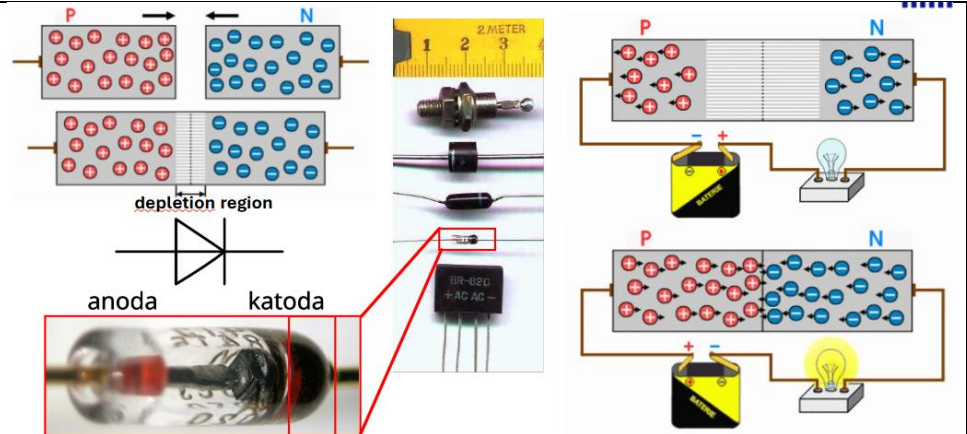
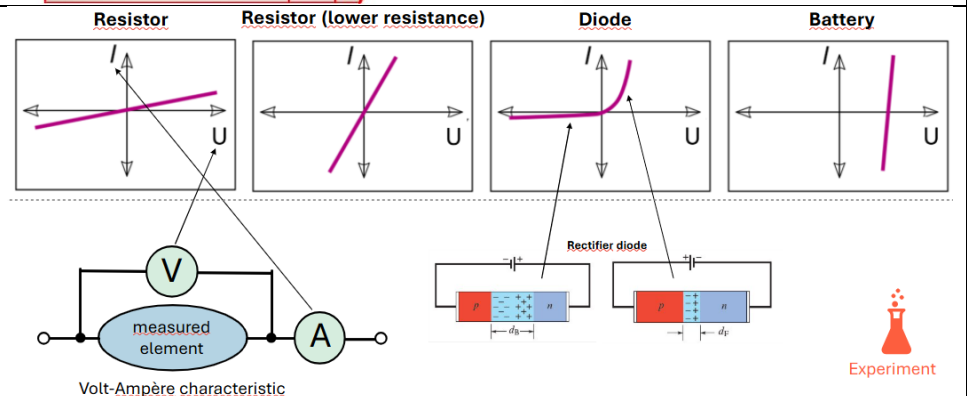
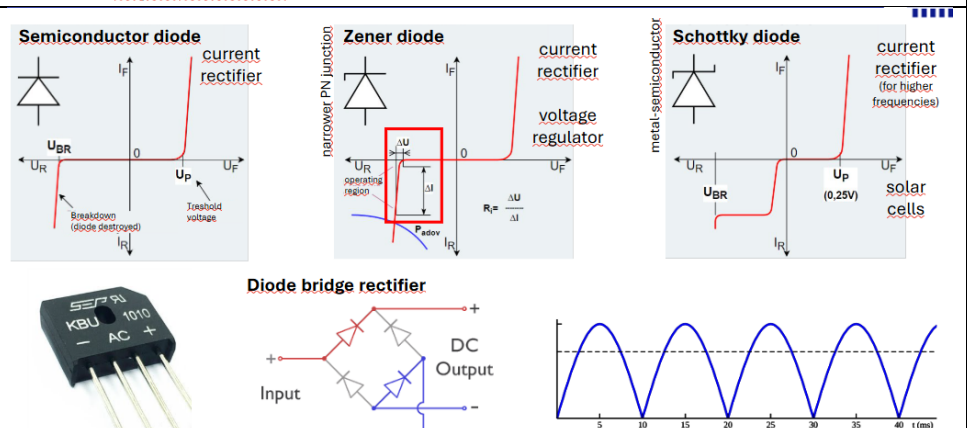
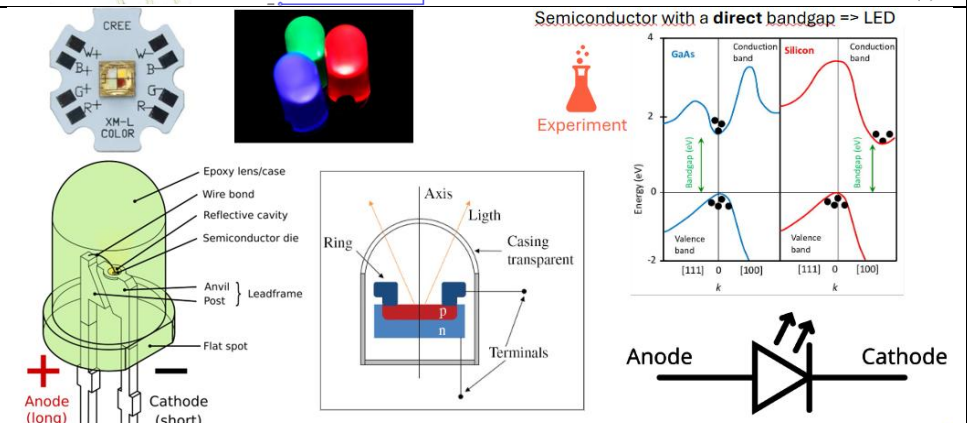


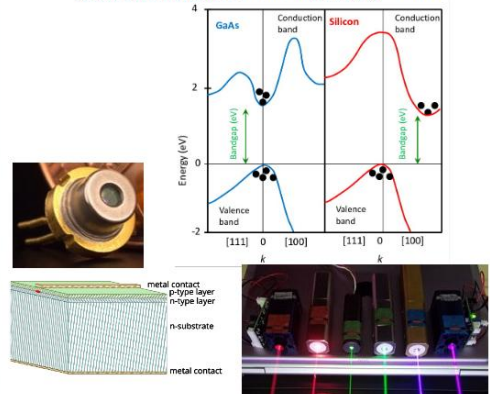
9.	Co je to polovodič?
Cílová skupina	Žáci, volitelně učitelé
Věk žáků	16–18
Doba trvání	1,5–2 hodiny
Co je to polovodič	intrinsic Pure Silicon covalent bond valence electrons Silicon atoms extrinsic P-Type Aluminum ==> p-type acceptor (accepts electrons) Boron atom Void (Hole) N-Type Phosphorus ==> n-type donor (donates electrons) Antimony atom Fifth valence electron
Shrnutí úvodu	metal (conductor) zero band gap semiconductor band gap: $5 \text{ eV} > E_G > 0.5 \text{ eV}$ dielectric (non-conductor) band gap: $E_G > 5 \text{ eV}$ Extrinsic semiconductors: Phosphorus ==> p-type donor Aluminum ==> p-type acceptor Electrical resistance (Ω) Experiment CHIPS of Europe – Creating Higher-Education Industry Programmes for the Semiconductor Industry of Europe www.chips4europe.eu
Video: Kovy a izolanty	METALS AND INSULATORS In quantum physics, an atom in a box displays discontinuous energy levels.

**Aplikace: PN přechod
→ Dioda**

**VA charakteristika
(lineární vs.
nelineární prvky)**

**VA charakteristika
(pokročilejší úroveň)**

**Dioda → LED
(elektroluminiscenční
dioda)**


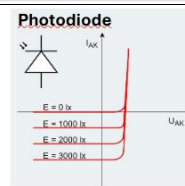
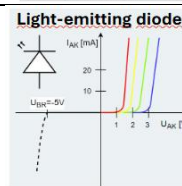
Dioda → LED → Polovodičový laser

Color	Wavelength (nm)	Voltage (V)	Semiconductor material
Infrared	$\lambda > 760$	$\Delta V \approx 1.9$	Gallium arsenide (GaAs) Aluminum gallium arsenide (AlGaAs)
Red	$610 < \lambda < 760$	$1.93 < \Delta V < 2.93$	Aluminum gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminum gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Orange	$590 < \lambda < 610$	$2.03 < \Delta V < 2.10$	Gallium arsenide phosphide (GaAsP) Aluminum gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Yellow	$570 < \lambda < 590$	$2.10 < \Delta V < 2.18$	Gallium arsenide phosphide (GaAsP) Aluminum gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Green	$500 < \lambda < 570$	$1.9^{III} < \Delta V < 4.0$	Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) Gallium(III) phosphide (GaP) Aluminum gallium indium phosphide (AlGaInP) Aluminum gallium phosphide (AlGaP)
Blue	$450 < \lambda < 500$	$2.48 < \Delta V < 3.7$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate — (under development)
Violet	$400 < \lambda < 450$	$2.76 < \Delta V < 4.0$	Indium gallium nitride (InGaN)
Purple	multiple types	$2.48 < \Delta V < 3.7$	Dual Infrared LEDs, blue with red phosphor, or white with purple plastic
Ultraviolet	$\lambda < 400$	$3.1 < \Delta V < 4.4$	Diamond (235 meV) ^[2] Boron nitride (215 meV) ^{[3][4]} Aluminum nitride (AlN) (210 meV) ^[5] Aluminum gallium nitride (AlGaIn) Aluminum gallium indium nitride (AlGaInIn) — (down to 210 meV) ^[6]
White	Broad spectrum	$2.7 < \Delta V < 3.5$	Blue diode with yellow phosphor or violet/UV diode with multi color phosphor

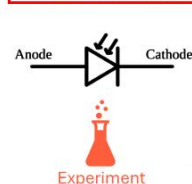
Semiconductor with a direct bandgap => LED



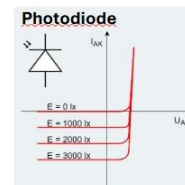
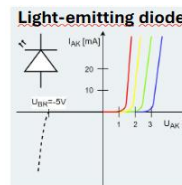
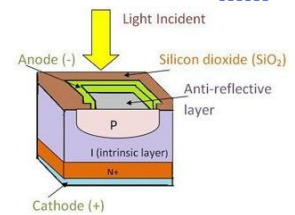
Dioda → LED → Fotodioda



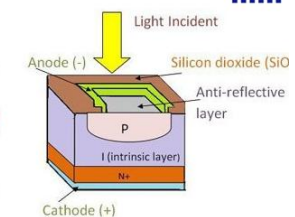
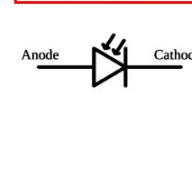
speaker vs. microphone LED vs. photodiode



Experiment



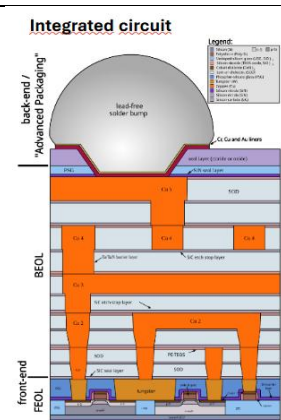
speaker vs. microphone LED vs. photodiode



Digital camera chip



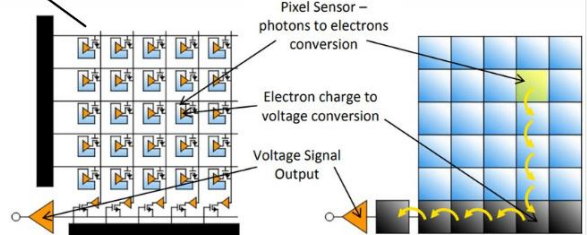
Dioda → LED → Fotodioda (CCD, CMOS)

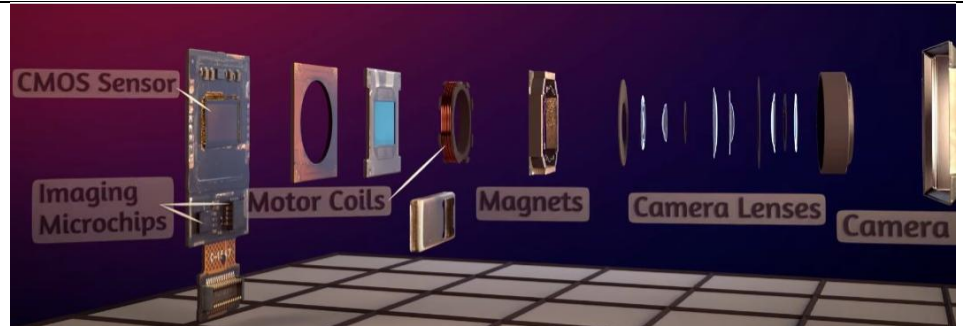
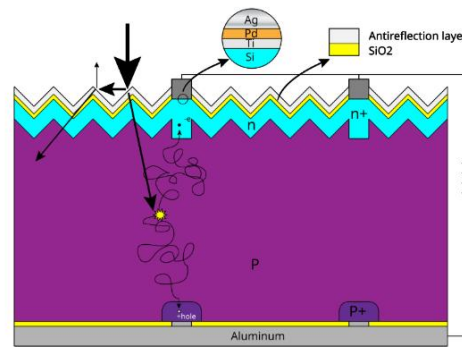
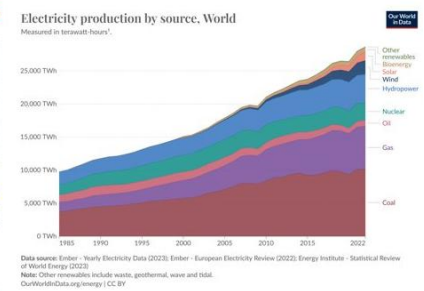
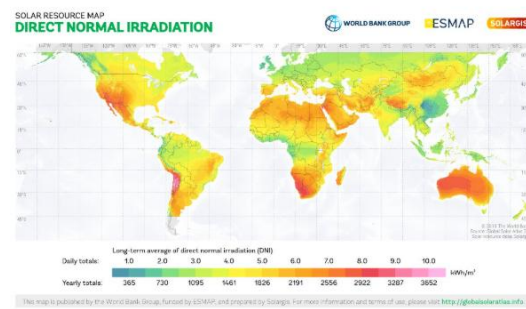
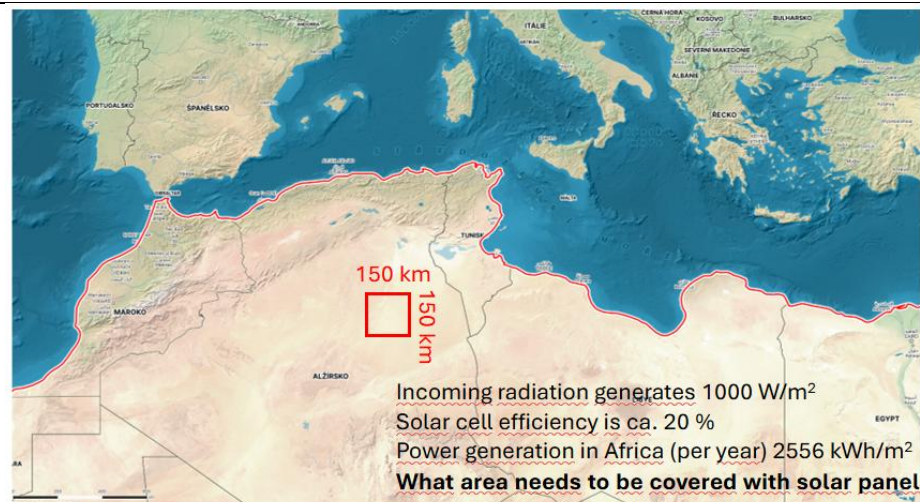


CMOS

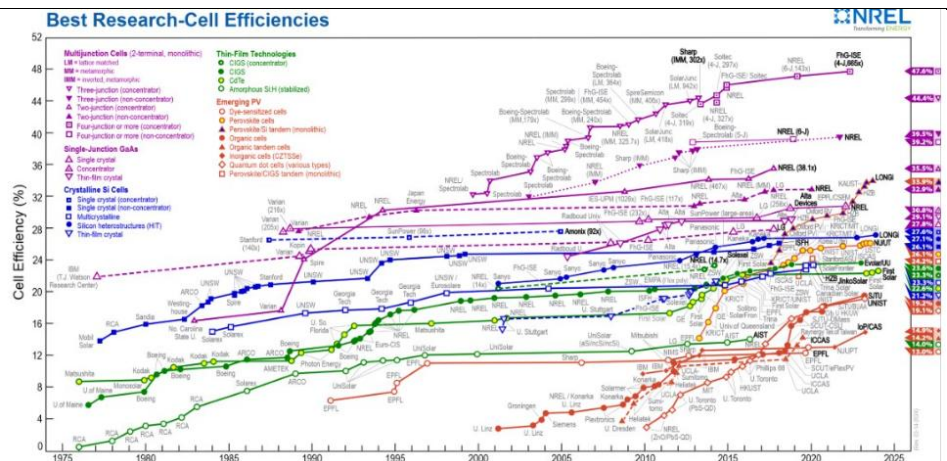


CCD



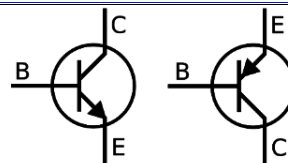
Fotoaparát mobilního
telefonuDioda → LED →
Fotodioda → Solární
článekSluneční záření vs.
spotřeba energieSolární články (proč,
kolik a jak?)

Solární články: účinnost

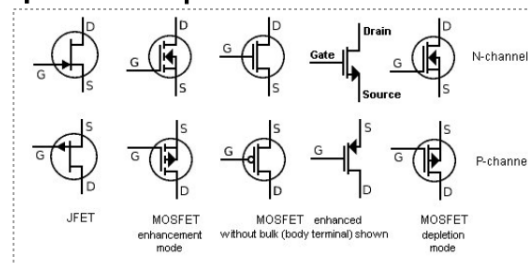


Tranzistor

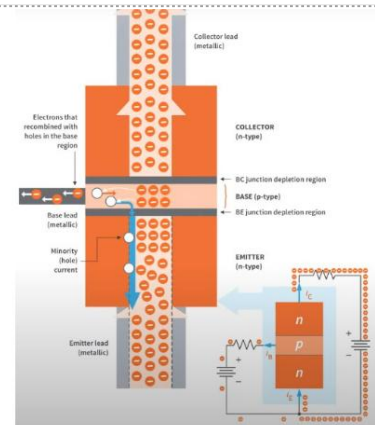
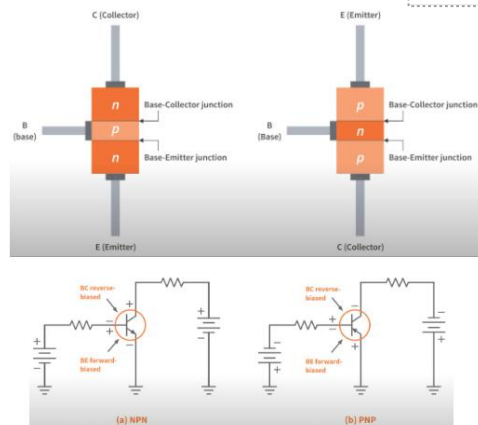
Bipolar junction transistor (BJT)



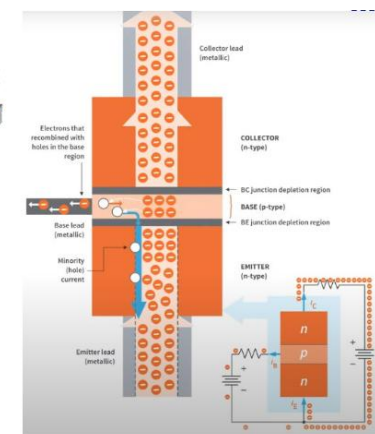
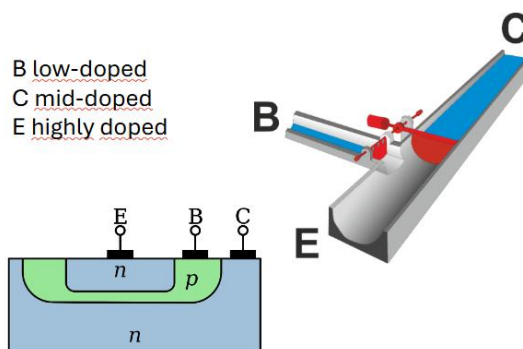
Unipolar transistor (FET)

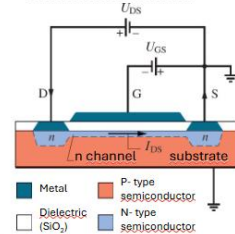
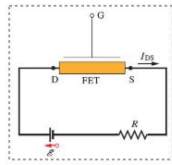


Bipolární tranzistor (BJT)

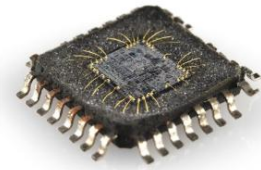


B low-doped
C mid-doped
E highly doped

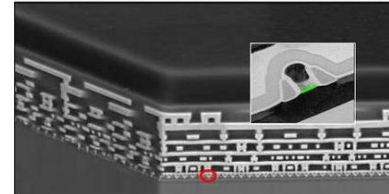




S-D current flows = 1
S-D current does not flow = 0
Very fast switching (~1 ps)



Microprocessor in cross-section



(with kind permission of prof. M. Kolibal)



William Shockley, John Bardeen, Walter Brattain
(Nobelova cena – 1956)



Julius Edgar Lillienfeld
(patent 8.10.1926)

(pouze návrh)

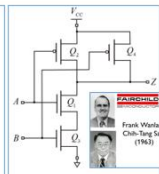


Shelton Fairchild
Zleva doprava: Gordon Moore, C. Sheldon Roberts, Eugene Klein, Robert Noyce, Victor Grinich, Julius Blank, Jean Hoerni and Jay L.
(1960)

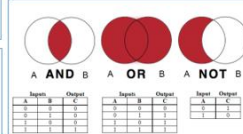
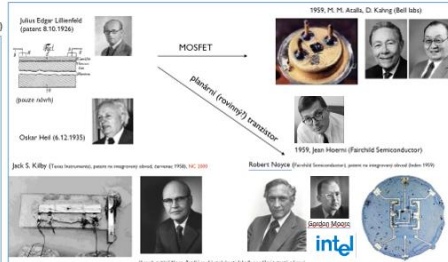
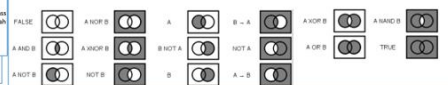
•1956 W Shockley založil Shockley Semiconductor Laboratory
•1957 vznik Fairchild Semiconductor odchodem osmi „arádů“

SILICON

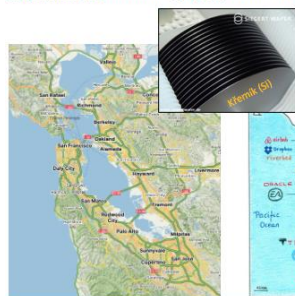
Chcěli založit novou firmu a hledali investora. Toho našli po **35** schůzkách. Firma Fairchild se rozhodla investovat a stali se tak součástí korporátní



CMOS NAND gate

George Boole
(1815 – 1864)

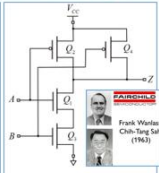
(with kind permission of prof. M. Kolibal)



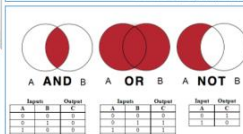
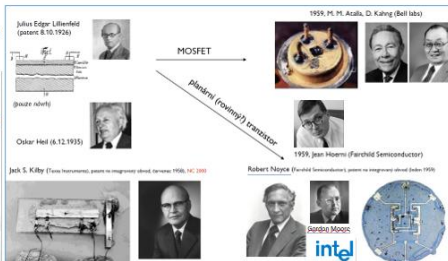
 
 Herman Fairchild
 Zieva doprava: Gordon Moore, C. Sheldon Roberts, Eugene Kleiner, Robert Noyce, Victor Grinich, Julius Blank, van Hoerni and Jay Last
 (1960)

•1956 W. Shockley založil Shockley Semiconductor Laboratory
•1957 vznik Fairchild Semiconductor odchodem osmi „prádčů“

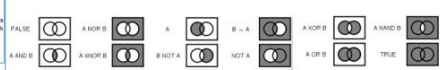
SILICON



CMOS NAND gate



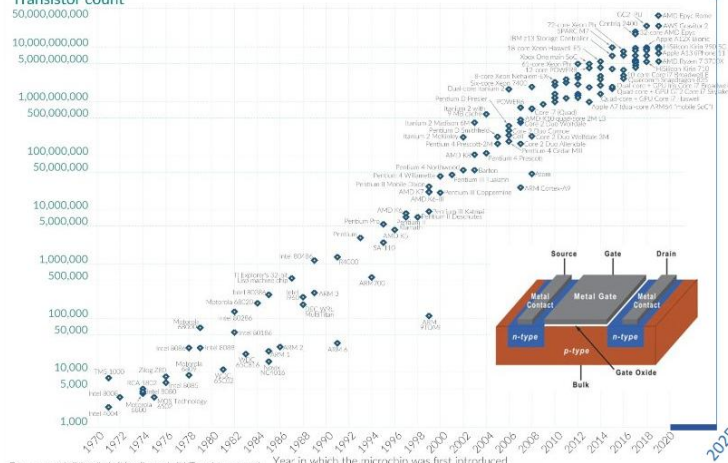
George Boole
(1815–1864)



Moore's Law: The number of transistors on microchips doubles every two years

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important for other aspects of technological progress in computing – such as processing speed or the price of computers.

Transistor count



Data source: Wikipedia (wikipedia.org/wiki/Transistor count)

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Our World in Data

~ 10¹¹

Semiconductor device fabrication



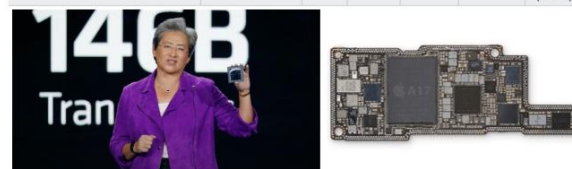
MOSFET scaling (process nodes)

- 20 µm – 1968
- 10 µm – 1971
- 6 µm – 1974
- 3 µm – 1977
- 1.5 µm – 1981
- 1 µm – 1984
- 800 nm – 1987
- 600 nm – 1990
- 350 nm – 1993
- 250 nm – 1996
- 180 nm – 1999
- 130 nm – 2001
- 90 nm – 2003
- 65 nm – 2005
- 45 nm – 2007
- 32 nm – 2009
- 28 nm – 2010
- 22 nm – 2012
- 14 nm – 2014
- 10 nm – 2016
- 7 nm – 2018
- 5 nm – 2020
- 3 nm – 2022

Future

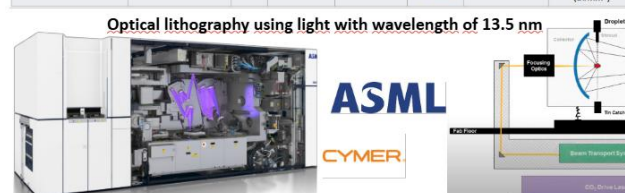
- 2 nm – 2025
- 1 nm – 2027

Apple M3 (octa-core 64-bit ARMv8 SoC, SIMD, caches)	25,000,000,000 ^[106]	2023	Apple	3 nm	?	?
Apple M3 Pro (dodeca-core 64-bit ARMv8 SoC, SIMD, caches)	37,000,000,000 ^[106]	2023	Apple	3 nm	?	?
Apple M3 Max (hexadeca-core 64-bit ARMv8 SoC, SIMD, caches)	92,000,000,000 ^[106]	2023	Apple	3 nm	?	?
Apple A17	19,000,000,000 (1B7)	2023	Apple	3 nm	103.8 mm ²	183,044,316
Sapphire Rapids quad-chip module (up to 80 cores and 112.5 MB of cache) ^[105]	44,000,000,000–48,000,000,000 ^[105]	2023	Intel	10 nm ESB (Intel 7)	1,600 mm ²	27,500,000–30,000,000
Apple M2 Pro (12-core 64-bit ARMv8 SoC, SIMD, caches)	40,000,000,000 ^[106]	2023	Apple	5 nm	?	?
Apple M2 Max (12-core 64-bit ARMv8 SoC, SIMD, caches)	67,000,000,000 ^[106]	2023	Apple	5 nm	?	?
Apple M2 Ultra (two M2 Max dies)	134,000,000,000 ^[7]	2023	Apple	5 nm	?	?
AMD Epyc Bergamo (4th gen/74 series) 9-chip module (up to 128 cores and 256 MB (L3) + 128 MB (L2) cache)	82,000,000,000 ^[101]	2023	AMD	5 nm (CCD) 6 nm (IOD)	?	?
AMD Instinct M300A (multi-chip module, 24 cores, 128 GB GPU memory + 256 MB (L3/L2) cache)	146,000,000,000 ^{[103][10]}	2023	AMD	5 nm (CCD, GCD) 6 nm (IOD)	1,017 mm ²	144,000,000



Graphics processing unit (GPU)

GH100 Hopper	80,000,000,000	2022	Nvidia	TSMC	4 nm	814 mm ²	98,280,000
AD102 Ada Lovelace	76,300,000,000	2022	Nvidia	TSMC	4 nm	606.4 mm ²	125,411,000
AD103 Ada Lovelace	45,900,000,000	2022	Nvidia	TSMC	4 nm	378.6 mm ²	121,240,000
AD104 Ada Lovelace	35,800,000,000	2022	Nvidia	TSMC	4 nm	294.5 mm ²	121,560,000
AD106 Ada Lovelace	?	2023	Nvidia	TSMC	4 nm	190 mm ²	?
AD107 Ada Lovelace	?	2023	Nvidia	TSMC	4 nm	146 mm ²	?
Navit 31 RDNA3	57,700,000,000 (MCM) 45,400,000,000 (GCD) 6+2,050,000,000 (MCD)	2022	AMD	TSMC	5 nm (GCD) 6 nm (MCD)	531 mm ² (MCM) 306 mm ² (GCD) 6+37.5 mm ² (MCD)	109,200,000 (MCM) 132,400,000 (GCD) 54,640,000 (MCD)
Navit 32 RDNA3	28,100,000,000 (MCM)	2023	AMD	TSMC	5 nm (GCD) 6 nm (MCD)	350 mm ² (MCM) 200 mm ² (GCD) 4+37.5 mm ² (MCD)	80,200,000 (MCM)
Navit 33 RDNA3	13,300,000,000	2023	AMD	TSMC	6 nm	204 mm ²	65,200,000
Aquia Varanaram CDNA3	153,000,000,000 (MCM)	2023	AMD	TSMC	5 nm (GCD) 6 nm (MCD)	?	?
GB200 Grace Blackwell	206,000,000,000	2024	Nvidia	TSMC	4 nm	?	?



Optical lithography using light with wavelength of 13.5 nm



Taiwan Semiconductor Manufacturing Company Limited
(TSMC, sometimes only Taiwan Semiconductor)



Thanks to nanotechnology!

**Unipolární tranzistor
MOSFET (Metal-
Oxide-
Semiconductor Field-
Effect Transistor)**

