A brief account of the development of semiconductors

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Universidade Federal de Santa Catarina

Lima - September 2024

CONTENTS:

Electronics Milestones

1874 Braun invents the solid-state rectifier.

1906 DeForest invents triode vacuum tube.

1907-1927 First radio circuits developed from diodes and triodes.

1925 Lilienfeld field-effect device patent filed.

1947 Bardeen and Brattain at Bell Laboratories invent bipolar transistors.

1952 Commercial bipolar transistor production at Texas Instruments.

1956 Bardeen, Brattain, and Shockley receive Nobel prize.

1958 Integrated circuits developed by Kilby and Noyce

1961 First commercial IC from Fairchild Semiconductor

1968 First commercial IC opamp

1970 One transistor DRAM cell invented by Dennard at IBM.

1971 4004 Intel microprocessor introduced.

1973 Martin Cooper demonstrated a prototype of Motorola's handheld mobile phone.

1974 8080 microprocessor introduced.

1978 First commercial 1-kilobit memory.

1974 8080 microprocessor introduced.

1984 Megabit memory chip introduced.

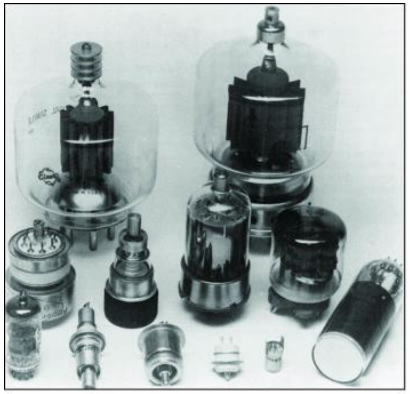
1995 Exp. Gigabit memory chip at ISSCC.

2000 Alferov, Kilby, and Kromer share Nobel prize for IC.

2009 Ten billion transistor integrated circuit chip presented at ISSCC

Evolution of Electronic Devices

Vacuum Tubes



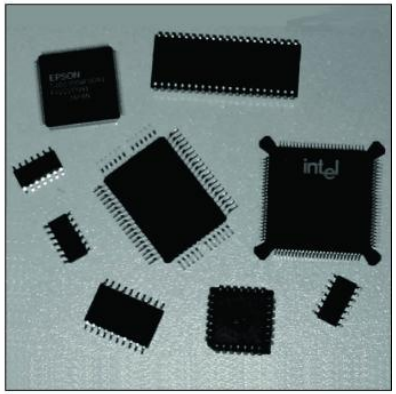
(a)

(b)

Discrete Transistors

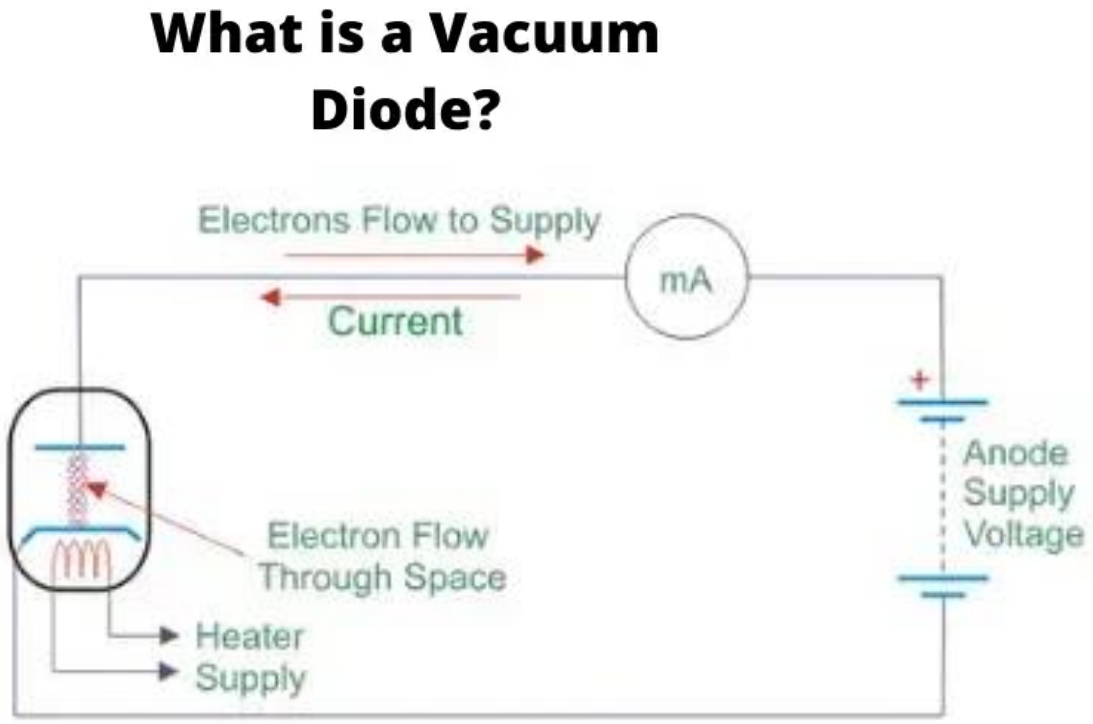
SSI and MSI Integrated Circuits

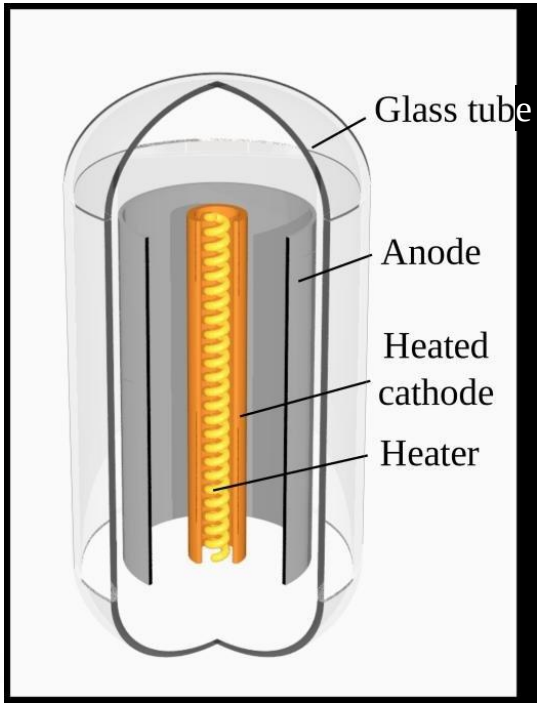
(c)



(d)

VLSI Surface-Mount Circuits





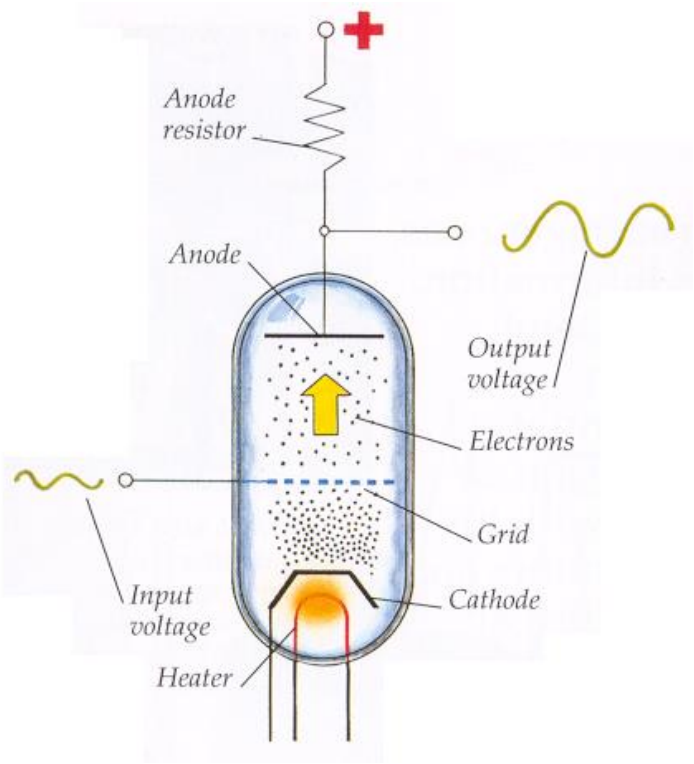
John Ambrose Fleming invented the first thermionic valve or (diode) vacuum tube.

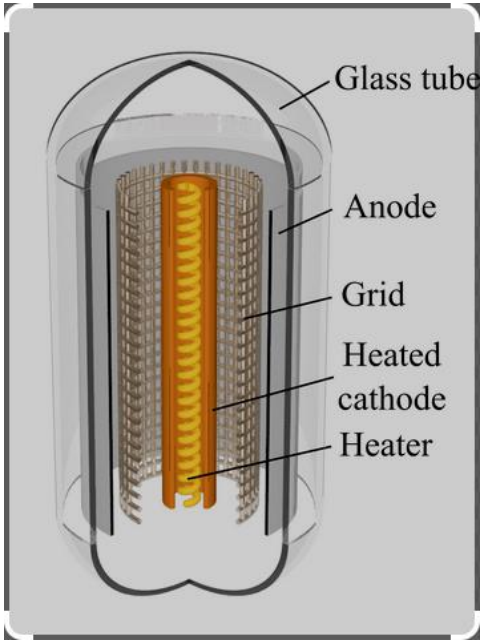
Patent US803,684 (Granted 1905)- INSTRUMENT FOR CONVERTING ALTERNATING ELECTRIC CURRENTS INTO CONTINUOUS CURRENTS

https://www.electrical4u.com/vacuum-diode-history-working-principle-and-types-of-vacuum-diode/

https://en.wikipedia.org/wiki/Vacuum_tube

1906 - Lee de Forest developed the triode vacuum tube
Age of electronics begins.

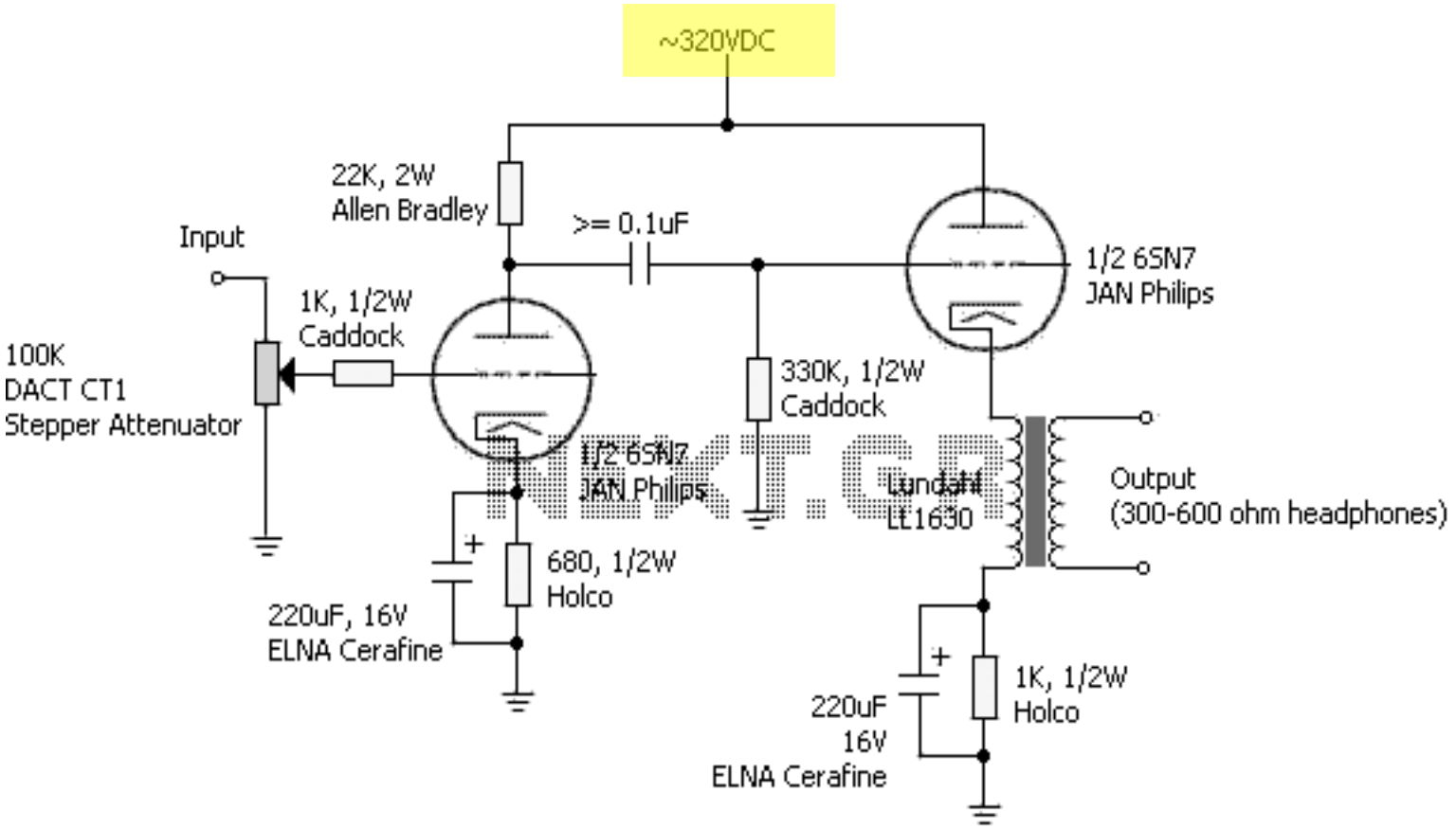




https://en.wikipedia.org/wiki/Vacuum_tube

The first practical electronic amplifier, the three-element "Audion" triode vacuum tube helped start the Electronic Age and enabled the development of the electronic oscillator. These made radio broadcasting and long-distance telephone lines possible, among countless other applications.

Vacuum tube amplifier



Two-Stage Transformer-Coupled Amplifier

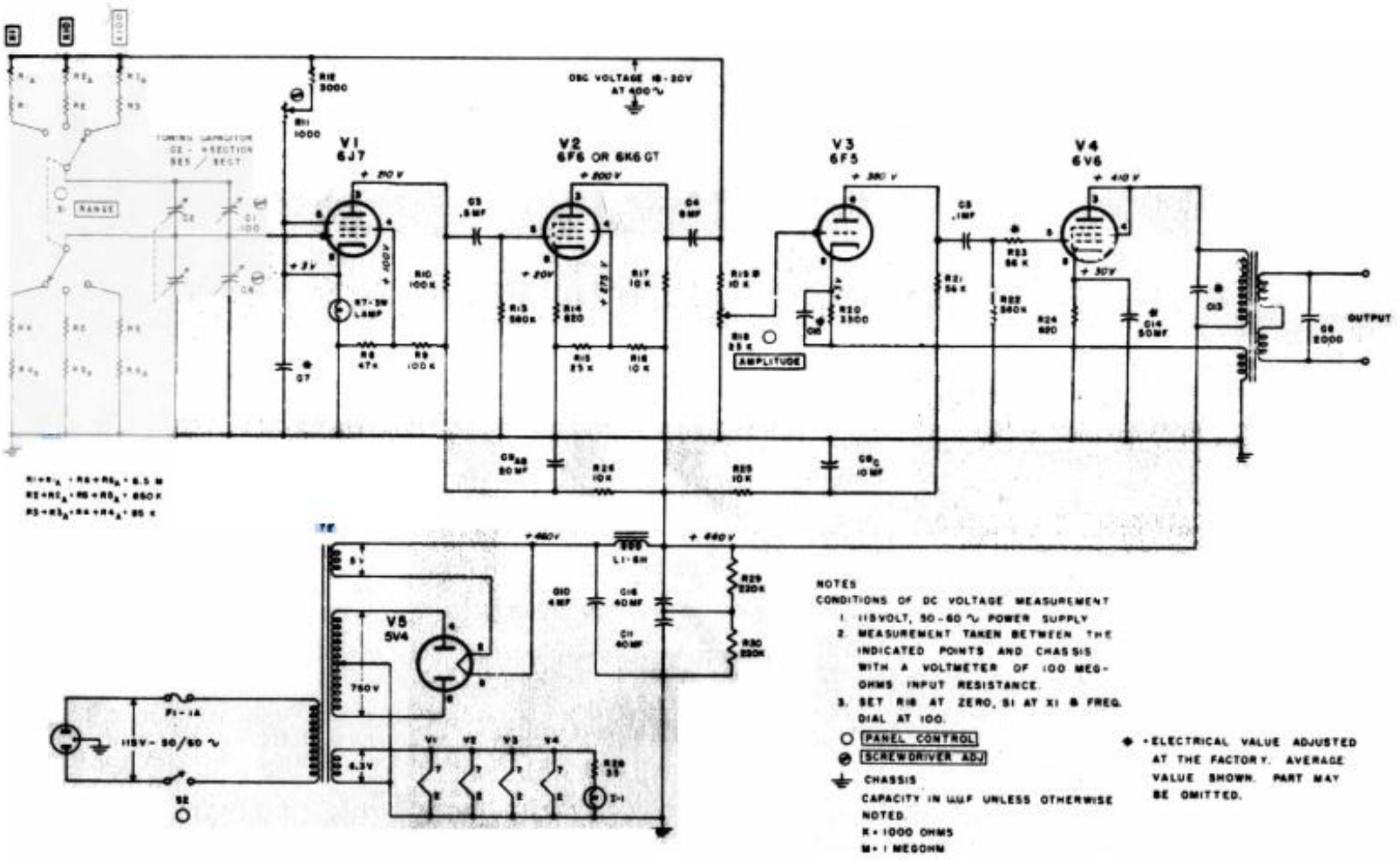
https://www.next.gr/audio/amplifiers/Tube-Headphone-Amplifier-E182CC-l7285.html

The electronic instruments of the first half of the 20th century used vacuum tubes and passive components.

Hewlett-Packard founded in a one-car garage in Palo Alto by Bill Hewlett and David Packard in 1939. Initially produced a line of electronic test and measurement equipment

The garage in Palo Alto, where Hewlett and Packard began the company

https://en.wikipedia.org/wiki/Hewlett-Packard



SCHEMATIC DIAGRAM OF MODEL 200 B
AUDIO OSCILLATOR

http://hparchive.com/Manuals/HP-200A-200B-Manual-1961.pdf

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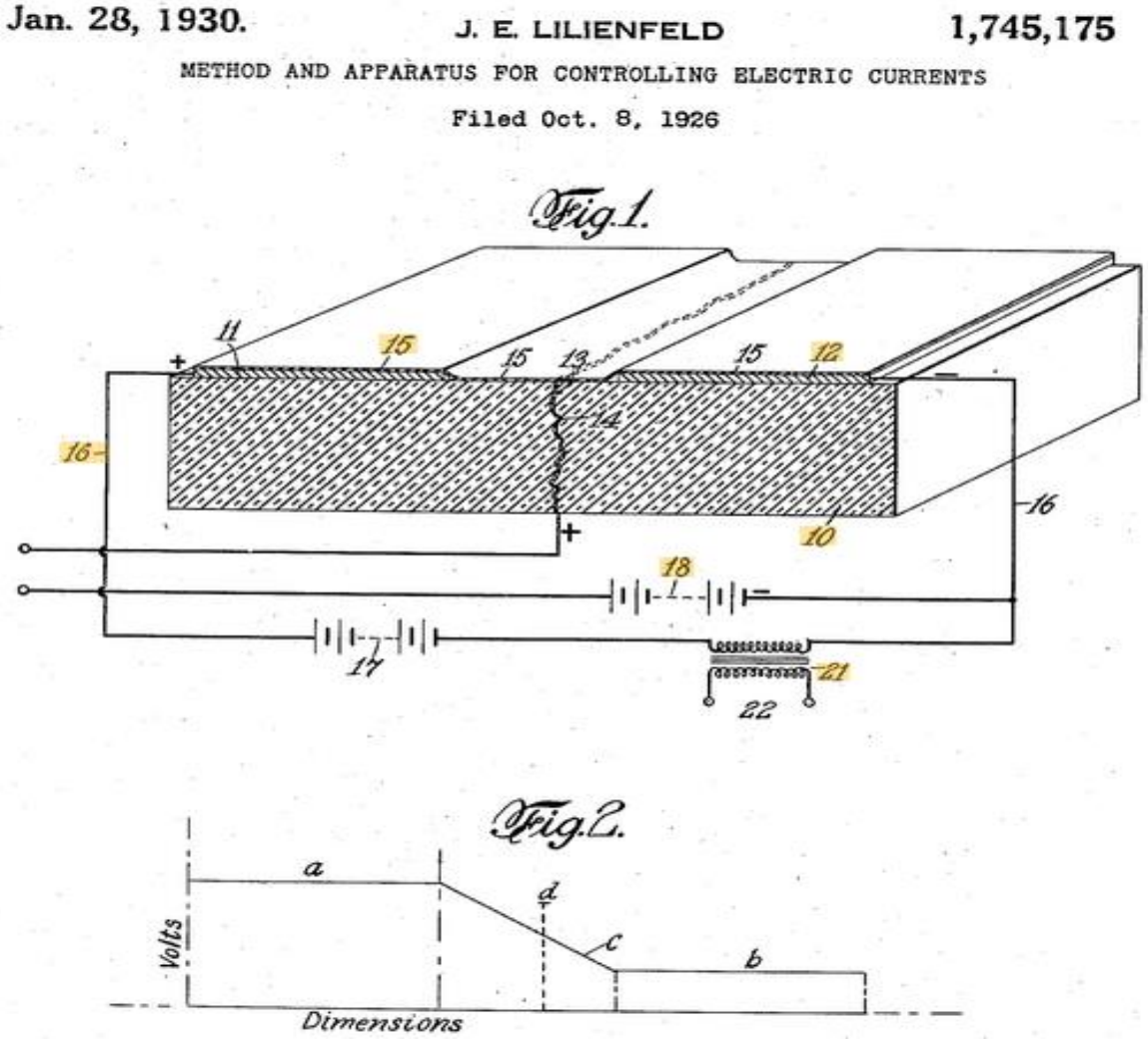
HP200A/B Audio Oscillator
Frequency range: 20 Hz – 20 kHz

Output power 1 W/ 500 Ω load

https://en.wikipedia.org/wiki/HP_200A

Julius Lilienfeld filed a patent for "Method and Apparatus for Controlling Electric Currents," in 1926


Jan. 28, 1930. J. E. LILIENFELD 1,745,175

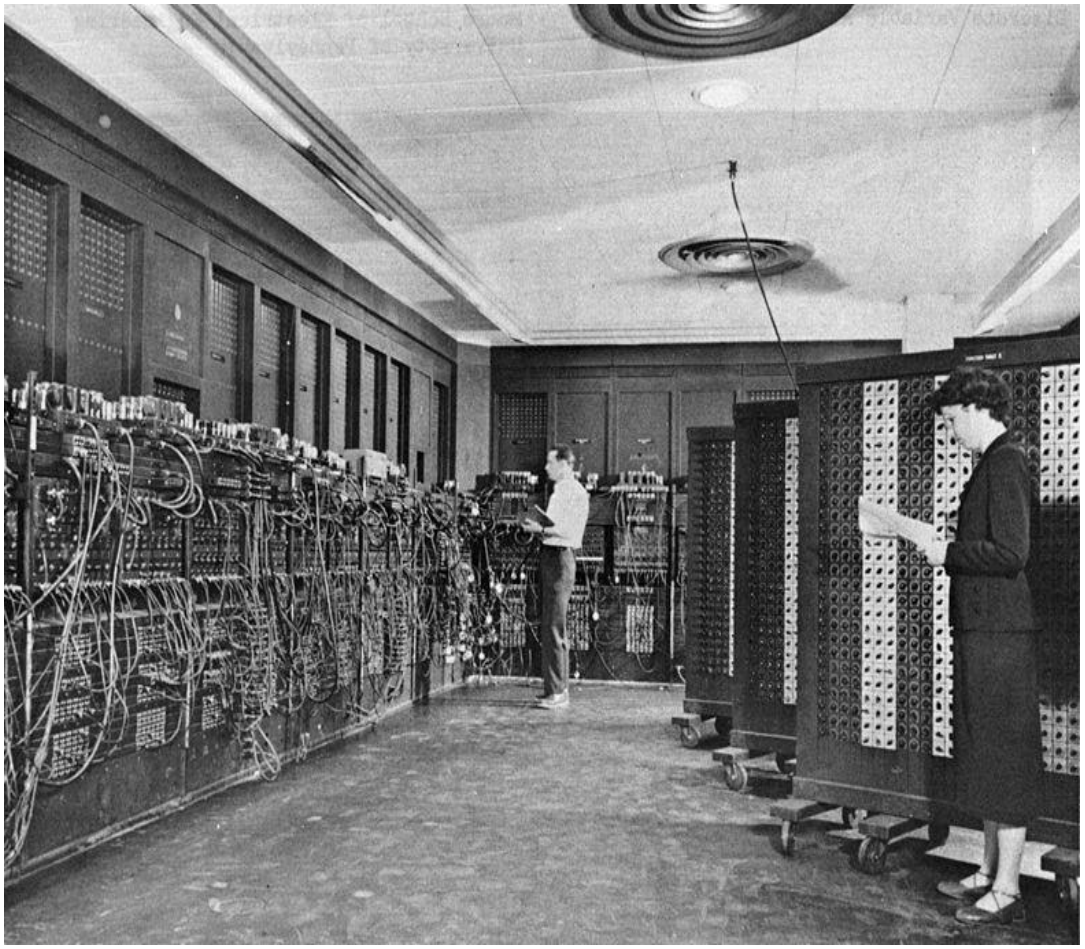
METHOD AND APPARATUS FOR CONTROLLING ELECTRIC CURRENTS

Filed Oct. 8, 1926

Fig. 1.

Fig. 2.

ENIAC (1946) - Electronic Numerical Integrator And Computer



17,468 vacuum tubes
7,200 crystal diodes,
1,500 relays,
70,000 resistors,
10,000 capacitors
~5 million hand-soldered
Weight ~ 27 t
Dimensions 2.4 m×0.9 m×30 m
Power: 150 kW
+AC power for heaters of tubes, card reader and card punch, and ventilating system
+78 different DC levels

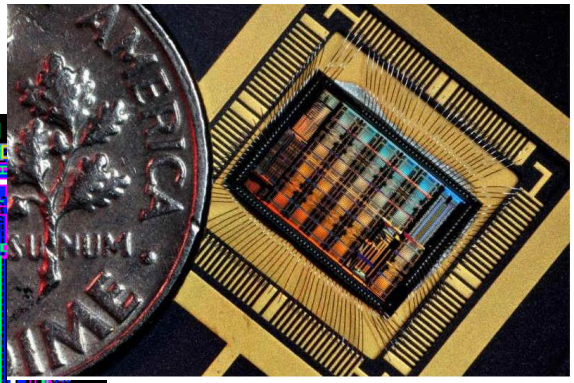
ENIAC used to calculate artillery firing tables for the United States Army's Ballistic Research Laboratory. Its first program was a study of the feasibility of the thermonuclear weapon.

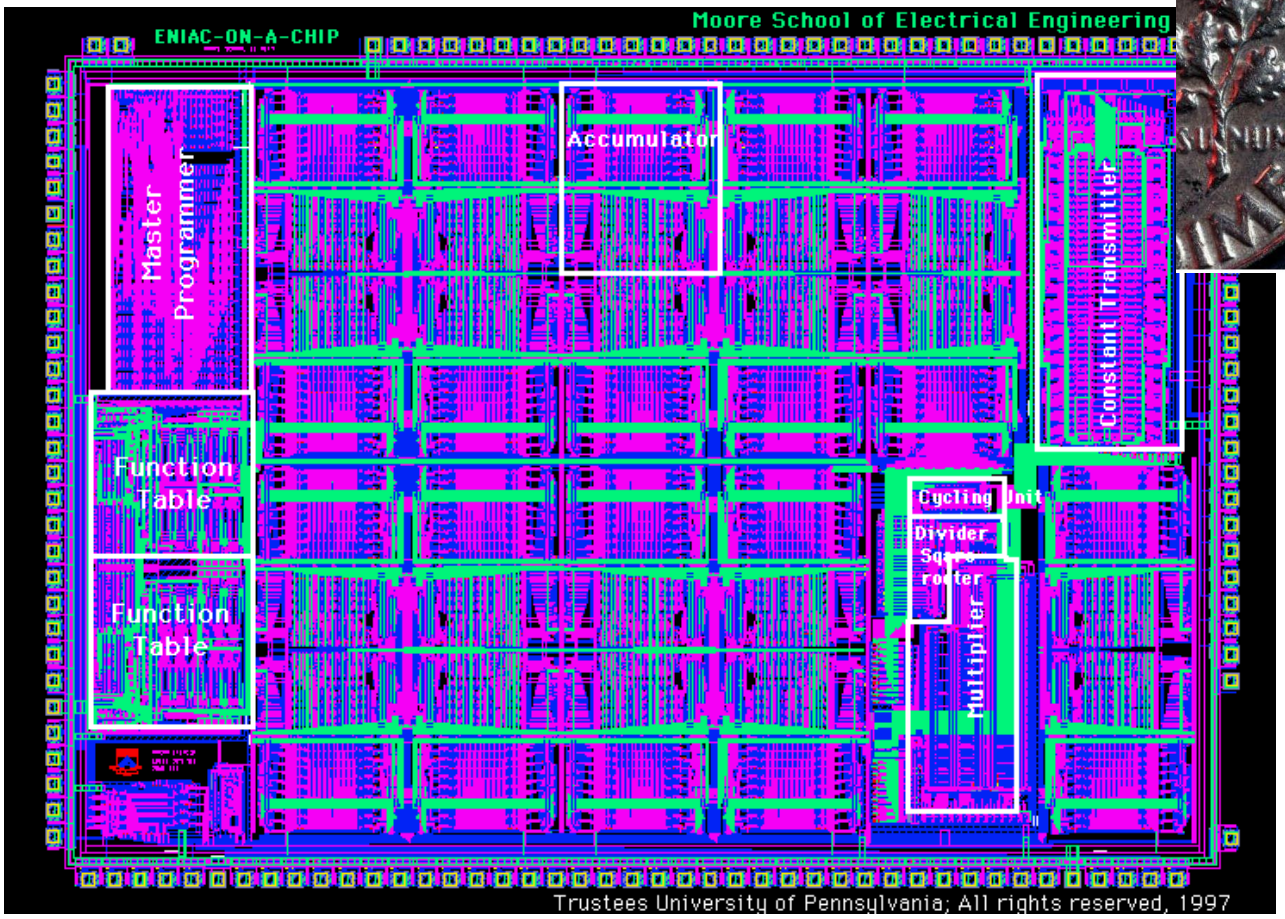
The ENIAC - History, Operation and Reconstruction in VLSI", J. Van der Spiegel, J. Tau, T. Alailima and L.P. Ang in *The First Computers--History and Architectures*, MIT Press, eds. R. Rojas, 2000.

https://en.wikipedia.org/wiki/ENIAC

Source

Eniac-on-a-Chip (1997)





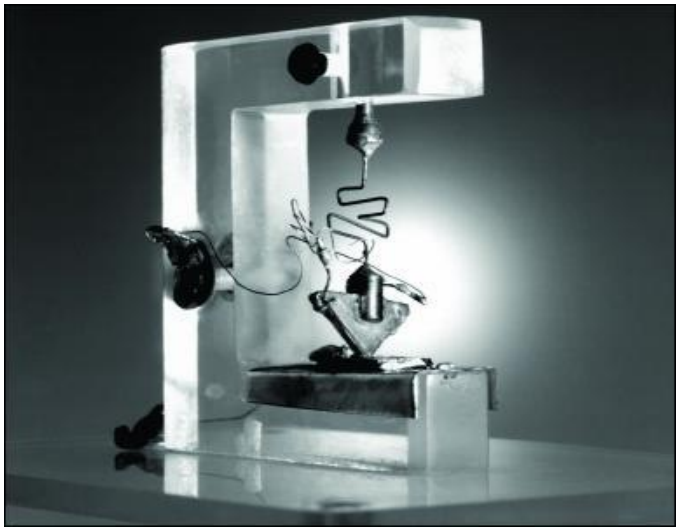
Chip size: 7.44mm x 5.29mm; 174,569 transistors; 0.5 um CMOS technology (triple metal layer), 5 V power supply, few watts of power dissipation.

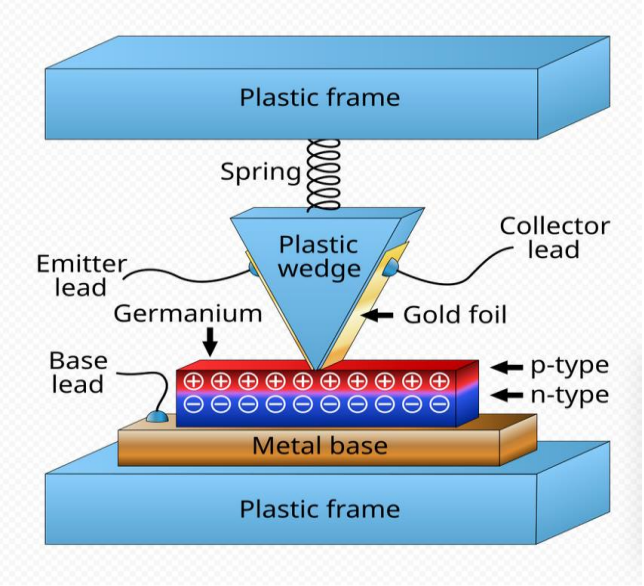
https://www.seas.upenn.edu/~jan/eniacproj.html

The ENIAC - History, Operation and Reconstruction in VLSI", J. Van der Spiegel, J. Tau, T. Alailima and L.P. Ang in *The First Computers--History and Architectures*, MIT Press, eds. R. Rojas, 2000.

The Start of the Modern Electronics Era

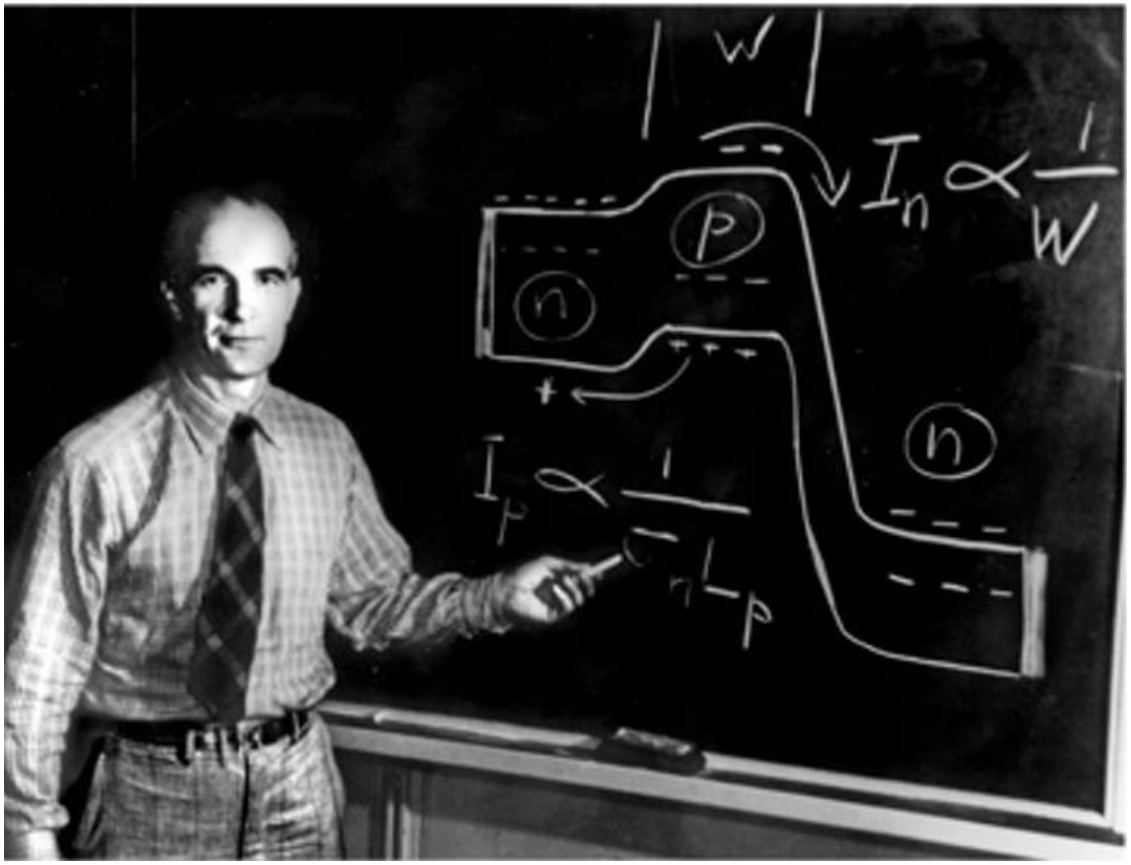
Bardeen, Shockley, and Brattain at Bell Labs - Brattain and Bardeen invented the point-contact transistor in 1947.





The first germanium bipolar transistor. Roughly 70 years later, electronics account for 10% (7 trillion dollars) of the world GDP.

1948: Conception of the Bipolar Junction Transistor



William Shockley describing junction transistor theory

https://www.computerhistory.org/siliconengine/

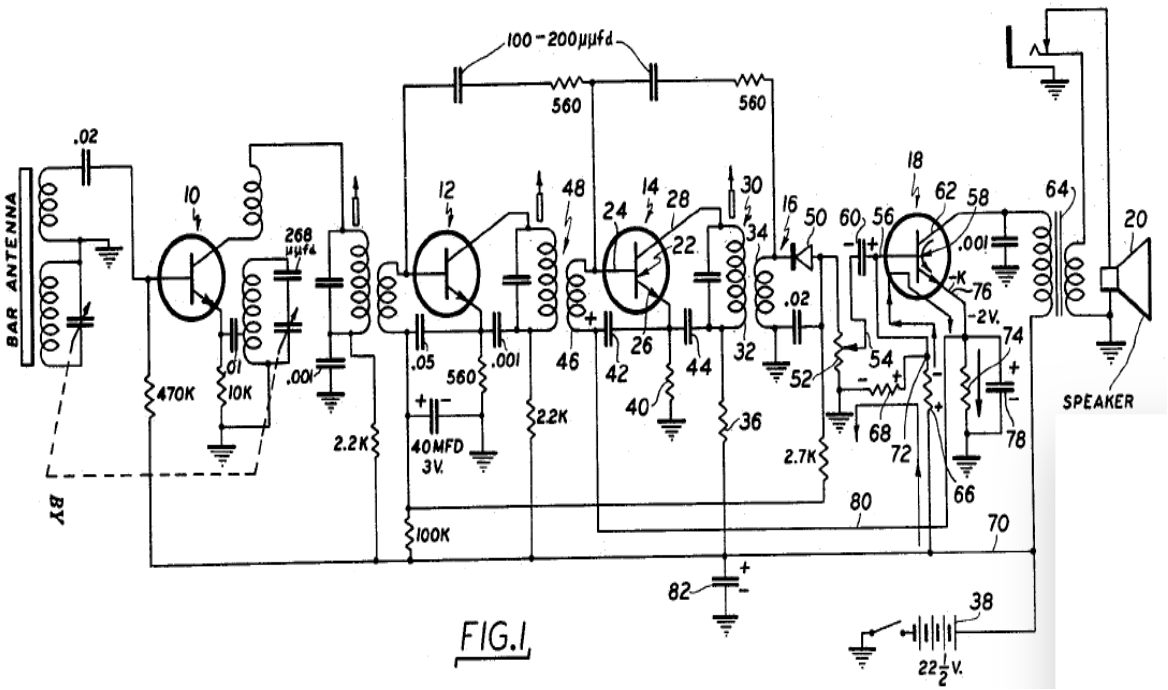
1952: Bell Labs Licenses Transistor Technology (40 companies paid US$ 25,000/license fee), which encourages semiconductor development.

The Sonotone 1010 (hearing aid) : First commercial product to use transistors. Vacuum tubes (2) were still used because transistors were very noisy. Even using one transistor considerably extended battery life.

https://hearingaidmuseum.com/gallery/Transistor%20(Body)/Sonotone/info/sonotone1010.htm

https://www.computerhistory.org/siliconengine/

The **Regency TR-1** was the first commercially manufactured transistor radio, introduced in 1954.
Price of $49.95 (less battery).
150,000 units sold
Novelty: small size and portability



https://www.edn.com/1st-commercial-transistor-radio-goes-on-sale-november-1-1954/

The origin of Silicon Valley

1955: the Shockley Semiconductor Laboratory (SSL) is founded

The original Shockley building at 391 San Antonio Road, Mountain View, California, was a produce market in 2006 and has since been demolished.

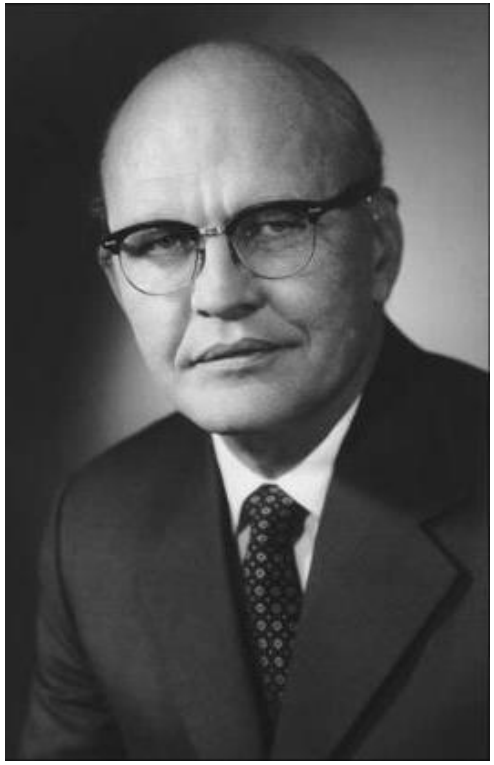
The Nobel Prize in Physics 1956 was awarded jointly to William Bradford Shockley, John Bardeen and Walter Houser Brattain "for their researches on semiconductors and their discovery of the transistor effect"

In 1957, the eight leading scientists (Julius Blank, Victor Grinich, Jean Hoerni, Eugene Kleiner, Jay Last, Gordon Moore, Robert Noyce, and Sheldon Roberts) resigned from SSL and became the core of what became Fairchild Semiconductor.

https://en.wikipedia.org/wiki/Shockley_Semiconductor_Laboratory

https://www.nobelprize.org/prizes/physics/1956/summary/

The Inventors of the Integrated Circuit



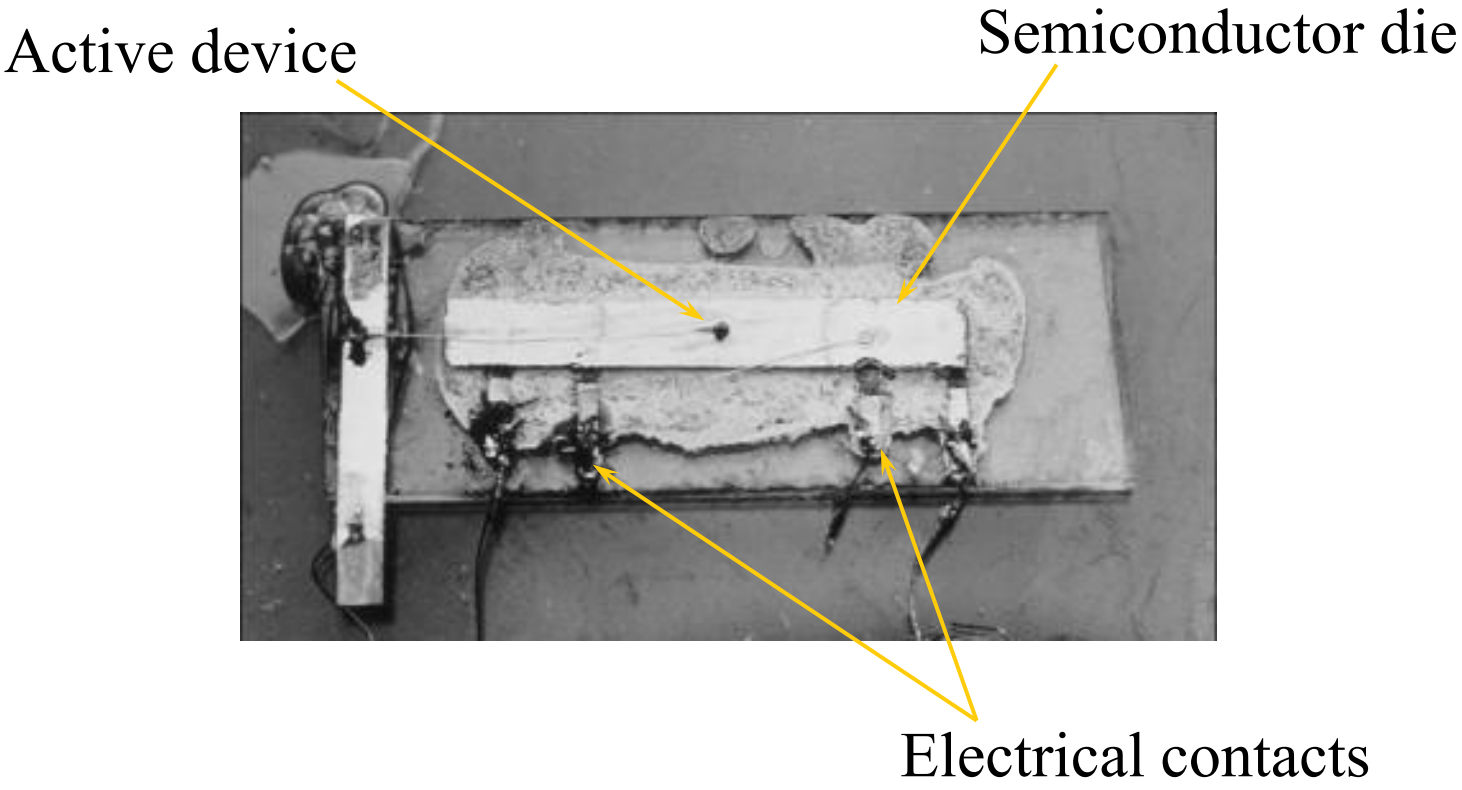
Jack Kilby

Andy Grove, Robert Noyce, and Gordon Moore with Intel 8080 layout.

2000 Nobel Prize in Physics for the invention of the integrated circuit. When receiving the award, Kilby said that if Noyce were still alive, he would definitely share the Nobel Prize with him.

Noyce died of a heart attack in 1990

The Kilby Integrated Circuit

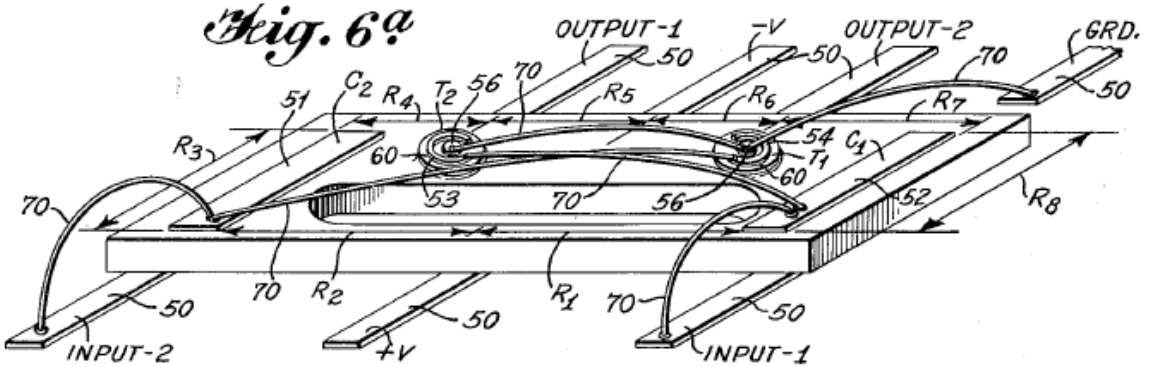


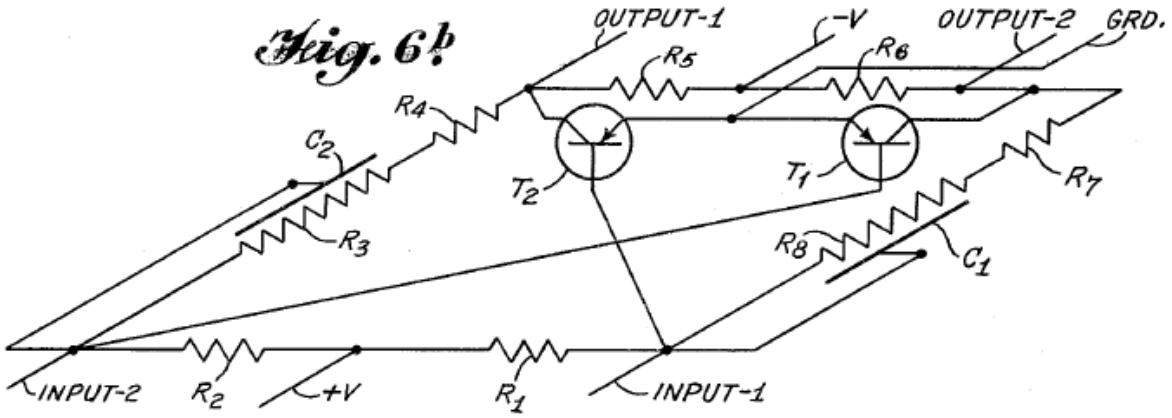
The Kilby Integrated Circuit

June 23, 1964 J. S. KILBY 3,138,743

MINIATURIZED ELECTRONIC CIRCUITS

Filed Feb. 6, 1959

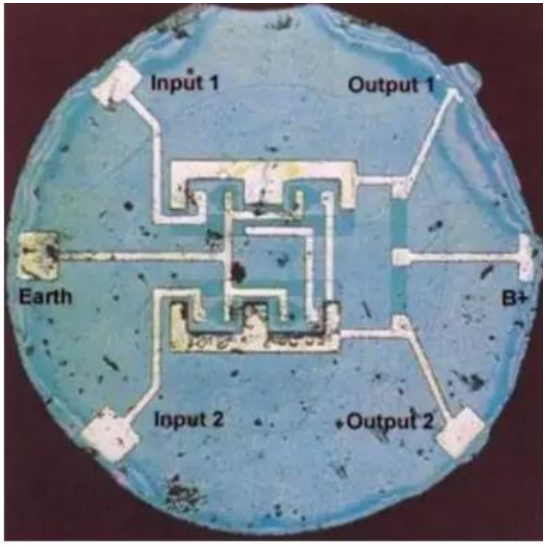




Principal object of the invention: to provide a miniaturized electronic circuit fabricated from a body of semicondutor containing a diffused p-n junction wherein all active and passive components are completely integrated into the body of the semiconductor material.

Bob Noyce patent

This invention relates to electrical circuit structures incorporating semiconductor devices. Its principal objects are these: to provide improved device-and-lead structures for making electrical connections to the various semiconductor regions; to make unitary circuit structures more compact and more easily fabricated in small sizes than has heretofore been feasible; and to facilitate the inclusion of numerous semiconductor devices within a single body of material.



The first planar process IC in the world

April 25, 1961 R. N. NOYCE 2,981,877
SEMICONDUCTOR DEVICE-AND-LEAD STRUCTURE
Filed July 30, 1959 3 Sheets-Sheet 2

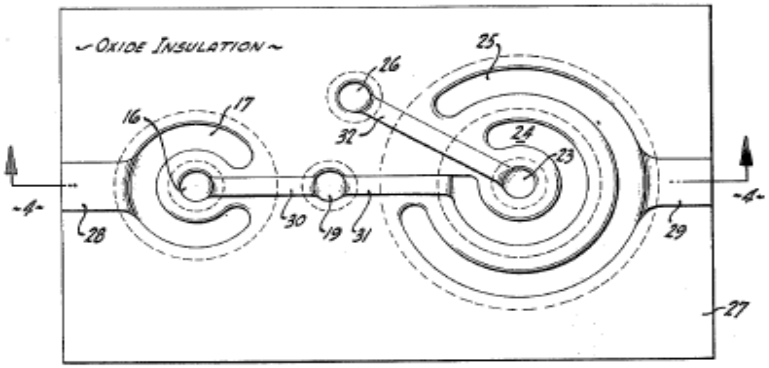


FIG. 3

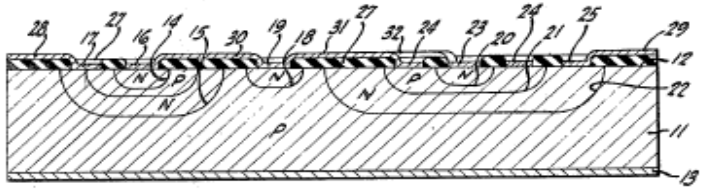


FIG. 4

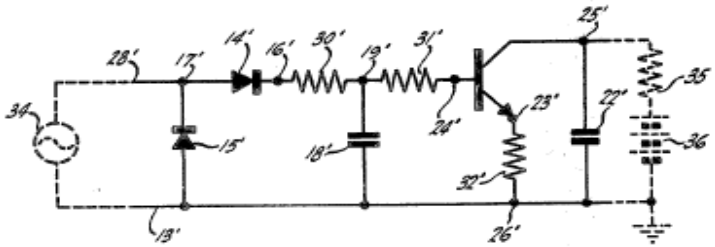
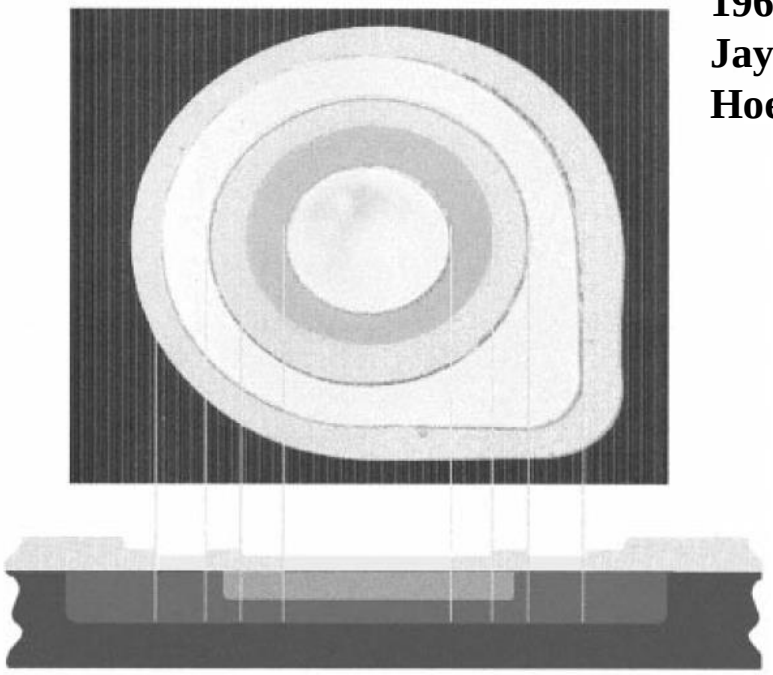


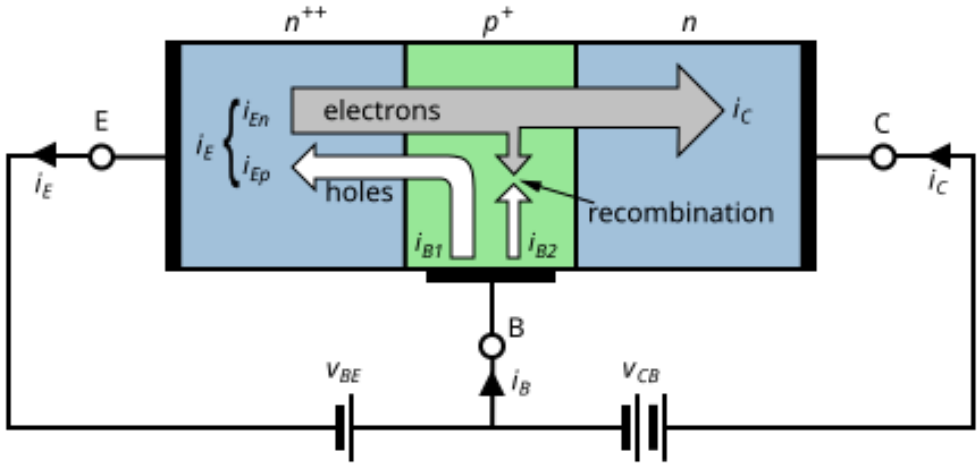
FIG. 5

INVENTOR.
ROBERT N. NOYCE
BY Lippincott & Ralls
ATTORNEYS

Lima - September 2024

1960: First Planar Integrated Circuit is Fabricated
Jay Last leads development of the first commercial IC based on Hoerni's planar process and Noyce's monolithic approach





https://en.wikipedia.org/wiki/Bipolar_junction_transistor

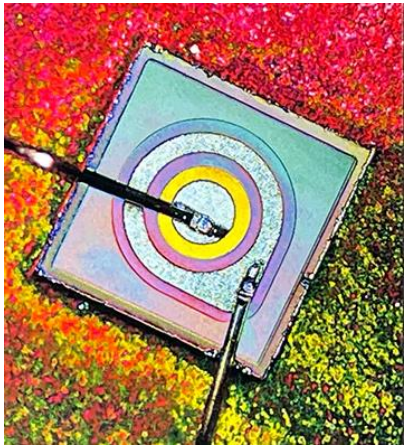


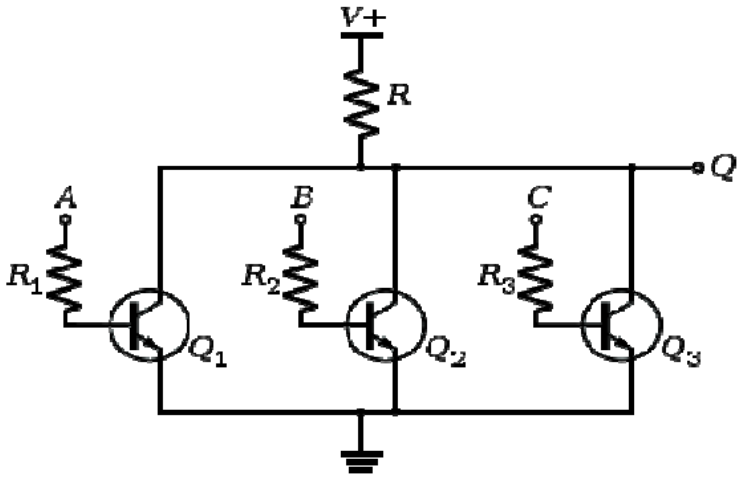
Fig. 4. Photomicrograph of the first planar transistor. The diameter of the circle that forms most of the outside ring is 0.030 in. The light areas are aluminum emitter and base electrodes. (From "A Solid State of Progress," Fairchild Camera and Instrument Corporation, 1979.)

The Fairchild 2N1613 – The First Planar Transistor

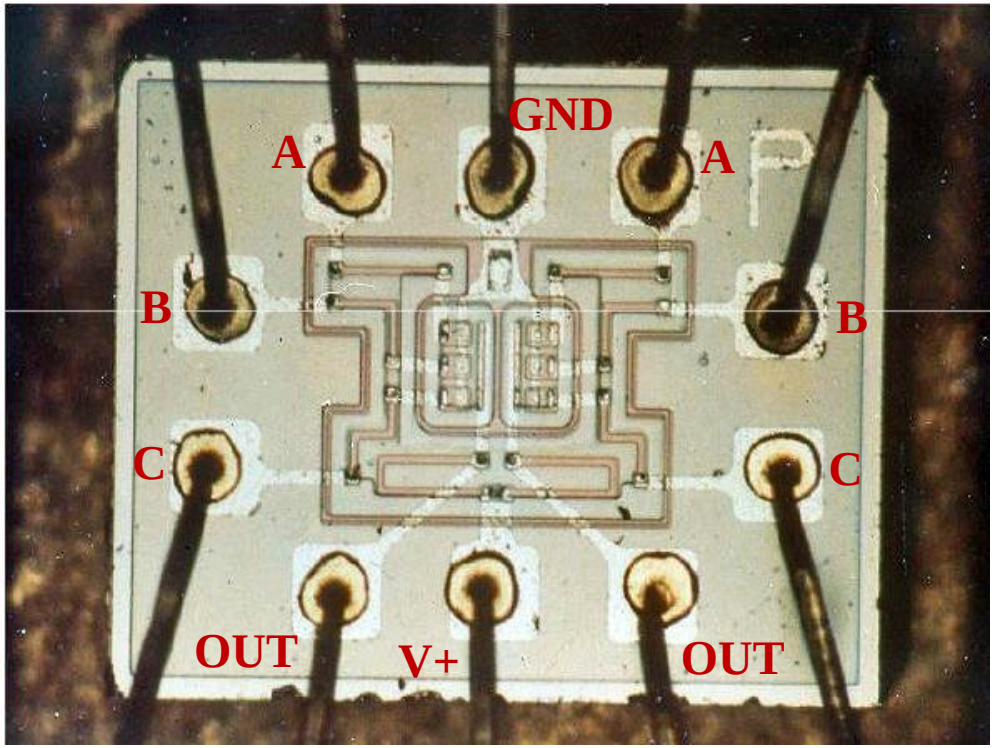
G. E. Moore, "The role of Fairchild in silicon technology in the early days of "Silicon Valley"," Proc. of the IEEE, vol. 86, no. 1, pp. 53-62, Jan. 1998.

The first monolithic planar integrated circuit (1960) was produced by Fairchild

RTL NOR gate



High power consumption!



Photograph of the dual NOR gate chip used to build the Apollo Guidance Computer

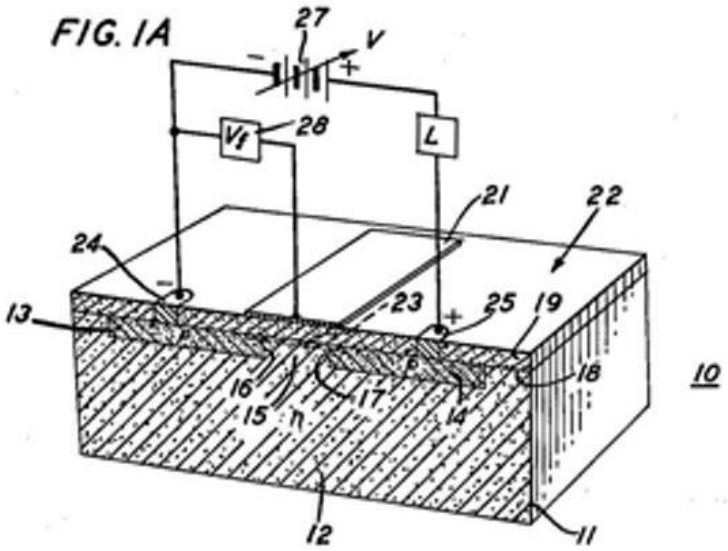
https://en.wikipedia.org/wiki/Invention_of_the_integrated_circuit

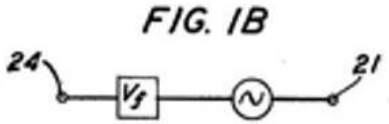
1960: Metal Oxide Semiconductor (MOS) Transistor Demonstrated

Aug. 27, 1963 DAWON KAHNG 3,102,230

ELECTRIC FIELD CONTROLLED SEMICONDUCTOR DEVICE

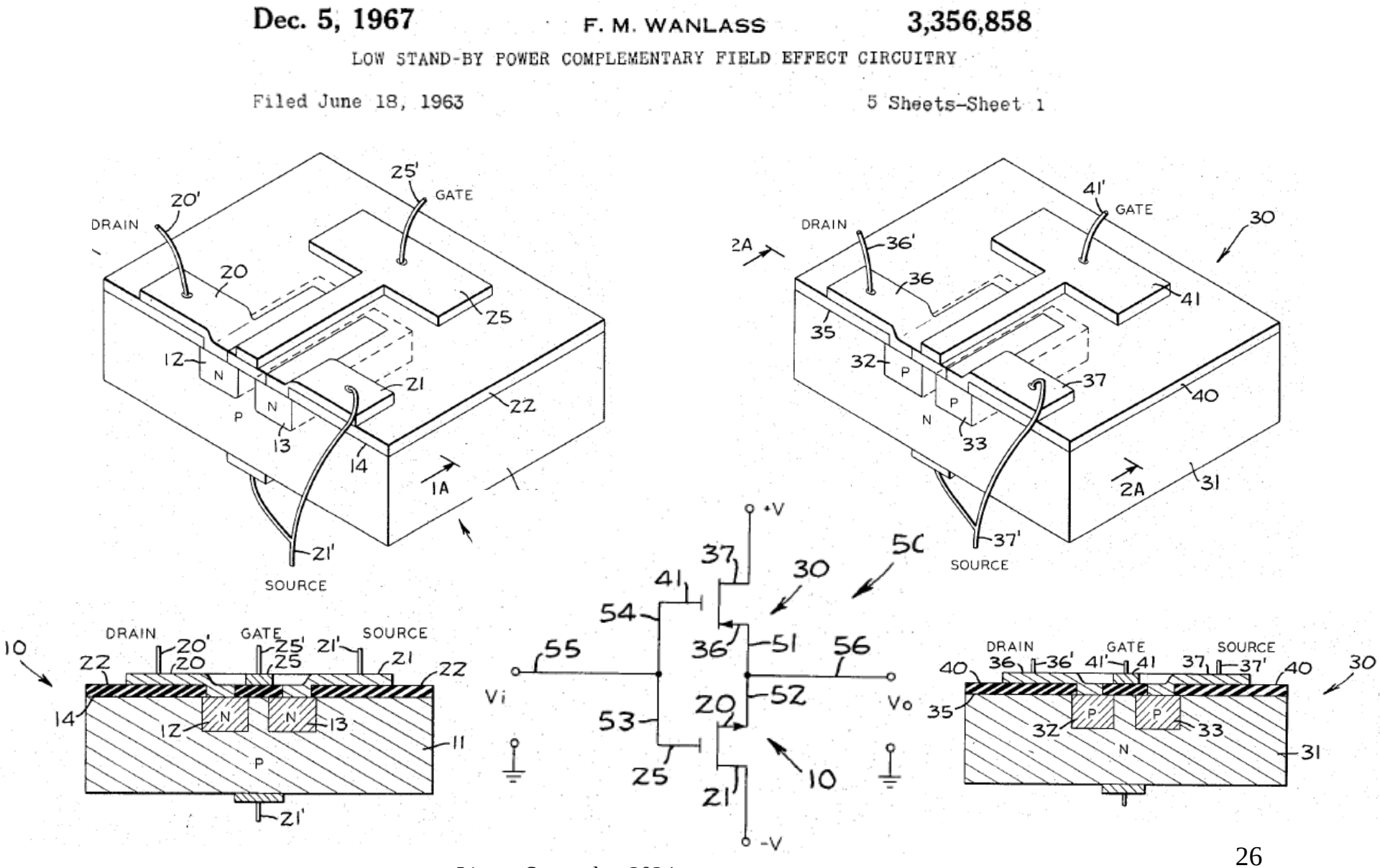
Filed May 31, 1960





John Atalla and Dawon Kahng fabricate working MOS transistors, which had been long anticipated by Lilienfeld, Heil, Shockley and others.

1963: Complementary MOS (CMOS) Circuit Configuration is Invented



1963 IEEE International Solid-State Circuits Conference.

WPM 3.5: Nanowatt Logic Using Field-Effect Metal-Oxide Semiconductor Triodes

F. M. Wanlass and C. T. Sah

Fairchild Semiconductor Div., Fairchild Camera-Instrument Corporation

Palo Alto. Calif.

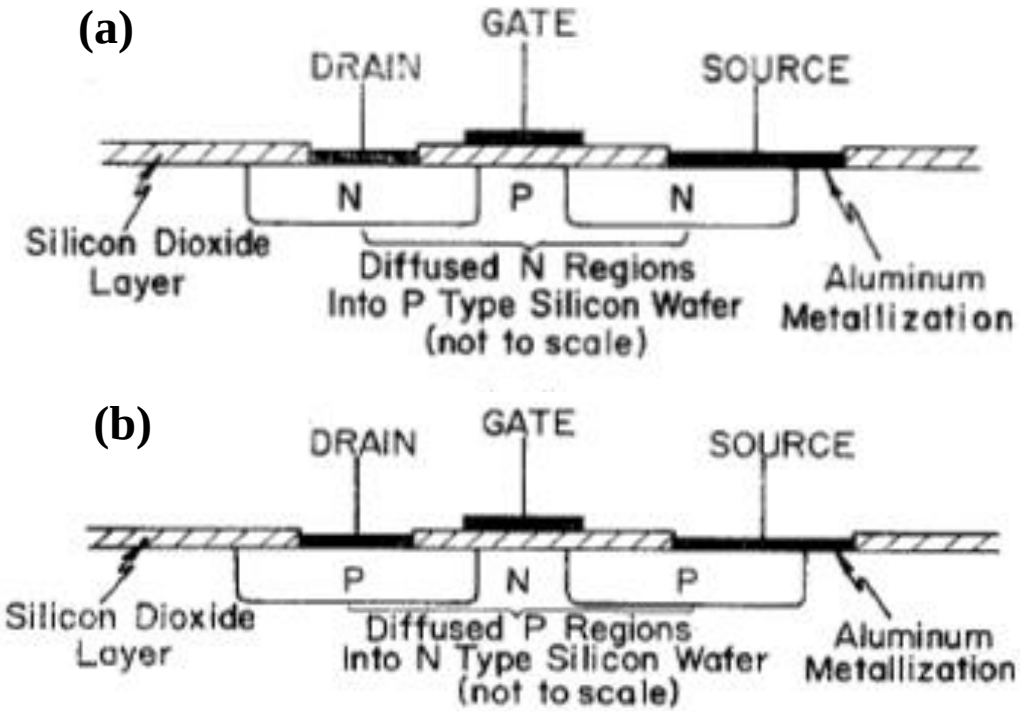
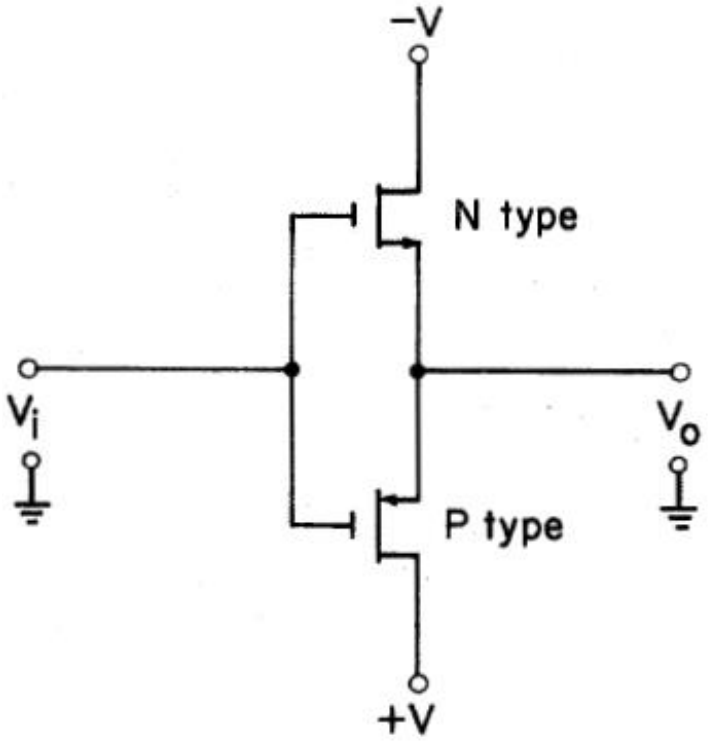


FIGURE 1—Cross sections of metal-oxide-semiconductor-triodes: *(a)* the *N* type element; *(b)* the *P* type element.



The CMOS inverter: the basic low-power logic gate

1965: "Moore's Law" Predicts the Future of Integrated Circuits

Fairchild's Director of R & D predicts the rate of increase of transistor density on an integrated circuit and establishes a yardstick for technology progress.

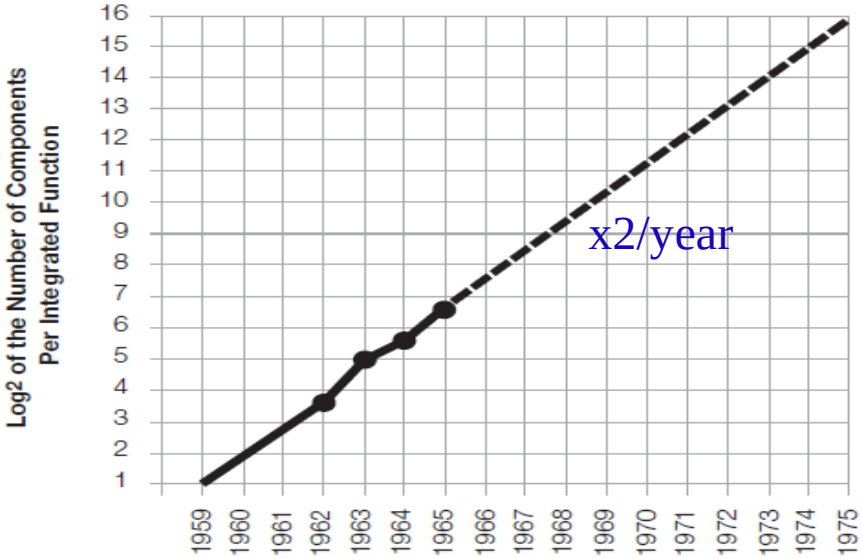
Cramming more components onto integrated circuits

With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore

Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

Electronics, Volume 38, Number 8, April 19, 1965

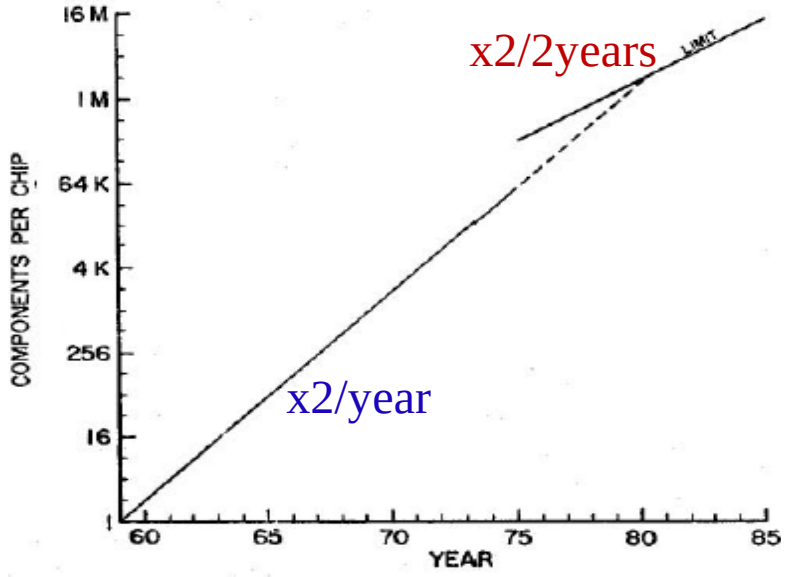


Progress In Digital Integrated Electronics

1975 IEEE Text Speech

Gordon E. Moore, Co-founder
Intel Corporation

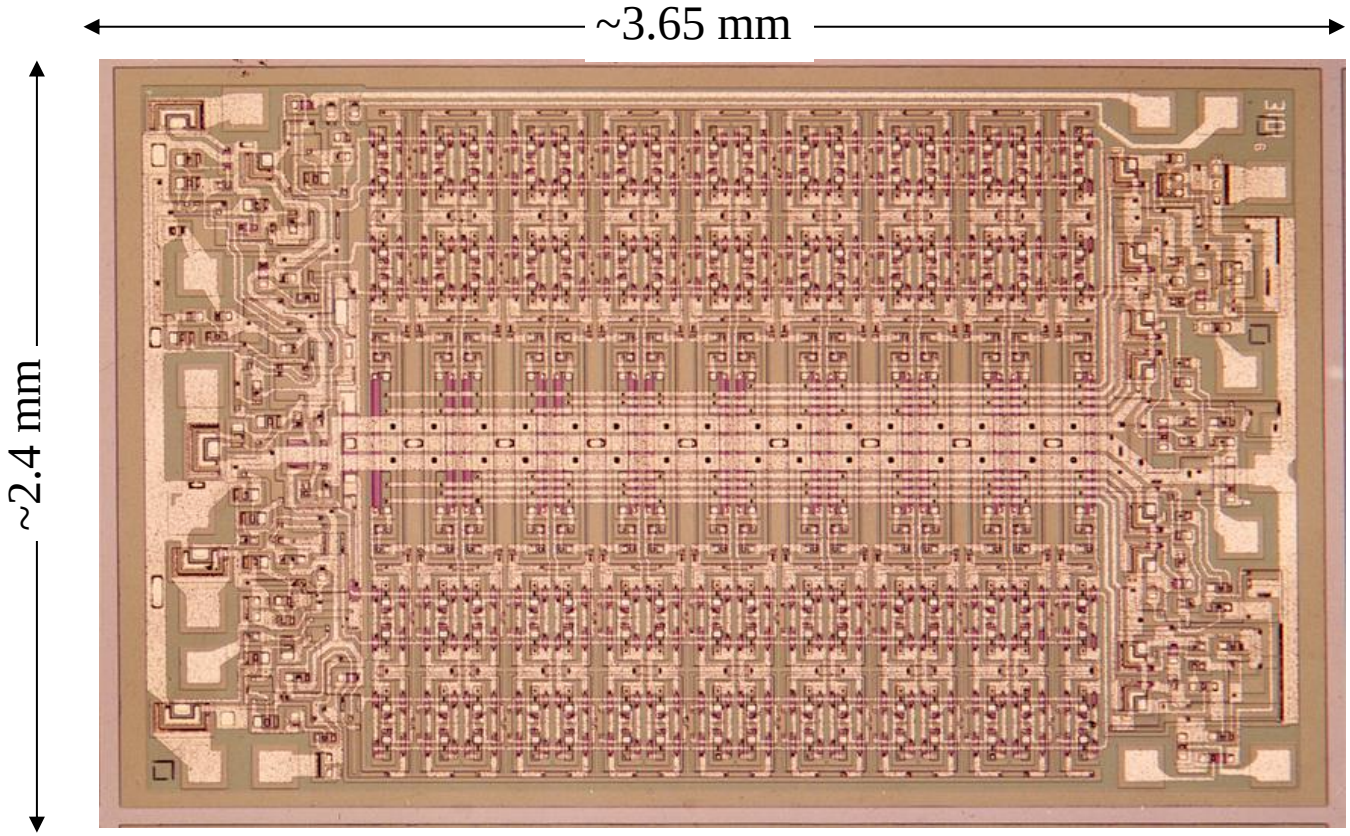
The new slope might approximate a doubling every two years, rather than every year, by the end of the decade.



https://www.computerhistory.org/siliconengine/

1968: Robert Noyce and Gordon Moore resigned from Fairchild and founded Intel to create a company that would reflect their belief in continuous innovation.

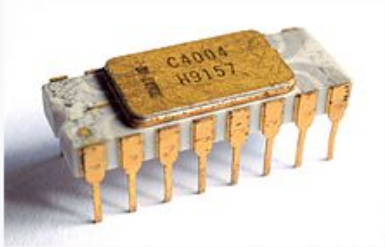
Intel's First Product – the 3101 64-bit bipolar SRAM



https://www.intel.com/content/www/us/en/history/virtual-vault/articles/intels-founding.html

http://www.righto.com/2017/07/inside-intels-first-product-3101-ram.html

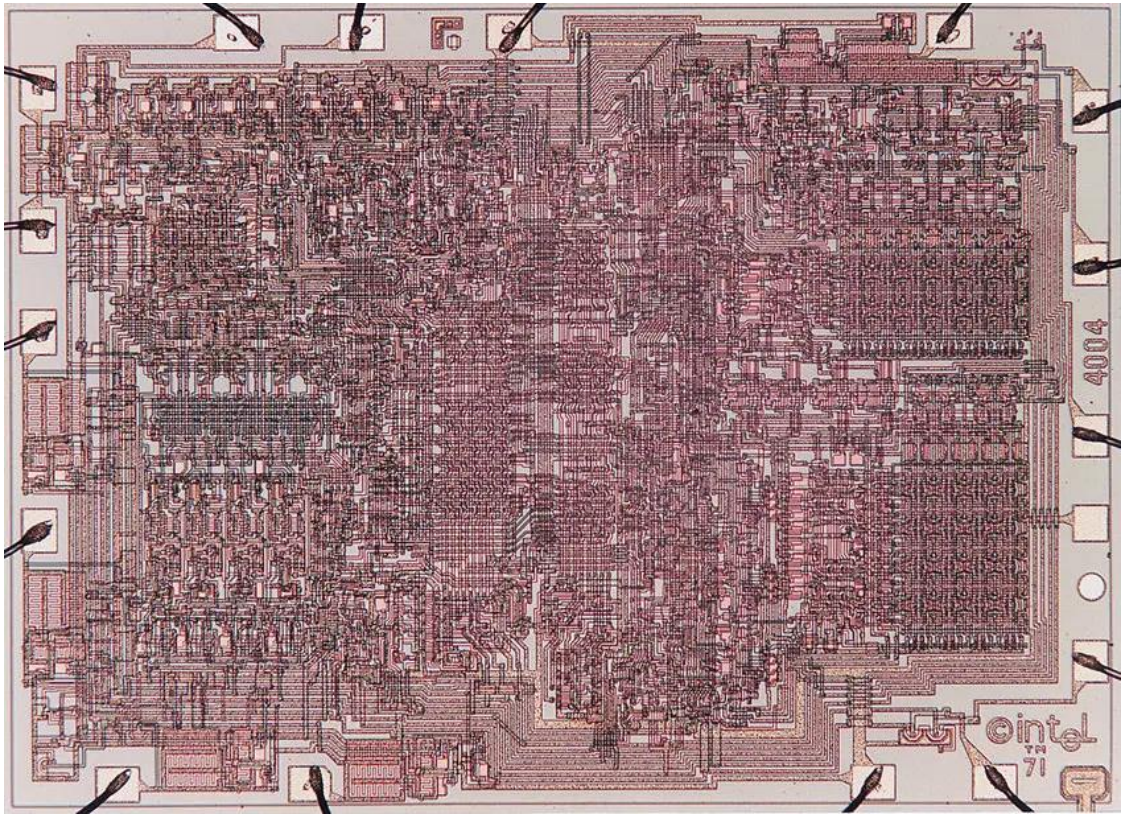
Intel 4004



Intel C4004 processor with grey traces

General information	
Launched	November 15, 1971
Discontinued	1981[1]
Marketed by	Intel
Designed by	Intel
Common manufacturer	Intel
Performance	
Max. CPU clock rate	740 KHz to 750 KHz
Data width	4 bits
Address width	12 bits (multiplexed)
Architecture and classification	
Application	Busicom calculator, arithmetic manipulation
Technology node	10 µm
Instruction set	4-bit BCD-oriented
Physical specifications	
Transistors	2,300

Ted Hoff and Stanley Mazor conceived Intel's first integrated CPU, the 4004 4-bit device.



12 mm² die

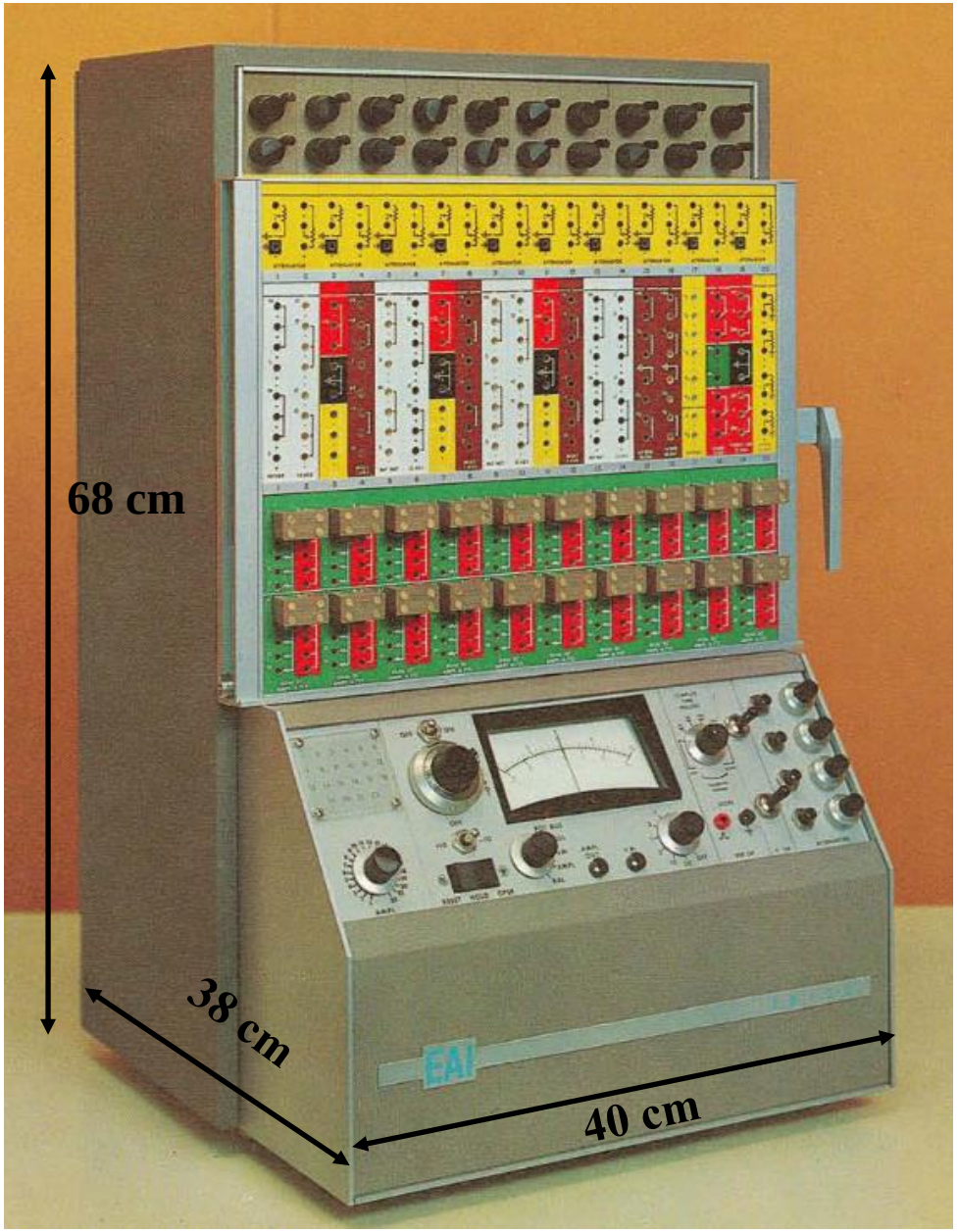
https://en.wikipedia.org/wiki/Intel_4004

https://www.computerhistory.org/siliconengine/

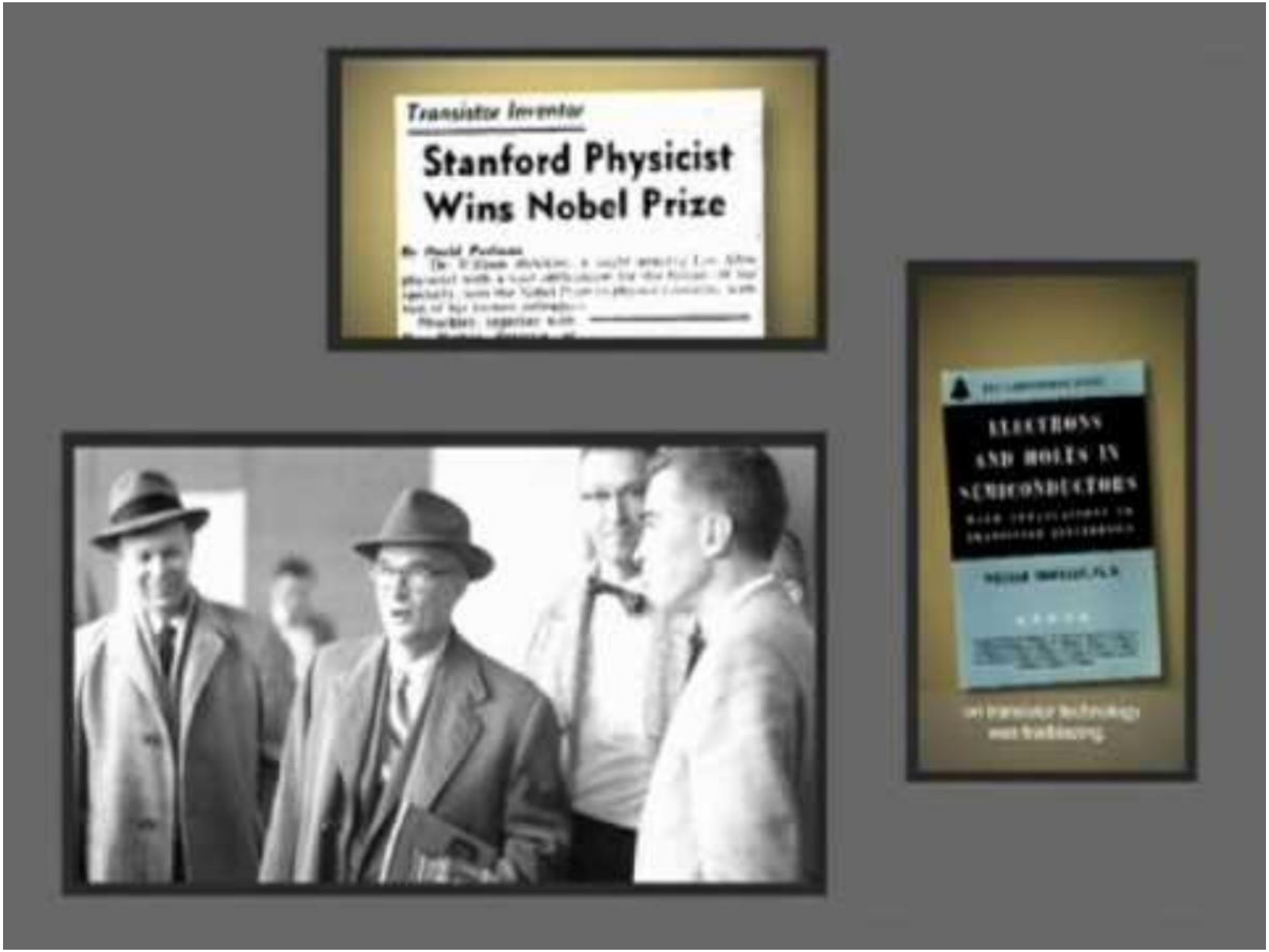
TR-20 Analog Computer

- Transistorized (BJT)
- 46 kg
- 20 amplifiers
- Linear and non-linear components
- Power < 60 W

Late 1960s and 1970s



http://s3data.computerhistory.org/brochures/eai.tr20tr48.1964.102646218.pdf

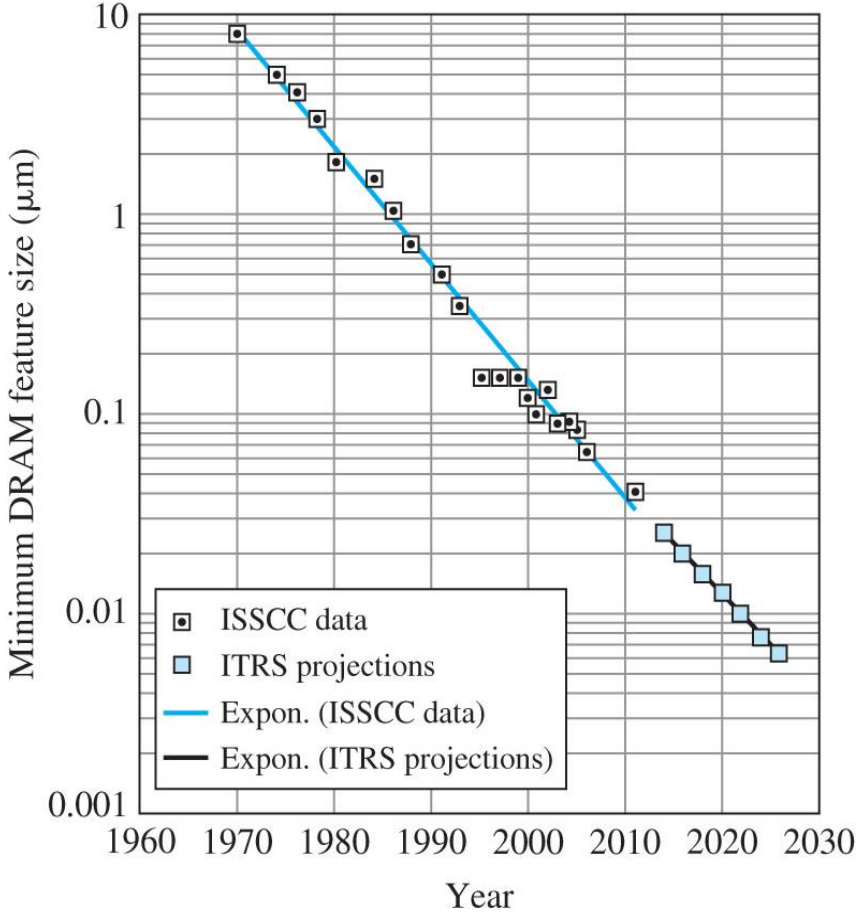


https://www.youtube.com/watch?v=cdqiP0aR1-Q

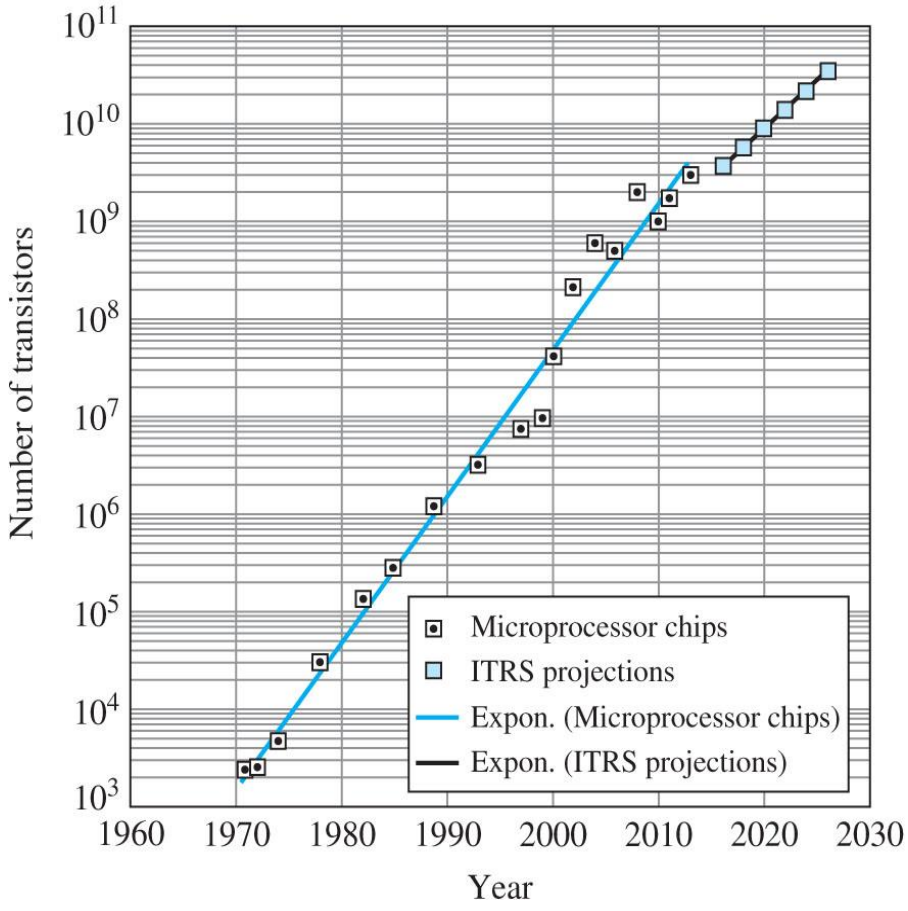
Rapid Increase in Density of Microelectronics

Feature size reductions enabled by process innovations.

Smaller features lead to more transistors per unit area and, therefore, higher density.

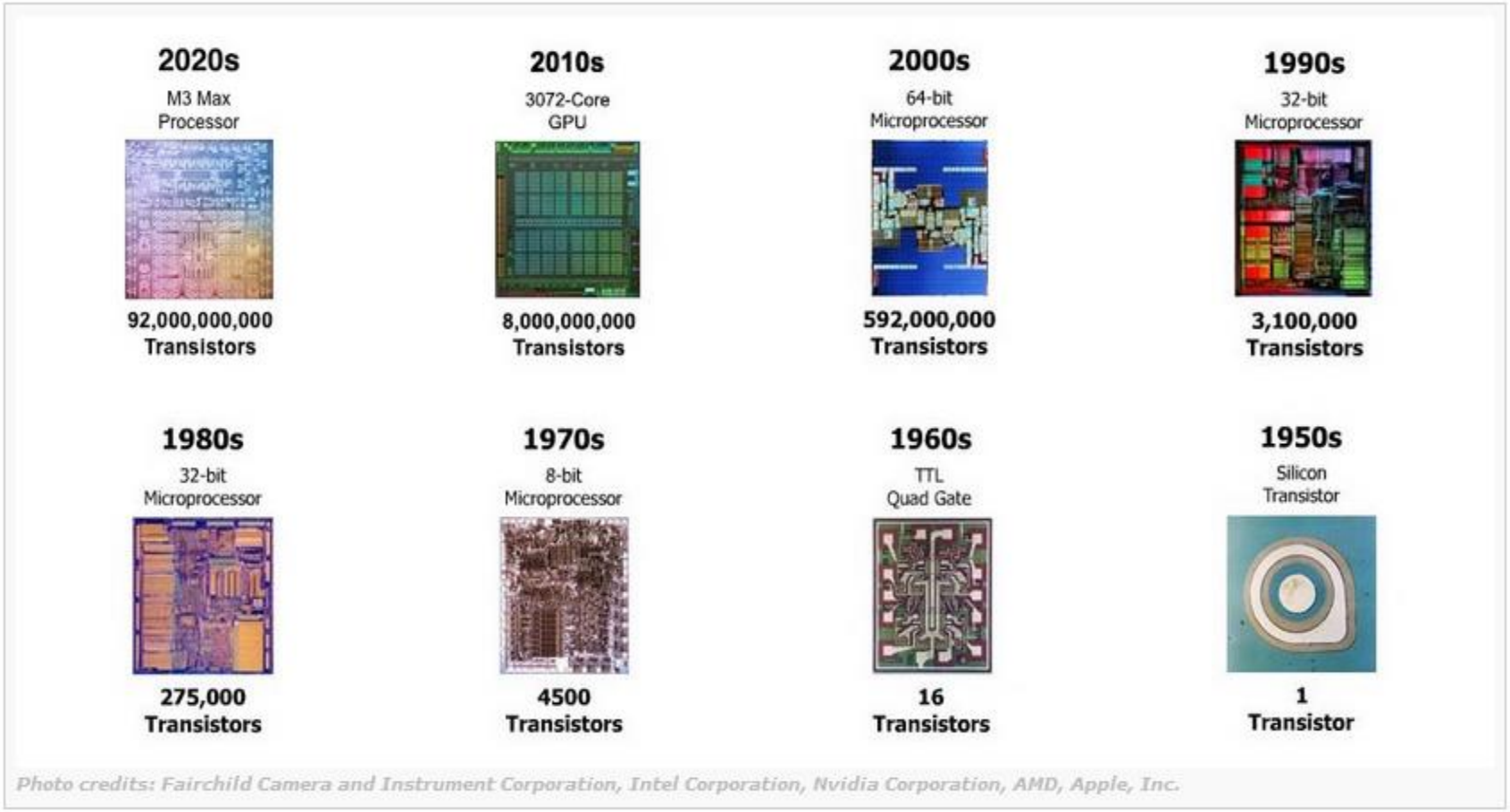


Memory chip feature size versus time.



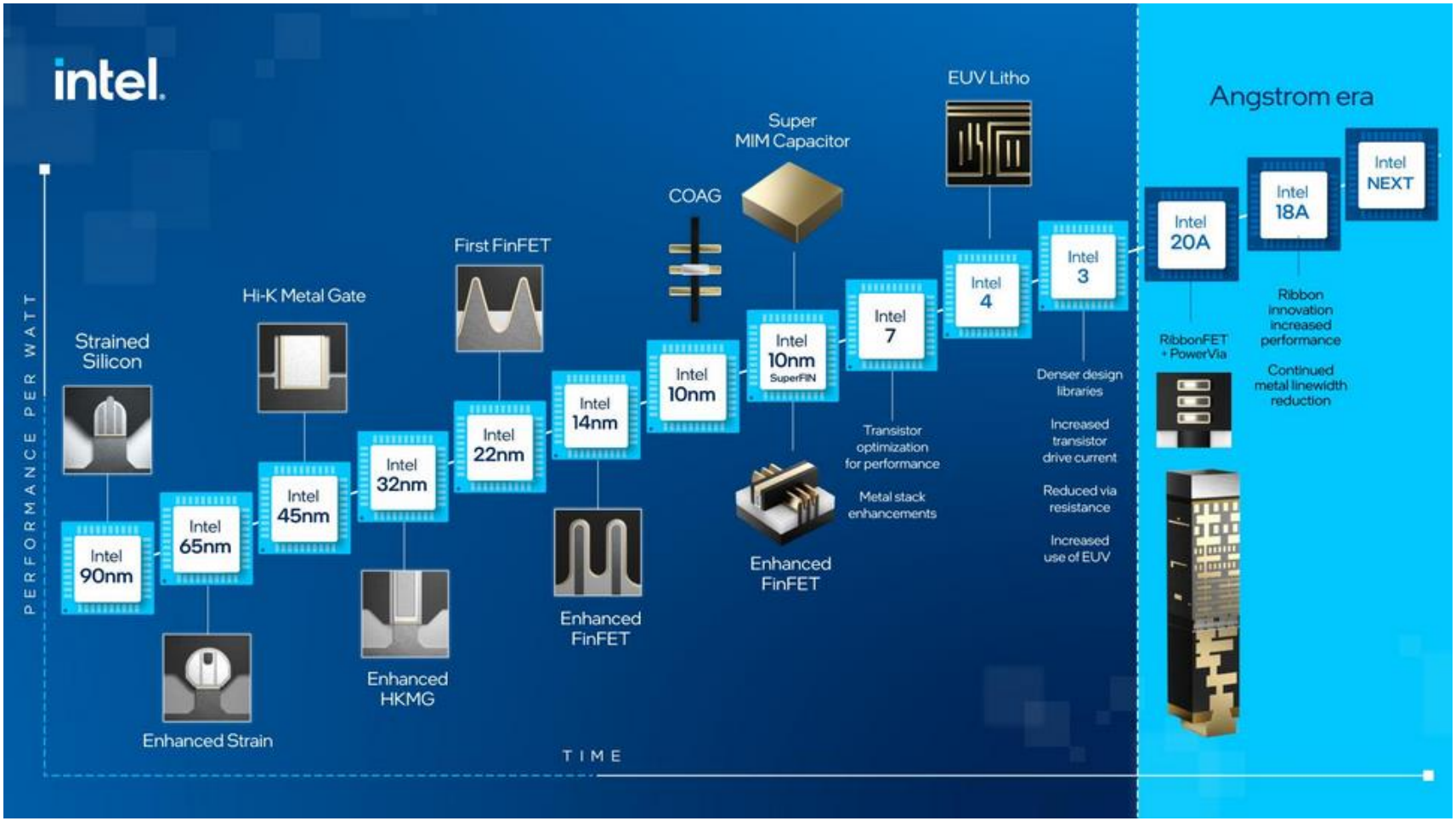
Microprocessor complexity versus time.

A TIMELINE OF SEMICONDUCTORS IN COMPUTERS



https://www.computerhistory.org/siliconengine/

Moore´s law: Transistor innovations over time

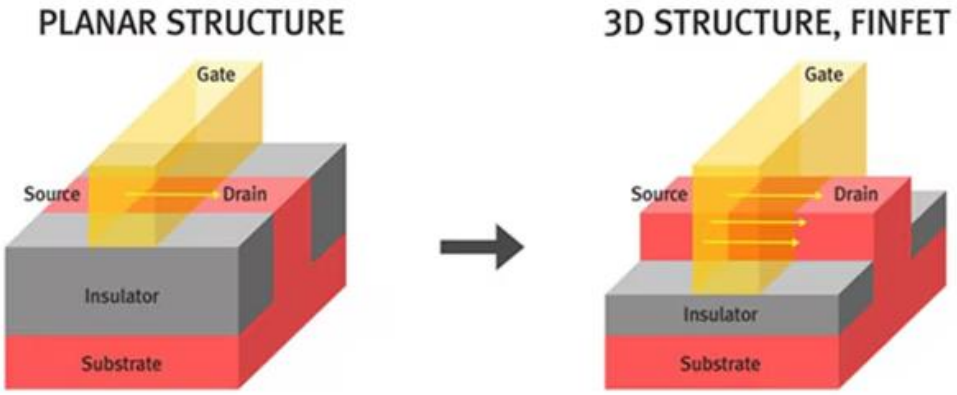


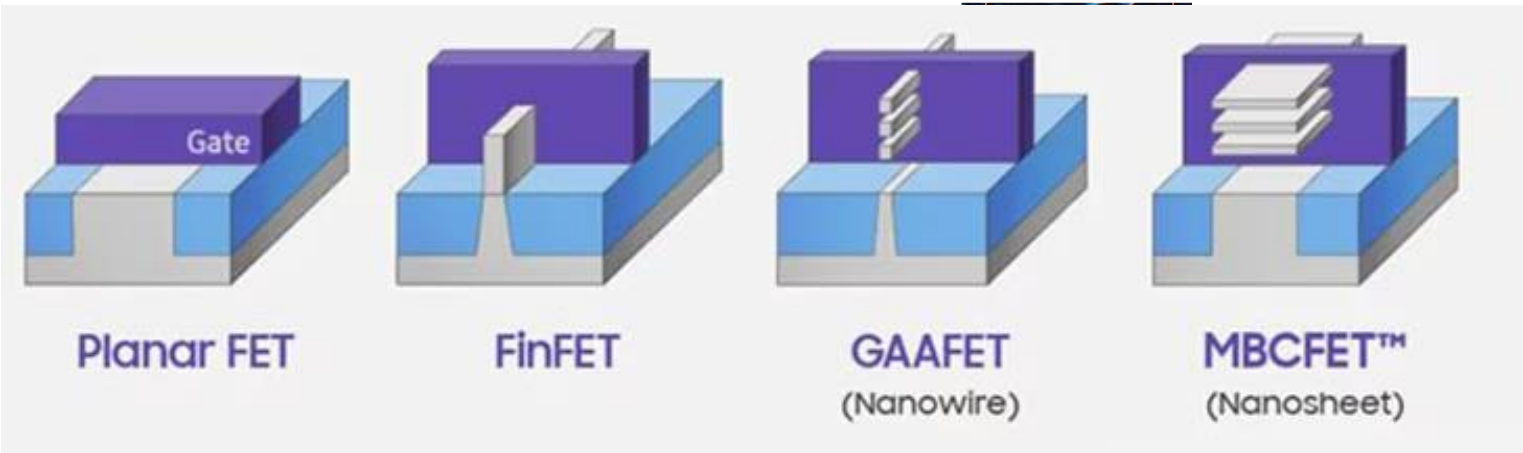
1.4 Fueling Semiconductor Innovation and Entrepreneurship in the Next Decade

Lip-Bu Tan

Chairman of Walden International,
Founding Managing partner of Walden Catalyst Ventures,
Senior Advisor & former CEO Cadence Design, San Francisco, CA

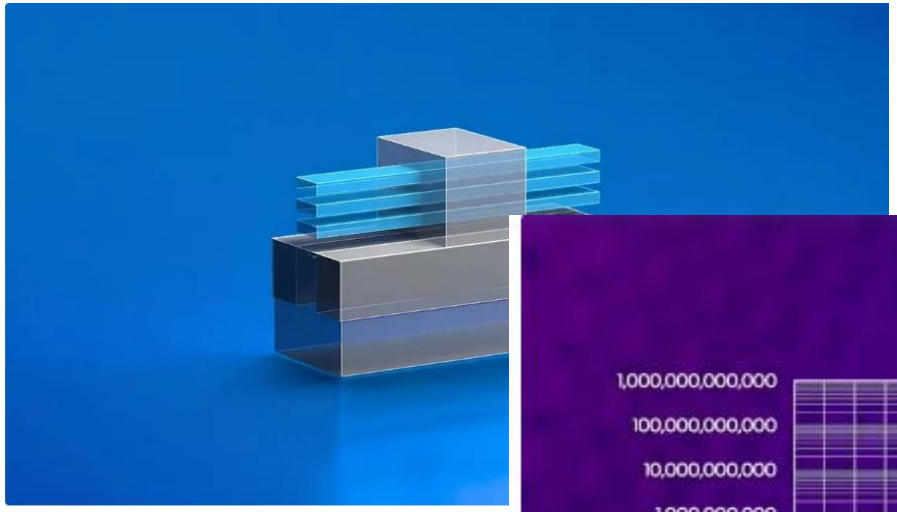
https://www.intel.com/content/www/us/en/newsroom/opinion/moore-law-now-and-in-the-future.html#gs.e1egua



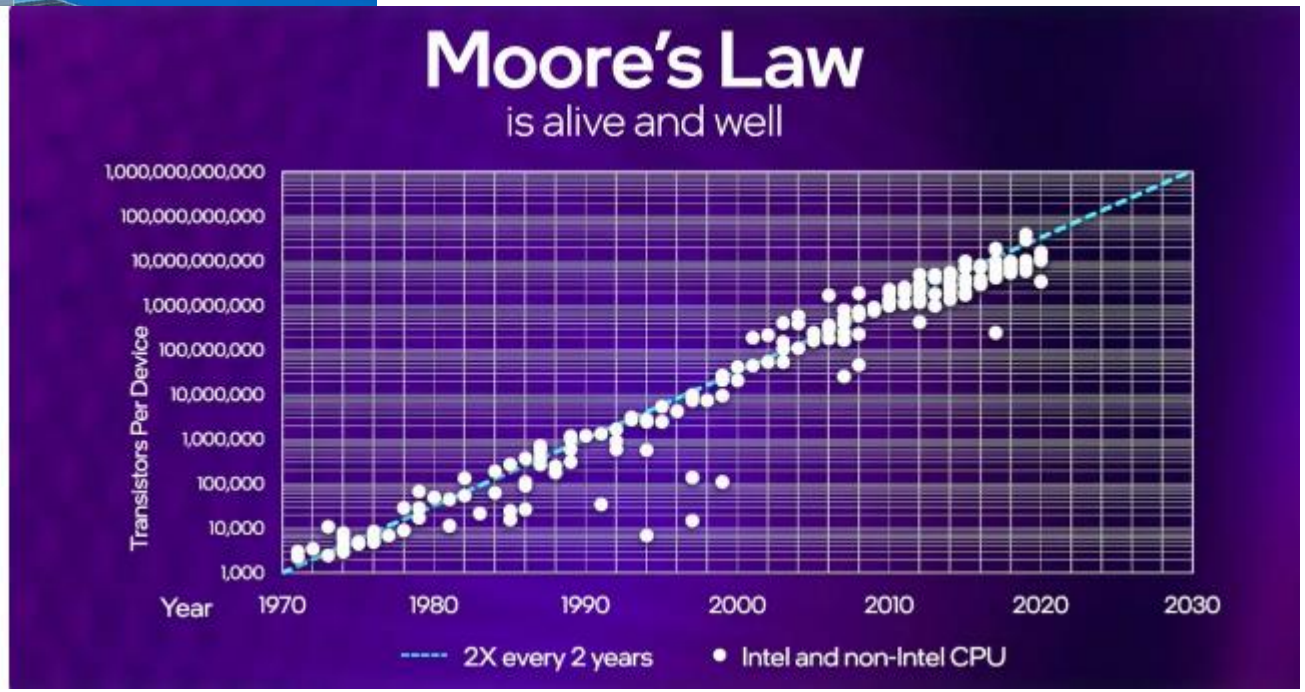


GAA -gate-All-Around
MBCFET -Multi Bridge Channel FET

https://semiconductor.samsung.com/support/tools-resources/dictionary/gaa-transistors-a-next-generation-process-for-next-generation-semiconductors/

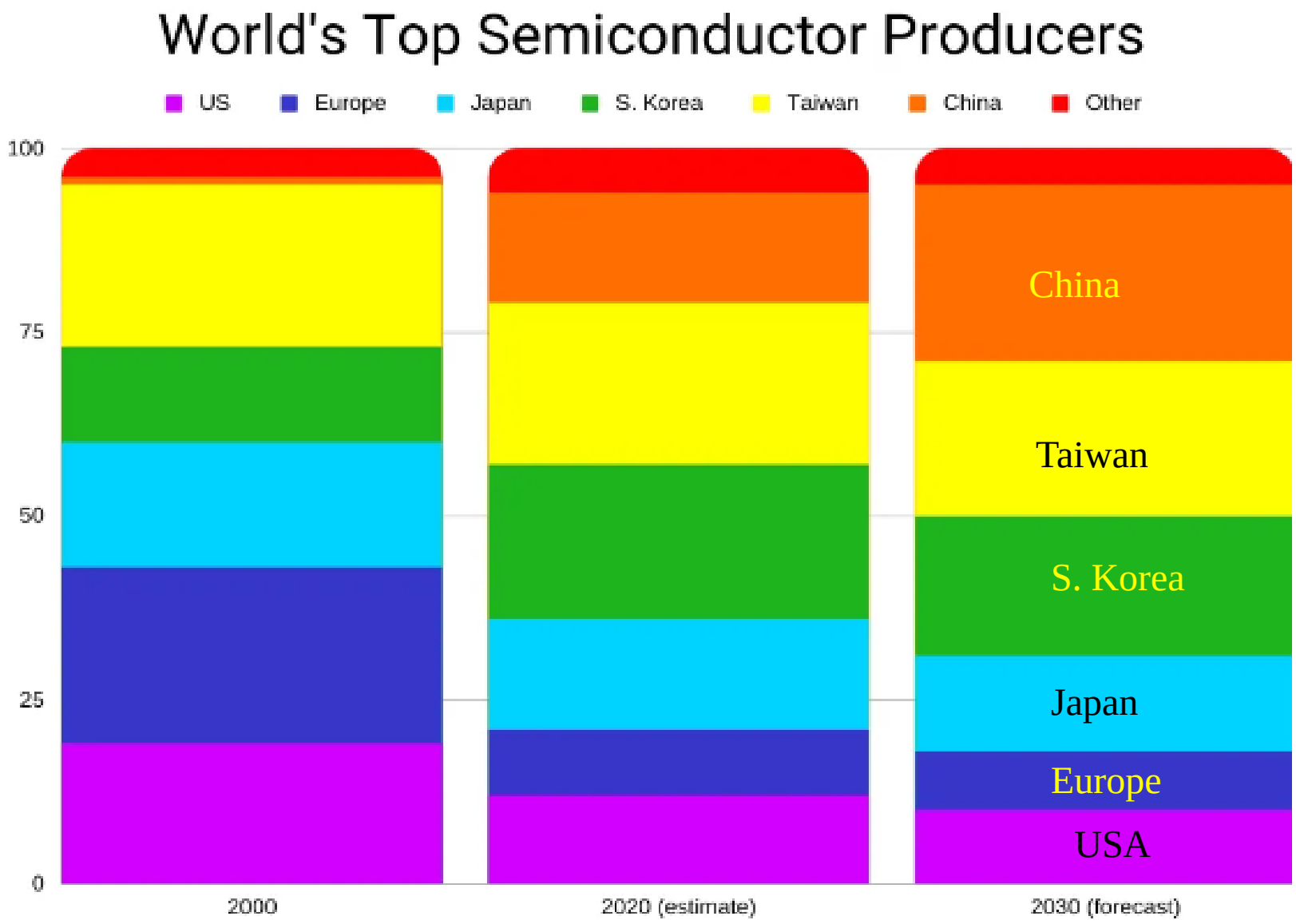


Intel RibbonFET transistors are a key part of the chipmaker's recovery plan.



Moore's Law: The rule that really matters in tech - CNET

http://s3.computerhistory.org/siliconengine/semiconductorlesson-innovation.pdf



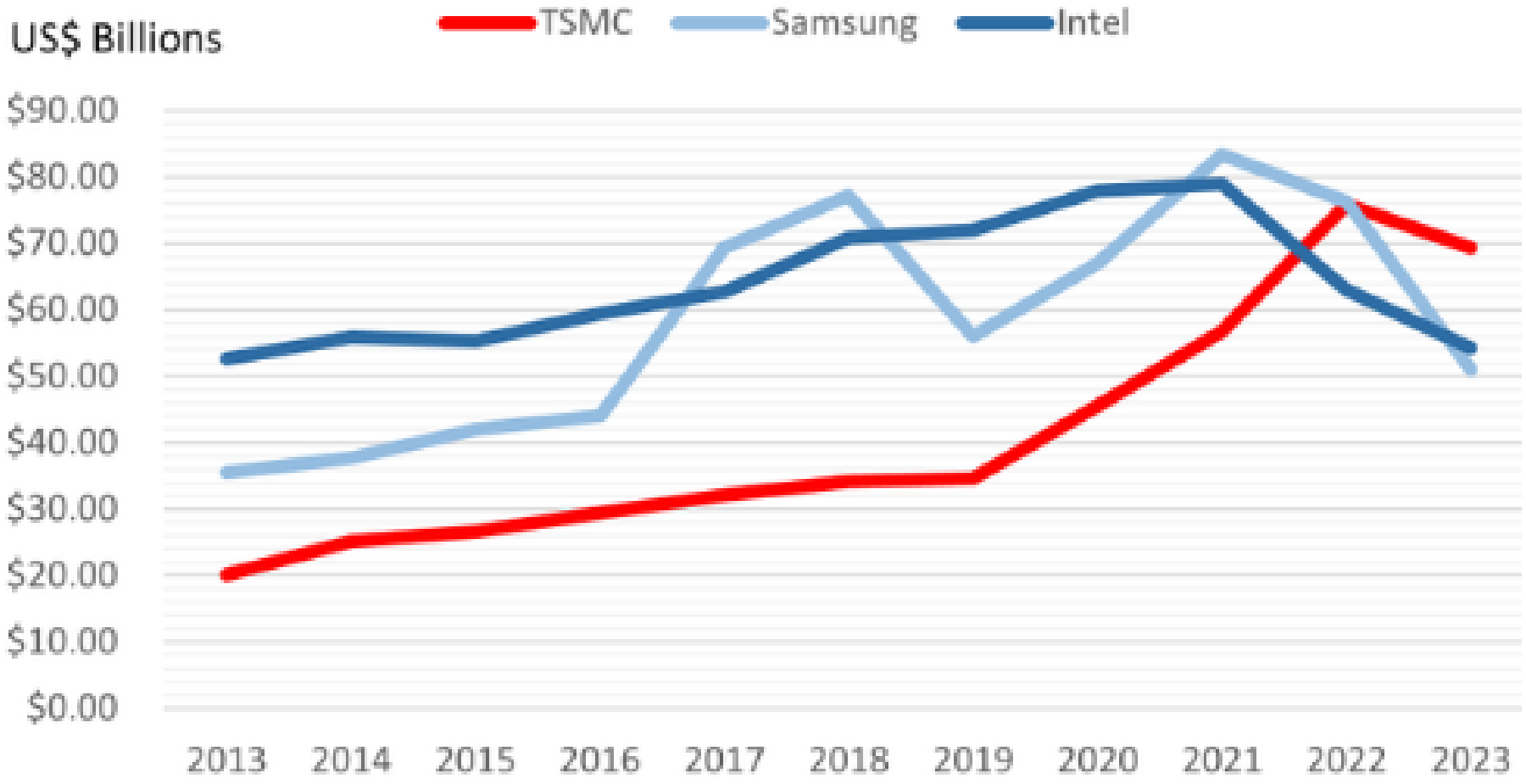
World's Top Semiconductor Producers | ShipHub

TOP 10 FOUNDRIES

Company	Market share	Country
TSMC	54%	Taiwan
Samsung	17%	South Korea
UMC	7%	Taiwan
GlobalFoundries	7%	U.S.
SMIC	5%	China
Other firms	5%	N/A
VIS	1%	Taiwan
Tower Semiconductor	1%	Israel
PSMC	1%	Taiwan
HH Grace	1%	China
DB HiTek	1%	China

The Top 10 Semiconductor Companies by Market Share (visualcapitalist.com)

TSMC 2023 World's Biggest Chip Manufacturer



TSMC earns $69.3 billion in 2023 becoming world's largest semiconductor company by revenue | TechSpot

USA and Europe: plan to bring the semiconductor manufacturing back to them.

Investments/incentives:

USA (2022): The **CHIPS and Science Act** (**$ ~53 billion 280 billion**)

Europe (2023): The **European Chips Act (> € 43 billion)**

Why?

- **Chips are indispensable to all modern societies**
- **Main suppliers of chips from Asia**
- **Geopolitical instability in East Asia (China/Taiwan)**

CHIPS and Science Act - Wikipedia

European Chips Act - European Commission (europa.eu)

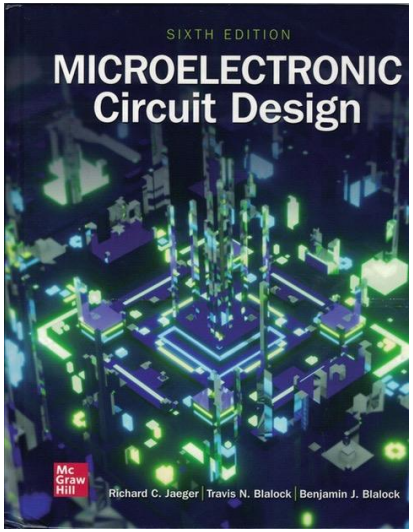
1 trillion: approximate #of chips fabricated in 2020
~130 chips/ inhabitant

2 trillion: predicted #of chips to be fabricated in 2030 (Artificial Intelligence – the most chip-demanding area)

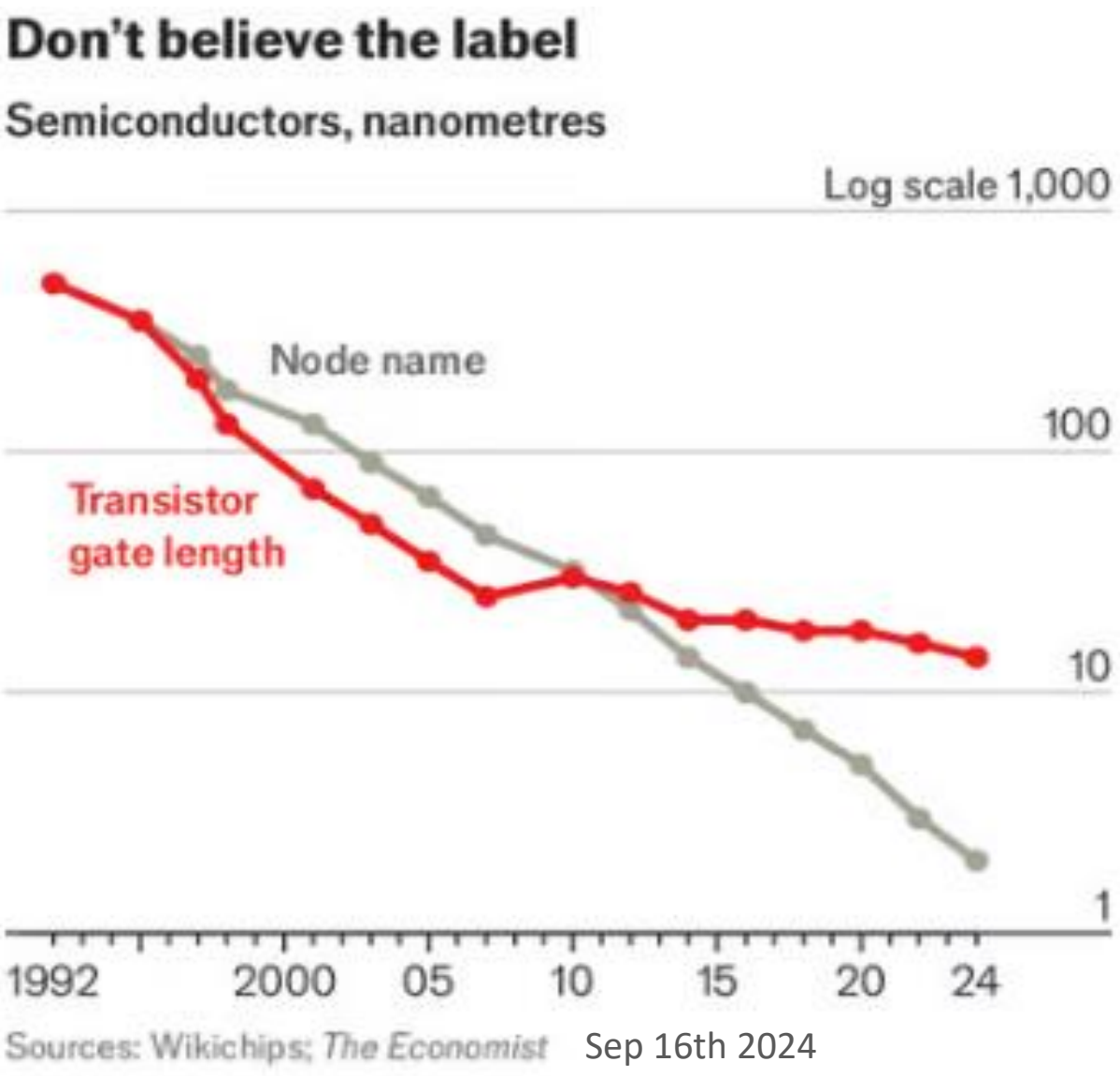
European Chips Act - European Commission (europa.eu)

https://www.computerhistory.org/siliconengine/

https://en.wikipedia.org/



THANK YOU VERY MUCH FOR YOUR ATTENTION!


Don't believe the label
Semiconductors, nanometres
Log scale 1,000
Node name
100
Transistor gate length
10
1
1992
2000
05
10
15
20
24
Sources: Wikichips; The Economist
Sep 16th 2024

TSMC's Latest Global Production Capacity Layout

Japan		
Location	W.Size	Process
Kumamoto	2	12/16、22/28 nm 6/7 nm

Germany		
Location	W.Size	Process
Dresden	1	12/16、22/28 nm

USA		
Location	W.Size	Process
Arizona	1	3-4 nm
Washington	1	0.18-0.35 μm

China		
Location	W.Size	Process
Nanjing	1	12/16、22/28 nm
Shanghai	1	0.11-0.35 μm

Taiwan		
Location	W.Size	Process
Hsinchu	6	2-90 nm, 0.11-0.35 μm, 0.35 μm and more mature Global R&D center
Taichung	2	6/7、22/28、1.4 nm
Tainan	3	3-5、12 nm-0.13 μm、0.11-0.18 μm
Kaohsiung	1	2 nm

https://www.trendforce.com/news/2024/03/07/news-tsmc-to-expand-production-with-new-facilities-across-taiwan-in-april/

Lima - September 2024