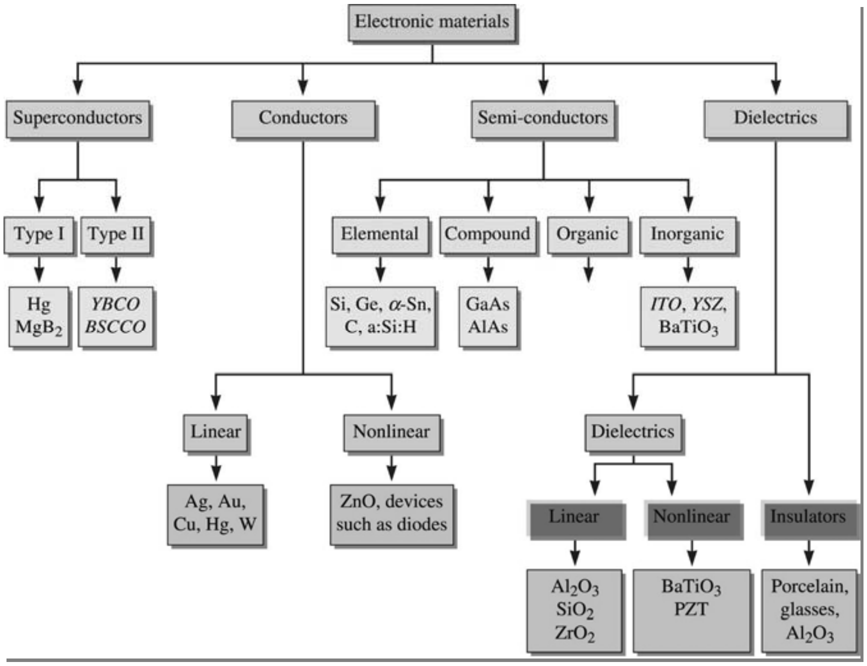
Chapter 19

Electronic Materials



We need some definitions for electrical resistivity and conductivity

Ohm's law: $R = \frac{V}{i}$ Units: R: ohms V: Volts i: Amps

Resistivity ρ $R = \rho \cdot \frac{\ell}{A}$ Units of ρ: Ω · m or μΩ · cm

The resistivity is the inverse of the conductivity: $\sigma = \frac{1}{\rho}$

Microscopic expression of Ohm's law: $\bar{J} = \frac{\bar{E}}{\rho} = \sigma \cdot \bar{E}$

where:

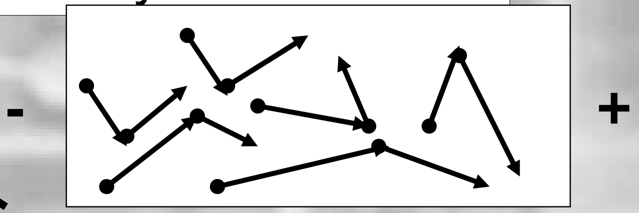
$\bar{J}$ is the current density in A/m^2

$\bar{E}$ is the electrical field in V/m (a gradient)

Have you seen a similar equation recently?

Electron Drift Velocity in Metals

$$\overline{v}_d = \mu \cdot \overline{E}$$



drift velocity mobility electrical field

[m/s] [$m^2 \cdot V^{-1} \cdot s^{-1}$] [V/m]

Therefore, the flux of electrons per unit area and unit time is:

$$\overline{J} = n \cdot e \cdot \overline{v}_d$$

e is the electron charge, *n* is the number of charges (electrons) crossing an area perpendicular to J at a speed of v_d

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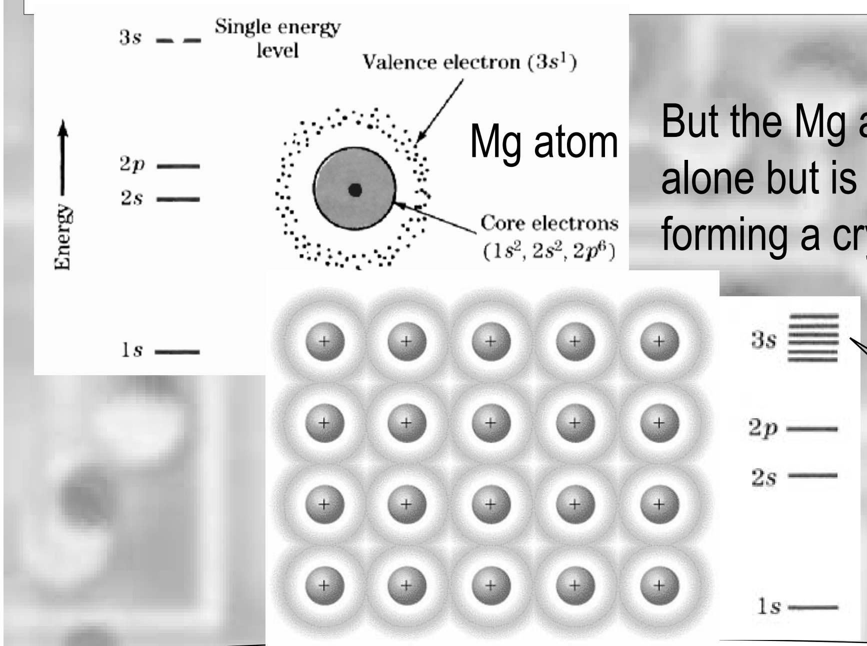
But why some materials conduct electricity better than others?



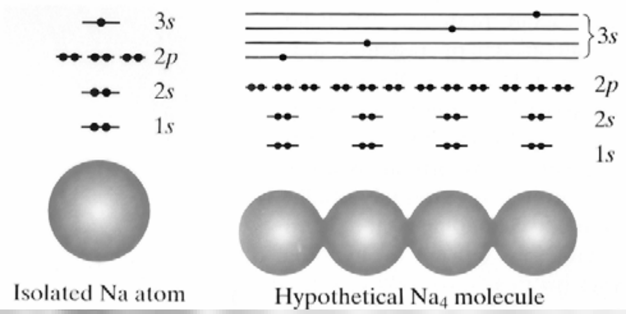
But the Mg atom is not alone but is one of many forming a crystal.

Effect of Pauli's Exclusion Principle

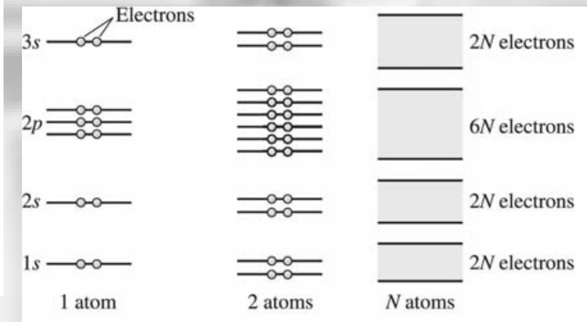
A new concept: Band structure in solids

So, according to Pauli's exclusion principle, *no two atoms can share the same energy level unless they have opposed spins (i.e. m_s= +½, -½)*

For one and four sodium atoms:

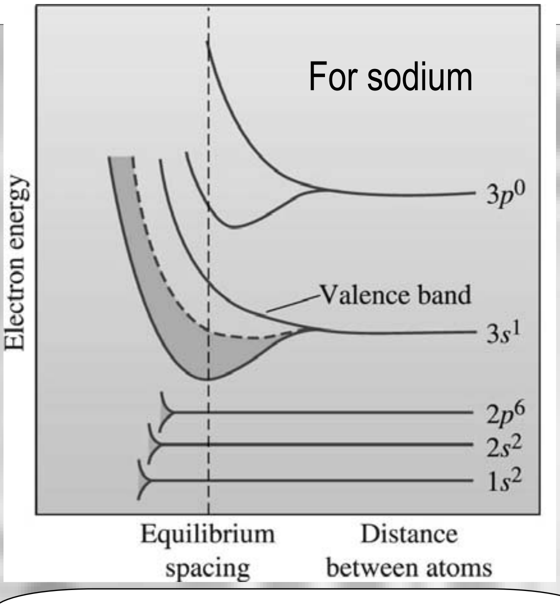


For one, two and N atoms of Mg:



Electrons cannot share the exact same energy level and need to be *distributed* in *zillion* levels forming bands rather than individual levels.

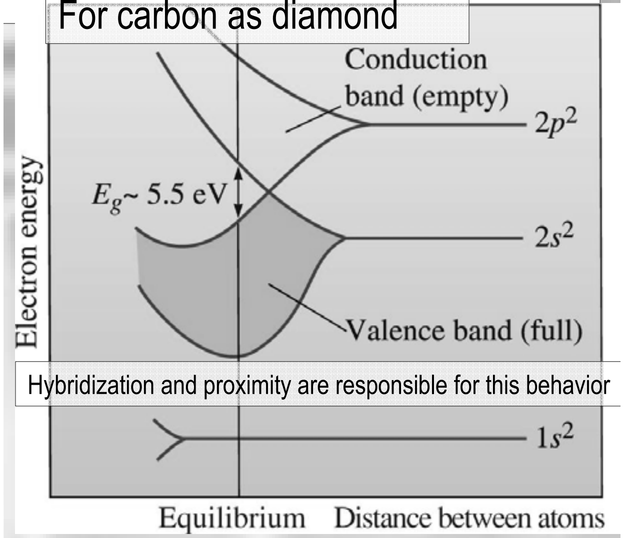
The energy curves transform into bands for the outermost electrons:



For sodium

Now, because of Pauli's principle the electrons will have to distribute in bands of energy!

For carbon as diamond



Hybridization and proximity are responsible for this behavior

Sodium is a metal conductor but diamond is not. So conductivity is defined by the relation between electrons in the valence and in the conduction band

Then the differences in band energies answer our question about materials with different resistivities.

Now the gap between bands is still finite but not large: Semiconductors may have reasonable conductivity under certain conditions

Lots of energy needed to promote an electron to the conduction band

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Let's first talk about good electrical conductors

Metals are the best examples of good electrical conductors:

The electrical resistivity can go from 1.48 μΩ·cm for Ag to 50 μΩ·cm in stainless steels.

In pure metals:

$$\rho_{total} = \rho_T + \rho_r \quad \text{(approx.)}$$

Drifting electrons are affected by phonons (elastic waves thermally excited)

→more temperature → more obstacles for electron movement → higher resistivity

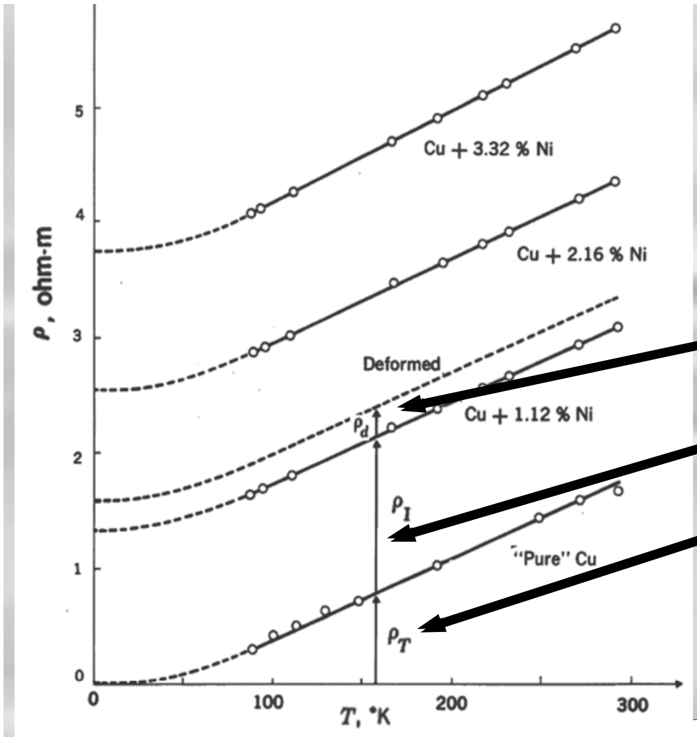
More on the Temperature Effect on the Electrical Resistivity of Metals

At higher temperatures there is an approximate linear dependence:

$$\rho_T = \rho_{0^\circ C} + \alpha_T \cdot T$$

where α_T is the temperature coefficient of resistivity and T is the temperature in ºC.

Temperature is not the only factor interacting with phonons. Impurities are also hurdles for phonons as we'll see next.



Mathiessen's Rule describes the additive nature of the resistivity of metals

Effect of deformation

Effect of impurities

Effect of temperature

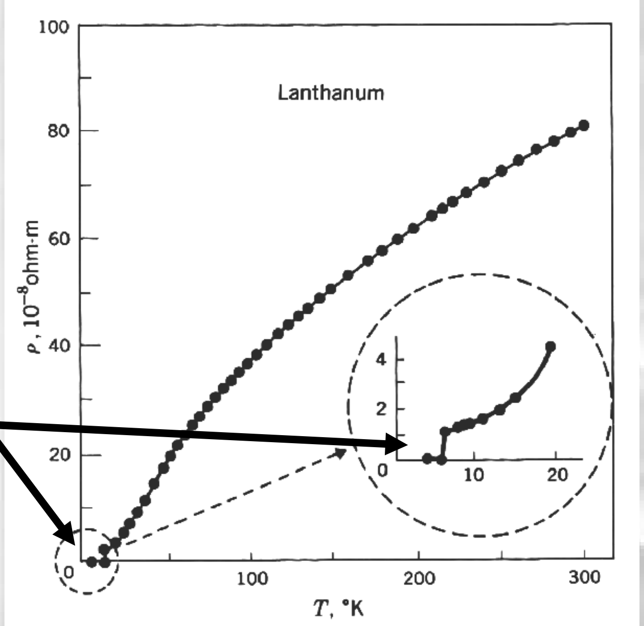
$$\rho_{total} = \rho_{Temperature} + \rho_{Impurities} + \rho_{deformation}$$

As the number of phonons increases with temperature, the electrical resistivity of conductors (metals) increases too.

At very low temperatures (close to 0K) there are two possibilities

Possibility I

The metal becomes a superconductor (negligible resistivity)

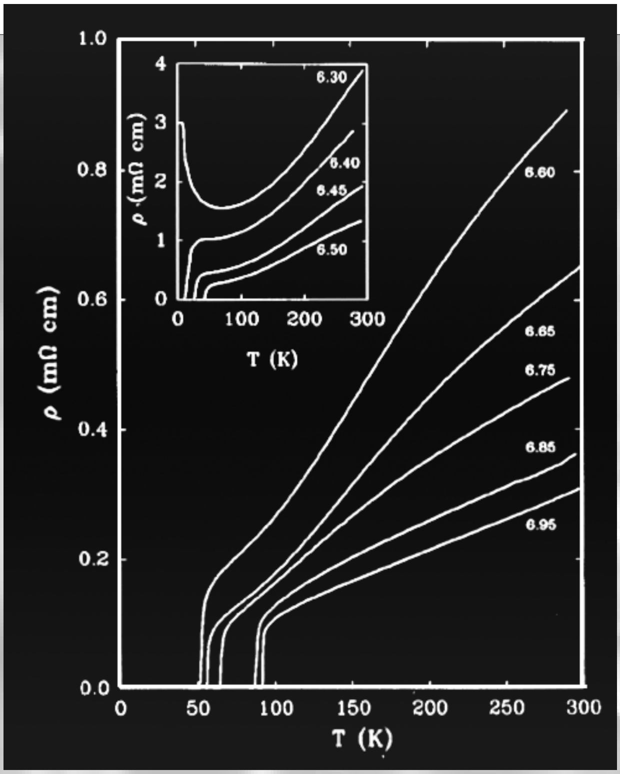


Modern superconductors are not metals but “weird” ceramics

$YBa_2Cu_3O_7$ or YBCO

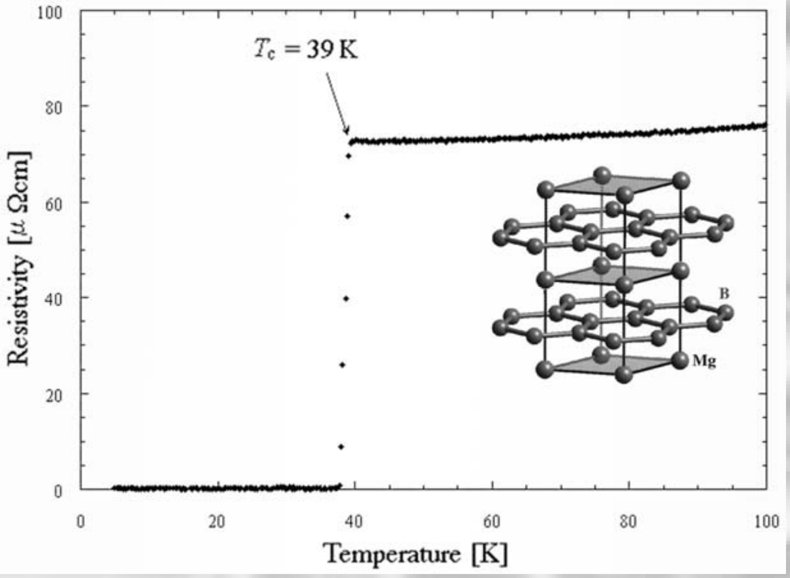
It has a perovskite crystal structure (like $BaTiO_3$) and is “oxygen deficient.”

How does T_c vary as a function of the amount of oxygen?



Another More Recent Example

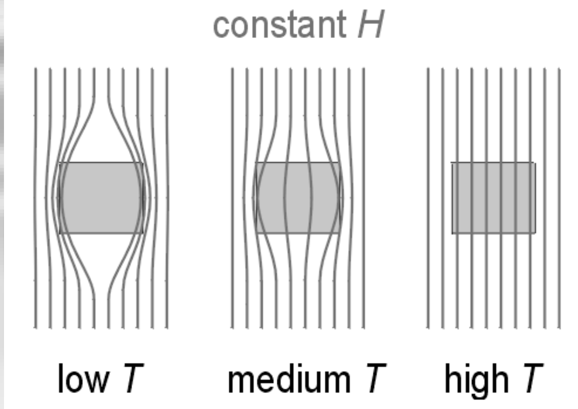
Nagamatsu *et al*. announced the discovery of superconductivity in magnesium diboride (MgB_2) in the journal *Nature* in March 2001



Meissner Effect in Superconductors

Applied magnetic field is represented by the red lines; the denser the lines, the stronger the field.

Superconducting phase ($T<T_c$) exclude the magnetic field (only a very thin surface layer is penetrated) *This allows for levitation!!*

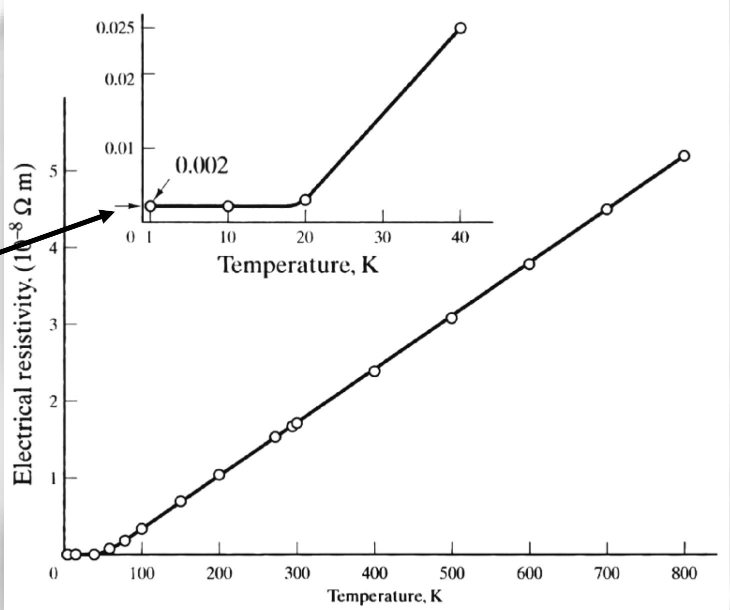


At T_c the mixed phase the field can penetrate the bulk of the superconductor, but is still weakened inside.

At $T>T_C$ (superconductivity is destroyed) the material is penetrated more or less uniformly by the applied magnetic field.

At low temperature most metals behave differently.

Possibility II



There is a residual (finite) resistivity. This is not a superconductor

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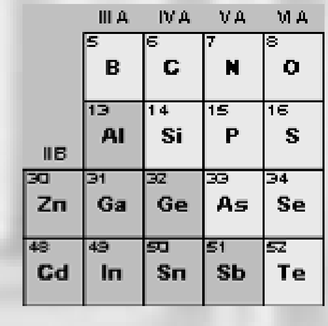
Let’s introduce the semiconductors

- Intermediate behavior between insulators and conductors.
- Their conductivity is highly dependent on temperature and chemical composition
- Two types:
  - –Intrinsic semiconductors
  - –Extrinsic semiconductors

Intrinsic semiconductors are those where except for temperature there is no external factor affecting their conductivity.

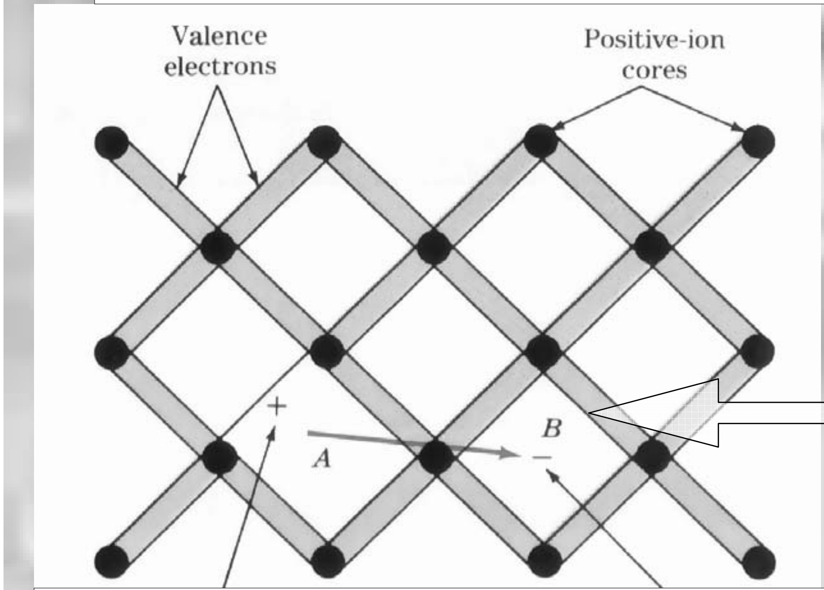
- Elements from Group IV-A (or 14) of the Periodic Table and some compounds.
- Silicon and germanium
- What do they have in common?



IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te

material	band gap (eV)
Si	1.11
Ge	0.67
GaP	2.25
CdS	2.40
GaAs	1.42

Intrinsic Semiconductors (cont.)



Let's knock-off an electron from the cubic structure of silicon

Both charges are mobile!!

What would happen if you put an electric field across the silicon piece?

Intrinsic Semiconductors (cont.)

The negative charges (electrons) are equal in number to the negative charges (holes).

Conductivity of semiconductors can be calculated as:

$$\sigma = n_i \cdot q \cdot (\mu_n + \mu_p)$$

n_i: number of charge carriers (electrons or holes)

q: electron or hole charge ($1.60 \cdot 10^{-19}$ Coulombs)

μ_n and μ_p: mobilities of electrons and holes, respectively

Intrinsic Semiconductors (cont.)

Remember that temperature measures internal energy.

Conductivity in semiconductors increases with temperature.

Could you explain why semiconductors behave much different from conductors? Think of the energy gaps.

$$n_i \propto e^{-E_g / 2kT}$$

Intrinsic Semiconductors (cont.)

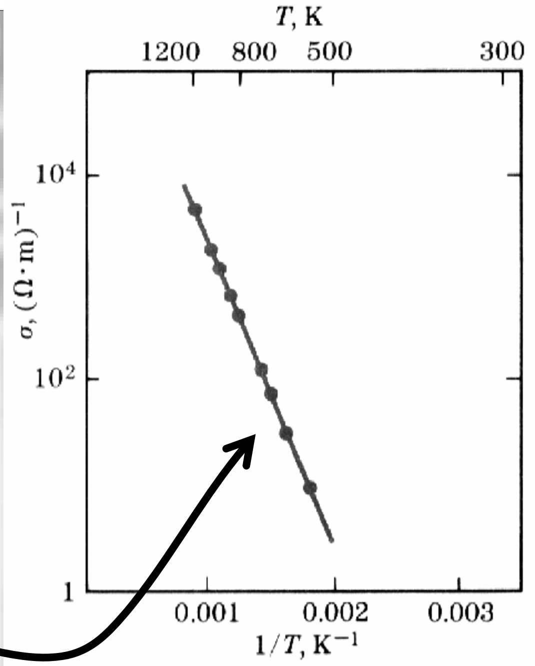
Since σ is proportional to the number of carriers:

$$\sigma = \sigma_0 e^{-E_g/2kT}$$

or

$$\ln \sigma = \ln \sigma_0 - \frac{E_g}{2kT}$$

So, how do you measure E_g from the graph?



Then what is the difference with metals?

Extrinsic Semiconductors

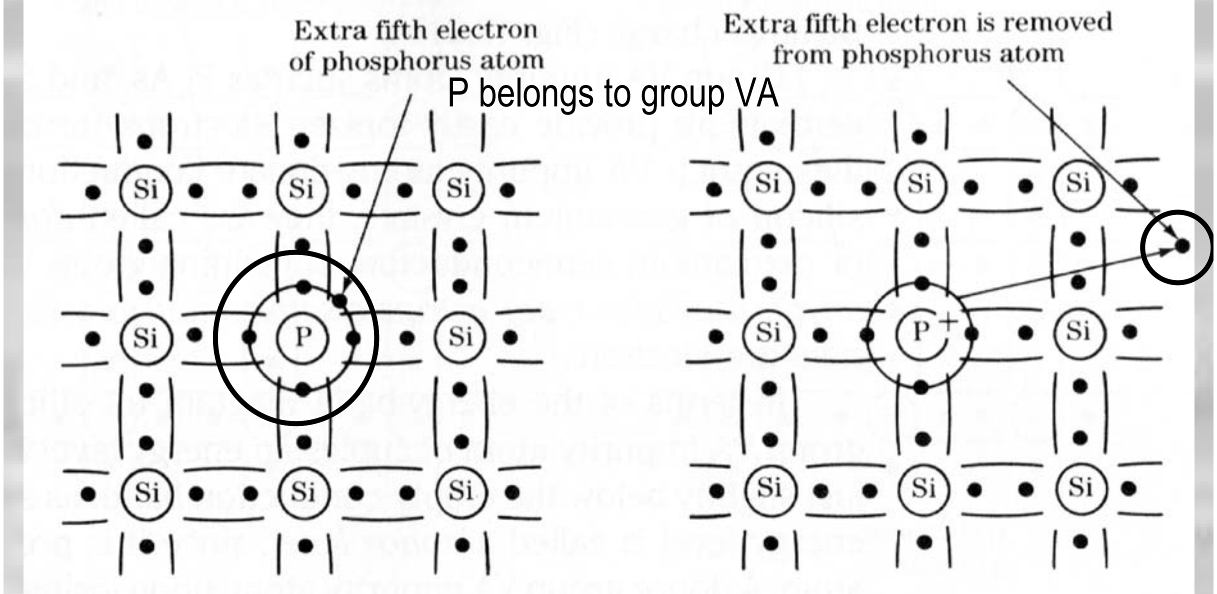
Let's intentionally add impurities with a valence of <u>one</u> higher or <u>one</u> lower, to silicon or germanium.

We need to have an excess of electrons or holes by unbalancing the electronic array of the crystal

Look at the periodic table for candidates!

n-Type Extrinsic Semiconductors

In a silicon lattice we replace one Si atom for a phosphorus atom. What happens to the electrons of the covalent bond?



P belongs to group VA

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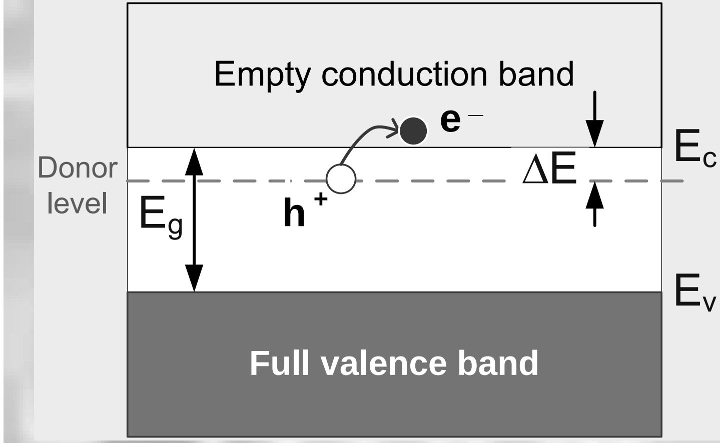
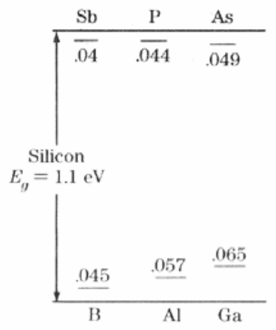
n-Type Extrinsic Semiconductors (cont.)

In the band model, notice how close we are now to the conduction band:

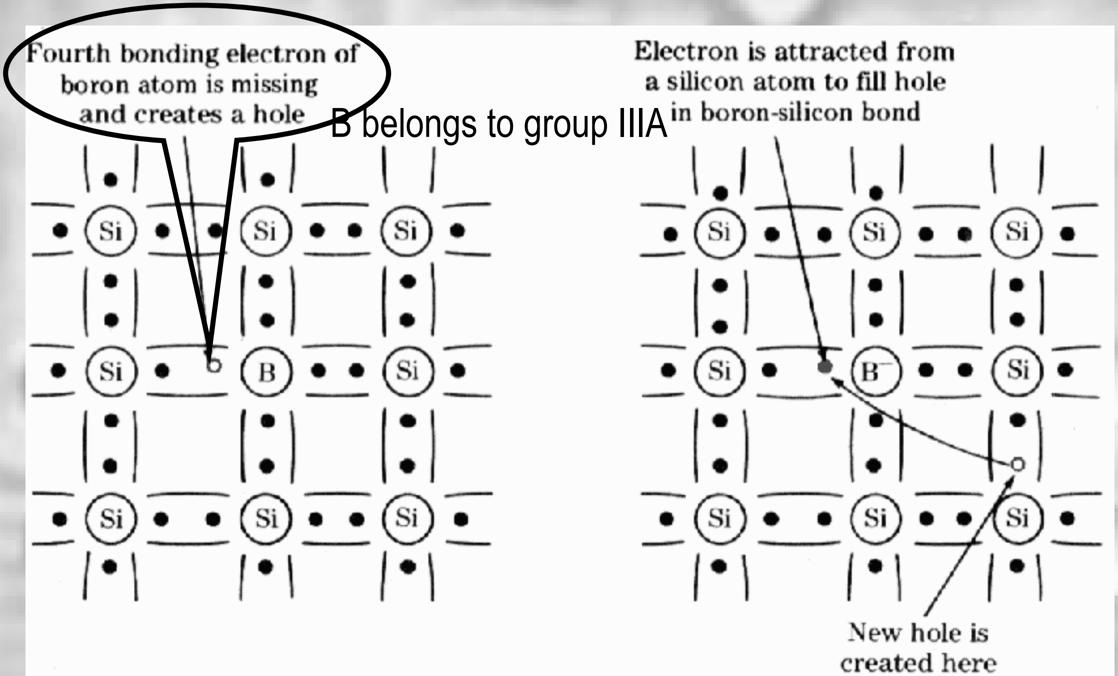


IVA	VA
C	N
Si	P
Ge	As
Sn	Sb



p-Type Extrinsic Semiconductors

Now let's dope Si with boron (valence +3):



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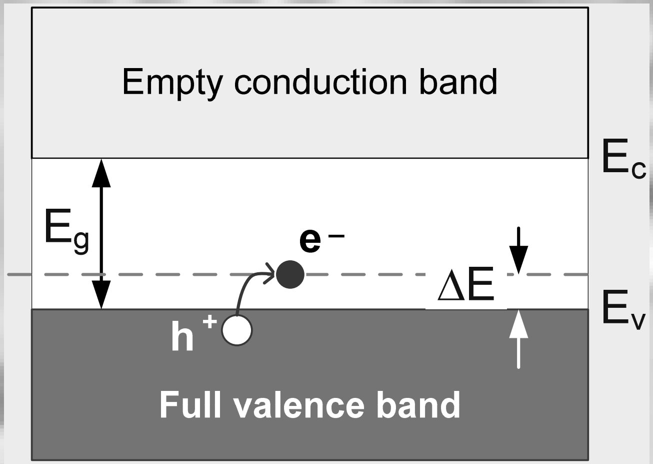
p-Type Extrinsic Semiconductors (cont.)

Now let's dope Si with boron (valence +3):

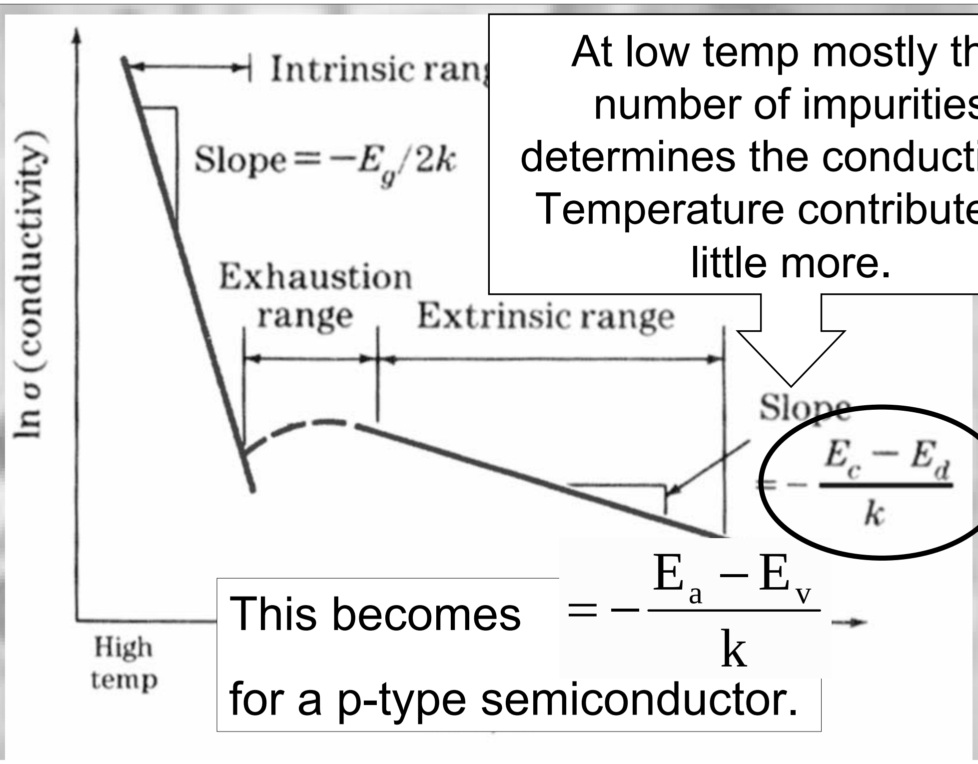


IIIA	IVA
B	C
Al	Si
Ga	Ge
In	Sn

$$\Delta E = E_a - E_v$$

We have reduced the gap size by ΔE

Effect of Temperature on Extrinsic Semiconductors



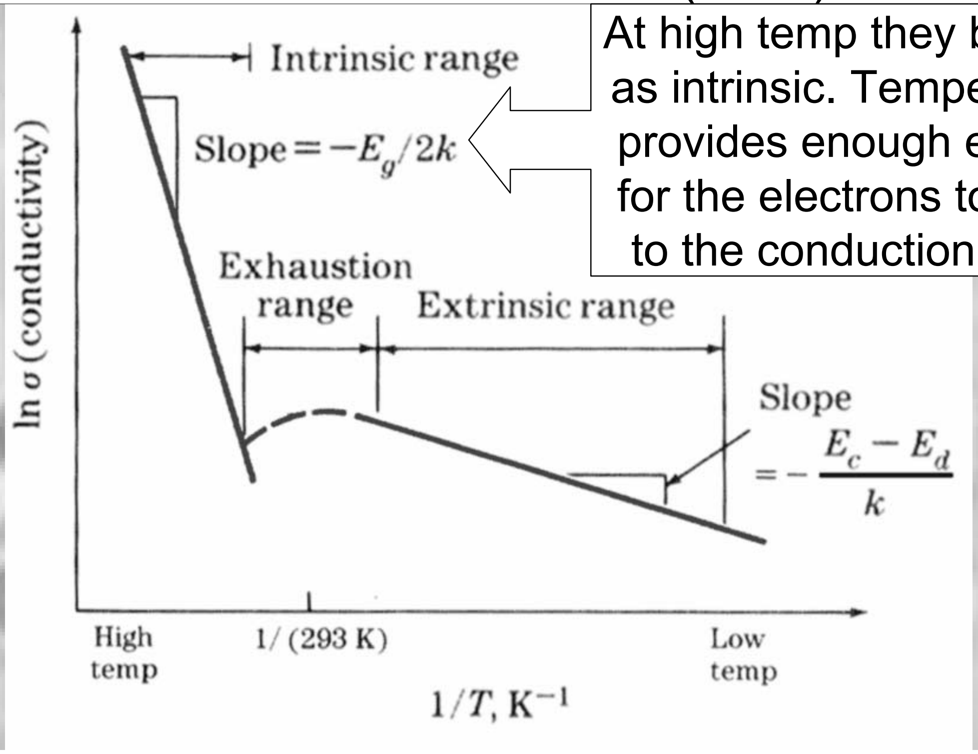
At low temp mostly the number of impurities determines the conductivity. Temperature contributes a little more.

This becomes $= -\frac{E_a - E_v}{k}$ for a p-type semiconductor.

n-type

p-type

Effect of Temperature on Extrinsic Semiconductors (cont.)

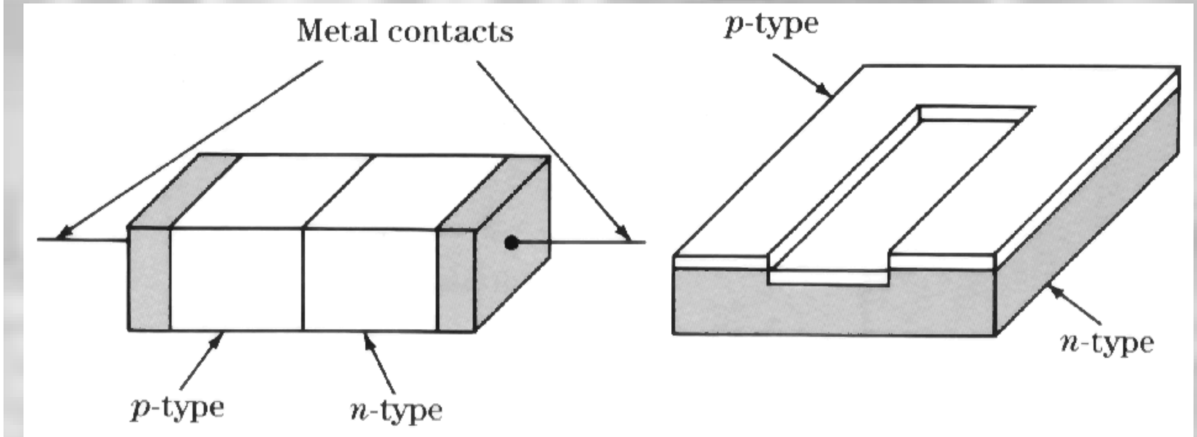


At high temp they behave as intrinsic. Temperature provides enough energy for the electrons to jump to the conduction band

Semiconductor Devices

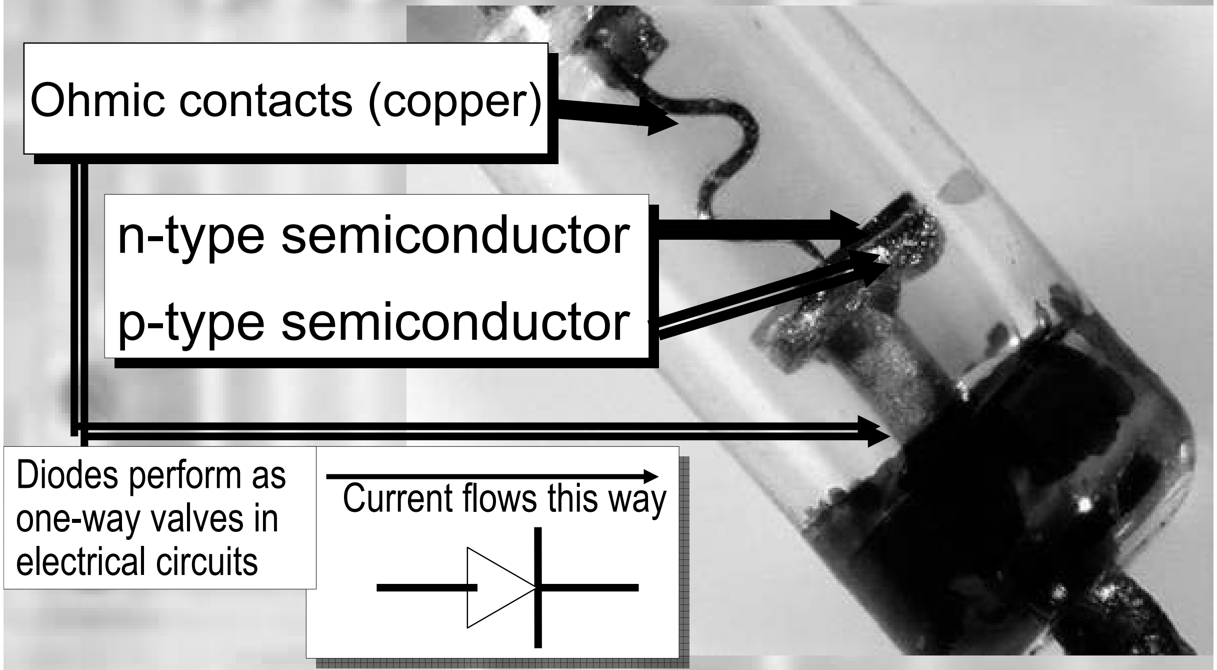
A p-n diode junction is put together linearly or planarly (for computer chips)

Silicon is grown as a single crystal. Doping is done with diffusion process (Chapter 5).



Semiconductor Devices (cont.)

A “cat-whisker”diode.



Ohmic contacts (copper)

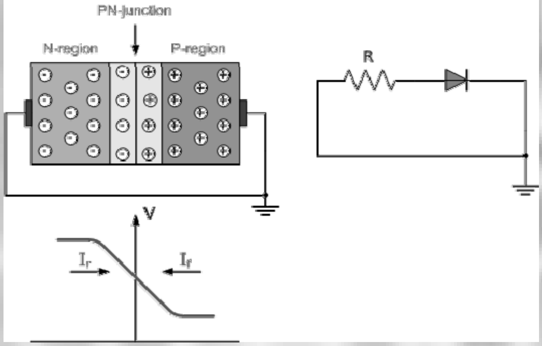
n-type semiconductor

p-type semiconductor

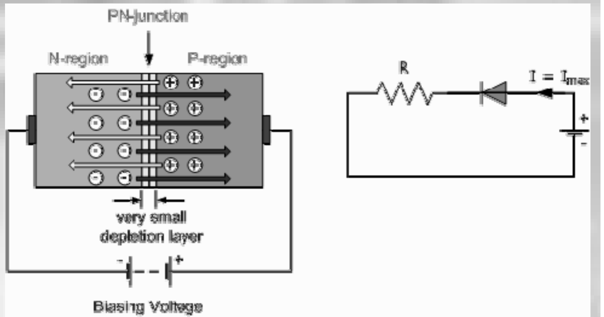
Diodes perform as one-way valves in electrical circuits

Current flows this way

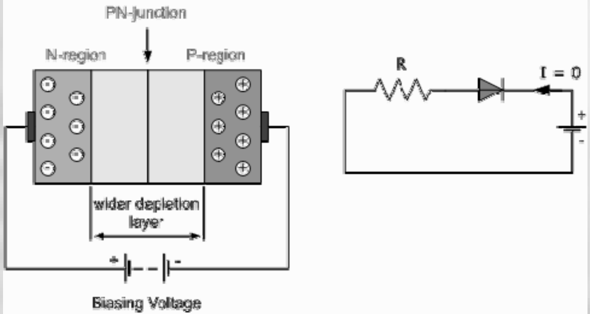
Semiconductor Devices (cont.)



Under zero bias (no external voltage applied) if the diode is *shortened* there are two small currents (h^+ and e^-) that can reach a dynamic equilibrium



Under forward biased conditions, the p-side is connected to the positive pole (very high current)



Under reverse biased conditions, the p-side is connected to the negative pole (very small current)

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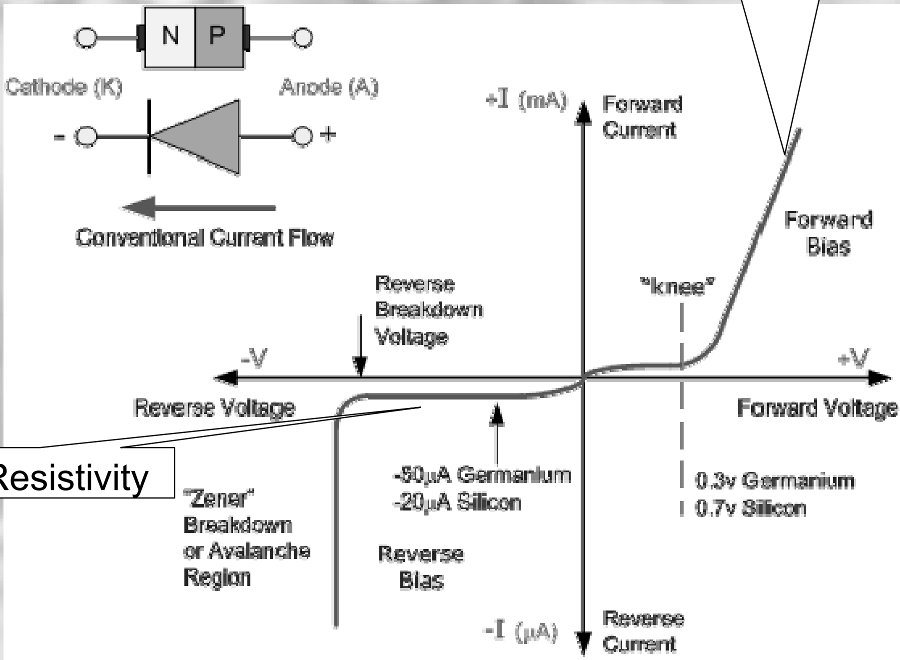
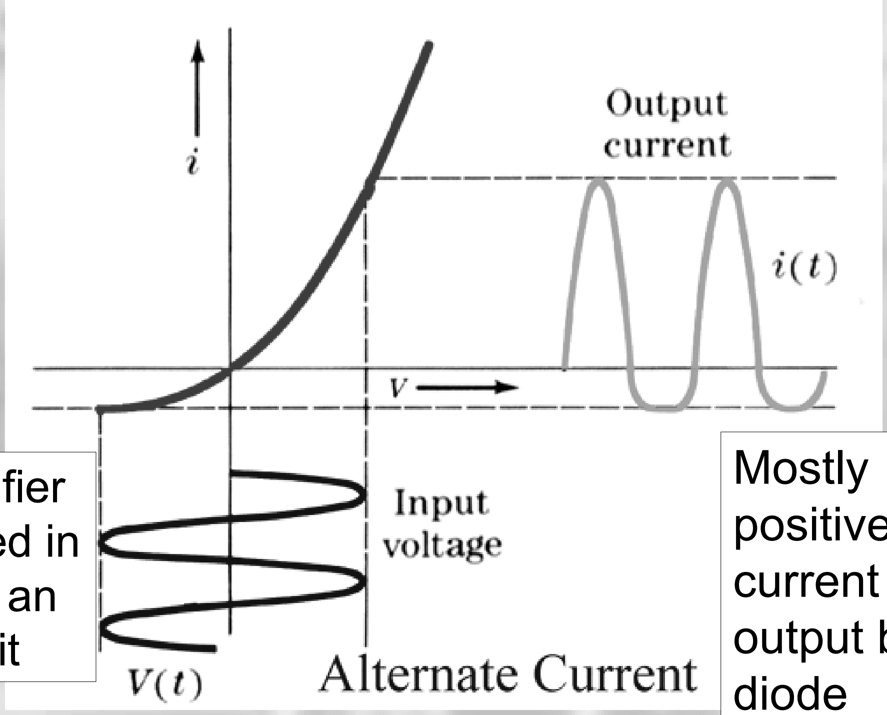
p-n Junction

Small Resistivity



Large Resistivity

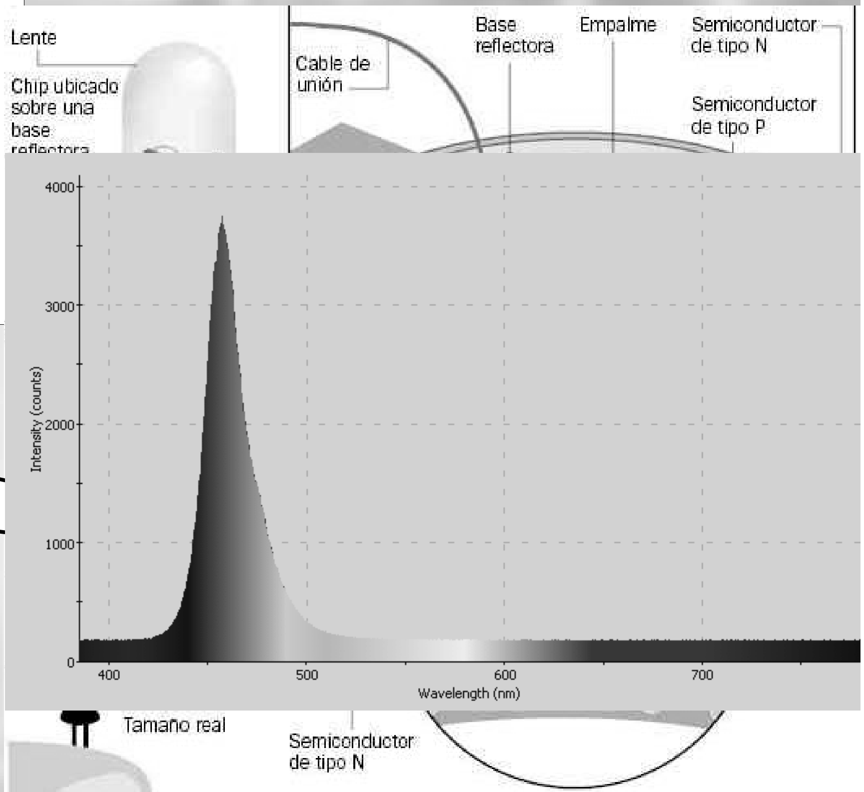
p-n Junction Rectifier (cont.)



The rectifier is inserted in series in an AC circuit

Mostly positive current is output by the diode

LED (Light Emitting Diodes) are another application of *p-n* junctions



Now recombination is accompanied by a photon emission.

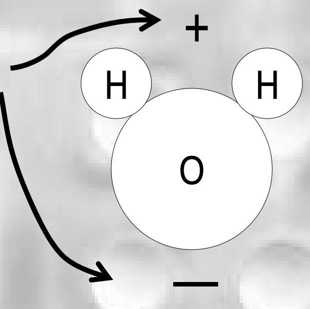
Other Electrical Properties of Materials: Ferroelectricity

Let's review the concept of dipolar moment.

Dipolar moment is due to local unbalance of charges in ionic or covalent molecule or crystal.

Remember: methane (CH_4) tetrahedron is "charge-symmetric" so there's no dipole moment.

H_2O molecule is not, so it forms a dipole:



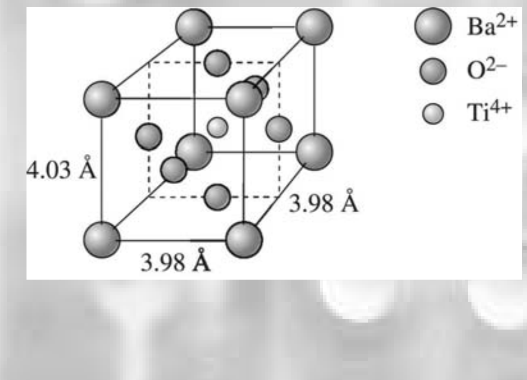
Ferroelectrics

Dielectric materials (large resistivity) that experience polarization in the absence of any electric field → strong dipole moments.

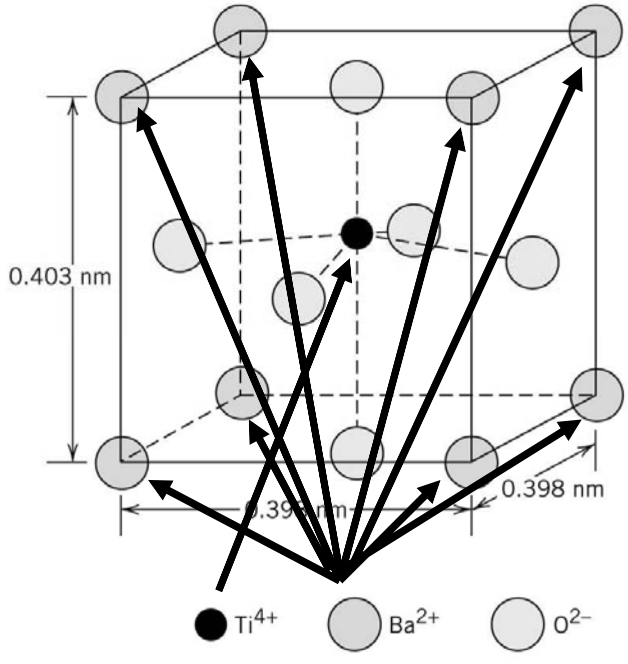
Classic example: barium titanate $BaTiO_3$

At room temp. → slightly asymmetric perovskite structure

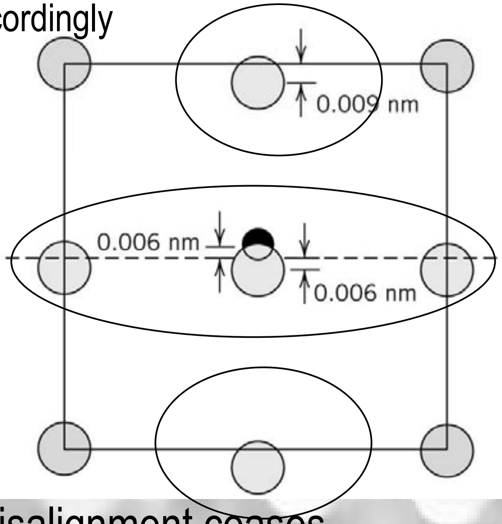
Ionic crystal with Ba^{2+}, Ti^{4+} and O^{2-} ions.



Barium Titanate



Below 120ºC the crystal is slightly asymmetric causing an spontaneous dipole (polarization). Neighboring crystals react accordingly



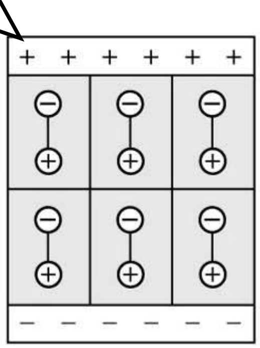
Above 120ºC (Curie temperature) the misalignment ceases.

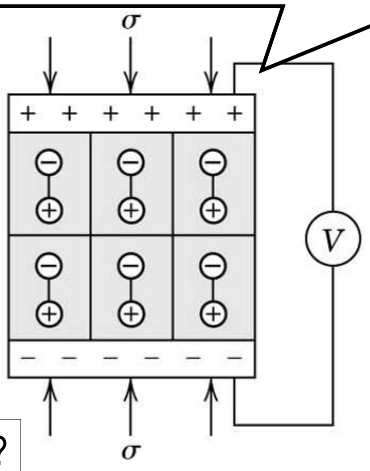
Piezoelectricity

This results from dielectrics (ceramics) with large <u>induced</u> polarization.

Under pressure, the crystals polarize and create an electric field.

And viceversa, with an applied electric field they react causing a pressure pulse.





Can you think of any use for these materials?

Piezoelectricity (cont.)

Example: lead zirconate or *PZT* $PbZrO_3$ (also a perovskite-type structure).

Uses of piezoelectric materials: transducers, speakers, ultrasonic probes (to break kidney stones), ultrasonic detectors, actuators, piezoelectric motors, etc.