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RESEARCH ARTICLE

# Doping Effects and Relationship between Energy Band Gaps, Impact of Ionization Coefficient and Light Absorption Coefficient in Semiconductors

Md. Bappi Pramanik[1,*], Md. Abdullah Al Rakib[2], Md. Abubakor Siddik[1], and Shorab Bhuiyan[1]

## ABSTRACT

**The doping process is very important in semiconductor technology that is widely used in the production of electronic devices. The effects of doping on the resistivity, mobility and energy band gap of semiconductors are significant and can greatly impact the performance of electronic devices. This thesis aims to investigate the impact of doping on the resistivity, mobility, energy band gap, impact of ionization coefficient, and light absorption coefficient of semiconductors. The study involves an in-depth analysis of the electronic properties of doped semiconductors and their behavior in various conditions. This thesis will provide a comprehensive understanding of the impact of doping on the electronic properties of semiconductors. The energy band gap, impact of ionization coefficient, and Light absorption coefficient were observed in this thesis. In the experimental result, the relation between energy band gap and atomic density, light absorption coefficient and atomic density, impact ionization and atomic density, impact ionization coefficient and Light absorption coefficient, resistivity and mobility has been found.**

**Keywords:** Impact ionization coefficient, light absorption coefficient, mobility, resistivity.

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[1] *City University, Bangladesh.*
[2] *American International University, Bangladesh.*

* ***Corresponding Author:***
e-mail: bppikhn@gmail.com

## 1. Introduction

The study of doping effects on resistivity and mobility in semiconductors is important because it helps us understand how to control the electronic properties of these materials. Doping is the addition of impurities to intrinsic semiconductors in order to change their characteristics. To dope silicon and germanium, typically trivalent and pentavalent elements are utilized. When a trivalent impurity is added to an intrinsic semiconductor, the result is a p-type semiconductor. When dopant concentrations surpass $2 \times 106$ cm, the standard study of electron mobility in n-type silicon is unable to accurately forecast the mobility values. A semiconducting material that is composed only of a single type of atom, such as a silicon atom, is known as a pure or intrinsic semiconductor. However, it is actually quite common to find semiconductors that contain certain impurities or atoms of more than one kind. Impurities are added into a semiconductor to actually increase the electric conductivity. The process of adding (increasing atomic number density) an impurity into the semiconductor to increase its ability to conduct electricity is known as doping, and the impure semiconductor is known as a doped semiconductor. There are two types of doped semiconductors: the n-type semiconductor and the p-type semiconductor.

A semiconductor is referred to as an n-type doped semiconductor when an impurity atom that has more valence electrons than the original semiconductor atom is added. However, this sort of semiconductor is known as a p-type doped semiconductor when we add an atom with fewer valence electrons [1]–[3]. The term "hole mobility" refers to the analogous quantity for holes in semiconductors. A semiconductor's conductivity may be calculated as the ratio of carrier concentration to carrier mobility. When all else is equal, greater mobility results in improved gadget performance [4]–[6].

## 2. Methodology

In this research, we used a web tool and Origin Pro software to find our simulation results and draw graphs.

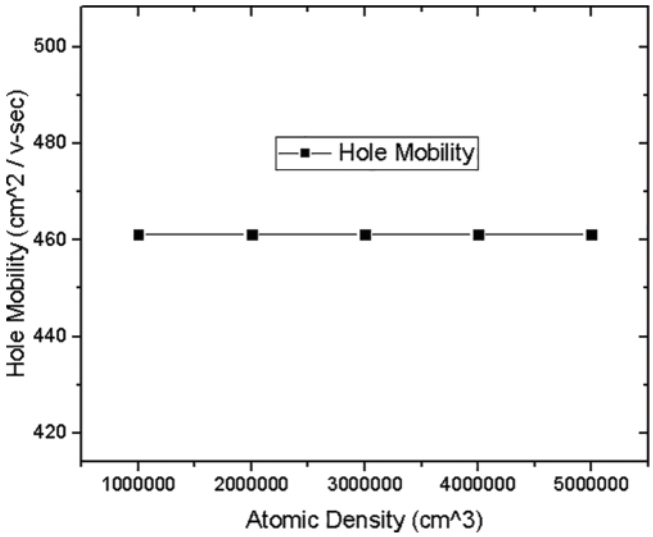


Fig. 1. Atomic density vs. hole mobility relation. Material: silicon, doping: P-type, temperature: 300 K.

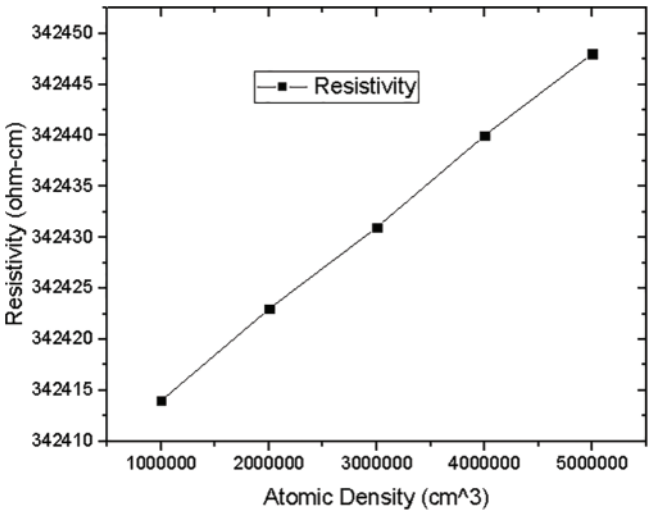


Fig. 2. Atomic density vs. resistivity relation, material: silicon doping: P-type temperature: 300 K.

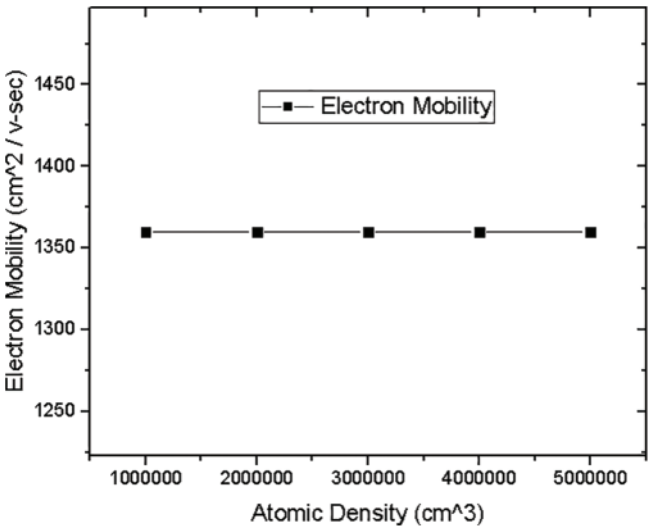


Fig. 3. Atomic density vs. electron mobility relation. Material: silicon, doping: N-Type, temperature: 300 K.

### 2.1. *Mobility and Resistivity*

The movement of electrons and holes through a lattice as a result of temperature and doping concentration in the presence of an electric field is known as carrier mobility. Temperature reduces effective mobility by causing more carrier-impairing lattice vibrations. Ionized dopants effectively scatter carriers.

Resistivity can be defined as a measure of a material's resistance to current flow. When a semiconductor material is doped n-type or p-type, scattering centers are added to the lattice. The scattering, as a result of doping, decreases the mobility of electrons and holes in the semiconductor. Doping also increases the number of electrons and holes conducting through the semiconductor lattice.

Hole mobility is the ability of a hole to move through a metal or semiconductor when there is an applied electric field. Electron mobility is the ability of an electron to move through a metal or semiconductor when there is an applied electric field. Charge carrier density, also known as carrier concentration, denotes the number of charge carriers in per volume. In SI units, it is measured in $m^{-3}$. As with any density, in principle, it can depend [7].

### 2.2. *Hole-Carrier Concentration and Electron-Carrier Concentration*

Hole-carrier concentration: The number of holes per unit volume in the valence band is called hole-carrier concentration. Electron-carrier concentration is the measure of how many electrons there are in the conduction band per unit volume.

### 2.3. *Relationship Between Atomic Density vs. Doping Property*

This equation has found from Fig. 1:

$$y = 460 \tag{1}$$

In Fig. 1, it has shown that if atomic density is increasing, then hole mobility will remain the same.

This equation has found from Fig. 2:

$$y = \frac{342410}{1000000}x \tag{2}$$

Fig. 2 shows that if atomic density increases, then resistivity will increase.

This equation has found from Fig. 3:

$$y = 1350 \tag{3}$$

In Fig. 3, it has shown that if atomic density increases, then electron mobility will remain the same.

This equation has found from Fig. 4:

$$1000000y = -342400x + 5000000 \tag{4}$$

In Fig. 4, it has shown that if atomic density is increasing, then resistivity will be decreased.

The following equation can be used to calculate the atomic number density (N: atoms/$cm^3$) of a pure material having an atomic or molecular weight (M: grams/mol) and the material density (grams/$cm^3$). This problem has been solved by (5):

$$N = \frac{\rho N_A}{M} \tag{5}$$

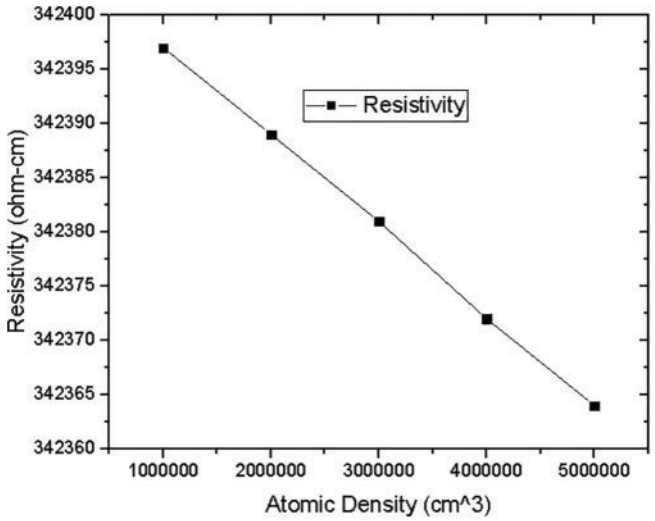


Fig. 4. Atomic density vs. resistivity relation, material: silicon, doping: N-type, temperature: 300 K.

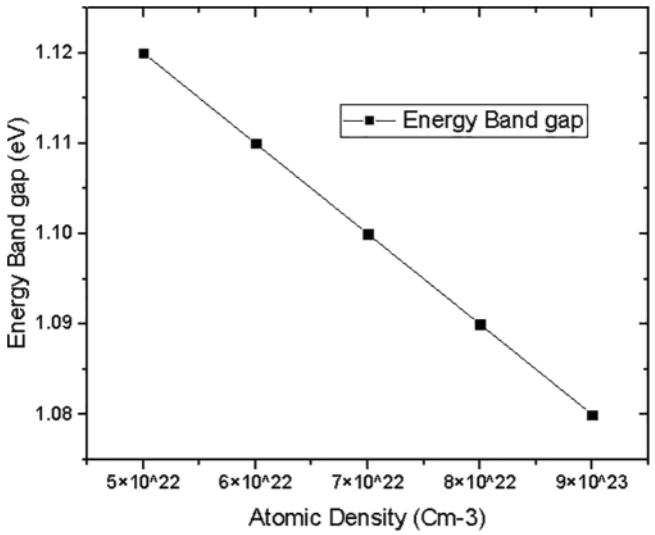


Fig. 5. Atomic density for (Si) increases band gap for (Si) also decreases.

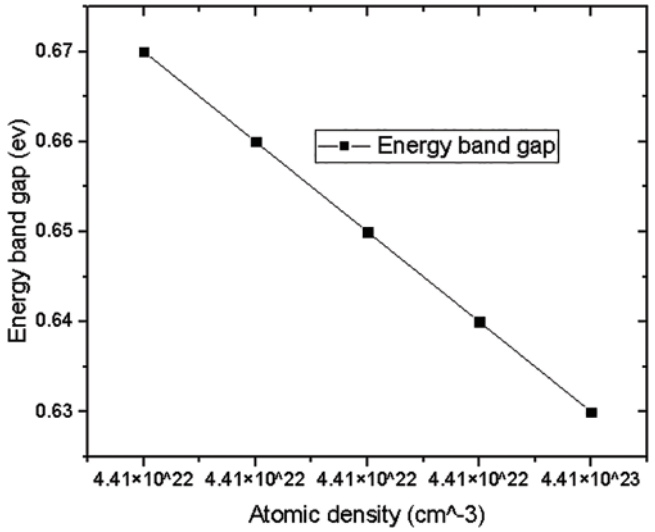


Fig. 6. Atomic density for (Ge) increases band gap for (Ge) also decreases.

where N = atomic number density, $\rho$ = *Density*, $N_A$ = 6.0221023 atoms or molecules per mole.

$$\rho = \frac{M}{V} \tag{6}$$

where, M = atomic molecular weight, V = Volume.

The equation of the energy band gap (E) is given below, which has helped us calculate the results [8]–[11]:

$$E = hv = \frac{hc}{\lambda_e} \tag{7}$$

where $h = 6.626 \times 10^{-34}$ Js, $c = 3 \times 10^3$, v is the frequency of the electromagnetic radiation and $\lambda$ is its wavelength. Energies in quantum physics are commonly expressed in electron volts (1 eV = $1.6 \times 10^{-19}$ J).

$$\lambda = \frac{hc}{E_e} \tag{8}$$

where, $\lambda$ = wavelength, E = energy band gap (E) [12], [13].

## 3. Result and Discussion

### *3.1. The Relation Between the Energy Band Gap and Atomic Density*

In general, a material's band gap decreases as its atomic density increases. This is due to the fact that materials with higher atomic densities often have stronger interatomic bonding, which causes a bigger overlap of electron orbitals and a smaller band gap.

Silicon (Si) Atomic number density and Silicon (Si) Energy Band gap: For Gallium Arsenide Atomic Number Density $5 \times 10^{22}$ $cm^{-3}$ and the Energy Band gap is 1.12 eV.

This equation has found from Fig. 5:

$$5 \times 10^{22}y = -1.12x + 5.12 \times 10^{22} \tag{9}$$

Germanium (Ge) Atomic number density and Germanium (Ge) Energy Band gap: For Germanium Atomic number Density is $4.41 \times 10^{22}$ $cm^{-3}$, and Energy Band gap is 0.67 eV.

The material's light absorption coefficient typically increases as the atomic density does as well. The greater likelihood of photons interacting with atoms in the substance is what causes this association. More atoms are accessible to absorb and interact with incident light when the atomic density is higher (10).

This equation has found from Fig. 6:

$$4.41 \times 10^{22}y = -0.67x + 2.9547 \times 10^{22} \tag{10}$$

Gallium Arsenide (GaAs) Atomic number density and Gallium Arsenide (GaAs) Energy Band gap: For Gallium Arsenide, the Atomic Number Density is 2.213 $\times 10^{22}$ $cm^{-3}$, and the Energy Band gap is 1.41 eV.

This equation has found from Fig. 7:

$$2.213 \times 10^{22}y = -1.41x + 3.12033 \times 10^{22} \tag{11}$$

### *3.2. Relation Between Atomic Density vs Light Absorption Coefficient*

The amount of light that is absorbed as opposed to transmitted or reflected is hence greater. It's crucial to

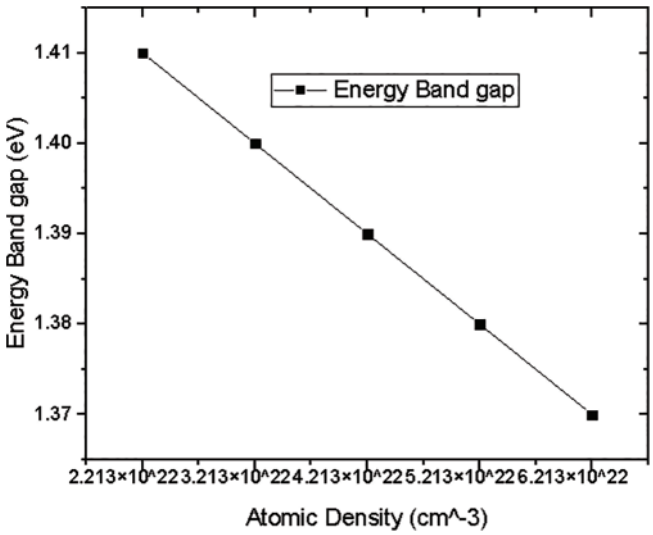


Fig. 7. Atomic density for (GaAs) increases band gap for (GaAs) also decreases.

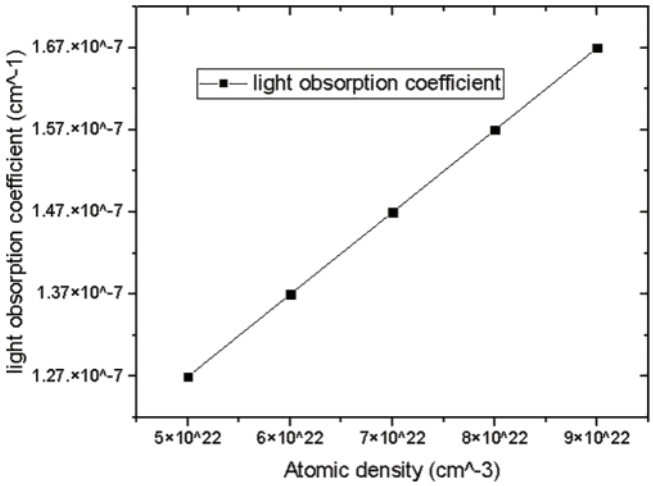


Fig. 8. Atomic density for (Si) increases light absorption coefficient for (Si) also increases.

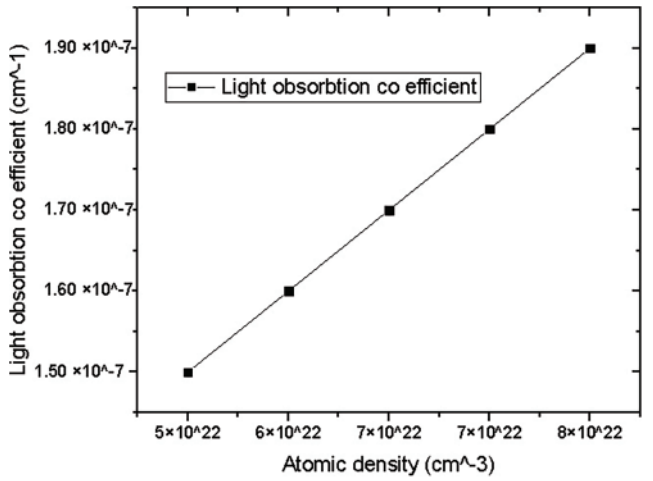


Fig. 9. Atomic density for (Ge) increases light absorption coefficient for (Ge) also increases.

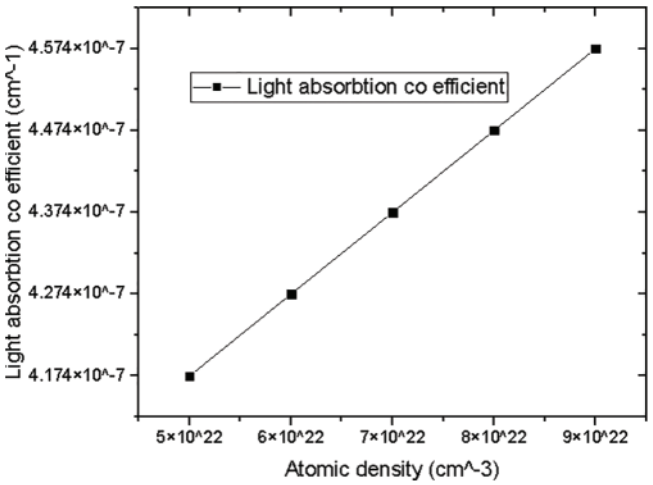


Fig. 10. Atomic density for (GaAs) increases, light absorption coefficient for (GaAs) also increases.

keep in mind that the precise correlation between atomic density and absorption coefficient can change based on the substance and the properties of the incident light, such as its wavelength or frequency [14].

Silicon (Si) Atomic number density and (Si) Light absorption coefficient: For silicon atomic number density is $5 \times 10^{22}$ $cm^{-3}$ and light absorption coefficient is $1.27 \times 10^{-7}$ $cm^{-1}$. This equation has found from Fig. 8:

$$Y = \frac{1.27 \times 10^{-7}}{5 \times 10^{22}} x \tag{12}$$

Germanium (Ge) Atomic number density and (Ge) Light absorption coefficient. For Germanium Atomic number Density is $5 \times 10^{22}$ $cm^{-3}$ and Light absorption coefficient is $1.50 \times 10^{-7}$ $cm^{-1}$

This equation has found from Fig. 9:

$$Y = \frac{1.50 \times 10^{-7}}{5 \times 10^{22}} x \tag{13}$$

Gallium Arsenide (GaAs) Atomic number density and (GaAs) Light absorption coefficient: For Gallium Arsenide Atomic number Density is $5 \times 10^{22}$ $cm^{-3,}$ and Light absorption coefficient is $4.174 \times 10^{-7}$ cm.

This equation has found from Fig. 10:

$$Y = \frac{4.174 \times 10^{-7}}{5 \times 10^{22}} x \tag{14}$$

### *3.3. The Relation between Impact Ionization Coefficient and Atomic Density*

As atomic density increases, so does the likelihood that an electron will collide with an atom or molecule and produce more electron-hole pairs. As a result, the impact ionization coefficient tends to rise as atomic density rises. In general, the impact ionization coefficient is denoted by the symbol and has inverse-distance units (such as $cm^{-1}$). It is a material-specific characteristic that is influenced by a number of variables, including the material's temperature, chemical content, and crystal structure. The impact ionization coefficient can be calculated theoretically or experimentally, and it is crucial for modelling and comprehending a wide range of phenomena in semiconductor physics and materials science, such as breakdown voltage, avalanche multiplication, and carrier generation and recombination.

### *3.4. The Relation between Impact Ionization Coefficient and Light Absorption Coefficient*

Two distinct parameters that describe various facets of semiconductor behavior associated with light absorption and carrier multiplication are the impact ionization coefficient and the light absorption coefficient. Although they are both significant in optoelectronic devices, they are not essentially connected. The amount of light that is absorbed by a semiconductor material per unit distance is measured by the light absorption coefficient ($\alpha$). It stands for the likelihood that photons will be absorbed and produce electron-hole pairs. The band gap of the material, energy levels, doping concentration, and incident photon energy are just a few of the variables that influence the absorption coefficient. Better light absorption and greater efficiency in converting light energy into electron-hole pairs are indicated by higher absorption coefficients. The rate at which electron-hole pairs are produced through impact ionization processes, on the other hand, is described by the impact ionization coefficient (i). When an energetic electron or hole gains sufficient energy to collide with another electron or hole, impact ionization takes place, producing more electron-hole pairs. The impact ionization coefficient can vary with carrier energy, temperature, and material properties and is typically determined experimentally. A greater chance of carrier multiplication through impact ionization is indicated by a higher impact ionization coefficient. The overall performance of optoelectronic devices is influenced by both the impact ionization coefficient and the light absorption coefficient despite the fact that they are not directly related. Better light harvesting is made possible by a higher absorption coefficient, which ensures that more photons are absorbed in the substance. As a result, there are more carriers available for impact ionization processes to take place. Therefore, a higher impact ionization rate may be indirectly caused by a higher absorption coefficient. The impact ionization coefficient describes the effectiveness of carrier multiplication through impact ionization, while the light absorption coefficient quantifies the light absorption capacity of a semiconductor. Despite the fact that they both matter for optoelectronic devices, they represent different facets of semiconductor behavior and are affected by various device and material parameters.

### *3.5. The Relation between Resistivity and Mobility*

While mobility increases, then resistivity will decrease. Conductivity is proportional to the product of mobility and carrier concentration. For example, the same conductivity could come from a small number of electrons with high mobility for each or a large number of electrons with small mobility for each. For semiconductors, the behavior of transistors and other devices can be very different depending on whether there are many electrons with low mobility or few electrons with high mobility. Therefore, mobility is a very important parameter for semiconductor materials. Almost always, higher mobility leads to better device performance, with other things equal.

## 4. Conclusion

One of the most important factors in determining the electrical properties of semiconductors is the effect of doping on resistivity and mobility. Doping is the deliberate addition of impurities to semiconductor crystal lattices in order to change their conductivity. The resistivity and mobility of the semiconductor material can be changed to meet the needs of a particular device by adding dopants selectively. One of the most important factors in determining the electrical properties of semiconductors is the effect of doping on resistivity, mobility resistivity, mobility, energy band gap, Light absorption coefficient and impact ionization coefficient. Doping is the deliberate addition of impurities to semiconductor crystal lattices in order to change their conductivity. The resistivity and mobility of the semiconductor material can be changed to meet the needs of a particular device by adding dopants selectively. Donors and acceptors are the two types of dopants most frequently used when an impurity is added to a semiconductor. Semiconductors are crucial for enhancing their efficiency in various optoelectronic devices, such as solar cells, photodetectors, and light-emitting diodes. Donors and acceptors are the two types of dopants most frequently used when an impurity is added to a semiconductor. While acceptors produce electron deficits or "holes" in the valence band, donors are atoms that add extra electrons to the semiconductor's conduction band. The amount of dopants in a material affects how electrically it behaves. Doping alters a semiconductor's charge carrier density and mobility, which has an impact on resistivity. The lower resistivity is caused by the increased number of charge carriers available for conduction at higher doping concentrations. On the other hand, because there are fewer charge carriers, higher resistivity results from lower doping concentrations. The amount of doping in a semiconductor affects the mobility of the charge carriers as well. In general, mobility rises with higher doping levels as more scattering events are possible due to the higher carrier density, which leads to better mobility. However, due to impurity scattering and other complicated effects, mobility can begin to decline at very high doping levels. Semiconductors are crucial for enhancing their efficiency in various optoelectronic devices, such as solar cells, photodetectors, and light-emitting diodes. Improving the impact ionization coefficient in semiconductors is important for enhancing their performance in devices such as avalanche photodiodes, avalanche transistors, and other high-gain and high-speed applications. Impact ionization refers to the process in which an energetic electron or hole collides with an atom, creating an electron-hole pair and contributing to the multiplication of charge carriers. The electrical conductivity and optical characteristics of a semiconductor are governed by the size of the band gap. Due to the comparatively high energy needed for electrons to shift to the conduction band, materials with greater band gaps are sometimes referred to be insulators. The term "semiconductors" refers to materials with narrower band gaps, which have improved electrical conductivity. The light absorption coefficient, which is a crucial metric in many scientific and technical areas, offers useful

information about how a material interacts with light. Its usefulness aids in the understanding and control of light-matter interactions and the construction of effective devices for a variety of applications. Ionization is important for the planning and improvement of semiconductor devices. To manage the electric fields reduce the effects of impact ionization, and provide the best possible device performance and reliability, engineers use a variety of strategies, including device shape, material selection, and doping profiles.

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## Conflict of Interest

Authors declare that they do not have any conflict of interest.

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