

JUNCTIONS

I. HARNESSING ELECTRICAL CONDUCTIVITY IN SEMICONDUCTOR MATERIALS

Intrinsic conductivity (Pure silicon)

Extrinsic conductivity (Silicon doped with selected different atoms)

II. ENERGY LEVELS DIAGRAM

p-material, n-material

Diode: p and n materials placed together

III. CHEMICAL POTENTIAL (FERMI LEVEL)

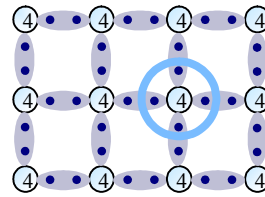
IV. COMPARISON of CHARGE-CARRIER POPULATION at EACH SIDE of the JUNCTION

V. FORWARD BIAS, REVERSE BIAS

I. HARNESSING ELECTRICAL CONDUCTIVITY IN SEMICONDUCTOR MATERIALS

Let's take Silicon as a typical example of semiconductor material. A **Silicon** atom has 4 valence electrons. Joined by covalent bonds, Si atoms form a lattice structure constituted by two interpenetrating periodic fcc lattices, having 5×10^{22} Si-atoms/cm³ (8 atoms in a cube of side 5.43 Angstroms).

At zero temperature **Silicon** is an **insulator** because all its valence electrons participate in the bonding. It lacks electrons that can wander free around the crystal structure.



At T = 0 K



Si: [Ne]3s²3p²

At T=0, conductivity $\sigma = 0$.

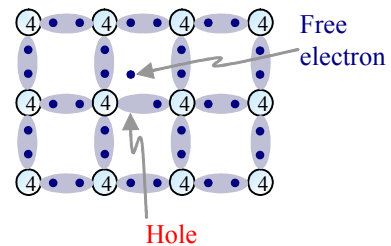
Intrinsic conductivity

Here we consider a Si material free of foreign atoms (just pure silicon atoms).

Thermal generation of conduction electrons

At room temperature ($kT \sim 0.025$ eV), thermal agitation of the crystalline host provides energy to electrons and there is a non-vanishing probability ($\sim e^{-E_g/2kT}$) that some of them will be able to break away from the ($E_g = 1.12$ eV) bonding and,

At T = 300 K



consequently, set almost “free” to wander around the crystal: they become *conduction electrons*. These electrons are able to participate in the conductivity of silicon under the presence of an external electric field.

A typical value of the concentration of conduction electrons generated in this manner, at room temperature, is $n_o \sim 1.4 \times 10^{10} \text{ e}^-/\text{cm}^3$.

Generation of holes

Notice that the creation of a new conduction electron leaves their Si atoms with one bonding vacancy. This **bonding vacancy** is called a “**hole**”.

Holes contribute to the conductivity. Indeed, under the presence of an external electric field, a bonded electron from a Si atom nearby will have a tendency to fill-in this bonding vacancy (the fact that the Si atom hosting the hole is a positive ion helps the process) and needs very little energy to do that. When that happens a new hole (with its associated positive ion) is left behind, which triggers the creation of another hole, and so on. The net result: a net positive charge is transported along the filling of holes.

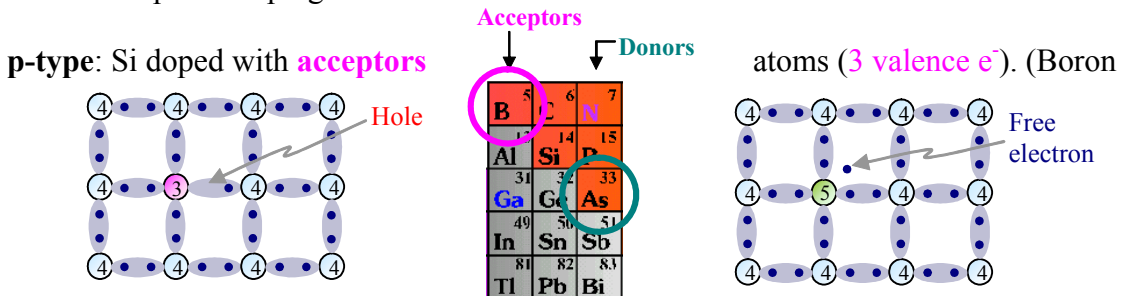
Since a hole is created simultaneously with a conduction electron, the concentration of holes p_o equals the concentration of electrons: $p_o = n_o$. This situation could be changed if selected foreigner atoms are introduced in the silicon crystalline structure.

Extrinsic conductivity

n-type: Si crystal doped with **donor** atoms (5 e^- in their valence shell).

Four e^- participate in the bonding with Si atoms, while the fifth becomes almost free of any bonding. With a little bit of energy this fifth e^- becomes free to wander around the entire silicon material.

Example of doping level:

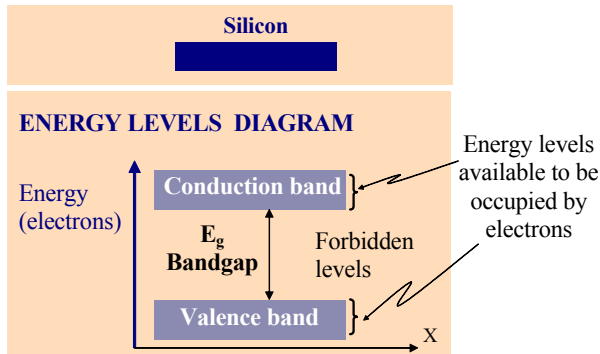


atoms, for example).

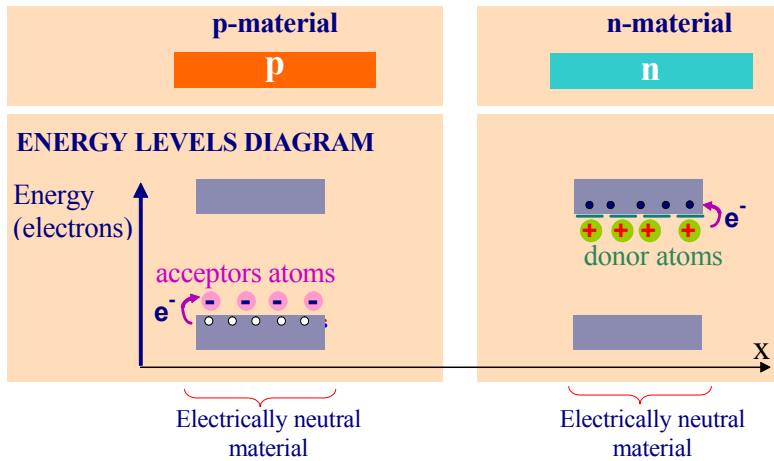
The three e^- participate in the bonding with Si atoms, creating a bond vacancy to be filled-in, that is, acceptor atoms create **holes**, which participate in the conductivity (as explained above).

So, the presence of donors and acceptors increases the electrical conductivity of the material.

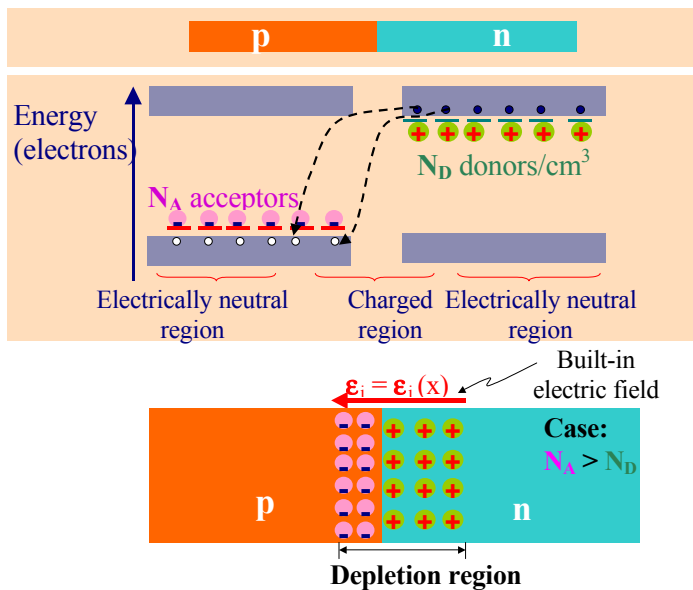
II. ENERGY LEVELS DIAGRAM



p-material and n-material



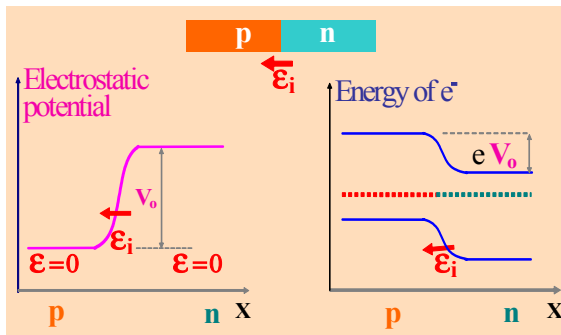
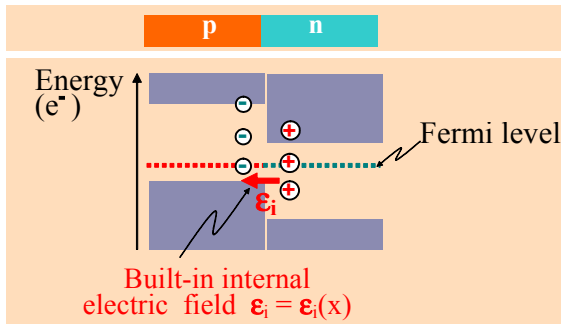
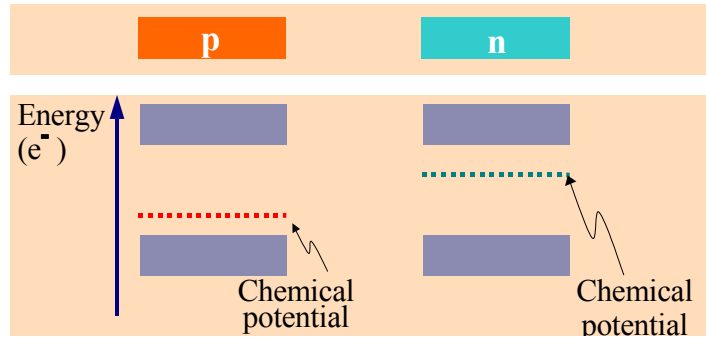
Materials placed together



When the **p** and **n** samples are placed together, electrons and holes diffuse and recombine, leaving behind unbalanced negative and positive regions that end up constituting what is called the depletion region.

III. CHEMICAL POTENTIAL (FERMI LEVEL)

At temperature T , semiconductor materials are characterized by their Chemical Potential, an energy level located somewhere in the band-gap; its exact location depending on the doping (acceptors and donors) concentrations.



When the materials are joined, electrons diffuse from n to p (leaving behind unbalanced positive donor ions) and recombine with hole in the p region (thus creating negative acceptor ions). Holes diffuse from p to n. While diffusion takes place, an electric field build-up that opposes the diffusion process. When equilibrium is reached a single Fermi level characterizes the whole system (the p-n junction).

IV. Comparison of charge-carrier population at each side of the junction

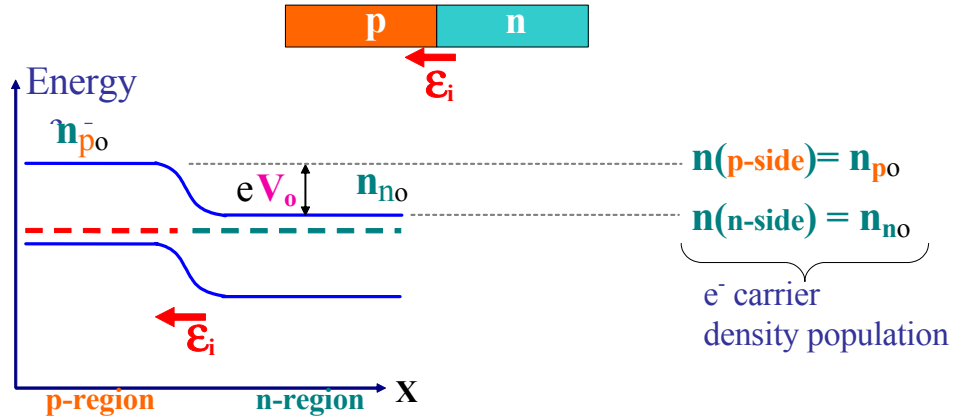
n_n : concentration of e^- in the n-side

n_p : concentration of e^- in the p-side

p_n : concentration of holes in the n-side

p_p : concentration of holes in the p-side

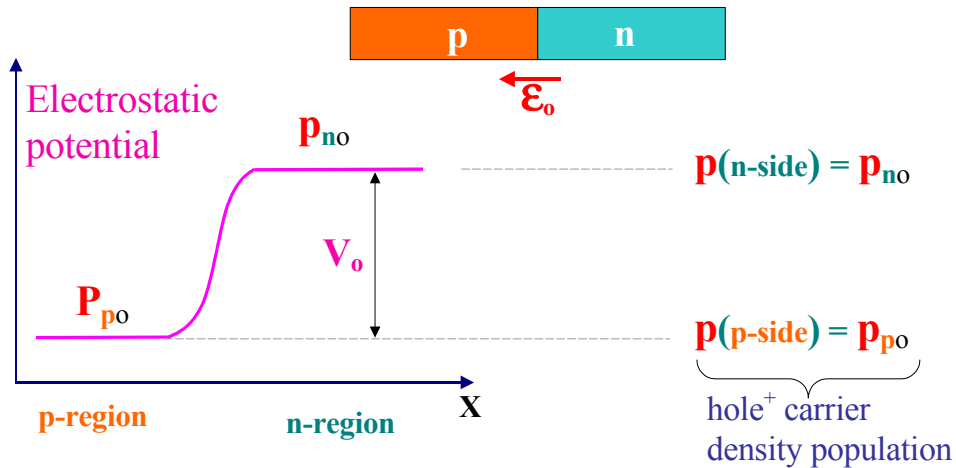
The sub-index $_0$ stands for “values when the system is in equilibrium”



From thermodynamics considerations:

$$n_{po} = n_{no} e^{-qV_0/kT} \quad (1)$$

Similarly:



From thermodynamics considerations:

$$p_{no} = p_{po} e^{-qV_0/kT} \quad (2)$$

From 1 and 2 :

$$n_{p0} p_{p0} = n_{n0} p_{n0}$$

In other words: $n_o p_o$ (p-side) = $n_o p_o$ (n-side)

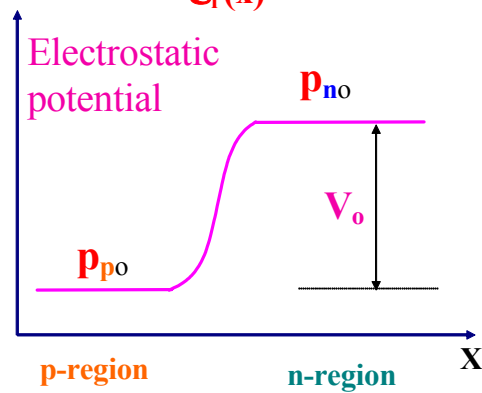
Minority and majority carriers

p_n : concentration of holes in the n-side p_p : concentration of holes in the p-side

The sub-index $_o$ stands for “values when the system is in equilibrium”



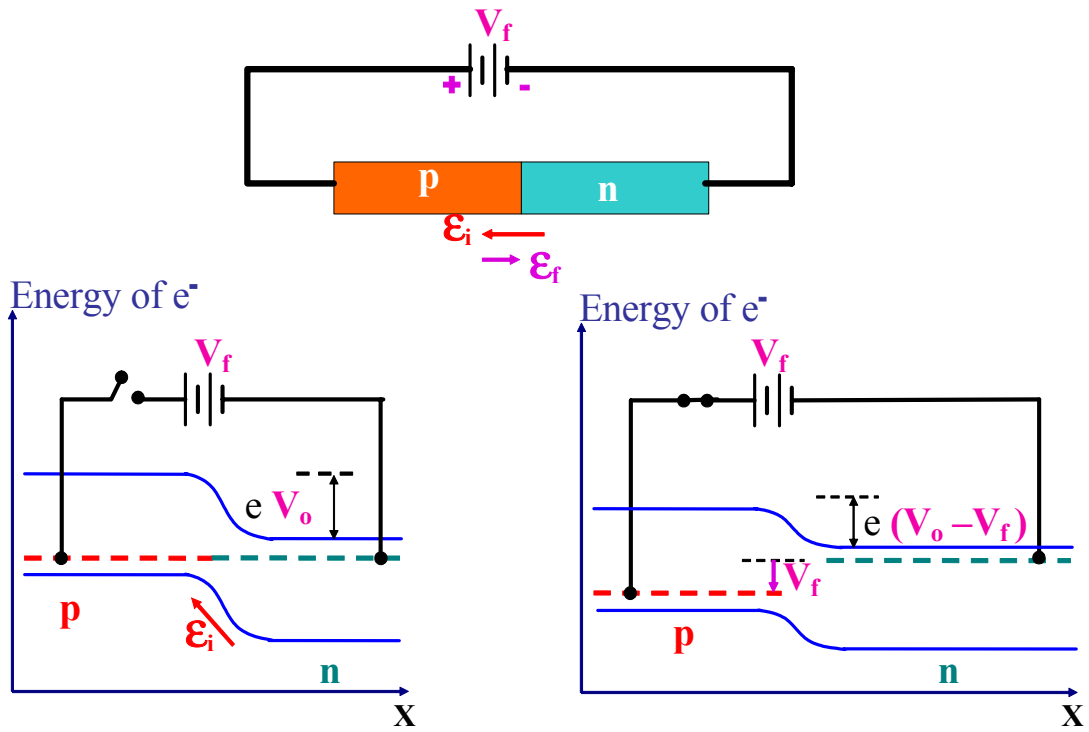
$$\vec{\epsilon}_i(x)$$



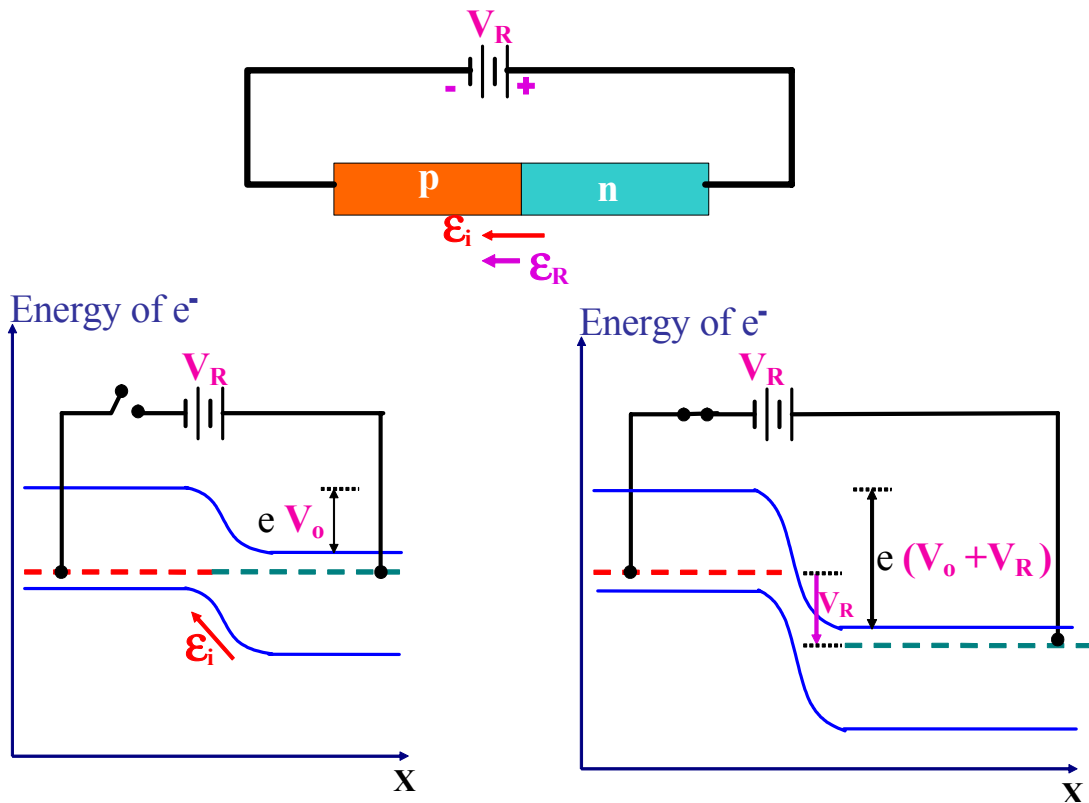
From thermodynamics considerations:

$$p_{n0} = p_{p0} e^{-qV_o/kT}$$

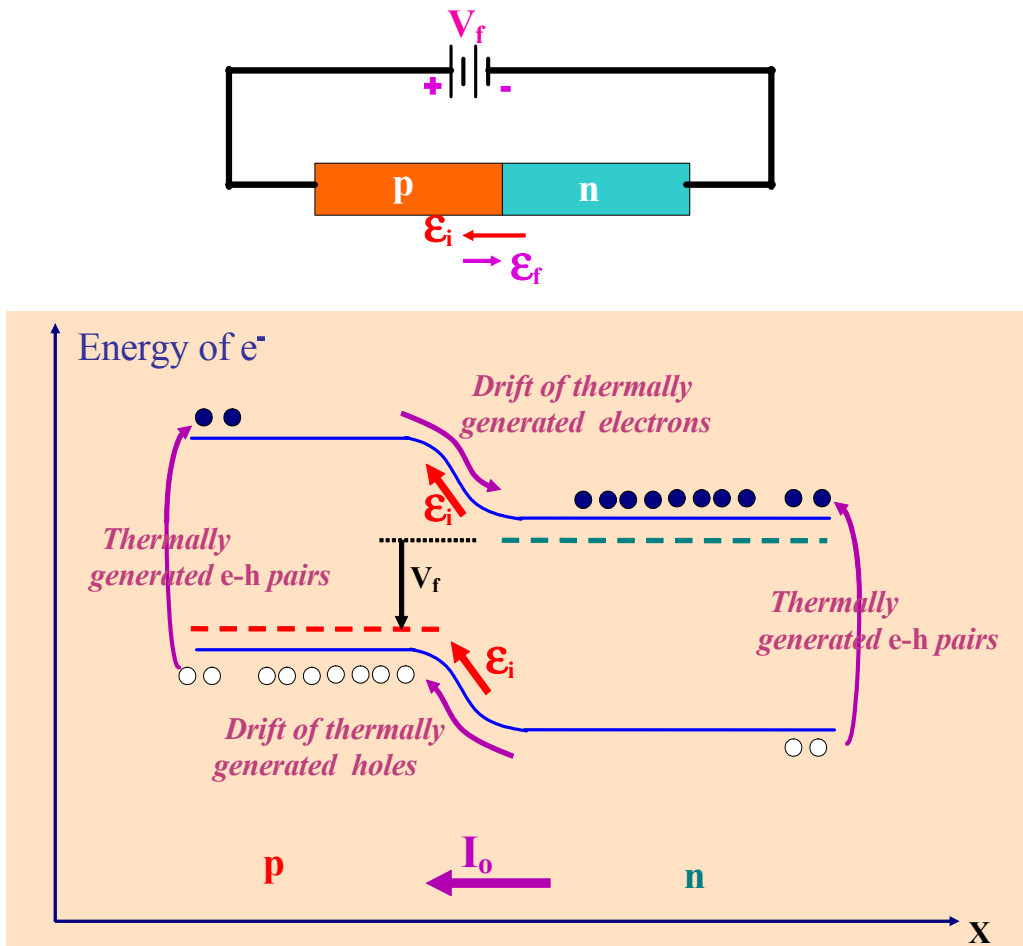
Forward bias



Reverse bias



Origin of the drift current I_0



Electrons thermally generated near the junction are swept by the internal electric field that exists across the junction. Similar situation happens to the thermally generated holes. The drift mechanism illustrated in the figure above constitute the origin of the unavoidable drift current I_0 .

Notice, the electrons and hole will be swept by whatever electric field is present across the junction, regardless of the actual value of \mathcal{E} . That is, the rate of charges crossing the junction is somehow independent of the forward or reverse bias voltages. Once they are generated nearby the junction, any electric field will sweep them across. Thus, I_0 depends only on how fast are the e-h pairs generated, which is influenced by the bandgap E_g and temperature.

<http://www.chemicool.com/>

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Uun								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Legend

- | | | | |
|-----------------|---------------------|-------------------|---------------------|
| Li Solid | Cs Liquid | Ar Gas | No Synthetic |
| Alkali metals | Alkali earth metals | Transition metals | Rare earth metals |
| Other metals | Noble gases | Halogens | Other nonmetals |

