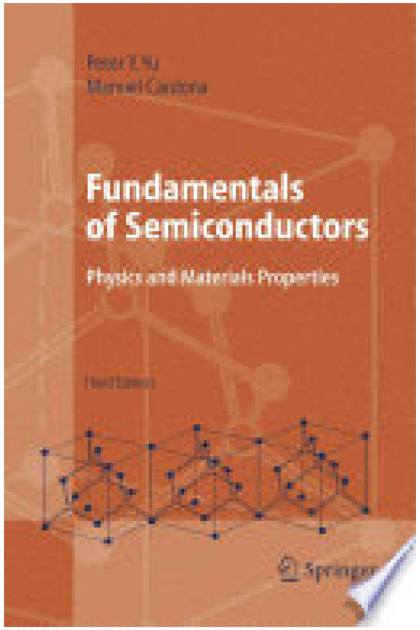
General Properties of Semiconductors

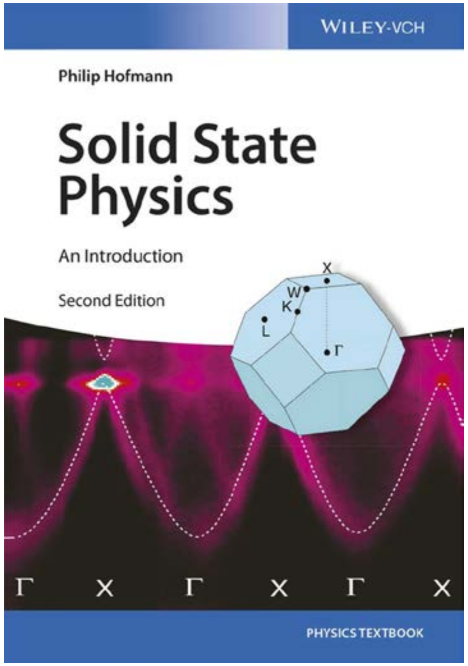
Topics

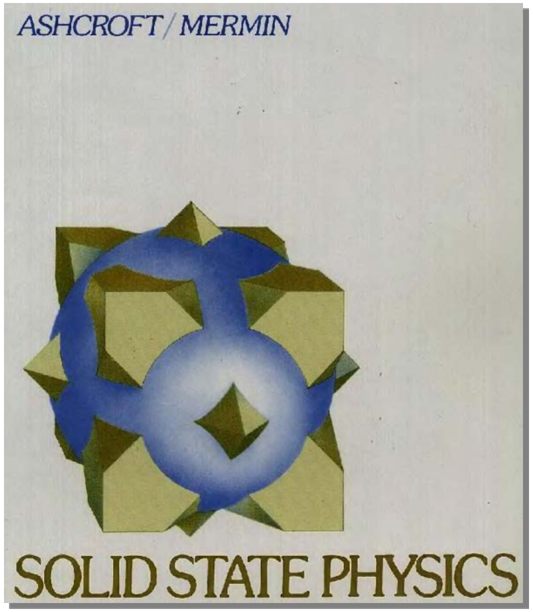
- General Properties of Semiconductors
- Crystal Structure
- *(Feiertag)*
- The Reciprocal Space & The Fourier Transform
- X-Ray Diffraction basics & Multipurpose X-Ray Diffraction systems with built-in intelligent guidance.
- Lattice Vibrations & Phonons / Dispersion Relations & Density of States (DOS)
- Phonon Spectroscopies: Raman & Infra Red
- Atomic Structure & Chemical Bonding
- Electronic properties of Semiconductors (intro.)
- Electronic properties of Semiconductors (cont.)
- *(Feiertag)*
- Electronic properties of Semiconductors (end)
- *(Feiertag)*
- Spectroscopic methods for electronic and optical properties characterization
- The Nano-World! (intro): From Micro to Nanospectroscopy/ from Micro to Nanomaterials
- Solid Surfaces & Interfaces
- Heterojunctions, Heterostructures and Quantum Confined Structures
- Techniques for Synthesis of Nanomaterials
- Understanding (the relevance of) Quantum Mechanics - a light introduction
- Dedicated sessions for revisions (lectures & exercises)

Recommended Literature

E- Books available via TUC library!







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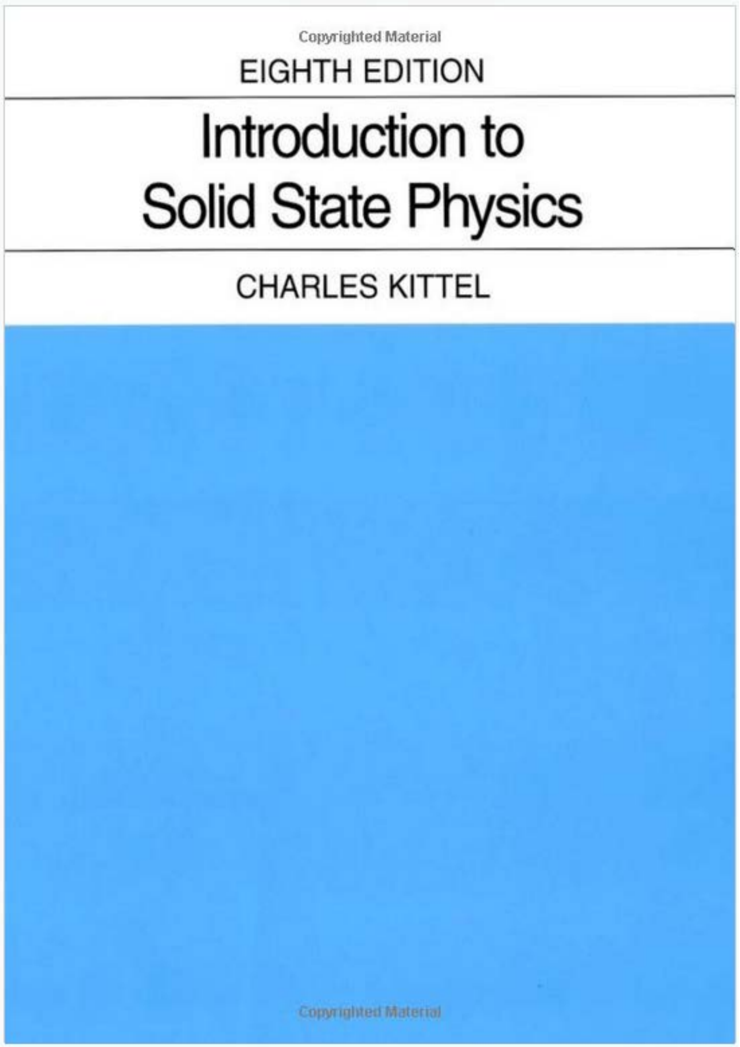
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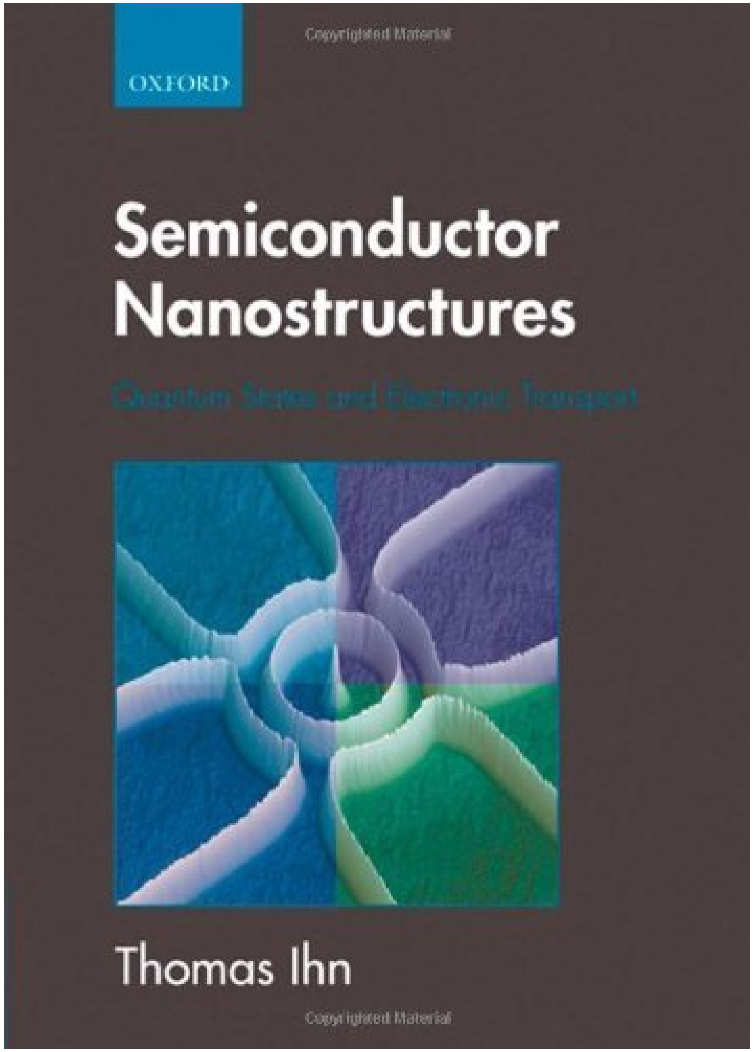
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THE HISTORY OF SEMICONDUCTORS

? HOW OLD IS SEMICONDUCTOR SCIENCE ?

Not clear!

First experiments performed 200 years ago!

The concept of ‘semiconductor’ appears in early 20th century.

History of Semiconductors

https://djena.engineering.cornell.edu/hws/history_of_semiconductors.pdf

1782 Alessandro Volta: "semiconducting" term is used for the first time.

1821 Humphry Devy: discovers the increase in resistivity of metals with increasing temperature.

1833 Michael Faraday: observed the first exception to Devy's experimental results: the decrease of resistivity to metallic values with increase of temperature of Silver Sulfide (Ag_2S).

1874 Karl Braun: discovers and documents the first semiconductor diode effect; he observed that current flows freely in only one direction at the contact between a metal point and a galena crystal.

1901 Jagadis Chandra Bose: invents and patents the very first semiconductor device called "cat whiskers". Cat whiskers was a point-contact semiconductor rectifier used for detecting radio waves.

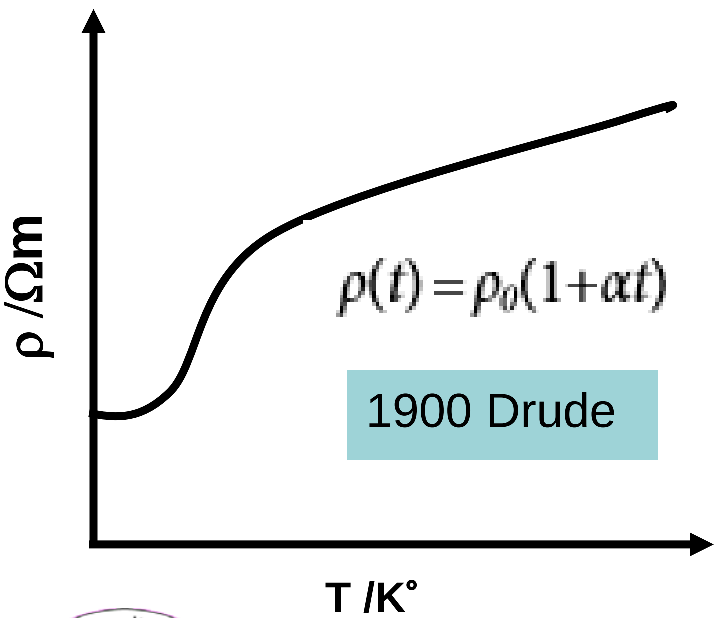
1901 Drude provides the first mathematical expression for the phenomena observed by H. Devy.

1908 Johann Koenigsberger and Schilling provide the first mathematical expression for the phenomena observed by of M. Faraday.

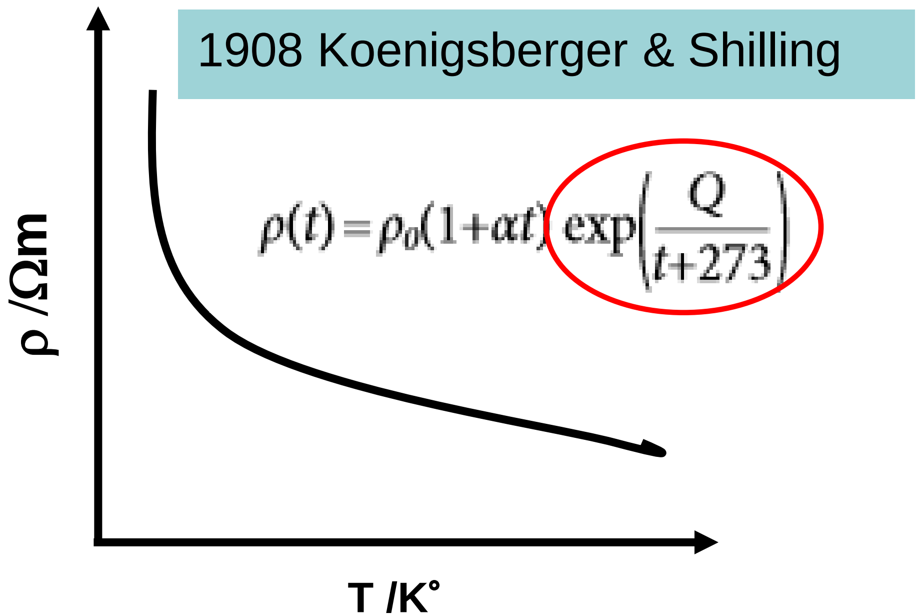
One of the first properties observed that distinguished semiconductors from conductors was the

Variation of resistivity (ρ) with temperature (T)

Conductor



Semiconductor



Koenigsberger could not propose any physical model for the origin of the dissociation Energy – Q – but based on this he divides all materials into:

metals insulators "variable conductors"

- ✓ for insulators Q is infinitely large (so there are no free electrons);
- ✓ for metals at high temperatures Q=0 (i.e. nr of electrons in metals is equal to the number of ions (= basic assumption of Drude's theory);
- ✓ for "variable conductors" Q is finite; therefore their resistivity decreases exponentially with increasing temperature;
- ✓ demonstrates experimentally that Q depends critically on the material purity and the presence of defects.

1931 Alan Wilson Proposes **Band Theory of Semiconductors** after quantum mechanics is established; draws the picture of energy bands and energy gaps in between, giving like this physical meaning to the Koenigsberger's dissociation energy.

1931 Werner Heisenberg Concept of "holes" - carriers with positive charge, presenting unoccupied positions in the mainly occupied valence band.

Birth of Semiconductor Science

↓

1914

↓

Koenigsberger

WHY ?!

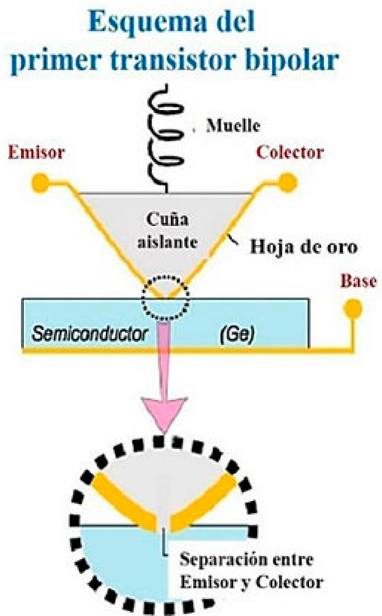
Since that time it was possible to speak about a new class of solids with strictly defined properties, rather than separate “anomalous” materials.

Although the basic features of semiconductor theory were developed in the 1930s, semiconductors remained “unpopular” until the mid 1940s for lack of suitable technologies.

All crystals were “dirty”, and results obtained were irreproducible!

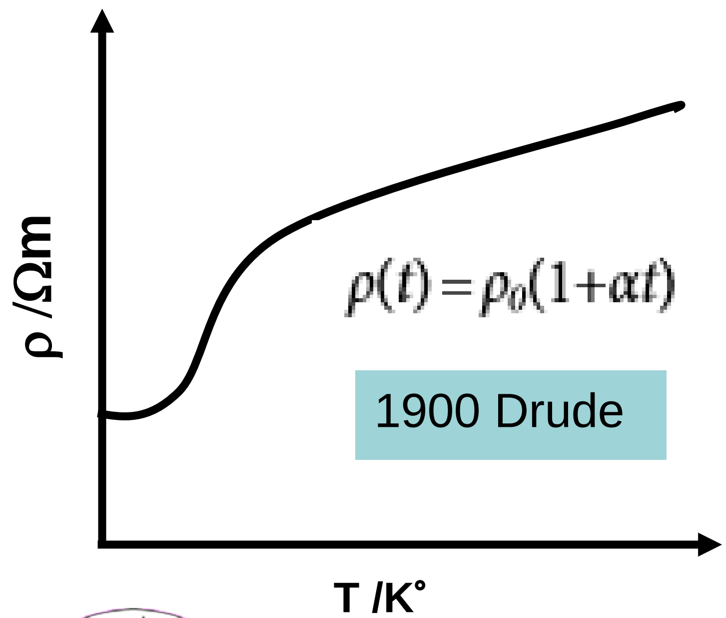
William Shockley, **John Bardeen** and **Walter Brattain,**
discover transistor action in germanium in 1947

1951
changed the situation after the fabrication of the first transistor on p-n junctions.

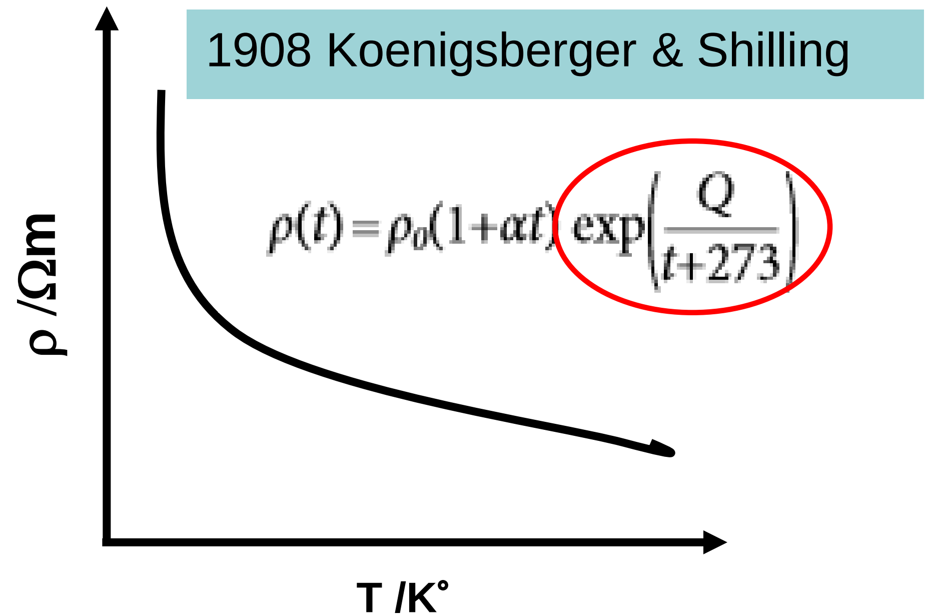


Resistivity (ρ) decreases with increasing temperature (T)

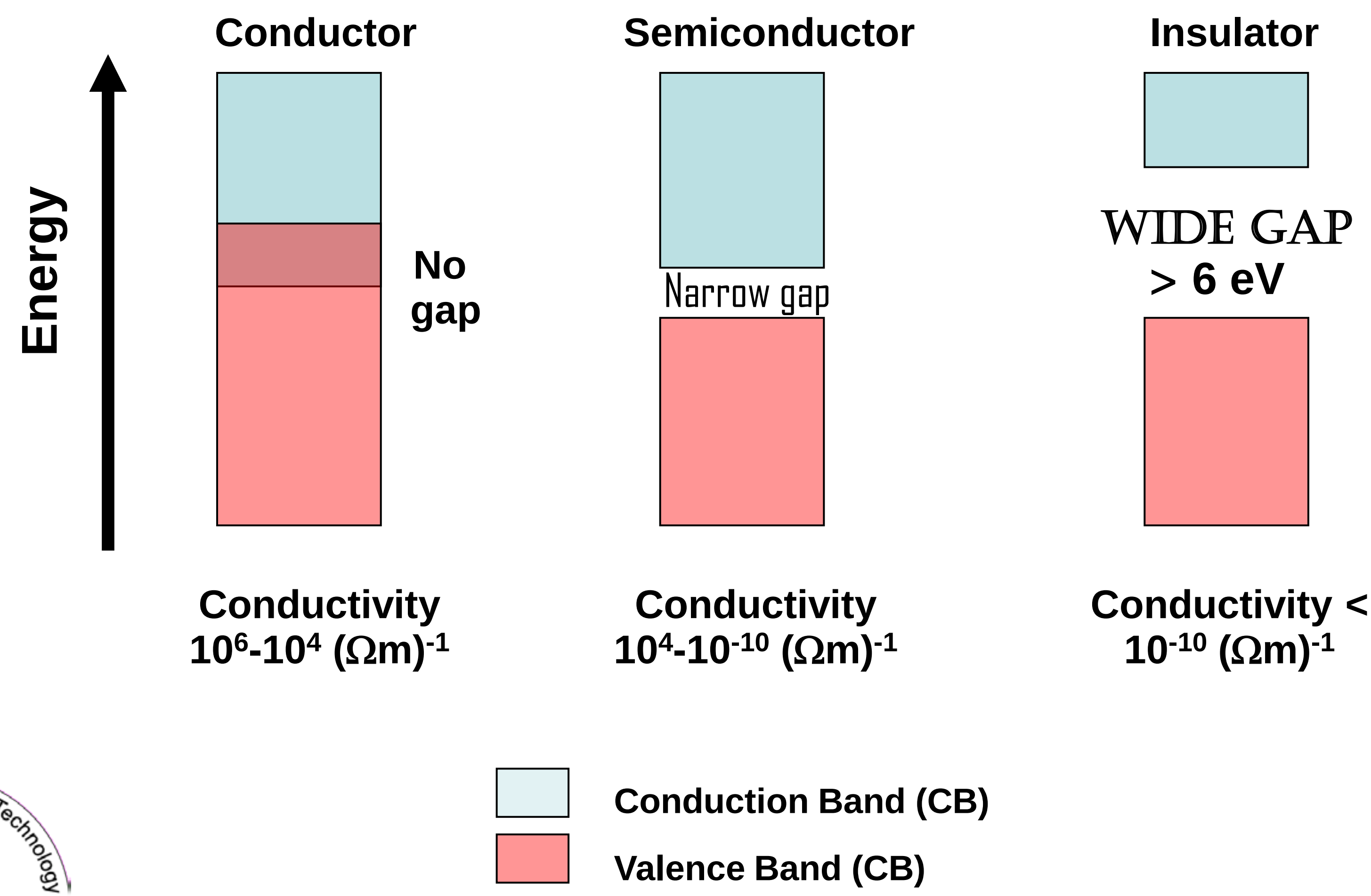
Conductor



Semiconductor

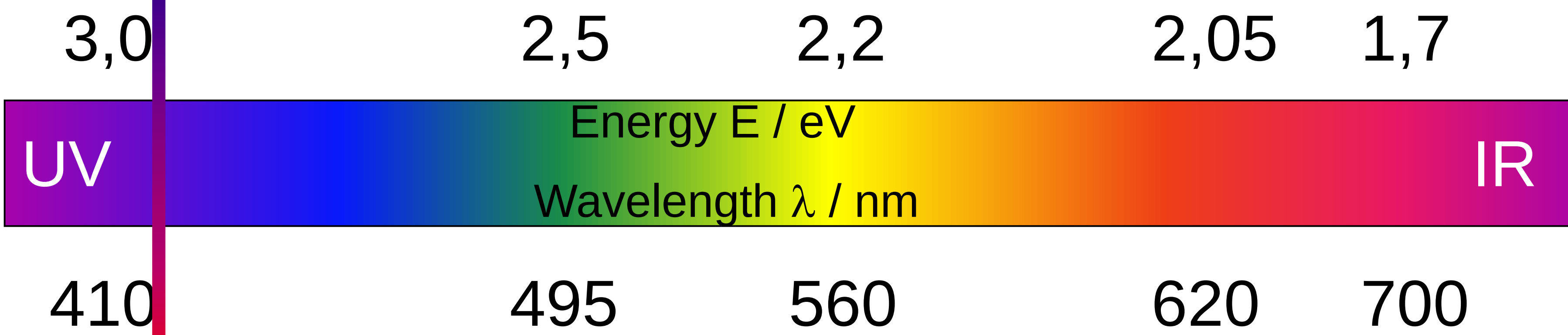


! Band Gap < 6 eV !


Conductor
Semiconductor
Insulator
Energy
No gap
Narrow gap
WIDE GAP
> 6 eV
Conductivity
10^{6}-10^{4} $(\Omega m)^{-1}$
Conductivity
10^{4}-10^{-10} $(\Omega m)^{-1}$
Conductivity <
10^{-10} $(\Omega m)^{-1}$
Conduction Band (CB)
Valence Band (CB)

Typical

energy range [eV] and absorption wavelengths [nm] of band gaps.



! More info in the Semiconductor Master Graph !

$$E[eV] = \frac{1240}{photon\ wavelength\ [nm]}$$

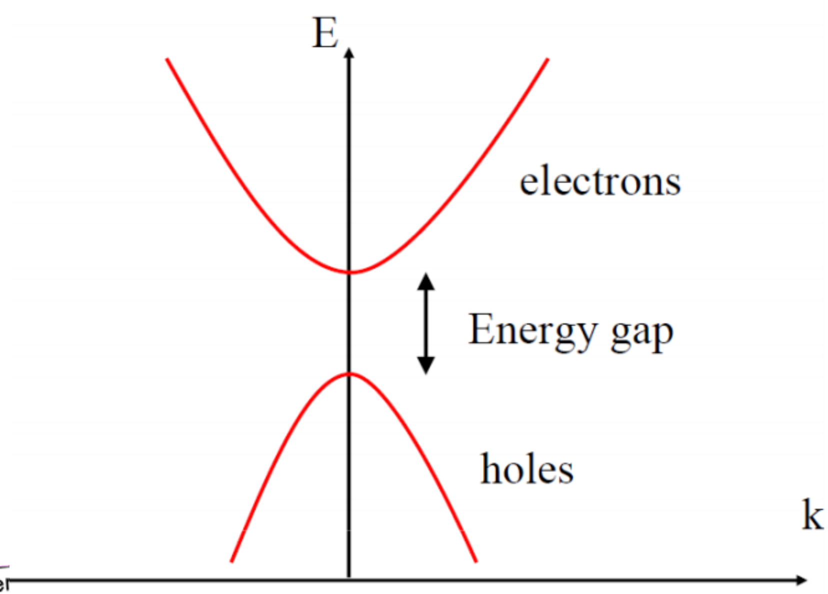
1 eV = 1,602×10^{-19} J

25 meV: thermal energy $k_B T$ at room temperature (300 K)

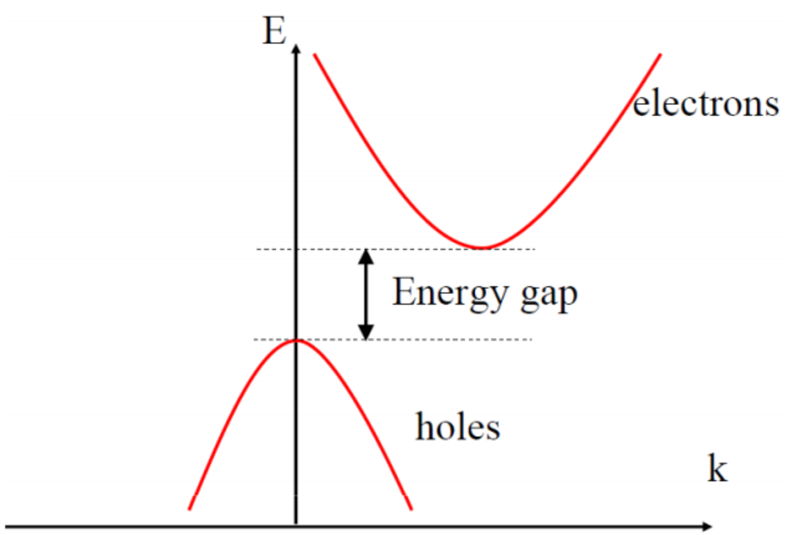
1 nm = 10^{-9} m = 10 Å

The band gap of a semiconductor is always one of two types:

direct band gap or **indirect** band gap



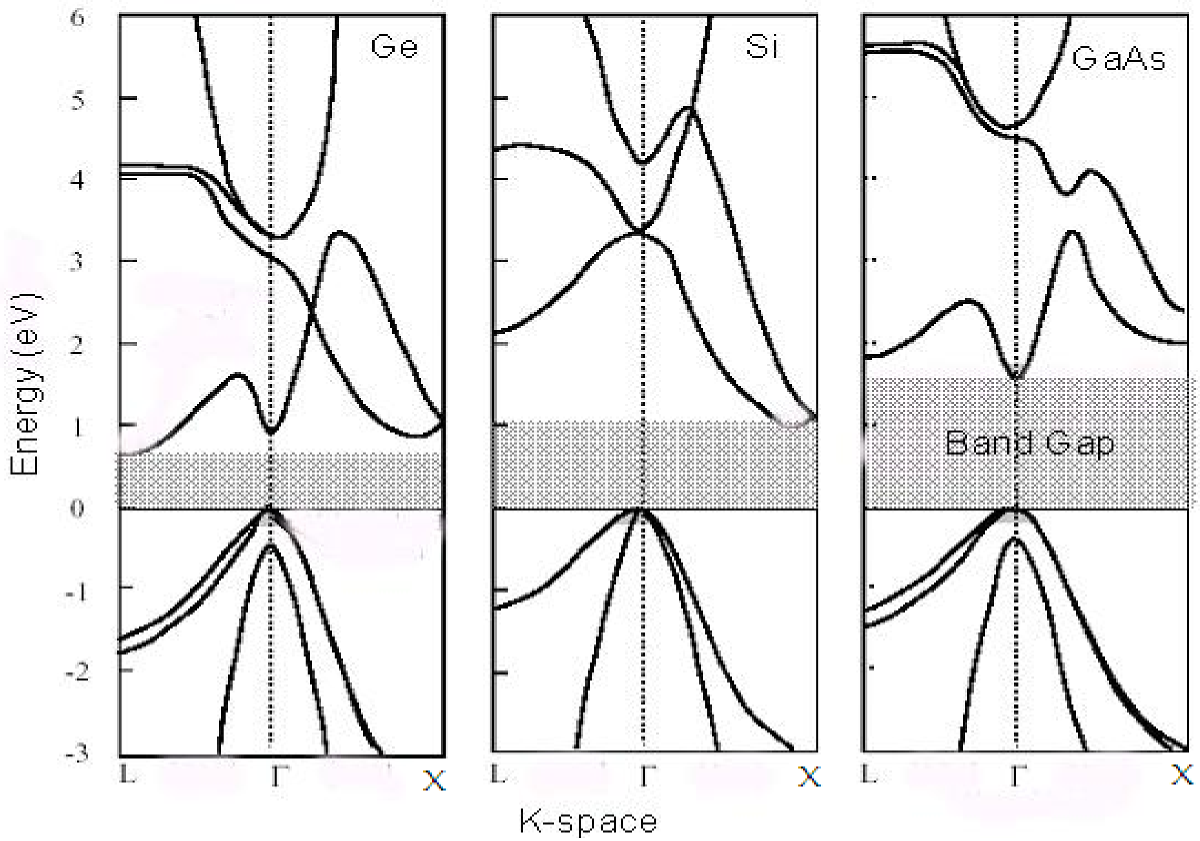
Direct bandgap semiconductors



Indirect bandgap semiconductors

In real life band gaps don't look like this are more complex due to semiconductors

Crystal Structure and atomic size

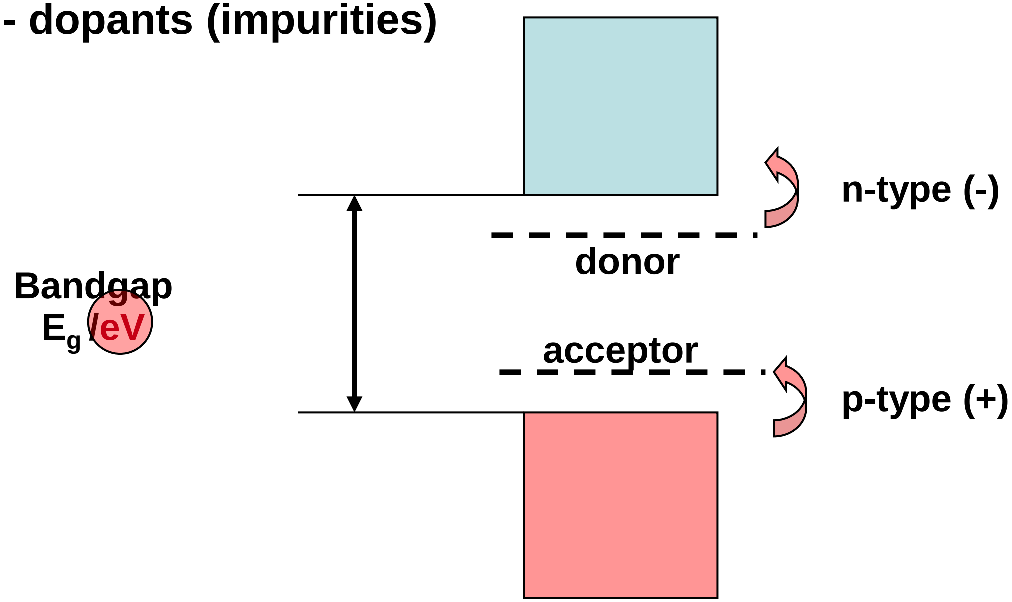


Energy band diagram of Germanium (Ge), Silicon (SI) and Gallium Arsenide (GaAs)

Intrinsic semiconductors

Extrinsic semiconductor

- dopants (impurities)

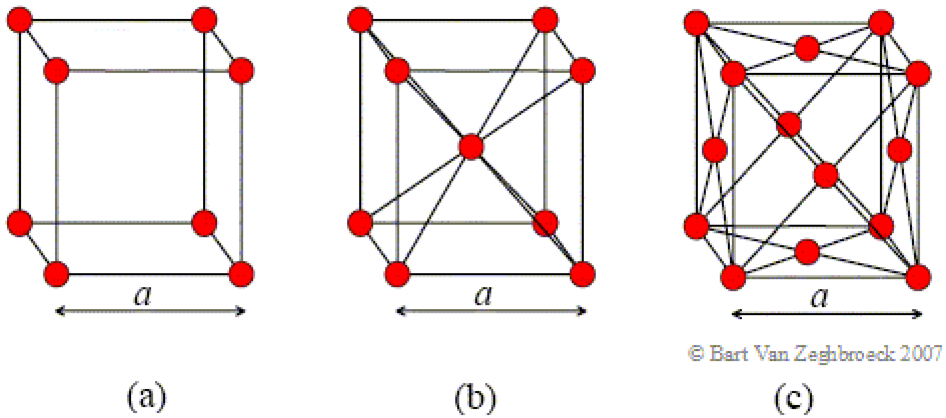


Which goes back to Koenigsburg observation:

Semiconductors properties vary with impurity and defects!

Semiconductors are also as a **crystalline material**, consisting of atoms arranged in a highly ordered pattern, called ***lattice*** (we shall discuss this little later).

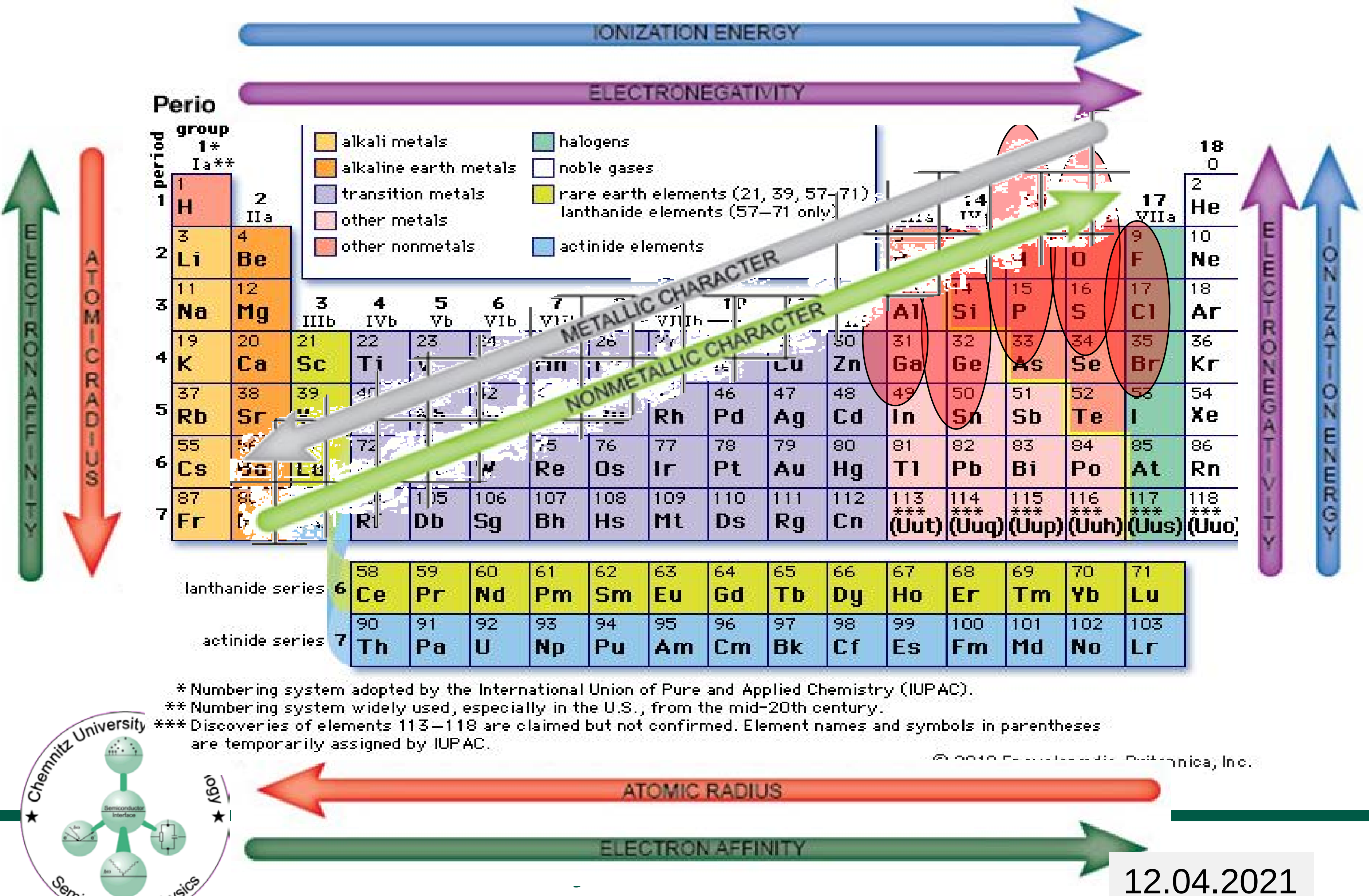
Typical Semiconductor Crystal Structures!



The simple cubic (a), the body-centered cubic (b) and the face centered cubic (c) lattice.

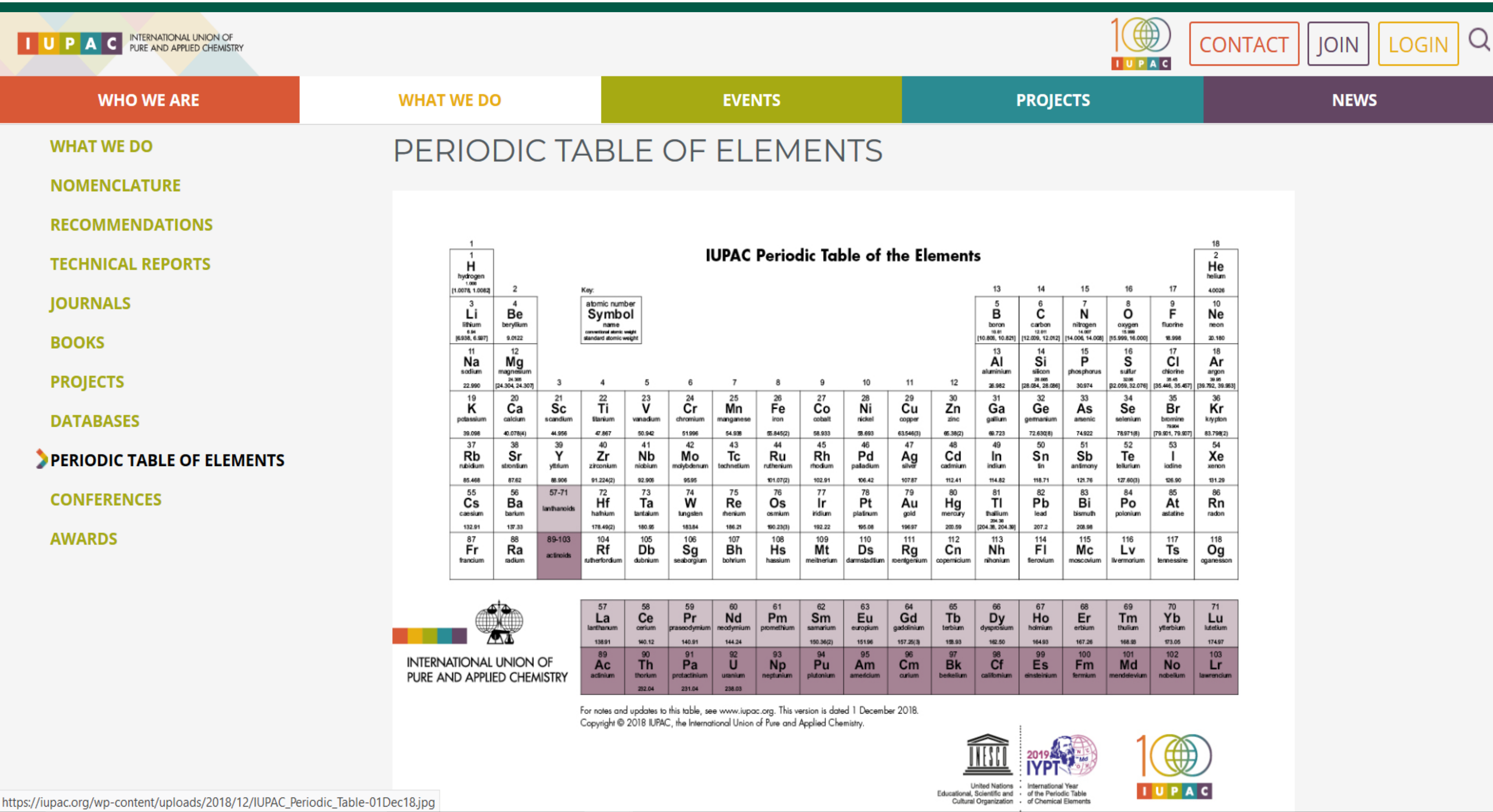
Though all materials may not be necessarily crystalline (could be either quasi crystalline or amorphous), but in the short-range or at the microscopic level, they are crystalline.

Once we treat the lattice as a periodic potential, we see remarkable properties that explain the physical nature of semiconductors.



IONIZATION ENERGY
ELECTRONEGATIVITY
ELECTRON AFFINITY
ATOMIC RADIUS
METALLIC CHARACTER
NONMETALLIC CHARACTER
alkali metals
alkaline earth metals
transition metals
other metals
other nonmetals
halogens
noble gases
rare earth elements (21, 39, 57–71)
lanthanide elements (57–71 only)
actinide elements
lanthanide series
actinide series
* Numbering system adopted by the International Union of Pure and Applied Chemistry (IUPAC).
** Numbering system widely used, especially in the U.S., from the mid-20th century.
*** Discoveries of elements 113–118 are claimed but not confirmed. Element names and symbols in parentheses are temporarily assigned by IUPAC.

IMPORTANT NOTICE! New IUPAC names:

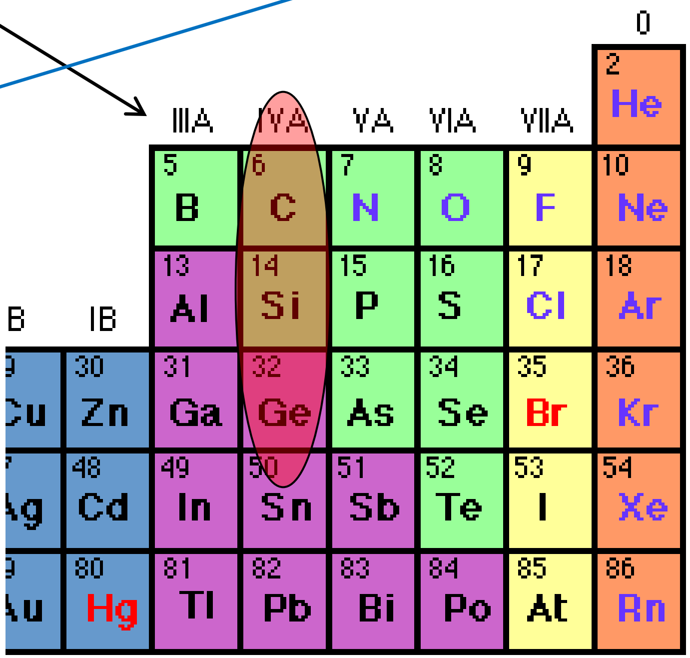


https://iupac.org/what-we-do/periodic-table-of-elements/

Old IUPAC notation BUT Semiconductors classified accordingly!

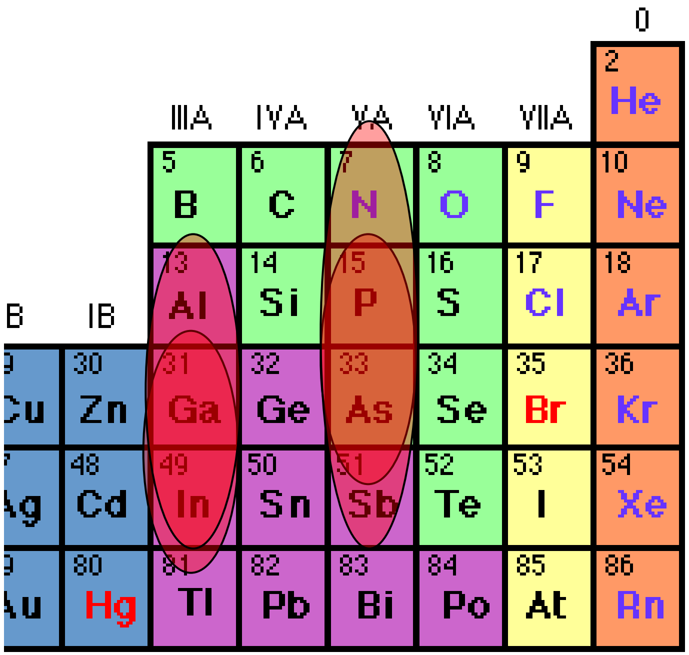
Elemental Semiconductors

Type	Elements	Bandgap (E_g) /eV
IV	C	5.3
IV	Si	1.1
IV	Ge	0.7
IV	SiC (binary compound)	2.8



Binary Compounds (covalent bonding)

Type	Elements	Bandgap (E_g) /eV
III-V	BN	5.2
III-V	AlN	6.3
III-V	GaN	3.4
	InN	0.7

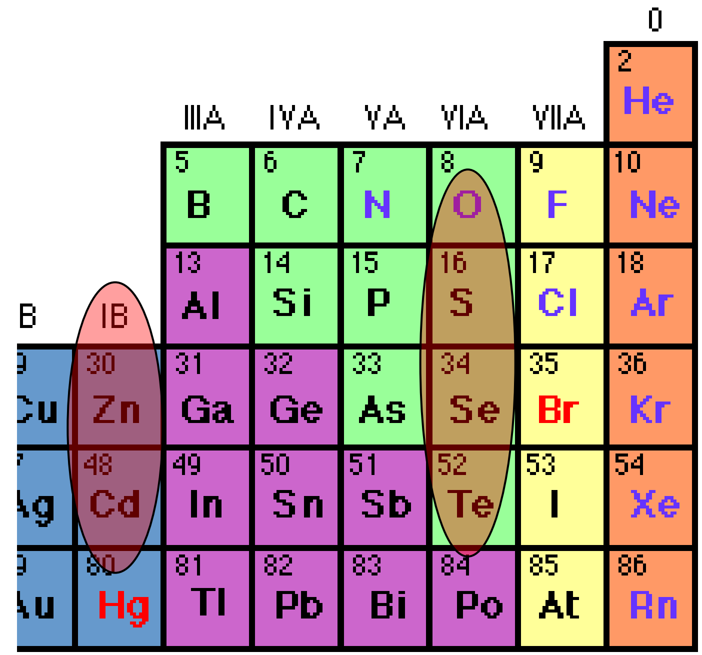


⇒ AlN (6.28), AlP (2.45), AlAs (2.15), AlSb (1.63), GaN (3.44), GaP (2.27), GaAs (1.43), GaSb (0.70), InN (0.77), InP (1.35), InAs (0.36), InSb (0.18)

⇒ **Tl** ← not used → **Bi**

Binary Compounds

Type	Elements	Bandgap (E_g) /eV
II-VI	ZnS	3.6
II-VI	ZnSe	2.7
II-VI	CdS	2.6
II-VI	CdSe	1.7
II-VI	CdTe	1.5



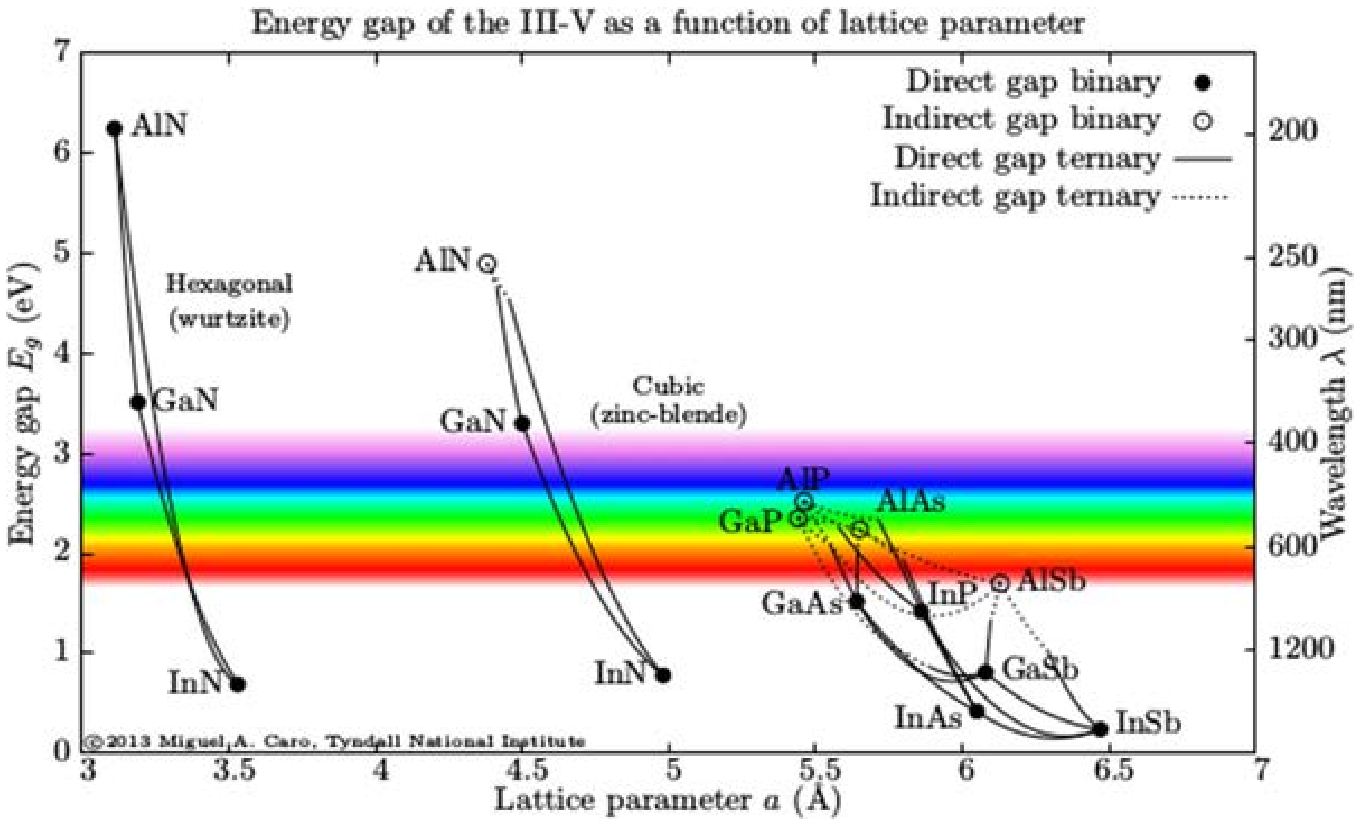
⇒ZnO (3.4), ZnS (3.68), ZnSe (2.7), ZnTe (2.26), CdS (2.48), CdSe (1.75), CdTe(1.43)

Mn -> sometimes used not used **<- Po**

Bandgap *vs.* Lattice constant

From binary to ternary compounds examples: AlGaN; AlGaAs; InGaAs

Semiconductor Master Graph



- ✓ Lines connecting two semiconductors indicate that some mixture of the two is possible, and how the lattice constant and the band gap will behave.
- ✓ The **GaAs** - **AsAl** case : the lattice constant does not change very much but the band gap changes from direct to indirect.
- ✓ The spectrum of light is schematically superimposed, to give some idea about the relation of the band gap energy to light color.

Oxides

- Most oxides are isolators;
- Current research in devolping semiconductor large band oxides for transparent electronics, e.g. ZnO, CuO, Cu_2O, Ga_2O_3 .

Layered Semiconductors

- Binary compounds with layered crystal structures such as: MoS_2, $MoSe_2$, GaSe, etc;
- bonding within the layers is typically covalent and much stronger than the bonding between the layers;
- behavior of electrons in the layers is quasi-two-dimensional.

It looks like we have a great selection of semiconductors and their mixtures to choose from.

BUT

Choosing is one thing, making the semiconductor of your choice is something else.

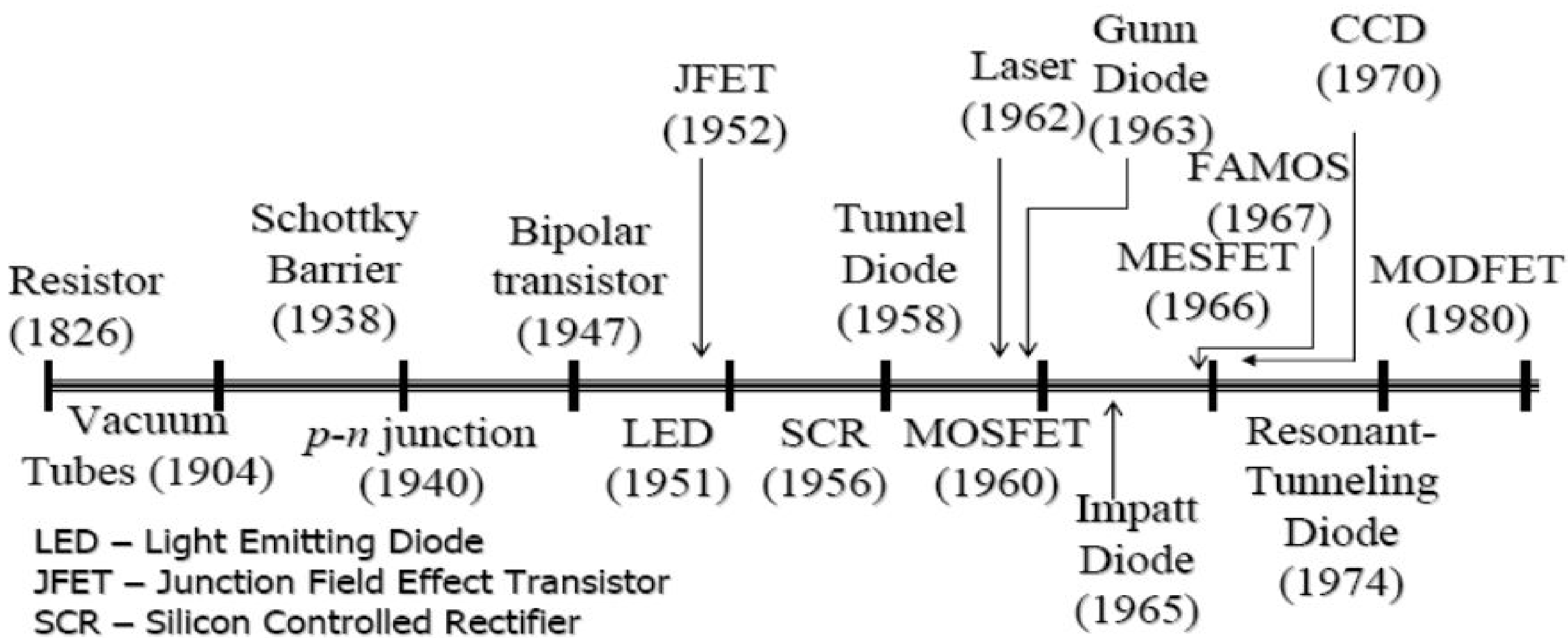
This where semiconductor technology comes in.

In reality, only a few of the many semiconductors shown in the Master Graph could be tamed to perform by now.

This is good news because it leaves something for us to do ☺ !

Applications as electronic components

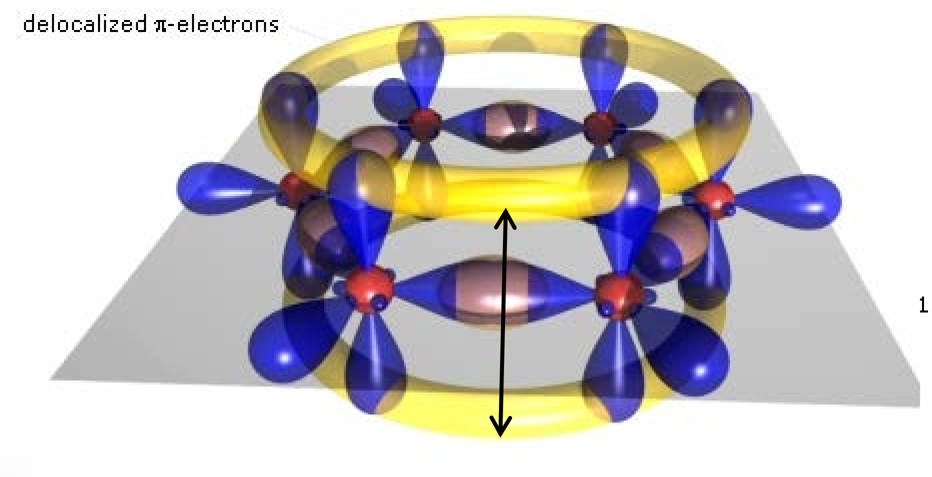
Semiconductor Materials

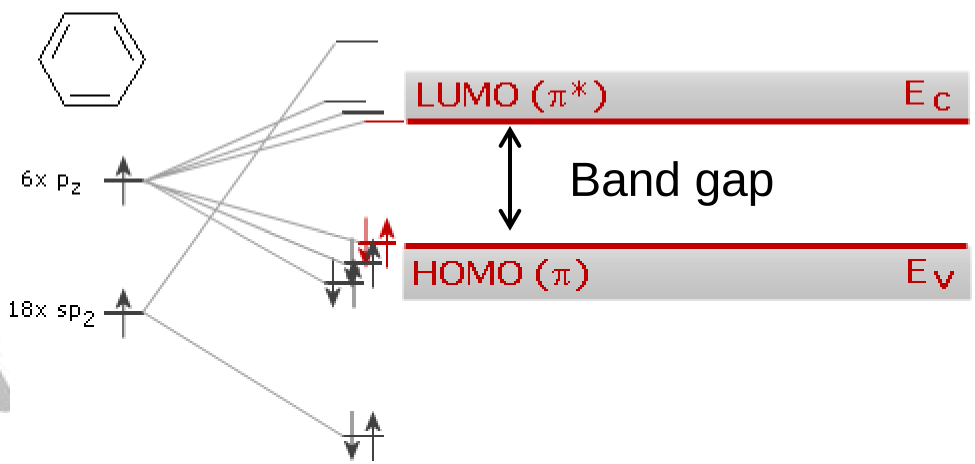


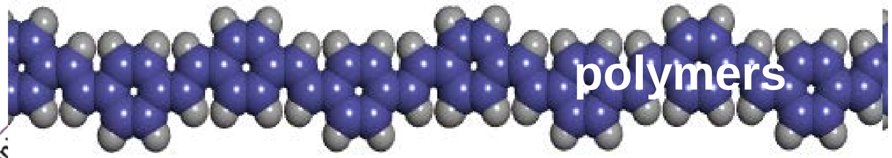
LED – Light Emitting Diode
JFET – Junction Field Effect Transistor
SCR – Silicon Controlled Rectifier
MOSFET – Metal-Oxide Semiconductor Field Effect Transistor
MESFET – Metal-Semiconductor Field Effect Transistor
FAMOS – Floating Gate Avalanche MOS
CCD – Charge-Couple Devices
MODFET – Modulation Doping Field-Effect Transistor

Organic Semiconductors

The **GAP** is between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO).







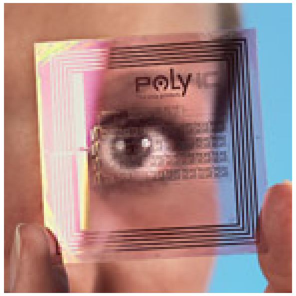
OLEDs & OFETs

Displays

Lightning

RFID

e-Paper



Organic Solar Cells

http://www.slideworld.org/viewslides.aspx/Organic-Semiconductor-and-its-applications-ppt-2100090

❑ Summary

~ 0.7 – 6 eV
IR – UV

--→ **BAND GAP** ←--

Semiconductors

Crystal structure & atomic size

Organic

Inorganic

- Direct
- Indirect

Cubic! ←--- inorganic

- Elemental
- Binary
- Ternary

- Intrinsic
- extrinsic

Purity & defects

Nr. of compounds

Covalent/ ionic bonding for binary and ternary compounds

Next lecture

CRYSTAL STRUCTURE