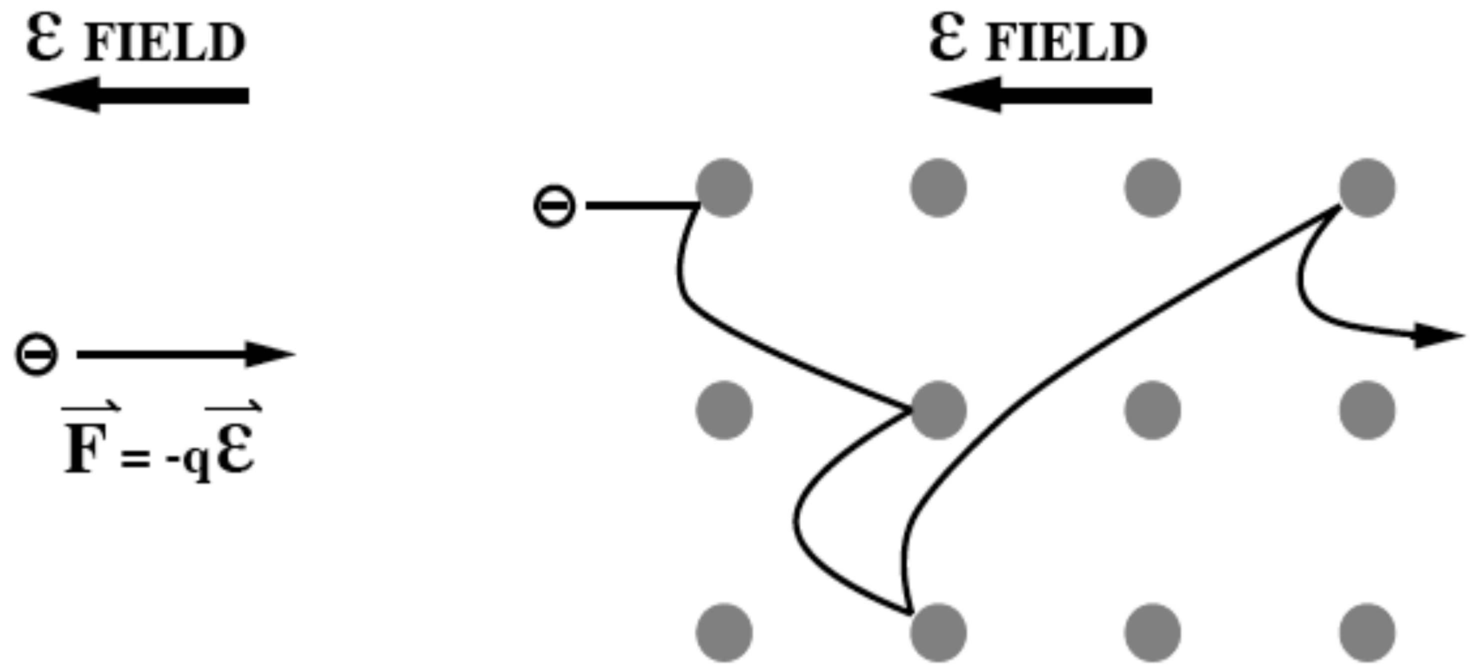
Studio 2 Review

- **Motion of carriers in semiconductor: Mobility μ**
- **Channel: Accumulation, Depletion, Inversion**
- **Threshold voltage V_{TH}**
- **Gate-source overdrive voltage V_{GS}-V_{TH}**
- **V-I characteristic of MOSFET channel**
  Small V_{DS}: D-S channel looks like resistance R_{on}
- **Overdrive voltage V_{GS}-V_{TH}**
  controls R_{on} resistance
- **Lab exercise: extract V_{TH}, mobility μ**
- **Text: Razavi sec. 2.1, 2.2, 2.3**
  J&M Sec 1.2, 1.7

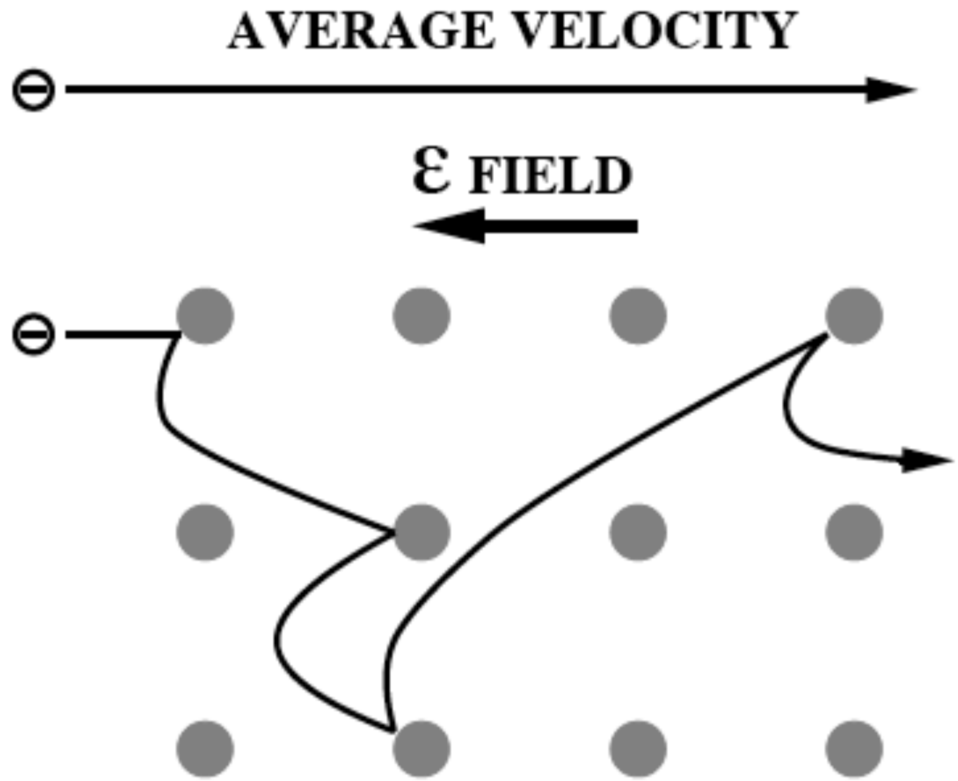
Motion of carriers due to electric field

Free Space **Semiconductor Lattice**

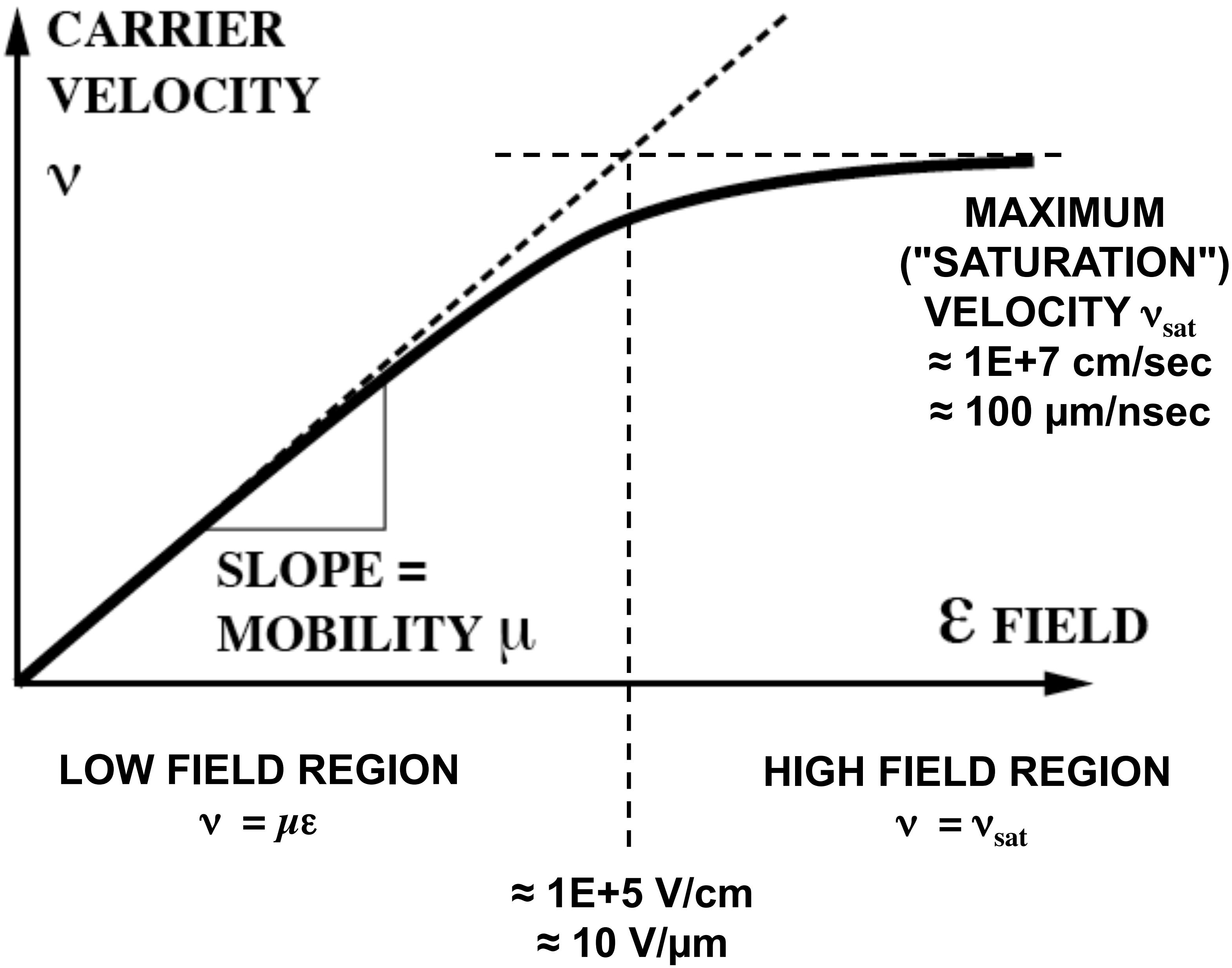


Mobility

- **Velocity with collisions "averaged out"**



Mobility: Units, typical Values



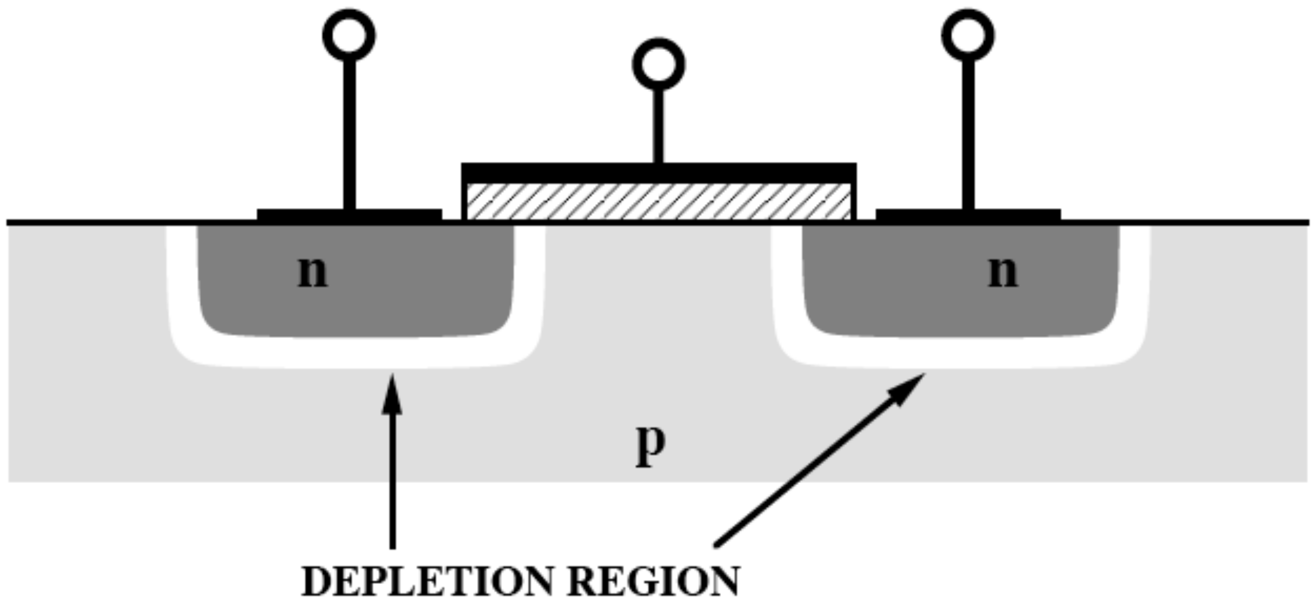
Mobility: Units, Typical Values

- $\nu = \mu \varepsilon \Rightarrow \mu = \nu / \varepsilon \Rightarrow$ cm^2/V•sec
- **Surface mobility:**
  e- $\mu_n \approx 600$ **cm^2/V•sec**
  hole $\mu_p \approx 200$ **cm^2/V•sec**

- **Velocity saturation important for short (<1μm) channel MOSFETs (see Razavi sec. 16.2)**

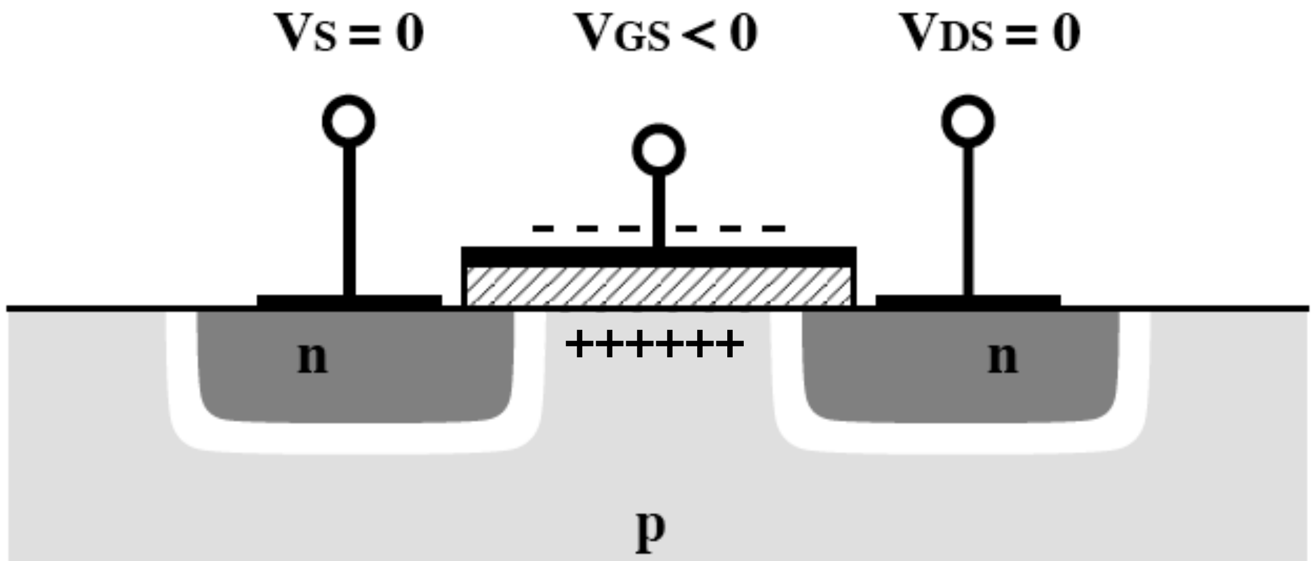
Channel $V_{GS} = 0$

- **N-channel MOSFET**



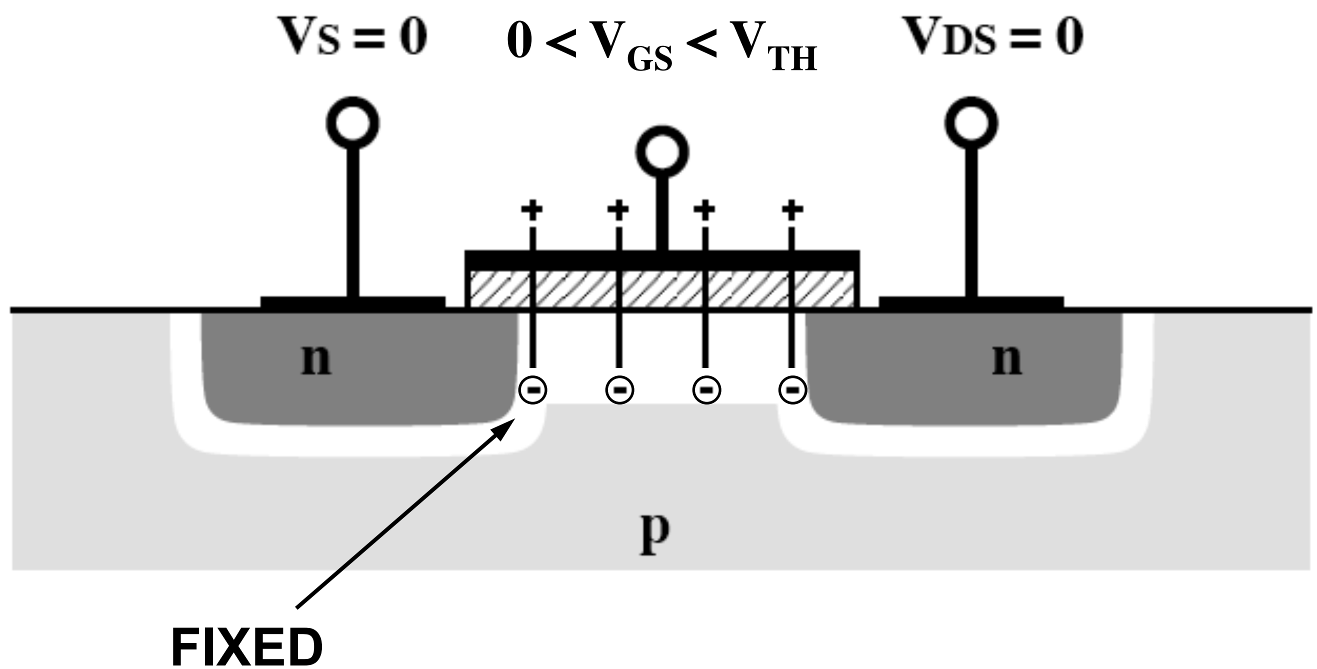
Channel $V_{GS} < 0$: Accumulation

- **Accumulate excess holes at surface**
- **Channel even more p-type: "wrong way"**



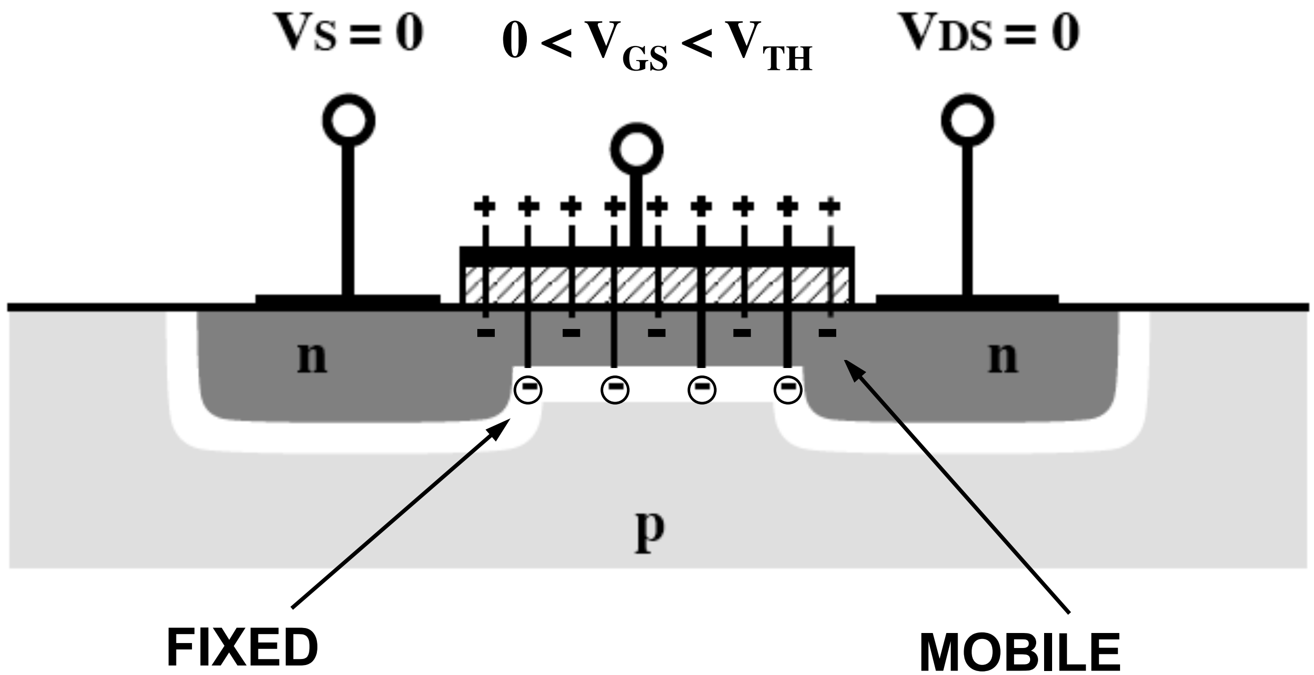
Channel $0 < V_{GS} < V_{TH}$: Depletion

- **Push mobile holes away: channel depleted**
- **Field lines from gate charges terminate on fixed charge**



Channel $V_{GS} > V_{TH}$ Inversion

- **Field from gate attracts mobile electrons**
- **Field lines from "new" gate charges terminate on <u>mobile charge in channel</u>**



Threshold Voltage V_{TH}

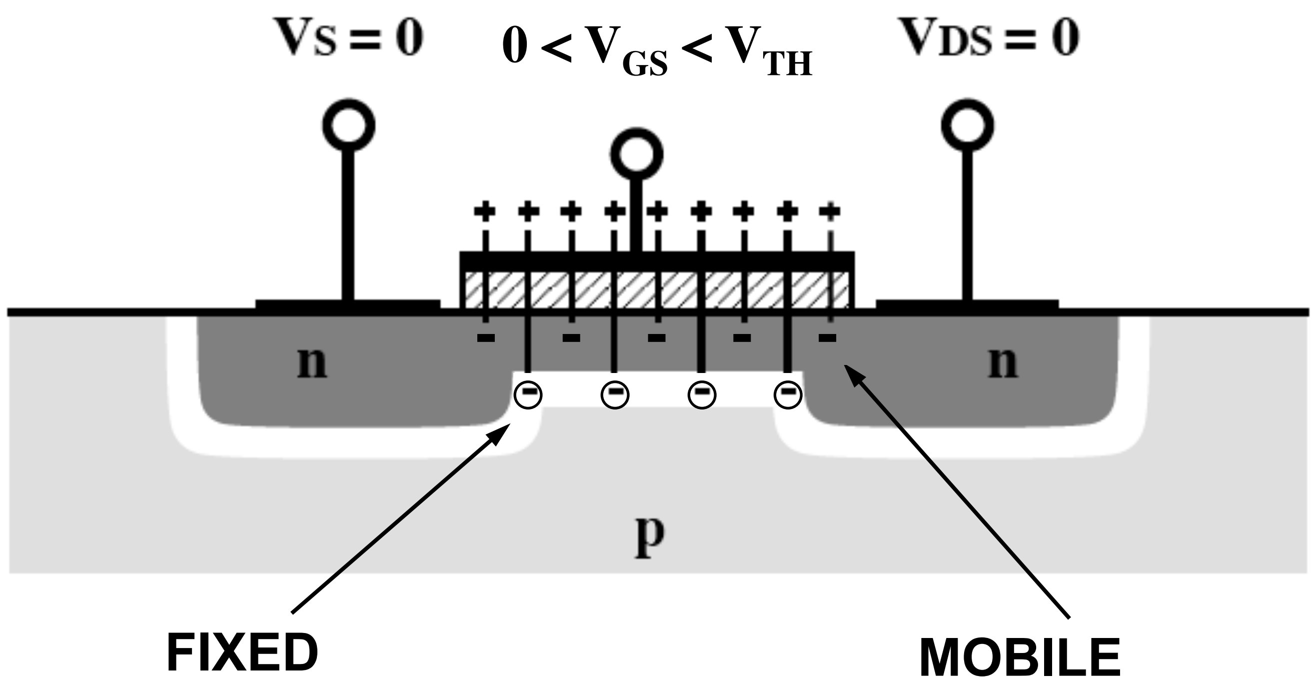
- **Value of V_{GS} for which carrier concentration in inverted channel equals "other" carrier concentration in substrate**
- **Arbitrary "dividing line" between channel**

$$\text{OFF } I_D = 0 \;\Leftrightarrow\; \text{ON } I_D > 0$$

- **Actually I_D shows smooth transition through "subthreshold" region near V_{TH}**

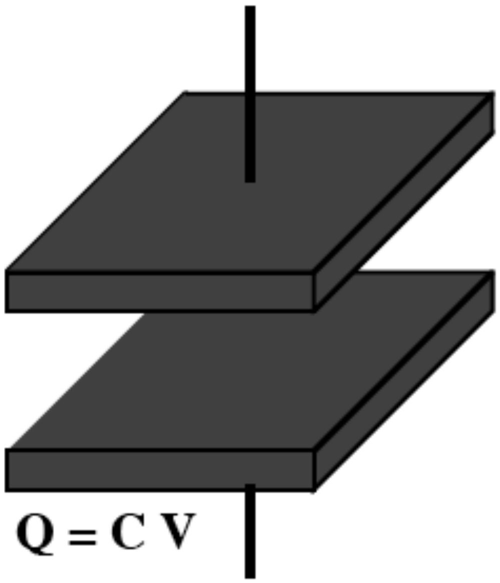
How much mobile charge in channel?

- Only V_{GS} beyond V_{TH} provides mobile charge
- V_{GS} - V_{TH} Gate-source overdrive voltage



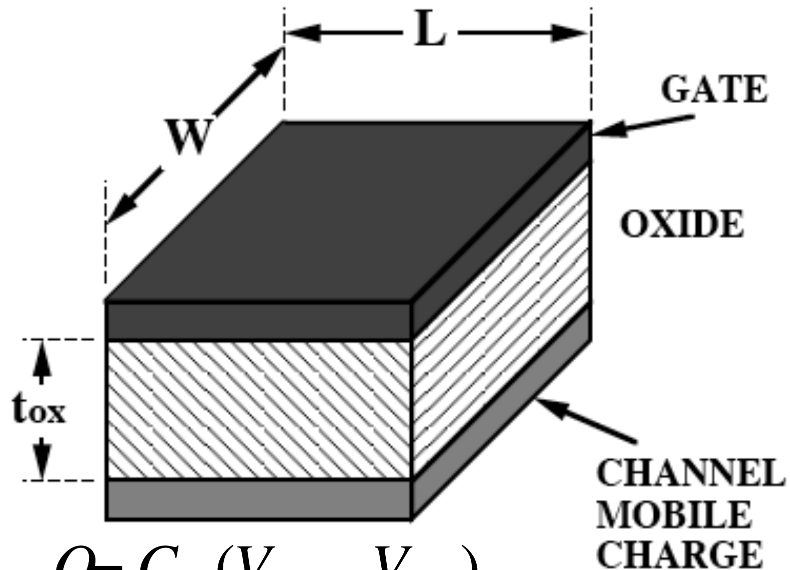
How much mobile charge in channel?

Ideal parallel plate capacitor



Q = C V

MOSFET gate capacitor



$$Q = C_{gs}(V_{GS} - V_{TH})$$

How much mobile charge in channel?

$$Q = C_{gs}(V_{GS} - V_{TH}) \qquad [2\text{-}1]$$

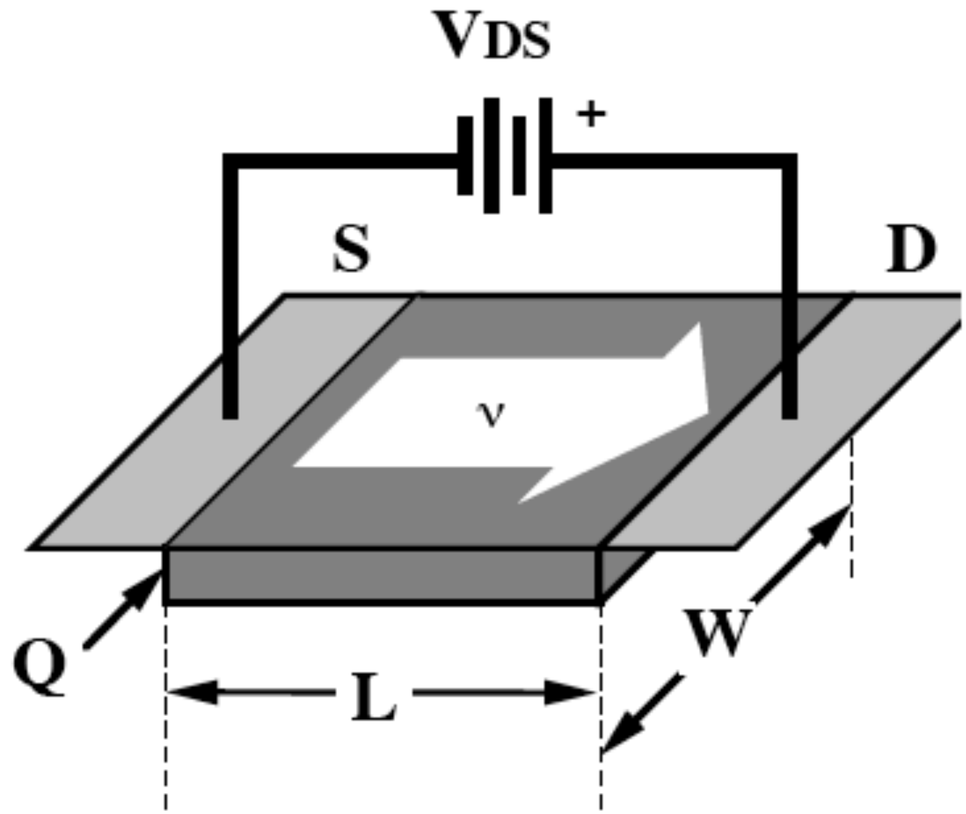
$$C_{gs} = \frac{\varepsilon\ A}{d} = \frac{\overbrace{K_{ox}\varepsilon_0}^{\varepsilon}\overbrace{WL}^{A}}{\underbrace{t_{ox}}_{d}} = \underbrace{\frac{K_{ox}\varepsilon_0}{t_{ox}}}_{C_{ox}} WL = C_{ox}WL \qquad [2\text{-}2]$$

- **C_{ox}: oxide capacitance per unit area**
  - **Fixed by process (oxide thickness t_{ox})**
- **WL: geometry**
  - **Can be controlled by designer**

$$Q = C_{ox}WL(V_{GS} - V_{TH}) \qquad [2\text{-}3]$$

Apply small V_{DS}

- **Horizontal component to ε field**
  - **Move carriers from source to drain**



Apply small V_{DS}

- Moving charge = current! How much?

Strategy:

- Start simple: DC current

  $I_D = \Delta Q / \Delta T$ [2-4]

- ΔQ charge in channel (from [2-3])

  $\Delta Q = C_{ox} WL (V_{GS} - V_{TH})$ [2-5]

- ΔT time for all of charge to move out
  - time for "last" charge to move distance L length of channel

ΔT Calculation

- **Velocity** $$\upsilon = \frac{L}{\Delta T} \Rightarrow \Delta T = \frac{L}{\upsilon} \quad [2\text{-}6]$$

- **From mobility definition** $$\upsilon = \mu_n \mathcal{E} \quad [2\text{-}7]$$

- **Field has units V/cm** $$\mathcal{E} = \frac{V_{DS}}{L} \quad [2\text{-}8]$$

- **Substitute [2-8] into [2-7]** $$\upsilon = \frac{\mu_n V_{DS}}{L} \quad [2\text{-}9]$$

- **Substitute [2-9] into [2-6]** $$\Delta T = \frac{L^2}{\mu_n V_{DS}} \quad [2\text{-}10]$$

Drain current expression

- **Substitute [2-10] into [2-4]**

$$I_D = C_{ox}WL\left(V_{GS} - V_{TH}\right)\frac{\mu_n V_{DS}}{L^2} \quad [2\text{-}11]$$

- **Massage**

$$I_D = \left(\mu_n C_{ox}\frac{W}{L}\left(V_{GS} - V_{TH}\right)\right)V_{DS} \quad [2\text{-}12]$$

- **Drain current proportional to drain voltage: Resistor!**

$$\boxed{R_{on} = \frac{V_{DS}}{I_D} = \frac{1}{\mu_n C_{ox}\frac{W}{L}\left(V_{GS} - V_{TH}\right)}} \quad [2\text{-}13]$$

- **Controlled by overdrive voltage V_{GS}-V_{TH}**

MOSFET functions

- **Analog switch (n-channel)**

  $V_{GS} < V_{TH}$ off

  $V_{GS} > V_{TH}$ on
  (R_{on} determined by gate overdrive V_{GS} - V_{TH})
- **Digital switch**
- **Resistor**
  - **Value of resistance looking into drain controlled by gate overdrive V_{GS} - V_{TH}**
- **Caution: requires V_{DS} small**
  - **Increase in V_{DS} changes charge distribution in channel**
- **How small is small???...**

Summary

- **Mobility: Carrier velocity proportional to E field**
- **Two steps to current through drain-source channel:**

1) Vertical field from gate V_G "inverts" channel

Charge in channel available to move

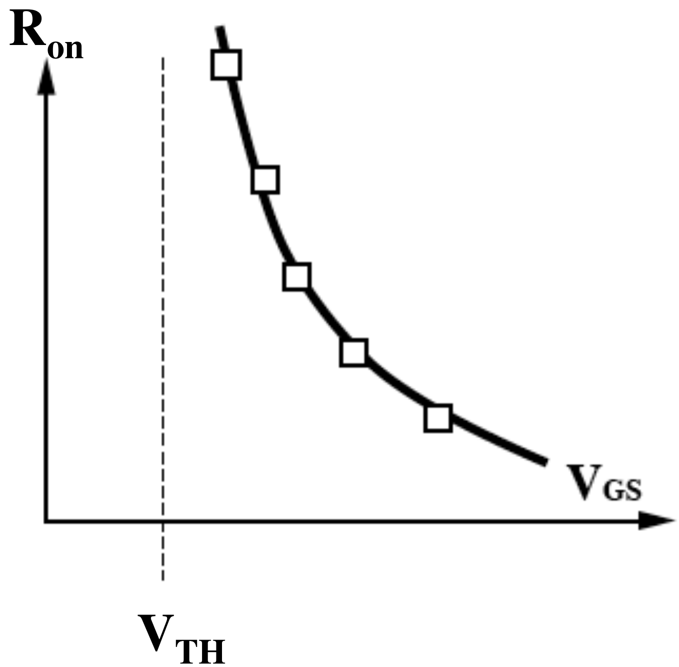
2) Horizontal field from V_{DS} moves charge

Drain-source channel "looks" resistive for small V_{DS}

- **Gate-source overdrive voltage V_{GS}-V_{TH}**
  - **Only gate voltage "beyond" threshold voltage V_{TH} corresponds to mobile charge in channel**
  - **Overdrive voltage V_{GS}-V_{TH} controls D-S channel resistance R_{on}**

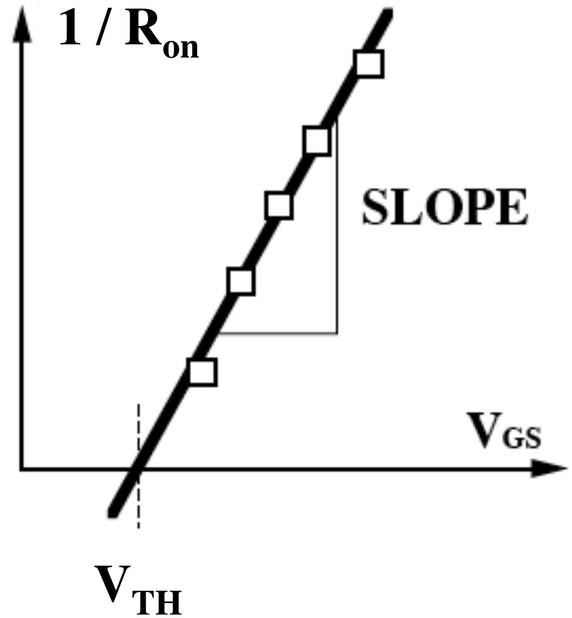
Lab exercise

Plot R_{on} vs V_{GS}



$$R_{on} = \frac{1}{\mu_n C_{ox} \frac{W}{L} \left(V_{GS} - V_{TH}\right)}$$

Plot $1/R_{on}$ vs V_{GS}



$$\frac{1}{R_{on}} = \underbrace{\left[\mu_n C_{ox} \frac{W}{L}\right]}_{SLOPE} \left(V_{GS} - V_{TH}\right)$$