Microelectronics

Prof. Dr. Michael Kraft
Lecture 1: Introduction, History and Market
History of Computing

- Babbage Difference Machine (1832)
  - Mechanical computer
  - 25000 parts, cost £17470

London Science Museum
Z3 by Konrad Zuse

- Electro-mechanical computer, 1941
- World's first working programmable, fully automatic digital computer
  - Z3 was built with 2000 relays, implementing a 22-bit word length that operated at a clock frequency of about 5–10 Hz
  - Program code and data were stored on punched film
ENIAC First Electronic Computer

- ENIAC contained 17,468 vacuum tubes, 7,200 crystal diodes, 1,500 relays, 70,000 resistors, 10,000 capacitors and around 5 million hand-soldered joints.

- First “general purpose computer”
  - digital, and capable of being reprogrammed to solve "a large class of numerical problems"
  - Used for to calculate artillery firing tables for the United States Army's Ballistic Research

- John Mauchly and J. Presper Eckert, 1946
Replacing a bad tube meant checking among ENIAC's 19,000 possibilities.
ENIAC ‘Boards’ and Operators
First Transistor - 1947

- 'Point Contact Transistor' made from Germanium
  - T-R-A-N-S-I-S-T-O-R: Resistor which can amplify electrical signals as they are transferred
- AT&T Bell Laboratories: William Shockley, Walter Brattain and John Bardeen
- 1956: Nobelpreis in physics
Transistor Patent

United States Patent Office

2,524,035

Three-electrode circuit element utilizing semi-conductive material

J. Bardeen, New York, N. Y.

Application filed Oct. 31, 1948. Serial No. 43,844

George E. Brattain, New York, N. Y.

Assignors to The Bell Telephone Laboratories, Incorporated, New York, N. Y., a corporation of New York

Filed: October 31, 1948

Claims:

1. A circuit element comprising a heavy doped non-conducting sheet, a conductor in contact with one face of the sheet, a contact for conducting current directly therethrough, and means for conducting current from said contact to an external circuit, wherein the contact is connected to said external circuit through the conducting sheet.

2. A circuit element comprising a heavy doped non-conducting sheet, a conductor in contact with one face of the sheet, a contact for conducting current directly therethrough, and means for conducting current from said contact to an external circuit, wherein the contact is connected to said external circuit through the conducting sheet.

3. A circuit element comprising a heavy doped non-conducting sheet, a conductor in contact with one face of the sheet, a contact for conducting current directly therethrough, and means for conducting current from said contact to an external circuit, wherein the contact is connected to said external circuit through the conducting sheet.

The present invention relates to an improved method of making a circuit element utilizing a semi-conductive material, and more particularly, to an improved method of making a circuit element utilizing a semi-conductive material such as selenium or zinc oxide, wherein the material is formed into a sheet or film, and the elements are formed into the sheet or film.

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Nobel Physics Prize Goes to 3 Americans: 2 Chemists Honored

By Felix Belair Jr.

Special to The New York Times

STOCKHOLM, Sweden, Nov. 1

The 1956 Nobel Prize in Physics was awarded today to three Americans who had worked as a team in developing the transistor. This is a tiny and highly efficient substitute for the vacuum tube in electronics.

The prize winners are Dr. William Shockley, the team captain; Dr. Walter H. Brattain and Dr. John Bardeen. The three, who did their work as research scientists of the Bell Laboratories of Murray Hill, N. J., will share the award of about $38,700 made under the terms of the will of Alfred Nobel, the Swedish inventor of dynamite.
First “Pocket Radio” - 1954

- Texas Instruments:
  "To sell a pocket radio at that point, it was our opinion that it would have to list at $50," Jonsson recalled. But four transistors times $16 wouldn't do it, so we had to design a manufacturing process so much better than any other at the time we could sell them for $2.50 each. We figured if we could get $10 for four transistors, the manufacturer could put the rest of the parts together for $17 or $18, sell a $50 radio, and still have a little left over for himself after paying a dealer. Well, we came up with the technique, and Regency bought the idea, and that radio went on the market at $49.95."
Design ‘Regency’

- Battery
- Speaker
- Adjustable capacitor

Antenna
‘Regency’ Circuit Diagram

RESISTANCE MEASUREMENTS

Based Upon Use of Meter With 1.5-Volt Internal Battery and 1,000-Ohm Center Range; All Measurements Taken With Positive Probe (Not Necessarily the Red Probe) Connected to Terminal Being Measured.

<table>
<thead>
<tr>
<th>TRANSISTOR</th>
<th>BASE</th>
<th>BASE (WITH METER LEADS REVERSED)</th>
<th>Emitter</th>
<th>COLLECTOR (MEASURED FROM B+ LINE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>7KΩ</td>
<td>3.0KΩ</td>
<td>10KΩ</td>
<td>2.2KΩ</td>
</tr>
<tr>
<td>X2</td>
<td>600Ω</td>
<td>3.0KΩ</td>
<td>750Ω</td>
<td>2.2KΩ</td>
</tr>
<tr>
<td>X3</td>
<td>750Ω</td>
<td>2.7KΩ</td>
<td>750Ω</td>
<td>2.2KΩ</td>
</tr>
<tr>
<td>X4</td>
<td>850Ω</td>
<td>3.5KΩ</td>
<td>750Ω</td>
<td>850Ω</td>
</tr>
</tbody>
</table>
First Silicon Transistor - 1954

Teal Gordon: 10 May 1954 at the Institute of Radio Engineers (IRE) National Conference on Airborne Electronics, in Dayton, Ohio:

"Some New and Recent Developments in Silicon and Germanium," an inauspicious title. The germanium transistor was no longer news. Industry-wide research had been conducted for some time on the use of silicon for transistors, because of its ability to withstand higher temperatures. However, as far as anyone knew, no one had been able grow silicon crystals with the characteristics needed for a workable transistor.

Speaker after speaker at the conference denied the near-term feasibility of the silicon transistor. Teal, next to last on the agenda, took his turn. TI cofounder Erik Jonsson recalled that Teal, "a quiet man," put everyone to sleep until, at the end of his speech, he calmly remarked, "Contrary to what my colleagues have told you about the prospects for silicon transistors, I happen to have a few here in my pocket". Teal's announcement that someone from TI was standing in the back of the auditorium with literature on the new device caused a stampede. "The poor last speaker was in trouble," Jonsson remembered. "He had no audience left."

Advantages of Si:
- Operating temp up to 150°C
- Higher output power
First Integrated Circuit- 1954

- Jack Kilby, Texas Instruments
  - [http://www.ti.com/corp/docs/company/history/tihistory.htm](http://www.ti.com/corp/docs/company/history/tihistory.htm)
- 1 Transistor, 1 capacitor, 3 resistors on one Germanium chip
- Nobel prize 2000
Planar Technology - 1959

- Much more effective fabrication
  - MESA – process suitable for volume production
- PNP Bipolar Transistor made from Silicon
First Commercial Planar Integrated Circuit - 1959

- Fairchild Electronics - Jean Hoerni und Robert Noyce: Planar Technology
- Fairchild – One Bit digital memory (flipflop) in resistor-transistor-logic (RTL)
  - 4 transistors, 5 resistors – Integration of more elements relatively simple
  - Advent of „Small Scale Integration“ : SSI
- Planar technology: doping by diffusion of other layers/elements
First MOSFET - 1962

- Metal-Oxide Semiconductor Field-Effect Transistor
- Radio Corporation of America (RCA)
- 'General Purpose Chip' with 16 transistors
RTL Logic - 1963

- Fairchild '907': RTL Logic: 4 Transistors, 5 resistors
- 'Buried Layer' under collector reduces resistance ⇒ higher speed
First Analogue IC- 1963

- Fairchild: Operational Amplifier (OpAmp) μA 702
- First integrated difference amplifier
OpAmp Bestseller - 1965

- Fairchild: OpAmp μA 709 – Designed by Robert ('Bob') Widlar
  - 14 transistors, 15 resistors
  - Still being fabricated
  - Gain ~70000
  - Price: $100 1968, today 0.5$

- Competition only in 1968
  μA 741 from Texas Instruments
Emitter Coupled Logic - 1966

- Motorola ECL Technology
  - Gate with 3 inputs
  - Bipolar transistors and resistors
- One metal layer
1st IC designed with CAD - 1967

- Fairchild: MICROMOSAIC
  - ca. 150 AND, OR, NOT gates
  - Generated from a pool of transistors by ‘application specific’ metallization
  - 'Mask programmable transistor array'
256 Bit Static RAM - 1970

- Fairchild: 4100
  - With decoder
  - 2.5mm x 3mm
  - Used in ILLIAC IV computer (NASA)
1024 Bit Dynamic RAM - 1970

- Intel Corporation
  - Founded 1968 by ex-Fairchild employees (Bob Noyce, Gordon Moore)
  - 4 x more bits on the same area as static RAMs
First Micro-Processor - 1974

- Intel 4004 (Marcian E. Hoff)
  - First ‘computer” on a chip
  - Advent of ‘large scale integration’ – LSI
  - 2300 MOSFETs
  - 4 bit
  - 108 kHz clock freq.
First EPROM - 1971

- Intel 1702
  - 2 kbit (256 x 8)
  - UV erasable
  - 3.7 mm x 4.1 mm
  - Customers could program $\mu$C
8080 Universal Processor - 1974

- Intel 8080
- 5000 Transistors
- 6 µm technology
- 2 MHz clock
- 8 bit
- 4mm x 5 mm
- Still produced in license by 12 companies
TI Competition - 1974

- TI IMS 1000 Micro Computer
  - CPU 4 bit
  - 256 RAM (right)
  - 1 kbit ROM (left)
- Used in pocket calculators and other consumer goods
8 bit DAC - 1974

- Precision Monolithic
  DAC08CPU 4bit
  - First hybrid IC
  - 140 ns settling time
  - Bipolar technology
  - Still being produced
  - 1.6 mm x 2.2 mm
AMD Fast µP - 1974

- AMD Advanced Micro Devices
- Bit slice processor: several processors work on wider data word
- Bipolar transistors:
  - High power consumption
  - But much faster than CMOS (at this time)
  - 10 MHz clock
Programmable Array Logic (PAL) - 1977

- MMI (Monolithic Memories Inc)
- Programmable logic with fuses
- PAL16L8
IBM starts chip business relatively late

Innovation:
- Memory chip with redundancy
- Bump bonds

65536 Bit Dynamic RAM - 1977
Motorola 16 Bits - 1979

- Motorola 68000
- NMOS transistors
- 16 bits but emulate 32 bits
- 50x faster than 8080
  - Multiplier on chip
Optical Mouse- 1980

- Xerox
- 16 optical detectors recognize the movement of illuminated background surface
Intel 80286 - 1982

- 6-12 MHz
- 16 bits
- 120000 transistors
- 1.5 μm technology
Intel Pentium - 1993

- 60 MHz
- 32 bits
- 3.1 mio transistors
- 0.8 μm technology
Intel Pentium IV - 2000

- 1.5 GHz
- 42 mio transistors
- 0.18 μm technology
Intel Pentium - 2009

- 1.5 GHz
- 2.9 billion transistors
- 0.022 μm technology
Moore’s Law

- In 1965, Gordon Moore noted that the number of transistors on a chip doubled every 18 to 24 months.
- He made a prediction that semiconductor technology will double its effectiveness every 18 months.
Moore’s Law

*Electronics, April 19, 1965.*
Transistor Number

Source: Intel

1 Billion Transistors

8086
80286
i386
i486
Pentium®
Pentium® Pro
Pentium® II
Pentium® III


Projected

Courtesy, Intel

K

1,000,000
100,000
10,000
1,000
100
10
1
Transistors on Lead Microprocessors double every 2 years
Die Size

Die size grows by 14% to satisfy Moore’s Law

~7% growth per year
~2X growth in 10 years

Courtesy, Intel
Clock Frequency

Doubles every 2 years

Lead Microprocessors frequency doubles every 2 years

Courtesy, Intel
Moore’s Law will come to an end (at least by simple scaling)
Power Dissipation

Power Trends in Intel's Microprocessors

Has been > doubling every 2 years

Has to stay ~constant
Power/Heat: Major Problem

S. Borkar, IEEE Micro 1999
P. Gelsinger: μProcessor for the New Millenium, ISSCC 2001
Power density too high to keep junctions at low temp
Technology Roadmap

Plan A: Extending Si CMOS
Plan B: Subsystem Integration
Plan C: Post Si CMOS Options
Plan Q: Quantum Computing

T.C. Chen, Where Si-CMOS is going: Trendy Hype vs. Real Technology, ISSCC'06
The semiconductor market will continue to grow.
Semiconductor Market Expansion

- Increasing semiconductor penetration in electronics

Source: WSTS, IC Insights, TSMC
Future Challenge: Technology Cost

- Capital expenditure for constructing a new fab is increasing
- Major factor for financing and future profit
Example Stepper ASML

- Price Tag: 100 Mio EUR!!
Future Challenge: ROI Risk Process

- Process technology developing costs are continuously increasing
Future Challenge: ROI Risk Product

- Design complexity and cost increase rapidly
- Short time to market
Ways To Overcome The Challenges

**Solution 1:**
IDM to foundry based model with many fabless companies

**Solution 2:**
Collaboration: Overcoming technical and financial challenges. Moreover, standardization of IP and EDA tools

**Solution 3:**
Minimize product risk and NRE through optimal system partition, good Design Infrastructure (SPICE, PDK) and Prototyping (MLM)

Source: TSMC
ITRS: International Technology roadmap for Semiconductors

- http://www.itrs.net/
System aspect roadmap