**Introduction**

A semiconductor material has an [electrical conductivity](https://en.wikipedia.org/wiki/Electrical_conductivity) value falling between that of a [conductor](https://en.wikipedia.org/wiki/Electrical_resistivity_and_conductivity), such as copper, and an [insulator](https://en.wikipedia.org/wiki/Insulator_(electrical)), such as glass. Their [resistance](https://en.wikipedia.org/wiki/Electrical_resistance) decreases as their temperature increases, which is behavior opposite to that of a metal. Their conducting properties may be altered in useful ways by the deliberate, controlled introduction of impurities ("[doping](https://en.wikipedia.org/wiki/Doping_(semiconductor))") into the [crystal structure](https://en.wikipedia.org/wiki/Crystal_structure). Where two differently-doped regions exist in the same crystal, a [semiconductor junction](https://en.wikipedia.org/wiki/Semiconductor_junction) is created. The behavior of [charge carriers](https://en.wikipedia.org/wiki/Charge_carrier) which include [electrons](https://en.wikipedia.org/wiki/Electron), [ions](https://en.wikipedia.org/wiki/Ion) and [electron holes](https://en.wikipedia.org/wiki/Electron_hole) at these junctions is the basis of [diodes](https://en.wikipedia.org/wiki/Diode), [transistors](https://en.wikipedia.org/wiki/Transistor) and all modern electronics.

[Semiconductor devices](https://en.wikipedia.org/wiki/Semiconductor_device) can display a range of useful properties such as passing current more easily in one direction than the other, showing variable resistance, and sensitivity to light or heat. Because the electrical properties of a semiconductor material can be modified by doping, or by the application of electrical fields or light, devices made from semiconductors can be used for amplification, switching, and [energy conversion](https://en.wikipedia.org/wiki/Energy_conversion).

The modern understanding of the properties of a semiconductor relies on [quantum physics](https://en.wikipedia.org/wiki/Quantum_physics) to explain the movement of charge carriers in a [crystal lattice](https://en.wikipedia.org/wiki/Crystal_structure).[[1]](https://en.wikipedia.org/wiki/Semiconductor#cite_note-Feynman-1) Doping greatly increases the number of charge carriers within the crystal. When a doped semiconductor contains mostly free holes it is called "[p-type](https://en.wikipedia.org/wiki/Extrinsic_semiconductor#P-type_semiconductors)", and when it contains mostly free electrons it is known as "[n-type](https://en.wikipedia.org/wiki/Extrinsic_semiconductor#N-type_semiconductors)". The semiconductor materials used in electronic devices are doped under precise conditions to control the concentration and regions of p- and n-type dopants. A single semiconductor crystal can have many p- and n-type regions; the [p–n junctions](https://en.wikipedia.org/wiki/P%E2%80%93n_junction) between these regions are responsible for the useful electronic behavior.

Some of the properties of semiconductor materials were observed throughout the mid-19th and first decades of the 20th century. The first practical application of semiconductors in electronics was the 1904 development of the [Cat's-whisker detector](https://en.wikipedia.org/wiki/Cat%27s-whisker_detector), a primitive semiconductor diode widely used in early radio receivers. Developments in quantum physics in turn allowed the development of the [transistor](https://en.wikipedia.org/wiki/Transistor) in 1947 and the [integrated circuit](https://en.wikipedia.org/wiki/Integrated_circuit) in 1958.

**Properties of Semiconductors**

**Variable conductivity**

Semiconductors in their natural state are poor conductors because a [current](https://en.wikipedia.org/wiki/Electric_current) requires the flow of electrons, and semiconductors have their [valence bands](https://en.wikipedia.org/wiki/Valence_band) filled, preventing the entry flow of new electrons. There are several developed techniques that allow semiconducting materials to behave like conducting materials, such as [doping](https://en.wikipedia.org/wiki/Doping_(semiconductor)) or [gating](https://en.wikipedia.org/wiki/Field_effect_(semiconductor)). These modifications have two outcomes: n-type and p-type. These refer to the excess or shortage of electrons, respectively. An unbalanced number of electrons would cause a current to flow through the material.

**Heterojunctions**

[Heterojunctions](https://en.wikipedia.org/wiki/Heterojunctions) occur when two differently doped semiconducting materials are joined together. For example, a configuration could consist of p-doped and n-doped [germanium](https://en.wikipedia.org/wiki/Germanium). This results in an exchange of electrons and holes between the differently doped semiconducting materials. The n-doped germanium would have an excess of electrons, and the p-doped germanium would have an excess of holes. The transfer occurs until equilibrium is reached by a process called [recombination](https://en.wikipedia.org/wiki/Recombination_(physics)), which causes the migrating electrons from the n-type to come in contact with the migrating holes from the p-type. A product of this process is charged [ions](https://en.wikipedia.org/wiki/Ion), which result in an [electric field](https://en.wikipedia.org/wiki/Electric_field).

**Excited electrons**

A difference in electric potential on a semiconducting material would cause it to leave thermal equilibrium and create a non-equilibrium situation. This introduces electrons and holes to the system, which interact via a process called [ambipolar diffusion](https://en.wikipedia.org/wiki/Ambipolar_diffusion). Whenever thermal equilibrium is disturbed in a semiconducting material, the amount of holes and electrons changes. Such disruptions can occur as a result of a temperature difference or [photons](https://en.wikipedia.org/wiki/Photon), which can enter the system and create electrons and holes. The process that creates and annihilates electrons and holes are called [generation](https://en.wikipedia.org/wiki/Carrier_generation_and_recombination) and [recombination](https://en.wikipedia.org/wiki/Carrier_generation_and_recombination).

**Light emission**

In certain semiconductors, excited electrons can relax by emitting light instead of producing heat. These semiconductors are used in the construction of light-emitting diodes and fluorescent quantum dots.  
**Thermal energy conversion**

Semiconductors have large thermoelectric power factors making them useful in [thermoelectric generators](https://en.wikipedia.org/wiki/Thermoelectric_generator), as well as high [thermoelectric figures of merit](https://en.wikipedia.org/wiki/Thermoelectric_figure_of_merit) making them useful in [thermoelectric coolers](https://en.wikipedia.org/wiki/Thermoelectric_cooler).

**Semiconductors Material**

A large number of elements and compounds have semiconducting properties, including:

* Certain pure elements are found in Group 14 of the periodic table; the most commercially important of these elements are silicon and germanium. Silicon and germanium are used here effectively because they have 4 valence electrons in their outermost shell which gives them the ability to gain or lose electrons equally at the same time.
* Binary compounds, particularly between elements in Groups 13 and 15, such as gallium arsenide, Groups 12 and 16, groups 14 and 16, and between different group 14 elements, e.g. silicon carbide.
* Certain ternary compounds, oxides and alloys.
* Organic semiconductors, made of organic compounds.

Most common semiconducting materials are crystalline solids, but amorphous and liquid semiconductors are also known. These include hydrogenated amorphous silicon and mixtures of arsenic, selenium and tellurium in a variety of proportions. These compounds share with better known semiconductors the properties of intermediate conductivity and a rapid variation of conductivity with temperature, as well as occasional negative resistance. Such disordered materials lack the rigid crystalline structure of conventional semiconductors such as silicon. They are generally used in thin film structures, which do not require material of higher electronic quality, being relatively insensitive to impurities and radiation damage.

### Preparation of semiconductor materials

Almost all of today's electronic technology involves the use of semiconductors, with the most important aspect being the [integrated circuit](https://en.wikipedia.org/wiki/Integrated_circuit) (IC), which are found in [laptops](https://en.wikipedia.org/wiki/Laptop_computer), scanners, [cell-phones](https://en.wikipedia.org/wiki/Cell-phone), etc. Semiconductors for ICs are mass-produced. To create an ideal semiconducting material, chemical purity is paramount. Any small imperfection can have a drastic effect on how the semiconducting material behaves due to the scale at which the materials are used.

There is a combination of processes that is used to prepare semiconducting materials for ICs. One process is called [thermal oxidation](https://en.wikipedia.org/wiki/Thermal_oxidation), which forms [silicon dioxide](https://en.wikipedia.org/wiki/Silicon_dioxide) on the surface of the [silicon](https://en.wikipedia.org/wiki/Silicon). This is used as a [gate insulator](https://en.wikipedia.org/wiki/Gate_dielectric) and [field oxide](https://en.wikipedia.org/wiki/LOCOS). Other processes are called [photomasks](https://en.wikipedia.org/wiki/Photomask) and [photolithography](https://en.wikipedia.org/wiki/Photolithography). This process is what creates the patterns on the circuity in the integrated circuit. [Ultraviolet light](https://en.wikipedia.org/wiki/Ultraviolet_light) is used along with a [photoresist](https://en.wikipedia.org/wiki/Photoresist) layer to create a chemical change that generates the patterns for the circuit.

Etching is the next process that is required. The part of the silicon that was not covered by the [photoresist](https://en.wikipedia.org/wiki/Photoresist) layer from the previous step can now be etched. The main process typically used today is called [plasma etching](https://en.wikipedia.org/wiki/Plasma_etching). Plasma etching usually involves an [etch gas](https://en.wikipedia.org/wiki/Plasma_etching) pumped in a low-pressure chamber to create [plasma](https://en.wikipedia.org/wiki/Plasma_(physics)). A common etch gas is [chlorofluorocarbon](https://en.wikipedia.org/wiki/Chlorofluorocarbon), or more commonly known [Freon](https://en.wikipedia.org/wiki/Freon). A high [radio-frequency](https://en.wikipedia.org/wiki/Radio-frequency) [voltage](https://en.wikipedia.org/wiki/Voltage) between the [cathode](https://en.wikipedia.org/wiki/Cathode) and [anode](https://en.wikipedia.org/wiki/Anode) is what creates the plasma in the chamber. The [silicon wafer](https://en.wikipedia.org/wiki/Wafer_(electronics)) is located on the cathode, which causes it to be hit by the positively charged ions that are released from the plasma. The end result is silicon that is etched [anisotropically](https://en.wikipedia.org/wiki/Anisotropy" \o "Anisotropy).

The last process is called [diffusion](https://en.wikipedia.org/wiki/Doping_(semiconductor)). This is the process that gives the semiconducting material its desired semiconducting properties. It is also known as [doping](https://en.wikipedia.org/wiki/Doping_(semiconductor)). The process introduces an impure atom to the system, which creates the [p-n junction](https://en.wikipedia.org/wiki/P-n_junction). In order to get the impure atoms embedded in the silicon wafer, the wafer is first put in a 1100 degree Celsius chamber. The atoms are injected in and eventually diffuse with the silicon. After the process is completed and the silicon has reached room temperature, the doping process is done and the semiconducting material is ready to be used in an integrated circuit.

### Energy bands and electrical conduction

A pure semiconductor, however, is not very useful, as it is neither a very good insulator nor a very good conductor. However, one important feature of semiconductors (and some insulators, known as semi-insulators) is that their conductivity can be increased and controlled by [doping](https://en.wikipedia.org/wiki/Doping_(semiconductor)) with impurities and [gating](https://en.wikipedia.org/wiki/Field_effect_(semiconductor)) with electric fields. Doping and gating move either the conduction or valence band much closer to the Fermi level, and greatly increase the number of partially filled states.

Some wider-[band gap](https://en.wikipedia.org/wiki/Band_gap) semiconductor materials are sometimes referred to as semi-insulators. When undoped, these have electrical conductivity nearer to that of electrical insulators, however they can be doped (making them as useful as semiconductors). Semi-insulators find niche applications in micro-electronics, such as substrates for [HEMT](https://en.wikipedia.org/wiki/High-electron-mobility_transistor). An example of a common semi-insulator is [gallium arsenide](https://en.wikipedia.org/wiki/Gallium_arsenide). Some materials, such as [titanium dioxide](https://en.wikipedia.org/wiki/Titanium_dioxide), can even be used as insulating materials for some applications, while being treated as wide-gap semiconductors for other applications.

### Charge carriers (electrons and holes)

The partial filling of the states at the bottom of the conduction band can be understood as adding electrons to that band. The electrons do not stay indefinitely (due to the natural thermal [recombination](https://en.wikipedia.org/wiki/Recombination_(physics))) but they can move around for some time. The actual concentration of electrons is typically very dilute, and so (unlike in metals) it is possible to think of the electrons in the conduction band of a semiconductor as a sort of classical [ideal gas](https://en.wikipedia.org/wiki/Ideal_gas), where the electrons fly around freely without being subject to the [Pauli exclusion principle](https://en.wikipedia.org/wiki/Pauli_exclusion_principle). In most semiconductors the conduction bands have a parabolic [dispersion relation](https://en.wikipedia.org/wiki/Dispersion_relation), and so these electrons respond to forces (electric field, magnetic field, etc.) much like they would in a vacuum, though with a different [effective mass](https://en.wikipedia.org/wiki/Effective_mass_(solid-state_physics)). Because the electrons behave like an ideal gas, one may also think about conduction in very simplistic terms such as the [Drude model](https://en.wikipedia.org/wiki/Drude_model" \o "Drude model), and introduce concepts such as [electron mobility](https://en.wikipedia.org/wiki/Electron_mobility).

### Doping

The conductivity of semiconductors may easily be modified by introducing impurities into their [crystal lattice](https://en.wikipedia.org/wiki/Crystal_lattice). The process of adding controlled impurities to a semiconductor is known as doping. The amount of impurity, or dopant, added to an [intrinsic](https://en.wikipedia.org/wiki/Intrinsic_semiconductor) (pure) semiconductor varies its level of conductivity. Doped semiconductors are referred to as [extrinsic](https://en.wikipedia.org/wiki/Extrinsic_semiconductor). By adding impurity to the pure semiconductors, the electrical conductivity may be varied by factors of thousands or millions.

A 1 cm3 specimen of a metal or semiconductor has of the order of 1022 atoms. In a metal, every atom donates at least one free electron for conduction, thus 1 cm3 of metal contains on the order of 1022 free electrons, whereas a 1 cm3 sample of pure germanium at 20 °C contains about 4.2×1022 atoms, but only 2.5×1013 free electrons and 2.5×1013 holes. The addition of 0.001% of arsenic (an impurity) donates an extra 1017 free electrons in the same volume and the electrical conductivity is increased by a factor of 10,000.

The materials chosen as suitable dopants depend on the atomic properties of both the dopant and the material to be doped. In general, dopants that produce the desired controlled changes are classified as either electron [acceptors](https://en.wikipedia.org/wiki/Acceptor_(semiconductors)) or [donors](https://en.wikipedia.org/wiki/Donor_(semiconductors)). Semiconductors doped with donor impurities are called n-type, while those doped with acceptor impurities are known as p-type. The n and p type designations indicate which charge carrier acts as the material's [majority carrier](https://en.wikipedia.org/wiki/Majority_carrier). The opposite carrier is called the [minority carrier](https://en.wikipedia.org/wiki/Minority_carrier), which exists due to thermal excitation at a much lower concentration compared to the majority carrier.

For example, the pure semiconductor [silicon](https://en.wikipedia.org/wiki/Silicon) has four valence electrons which bond each silicon atom to its neighbors. In silicon, the most common dopants are group III and group V elements. Group III elements all contain three valence electrons, causing them to function as acceptors when used to dope silicon. When an acceptor atom replaces a silicon atom in the crystal, a vacant state (an electron "hole") is created, which can move around the lattice and functions as a charge carrier. Group V elements have five valence electrons, which allows them to act as a donor; substitution of these atoms for silicon creates an extra free electron. Therefore, a silicon crystal doped with [boron](https://en.wikipedia.org/wiki/Boron) creates a p-type semiconductor whereas one doped with [phosphorus](https://en.wikipedia.org/wiki/Phosphorus) results in an n-type material.

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**SEMICONDUCTOR DEVICES**

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