Unit 1: Transistor Fundamentals

Lecture 1.4: Transistors to Circuits

Mark Lundstrom
lundstro@purdue.edu
Electrical and Computer Engineering
Birck Nanotechnology Center
Purdue University, West Lafayette, Indiana USA
Lecture 1.3 Summary

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. threshold voltage: $V_T$ (lin) and $V_T$ (sat)
6. Drain to source resistance: $R_{DS}$
7. drain saturation voltage: $V_{DSAT}$
8. output resistance: $r_o$
9. transconductance: $g_m$

How do these device parameters affect circuit performance?
N-MOSFETs

\[ V_{GS} > V_T \quad V_T > 0 \]
\[ V_{DS} > 0 \]
P-MOSFETs

PMOS

\[ I_{DS} \]

\[ V_{DS} \]

\[ -V_{GS} \]

\[ V_{GS} = -V_{DD} \]

\[ V_{GS} < V_T \quad V_T < 0 \]

\[ V_{DS} < 0 \]

Lundstrom: Nanotransistors 2015
Ideal CMOS inverter

\[ V_{GSP} = V_{in} - V_{DD} \]

\[ V_{GSN} = V_{in} \]

Lundstrom: Nanotransistors 2015
Ideal CMOS inverter

\[ V_{in} = 0 \]
\[ V_{in} = V_{DD} \]

\[ V_{out} = V_{DD} \]
\[ V_{out} = 0 \]

PMOS

NMOS

transfer characteristic

\[ V_{in} \rightarrow \]

Lundstrom: Nanotransistors 2015
2-input NAND gate

AND
A  B  C
0  0  0
0  1  0
1  0  0
1  1  1

NAND
A  B  C
0  0  1
0  1  1
1  0  1
1  1  0

Lundstrom: Nanotransistors 2015
CMOS inverter

Real transfer characteristic

Lundstrom: Nanotransistors 2015
CMOS inverter: $V_{out}$ vs. $V_{in}$

$V_{DD} = 1.0$ V

$V_{TN} = -V_{TP} = 0.15$ V

$V_{out}$

$Lundstrom: Nanotransistors 2015$
CMOS inverter: $V_{out}$ vs. $V_{in}$

$V_{DD} = 1.0$ V

$V_{TN} = -V_{TP} = 0.15$ V

$V_{GS} = V_{in} - V_{DD}$

$V_{DS} = V_{out} - V_{DD}$

PMOS
CMOS inverter: $V_{out}$ vs. $V_{in}$

$V_{DD} = 1.0 \text{ V}$

$V_{TN} = -V_{TP} = 0.15 \text{ V}$
CMOS inverter: current

Vin = 0: No current flows!

Vin = 1: No current flows!

No static power dissipation!

In practice: Little power dissipation when I_{OFF} is small!
CMOS inverter: noise margins

\[ S \quad D \]

\[ V_{DD} \]

\[ V_{in} \rightarrow V_{out} \]

\[ V_{out} \]

\[ V_{DD} \]

\[ V_{DD}/2 \]

\[ NM_L \]

\[ slope = -1 \]

\[ NM_H \]

\[ V_{in} \]

\[ V_{DD} \]

Lundstrom: Nanotransistors 2015
Importance of gain

$Lundstrom: Nanotransistors 2015$

**Must have gain to have noise margins**

\[
\frac{dV_{out}}{dV_{in}} = A_v
\]

\[
\left| A_v \right| = 1
\]

\[
\frac{dV_{out}}{dV_{in}} = \frac{dV_{out}}{dI_{DS}} \frac{dI_{DS}}{dV_{in}} = r_0 g_m
\]

**Must have adequate** \(g_m r_o\).
CMOS inverter: summary

“pull up transistor”

1) Little current flow unless switching. (small power dissipation - low $I_{off}$).

2) Good noise margins if device has high gain (adequate $g_m r_o$).

“pull down transistor”

Next: understand speed and power.
Dynamic performance
Power dissipation

\[ E_C(0) = \frac{1}{2} C_{sw} V_{DD}^2 \]

\[ E_C(T / 2) = 0 \]

\[ P_{dynamic} = \frac{\Delta E}{T / 2} = \frac{C_{sw} V_{DD}^2}{T} \]

Low power requires low voltage!

“activity factor”
Speed

\[ V_{in}(t) \] 

\[ V_{DD} \]

\[ V_{out}(t) \]

\[ C_{sw} \]

\[ I = C \frac{dV}{dt} \sim e^{-t/\tau} \]

input voltage

\[ V_{in}(t) \]

\[ V_{DD} \]

\[ t_0 \]

output voltage

\[ V_{out}(t) \]

\[ V_{DD} \]

\[ V_{DD} - \text{const}(t-t_0) \]

\[ t \]

\[ t_0 \]

\[ t_1 \]
Speed

\[ I = C \frac{dV}{dt} \]

\[ I_{ON} = C_{SW} \frac{\Delta V}{\Delta t} = C_{SW} \frac{V_{DD}/2}{\tau} \]

\[ \tau = \frac{1}{2} \frac{C_{SW} V_{DD}}{I_{ON}} \]

Speed is determined by the on-current!
Circuit performance

1) Switching energy: \[ E_S = \frac{1}{2} C_{sw} V_{DD}^2 \]

2) Dynamic power: \[ P_D = \alpha f C_{sw} V_{DD}^2 \]

3) Standby power: \[ P_{SB} = I_{OFF} V_{DD} \]

4) Switching delay: \[ \tau = \frac{C_{sw} V_{DD}}{2 I_{ON}} \]

5) Noise margins: \[ |A_v| = g_m r_0 > 1 \]
Power constrained design

\[ P_{\text{max}} = 100 \text{ W/cm}^2 \]

(Dave Frank, IBM)
Now that we understand a little bit about how circuit performance is related to key device metrics, we will focus for the rest of the course on how nanoscale transistors work.

**Next topic:** A simple (energy band) view of how MOSFETs work.