MŰEGYETEM 1782

Budapest University of Technology and Economic
Department of Electron Devices

Technology of IT Devices

Lecture 2

- Microelectronics
- Trends in Integrated Circuit Technology
- VLSI basic terms
- Basic properties of semiconductors
- MOS transistor

Microelectronics

- Microelectronics is a subfield of electronics, and it relates to the study and manufacture (or microfabrication) of very small electronic designs and components
  - These devices are typically made from semiconductor materials.
  - Digital integrated circuits (ICs) consist mostly of transistors.
  - Analog circuits commonly contain resistors and capacitors as well. Inductors are used in some high frequency analog circuits, but tend to occupy a large chip area if used at low frequencies.
  - Integrated circuits are mass producible
    - the cost per IC is low

Moore's law

- IC production is one of the fastest growing industries.
- Gordon Moore made a prediction in 1965, that the number of transistors integrated on one chip would double every 18-24 month (exponential growth).
- He thought it would stand for the next decade, **it's still true today.**
- The 1 million transistors per chip barrier was broken through in the 80's:
  - 1971: 2300 transistors, clock frequency: 1 MHz (Intel 4004)
  - 2001: 42 million transistors, clock frequency: 2 GHz (Intel P4) – 2001
  - 2016: 7,2 billion transistors, 22-core Xeon Broadwell-E5
    - 2,2GHz (3,6GHz in turbo mode), 55MB smart cache, 456mm^2
    - Datasheet
  - FPGA: 30 billion transistors, Stratix 10 10GX5500/10SX5500
    - Datasheet
  - **More than Moore:** growth of an even higher rate is possible by using 3D structures (e.g. in RAMs)

The original figure in Moore's paper showing the prediction

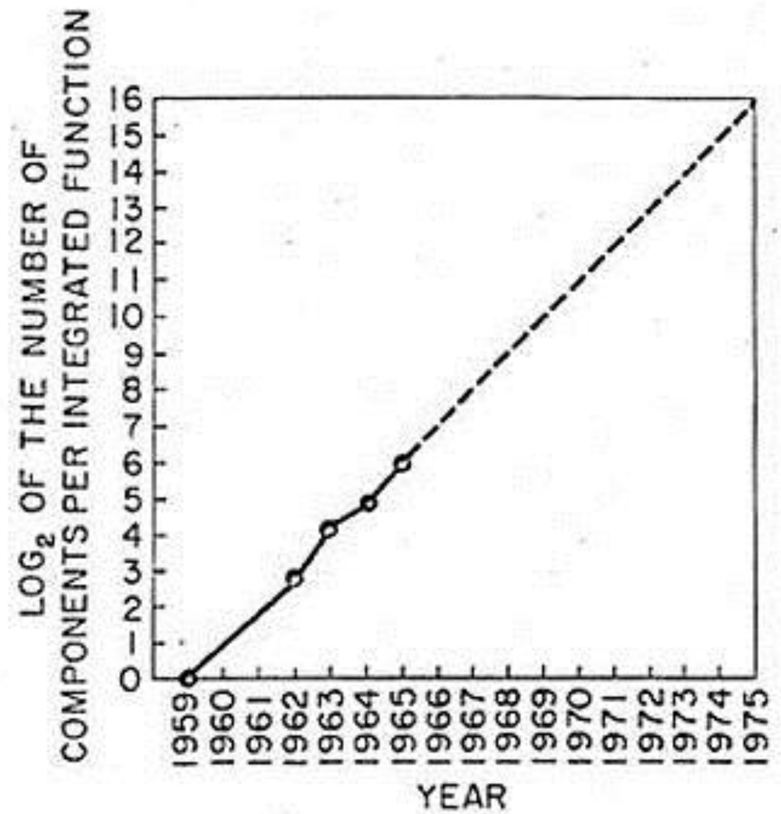
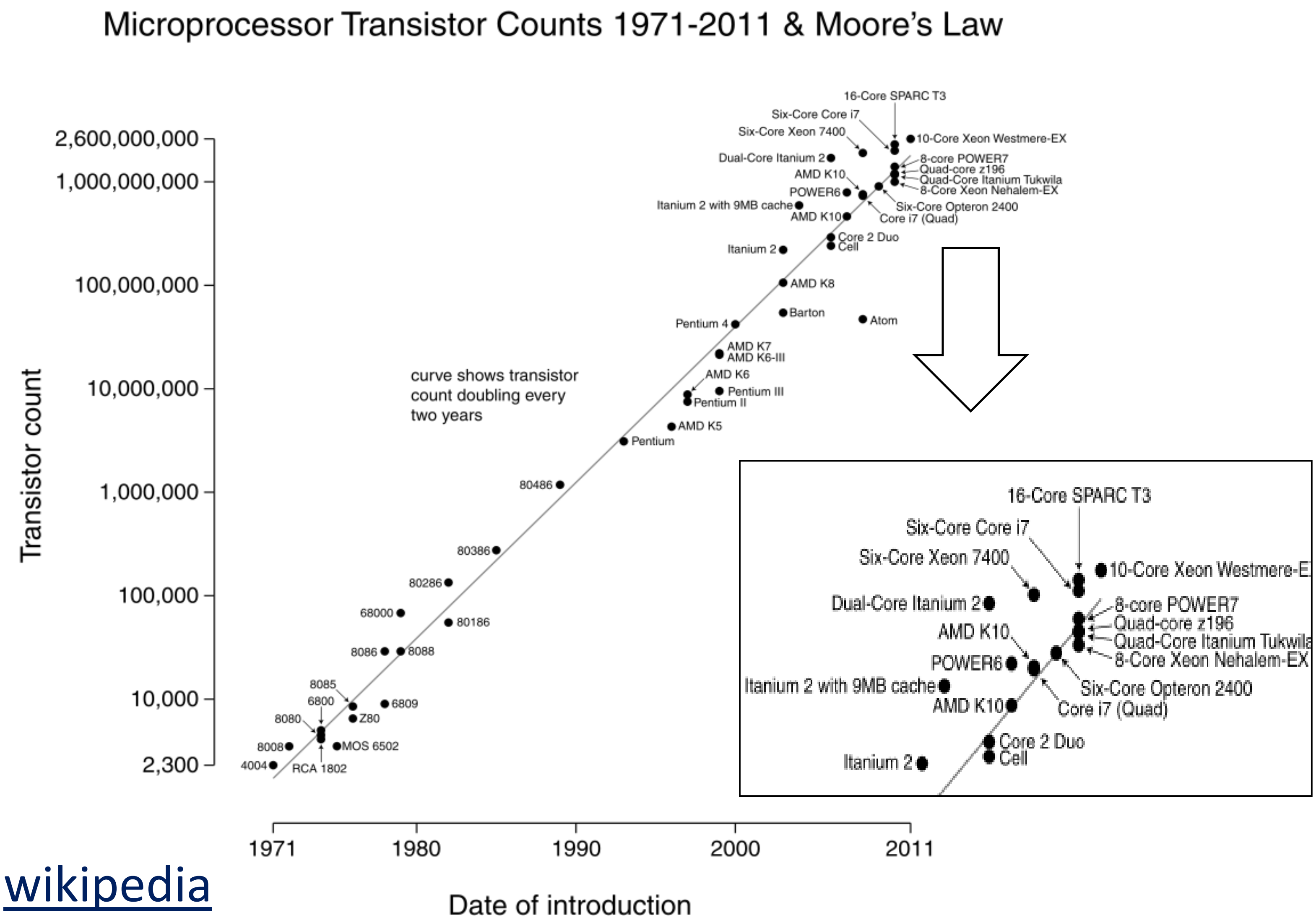


Fig. 2 Number of components per integrated function for minimum cost per component extrapolated vs time.

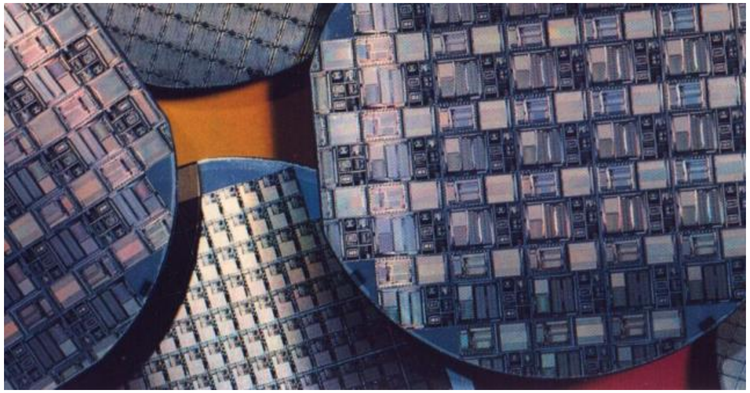
Evolution of Microprocessors



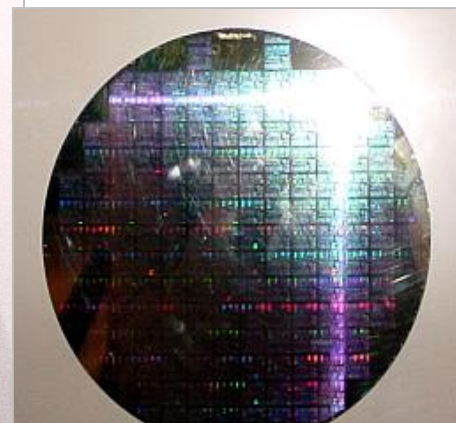
- Source: [wikipedia]()

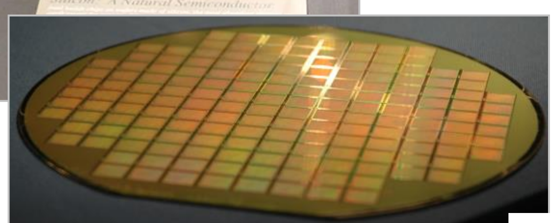
Planar technology

- VLSI – very large scale integration.
  - Since 1980, more than 10 000 transistors
- The word planar implies that the devices are fabricated on the surface of the silicon wafer in a 2D structure.
- The basis is a silicon ingot made up of monocrystalline silicon.
- The ingot is sliced into wafers:
  - Diameter: 2-12”
  - Width: 0.25-0.7 mm
- A wafer can contain thousands of ICs that are manufactured at the same time.



Si ingots and wafers





Si wafer after processing

Lithography

- Lithography creates the patterns.
- A special agent called a photoresist is deposited on the surface.
  - organic material, a photoresist changes its chemical properties and becomes soluble or non-soluble by etchants
  - if the photoresist is exposed to light through a mask, it changes its properties in a pattern.
- After the exposure, the parts of the resist that are soluble are etched away, which leaves a protective layer over the wafer where the etching is unwanted.

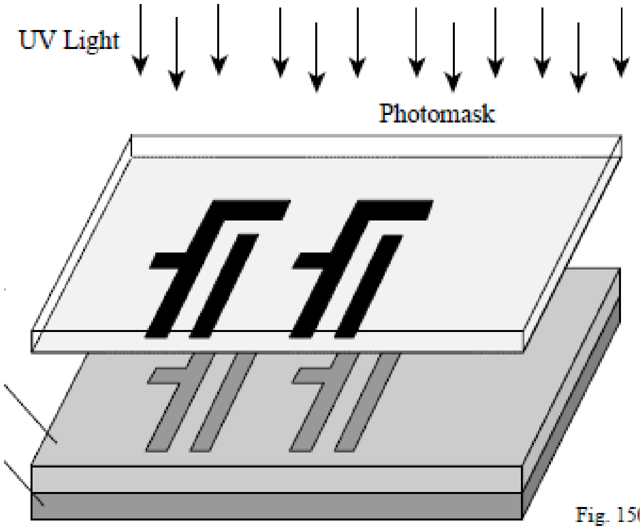
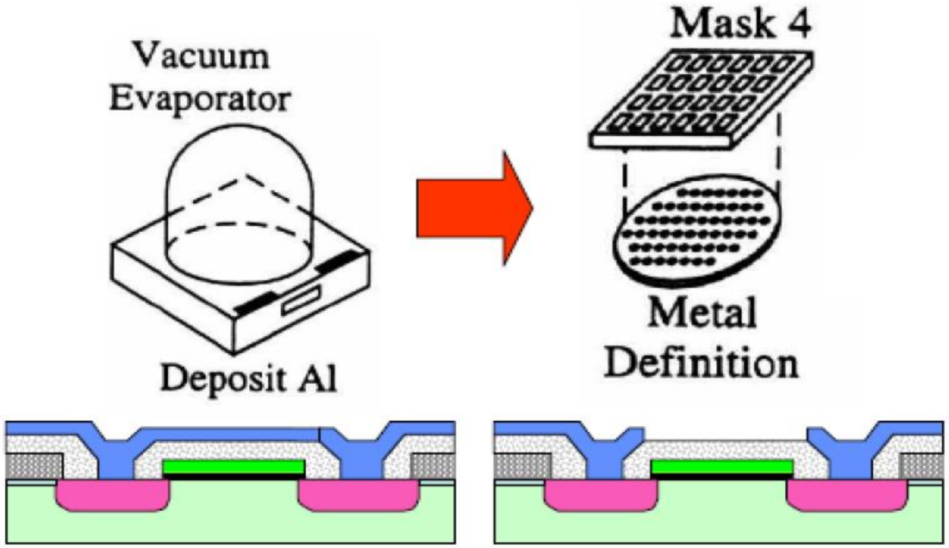


Fig. 150-1

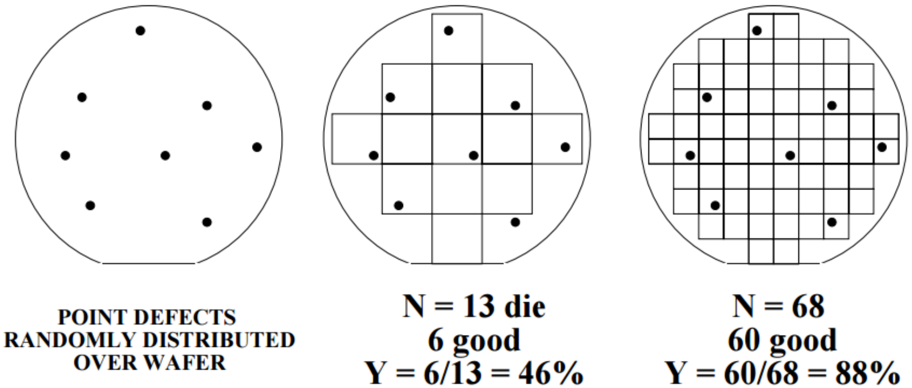
Example: basic steps of forming interconnects

- A layer of metal is deposited over the whole surface
- The metal is then removed from areas where it is not desired (by lithography and dry etching)
  - Creating the pattern by lithography
  - Using wet or dry etching



Scaling

- The number of components can be increased in two ways
  - Increasing the size of chip.
    - But it ends up with more failures per wafer (lower yield) due to randomly distributed defects on wafers.
    - Optimal chip area is about 500mm^2

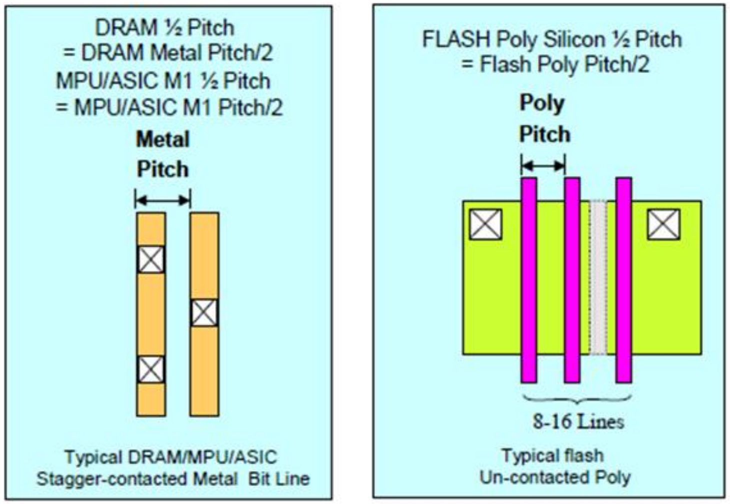


  - If we can decrease every physical size by the factor of 2, we can produce 4 times more components
  - This is called scaling
- Effects of scaling
  - Delay can be decreased (clock frequency can be increased)
  - power consumption of logic gates decreases
  - power dissipation density increases!

Scaling

- "*x* nm" technology
  - It means the smallest object in nm.
- This is called MFS (minimum feature size)
- 1970: ca. 10µm (10 000nm) volt.
- 2016: 14nm, in production
  - Intel, Samsung
- Lattice constant (the distance between two atoms is 0.543 nm)

Pitch is the distance between identical features in an array



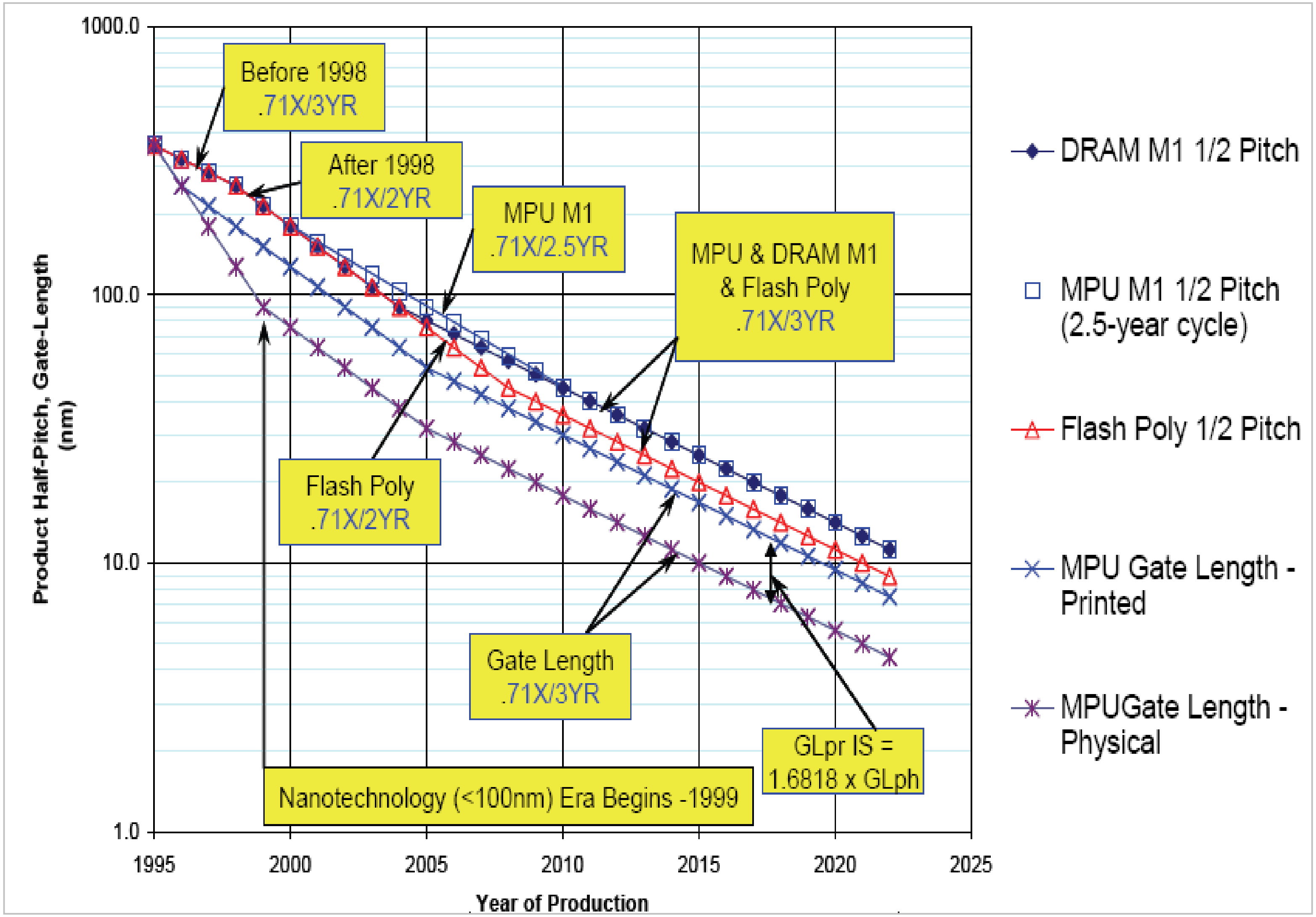
ITRS roadmap

- The ITRS roadmaps always contain the latest predictions and directions of the development.
- They are created by the leaders of the industry.
- Forecast in 2015 can be found here.

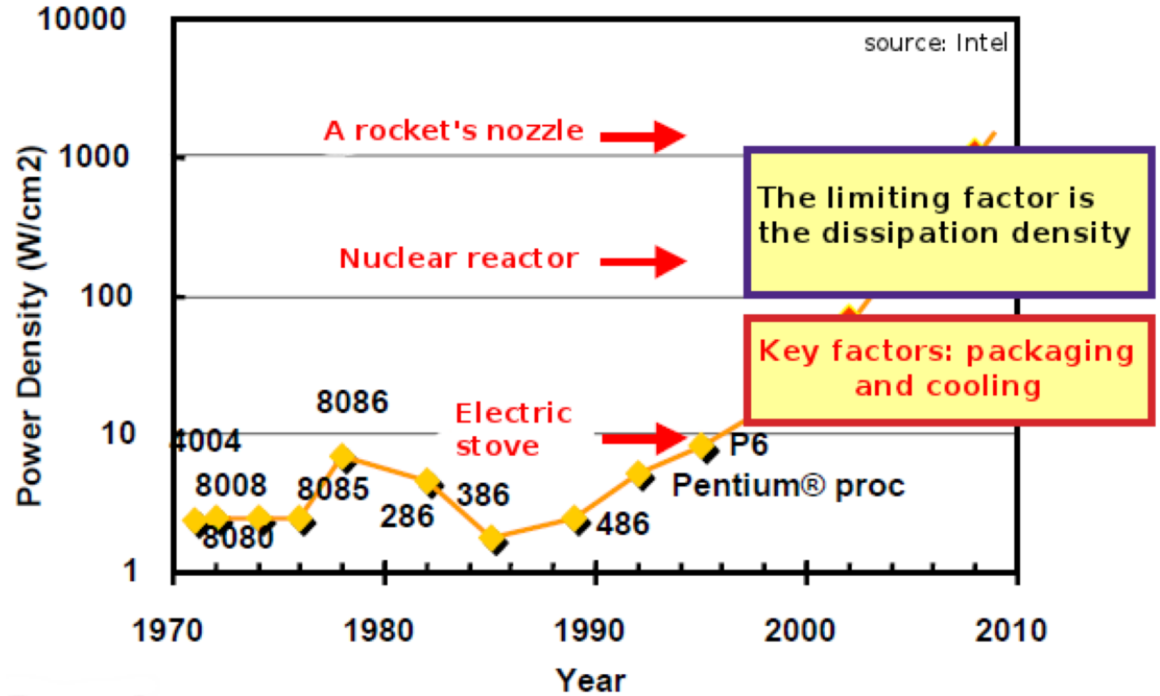
YEAR OF PRODUCTION	2015	2017	2019	2021	2024	2027	2030
Logic device technology naming	P70M56	P48M36	P42M24	P32M20	P24M12G1	P24M12G2	P24M12G3
Logic industry "Node Range" Labeling (nm)	"16/14"	"11/10"	"8/7"	"6/5"	"4/3"	"3/2.5"	"2/1.5"
Logic device structure options	FinFET FDSOI	FinFET FDSOI	FinFET LGAA	FinFET LGAA VGAA	VGAA, M3D	VGAA, M3D	VGAA, M3D

- We will meet these abbreviations (FinFET, FDSOI, LGAA, VGAA) later

Forecast at different nodes



Increase in dissipation density

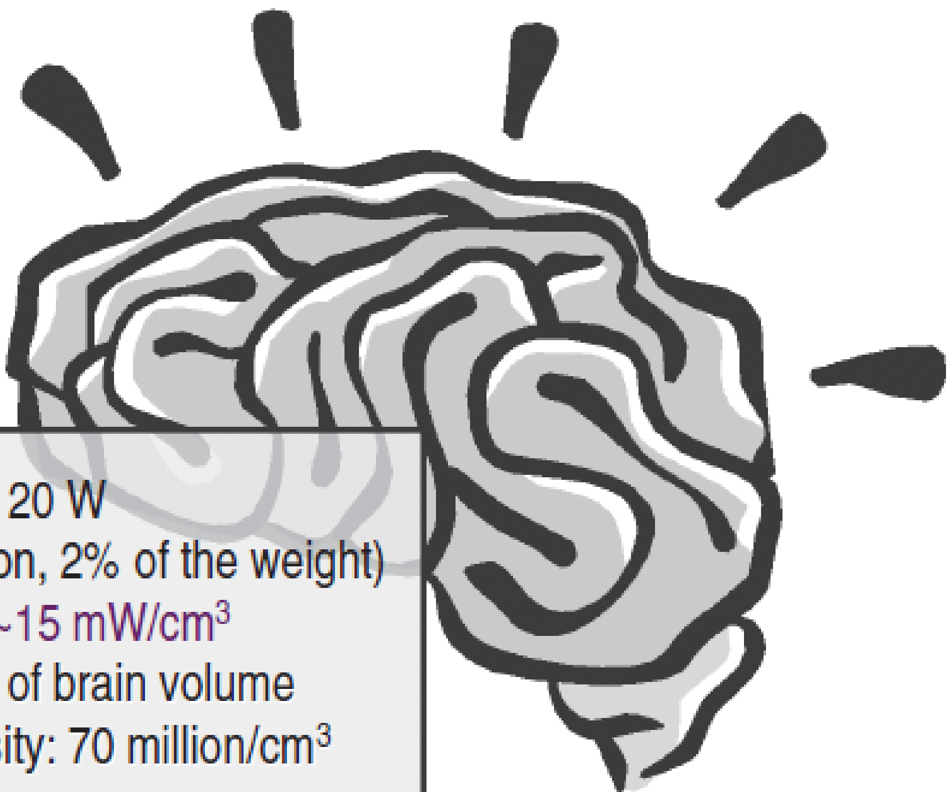


- This reason led us to design multi-core processors
  - 2004: Power Wall, which has limited the frequency to 3-4GHz

Human brain

A Side Note: What Can One Do with 1 cm^3?

Reference case: the human brain



P_{avg}(brain): 20 W
(20% of the total dissipation, 2% of the weight)
Power density: ~15 mW/cm^3
Nerve cells only 4% of brain volume
Average neuron density: 70 million/cm^3

Semiconductors

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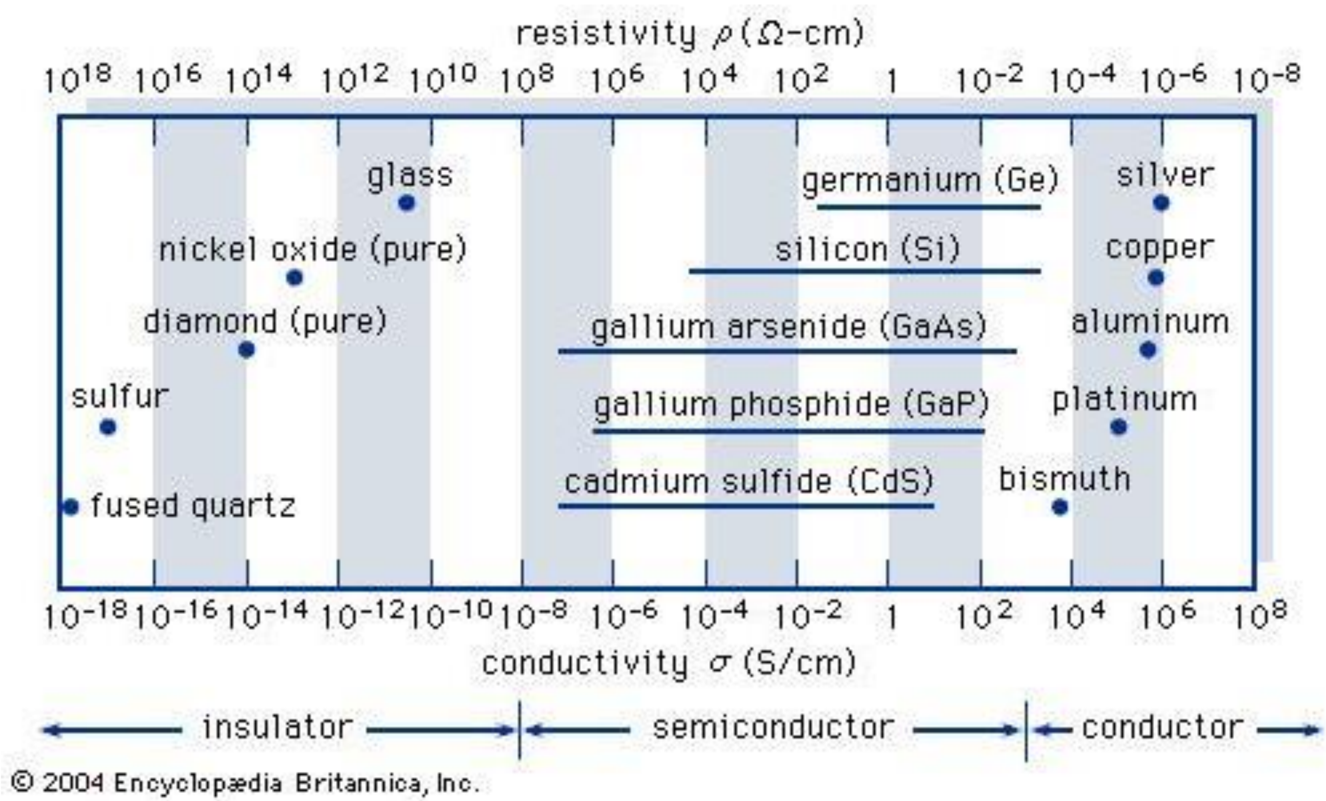
Semiconductors

- Semiconductors’ conductance is between that of conductors and insulators

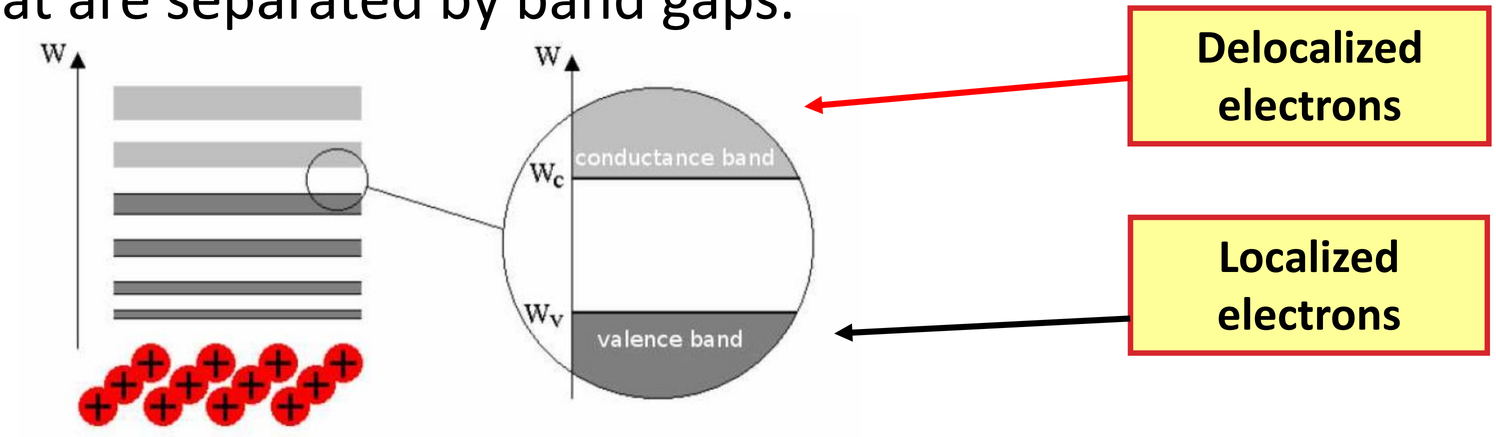


Semiconductors

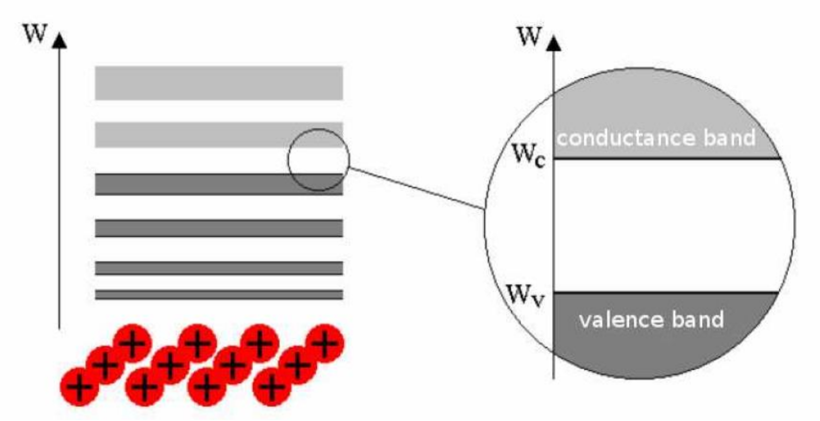
- Semiconductors' conductance is between that of conductors and insulators
- They conduct current
  - Semiconductors have a negative thermal coefficient (NTC)
  - It means their conductivity increases when temperature rises.
  - This is exactly the opposite behaviour of metals.
- The most important semiconductors:
  - Monocrystalline or single-crystal materials:
    - Semiconductor elements: Si (silicon), Ge (germanium)
    - Compound semiconductors: GaAs (gallium arsenide), GaAsP (gallium arsenide phosphide). They are used to create LEDs.
  - Amorphous semiconductors: amorphous Si mainly
  - TFT, solar cells, etc.
- Organic semiconductors: OLEDs (Organic LEDs)

The band structure

- An electron's energy is a quantized quantity – there are certain energy levels that are allowed for electrons, the rest of the levels are forbidden.
- When electrons take part in a system (an atom or a crystalline consisting of many atoms), every electron has to be at a different level. The electrons take energy levels very close to the allowed levels – thus in large systems the electrons take place in energy bands that are separated by band gaps.

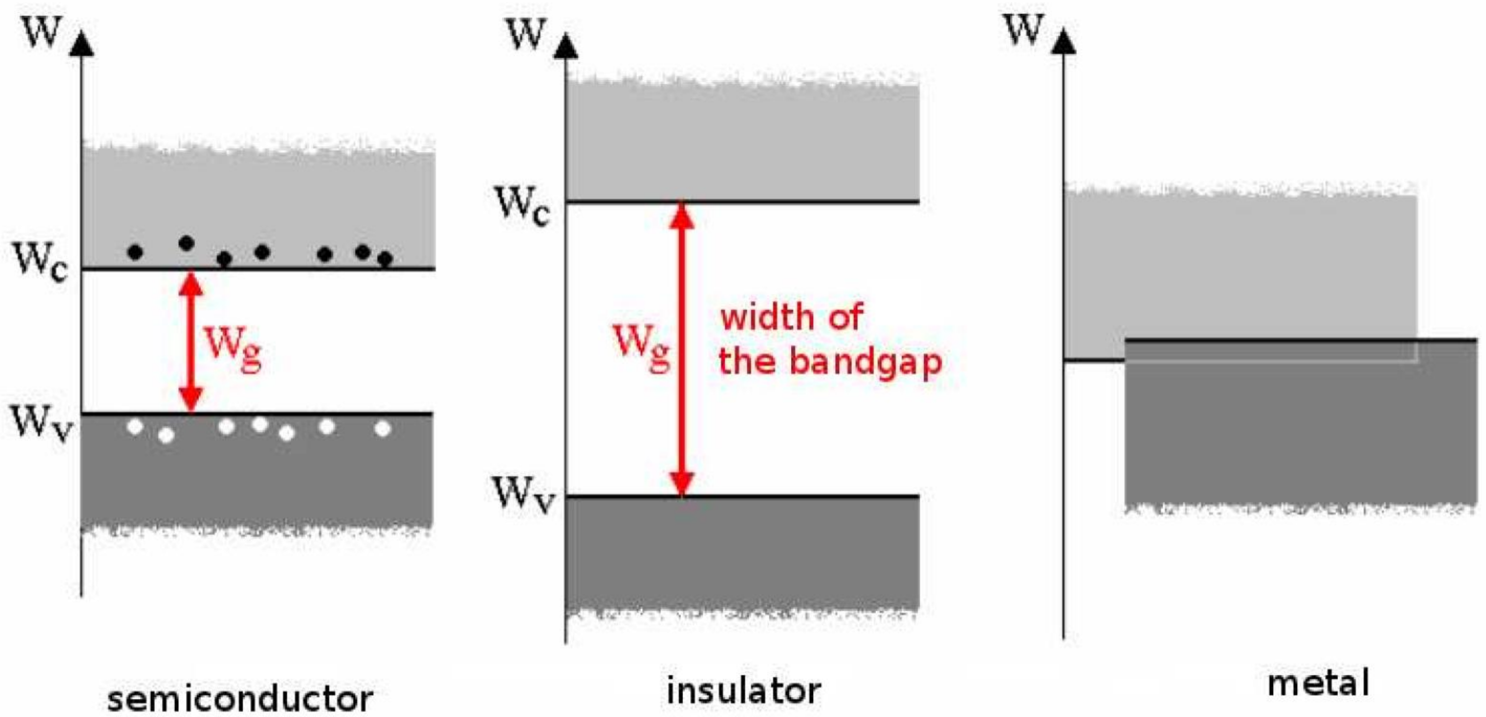


The band structure



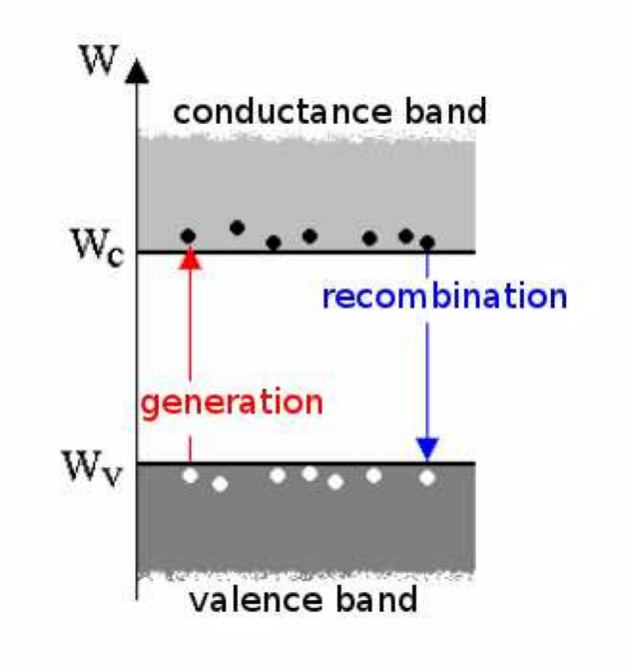
- Conductance band:
  - electrons that can move freely.
- Valence band:
  - electrons that take part in bonds and thus are bound to atoms.

- From the viewpoint of conductance the important bands:
  - The highest band that contains electrons (valence band).
  - The band above the valence band, which is almost empty (conductance band).
  - The band gap between them.



- Insulators and semiconductors
    - there are bandgaps – the width of the bandgap (Wg) decides whether a material is an insulator or a semiconductor.
- Conductors: the valence band and the conductance bands overlap.

Charge carriers

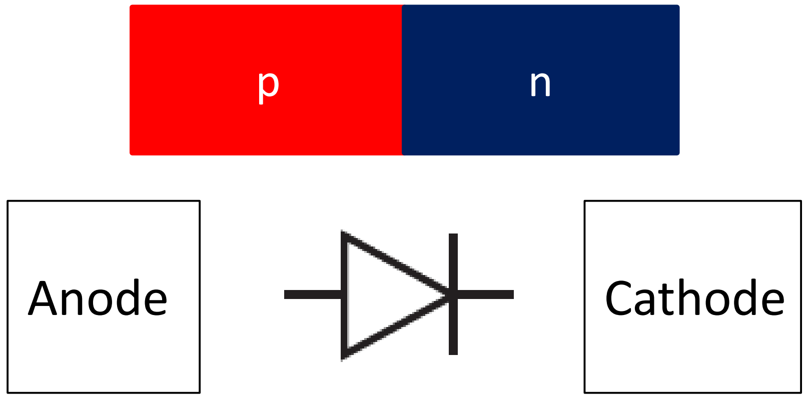


- Electrons: at the bottom of the conductance band
- Holes: at the top of the valence band – a hole is an absence of electron.
- **Both electrons and holes take part in conduction!**
- Generation: happens when an electron gets to the conductance band from the valence band.
  - This means that two charge carriers are created: an electron in the conductance band and a hole in the valence band.
- Recombination: the opposite of generation – when an electron falls back to the valence band.

Doping

- A small number of atoms of a different element are injected into the crystal structure.
- This is done in a way that the dopants are placed in positions where Si atoms are normally located.
- There are two types of doping
  - n-type doping:
    - Donor dopants: dopants that inject atoms that have one extra electrons at their valence band (P (phosphorus), As (arsenic))
    - **Electrons** are the majority charge carriers, **holes** are the minority charge carriers
  - p-type doping:
    - dopants that inject atoms that have one less electrons at their valence band (B (boron)),
    - Electrons are the minority charge carriers, holes are the majority charge carriers

The pn-junction: a semiconductor diode

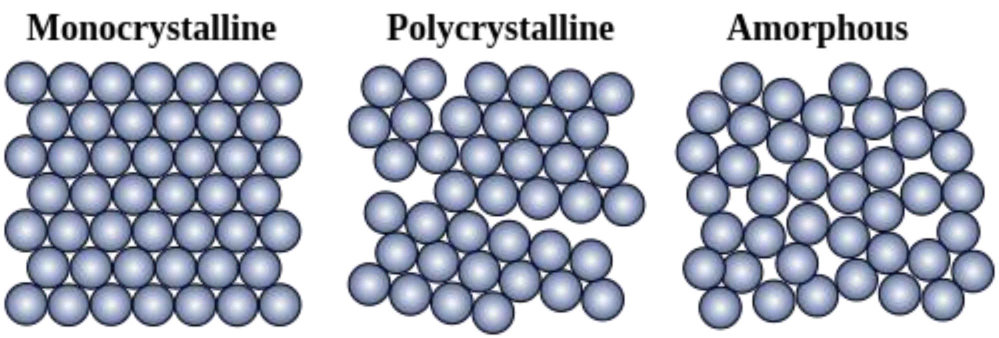


- A pn-junction is a monocrystalline transitional area where a p-type and an n-type semiconductor are next to each other.
- When a forward voltage is applied to it, its current is an exponential function of the voltage.
- Forward direction: the p side is at a higher potential.
- In the reverse direction its current is very-very low and is independent of the voltage
- Diodes can be used for rectification (AC-DC conversion)

MOS transistor

- MOS: Metal-Oxide-Semiconductor
  - metal: in the early days aluminum was used, then poli-Si became the standard material for this role and nowadays metals are used again
  - oxide: the oxide of the semiconductor (SiO_2) – aka. quartz
  - semiconductor: silicon.
- History
  - 1957: the first MOS was manufactured
  - 1970: first IC manufactured in large volumes (1 kbit RAM consisting of 3-transistor cells by Intel),
  - In 2005 more transistors were manufactured than rice grains grown.

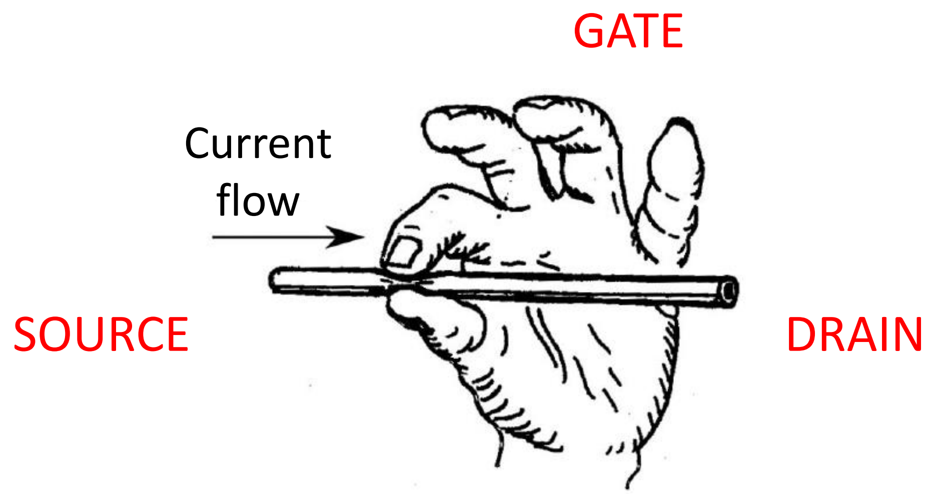
Types of Crystal: monocrystalline, polycrystalline, amorphous

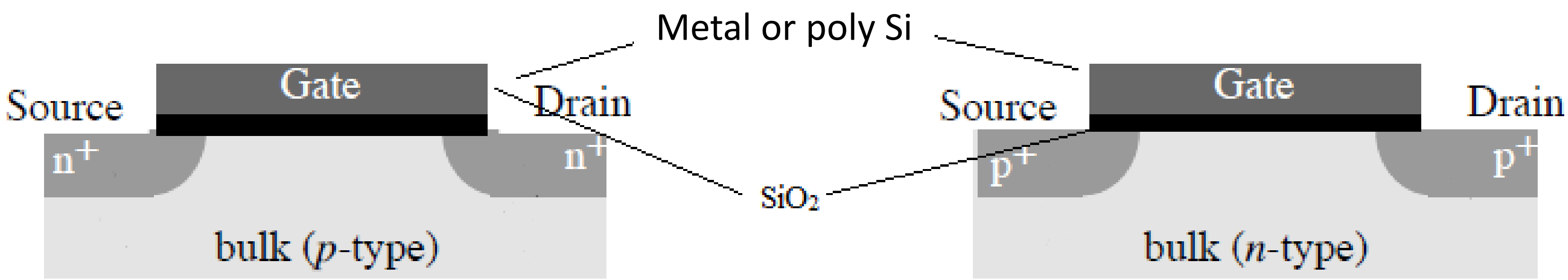


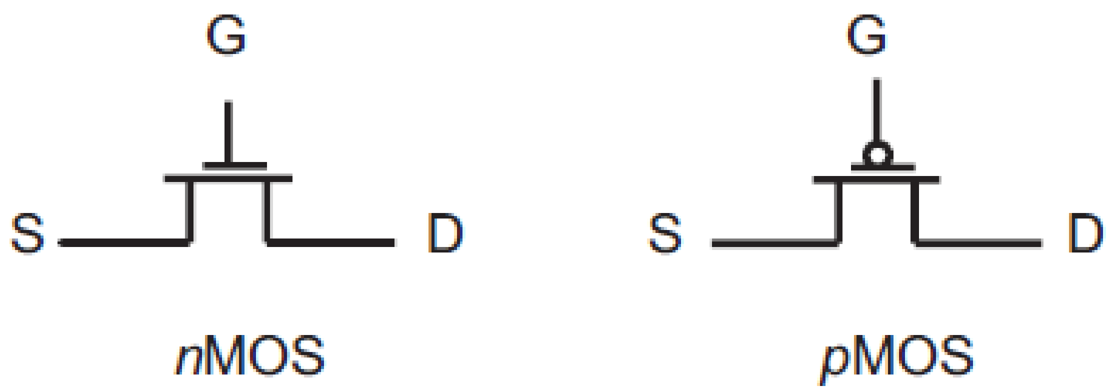
- Monocrystalline material: perfect ordering
- Polycrystalline material: made of tiny crystalline grains
- Amorphous material: no significant ordering

MOS transistors

- The principle of operation:
  - On a single crystal silicon chip (substrate) we create two contacts. The current flow can be controlled between the contacts
  - The name of contacts are „**source**” and „**drain**”
  - The **source** is so named because it is the source of the charge carriers, he **drain** is where the charge carriers leave the channel.
  - The name of control terminal: **gate**







- There are two types of MOS transistors.
  - nMOS: the bulk is p-type silicon (the inversion channel is n-type)
  - pMOS: the bulk is n-type silicon (the inversion channel is p-type)

The operation of MOS transistors

- Normally it is an open circuit, does not conduct any current
- When the gate voltage exceeds a certain value, charge carriers appear below the gate (inversion charge)
- The voltage that is needed to create the inversion layer is the **threshold voltage** (V_T).
- The device operates as a **relay** – when the control voltage on the gate is above the threshold voltage, a conducting channel connects the source and the drain, otherwise it behaves as an open circuit.

MOS transistor as a switch

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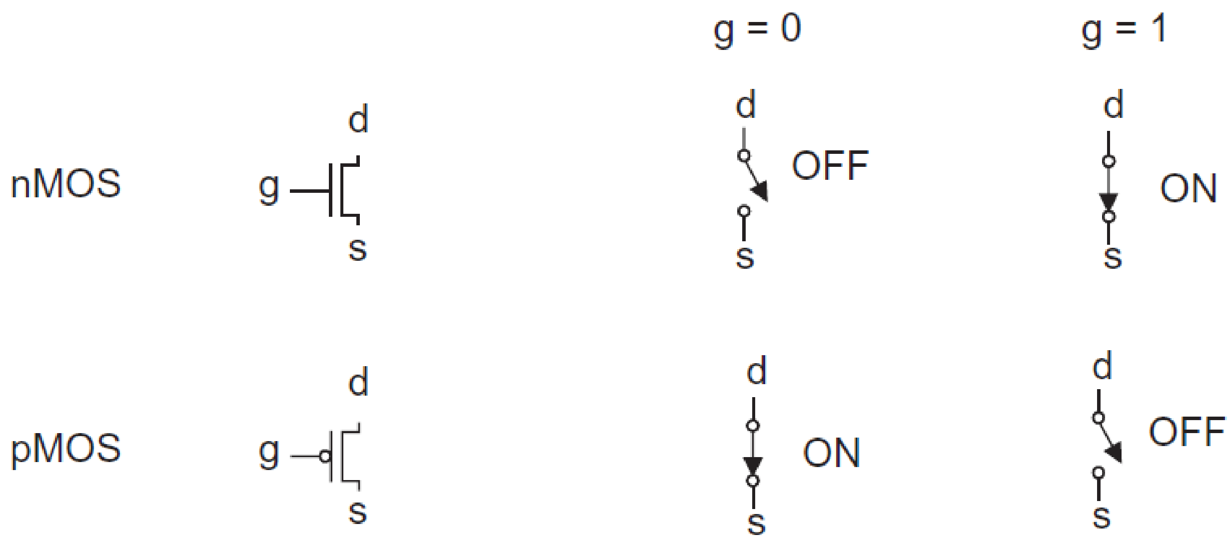

- nMOS
  - In case of logical 0: open switch (does not conduct current)
  - In case of logical 1: closed switch (conducts current)
- pMOS
  - logical 0: conducts current,
  - logical 1: does not conduct current
- The symbol of pMOS transistor has a circle at the gate terminal

CMOS

- Complementary MOS
  - They consist of two types of MOSFETs: n-type and p-type
  - Every logic circuit is CMOS nowadays.
- We have two complementary transistors:
  - One conducts when the input logic level is high
  - Other conducts when the input logic level is low
  - Hence the name
- We can create
  - Inverters
  - Basic logic gates (and, or, etc.)
  - Complex logic gates
- The next lesson will be on static CMOS logic