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Introduction to VLSI Digital Design

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Joint ICTP-TWAS Latin-American Advanced Course on FPGA Design for Scientific Instrumentation

Introduction to VLSI Digital Design

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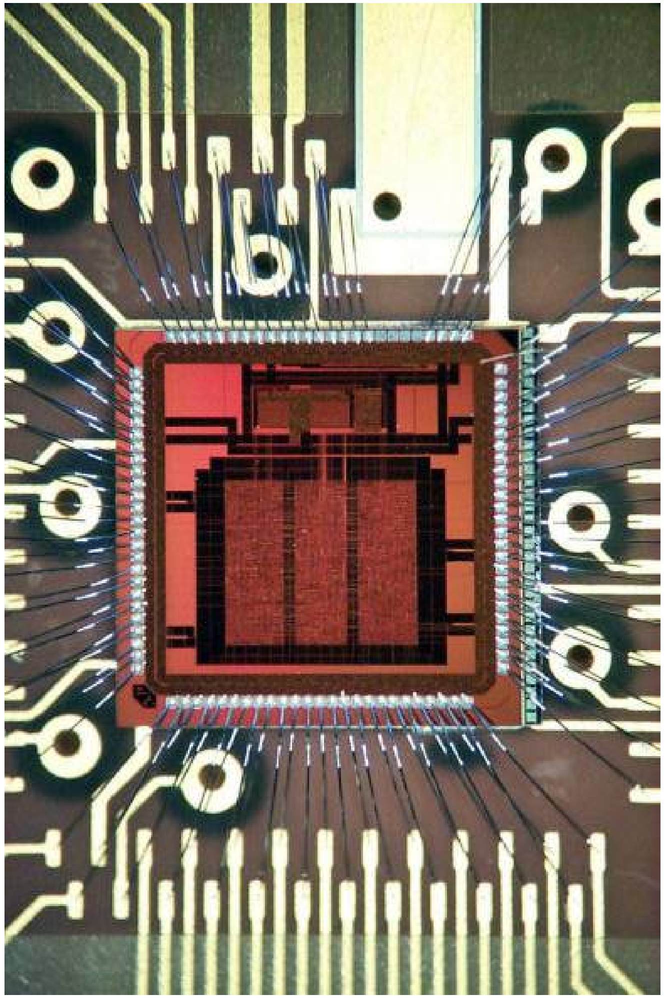
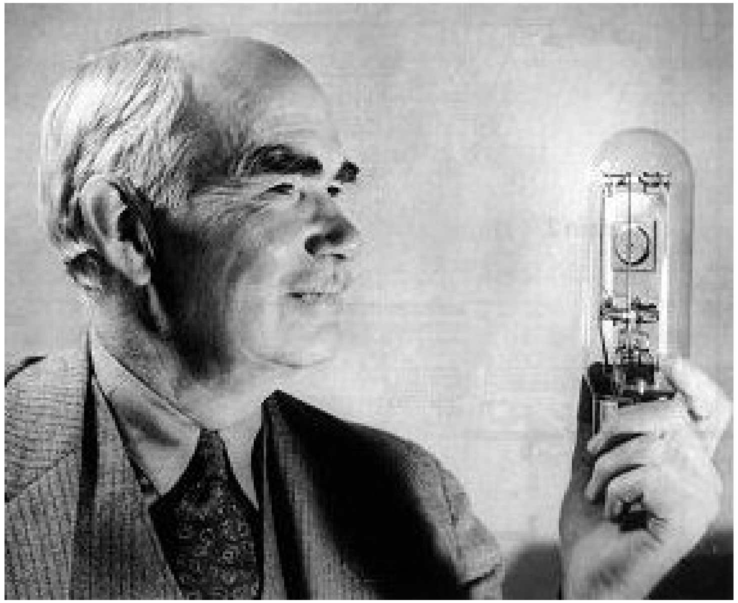
Outline

- Introduction
- Transistors
- The CMOS inverter
- Technology
- Scaling
- Gates
- Sequential circuits
- Storage elements



History: Before the Transistor

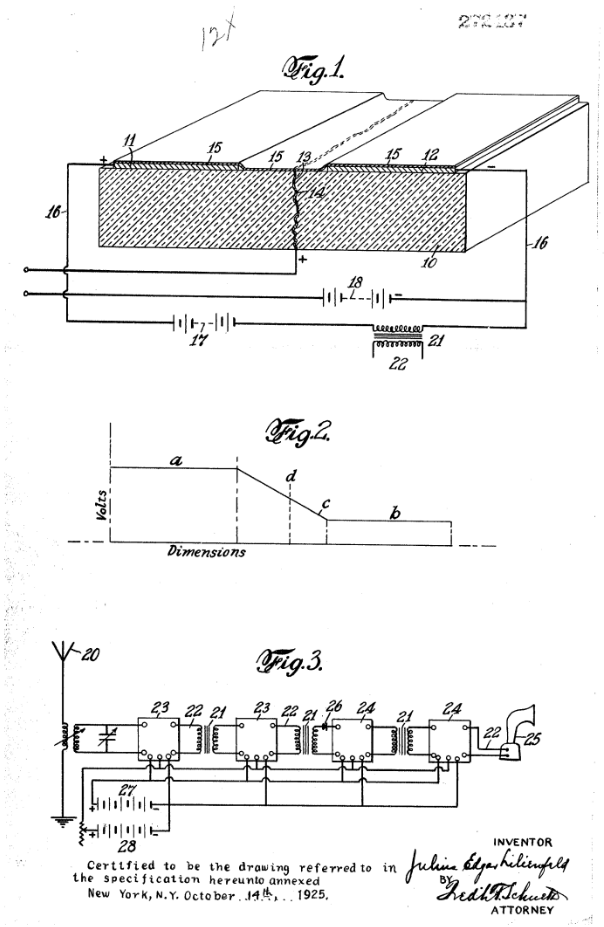
1906



Audion (Triode)
1906, Lee De Forest

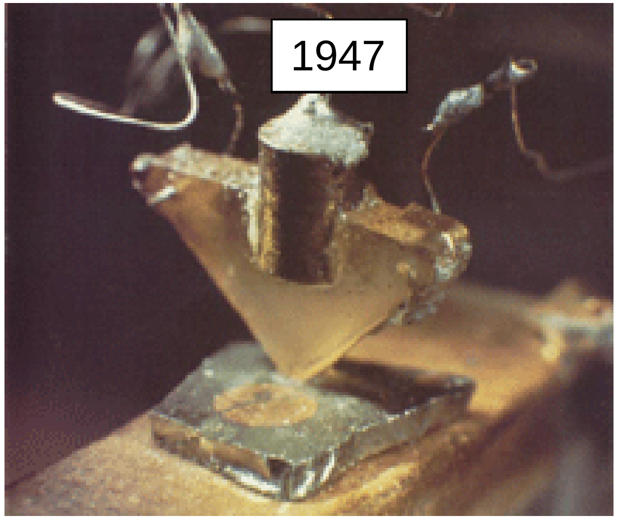
- 1883 Thomas Alva Edison ("*Edison Effect*")
  - While experimenting with light bulbs, Edison found that a current can flow through vacuum from the lighted filament to a positively biased metal plate but it does not flow to a negatively biased one.
- 1904 John Ambrose Fleming ("Fleming Diode")
  - Recognizes the importance of Edison's discovery.
  - Demonstrates the rectification of alternating current signals.
  - Applies the principle to radio reception.
- 1906 Lee de Forest ("Triode")
  - Adds an electrode (the "grid") to the Fleming diode between the anode and the cathode.
  - With the grid the "diode" becomes an active device. That is, it can be used for the amplification of signals. (Anode current controlled by the grid.)
- Vacuum tube devices continued to evolve
  - They dominated the radio and TV industry till the sixties.
  - They have coexisted with the transistor and even with integrated circuits. (Till recently, they were used as TV screens or computer monitors.)
  - By the way, they are miniature particle accelerators.
  - They were the "genesis" of today's huge electronics industry.
  - They were however, fragile, relatively large, power hungry, and costly to manufacture. The industry needed something better.

History: First Ideas

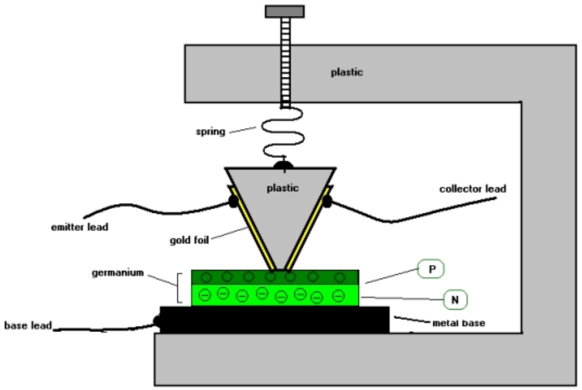


- 1925 J. Lilienfeld ("MESFET")
  - Canada patent was filed in 1925 and granted in 1927. The device described is what today would be called a Metal Semiconductor Field Effect Transistor.
  - Patent CA272437 : "Method and apparatus for controlling electric current"
- 1928 J. Lilienfeld ("MOSFET")
  - US patent filed in 1928 and granted in 1933. The device proposed is similar to a modern Metal Oxide Semiconductor FET. The dielectric proposed was the Aluminum Oxide
  - Patent US1900018: "Device for controlling electric current"
- It was necessary to wait till 1960 to have a technology capable of producing "similar" working devices!
  - When Bell labs attempted to patent the junction transistor, they found that Lilienfeld held it and had to work out an agreement with him

History: Bipolar FET Transistors



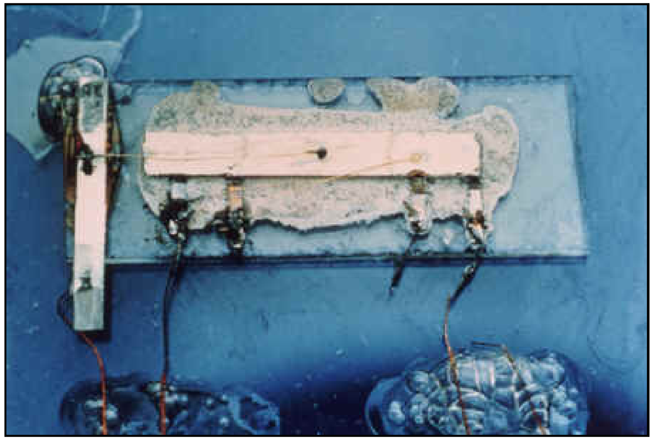
First point contact transistor (germanium)
1947, John Bardeen and Walter Brattain
Bell Laboratories



- 1940 Russel Ohl (PN junction)
  - The PN junction is developed at Bell Labs. The device produces 0.5 V across the junction when exposed to light.
- 1947 Bardeen and Brattain (Transistor)
  - 1945 Bell labs establish a group to develop an alternative to the vacuum tube. The group was lead by William Shockley.
  - Bardeen and Brattain succeeded in creating an amplifying circuit utilizing a point-contact "transfer resistance" device (the transistor).
  - The transistor was built on germanium.
  - U.S. patent # 2,524,035 (1950)
- 1950 William Shockley (Junction transistor)
  - Higher manufacturability yield than the point-contact transistor.
  - By the mid fifties the junction transistor replaces the point-contact transistor
  - Main use: telephone systems
- 1952 Single crystal silicon is fabricated
- 1954 First commercial silicon transistor
  - Texas instruments
- 1954 First transistor radio (Regency TR-1)
  - Industrial Development: Engineer Associates
  - Four germanium transistors from Texas Instruments

History: Integrated Circuits

1958

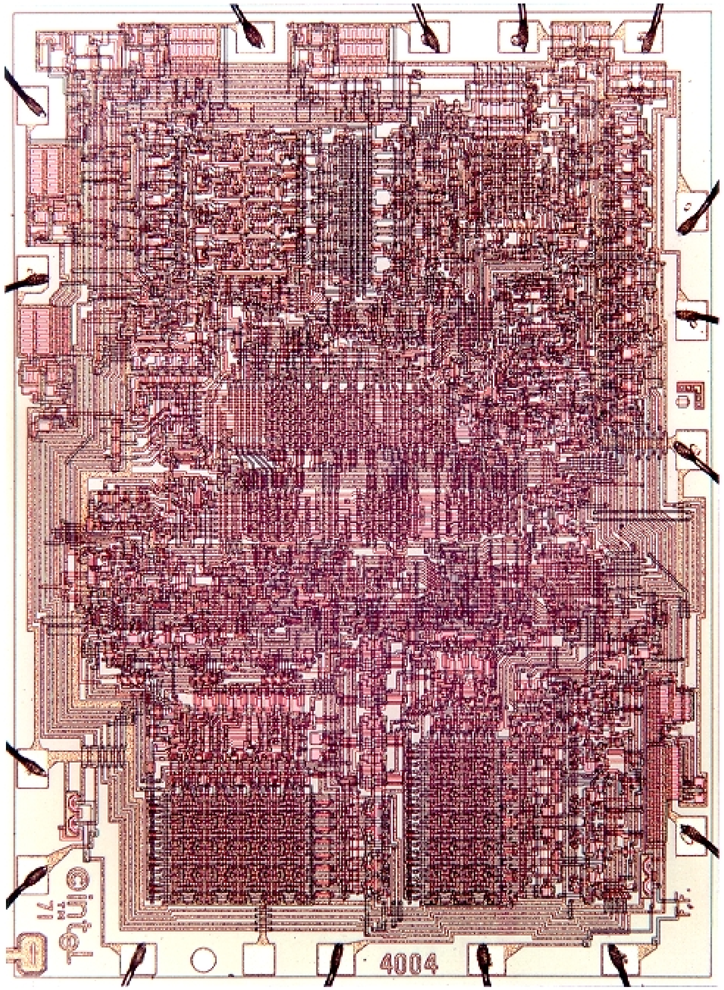


First integrated circuit (germanium), 1958
Jack S. Kilby, Texas Instruments

Contained five components, three types: transistors resistors and capacitors

- 1952 Geoffrey W. A. Dummer (IC concept)
  - 1952 IC concept published
  - 1956 Failed attempt
- 1954 Oxide masking process developed
  - Developed at Bell Labs this is the foundation of IC production
  - The process involves: oxidation, photo-masking, etching and diffusion
- 1958 Jack Kilby (Integrated circuit)
  - Working at Texas Instruments Kilby built a simple oscillator IC with five integrated components
  - U. S. patent # 3,138,743 (1959)
- 1959 Planar technology invented
  - The planar technology was developed from the contributions of: Jean Hoerni and Robert Noyce (Fairchild) and Kurt Lehovec (Sprag Electric)
  - The planar technology is still the process used today.
- 1960 First MOSFET fabricated
  - At Bell Labs by Kahng
- 1961 First commercial ICs
  - Fairchild and Texas Instruments
- 1962 TTL invented
- 1963 First PMOS IC produced by RCA
- 1963 CMOS invented
  - Frank Wanlass at Fairchild Semiconductor
  - U. S. patent # 3,356,858
  - Standby power reduced by six orders of magnitude

History: Microprocessors



- 1971 Microprocessor invented
  - Intel produces the first 4-bit microprocessor the 4004
  - The 4004 was a 3 chip set
    - 2 kbit ROM IC
    - 320 bit RAM IC
    - 4-bit processor
    - Each housed in a 16-pin DIP package
  - Processor:
    - 10 μm silicon gate PMOS process
    - ~2300 transistors
    - Clock speed: 0.108 MHz
    - Die size: 13.5 mm^2
- 1972: 8008, 8-bit processor, 0.8 MHz, 10um
- 1974: 8080, NMOS logic, 2 MHz, 6um
- 1978: 8086, CMOS logic, 10 MHz, 3um

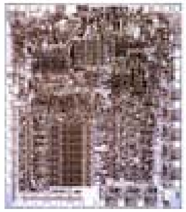
History: Microprocessors

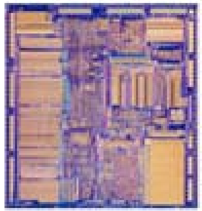
1950s
Silicon Transistor

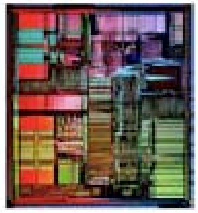
1 Transistor

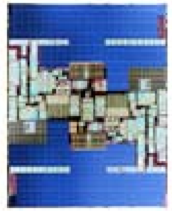
1960s
TTL Quad Gate

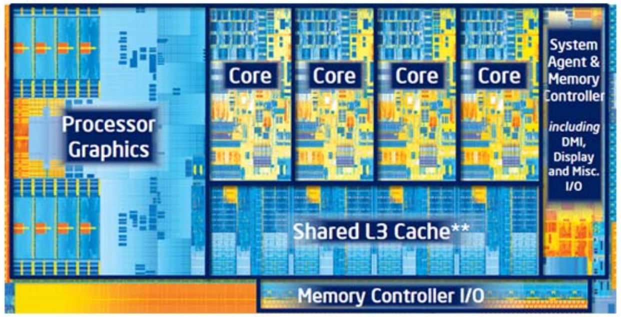
16 Transistors

1970s
8-bit Microprocessor

4500 Transistors

1980s
32-bit Microprocessor

275,000 Transistors

1990s
32-bit Microprocessor

3,100,000 Transistors

2000s
64-bit Microprocessor

592,000,000 Transistors

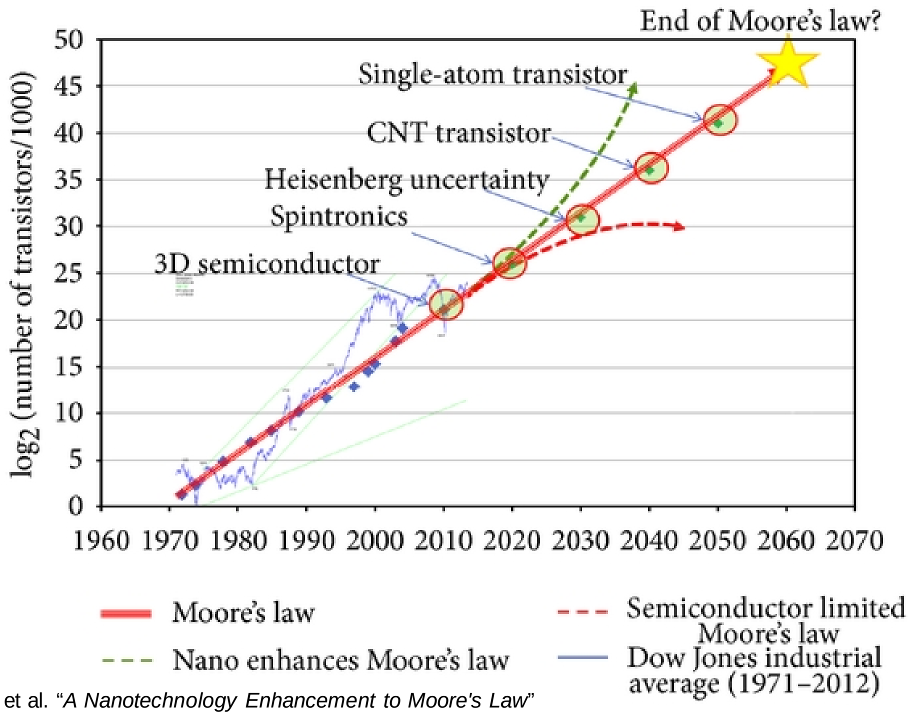
2011
64-bit Multi core


1,400,000,000 Transistors

(Borrowed from A. Marchioro / CERN)

"Moore's Law"

- In 1965 Gordon Moore (then at Fairchild Corporation) noted that:
  - ***"Integration complexity doubles every three years"***
  - This statement is commonly know as "Moore's Law"
  - It has proven to be "correct" till this day



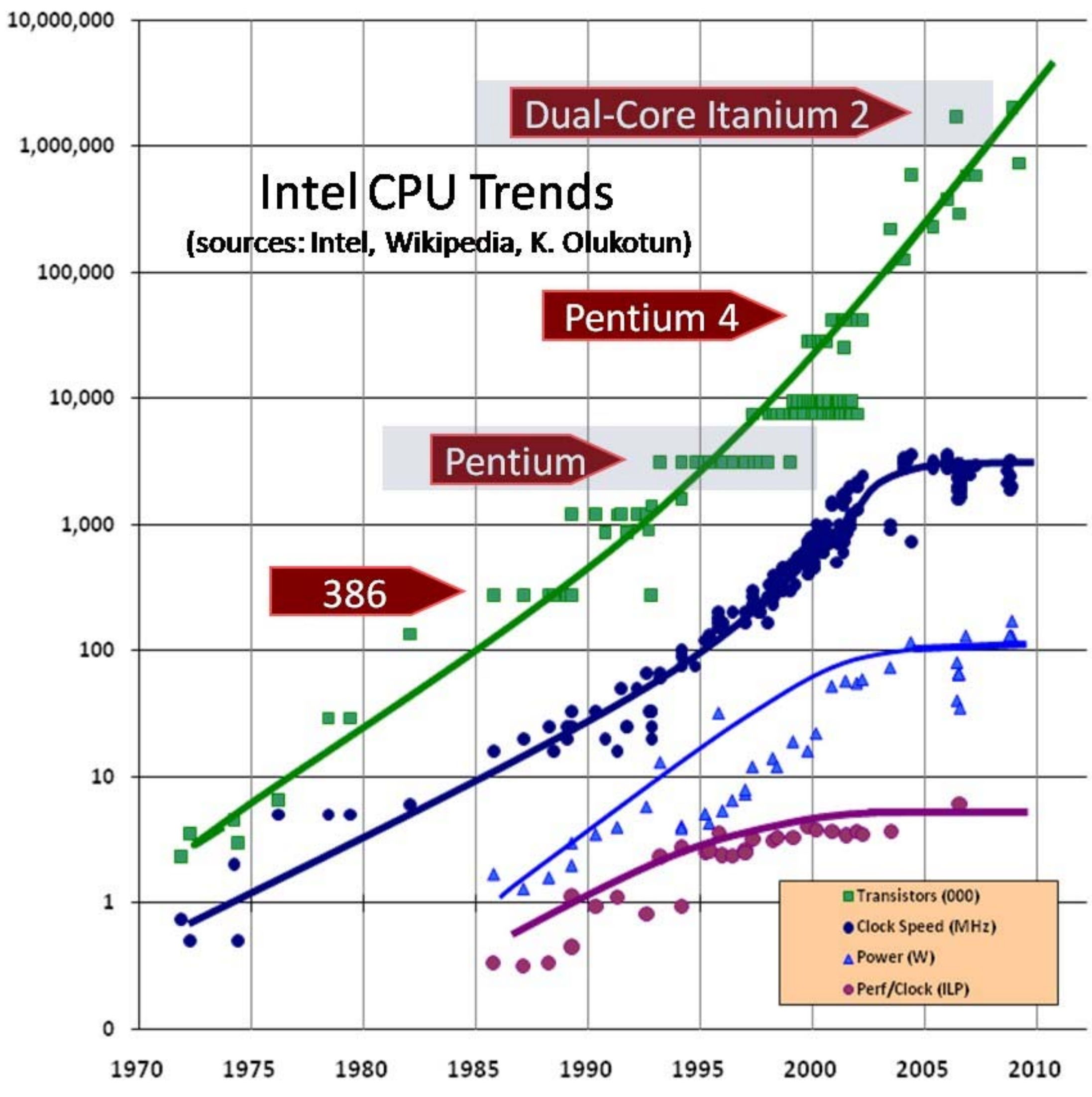
Jerry Wu et al. "*A Nanotechnology Enhancement to Moore's Law*"

- What is behind this fantastic pace of development of the IC technologies?
  - Is it the "technological" will and motivation of the people involved?
  - Or/and is it the economical drive the main force?
  - Semiconductor industry sales:
    - 1962 > $1 – billion
    - 1978 > $10 – billion
    - 1994 > $100 – billion
    - 2007 > $268 – billion
    - 2009 > $226 – billion (-11.4% than in 2008)
    - 2010: $304 billion (DRAM and Flash boom, +80% in that sector with respect to 2009)
    - 2011: $311 billion
    - 2012: $303 billion (-2.4% than in 2011)

From 1960 until 2000, worldwide semiconductor revenues have increased an average of 14.9% per year!

Source: IC Knowledge LLC, "Revenue trends," September 4, 2006

Trends in CPU parameters



- Integration complexity continues to rise
  - Though at a slower pace
  - More cores in a chip
- CPU frequency stall
  - In the GHz range
  - Maximum power reached
- Impact on semiconductor market
  - Semiconductor revenues increasing at slower pace

Semiconductor Companies & Foundries

Rank 2012	Company	Country of origin	Revenue (million USD)	2012/2011 changes	Market share
1	Intel Corporation	USA	47,543	-2.40%	15.70%
2	Samsung Electronics(1)	South Korea	30,474	6.70%	10.10%
3	Qualcomm	USA	12,976	27.20%	4.30%
4	Texas Instruments	USA	12,008	-14.00%	4.00%
5	Toshiba Semiconductor	Japan	10,996	-13.60%	3.60%
6	Renesas Electronics	Japan	9,430	-11.40%	3.10%
7	SK Hynix	South Korea	8,462	-8.90%	2.80%
8	STMicroelectronics	France/Italy	8,453	-13.20%	2.80%
9	Broadcom	USA	7,840	9.50%	2.60%
10	Micron Technology	USA	6,955	-5.60%	2.30%
11	Sony	Japan	6,025	20.10%	2.00%
12	AMD	USA	5,300	-17.70%	1.70%
13	Infineon Technologies	Germany	4,826	-9.10%	1.60%
14	NXP	Netherlands	4,096	6.90%	1.40%
15	NVIDIA	USA	3,923	8.70%	1.30%
16	Freescale Semiconductor	USA	3,775	-14.40%	1.20%
17	MediaTek	Taiwan	3,472	4.90%	1.10%
18	Elpida Memory	Japan	3,414	-12.20%	1.10%
19	Rohm Semiconductor	Japan	3,170	-3.00%	1.00%
20	Marvell Technology Group	USA	3,113	-8.30%	1.00%
	Others		106,768	-2.40%	35.20%
	TOTAL		303,019		

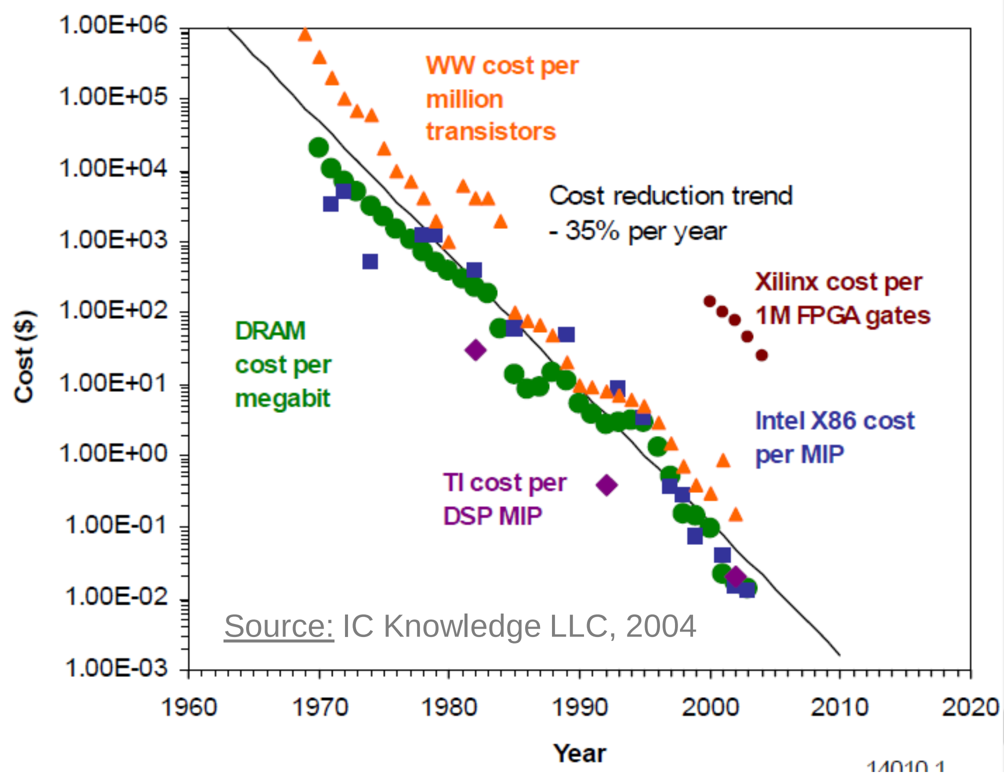
Rank	Company	Foundry Type	Country of origin	Revenue (million $USD)
1	TSMC	Pure-play	Taiwan	14,600
2	UMC	Pure-play	Taiwan	3,760
3	Globalfoundries	Pure-play	United States	3,580
4	Samsung Semiconductor	IDM	South Korea	1,975
5	SMIC	Pure-play	China	1,315
6	TowerJazz	Pure-play	Israel	610
7	Vanguard (VIS)	Pure-play	Taiwan	519
8	Dongbu HiTek	Pure-play	South Korea	500
9	IBM	IDM	United States	445
10	MagnaChip	IDM	South Korea	350
11	SSMC	Pure-play	Singapore	345
12	Hua Hong NEC	Pure-play	China	335
13	Win Semiconductors	Pure-play	Taiwan	300
14	X-Fab	Pure-play	Germany	285

- **Pure-play**: semiconductor fabrication plant focused on producing ICs for other companies
- **Integrated Device Manufacturer (ID**M): provide foundry services as long as there is no conflict of interest between relevant parties

Driving force: Economics

- Increase productivity:
  - Increase equipment throughput
  - Increase manufacturing yields
  - Increase the number of chips on a wafer:
    - reduce the area of the chip:
      - smaller feature size & redesign
  - Use the largest wafer size available
- High volume factory:
  - Total capacity: 40K Wafer Starts Per Month (WSPM) (20 nm tech. / 300mm)
  - Total capital cost: $9B

Example of a cost effective product (typically DRAM): the initial IC area is reduced to 50% after 3 years and to 35% after 6 years.



Transistor Count is not all

	Intel Core Duo	Human Brain
Power	5 – 70 W	10 – 40 W
Typical Frequency	1 GHz	0.1 Hz – 10 kHz (pulses of 1-100 ms)
Number of Elements	~ 10^9 transistors ~ 10^8 gates	~ 10^{11} neurons
Interconnections per element	2-4 In / 1-3 out	~7,000 I/O
Elementary operation	Simple, Boolean	Complex, Nonlinear (choice)
Capacitance per interconnection	0.2 pF /mm	~1 pF

- Massively parallel, asynchronous
- Can solve non-well-posed problems
  - Well-posed problem:
    - A solution exists
    - The solution is unique
    - The solution's behavior changes continuously with the initial conditions.

(Borrowed from A. Marchioro / CERN)