Lecture #16

OUTLINE

- MOSFET I_D *vs.* V_{GS} characteristic
- Circuit models for the MOSFET
  - resistive switch model
  - small-signal model

Reading

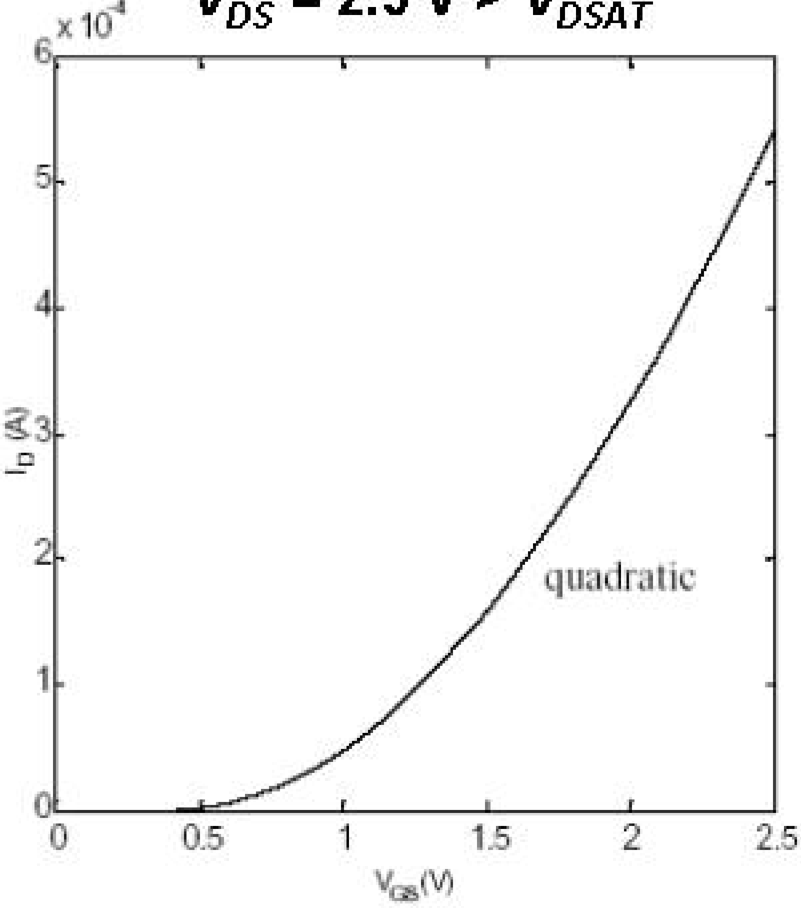
- **Rabaey *et al.*:** Chapter 3.3.2

MOSFET I_D vs. V_{GS} Characteristic

- Typically, V_{DS} is fixed when I_D is plotted as a function of V_{GS}

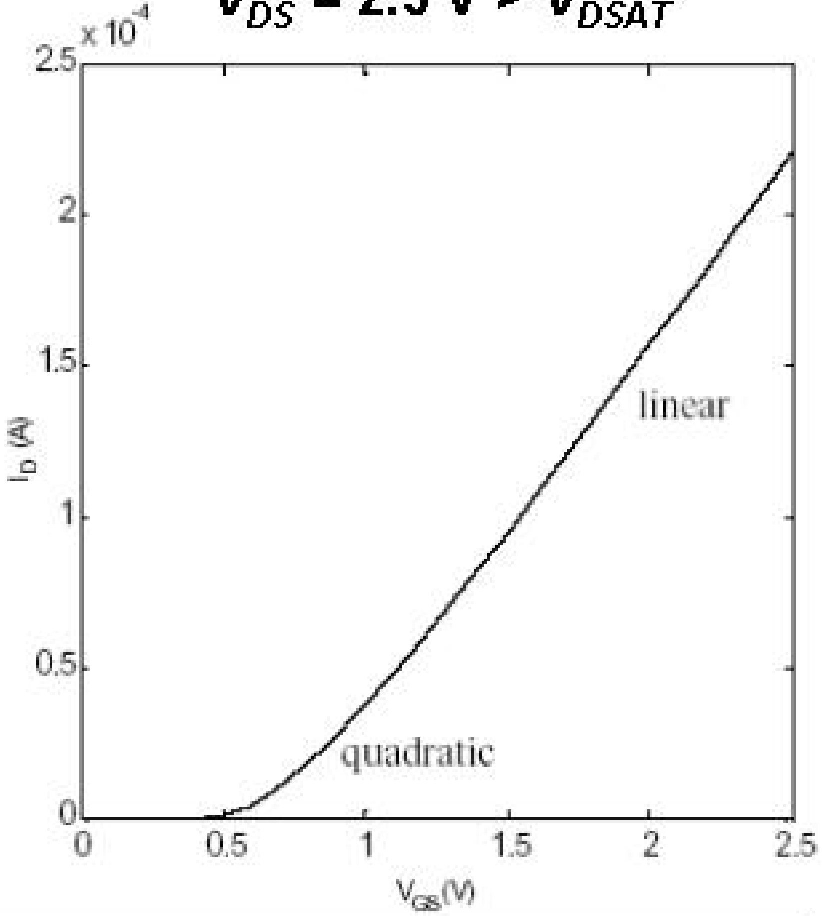
Long-channel MOSFET

V_{DS} = 2.5 V > V_{DSAT}



Short-channel MOSFET

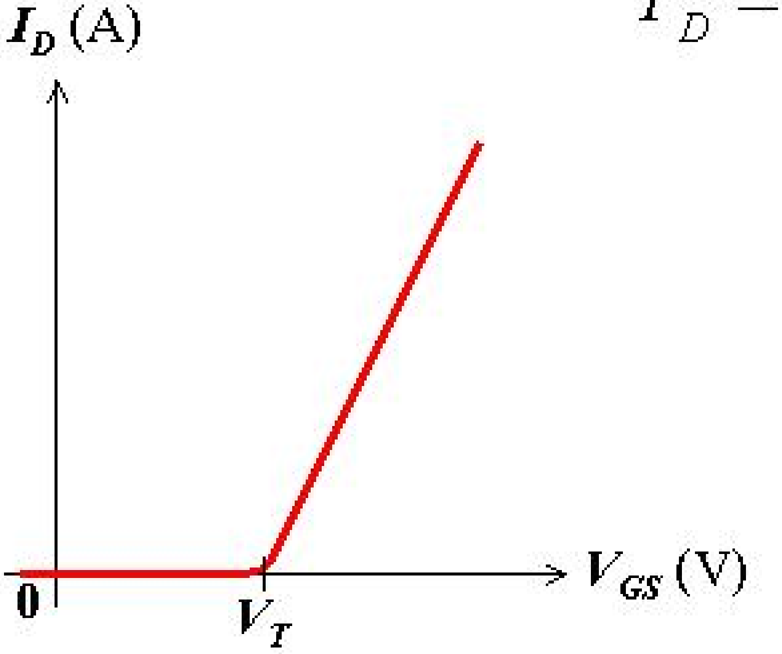
V_{DS} = 2.5 V > V_{DSAT}



MOSFET V_T Measurement

- V_T can be determined by plotting I_D vs. V_{GS}, using a low value of V_{DS} :

$$I_D = k_n' \frac{W}{L}\left[V_{GS} - V_T - \frac{V_{DS}}{2}\right]V_{DS}$$



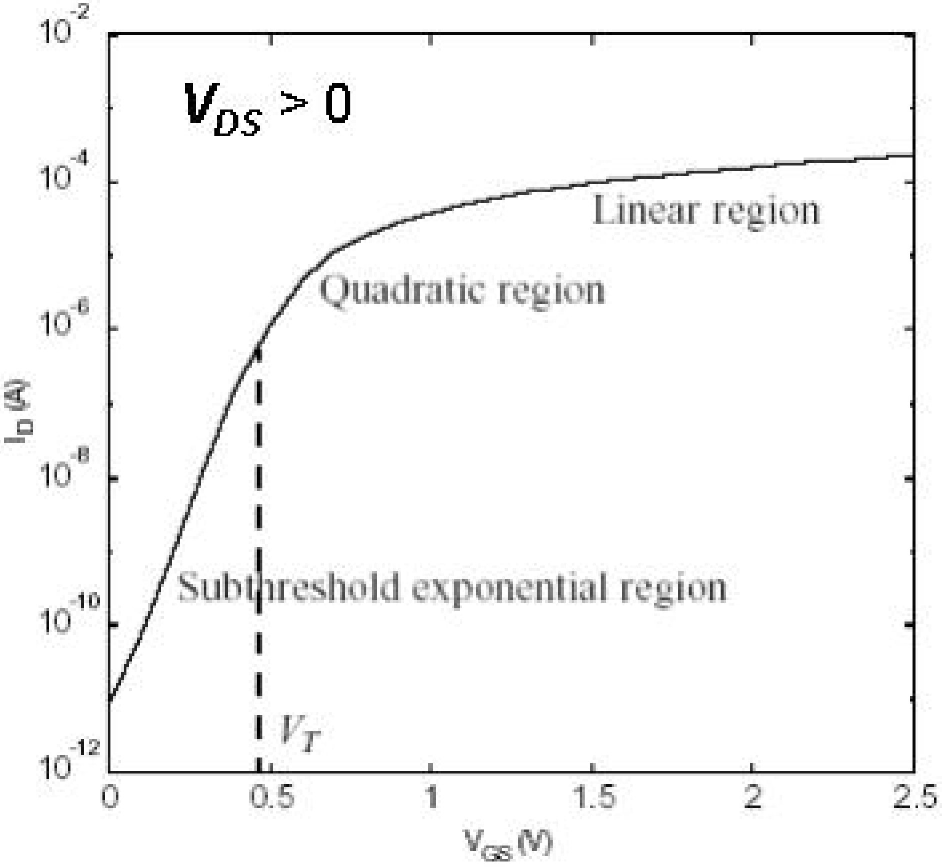
Subthreshold Conduction (Leakage Current)

- The transition from the ON state to the OFF state is gradual. This can be seen more clearly when I_D is plotted on a logarithmic scale:

- In the subthreshold ($V_{GS} < V_T$) region,

$$I_D \propto \exp\left(\frac{qV_{GS}}{nkT}\right)$$

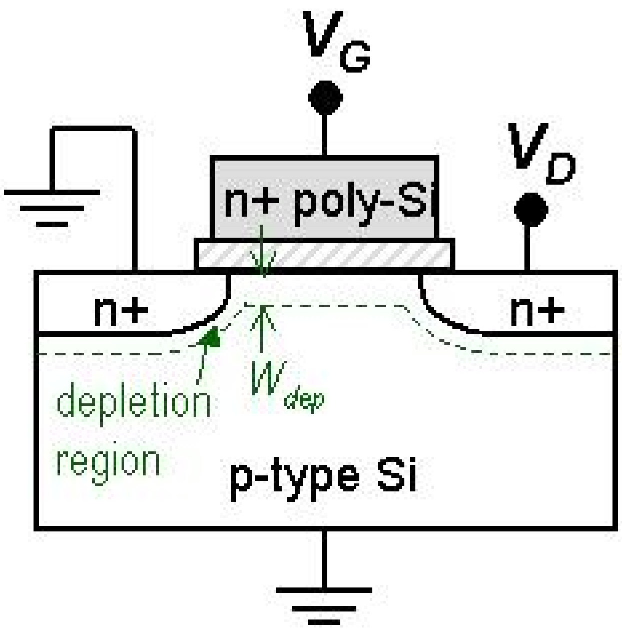
This is essentially the channel-source pn junction current.
(Some electrons diffuse from the source into the channel, if this pn junction is forward biased.)



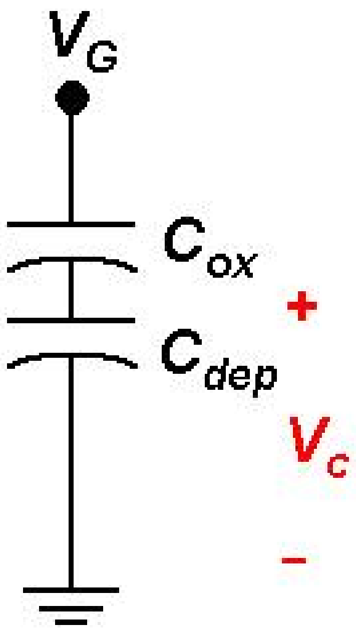
Qualitative Explanation for Subthreshold Leakage

- The channel V_c (at the Si surface) is capacitively coupled to the gate voltage V_G:

DEVICE



CIRCUIT MODEL



Using the capacitive voltage divider formula (Lecture 12, Slide 7):

$$\Delta V_c = \frac{C_{ox}}{C_{ox} + C_{dep}} \Delta V_G$$

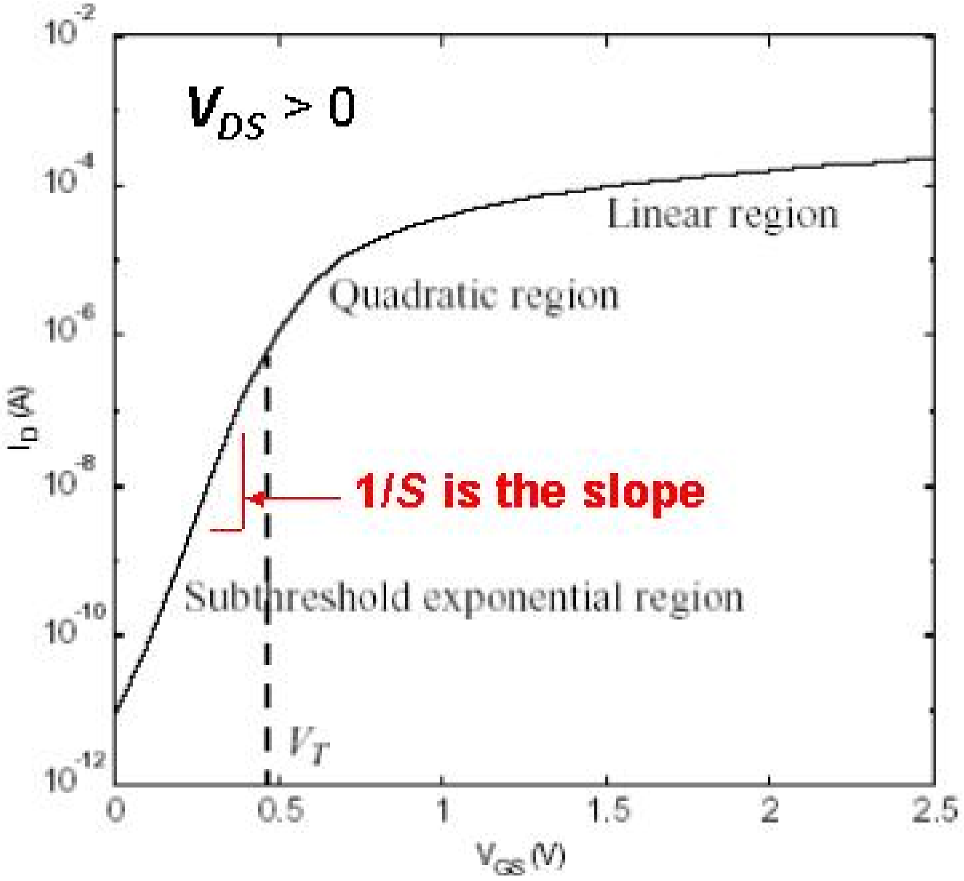
The forward bias on the channel-source pn junction increases with V_G scaled by the factor $C_{ox} / (C_{ox}+C_{dep})$

$$C_{dep} = \frac{\varepsilon_{Si}}{W_{dep}} \propto \sqrt{\frac{1}{N_A}}$$

$$\Rightarrow \boxed{n = \frac{C_{ox} + C_{dep}}{C_{ox}} = 1 + \frac{C_{dep}}{C_{ox}}}$$

Slope Factor (or Subthreshold Swing) *S*

- ***S*** is defined to be the inverse slope of the log (I_D) *vs.* V_{GS} characteristic in the subthreshold region:



$$\boxed{S \equiv n\left(\frac{kT}{q}\right)\ln(10)}$$

<u>Units</u>: Volts per decade

Note that ***S*** $\geq$ 60 mV/dec at room temperature:

$$\left(\frac{kT}{q}\right)\ln(10) = 60\,\text{mV}$$

V_T Design Trade-Off

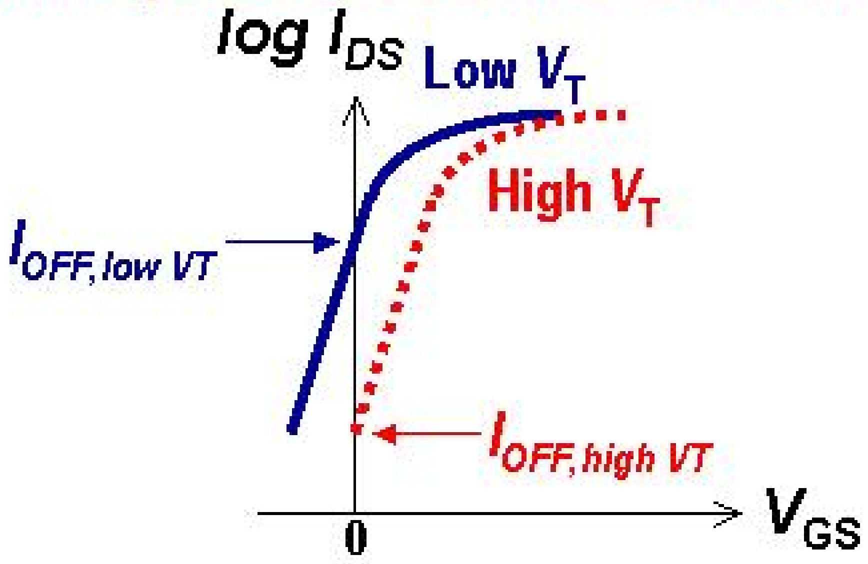
(Important consideration for digital-circuit applications)

- Low V_T is desirable for high ON current

$$I_{DSAT} \propto (V_{DD} - V_T)^{\eta} \qquad 1 < \eta < 2$$

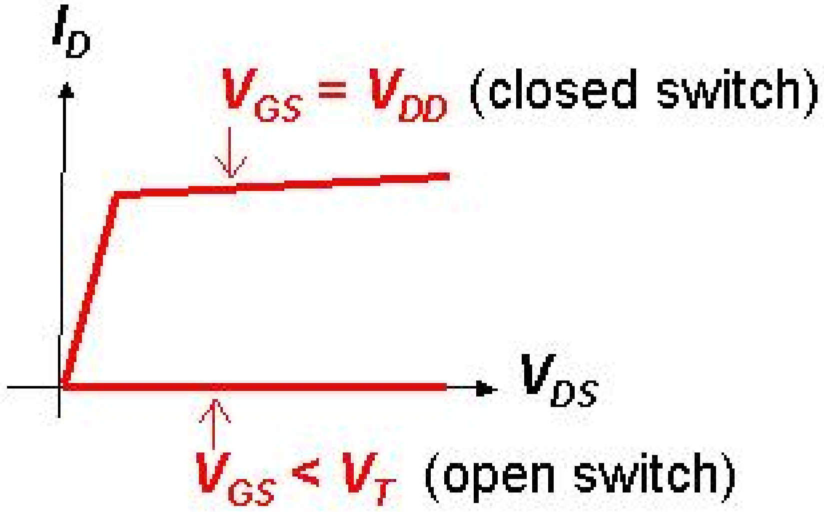
where V_{DD} is the power-supply voltage

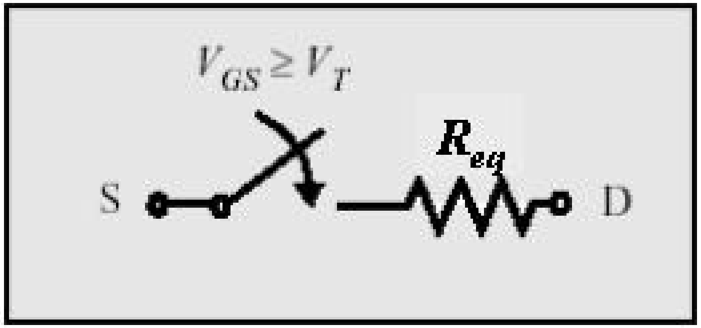
...but high V_T is needed for low OFF current



The MOSFET as a Resistive Switch

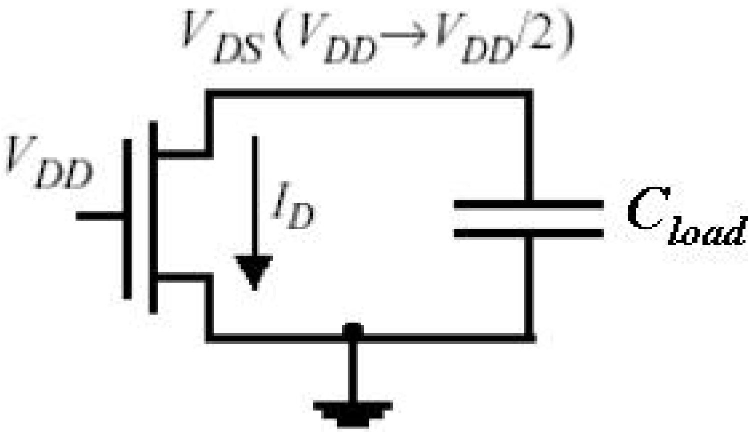
- For digital circuit applications, the MOSFET is either OFF ($V_{GS} < V_T$) or ON ($V_{GS} = V_{DD}$). Thus, we only need to consider two I_D vs. V_{DS} curves:
  1. the curve for $V_{GS} < V_T$
  2. the curve for $V_{GS} = V_{DD}$





Equivalent Resistance R_{eq}

- In a digital circuit, an n-channel MOSFET in the ON state is typically used to discharge a capacitor connected to its drain terminal:
  - gate voltage $V_G = V_{DD}$
  - source voltage $V_S = 0$ V
  - drain voltage V_D initially at V_{DD}, discharging toward 0 V



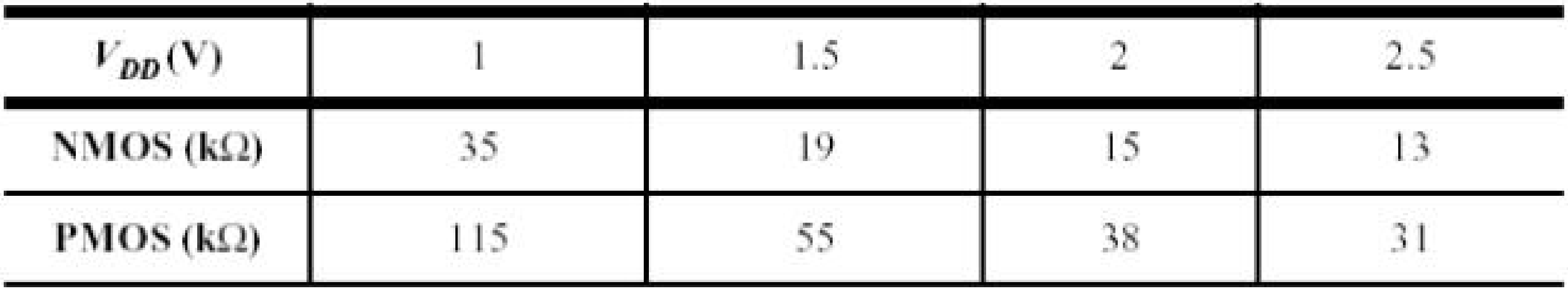
The value of R_{eq} should be set to the value which gives the correct propagation delay (time required for output to fall to ½V_{DD}):

$$I_{DSATn} = \frac{k_n'}{2}\frac{W}{L}\left(V_{DD} - V_{Tn}\right)^2 \longrightarrow \boxed{R_{eq} \cong \frac{3}{4}\frac{V_{DD}}{I_{DSATn}}\left(1 - \frac{5}{6}\lambda_n V_{DD}\right)}$$

Typical MOSFET Parameter Values

- For a given MOSFET fabrication process technology, the following parameters are known:
  - V_T (~0.5 V)
  - C_{ox} and k' (<0.001 A/V^2)
  - V_{DSAT} (≤ 1 V)
  - λ (≤ 0.1 V^{-1})

Example R_{eq} values for 0.25 μm technology ($W = L$):



V_{DD} (V)	1	1.5	2	2.5
NMOS (kΩ)	35	19	15	13
PMOS (kΩ)	115	55	38	31

How can R_{eq} be decreased?