TOSHIBA

e-Learning

Basics of Schottky Barrier Diodes

Chapter1 Basics of Schottky Barrier Diodes
(Basic of Semiconductor Device)

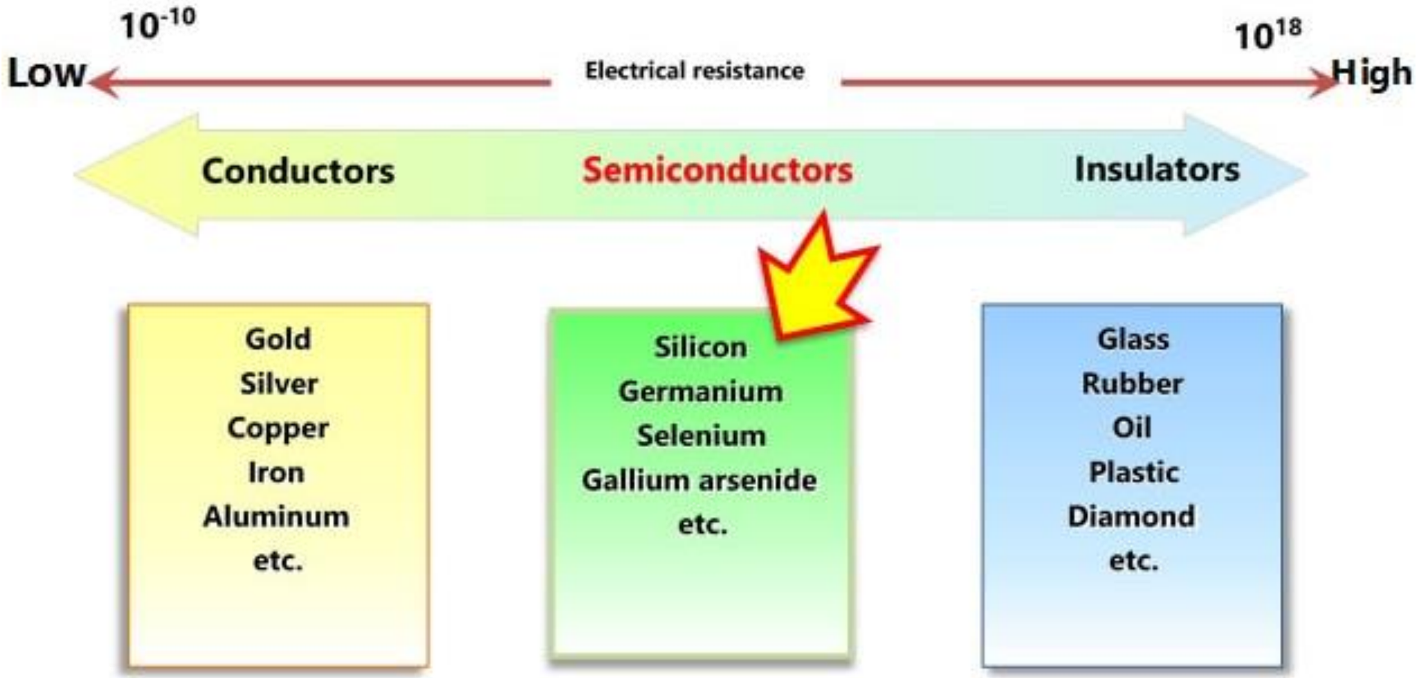
Toshiba Electronic Devices & Storage Corporation

1. Conductors, semiconductors, and insulators

Materials can be divided into three categories according to their ability to conduct an electric current:

- Conductors: Materials that easily conduct electricity (i.e., materials with high electrical conductivity and low electrical resistivity)
- Semiconductors: Materials with an electrical conductivity value that falls between that of a conductor and that of an insulator
- Insulators: Materials that do not readily conduct electricity (i.e., materials with high electrical resistivity)

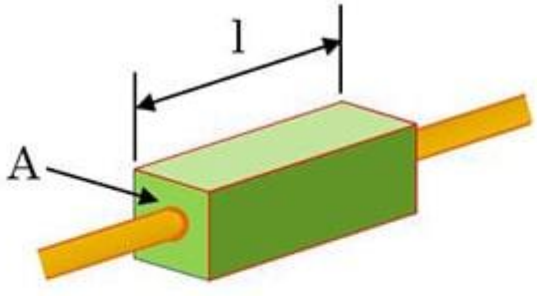
Conductors have electrical resistivity on the order of 10^{-8} to 10^{-4} Ωcm whereas insulators have electrical resistivity on the order of 10^{8} to 10^{18} Ωcm. Semiconductors have an electrical resistivity value between those of conductors and insulators—10^{-4} to 10^{8} Ωcm.



1. Conductors, semiconductors, and insulators

Electrical resistance (R) is the resistance to a flow of electric current through a material. The electrical resistance of a material is proportional to its length (l) and inversely proportional to its cross-sectional area (A). Each material has also an intrinsic property called electrical resistivity (ρ). Electrical resistance (R) is expressed as follows as a function of ρ, I and A. Electrical resistivity (ρ) is determined by the energy level (band) of the electrons in the outermost shell of an atom, crystalline states, and other factors.

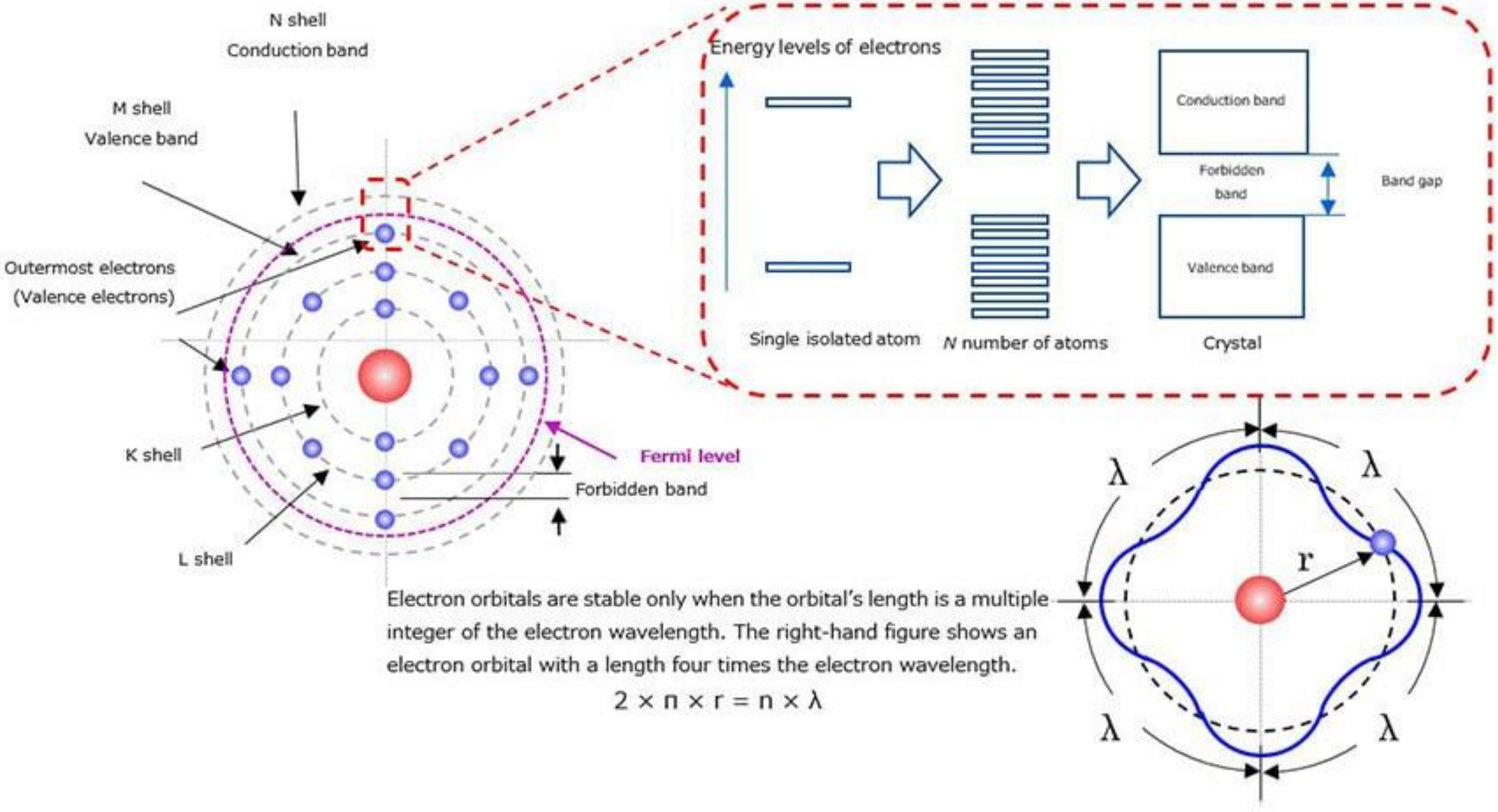
$$R = \rho \times \frac{l}{A}$$



1.1. Energy band diagram

Free electrons in a material allow a free flow of electricity. Although being part of atoms, free electrons are so loosely bound to atoms in a material, they can move about freely.

In classical physics, the Bohr model is a physical model that consists of a small atomic nucleus of protons and neutrons around which electrons travel in multiple orbits. Each element has a fixed number of electrons, which are placed from the orbit closest to the nucleus. For example, silicon (Si), a semiconductor, has 14 electrons. Figure shows the Bohr model of silicon.

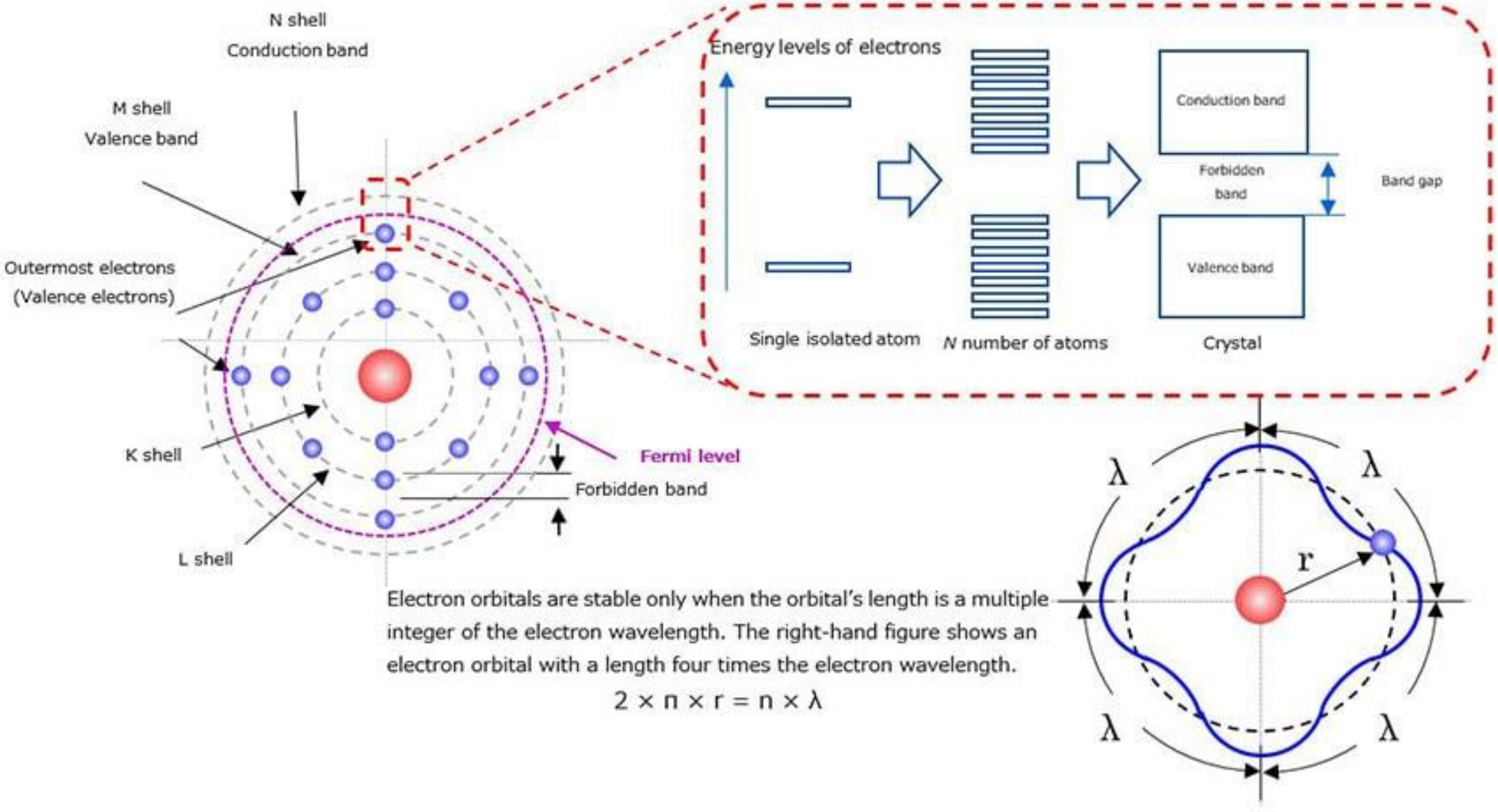


Electron orbitals are stable only when the orbital's length is a multiple integer of the electron wavelength. The right-hand figure shows an electron orbital with a length four times the electron wavelength.

$$2 \times \pi \times r = n \times \lambda$$

1.1. Energy band diagram

Since electrons have a wave nature, they are stable only on an orbital with a radius that is an integer multiple of their wavelength. Therefore, electrons move in discrete orbitals as represented by the Bohr model.
The electron orbital in a single isolated atom has an extremely narrow energy band. However, according to the Pauli exclusion principle, two or more electrons cannot occupy the same orbital. Therefore, as the state of matter changes from a single atom to a molecule to a crystal, their electron orbitals come to form a continuous band structure of energy levels.

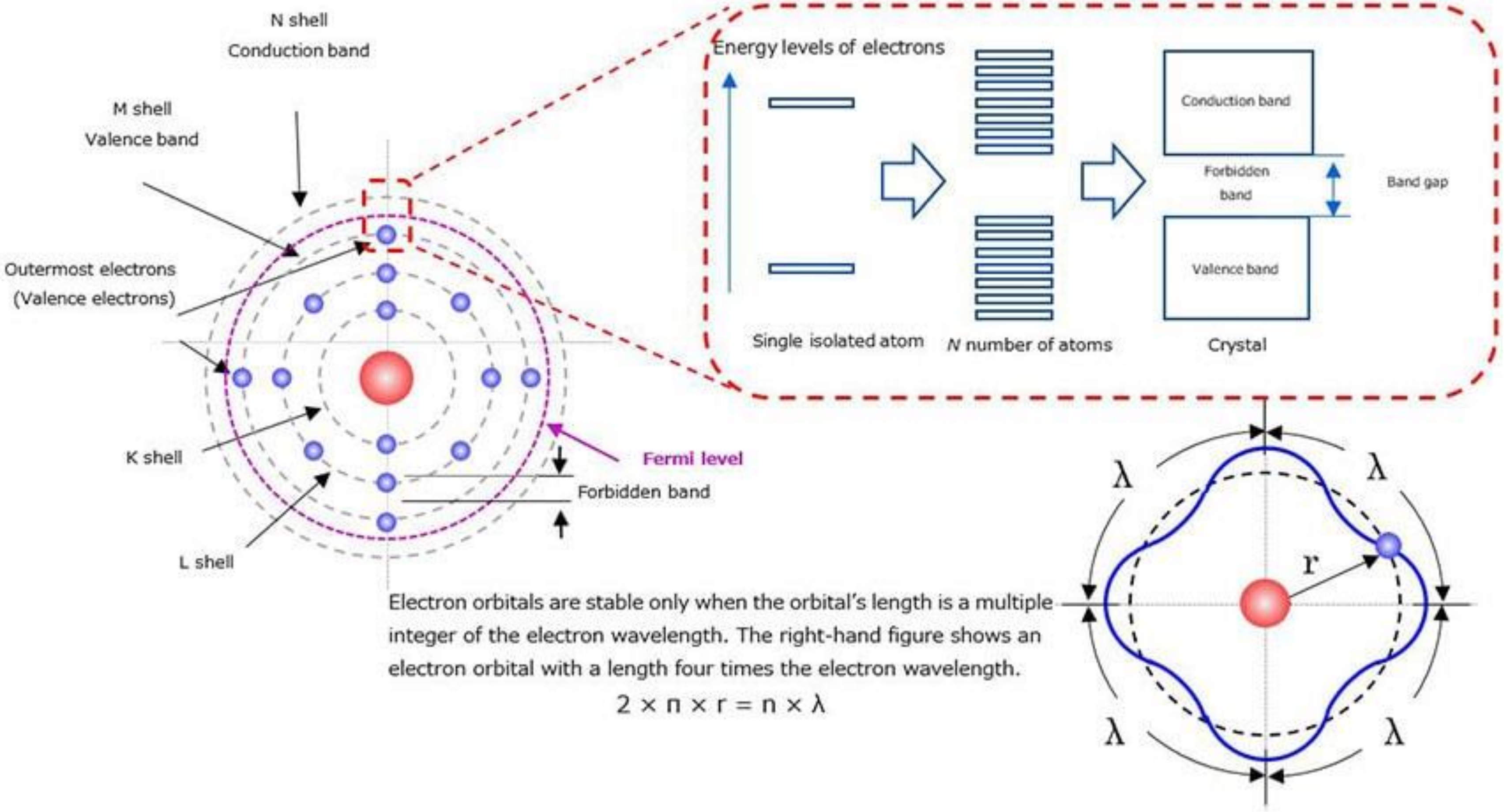


Electron orbitals are stable only when the orbital's length is a multiple integer of the electron wavelength. The right-hand figure shows an electron orbital with a length four times the electron wavelength.

$$2 \times n \times r = n \times \lambda$$

1.1. Energy band diagram

The closer the electrons are to the nucleus, the more tightly bound they are to the nucleus. The most loosely bound electrons in the outermost shell are called valence electrons. This outermost shell is called the valence band. The area beyond the outermost shell is called the conduction band. Since electrons have a wave nature as described above, there is an energy gap between the valence and conduction bands where electrons cannot exist. This energy gap is called a forbidden band.

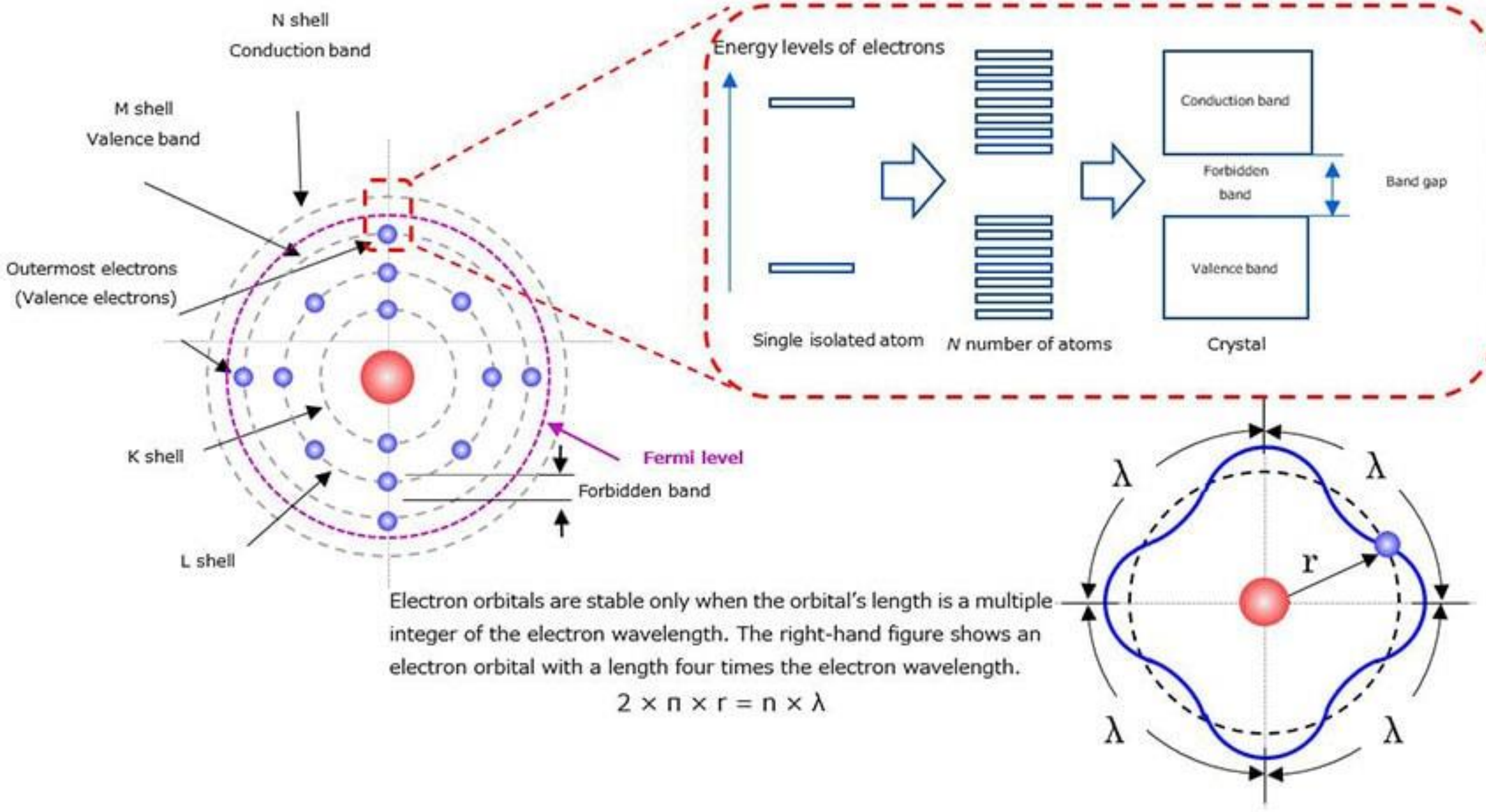


Electron orbitals are stable only when the orbital's length is a multiple integer of the electron wavelength. The right-hand figure shows an electron orbital with a length four times the electron wavelength.

$$2 \times \pi \times r = n \times \lambda$$

1.1. Energy band diagram

Electrons in a valence band cannot move freely since they are bound to the nucleus. For these electrons to move freely between atoms, they have to absorb enough heat or light energy to be excited from the valence band to the conduction band (e.g., from the M shell to the N shell). The minimum amount of energy required for this electron excitation is the band gap.

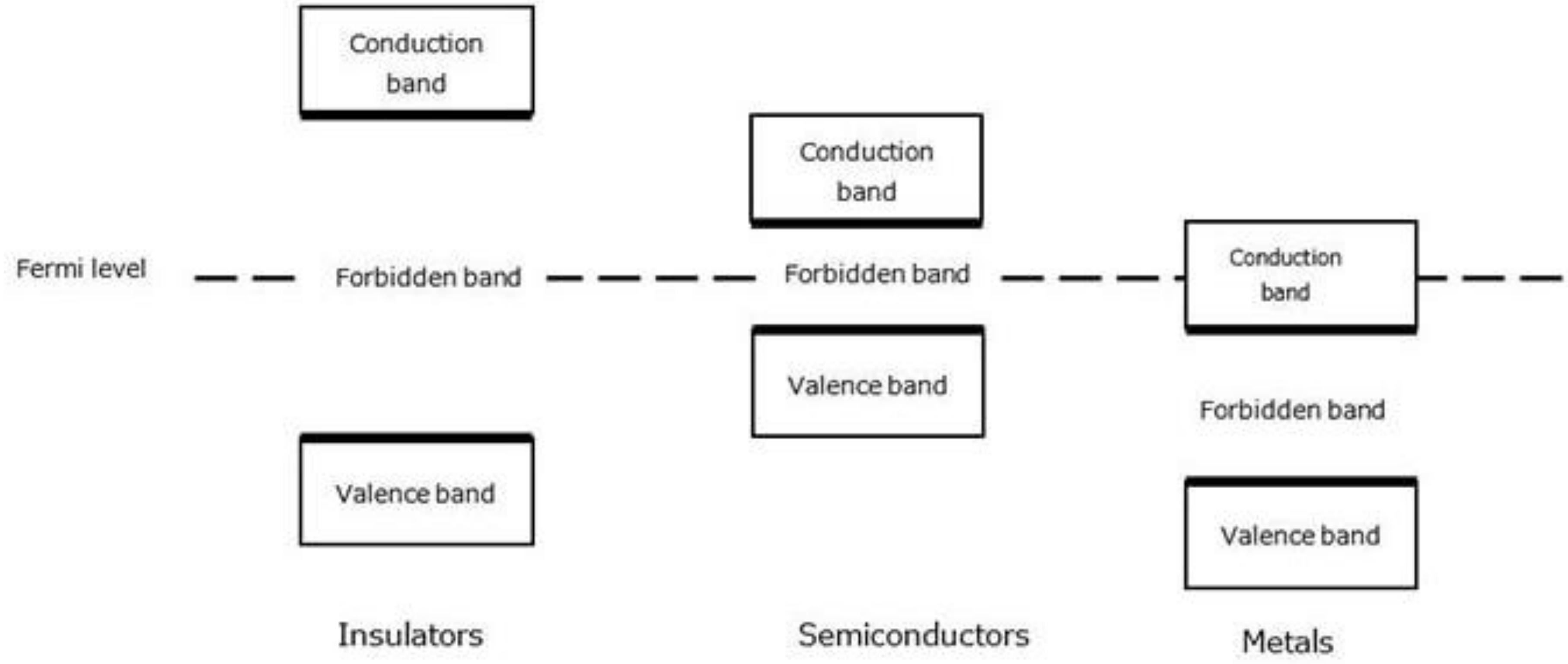


Electron orbitals are stable only when the orbital's length is a multiple integer of the electron wavelength. The right-hand figure shows an electron orbital with a length four times the electron wavelength.

$$2 \times \pi \times r = n \times \lambda$$

1.1. Energy band diagram

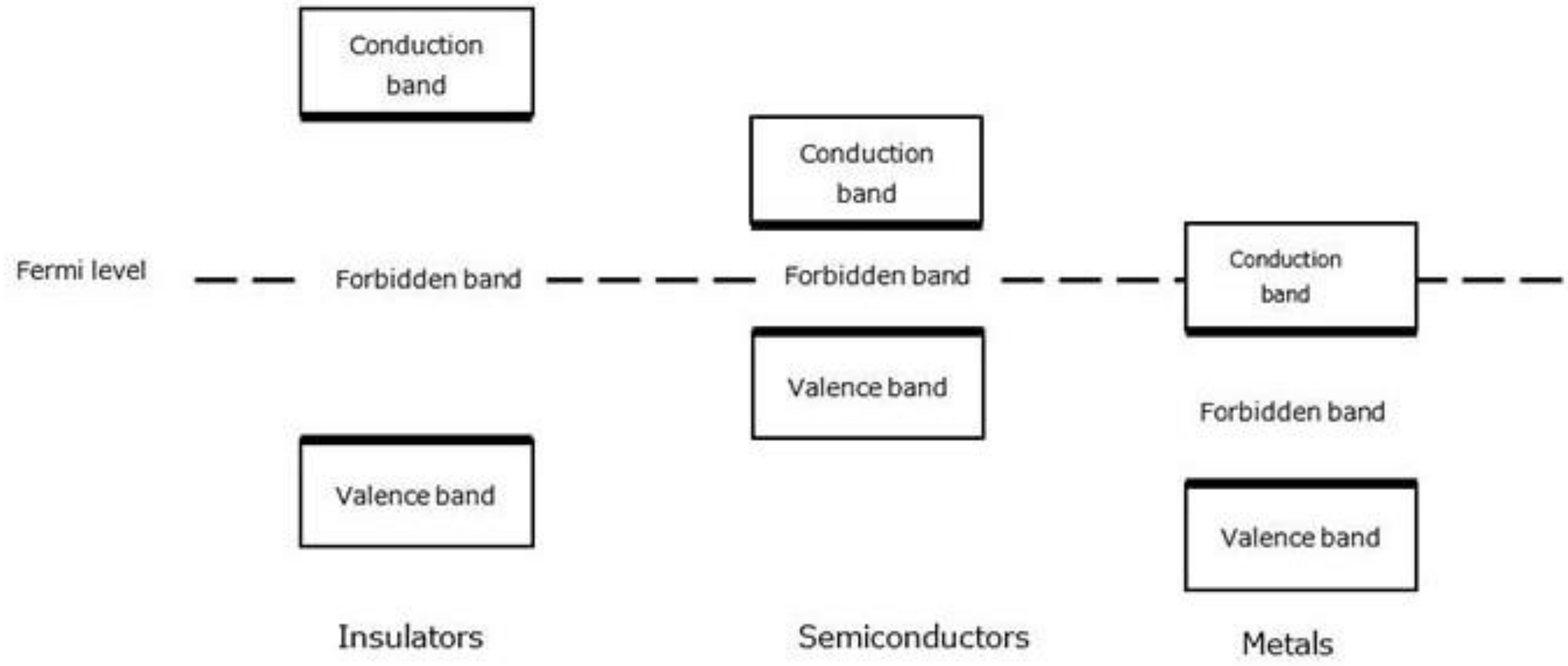
Figure shows the energy bands of insulators, semiconductors, and metals.
In the case of insulators and semiconductors, the outermost shell occupied by electrons is called the valence band, and the shell that is not populated by any electrons is called the conduction band. In the case of metals, not all the orbitals in the outermost conduction band are populated by electrons. Because metals have empty orbitals, electrons are free to move in metals.



1.1. Energy band diagram

The valence and conduction bands are separated by a forbidden band where electrons cannot exist in a stable state. The energy width of the forbidden band is called a band gap. Semiconductors have a narrower forbidden band (i.e., smaller band gap) than insulators.

Insulators and semiconductors have a Fermi level between the conduction and valence bands. The Fermi level of metals lies inside the conduction band. Although the Fermi level is defined as the energy level at which an orbital has a 50% probability of being occupied by electrons at any given time, the Fermi level of insulators and semiconductors falls in the forbidden band where no electrons exist.

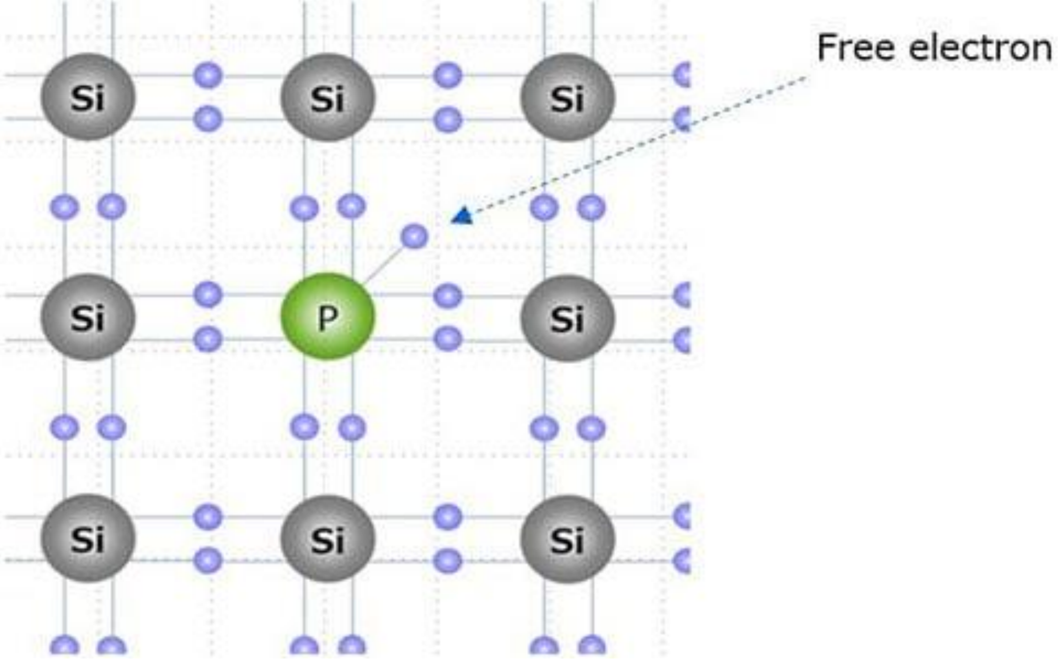


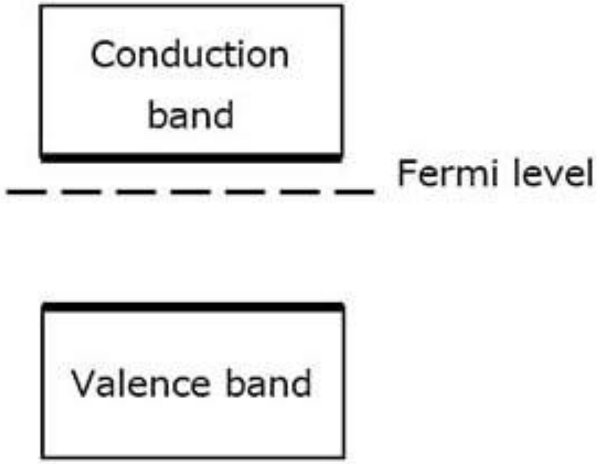
1.1. Energy band diagram

The following paragraphs describe n-type and p-type semiconductors that are created by adding impurities (called dopants) such as phosphor (P) and boron (B) to an intrinsic semiconductor, i.e., an undoped (pure) semiconductor.

n-type semiconductor:

Silicon has a valence of 4 with four bonding hands. It is an intrinsic semiconductor without any dopants or impurities. Let us see what occurs when the silicon crystal is doped with a valence of 5 elements (phosphorus (P), arsenic (As), or antimony (Sb)). Figure shows that the phosphorus atom is able to bond with four silicon atoms, but since it has five valence electrons to offer, the fifth valence electron is left with nothing to bond to. Therefore, only a small amount of energy causes the fifth valence electron to be released as a free electron. Since the n-type semiconductor has extra electrons, its Fermi level approaches the conduction band at room temperature.



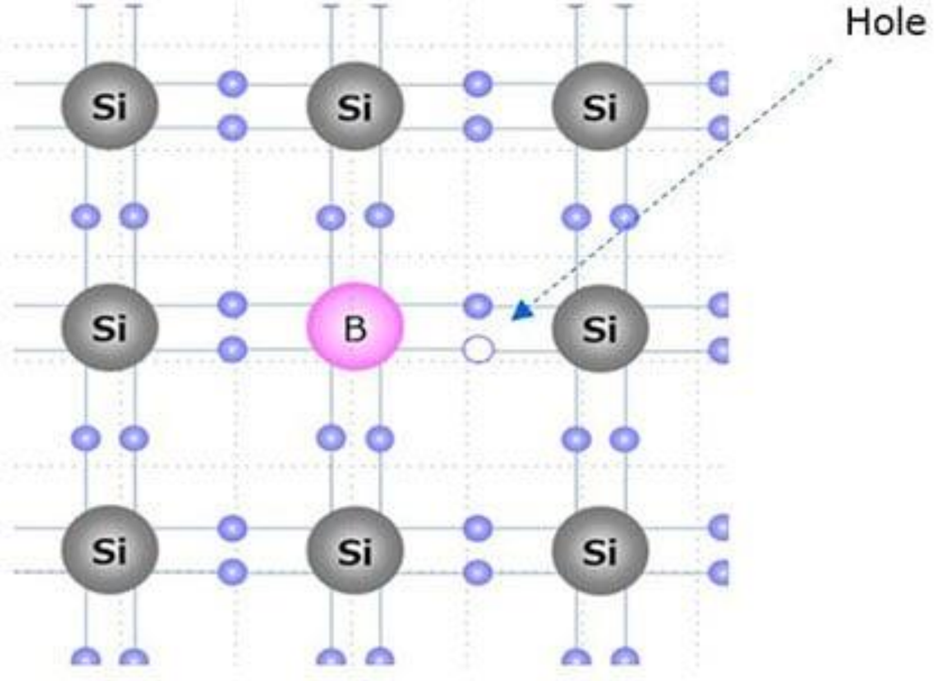


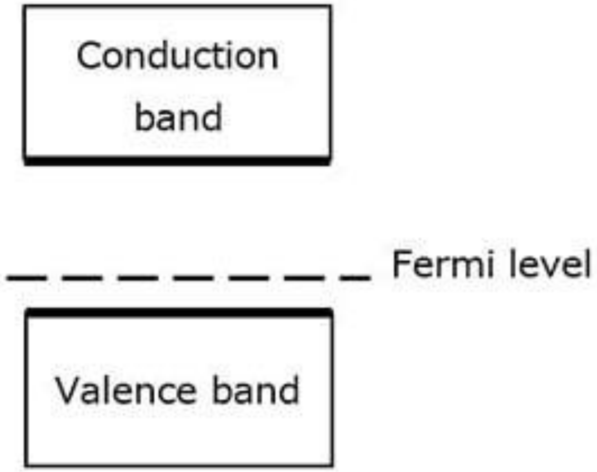
Energy band diagram

1.1. Energy band diagram

p-type semiconductor:

To create a p-type silicon semiconductor, a valence of 3 elements (boron (B), indium (In), or gallium (Ga)) is used as a dopant. Since a valence of 3 elements has only three electrons in the valence band, it attracts an electron from a silicon atom. The resulting empty bond site is called a hole, which is free to move in the silicon crystal just like free electrons. Since the p-type semiconductor has extra holes, its Fermi level approaches the valence band at room temperature.





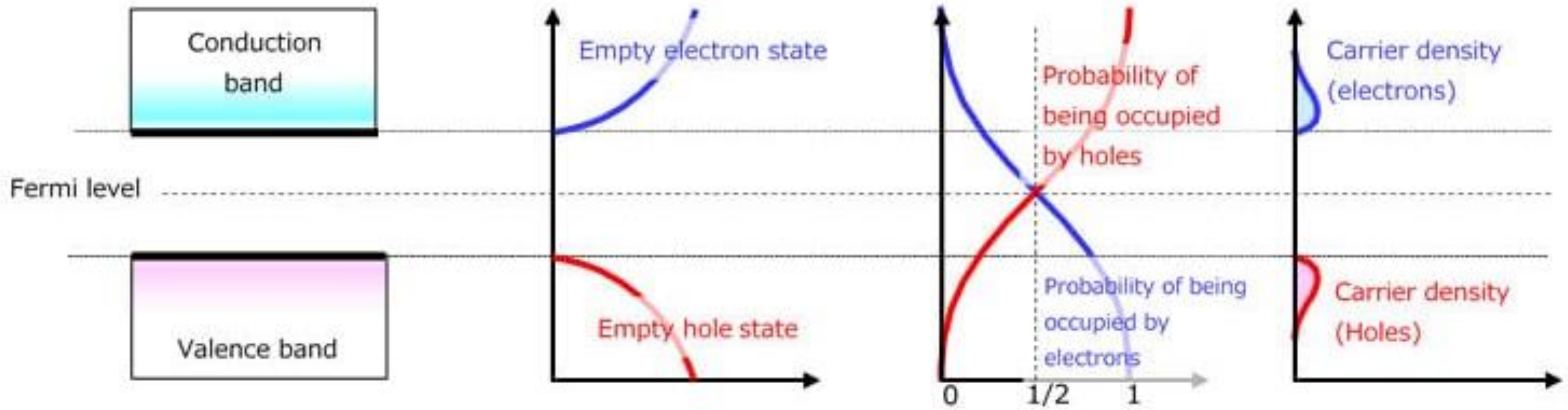
Energy band diagram

1.2. Characteristics of an intrinsic silicon semiconductor

The electrons in the conduction band and the holes in the valence band are free to move, carrying an electric charge. Therefore, they are called charge carriers or simply carriers. The number of charge carriers determines the magnitude of electric current. A detailed equation for the carrier density is omitted here, but it can be calculated as:

state density function (Density of energy states that can be occupied by electrons) × distribution function (Fermi–Dirac distribution) = carrier density

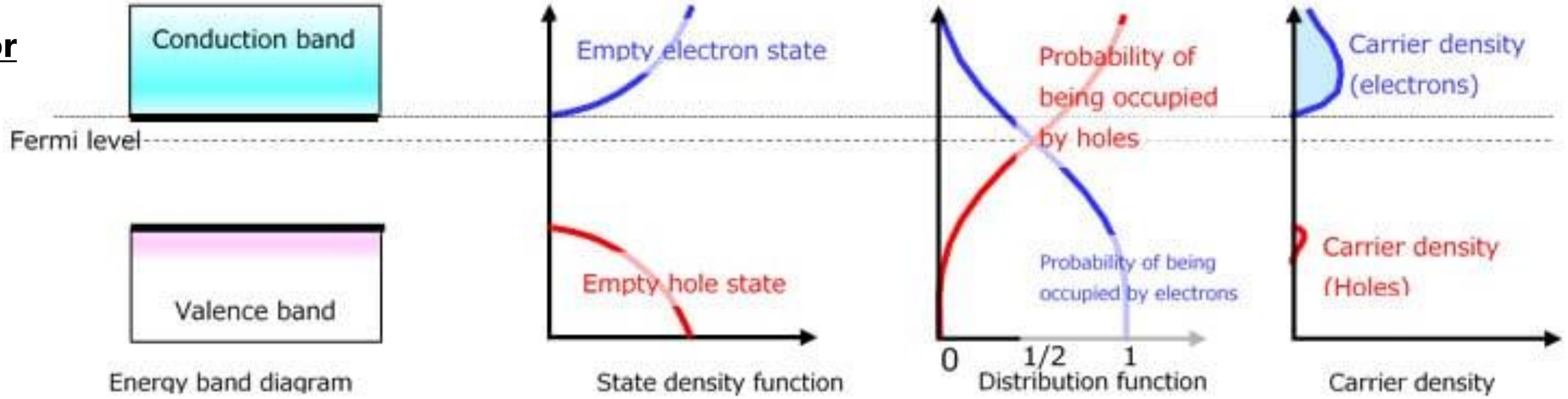
Figure shows the energy states of undoped silicon. It has a very small amount of electrons in the conduction band and a very small amount of holes in the valence band. Having equal energy levels, these electrons and holes freely move around in a material so that its carrier density becomes uniform.



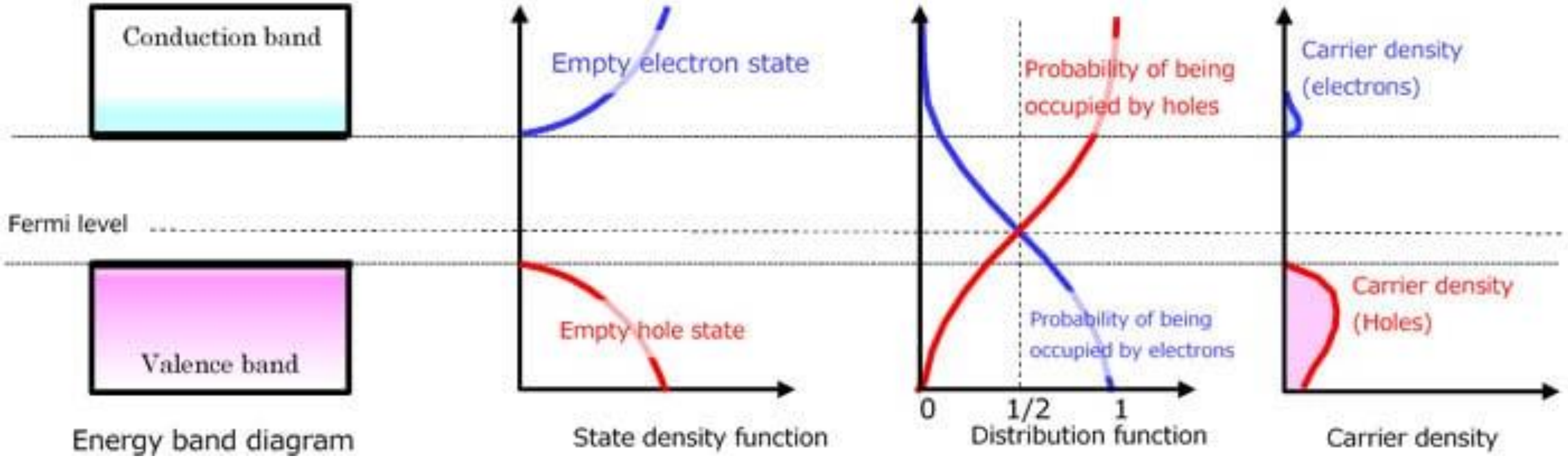
1.2. Characteristics of an intrinsic silicon semiconductor

Figures show the carrier density curves of the n-type and p-type semiconductors, respectively.

n-type semiconductor

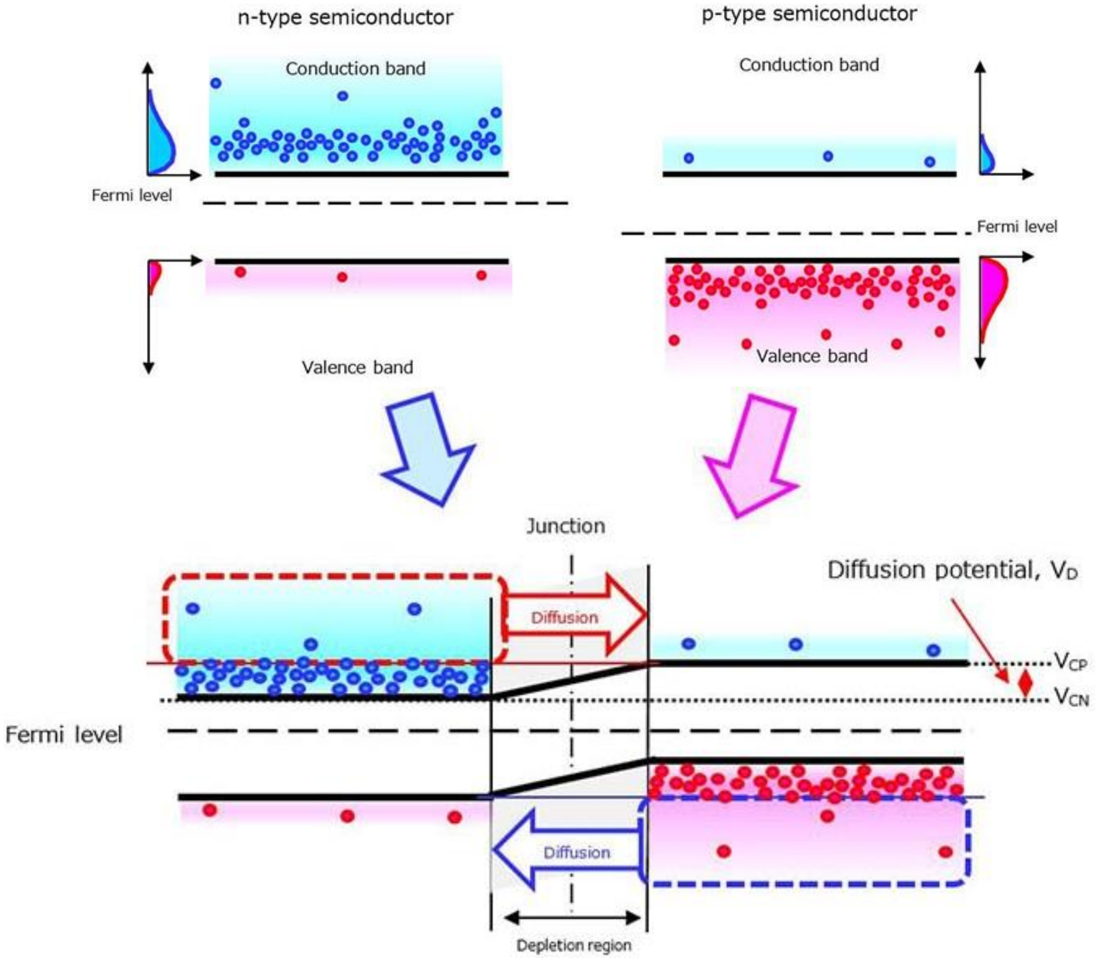


p-type semiconductor



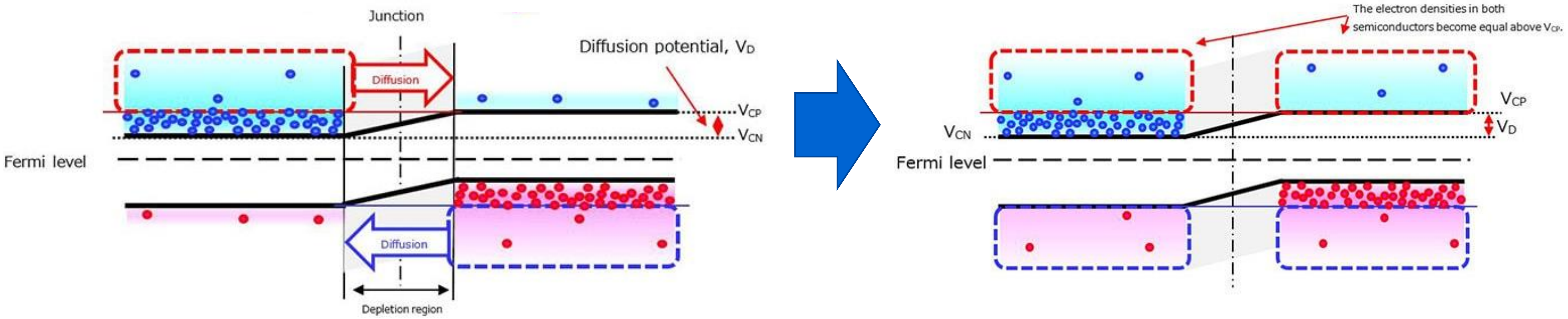
1.3. pn junction

Before discussing Schottky barrier diodes (SBDs), let us learn how a pn junction works since it is the most basic junction for forming a diode.
When p-type and n-type semiconductors are joined together, their Fermi levels become equal. This creates a difference in potential between the lower edges of the conduction bands of the n-type and p-type semiconductors (V_{CN} and V_{CP} respectively). This difference in potential is called the diffusion potential (V_D) or built-in potential.



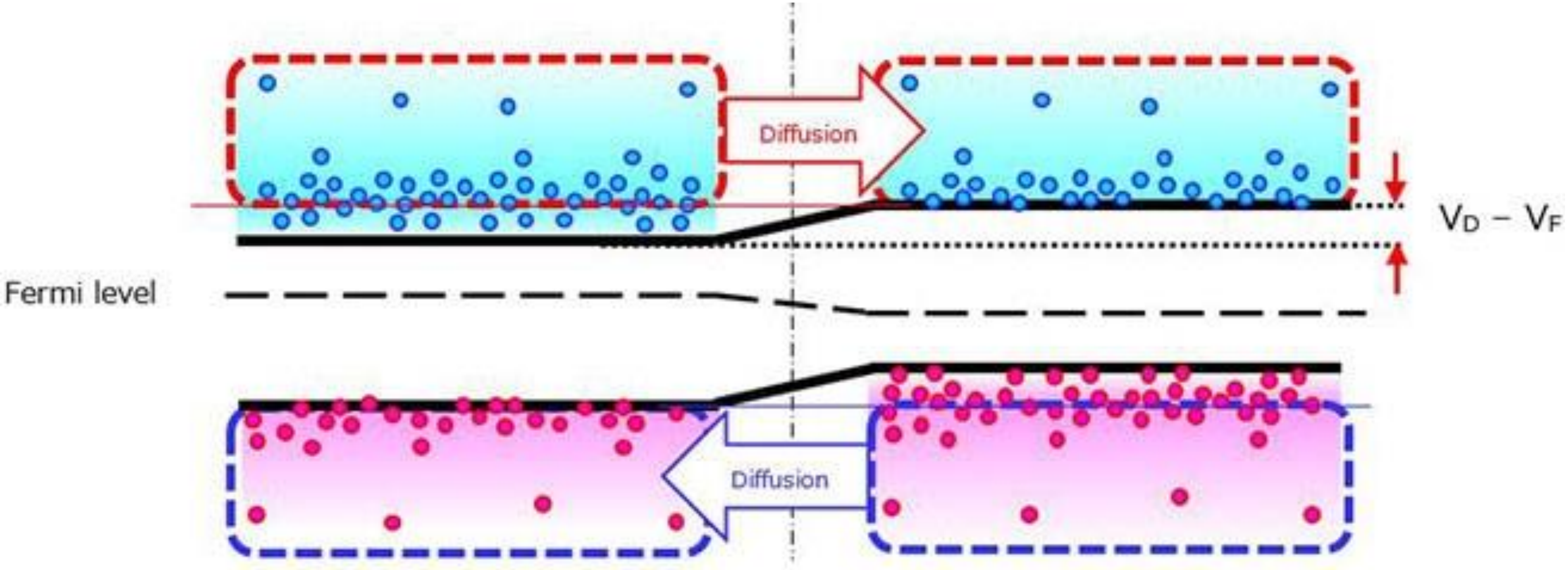
1.3. pn junction

Electrons are the majority charge carriers in the n-type semiconductor whereas holes are the majority charge carriers in the p-type semiconductor. Near the junction, electrons in the n-type semiconductor and holes in the p-type semiconductor are attracted and bound to each other and disappear, creating a region called a depletion layer where no carrier exists. Then, some electrons in the n-type semiconductor diffuse into the p-type semiconductor as they have energy exceeding V_D. Therefore, above V_D, the electron densities in both semiconductors become equal. Likewise, some holes in the p-type semiconductor diffuse into the n-type semiconductor. The current that flows as a result of diffusion of charge carriers (electrons and holes) is called diffusion current. The application of voltage (i.e., an electric field) across the junction also causes drift current to flow. However, the diffusion current is dominant except in a depletion region. When the pn junction is unbiased, current stops flowing once the junction reaches an equilibrium state.



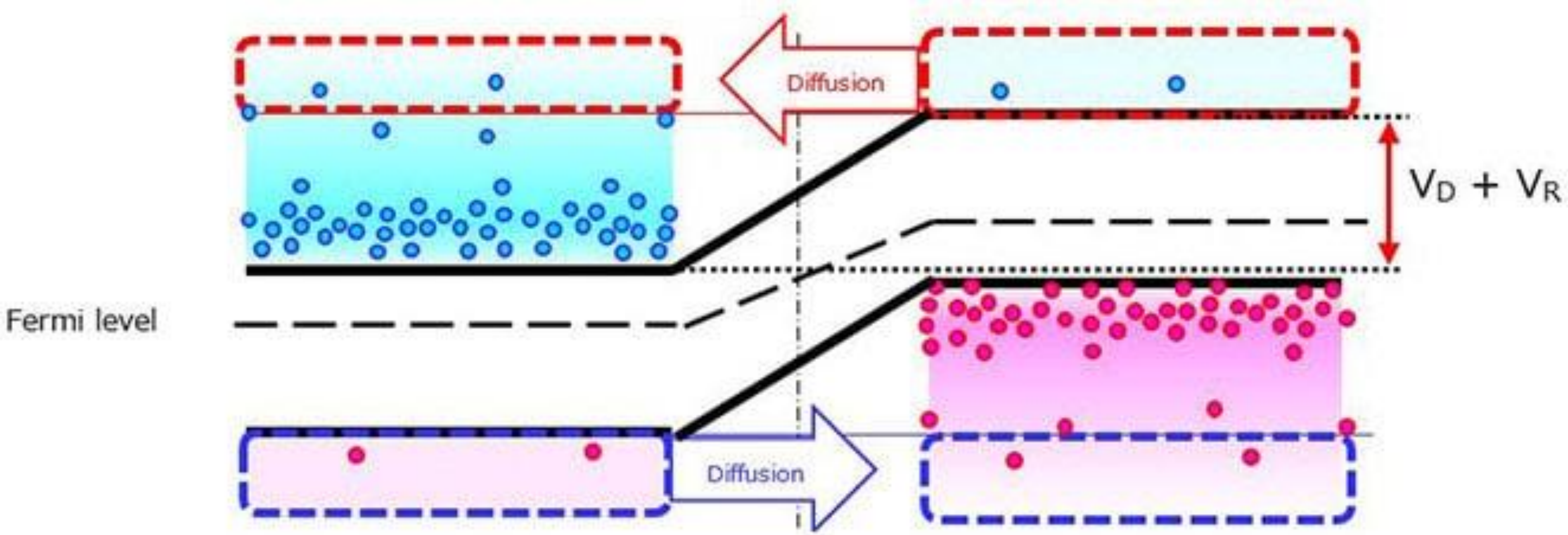
1.3.1. Forward biasing

In forward bias, the p-type side is more positively biased than the n-type side. When a pn junction diode is forward-biased at V_F, most of it is applied across the pn junction, causing the diffusion potential to decrease by V_F. As a result, electrons, the majority carriers in the n-type semiconductor, diffuse from a region with a higher carrier density. (Similarly, holes, the majority carriers in the p-type semiconductor, diffuse from a region with a higher carrier density.) Electrons are injected into the n-type semiconductors from the bias to compensate for the amount of electrons reduced by diffusion whereas holes are injected into (i.e., electrons are drawn away from) the p-type semiconductor. As a result, current continues flowing.



1.3.2. Reverse biasing

A reverse bias of V_R causes the diffusion potential to increase by V_R. Although electrons are the majority carriers in the n-type semiconductor and the minority carriers in the p-type semiconductor, the electron density of the p-type semiconductor becomes higher than that of the n-type semiconductor above the diffusion barrier, $V_D + V_R$ (as opposed to the unbiased and forward-biased states). As a result, electrons, the minority carriers in the p-type semiconductor, diffuse into the n-type semiconductor. The amount of minority carrier diffusion that occurs under reverse bias is much smaller than that that occurs under forward bias. However, under reverse bias, electrons are injected into the p-type semiconductor to compensate for the diffusion while holes are injected into (i.e., electrons are drawn away from) the n-type semiconductor. Therefore, under reverse bias, current flows in the direction opposite to the one under forward bias. The reverse current is very low as it is due to minority carrier diffusion.



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