The current in MOSFETs

[Razavi, p. 15]

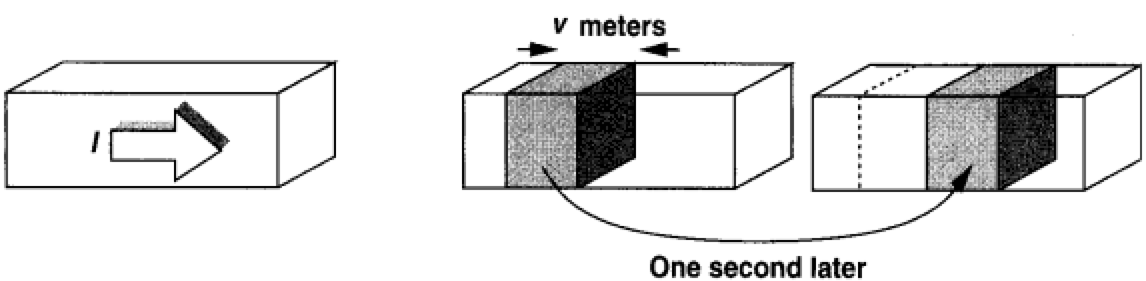
Just to begin

- In a semiconductor

$$I = Q_d \cdot v.$$

where Q_d is the linear charge density, i.e. the charge per unit length (in C/m)

  - in fact, if A is the cross section area, $J = I/A = (Q_d / A)\, v$



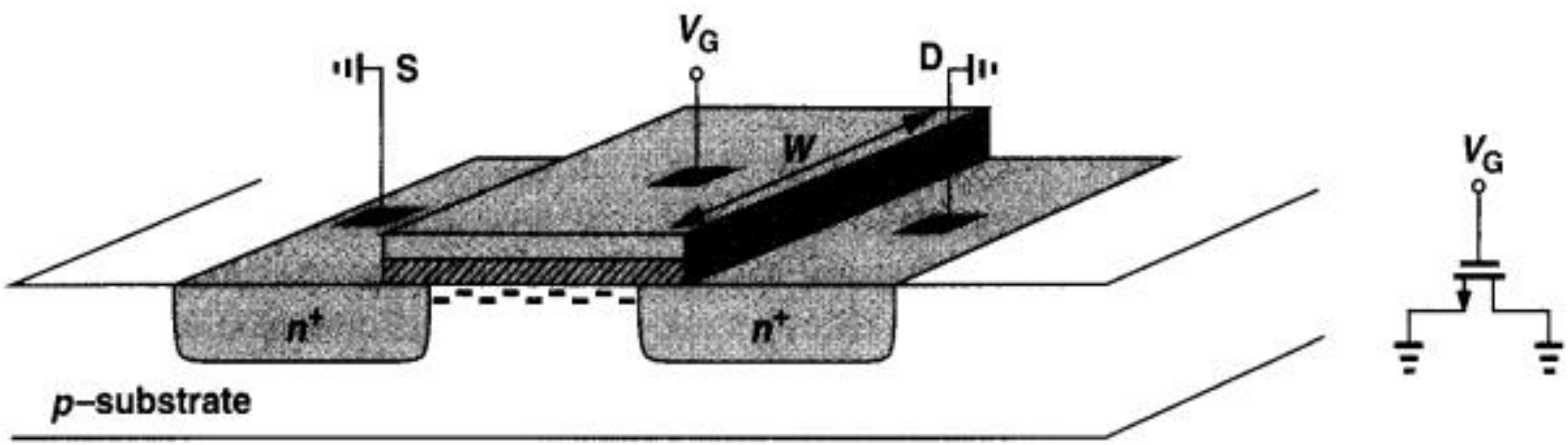
- In these slides, the threshold voltage is called V_{TH}

V_{BS}=0, 0<V_{GS}<V_{TH}, V_{DS}=0

- Holes are repelled by the positive gate => depletion layer appears below the gate

V_{BS}=0, V_{GS}=V_{TH}, V_{DS}=0

- Electrons are attracted by the gate: a thin *sheet* of electrons (the *channel*) is formed below the gate: we have the onset of *inversion*



V_{BS}=0, V_{GS}>V_{TH}, V_{DS}=0

- For $V_{GS} > V_{TH}$, when V_{GS} increases

  - the width of the depletion layer remains (approximately) constant, and so does its charge

  - the number of electrons in the channel increases: their charge will be proportional to $V_{GS} - V_{TH}$

$$Q_d = WC_{ox}(V_{GS} - V_{TH}),$$

With

Q_d : linear charge density, i.e. charge per unit length

C_{ox} : capacitance per unit area

W : channel width

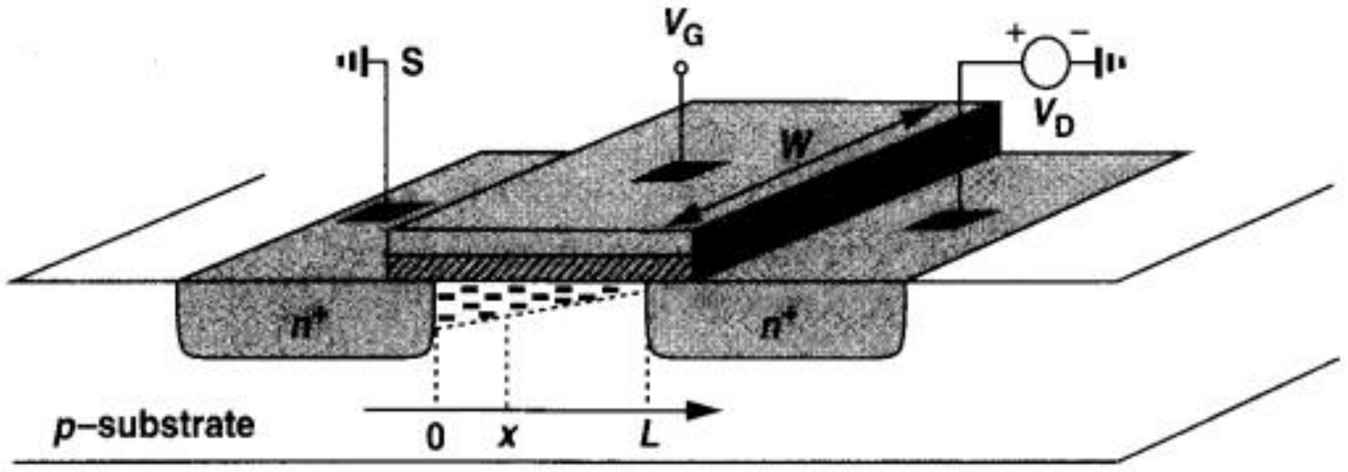
WC_{ox} : capacitance per unit length

V_{BS}=0, V_{GS}>V_T , V_{DS}>0

- In order to compute the current, we must evaluate the number of available carriers, i.e. the mobile charge
- Let *V(x)* be the potential at *x;* the potential difference between gate and channel varies along the channel
- So the charge density along the channel is

$$Q_d(x) = WC_{ox}[V_{GS} - V(x) - V_{TH}],$$

- and the current is $$I_D = -WC_{ox}[V_{GS} - V(x) - V_{TH}]v,$$



- With $v = \mu_n E$ and $E(x) = - dV/dx$

$$I_D = WC_{ox}[V_{GS} - V(x) - V_{TH}]\mu_n \frac{dV(x)}{dx},$$

- with L channel length, $V(0)=0$, and $V(L)=V_{DS}$. Then

$$\int_{x=0}^{L} I_D dx = \int_{V=0}^{V_{DS}} WC_{ox}\mu_n[V_{GS} - V(x) - V_{TH}]dV.$$

- and since I_D is constant along the channel, at the left we have just $I_D L$:

$$I_D = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_{TH})V_{DS} - \frac{1}{2} V_{DS}^2 \right]$$

- These are parabolas

- The peaks occur at

  $V_{DS}=V_{GS}-V_{TH}$

  i.e.

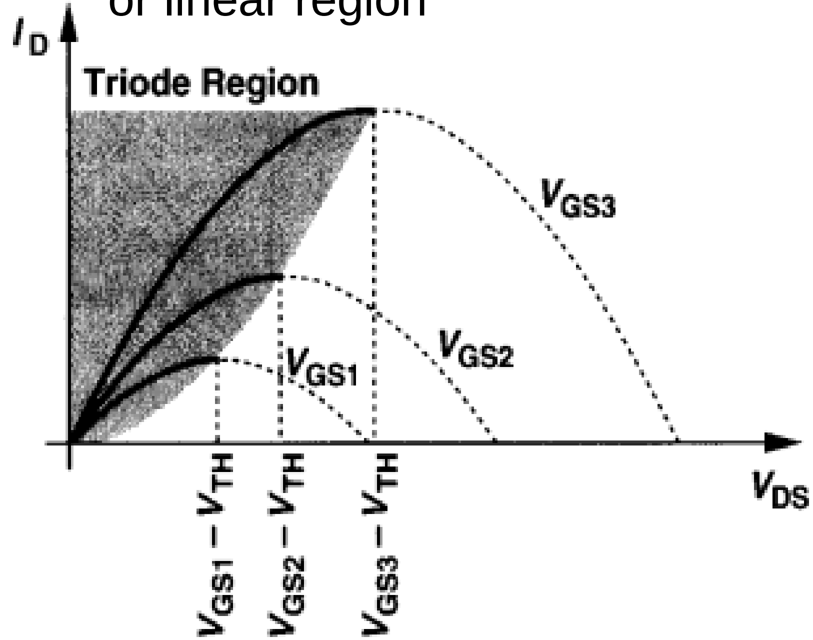
  $V_{GD}=V_{TH}$

  where the peak current is

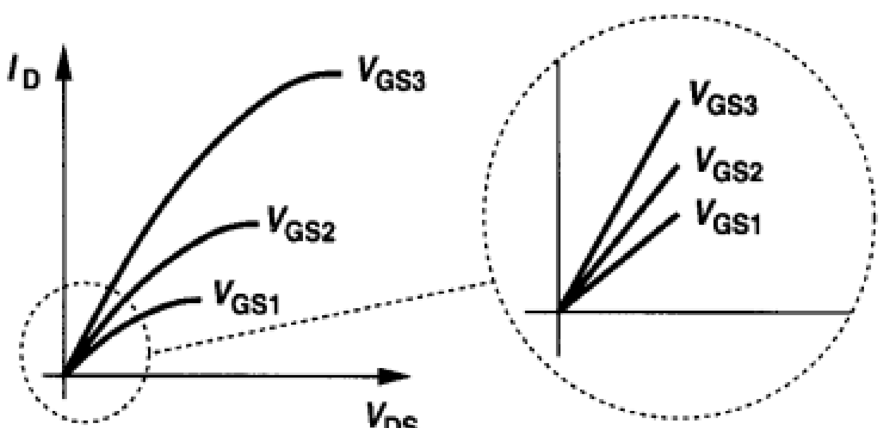
$$I_{D,max} = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})^2.$$

this is K

or linear region



- For $V_{DS}\sim 0$, I_D is almost linear: *triode*, or *linear region*



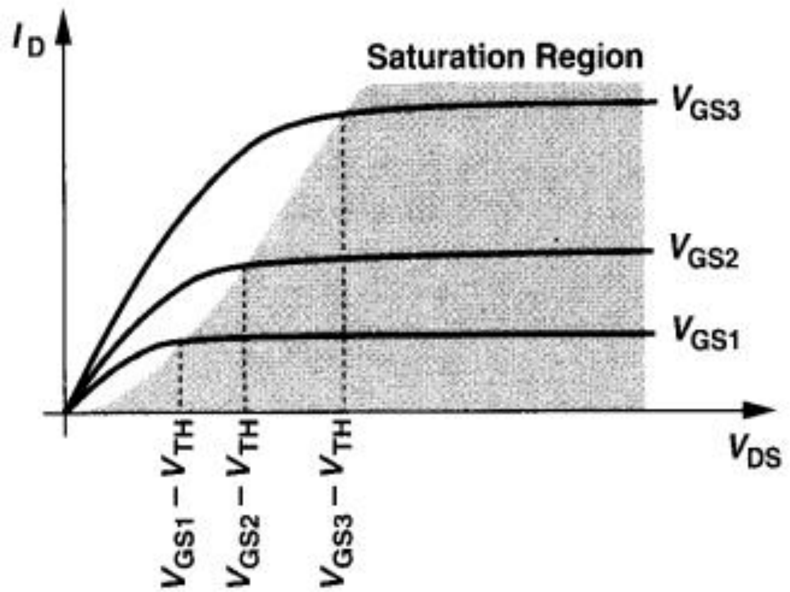
At the beginning of pinch-off

- the potential difference between the gate and the channel near the drain is not able to support the inversion:

  $V_G - V(x=L) = V_{GS} - V_{DS} = V_{GD} = V_{TH}$

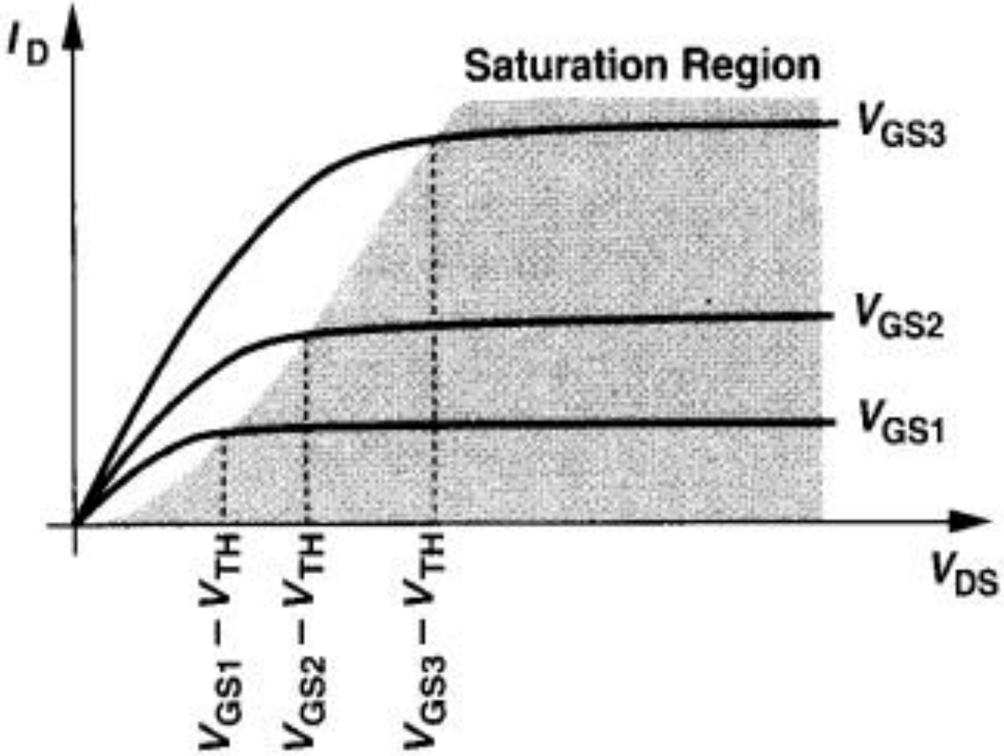
- i.e. $V_{DS} = V_{GS} - V_{TH}$
- and we get the equation of the curve which separates triode (i.e. linear) and saturation regions

  $I_D = K/2 \cdot (V_{GS} - V_{TH})^2 = K/2 \cdot V_{DS}^2$



In full pinch-off

- the current (in a first approximation) does not change with V_{DS}, so that also in saturation it holds
  $I_D = K/2 \cdot (V_{GS} - V_T)^2$



Somewhere along the channel, at $x_2 = L'$, the local potential difference is not able to support the inversion: $V_{GS} - V(x_2) = V_{TH}$

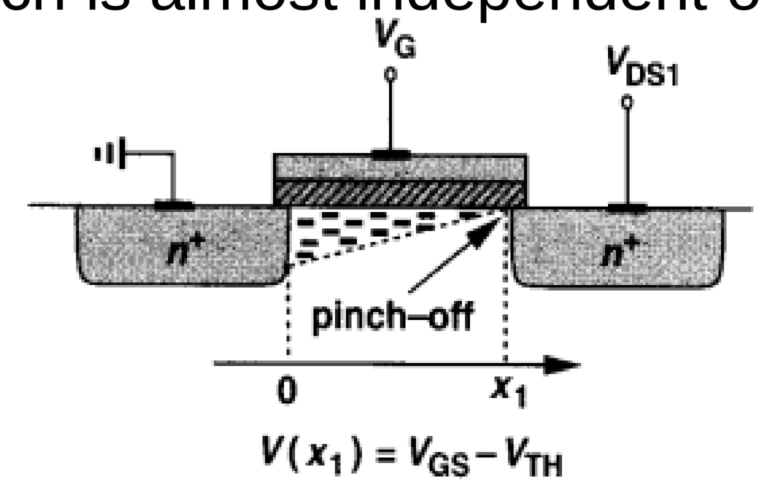
The integral

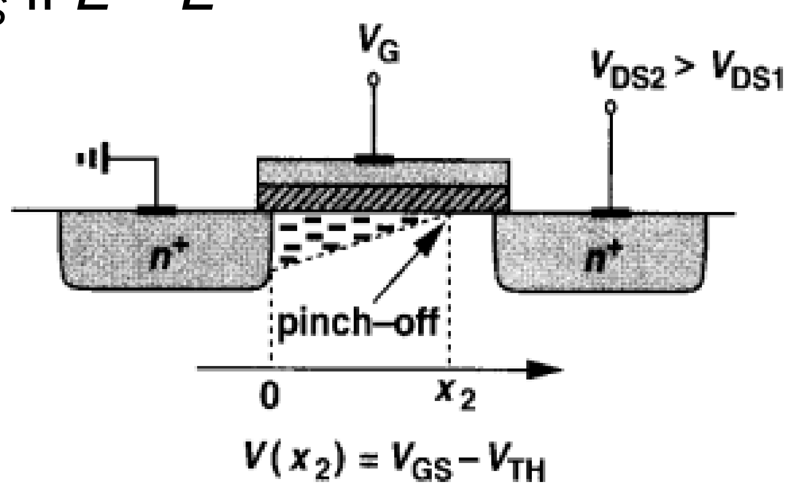
$$\int_{x=0}^{L} I_D dx = \int_{V=0}^{V_{DS}} W C_{ox} \mu_n [V_{GS} - V(x) - V_{TH}] dV.$$

must be computed from $x=0$ to $x=L'$ and from $V(x)=0$ to $V(x_2)=V_{GS} - V_{TH}$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L'} (V_{GS} - V_{TH})^2,$$

which is almost independent on V_{DS} if $L' \sim L$





- In an *enhancement* MOS, for $V_{GS} = 0$ the channel does not exist; it must be formed

  N channel: $V_{TH} > 0$,

  P channel: $V_{TH} < 0$
- In a *depletion* MOSFET, for $V_{GS} = 0$ the channel already exists; it can be depleted, or further enhanced

  N channel: $V_{TH} < 0$,

  P channel: $V_{TH} > 0$