EE40: Introduction to Microelectronic Circuits

Summer 2006

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First Week Announcements

- Class web page will be up today. 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 section: Th 12-2.
- Labs begin this week. Attend your only second lab slot this week.
  - Cancelled labs: ThF 2-5.
  - 8 Labs and 2 Project Labs.
- Weekly homeworks
  - Assignment on web on Monday. Due following Monday in hw box at 6pm.
  - 1^{st} Homework online today and next Monday. Sorry!
- 2 Midterms
  - Tentatively on 07/11 and 07/27.

Announcements cont'd

- My Office Hours
  - M,W,F 11-12 in Cory 382
  - Or just e-mail me at ***florescu@eecs***
- TAs:
  - Lab TA: Mary Knox, ***knoxm@eecs***
  - Discussion TA: Micheal Krishnan, ***mnk@berkeley***
  - Reader: Bill Hung, ***billhung@berkeley***
- TA Office Hours
  - TBD

Lecture 1

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

EE40: Course Overview

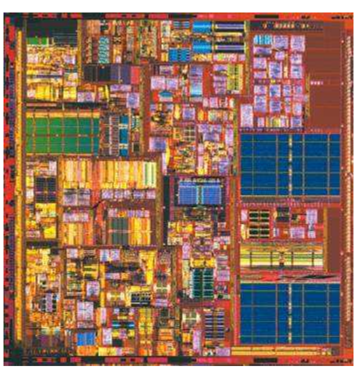
- EECS 40:
  - One of five EECS core courses (with 20, 61A, 61B, and 61C)
    - introduces "hardware" side of EECS
    - prerequisite for EE105, EE130, EE140, EE141
  - Prerequisites: Math 1B, Physics 7B
- Course content:
  - Electric circuits
  - Integrated-circuit devices and technology
  - CMOS digital integrated circuits

Course Overview Cont'd

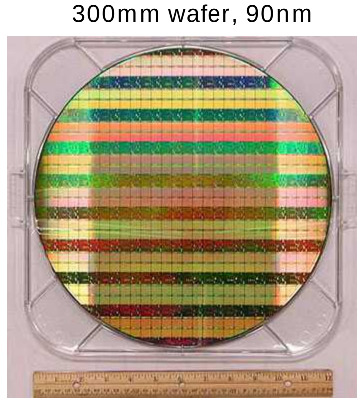
- Circuit components
  - Resistor, Dependent sources, Operational amplifier
- Circuit Analysis
  - Node, Loop/Mesh, Equivalent circuits
  - First order circuit
- Active devices
  - CMOS transistor
- Digital Circuits
  - Logic gates, Boolean algebra
  - Gates design

What is an Integrated Circuit?

P4 2.4 Ghz, 1.5V, $131mm^2$

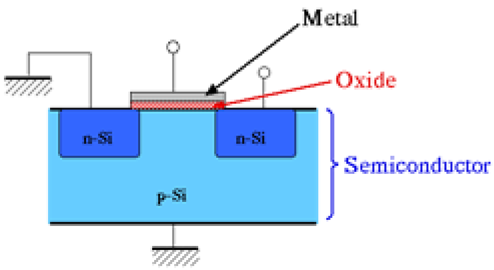


300mm wafer, 90nm

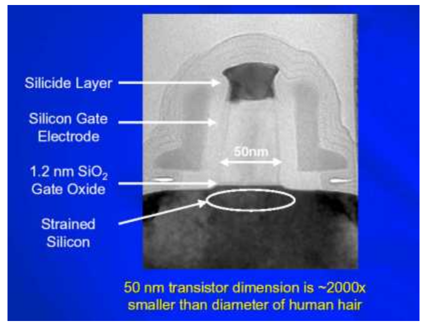


- Designed to performs one or several functions.
- Composed of up to 100s of Millions of transistors.

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

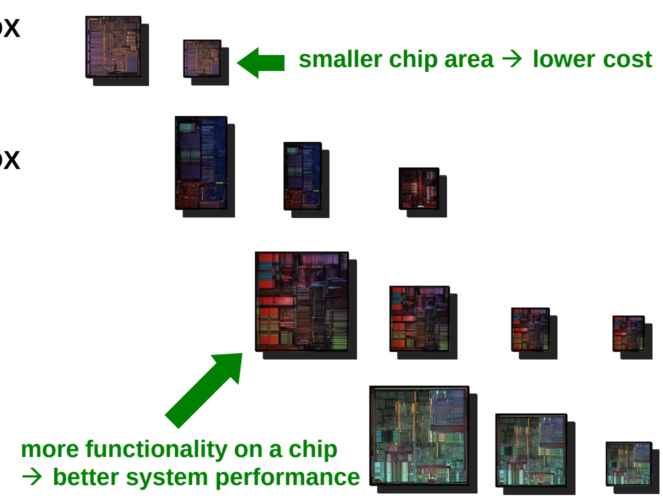
Generation: **1.5µ** **1.0µ** **0.8µ** **0.6µ** **0.35µ** **0.25µ**

Intel386™ DX Processor

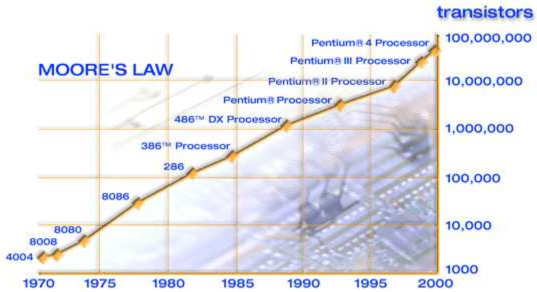
Intel486™ DX Processor

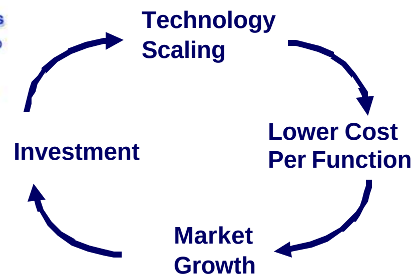
Pentium® Processor

Pentium® II Processor



Technology Scaling: Moore's Law



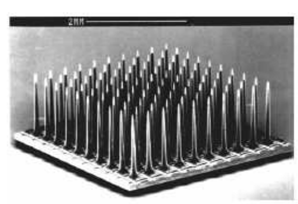


- Number of transistors double every 18 months
  - Cost per device halves every 18 months
  - More transistors on the same area, more complex and powerful chips
  - Cost per function decreases

Some Applications



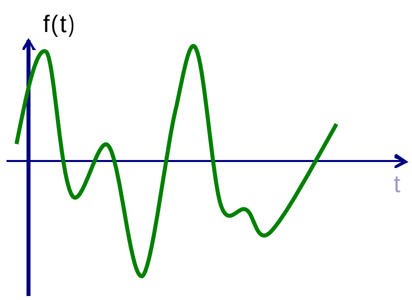
- Computers
- Communication Devices
- Automotive sensors/actuators
- Biotechnology



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



g(z)

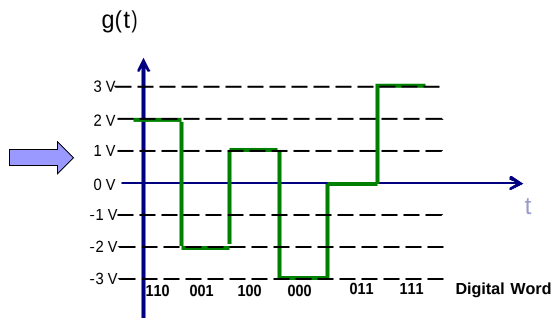
110, 001, 100, 000, 011, 111…

- Analog
  - May represent a physical phenomenon directly
  - Continuous in time
  - f(t) is a real scalar
- Digital
  - Array of discrete words
  - *z* in *g(z)* is integer and indexes one discrete word of the array

Digital Representation

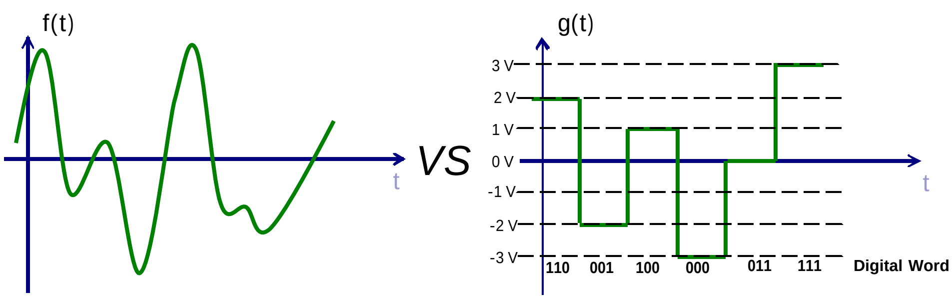
g(z)

110, 001, 100, 000, 011, 111…



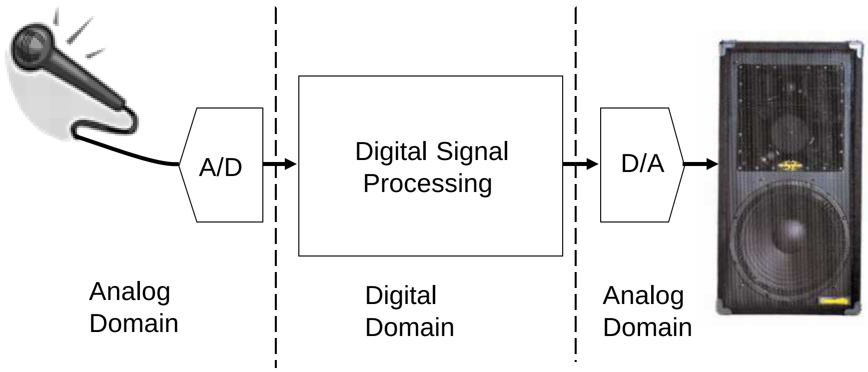
- Each digital word can be represented by a discrete amplitude
- Can be a quantization of an analog signal
- g(t) takes on discrete, quantized values

Analog *vs.* Digital Signals



- Most (but not all) observables are analog.
- The most convenient/efficient way to represent, transmit and manipulate information electronically is to use digital signals.
- Analog-to-digital (A/D) & digital-to-analog (D/A) conversion is essential and nothing new; think sheet music converted to song.

Typical Microelectronic System: Audio System



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 -1.6×10^{-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 ($\sim 5 \times 10^{22}$ 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.

$$I = \frac{Q}{t} = \frac{10^5 \times 1.6\times10^{-19}}{10^{-9}} = 1.6\times10^{-5}\ \text{A}$$

2. 10^5 electrons flow to the right ($+x$ direction) every 15 microseconds.

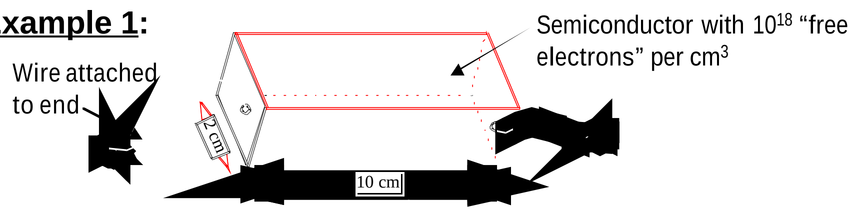
Current Density

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?

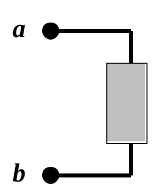
Electric Potential (Voltage)

- **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} $v_a - v_b$

Electric Power

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

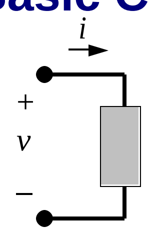
$$p = dw/dt = (dw/dq)(dq/dt) = vi$$

- **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

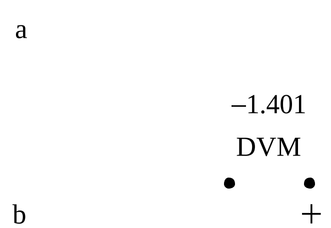
A problem like “Find the current” or “Find the voltage” is always accompanied by a definition of the direction:

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.

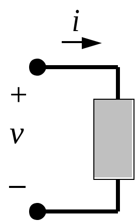
Which is the positive battery terminal?

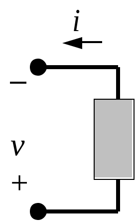
Note that we have used the “ground” symbol (▽) for the reference node on the DVM. Often it is labeled “C” for “common.”

Sign Convention for Power

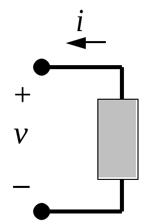
<u>**Passive sign convention**</u>

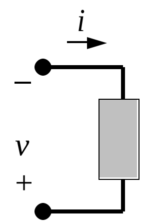
p* = *vi





p* = -*vi



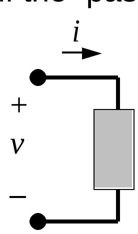


- **If $p > 0$, power is being delivered to the box.**
- **If $p < 0$, power is being extracted from the box.**

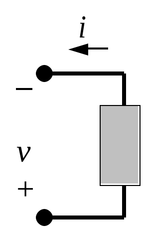
Power

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:



or

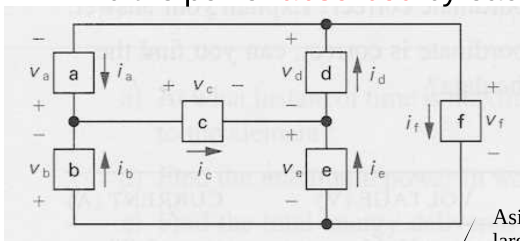


How can a circuit element absorb power?

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

Find the power absorbed by each 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