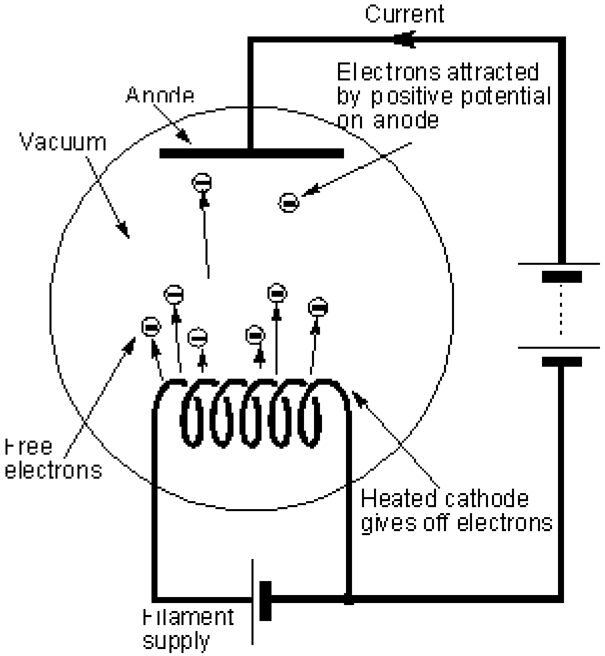
5. Electronics

Repetition from the last lecture

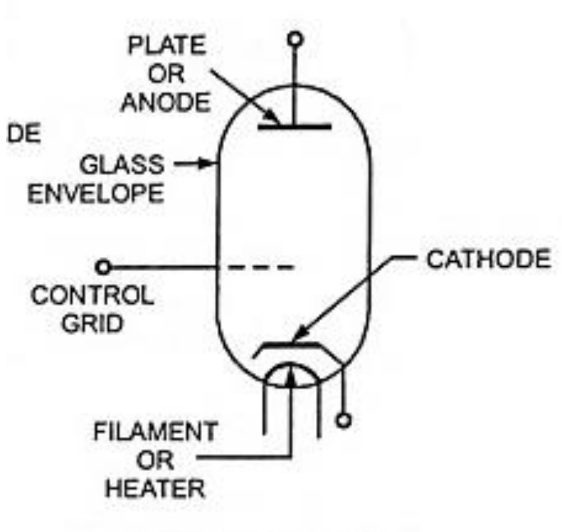
- What are the 2 sources of magnetic moment of matter?
- What are the macroscopic regions of solids with the same direction of magnetization called?
- What happens to the magnetic coercivity of a ferromagnetic particle if its dimensions are reduced below the dimensions of the magnetic domain? What is this phenomenon called?
- What is spintronics concerned with?

Beginning of Electronics

- 1904 – vacuum diode
  - rectification of the electric current, electrons can only flow in one direction
- 1906 – vacuum triode
  - amplification and control of high frequency signals. Predecessor of the transistor.



Diode

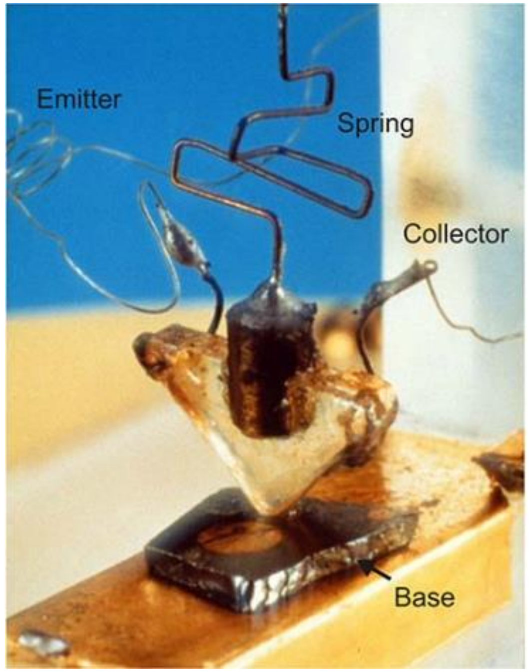


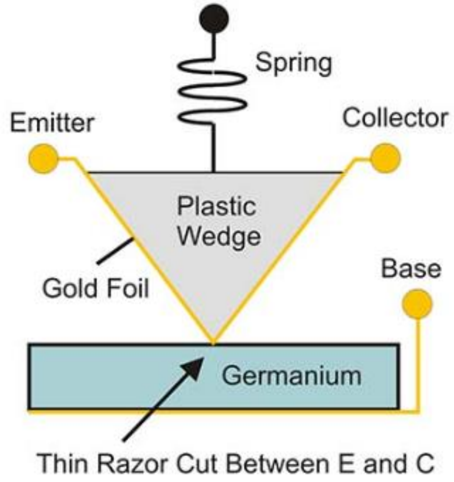
Triode

http://todayscircuits.blogspot.com/2011/06/vacuum-tube-diodes.html#.Y0PGS3ZByJN
https://www.eeguide.com/vacuum-triode-construction-and-working/

Semiconductor Transistor

- 1947 – John Bardeen, Walter Brattain, William Shockley (AT&T's Bell Laboratories) - first semiconductor transistor (Nobel Prize 1956)
    - Two gold strips locally attached to a germanium semiconductor. Current through one contact (emitter-base) amplifies current flowing through the other contact (base-collector). Shockley enhanced the effect by joining layers of germanium with n a p conductivity - creating a PN junction.

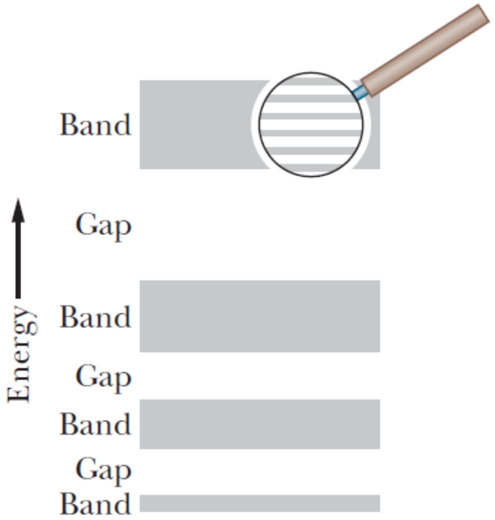


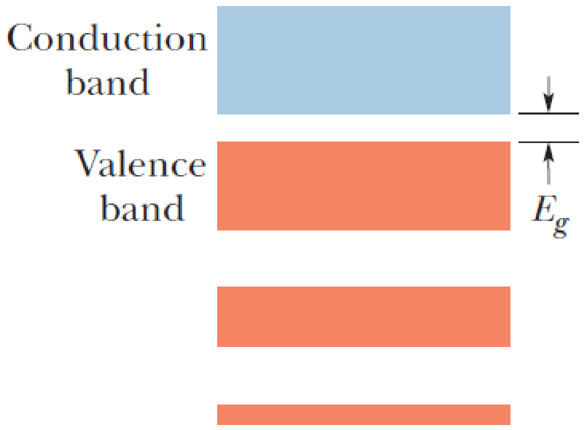


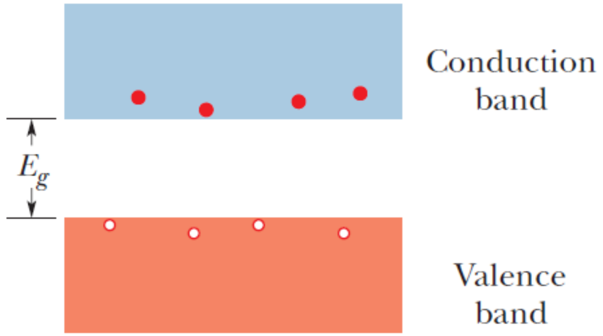
https://www.nutsvolts.com/magazine/article/the-story-of-the-transistor
https://www.edn.com/1st-successful-test-of-the-transistor-december-16-1947/

Semiconductors

- Isolants with a narrow band gap (< 5 eV)
- InSb (0.23 eV), InAs (0.354 eV), Ge (0.664 eV), Si (1.124 eV), GaAs (1.424 eV), CdTe (1.457 eV), GaN (3.503 eV), V (5.5 eV)
- Intrinsic semiconductors - conductivity is provided by electrons thermally excited from the valence to the conduction band. A hole (virtual positive charge) remains in the valence band.

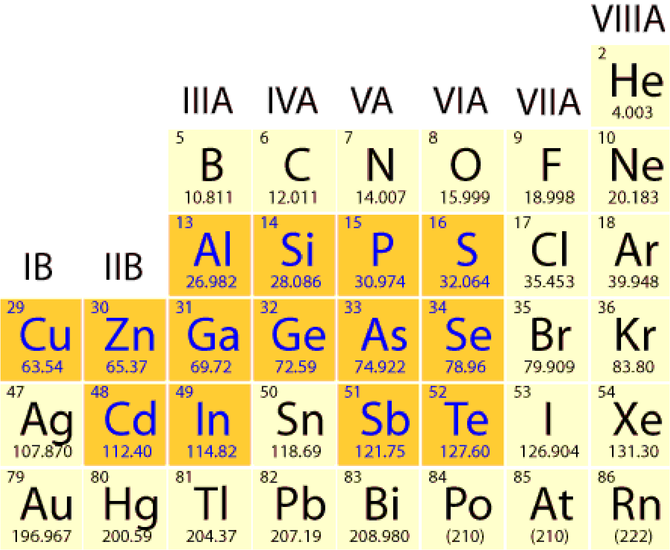






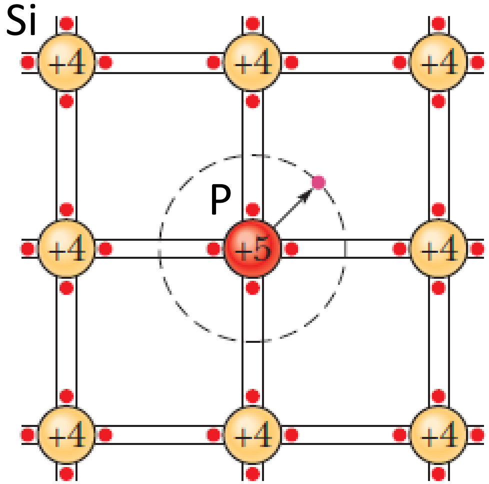
J. Walker, D. Halliday, R. Resnick, Fundamentals of physics – 10th edition

Extrinsic Semiconductors

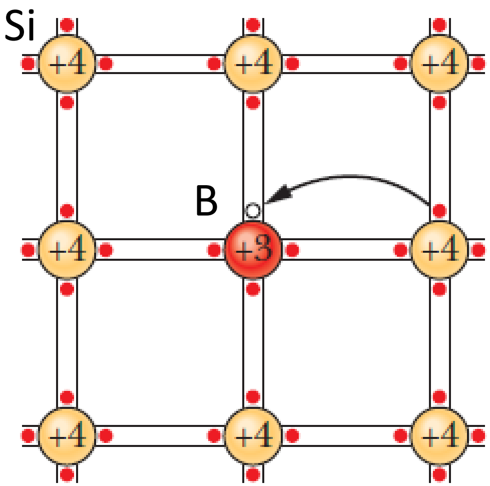


IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
							2 He 4.003
		5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
		13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)

- By using a small amount of impurities (1:10^6) it is possible to significantly change the electrical conductivity of a semiconductor.
- Donor semiconductors
  - Atoms with an extra electron
  - Only low energy is needed to release an electron from the donor into the conduction band
  - Majority carriers are electrons - N-type semiconductor
- Acceptor semiconductors
  - Electron-deficient atoms
  - Formation of an empty vacancy level in the acceptor atom. Only low energy is needed to excite an electron from the valence band to the acceptor level and to form a hole. This can be occupied by neighbouring valence electrons - the hole will move.
  - The majority of the charge carriers are holes – P-type semiconductor.



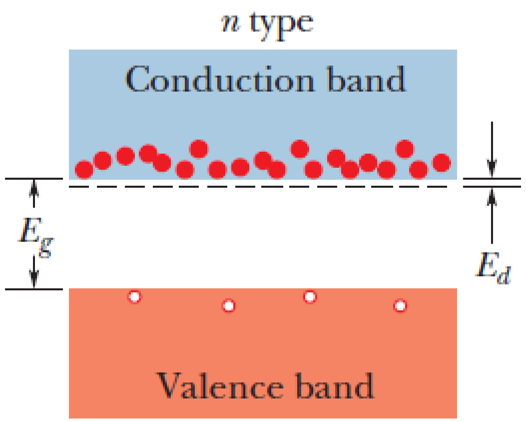
N-type semiconductor



P-type semiconductor

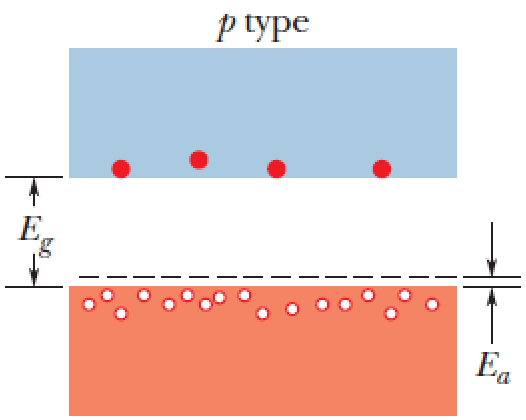
http://conocimientossemiconductorequilibrium.blogspot.com/2010/02/semiconductors.html
J. Walker, D. Halliday, R. Resnick, Fundamentals of physics – 10th edition

Extrinsic Semiconductors II



(*a*)

Electrons jump up from donors at the dashed level.



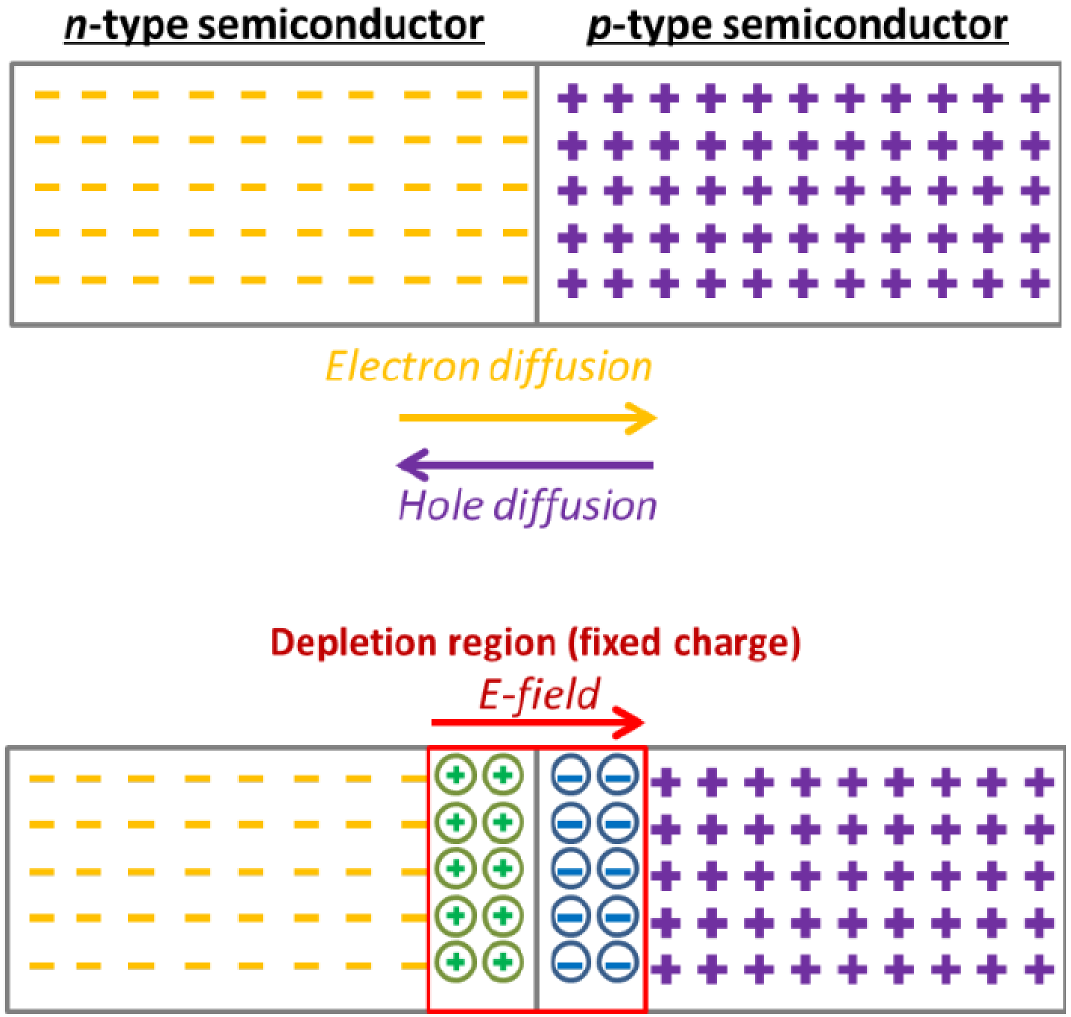
(*b*)

Electrons jump up to acceptors at the dashed level, leaving holes.

J. Walker, D. Halliday, R. Resnick, Fundamentals of physics – 10th edition

P-N Junction

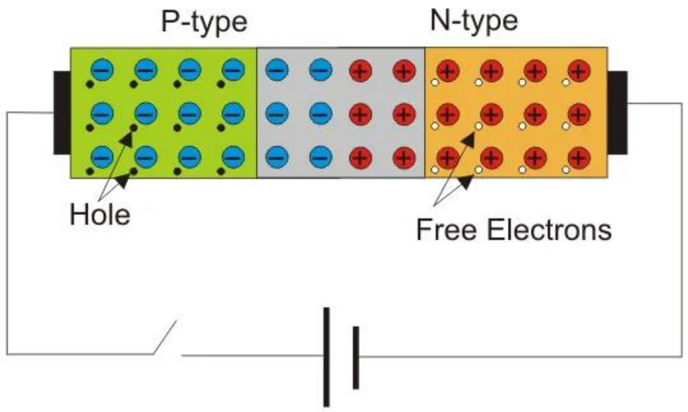
- When we combine P and N semiconductors, the moving electrons and holes diffuse into an adjacent type of semiconductor where they recombine. Leaving behind the immobile impurity ions. This creates a depletion region in the transition region without free charges, where there a permanent electric field arises (space charge region).

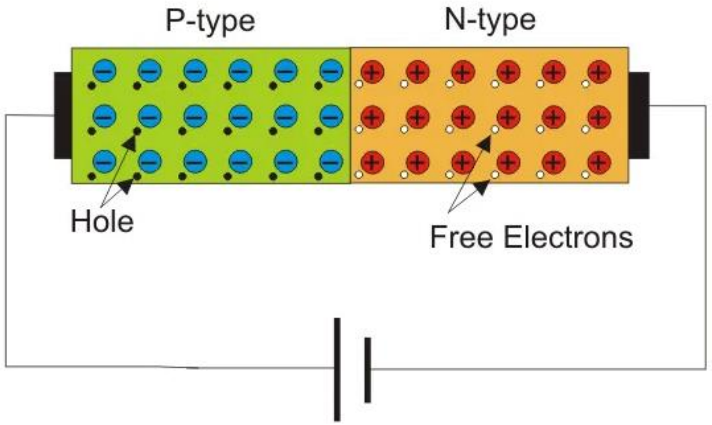


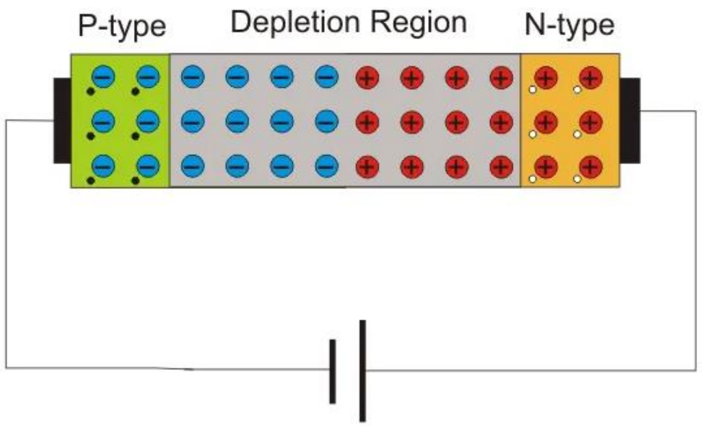
https://www.researchgate.net/figure/p-n-junction-When-a-metallurgical-junction-is-formed-between-an-n-type-and-a-p-type_fig3_279810779

Contacting the P-N Junction

- Contacting in the forward bias
  - Semiconductor P is connected to + and semiconductor N to -
  - We „dope" semiconductor P with holes and N with electrons, which recombine with ions in the transition region and make this region thinner. Electron and hole currents can then pass through
- Contacting in the reverse bias
  - Semiconductor P is connected to - and semiconductor N to +
  - Electrons are attracted to the + pole of the source and holes to the – pole of the source. The depletion region is enlarged. Current does not flow.



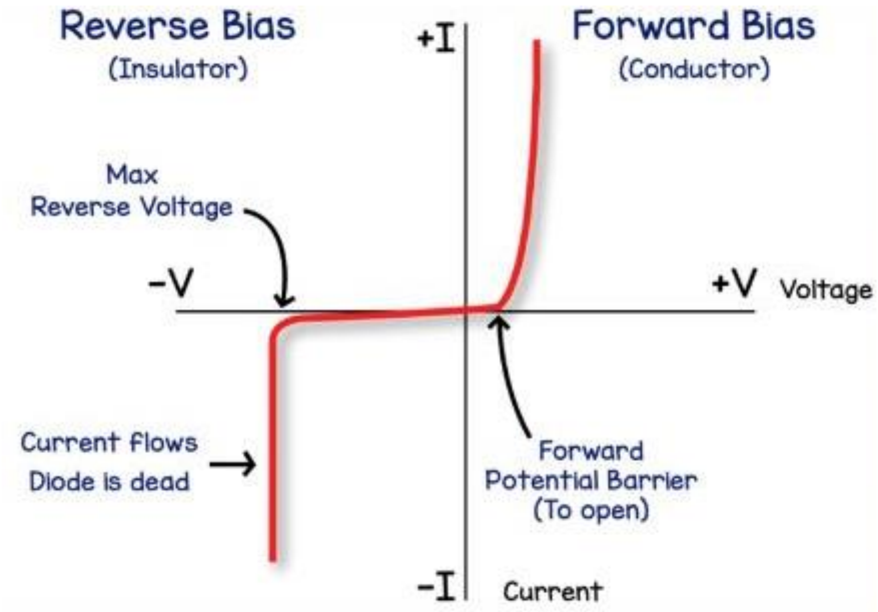




https://www.electrical4u.com/pn-junction/

I-V Characteristic of the Diode

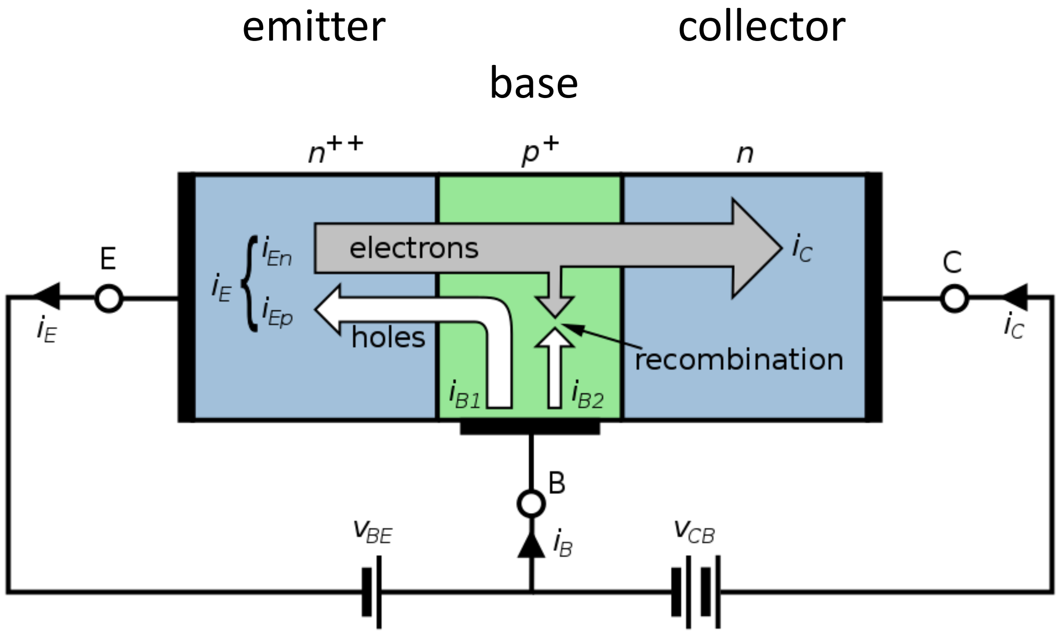
- Forward bias
- Reverse bias
- Remark:
  - If charge recombination in the transition region is associated with photon emission - LED (light emitting diode; GaAs, GaP, GaAsP). The N semiconductor is typically more doped than the P one.
  - If the impact of a photon creates an electron-hole pair in the P-N transition region, which is then sepparated by permanent voltage in the transition region - a photovoltaic cell



https://theengineeringmindset.com/the-basics-of-diodes-explained/diode-iv-2/

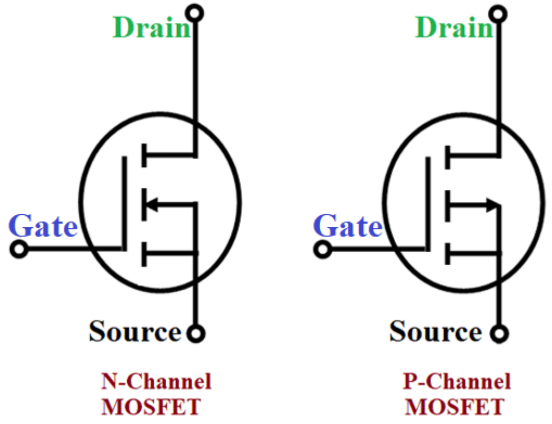
Bipolar Junction Transistor

- Transistor = transfer + resistor
- 2 PN junctions (NPN or PNP)
- NPN - heavily doped N emitter region, weakly P doped base, weakly N doped collector
- Electrons accelerated by voltage V_{BE} penetratethrough the weakly doped base. Due to the weak doping amd a small thickness of the base, only a small number of electrons recombine there. A large number (> 90%) of electrons pass through the base into the collector region where they are further accelerated by voltage V_{CB}. This reduces the electrical resistance in this region.
- With a small voltage/current we are able to control large currents

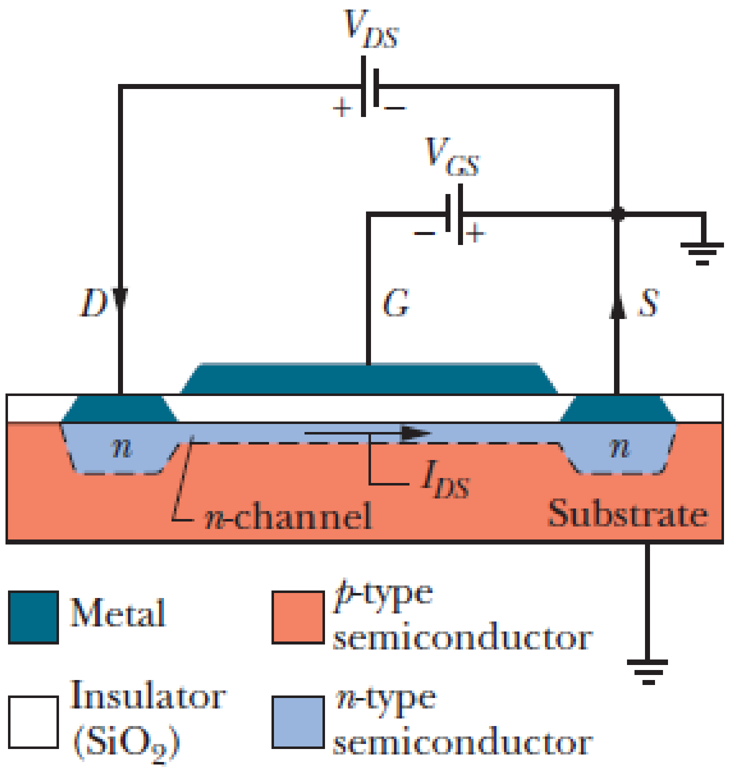


https://en.wikipedia.org/wiki/Bipolar_junction_transistor

MOSFET (Metal-Oxide-Semiconductor Field-Effect Transistor)



- Slightly p-doped substrate, n doped islands S (source) and D (drain) and a narrow channel between them. On the substrate there is a thin non-conducting layer of SiO_2 through which the metal contacts to S and D lead.
- If V_{GS} voltage is not applied, current ("1") flows between S and D. If it is applied with opposite voltage polarity on the transistor to the substrate (- for a P-doped substrate), this voltage will repel electrons from the channel down to the substrate. This will increase the natural depletion region between the P doped substrate and the N doped channel, which is "pinched". At sufficient voltage, the channel closes and no current ("0") flows between S and D.
- No current flows between G and the substrate - no current and energy losses.
- The basis of computer chips.
- Due to the thickness of the n channel, the MOSFET is a nano- (quantum) component

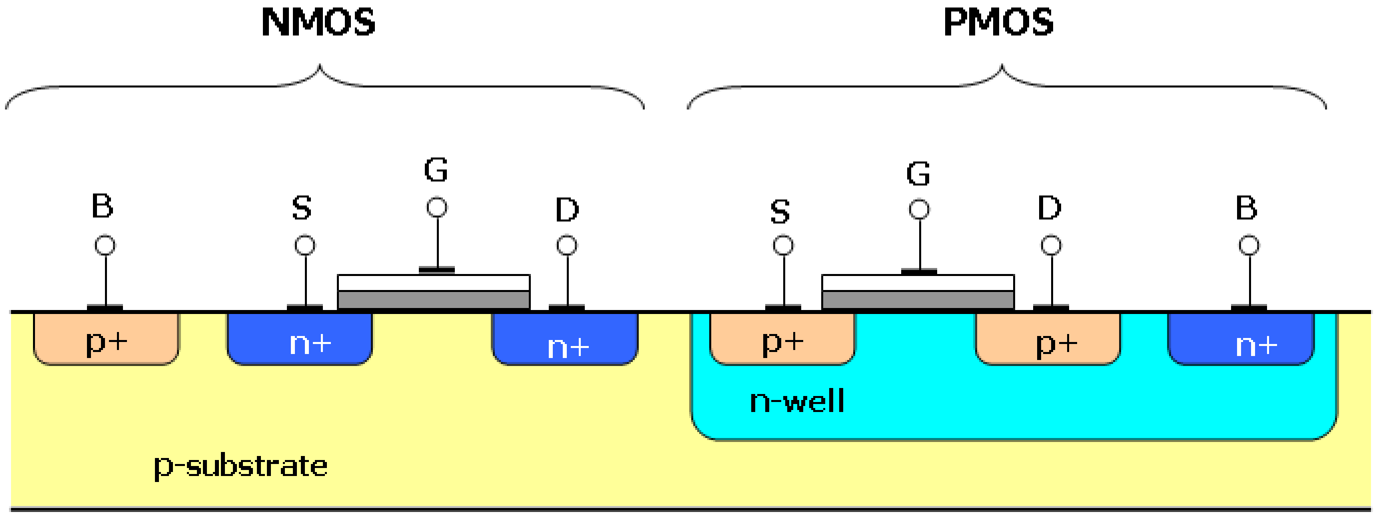


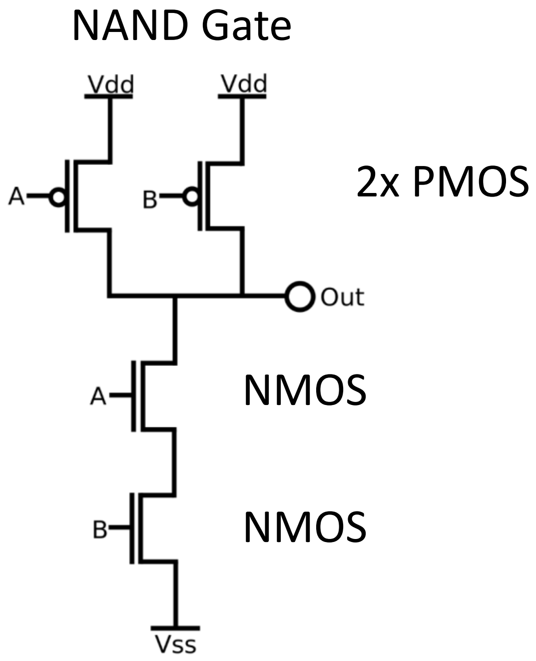
https://www.rs-online.com/designspark/what-is-mosfet-a-detailed-guide-on-mosfet

J. Walker, D. Halliday, R. Resnick, Fundamentals of physics – 10th edition

Microelectronics – CMOS (Complementary MOSFET)

- Transistors can be used to construct logic circuits (logic gate)



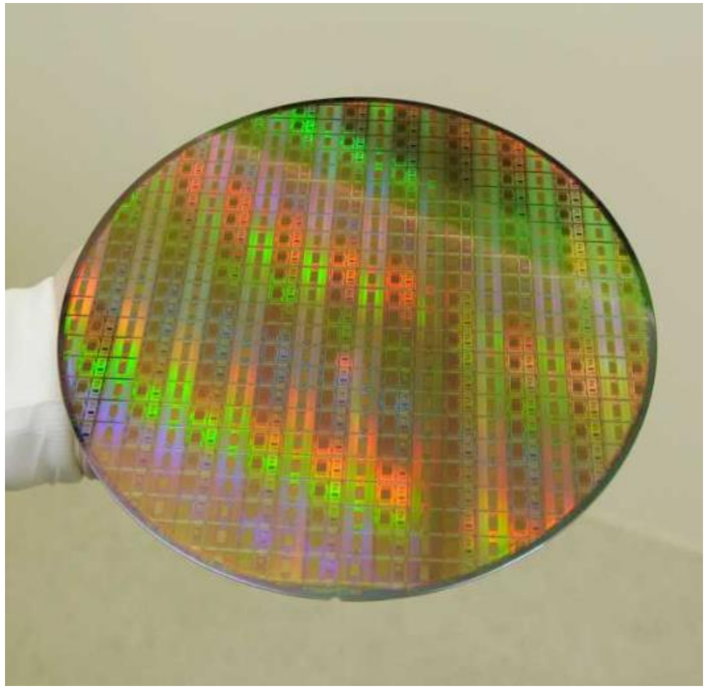


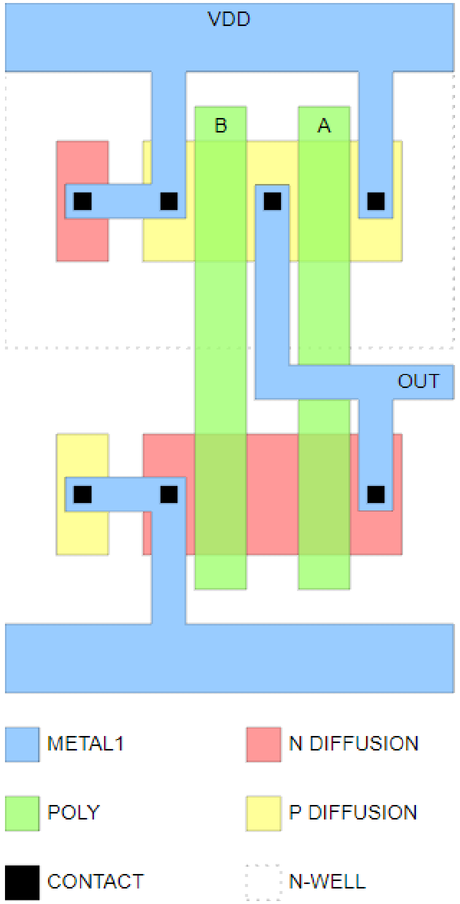
A	B	NAND out
1	1	0
1	0	1
0	1	1
0	0	1

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

CMOS – Layout

- The individual areas are prepared on a silicon wafer in several layers



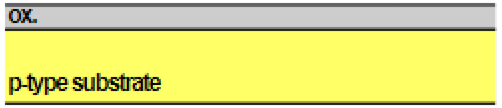


https://bsse.ethz.ch/research/facilities/cleanroom-facility.html
https://en.wikipedia.org/wiki/CMOS

CMOS Production

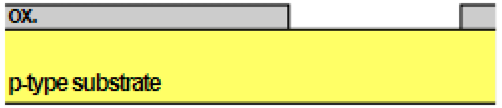
- Production consists of many sub-steps (top-down)
  - Thermal oxidation of wafer

1. Grow field oxide



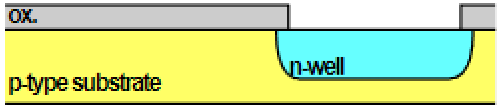
  - Chemical/physical substrate etching

2. Etch oxide for pMOSFET



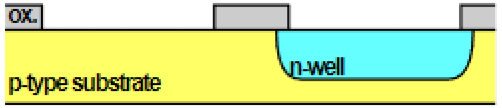
  - Diffusion of donor

3. Diffuse n-well



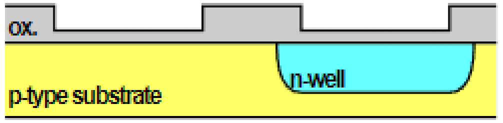
- Chemical/physical etching of oxide

4. Etch oxide for nMOSFET



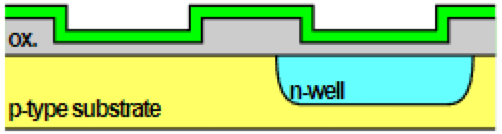
- Oxidation for gate

5. Grow gate oxide



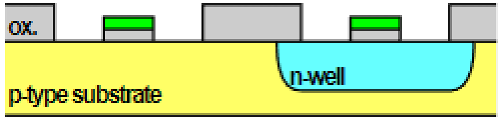
- Deposition of gate material

6. Deposit polysilicon



- Etching of gate

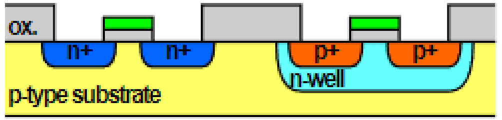
7. Etch polysilicon and oxide



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

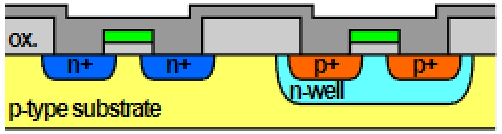
CMOS Production II

- Donor and acceptor implantation into Source and Drain



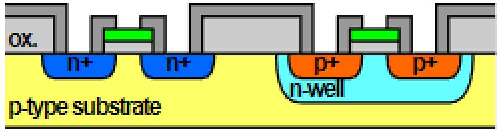
8. Implant sources and drains

- Deposition of protective nitride



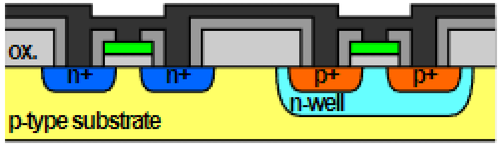
9. Grow nitride

- Nitride etching



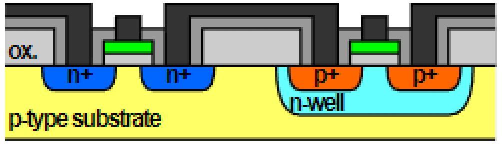
10. Etch nitride

- Metal deposition



11. Deposit metal

- Etching of metal contacts

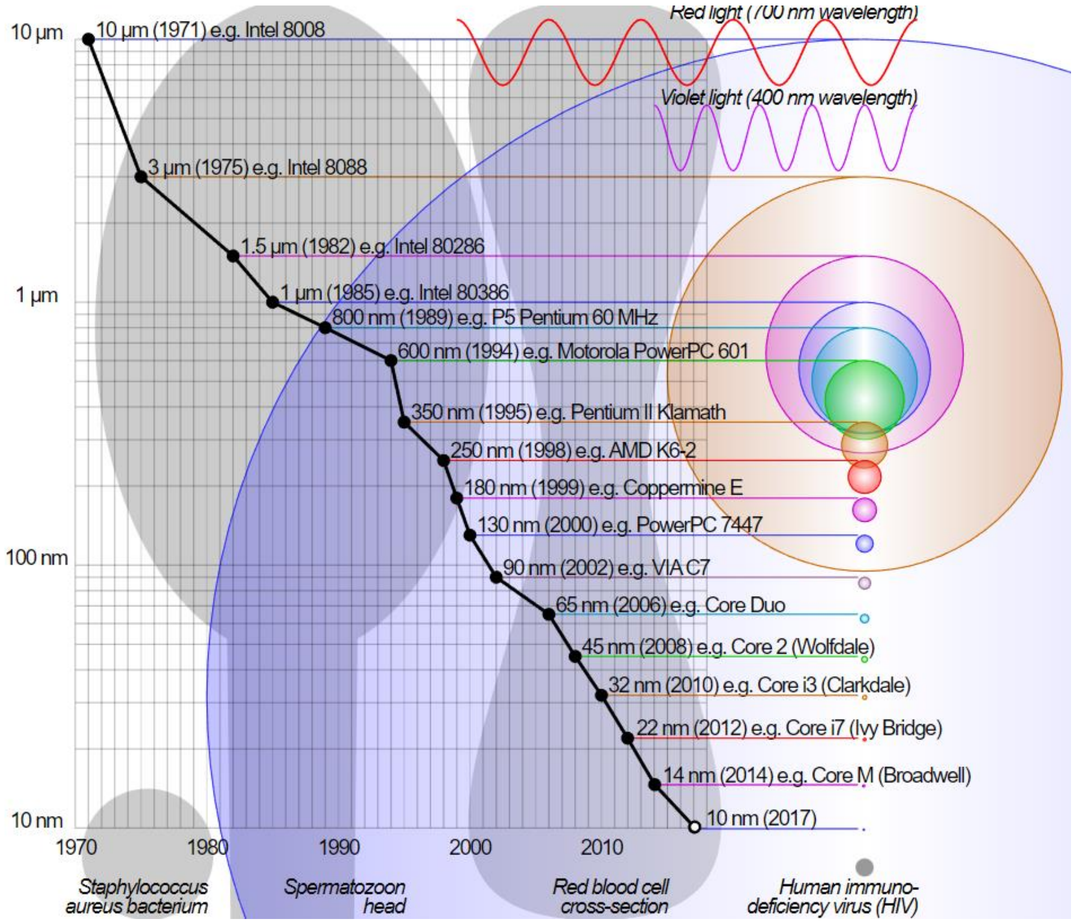


12. Etch metal

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

Limits of Current Technology

- By thinning the SiO_2 layer to a few nm we lose its insulating properties
- By shrinking the structures, the original band structure is lost (change in electrical conductivity)
- Due to the low concentration of impurities, the individual structures are no longer the same in nm^3
- The cost of production increases (cleanliness of the environment, materials, lithographic techniques)
- Non-standard phenomena in nanostructures – ballistic collisionless charge transport
- Heat loss (more than $100 W/cm^2$)

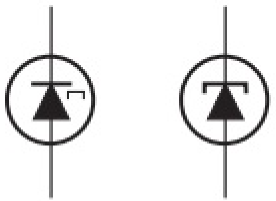


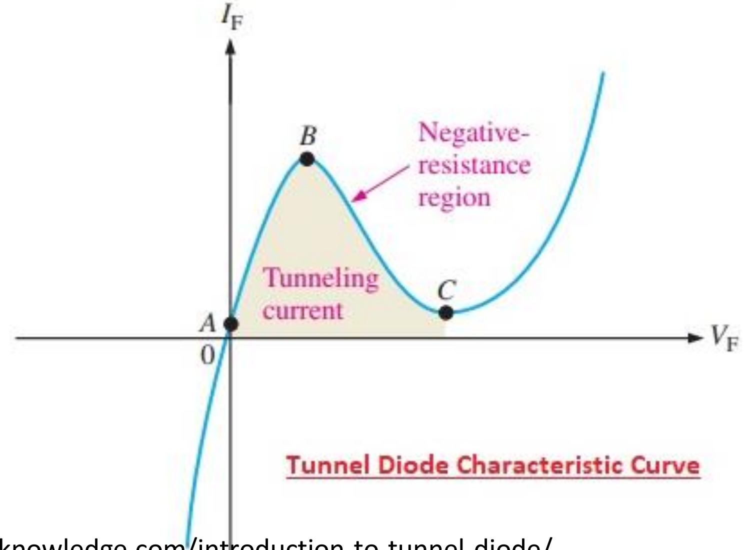
https://en.wikipedia.org/wiki/Microprocessor_chronology

Nanoelectronic Components

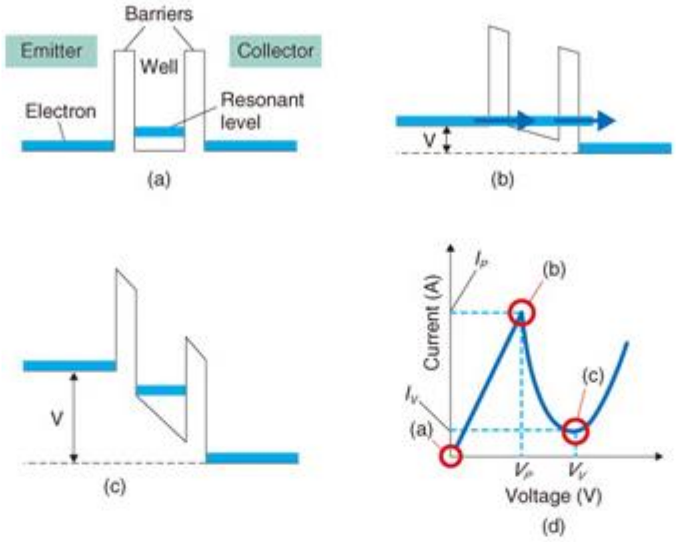
- Tunnel diode
  - Very fast switching diode (< 100 ps), high frequency oscillator, damping suppression in oscillator circuits
  - Typically made of very heavily doped germanium, resulting in a small pn transition region

- Double-barrier resonant-tunneling diode
  - High speed switching, oscillators and switches up to THz frequencies
  - Transition coefficient non-monotonically depends on electron energy – for certain energies this barrier is completely transparent – tunneling will always occur





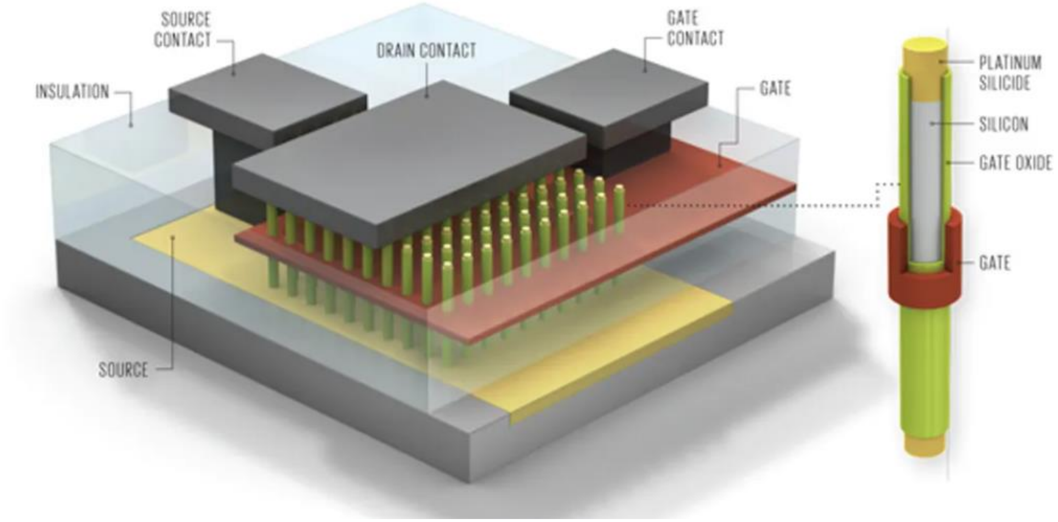
Tunnel Diode Characteristic Curve

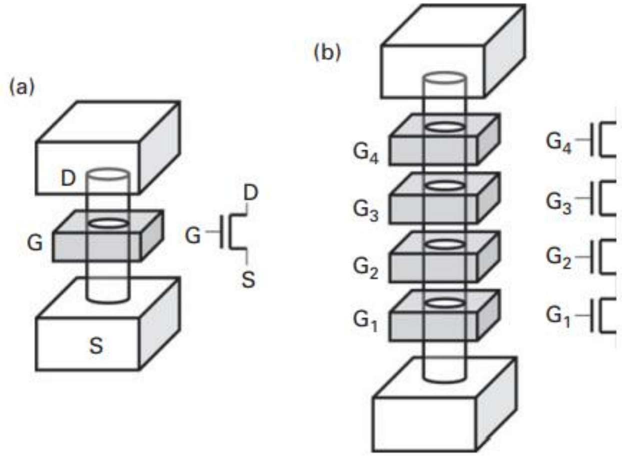


https://www.theengineeringknowledge.com/introduction-to-tunnel-diode/
https://www.ntt-review.jp/archive/ntttechnical.php?contents=ntr201110fa2.html

Nanowire FET Transistors

- Further miniaturization of transistors.
- The current between source and drain flows through nanowires.
- A new building block for future chips

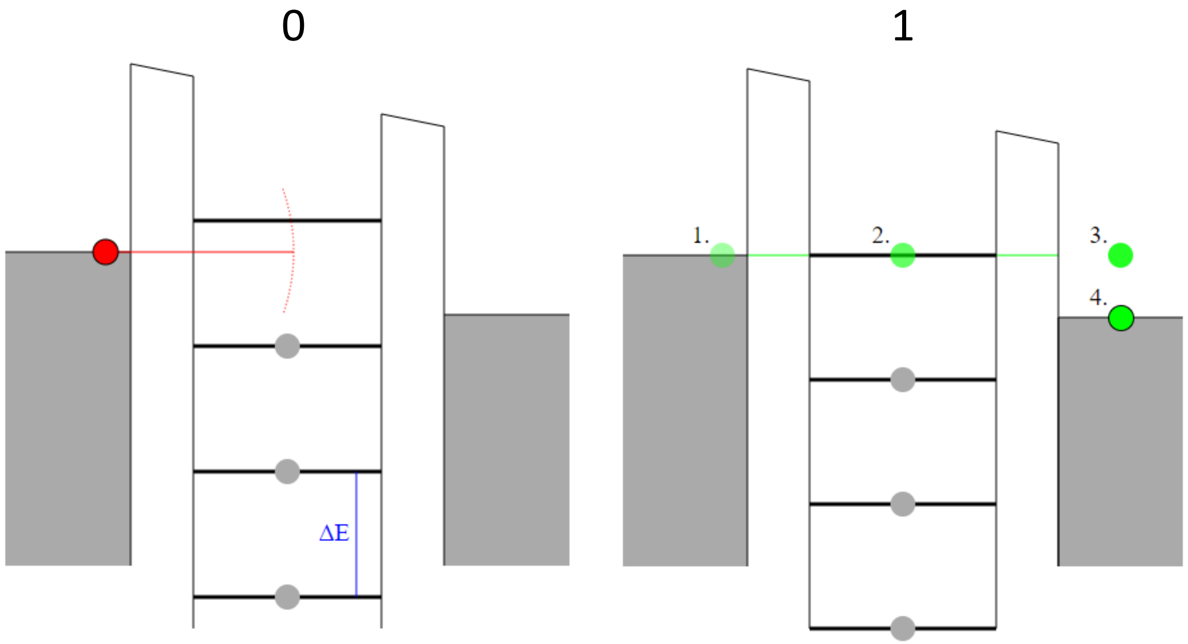




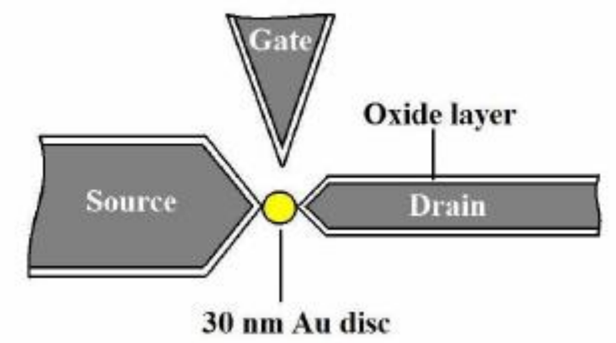
https://spectrum.ieee.org/nanowire-transistors-could-keep-moores-law-alive
JP Colinge, JC Greer, Nanowire transistors,Cambridge University Press 2016

Single Electron Transistor – SET

- 1 bit = 1 electron
- The electron going from source to drain must pass through a double quantum tunneling through a quantum nanoparticle (quantum dot; Coulomb island), which is separated from both S and D by about 1 nm of insulator
- Works on the principle of Coulomb blockade
- For a reliable SET function, different dots in different transistors need to have the same capacitance. We cannot provide this yet .

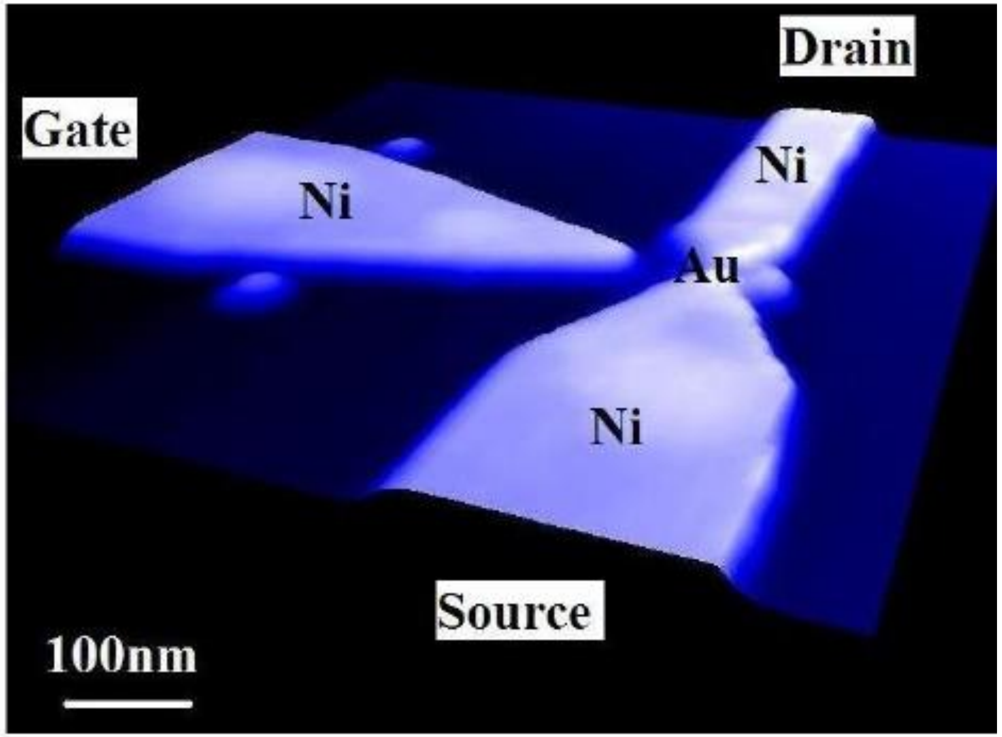


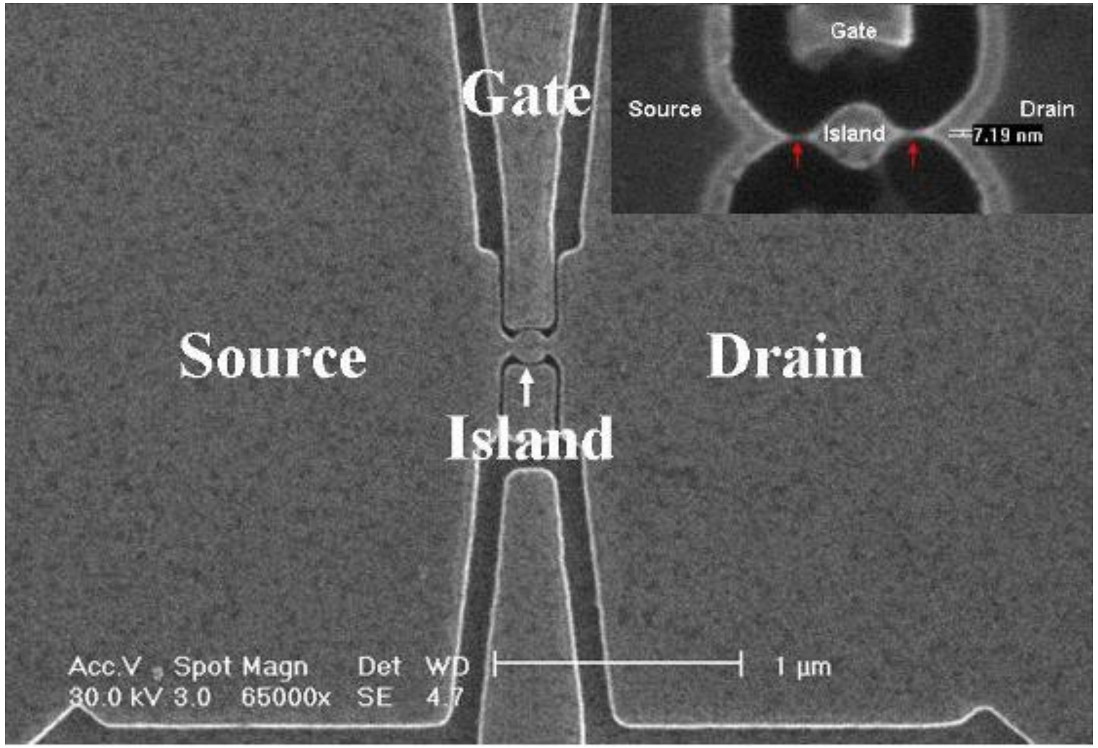
- $\Delta E = e^2/C$



https://en.wikipedia.org/wiki/Single-electron_transistor
JP Colinge, JC Greer, Nanowire transistors,Cambridge University Press 2016

SET



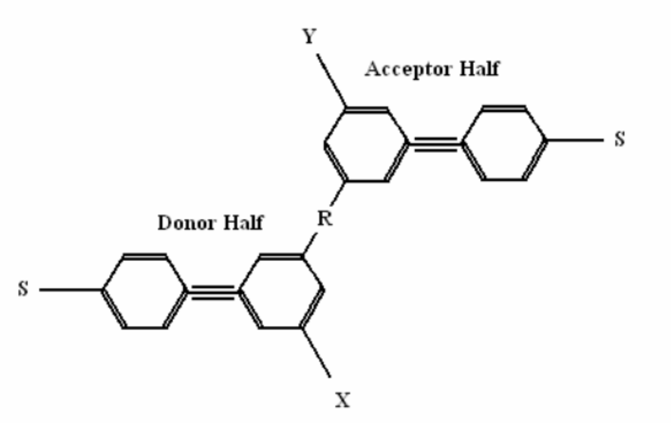


https://www.intechopen.com/chapters/8670
JP Colinge, JC Greer, Nanowire transistors,Cambridge University Press 2016

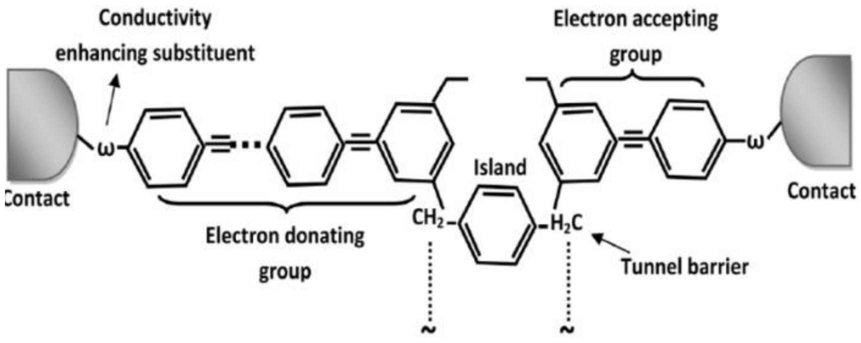
Molecular Electronics

- Electronic circuits made from molecules could solve many of the problems of silicon technology, such as the reproducibility of small structures. They are also flexible.
- In the 1970s – the first theoretical design of a diode molecule
- First preparation 1997
- Polyphenylene chains (a chain of benzene nuclei lacking 2 hydrogens) and carbon nanotubes are most often investigated as conductors – Aliphatic hydrocarbons (without benzene nucleus) are investigated as insulators

Diode

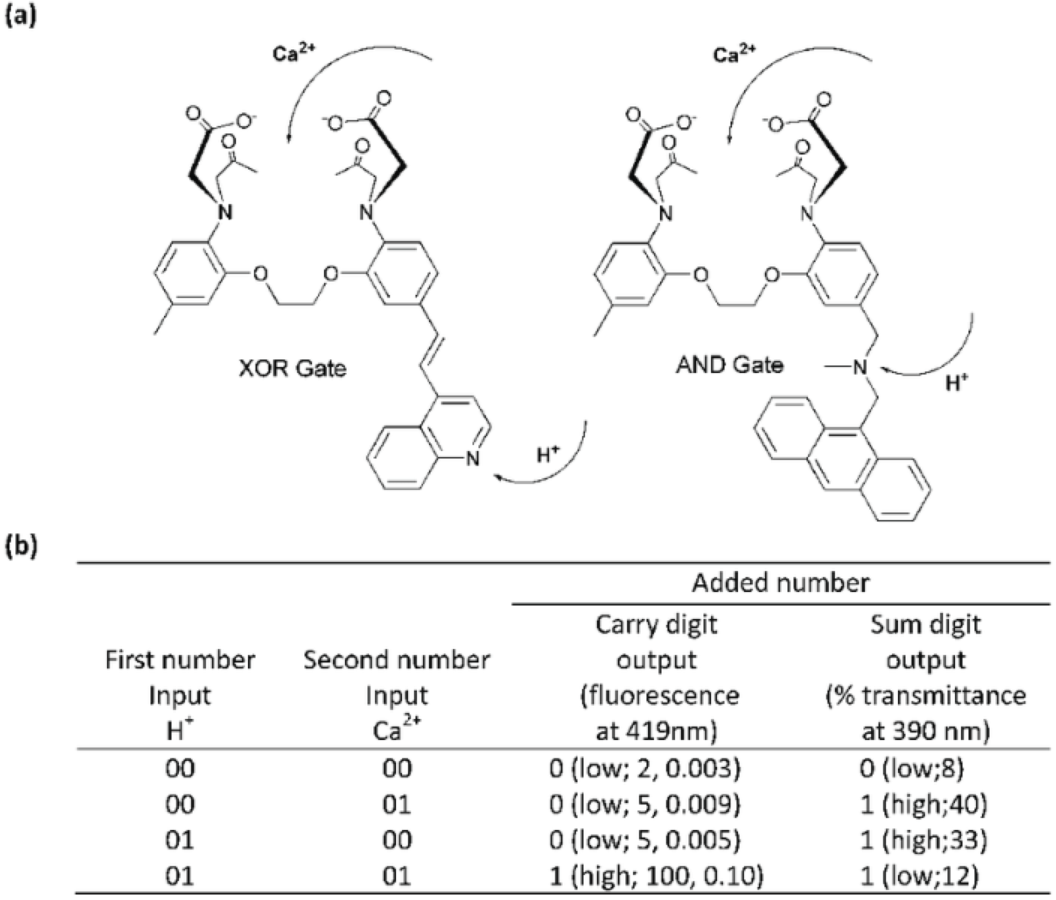


Double resonant tunneling diode



https://www.researchgate.net/publication/32897030_Fault_tolerance_issues_in_nanoelectronics
https://www.researchgate.net/publication/51988506_A_New_Full_Adder_Cell_for_Molecular_Electronics

Logic Gates for Computers



(b)

		Added number	
First number Input H^+	Second number Input Ca^{2+}	Carry digit output (fluorescence at 419nm)	Sum digit output (% transmittance at 390 nm)
00	00	0 (low; 2, 0.003)	0 (low;8)
00	01	0 (low; 5, 0.009)	1 (high;40)
01	00	0 (low; 5, 0.005)	1 (high;33)
01	01	1 (high; 100, 0.10)	1 (low;12)

https://www.researchgate.net/publication/323500234_Molecular_logic_gates_The_past_present_and_future

Conclusion

- What is and how does PN transition work
- What is a diode, transistor, MOSFET
- How transistors are applied in logic chip design
- Manufacturing chips
- Physical limitations of current technologies
- Some nanoelectronic components
- Molecular electronics