

Lecture SCT2 - Process Integration

2. Web-based virtual Lecture: April 22 2021
Prof. Dr. Johann W. Bartha

Inst. f. Halbleiter und Mikrosystemtechnik
Technische Universität Dresden

Summer Semester 2021

Start lecture here



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Lecture Semiconductor Technology I,
Prof. Dr. J. W. Bartha

Content

- 1. Introduction**
- 2. Silicon as Substrate Material**
 - 2.1 The Silicon Crystal
 - 2.2 Crystal Defects
 - 2.3 Conductivity and Doping
 - 2.4 Si as the most important material of Microelectronics
 - 2.4.1 Fabrication of pure Silicon
 - 2.4.2 Si Wafer Fabrication
- 3. The Oxidation of Silicon**
 - 3.1 Growth model after Deal and Grove
 - 3.2 Dependency on Process parameters
 - 3.3 Oxidation technique
 - 3.4 Stress and Oxidation
- 4. Lithography**
 - 4.1 Process sequence
 - 4.1.1 Negative Resist
 - 4.1.2 Positive Resist
 - 4.2 Multi-Layer Resists
 - 4.3 Image Reversal
 - 4.4 Pattern Enhancement
- 5. Doping**
 - 5.1 Diffusion
 - 5.1.1 ...from an infinite Source
 - 5.1.2 ...from a finite Source
 - 5.1.3 Two step Diffusion
 - 5.1.4 Further Effects
 - 5.1.5 Practical Realization
 - 5.2 Implantation
 - 5.2.1 Projected Range
 - 5.2.2 Implantation - Mask
 - 5.2.3 Channeling
 - 5.2.4 Further Effects
 - 5.2.5 Healing and Activation
 - 5.2.6 Implantation Systems

- 6. Epitaxy**
 - 6.1 Gas Phase Epitaxy
 - 6.1.1 Uniformity
 - 6.1.2 Reaction Kinetics
 - 6.1.3 Monocrystalline vs. Polycrystalline
 - 6.1.4 Pattern Displacement
 - 6.1.5 Doping
 - 6.1.6 Epi-Reactor + Process
 - 6.1.7 Selective Epitaxy
 - 6.2 Molecular Beam Epitaxy

- 7. Chemical Vapor Deposition CVD**
 - 7.1 Poly-Silizium
 - 7.2 Siliconoxide SiO_2
 - 7.3 Silicon nitride Si_3N_4
 - 7.4 PECVD
 - 7.5 Tungsten W

7.6 ALD

- 8. Plasma based Deposition and Etch**
 - 8.1 Plasma technology
 - 8.1.1 Basic Processes in a Plasma
 - 8.1.2 Energy Absorption by the Electric Field
 - 8.1.3 Plasma Properties
 - 8.1.4 Plasma Generation
 - 8.2 Sputter Deposition
 - 8.2.1 Sputter Deposition of Alloys
 - 8.2.2 Reactive Sputtering
 - 8.2.3 Magnetron Sputtering
 - 8.2.4 Bias-Sputtering
 - 8.3 Plasma induced Etching
 - 8.3.1 Sputter-Etching
 - 8.3.2 Plasma Induced Chemical Etching
 - 8.3.3 Reactive Ion Etching
 - 8.3.4 Process Parameters
 - 8.3.5 Plasmatools

ECD + CMP

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| | Lect |
| 1. | Introduction |
| 2. | Silicon as S |
| 2.1 | The Silicon C |
| 2.2 | Crystal Defec |
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| 5.2.4. | Further Effec |
| 5.2.5. | Healing and |
| 5.2.6. | Implantation |

- 0. Introduction/Lab organization/DMA/SCT1/Motivation
- 1. Process integration
 - 1.MOS Structure, MOS Capacitor
 - 2.Structure of a MOSFET
 - 3.I/V behaviour
- 2. Circuits in Metal-Gate FET Technology
 - 1.Process sequence of N-MOSFET in Metal Gate
 - 2.From inverter to memory cell
 - 3.SRAM in NMOS Metal Gate
 - 4.The threshold voltage of the MOSFET
 - 1.Parasitic FET
 - 2.Enhancement/Depletion Transistor
 - 3.N-MOS Logic by E/D Transistors
 - 4.Process sequence of the N-MOS E/D Process
- 3. Self aligned Process
 - 1.Metal Gate -> Si Gate
 - 2. Channel-Stop & LOCOS Technology
 - 1.Example: Process flow of E/D SiGate LOCOS Inverter
 - 2.LOCOS Variation
 - 3.Shallow Trench Isolation
 - 3.Lightly doped drain
 - 4.SALICIDE
 - 5. Self Aligned Contacts (SAC)
 - 6. Resist trimming
- 4.Transition to CMOS Technology
 - 1.MOS Transistor Types
 - 2.CMOS Inverter
 - 1.Consideration NMOS E/D Inverter
 - 2.Comparison CMOS Inverter
 - 3.CMOS Process flow (Example CMOS 180 nm process)
- 5. Further Considerations
 - 1. Scaling
 - 1. Challenges
 - 2.Material Equivalent Scaling
 - 3.Further Concepts

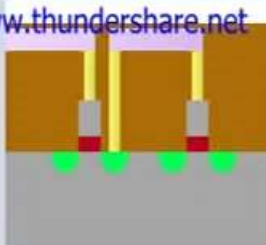
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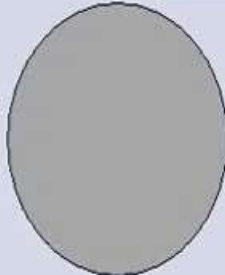
| | | | | | | | | |
|--------|-----------------------------------|---------------------------|---------------------------|-----------------------|-----------------------------------|---------------------|--|-----------------|
| | Clean | Oxidation | Photo Resist | Pattern | Etch | Ion Implantation | Control Panel <input checked="" type="radio"/> Aluminum <input type="radio"/> Copper Run Also Next Step | |
| Resist | Click on a machine to see details | | | | | | | Finished Wafers |
| | Photo Resist Strip | Chemical Vapor Deposition | Physical Vapor Deposition | Barrier / Copper Seed | Chemical Mechanical Planarization | Copper Electroplate | | |

Wafer Ready for Processing

Semiconductor devices are manufactured using a precise, but repetitive process. The process begins with a thin slice of silicon, called a wafer. Many devices are constructed on each wafer, and are later separated and packaged. These processes take place in a highly-filtered cleanroom.


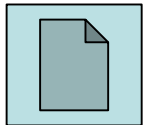
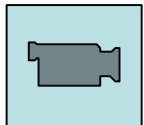


Wafer Side View



Wafer Top View

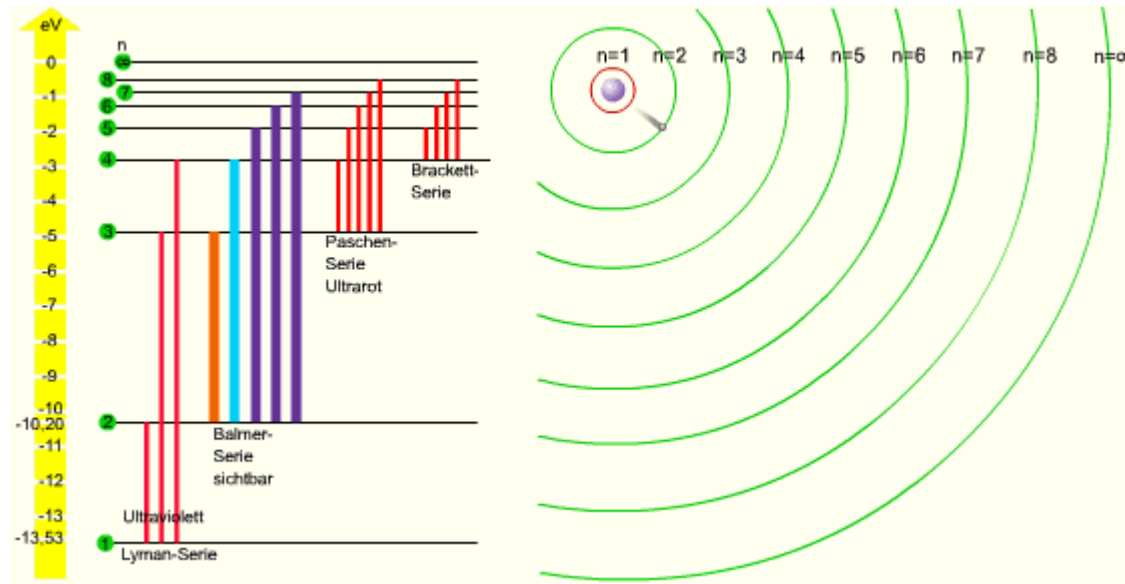
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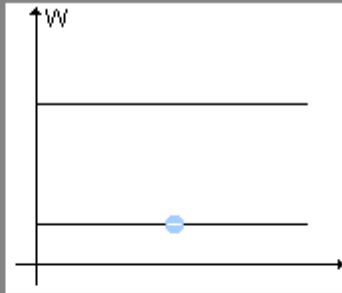
This chapter is not listed in the outline!



Energy states of electrons in atoms



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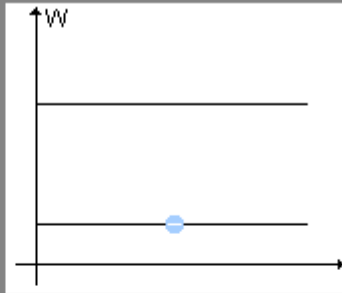
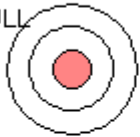


Zero
Temp

v0.9a / UniBw HH

<http://smile.unibw-hamburg.de/smile/toc.htm>

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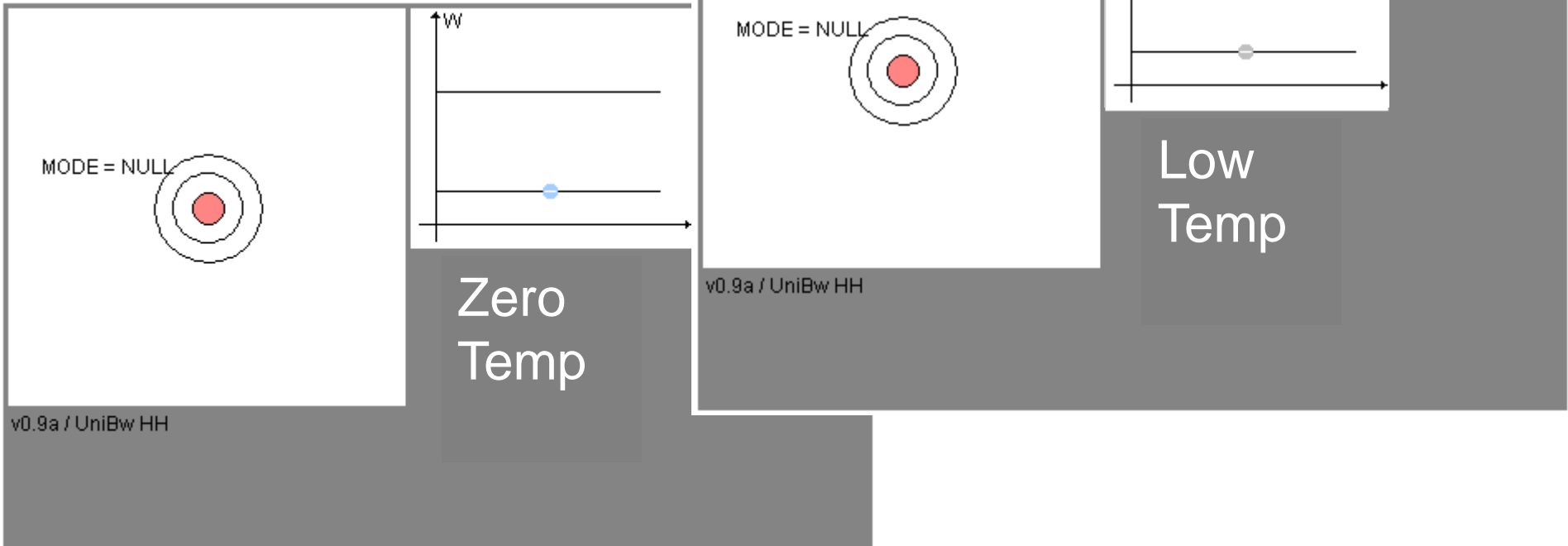


Zero
Temp

v0.9a / UniBw HH

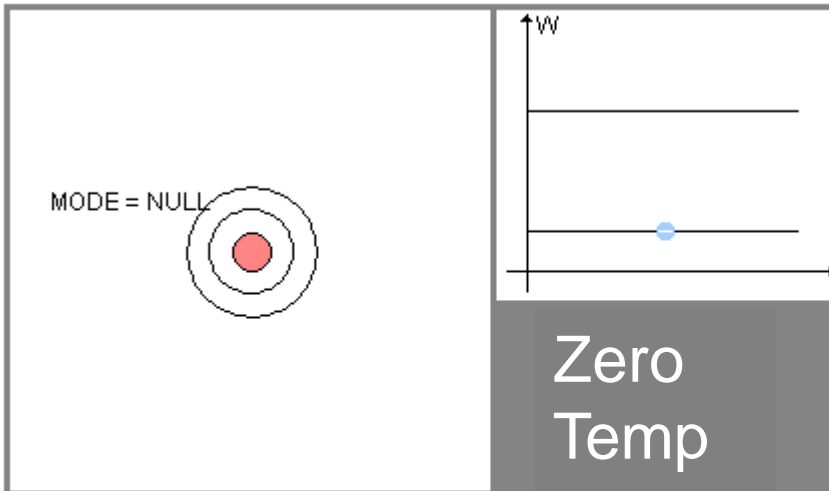
<http://smile.unibw-hamburg.de/smile/toc.htm>

Temporary occupation
of states depends on
temperature
 $3/2kT(RT)=25meV$



<http://smile.unibw-hamburg.de/smile/toc.htm>

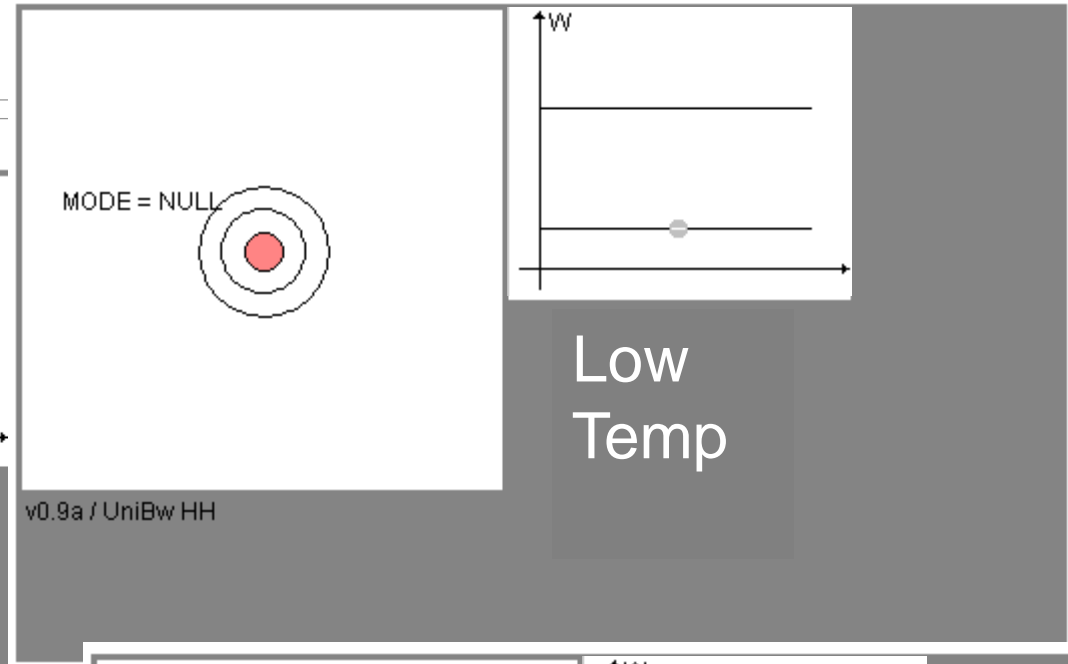
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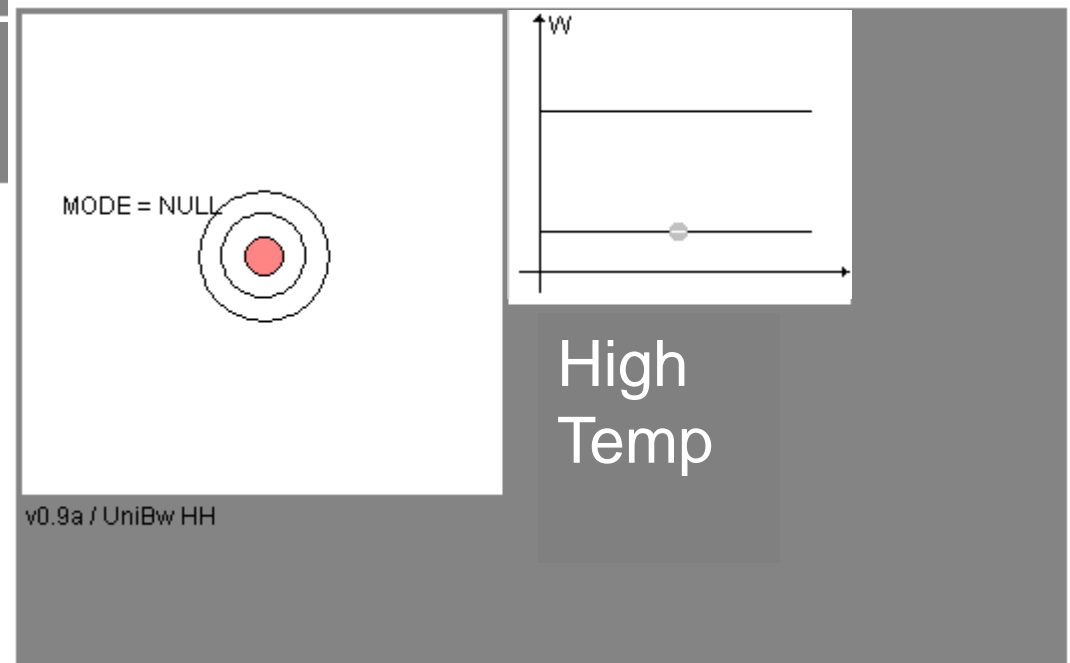
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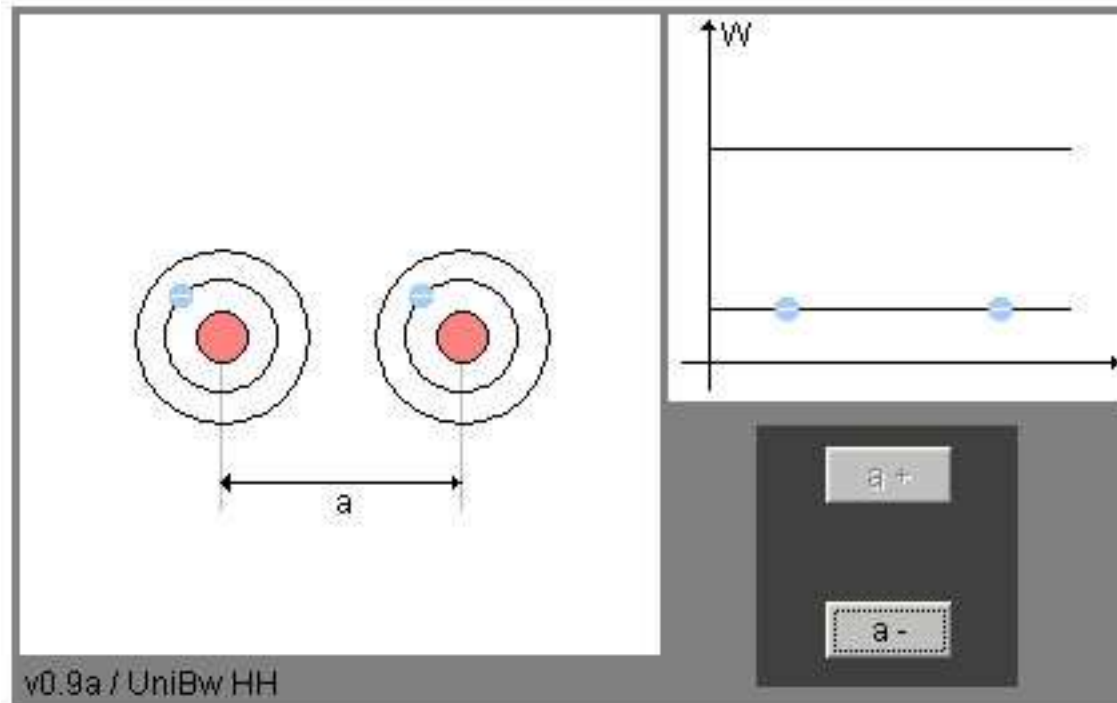


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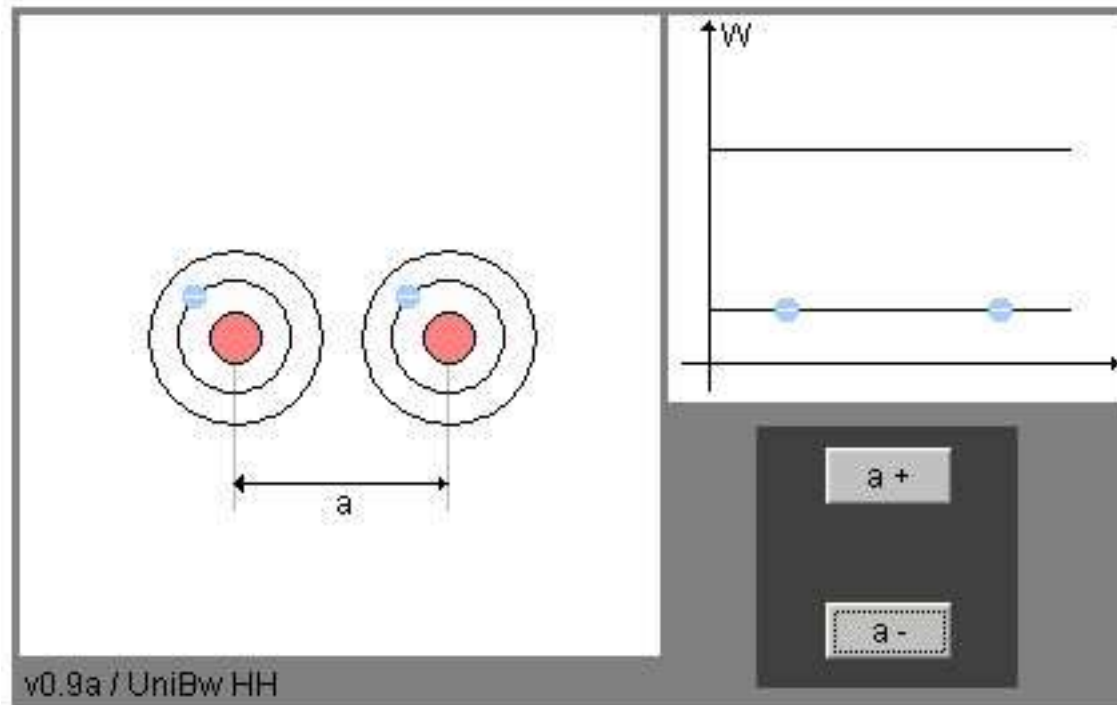


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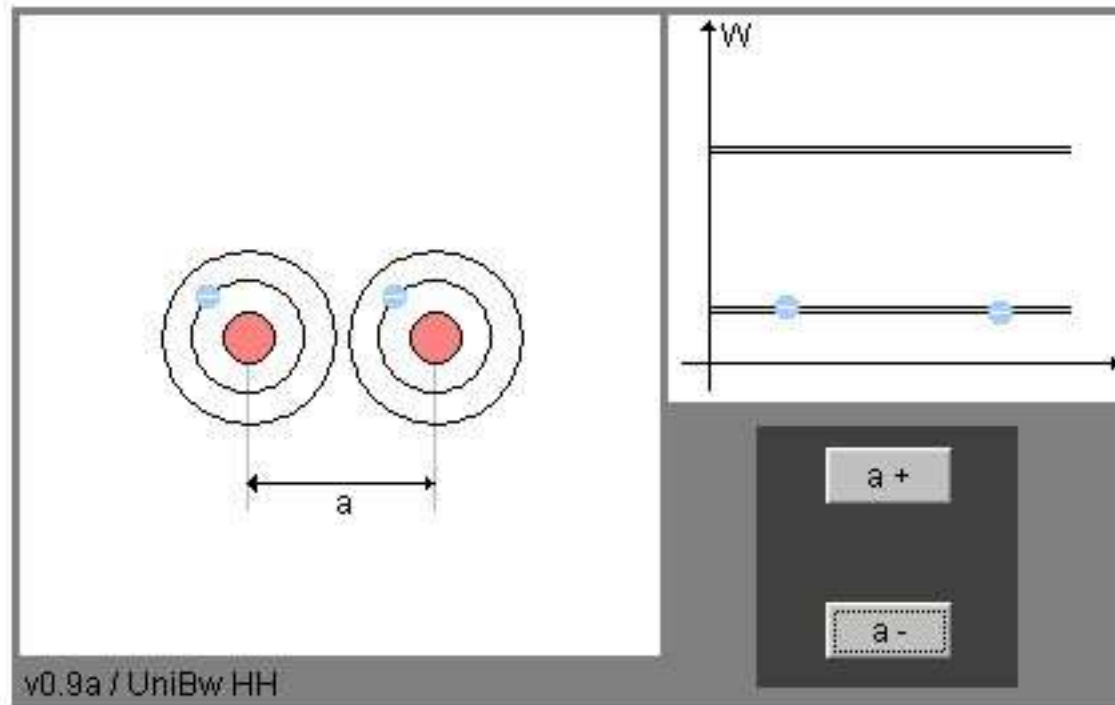
Interaction of atoms causes splitting of energy states



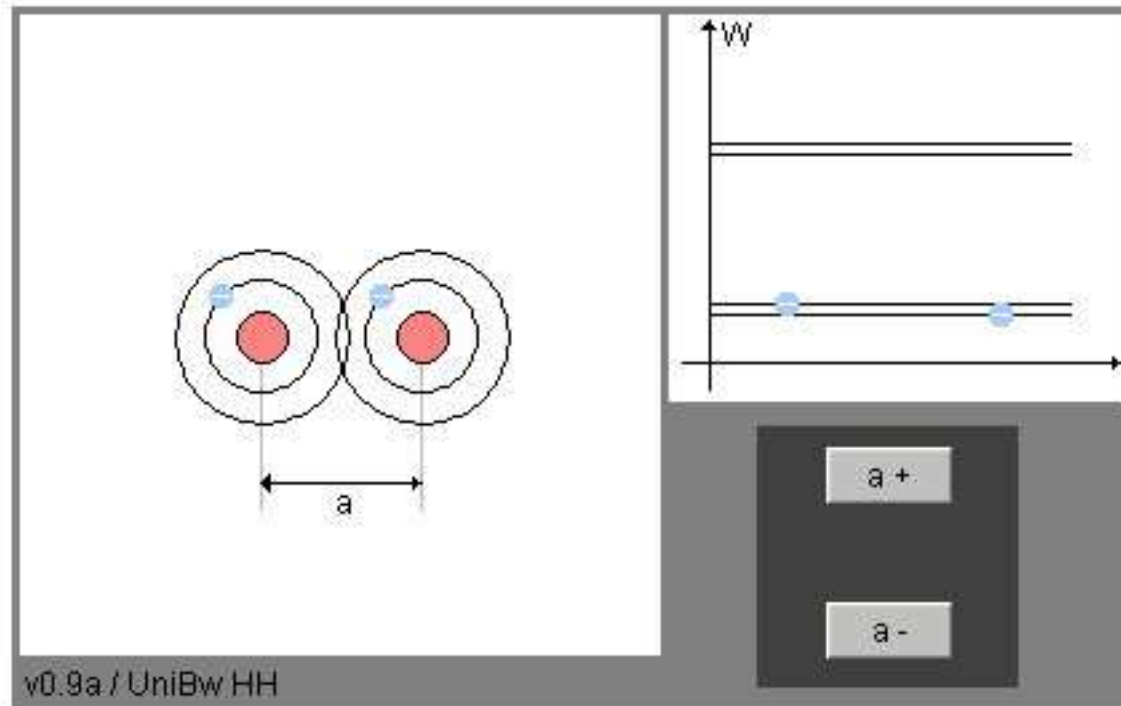
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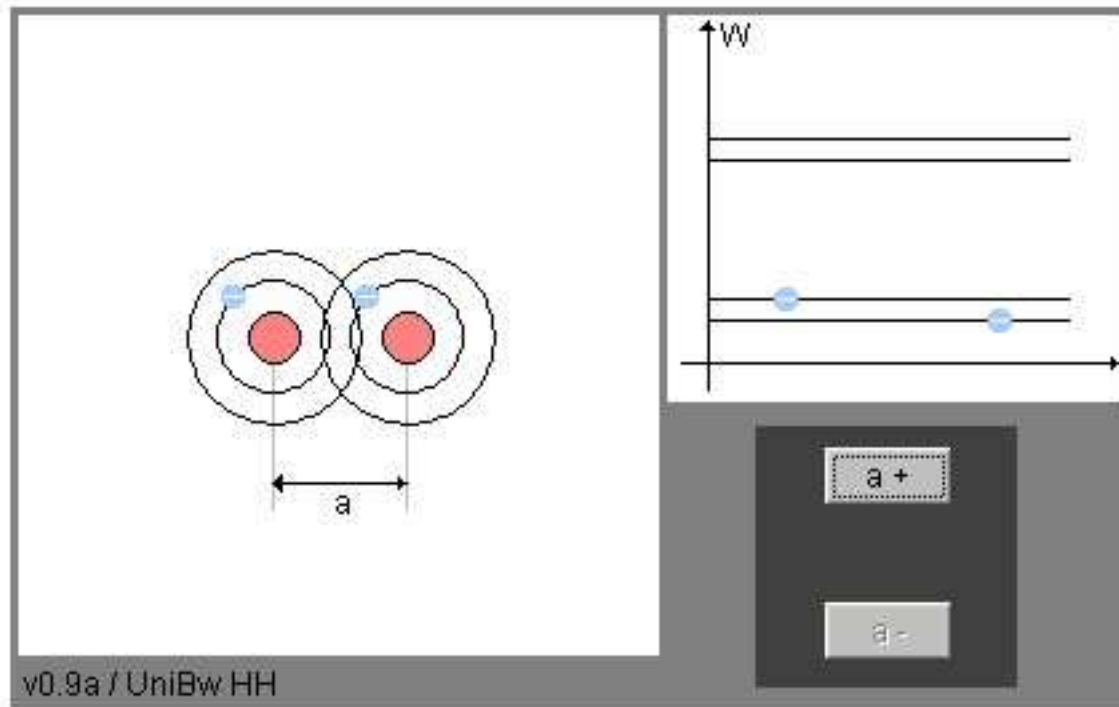
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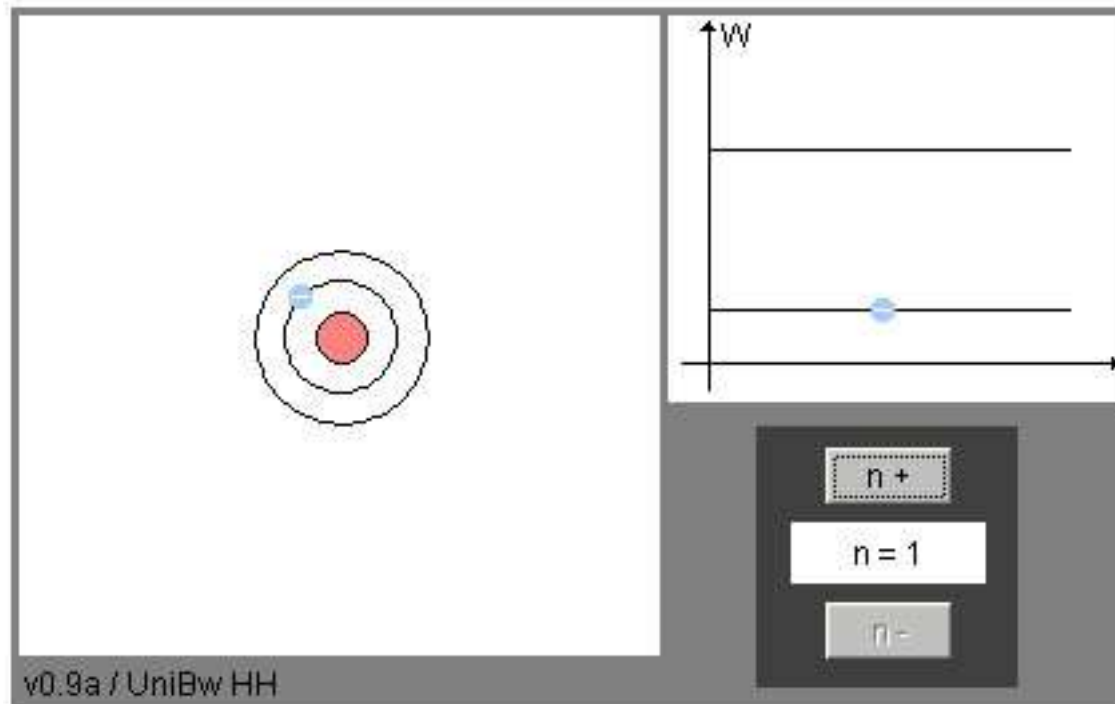
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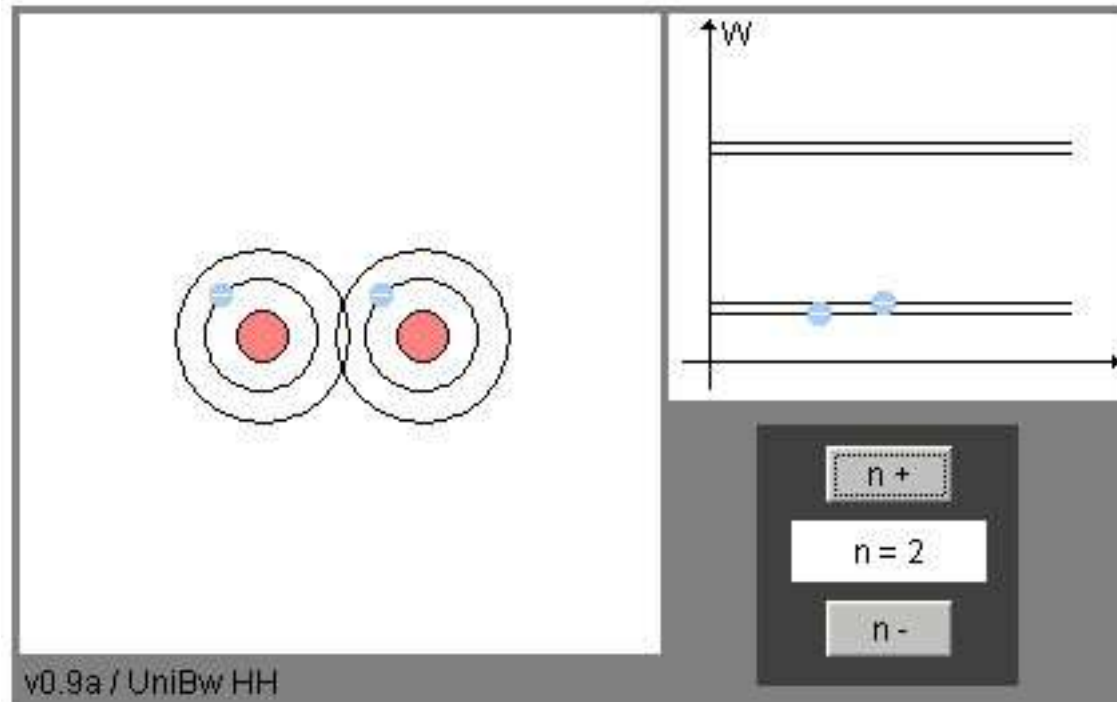
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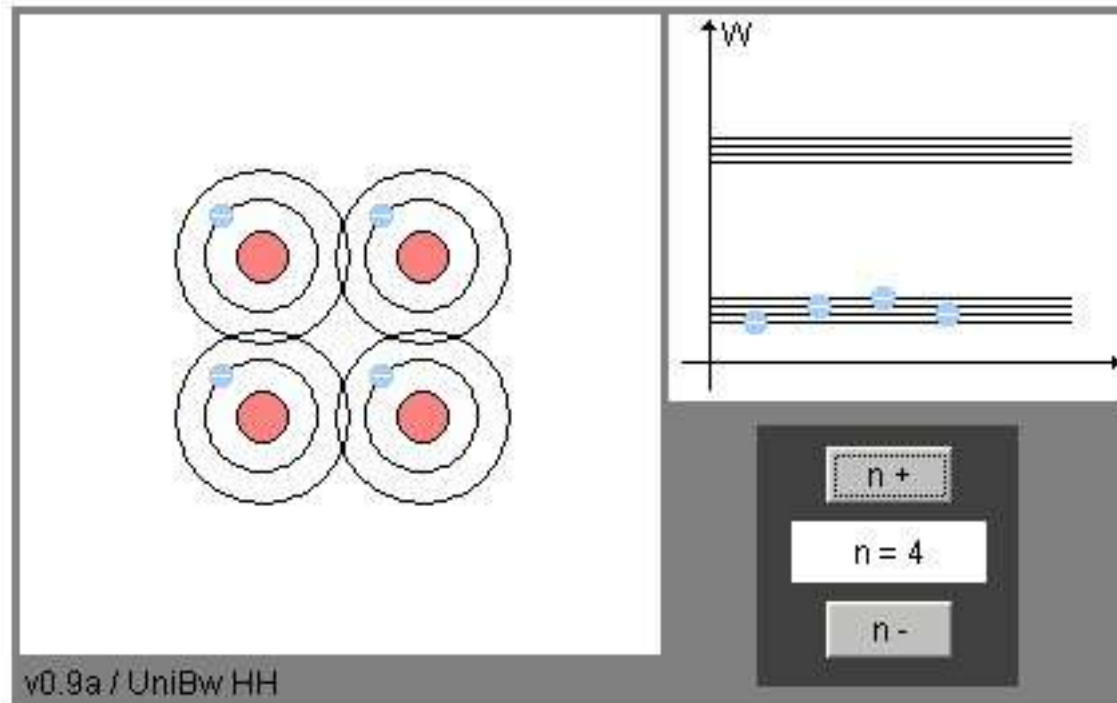
Transition from states in atoms to bands in solids



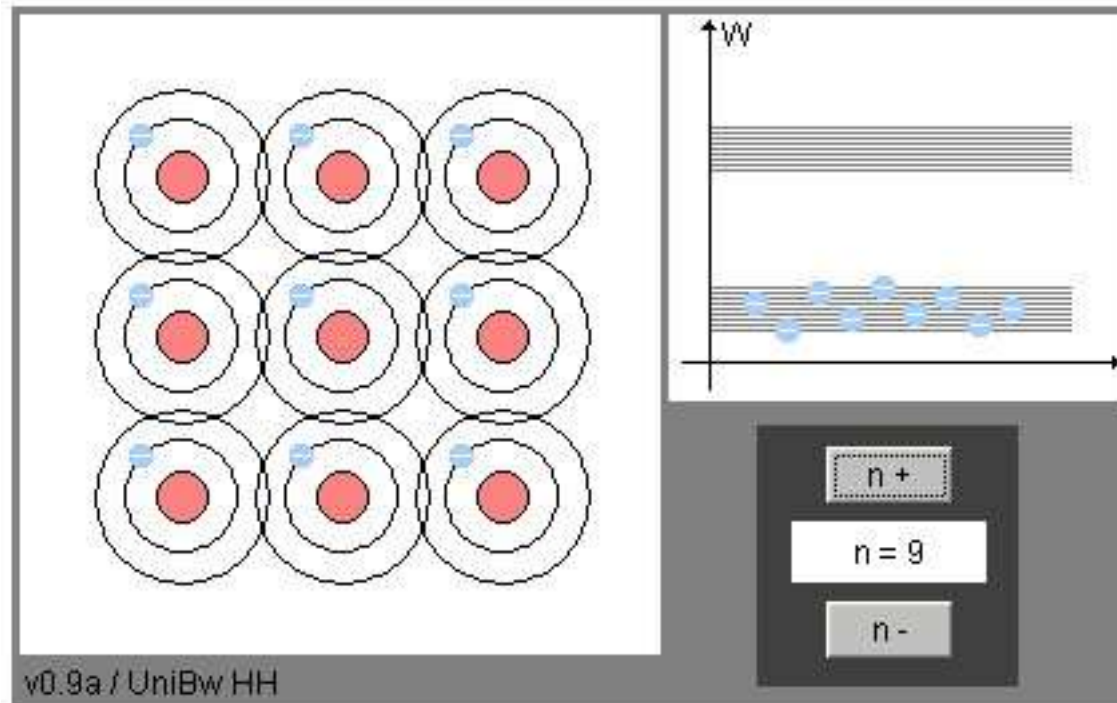
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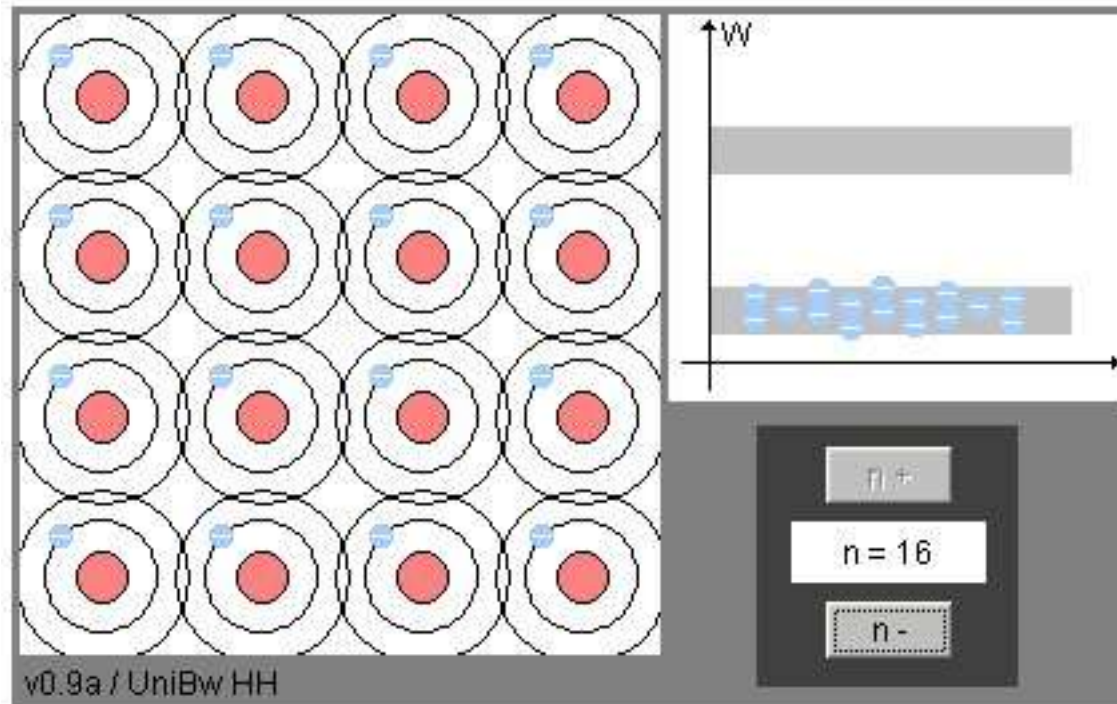
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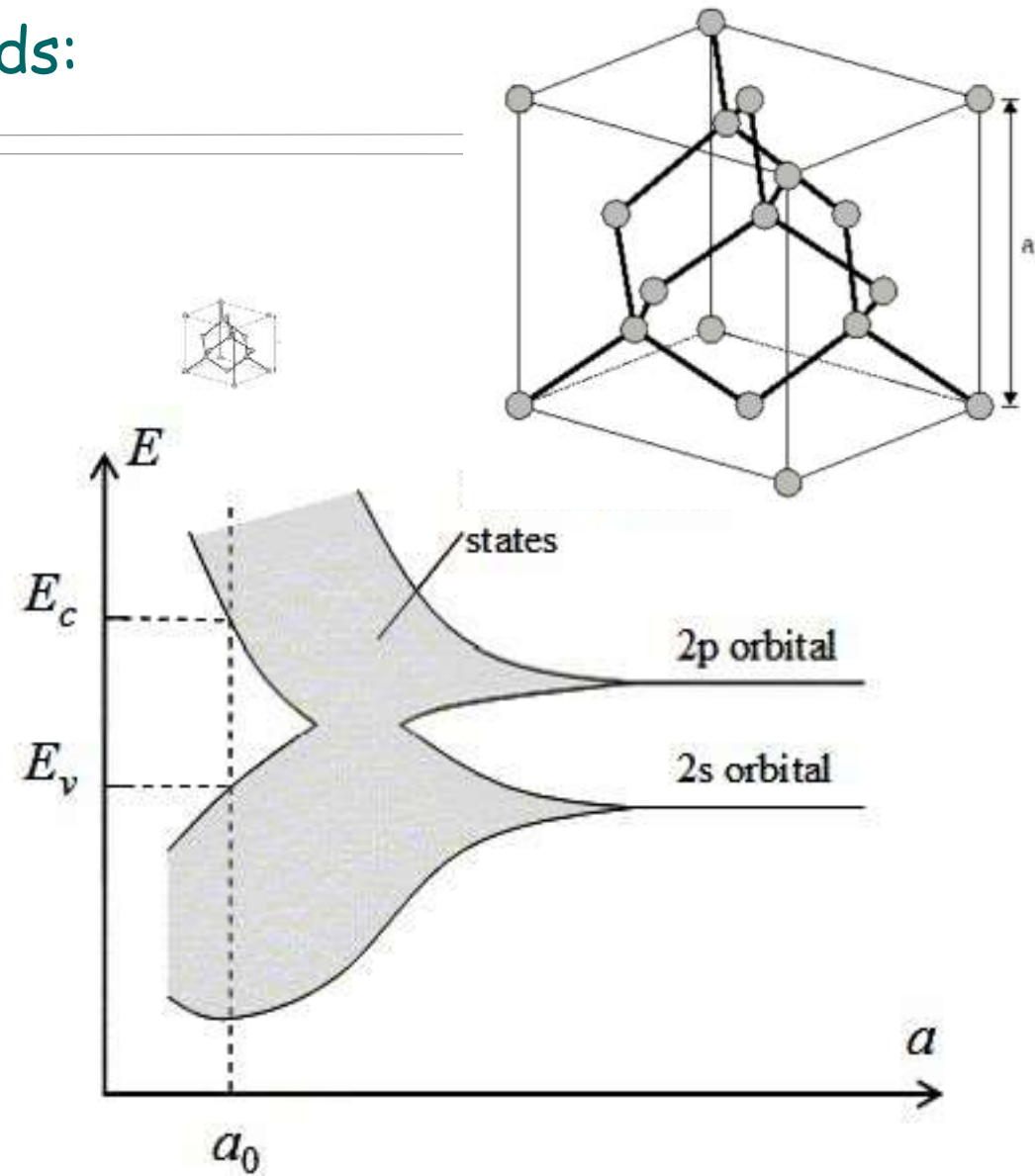
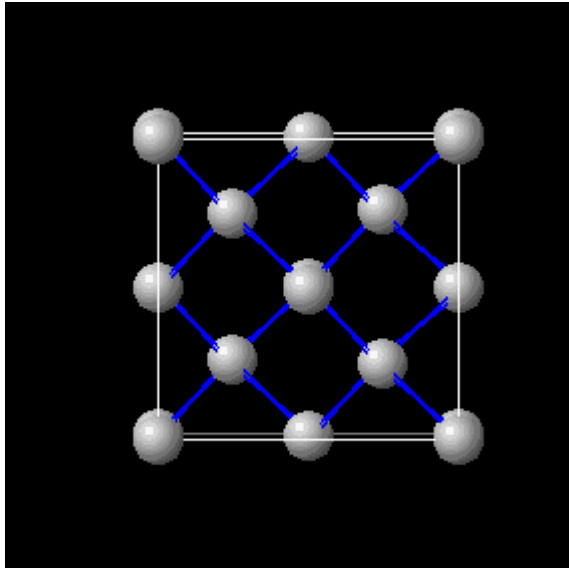
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Transition from states in atoms to bands in solids

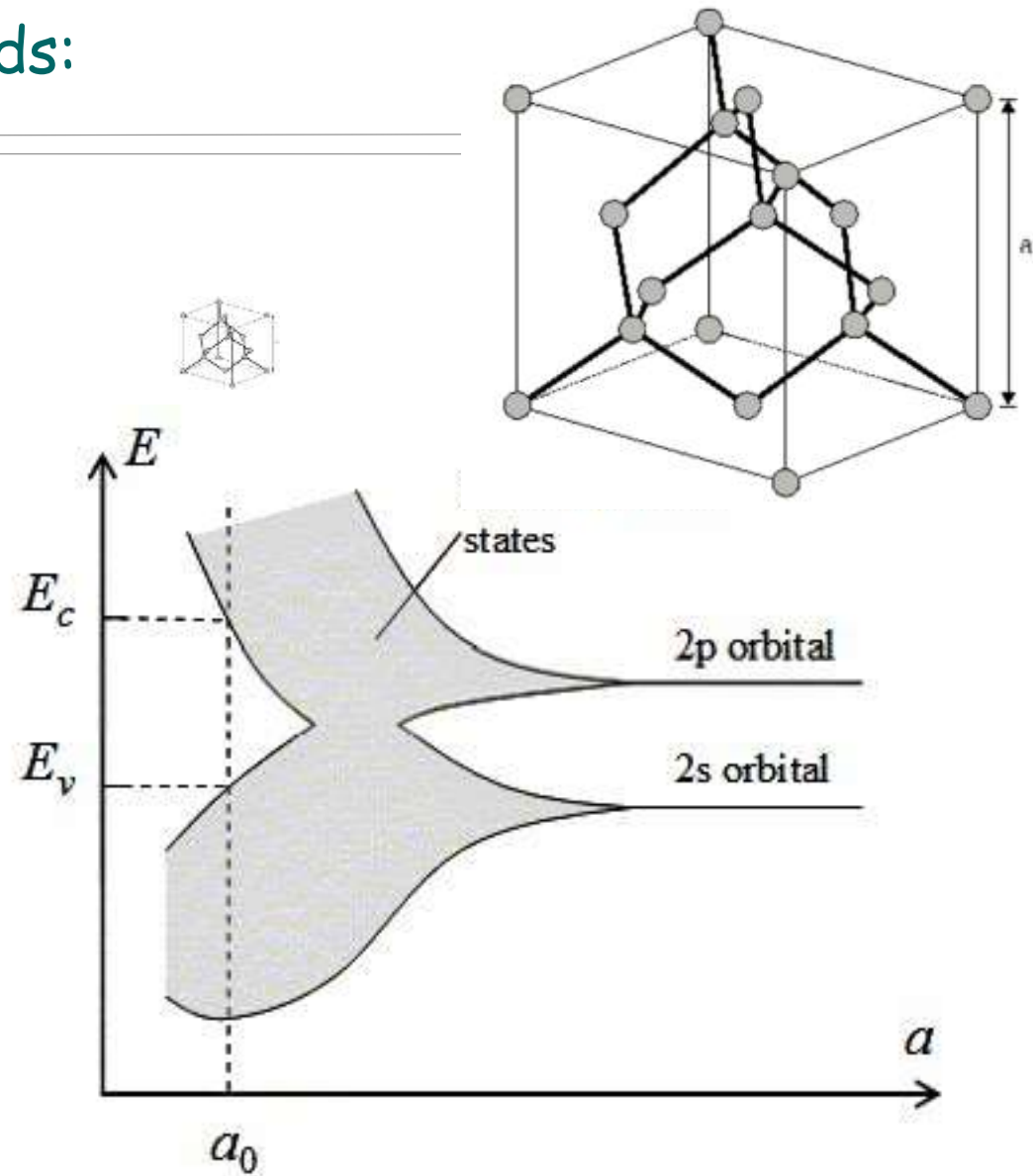
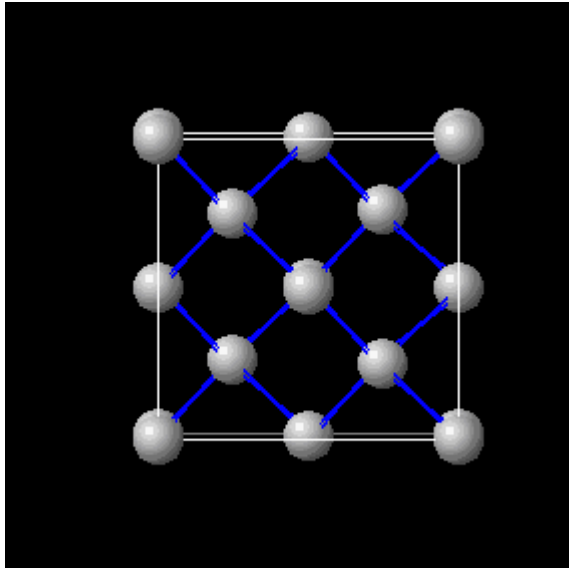


Origin of bands:



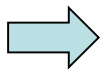
Energy bands for diamond versus lattice constant.

Origin of bands:

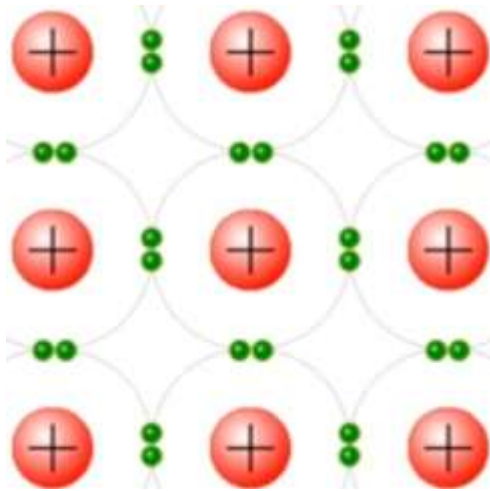


Energy bands for diamond versus lattice constant.

Continue

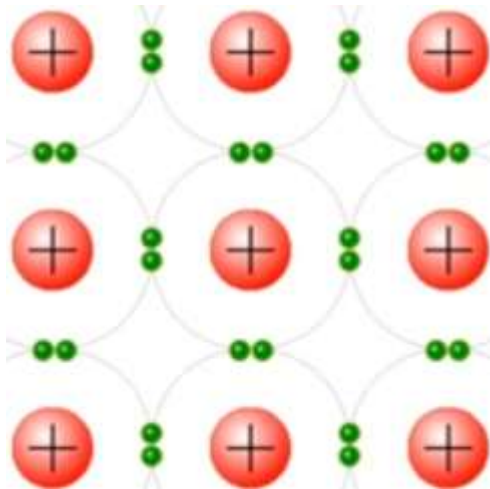


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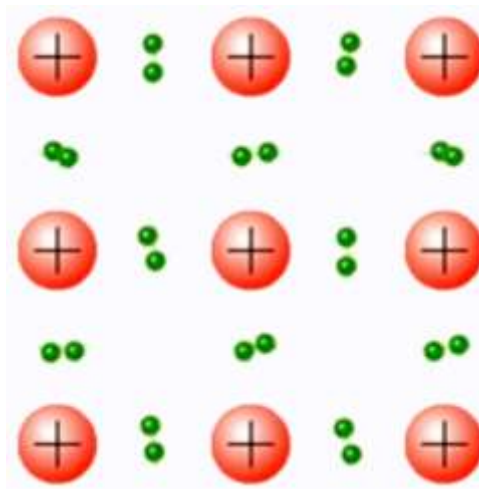


$T=0K$

Considering one material
at different temperatures



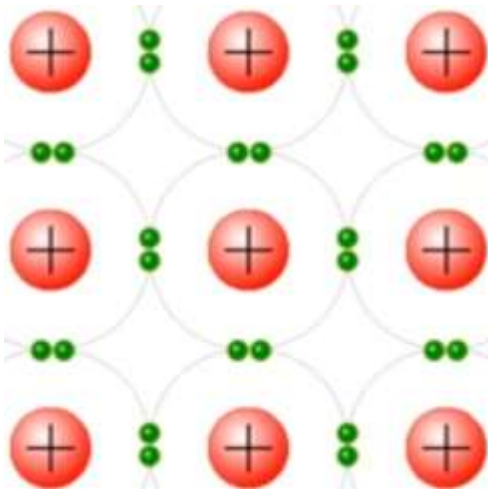
$T=0K$



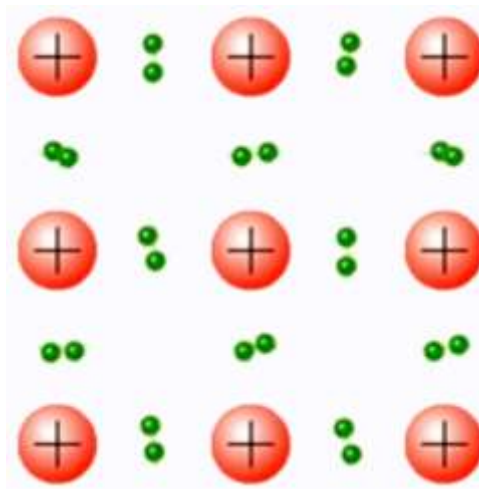
$T=low$

Considering one material
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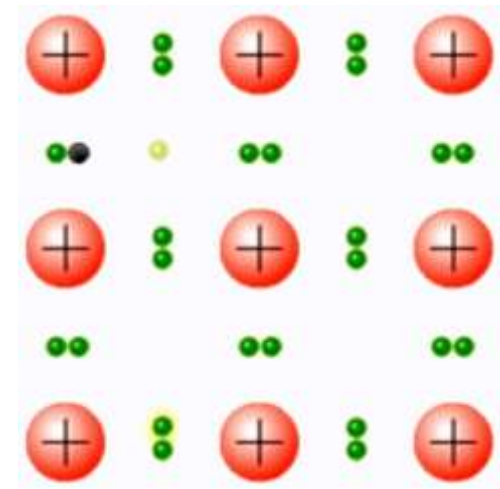
Situation of the valence electrons



$T=0K$



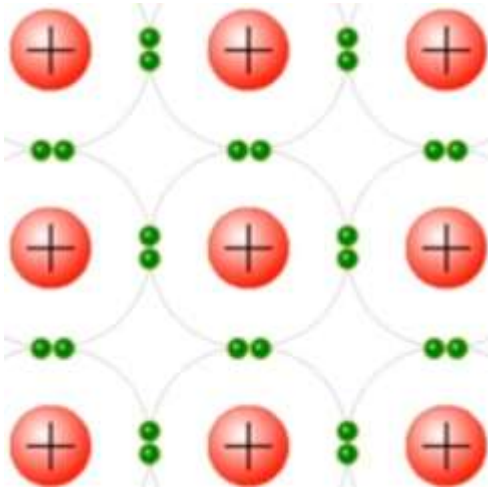
$T=low$



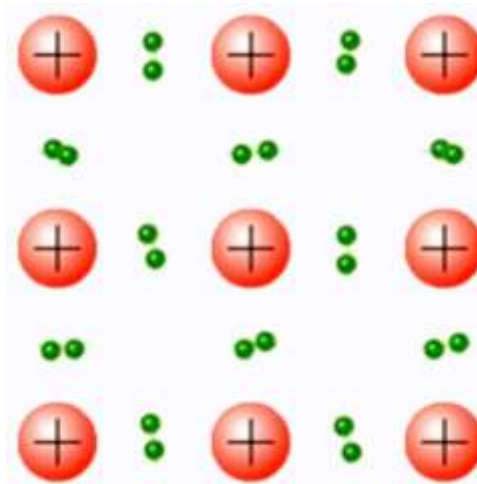
$T=higher$

Considering one material
at different temperatures

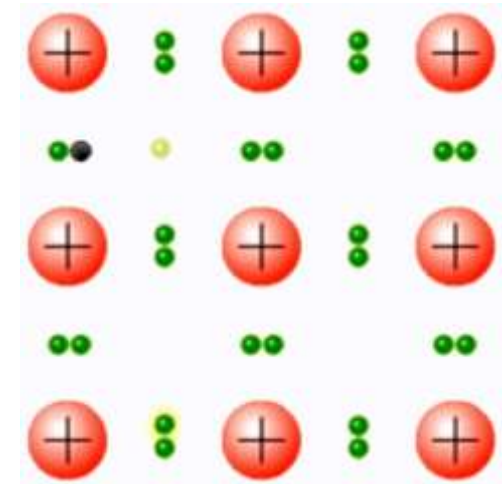
Situation of the valence electrons



$T=0K$



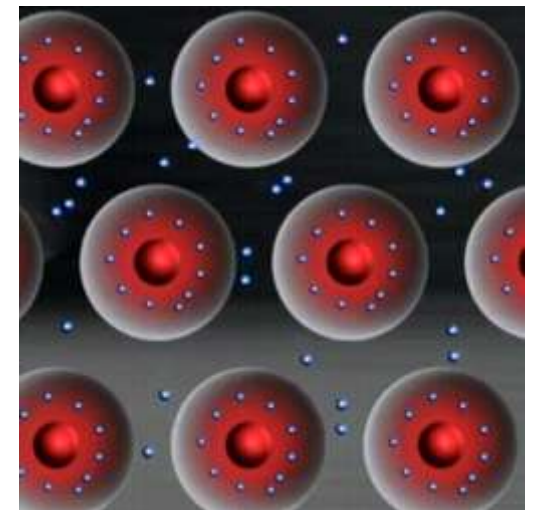
$T=low$



$T=higher$

Considering one material
at different temperatures

$T=very\ high$

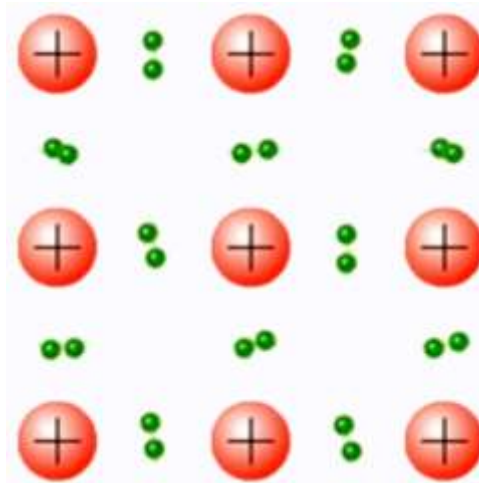


Or fixing T at
room emperature
($\sim 300\text{K}$) and

considering
different kind of
materials with
different binding
energies of the
valence electrons

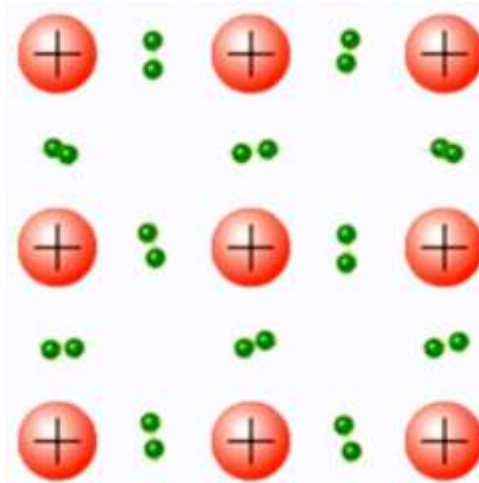
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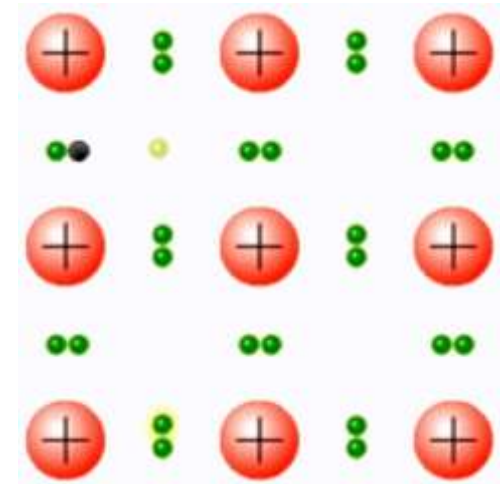
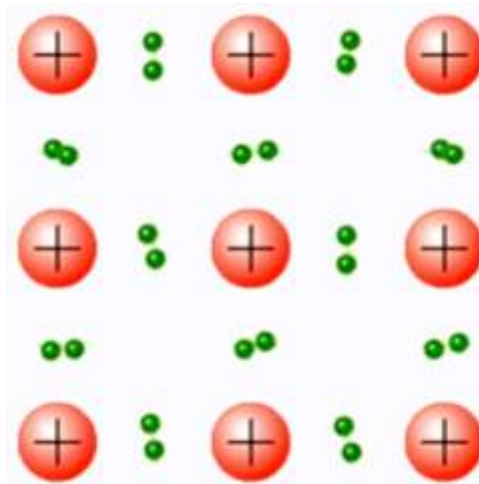
considering
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Insulator

Or fixing T at room emperature ($\sim 300\text{K}$) and

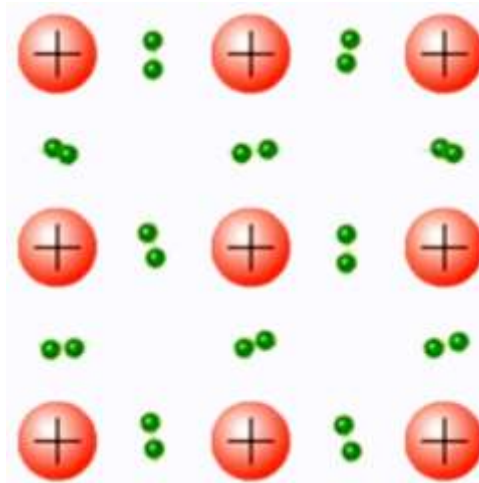
considering different kind of materials with different binding energies of the valence electrons



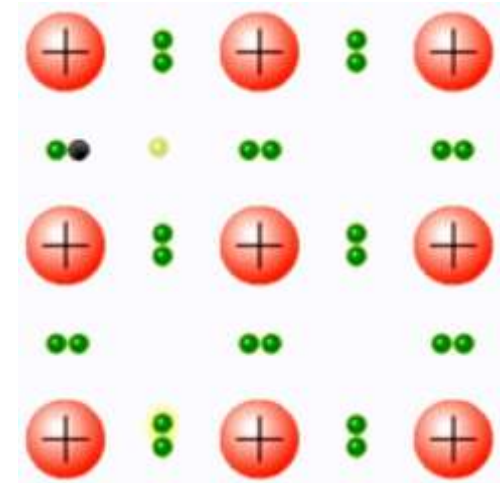
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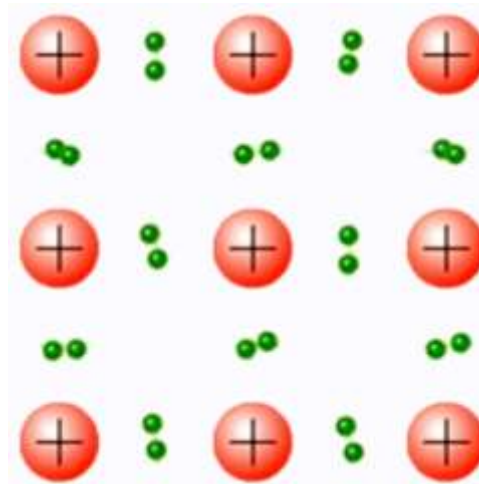
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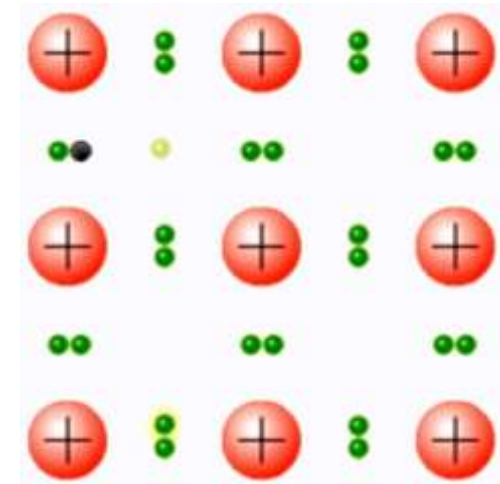
Semiconductor

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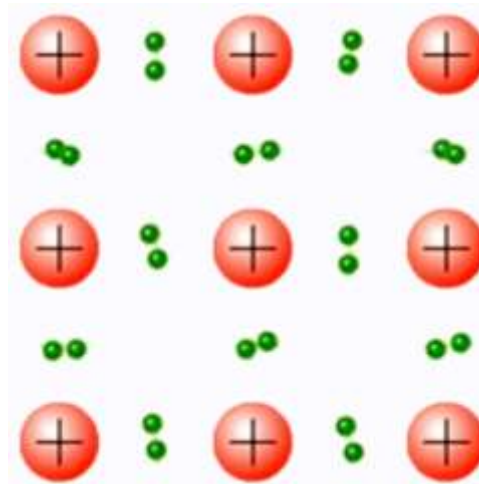
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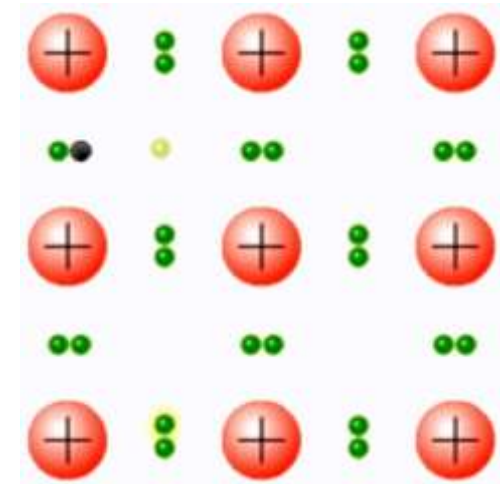
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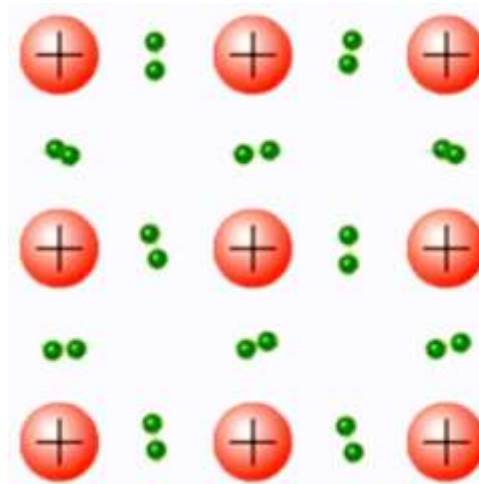
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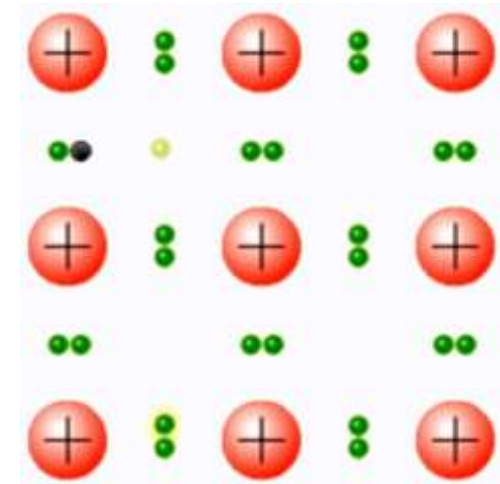
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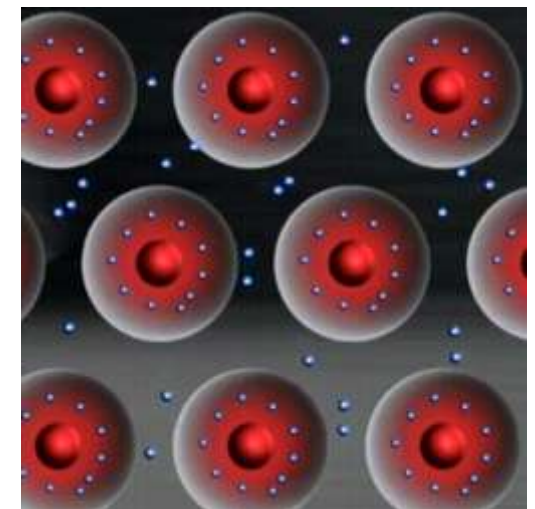


Insulator

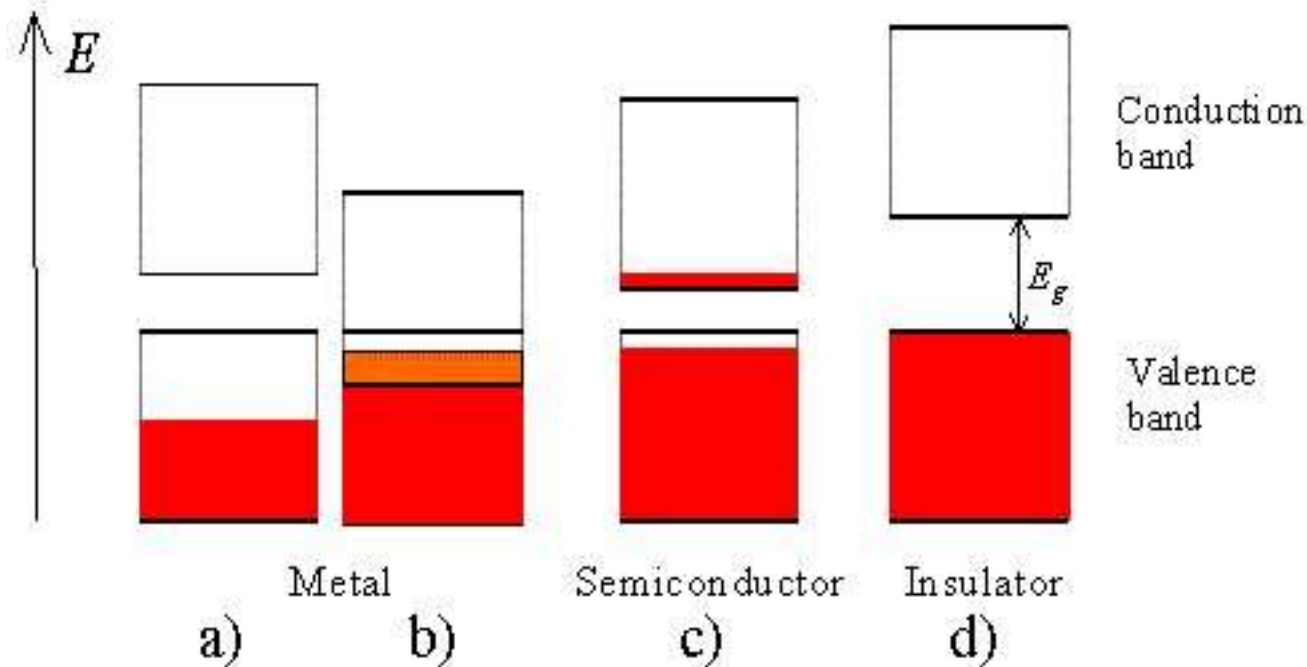


Semiconductor

Metal

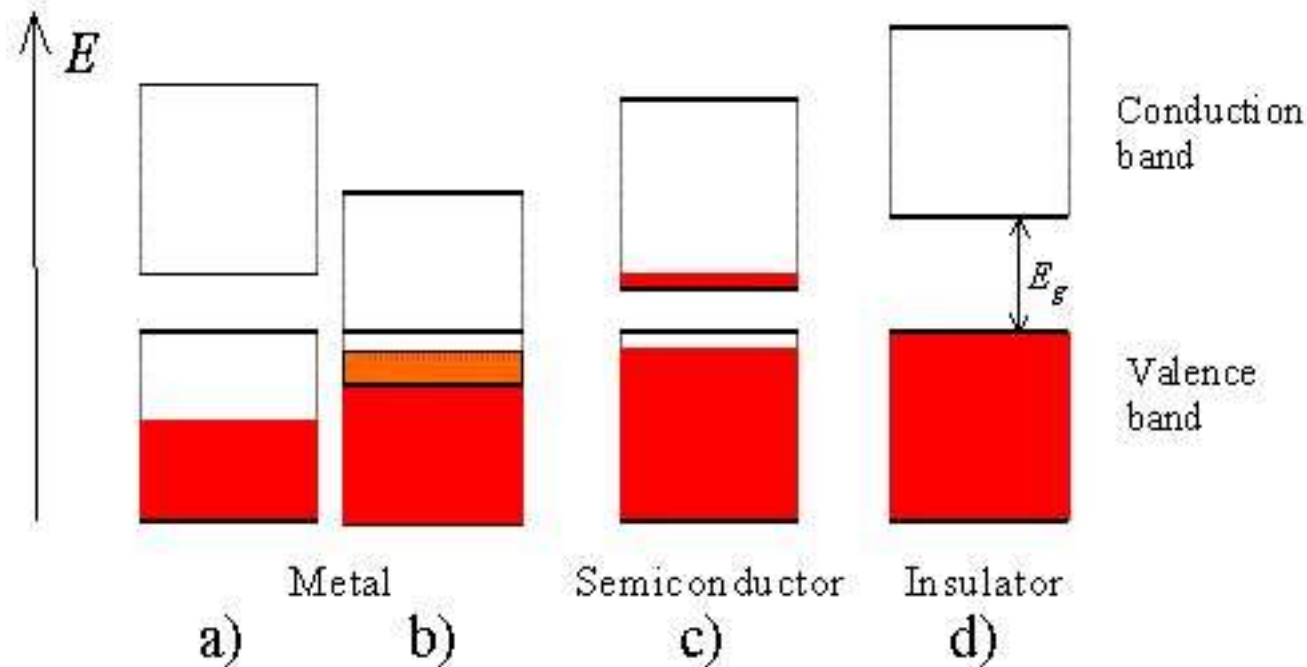


Electrical conductivity and bandgap



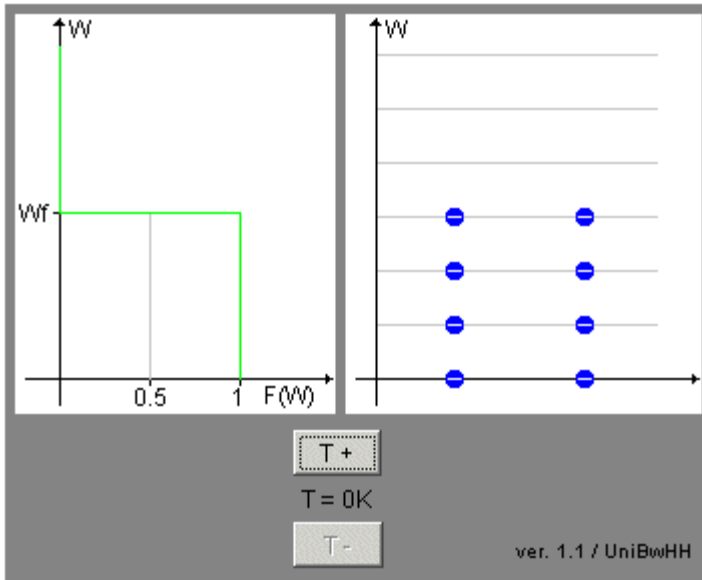
Possible energy band diagrams of a crystal. Shown are: a) a half filled band, b) two overlapping bands, c) an almost full band separated by a small bandgap from an almost empty band and d) a full band and an empty band separated by a large bandgap.

Electrical conductivity and bandgap

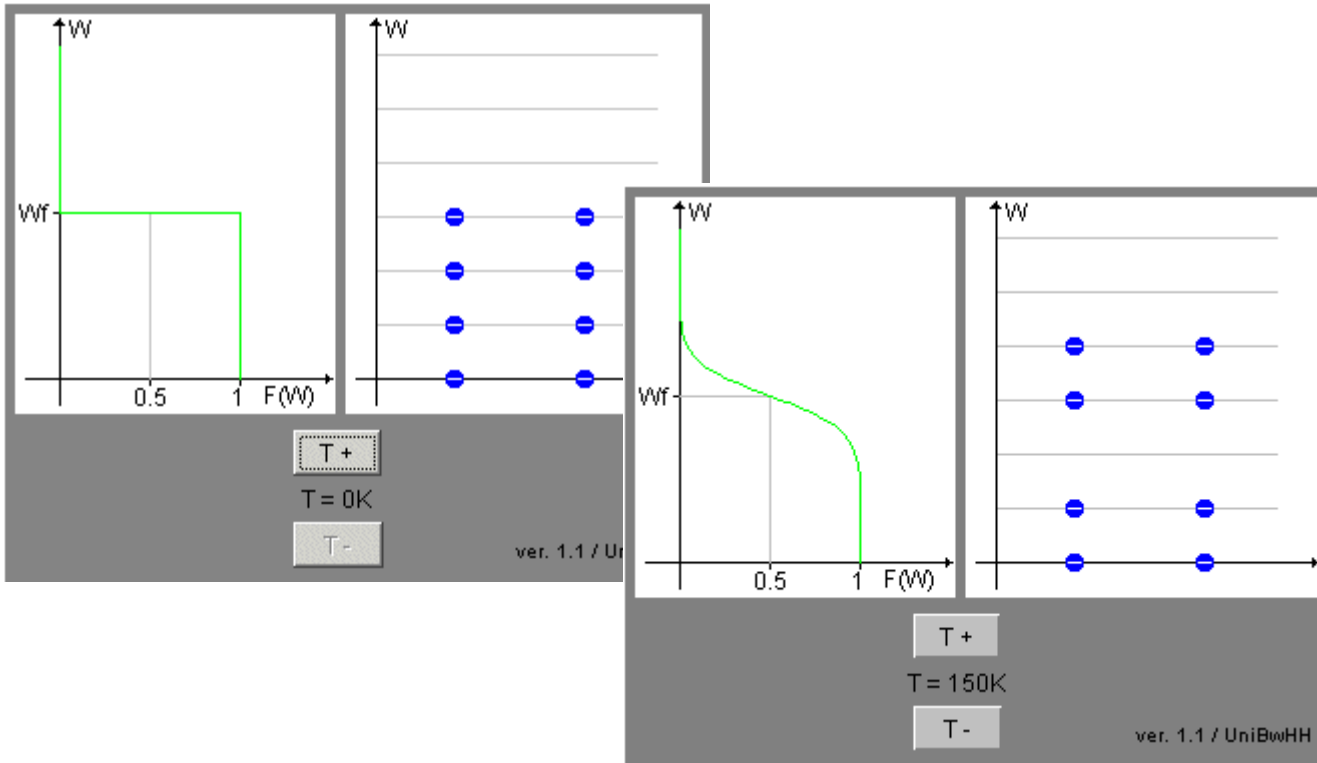


Possible energy band diagrams of a crystal. Shown are: a) a half filled band, b) two overlapping bands, c) an almost full band separated by a small bandgap from an almost empty band and d) a full band and an empty band separated by a large bandgap.

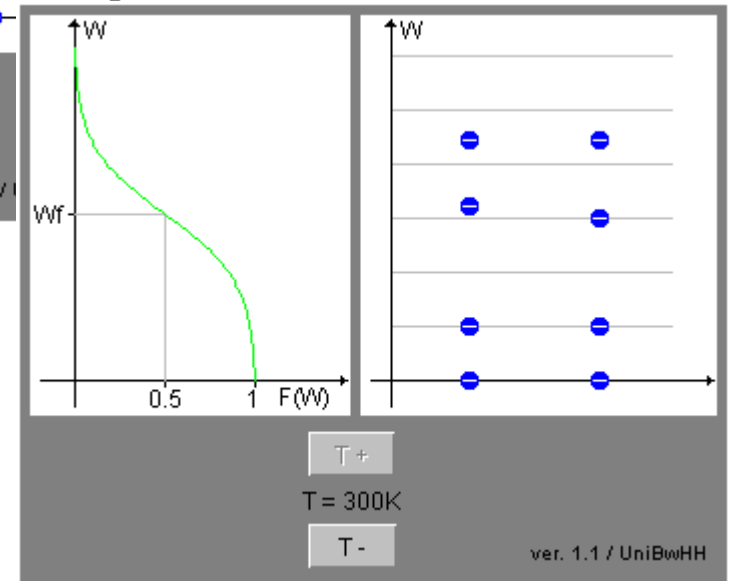
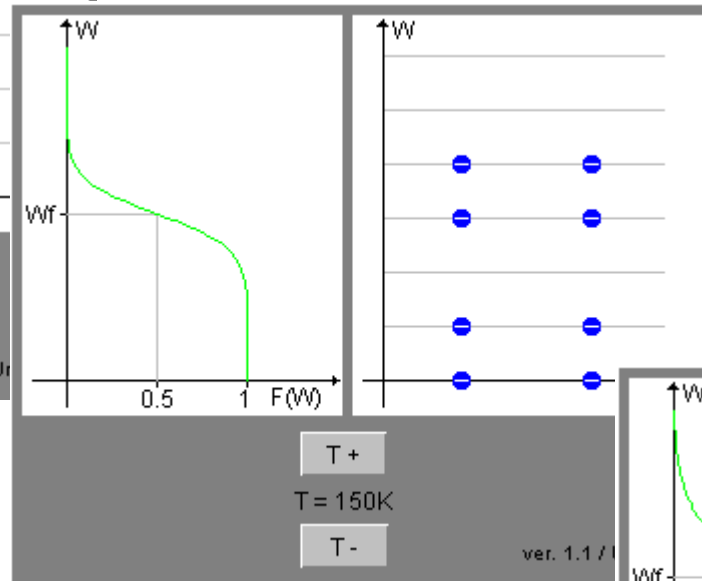
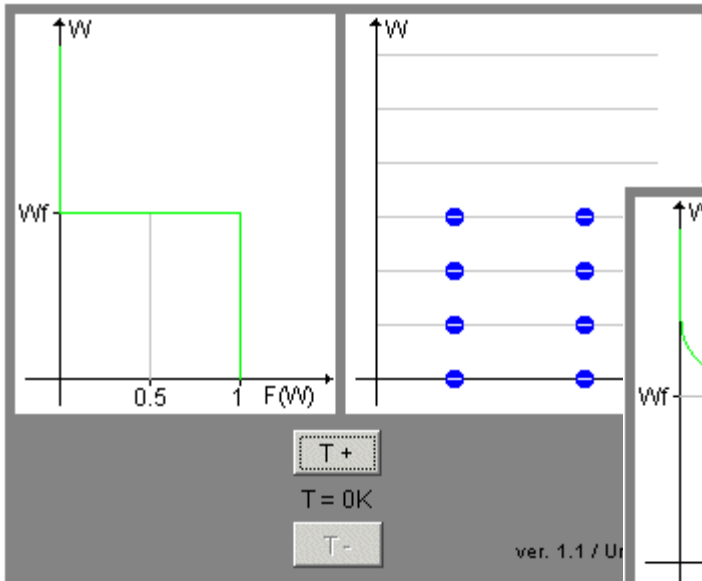
Occupation of states vs. temperature for metal



Occupation of states vs. temperature for metal



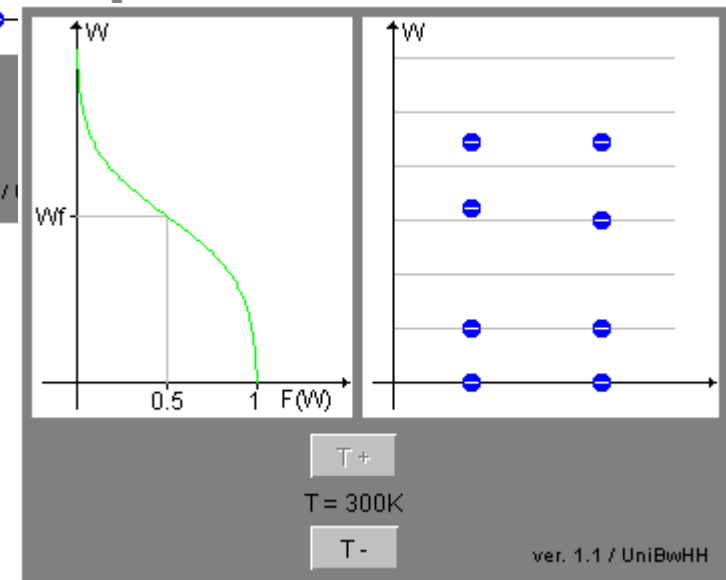
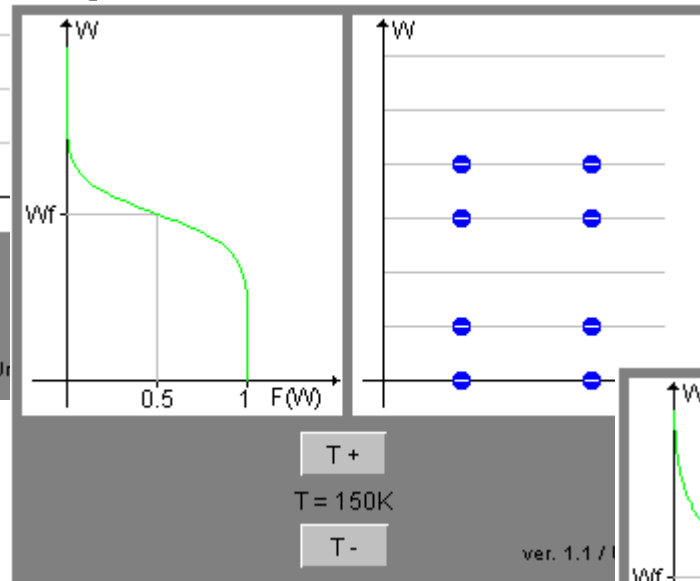
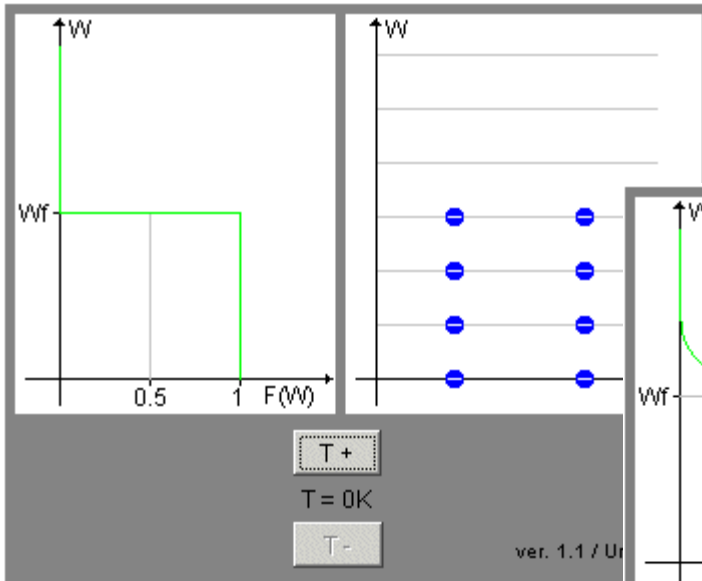
Occupation of states vs. temperature for metal



Occupation of states vs. temperature for metal

Fermi Distribution function

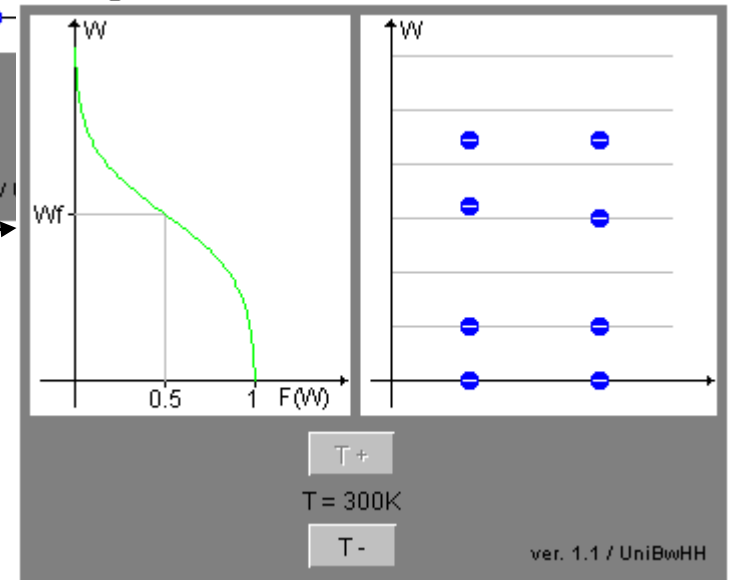
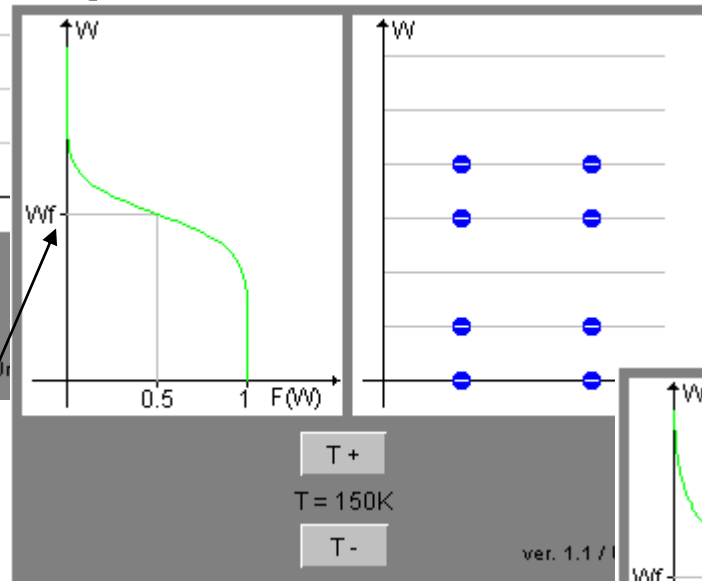
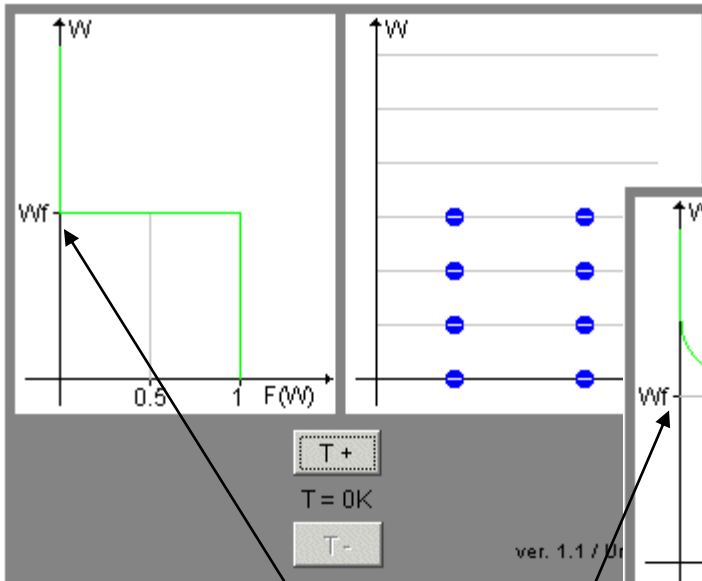
$$f(E) = \frac{1}{1 + e^{(E - E_f) / kT}}$$



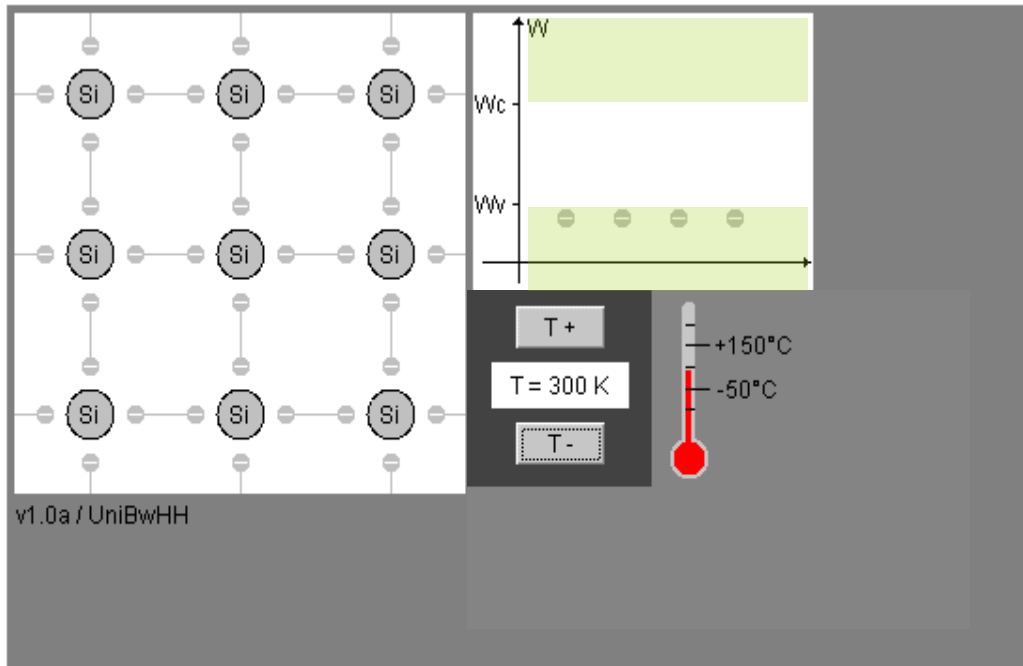
Occupation of states vs. temperature for metal

Fermi Distribution function

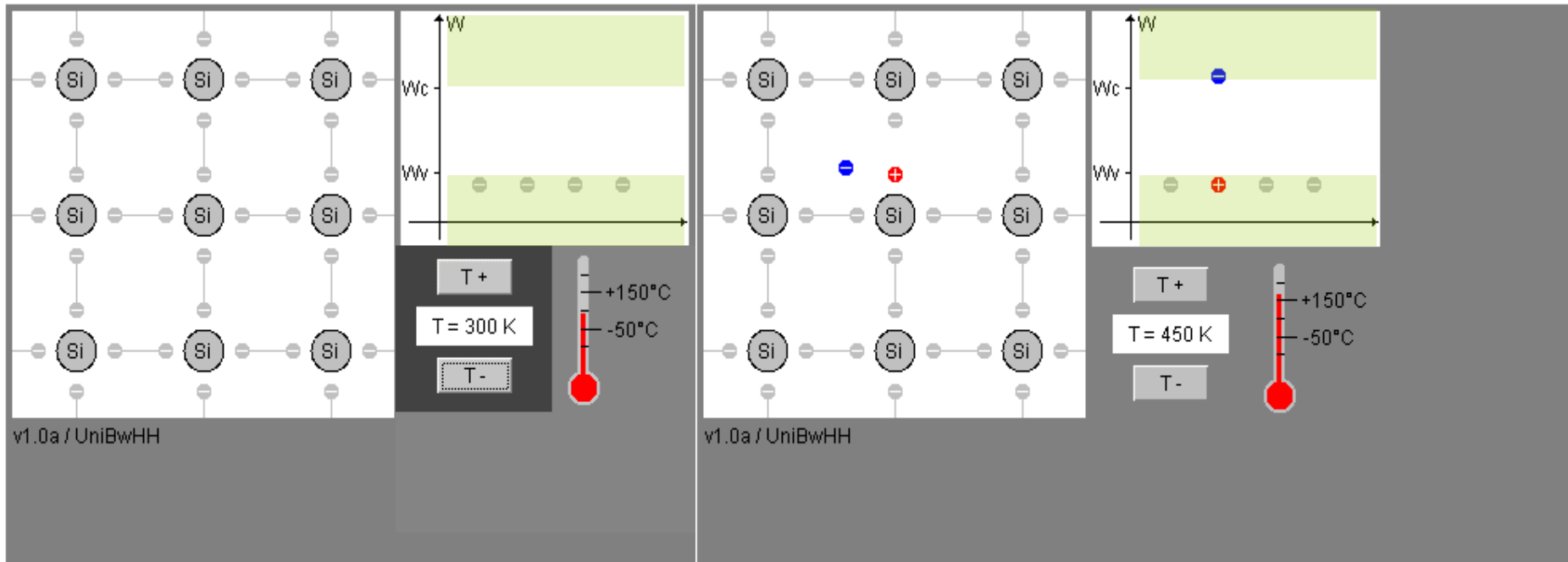
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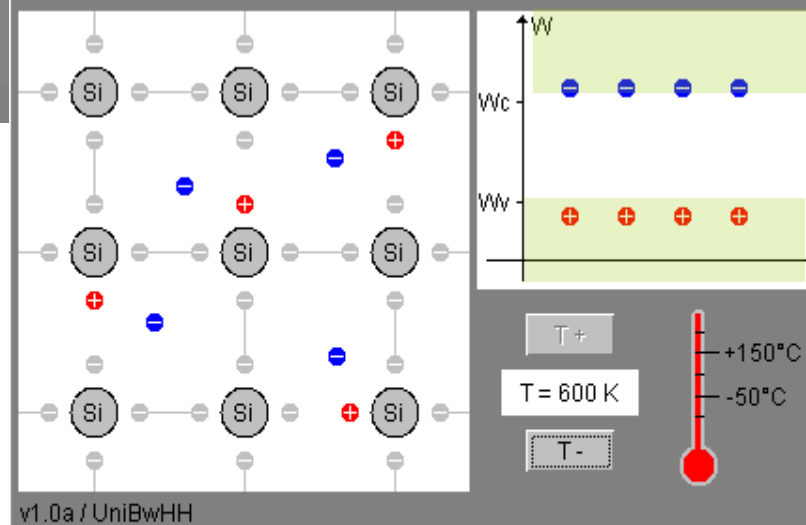
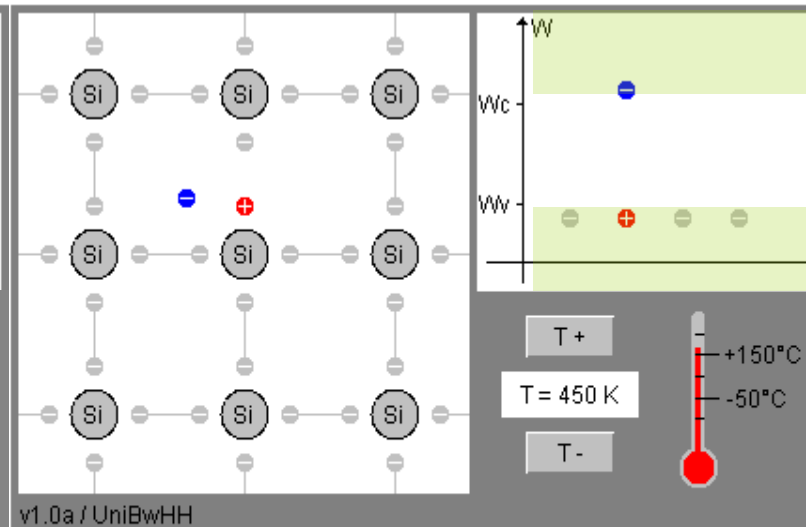
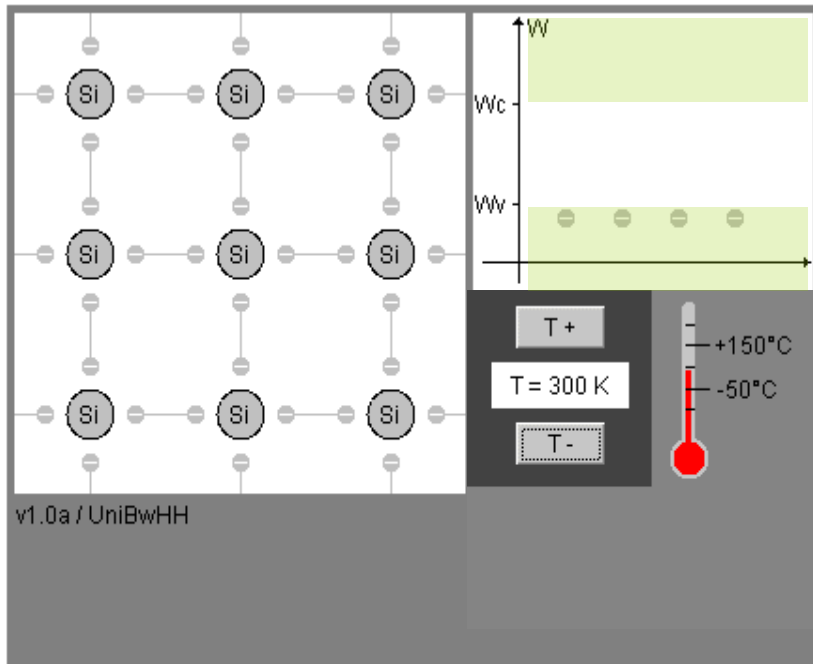
Fermi energy E_f = energy at which occupation probability is 0.5



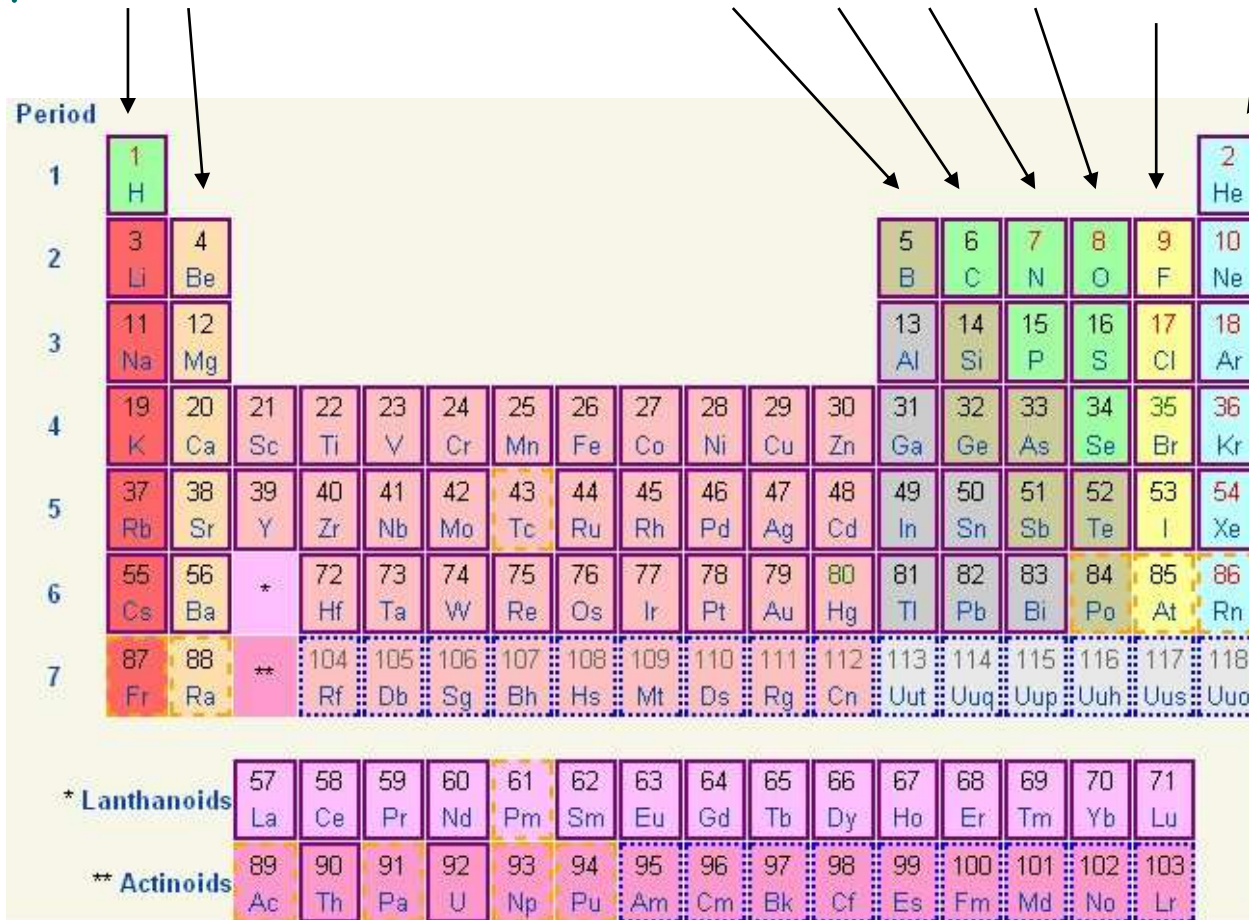
Occupation of states vs. temperature for Semiconductors



Occupation of states vs. temperature for Semiconductors



Group: I II Transition III IV V VI VII VIII



The periodic table is organized into 7 periods and 8 groups. The groups are labeled as follows:

- Group I: Hydrogen (H)
- Group II: Beryllium (Be)
- Transition: Groups III through X
- Group III: Boron (B)
- Group IV: Carbon (C)
- Group V: Nitrogen (N)
- Group VI: Oxygen (O)
- Group VII: Fluorine (F)
- Group VIII: Helium (He)

| Period | Group I | Group II | Transition | Group III | Group IV | Group V | Group VI | Group VII | Group VIII | | | | | | | | | |
|--------|----------|----------|------------------|-----------|-----------|-----------|-----------|-----------|------------|-----------|-----------|-----------|------------|------------|------------|------------|------------|------------|
| 1 | 1 H | | | | | | | | 2 He | | | | | | | | | |
| 2 | 3 Li | 4 Be | | 5 B | 6 C | 7 N | 8 O | 9 F | 10 Ne | | | | | | | | | |
| 3 | 11 Na | 12 Mg | | 13 Al | 14 Si | 15 P | 16 S | 17 Cl | 18 Ar | | | | | | | | | |
| 4 | 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 |
| 5 | 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 |
| 6 | 55 Cs | 56 Ba | * Lanthanoids | 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 |
| 7 | 87 Fr | 88 Ra | ** Actinoids | 104 Rf | 105 Db | 106 Sg | 107 Bh | 108 Hs | 109 Mt | 110 Ds | 111 Rg | 112 Cn | 113 Uut | 114 Uuq | 115 Uup | 116 Uuh | 117 Uus | 118 Uuo |

| * Lanthanoids | 57 La | 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 |
|---------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|-----------|
| ** Actinoids | 89 Ac | 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 |

Substitutional element in the silicon lattice:

Boron

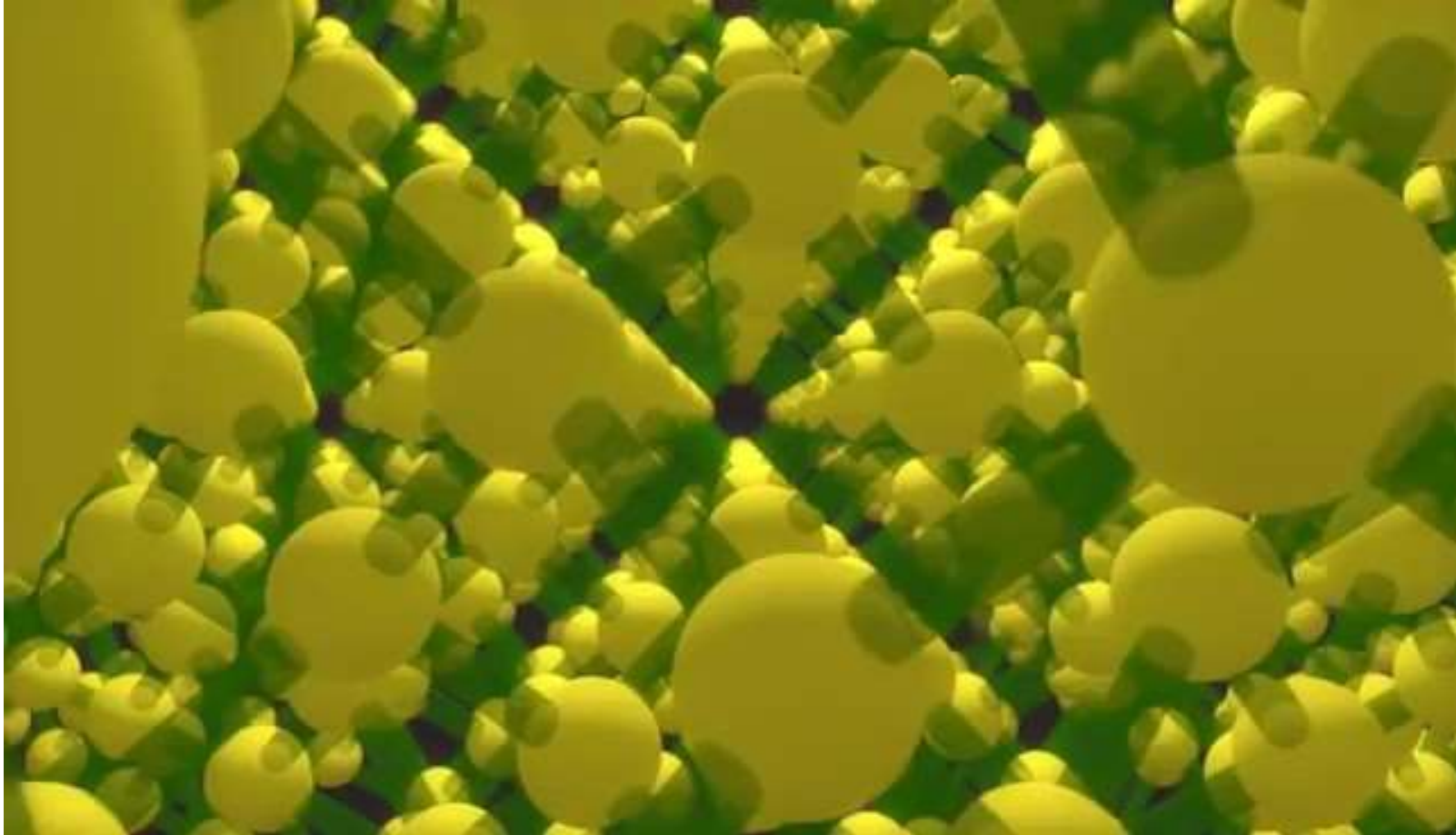
(one electron less than Si)

| III | IV | V |
|----------|----------|----------|
| 5 B | 6 C | 7 N |
| 13 Al | 14 Si | 15 P |
| 31 Ga | 32 Ge | 33 As |
| 49 In | 50 Sn | 51 Sb |

Substitutional element in the silicon lattice:

Phosphorus
Arsenic
Antimon

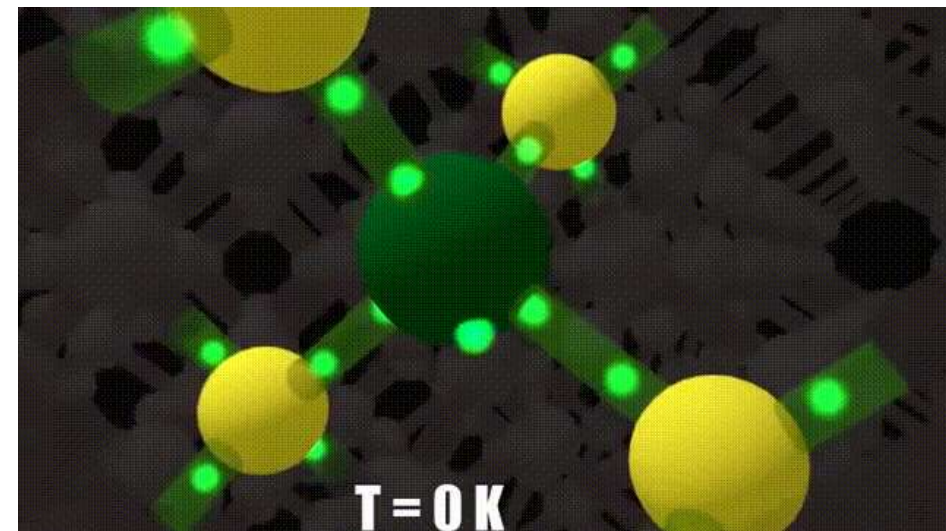
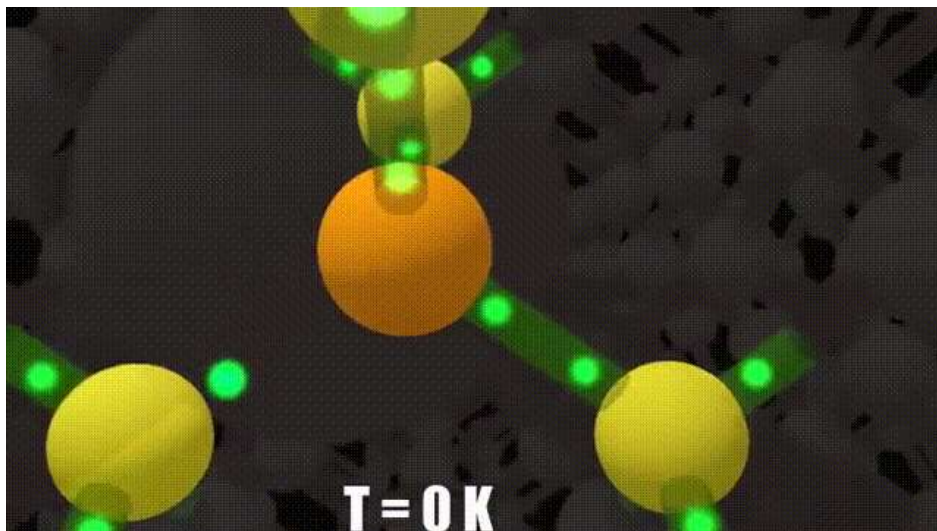
(one electron more than Si)



Taken from:
<https://www.youtube.com/watch?v=JBtEckh3L9Q&t=4s>

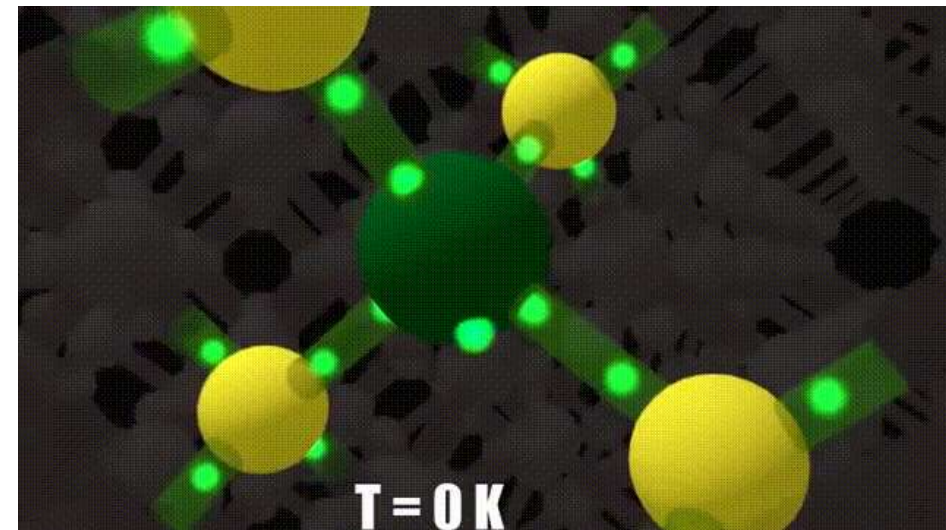
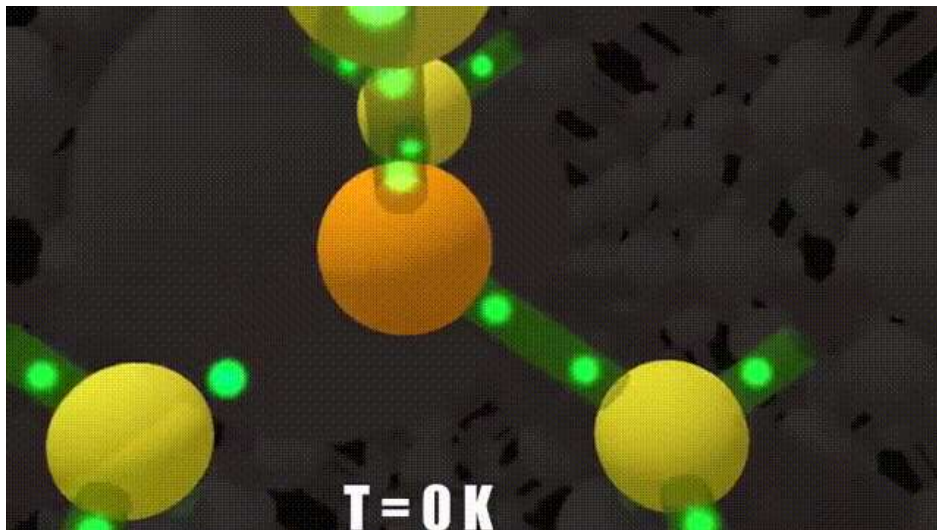
P - type

n - type



P - type

n - type



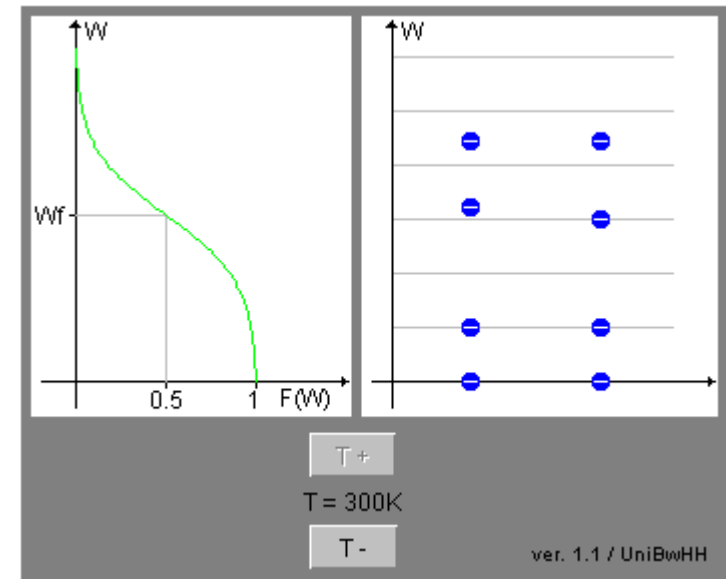
Continue 

"SCT_SS20_02.5" 13:41



Fermi Distribution function

$$f(E) = \frac{1}{1 + e^{(E - E_f)/kT}}$$

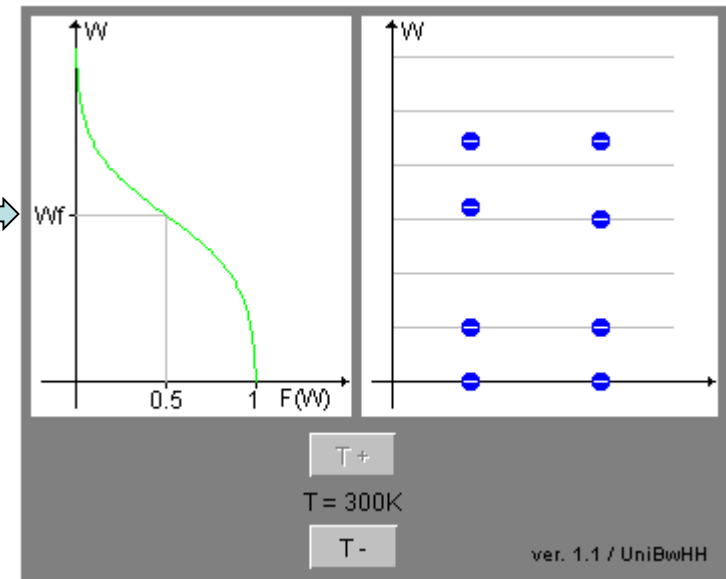


Occupation of states for a metal

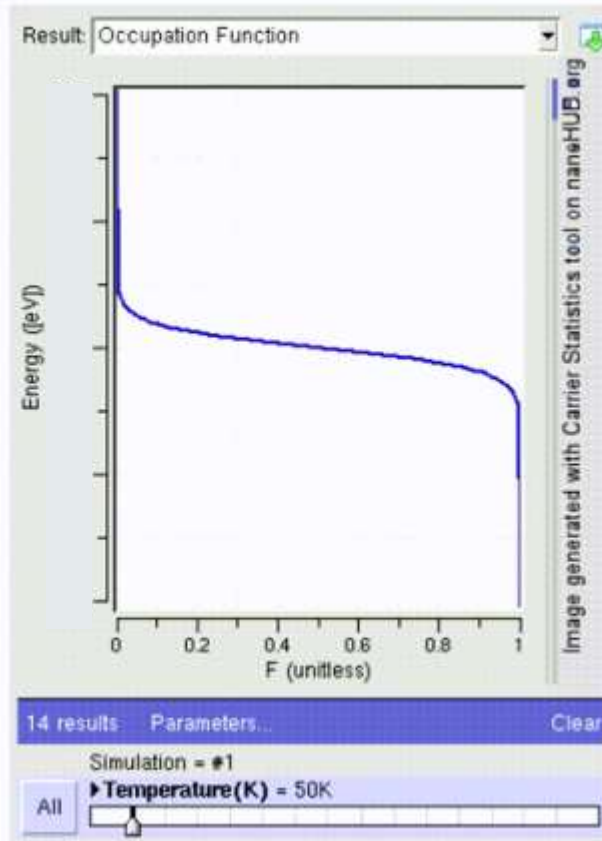
Fermi Distribution function

$$f(E) = \frac{1}{1 + e^{(E - E_f) / kT}}$$

Parameter:
Fermi-Level
 Energy at which
 occupation
 probability = 0,5



Parameter:
Temperature

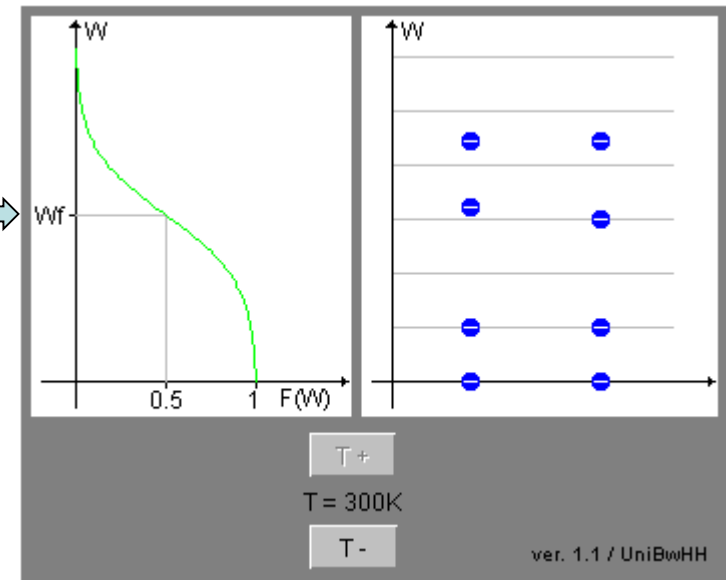


<http://ecee.colorado.edu/~bart/book/contents.htm>

Parameter:
Fermi-Level
Energy at which
occupation
probability = 0,5

Fermi
Distribution function

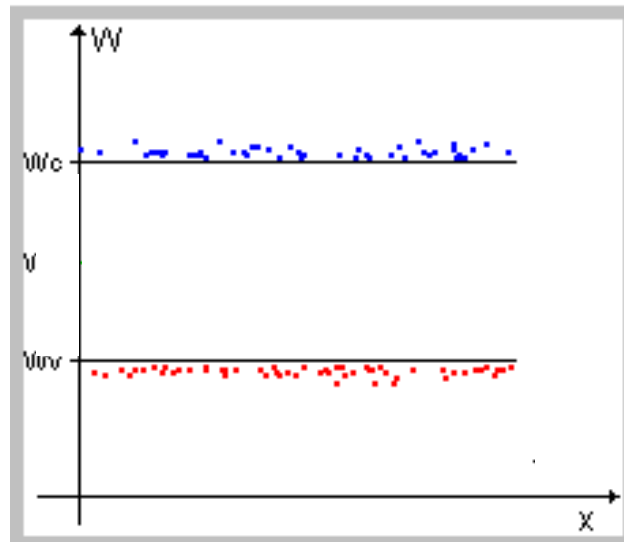
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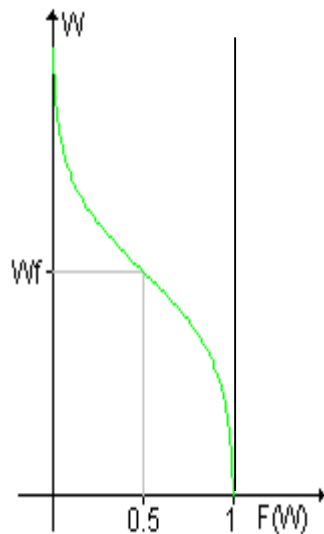
Where do we locate the Fermi level?

intrinsic

$p=n$

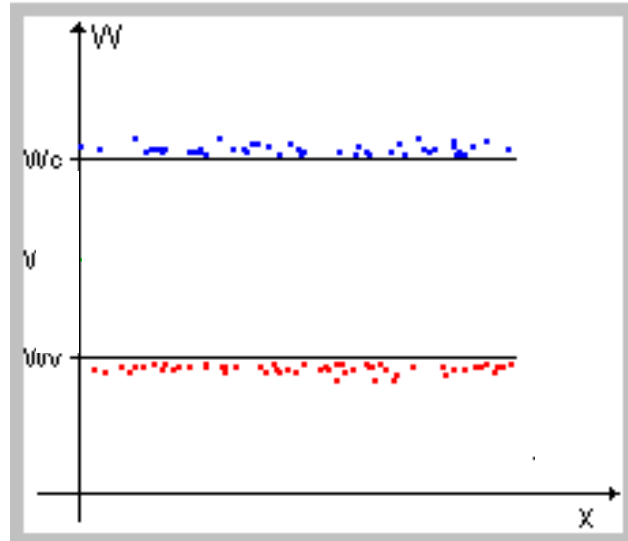


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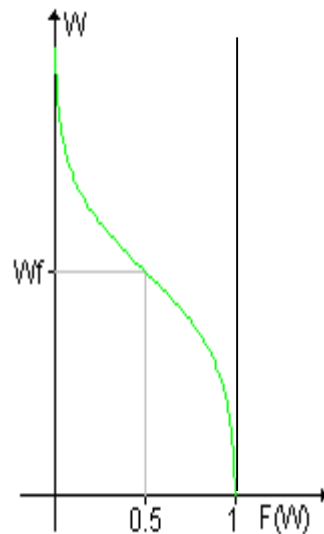


intrinsic

$p=n$

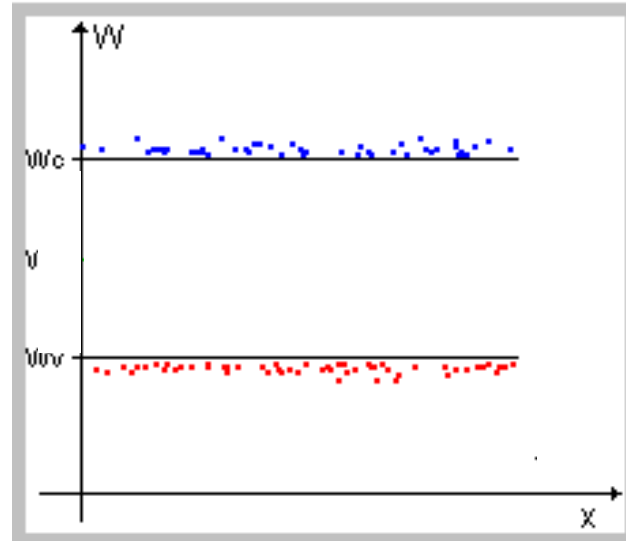


Where do we locate the Fermi level?



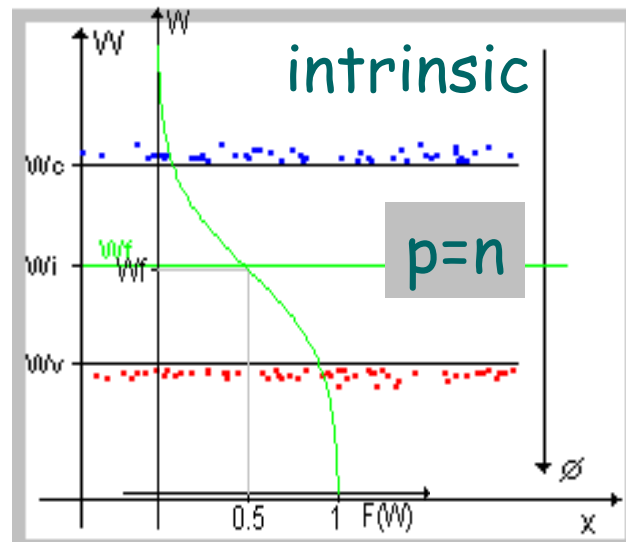
intrinsic

$p=n$

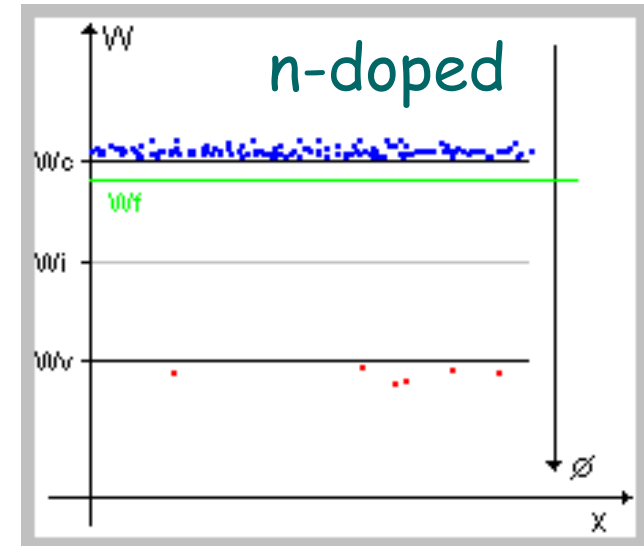
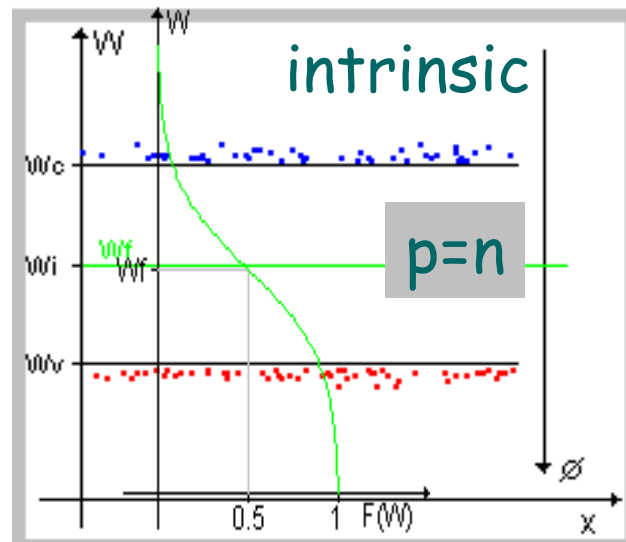


For intrinsic Si it must be in the middle of the bandgap!

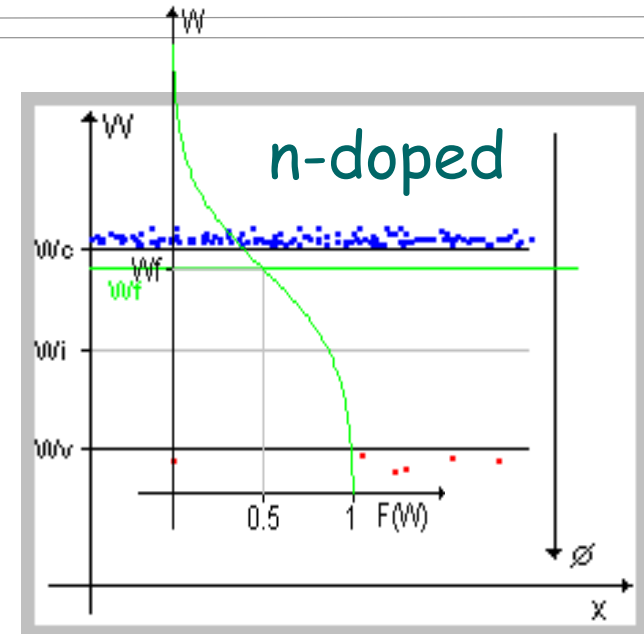
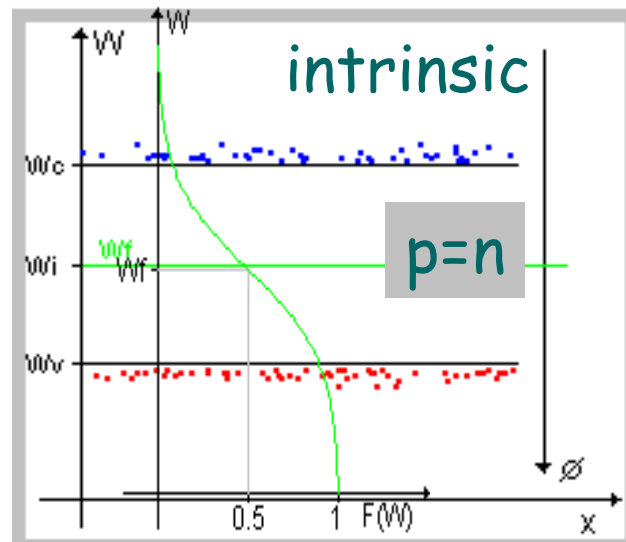
Doping and Fermi level for a semiconductor



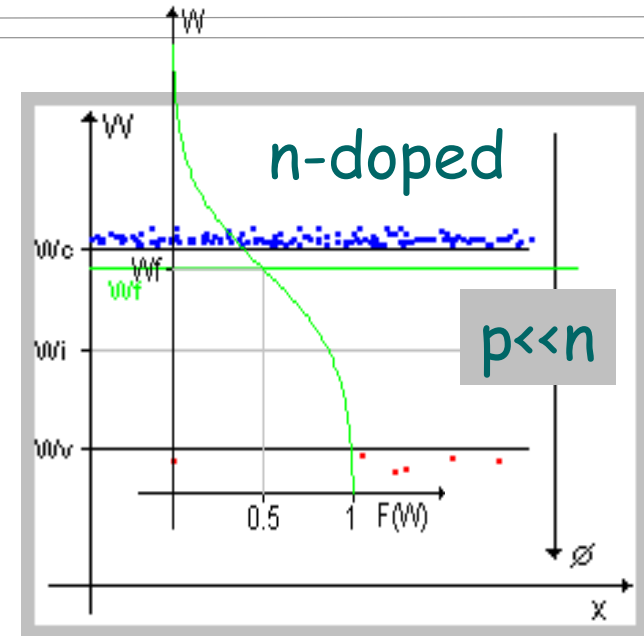
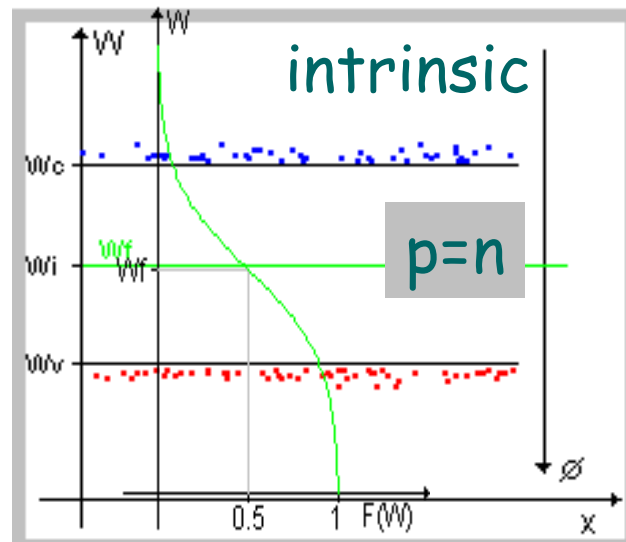
Doping and Fermi level for a semiconductor



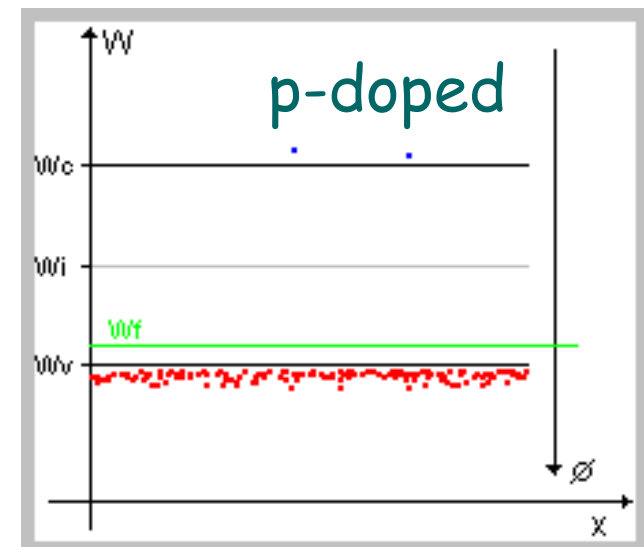
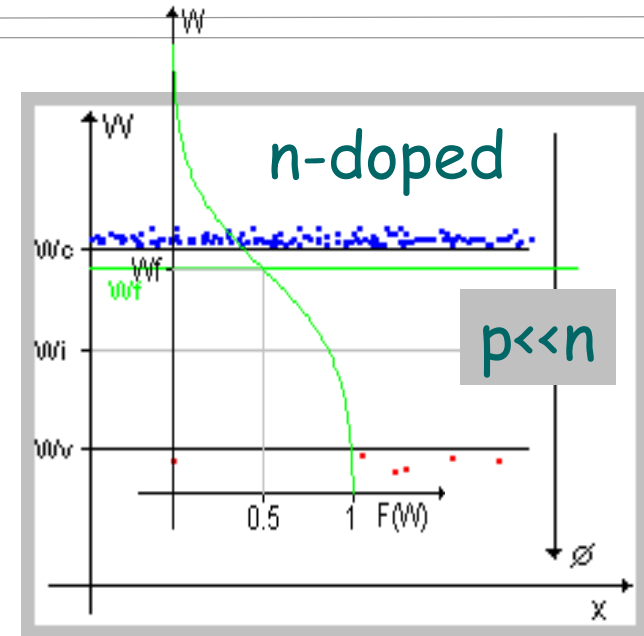
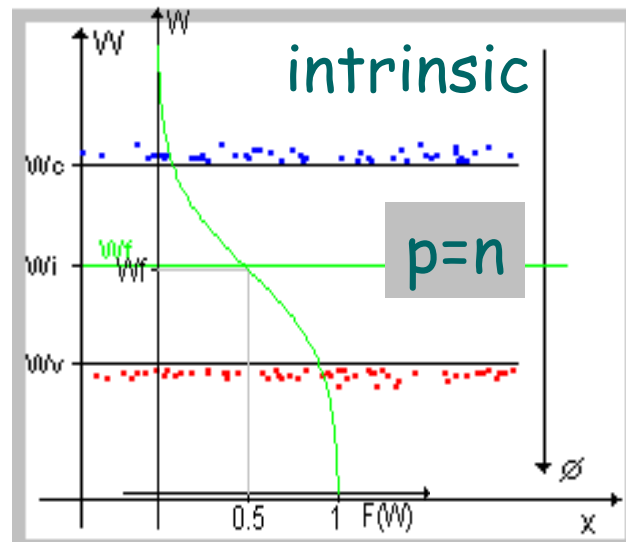
Doping and Fermi level for a semiconductor



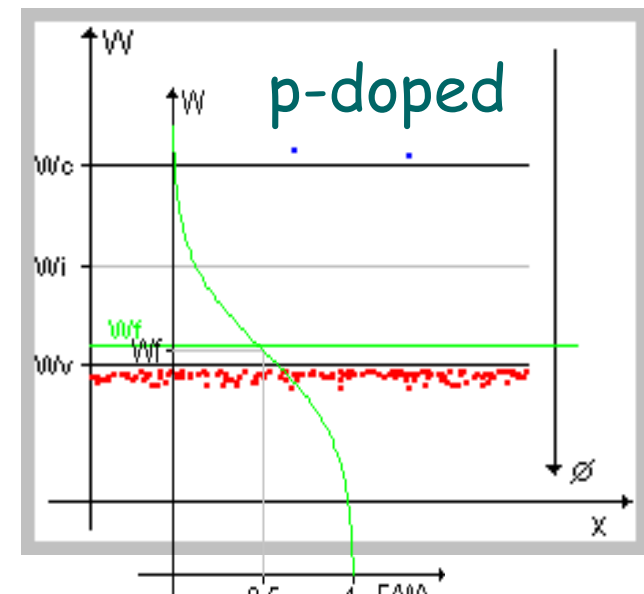
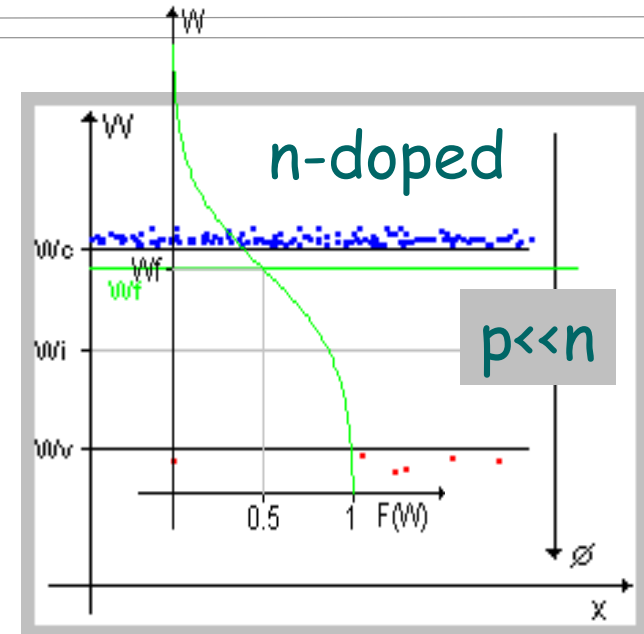
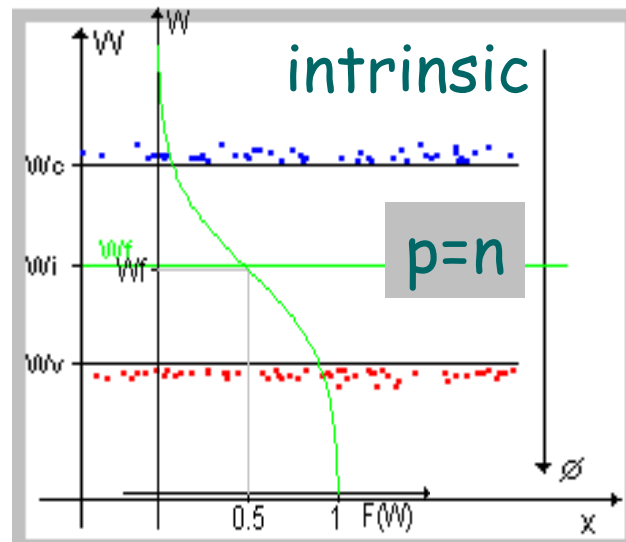
Doping and Fermi level for a semiconductor



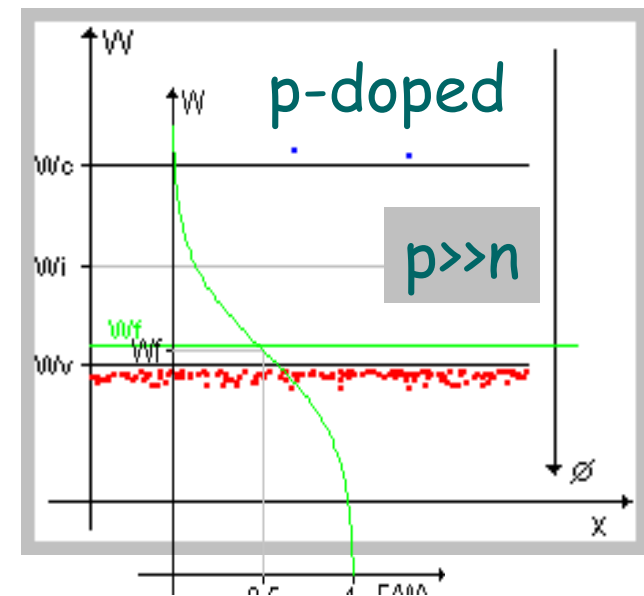
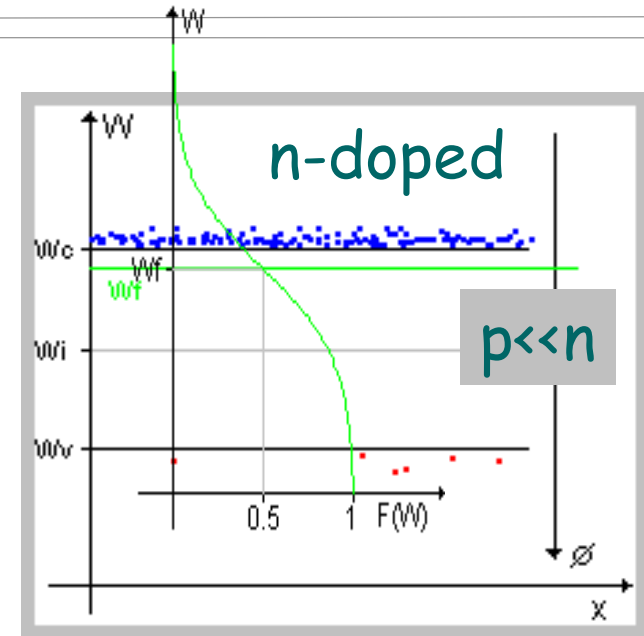
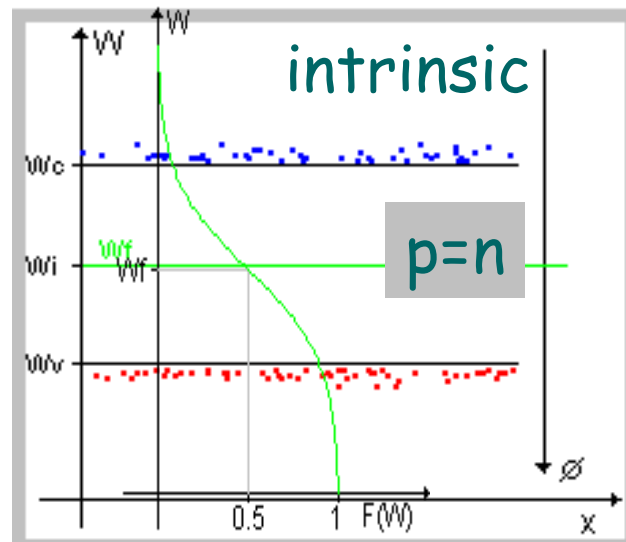
Doping and Fermi level for a semiconductor



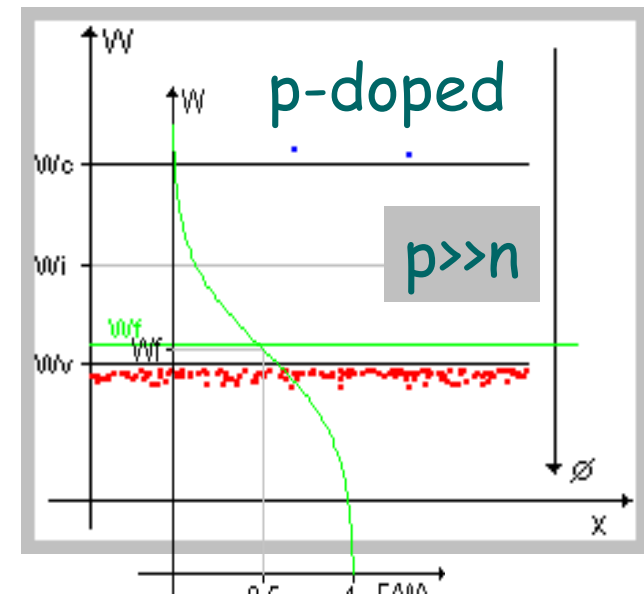
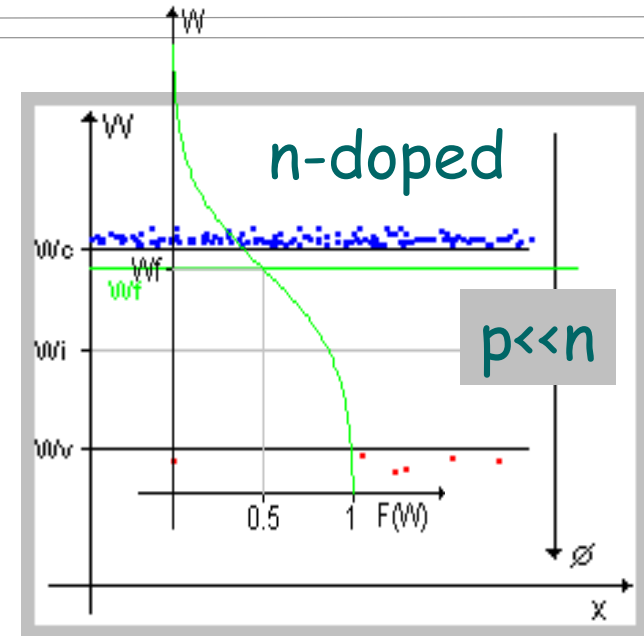
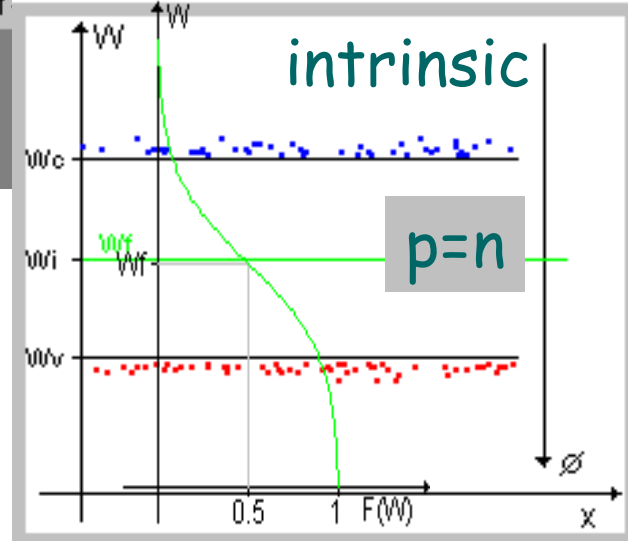
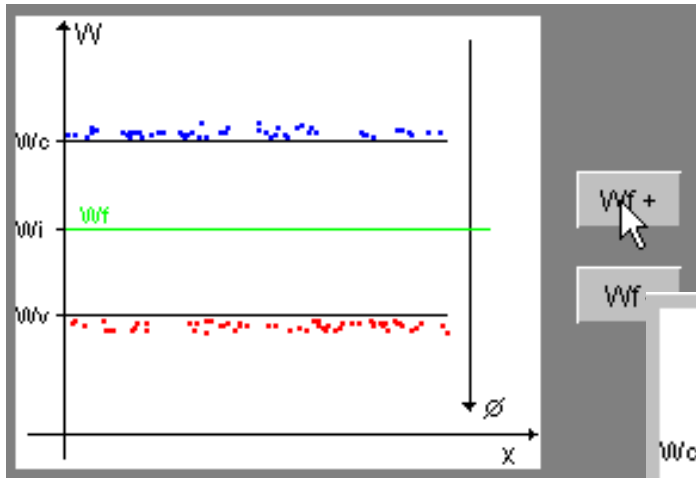
Doping and Fermi level for a semiconductor



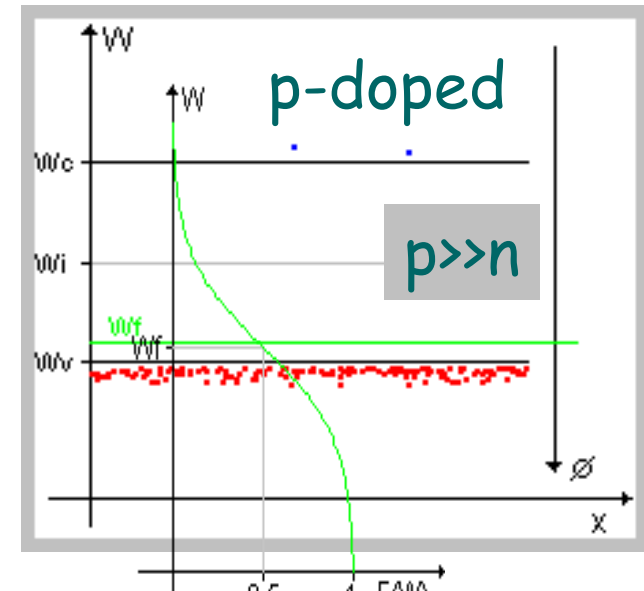
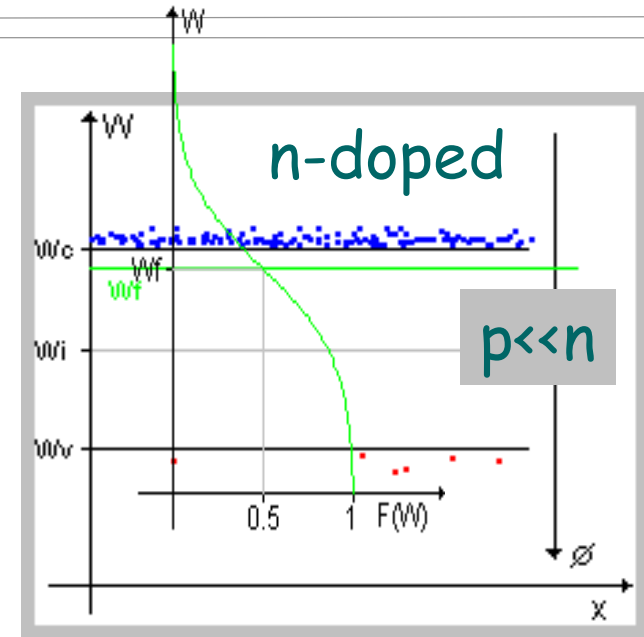
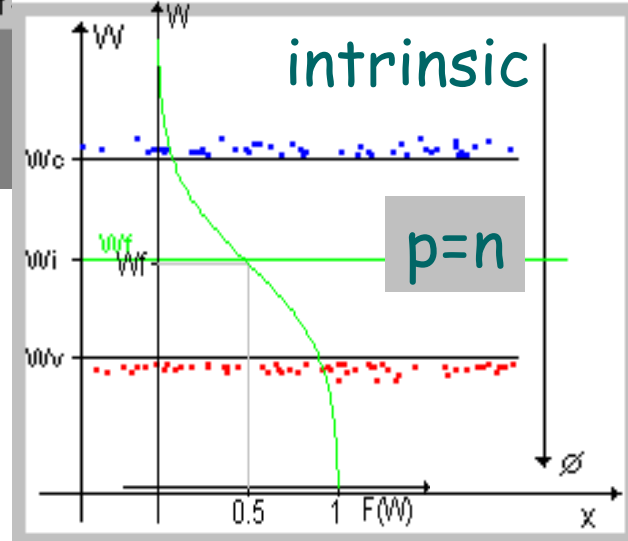
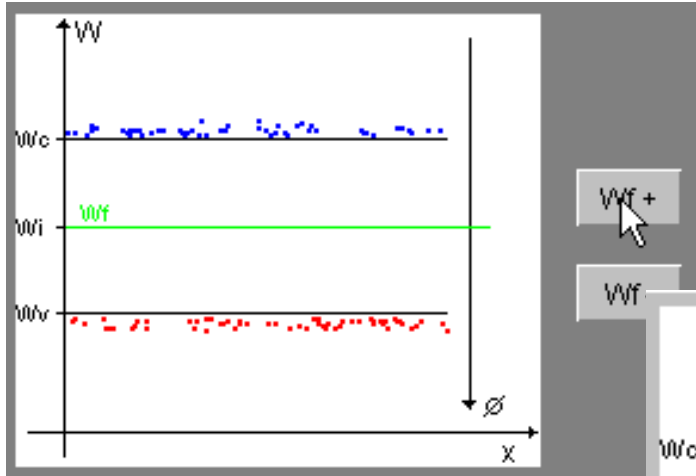
Doping and Fermi level for a semiconductor



Doping and Fermi level for a semiconductor

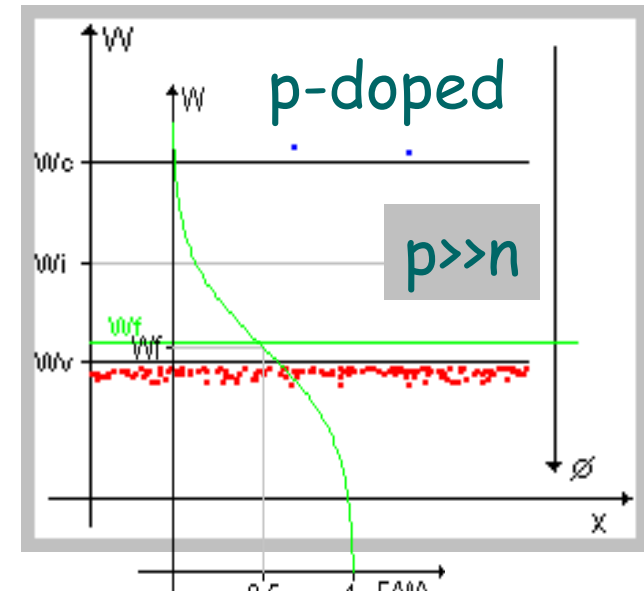
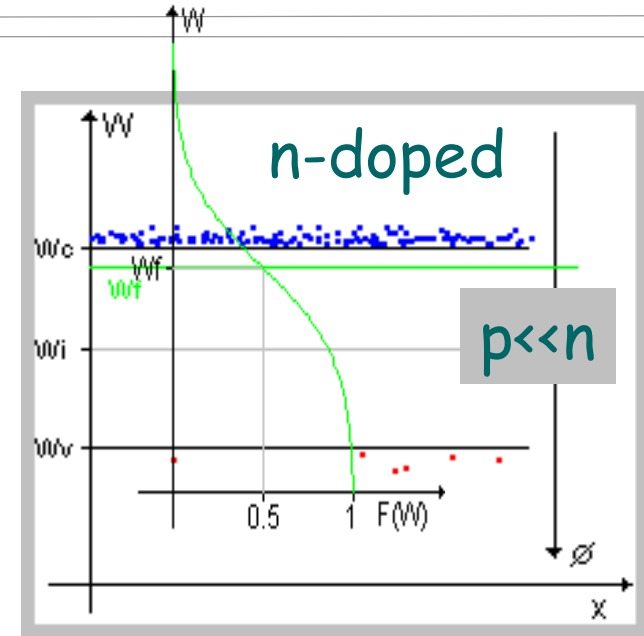
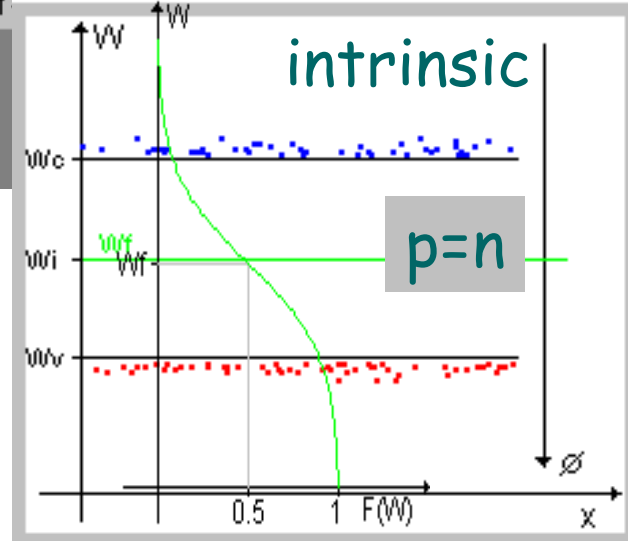
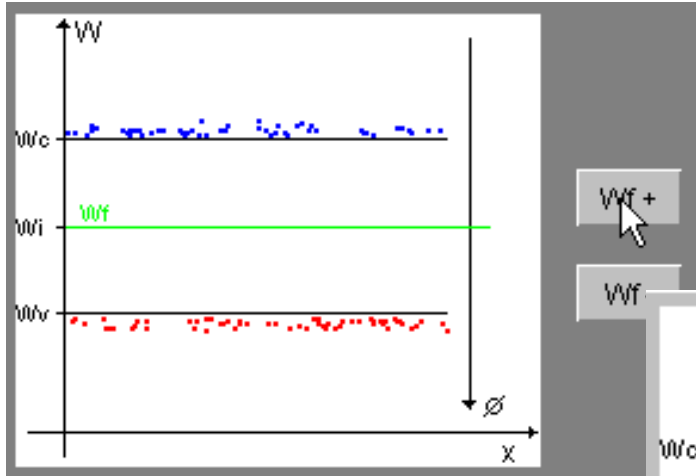


Doping and Fermi level for a semiconductor



Product of hole concentration times electron concentration is a constant: $p \cdot n = n_i^2$

Doping and Fermi level for a semiconductor



Product of hole concentration times electron concentration is a constant: $p \cdot n = n_i^2$

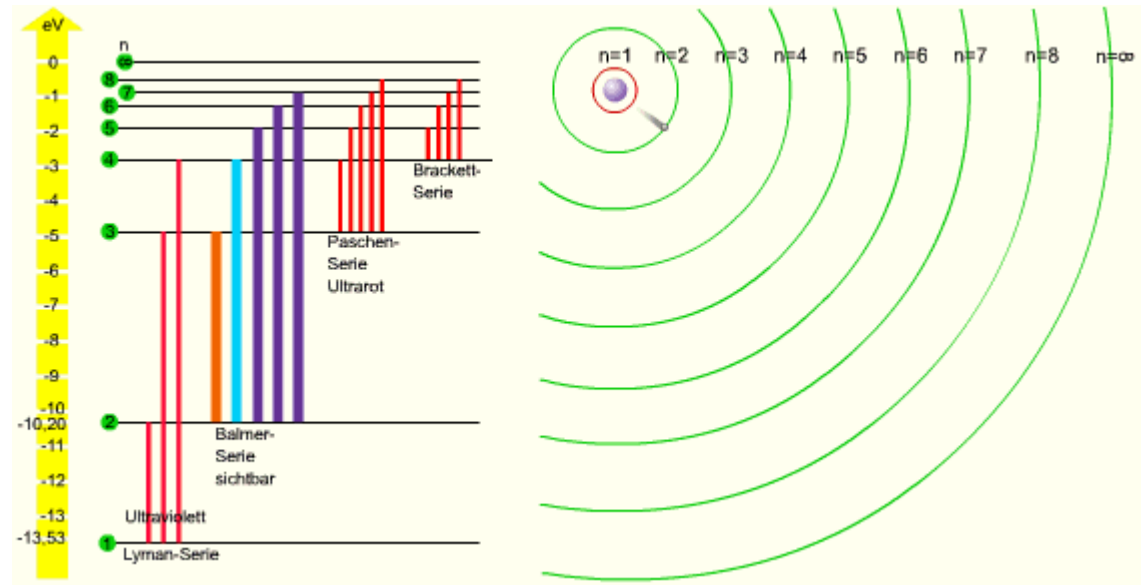
But where do we locate E_f on the E scale **Continue**

"SCT_SS20_02.6" 11:30



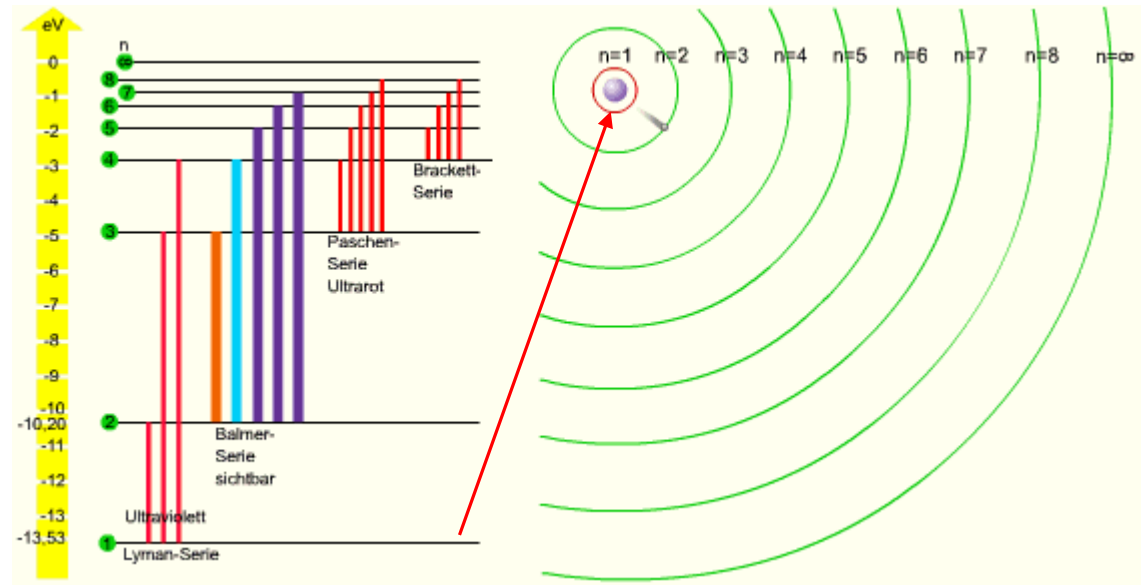
O.K. Fermi level relative to band edges, but where on an absolute scale?

Reminder:
Energy states of electrons in atoms



O.K. Fermi level relative to band edges, but where on an absolute scale?

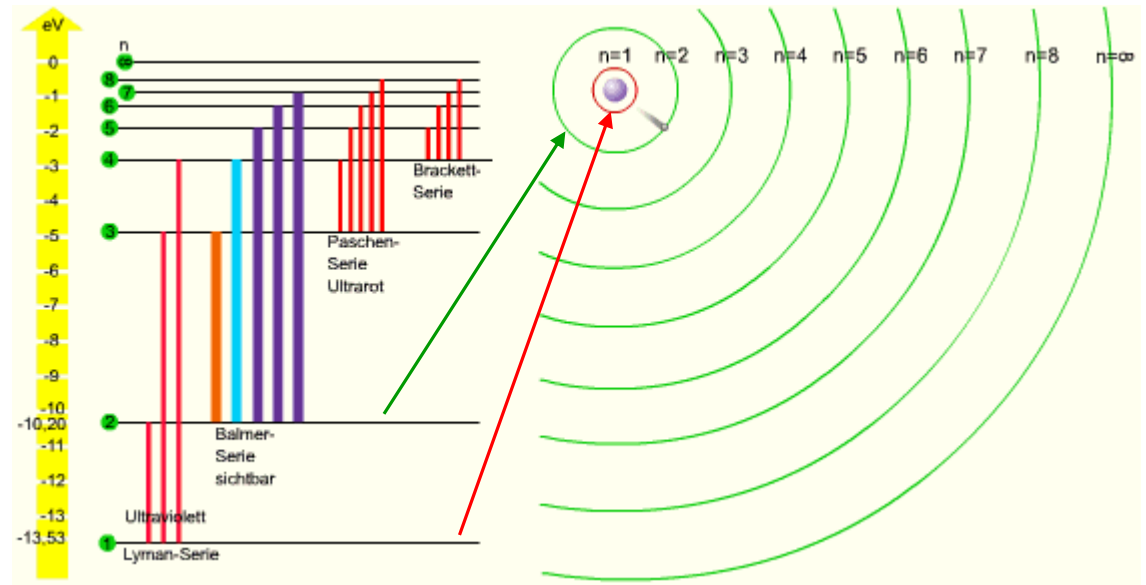
Reminder:
Energy states of electrons in atoms



Strongest bonded state 1 →

O.K. Fermi level relative to band edges, but where on an absolute scale?

Reminder:
Energy states of electrons in atoms



Weaker bonded state 2 \Rightarrow

Strongest bonded state 1 \Rightarrow

O.K. Fermi level relative to band edges, but where on an absolute scale?

Reminder:
Energy states of electrons in atoms

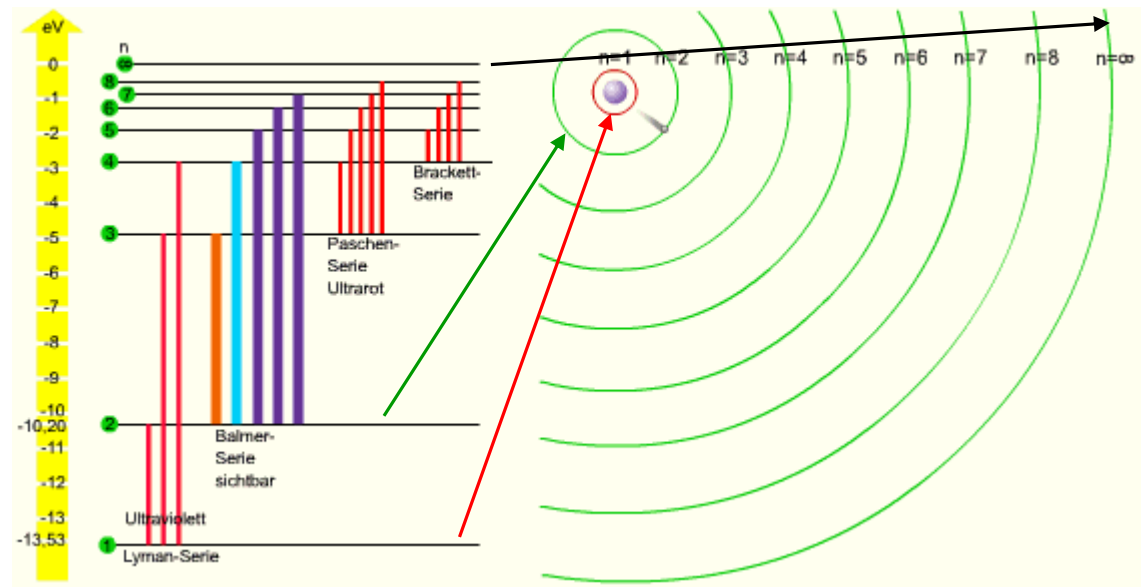
Very weakly bonded state
large # n



Weaker bonded state 2



Strongest bonded state 1



O.K. Fermi level relative to band edges, but where on an absolute scale?

Reminder:

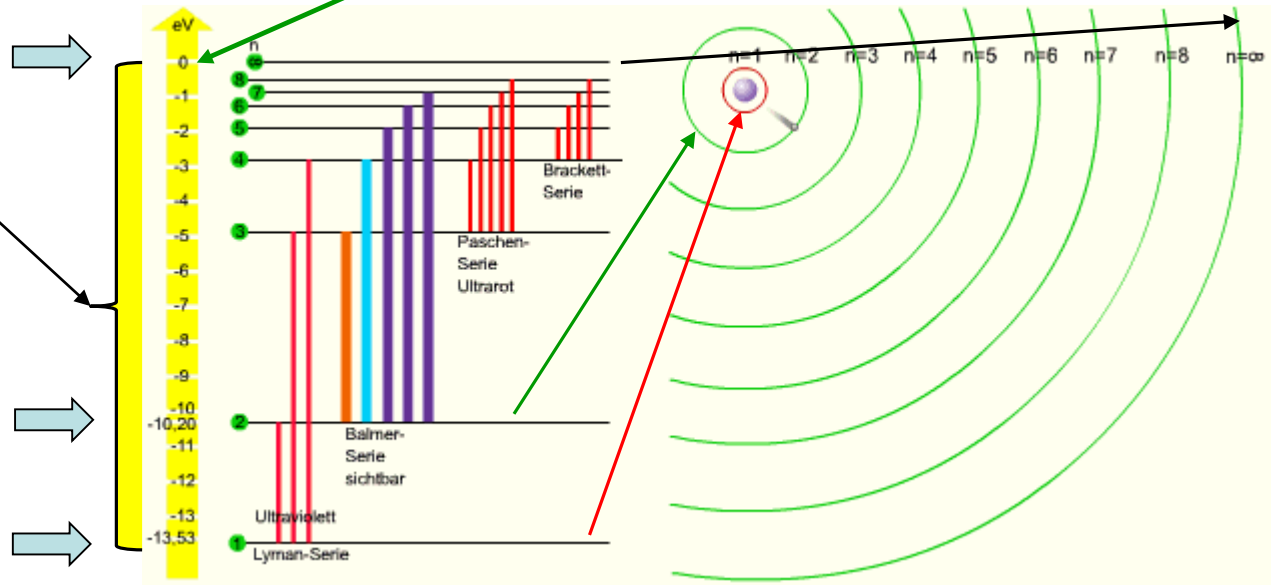
Energy states of electrons in atoms

Conveniently the energy between the loosest bonded state and the next energy above at which an electron is released is used as zero point on the scale. The Energy difference between the highest occupied state and zero is called ionization potential.

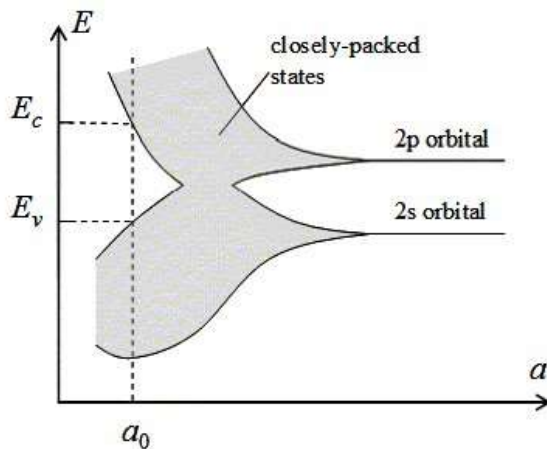
Very weakly bonded state
large # n

Weaker bonded state 2

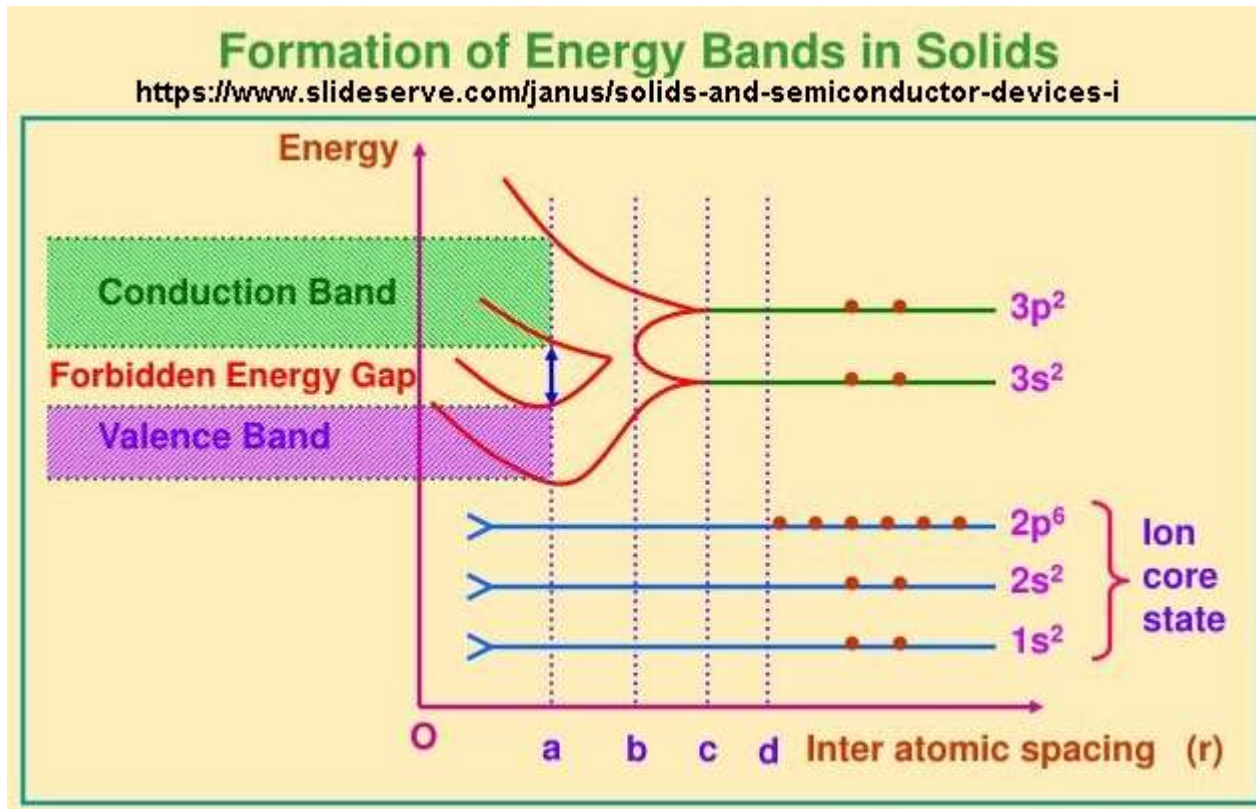
Strongest bonded state 1



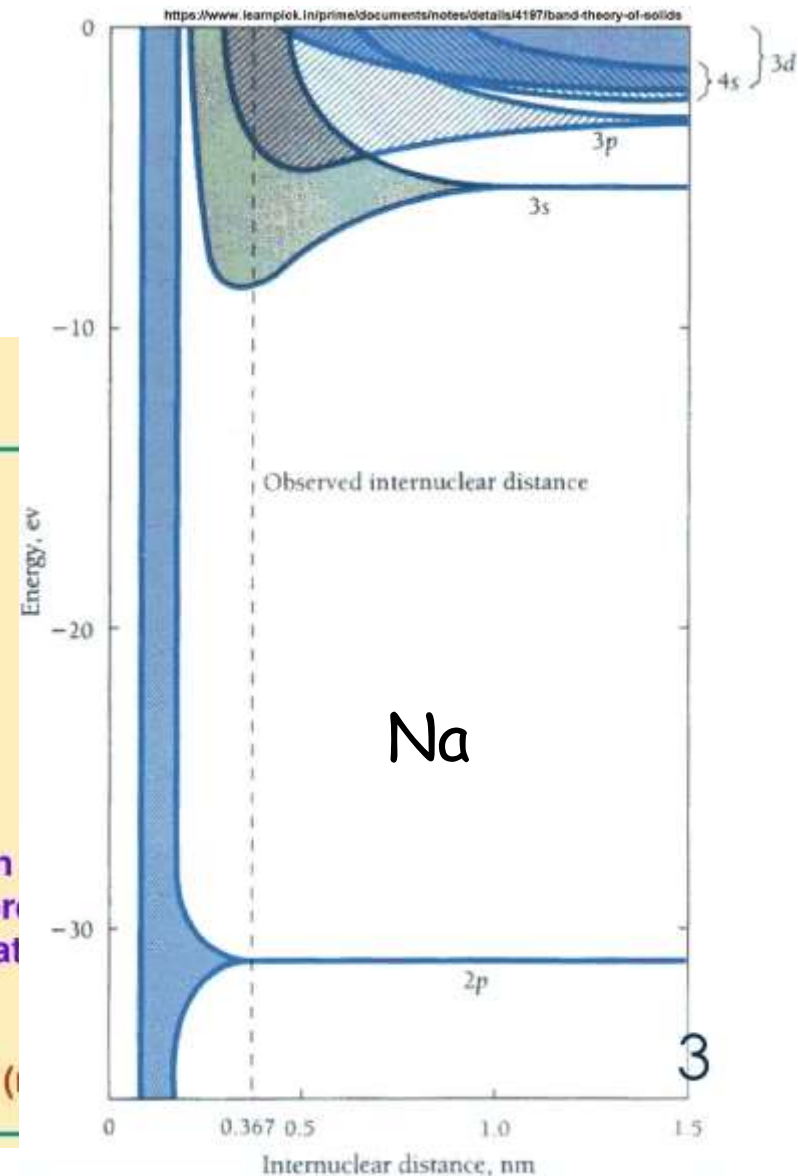
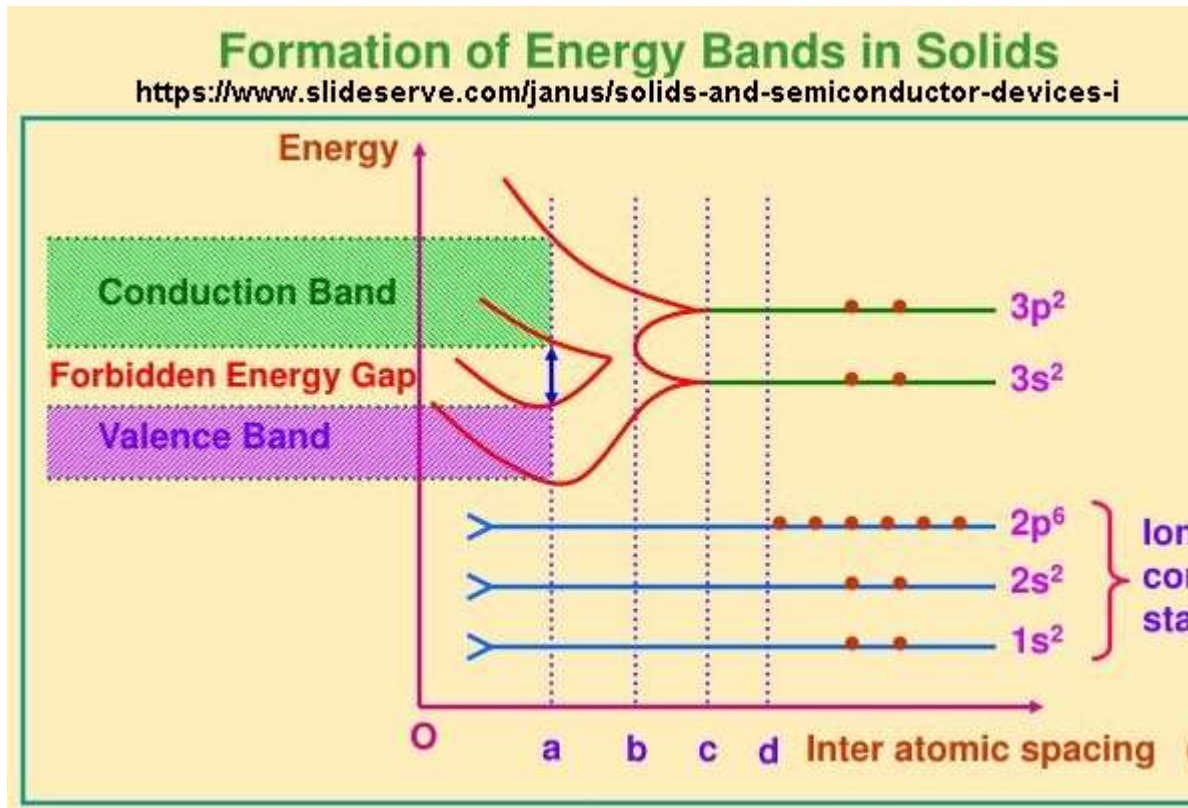
Energy states of electrons in solids



Energy bands for diamond versus lattice constant.

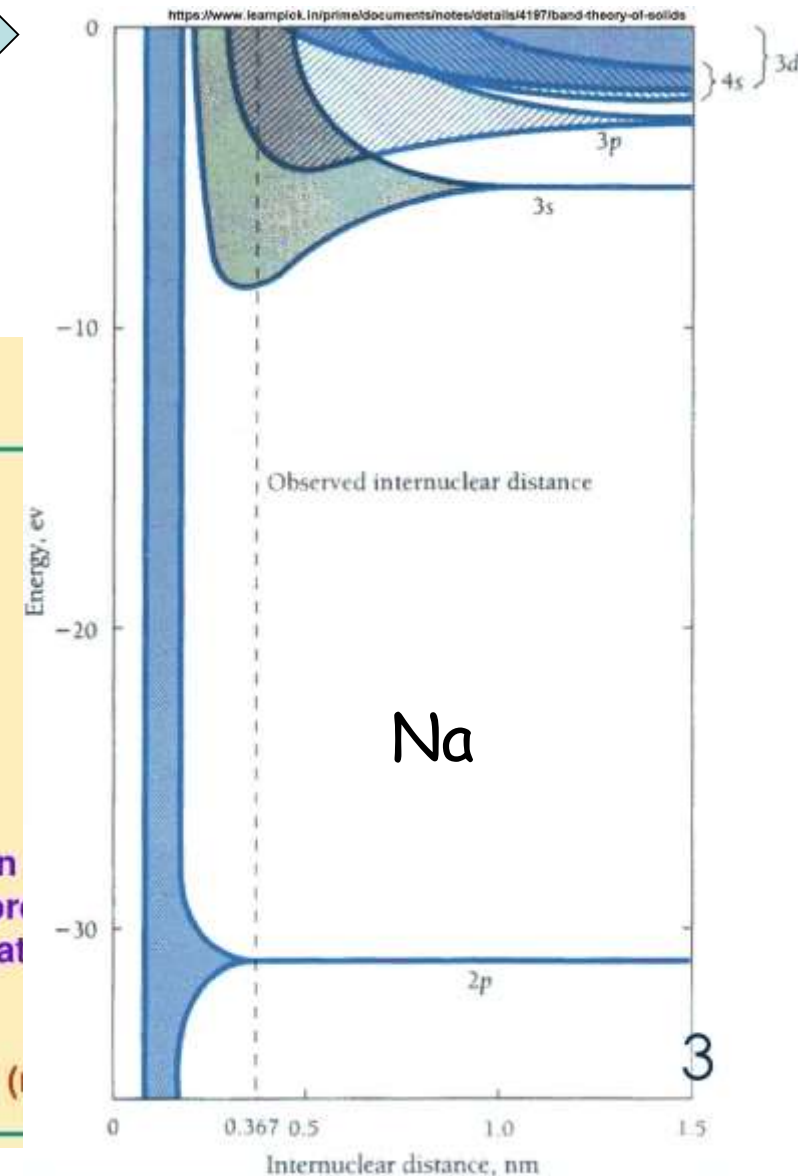
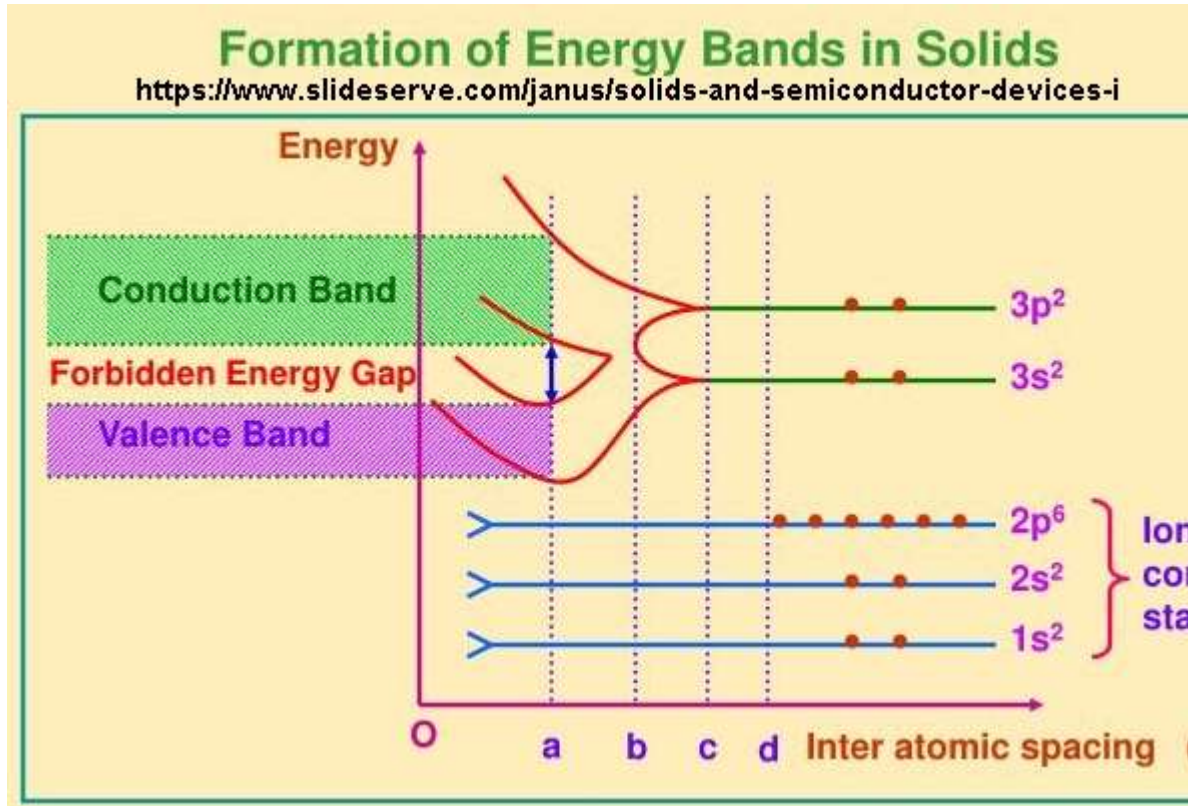


Energy states of electrons in solids



Energy states of electrons in solids

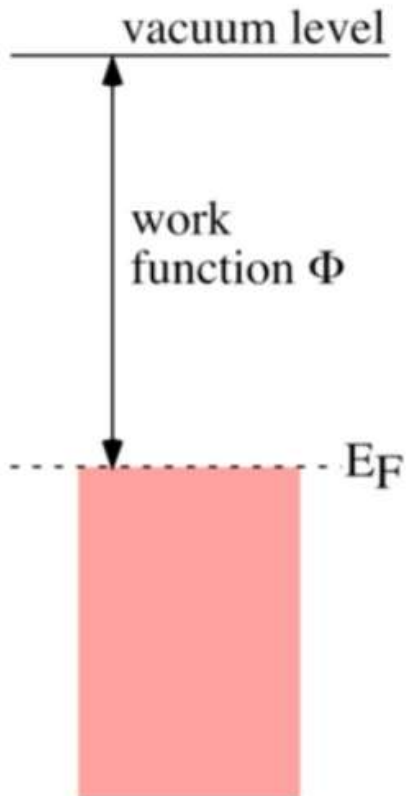
Binding energy 0 corresponds to the point at which the electron is released. For a solid this is named **Vacuum Level**



work function (German: Austrittsarbeit)

The work function is the energy required to release an electron from a solid

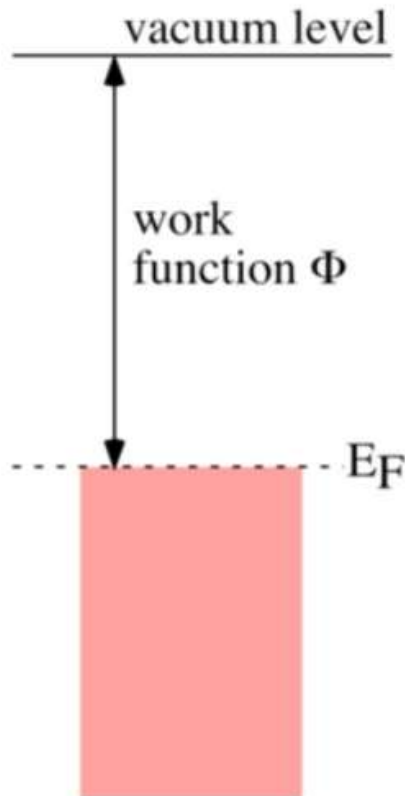
For a metal:



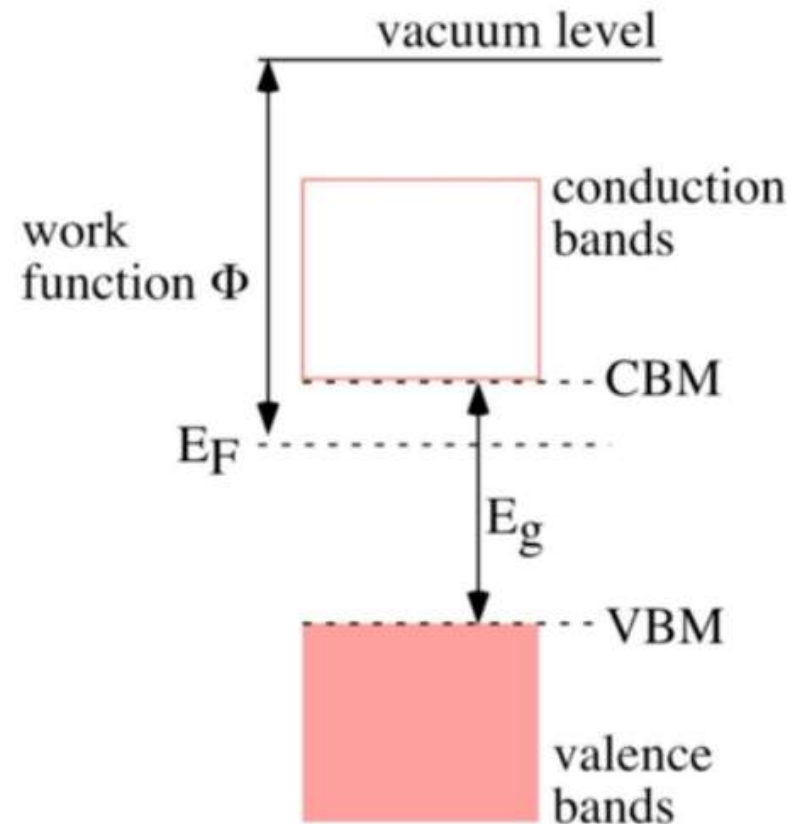
work function (German: Austrittsarbeit)

The work function is the energy required to release an electron from a solid

For a metal:



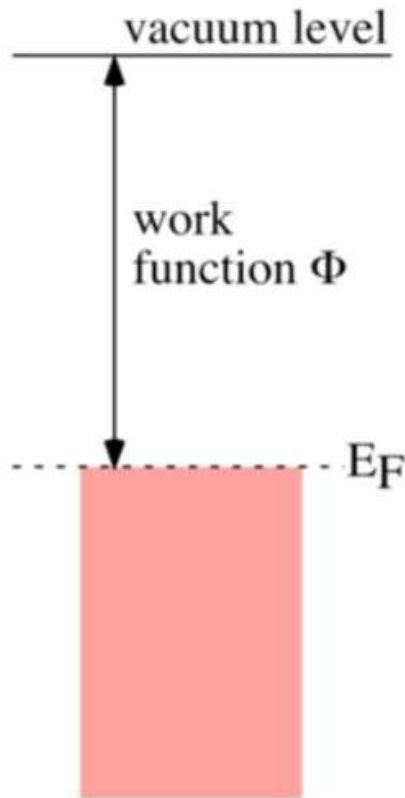
For a Semiconductor:



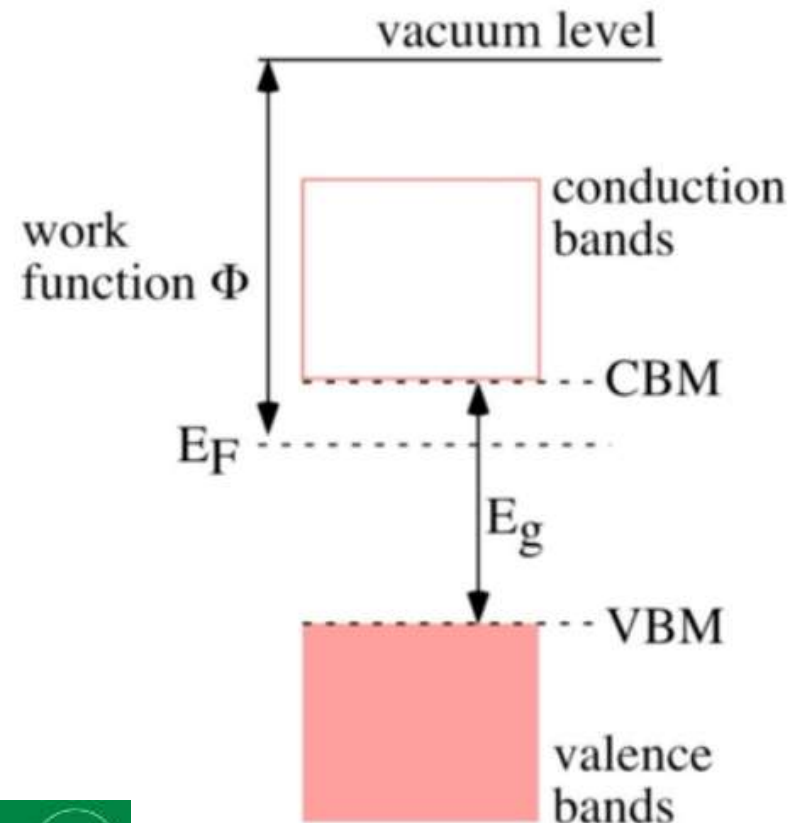
work function (German: Austrittsarbeit)

The work function is the energy required to release an electron from a solid

For a metal:



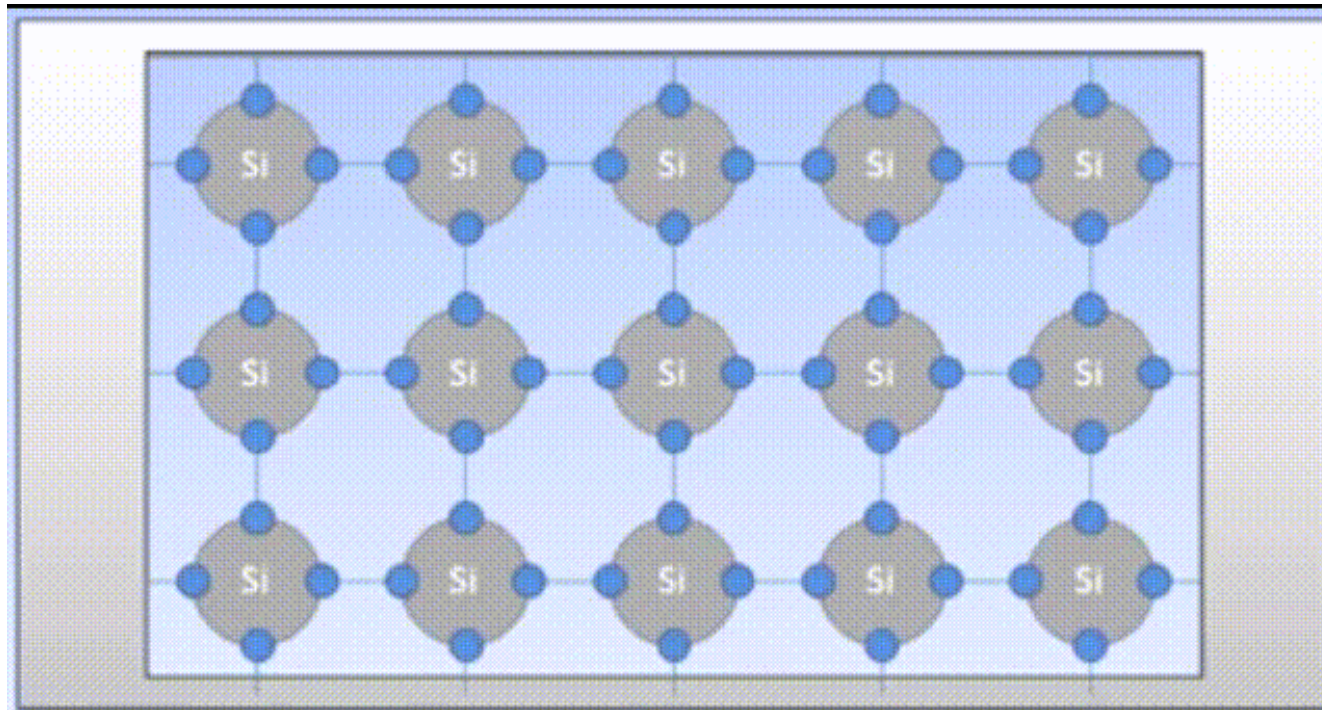
For a Semiconductor:



How about conduction **Continue**
"SCT_SS20_02.7" 4:39

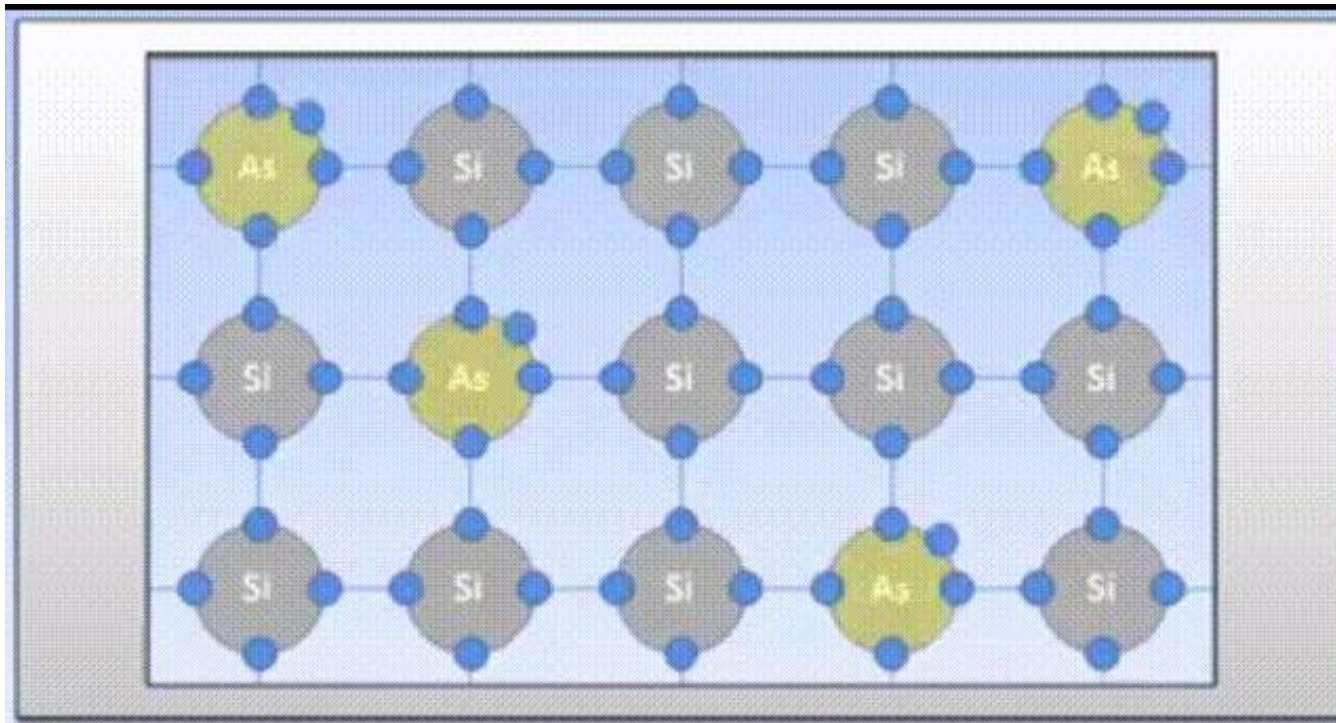


Conduction in an intrinsic semiconductor:



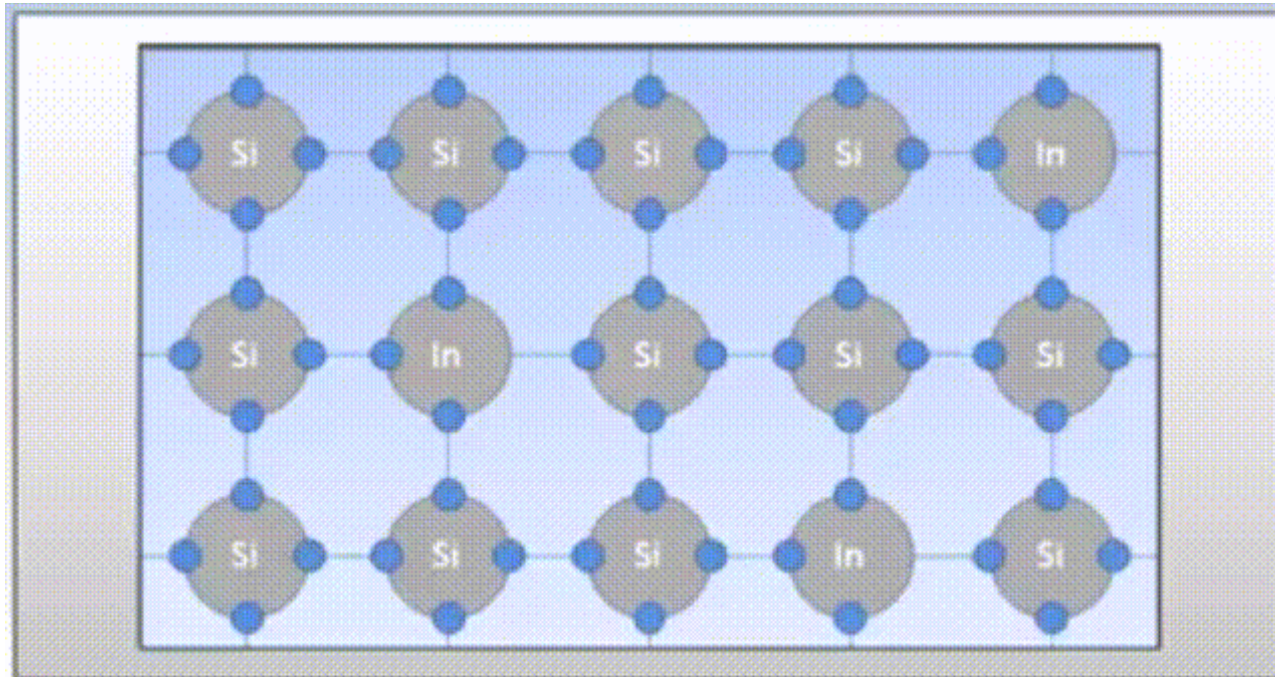
Conduction in an extrinsic semiconductor:

n- conduction

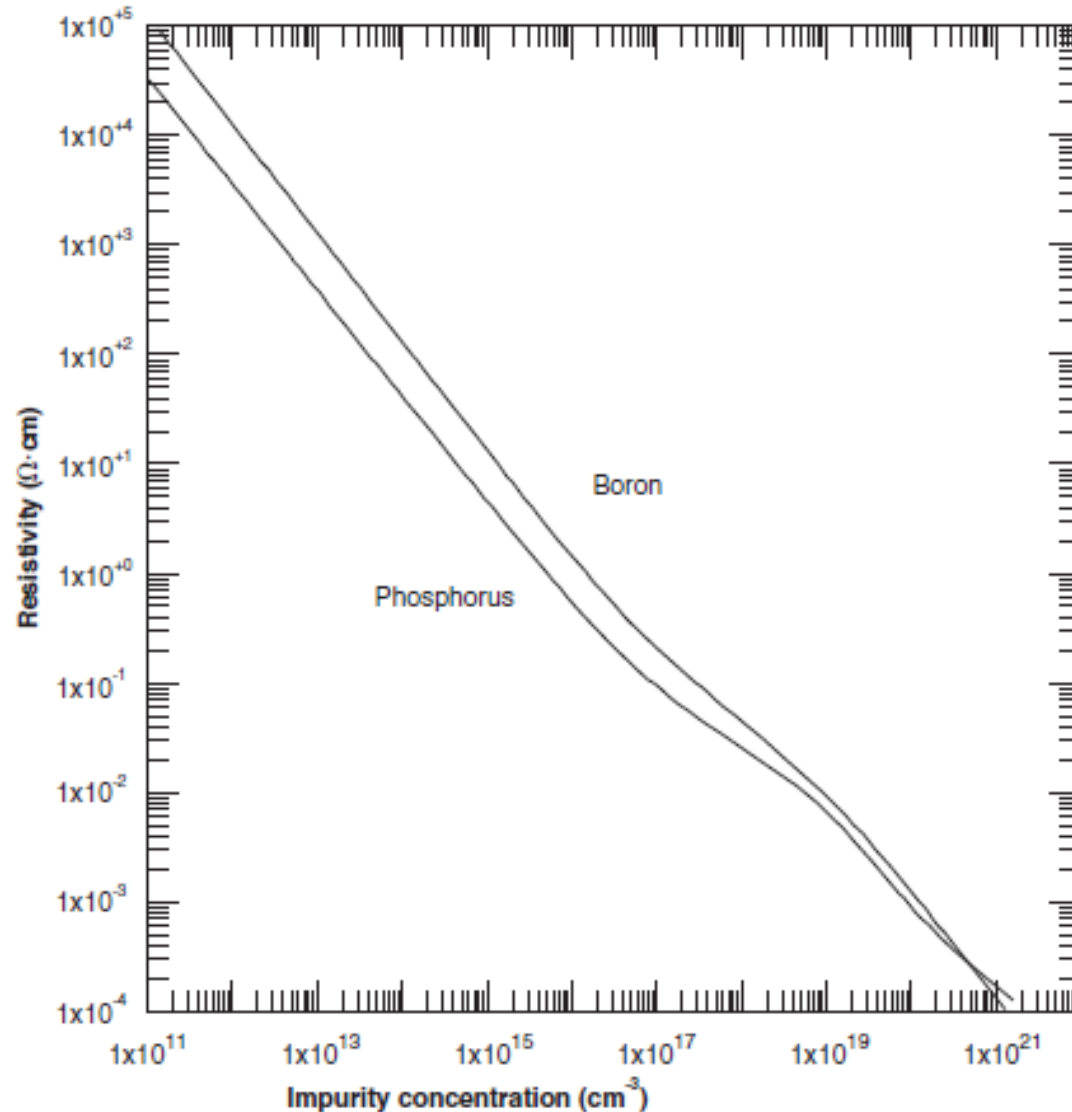


Conduction in an extrinsic semiconductor:

p- conduction

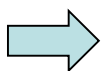


Si - Resistivity vs. doping

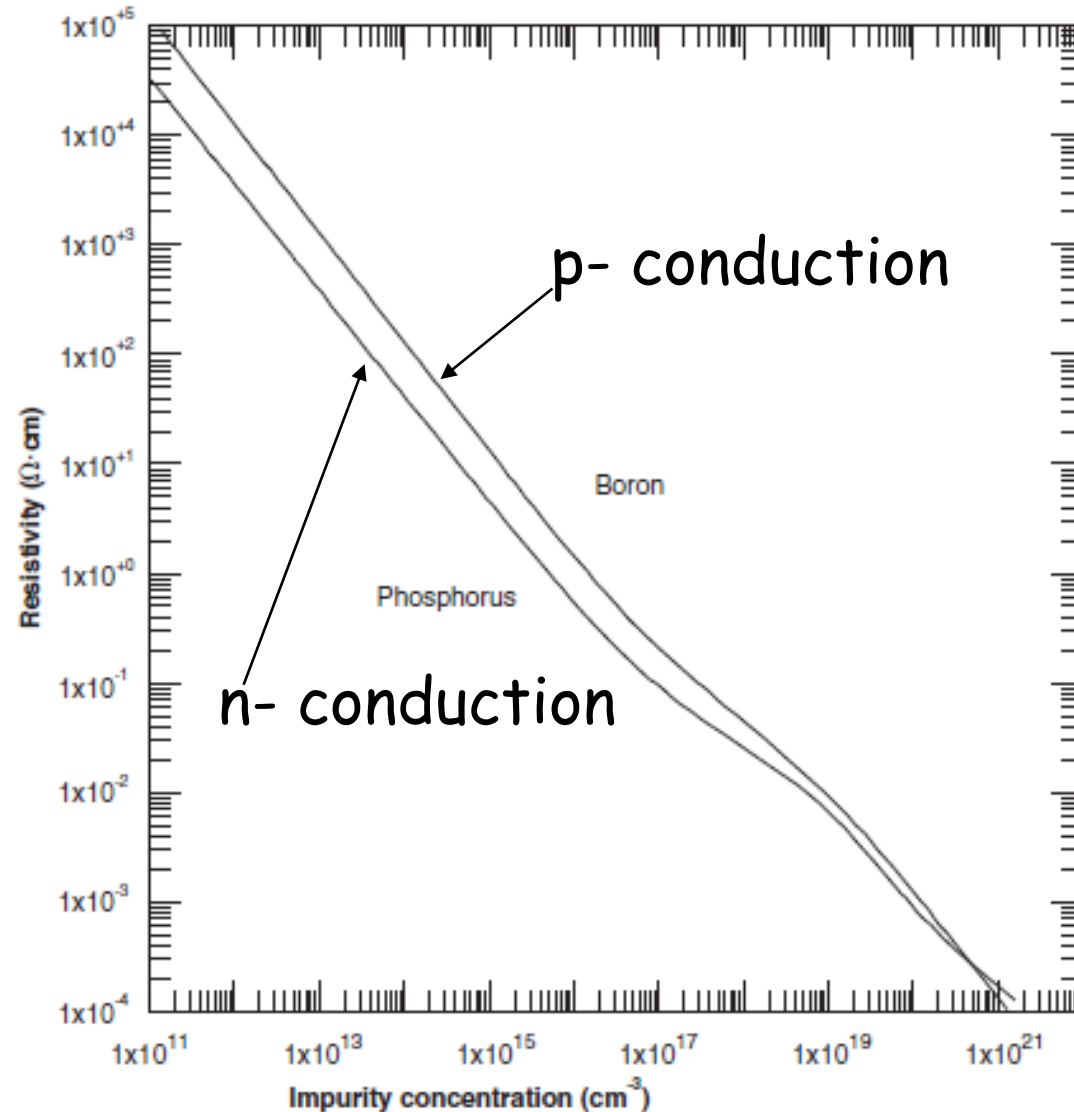


And now the p/n junction

Continue

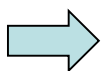


"SCT_SS20_02.8" 15:24



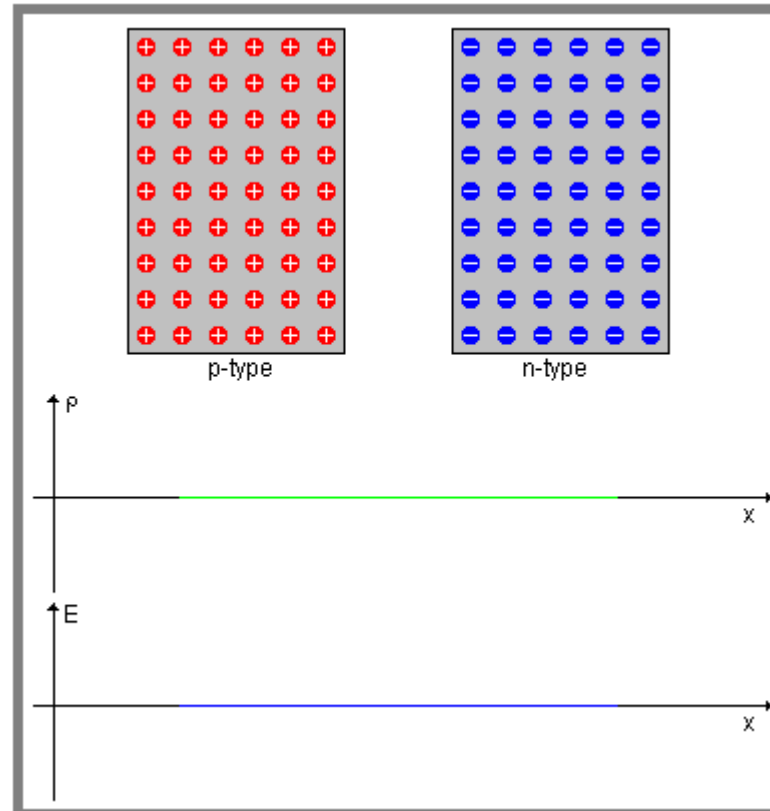
And now the p/n junction

Continue

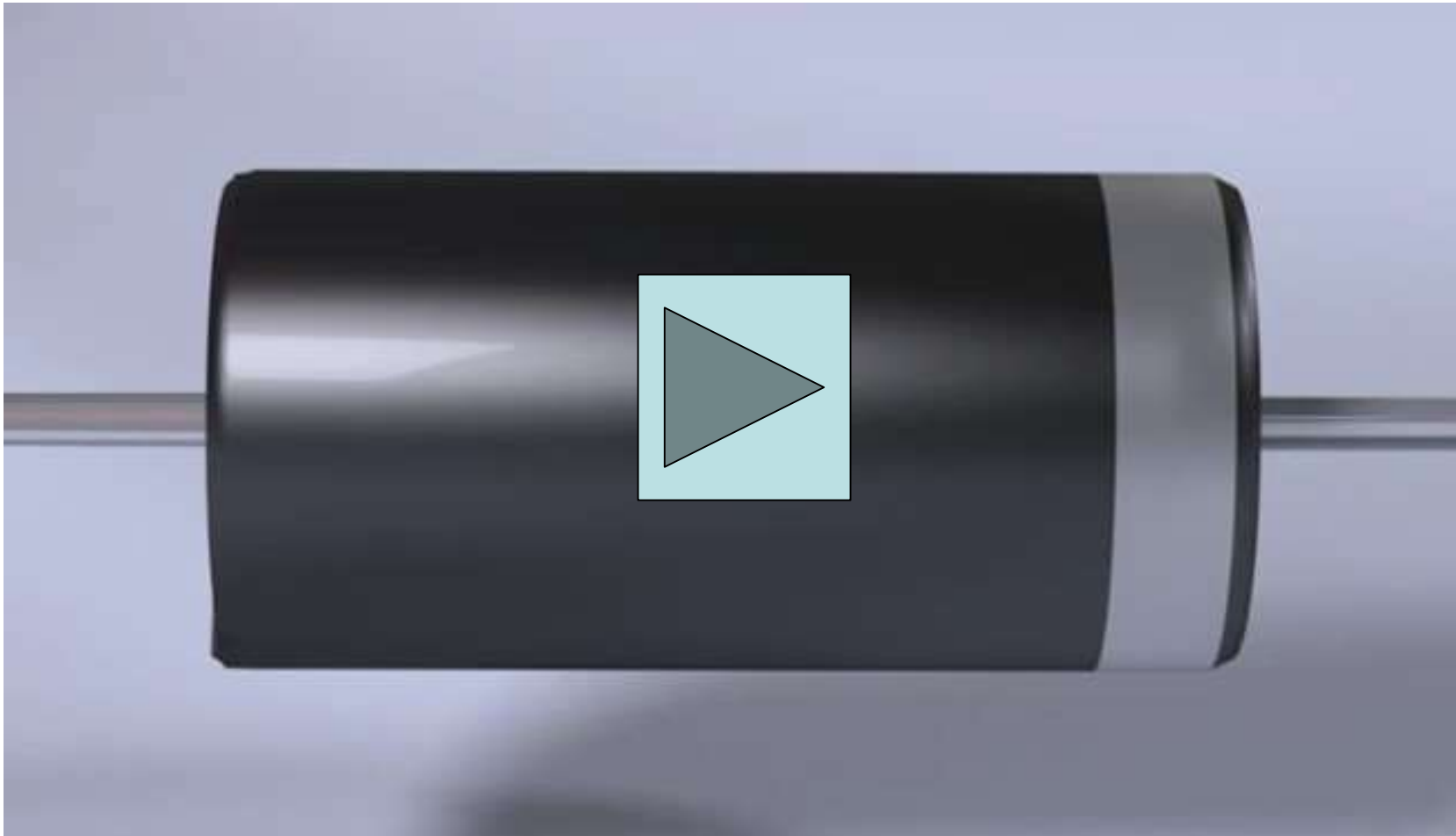


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p/n junction

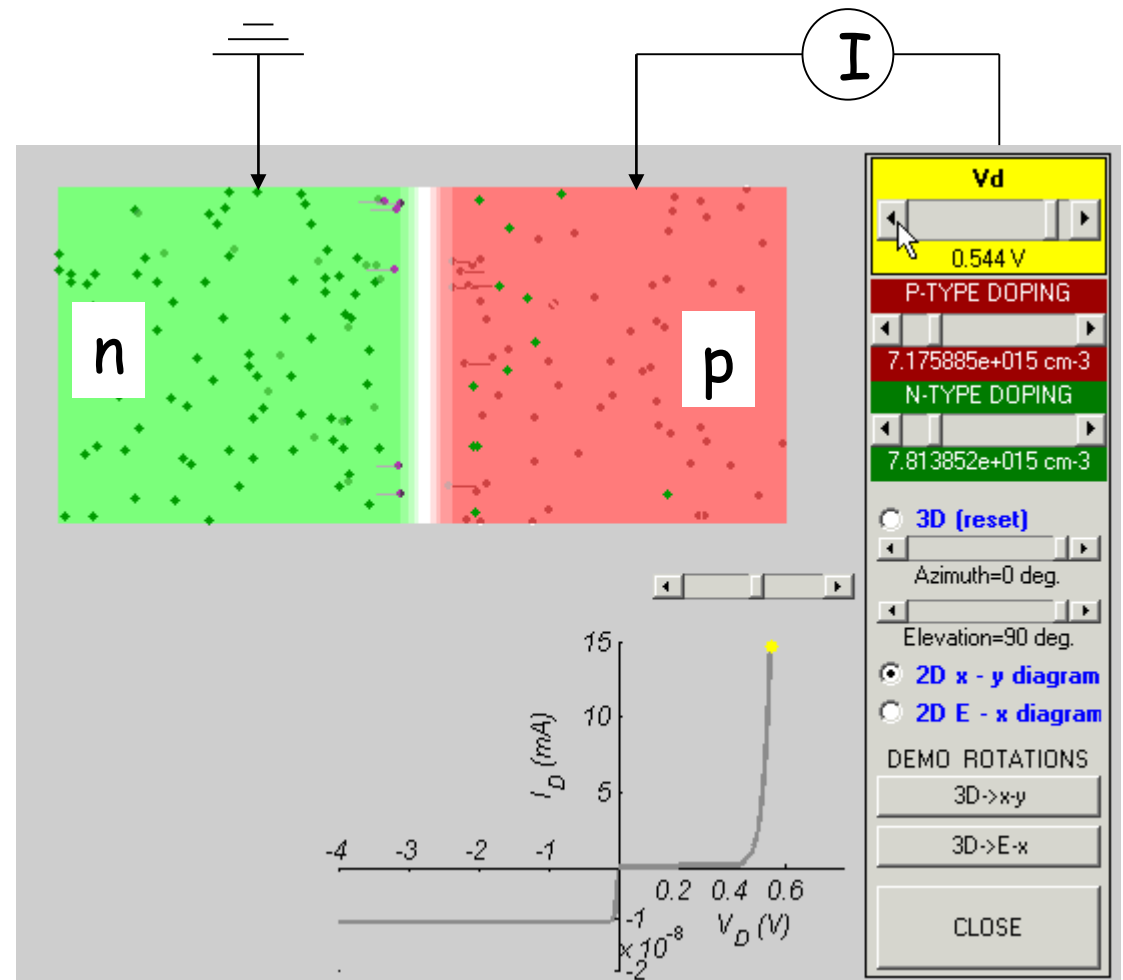


p/n junction



Taken from:
<https://www.youtube.com/watch?v=JBtEckh3L9Q&t=4s>

p/n junction



From:
 Sima Dimitrijević, *Understanding Semiconductor*, Oxford University Press 2000



End of the chapter on
semiconductor basics!



»Wissen schafft Brücken.«