TEMPERATIVE DEPENDENCE OF ELECTRICAL CONDUCTIVITY IN SEMICONDUCTORS

Abstract

The electrical conductivity of a semiconductor material is between that of a conductor, such as metallic copper, and that of an insulator, such as glass. Its resistivity decreases as the temperature rises, whereas metals have the reverse effect. By adding impurities ("doping") into the crystal structure, its conducting characteristics can be changed in beneficial ways. A semiconductor junction is formed when two differentially doped areas in the same crystal occur. Diodes, transistors, and most contemporary electronics are built on the behavior of charge carriers such as electrons, ions, and electron holes at these junctions.Silicon, germanium, gallium arsenide, and elements near the periodic table's "metalloid staircase" are examples of semiconductors. Gallium arsenide is the second most common semiconductor after silicon, and it's utilized in things like laser diodes, solar cells, and microwave-frequency integrated circuits. Silicon is a crucial component in the production of most electrical circuits.The electrical conductivity of semiconductors varies significantly with temperature. It acts as an insulator at absolute zero. Some of the semiconductor's covalent bonds disintegrate at room temperature due to thermal energy.

Keywords: Temperature, Semiconductor, Conductivity, Resistivity.

Introduction

A semiconductor is a substance with electrical conductivity that falls between that of a conductor and that of an insulator. Semiconductors include silicon, germanium, and graphite, to name a few. Semiconductors, which include transistors, light-emitting diodes, and solar cells, are the building blocks of contemporary electronics. Semiconductors are the building blocks of numerous electrical devices, including transistors, switches, diodes, and solar cells. It's a substance with a conductance value that falls in between insulators and conductors.Conduction caused by thermally produced charge carriers (extrinsic conduction) termed dopants in semiconductor devices is the only difference between them and insulators. It is possible to produce semiconductor materials, n-type materials, and p-type materials, by adding the appropriate dopants (Lin et, al., 2014). Semiconductors, which include transistors, light-emitting diodes, and solar cells, are the building blocks of contemporary electronics. It is made up of three bands: the conduction band, the prohibited gap, and the valence band.

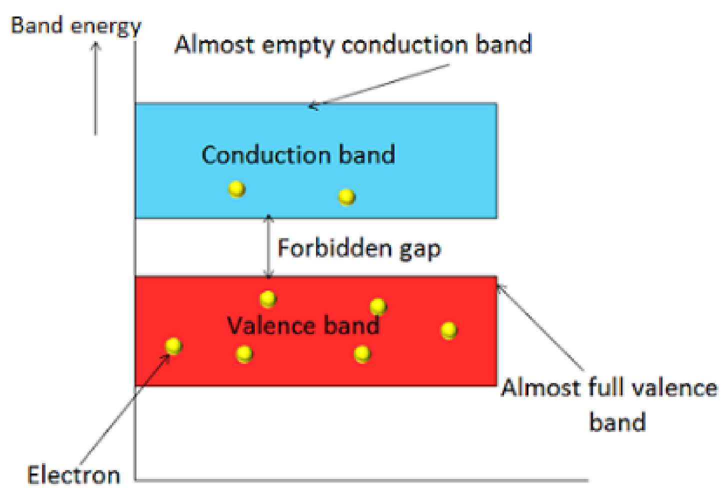

Fig. 1: semiconductor parameters

The most essential metric for defining the transport properties in semiconductor devices is electron conductivity. The prohibited gap between the valence band and the conduction band in semiconductors is relatively tiny. It has roughly a 1 electron volt (eV) forbidden gap (Brooks, 2015).Because the electrons in the valence band do not have enough energy to migrate into the conduction band at low temperatures, the valence band is entirely filled with electrons and the conduction band is empty. As a result, at low temperatures, a semiconductor acts as an insulator (Dingle, 2015).

However, at room temperature some of the electrons in valence band gains enough energy in the form of heat and moves in to conduction band. When the valence electrons moves in to conduction band they becomes free electrons. These electrons are not attached to the nucleus of an atom, So they moves freely (Barber, 2017).

The conduction band electrons are responsible for electrical conductivity. The measure of ability to conduct electric current is called an electrical conductivity.When the temperature goes on increasing, the number of valence band electrons moving in to conduction band also increases. This shows that electrical conductivity of the semiconductor increases with increase in temperature. i.e. a semiconductor has negative temperature co-efficient of resistance. The resistance of semiconductor decreases with increase in temperature (Conwell and Weisskopf, 2015).

Properties of Semiconductors

Semiconductors can conduct electricity under preferable conditions or circumstances. This unique property makes it an excellent material to conduct electricity in a controlled manner as required.

Unlike conductors, the charge carriers in semiconductors arise only because of external energy (thermal agitation). It causes a certain number of valence electrons to cross the energy gap and jump into the conduction band, leaving an equal amount of unoccupied energy states, i.e. holes. Conduction due to electrons and holes are equally important.

- **Resistivity:** 10^{-5} to 10^{6} Ωm
- **Conductivity:** 10^{5} to 10^{-6} mho/m
- **Temperature coefficient of resistance:** Negative
- **Current Flow:** Due to electrons and holes

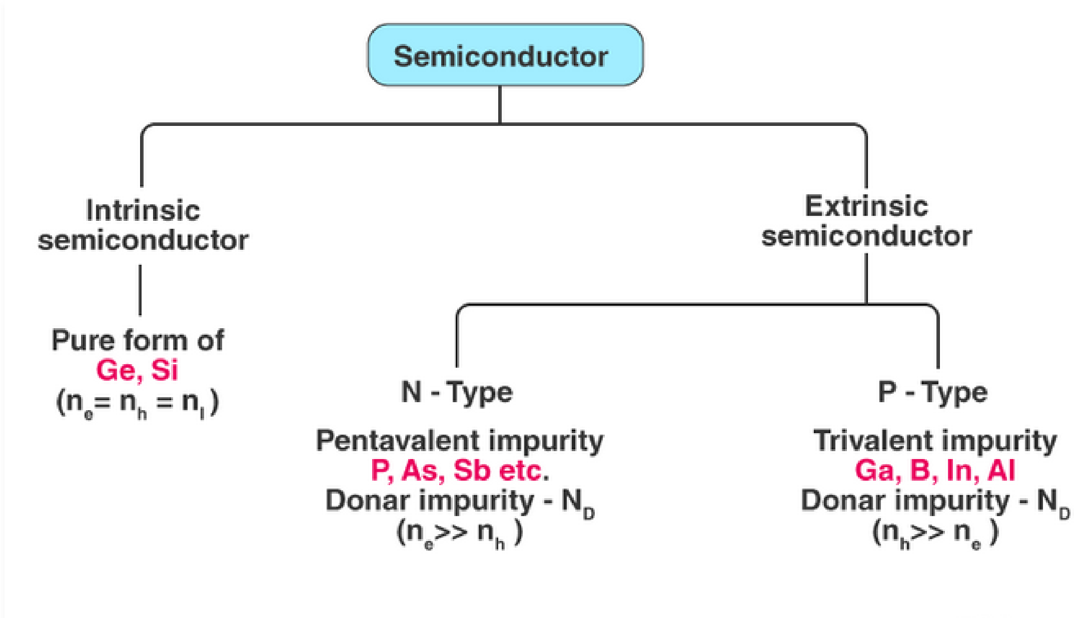

Fig. 2: Classification of Semiconductors

Types of semiconductors

Extrinsic semiconductor

An extrinsic semiconductor is one that has been doped, meaning that during the manufacturing of the semiconductor crystal, a trace element or chemical known as a doping agent has been chemically incorporated into the crystal to give it different electrical properties than a pure semiconductor crystal, which is known as an intrinsic semiconductor. These foreign dopant atoms in the crystal lattice of an extrinsic semiconductor are primarily responsible for providing charge carriers that transmit electric current through the crystal. There are two types of doping agents employed, resulting in two types of extrinsic semiconductors.When an electron donor dopant is integrated into a crystal, it releases a mobile conduction electron into the lattice. An n-type semiconductor is an extrinsic semiconductor that has been doped with electron donor atoms because the bulk of charge carriers in the crystal are negative electrons. An electron acceptor dopant is an atom that accepts an electron from the lattice, producing a vacancy in the crystal where an electron should be termed a hole and can pass through it like a positively charged particle. An extrinsic semiconductor which has been doped with electron acceptor atoms is called a p-type semiconductor, because the majority of charge carriers in the crystal are positive holes.

Doping is the key to the extraordinarily wide range of electrical behavior that semiconductors can exhibit, and extrinsic semiconductors are used to make semiconductor electronic devices such as diodes, transistors, integrated circuits, semiconductor lasers, LEDs, and photovoltaic cells. Sophisticated semiconductor fabrication processes like photolithography can implant different dopant elements in different regions of the same semiconductor crystal wafer, creating semiconductor devices on the wafer's surface. For example a common type of transistor, the n-p-n bipolar transistor, consists of an extrinsic semiconductor crystal with two regions of n-type semiconductor, separated by a region of p-type semiconductor, with metal contacts attached to each part.

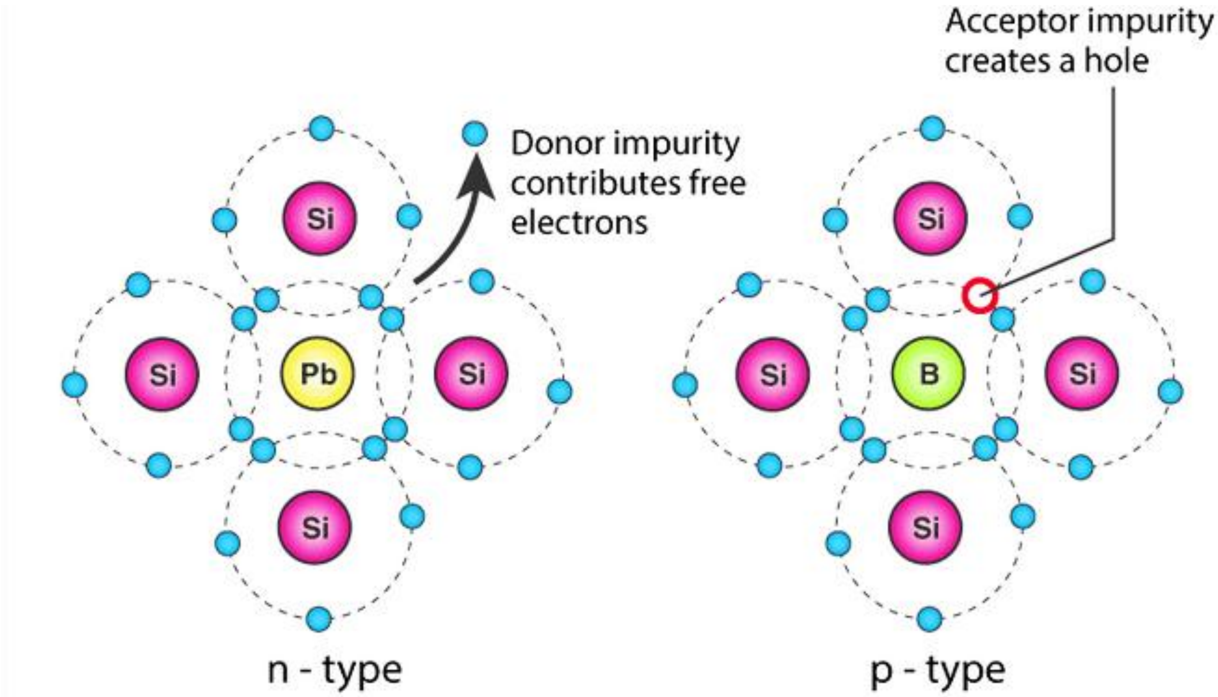

Image 1 : Extrinsic semiconductor

Intrinsic(pure) semiconductor

An intrinsic (pure) semiconductor, also known as an undoped semiconductor or i-type semiconductor, is a semiconductor that is completely free of dopant species. The quantity of charge carriers is thus governed by the material's characteristics rather than the amount of impurities. The number of excited electrons and holes in intrinsic semiconductors are equal: n = p. This may be true even after the semiconductor has been doped, but only if both donors and acceptors have been equally doped. In this case, n = p still holds, and the semiconductor remains intrinsic, though doped.

The electrical conductivity of intrinsic semiconductors can be due to crystallographic defects or electron excitation. In an intrinsic semiconductor the number of electrons in the conduction band is equal to the number of holes in the valence band. An example is $Hg_{0.8}Cd_{0.2}Te$ at room temperature.

The highest energy of the valence band occurs at a different k (k-space wave vector) than the minimum energy of the conduction band in an indirect band gap intrinsic semiconductor. Silicon and germanium are two examples. A direct band gap intrinsic semiconductor is one in which the valence band's greatest energy coincides with the conduction band's minimum energy. Gallium arsenide is one example.

A silicon crystal is different from an insulator because at any temperature above absolute zero, there is a non-zero probability that an electron in the lattice will be knocked loose from its position, leaving behind an electron deficiency called a "hole". If a voltage is applied, then both the electron and the hole can contribute to a small current flow.

The conductivity of a semiconductor can be modeled in terms of the band theory of solids. The band model of a semiconductor suggests that at ordinary temperatures there is a finite possibility that electrons can reach the conduction band and contribute to electrical conduction. The term intrinsic here distinguishes between the properties of pure "intrinsic" silicon and the dramatically different properties of doped n-type or p-type semiconductors.

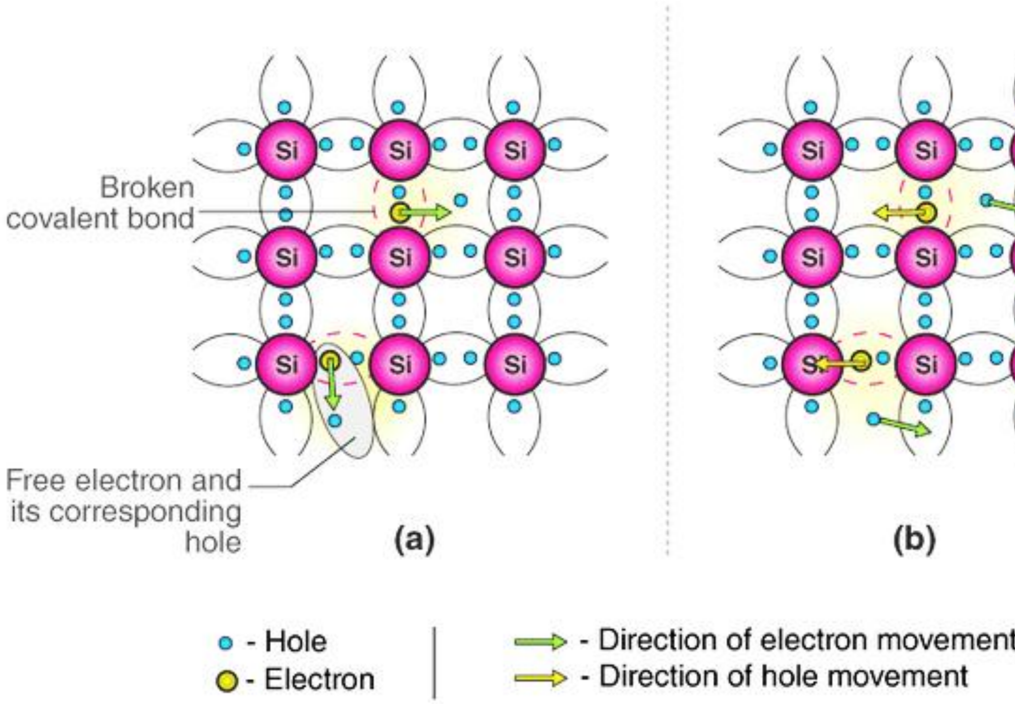

Fig. 3: Conduction Mechanism in Case of Intrinsic Semiconductors (a) In absence of electric field (b) In presence of electric Field

Conductivity of a semiconductor

The conductivity of a semiconductor is given by:

$$\sigma = q(\mu_n n + \mu_p p) \quad (1)$$

where μ_n and μ_p refer to the mobilities (see Prof. Shum's note) of the electrons and holes, and n and p refer to the density of electrons and holes, respectively. A *doped* semiconductor, majority carriers greatly outnumber minority carriers, so that Equation 1 can be reduced to a single term involving the majority carrier.

Doping

Impurities may readily be introduced into the crystal lattice of semiconductors to change their conductivity. Doping is the process of introducing controlled impurities to a semiconductor. The quantity of impurity (or dopant) introduced to an intrinsic (pure) semiconductor affects its conductivity level Yacobi (2003). Extrinsic semiconductors are doped semiconductors. The electrical conductivity of pure semiconductors can be changed by hundreds or millions of times by introducing impurities.

The number of atoms in a 1 cm3 metal or semiconductor specimen is on the order of 1022. Every atom in a metal gives at least one free electron for conduction, resulting in on the order of 1022 free electrons per cubic centimeter of metal (Donovan, 2016). At 20 °C, a 1 cm3 sample of pure germanium has around 4.21022 atoms but only 2.51013 free electrons and 2.51013 holes. The addition of 0.001% arsenic (an impurity) gives an additional 1017 free electrons in the same volume, resulting in a 10,000-fold improvement in electrical conductivity (Kahng and Sze, 2017).

The materials used as dopants are determined by the atomic characteristics of both the dopant and the doped material. Electron acceptors and donors are the two types of dopants that generate the required regulated modifications. The n-type semiconductors are doped with donor impurities, whereas the p-type semiconductors are doped with acceptor impurities. The n and p type designations denote which charge carrier is the majority carrier for the substance. The minority carrier, on the other hand, exists because of thermal excitation at a considerably lower concentration than the dominant carrier.

For example, each silicon atom contains four valence electrons that bind it to its neighbors in the pure semiconductor silicon. Group III and group V elements are the most prevalent dopants in silicon. When used to dope silicon, Group III elements all have three valence electrons, leading them to act as acceptors. When an acceptor atom in the crystal substitutes a silicon atom, an empty state (an electron "hole") is formed that may travel across the lattice and serve as a charge carrier. Group V elements contain five valence electrons, allowing them to function as donors; when these atoms are substituted for silicon, an additional free electron is created.

Therefore, a silicon crystal doped with boron creates a p-type semiconductor whereas one doped with phosphorus results in an n-type material *(*Busch, 2019).

During manufacture, dopants can be diffused into the semiconductor body by contact with gaseous compounds of the desired element, or ion implantation can be used to accurately position the doped regions.

Effect of temperature on conductivity of semiconductor

Electrical conductivity of semiconductor changes appreciably with temperature variations. At absolute zero, it behaves as an insulator. At room temperature, because of thermal energy, some of covalent bonds of the semiconductor break. The breaking of bonds sets those electrons free, which are engaged in the formation of these bonds. This results in few free electrons. These electrons constitute a small current if potential is applied across the semiconductor crystal. This shows the conductivity for intrinsic semiconductor increases with increase in temperature as given by $\eta = A_{exp}(-E_g / 2kt)$ where η is the carrier concentration, Eg is the band gap, T is the temperature and A is constant. In case of extrinsic semiconductors, addition of small amount of impurities produces a large number of charge carriers. This number is so large that the conductivity of an extrinsic semiconductor is many times more than that of an intrinsic semiconductor at room temperature. In n - type semiconductor all the donors have donated their free electrons, at room temperature. The additional thermal energy only serves to increase the thermally generated carriers. This increases the minority carrier concentration. A temperature is reached when number of covalent bonds that are broken is large, so that number of holes is approximately equal to number of electrons. The extrinsic semiconductor then behaves like intrinsic semiconductor.

Effects of temperature and doping on mobility of a semiconductor

As given in Eq. (1), conductivity of a material is determined by two factors: the concentration of free carriers available to conduct current and their mobility (or freedom to move). In a semiconductor, both mobility and carrier concentration are temperature dependent. Thus, it is important to view the conductivity as a function of temperature which is expressed by:

$$\sigma = q\left[\mu_n(T)n(T) + \mu_p(T)p(T)\right] \qquad (2)$$

There are two basic types of scattering mechanisms that influence the mobility of electrons and holes: lattice scattering (also called phonon scattering) and impurity scattering. We have already discussed lattice scattering in the class; we know that lattice vibrations cause the mobility to decrease with increasing temperature.

However, the mobility of the carriers in a semiconductor is also influenced by the presence of *charged impurities*. Impurity scattering is caused by crystal defects such as ionized impurities. At lower temperatures, carriers move more slowly, so there is more time for them to interact with charged impurities. As a result, as the temperature decreases, impurity scattering *increases* and the mobility *decreases.* This is just the opposite of the effect of lattice scattering.

The total mobility then is the sum of the phonon-scattering mobility and the impurity-scattering mobility. Figure 4 shows how the total mobility has a temperature at which it is a maximum. The approximate temperature dependence of mobility due to lattice scattering is $T^{-3/2}$, while the temperature dependence of mobility due to impurity scattering is $T^{+3/2}$ (see Figure 4). In practice, impurity scattering is typically only seen at very low temperatures. In the temperature range we will measure, only the influence of lattice scattering will be expected.

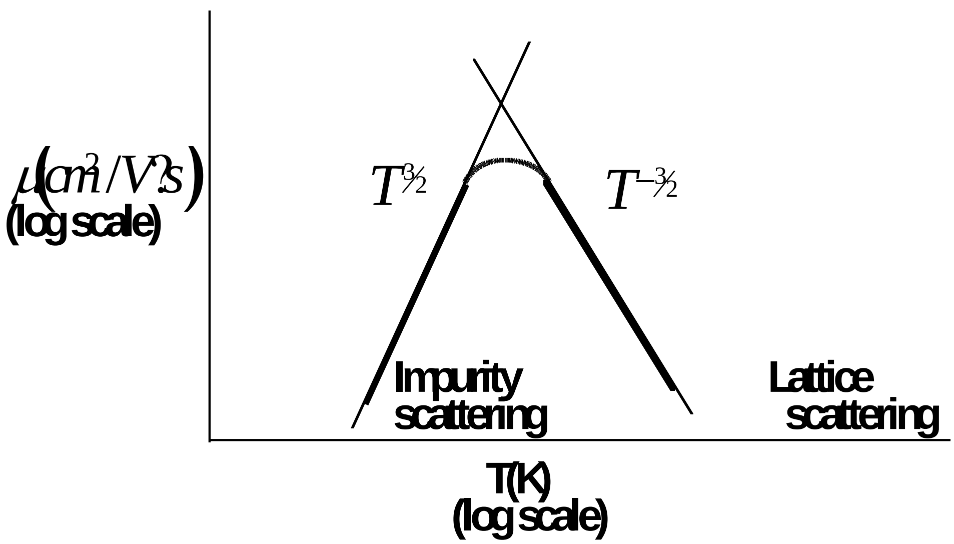

Fig. 4. Approximate temperature dependence of mobility with both lattice and impurity scattering

Effect of temperature on semiconductor parameters

The most commonly used semiconductor parameters are intrinsic concentration, forbidden energy gap, mobility and conductivity. The effect of temperature on these parameters is discussed below.

Intrinsic concentration (ni): The number of holes or electrons present in an intrinsic semiconductor at any temperature is called intrinsic carrier concentration (ni). It depends upon temperature of an intrinsic semiconductor. In N type semiconductor, the number of free electrons (n) does not change appreciably with the increase in temperature, but number of holes (p) increases. In P type semiconductor, the number of free electrons (n) increases with the increase in temperature, but number of holes remains constant.

Forbidden energy gap (EG): The energy required to break a covalent bond in a semiconductor is known as energy gap. It is equal to the difference of energy levels between the conduction band and valence band of the semiconductor crystal structure. The forbidden energy gap decreases with the increase in temperature.

Mobility (μ): The mobility means the movement of charge carriers. The mobility of intrinsic semiconductor decreases with increase in temperature because at higher temperature, the numbers of carriers are more and they are energetic also. This causes an increased number of collisions of charge carriers with the atoms and thus the mobility decreases.

Conclusion

Semiconductors are materials with conductivity intermediate between conductors (usually metals) and non-conductors or insulators (such as ceramics). Semiconductors are made up of compounds like gallium arsenide or pure elements like germanium or silicon. The ideas, characteristics, and mathematical methods that control semiconductors are explained in physics.The electrical conductivity of semiconductors varies significantly with temperature. It acts as an insulator at absolute zero. Some of the semiconductor's covalent bonds disintegrate at room temperature due to thermal energy.

Temperature Dependence of Conductivity for a Semiconductor

Because conductivity is dependent on both carrier concentration and mobility, as shown in Equation 1, there are a number of potential temperature dependencies for conductivity. For example, at low temperatures (less than 200K), impurity scattering (T3/2) may be the main scattering mechanism, whereas extrinsic doping (n = ND+) determines the carrier concentration, As a result, conductivity would be expected to rise as temperature rose (T3/2). Other options will exhibit variable temperature dependency of conductivity depending on the material, doping, and temperature. When carrier concentration is intrinsic (Equation 4) and mobility is controlled by lattice scattering (T-3/2) at high temperatures (over 400K or more), one especially intriguing scenario arises. In such circumstances, it is simple to demonstrate that conductivity varies with temperature as follows:

$$\sigma \propto \exp\left(\frac{-E_g'}{2kT}\right) \quad (5)$$

Conductivity is solely determined by the semiconductor bandgap and temperature in this situation. The semiconductor bandgap energy, Eg, may be determined using observed conductivity data in this temperature range.

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