Semiconductor Devices

Introduction to Semiconductors

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  - high-efficiency solar cells

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  - 10^7/cm^2: number of MOS transistors in a modern processor chip

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  - 535 kHz to 1605 kHz: AM radio frequency range (Medium Wave)

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  - 4×10^{14} Hz to 8×10^{14} Hz: frequency of visible light
  - 20 Hz to 20 kHz: frequency range of hearing for humans
  - 70 Hz to 150 kHz: frequency range of hearing for whales and dolphins
  - 535 kHz to 1605 kHz: AM radio frequency range (Medium Wave)
  - 88 MHz to 108 MHz: FM radio frequency range

A sense of scale

* Temperature
  - $0\,^\circ$C to $70\,^\circ$C: operating temperature range for a commercial-grade semiconductor device
  - $-55\,^\circ$C to $125\,^\circ$C: operating temperature range for a military-grade semiconductor device
  - $800\,^\circ$C to $1000\,^\circ$C: typical furnace temperatures used in IC technology
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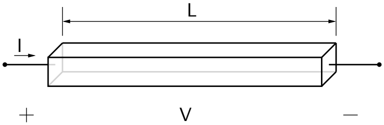
  - 88 MHz to 108 MHz: FM radio frequency range
  - $\sim$ 900 MHz: frequency for mobile communication (GSM standard)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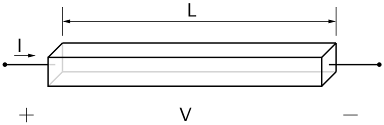
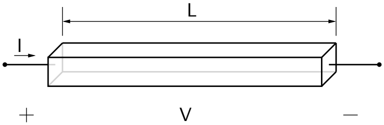


Electric field $\mathcal{E} = \dfrac{V}{L}$ (assuming uniform current flow).



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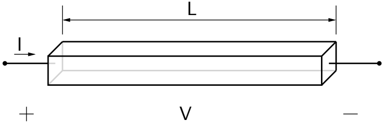

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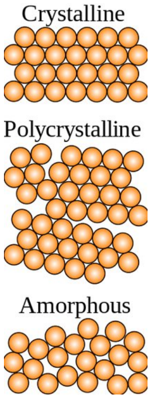
Material	Type	$\sigma\,(\Omega\text{-cm})^{-1}$
Copper	conductor	$\sim 6 \times 10^5$
Glass	insulator	10^{-17} to 10^{-13}
Silicon	semiconductor	$\sim 10^{-5}$

Solids may be classified as

* Crystalline: Atoms are arranged in a periodic manner.



(Ref.: wikipedia)

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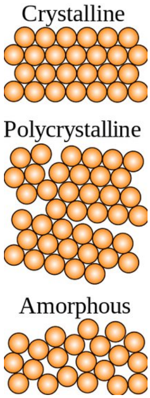

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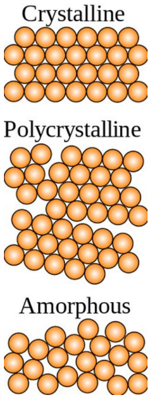

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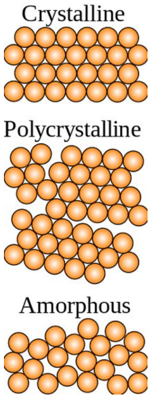

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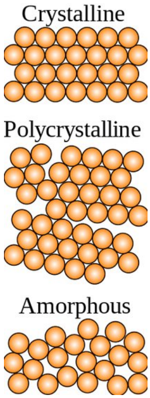
Polycrystalline and amorphous semiconductors have relatively poor properties, but the ease of manufacturing and low cost makes them attractive for certain applications. e.g., as solar cells, thin-film transistors for display devices.



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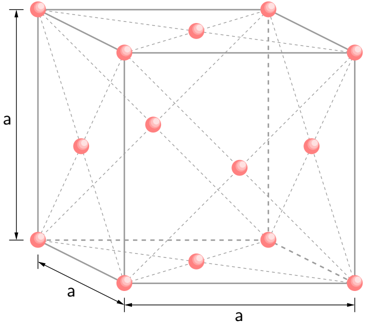
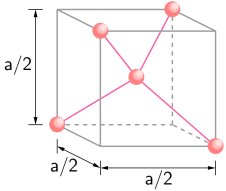


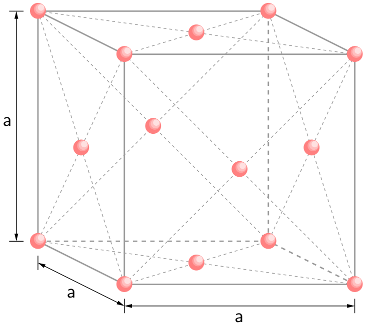
FCC lattice



Diamond structure

* Si and GaAs have the diamond structure.

Crystal structure of Si and GaAs



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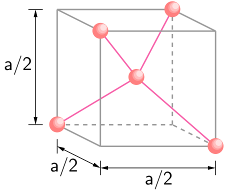

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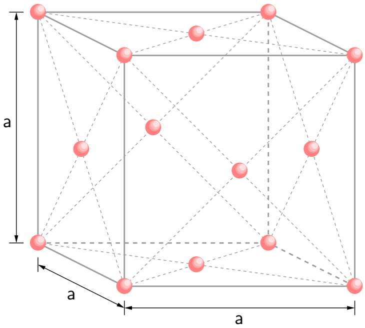

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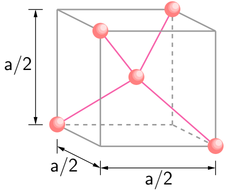

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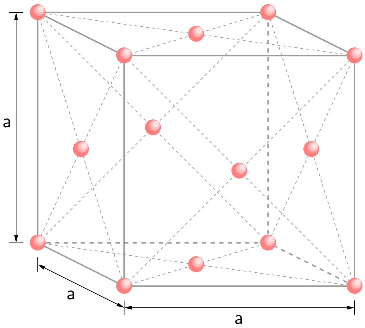

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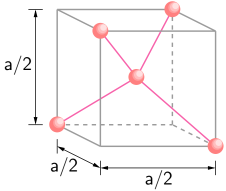

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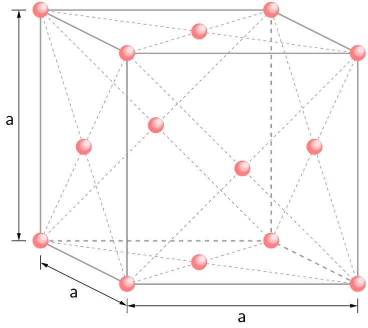
* The structure of GaAs is similar. Each Ga atom has four As neighbours, and *vice versa*.



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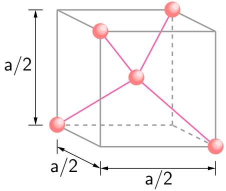

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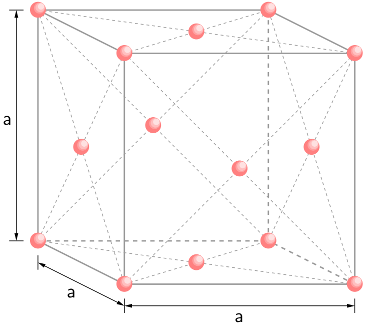
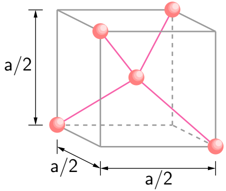
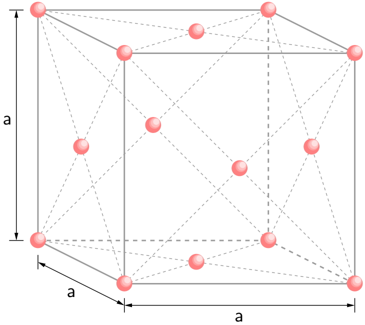


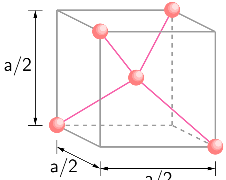


* In silicon, the distance between neighbouring atoms is $\sqrt{3}\,a/4$, with $a = 5.43\,\AA$.

Crystal structure of Si and GaAs



FCC lattice



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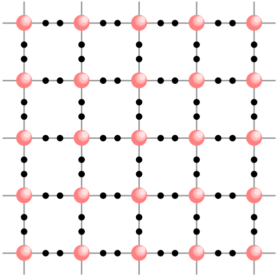
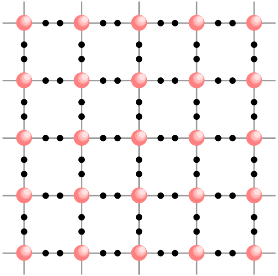
* In silicon, the distance between neighbouring atoms is $\sqrt{3}\,a/4$, with $a = 5.43\,\AA$.
* There are 5×10^{22} atoms per cm^3.



2–D representation of silicon lattice



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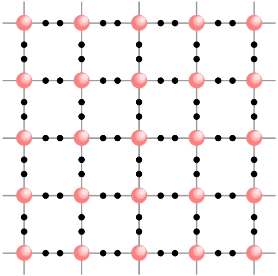

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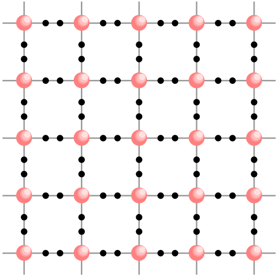

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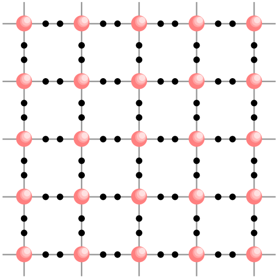

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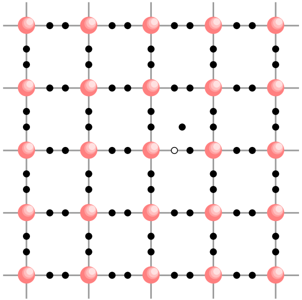
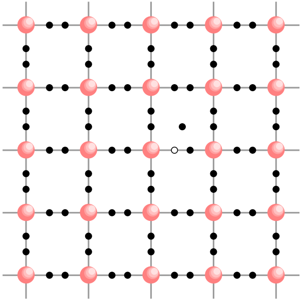
* At 0 K, all valence electrons are held by the covalent bonds, no electrons are available for conduction, and the material behaves like an insulator.





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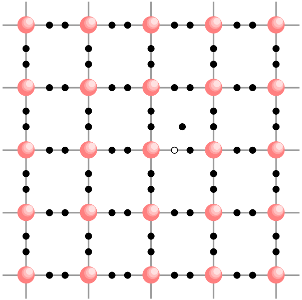

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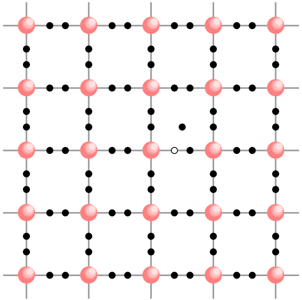

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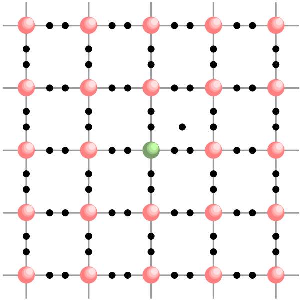
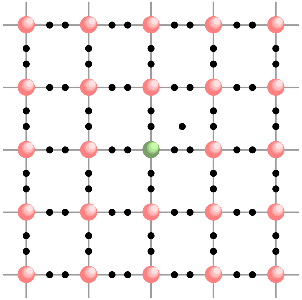
* These free electrons and holes are available for conduction.



Suppose one of the silicon atoms is replaced with a group V atom (e.g., P or As).



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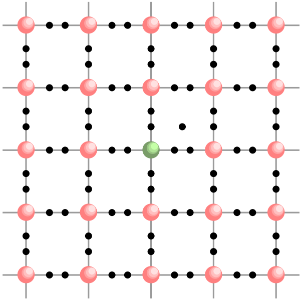

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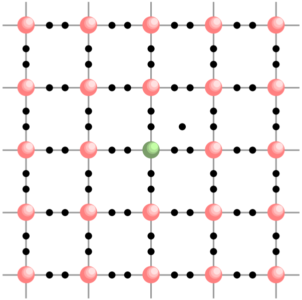

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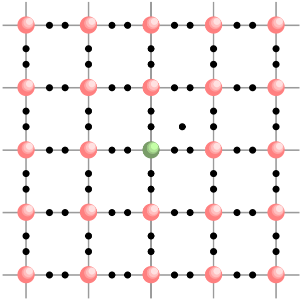
Electrons and holes: the bond picture



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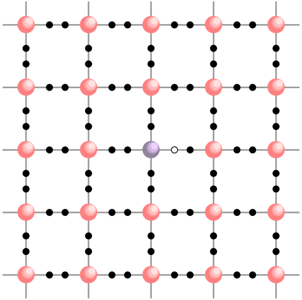
* We say that the group V atom has "donated" a free electron to the lattice which is available for conduction.



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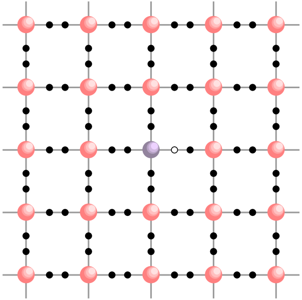

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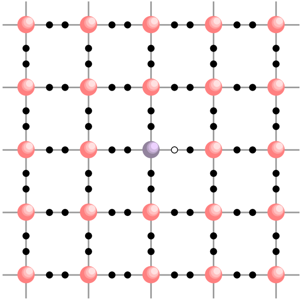

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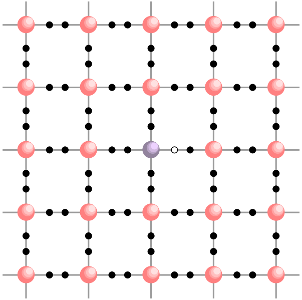

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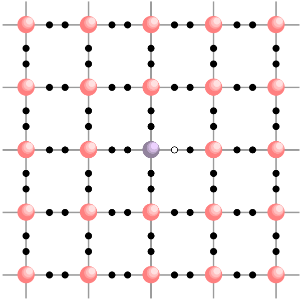

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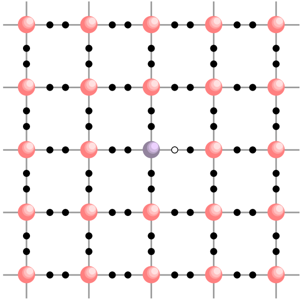

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* We say that the group III atom has "accepted" an electron from a Si-Si bond, which is equivalent to transferring the vacancy (hole) to that bond.

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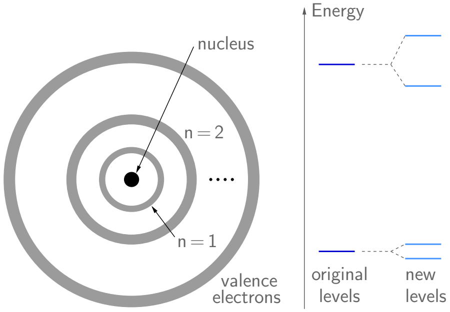
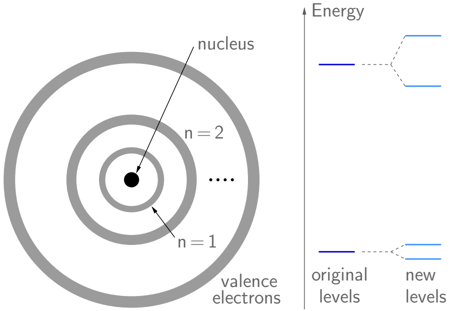
* Can *any* group V atom serve as a donor in silicon?

Electrons and holes: the band picture





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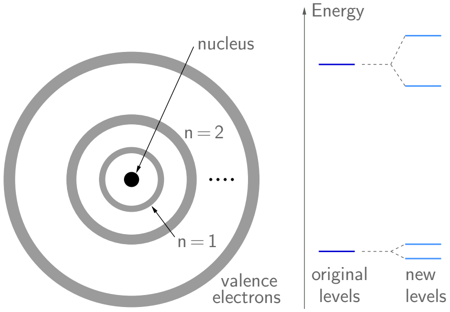

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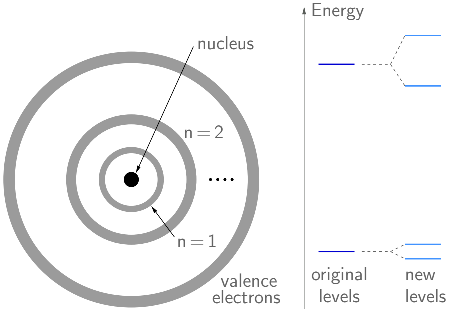

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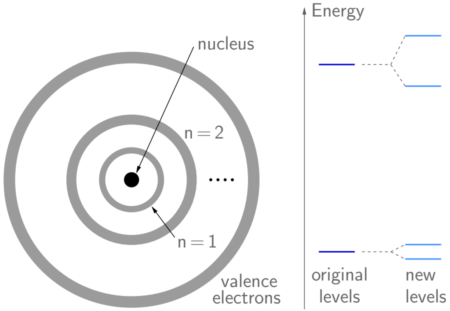

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* An electron can only occupy one of these wave functions ("orbit" or "state").
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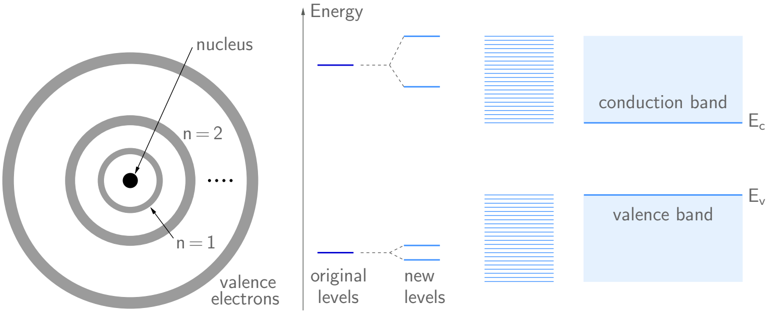
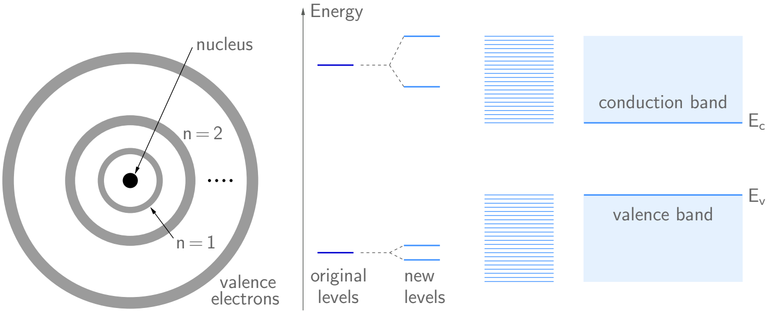
* Each of the energy level splits into two levels (states).

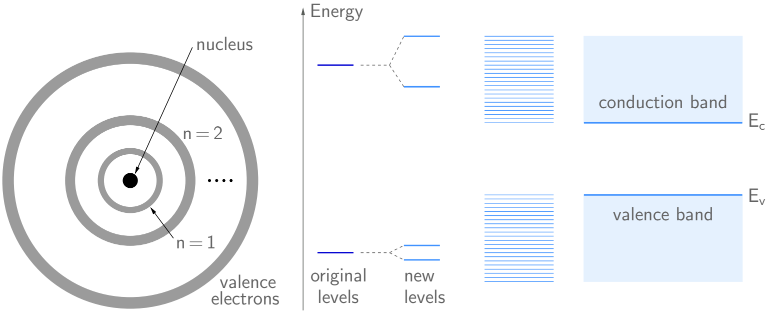
Electrons and holes: the band picture



Electrons and holes: the band picture



* In a crystal, the problem is much more complex since the wave functions of several atoms overlap.



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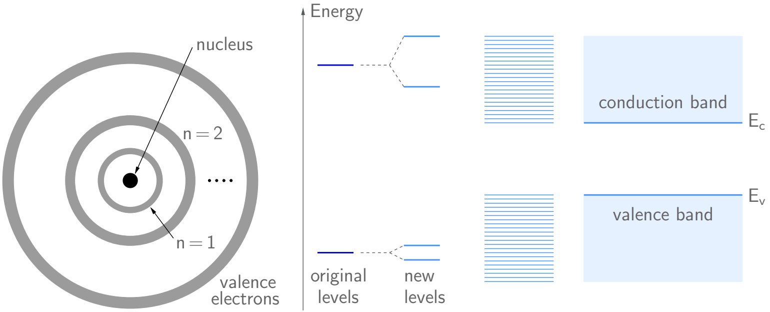

* In a crystal, the problem is much more complex since the wave functions of several atoms overlap.
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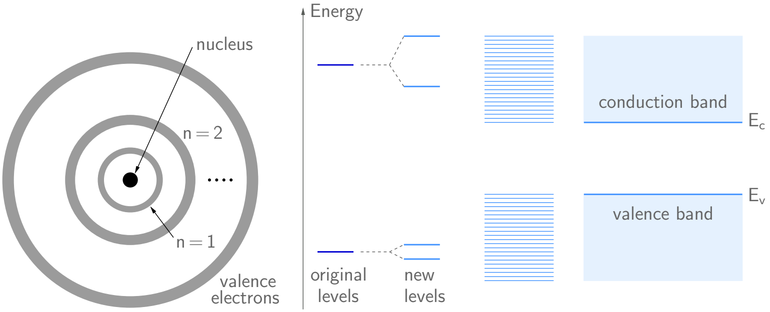
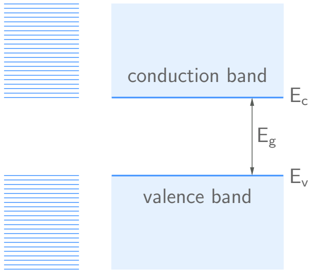
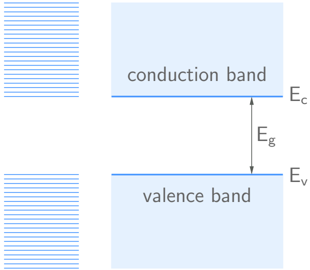
Electrons and holes: the band picture



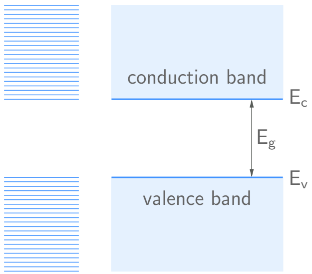
* In a crystal, the problem is much more complex since the wave functions of several atoms overlap.
* The original energy levels split into a large number of levels.
* The number of levels is so large that we can treat them as a *continuum* or "band" of levels (states).
* For semiconductors, the states get bunched such that, in a certain energy range, $E_v < E < E_c$, there are no states at all.

Electrons and holes: the band picture

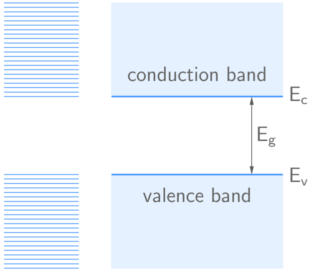




* The bottom edge of the conduction band is denoted by E_c, and the top edge of the valence band by E_v.



* The bottom edge of the conduction band is denoted by E_c, and the top edge of the valence band by E_v.
* The difference $E_c - E_v$ is called the "energy gap" (E_g), and it plays a fundamental role in the electrical and optical properties of a semiconductor.



Semiconductor	E_g (eV)
Ge	0.67
Si	1.1
GaAs	1.43
GaP	2.26
GaN	3.4

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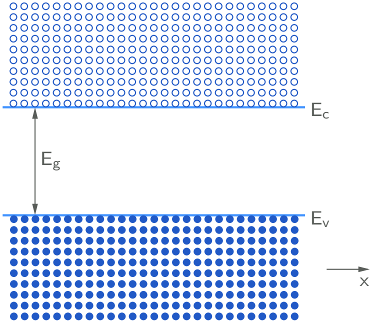
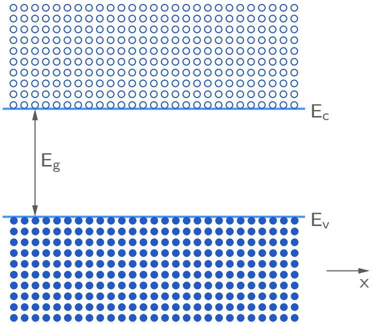


Filled and empty electron states at 0 K.

(Note: This is a schematic representation;
in reality, the density of states varies with E.)



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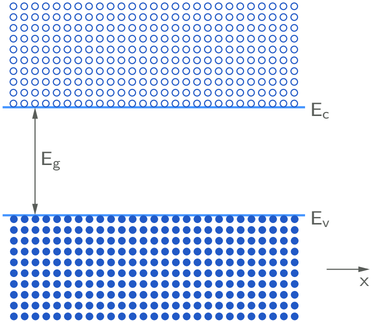

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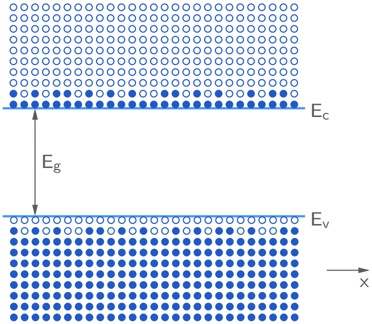
* At $T = 0\,\mathrm{K}$, the valence band is completely full of electrons, and the conduction band is completely empty.
* There is no possibility of conduction.



Filled and empty electron states at 300 K.

(Note: This is a schematic representation;
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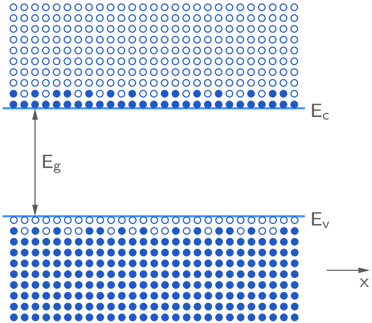
Electrons and holes: the band picture



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(Note: This is a schematic representation;
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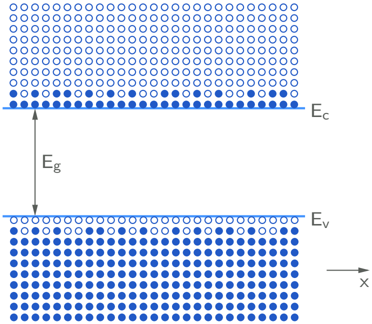
* As the lattice temperature is increased, the probability of occupation of conduction band states by electrons increases.

Electrons and holes: the band picture



Filled and empty electron states at 300 K.

(Note: This is a schematic representation;
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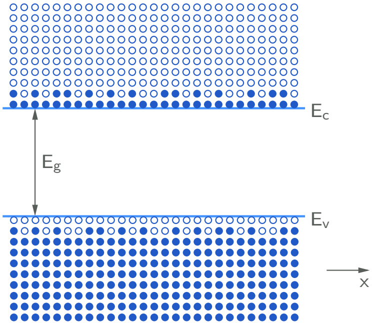
* As the lattice temperature is increased, the probability of occupation of conduction band states by electrons increases.
* In a pure or "intrinsic" semiconductor, the number of electrons in the conduction band must be equal to the number of vacancies (holes) in the valence band.

Electrons and holes: the band picture



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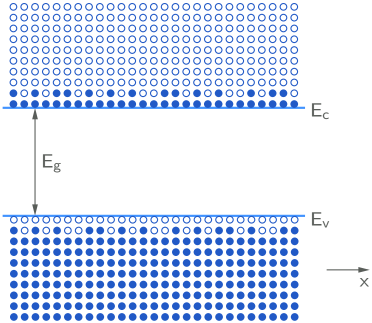
* In a pure or "intrinsic" semiconductor, the number of electrons in the conduction band must be equal to the number of vacancies (holes) in the valence band.
* The density of electrons (or holes) in the above situation is denoted by n_i, the "intrinsic carrier concentration," and it is about $10^{10}\,\text{cm}^{-3}$ for Si at $T = 300\,\text{K}$. (Note that it is much smaller than the density of silicon atoms in the crystal, i.e., $5 \times 10^{22}\,\text{cm}^{-3}$).



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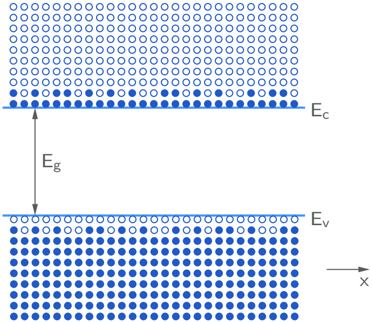

Filled and empty electron states at 300 K.

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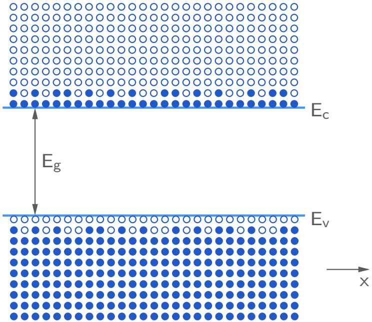
* An electron in the conduction band can move to one of the large number of empty states in the conduction band and contribute to a current.

Electrons and holes: the band picture



Filled and empty electron states at 300 K.

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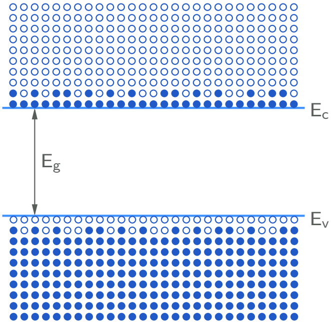
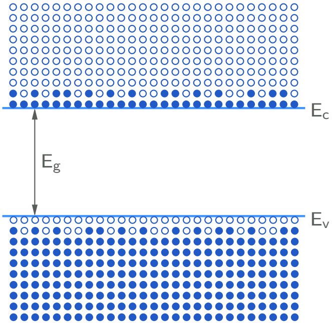
* An electron in the conduction band can move to one of the large number of empty states in the conduction band and contribute to a current.
* Similarly, a hole in the valence band can move to one of the large number of filled states in the valence band and contribute to a current.

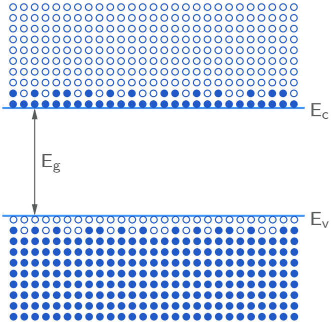
Electrons and holes: the band picture





* Filled states in the conduction band (the mobile electrons or simply "electrons") and empty states in the valence band (the mobile vacancies or "holes") are confined to a narrow energy range near E_c and E_v, respectively ($\sim$ 100 meV at 300 K).

Electrons and holes: the band picture



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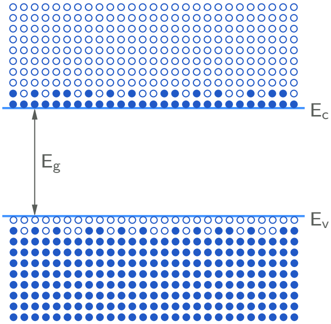
* The actual extent of the conduction or valence band does not affect the electron or hole statistics, and it is a common practice to show the conduction band extending to $+\infty$ and the valence band to $-\infty$.

Electrons and holes: the band picture



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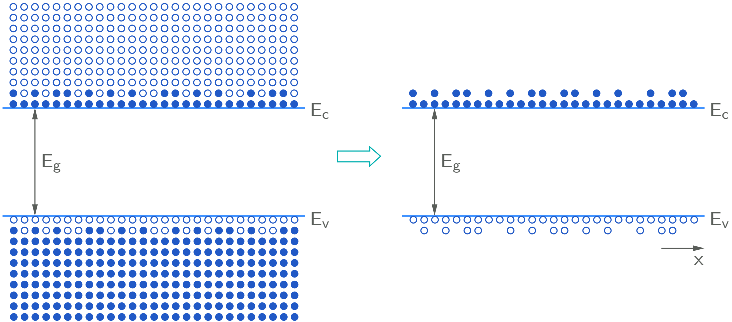

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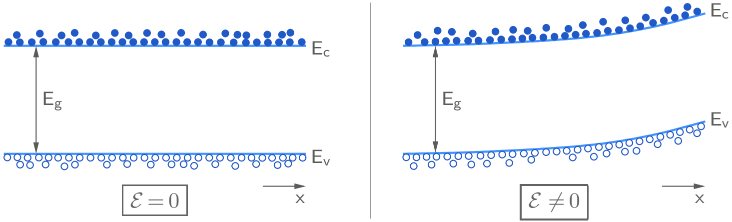
Effect of electric field



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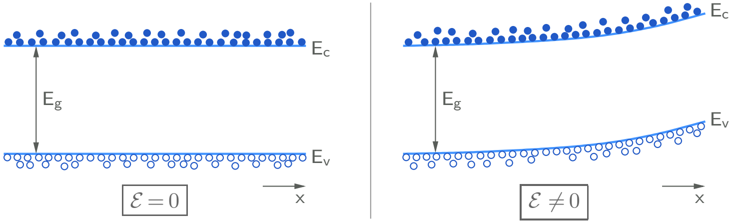

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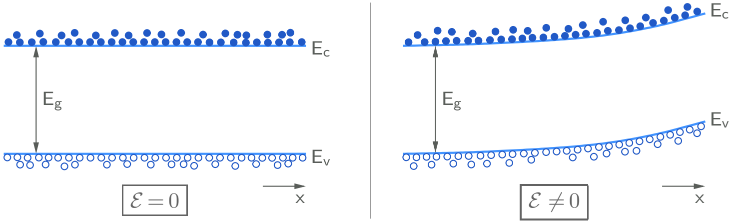
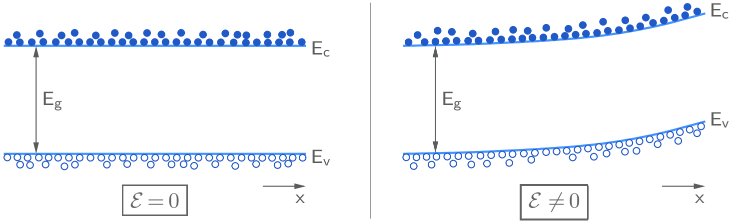
Effect of electric field



* If the electrostatic potential varies with space, it causes "band bending."
* Since E_c and E_v refer to energy of an electron with a negative charge $-q$,
  $E_c(x) = -q\,\psi(x) + \text{constant}, \quad E_v(x) = E_c(x) - E_g$.

Effect of electric field



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  $\rightarrow \mathcal{E} = \dfrac{1}{q}\,\dfrac{dE_c}{dx} = \dfrac{1}{q}\,\dfrac{dE_v}{dx}$

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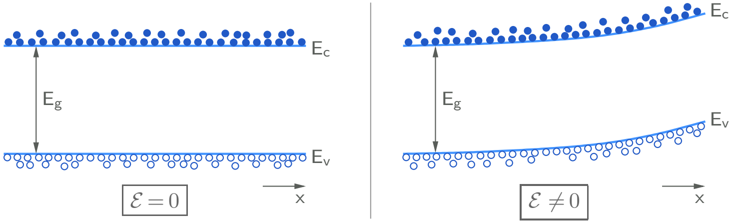

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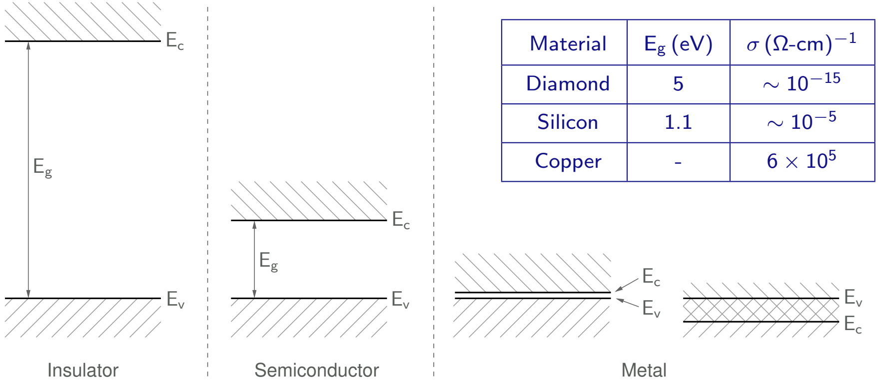
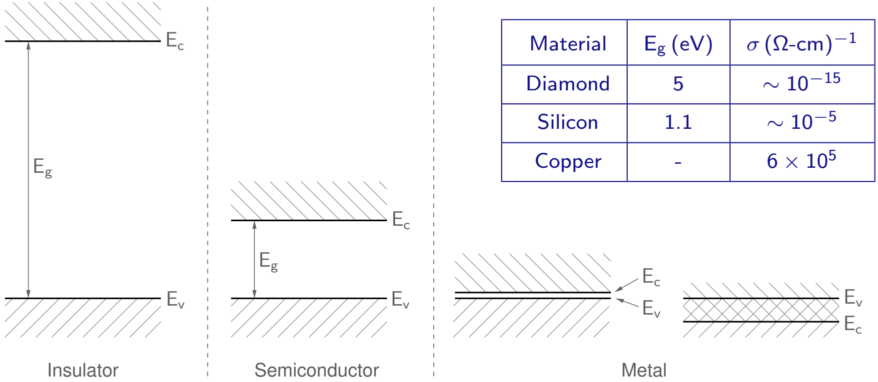
  $\rightarrow \mathcal{E} = \dfrac{1}{q}\,\dfrac{dE_c}{dx} = \dfrac{1}{q}\,\dfrac{dE_v}{dx}$
* The constant in the above equation is irrelevant because only differences such as $(E_c(x_1) - E_c(x_2))$ are important, and the constant drops out.



Material	E_g (eV)	$\sigma\ (\Omega\text{-cm})^{-1}$
Diamond	5	$\sim 10^{-15}$
Silicon	1.1	$\sim 10^{-5}$
Copper	-	6×10^5

Energy gap and conductivity



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* The electrical conductivity of a crystalline material depends on its energy gap E_g.

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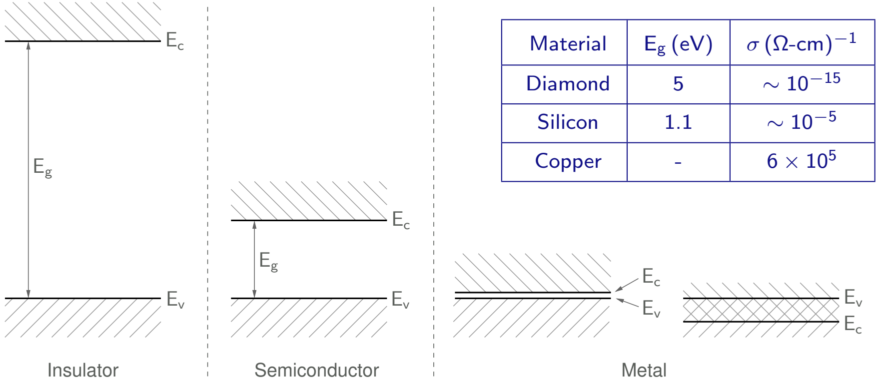

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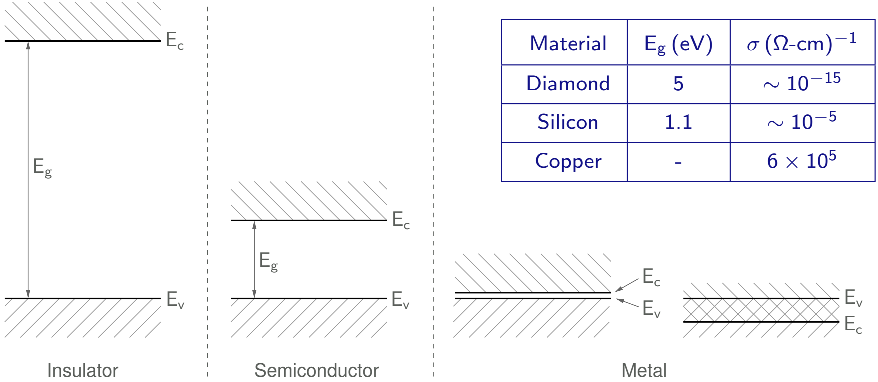
Energy gap and conductivity



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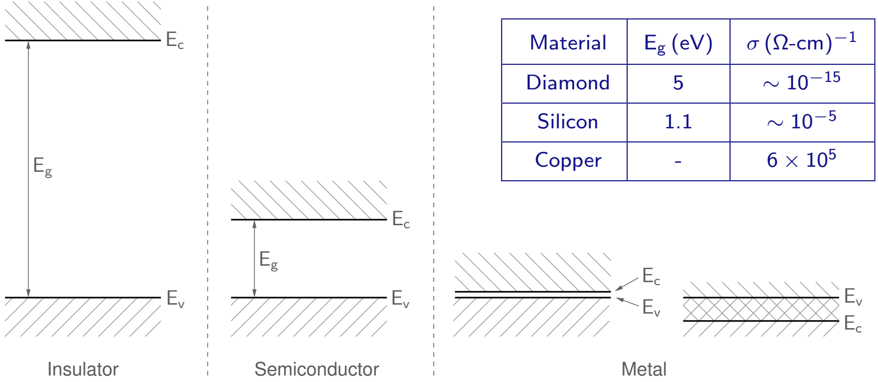
* In an insulator, E_g is so large that there are no electrons (in the conduction band) or holes (in the valence band) at room temperature $\rightarrow$ low conductivity.
* In a metal, E_g is either very small or non-existent. As a result, electrons in the filled states can move to one of the large number of vacant states $\rightarrow$ high conductivity.

Energy gap and conductivity



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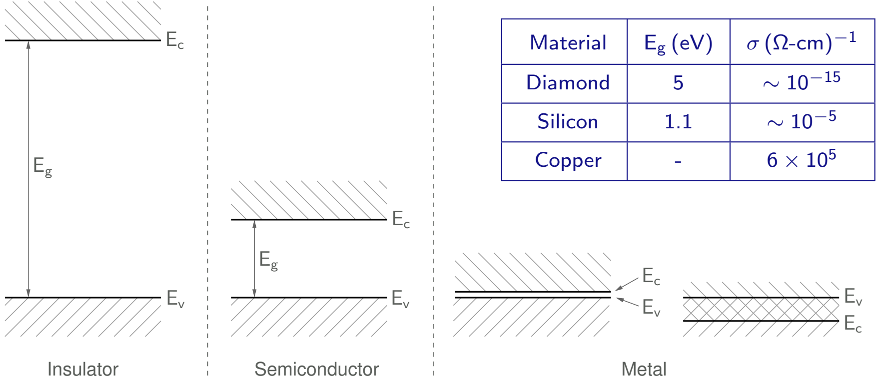

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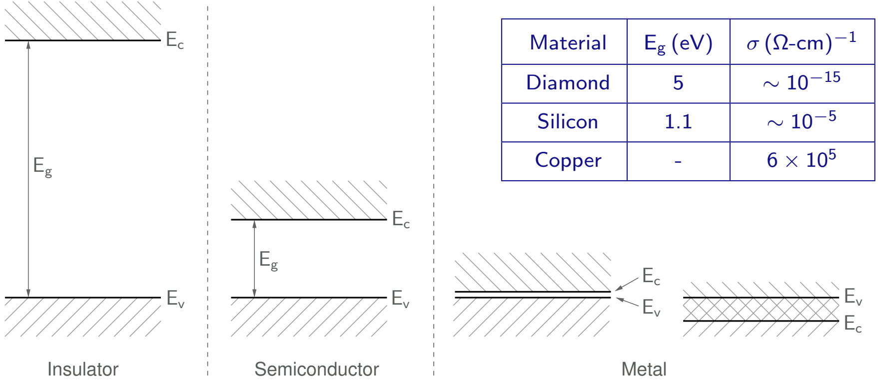
* For a semiconductor, the situation is between these two extremes $\rightarrow$ moderate conductivity.

Energy gap and conductivity



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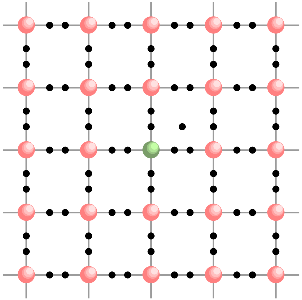
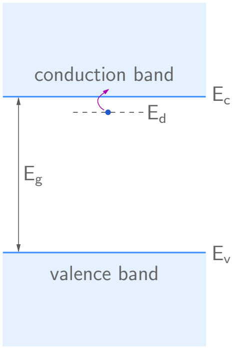
* For a semiconductor, the situation is between these two extremes $\rightarrow$ moderate conductivity.
* Note that we have only looked at an "intrinsic" semiconductor. With addition of appropriate impurity (donor or acceptor) atoms, the conductivity of a semiconductor can be changed very significantly.

Band picture: effect of a donor atom





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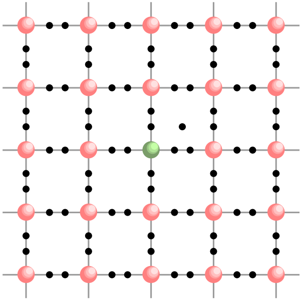
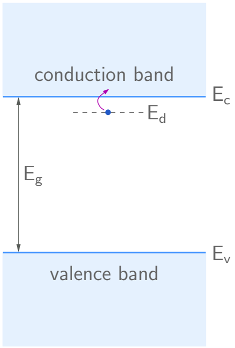
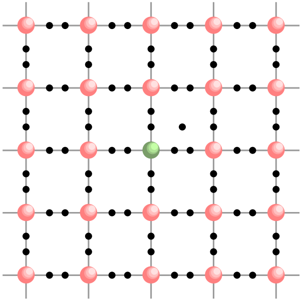
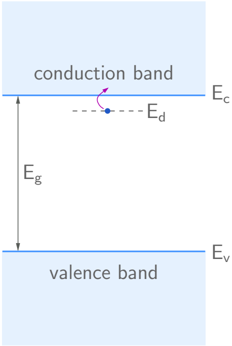




* When a silicon atom is replaced with a donor (group V) atom, it introduces an energy level (state) in the forbidden gap, which is close to E_c.

Band picture: effect of a donor atom





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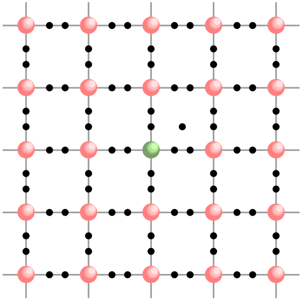

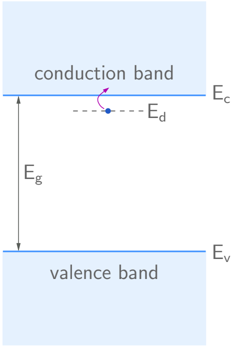

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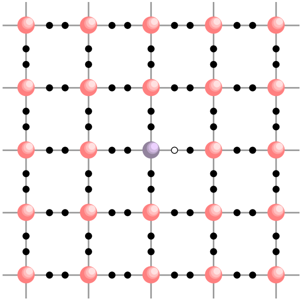
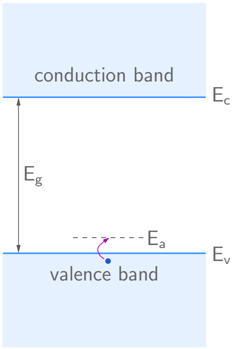
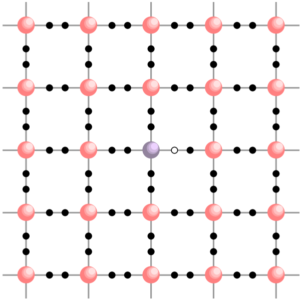
* At low temperatures, the donor state is occupied, i.e., the electron is bound to the donor atom.
* At high temperatures, the electron can cross the energy barrier $(E_c - E_d)$ and enter the conduction band.

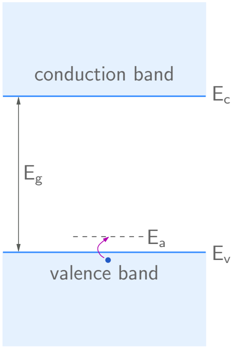
Band picture: effect of an acceptor atom



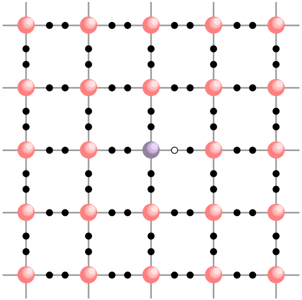


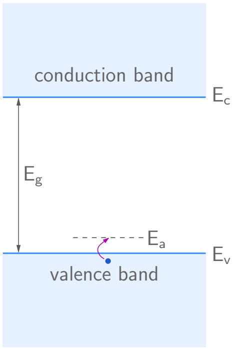
Band picture: effect of an acceptor atom





* When a silicon atom is replaced with an acceptor (group III) atom, it introduces an energy level (state) in the forbidden gap, which is close to E_v.





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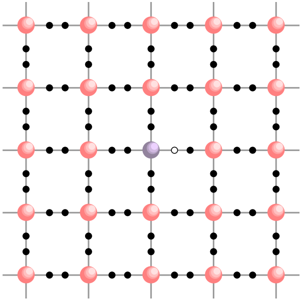

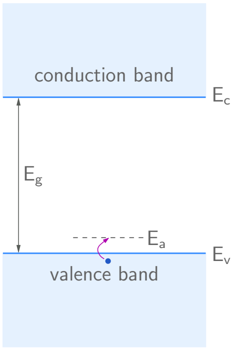

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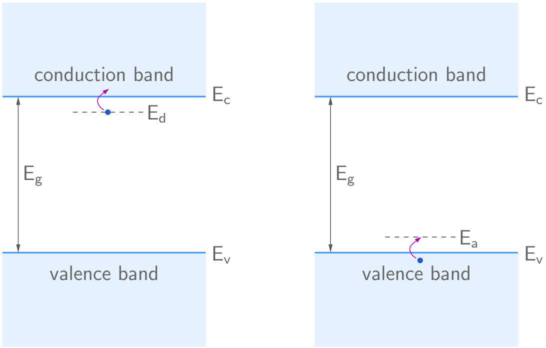
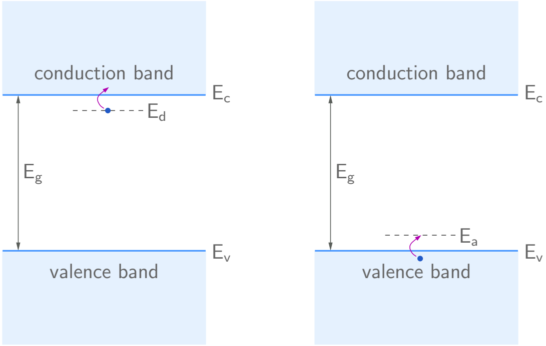
* At low temperatures, the acceptor state is empty, i.e., there is a vacancy around the acceptor atom.
* At high temperatures, an electron from the valence band can cross the energy barrier $(E_a - E_v)$, leaving a hole in the valence band.

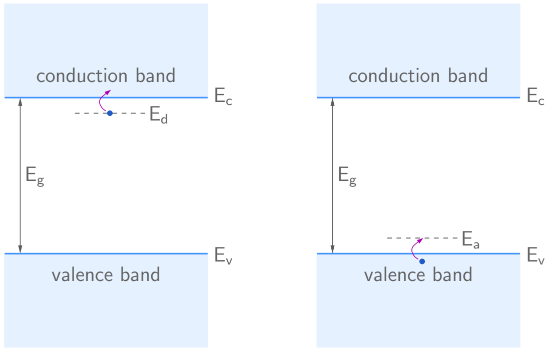
Donor and acceptor levels





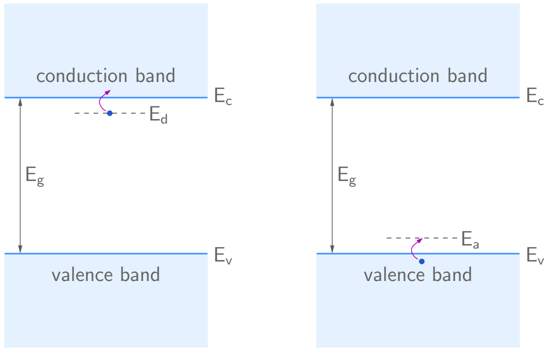
* The effectiveness of a donor atom to contribute an electron depends on the binding energy $E_B = E_c - E_d$.

Donor and acceptor levels



* The effectiveness of a donor atom to contribute an electron depends on the binding energy $E_B = E_c - E_d$.
* For a "shallow" donor, this energy is typically a few tens of meV (45 meV for P and 54 meV for As in silicon).

Donor and acceptor levels



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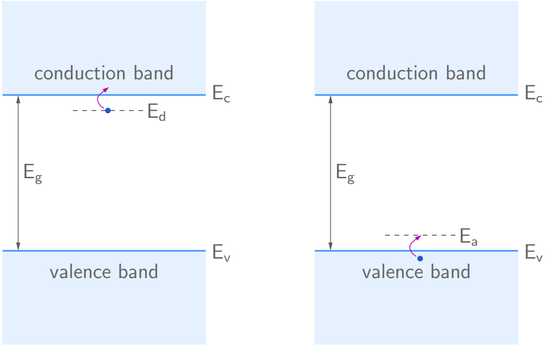
* Similarly, the effectiveness of an acceptor atom to contribute a hole depends on the binding energy $E_B = E_a - E_v$.

Donor and acceptor levels



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* Similarly, the effectiveness of an acceptor atom to contribute a hole depends on the binding energy $E_B = E_a - E_v$.
* For a "shallow" acceptor, this energy is typically a few tens of meV (45 meV for B in silicon).