



## A Review on Type, Structure and Applications of Semiconductors

Bappy Rai<sup>1</sup>, Dr. Sanjay Rathore<sup>2</sup>

Research Scholar, Dept. of Physics, SSSUTMS, Sehore, M.P., India<sup>1</sup>

Research Guide, Dept. of Physics, SSSUTMS, Sehore, M.P., India<sup>2</sup>

**Abstract:** Electrical current may readily flow through a conductor. The vast majority of metals function well as conductors. Silver, gold, and aluminum are all good conductors because they have only one valence electron and are thus extremely loosely connected to their atoms. With the addition of a little amount of energy, these weakly linked valence electrons may become free electrons and leave the atom. As a result, the free electrons in a conductive substance may convey electricity. In this article, semiconductors types, structure and its applications was highlighted.

**Keywords:** Electricity, Insulator, Semiconductors.

### 1. Introduction

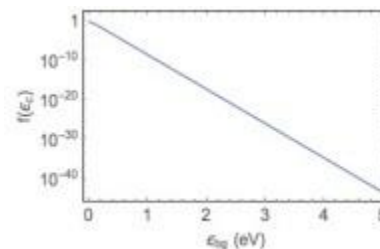
When it comes to conducting electricity, semiconductors fall somewhere in the middle between conductors and insulators. In its pure (intrinsic) form, a semiconductor is neither a conductor nor an insulator. Anode materials consisting of just one element include antimony (Sb), arsenic (As), astatine (At), boron (B), polonium (Po), tellurium (Te), tellurium (Te), silicon (Si), and germanium (Ge). There are also a number of other types of compound semiconductors that are regularly employed, including gallium arsenide, silicon carbide, indium phosphate, gallium nitride and silicon germanium. The four-valence electron atoms distinguish single-element semiconductors. The most prevalent semiconductor is silicon.

### 2. Semiconductors

Between conductors (mostly metals) and non-conductors (or insulators), there exist semiconductors (such as ceramics). Gallium arsenide and pure elements like silicon and germanium are examples of semiconductors. Semiconductors are governed by physics, which explains their theories, characteristics, and mathematical approach [1].

We can begin categorizing materials now that we know how genuine bands form in real components. Some additional terminology beforehand. Conduction and valence bands are used if the Fermi level is located in the middle of two bands. The band gap is the difference in energy between the conduction and valence bands. The valence and conduction bands of a metal overlap because the Fermi level is contained inside a band. A wide band gap exists in an insulator. An insulator-conductor transitional material with a band gap generally

on the order of one electron volt (eV). Where does the band gap size 1 eV come from? First of all, recall the Fermi distribution  $f(\epsilon) = \frac{1}{e^{(\epsilon - \epsilon_F)/kT} + 1}$  (1) Here we have taken  $\epsilon = \epsilon_F$  which is exactly true only at  $T = 0$ , but very close to being true in metals, since they have  $T \ll T_F$  (recall the numbers  $T_F = 80000K$  and  $\epsilon_F = 7eV$  for copper). Since we are no longer utilizing a free electron gas model,  $\epsilon_F$  cannot be calculated from rest principles. As it turns out, the only thing that counts is  $\epsilon_F$ 's relative energy. You'll see that  $f(\epsilon_F) = 1/2$ . This implies that the energy level  $\epsilon_F$  in a conductor is 50% likely to be occupied. To enter the conduction band, electrons in an insulator or semiconductor must cross the band gap. There must thus be equal numbers of holes and excitations in the valence band and in the conduction band, such that the Fermi distribution must be symmetric [2]. Alternatively, the Fermi level is always near the centre of the band gap when it's in a band gap. This is a universal truth that is crucial to comprehending doped semiconductors below this level of abstraction. Now, at room temperature  $kBT = 0.025eV$ . We can then compute the probability of finding an electron at the base of the conduction band, at energy  $\epsilon_c = \epsilon_F + 1/2 \epsilon_{bg}$  as  $f(\epsilon_c) = \frac{1}{e^{(\epsilon_c - \epsilon_F)/kT} + 1} = \frac{1}{e^{\epsilon_{bg}/2kT} + 1} \approx \frac{1}{2} e^{-\epsilon_{bg}/2kT}$





We see that this function is exponentially falling. At  $E_g=1\text{eV}$ , the base of the conduction band only has a  $10^9$  chance of being occupied. At  $E_g=2\text{eV}$  the probability is already down to  $10^{18}$ , and at  $E_g=3\text{eV}$  it's down to  $10^{27}$ . Considering there are of order  $NA \approx 10^{24}$  electrons around, we conclude that a band gap of order  $E_g \approx 1\text{--}2\text{eV}$  is the appropriate scale for determining what can conduct. To get a sense of the numbers, the band gap in NaCl, which forms an ionic solid, is  $E_g = 8.9\text{eV}$ , making it an insulator. Diamond (a solid form of carbon) at room temperature is  $E_g = 5.4\text{eV}$ . Thus diamond is also an insulator. Silicon, below diamond, has  $E_g = 1.08\text{eV}$  making it on the boundary between conductor and insulator: silicon is a semiconductor. An important characteristic of a semiconductor is number density of conduction electrons (in the conduction band) [3]. To compute this, we can treat the electrons in the conduction band as having the usual non-relativistic dispersion relation:  $E = E_c + \frac{\hbar^2 k^2}{2m_e}$  where  $E_c = E_g$  is the energy at the bottom of the conduction band. Then the density of states for conduction electrons is as in the free-electron gas,  $g(E) = \frac{V}{2\pi^2} \left(\frac{2m_e}{\hbar^2}\right)^{3/2} \sqrt{E - E_c}$ . Approximating  $f(E) \approx \exp\left(-\frac{E - E_c}{k_B T}\right)$  in Eq. (2) we then get  $n_e = \frac{V}{2\pi^2} \left(\frac{2m_e}{\hbar^2}\right)^{3/2} \int_{E_c}^{\infty} \sqrt{E - E_c} \exp\left(-\frac{E - E_c}{k_B T}\right) dE = 2 \left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E_g}{k_B T}\right)$

Similarly the density of holes is  $n_h = \frac{V}{2\pi^2} \left(\frac{2m_e}{\hbar^2}\right)^{3/2} \int_{-\infty}^{E_v} \sqrt{E_v - E} \exp\left(-\frac{E_v - E}{k_B T}\right) dE = 2 \left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{E_g}{k_B T}\right)$

So, in a pure intrinsic semiconductor the densities of electrons and holes are the same:  $n_e = n_h = n_i$ .  $n_i$  is called the intrinsic carrier concentration. Plugging in the numbers for silicon we get  $n_i = 2 \left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{1.08\text{eV}}{k_B T}\right) = 10^{19} \text{ cm}^{-3}$

$2 \left(\frac{m_e k_B T}{2\pi\hbar^2}\right)^{3/2} \exp\left(-\frac{1.08\text{eV}}{k_B T}\right) = 10^{19} \text{ cm}^{-3}$

For semiconductors, this equation is frequently referred to as the law-of-mass-action, since it relates the equilibrium concentrations of electrons and holes. In order to better understand why carbon is an insulator and silicon is a semiconductor, let's look at the properties of both. Carbon's formula is  $C = [\text{He}]2s^2 2p^2$ . In a covalent network, it has four valence electrons, which enable it to create four covalent bonds. As opposed to creating metallic connections, this is more stable.  $a_C = 0.154\text{nm}$  is the atomic distance between diamond atoms.  $\rho_C = 10^{14} \text{ m}$  is its electrical resistivity. Silica is the chemical compound  $\text{SiO}_2 = [\text{Ne}]3s^2 3p^2$ . As with carbon, silicon forms covalent bonds, but the valence electrons of silicon are further out, making the bonds weaker. Silicate bonds are weaker than those in diamond, which is why the distance between silicon's nuclei is nearly twice as great as that between diamond's. As a result, silicon may be conceived of as having metallic bonding rather than being covalently bound. Our ability to interpolate between covalent and metallic can be

facilitated by the tight-binding hypothesis. In comparison to metals like copper, which has a resistivity of  $1.7 \times 10^{-8} \text{ m}$ , silicon has a resistivity of  $\rho_{\text{Si}} = 0.001 \text{ m}$ , which is hundreds of orders of magnitude higher than diamond's [4]. There is a metal next to silicon on the periodic table called germanium:  $\text{Ge} = 104s$

$2p^2$ .  $E_g = 0.67\text{eV}$ , lattice spacing =  $0.243\text{nm}$ , and resistivity equal to nearly half of that of silicon are all values derived from the bandgap (the distance between the electrons in the crystal) of germanium gallium germanium (GeGa). So semiconductors are silicon and germanium. Gallium arsenide GaAs is an important semiconductor.  $E_g = 1.43\text{eV}$ . [7]

Examples of Semiconductors:

Some of the most often used semiconductors are gallium arsenide, germanium, and silicon. Gallium arsenide (GaAs) is utilized in solar cells, laser diodes, etc., whereas silicon is employed in electrical circuit construction.

### 3. Types of Semiconductor

#### 3.1 Intrinsic Semiconductor

We'll use the most popular examples of Ge and Si, whose lattice structure has a regular hexagonal configuration. The diamond-like structures are a kind of structure. Four of an atom's closest neighbours encircle it. Si and Ge both contain four valence electrons, as we well know. One of each Si or Ge atom's four valence electrons is shared with each of its four closest neighbours in the crystal structure, and one electron is taken from each of these neighbours. Covalent bonds, also known as valence bonds, are formed when two atoms share electrons. Si and Ge structures may be seen as two-dimensional representations of the covalent bond because the two shared electrons can be considered to move back and forth between the related atoms keeping them together [5].

At low temperatures, this may happen. Because of the increased amount of thermal energy, some of these electrons could break-away when the temperature rises (becoming free electrons contributing to conduction). Only a few atoms in the crystalline lattice are efficiently ionized by the heat energy and a vacancy is created in the link. Free electrons (charge  $-q$ ) leave behind an effective charge ( $+q$ ) in the neighbourhood where they came from. A hole is a void that has an effective positive charge. The hole seems to be a free particle with an effective charge of positive polarization. There are exactly as many free electrons as there are holes in an intrinsic semiconductor, which is why intrinsic semiconductors are called semiconductors [6].

In other words, the intrinsic carrier concentration is  $n_e = n_h = n_i$ . Semiconductors have a unique characteristic that allows electrons and holes to travel at the same time. There is a hole at the location. It is possible to see the movement of holes. There is a possibility that an electron from the covalent link at site 2 might move to the unoccupied site 1. (hole). As a result, the hole has moved to site 2 and the electron has moved to site 1. Consequently, it seems that the hole has shifted to site 2. The electron that was released is not a part of this process of hole movement. When an electric field is applied, an electron current,  $I_e$ , is generated because the free electron acts as a conduction electron and travels fully independently. Recall that the movement of a hole is only a handy technique to describe bound electrons' real mobility when there is an empty link in the crystal. An electric field causes these holes to flow towards a negative potential, resulting in the hole current  $I_h$ . That's because the electron and hole currents add up to one big total current,  $I_h$ :

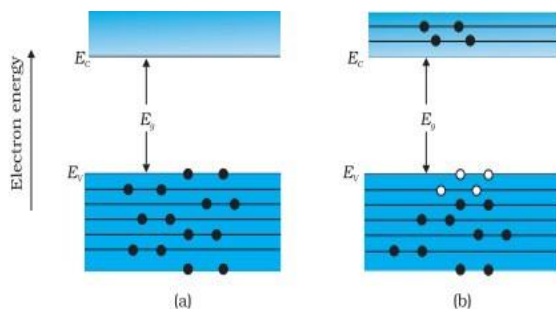
$$I = I_e + I_h$$

Conduction electrons and holes are generated, but at the same time the electrons and holes are also recombined in the process of recombination. The generation rate and the recombination rate of charge carriers are identical when the system is in equilibrium. When an electron and a hole collide, recombination occurs.

If you set  $T = 0$  K, an intrinsic semiconductor will act as an insulator

(a). Higher temperatures ( $T > 0$ K) excite certain electrons from the valence band to the conduction band by exchanging energy with them. The conduction band is partly occupied by these excited electrons at temperatures above zero degrees Celsius. Because of this, an intrinsic semiconductor's energy band diagram will appear as depicted.

(b). Electrons in the conduction band may be seen in this illustration. There are equal numbers of holes in the valence band because of this.



When  $T = 0$  K, an intrinsic semiconductor is insulating. Four pairs of electron-hole pairs at temperatures greater

than 0 K. The electrons (filled circles) and holes (empty circles) are shown in the diagram.

### 3.2 Extrinsic Semiconductor

(i) An intrinsic semiconductor's conductivity varies with temperature, although it is very low at ambient temperature. So these semiconductors can't be used to create any significant electronic gadgets. As a result, increasing their conductivity is a must. With the help of impurities, it is possible to do this. It is possible to greatly improve the conductivity of a pure semiconductor by adding only a few parts per million (ppm) of an appropriate impurity. Extrinsic semiconductors or impurity semiconductors are the terms used to describe these types of materials. An impurity atom, or "dopant," that is added deliberately is termed doping. A doped semiconductor is another name for this kind of material [7].

(ii) Dopants must be chosen such that they do not alter the native crystal lattice structure of the semiconductor. It merely takes up a tiny fraction of the crystal's initial semiconductor atom locations. To do this, the dopant and semiconductor atoms' diameters must be almost identical. It's possible to dope the tetravalent Si or Ge using two kinds of dopants:

(iii) Pentavalent (valency 5); like Arsenic (As), Antimony (Sb), Phosphorous (P), etc.

For example, Indium (In), Boron (B), and Aluminum (Al) are all trivalent elements with valency three. Here, we'll explain how doping affects the amount of charge carriers (and hence the conductivity) in semiconductors. We chose a dopant element from the neighbouring fifth or third group because Si or Ge belongs to the fourth group in the Periodic table and because we anticipate and take care that the size of the dopant atom is almost the same as that of Si or Ge. There are two distinct kinds of semiconductors produced by penta- and trivalent dopants in Si and Ge, as will be explored more below [8].

The deliberate addition of impurities to the intrinsic (pure) semi conductive material may greatly boost the conductivity of semiconductors, which is typically a poor conductor. Doping is a technique used to increase the number of active users (electrons or holes). n-type and p-type impurities are the two types of impurities.

### 3.3 N-Type and P-Type Semiconductors: N-Type Semiconductor

Pentavalent impurity atoms are introduced to intrinsic silicon to enhance the amount of electrons in the conduction band. Arsenic (As), phosphorous (P), bismuth (Bi), and antimony (As) are examples of atoms containing five valence electrons (Sb).



Antimony forms covalent connections with four neighbouring silicon atoms for each pentavalent element. The antimony atom uses four of its valence electrons to create covalent connections with silicon atoms, leaving an additional electron. Because it isn't engaged in bonding, the additional electron is classified as a conduction electron. Because it gives away an electron, the pentavalent atom is referred to as a donor atom. Silicon may be finely tuned by the quantity of impurity atoms that are introduced to the material. This doping method does not leave a hole in the valence band because the number of conduction electrons generated exceeds the amount necessary to fill the valence band.

Carriers belonging to both the majority and the minority When doped with pentavalent atoms, silicon (or germanium) is an n-type semiconductor because most of the current carriers are electrons (the n stands for the negative charge on an electron). In n-type materials, electrons are referred to as the majority carriers. Even though electrons make up the bulk of n-type material's current carriers, the thermal generation of electron-hole pairs creates a few holes. The pentavalent impurity atoms do not contribute to the formation of these holes. Minority carriers refer to holes in an n-type material.

Let's say a pentavalent element is used to numb Si or Ge. Assuming that the +5 element inhabits the crystal lattice of Si, four of the element's electrons link with four silicon neighbours, while the fifth stays tethered to its parent. This is because the fifth electron considers the four electrons involved in bonding to be a component of the atom's effective core. As a consequence, the ionization energy necessary to liberate this electron is very low, and it will be free to travel inside the semiconductor lattice even at normal temperature.

So, for germanium, it takes around 0.01 eV of energy to detach one electron from its atom, whereas for silicon, the energy needed is about 0.05 eV of energy. At ambient temperature, the energy needed to leap the forbidden band (0.7 eV for germanium and 1.1 eV for silicon) is much lower. Because the pentavalent dopant is providing an additional electron for conduction, it's called the donor impurity. A rise in ambient temperature has no effect on the number of electrons made accessible for conduction by dopant atoms. When it comes to free electrons and holes created by Si atoms, however, temperature has a negligible effect on this. Donor- and intrinsically-produced electrons account for the majority of the conduction electrons in a doped semiconductor, but the vast majority of the semiconductor's holes (nh) are created entirely by the intrinsic source. However, as the number of electrons grows, so will the rate of hole recombination. Thus, the number of holes would continue to be lowered. As a result, the number of conduction electrons may be increased significantly more than the number of holes by using correct doping levels. As a

result, electrons predominate over holes in an extrinsic semiconductor doped with pentavalent impurities. The n-type semiconductors are so referred to as such. We have  $n_e > n_h$  for n-type semiconductors [9].

### 3.4 P-Type Semiconductor

Trivalent impurity atoms are used to boost the intrinsic silicon's number of holes. For example, the boron trivalent atom makes covalent connections with four nearby silicon atoms (in this instance, four adjacent silicon atoms). There are four electrons in total needed to form each covalent link, therefore each additional boron atom leaves a hole in the molecule. Term "acceptor atom" refers to the fact that the trivalent atom may accept an electron With the right amount of trivalent impurity atoms, the number of holes may be precisely regulated. A conduction (free) electron does not accompany a hole that is formed as a result of this doping process.

Carriers belonging to both the majority and the minority P-type semiconductors are silicon (or germanium) doped with trivalent atoms because most of the current carriers are holes. In p-type materials, holes are the primary carriers. Despite the fact that the bulk of the material's current carriers are holes, thermally produced electron-hole pairs do produce a small number of conduction- band electrons. The trivalent impurity atoms do not contribute to the generation of these conduction- band electrons. There are just a few electrons in the conduction band in p-type materials.

Doping Si or Ge with a trivalent impurity such as Al, B, In, etc. results in this. Unlike Si or Ge, dopants have just one extra electron in their valence shells, therefore they may form covalent bonds with three Si atoms but not with the fourth Si atom. A hole exists in the link between the trivalent atom and its fourth neighbour. An electron in the outer orbit of an atom in the vicinity may hop to fill this vacancy, leaving a vacancy or hole at its own location because the next Si atom in the lattice desires an electron in lieu of a hole. As a result, conduction may now occur via the hole. When a neighbouring Si atom exchanges a fourth electron with a trivalent foreign atom, the atom becomes effectively negatively charged. A single negative charge may be generated by treating the dopant atom of the p-type material as the core together with its corresponding hole.

A single acceptor atom leaves a single hole, as is clear. Additional to the inherently produced holes, conduction electrons are formed exclusively by intrinsic production. In this case, the majority carriers are holes, whereas the minority carriers are electrons. Therefore, p-type semiconductors are extrinsically doped semiconductors with trivalent impurities. Recombination will lower the quantity of intrinsically produced electrons



(ni) to ne in p-type semiconductors. The p-type semiconductors are available.

$$n_h \gg n_e$$

The overall charge neutrality of the crystal is maintained because the extra charge carriers in the lattice have the same charge as the ionized cores. Extrinsic semiconductors contain a high concentration of majority current carriers and hence, the thermally generated minority current carriers have a greater probability of encountering and being destroyed by the majority current carriers. As a result, the dopant indirectly aids in reducing the inherent concentration of minority carriers by introducing a high number of current carriers of one kind that become the majority carriers. Doping has an effect on the semiconductor's energy-band structure. Extrinsic semiconductors have extra energy states owing to donor (ED) and acceptor (EA) impurities. N-type Si semiconductor's energy band diagram shows that electrons from the donor energy level ED enter the conduction band with a modest amount of energy, just above the bottom energy level EC. There are just a few (10<sup>12</sup>) atoms of Si that are ionized at ambient temperature.

As a result, the donor impurities will be the primary source of electrons in the conduction band. Similarly, the acceptor energy level EA is somewhat above the top EV of the valence band for p-type semiconductors [10]. An electron from the valence band may jump to the level EA and ionise the acceptor negatively with a relatively tiny input of energy. We may also argue that the hole from level EA dips down into the valence band with a very modest supply of energy. When they obtain energy from somewhere else, electrons rise and holes sink.) Most of the acceptor atoms are ionized at ambient temperature, leaving valence band holes. This means that at ambient temperature, the valence band hole density is mostly caused by extrinsic semiconductor impurity. ne is the concentration of electrons and holes in a semiconductor in thermal equilibrium.

$$n_h = n_i^2$$

It's a rough approximation, but it helps explain the distinction between metals, insulators and semiconductors (extrinsic and intrinsic) in a straightforward way. As their conduction and valence bands' energies diverge, C, Si, and Ge exhibit a wide range of resistivity differences. The energy gaps are 5.4 eV, 1.1 eV, and 0.7 eV, respectively, for C (diamond), Si, and Ge. Sn is likewise a group IV element, but its energy gap is zero eV, making it a metal.

### 3. Semiconductor Structure

There are 8 electrons around each semiconductor, which is composed of atoms bound together in a regular, periodic configuration. This makes up the nucleus of an

atom, which is made up of a core of protons (positively charged particles) and neutrons (non-charged particles). The atom is electrically neutral because the quantity of electrons and protons are equal. Depending on how many electrons an atom has, the electrons inhabit various energy levels. This is true for each element in the periodic table.

Materials from group IV of the periodic table or a mixture of groups III and V (referred to as III-V semiconductors) or combinations of groups II and VI provide the building blocks for semiconductor atoms (called II-VI semiconductors). Because it is the foundation of integrated circuits (ICs), silicon is the most widely utilised semiconductor material. In addition, silicon is the primary component of the vast majority of solar cells.

It is the semiconductor's bond structure that dictates its physical characteristics. To begin with, it restricts electrons' ability to travel about the crystal lattice and the energy levels they may occupy. A covalent link connects the electrons around each atom in a semiconductor. An 8-electron orbit around each atom in a covalent connection is the result of the electrons "sharing" between two atoms. The electrons in a covalent bond are constrained to the area around the atom because of the bond's holding power. Electrons in a bond cannot participate in current flow, absorption, or other physical processes that require the presence of free electrons since they cannot move or alter their energy [4,6].

However, only at absolute zero do all electrons form bonds. At higher temperatures, the electron may obtain enough energy to break out of its link, allowing it to roam freely across the crystal lattice and participate in conduction. With enough free electrons, a semiconductor can conduct current at normal temperature, but an insulator is what it is when it is at or near absolute zero degrees. Because of the connection, the electrons may now exist in two different energy levels. The electron's lowest-energy state is when it is bound. Electrons can only be liberated from their bonds if they have enough thermal energy to do it themselves. The electron is either in a low-energy position in the bond, or it has gathered enough energy to break out and consequently has a specific minimum energy. There is no middle ground for the electron. It's known as the band gap of a semiconductor because of this minimal energy. Electronic gadgets work because of the quantity and energy of free electrons. A covalent bond may pass from one electron to another across the crystal lattice because of the space left by the electrons. This positive-charged void is frequently referred to as a "hole," and it resembles an electron.

### 4. Applications

Let's take a closer look at how semiconductors are used in everyday life. There are practically no electronic gadgets



that don't require semiconductors. Our lives would be vastly different if it weren't for them.

Their durability, compactness, cheap cost, and ability to regulate the flow of electricity make them excellent for a broad range of applications in a variety of components and systems. To put it another way: everything from diodes and transistors to microcontrollers and integrated circuits is built on the foundation of semiconductors.

## 5. Conclusion

Electronic devices and solar cells depend heavily on the following characteristics of semiconductor materials:

- The band gap;
- The number of free carriers available for conduction; and
- The "generation" and recombination of free carriers in response to the electric field, temperature and light shining on the material.

## References

- [1] Davy, H. Farther researches on the magnetic phenomena produced by electricity; with some new experiments on the properties of electrified bodies in their relations to conducting powers and temperature. *Phil. Trans. R. Soc. Lond.* 111, 425–439, <https://doi.org/10.1098/rstl.1821.0030> (1821).
- [2] Faraday, M. On a new law of electric conduction. *Phil. Trans. R. Soc. Lond.* 123, 507–522, <https://doi.org/10.1098/rstl.1833.0022> (1833).
- [3] Hittorf, J. W. Ueber das elektrische leitungsvermögen des schwefelsilbers und halbschwefelkupfers. *Ann. Phys.* 160(9), 1–28, <https://doi.org/10.1002/andp.18511600902> (1851).
- [4] Becquerel, A. E. On the electric effects under the influence of solar radiation. *C. R. Acad. Sci.* 9, 561–567 <http://gallica.bnf.fr/ark:/12148/bpt6k2968p/f561.image> (1839).
- [5] Fritts, C. E. On a new form of selenium cell, and some electrical discoveries made by its use. *Am. J. Sci.* 26(156), 465–472, <https://doi.org/10.2475/ajs.s3-26.156.465> (1883).
- [6] Koenigsberger, J. & Weiss, J. Über die thermoelektrischen effekte (thermokräfte, thomsonwärme) und die wärmeleitung in einigen elementen und verbindungen und über die experimentelle prüfung der elektronentheorien. *Ann. Phys.* 340(6), 1–46, <https://doi.org/10.1002/andp.19113400602> (1911).
- [7] Busch, G. Early history of the physics and chemistry of semiconductors - from doubts to fact in a hundred years. *Eur. J. Phys.* 10(4), 254–264, <https://doi.org/10.1088/0143-0807/10/4/002> (1989).
- [8] Ohl, R. S. Alternating current rectifier. US Patent 2 402

661<https://patentimages.storage.googleapis.com/46/c0/0c/c474c57f46b75e/US2402661.pdf> (1941).

- [9] McAfee, K. B. & Pearson, G. L. Te electrical properties of silicon p-n junctions grown from the melt. *Phys. Rev.* 87((1)), 190-E6 (1952).
- [10] Pearson, G. L. & Fov, P. W. Silicon p-n junction diodes prepared by the alloying process. *Phys. Rev.* 87((1)), 190- E7.