EE40: Introduction to Microelectronic Circuits

Summer 2005
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First Week Announcements

- Class web page http://inst.eecs.berkeley.edu/~ee40/ will have class syllabus, staff, office hours, schedule, exam, grading , etc. info
- Text (Hambley, "Electrical Engineering: Principles and Applications", 3rd ed.) covers most of class material. Reader will be available later in the semester for digital IC and fabrication subjects
- Lectures to be available on web, day before each class. Please print a copy if you wish to have it in class.

Announcements cont'd

- Sections begin this week
  - Cancelled Sections: Th 12-2.
- Labs begin this week. Attend your only second lab slot this week.
  - Cancelled labs: ThF 8-11, 2-5. Please check your Lab section.
  - 8 Labs and 2 Project Labs.
- Weekly homeworks
  - Assignment on web on Thursday. Due following Thursday in hw box at 6pm.
  - 1st Homework online today and due Friday. Sorry!
- 2 Midterms in class.
  - Tentatively on 07/12 and 07/28.

Lecture 1

- Course overview
- Introduction: integrated circuits
- Energy and Information
- Analog *vs.* digital signals
- Circuit Analysis

EE40: Course Overview

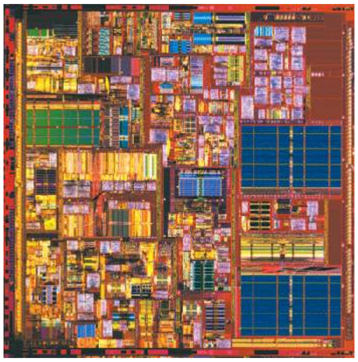
- EECS 40:
  - One of five EECS core courses (with 20, 61A, 61B, and 61C)
    - introduces "hardware" side of EECS
    - prerequisite for EE105, EE130, EE141, EE150
  - Prerequisites: Math 1B, Physics 7B
- Course content:
  - Electric circuits
  - Integrated-circuit devices and technology
  - CMOS digital integrated circuits

Course Overview Cont'd

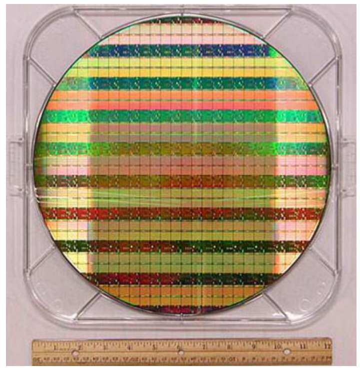
- Circuit components
  - Resistor, Dependent sources, Operational amplifier
- Circuit Analysis
  - Node, Loop/Mesh, Equivalent circuits
  - First order circuit
- Active devices
  - CMOS transistor
- Digital Circuits
  - Logic gates, Boolean algebra
  - Gates design

What is an Integrated Circuit?

P4 2.4 Ghz, 1.5V, 131mm^2

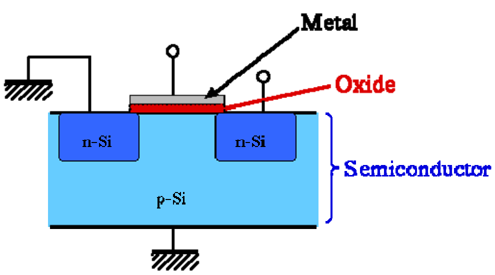


300mm wafer, 90nm

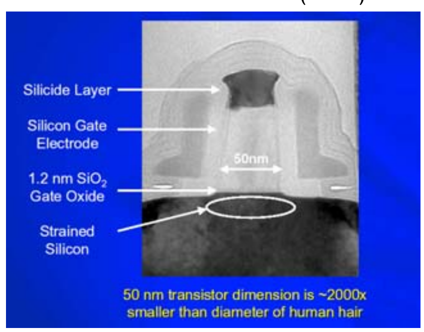


- Designed to performs one or several functions.
- Composed of up to 100s of Millions of transistors.

Transistor in Integrated Circuits



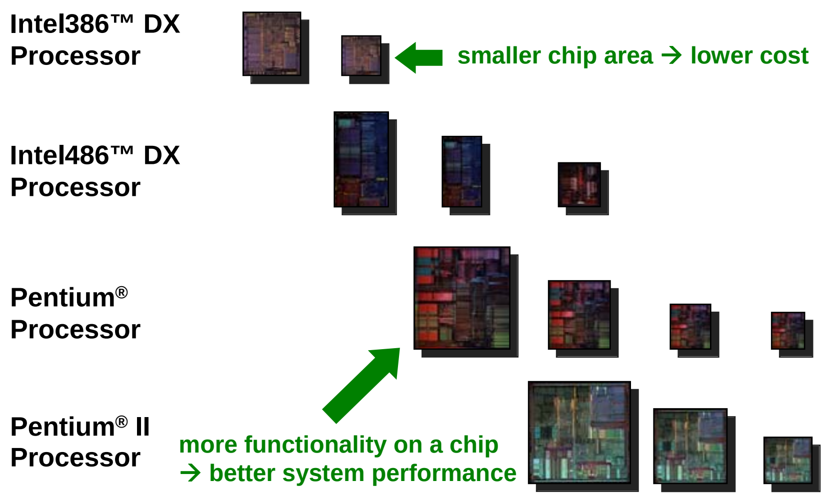
90nm transistor (Intel)



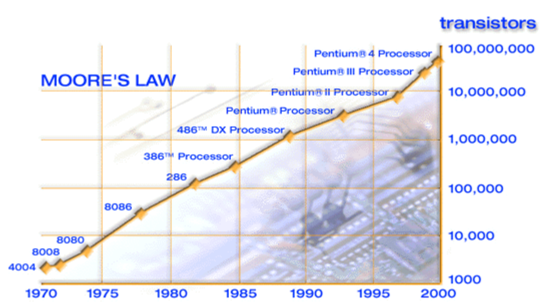
- Transistors are the workhorse of modern ICs
  - Used to manipulate signals and transmit energy
  - Can process analog and digital signals

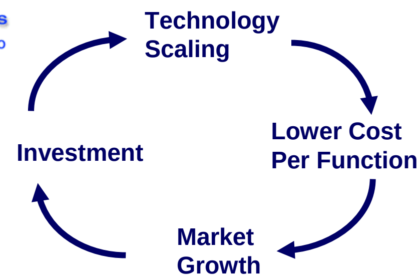
Benefit of Transistor Scaling

Generation: 1.5µ 1.0µ 0.8µ 0.6µ 0.35µ 0.25µ



Technology Scaling: Moore's Law



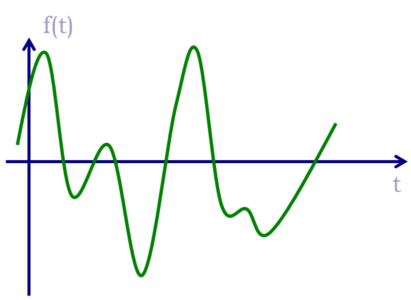


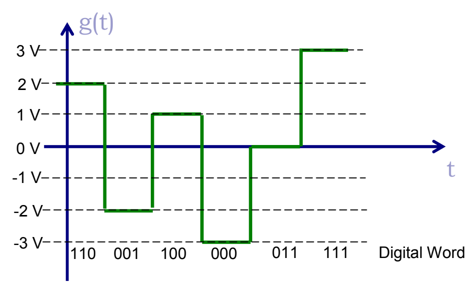
- Number of transistors double every 18 months
  - Cost per device halves every 18 months
  - More transistors on the same area, more complex and powerful chips
  - Cost per function decreases

Energy and signals in an IC

- Electrical circuits function to condition, manipulate, transmit, receive electrical power (energy) and/or information represented by electrical signals
- Energy System Examples: electrical utility system, power supplies that interface battery to charger and cell phone/laptop circuitry, electric motor controller, ….
- Information System Examples: computer, cell phone, appliance controller, …..

Signals in Integrated Circuits: Analog and Digital





- Analog
  - Usually represents a physical phenomenon.
  - Continuous in time.
  - f(t) is a real scalar.
- Digital
  - Each digital word is represented by an amplitude.
  - Can be a quantization of an analog signal.
  - g(t) takes on discrete, quantized values.

Analog *vs.* Digital Signals

- **Most** (but not all) **observables are analog**

  think of analog vs. digital watches

but the most convenient way to represent & transmit information electronically is to use digital signals

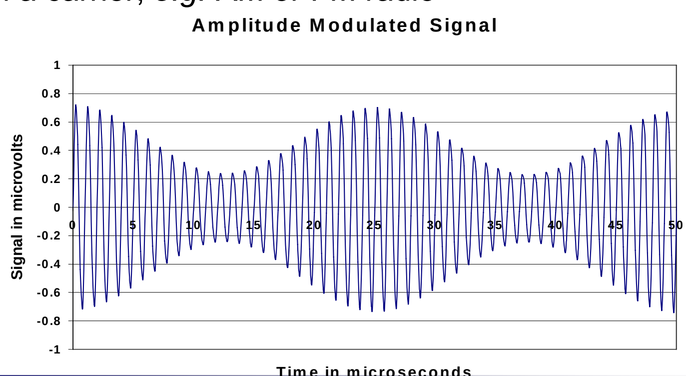
think of telephony

→ Analog-to-digital (A/D) & digital-to-analog (D/A) conversion is essential (and nothing new)

think of a piano keyboard

Analog Signals

- May have direct relationship to information presented
- In simple cases, are waveforms of information *vs.* time
- In more complex cases, may have information modulated on a carrier, *e.g.* AM or FM radio



Digital Signal Representations

Binary numbers can be used to represent any quantity.

We generally have to agree on some sort of "code", and the dynamic range of the signal in order to know the form and the number of binary digits ("bits") required.

Example 1: Voltage signal with maximum value 2 Volts

- Binary two (**10**) could represent a 2 Volt signal.
- To encode the signal to an accuracy of 1 part in 64 (1.5% precision), 6 binary digits ("bits") are needed

Example 2: Sine wave signal of known frequency and maximum amplitude 50 μV; 1 μV "resolution" needed.

Reminder About Binary and Decimal Numbering Systems

$$
\begin{aligned}
110001_2 &= 1\times2^5 + 1\times2^4 + 0\times2^3 + 0\times2^2 + 0\times2^1 + 1\times2^0 \\
&= 32_{10} + 16_{10} + 1_{10} \\
&= 49_{10} \\
&= 4\times10^1 + 9\times10^0
\end{aligned}
$$

Example 2 (continued)

Possible digital representation for the sine wave signal:

Analog representation: Amplitude in μV	**Digital representation:** Binary number
1	000001
2	000010
3	000011
4	000100
5	000101
8	001000
16	010000
32	100000
50	**110010**
63	111111

Why Digital?

(For example, why CDROM audio *vs.* vinyl recordings?)

- Digital signals can be transmitted, received, amplified, and re-transmitted with no degradation.
- Digital information is easily and inexpensively stored (in RAM, ROM, *etc*.), with arbitrary accuracy.
- Complex logical functions are easily expressed as binary functions (*e.g.* in control applications).
- Digital signals are easy to manipulate (as we shall see).

Digital Representations of Logical Functions

Digital signals offer an easy way to perform logical functions, using Boolean algebra.

- Variables have two possible values: **"true"** or **"false"**
  – usually represented by **1** and **0**, respectively.

All modern control systems use this approach.

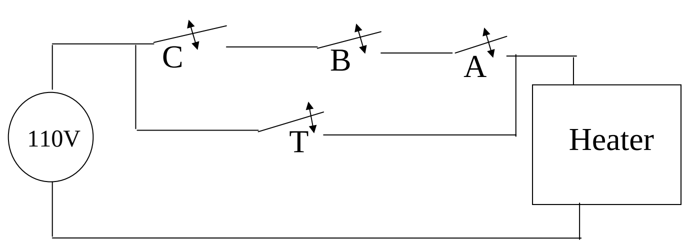
Example: Hot tub controller with the following algorithm

Turn on the heater if the temperature is less than desired ($T < T_{set}$) ***and*** the motor is on ***and*** the key switch to activate the hot tub is closed. Suppose there is also a "test switch" which can be used to activate the heater.

Hot Tub Controller Example

- Series-connected switches:
  - A = thermostatic switch
  - B = relay, closed if motor is on
  - C = key switch
- Test switch T used to bypass switches A, B, and C

Simple Schematic Diagram of Possible Circuit



"Truth Table" for Hot Tub Controller

A	B	C	T	H
0	0	0	0	0
0	0	1	0	0
0	1	0	0	0
0	1	1	0	0
1	0	0	0	0
1	0	1	0	0
1	1	0	0	0
1	1	1	0	1
0	0	0	1	1
0	0	1	1	1
0	1	0	1	1
0	1	1	1	1
1	0	0	1	1
1	0	1	1	1
1	1	0	1	1
1	1	1	1	1

Notation for Logical Expressions

Basic logical functions:

AND: "dot" Example: X = A·B

OR: "+ sign" Example: Y = A+B

NOT: "bar over symbol" Example: Z = A

- **Any logical expression can be constructed using these basic logical functions**

Additional logical functions:

Inverted AND = NAND: $\overline{AB}$ (only 0 when A and $B=1$)

Inverted OR = NOR: $\overline{A+B}$ (only 1 when $A=B=0$)

Exclusive OR: $A \oplus B$ (only 1 when A, B differ)
i.e., $A+B$ **except** $A \cdot B$

Hot Tub Controller Example (cont'd)

First define logical values:

• closed switch = "true", *i.e.* boolean **1**

• open switch = "false", *i.e.* boolean **0**

Logical Statement:

Heater is on (H = 1) if A and B and C are 1, or if T is 1.

Logical Expression:

H=**1** if (A **and** B **and** C are **1) or (**T is **1)**

Boolean Expression:

$H = (A \cdot B \cdot C) + T$ ← **Implemented using digital logic gates**

Summary

Attributes of digital electronic systems:

1. Ability to represent real quantities by coding information in digital form

2. Ability to control a system by manipulation and evaluation of binary variables using Boolean algebra

Introduction to circuit analysis

OUTLINE

- Electrical quantities
  - Charge
  - Current
  - Voltage
  - Power
- The ideal basic circuit element
- Sign conventions

Reading

Chapter 1

Circuit Analysis

- **Circuit analysis is used to predict the behavior of the electric circuit, and plays a key role in the design process.**
  - Design process has analysis as fundamental 1st step
  - Comparison between desired behavior (specifications) and predicted behavior (from circuit analysis) leads to refinements in design
- **In order to analyze an electric circuit, we need to know the behavior of each circuit element (in terms of its voltage and current) AND the constraints imposed by interconnecting the various elements.**

Electric Charge

Macroscopically, most matter is electrically neutral most of the time.

Exceptions: clouds in a thunderstorm, people on carpets in dry weather, plates of a charged capacitor, *etc.*

Microscopically, matter is full of electric charges.

- **Electric charge exists in discrete quantities, integral multiples of the electronic charge -1.6 x 10^{-19} coulombs**

- **Electrical effects are due to**
  - **separation of charge** → electric force **(*voltage*)**
  - **charges in motion** → electric flow **(*current*)**

Classification of Materials

Solids in which all electrons are tightly bound to atoms are ***insulators***.

Solids in which the outermost atomic electrons are free to move around are ***metals***.

Metals typically have ~1 "free electron" per atom (~5 ×10^{22} free electrons per cubic cm)

Electrons in ***semiconductors*** are not tightly bound and can be easily "promoted" to a free state.

insulators	semiconductors	metals
Quartz, SiO_2	Si, GaAs	Al, Cu
dielectric materials		excellent conductors

Electric Current

Definition: rate of positive charge flow
Symbol: i
Units: Coulombs per second ≡ Amperes (A)

$$i = dq/dt$$

where q = charge (in Coulombs), t = time (in seconds)

Note: Current has polarity.

Electric Current Examples

1. 10^5 positively charged particles (each with charge 1.6×10^{-19} C) flow to the right ($+x$ direction) every nanosecond

$$I = \frac{Q}{t} = +\frac{10^5 \times 1.6 \times 10^{-19}}{10^{-9}} = 1.6 \times 10^{-5} \text{ A}$$

2. 10^5 electrons flow to the right ($+x$ direction) every microsecond

$$I = \frac{Q}{t} = -\frac{10^5 \times 1.6 \times 10^{-19}}{10^{-9}} = -1.6 \times 10^{-5} A$$

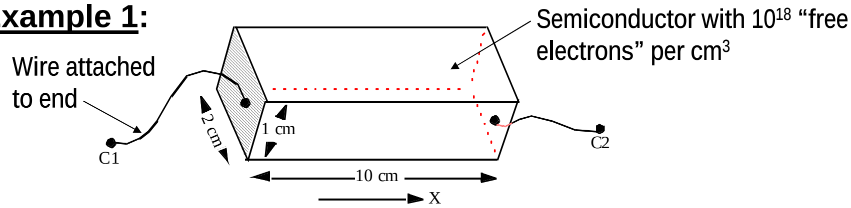
Current Density

Definition: rate of positive charge flow per unit area

Symbol: J

Units: A / cm^2

Example 1:



Suppose we force a current of 1 A to flow from C1 to C2:

- Electron flow is in $-x$ direction:

$$\frac{1C/\sec}{-1.6\times10^{-19}C/electron} = -6.25\times10^{18}\frac{electrons}{\sec}$$

Current Density Example (cont'd)

What is the current density in the semiconductor?

Example 2:

Typical dimensions of integrated circuit components are in the range of 1 μm. What is the current density in a wire with 1 μm² area carrying 5 mA?

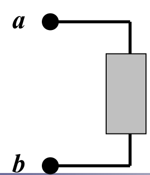
Electric Potential (Voltage)

- **Definition**: energy per unit charge
- **Symbol**: v
- **Units**: Joules/Coulomb ≡ Volts (V)

$$v = dw/dq$$

where w = energy (in Joules), q = charge (in Coulombs)

Note: Potential is always referenced to some point.



Subscript convention:

v_{ab} means the potential at a minus the potential at b.

$$v_{ab} \equiv v_a - v_b$$

Electric Power

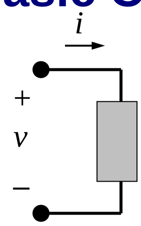
- **Definition**: transfer of energy per unit time
- **Symbol**: p
- **Units**: Joules per second ≡ Watts (W)

$$p = dw/dt = (dw/dq)(dq/dt) = vi$$

- **Concept**:

  As a positive charge q moves through a drop in voltage v, it loses energy
  - energy change = qv
  - rate is proportional to # charges/sec

The Ideal Basic Circuit Element



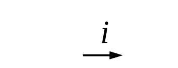
- Polarity reference for voltage is indicated by plus and minus signs
- Reference direction for the current is indicated by an arrow

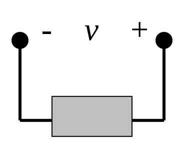
Attributes:

- Two terminals (points of connection)
- Mathematically described in terms of current and/or voltage
- Cannot be subdivided into other elements

A Note about Reference Directions

A problem like "Find the current" or "Find the voltage" is always accompanied by a definition of the direction:



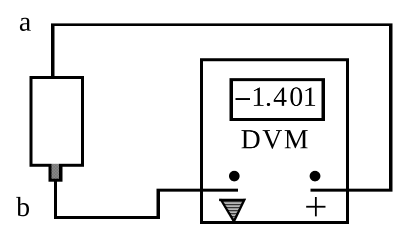


In this case, if the current turns out to be 1 mA flowing to the left, we would say i = -1 mA.

In order to perform circuit analysis to determine the voltages and currents in an electric circuit, you need to specify reference directions. There is no need to guess the reference direction so that the answers come out positive, however.

Sign Convention Example

Suppose you have an unlabelled battery and you measure its voltage with a digital voltmeter (DVM). It will tell you the **magnitude and sign** of the voltage.



With this circuit, you are measuring v_{ab}.

The DVM indicates −1.401, so v_a is lower than v_b by 1.401 V.

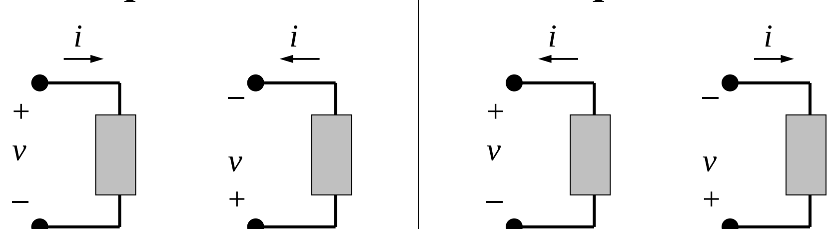
Which is the positive battery terminal?

Note that we have used the “ground” symbol (▼) for the reference node on the DVM. Often it is labeled “C” for “common.”

Sign Convention for Power

Passive sign convention

$p = vi$ $p = -vi$

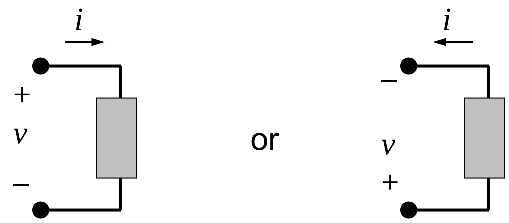


- **If $p > 0$, power is being delivered to the box.**
- **If $p < 0$, power is being extracted from the box.**

Power

If an element is absorbing power (*i.e.* if $p > 0$), positive charge is flowing from higher potential to lower potential.

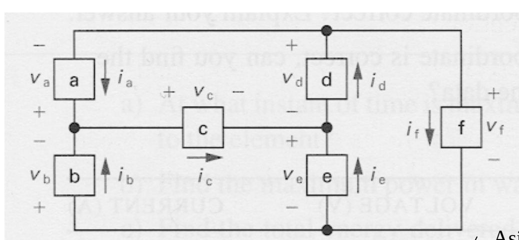
$p = vi$ if the "passive sign convention" is used:



How can a circuit element absorb power?

By converting electrical energy into heat (resistors in toasters), light (light bulbs), or acoustic energy (speakers); by storing energy (charging a battery).

Power Calculation Example



h element:

Conservation of energy
➔ total power delivered
equals
total power absorbed

Aside: For electronics these are unrealistically large currents – milliamperes or smaller is more typical

ELEMENT	VOLTAGE (V)	CURRENT (A)	*vi* (W)	*p* (W)
a	–18	–51	**918**	
b	–18	45	**- 810**	
c	2	–6	**- 12**	
d	20	–20	**- 400**	
e	16	–14	**- 224**	
f	36	31	**1116**	

Summary

- ***Current*** = rate of charge flow
- ***Voltage*** = energy per unit charge created by charge separation
- ***Power*** = energy per unit time
- ***Ideal Basic Circuit Element***
  - 2-terminal component that cannot be sub-divided
  - described mathematically in terms of its terminal voltage and current
- ***Passive sign convention***
  - Reference direction for current through the element is in the direction of the reference voltage drop across the element