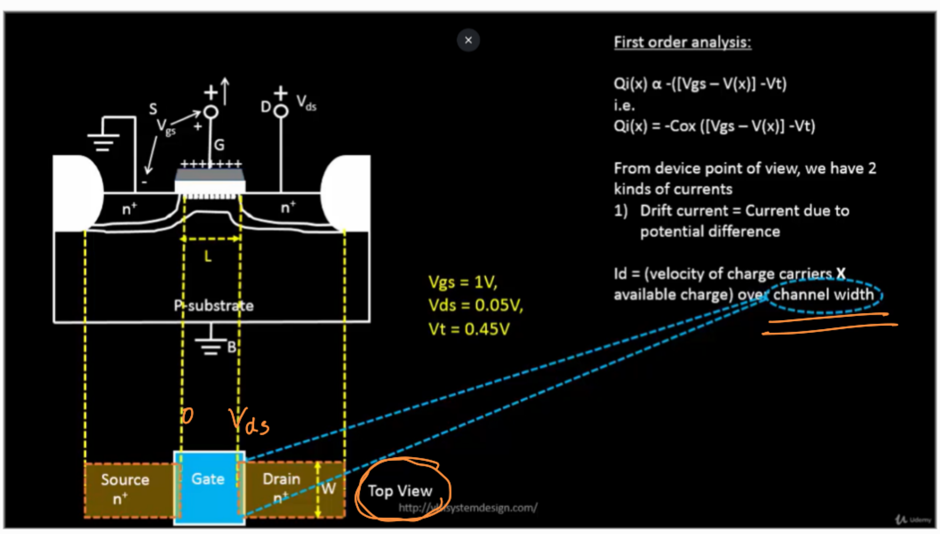
Induced charge at each point

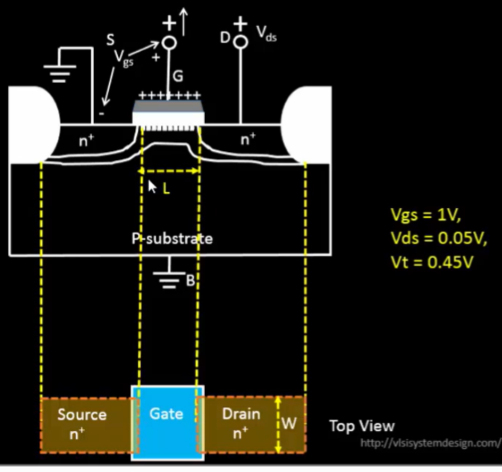
C_{ox} = Gate oxide capacitance

$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$

t_{ox} = oxide thickness







Vgs = 1V,
Vds = 0.05V,
Vt = 0.45V

First order analysis:

Qi(x) α -([Vgs – V(x)] -Vt)
i.e.
Qi(x) = -Cox ([Vgs – V(x)] -Vt)

From device point of view, we have 2 kinds of currents

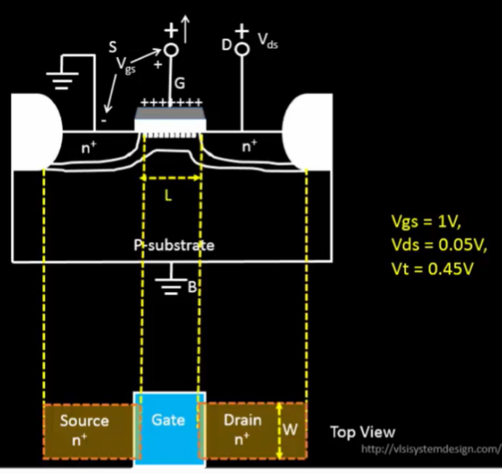
1) Drift current = Current due to potential difference

Id = (velocity of charge carriers **X** available charge) over channel width

Id = -Vn(x) . Qi(x) . W

Velocity Vn(x) = mobility . electric field
= μn . dV/dx

Id = -Vn(x) . Qi(x) . W
Substituting and Integrating dx over channel length L will give the V-I relation of NMOS transistor



Vgs = 1V,
Vds = 0.05V,
Vt = 0.45V

First order analysis:

Qi(x) α -([Vgs – V(x)] -Vt)
i.e.
Qi(x) = -Cox ([Vgs – V(x)] -Vt)

Id = -Vn(x) . Qi(x) . W
= μn . dV/dx . Cox ([Vgs – V(x)] -Vt) . W

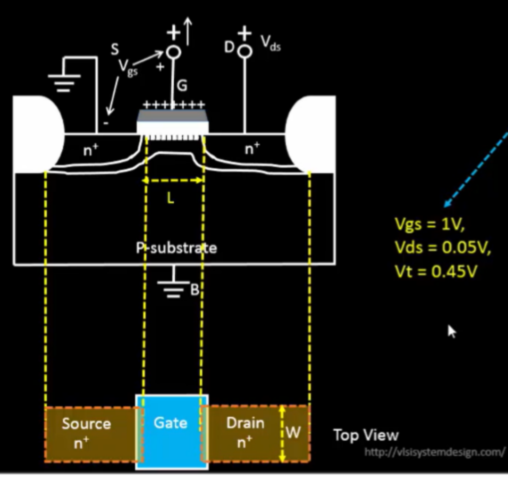
Id . dx = μn . Cox . W ([Vgs – V(x)] -Vt) . dV

Integrate over Length 'L' on LHS and over drain-source voltage Vds on RHS, we get the below

$\boxed{\text{Id} = \mu n \cdot \text{Cox} \cdot (W/L)\,[(\text{Vgs} - \text{Vt})\text{Vds} - \text{Vds}^2/2]}$

Id = kn' . (W/L) [(Vgs - Vt)Vds – Vds^2/2
Where kn' = process transconductance

$\boxed{\text{Id} = \text{kn} \cdot [(\text{Vgs} - \text{Vt})\text{Vds} - \text{Vds}^2/2}$
Where kn = kn' . (W/L) = gain factor



Vgs = 1V,
Vds = 0.05V,
Vt = 0.45V

Id = kn . [(Vgs - Vt)Vds – Vds^2/2
= kn . [(1 – 0.45) 0.05 – 0.05^2/2
= kn . [0.0275 – 0.00125]

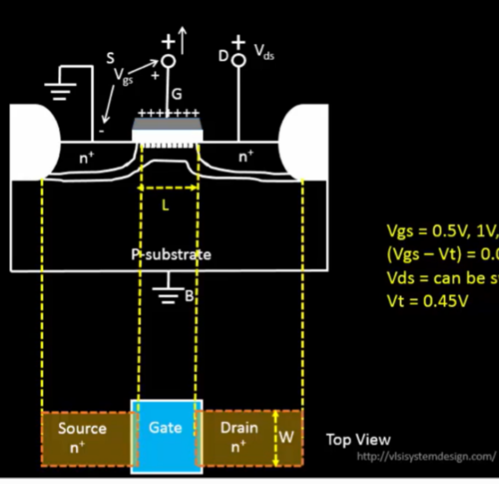
≈ 0 for Vds <= (Vgs – Vt)

Id = kn . 0.0275 → Linear or resistive region of operation

Id = <u>*kn . (Vgs – Vt)*</u> Vds → linear f(Vds)

In linear region
when $V_{ds} <= V_{gs} - V_t$

$\boxed{\text{Id} = \text{kn} \cdot [(\text{Vgs} - \text{Vt})\text{Vds} - \text{Vds}^2/2}$
Where kn = kn' . (W/L) = gain factor



Id = kn . [(Vgs - Vt)Vds – Vds^2/2
= kn . [(1 – 0.45) 0.05 – 0.05^2/2
= kn . [0.0275 – 0.00125]

≈ 0 for Vds <= (Vgs – Vt)

Id = kn . 0.0275 → Linear or resistive region of operation

Id = <u>*kn . (Vgs – Vt)*</u> Vds → linear f(Vds)

Vgs = 0.5V, 1V, 1.5V, 2V, 2.5V
(Vgs – Vt) = 0.05V, 0.55V, 1.05V, 1.55V, 2.05V
Vds = can be sweeped from 0 to 2.05
Vt = 0.45V

$\boxed{\text{Id} = \text{kn} \cdot [(\text{Vgs} - \text{Vt})\text{Vds} - \text{Vds}^2/2}$
Where kn = kn' . (W/L) = gain factor

Question = How do we calculate Id for different values of 'Vgs' and at every value of Vgs, sweep Vds till (Vgs – Vt) using linear equation for Id ?

Id = kn . [(Vgs - Vt)Vds – Vds^2/2
= kn . [(1 – 0.45) 0.05 – 0.05^2/2
= kn . [0.0275 – 0.00125]

≈ 0 for Vds <= (Vgs – Vt)

Id = kn . 0.0275 → Linear or resistive region of operation

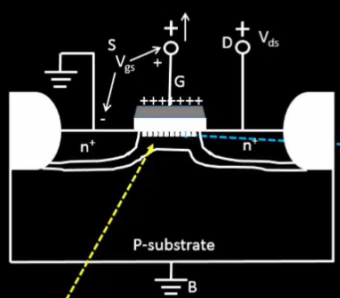
Id = <u>*kn . (Vgs – Vt)*</u> Vds → linear f(Vds)

SPICE SIMULATIONS

Vgs = 0.5V, 1V, 1.5V, 2V, 2.5V
(Vgs – Vt) = 0.05V, 0.55V, 1.05V, 1.55V, 2.05V
Vds = can be sweeped from 0 to 2.05
Vt = 0.45V

Saturation Region

Channel voltage = Vgs - Vds



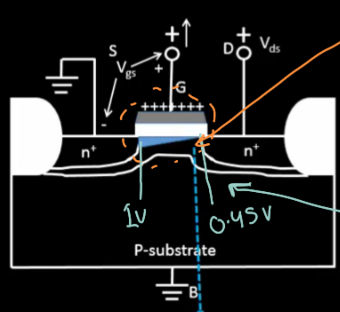
V(x) is voltage at a point 'x' along channel
Vgs – V(x) is the gate-to-channel voltage at that point.

Linear region

Vgs = 1V,
Vds = 0.05V,
Vt = 0.45V

Vgs	Vds	Vgs - Vds		Vt
1	0.05	0.95	>	0.45
1	0.15	0.85	>	0.45
1	0.25	0.75	>	0.45
1	0.35	0.65	>	0.45
1	0.45	0.55	>	0.45
1	0.55	0.45	=	0.45
1	0.65	0.35	<	0.45
1	0.75	0.25	<	0.45
1	0.85	0.15	<	0.45
1	0.95	0.05	<	0.45

Channel voltage = Vgs - Vds



Pinch off channel disappears on this point

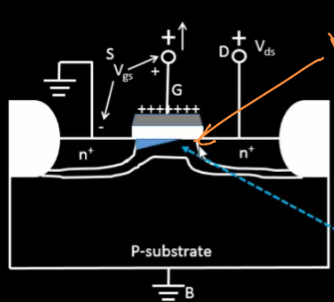
V(x) is voltage at a point 'x' along channel
Vgs – V(x) is the gate-to-channel voltage at that point.

Pinch-Off phenomenon started - channel begins to disappear

Vgs = 1V,
Vds = 0.05V,
Vt = 0.45V

Vgs	Vds	Vgs - Vds		Vt
1	0.05	0.95	>	0.45
1	0.15	0.85	>	0.45
1	0.25	0.75	>	0.45
1	0.35	0.65	>	0.45
1	0.45	0.55	>	0.45
1	0.55	0.45	=	0.45
1	0.65	0.35	<	0.45
1	0.75	0.25	<	0.45
1	0.85	0.15	<	0.45
1	0.95	0.05	<	0.45

Channel voltage = Vgs - Vds



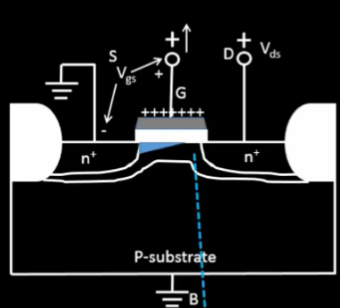
No channel at this point

V(x) is voltage at a point 'x' along channel
Vgs – V(x) is the gate-to-channel voltage at that point.

Vgs = 1V,
Vds = 0.05V,
Vt = 0.45V

Vgs	Vds	Vgs - Vds		Vt
1	0.05	0.95	>	0.45
1	0.15	0.85	>	0.45
1	0.25	0.75	>	0.45
1	0.35	0.65	>	0.45
1	0.45	0.55	>	0.45
1	0.55	0.45	=	0.45
1	0.65	0.35	<	0.45
1	0.75	0.25	<	0.45
1	0.85	0.15	<	0.45
1	0.95	0.05	<	0.45

Channel voltage = Vgs - Vds



V(x) is voltage at a point 'x' along channel
Vgs – V(x) is the gate-to-channel voltage at that point.

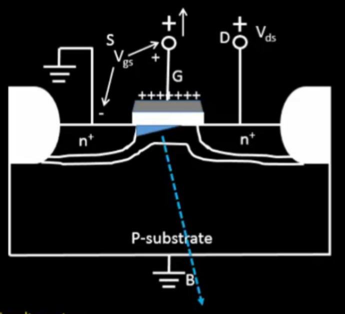
Pinch-Off region – no channel near drain region
Pinch-off condition : $\boxed{Vgs – Vds \le Vt}$

Vgs = 1V,
Vds = 0.05V,
Vt = 0.45V

Vgs	Vds	Vgs - Vds		Vt
1	0.05	0.95	>	0.45
1	0.15	0.85	>	0.45
1	0.25	0.75	>	0.45
1	0.35	0.65	>	0.45
1	0.45	0.55	>	0.45
1	0.55	0.45	=	0.45
1	0.65	0.35	<	0.45
1	0.75	0.25	<	0.45
1	0.85	0.15	<	0.45
1	0.95	0.05	<	0.45

Channel voltage = Vgs - Vds

Vgs	Vds	Vgs - Vds		Vt
1	0.05	0.95	>	0.45
1	0.15	0.85	>	0.45
1	0.25	0.75	>	0.45
1	0.35	0.65	>	0.45
1	0.45	0.55	>	0.45
1	0.55	0.45	=	0.45
1	0.65	0.35	<	0.45
1	0.75	0.25	<	0.45
1	0.85	0.15	<	0.45
1	0.95	0.05	<	0.45

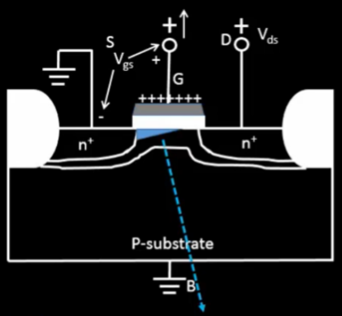


Vgs = 1V,
Vds = 0.05V,
Vt = 0.45V

V(x) is voltage at a point 'x' along channel Vgs – V(x) is the gate-to-channel voltage at that point.

Voltage over the channel remains constant = Vgs – Vt

Channel voltage = Vgs - Vds



Id = kn . [(Vgs - Vt)Vds – Vds²/2
Where kn = kn' . (W/L) = gain factor

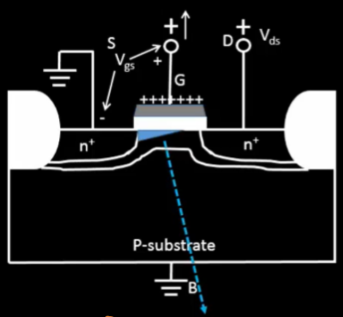
Id = kn . (Vgs – Vt) Vds → linear f(Vds)

Vgs = 1V,
Vds = 0.05V,
Vt = 0.45V

V(x) is voltage at a point 'x' along channel Vgs – V(x) is the gate-to-channel voltage at that point.

Voltage over the channel remains constant = Vgs – Vt

Channel voltage = Vgs - Vds



Id = kn . [(Vgs - Vt)(Vgs – Vt) – (Vgs – Vt)²/2
Where kn = kn' . (W/L) = gain factor

Id = kn/2 . (Vgs – Vt)² → (no more linear f(Vds))

kn = kn' . (W/L) = μn . Cox . (W/L)

$$Id = \frac{Kn'}{2} \cdot \frac{W}{L} \cdot (Vgs - Vt)^2$$

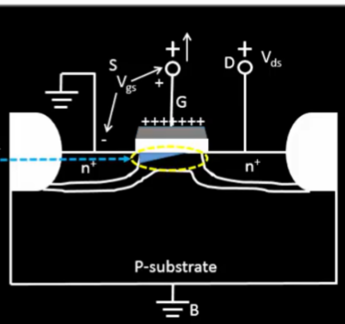
All constant. However L depends on V_{ds}

Vgs = 1V,
Vds = 0.05V,
Vt = 0.45V

V(x) is voltage at a point 'x' along channel Vgs – V(x) is the gate-to-channel voltage at that point.

Voltage over the channel remains constant = Vgs – Vt

Replace Vds by Vgs – Vt




```
Effective conductive channel length
is modulated by applied Vds
Vds↑ Depletion region at drain↑
Effective channel length↓
```

```
Looks like perfect current source
i.e current is constant.
Not 'correct'
```

$$Id = \frac{Kn'}{2} \cdot \frac{W}{L} \cdot (Vgs - Vt)^2 [1 + \lambda Vds]$$

```
More accurate equation, and λ =
channel length modulation
```