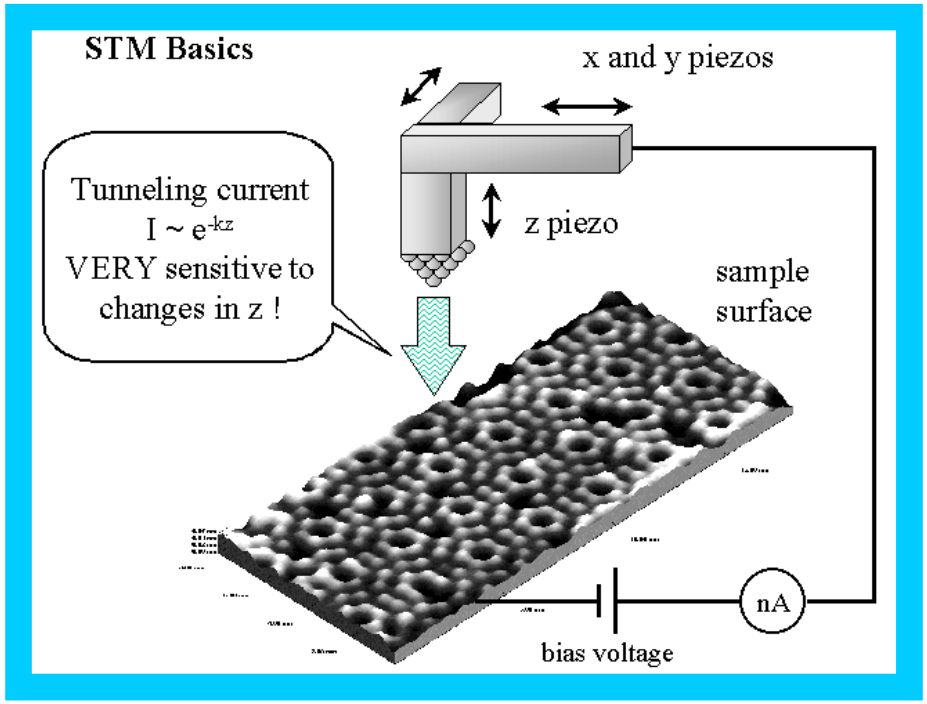
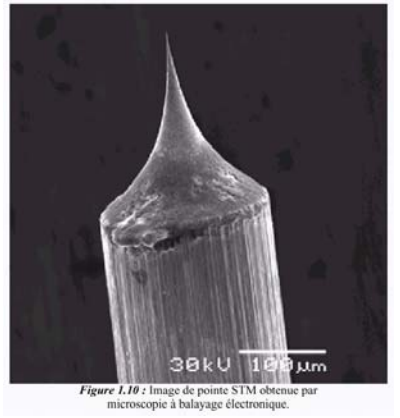
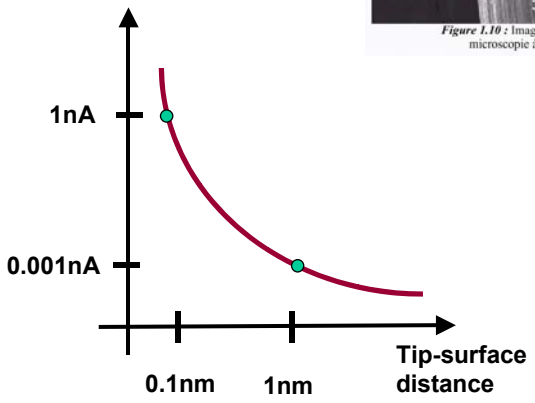
Scanning tunneling microscope





STM tip



1981: Gerld Binnig, Heinrich Röhrer

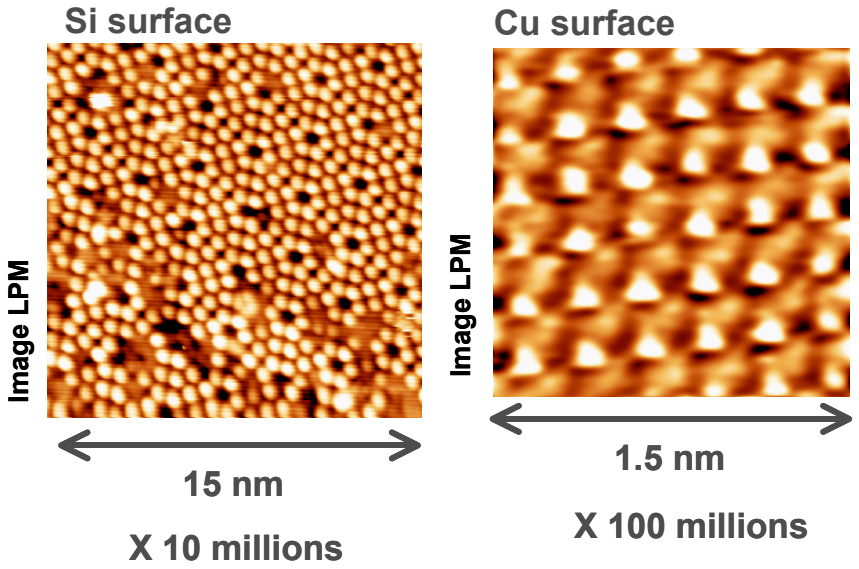
Nobel Prize 1986

IBM - Zurich

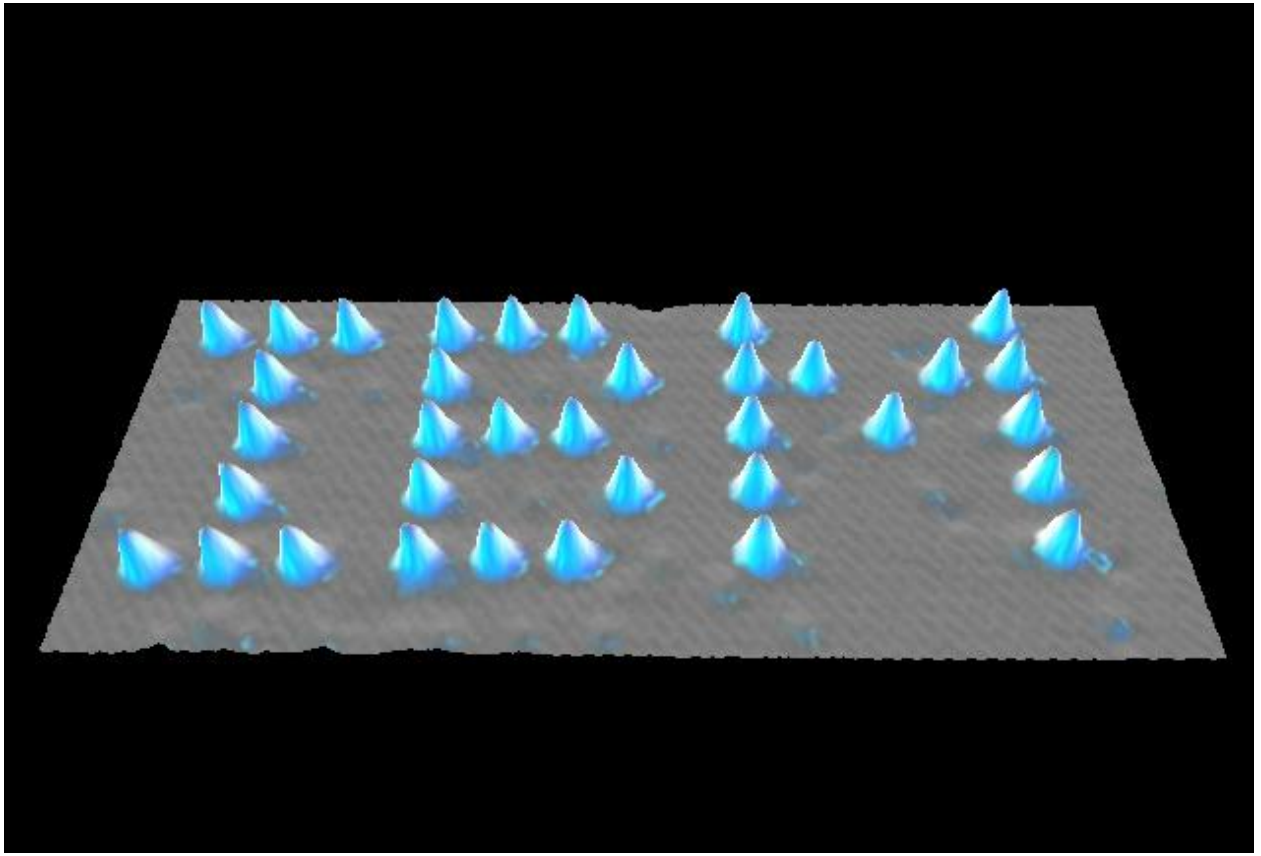
STM:

Looking to atoms…

atomic resolution



Moving atoms one by one by STM



Title : *The Beginning*

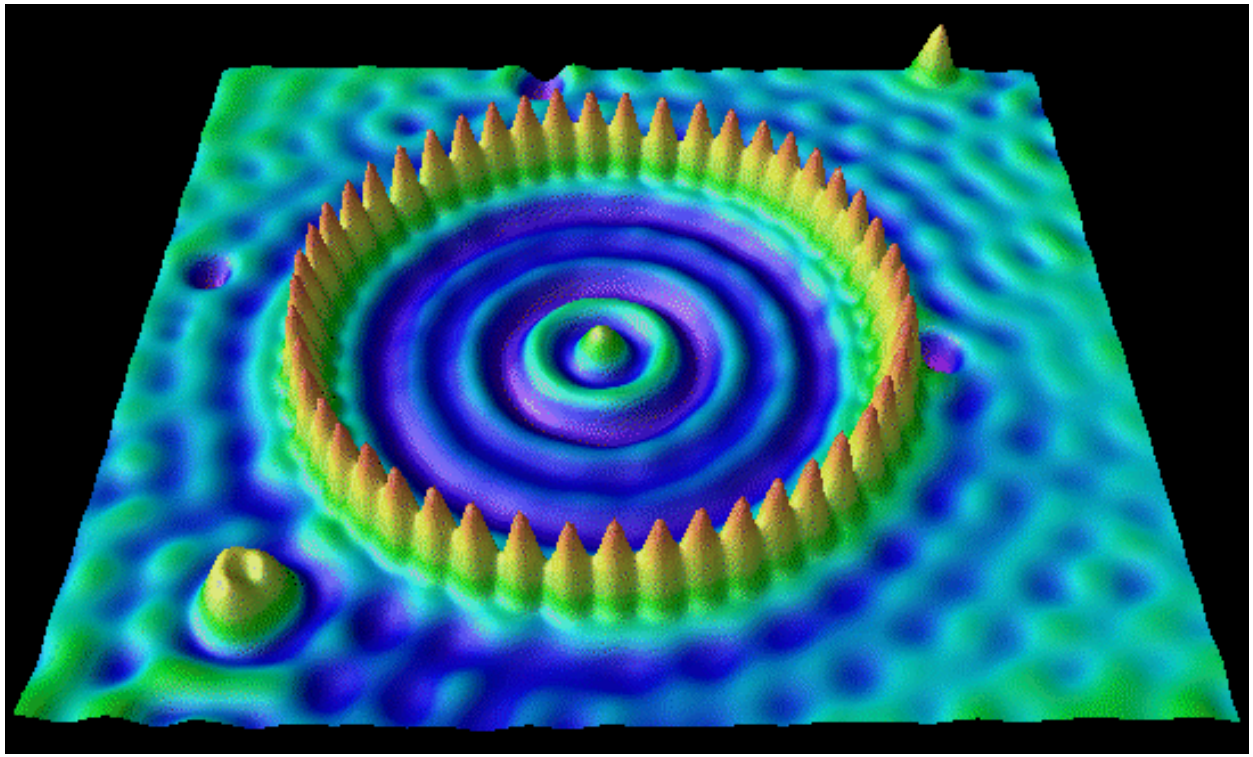
1988 Donald Eigler IBM *Xenon on Nickel (110)*

Artists have almost always needed the support of patrons (scientists too!). Here, the artist, shortly after discovering how to move atoms with the STM, found a way to give something back to the corporation which gave him a job when he needed one and provided him with the tools he needed in order to be successful.

2D finite potential well =» **QUANTUM CORAL**

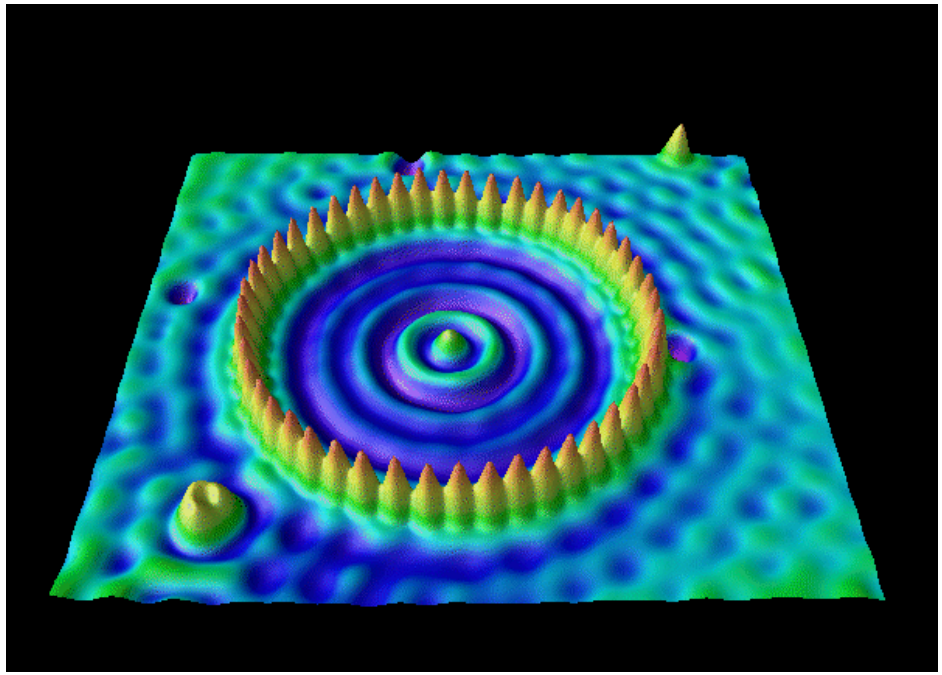
To make this image, 48 iron atoms (shown as yellow peaks) were placed in a circle on a copper surface. The "elevation" at each point inside the circle indicates the electron density within the circle. The standing-wave pattern is very similar to the probability distribution function for a particle in a one-dimensional finite potential well:

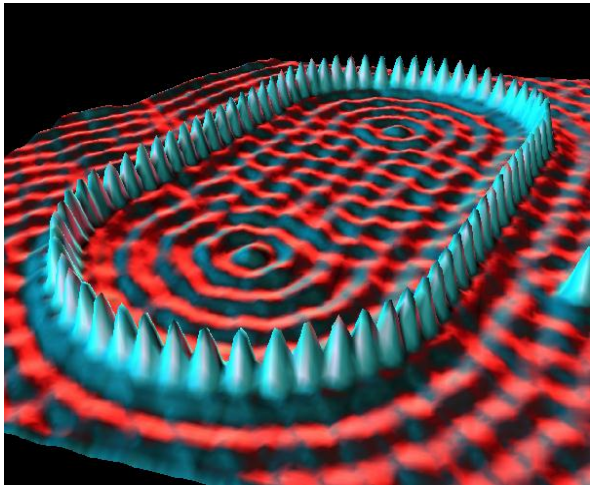
$$e\left|\Psi(x,y)\right|^2$$

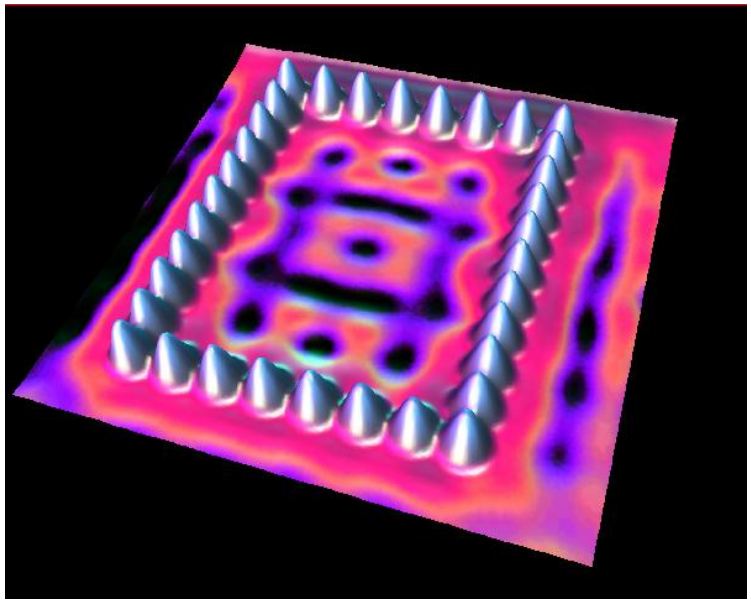


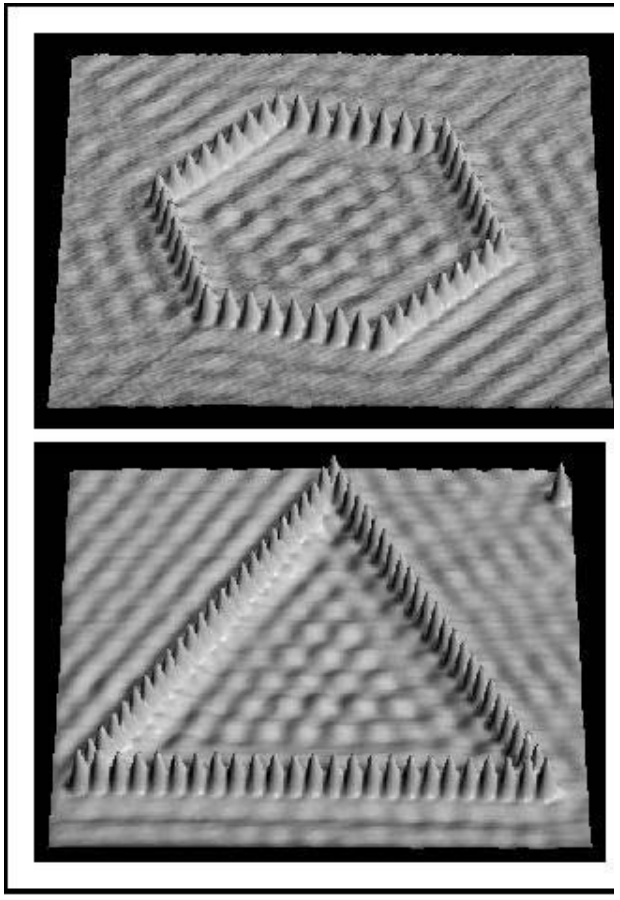
IBM- ***M.F. Crommie, C.P. Lutz, D.M. Eigler, Science 262, 218-220 (1993).***

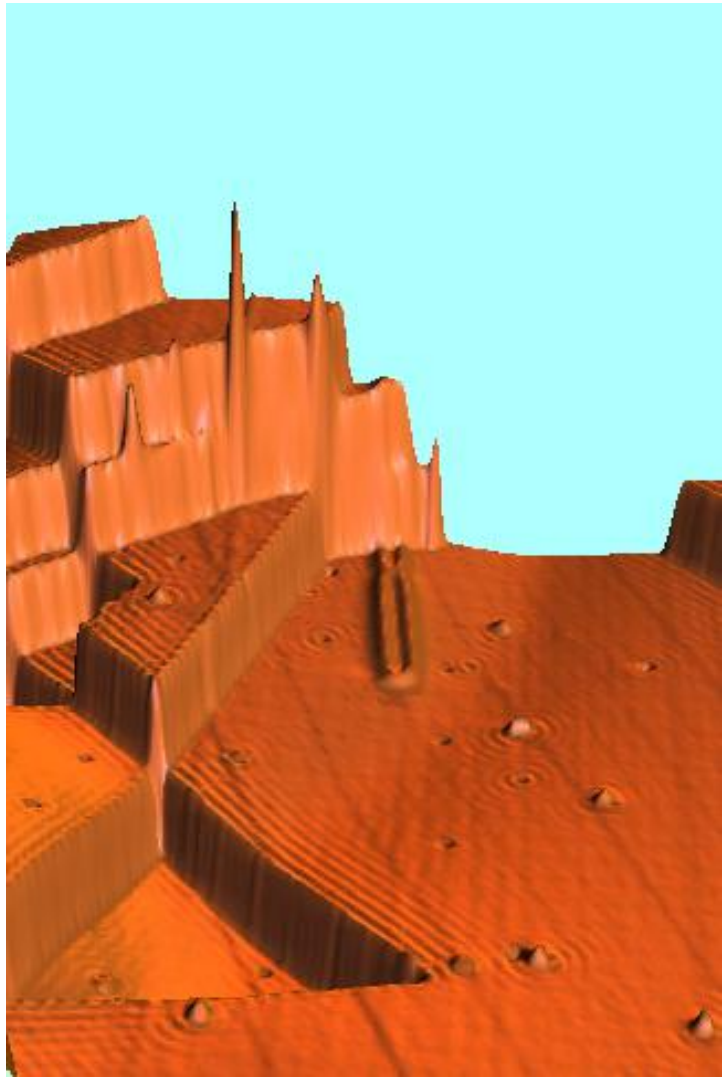
Quantum corrals









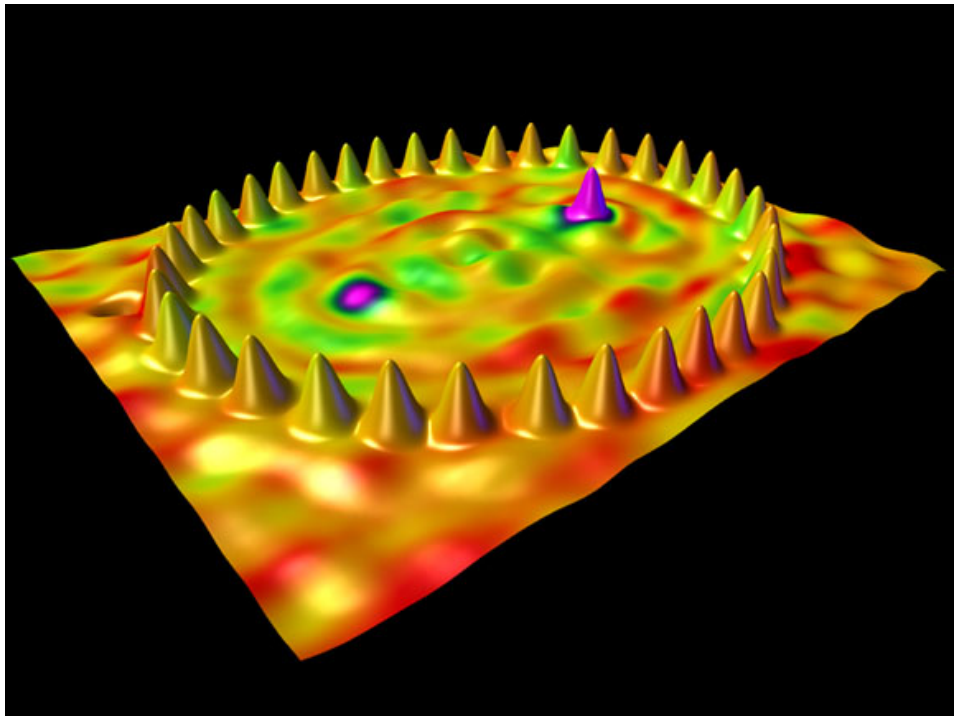


Reminiscent of formal Japanese rock gardens, here we see ripples surrounding features on the copper (111) surface.

The artists' fortunes took a major turn upward when they determined that the ripples were due to "surface state electrons."
These electrons are free to roam about the surface but not to penetrate into the solid. When one of these electrons encounters an obstacle like a step edge, it is partially reflected.

The ripples extending away from the step edges and the various defects in the crystal surface are just the standing waves that are created whenever a wave scatters off of something. The standing waves are about 15 Angstroms (roughly 10 atomic diameters) from crest to crest. The amplitude is largest adjacent to the step edge where it is about 0.04 Angstroms from crest to trough.

Quantum mirage



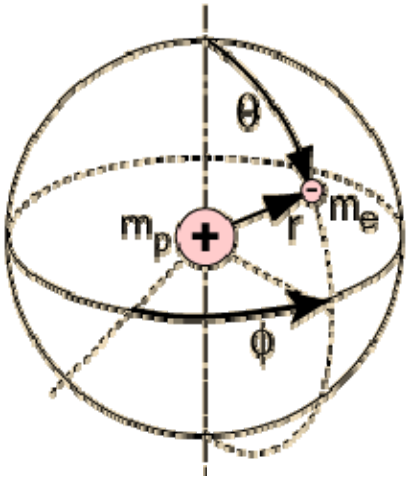
36 cobalt atoms in an elliptical structure known as a "quantum corral." Electron waves moving in the copper substrate interact both with a magnetic cobalt atom carefully positioned at one of the foci of the ellipse and apparently with a "mirage" of another cobalt atom (that isn't really there) at the other focus.

Donald Eigler IBM Almaden

ATOMUL DE HIDROGEN

Energia potentiala a electronului care se misca in jurul nucleului are simetrie sferica, depinzand doar de distanta:

$$r = \sqrt{x^2 + y^2 + z^2}$$

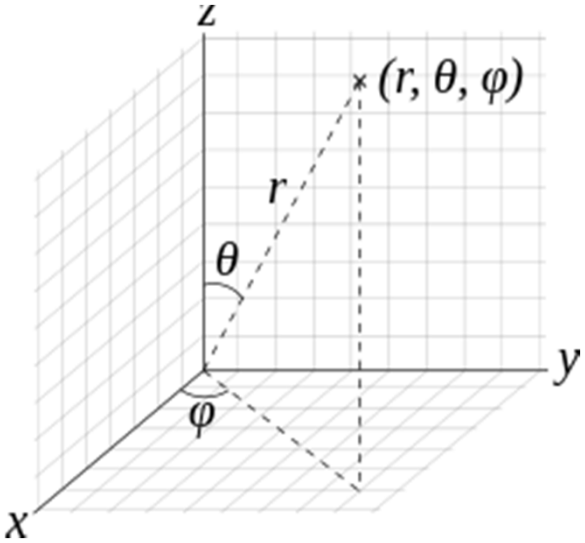


$$U(r) = \frac{e^2}{4\pi\varepsilon_0 r}$$

Legatura ***coordonate carteziene-coordonate sferice***

$$\begin{cases} x = r\cos\theta\sin\varphi \\ y = r\sin\theta\sin\varphi \\ z = r\cos\theta \end{cases}$$

Coordonate sferice: (r, θ, φ)



Ecuatia Schrodinger 3D

$$\hat{H}\Psi(\mathrm{r},\theta,\phi) = \mathrm{E}\,\Psi(\mathrm{r},\theta,\phi)$$

$$\hat{H} = -\frac{\hbar^2}{2m}\Delta + U(x,y,z)$$

$$\Delta = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

Operatorul Laplace Δ(x,y,z) se poate transforma/scrie in coordonate sferice Δ(r, θ, φ)

$$\Delta = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\right) + \frac{1}{\sin\theta}\left[\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right) + \frac{1}{\sin\theta}\frac{\partial^2}{\partial\varphi^2}\right]$$

Ecuatia lui Schrödinger pentru atomul de hidrogen

$$\hat{H}\Psi(\mathrm{r},\theta,\phi) = \mathrm{E}\,\Psi(\mathrm{r},\theta,\phi)$$

$$H = -\frac{\hbar^2}{2mr^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial}{\partial r}\right) - \frac{\hbar^2}{2mr^2}\frac{1}{\sin\theta}\left[\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right)+\frac{1}{\sin\theta}\frac{\partial^2}{\partial\phi^2}\right]+U(r)$$

Stari stationare ale electronului in atomul de hidrogen

- **Intr-o dimensiune**, cuantificarea anergiei apare ca si o consecinta a conditiilor la limita a functiei de unda (restrangerii spatiale). Aceasta implica faptul ca doar pentru anumite valori discrete ale energiei, caracterizate de numarul cuantic n, solutiile ecuatie Schodinger satisfac conditiile la limita.

- **In 3 Dimensiuni,** functia de unda trebuie sa satisfaca 3 conditii limita diferite. In consecinta, solutia ecuatiei lui Schrodinger 3D va fi caracterizata de 3 numere cuantice care fiecare va cuantifica o marime fizica distincta.

$$\Psi(r,\theta,\phi) = R(r)P(\theta)F(\phi)$$

n — Numar cuantic principal

ℓ — Numar cuantic orbital

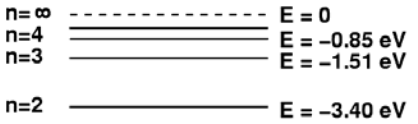
m_ℓ — Numar cuantic magnetic

1. Cuantificarea energiei totale

n = Numar cuantic principal

$$E_n = -\frac{1}{(4\pi\epsilon_0)^2}\frac{m_r e^4}{2n^2\hbar^2} = -\frac{13.60\ \text{eV}}{n^2}$$

Nivele de energie ale H



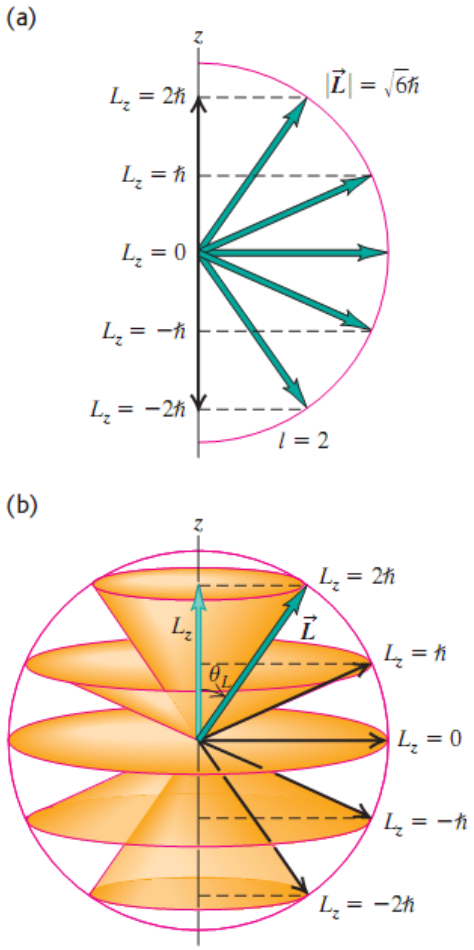
2. Cuantificarea momentului cinetic orbital

Origind: conditia la limita $\Theta(\theta)$ Trebuie sa fie finita in in 0 si π

l numar cuantic orbital

$$L = \sqrt{l(l+1)}\hbar \qquad (l = 0, 1, 2, \ldots, n-1)$$

Modulul momentului cinetic orbital



3. Cuantificarea componentei momentului cinetic orbital pe o anumita directie (ex. L_z-directia aplicarii unui camp magnetic)

Origine: conditie limita periodica $\Phi(\phi) = \Phi(\phi + 2\pi)$

$\mathbf{m_l}$ = numar cuantic magnetic

$$L_z = m_l\hbar \qquad (m_l = 0, \pm 1, \pm 2, \ldots, \pm l)$$

Componenta z a momentului cinetic orbital

Stari cuantice ale atomului de Hidrogen

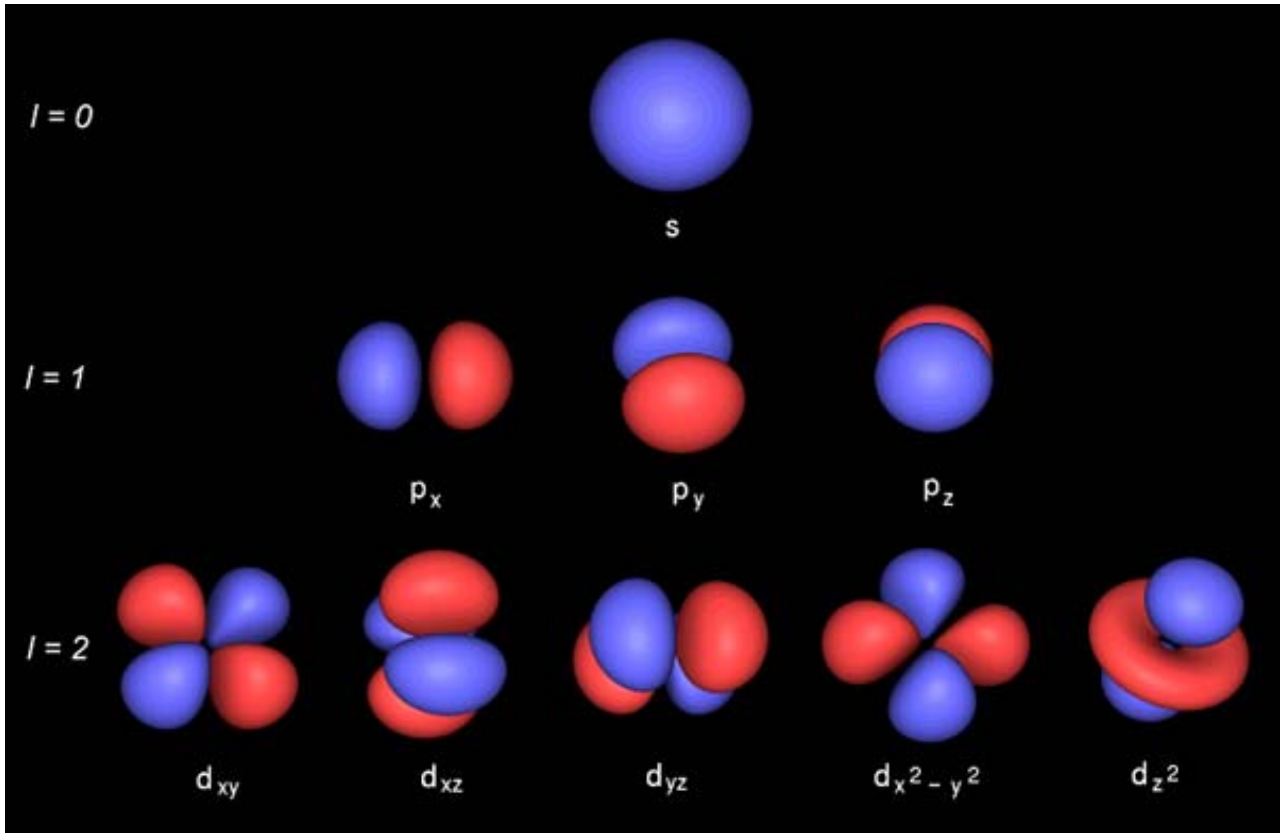
n	l	m_l	Notatie spectroscopica	Stratul
1	0	0	$1s$	K
2	0	0	$2s$	L
2	1	$-1, 0, 1$	$2p$	
3	0	0	$3s$	
3	1	$-1, 0, 1$	$3p$	M
3	2	$-2, -1, 0, 1, 2$	$3d$	
4	0	0	$4s$	N

etc...

Distributia de probabilitate a prezentei electcronului/orbitali

$$\left|\Psi_{n,l,m_l}(r,\theta,\phi)\right|^2$$

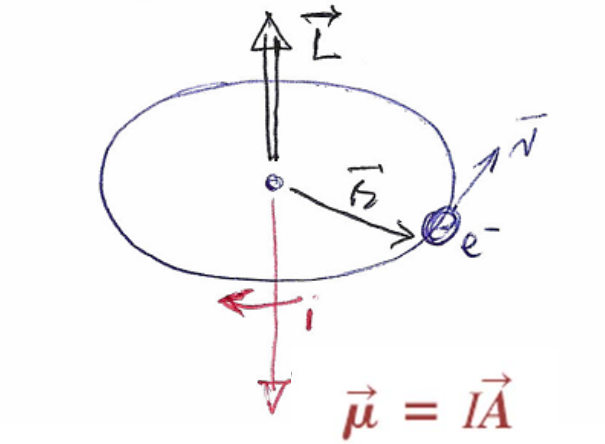
Distributii de probabilitate 3D pentru cateva stari cuantice ale atomului de H



Spinul electronului

Efectul Zeeman *consta in despicarea nivelelor de energie atomice si a liniilor spectrale asociate cand atomul este plasat intr-un camp magnetic extern.*

Momentul magnetic orbital al electronului



Cand un dipol magnetic de moment μ este plasat intr-un camp magnetic **B** energia potentiala de interactiune va fi:

$$U = -\vec{\mu} \cdot \vec{B}$$

$$\mu = \frac{e}{2m} L$$

Daca B este orientat de-a lungul axei oZ

$$U = -\mu_z B = m_l \frac{e\hbar}{2m} B \qquad (m_l = 0, \pm 1, \pm 2, \ldots, \pm l)$$

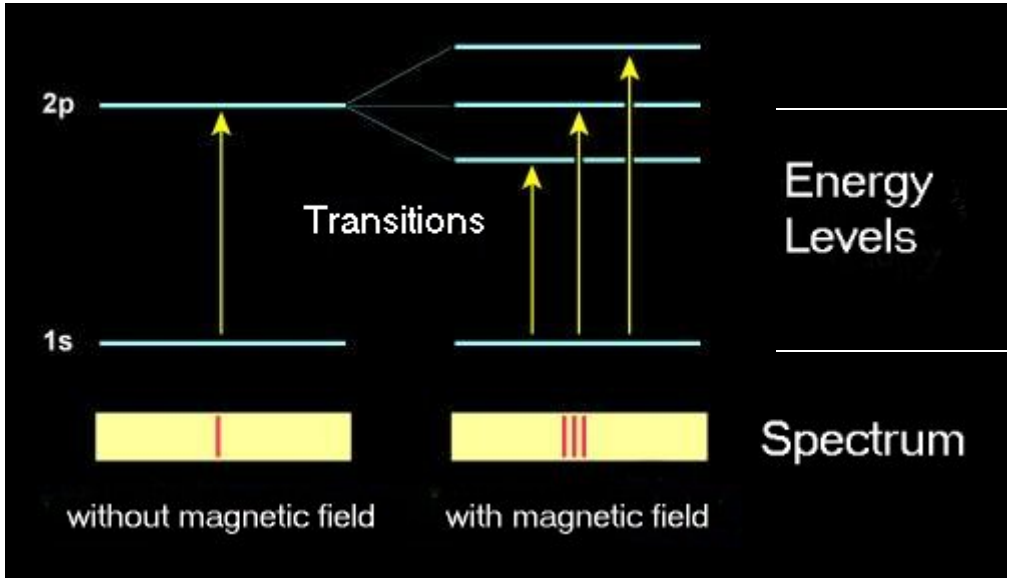
$$U = m_l \mu_B B$$

Energie de interactiune magnetica orbitala

Despicarea Zeeman

$$U = m_l \mu_B B$$

- Campul magnetic decaleaza energia fiecarei stari orbitale cu o cantitate *U.*
- Energia de interactiune *U* depinde de valoarea lui m_l deoarece m_l determina orientarea momentului magnetic orbital relativa la campul magnetic.
- Valorile lui m_l sunt cuprinse intre *-l* to *l* in pasi de unu, deci un nivel de energie cu o valoare particulara a numarului cuantic orbital contine *(2l+1)* stari orbitale diferite.
- In absenta unui camp magnetic extern aceste stari au toate aceasi energie (degenerate). Campul magnetic ridica degenerarea: in prezenta campului magnetic fiecare nivel de energie degenerat este separat in *(2l+1)* nivele distincte;

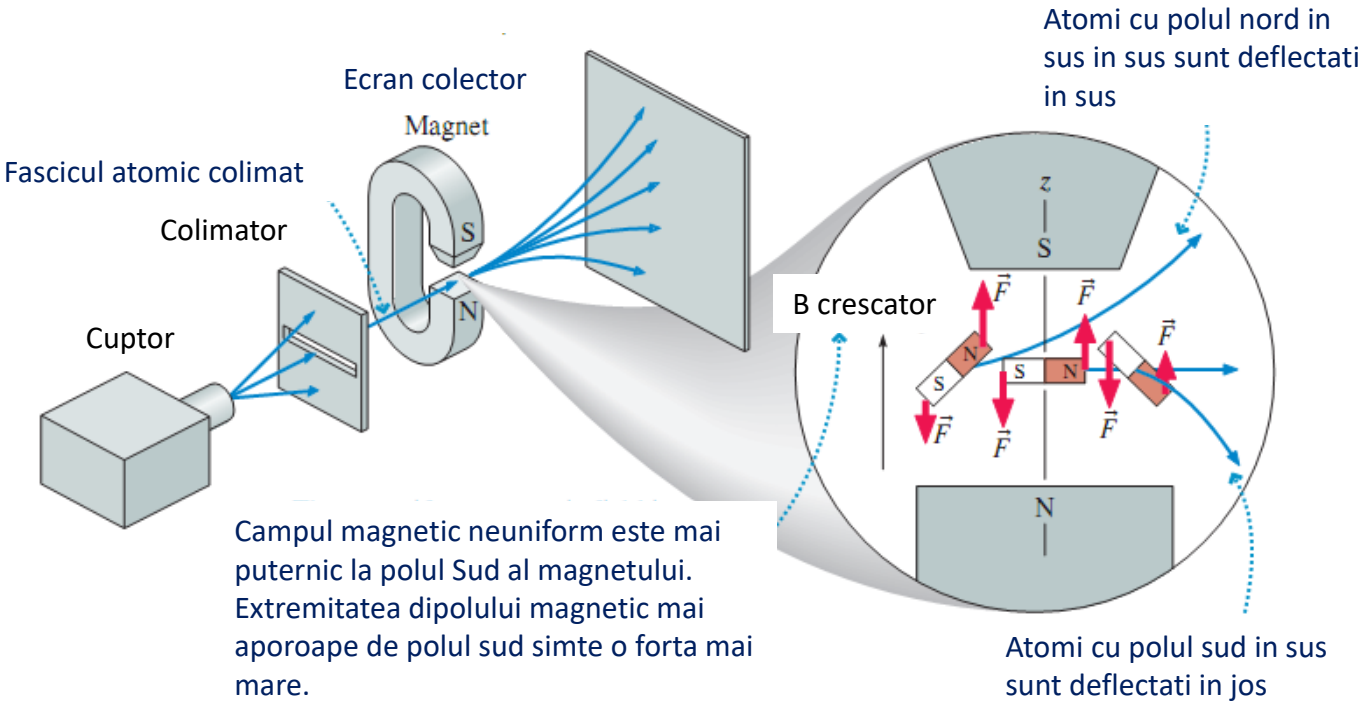


l=1
despicat in 2X1+1=3

l=0 nu este despicat

Experimentul Stern–Gerlach

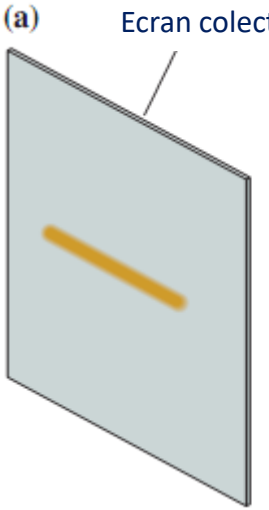
La inceputul anilor 1920, fizicienii germani Otto Stern si Walter Gerlach dezvolta o tehnica pentru masurarea momentului magnetic al atomilor. Dispozitivul lor prepara un fascicul atomic evaporand atomi intr-un cuptor din care pot iesi printr-un orificiu ingust. Acesti atom se deplaseaza in vid traversand un sector de camp magnetic neuniform (gradient de camp obtinut prin forma polilor magnetilor). Reducand marimea polului superior conduce la un cam magnetic mai puternic la polul superior.



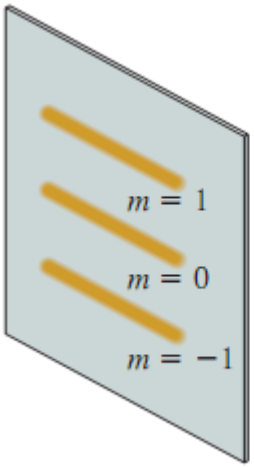
$$F_z = \mu_z \frac{\partial B}{\partial z}$$

Forta $$F_z = \mu_z \frac{\partial B}{\partial z} = \frac{e}{2m} L_z \frac{\partial B}{\partial z} = \frac{e}{2m} (m_l \hbar) \frac{\partial B}{\partial z}$$

Observatie experimentala:



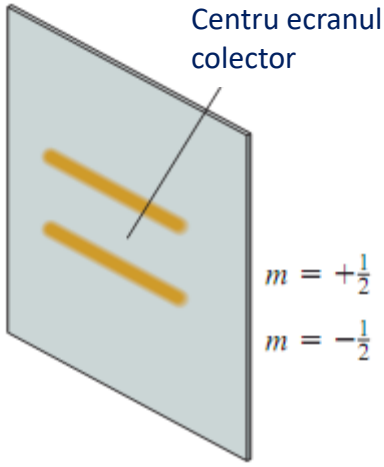
Magnet oprit: camp magnetiz zero, toti atomii cu *l=0* ajung in centru



Magnet pornit: camp magnetic diferit de zero, atomii cu l=1 au trei valori Lz conduc la 3 spoturi

In 1927, odata dezvoltata teoria cuantica a lui Schrödinger, tehnica Stern-Gerlach a fost folosita pentru masurarea momentului magnetic al atomilor de hidrogen. Starea fundamentala a atomului de hidrogen este 1*s, cu l = 0, astfel incat atomul nu ar trebui sa aiba mamoment magnetic deci nu ar trebui sa se observe deflectie deloc.*

In realitate experimentul demostreaza o despicare in doua a fascicolului.



O explicare a acestor observatii a fost sugerata si apoi confirmata ulterior: electronul are un *moment magnetic intrinsec*. In consecinta el are si un moment cinetic intrinsec.

Acest moment cinetic propriu intrinsec este numit **spin** $\vec{S}$

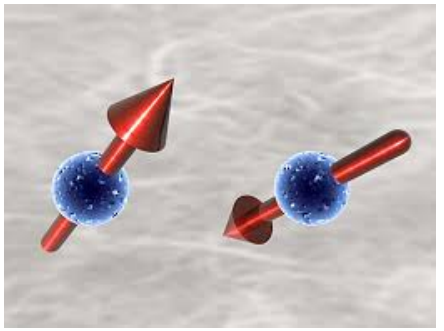
Experimentul Stern-Gerlach ne spune ca componenta *z- a momentului cinetic de spin poate lua doar doua valori:*

$$S_z = m_s\hbar \quad \text{where } m_s = +\tfrac{1}{2} \text{ or } -\tfrac{1}{2}$$

m_s= **numar cuantic magnetic de spin**

Starea $m_s = \frac{1}{2}$ cu $S_z = +\frac{1}{2}\hbar$ Se numeste stare SPIN UP

Starea $m_s = -\frac{1}{2}$ cu $S_z = -\frac{1}{2}\hbar$ Se numeste stare SPIN DOWN



Analog cuantificarii modului momentului cinetic orbital, avem si aici:

$$S = \sqrt{s(s+1)}\hbar$$

cu **s =1/2** numar cuantic de spin

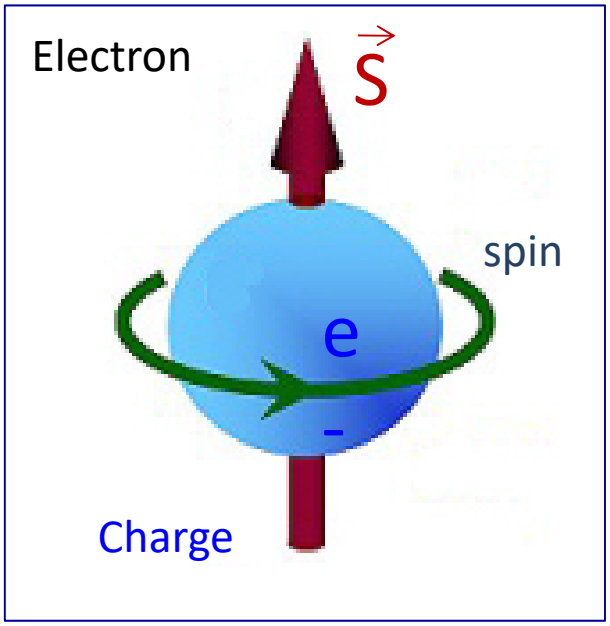
Moment cinetic de spin

- Spinul electronului are implicatii semnificative pentru structura atomului. Solutiile ecuatiei Schrödinger pot fi descrise de trei numere cuantice **n, l**, si **m**, insa experimentul Stern-Gerlach ne arata faptul ca aceasta nu este o descrierer completa a atomului.
- In realitate avem nevoie de patru numere cuantice **(n, l, m_l, m_s)** pentru a caracteriza o stare stationara a atomului.
- Orientarea spinului nu afecteaza energia atomului, astfel incat in starea fundamentala electronul poate fi ori in stare spin-up (1,0,0,+1/2) or in stare spin-down (1,0,0,-1/2).

Recapitulare

Numar cuantic	Simbol	Valori permise	Descrie/cuantifica
Principal	n	1,2,3,…	Distanta fata de nucleu/energia totala
Orbital	l	0,1,2…,(n-1)	Momentul cinetic orbital
Magnetic orbital	m_l	0,±1, ±2,…, ±l	Componenta z a momentului cinetic orbital
Spin	s	1/2	Momentul cinetic de spin
Magnetic de spin	m_s	±1/2	Componenta z a momentului cinetic de spin

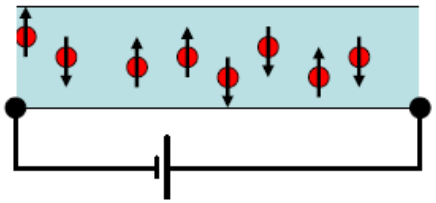
SPINTRONICS

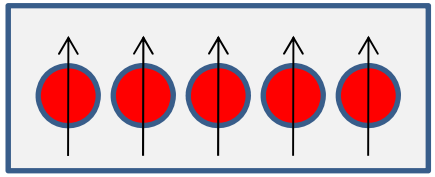


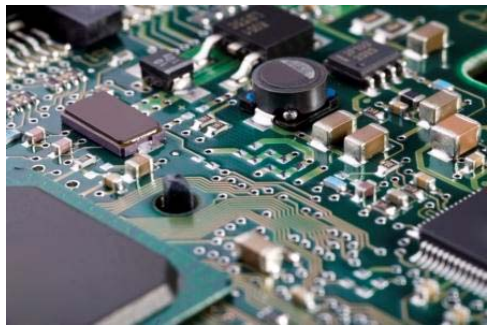
Electron = charge + spin

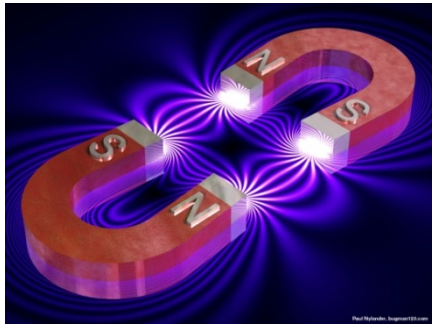
electronics

magnetism







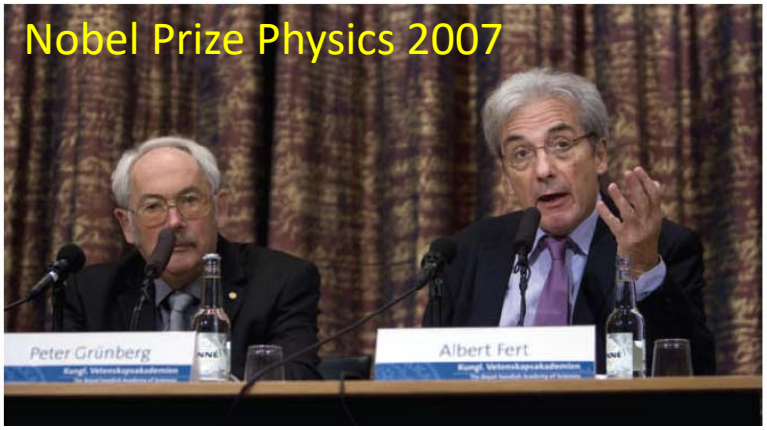


Purpose of spin-electronics:

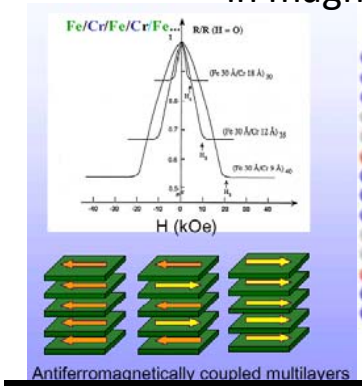
combine electronics and magnetism in order to make new devices
in which both the charge and the spin of the electron play an active role

``Teaching electrons new tricks´´ by manipulating the electron spin in solid state electronic devices…

SPINTRONICS: excellence research area



1988: The giant magnetorezistance (GMR)
in magnetic multilayers



Baibich et al. Phys. Rev. Lett. 61 (1988) 2472
G. Binash et al., Phys. Rev. B, 39, 4828 (1989)

HDD read heads

Magnetic field sensors

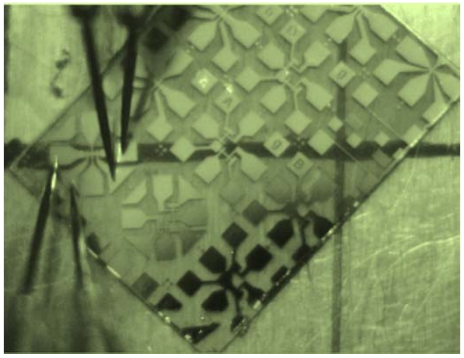
Race track

Non volatileMRAM

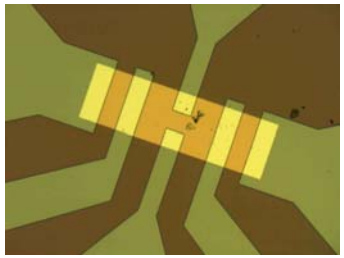
Spin transfer

Microwave generation,
High frequency oscillators

❑ SPINTRONIC DEVICES

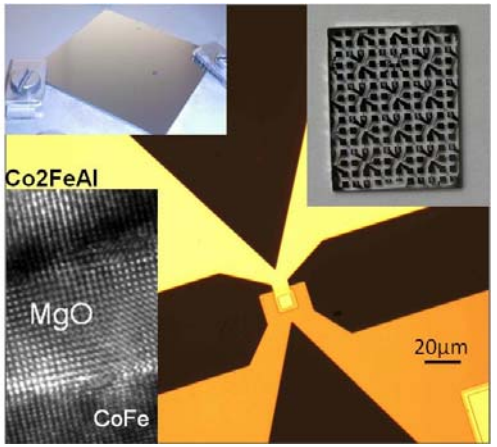


CIP

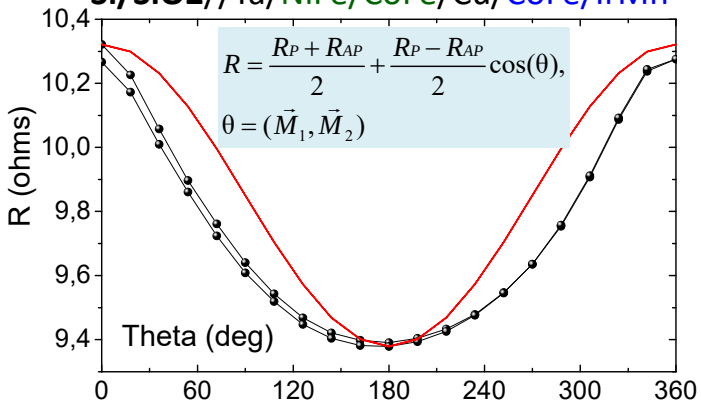


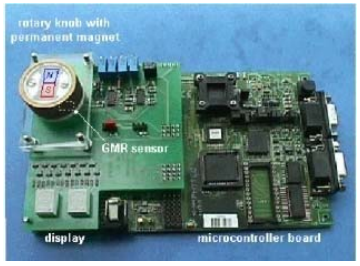
- Sensors : field, position (compass, ABS ,…)
- Read heads HDD
- Nonvolatile memories
- HF oscillators
- Logic elements…

CPP

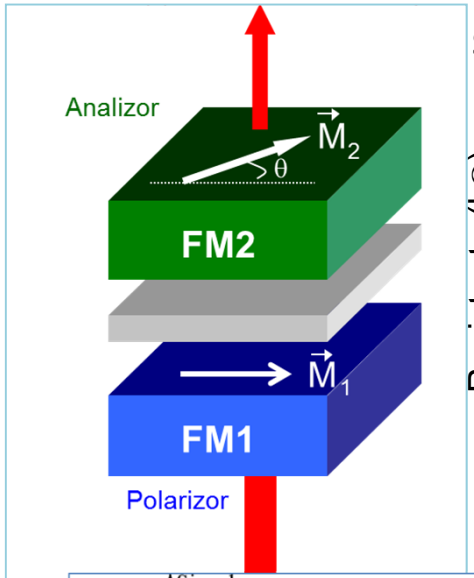


Si/SiO2//Ta/NiFe/CoFe/Cu/CoFe/IrMn

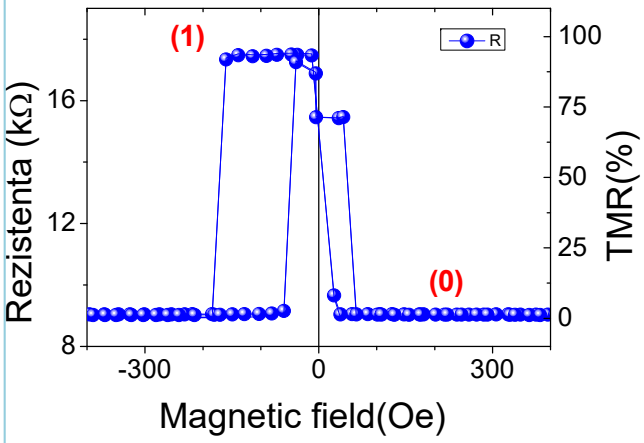


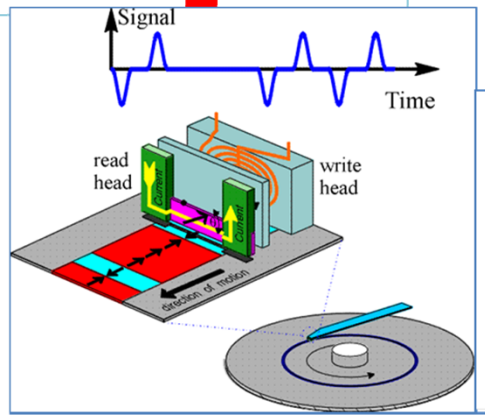


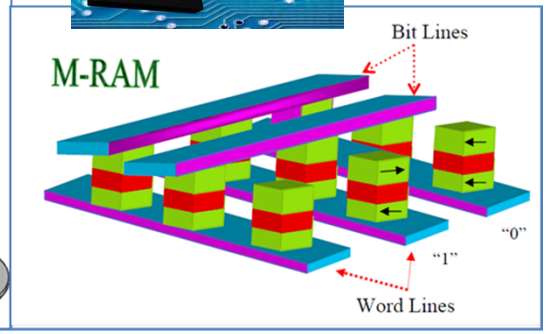
Current I=f(θ)- spin valve effect



Si/SiO2//Ta/Co2FeAl/MgO/CoFe/IrMn







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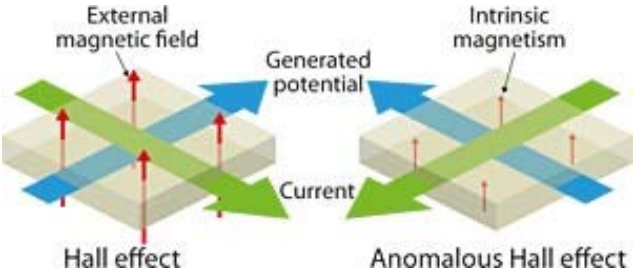
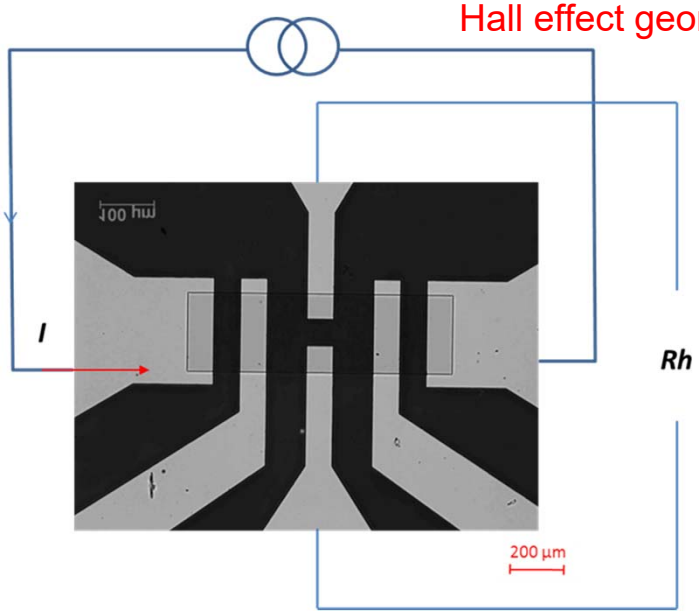
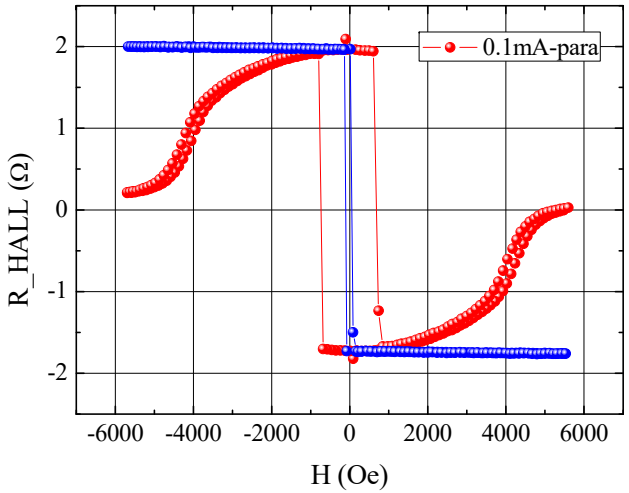
SPINTRONICS at TUC-N

AHE in perpendicular magnetization films

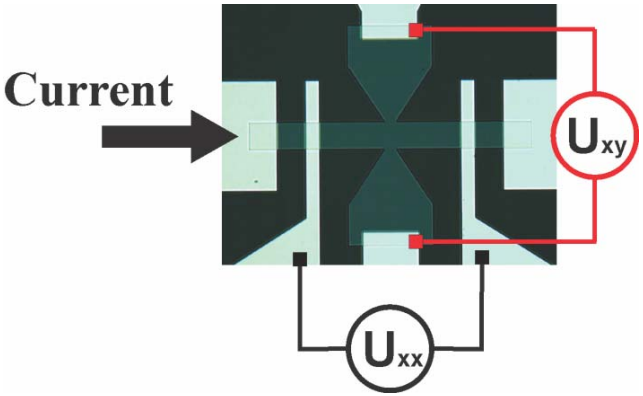


Hall effect geometry

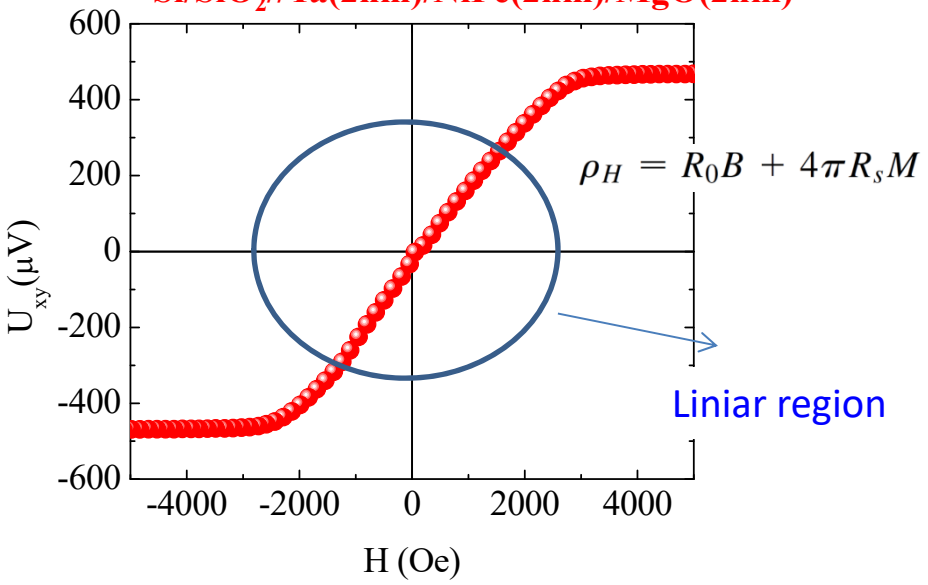




U(xy) and R_H~ perpendicular component of magnetization



Si/SiO_2//Ta(2nm)/NiFe(2nm)/MgO(2nm)



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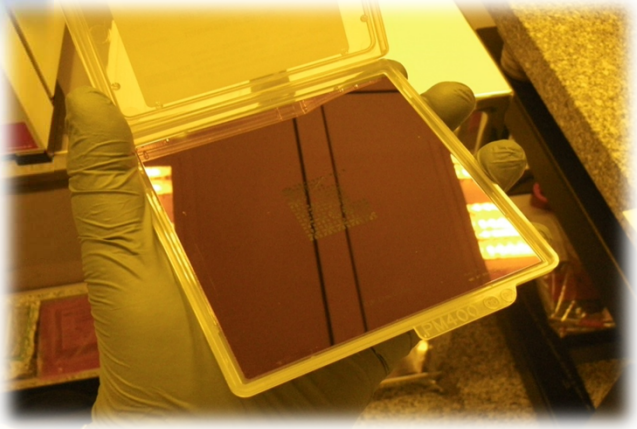
Cod SMIS-CSNR: 12467

TOP-DOWN **Micro and Nanotechnologies**

TECHNICAL UNIVERSITY OF CLUJ-NAPOCA

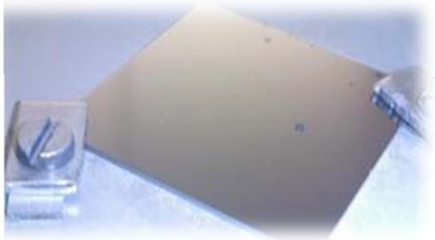
Clean room facilities (100 class)

- Optical lithography (MBJ4 SUSS mask aligner)
- Ion Beam Etching assisted by Auger spectroscopy
- Nanolithography facilities available in the chemistry lab

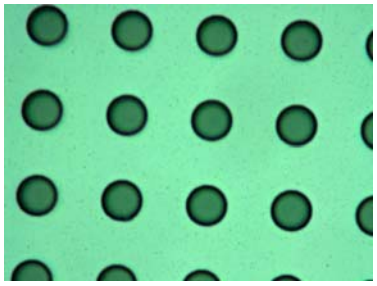


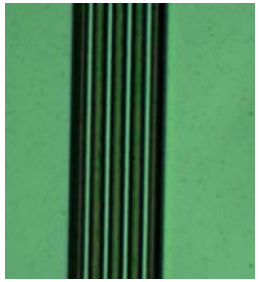
TOP-DOWN

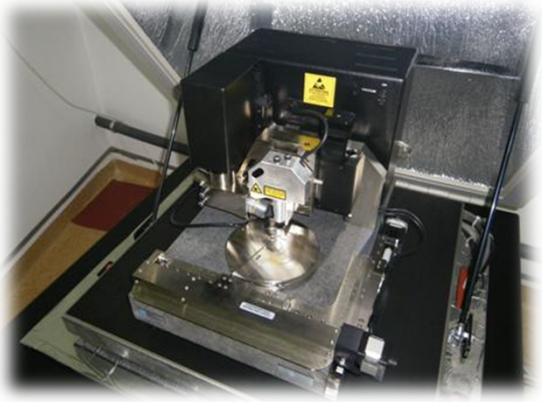
From continuous thin films to micro and nanostructures
3D (x, y, z) reducing of dimensionality



> 1 μm MICRO -LITHOGRAPHY

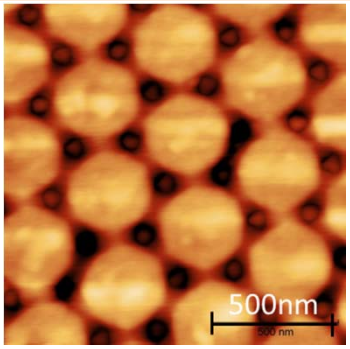




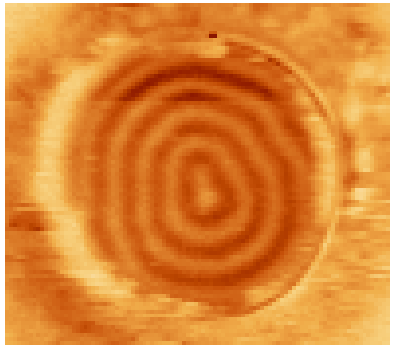


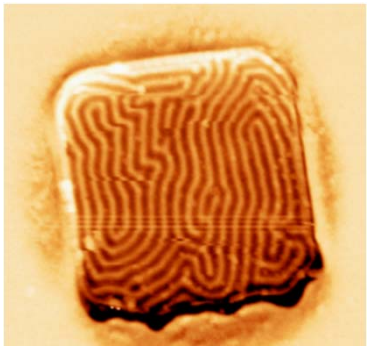
Atomic/Magnetic Force Microscopy

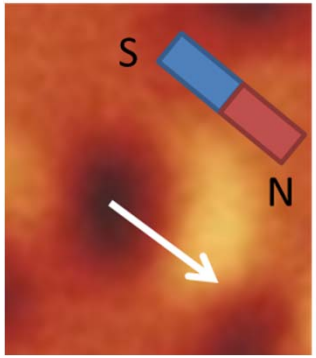
< 1 μm NANO -LITHOGRAPHY

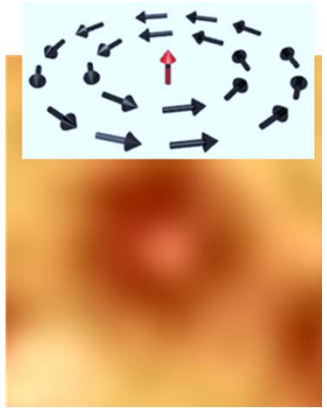


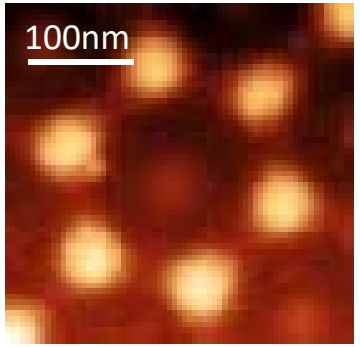
- Magnetic structures with tailored magnetic properties via shape and dimensionality





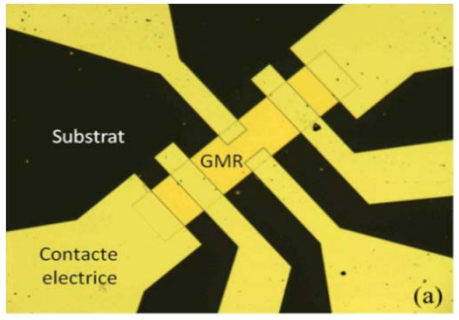


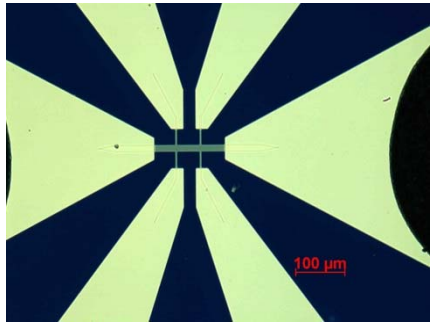




- Spintronic devices

Co nano- dots





- Nano-engineering of magnetic properties
  - nonvolatile data storage
  - nano-oscilators with adjustable frequency
- Nano centers for vortex pinning in superconducting films

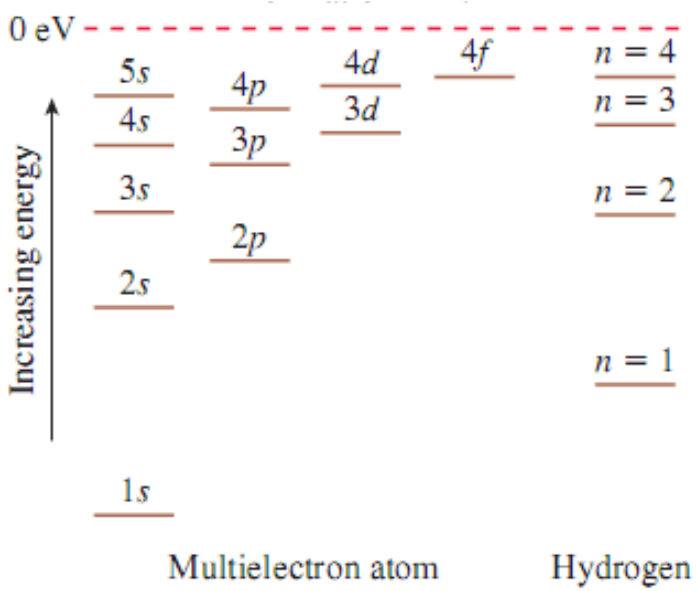
Atomii cu mai multi electroni. Principiul lui Pauli.

Modul de asezare al electronilor intr-un atom poarta poarta numele de configuratie electronica

Configuratia electronica se poate determina daca se tine seama de urmatoarele doua principii:

1. **principiul lui Pauli** intr-un atom sau sistem atomic nu poate exista decat un singur electron caracterizat de acelasi grup de 4 numere cuantice n, l , m , si ms.
2. Un sistem de particule este stabil atunci cand energia sa este minima.

$$E_n = -\frac{1}{(4\pi\epsilon_0)^2}\frac{m_r Z^2 e^4}{2n^2\hbar^2} = -\frac{Z^2}{n^2}(13.6\text{ eV})$$

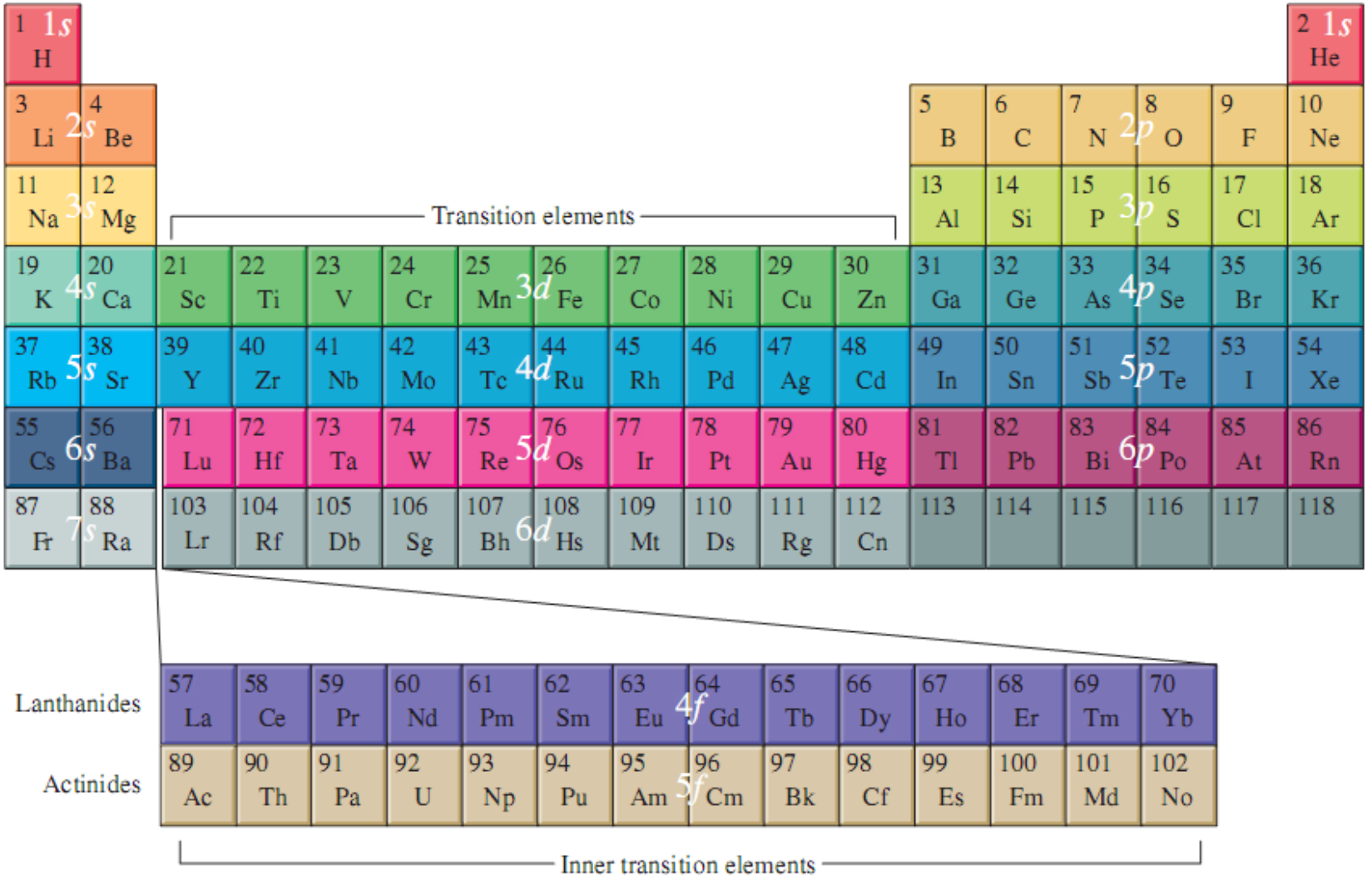


Regulile lui Hund:

1. electronii tind sa evite situarea pe acelasi orbital
2. doi electroni situati pe orbitali diferiti dar echivalenti au spiniparaleli in starea fundamentala , starea cu cea mai joasa energie .prin urmare ordinea de ocupare a subpaturilor electronice este urmatoarea 1s,2s,2p,3s,3p,4s,3d,4p,5s,4d,,5p,6s,4f,5d,6p.

Sistemul periodic al elementelor(Mendeleev in 1869)

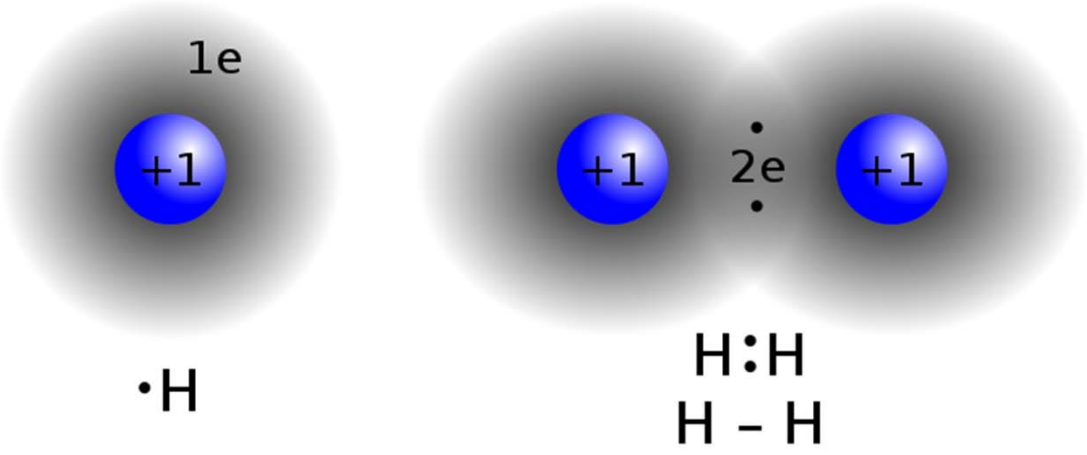
- sucesiune a elementelor dupa masa atomica si asemanarile chimice.
- Mendeleev a aratat ca atunci cand aranjam elementele in numarului atomic Z proprietatile lor fizice si chimice se repeta periodic. Periodicitatea in proprietatile elementelor se explica prin faptul ca electronii se dispun in paturi si subpaturi de un anumit fel.

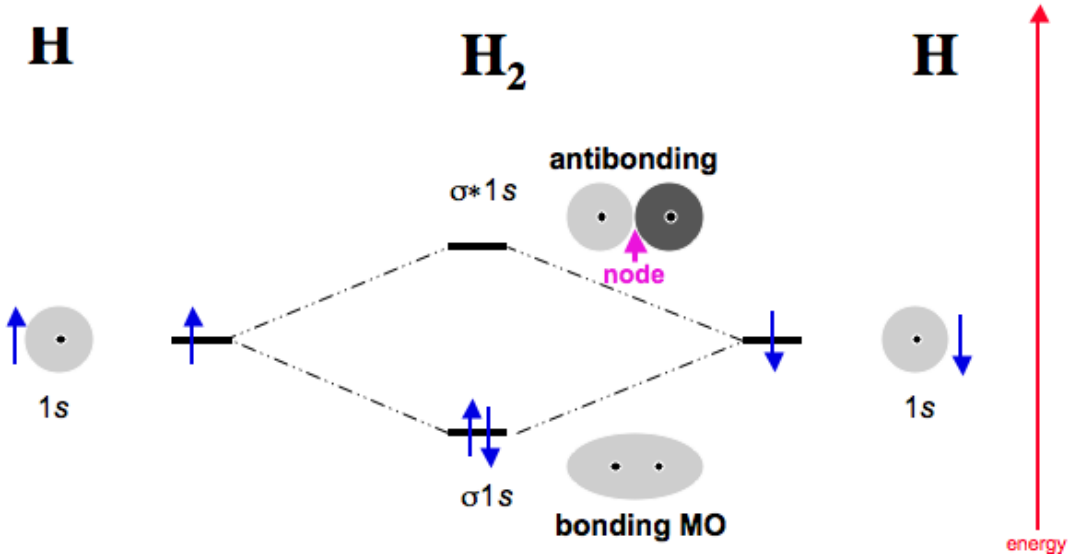


De la atom la molecula si corp solid

Atom

Apropiere => Interactiune



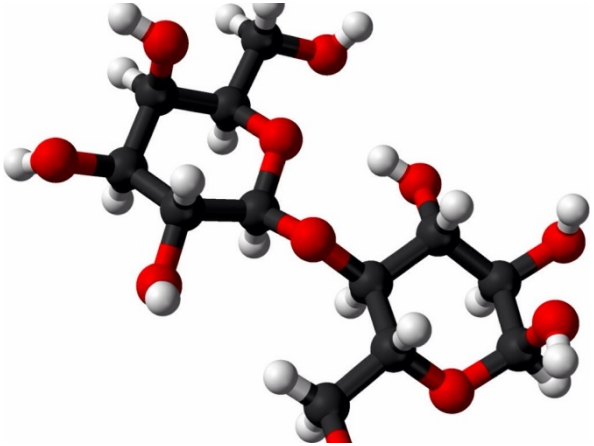


Molecula diatomica:

Nivelele atomice se despica in doua

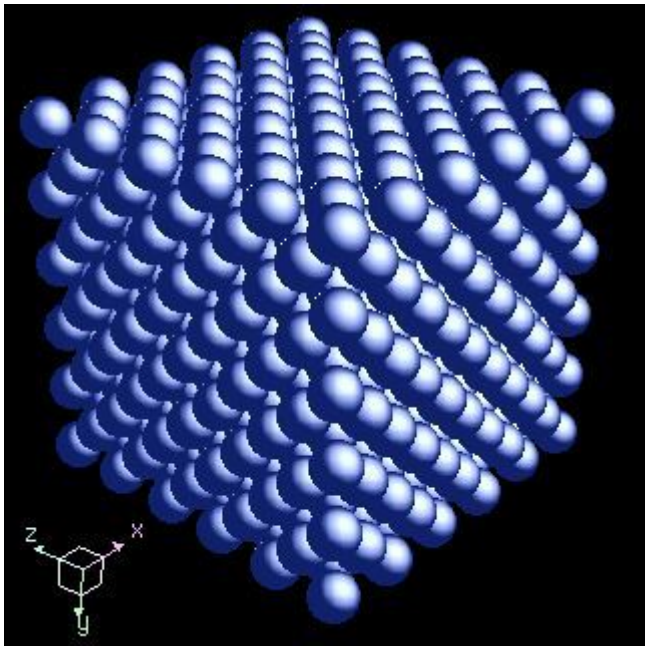
- ❑ Orbital de legatura
- ❑ Orbital de antilegatura

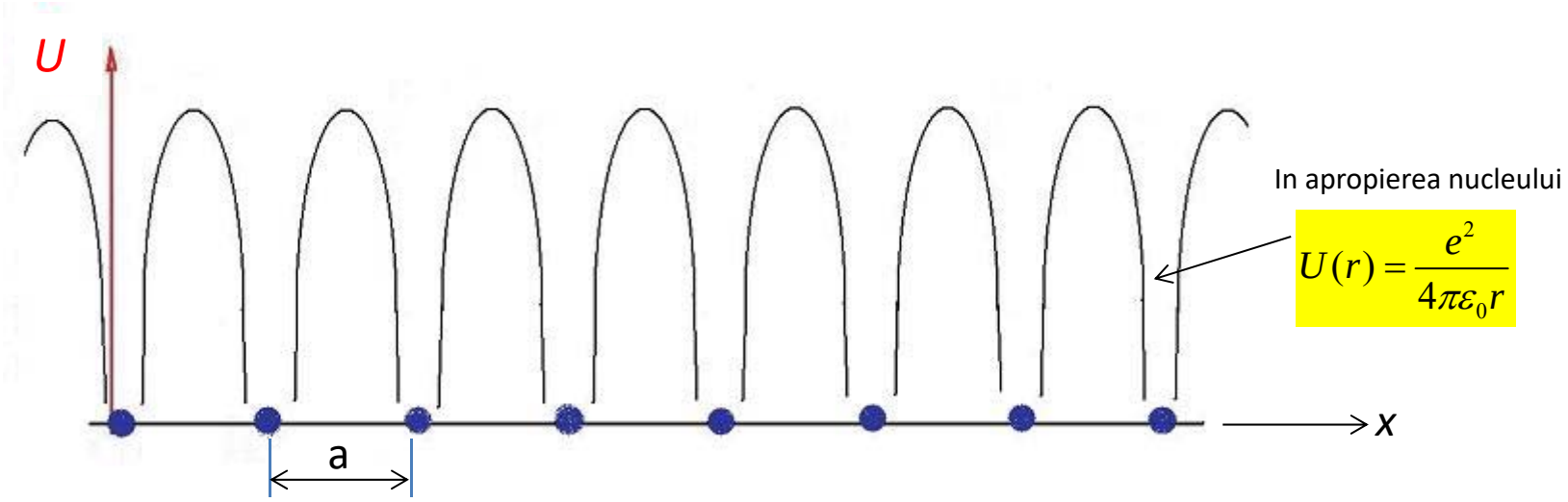
De la macromolecule la cristale



Cristal: structura periodica

- Atomi in interactiune
- Electroni in potential periodic





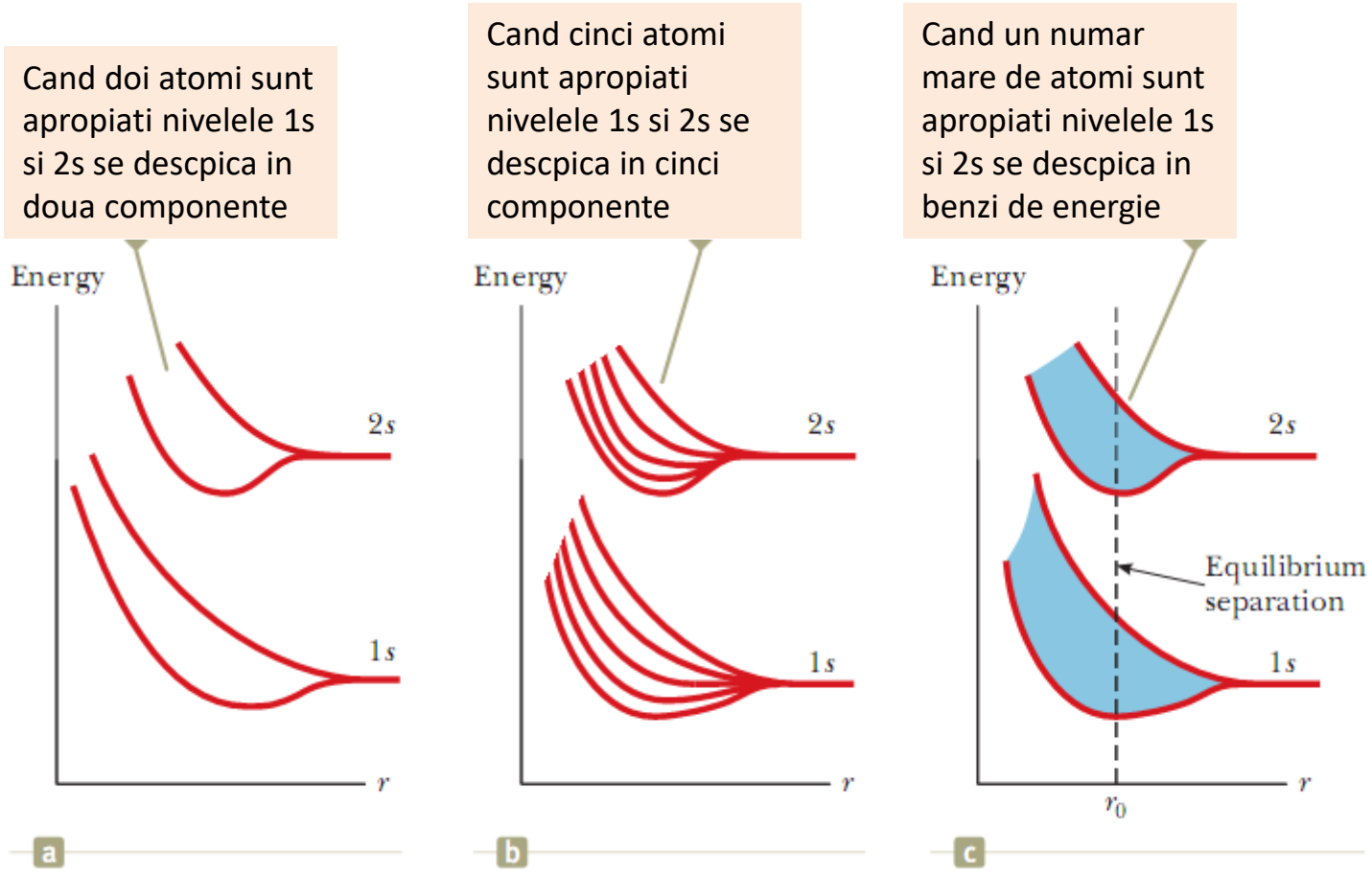
In apropierea nucleului

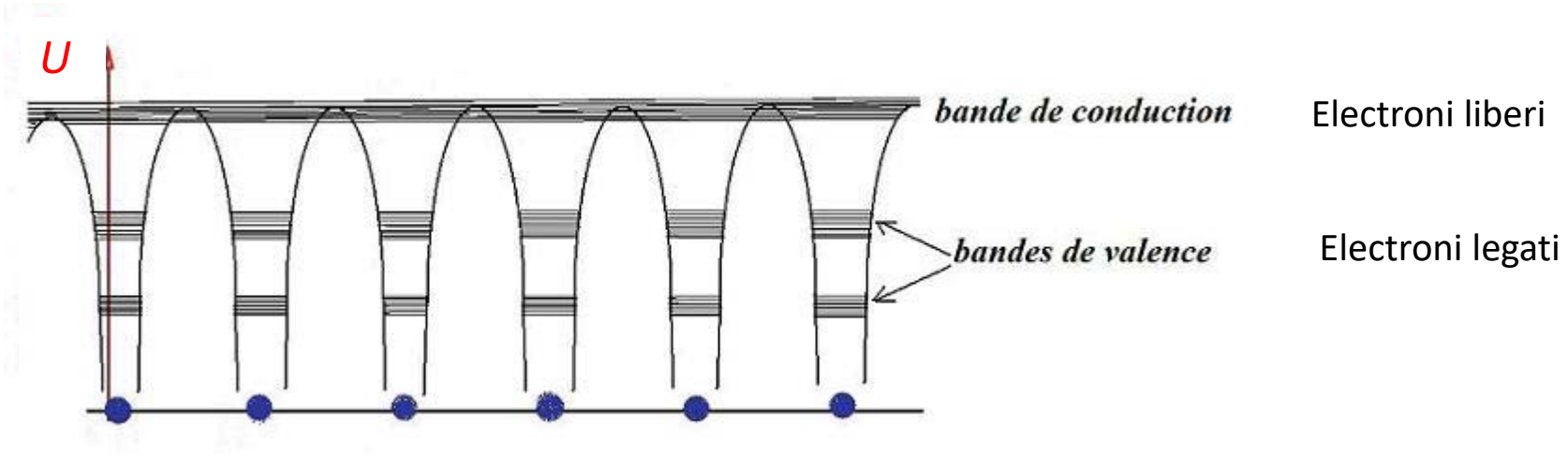
$$U(r) = \frac{e^2}{4\pi\varepsilon_0 r}$$

U(x)=U(x+a)

Originea benzilor de energie in solide

Cand distanta r_0 dintre atomi descreste si apare interactiunea nivelele de energie se largesc in benzi. Lina punctata verticala indica distanta interatomica in cristal.





BENZI DE VALENTA

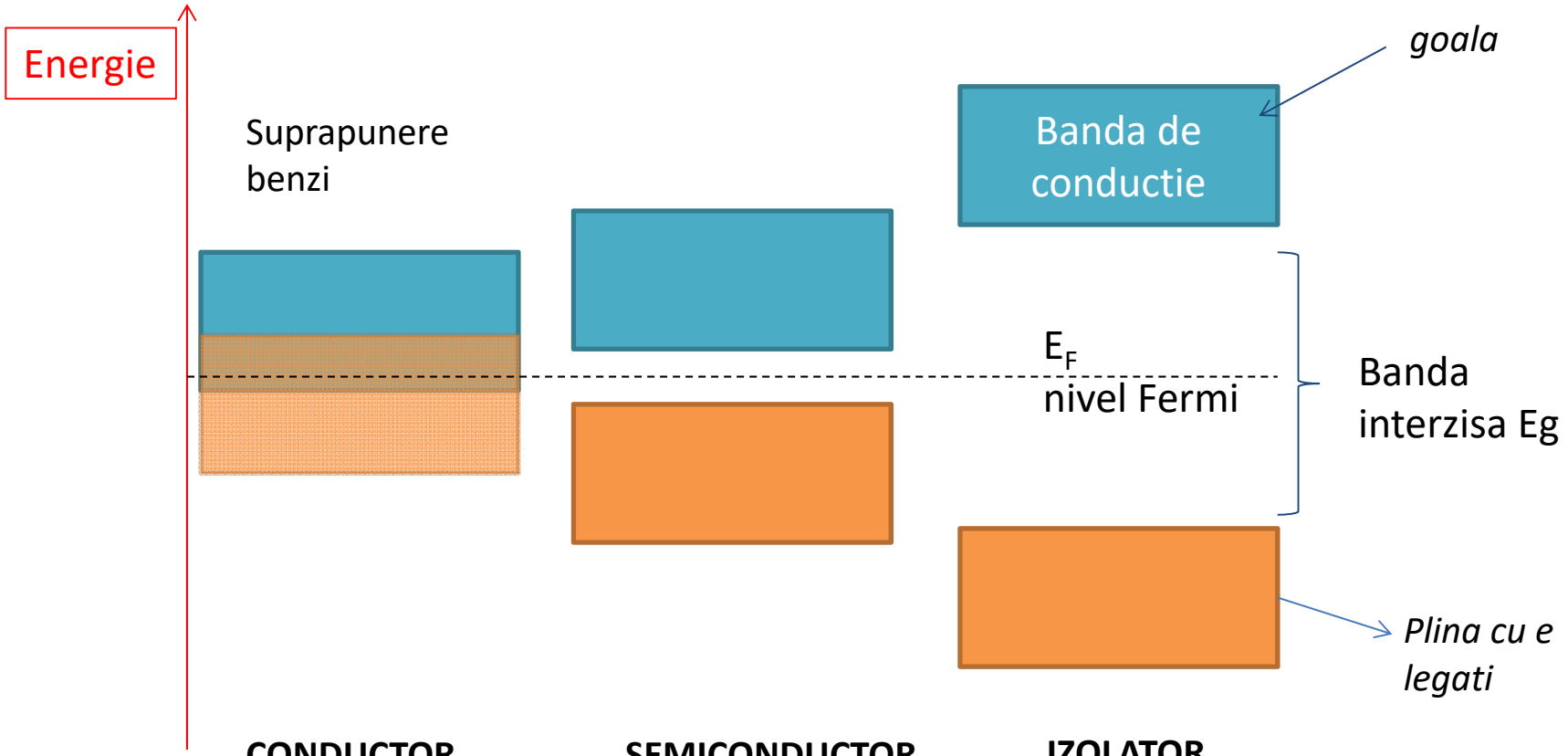
Benzile din gropile de potential de simetrie sferica din jucrul atomului contin electroni legati de nuclee care nu participa la conductie (nu se pot deplasa intre atomi), nu raspund la un stimul extern si nu confera proprietatile cristalului.

BENZI DE CONDUCTIE

Benzile aproape de varful gropilor de potential participa la conductie (se pot deplasa intre atomi) si raspund la stimuli externi.

Intre benzile de energie permise intr-un cristal exista **benzi interzise**.

Clasificarea solidelor in metale, semiconductoare, izolatoare



CONDUCTOR

BC, BV se suprapun
Electroni liberi disponibili pentru conductie

SEMICONDUCTOR
Eg<2 eV

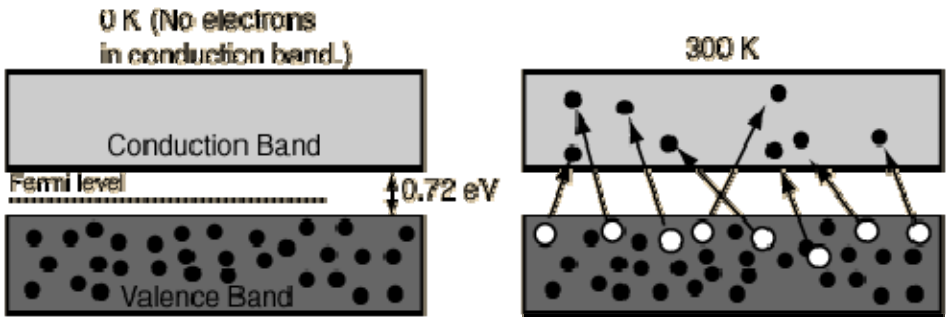
BC, BV separate de banda interzisa
e- pot fi activati termic din BV in BC si participa la conductie

IZOLATOR
Eg=2-9eV

BC, BV separate de banda interzisa larga
E- **NU** pot fi activati termic din BV in BC

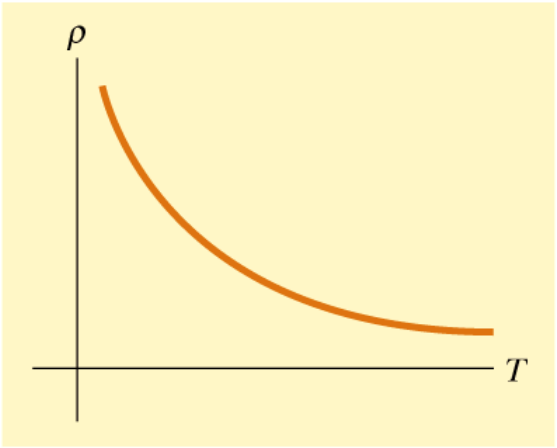
Dependenta rezistivitatii electrice cu temperatura

Semiconductor

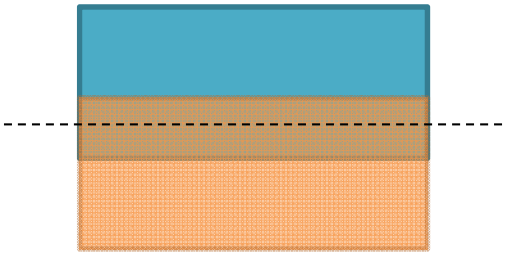


$$n = n_0 e^{\frac{E_g}{2k_B T}}$$

Numarul de purtatori din BC creste exponential cu temperatura (activare termica) => conductivitatea creste (rezistivitatea scade) exponential cu cresterea T

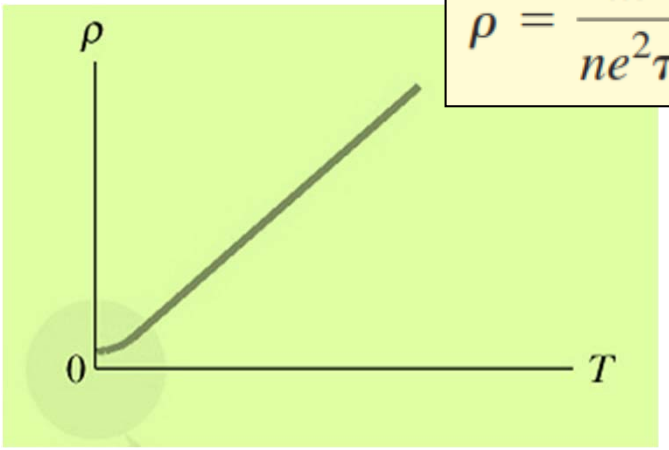


Metal



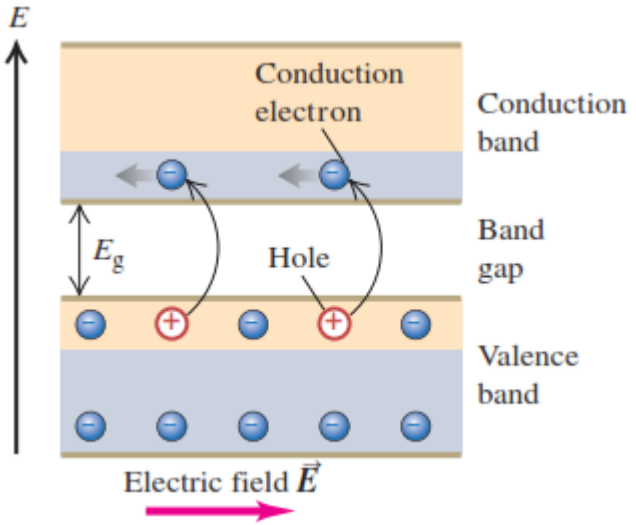
Numarul de purtatori din BC este constant cu T => conductivitatea scade liniar cu T datorita cresterii probabilitatii de ciocnire a electronilor cu reteaua cristalina (scaderea liberului parcurs mediu)

$$\rho = \frac{m}{ne^2\tau}$$



Clasificarea semiconductorilor

Intrinseci (puri)



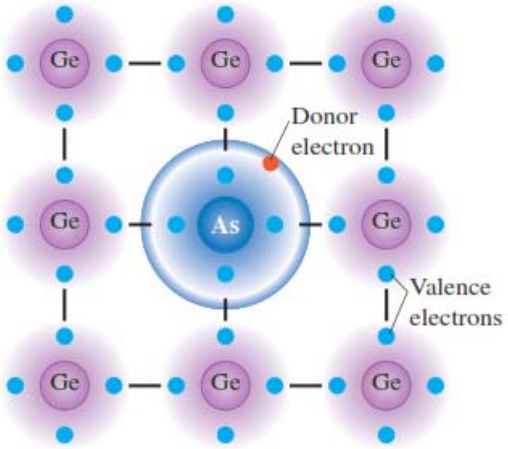
Conductia se face prin electroni in BC
si absenta electronilor (goluri) in BV
insa intr-un SC intrinsec densitatea de purtatori este mica

Table 43.3 Energy-Gap Values for Some Semiconductors

	E_g (eV)	
Crystal	**0 K**	**300 K**
Si	1.17	1.14
Ge	0.74	0.67
InP	1.42	1.34
GaP	2.32	2.26
GaAs	1.52	1.42
CdS	2.58	2.42
CdTe	1.61	1.56
ZnO	3.44	3.2
ZnS	3.91	3.6

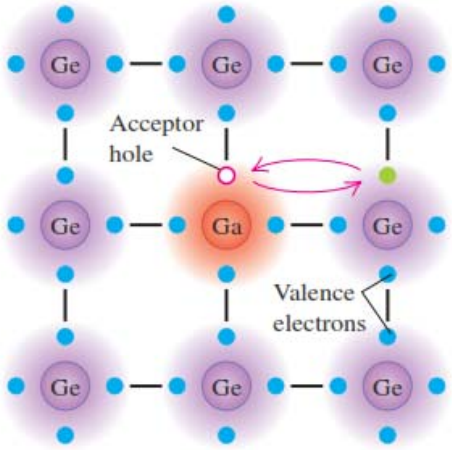
Extrinseci (dopati cu impuritati)

Donoare
=> Tip ***n***
e- purtatori
majoritari



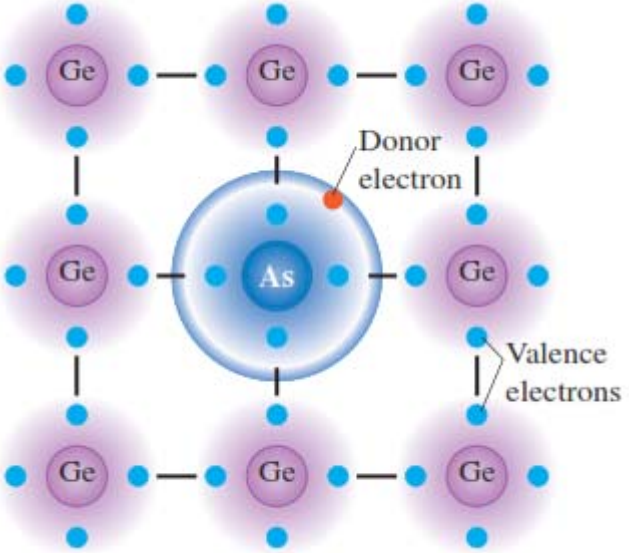
As -> extraelectron

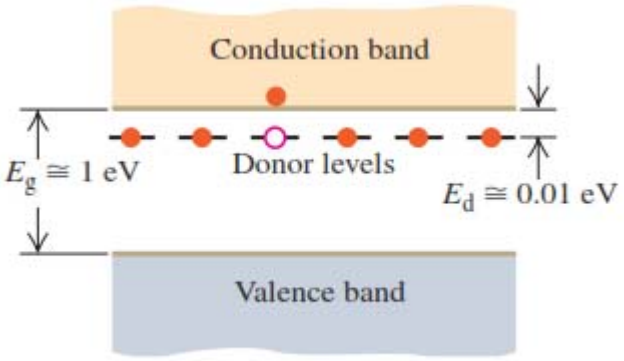
Acceptoare
=> Tip ***p***
goluri
purtatori
majoritari

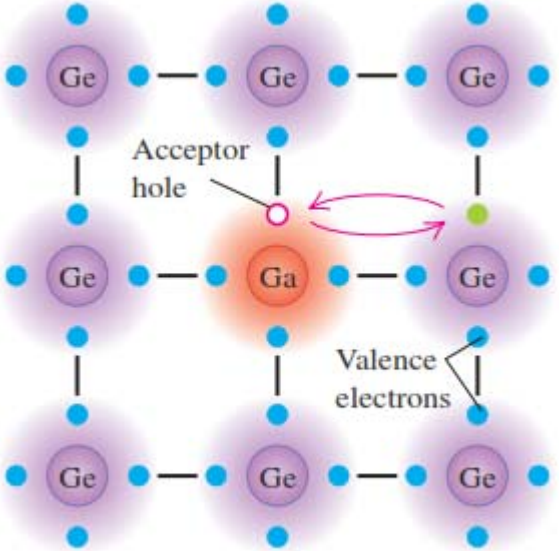


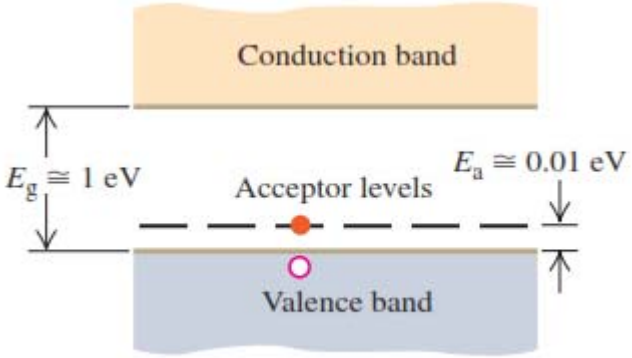
Ga -> un e- in minus

Prin dopare se adauga nivele de energie donoare (tip n) sau acceptoare (tip p) in banda interzisa







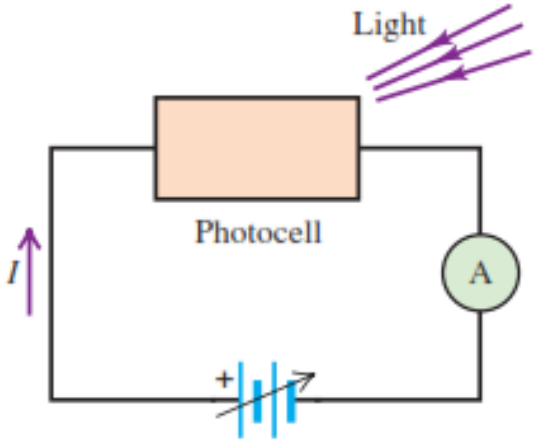


Astfel, prin dopaj/modularea numarului de purtatori (electroni sau goluri) se controleaza proprietatile electrice ale semiconductorului.

Dispozitive electronice semiconductoare

Sunt dispozitive care realizeaza anumite dependente functionale intre marimile electrice, - curenti si tensiuni, prin mecanismul conductiei electrice in medii semiconductoare, adecvat dopate cu impuritati (diode, tranzistori, etc…).

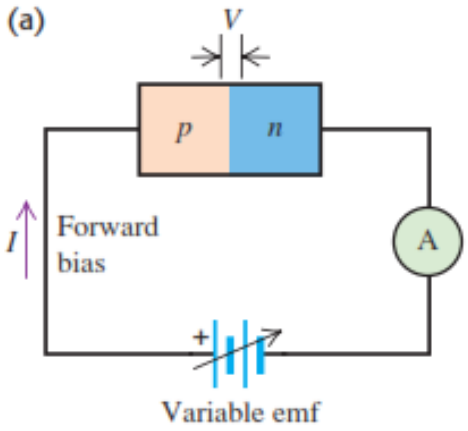
Fotocelula

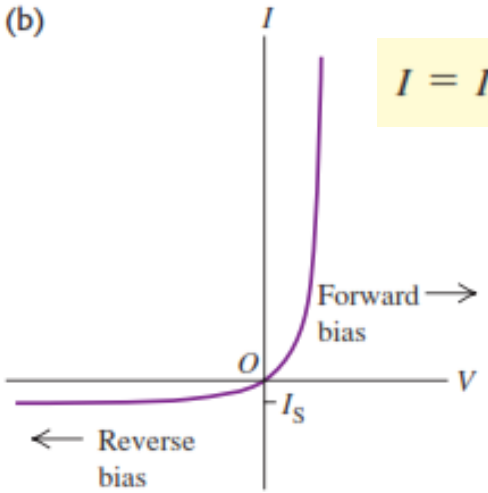


Realizata ditr-un strat subtire semiconductor

La iluminare, cand energia fotonilor incidenti devinse superioara Eg dintre BV si BC in BC se activeaza electroni care duc la aparitia unui curent electric (efect fotoelectric extern)

Jonctiunea pn

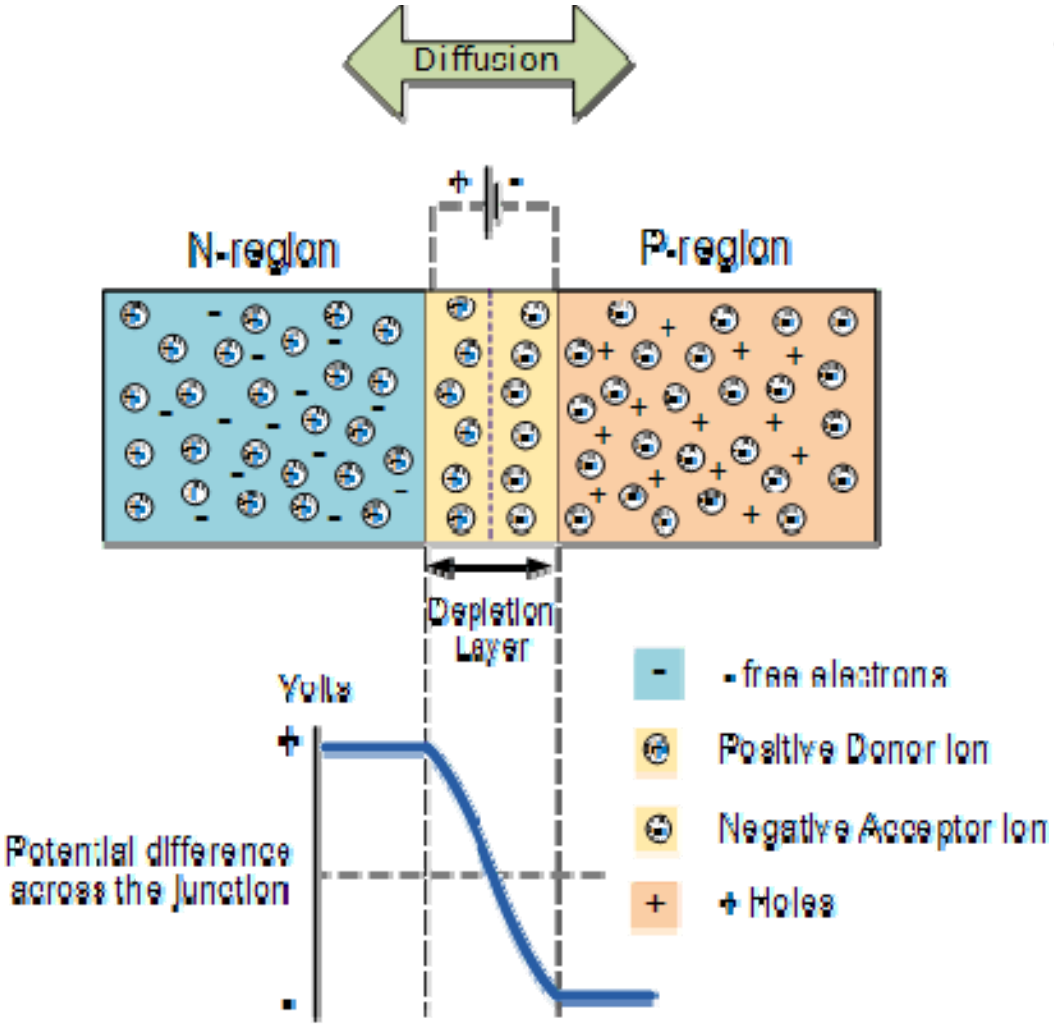




$$I = I_S(e^{eV/kT} - 1)$$

Caracteristica de redresare

Depletion region – built-in potential difference



This electric field created by the diffusion process has created a "built-in potential difference" across the junction with an open-circuit (zero bias) potential of:

$$E_o = V_T \ln\left(\frac{N_D \cdot N_A}{n_i^2}\right)$$

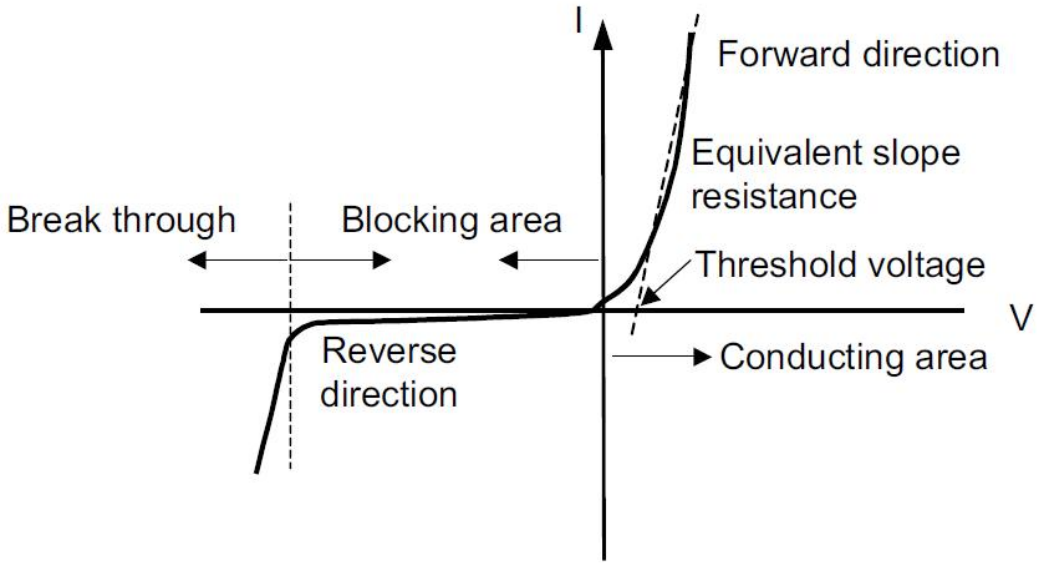
E_o is the zero bias junction voltage, V_T the thermal voltage of 26mV at room temperature (k_BT), N_D and N_A are the impurity concentrations and n_i is the intrinsic concentration.

- Typically at room temperature the voltage across the depletion layer for:
  silicon is about 0.6 – 0.7 volts
  germanium is about 0.3 – 0.35 volts.

This potential barrier will always exist even if the device is not connected to any external power source.

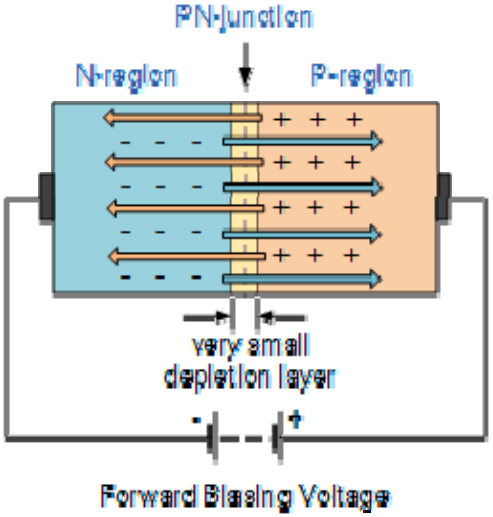
- The significance of this built-in potential across the junction, is that it opposes both the flow of holes and electrons across the junction and is why it is called the **potential barrier**. In practice, a **PN junction** is formed within a single crystal of material rather than just simply joining or fusing together two separate pieces.

- The result of this process is that the PN junction has **rectifying current–voltage (IV or I–V) characteristics**. Electrical contacts are fused onto either side of the semiconductor to enable an electrical connection to be made to an external circuit. The resulting electronic device that has been made is commonly called a PN junction Diode or simply Signal Diode.



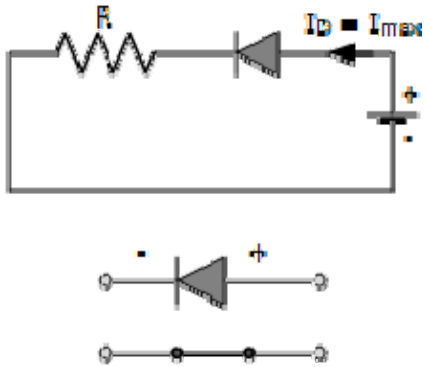
Forward Biased PN Junction Diode

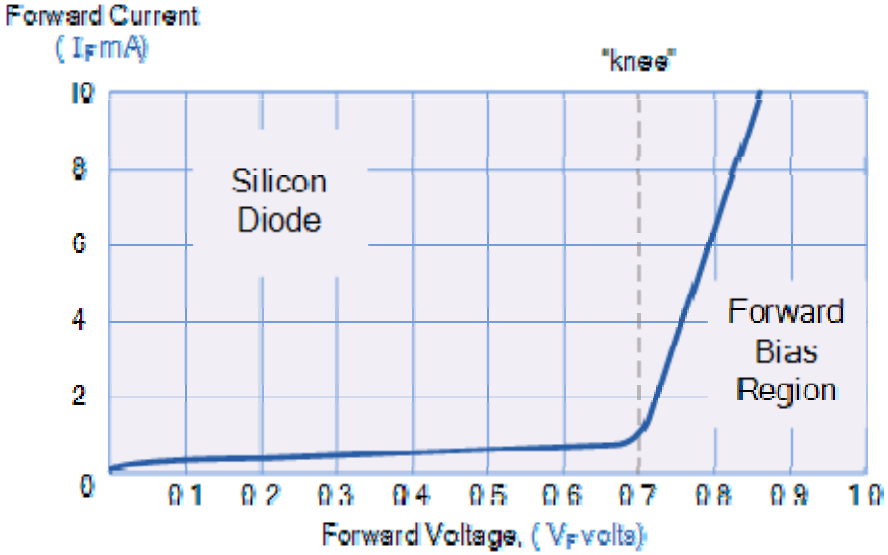
Negative voltage is applied to the **N-type** material and a **positive voltage** is applied to the **P-type** material. If this external voltage becomes greater than the value of the potential barrier, (Si: 0.7 V, Ge: 0.3 V), the potential barriers opposition will be overcome and current will start to flow.



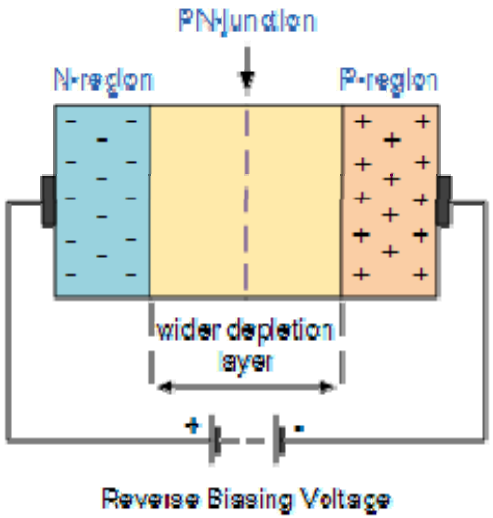
because the negative voltage pushes or repels electrons towards the junction giving them the energy to cross over and combine with the holes being pushed in the opposite direction towards the junction by the positive voltage. This results in a characteristics curve of zero current flowing up to this voltage point, called the “knee” on the static curves and then a high current flow through the diode with little increase in the external voltage as shown below.

Reduction in the Depletion Layer due to Forward Bias





Reverse Biased PN Junction Diode



A positive voltage is applied to the N-type material and a negative voltage is applied to the P-type material.

The positive voltage applied to the N-type material attracts electrons towards the positive electrode and away from the junction, while the holes in the P-type end are also attracted away from the junction towards the negative electrode.

The net result is that the depletion layer grows wider due to a lack of electrons and holes and presents a high impedance path, almost an insulator. The result is that a high potential barrier is created thus preventing current from flowing through the semiconductor material.

Increase in the Depletion Layer