Essentials of MOSFETs

Unit 1: Transistors and Circuits

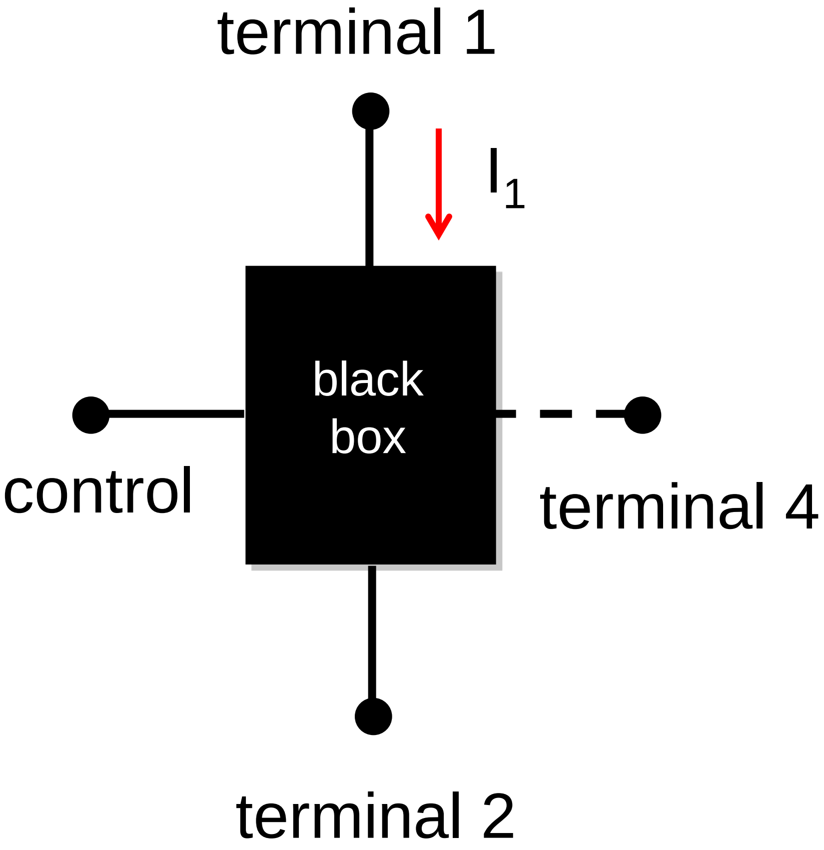
Lecture 1.6: Unit 1 Recap

Mark Lundstrom

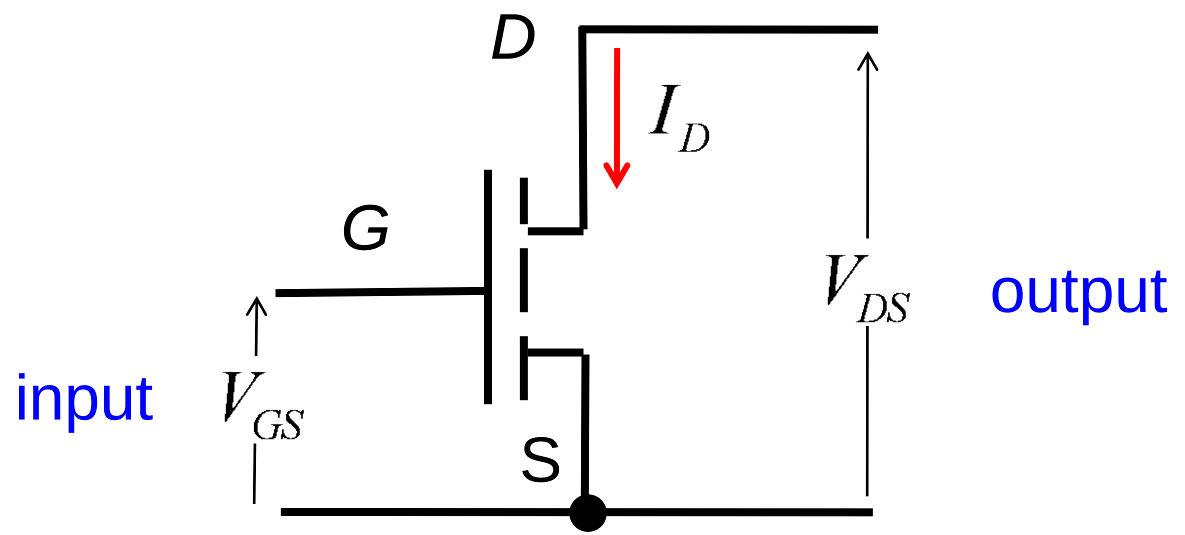
lundstro@purdue.edu
Electrical and Computer Engineering
Purdue University
West Lafayette, Indiana USA

PURDUE UNIVERSITY

The transistor as a "black box"



The MOSFET as a 2-port device



common source

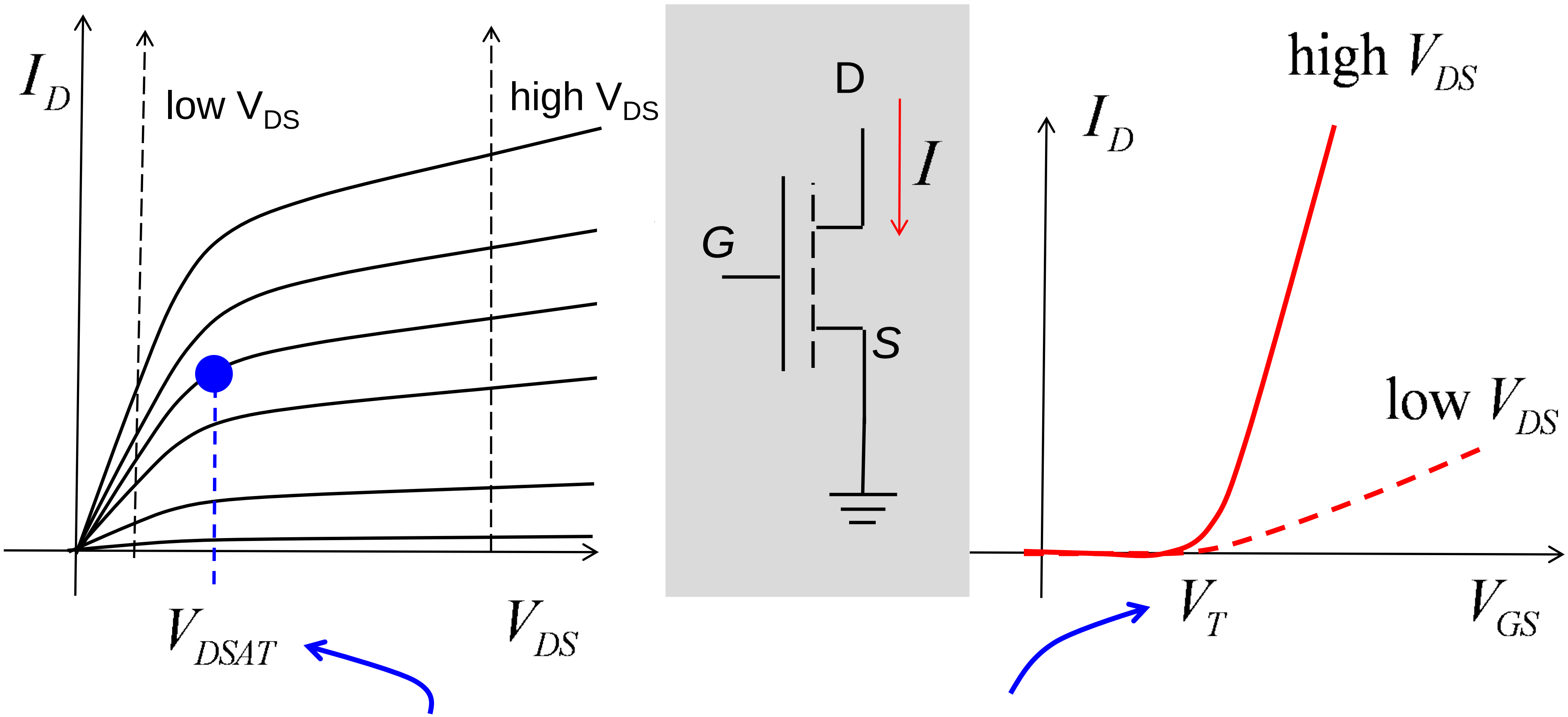
$I_D(V_{GS})$ at a fixed V_{DS} Transfer characteristics

$I_D(V_{DS})$ at a fixed V_{GS} Output characteristics

Output vs. transfer characteristics

output characteristics

transfer characteristics

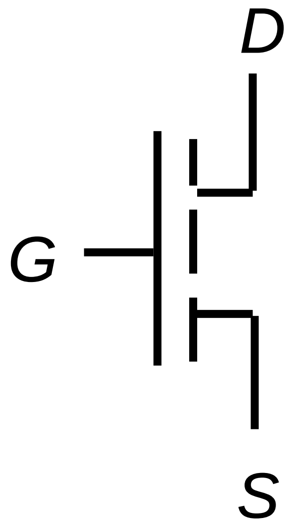


“saturation voltage”

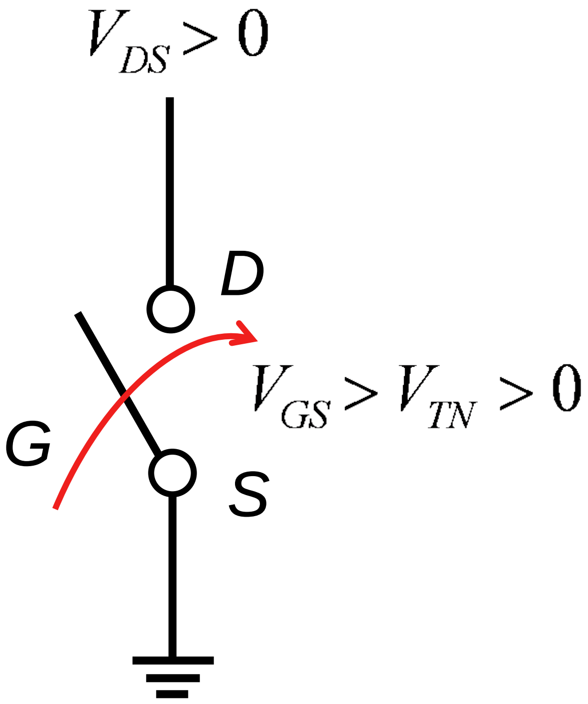
“threshold voltage”

Digital electronics

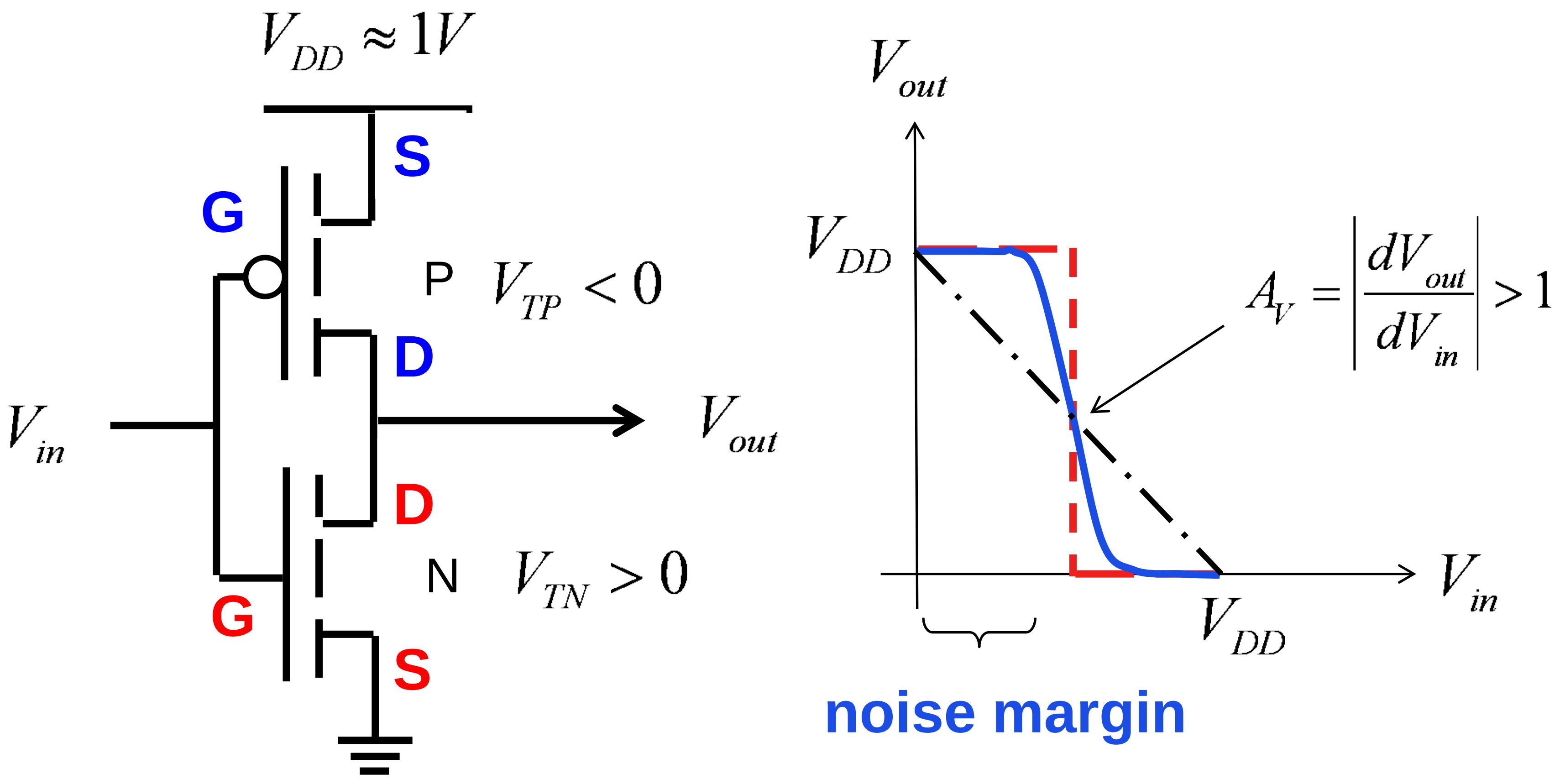
N-MOSFET
symbol



switch



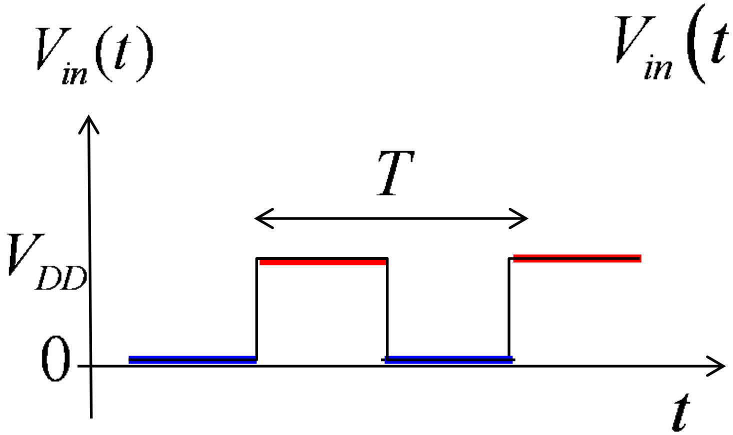
CMOS Inverter

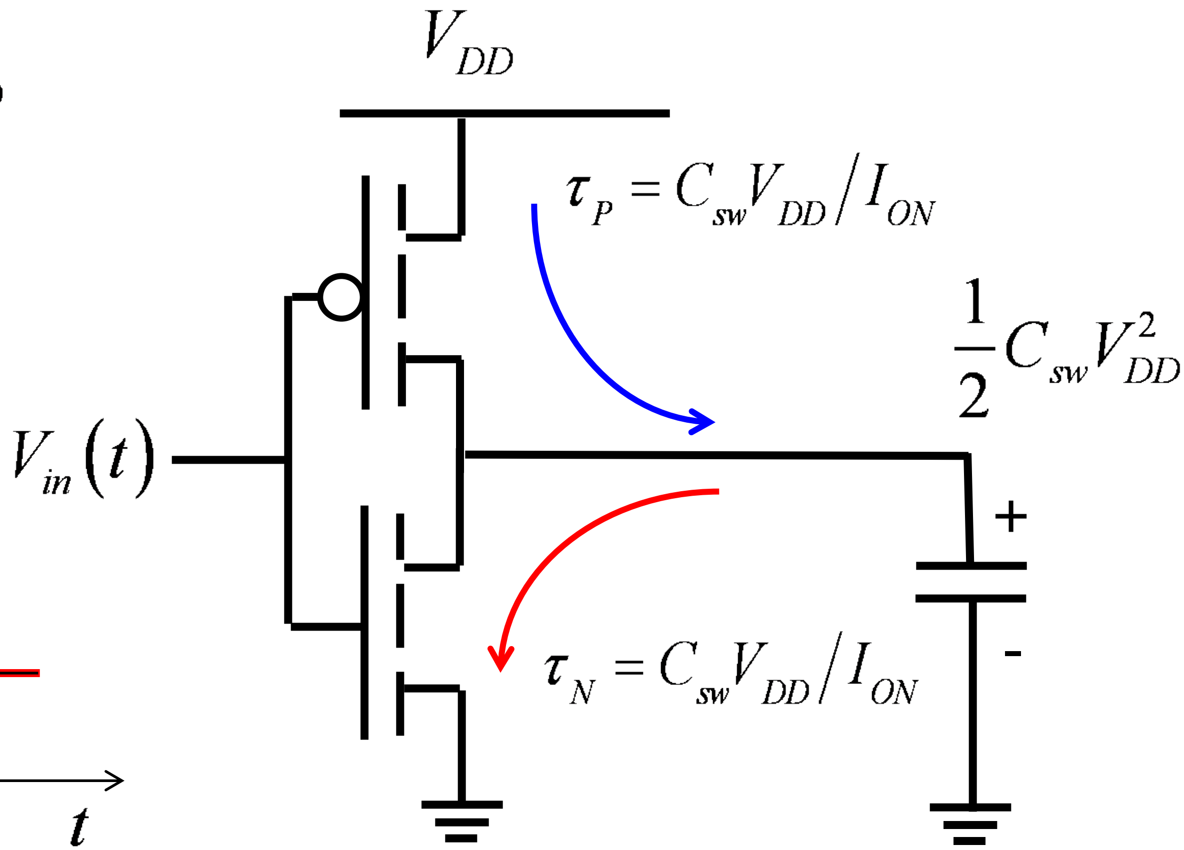


Switching

$$P_{\text{dynamic}} = \alpha f C_S V_{DD}^2$$

$$P_{\text{static}} = N_G I_{OFF} V_{DD}$$





CMOS speed and power

$$\tau = C_{sw} V_{DD} / I_{ON} \qquad P_{\text{dynamic}} = \alpha f C_S V_{DD}^2 \qquad P_{\text{static}} = N_G I_{OFF} V_{DD}$$

1) Higher on-current means higher speed

2) Faster operation means more dynamic power

3) Lower V_{DD} means lower power

4) More leakage means more power dissipation

Key Figures of Merit for digital applications

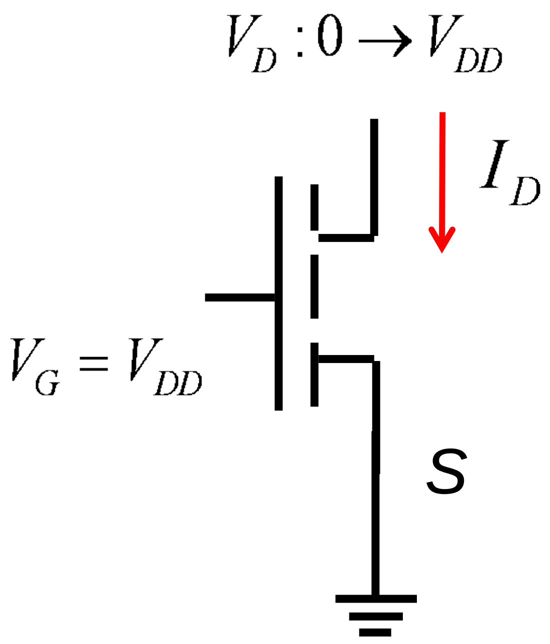
1) On current

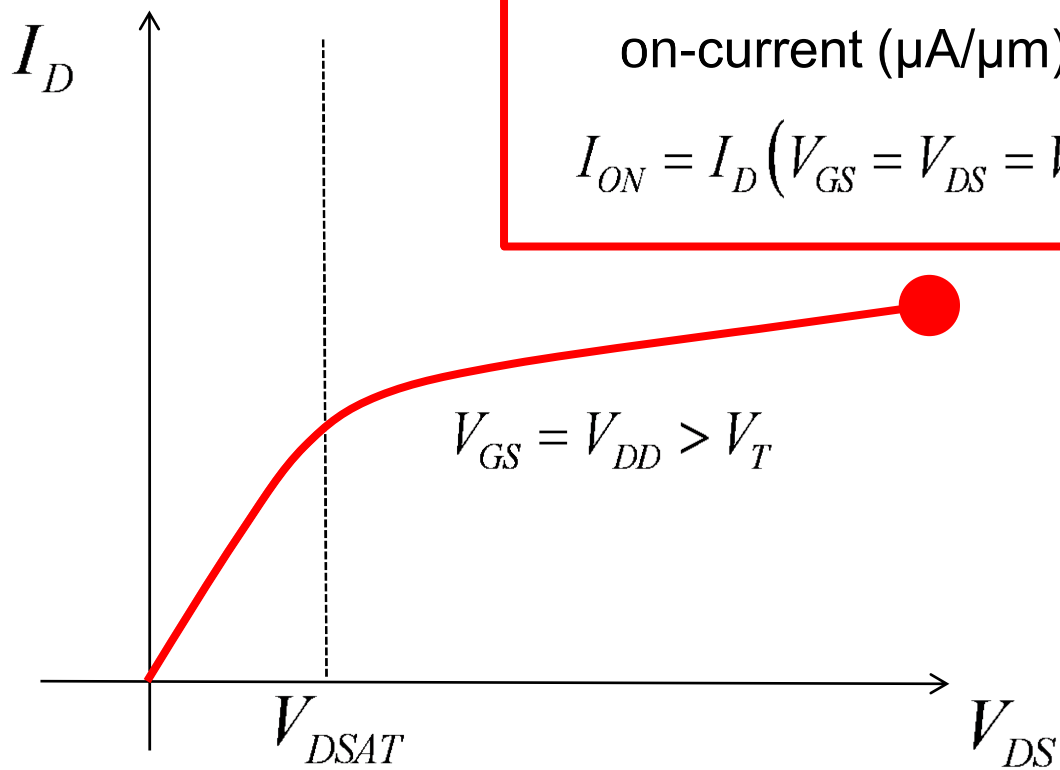
2) Off-current

3) Subthreshold swing

4) DIBL

1) On-current





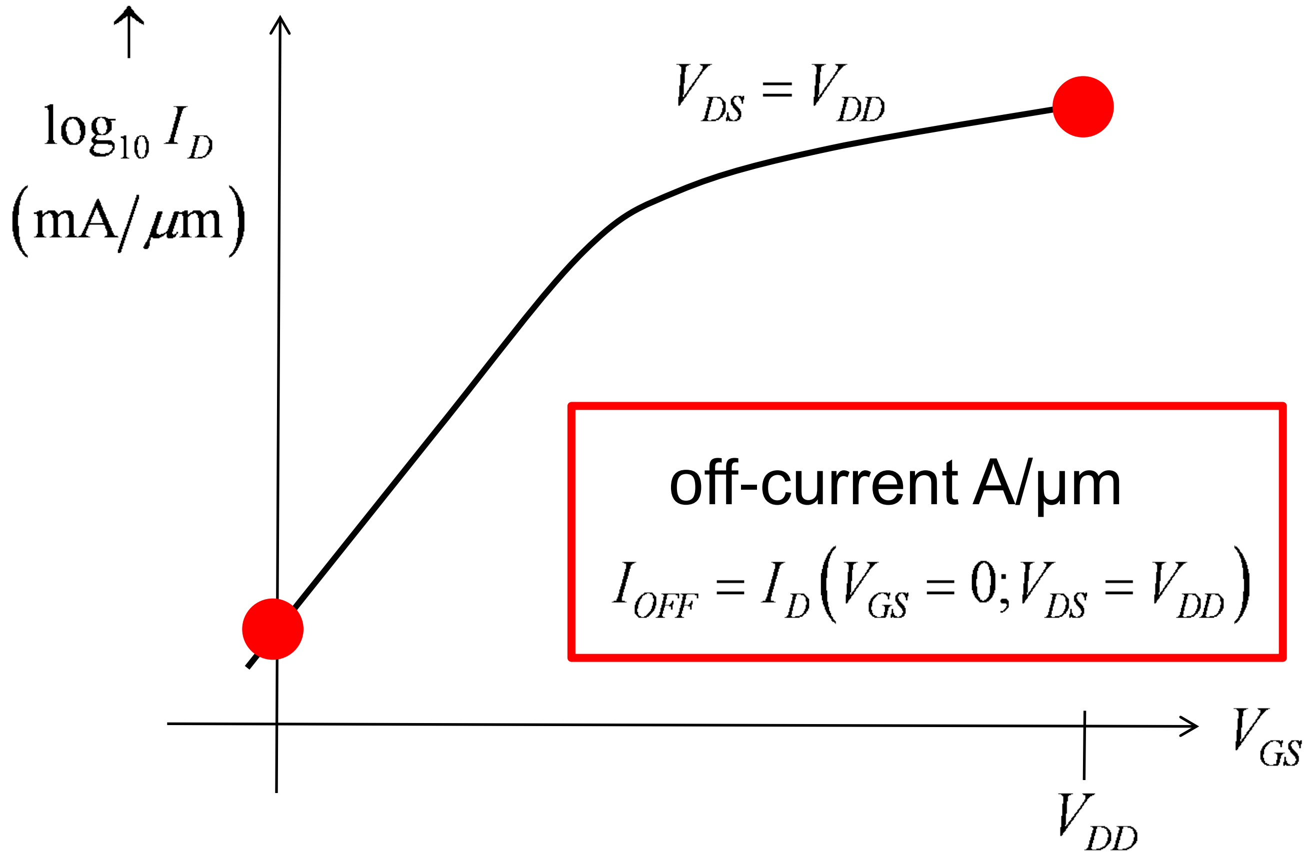
on-current (μA/μm)

$$I_{ON} = I_D\left(V_{GS} = V_{DS} = V_{DD}\right)$$

output characteristic:
I_D vs. V_{DS} at fixed V_{GS}

2) Off-current

transfer characteristic on a semi-log plot:

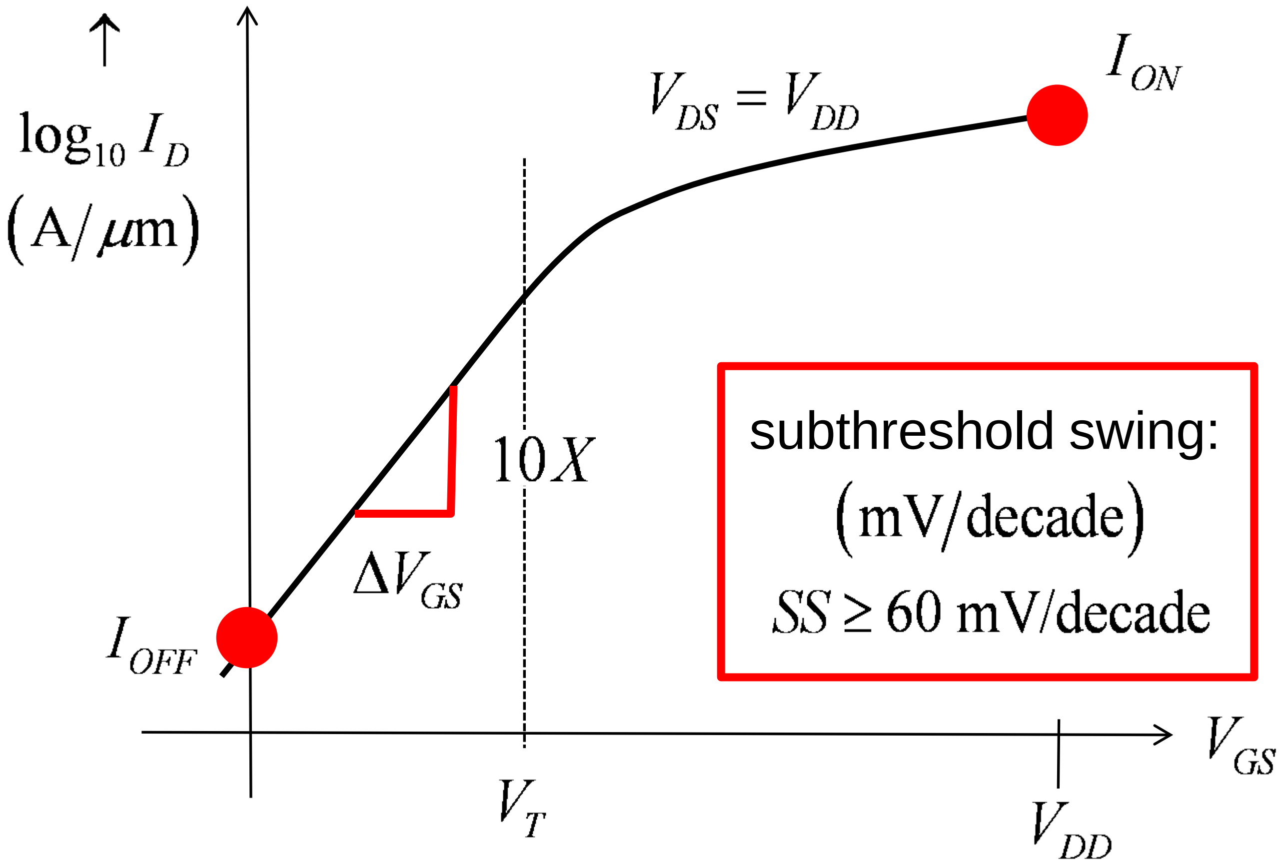


off-current A/μm

$$I_{OFF} = I_D\left(V_{GS} = 0; V_{DS} = V_{DD}\right)$$

3) The Subthreshold Swing

transfer characteristics:



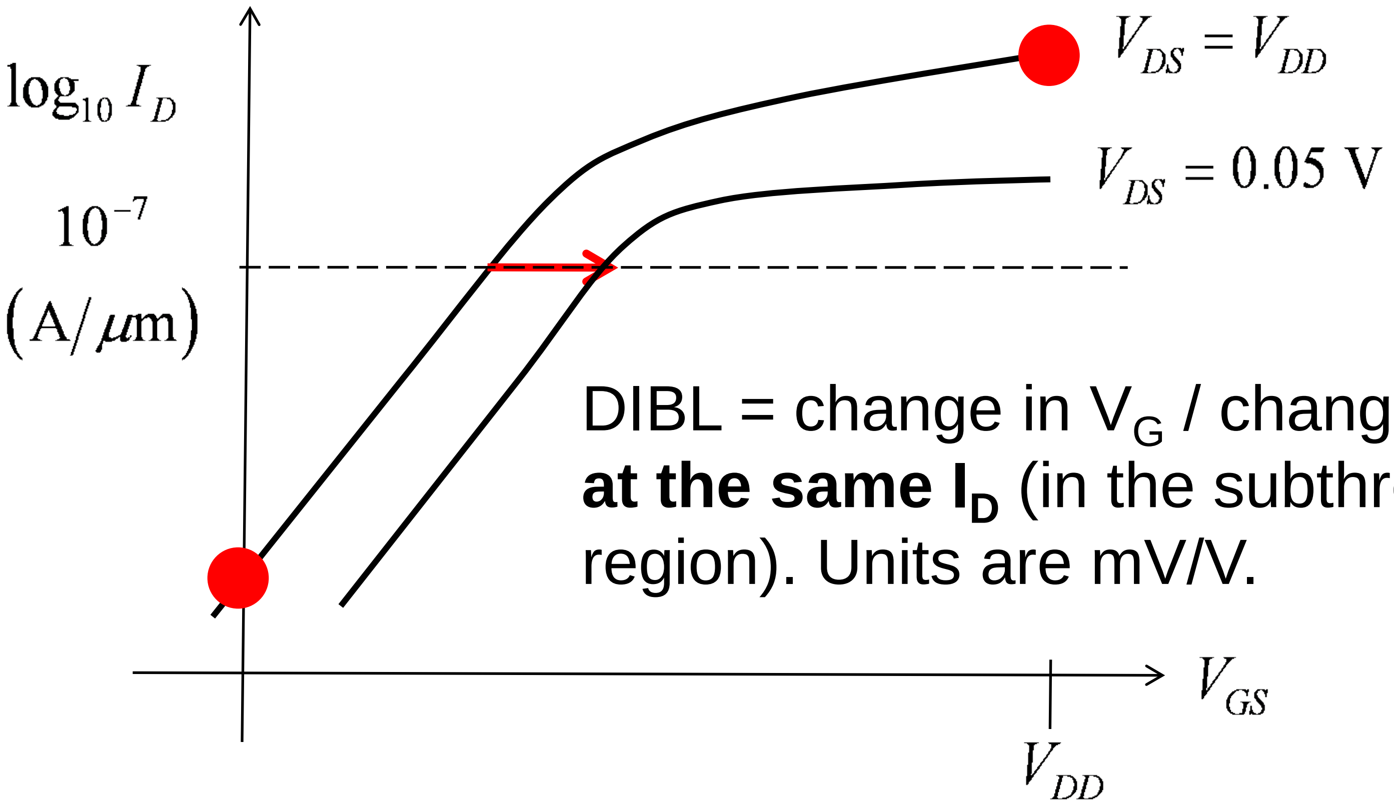
subthreshold swing:

$(\mathrm{mV/decade})$

$SS \geq 60\ \mathrm{mV/decade}$

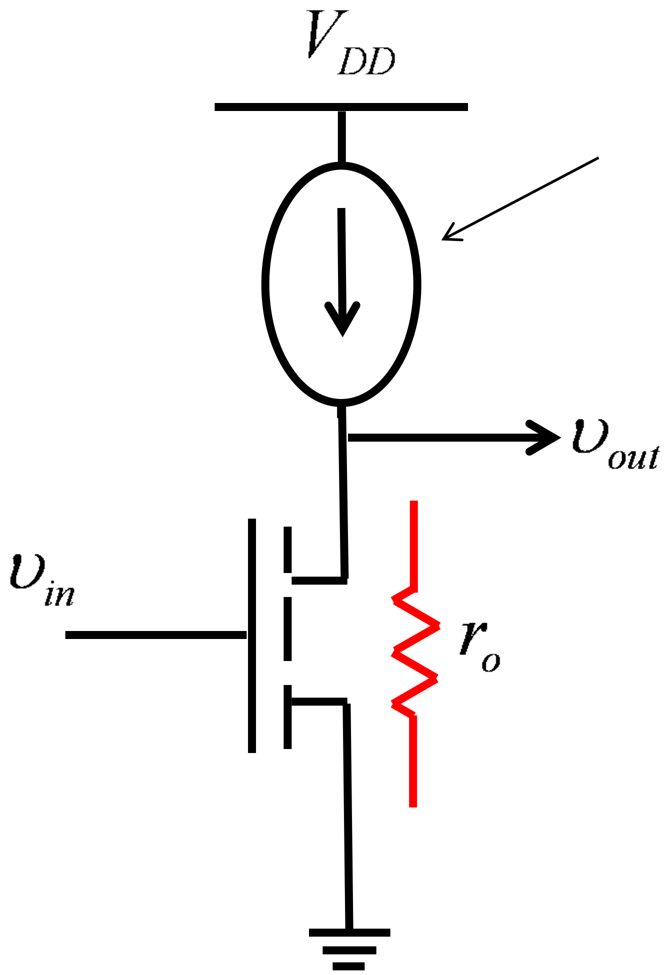
4) DIBL

transfer characteristics:



DIBL = change in V_G / change in V_D **at the same I_D** (in the subthreshold region). Units are mV/V.

Analog / RF



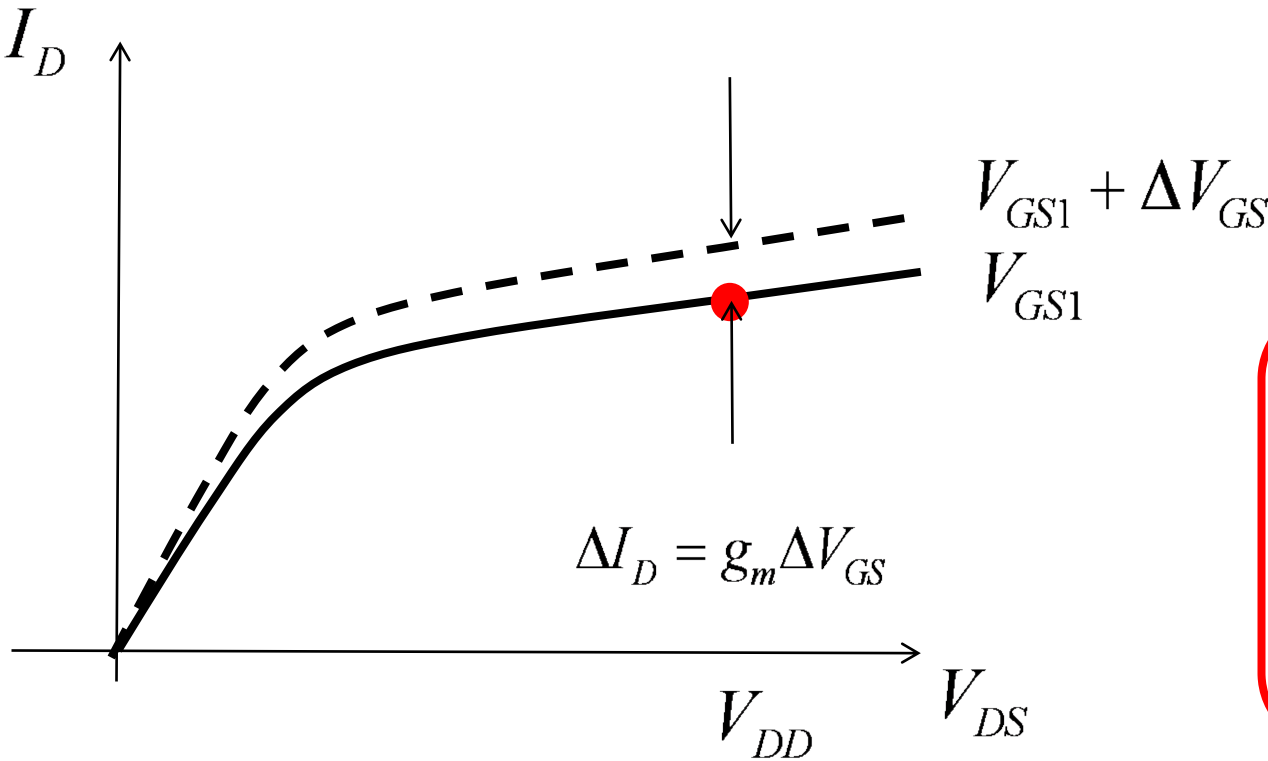
high impedance current source

$$\boxed{A_\upsilon(\max) = -g_m r_0}$$

The **transconductance**, g_m, and **output resistance**, r_0, of the MOSFET are important figures of merit.

So is the **self gain**, $g_m r_0$.

Transconductance

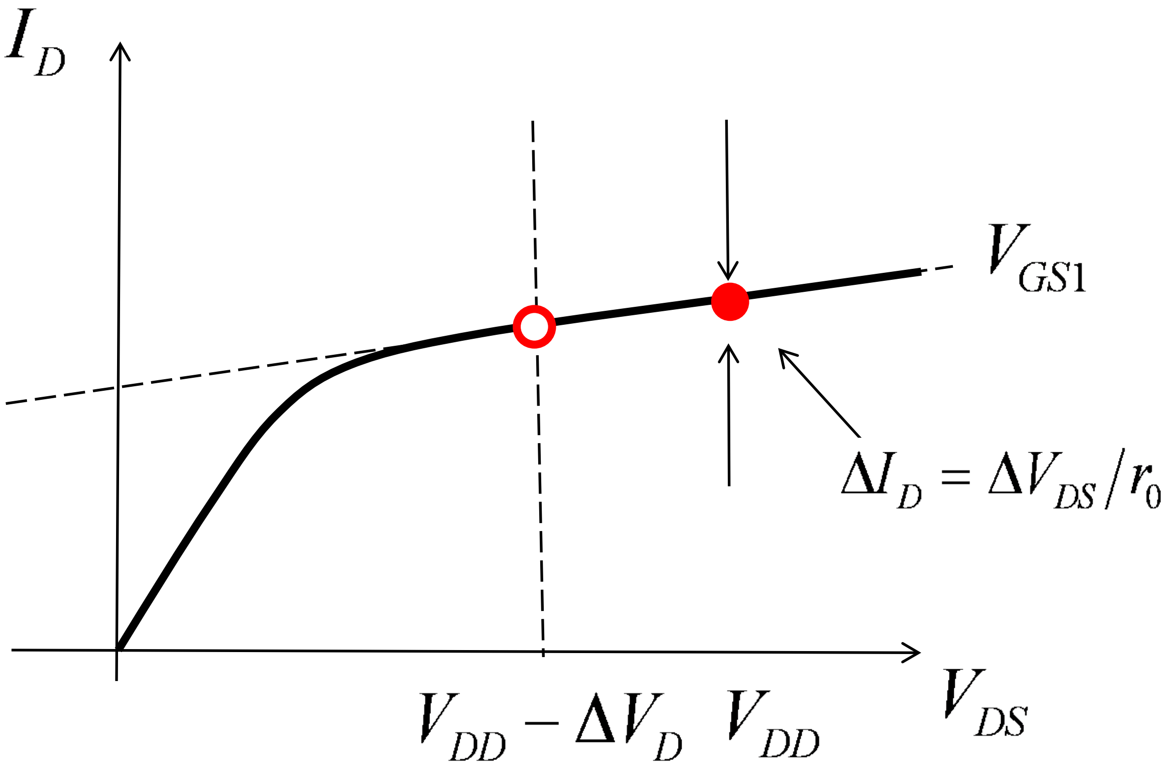


$$g_m \equiv \left.\frac{\partial I_D}{\partial V_{GS}}\right|_{V_{DS}}$$

$$(\mu\text{S}/\mu\text{m})$$

Lundstrom: 2018

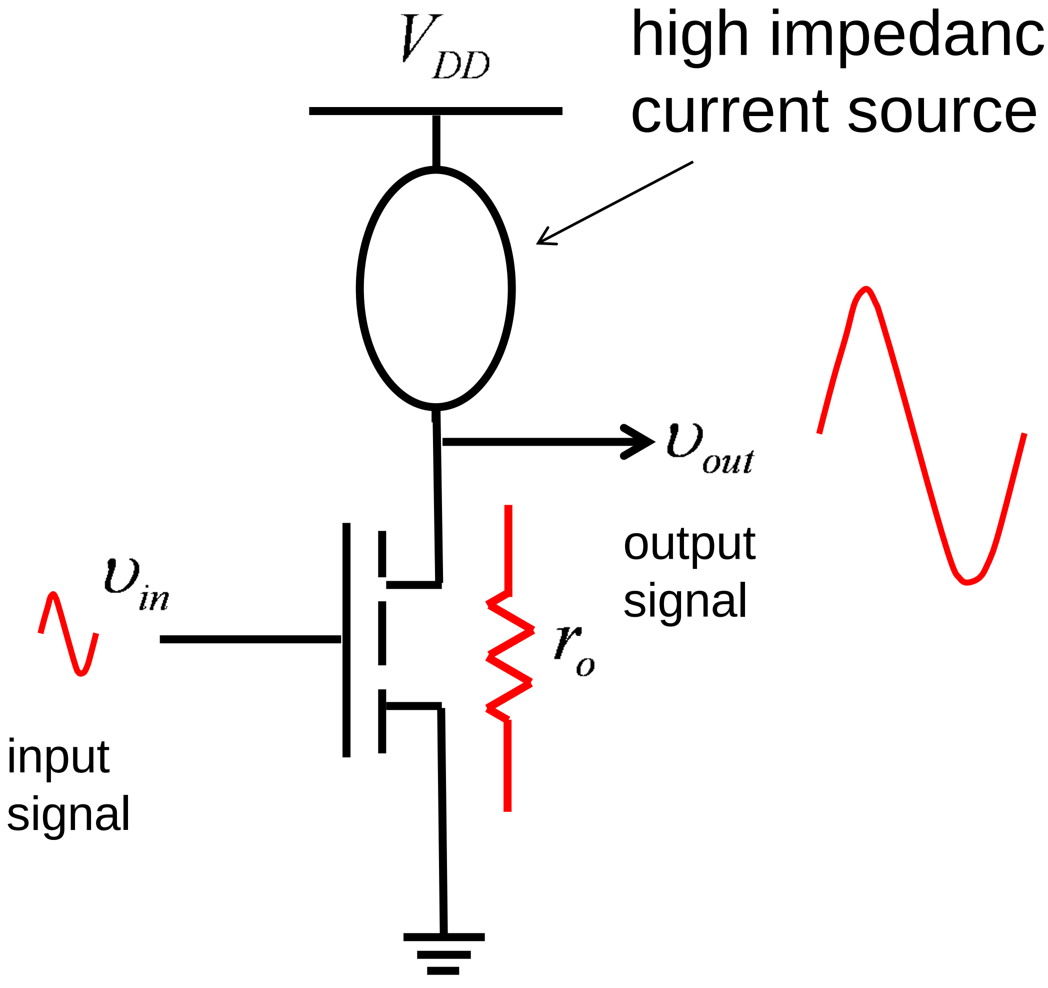
Output resistance



$$r_0 \equiv \left(\left. \frac{\partial I_D}{\partial V_{DS}} \right|_{V_{GS}} \right)^{-1}$$

$\Omega - \mu\text{m}$

Other analog device metrics



$$\boxed{A_v(\max) = -g_m r_o}$$

g_m and r_0 are important analog device metrics

But also f_T, f_{max}, linearity, noise, mismatch, etc.

Recap

Given the measured characteristics of a MOSFET, you should be able to determine:

1. on-current: I_{ON}
2. off-current: I_{OFF}
3. subthreshold swing, SS
4. drain induced barrier lowering: DIBL

5. output resistance: r_o
6. *transconductance:* g_m

threshold voltage: V_T (lin) and V_T (sat)
drain saturation voltage: V_{DSAT}

Our goal in this course is to understand these device metrics and parameters.

Two types of compact models

In the course, we will distinguish between two different types of compact models:

1) **Compact physical models**

   These models aim to describe a device in terms of a few parameters with strong physical significance. These kinds of models are useful for device characterization, process monitoring, and for the conceptual understanding that guides device research.

Our focus in this course is on this type of compact model.

Second type of compact models

2) Compact device models for circuit simulation

These models accurately relate the currents that flow into a device's terminals to the voltages on the leads **in a form suitable for use in numerical circuit simulation programs**. To describe everything relevant to a circuit, these models are more complex, but the core of the model is usually a compact physics model.

These kinds of compact models play a critical role in connecting semiconductor R&D and manufacturing to product design.

Summary

Be sure that you are familiar with the shape of a transistor IV characteristic (linear and saturation regions, sub-threshold and above threshold, output and transfer characteristics, etc.)

You should also be familiar with the key metrics for digital applications (on- and off-currents, SS, DIBL) and for analogue applications (and how to extract them from measured IV characteristics.

Next, in Unit 2, we will start looking inside the transistor "black box".