Lecture 1: The Most Important Invention of the 20th Century?

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"The Transistor was probably the most important invention of the 20th Century, and the story behind the invention is one of clashing egos and top secret research."

- Ira Flatow, Transistorized!

http://www.pbs.org/transistor/
transistors

point contact transistor
bipolar transistor
MOSFET
JFET
SOI MOSFET
SB FET
FinFET
MODFET (HEMT)
heterojunction bipolar transistor
velocity modulation transistor
BTBT FET
SpinFET
...

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the MOSFET as a 2-port device

MOSFET circuit symbol

\[ I_D \]  
\[ V_{GS}, V_S, V_D \]

common source

\[ I_D(V_{GS}) \text{ at a fixed } V_{DS} \]
\[ I_D(V_{DS}) \text{ at a fixed } V_{GS} \]
IV characteristics: resistor

$I = V/R$  Ohm’s Law

Georg Ohm, 1827

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IV characteristics: ideal current source

$I = I_0$

$I = I_0$

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IV characteristics: real current sources

\[ I = I_0 + \frac{V}{R_0} \]
IV characteristics: transistors

n-channel enhancement mode MOSFET

gate voltage controlled resistor “linear region”

gate voltage controlled current source “saturation region”
IV characteristics: transistors

n-channel enhancement mode MOSFET

$V_{DS}$

$V_{GS}$

$I_D$

“subthreshold region”

“linear region”

“saturation region”

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output and transfer characteristics

output characteristics

“saturation voltage” $V_{DSAT}$

“threshold voltage” $V_T$

$I_D$ vs. $V_{DS}$

$V_{DS2} > V_{DS1}$

IGD: D

$G$

$I$

$S$

$V_T$

$V_{GS}$

$V_{DS}$

low $V_{DS}$

high $V_{DS}$
the physical structure of a MOSFET

“cartoon” figure

V_s = 0  V_G  V_D

n-Si  S  p-type silicon  D  n-Si

SiO₂

side view
the physical structure of a MOSFET

“cartoon” figure

source

drain

$L$

$W$

$D$

$S$

$G$
nanoscale bulk MOSFETs

S  G  D

source  channel  drain

SiO2

“metal” gate electrode

gate oxide
EOT ~ 1.1 nm

channel
~ 32 nm

(Texas Instruments, ~ 2000)
Silicon on Insulator (SOI) MOSFETs

FinFETs and tri-gate FETs

http://en.wikipedia.org/wiki/Multigate_device
applications of MOSFETs

symbol

switch

amplifier

input signal

output signal

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n-channel vs. p-channel MOSFET

n-MOSFET

\[ V_S = 0, \quad V_G > V_T, \quad V_D > 0 \]

p-MOSFET

\[ V_S = 0, \quad V_G < V_T, \quad V_D < 0 \]

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CMOS digital gates

“1” in:
\[ V_{IN} = V_{DD} \]
\[ V_{GS}^N = V_{DD} > V_{TN} \]
\[ V_{OUT} = 0 \]

“0” in:
\[ V_{IN} = 0 \]
\[ V_{GS}^P = -V_{DD} < V_{TP} \]
\[ V_{OUT} = 1 \]

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MOSFET device metrics

- on-resistance: \( R_{ON} (\Omega - \mu m) \)
- output resistance: \( r_d (\Omega - \mu m) \)
- on-current (mA/\( \mu m \))
  \[ I_D(V_{GS} = V_{DS} = V_{DD}) \]
- transconductance
  \[ g_m \equiv \left. \frac{\Delta I_D}{\Delta V_{GS}} \right|_{V_{DS}} \]

\( \mu S/\mu m \)
MOSFET device metrics (ii)

transfer characteristics:

\[ I_D \quad (\text{mA/\mu m}) \]

- \( V_{DS} = V_{DD} \)
- \( V_{DS} = 0.05 \text{ V} \)

off-current

threshold voltage
MOSFET device metrics (iii)

transfer characteristics:

\[ \log_{10} I_D \] (mA/µm)

\[ V_{DS} = V_{DD} \]

\[ V_{DS} = 0.05 \text{ V} \]

DIBL (drain-induced barrier lowering)

(mV/V)

subthreshold swing:

(mV/decade)

off-current
transistors (and IC’s) created the modern world

- supercomputers
- PCs
- cell phones
- communication satellites
- tablets
- fiber optics / Internet
Moore’s Law: 2011

http://en.wikipedia.org/wiki/Moore's_law
The number of transistors manufactured in 1997 exceeded the number of ants on the planet.

The cost of an IC “fab” is more than $3B, but the cost of a transistor has dropped by more than a factor of one million over the past 30 years.

If the definition of a nanodevice is one that has two dimensions less than 100 nm, then the silicon transistor is the most successful nanodevice currently in production.

(channel length 22 nm and gate oxide thickness, < 2 nm)
Nanoscale Transistors: the course

In this course we aim to develop a simple, physical understanding of:

- how nanoscale MOSFETs work
- what limits their performance
- how small they can be made

We’ll aim for a “big picture” understanding of important concepts, but will provide pointers for those who wish to delve more deeply.
references

For a list of different types of transistors, see:
