Lecture 25 - The "Long" Metal-Oxide-Semiconductor Field-Effect Transistor

April 9, 2007

Contents:

1. Qualitative operation of the ideal MOSFET
2. Inversion layer transport
3. I-V characteristics of ideal MOSFET

Reading assignment:

del Alamo, Ch. 9, §§9.2-9.4 (9.4.1, 9.4.2)

Announcements:

Quiz 2: April 10, 7:30-9:30 PM; lectures #12-23.
Open book. *Calculator required.*

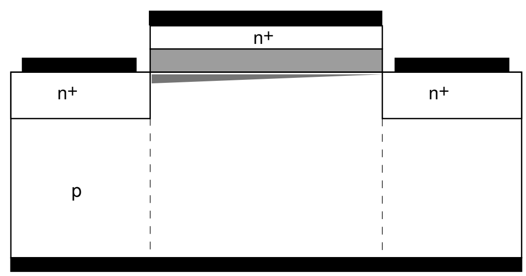
Key questions

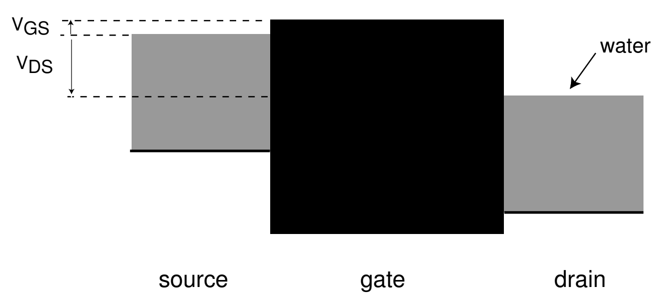
- How does lateral transport through the inversion layer take place?
- What are the most important regimes of operation of a MOSFET?
- What are the key functional dependencies of the MOSFET drain current on the gate and drain voltage?
- Why under some conditions does the drain current saturate?

1. Qualitative operation of the ideal MOSFET

Water analogy of MOSFET:

- *Source*: water reservoir
- *Drain*: water reservoir
- *Gate*: gate between source and drain reservoirs





Want to understand MOSFET operation as a function of:

- gate-to-source voltage (gate height over source water level)
- drain-to-source voltage (water level difference between reservoirs)

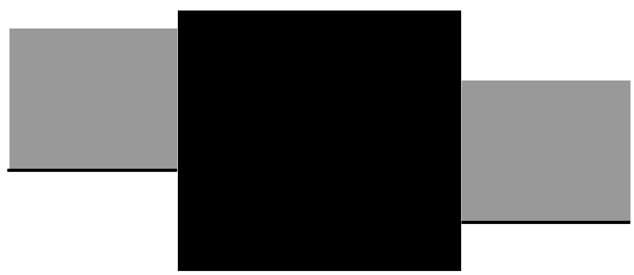
Initially consider source tied up to body (substrate or back).

Three regimes of operation:

□ *Cut-off regime*:

• MOSFET: $V_{GS} < V_T$, $V_{GD} < V_T$ with $V_{DS} > 0$.

• Water analogy: gate closed; no water can flow regardless of relative height of source and drain reservoirs.



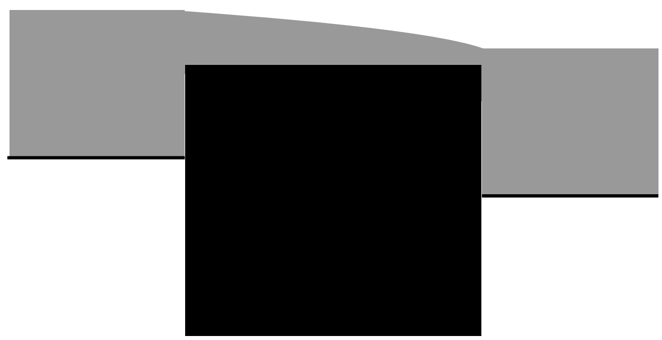
cut-off

$I_D = 0$

□ *Linear* or *Triode regime*:

• MOSFET: $V_{GS} > V_T$, $V_{GD} > V_T$, with $V_{DS} > 0$.

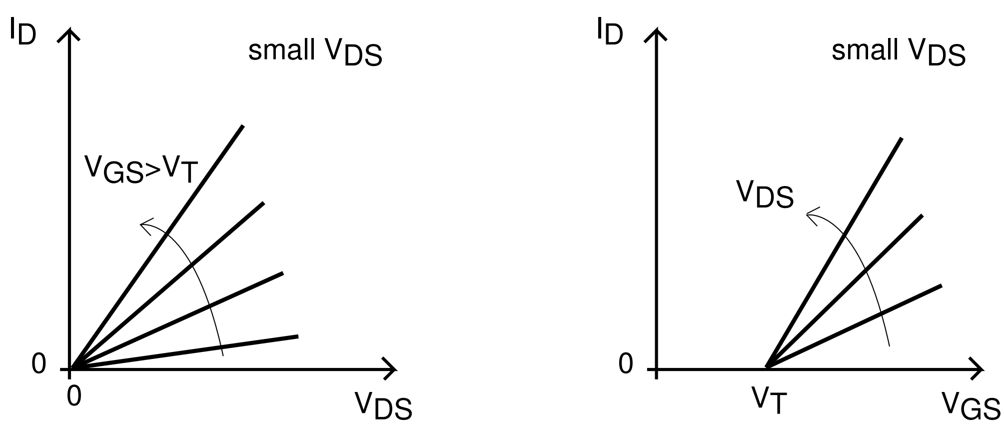
• Water analogy: gate open but small difference in height between source and drain; water flows.



Electrons drift from source to drain ⇒ electrical current!

• $V_{GS} \uparrow \rightarrow \ |Q_i| \uparrow \rightarrow \ I_D \uparrow$

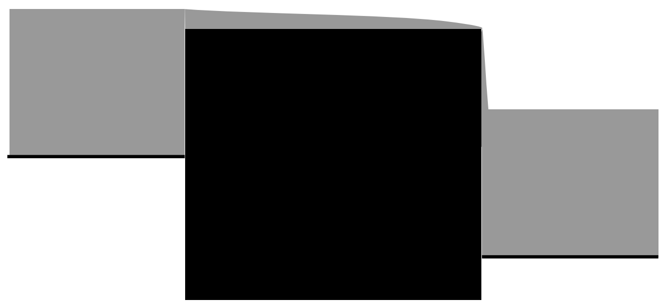
• $V_{DS} \uparrow \rightarrow \ \mathcal{E}_y \uparrow \rightarrow I_D \uparrow$



□ *Saturation regime*:

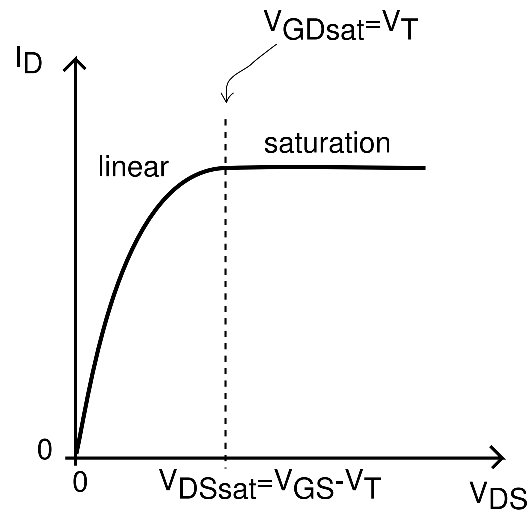
• MOSFET: $V_{GS} > V_T$, $V_{GD} < V_T$ ($V_{DS} > 0$).

• Water analogy: gate open; water flows from source to drain, but free-drop on drain side ⇒ total flow independent of relative reservoir height!



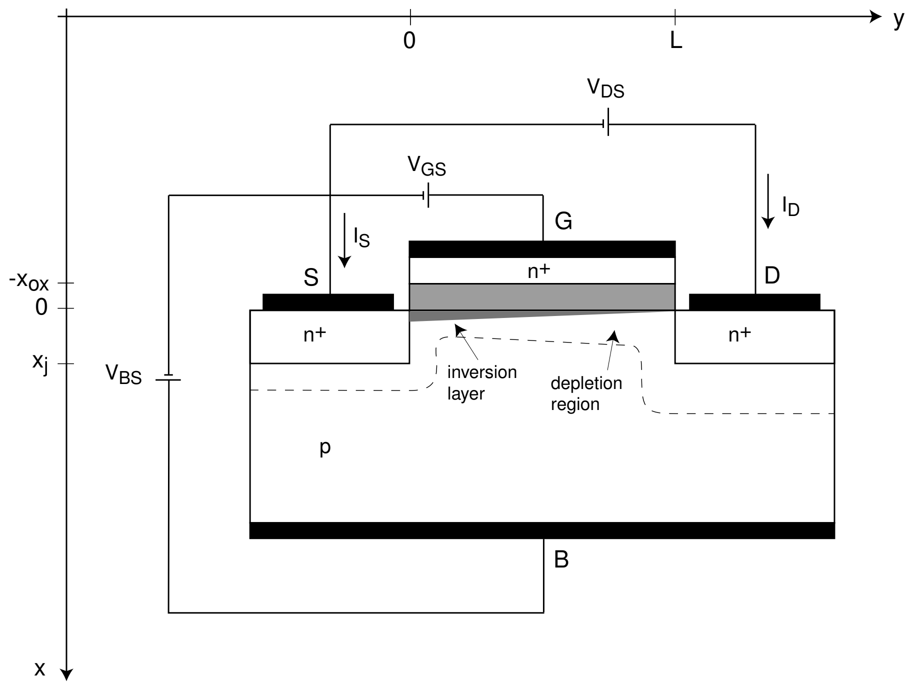
saturation

I_D independent of V_{DS}: $I_D = I_{Dsat}$



2. Inversion layer transport

Want a formalism to describe *lateral* current along inversion layer.



Not interested in details of electron distribution in *depth* (along x).

Define *sheet carrier concentration*:

$$n_s(y) = \int_0^{\infty} n(x, y)dx \qquad [cm^{-2}]$$

General expression for inversion layer current:

$$I_e \simeq -qWv_{ey}(y)n_s(y)$$

Note: I_e independent of y.

Define *sheet charge density* of inversion layer:

$$Q_i(y) = -qn_s(y) \qquad [C/cm^2]$$

Rewrite current equation:

$$I_e \simeq Wv_{ey}(y)Q_i(y)$$

We have just performed the *sheet charge approximation* (SCA).

- it is physically meaningful to define an *average* lateral velocity for all electrons in inversion layer
- SCA suitable if distribution of v_{ey} in depth does not change too rapidly in the scale of the changes that are taking place in n

Assume now mobility-limited electron drift (low lateral field) [we will undo this for the short MOSFET]:

$$v_{ey}(y) \simeq -\mu_e \mathcal{E}_y(y)$$

Then:

$$I_e \simeq -W\mu_e \mathcal{E}_y(y)Q_i(y)$$

$$I_e \simeq -W\mu_e\mathcal{E}_y(y)Q_i(y)$$

Rewrite this in terms of $V(y)$, the voltage along the inversion layer.

Definition of $V(y)$:

$$V(y) = \phi_s(y) - \phi_s(y = 0)$$

The source (located at $y = 0$) is reference for V.

Then, lateral electric field along inversion layer is:

$$\mathcal{E}_y(y) = -\frac{dV(y)}{dy}|_y$$

Insert this in current equation:

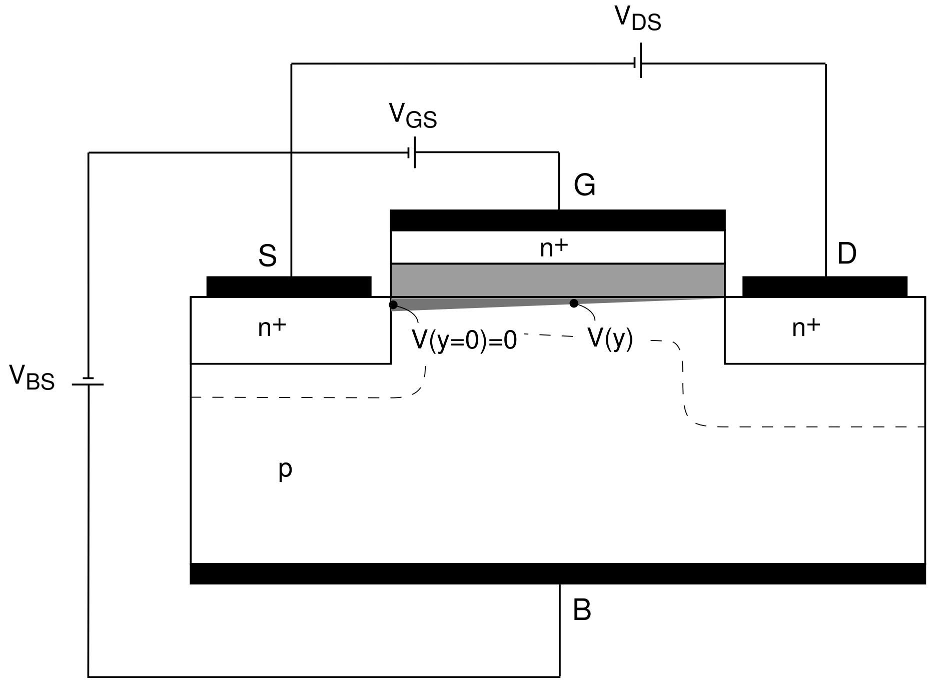
$$I_e = W\mu_e Q_i(y)\frac{dV(y)}{dy}|_y$$

Now need to relate $Q_i(y)$ with $V(y)$.

Remember fundamental charge-control relationship for inversion layer in two-terminal MOS structure:

$$Q_i = -C_{ox}(V_G - V_T)$$

In MOSFET, this equation only applies at source end, where $V(0) = 0$.



For rest of the channel, reuse this relationship accounting for local potential drop:

$$Q_i(y) \simeq -C_{ox}[V_{GS} - V(y) - V_T]$$

Q_i depends on y through local inversion layer voltage $V(y)$.

This is called the *gradual-channel approximation* (GCA).

GCA allows break up of 2D electrostatics problem into two simpler quasi-1D problems:

- vertical electrostatics control inversion layer charge,
- lateral electrostatics control lateral flow of charge.

Note: V_T is function of y through body effect [will examine implications later].

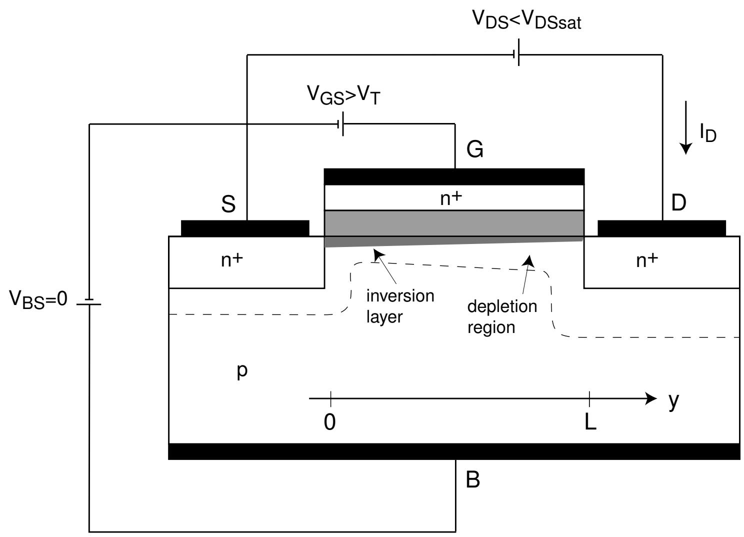
Under GCA, current equation becomes:

$$I_e = -W\mu_e C_{ox}[V_{GS} - V(y) - V_T]\frac{dV(y)}{dy}|_y$$

First-order differential equation in terms of $V(y)$.

3. I-V characteristics of ideal MOSFET

□ Consider MOSFET in *linear regime* ($V_{GS} > V_T, V_{GD} > V_T$):



Inversion layer everywhere under gate. Lateral field set up along channel → current flows.

Electrons drift from source to drain ⇒ electrical current!

- $V_{GS} \uparrow \rightarrow\ |Q_i| \uparrow \rightarrow\ I_D \uparrow$
- $V_{DS} \uparrow \rightarrow\ \mathcal{E}_y \uparrow \rightarrow I_D \uparrow$

Also called *triode* regime.

Develop first-order model.

Separate variables:

$$I_e dy = -W\mu_e C_{ox}(V_{GS} - V - V_T)dV$$

Integrate from $y = 0$ ($V = 0$) to $y = L$ ($V = V_{DS}$):

$$I_e \int_0^L dy = -W\mu_e C_{ox} \int_0^{V_{DS}} (V_{GS} - V - V_T)dV$$

To get:

$$I_e = -\frac{W}{L}\mu_e C_{ox}(V_{GS} - \frac{1}{2}V_{DS} - V_T)V_{DS}$$

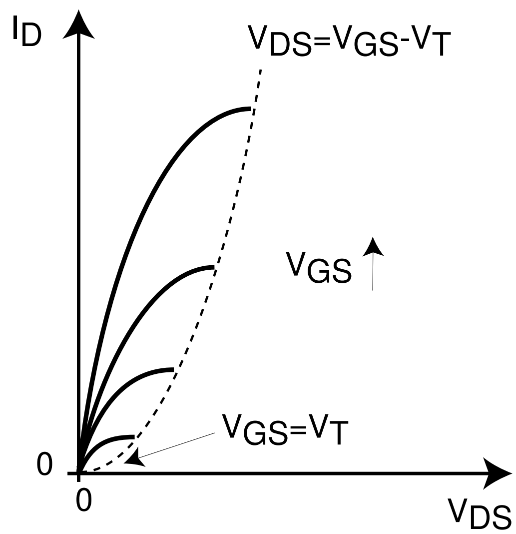
Terminal drain current:

$$I_D = -I_e = \frac{W}{L}\mu_e C_{ox}(V_{GS} - V_T - \frac{1}{2}V_{DS})V_{DS}$$

Result valid as long as strong inversion prevails in all points of channel. Worst point: $y = L$, for which:

$$Q_i(y = L) = -C_{ox}(V_{GS} - V_{DS} - V_T)$$

Therefore, need $V_{DS} < V_{GS} - V_T$, or $V_{GD} > V_T$.

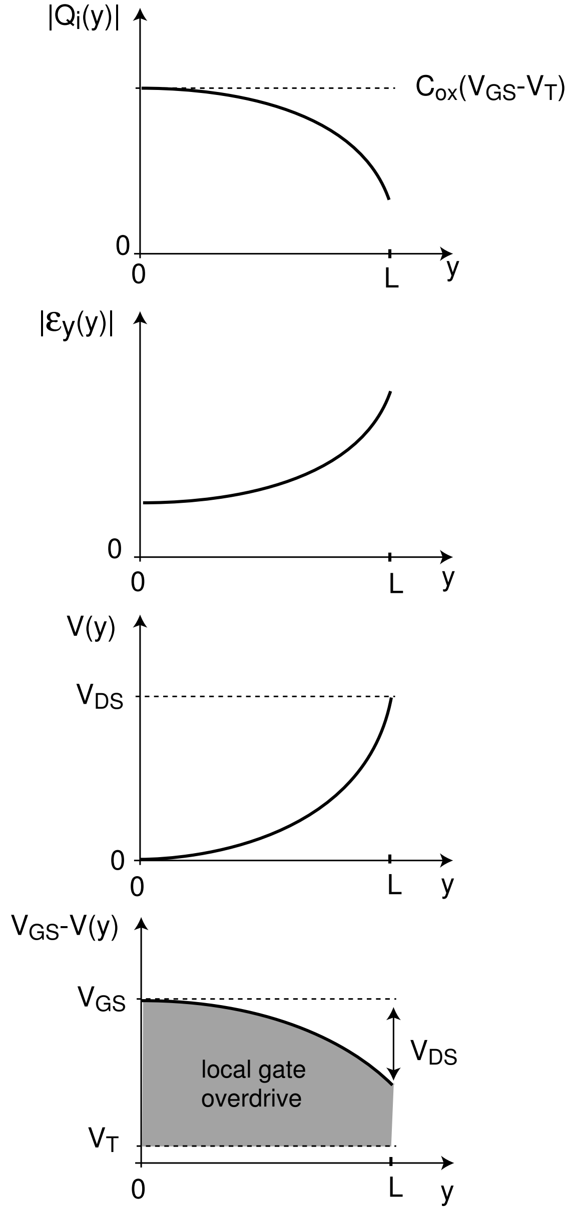


$$I_D = \frac{W}{L}\mu_e C_{ox}(V_{GS} - V_T - \frac{1}{2}V_{DS})V_{DS}$$

Key dependences of I_D in linear regime:

- $V_{DS} = 0 \;\Rightarrow\; I_D = 0$ for all V_{GS}.
- For $V_{GS} > V_T$: $V_{DS} \uparrow \Rightarrow\; I_D \uparrow$ (but eventually I_D saturates).
- For $V_{DS} > 0$ and $V_{GS} > V_T$: $V_{GS} \uparrow \Rightarrow\; I_D \uparrow$.
- For $V_{GS} = V_T \;\Rightarrow\; I_D = 0$

Study lateral electrostatics:

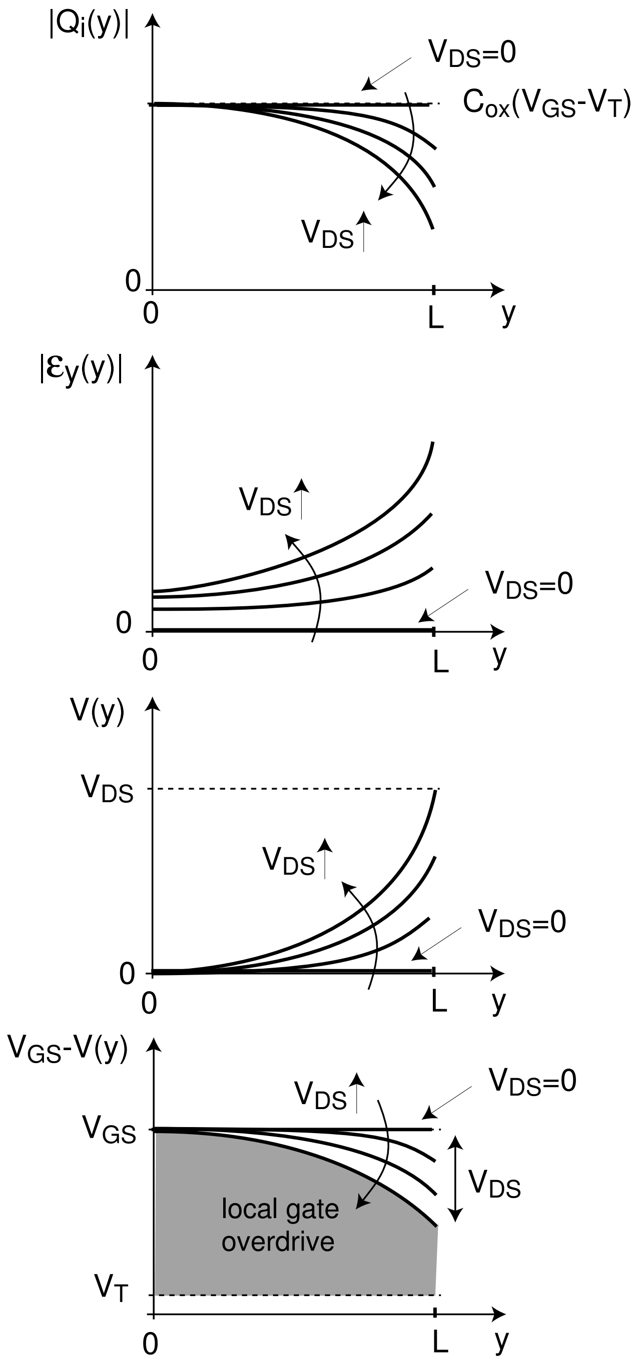


Along channel from source to drain:

$$V \uparrow \Rightarrow \; V_{GS} - V(y) - V_T \downarrow \Rightarrow \; |Q_i| \downarrow \Rightarrow \; |\mathcal{E}_y(x=0)| \uparrow$$

Local overdrive on gate reduced the closer to the drain.

Impact of V_{DS}:



As V_{DS} ↑ channel debiasing more prominent.

Channel debiasing results in current saturation.

Go back to fundamental current equation:

$$I_e \simeq W v_{ey}(y) Q_i(y)$$

At the source end:

$$I_e \simeq W v_{ey}(0) Q_i(0)$$

- Q_i at source end is set entirely by V_{GS}:

  $$Q_i(0) = -C_{ox}(V_G - V_T)$$

  Q_i is independent of what happens down the channel.

- V_{DS} dependence in current equation comes entirely from $v_{ey}(0)$. In mobility regime:

  $$v_{ey}(0) \simeq -\mu_e \mathcal{E}_y(0)$$

  At high V_{DS}, channel debiasing implies that the rise of $\mathcal{E}_y(0)$ with V_{DS} slows down and eventually, it does not increase anymore.

Key conclusions

- *Sheet-charge approximation*: inversion layer very thin in scale of vertical dimensions ⇒ current formulation in terms of Q_i.
- *Gradual-channel approximation*: electric field changes relatively slowly along channel ⇒ GCA breaks 2D electrostatics problem into two quasi-1D problems:
  - vertical electrostatics control inversion layer charge
  - lateral electrostatics control lateral flow of charge
- Consequence of GCA: local inversion layer sheet-charge density:

$$Q_i(y) \simeq -C_{ox}[V_{GS} - V(y) - V_T]$$

- In linear regime, I_D modulated by V_{GS} and V_{DS}:
  - V_{GS}, to first order, controlles electron concentration in channel
  - V_{DS}, to first order, controlles lateral electric field in channel
- MOSFET current in linear regime:

$$I_D = \frac{W}{L}\mu_e C_{ox}(V_{GS} - V_T - \frac{1}{2}V_{DS})V_{DS}$$