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e-learning

Basic Knowledge of Discrete Semiconductor Device

Chapter I Basis of Semiconductors

Toshiba Electronic Devices & Storage Corporation
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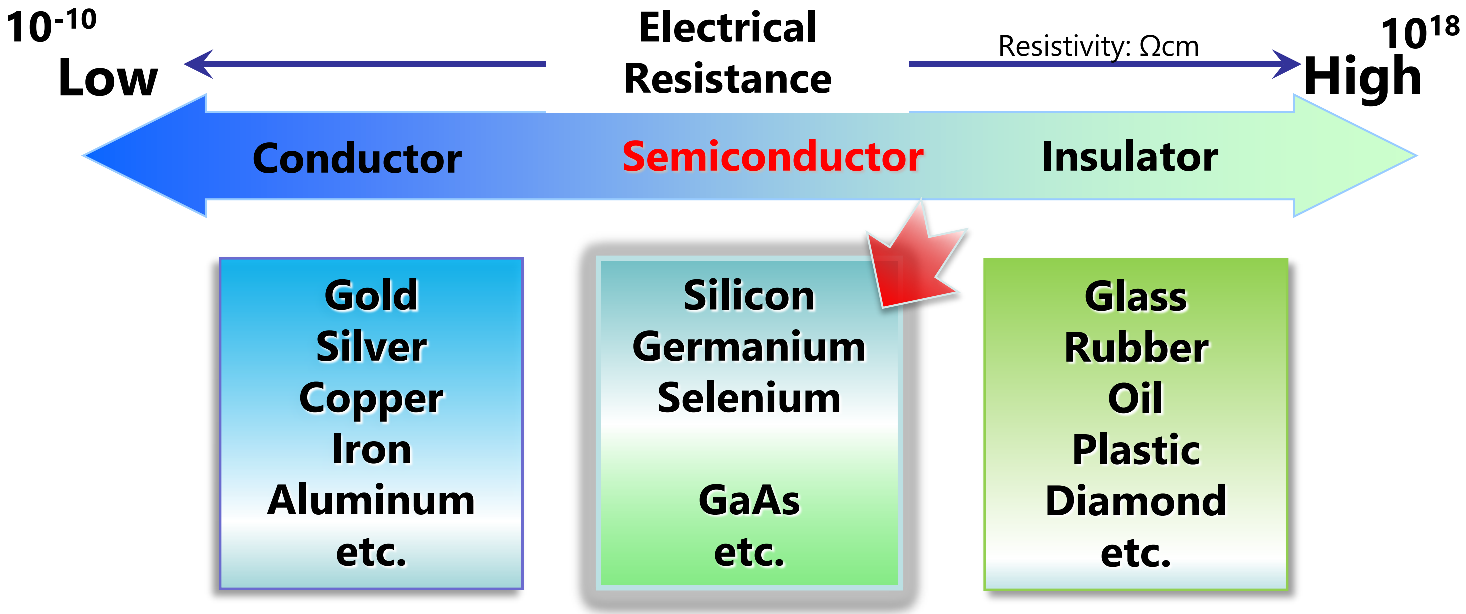
What is a Semiconductor?

A "semiconductor" is a material with intermediate properties between a "conductor" that conducts electricity well, like metals, and an "insulator" that barely conducts electricity. Two types of semiconductors, N-type and P-type, can be created by adding impurities (diffusion/doping) to an intrinsic semiconductor that does not contain impurities. These will exhibit the properties of a conductor or insulator when voltage, current, light, heat, etc., are applied. Furthermore, by combining these, devices such as diodes, transistors, and ICs (integrated circuits) can be created.

The ease with which electricity flows is related to the magnitude of the material's electrical resistance. If the electrical resistance is high, the current will not flow easily, and if the electrical resistance is low, the current will flow easily. When the ease with which electricity passes is expressed as resistivity, conductors are: 10^{-8} to 10^{-4} Ωcm, insulators are: 10^{8} to 10^{18} Ωcm, while semiconductors are in the range of around 10^{-4} to 10^{8} Ωcm. Conductors include gold, silver, copper, iron, and aluminum. Insulators include glass, rubber, oil, and plastic. Semiconductors include single elements such as silicon (Si) and germanium (Ge), and compounds such as gallium arsenide (GaAs), silicon carbide (SiC), silicon germanium (SiGe), and gallium nitride (GaN).



Semiconductor raw materials

Silicon (Si) and germanium (Ge), which are the main raw materials for semiconductors, belong to Group IV.* Pure crystals (intrinsic semiconductors) have properties close to those of an insulator. However, adding trace amounts of impurities (diffusion or doping) significantly reduces the electrical resistance and makes them exhibit the properties of a conductor. Depending on the type of impurity added, n-type and p-type semiconductors can be formed. Impurities used to form n-type semiconductors include phosphorus (P), arsenic (As), and antimony (Sb). Impurities used to form p-type semiconductors include boron (B), gallium (Ga), and indium (In).

Compound semiconductors are made from multiple elements, unlike silicon semiconductors, which are made from a single element. Examples of combinations include elements from group III and group V, group II and group VI, and group IV elements. SiC and GaN, which are wide band gap semiconductors that have been in the spotlight recently, are also compound semiconductors.

*: Currently, the long periodic table is generally used, but the short periodic table is used here because it is easier to explain the properties and behavior of the elements that are the raw materials for semiconductors, as they are arranged based on the electron shells of the atoms. In the short periodic table, the groups of elements are designated by Roman numerals, while in the long periodic table, they are designated by Arabic numerals, and their values are also different. For example, Si is both in group IV and group 14.

*Doping phosphorus (P) of **Group V** into silicon (Si) of **Group IV** makes **n-type semiconductor**.

*Doping boron (B) of **Group III** into silicon (Si) of **Group IV** makes **p-type semiconductor**.

Element(s)	Material
Single	Si, Ge
Compound	Group II-VI **ZnSe CdTe**
	Group III-V **GaAs InGaN InP**
	Group IV-IV **SiC**

Group II	Group III	Group IV	Group V	Group VI
Be Beryllium	**B** Boron	**C** Carbon	**N** Nitrogen	**O** Oxygen
Mg Magnesium	**Al** Aluminum	**Si** Silicon	**P** Phosphorus	**S** Sulfur
Zn Zinc	**Ga** Gallium	**Ge** Germanium	**As** Arsenic	**Se** Selenium
Cd Cadmium	**In** Indium	**Sn** Tin	**Sb** Antimony	**Te** Tellurium
Hg Mercury	**Tl** Thallium	**Pb** Lead	**Bi** Bismuth	**Po** Polonium

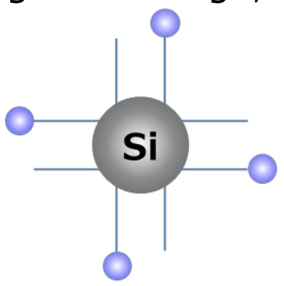
n-type Semiconductor

An n-type semiconductor is a group IV intrinsic semiconductor such as silicon (Si) doped with group V elements such as phosphorus (P), arsenic (As), or antimony (Sb) as an impurity.

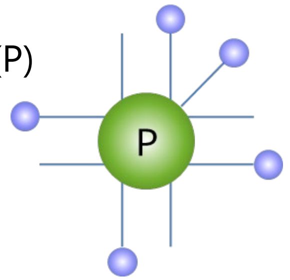
Group IV elements are tetravalent elements with four valence electrons, while group V elements are pentavalent elements with five valence electrons. A single crystal made only of tetravalent elements such as Si is bound to other elements by covalent bonds, and has no excess electrons or holes. This state without impurities is an intrinsic semiconductor. When a small amount of phosphorus is added to this single crystal (diffusion/doping), one of the valence electrons of the phosphorus becomes an excess electron that can move freely (free electron). When a voltage is applied, this free electron is attracted to the positive electrode and moves, causing a current to flow. For this reason, the resistivity of n-type semiconductors (and p-type semiconductors described below) decreases as the impurity concentration increases.

Si and impurities such as P that make up n-type semiconductors are electrically neutral as single atoms. Therefore, n-type semiconductors are also electrically neutral. However, in n-type semiconductors, the particles (carriers) that carry the charge are free electrons. These carriers have a negative charge, which is why they are called n-type.

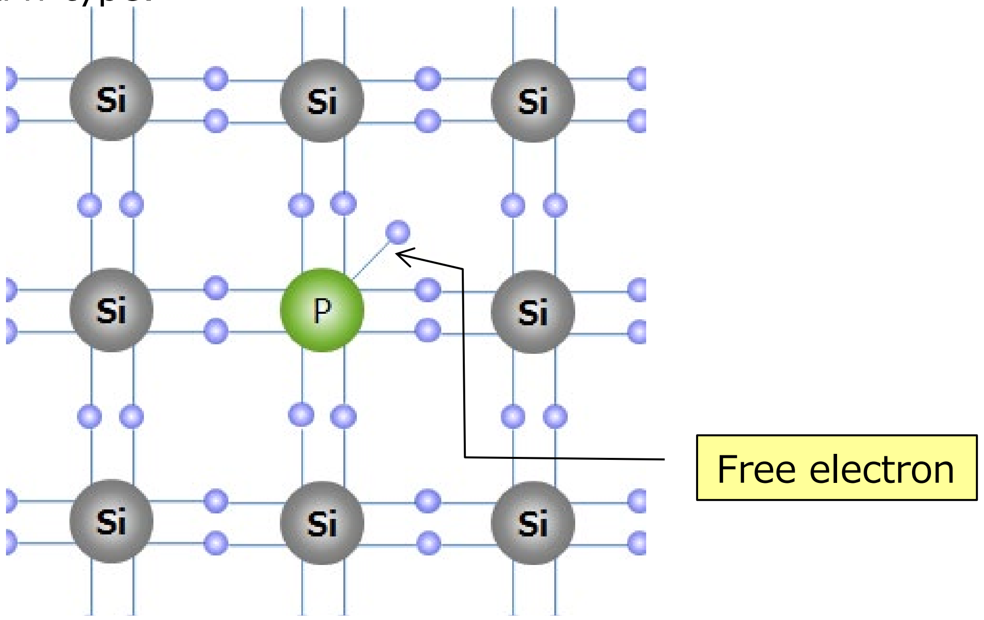
Silicon (Si): four valence electrons



Phosphorus: (P) five valence electrons



Adding phosphorus to a pure silicon crystal results in a surplus electron, which becomes a free electron.



<u>* This free electron is the carrier of an n-type semiconductor.</u>

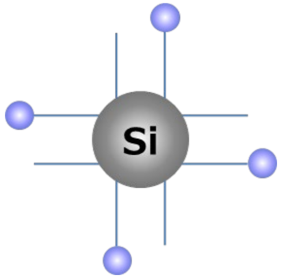
p-type Semiconductor

A p-type semiconductor is a group IV intrinsic semiconductor such as silicon (Si) doped with group III boron (B) or indium (In) as an impurity.

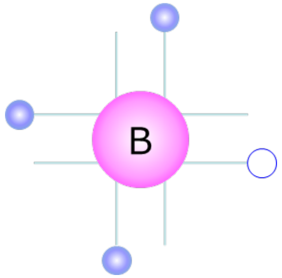
Group IV elements are tetravalent elements with four valence electrons, while group III elements are trivalent elements with three valence electrons. A single crystal made only of tetravalent elements such as Si is an intrinsic semiconductor in which all bonds are connected to other elements by covalent bonds. When a small amount of boron is added to this single crystal (diffusion/doping), an electron becomes insufficient at one of the bonds between silicon and boron, creating a hole where an electron is missing. This hole is called a hole. When a voltage is applied in this state, a nearby electron moves to the hole, so the place where the electron was becomes a new hole, and it appears that the holes move one after another to the negative pole.

In a p-type semiconductor, the particles (carriers) that carry the charge are holes. Since holes are the parts where there is a shortage of electrons, they have a positive charge. For this reason, they are called p-type.

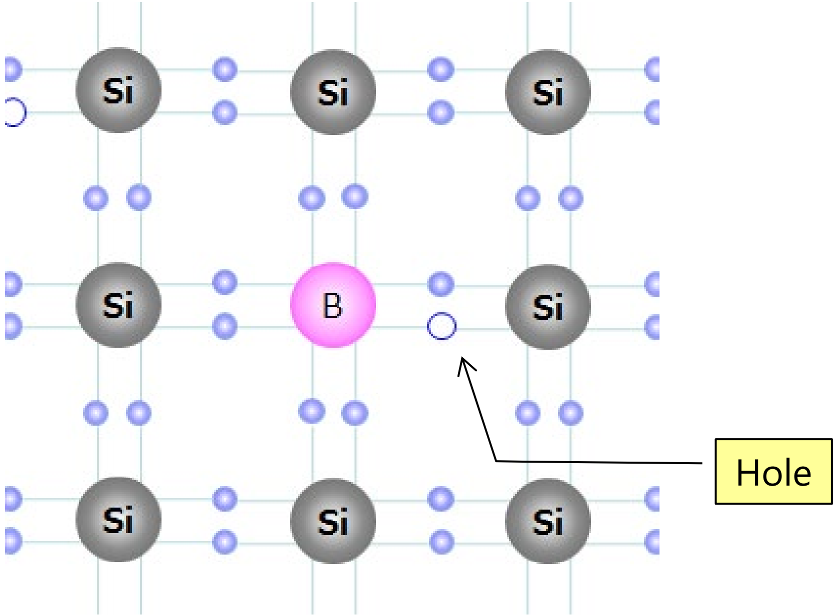
Silicon (Si): Four valence electrons



Boron (B): Three valence electrons



Adding boron to pure silicon crystal results in lack of an electron. And it becomes a hole.



* This hole is the carrier of a p-type semiconductor.

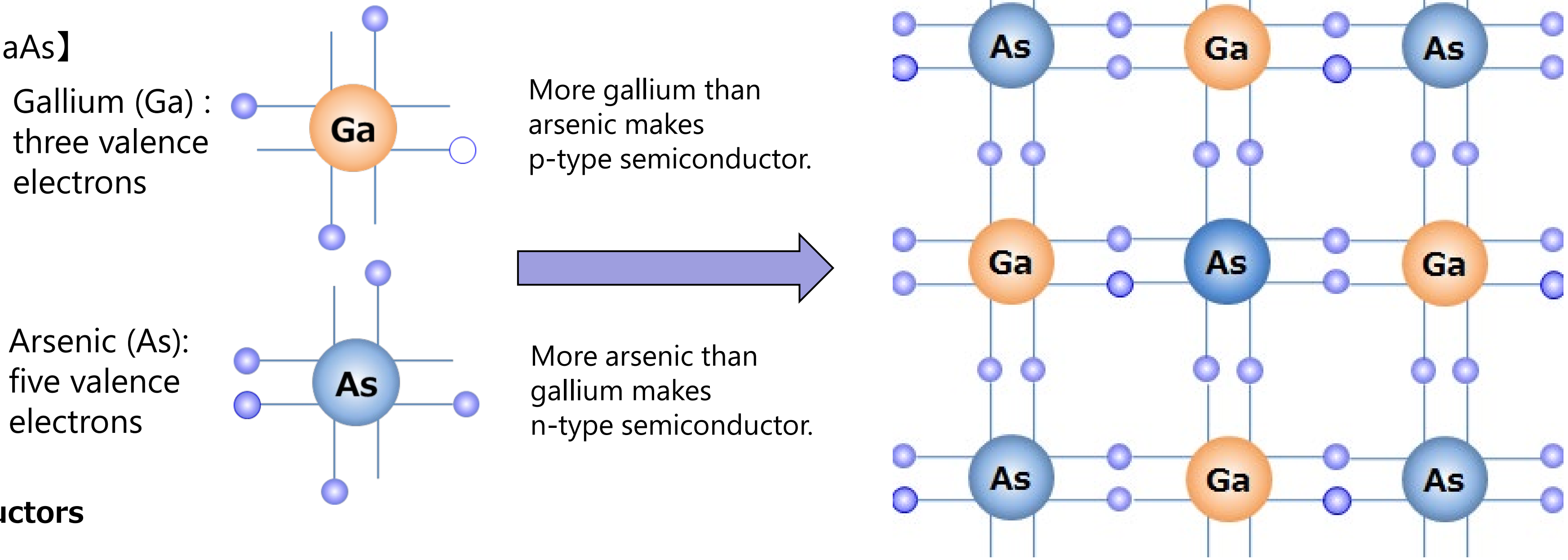
Compound Semiconductor

Compound semiconductors are compounds made of two or more elements, unlike semiconductors made of a single element such as Si, which is the mainstream of semiconductors.

There are compound semiconductors that combine elements from group III and group V, elements from group II and group VI, and elements from group IV. Examples include GaAs, InP, InGaAlP, and SiGe, which have traditionally been used as high-frequency devices and optical semiconductors. InGaN has also attracted attention as a blue LED and laser diode, and SiC and GaN have been commercialized as materials for power semiconductors.

Compound semiconductors used in devices have higher mobility (high frequency, high switching, high efficiency) than single-element semiconductors such as Si, and have a wide band gap (high temperature operation, high voltage resistance) due to the strong bonding force between atoms. As a result, compound devices are used in power devices, optical devices such as LEDs, and high-frequency devices. Semiconductors with wide band gaps, including single-element semiconductors (such as diamond), are also called wide-band gap semiconductors.

【Example of GaAs】



Typical compound semiconductors

Group II-VI : ZnSe
Group III - Group V : GaAs, GaN, InP, InGaAlP, InGaN
Group IV - Group IV : SiC, SiGe

pn Junction

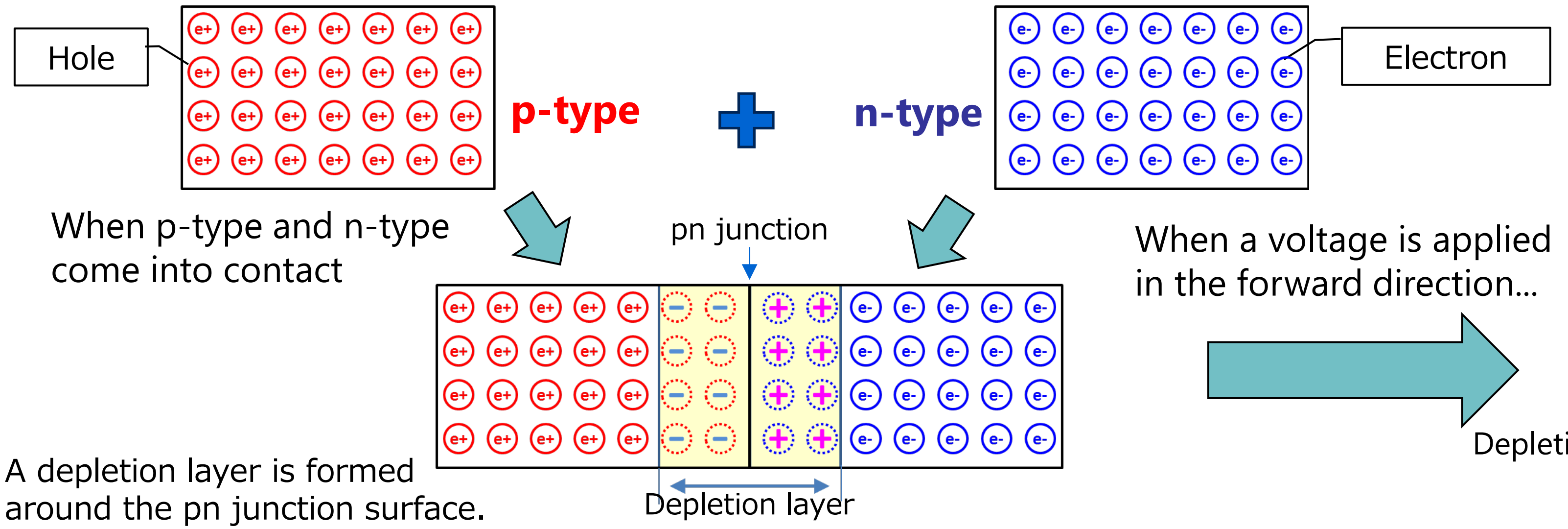
The interface between a p-type semiconductor and an n-type semiconductor is called a pn junction. When a p-type semiconductor and an n-type semiconductor are joined (not actually joined, but formed by doping so that they are adjacent to each other), the carriers, holes and free electrons, are attracted to each other and combine and disappear near the boundary. Since there are no carriers in this area, it is called a depletion layer and is in the same state as an insulator. (No bias state)

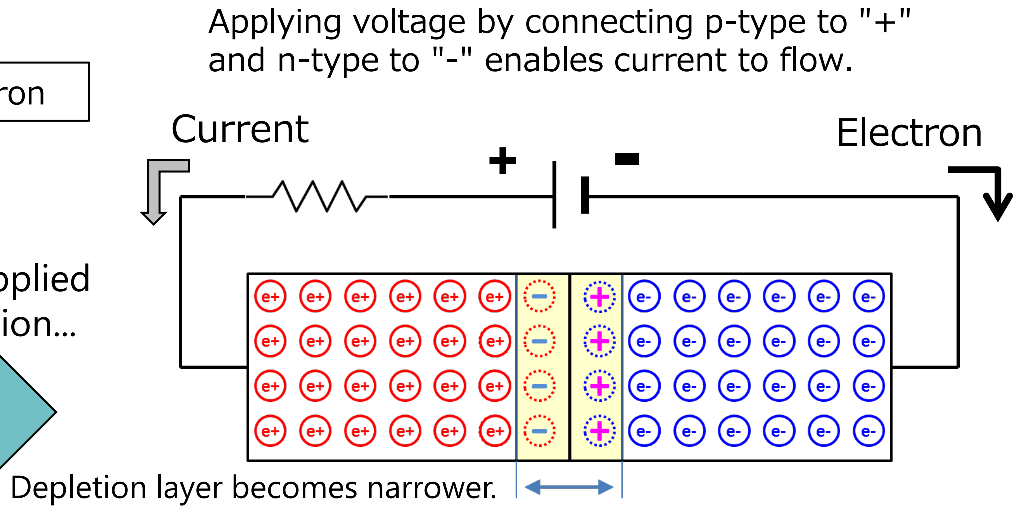
- **Forward direction** (connect the positive pole to the p-type region and the negative pole to the n-type region and apply voltage):

When the applied voltage is gradually increased and exceeds the forward voltage (about 0.7V for Si), electrons flow one after another from the n-type region to the p-type region, and electrons that do not combine with holes and disappear move to the positive pole, allowing current to flow. For an explanation of the physical properties of a pn junction, see the following e-learning.

Basics of Schottky Barrier Diodes 1-3. pn junction

Reverse direction (connect the negative pole to the p-type region and the positive pole to the n-type region and apply voltage):
No current flows. In the normal voltage range, the excess electrons in the n-type semiconductor move away from the boundary surface. The holes in the p-type semiconductor also move away from the boundary surface. This causes the depletion layer near the boundary surface to expand. However, if a voltage exceeding the breakdown voltage is applied, the pn junction enters a breakdown state due to the Zener effect (avalanche effect) and current flows suddenly. In a typical diode, this breakdown causes the performance to deteriorate and be destroyed.





Types of Semiconductor Devices

Electronic parts using semiconductors are called semiconductor devices.
Many kinds of semiconductor devices have been developed in line with the expansion of application fields and the progress of electronic equipment. “Discrete semiconductors” are single devices with a single function, such as transistors and diodes. “Integrated circuits (ICs)” are devices with multiple functional elements mounted on one chip. Typical ICs include memories, microprocessors (MPUs), and logic ICs. LSIs raised the degree of integration of ICs. Classification by general function/structure is shown below.

Semiconductor Devices

Discrete devices

- Diodes
  - General-purpose rectifiers
  - High-speed rectifiers
  - Switching diodes
  - Zener diodes
  - TVS diodes
  - Variable-capacitance diodes
- Transistors
  - MOSFETs
  - Junction FETs
  - Bipolar transistors
  - IGBTs
- Thyristors
- Modules

Optical devices

- Light-emitting devices
  - LEDs
  - Laser diodes
- Photodetectors
  - Photodiodes
  - Phototransistors
  - Photothyristors
  - Phototriacs
  - Image sensors
- Composite optical devices
  - Photocouplers
  - Photorelays
  - Photointerrupters
- Optical communication devices

Microwave devices

- Discrete
  - High-frequency diodes
  - High-frequency transistors
- ICs
  - GaAs ICs
  - MMICs
- Modules

Sensors

- Sensor
  - Thermal sensors
  - Pressure sensors
  - Acceleration sensors
  - Magnetic sensors
  - Illuminance sensors
  - Accessing sensors

ICs

- Memories
  - Volatile memories
  - Non-volatile memories
- MPUs
- Logic ICs
  - General-purpose logic ICs
    - Bus switches
    - CMOS logic ICs
- Analog ICs
  - General-purpose linear ICs
    - Power Supply ICs
    - Op. Amps
    - Driver ICs
  - Mixed-signal ICs

Hybrid ICs

- Thin membrane
- Thick membrane

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