E40M

MOS Transistors, CMOS Logic Circuits, and Cheap, Powerful Computers
Reading

- Chapter 4 in the reader

- For more details look at
  - A&L 5.1 Digital Signals
    (goes in much more detail than we need)
  - A&L 6-6.3 MOS Devices
MOSFET a.k.a. MOS Transistor

• Are very interesting devices
  – Come in two “flavors” – pMOS and nMOS
  – Symbols and equivalent circuits shown below

• Gate terminal takes no current (at least no DC current)
  – The gate voltage* controls whether the “switch” is ON or OFF

* actually, the gate – to – source voltage, $V_{GS}$
nMOS i-V Characteristics

- nMOS is still a device
  - Defined by its relationship between current and voltage
  - But it has 3 terminals!
    - Current only flows between the source and drain
    - No current flows into the gate terminal!

Remember the resistor?

\[
i \rightarrow \begin{array}{c}
\text{i} \\
\text{v}
\end{array} \rightarrow \text{v}
\]

\[
i_{DS} \rightarrow \begin{array}{c}
\text{i}_{DS} \\
\text{V}_{DS}
\end{array} \rightarrow \text{V}_{DS}
\]
Simple Model of an nMOS Device

- We will model an nMOS device by components we know
  - Resistor
  - Switch

- NMOS
  Source = Gnd
  Gate = Gnd => Off
  Gate = Vdd => On

- This really simple model is suitable for applications where there’s one value of “On” voltage.
How Does an nMOS Transistor Actually Work? (FYI – not essential for this course)
Problem With nMOS Device

• While an nMOS device makes a great switch to Gnd

• It doesn’t work that well if we want to connect to Vdd
  – To turn transistor on
    • Gate needs to be higher than source
  – But we want the source to be at Vdd
    • Oops …
pMOS $i_{DS}$ vs. $V_{DS}$ Characteristics

• Similar to nMOS, but upside down!
  – Turns on when the gate-to-source voltage is $< -1 \text{ V}$
  – And the drain-to-source voltage should be negative
    • Source should be the terminal with the higher voltage!
Simple Model of a pMOS Device

- We will model an pMOS device by components we know
  - Resistor
  - Switch

- NMOS
  Source = Vdd
  Gate = Gnd => On
  Gate = Vdd => Off
How Does a pMOS Transistor Actually Work? (FYI – not part of this course)
nMOS and pMOS Devices “Complement” Each Other – Complementary MOS or CMOS

- **PMOS**
  - Source = Vdd (+ supply)
  - Gate = Gnd => On
  - Gate = Vdd => Off

- **NMOS**
  - Source = Gnd
  - Gate = Gnd => Off
  - Gate = Vdd => On
MOS Transistor Summary

- MOS transistors are *extremely* useful devices
  - Almost all of your electronics uses them on the inside
  - Including your phone, laptop, WiFi and Bluetooth, and your Arduino
- Come in two “flavors”
  - nMOS
    - It is a switch which connects source to drain
    - If the gate-to-source voltage is greater than $V_{th}$ (around 1 V)
      - Positive gate-to-source voltages turn the device on.
  - pMOS
    - It is a switch which connects source to drain
    - If the gate-to-source voltage is less than $V_{th}$ (around -1 V)
      - Negative gate-to-source voltages turn the device on.

... and there’s zero current into the gate!
MOS Logic Gates
What Does This Circuit Do?

- Is the output a logic function of the input? Consider $V_{in} = GND$
What Does This Circuit Do?

- Now consider $V_{in} = V_{DD}$
Building Logic Gates from MOS Transistors

• Remember Boolean Logic?
  – AND, OR
  – NAND = Not-AND = AND followed by Inverter
    • Output is only low when A and B are true (high)
  – NOR = Not-OR = OR followed by Inverter
    • Output is low when either A or B is true (high)

• You can make them from MOS devices
  – But only the inverting gates (NOR and NAND)
Building a CMOS NAND Gate

- Output should be low if both input are high (true)
- Output should be high if either input is low (false)
Logic Symbols

- NOT
- AND
- NAND
- OR
- NOR
- XOR
If You Look At Your Computer Chip

• It is just billions of transistors
  – Creating many logic gates, and memory

• Take EE108A if you want know how we do that …
HOW THE MOS TRANSISTOR CHANGED THE WORLD …
First Computing Machines Were Mechanical

Picture of a version of the Babbage difference engine built by the Museum of Science, UK

“The calculating section of Difference Engine No. 2, has 4,000 moving parts (excluding the printing mechanism) and weighs 2.6 tons. It is seven feet high, eleven feet long and eighteen inches in depth”
Moving Electrons is Easier than Moving Metal

• Building electronics:
  – Started with tubes, then miniature tubes
  – Transistors, then miniature transistors
  – Components were getting cheaper, more reliable but:
    • There is a minimum cost of a component (storage, handling …)
    • Total system cost was proportional to complexity

• Integrated circuits changed that
  – Printed a circuit, like you print a picture,
    • Create components in parallel
    • Cost no longer depended on # of devices
A Little History

1st (Bipolar Junction) Transistor
Christmas Eve 1947
By Bardeen, Brattain, and Shockley,
Nobel Laureates in Physics 1956

1st Integrated Circuit
Jack Kilby, Nobel Laureate in Physics 2000
Bob Noyce

(Courtesy of TI and Huff, SEMATECH)

(http://www.bellsystemmemorial.com/belllabs_transistor.html)
What is an Integrated Circuit?

- A device having multiple electrical components and their interconnects manufactured on a single substrate.

- First IC 1958
  - Jack Kilby at TI
  - Germanium
  - A hack
    - Wax support
  - Made history

- Planar Process 1961
  - Bob Noyce at Fairchild
  - Silicon

Image from State of the Art © Stan Augarten
Miniaturization Progress Over 50 Years

From This

To This

To This

Point Contact Transistor

First Integrated Circuit

Modern Microprocessor

• Modern silicon chips have $> 10^9$ components in 1 cm$^2$ area.
Moore’s “Law”

- “The complexity for minimum component costs has increased at a rate of roughly a factor of 2 per year.” Gordon Moore, 1965
Intel 10 nm hyper scaling features result in Transistor Density above 100MTr/mm²

TECHNOLOGY AND MANUFACTURING DAY
Source: Intel. 2017-2020 are estimates based upon current expectations and available information.

Kaizad Mistry, Intel Technology and Manufacturing Day, March 28, 2017
What This Means

1985 (Intel 80386)
275,000 transistors
104 mm\(^2\); 2640 Tr/mm\(^2\)

1989 (Intel 80486)
1,180,235 transistors
16,170 Tr/mm\(^2\)

80386 chip area shrinks to 17 mm\(^2\)
80386 die size shrinks to 0.05 mm\(^2\)

… or the original chip area could contain > 10 billion transistors!

*Kaizad Mistry, Intel Technology and Manufacturing Day, March 28, 2017
Take The Cover Off A Microprocessor

Full wafer (100s of dies)

modern wafers: 200-300 mm
diameter (8-12 inches)
Learning Objectives

• Understand how nMOS and pMOS transistor work
  – Voltage controlled switch, the gate voltage controls whether
    the switch is ON or OFF
  – nMOS devices connect output to Gnd
  – pMOS devices connect the output to Vdd

• Be able to create MOS NAND, NOR and Inverter circuits
  – Using pMOS and nMOS devices