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Theoretical Analysis of Semiconductor Diodes: Working Principles and Characteristics

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Abstract

This paper presents a comprehensive theoretical analysis of semiconductor diodes, covering their working principles, operational characteristics, and key applications. The study begins with an exploration of semiconductor theory, focusing on energy bands, doping, and carrier transport mechanisms that govern diode behavior. It details the formation of the PN junction and examines diode operation under forward and reverse bias conditions, highlighting the influence of barrier potential and charge movement. The paper further explores small-signal and large-signal behaviors to understand diode response under different electrical stimuli. A comparative evaluation of various diode types—including Zener, Schottky, Light Emitting Diode (LED), photodiode, and tunnel diode—is presented, discussing their unique features and functional differences. Special attention is given to temperature effects on I-V characteristics and the deviations between ideal and practical diodes. The study concludes with an overview of semiconductor diode applications in communication circuits and addresses limitations and performance factors affecting their efficiency. The theoretical models and principles discussed serve as a valuable resource for engineers and researchers involved in the design and analysis of electronic systems.

Keywords: Semiconductor Diode, PN Junction, Forward Bias, Reverse Bias, Zener Diode, Schottky Diode, LED, Photodiode, Tunnel Diode, Small-Signal Behavior, Large-Signal Behavior.

Introduction

Semiconductor diodes play an important role in present-day electronics. The use of semiconductor diodes ranges from simple rectification to complex radio counselling. Radio circuits use different types of special-purpose diodes. Theoretical basics of different types of semiconductor diodes and their characteristics are discussed here. The behaviour of charge-neutral solids is governed by the properties and motion of electrons. To understand how electrons move in a solid, it is important to recognize that the structure of a solid is periodic in nature. This periodic structure causes the electrons of a free atom to come very close to each other in a solid. The electrons of one atom interact with the electrons of the other. The electrons with the same spin are kept apart by the Pauli's exclusion principle and the electrons with opposite spin repel each other. Numerous Coulombic interactions cause the discrete energy levels of the atom to split into many closely spaced levels in the solid. The many closely spaced levels form an allowed energy band in the crystal. These allowed energy bands are separated by forbidden energy bands where the electrons cannot exist. The ability of the atom to distort and respond to the charge of the electron in its vicinity and also its ability to allow the electrons to move slowly through it is called the dielectric constant and the effective mass, respectively.

The scope and importance of semiconductor diodes in electronic and telecommunication equipment are outlined. The aim of the study is forming a theoretical analysis on the types of semiconductor diodes and giving elaborations about the working principles of these diodes.

The main motivation behind the study is the widespread usage of semiconductor diodes in real-life applications. A theoretical model detailing the operation of the diode components in connection with the theoretical base is constructed and the accuracy of the modeling approach examined. The methods and principles developed in the study would be applicable for the engineers and researchers interested in a novel framework requiring accurate modeling of the diodes.

Semiconductor Theory

A comprehensive understanding of semiconductor devices and operation of electronic systems is of great importance to the contemporary electronics industry, underpinning technologies such as computers, digital circuits and communication systems. Semiconductor materials are used to create a number of different components, the most fundamental being the semiconductor diode. These devices consist of two terminals formed from a PN junction, serving a wide range of functions in commercial applications. The diode structure was first reported as the crystal detector by Braun in 1876 and became the basis for vacuum diodes two decades later. The study of diodes itself dates back further, with the theory being first proposed nearly seventy years earlier by Edmond Becquerel in 1839.

Semiconductor devices operate through control of current-voltages at the interface between different regions. The basic requirement to establish a field-dependent current at the interface between two dissimilar regions is that it must contain a potential barrier. Most devices utilise two regions of semiconductor with different electrical characteristics, called a junction (chapter 4 extit{Semiconductor Theory}). One region is doped with excessive negative mobile electrons, the other excessive positive mobile holes. These two regions are called n and p type respectively; the boundary between them is the pn junction, and the current-voltage characteristic of the device is essentially the current-voltage characteristic of the pn junction.

The boundaries within semiconductor devices are therefore regions of transition from one type of material to another. Transition can be between an insulator and a conductor, two different dopant concentrations, or different energy gap valued materials; in each case the electrical conditions are usually very different on the two sides of the boundary. Free carriers in a region migrate from the boundary to other regions if the region adjacent to the boundary has lower carrier concentrations than the originally considered region. There exists a potential gradient associated with regions of higher carrier concentration which prevent free carriers from diffusing away from the pn junction. The extent of migration of both electrons and holes constitutes the fundamental form of current transport in semiconductors, commonly known as diffusion current (Nicholls et al., 2019).

Energy Bands: The band structure of a solid governs the electrical properties of that solid. At absolute zero, the valence band of semiconductors is completely filled, while the conduction band is nearly empty. The conduction band consists of empty orbitals that can accept electrons, while the valence band consists of orbitals containing electrons that can be excited into the conduction band and then participate in conduction. The energy gap separates the valence band from the conduction band (R. Frensley, 2017). At absolute zero, no electrons exist in the conduction band of a semiconductor. At higher temperatures, some electrons are thermally excited across the gap, creating mobile conduction electrons in the conduction band. The excitation of conduction electrons leaves behind holes in the valence band. Conduction electrons and holes are the charge carriers in semiconductors with concentration n and p, mobility ì_n and ì_p, and charge ”vL,”^{4}q and q, respectively. To a good approximation, the charge carriers obey the ideal classical descriptions of particles with an energy-dependent effective mass, m_n*(E) or m_p*(E), so that an energy minimum in the conduction band acts like a positive potential well, while an energy maximum near the top of the valence band acts like a negative potential well (Mehrad, 1987).

The generation of conduction electrons and holes in intrinsic semiconductors is controlled by thermal excitation. The number of electrons in the conduction band is balanced on average by an equal number of holes in the valence band. The creation of conduction-band electrons and valence-band holes plays a central role in semiconductor devices. Ionization in gases or electrolytes produces only one type of carrier, but semiconductors differ in that semiconduction is possible with either positive (hole) or negative (electron) particles. Doping (the introduction of controlled impurities) leads to heavily doped materials in which the band gap is only weakly modified. When the doping level is very high, the gap may vanish or be strongly deformed (Todd Rollins, 1988).

Doping: Impurity doping is an important process that alters semiconductor properties. In the doping process, an "impurity" material with either five or three valence electrons is added to the semiconductor (Musa Lariski & Babaji, 2018). For example, phosphorous has five valence electrons, whereas aluminum has three. By adding phosophorous to the semiconductor, a majority of the charge carriers become electrons. This type of semiconductor is called an n-type semiconductor. Conversely, when aluminum is added, a majority of the charge carriers become holes, resulting in a p-type semiconductor. Thus, doping introduces the variation in charge carrier concentration that is required to construct a semiconductor diode (Oeba et al., 2023).

Carrier Transport: Carrier transport in semiconductors is typically described by two current equations. A common approach to incorporate electron–hole scattering involves modifying the carrier mobilities. However, this method can disrupt Einstein's relation and yield a carrier-density-dependent ambipolar diffusion coefficient, which conflicts with many experimental observations. An alternative strategy derives the current equations either from phenomenological plasma-like models or directly from the Boltzmann equation. Practical implementation necessitates knowledge of certain coefficients that are challenging to compute theoretically, making experimental determination preferable. One practical technique utilizes conductivity measurements on lightly doped semiconductors subjected to high excitation levels. Under these conditions, assuming that the experimentally measured conductivity coincides with the theoretical value allows estimation of electron–hole scattering effects (Velmre, 1989).

PN Junction Formation

A PN junction is formed by joining p-type and n-type semiconductor materials, characterized by an abrupt change in doping at the metallurgical interface (Khorasani, 2016). Initially, holes diffuse from the p-type region with higher hole concentration into the n-type region with lower hole concentration near the boundary, while electrons similarly diffuse from the n-type region into the p-type region. This diffusion results in the creation of charged ions on either side, establishing a depletion region that introduces a drift electric field opposing further diffusion. Under steady-state conditions, diffusion currents are balanced by drift currents, maintaining charge neutrality and the isolation of the p-type and n-type regions.

The formation of the PN junction relies on the combined principles of semiconductor theory and carrier transport. Drawing from semiconductor theory, an n-type semiconductor possesses an electron concentration substantially exceeding the intrinsic carrier density (n k" n_i), whereas a p-type semiconductor maintains a hole concentration greatly surpassing n_i (p k" n_i). These doping profiles drive the initial carrier diffusion described in carrier transport, wherein diffusion currents from regions of higher carrier concentration to lower carrier concentration precede the establishment of a depletion field. Therefore, the PN junction arises through a dynamic interplay of these fundamental semiconductor theories.

6. Working Principles

An ideal diode is modelled by the following mathematical operation on the voltage across the diode terminals, v,: vI=5>,0<v;"",vd"0 The constitutive I–V relation of a practical diode is modelled by the Shockley equation (Mehrad, 1987) : Id=I0(expVT)"1 where Id is the current, I0 the reverse saturation current, and VT the thermal voltage. Beyond the definition of an ideal diode, the behavior of the diode depends on temperature and frequency. The variation of the current and voltage signals from low level modulation to high level signals is the large-signal behaviour of the diode.

(i) When used in forward bias, the PN junction operates in the first quadrant of the current-voltage plane. The current in this quadrant increases exponentially with anodic voltage, provided the magnitude of the voltage is approximately equal to the junction potential. Applying an external voltage with polarity indicated on the figure reduces the barrier causing the potential difference between the P-side and N-side quasi-Fermi-energy levels to increase. In regions where the semiconductor is quasi-neutral, both majority and minority carriers (holes and electrons) will be present. The concentration of positively charged holes in the P-type region increases towards the junction, causing a corresponding decrease in majority carrier concentration, while the concentration of negatively charged electrons in the N-type region behaves in an analogous way (Parekh, 1964).

(ii) Reverse biasing a PN junction involves connecting the P-type region to the negative terminal of a voltage source and the N-type region to the positive terminal. This arrangement does not place the diode at a zero potential difference like forward biasing does; instead, the applied voltage opposes the built-in barrier potential across the junction, influencing the width and height of the potential barrier () (Parekh, 1964). The depletion region widens, and the formation of the potential barrier () inhibits the diffusion of free current carriers across the barrier. At room temperature, the only other current carriers are minority carriers. The electric field produced by the charge in the depletion region sweeps minority carriers (electrons in P-type material and holes in N-type material) across the junction, resulting in a small carrier movement. Reverse biasing blocks current flow except for this tiny carrier drift, yielding a very low current known as leakage or reverse saturation current ( ) through the junction. Diodes are designed so that this leakage current is small even with relatively large reverse voltages (Nicholls et al., 2019).

(iii) When a PN junction forms, the initially sharp transition involving electrons and holes begins diffusion due to concentration gradients (Nicholls et al., 2019). Electrons flow from the N-side to the vacant holes in the P-side, while holes flow from the P-type region to the free electron N-type region. As a result, the free electrons in the N-region and holes in the P-region are depleted near the junction, leaving charged ions exposed. The ions become negatively charged on the N-side and positively charged on the P-side since they still have the impurities' extra electrons or holes but cannot move. These charges create an electric field from the P to the N-region, opposing further diffusion of electrons and holes. This electric field creates a voltage across the depletion region known as the barrier potential or contact potential. The barrier potential is expressed by the general formula

(6.6) V barrier = (kT/q) ln(NaND/ni2),

where k is Boltzmann's constant, T is the absolute temperature, q is the electron's charge, and ni is the intrinsic concentration. In silicon at 300 K, the barrier potential becomes 0.7 V, while in germanium at the same temperature it is 0.3 V. The barrier potential decreases with the applied forward voltage; when the forward value equals the barrier potential, electrons flow unfettered across the PN junction. The physical understanding in terms of the energy band theory is that the Fermi level is different in P and N material, being the highest occupied energy level at 0 K. When P and N semiconductors come together to form the PN junction, the different Fermi level become equal. This means that the forbidden gap cannot be constant across the junction, resulting in the band bending shown in Figure 6.8. The bending of the conduction and valence band explains the creation of the electric field within the depletion region. This field is a result of the electron band either increasing or decreasing across the junction which either repels or attracts electrons and holes respectively.

(iv) The conducting current through a p-n junction represents the net charge transferred across the transition region per unit time. Various mechanisms contribute to the transport of this charge, leading to a detailed expression for the current (D. Middlebrook, 1959). Consider a boundary located within the charge-neutral n-region, at a distance sufficiently large so that minority diffusion currents are negligible; the current at that boundary can be determined by evaluating the current density at the semiconductor surface. Similarly, an analogous boundary can be established within the p-type side of the structure, enabling a comprehensive analysis of charge transport from either side.

7. I-V Characteristics

With the increase of temperature, the forward current decreases at a constant voltage level; the reverse current, on the other hand, rises significantly. Increasing temperature results in a substantial increase in the number of charge carriers. When reverse-biased, although current increases strongly with temperature, the results permit electron multiplication and tunnelling processes to be discounted as a basis for a temperature test diode. At low bias and temperature, the GaAs diode acts effectively as a P-N structure, with a very low, essentially constant, generation current. At elevated temperatures and voltages, the diode approaches N-junction behaviour and generation currents increase substantially (Parekh, 1964).

In 1949, Shockley proposed the modern P-N junction theory based on the solution of the transport equation in the one-dimensional diffusion approximation with low injected minority-carrier density and uniform doping on both sides of the junction. Significant departures from Shockley's ideal I-V characteristics are observed in silicon at room temperature. Several current transport mechanisms have been proposed that modify the ideal law one or more n factors, including recombination and generation within the depletion region, tunnelling or field emission in highly doped semiconductors, and high-injection effects at large forward biases. Others result from fabrication imperfections such as series and shunting resistances, and edge leakage currents. These imperfections can be minimized by using good contact metals, carefully controlling the metallurgical properties of the semiconductor surface, and employing a well-designed device structure. Deviations from simple diffusion lead to poor rectification, low open-circuit voltages, parasitic resistive losses, and reduced device efficiency. The ideal I-V curve shows a diode n factor of 1; space charge recombination gives an n factor of 2. Elevated n factors at small forward or small reverse voltages can be caused by shunting resistance; high series and sheet resistances give elevated n factors at large forward voltages. Knowledge of the dark I-V characteristics is thus essential in the evaluation of a given solar-cell structure; the efficiency and power output that can be expected from a cell under illumination can be roughly assessed from its dark I-V curve (R. Hauser & C. Y. Fang, 1977).

Temperature Effects

The temperature dependence of semiconductor diodes is an important practical consideration. When the temperature of a diode changes, various parameters, including the diffusion coefficient of intrinsic carriers, the intrinsic-carrier concentration, and the built-in potential of the PN junction, are affected (Parekh, 1964). These, in turn, influence the diode's forward current and voltage. The ideal-diode equation indicates that as temperature increases, and an experiment shows that at a fixed forward current the forward voltage decreases (Fei et al., 2018). For example, a measurement taken at 1 mA reveals this effect clearly.

Theoretical Models of Diodes

Semiconductor diodes, pivotal for electronic and telecommunication circuits, embody foundational nonlinear circuit elements that govern the amplitude or strength of electric signals. The basic theoretical framework discusses energy bands and the doping of impurities in semiconductors, elucidating vacancies that form current carriers. Semiconductor theory clarifies the conduction and valence band energies of an atom as molecular orbital energies of a crystal lattice, while doping—substituting host atoms with impurities—produces n-type and p-type materials, a process that converts semiconductors into nonlinear circuit elements capable of generating, amplifying, modifying, and even memorizing electronic signals. The formation of PN junctions emerges naturally from the transport properties of these materials, providing the basic framework for device operation. The working principle centers on the establishment of the PN junction by impurity doping, where a barrier potential arises due to opposing diffusion and electric field forces governing majority-carrier transport. Applied voltage either enhances or diminishes the diffusion force, allowing for charge provision or withdrawal from the depletion region, which determines the tunneling possibility of charges.

The I-V characteristics begin by noting the ideal values for voltage coefficients, constants, and ideality factors, as well as the governing equations, yet practical devices exhibit deviations. Temperature exerts a significant influence on many portions of the characteristic curve. The study then details the operation and characteristics of several special types of diodes: the Zener diode, where the current is the difference of two semiconductor diode currents; the Schottky diode, characterized by current resulting from both thermionic emission and tunneling; the LED, where recombination of injected electrons and holes generates photons; the photodiode, acting as a BPW34 silicon PIN diode; and the tunnel diode, distinguished by a negative resistance region in the forward-voltage region, enabling oscillations at high frequencies (Nicholls et al., 2019) (Maccagnani & Pieruccini, 2024).

Small-Signal Behavior

The small-signal model of a PN junction diode may be obtained by linearizing the current-voltage characteristics about some operating point (D. Middlebrook, 1959). When the incremental voltage is sufficiently small to give a linear relationship between the incremental current and voltage, the junction is said to be under small-signal bias conditions (K. Katib, 1976). At the voltage V0, the current through the diode is I0. If a signal voltage v and the corresponding current i are applied, then the junction current is the linear sum of dc and ac components, or iref = I0 + i (1) and the pn-junction potential is vref = V0 + v. (2) Linearizing the diode characteristics about the dc operating point (V0,I0) gives the smallsignal equivalent circuit of figure 10-1; r, is the diode dynamic or ac resistance and is given by the expression r = ("Id/"Vd)"1 = V T/Id (3) where Id is the diode current at the operating point and VT is the diffusion voltage (KT/q). The numerical value of r, can be considered as practically constant over the normal operating range of a small-signal, low-level waveform.

Large-Signal Behavior

The transition-region capacitance of a metal-to-semiconductor junction can be modeled by an expression derived by considering the dependence of the transition-region thickness on applied voltage. A current-voltage relation that neglects minority carriers predicts an abrupt transition region with zero thickness and zero transition-region capacitance. In actual diodes, this abrupt model is not attained because of diffusion tails or deep traps (D. Middlebrook, 1959). Further, the properties of a metal-to-n-type semiconductor junction correspond to the Schottky barrier only when the metal's work function exceeds that of the semiconductor; in the reverse condition, the contact forms an ohmic or accumulation junction limited only by the semiconductor resistance. Comparable considerations apply to metal-to-p-type semiconductor contacts, which are rectifying if the metal's work function is smaller than that of the semiconductor, and ohmic if the reverse case holds. When a junction operates within its linear range, the voltage can be expressed in terms of the current as a power series, or ultimately as the power series inverse of the exponential current-voltage relation.

Reference operates in the linear regime, the internal diode voltage can be expressed as a current power series derived from the inversion of the exponential current-voltage characteristic. In principle, for sufficiently small signals any nonlinear device can be represented by a power series equivalent-circuit current; therefore, the issue reduces to whether only a few terms are needed or whether additional terms degrade results—an aspect that can be evaluated through harmonic generation analysis.

Introducing a small-signal ac voltage superimposed on a dc bias to an arbitrary nonlinear device generally results in an output current containing harmonics of the fundamental frequency, as well as dc and potential intermodulation components. The amplitude of the current at each harmonic can be expressed in terms of the device parameters and the applied signal amplitude. Any measured deviations from these theoretical amplitudes can yield insight into additional device phenomena. Since only a fundamental-frequency ac voltage source is applied, all generated harmonics originate within the device, enabling their measurement to provide a sensitive probe for small nonlinear behavior (K. Katib, 1976).

Applications in Communication Circuits

Semiconductor diodes are fundamental components in electronic communication circuits, widely used as rectifiers, bolts, clippers, voltage regulators, and frequency converters at microwave frequencies (K. Katib, 1976). Their electrical properties and large-signal behaviour, highly dependent on device geometry and semiconductor materials, influence their performance in these applications, particularly at higher frequencies where the nonlinear response becomes critical. Designing and optimizing transmitter and receiver circuits, frequency multiplication, detection, and detection devices require a thorough understanding of the large-signal response of semiconductor diodes.

Limitations and Performance Factors

It is important to be aware of some restrictions and performance factors associated with semiconductor diodes. The most obvious is the inherently nonlinear characteristic of the diode. Besides resulting in harmonic terms, the fundamental frequency itself is frequency-modulated and this phenomenon is of considerable interest in signal transmission. The nonlinear term mio should not be small relative to m ù (i.e. m ù/m io should not be very small); otherwise, the side frequencies produced become insignificant. Generally, the large-signal analysis is valid only for moderate signal levels i.e. because m ù becomes comparable to m io as the signal level increases (Parekh, 1964).A further restriction on maximum signal level relates to the time lag T. If the time delay is very large, D.C. voltages and currents are unable to keep up with changing signal and a more refined diode theory becomes necessary. If some chemical impurities like oxygen, water etc. are present on the contact surface, then the diode turn-on effect and turn-off effect (carrier injection/withdrawal) occurs at a much lower voltage than the barrier potential, which is not predicted by a simplified theory. Such reduced barrier may arise from tunneling through a thin barrier and the barrier potential quoted in previous sections represents the Ohmic contact instead of the rectifying barrier (Mehrad, 1987). Furthermore, the operation of the device is limited by the reverse power and average power. These and other limitations can be modified and can be overcome easily without disturbing the internal working of the diode and hence the theory of operation remains valid.

Conclusion

Semiconductor diodes are unidirectional devices widely used in several fields. Numerous diodes are fabricated by doping semiconductors to form the junctions. The working principles of these devices, their operation, equations, and the behavior of different diode types are studied in detail in this paper. Semiconductor theory is used to understand the properties of semiconductors and the transport phenomena inside semiconductor diodes. The fabrication of the PN junction and the barrier potential formulation are also explored. The diode operation is examined based on the potential barrier, from which a theoretical relationship between the voltage and current is proposed. The IV characteristics of the ideal diode are analyzed for both forward and reverse bias operation. Temperature influence on the IV characteristics is also discussed. Zener, Schottky, LED, Photodiode, and Tunnel diodes are covered by their theoretical operation and distinct features. Theoretical models that describe various diodes under different conditions are formulated. Small-signal and large-signal behaviors are studied to investigate diode responses to different signal levels. Finally, the application of semiconductor diodes in electronic communication circuits is reviewed, considering the previously discussed behavior and characteristics.

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