MICROELECTRONICS

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Recommended Reading

- I. Sutherland, B. Sproull, D. Harris, "Logical Effort - Designing Fast CMOS Circuits", Morgan Kaufmann Publishers 1999; http://www.mkp.com/Logical_Effort
- W. Marciniak “Przyrządy półprzewodnikowe MOS”, WNT 1991
Syllabus

• Introduction
• The MOS Transistor
• Integrated Circuits (IC) Manufacturing Technologies
• MOS Digital Circuit Families
• Delay Calculation in CMOS Circuits – Logical Effort
• IC Design Methodologies
• MICROELECTRONICS [gr.], branch of electronics dealing with operation, construction and technology of → integrated circuits.

• INTEGRATED CIRCUIT, miniature electronic circuit, which part or all components are manufactured together with the interconnections in one technological cycle in or on the surface of a common substrate.
The History of Computing
• Abacus – 3000 BC
• Adding machine: B. Pascal – 1642
• Multiplying machine: G. Leibniz – 1694
• Difference engine: Charles Babbage 1823
• Analytical machine: Charles Babbage 1833
  – The mill (CPU), the store (memory), control, punched card reader, card puncher
  – Control from the external source (punched cards)
  – Ada (Byron) Lovelace - considered a world's first programmer
Mechanical
• Electromechanical calculator with punched cards H. Hollerith 1890.

• Electromechanical calculator Mark I 1944
  – H. Aiken: 1937-1944, USA, Harvard University + IBM
  – 750 000 components, 900 km of wires, weight 5 T
  – addition 0.3 s, multiplication 6 s
Photo # NH 96566-KN  First Computer "Bug", 1945

0800  Andam started           1.2100  9.037 847 025
1000  stopped - andam ✓       9.037 846 945  control
MP - MC  1.305 5495 000 7.615 925069 (.)
033   PRO 2  2.130476816
control 2.130676815

Relays 6-2 in 033 failed speed square test
In Relay
Relays changed
Relays changed (Sine chest)
1525  Started Cosine Tape
1545  Started Multi + Adder Test.
Relay #70 Panel F
(moth) in relay.

First actual case of bug being found.
1900  Andam started.
1700  Crash down.
1941 – John Atanasoff and Clifford Berry - ABC (calculator) – vacuum tubes
• 1943 – Colossus - code cracking calculator (1500 vacuum tubes)
  – data on perforated paper tape
• 1944 – Colossus 2 (2500 tubes)
I Generation Computers (1945-1953)

1943-1946 – ENIAC – the first electronic computer
- Electronic Numerical Integrator And Computer
- John Eckert, John Mauchly
- 18,000 vacuum tubes, 70,000 resistors, 1,500 relais, weight 30 T,
- Power consumption 174 kW, cost 750,000 $
- Addition: 0.2 ms
- Numbers encoded in decimal, every digit stored in 10-position counter (36 tubes), 10 digits stored in an accumulator.
  - The whole machine: 20 accumulators.
- The control of the machine operation: setting 10-position electric switches
Replacing a bad tube meant checking among ENIAC's 19,000 possibilities.
I Generation Computers

- 1944 – 1949 EDVAC  John von Neumann et al
- Electronic Discrete Variable Automatic Computer
  - stored program machine;
  - basic components:
    - arithmetical and logical unit, memory, input, output, control
    - binary system
    - memory - mercury delay line
- 1951 – UNIVAC I - first successfull commercial computer
Mercury Memory
II Generation Computers (1954-1964)

- **Technology:**
  - digital circuits: transistors
  - memories: drum memory (initially), ferrite memory
III Generation Computers (1965-1971)

• Technology:
  – Digital circuits: low and medium scale of integration integrated circuits
  – Memories: ferrite memory (initially), integrated circuits
III Generation Computers

- Interesting dates:
  - 1965 – IBM 360
  - 1971 – IBM 370 - 70 % of computer market
  - 1968 – PDP-8 - 12-bit minicomputer with a bus architecture
  - 1970 – PDP 11 - 16-bit minicomputer with a bus architecture
  - 1972 – Illiac IV - matrix computer with 64 processing units
IV Generation Computers (1971 - now)

• **Technology:**
  – Digital circuits: very-large scale of integration digital circuits
  – Memories: VLSI circuits
History of Electronics
Ambrose Fleming at Marconi Company patents the two-electrode radio rectifier, which he called the thermionic valve; it is also known as the vacuum diode, kenotron, thermionic tube, and Fleming valve.
Lee De Forest devises a three-electrode tube, or triode; the device is capable of detecting and amplifying radio signals. It was also known as an 'Audion valve'.

On December 23, 1947 William Shockley, Walter Brattain and John Bardeen at Bell Labs demonstrate their new invention of the point-contact transistor amplifier. The name transistor is short for "transfer resistance".
William Shockley, co-inventor of the transistor seven years earlier, founds Shockley Semiconductor Laboratories in Santa Clara Valley. He recruits 12 young scientists dedicated to the use of germanium and silicon for transistors -- his “Ph.D. production line.” Shockley wins the Nobel Prize for Physics in 1956, but his management style and disenchantment with pure research causes the eight young scientists to leave company.

The silicon and germanium mesa allows manufacturers to produce multiple transistors on a single wafer.

Fairchild Camera and Instrument Corporation invests $1.5 million in return for an option to buy the company within eight years. On October 1, 1957, Fairchild Semiconductor is born. The new company is profitable in six months with the help of its first sale: an order from IBM™ for 100 transistors at $150 a piece.
At Texas Instruments, Jack Kilby builds the first integrated circuit – an oscillator consisting of one transistor, two resistors and one capacitor – all of them made of germanium.

On September 12, 1958, Texas Instruments executives gathered around Kilby's oscillator, a complete circuit on a chip less than half an inch long. Kilby pushed the switch, and a bright green thread of light snaked across the screen. The integrated circuit worked, and a new era in microelectronics was born.
Jean Hoerni at Fairchild Semiconductors invents a planar transistor, where a collector, base and emitter are all on one plane. Using this device, Robert Noyce develops the monolithic integrated circuit -- a flip-flop consisting of six devices on a fingernail-size wafer of silicon. Today, nearly fifty years later, the planar process is the primary method for producing transistors.
Types of Integrated Circuits

- Hybrid
  - Thick-film
  - Thin-film
- Monolithic
Thick-Film Circuits

Unpackaged components

- Wire connection
- Ball-grid Array
- Tape connections

Packaged Component

- Solder
- Thin-film resistor
- Substrate
- Discrete capacitor
Thick-Film Circuits
Thin-Film Circuits

![Diagram of a thin-film transistor (TFT)](image)

- Polaizer film
- Upper glass substrate
- Color filter
- Transparent electrodes
- Liquid crystal display
- Signal electrodes
- Scanning electrodes
- Thin Film Transistor (TFT)
- Lower glass substrate
- Transparent electrodes
- Polaizer film

Light
Monolithic Circuits

Package (FR4)

Integrated circuit (Silicon)

Balls for interconnection

Main printed circuit board

Active part of the IC

Silicon die (350μm thick, 1cm width)

Solder bumps to link the IC to the package (Narrow pitch)

FR4 package

Metal interconnects

Printed circuit board

Solder bumps to link the package to the printed circuit board (Large pitch)
Advantages of Integrated Circuits

- Low cost
- Low size
- High quality and reliability
- Same temperature characteristics of all the components
IC Development

- The 60’s: First ICs
- The 70’s: Microprocessors
- The 80’s: ASICs (Application Specific Integrated Circuits)
- The 90’s: Micro Electro-Mechanical Systems (MEMS)
- The 2000’s: System on Chip
The 60’s – First ICs

1958 First IC (J. Kilby - T.I.)
1960 First commercial IC - logic RTL circuits MICROLOGIC - (Fairchild)
1964 TTL circuits (series 54 i 74 - Texas Instruments)
1965 First Operational Amplifier μA 702 - (Fairchild)
1967 OPAMP with high input impedance μA 709, first comparator μA 710
1967 First ROM memory 64 bits - (MOS technology, Fairchild)
1968 μA 741
1968 OPAMP with input JFET transistors
1968 CMOS technology (RCA), calculators, watches, …
1968 ROM memory 1024 bits (PHILCO)
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>INTEL first commercial 4 bit microprocessor 4004, with 45 instructions. PMOS Technology, 2300 transistors.</td>
</tr>
<tr>
<td>1972</td>
<td>First 8 bit microprocessor 8008 (INTEL).</td>
</tr>
<tr>
<td>1973</td>
<td>INTEL 8080, NMOS technology, improved by Zilog - Z80</td>
</tr>
<tr>
<td>1974</td>
<td>First CMOS microprocessor-1802 (RCA).</td>
</tr>
<tr>
<td>1974</td>
<td>MOTOROLA 6800 - single 5V supply voltage.</td>
</tr>
<tr>
<td>1976</td>
<td>First microcontroller 8048 (INTEL).</td>
</tr>
</tbody>
</table>
Intel 4004

- 2,300 transistors
- 10-micron technology
- 46 instructions
- 40,000 instructions per second
- 4-bit data/address bus.
- 4-bit accumulator with separate carry and test bits,
- Sixteen 4-bit 'scratch-pad' registers (which can be used as eight 8-bit registers),
- A 12-bit PC (program counter), and three more 12-bit registers comprising an address stack

In 1972 on board of Pioneer 10, until 1998 the most distant human-made object (currently Voyager 1)
INTEL Processors

1978 INTEL 8086
1982 INTEL 80286
1989 INTEL 80486
1993 INTEL Pentium
1999 INTEL Pentium III
2000 INTEL Pentium 4
2004 INTEL Itanium 2
2006 INTEL Core Duo Processor
2007 INTEL Core 2 Quad Processor

Photo of a die of dual-core Intel Penryn processor (45 nm) introduced in second half of 2007
## Number of Transistors in Different Processors

<table>
<thead>
<tr>
<th>Year of introduction</th>
<th>Processor</th>
<th>Number of transistors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>4004</td>
<td>2,300</td>
</tr>
<tr>
<td>1972</td>
<td>8008</td>
<td>2,500</td>
</tr>
<tr>
<td>1974</td>
<td>8080</td>
<td>4,500</td>
</tr>
<tr>
<td>1978</td>
<td>8086</td>
<td>29,000</td>
</tr>
<tr>
<td>1982</td>
<td>Intel286</td>
<td>134,000</td>
</tr>
<tr>
<td>1985</td>
<td>Intel386™ processor</td>
<td>275,000</td>
</tr>
<tr>
<td>1989</td>
<td>Intel486™ processor</td>
<td>1,200,000</td>
</tr>
<tr>
<td>1993</td>
<td>Intel® Pentium® processor</td>
<td>3,100,000</td>
</tr>
<tr>
<td>1997</td>
<td>Intel® Pentium® II processor</td>
<td>7,500,000</td>
</tr>
<tr>
<td>1999</td>
<td>Intel® Pentium® III processor</td>
<td>9,500,000</td>
</tr>
<tr>
<td>2000</td>
<td>Intel® Pentium® 4 processor</td>
<td>42,000,000</td>
</tr>
<tr>
<td>2001</td>
<td>Intel® Itanium® processor</td>
<td>25,000,000</td>
</tr>
<tr>
<td>2002</td>
<td>Intel® Itanium® 2 processor</td>
<td>220,000,000</td>
</tr>
<tr>
<td>2004</td>
<td>Intel® Itanium® 2 process or (9MB cache)</td>
<td>592,000,000</td>
</tr>
<tr>
<td>2006</td>
<td>Dual-Core Intel Itanium 2</td>
<td>1,720,000,000</td>
</tr>
</tbody>
</table>
Moore’s Law (1965) – number of transistors in an integrated circuit doubles every 18 months

Gates’ Law

The speed of software halves every 18 months.

<table>
<thead>
<tr>
<th>Year</th>
<th>Memory [MB]</th>
<th>Processor Speed [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1991</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1992</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>1993</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>1994</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>1995</td>
<td>Windows 95</td>
<td>Windows 95</td>
</tr>
<tr>
<td>1996</td>
<td>Windows 98</td>
<td>Windows 98</td>
</tr>
<tr>
<td>1998</td>
<td>Windows XP</td>
<td>Windows XP</td>
</tr>
<tr>
<td>1999</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td></td>
<td></td>
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<tr>
<td>2001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2003</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
VLSI Feature Size

Feature Size [nm]

Year


1994 SIA Roadmap
1997 SIA Roadmap
1999 SIA Roadmap
Actual

Bacteria ca. 0.1 µm
## Rising Fab Costs

<table>
<thead>
<tr>
<th>Year</th>
<th>Wafer</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983</td>
<td>4&quot;/5&quot;</td>
<td>1.2-um</td>
</tr>
<tr>
<td>1987</td>
<td>5&quot;/6&quot;</td>
<td>1.0-um</td>
</tr>
<tr>
<td>1990</td>
<td>6&quot;</td>
<td>0.8-um</td>
</tr>
<tr>
<td>1994</td>
<td>6&quot;/8&quot;</td>
<td>0.5-um</td>
</tr>
<tr>
<td>1997</td>
<td>8&quot;</td>
<td>0.35-um</td>
</tr>
<tr>
<td>1999</td>
<td>8&quot;</td>
<td>0.25-um</td>
</tr>
<tr>
<td>2001</td>
<td>12&quot;</td>
<td>0.13-um</td>
</tr>
<tr>
<td>2003</td>
<td>12&quot;</td>
<td>0.09-um</td>
</tr>
</tbody>
</table>

Source: Dataquest, UMC
**Miniaturization**

- **PCB**
- **Diced chip**
- **MEMS devices**
- **TR on IC**
- **Nanotube FET**

**Measurement Scale**

- **m**
- **cm**
- **mm**
- **µm**
- **nm**
- **Å**

**Examples**

- **Human**: ~ 2 m
- **Ant**: ~ 5 mm
- **Grain of sand**: ~ 1 mm
- **Hair**: ~ 100 µm
- **Ant eye segment**: ~ 5 µm
- **DNA**: ~ nm
- **Bacteria**: ~ 0.1 µm
- **Atom**: ~ Å
Miniaturization
- Basic parameters
  - Logic gate delay
  - Power dissipation
- Synthetic parameter
  - Power-delay product
• Standard
• Application Specific Integrated Circuits (ASIC)
• Application Specific Standard Product (ASSP)
Standard ICs

- **Advantages of Standard ICs**
  - Low cost
  - “Off-the-shelf” availability
  - Known reliability
  - Many suppliers (usually)

- **Disadvantages of Standard ICs**
  - Not optimized for a specific system
  - Hard to create a unique product
  - High area consumption
The 80’s – The ASIC Circuits

ASIC

CUSTOM

SEMI-CUSTOM

CELL-BASED

ARRAY-BASED

STANDARD CELLS

MACRO CELLS

CUSTOM ROUTING

PROGRAMMABLE,
FUSABLE (FPGA)
Classification of ASICs

- **Semicustom**
  - Interconnection masks customized

- **Custom**
  - All masks customized
    - Standard Cell
    - Full Custom

- **Programmable (Field Programmable Logic Devices)**
  - Writable (Laser, Fuse, Antifuse, OTP EPROM)
  - Writable/erasable (EPROM, EEPROM, Flash memory, Ferroelectric)
  - Volatile (SRAM, FPGA)
“Field Engineer”
PROM

- The simplest Programmable Logic Device
- Predefined AND matrix, programmable OR matrix
Programmed PROM

Predefined AND array

Address 0
Address 1
Address 2
Address 3
Address 4
Address 5
Address 6
Address 7

Programmable OR array

$
\begin{align*}
\text{w} & = (a \& b) \\
\text{x} & = \neg(a \& b) \\
\text{y} & = (a \& b) \oplus c
\end{align*}
$
PLA (Programmable Logic Array)

Predefined AND array

Programmable OR array

- Predefined link
- Programmable link

a!a b!b c!c

w x y

N/A N/A N/A N/A
Programmed PLA

- Programable OR and AND matrices

\[
\begin{align*}
w &= (a \land c) \lor (!b \land \neg c) \\
x &= (a \land b \land c) \lor (!b \land \neg c) \\
y &= (a \land b \land c)
\end{align*}
\]
• Complementary to PROM
• Programmable AND matrix, predefined OR matrix
Complex Programmable Logic Devices

- Macrocells
- Fully programmable AND/OR array
FPGAs

- Three main components:
  - Configurable Logic Blocks (CLB)
  - Programmable input/output blocks
  - Programmable connections
• Every slice contains two logic cells
LUT (Look-Up Table)

Required function:
\[ y = (a \& b) \mid \neg c \]

Truth table:

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>c</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
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<tr>
<td>0</td>
<td>1</td>
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<td>1</td>
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<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Programmed LUT:

SRAM cells

8:1 Multiplexer

\[ y \]
Leading FPGA Manufacturers

• Xilinx Inc. – www.xilinx.com
• Altera Corp.– www.altera.com
• Atmel Corp.– www.atmel.com
• Lattice Semiconductor Corp. – www.latticesemi.com
• Actel Corp.–www.actel.com
• QuickLogic Corp. – www.quicklogic.com
FPGA Market – Q1 2005

**PLD Segment**
- Actel: 5%
- Lattice: 7%
- QuickLogic: 2%
- Other: 2%

**FPGA Sub-Segment**
- Xilinx: 58%
- Altera: 31%
- All Others: 11%

*Source: Microelectronics*
Xilinx

• Main products: FPGA circuits and design software

• The company does not own a silicon foundry (fabless company)

• Manufactures its chips in the factories of:
  – UMC (Taiwan)
    • Xilinx owns UMC shares since 1996
  – Seiko Epson (Japan)
  – TSMC (Taiwan)
ASIC Advantages and Shortcomings

• ASIC Advantages
  – Optimized for a specific application
  – Effective area consumption
  – Higher performance (because of replacing a few circuits by one)

• ASIC Disadvantages
  – Higher cost
  – Development cost paid by the user
  – Single supplier
  – Need for own specialists in IC design
  – Long development cycle
The 90’s – MEMS (Micro Electro-Mechanical Systems)
MEMS Application – Projection TV

3 Pixel Image

Light Source

Projection Lens

Light Absorber

3 Pixel on Screen

3 DMD™ Micromirrors (Actual Top View)
MEMS Applications

- Automotive sensors
  - Accelerometers, force/torque sensors, pressure sensors
- Bio MEMS
  - Micro total analysis system (μTAS), DNA sequencing chips, clinical diagnostics, drug delivery systems
- Chemistry
  - Lab-on-a-chip, microreactor
- Optics
  - Digital micromirror devices (TI), grating light valve (GLV)
  - Optical interconnects, switching
- Data storage
  - Precision servo, shock sensors for HDD, new data storage mechanisms
- RF, microwave for communication
- Power generation
  - Micromachined turbine engines, MEMS power generators
- Recent researches
  - Harsh environment MEMS, MEMS/nano hybrid system (NEMS)
The 2000’s – System on Chip (SoC)

- Processor core with external hardware (network, USB, PCI interface ...) on the same chip
- Intellectual property (IP) -based design
- Design reuse
- Hardware-software co-design
- Custom or FPGA-based
Altera Excalibur Architecture
Tasks of A Designer

- Draw the schematic
- Draw the state diagram
- Describe in Hardware Description Language, e.g. VHDL* or Verilog
- Draw the masks

*VHDL - Very High Speed Integrated Circuits Hardware Description Language
Draw The Schematic
Draw The State Diagram

- **Idle**:
  - GATE=1'b0; END_MEASURE=1'b1; ENABLE=1'b0;

- **End Cycle**:
  - GATE=1'b0; END_MEASURE=1'b0; ENABLE=1'b0;

- **Convert**:
  - GATE=1'b0; END_MEASURE=1'b0; ENABLE=1'b1;

- **Open Gate**:
  - GATE=1'b1; END_MEASURE=1'b0; ENABLE=1'b0;

- **Close Gate**:
  - GATE=1'b0; END_MEASURE=1'b0; ENABLE=1'b0;
module mux (f, a, b, sel);
  output  f;
  input   a, b, sel;
  and #5  g1 (f1, a, nsel),
           g2 (f2, b, sel);
  or #5   g3 (f, f1, f2);
  not     g4 (nsel, sel);
endmodule
Draw The Masks
Draw The Masks

METROPOLIS – Your capital city has now achieved the status of metropolis. The current population is 100,000. With your planning skills, you should consider running for governor, or maybe VLSI design.

Continue
Draw The Masks
Masks and Schematic in Cadence
IC Layout

- Internal ground and power rings
- Supply pad
- Ground and power rings
- Output pad
- Input pad
- Routing channel
- Ground pad
- Row of standard cells
Design Tools

• Xilinx
• Synopsis
• Compass
• Cadence
• Mentor Graphics
Functions of the Design Tools

- Edition of text, schematic, layout
- Logic synthesis
- Layout versus Schematic (LVS)
- Design/Electrical Rule Checking (DRC/ERC)
- Place and Route
- Simulation
• Programmable circuits
• EUROPRRACTICE
• IET Experimental Line
• Western/Far East Silicon Foundries