SEMICONDUCTOR NANOSCALE DEVICES: MATERIALS AND DESIGN CHALLENGES

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Semiconductor Nanoscale Devices: Materials and Design Challenges

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FOREWORD

"Semiconductor Nanoscale Devices: Materials and Design Challenges" provides a timely and comprehensive examination of the advancements in this rapidly evolving field. This book addresses the intricate balance between theoretical understanding and application, offering valuable insights into the material properties and design principles that define the behavior of nanoscale devices. The pursuit of smaller, more efficient transistors has led to the exploration of novel materials and innovative design structures. Nano-FET devices, with their potential to operate at low power and high frequencies, exemplify the kind of breakthroughs that are possible. However, the transition from conventional technologies to nanotechnologies brings with it a host of challenges that must be understood and overcome.

The editors and authors have meticulously compiled a body of work that not only charts the current landscape of semiconductor nanoscale devices, but also points towards future directions and possibilities. Their collective expertise and dedication to advancing knowledge in this domain are evident throughout the chapters. "Semiconductor Nanoscale Devices: Materials and Design Challenges" is more than just a textbook; it is a guide to the future of semiconductor technology. As we stand on the brink of new technological horizons, this book will undoubtedly serve as a critical reference for those striving to push the boundaries of what is possible in VLSI design.

This book is an essential resource for engineers, researchers, and students who are navigating the complexities of nanoscale device technology. It bridges the gap between foundational concepts and advanced research, making it accessible to those new to the field, while also providing depth for experienced practitioners. The detailed exploration of quantum effects, scaling issues, and material properties offers a robust framework for understanding and innovating in nanoscale device design.

I am confident that readers will find this book an invaluable addition to their professional libraries, providing both the inspiration and the knowledge necessary to drive forward the next generation of semiconductor devices.

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PREFACE

The relentless miniaturization in semiconductor technology has paved the way for nanoscale devices to become pivotal components in modern electronic systems. These advancements have brought about unprecedented opportunities and challenges, especially in materials selection and device design. "Semiconductor Nanoscale Devices: Materials and Design Challenges" aims to provide a comprehensive exploration of these cutting-edge technologies, offering insights into both the theoretical foundations and practical implementations.

As the VLSI industry continues to evolve, the reduction in transistor size has been instrumental in integrating more functionality onto silicon wafers and minimizing power consumption. This progress has led to the realization of nano-FET devices using various innovative materials and structures, demonstrating significant potential for low-power and high-frequency applications. The continuous pursuit of enhancing performance while addressing the complexities of nanoscale phenomena underscores the importance of a comprehensive guide to these advancements.

"Semiconductor Nanoscale Devices: Materials and Design Challenges" serves as a concise benchmark for beginners and experienced practitioners alike. It is tailored for those who are just getting started with nanoscale device technology and for those looking to design integrated circuits using novel FET devices. This book aims to be a valuable resource, inspiring new discoveries, innovations, and advancements at the forefront of electronic engineering. We hope that this book will serve as a guide and inspiration for researchers, engineers, and students, unlocking the potential of nanoscale semiconductor devices and contributing to the continuous evolution of electronic technology.

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DEDICATION

I dedicate this book to my beloved mother, Veena Saxena, my father, R. R. Saxena, my wife, Deepti Saxena, and my daughter, Arshika Saxena. Their unwavering love and support have been the cornerstone of my success. I am deeply grateful for everything they have done and continue to do for me. This book is a testament to their belief in me and a symbol of my heartfelt appreciation.

— Dr. Ashish Raman

I dedicate this book to my loving mother Shakuntala Singh, father Dinesh Singh, and brother Prasoon Singh, as a token of my appreciation for everything they have done and continue to do for me. Their love and support are the foundation of my success, and I am blessed to have them as a part of my life. Their love and belief in me mean everything. This book is dedicated to them as a symbol of my gratitude for all they have done.

— Dr. Prabhat Singh

This book is dedicated to my beloved wife, Nisha Chaudhary, and our wonderful son, Zishaan Kumar, whose love and encouragement have been my greatest motivation. Special thanks to my parents, Smt. Indu Devi, and Shri. Rajpal Singh, for their unwavering support and sacrifices, and to my brother, Nitish Kumar, for always being there for me. I am deeply grateful to my mentors, Dr. Ashish Raman and Prof. Vihar Georgiev, for their invaluable guidance and wisdom. I also extend my heartfelt appreciation to my supervisors, colleagues, and friends, whose support and encouragement have been instrumental in the completion of this work.

— Dr. Naveen Kumar

I want to begin by thanking my entire family for their unwavering support and encouragement throughout this journey. My mother Kusum Kumari and father Raj Nandan, their constant faith in me gave me the courage. Their wisdom and guidance have been invaluable, and I am forever grateful. I dedicate this book to my spouse, Chandni Kumari, son Reyansh Raj, and daughter Reeva Raj as their patience and understanding have been my bedrock. I thank them for believing in me and giving me the time.

— Dr. Ravi Ranjan

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CHAPTER 1

Nanoscale Technologies: Design Challenges and Advancements

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Abstract: This chapter delves into nanoscale technologies within semiconductor devices, covering design principles, challenges, and recent advancements. It examines the fundamental aspects of nanoscale device design, addressing key challenges and highlighting the latest developments in the field. The chapter navigates integration and interconnect challenges, design optimization techniques, and diverse applications across various fields. Nanoscale technologies, fundamental to semiconductor innovation, offer a spectrum of opportunities and hurdles. By addressing design intricacies and technological barriers, researchers aim to unlock the full potential of nanoscale devices. Additionally, the chapter discusses optimization strategies to enhance device performance and functionality. It sheds light on the intricate interplay between nanoscale technologies and their applications in electronics, photonics, and biotechnology. By comprehensively examining design methodologies and real-world applications, this chapter provides valuable insights into the evolving landscape of nanoscale technologies within the semiconductor domain. Focusing on recent advancements, the chapter explores how these technologies are integrated into current semiconductor devices and the challenges associated with their implementation. It also highlights the importance of continuous research and development to overcome existing technological barriers. The discussion extends to various design optimization techniques aimed at improving device efficiency, reliability, and overall performance. Overall, this chapter serves as a comprehensive guide to understanding the complexities and innovations of nanoscale technologies in semiconductor devices, offering readers an in-depth look at the design principles, challenges, and advancements shaping the future of this critical field.

Keywords: Applications, Advancements, Challenges, Design principles, Design optimization, Integration, Interconnect, Nanoscale technologies.

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INTRODUCTION

In the realm of modern engineering, nanoscale technologies have emerged as a transformative force, ushering in a new era of innovation and exploration. These technologies operate at the molecular and atomic levels, offering unparalleled opportunities to manipulate matter with unprecedented precision [1 - 4].

The chapter at hand embarks on a comprehensive journey through the landscape of nanoscale technologies, aiming to provide a thorough understanding of their design principles, challenges, and recent advancements [5].

At the core of nanoscale technologies lies a profound understanding of the fundamental principles governing matter at the nanoscale. Designing devices at such minute scales requires a deep appreciation of quantum mechanics, material properties, and advanced fabrication techniques. Quantum effects, such as tunneling and confinement, become increasingly pronounced at the nanoscale, necessitating a departure from classical design methodologies. Moreover, the choice of materials and fabrication processes plays a pivotal role in determining the performance and functionality of nanoscale devices [6 - 9].

Despite their immense potential, nanoscale technologies are not without their challenges. Manufacturing constraints, reliability issues, and thermal management pose significant hurdles in the development and deployment of nanoscale devices. The intricacies of nanoscale phenomena demand innovative solutions and interdisciplinary collaboration to overcome these challenges effectively. Furthermore, the scaling laws that govern traditional engineering principles often break down at the nanoscale, necessitating novel approaches to device design and optimization [10].

Recent years have witnessed remarkable advancements in nanoscale device design, driven by breakthroughs in materials science, fabrication techniques, and device architectures. These advancements have unlocked new possibilities for nanoscale devices, enabling improvements in performance, efficiency, and functionality. From novel materials with tailored properties to innovative device architectures with enhanced performance characteristics, the field of nanoscale technologies is evolving at an unprecedented pace [11 - 14].

Integration and interconnect challenges pose additional complexities in the realization of nanoscale devices. As devices shrink to ever-smaller dimensions, the compatibility, scalability, and reliability of integration processes become increasingly critical [15]. Interconnect challenges, including signal propagation delay and cross-talk, further compound the integration process, requiring sophisticated solutions to ensure seamless operation of nanoscale systems [16].

In the quest for optimal device performance, design optimization techniques play a crucial role. Simulation tools, machine learning algorithms, and design automation techniques enable engineers to explore vast design spaces and identify optimal solutions efficiently [17]. These techniques empower designers to achieve optimal device performance while minimizing development time and cost, accelerating the pace of innovation in nanoscale technologies [18].

Beyond the realm of fundamental research and development, nanoscale technologies have found applications across diverse fields, including electronics, photonics, biotechnology, and energy. From ultra-efficient electronics and high-performance sensors to advanced drug delivery systems and renewable energy technologies, the potential applications of nanoscale technologies are vast and varied [19 - 22]. By harnessing the unique properties of nanomaterials and devices, researchers and engineers are pushing the boundaries of what is possible in fields ranging from healthcare to environmental sustainability [23].

Fig. (**1**) shows the nanoscale MOSFET (Metal-oxide-semiconductor Field-effect Transistor), a key semiconductor device for signal amplification and switching at nanometer scales. Its design involves miniaturization to enhance performance, but faces challenges, like quantum effects, leakage currents, and manufacturing precision, requiring innovative solutions for efficient operation and reliability.

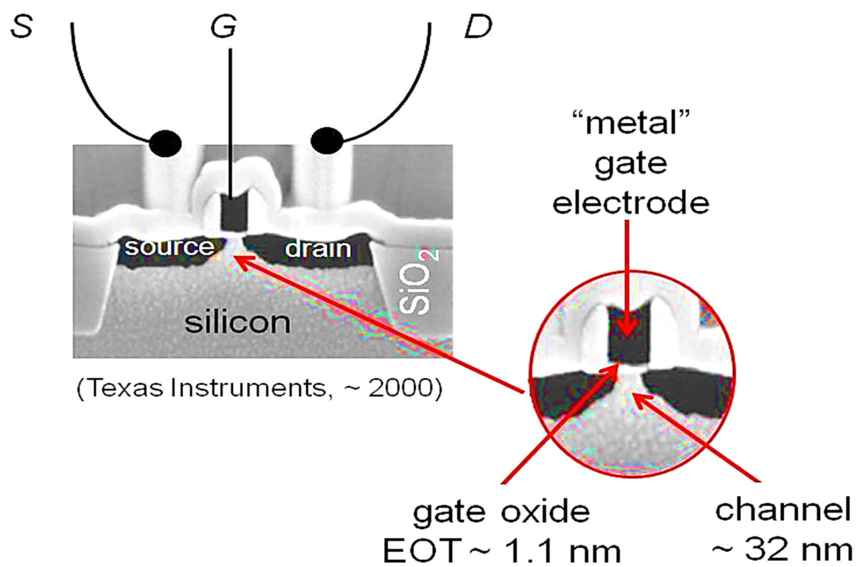

Fig. (1). Nanoscale MOSFET.

In conclusion, nanoscale technologies represent a paradigm shift in modern engineering, offering unprecedented opportunities for innovation and

CHAPTER 2

Materials Used in the Design of Semiconductor Devices

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Abstract: The design and advancement of semiconductor devices are fundamentally rooted in the diverse range of materials utilized, each selected for its unique properties and contributions to device performance. This chapter explores the necessity and history of semiconductor materials, tracing their evolution and wide-ranging applications. Central to this discussion are the elemental semiconductors derived from the periodic table, focusing on silicon, germanium, and gray tin, which have historically underpinned the semiconductor industry. Also, this chapter differentiates between intrinsic and extrinsic semiconductors, highlighting their respective roles and characteristics in device functionality. Intrinsic semiconductors, with their pure form, contrast with extrinsic semiconductors, which are doped to enhance specific electrical properties, catering to various application needs. Furthermore, the study delves into compound semiconductor materials, showcasing their importance in modern technology. Compounds, like silicon carbide, boron nitrate, red selenium, boron phosphide, and boron arsenide, are examined for their exceptional electrical and thermal properties. The chapter also discusses aluminum-based compounds, including aluminum nitride, phosphide, and arsenide, and their applications in high-power and high-frequency devices. The study extends to gallium-based compounds, like gallium nitride, phosphide, and arsenide, known for their high electron mobility and applications in optoelectronics. Additionally, zinc and cadmium compounds, such as zinc oxide, cadmium arsenide, zinc phosphide, and zinc antimonide, are analyzed to enhance device performance and efficiency. This comprehensive study underscores the critical role of diverse semiconductor materials in the ongoing innovation and optimization of electronic, optoelectronic, and power devices, meeting the escalating demands of modern technology.

Keywords: Compound semiconductors, Extrinsic, Intrinsic, Materials, Semiconductor devices.

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INTRODUCTION

Semiconductors are widely used in various applications, such as power semiconductor devices, integrated circuits, amplifiers, power control, telecommunications, optoelectronics, medical devices, *etc* [1–3]. Thus, they are in demand in most applications; hence, they require more research and development. The primary focus of research on semiconductor devices is on the material used in them. So this chapter provides fundamental aspects of semiconductor materials and how semiconductor materials are classified from the periodic table; moreover, to achieve better performance, there is a need for compound or hybrid semiconductor devices. Thus, this chapter provides a clear understanding of all the above aspects.

FUNDAMENTALS OF SEMICONDUCTOR MATERIALS

Based on contemporary technology, semiconductor materials power everything from solar cells to computers and cell phones.

Necessity of Semiconductor Materials

For several reasons, semiconductor materials are essential to contemporary technology [4].

i. Electronic components, including Integrated Circuits (ICs), diodes, and transistors, are built on semiconductors. Almost all electronic systems, including those found in computers, cellphones, televisions, and automobile electronics, depend on these gadgets.
ii. Semiconductors facilitate the digital revolution because they provide the foundation for binary logic processes. Binary digits (bits) of information are processed using digital circuits made of transistors, which can also function as switches. Computers and digital communication systems operate on this foundation.
iii. Electrical power can be managed and transformed through power transistors, thyristors, and other semiconductor devices. This technology finds application in power supplies, motor drives, renewable energy systems, electric vehicles, and other electronic devices.
iv. Semiconductors make communication systems' signal processing, reception, and transmission possible. Semiconductors are crucial in Digital Signal Processing (DSP) processors and Radio Frequency (RF) amplifiers, essential components of wireless devices, internet, and telecommunication networks.
v. Medical diagnostics, imaging technologies (such as MRIs and CT scans), and biotechnology applications all involve semiconductor-based sensors and

imaging equipment. They make improvements in illness identification, monitoring, and treatment possible.

vi. Materials for semiconductors are necessary for many applications involving the environment and energy. These comprise photovoltaic cells for solar energy conversion, semiconductor-based catalysts for pollution control, and sensors for environmental monitoring.

Semiconductor materials are essential to modern society's operation because they fuel an extensive array of technologies that affect almost every facet of human existence, from communication and entertainment to healthcare and environmental sustainability.

History of Semiconductor Materials

The history of semiconductor materials is a fascinating journey spanning decades of scientific discovery and technological growth. Here is a provided a quick rundown:

The late 19th and early 20th century saw the beginning of our understanding of semiconductors and the development of various semiconductor switches, as shown in Fig. (**1**). Michael Faraday noted in 1833 that a tiny covering of Ag2S had the "extraordinary effect" of lowering silver's electrical resistance. Karl Ferdinand Braun laid the foundation for semiconductor diodes in 1874 when he discovered the rectifying characteristic of metal-semiconductor junctions.

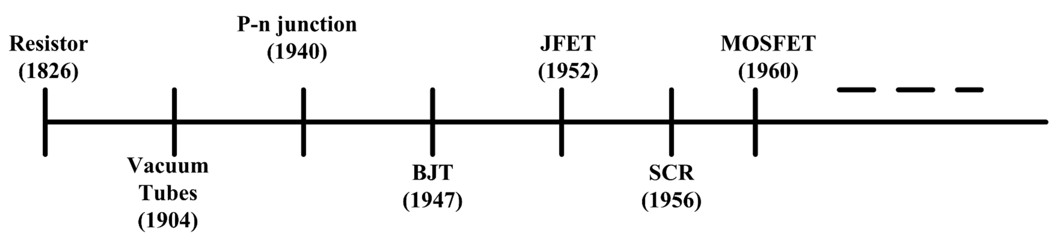

Fig. (1). History of semiconductor switches.

In the early 20th century, scientists, like Lee De Forest, Jagadish Chandra Bose, and Ferdinand Braun, advanced the understanding of semiconductor materials and developed primary semiconductor devices, like the crystal detector for radio receivers.

Due to germanium's (Ge) availability and semiconductor qualities, researchers concentrated on studying semiconductor materials in the 1940s. John Bardeen, Walter Brattain, and William Shockley of Bell Laboratories created the first

CHAPTER 3

A Comprehensive Overview of the Foundations of Semiconductor Materials

Agnibha Dasgupta[1,*], **Soumya Sen**[2], **Prabhat Singh**[3] and **Ashish Raman**[3]

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Abstract: In the recent era, the semiconductor industry, which plays a pivotal role in powering today's cutting-edge technologies, relies heavily on a broad spectrum of materials, entailing of silicon and rare earth elements. These materials serve as the backbone for crucial components, such as solar cells, transistors, IoT sensors, and the intricate circuits found in self-driving cars. Consequently, there is a notable surge in demand for these devices, marking a paradigm shift in the technological landscape.

The first section of this comprehensive exploration delves deeply into semiconductor materials. Understanding their profound impact on electronic devices and the intricacies of the manufacturing process is fundamental for anyone seeking a comprehensive grasp of this dynamic industry. Moving forward, the second part focuses on the properties and physics governing semiconductor materials. The electronic conductivity of these materials is of paramount importance, and the chapter unravels the challenges involved in the efficient and cost-effective large-scale manufacturing of new materials with these crucial properties.

Segment three navigates through the vast realm of semiconductor applications, shedding light on their pivotal role in various electronic devices and cutting-edge technologies. It accentuates the unique electrical properties that make semiconductors indispensable in industrial settings.

In the fourth section, attention is paid to the present market scenario, where the semiconductor market stands out for its stability across diverse industrial sectors. The chapter meticulously examines the production expenses associated with different materials, ranging from the widely used silicon to the more exotic rare earth metals.

Essentially, this chapter guides readers through the complex trends in the semiconductor industry, offering a concise overview of material development and

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influential factors. It also encourages the exploration of innovative solutions to propel the Very Large Scale Integration (VLSI) industry toward unprecedented advancements.

Keywords: Electrical conductivity, IoT sensors, RREs, Semiconductor materials.

INTRODUCTION

Semiconductor devices stand as the cornerstone of modern electronic systems, propelling the technology that shapes our daily lives. The efficacy and performance of these devices are intricately tied to the design elements incorporated into their construction. The pursuit of smaller, faster, and more energy-efficient semiconductor devices has fuelled continuous advancements in the realm of science dedicated to these intricate structures. This introduction provides an overarching view of the key components instrumental in shaping semiconductor devices, shedding light on their roles, properties, and the pivotal influence they wield over device functionality.

The foundation of electronic components lies in semiconductor materials, facilitating the controlled flow of electric current. Silicon, renowned for its remarkable properties, has historically served as the primary component for semiconductor devices. Its crystalline structure, stability, and capacity to form a robust oxide layer make it an ideal choice for manufacturing integrated circuits. Nevertheless, as technology progresses, novel alternatives emerge to address the limitations inherent in conventional options [1 - 4].

Types of Semiconductor Materials

Beyond silicon, compound semiconductors, such as gallium arsenide (GaAs), gallium nitride (GaN), and indium phosphide (InP), have ascended to prominence. These compounds manifest distinctive electrical and thermal attributes that render them suitable for specialized deployments, including high-frequency devices, power amplifiers, and optoelectronics.

In addition to the aforementioned, the significance of dielectric materials, essential for insulating and isolating different components of a device, cannot be overstated. Insulating materials, like silicon dioxide (SiO_2) and various high-k dielectrics, play a critical role in ameliorating power consumption and enhancing the overall performance of semiconductor devices.

Furthermore, the interconnect elements utilized in the fabrication of integrated circuits play a pivotal role in determining the speed and efficiency of signal transmission. Copper and, more recently, low-k dielectric materials have become integral in surmounting the challenges associated with the increasing complexity and miniaturization of semiconductor devices.

Considering the demand involving quicker, petite, and economical electronic devices, researchers and engineers are exploring creative design elements and manufacturing methods. They are striving to discover fresh solutions, such as 2D materials, like graphene and transition metal dichalcogenides, in order to achieve the goal of advancing semiconductor technology. This endeavour aims to unlock fresh opportunities for the future evolution of electronic devices.

In the expansive field of semiconductor materials, III-V compounds occupy a distinctive and pivotal position, offering a unique array of properties that significantly contribute to the relentless advancement of electronic devices. The nomenclature "III-V" denotes elements derived from groups III and V of the periodic table, notably including gallium (Ga), indium (In), aluminum (Al) from group III, and nitrogen (N), phosphorus (P), arsenic (As), and antimony (Sb) from group V. This class of semiconductors has become a focal point of research and application due to its exceptional electrical, optical, and thermal characteristics.

Among the standout constituents of III-V semiconductors is gallium arsenide (GaAs), renowned for its direct bandgap feature, high electron mobility, and impeccable thermal stability. The direct bandgap represents a distinctive class of semiconductor materials that exhibit a specific electronic property crucial for various optoelectronic applications. This term refers to the alignment of the conduction band minimum and valence band maximum occurring at the unvarying momentum in the electronic band structure. Fig. (**1**) shows the energy *versus* momentum curve for the direct and indirect bandgap materials. This unique characteristic makes direct bandgap semiconductors highly efficient in radiative recombination processes, enabling the direct conversion of electrical energy into light or *vice versa*. GaAs is extensively employed in a myriad of electronic and optoelectronic applications, finding its niche in high-frequency devices, like microwave transistors and high-speed field-effect transistors, courtesy of its superior electron transport properties.

Indium phosphide (InP) is another luminary in the realm of III-V semiconductors, boasting a direct bandgap that renders it particularly apt for optoelectronic devices. Its applications span a wide spectrum, encompassing high-speed electronic and optoelectronic devices, such as high-frequency transistors, lasers, and photodetectors. The distinctive bandgap characteristics of InP make it especially valuable in the realms of telecommunications and high-speed data transmission [2 - 9, 15 - 18].

Gallium nitride (GaN) has emerged prominently in recent years, lauded for its wide gap, high breakdown voltage, and stellar thermal conductivity. This trifecta of properties positions it as a preferred choice for applications involving

CHAPTER 4

Innovative Materials Shaping the Future: A Deep Dive into the Design of Semiconductor Devices

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Abstract: The pursuit of advanced semiconductor materials drives innovations across various technological domains. This chapter explores cutting-edge materials essential for semiconductor device development. Key applications include solar cells, capacitors, supercapacitors, thermoelectric devices, sensors, and reactions, such as the Hydrogen Evolution Reaction (HER) and Oxygen Evolution Reaction (OER), also known as water splitting. For solar cells, the chapter highlights materials engineered to boost efficiency and durability, reflecting the evolving landscape of photovoltaic technologies. Capacitors and supercapacitors are analyzed for their energy storage capabilities, with a focus on novel materials promising improved performance and longevity. Thermoelectric materials are examined for their ability to convert waste heat into electrical energy. Sensor technologies are explored, emphasizing materials designed to enhance sensitivity, selectivity, and response times. The chapter also delves into electrocatalysis, specifically addressing semiconductor materials used in water splitting. As the demand for sustainable energy grows, understanding the role of semiconductor materials in these catalytic reactions becomes crucial. This comprehensive exploration provides researchers, engineers, and scientists with a deep understanding of the diverse semiconductor materials shaping the future of electronic and energy applications. Through a multidimensional perspective, it underscores the pivotal role of innovative materials in advancing semiconductor nanoscale devices toward new levels of performance and functionality.

Keywords: Electrocatalysis, Nanomaterials, Solar cells, Supercapacitors, Thermoelectric materials.

INTRODUCTION

The field of semiconductor devices has been a cornerstone of technological progress, driving innovation across a myriad of applications, ranging from electronics to renewable energy. As the demand for smaller, faster, and more

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energy-efficient devices continues to surge, researchers and engineers are increasingly turning their attention to the critical role that materials play in shaping the future of semiconductor devices. "Innovative Materials Shaping the Future: A Deep Dive into the Design of Semiconductor Devices" represents a significant contribution to this evolving landscape. The chapter emerges against the backdrop of the ever-expanding exploration of advanced semiconductor materials, which has become a focal point of contemporary research. The relentless pursuit of materials with enhanced properties has the potential to revolutionize the design and performance of semiconductor devices, paving the way for unprecedented technological advancements. The chapter aims to provide a comprehensive overview of the cutting-edge materials that are poised to redefine the landscape of semiconductor technology. By focusing on pivotal applications, such as solar cells, capacitors, supercapacitors, thermoelectric devices, sensors, and water-splitting materials, the chapter addresses the diverse facets of semiconductor materials' impact on various technological domains [1-6].

The intricate design challenges and opportunities associated with each application are explored, offering a deep dive into the complexities that researchers and engineers face in harnessing the full potential of innovative materials. From enhancing the efficiency and durability of solar cells to unlocking energy storage capabilities in capacitors and supercapacitors, the chapter navigates through the multifaceted world of semiconductor materials [7-9]. Moreover, the exploration extends to thermoelectric materials, shedding light on the unique properties that make certain semiconductors ideal for converting waste heat into valuable electrical energy [10, 11]. The examination of sensors emphasizes the role of semiconductor materials in amplifying sensitivity, selectivity, and response times, essential for a myriad of applications.

The chapter delves into the fascinating realm of electrocatalysis, addressing semiconductor materials employed in water splitting [12-14]. This becomes particularly pertinent as the global demand for sustainable energy sources intensifies, highlighting the importance of understanding semiconductor materials in catalysing these reactions. Lastly, the exploration extends to the role of semiconductor materials in electrochemical sensing, showcasing their significance in developing sensitive and reliable devices for real-time detection and monitoring.

The significance of advanced semiconductor materials in contemporary research and technology cannot be overstated. As the backbone of electronic devices and an essential component in various technological applications, semiconductors play a pivotal role in shaping the landscape of modern innovation. The relentless pursuit of advanced semiconductor materials stems from the ever-growing demand for more efficient, powerful, and compact electronic devices [15-18]. These materials are crucial in enhancing the performance of devices, such as transistors, integrated circuits, and sensors. The advent of nanotechnology has further underscored the importance of innovative semiconductor materials, as researchers explore nanoscale structures to unlock new functionalities and properties [19-21]. Additionally, in the context of renewable energy, semiconductor materials are key players in the development of solar cells, photodetectors, and energy storage devices. Their unique electronic properties make them indispensable in converting and manipulating electrical signals. The ongoing quest for materials with superior conductivity, stability, and other tailored properties is driving research forward, offering the promise of more sophisticated and sustainable technologies that will shape the future of electronics and energy systems [22 - 24]. Ultimately, the significance of advanced semiconductor materials lies in their transformative potential to revolutionize the design and performance of a wide array of devices, contributing to advancements that permeate every aspect of our interconnected, technology-driven world.

SOLAR CELLS: ENHANCING EFFICIENCY AND DURABILITY

OVERVIEW OF SOLAR CELL TECHNOLOGIES

Solar cell technologies represent a critical frontier in the pursuit of sustainable energy sources. As the global demand for clean and renewable energy intensifies, solar cells play a pivotal role in harnessing the power of the sun and converting it into electricity. At present, there are six types of Solar Cells (SC) that use different semiconductor materials for enhancing the efficiency of solar cell applications, including crystalline silicon SC, thin-film SC, organic SC, perovskite SC, multi-junction SC, and tandem SC.

Among the most established solar cell technologies, crystalline silicon solar cells dominate the market. These cells are characterized by their high efficiency and reliability. Monocrystalline and polycrystalline silicon variants are the primary categories, with monocrystalline offering higher efficiency due to its uniform crystal structure. These cells are widely deployed in both residential and commercial solar installations [25]. While generally less efficient than crystalline silicon cells, thin-film technologies excel in specific applications where flexibility and lower production costs are paramount [26]. Organic solar cells, also known as Organic Photovoltaics (OPVs), leverage organic compounds as the active material. These cells offer the advantage of being lightweight, flexible, and potentially cost-effective. However, their efficiency is currently lower than traditional solar cell technologies, and research efforts focus on improving their performance to make them more competitive in the market [27]. Perovskite solar cells have garnered significant attention for their rapid advancements in

CHAPTER 5

Measurement Techniques for Determining the Thermal Conductivity of Bulk Samples and Thin Films

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Abstract: Thermal conductivity is one class of basic transport properties of materials that characterizes the flow of heat through it. Over recent years, the transformation of smart materials of atomically thin layers to small-size bulk samples has further made it difficult to determine the thermal conductivity more accurately due to the second law of thermodynamics, which prevents full control over heat flux during measurement. Heat flux and small temperature gradients are the two most important parameters that need to be considered while measuring the thermal properties of small dimensional samples. The difficulty in thermal measurements is associated with the thermal anchoring and controlling the heat loss that takes place due to conduction, convection, and radiation processes. In addition, controlled temperature difference coupled with high-speed data acquisition allows to study the thermal properties in a more extensive way. In this chapter, some of the reliable and effective techniques are mentioned that can help us to measure thermal conductivity with the lowest possible error. The importance of maintaining a high vacuum, choosing a proper heat source, and selecting heat sinks with desirable electrical outlets is also discussed here. Moreover, depending on the nature and dimension of the samples, different measuring techniques need to be used to extract the thermal conductivity of samples accurately. In general, understanding these properties is significant for predicting the performance of electronic materials in real-world applications, such as heat exchangers, evaporators, thermocouples, refrigerators, gas turbine engine applications, automotive parts, and biomedical parts. Further, these properties can be helpful in analyzing carbon nanotubes, selecting suitable ceramic coatings, assessing polymers, *etc*.

Keywords: Bulk sample, Heat flux, Heat sink, Radiation, Thin film, Temperature gradient.

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INTRODUCTION

Thermal conductivity is an important parameter in the preparation of devices using solid-state materials where temperature and thermal flux are of primary concern. However, the characterization of the thermal conductivity of bulk or thin film samples always remains an uphill task as the second law of thermodynamics denies full control over heat flux during measurement. For instance, the interaction of the sample with its surroundings leads to continuous heat exchange, which facilitates unavoidable power loss owing to erroneous thermal measurements. To date, various measuring techniques have been adopted to determine the thermal conductivity of various dimensional systems. This chapter provides an overview of thermal measuring techniques and the possible errors corresponding to each type of measurement. The discussion can help the researchers to combat unwanted errors while performing these experiments.

Depending on the nature, geometry, and size limitations of samples, the measurement technique for thermal conductivity could be sample-specific. For characterizing the thermal properties of bulk materials, measurement techniques, like the steady state method (absolute and comparative technique), transient dynamic technique, and laser flash analysis, are widely accepted [1 - 4]. Each of these techniques has its own merits and limitations depending on the sample specimen. However, the same thermal measurement techniques may not be supported by thin films whose thickness ranges from a few nanometers to hundreds of micrometers grown on different substrates. A new approach corresponding to thin films, like 3ω and the transient thermoreflectance technique, has proven to be more flexible, formidable, and reliable [5, 6].

Thermal conductivity is a property of the materials to carry heat along the temperature gradient. The measurement of the thermal properties of solid-state materials has been carried out since 1950. Over the period, new materials have emerged with dimensions ranging from bulk to a single atomic layer [7 - 13]. This development has also urged scientific engineers to redesign and modify transport measuring techniques, which is crucial and tricky at the same time. These days, commercial instruments are extensively used to measure the thermal conductivity of samples [14 - 16]. However, to modify the measurements, students and researchers should have a clear picture of how these experimental techniques are carried out. How to control heat loss through conduction, convection, and radiation processes; what effort a sample preparation needs, and how to measure temperature gradient are some of the questions that need to be addressed in this context. Moreover, controlled temperature difference coupled with high-speed data acquisition allows to study the thermal properties in a more extensive way. Hopefully, this short review of measurement techniques will benefit both the readers and the scientific community in understanding the fundamentals of science and possible sources of error in thermal conductivity measurements.

STEADY-STATE METHOD FOR BULK SAMPLES

Absolute Technique

Thermal characterization of materials can pose various types of problems depending on which measurement technique one is using. According to the fundamental concept of heat flow, thermal conductivity κ can be extracted if a temperature gradient ΔT across a sample is measured when a certain amount of heating power is applied. In mathematical terms, it is represented as:

$$\kappa = \dot{Q}\, l/(A\Delta T) \quad \textbf{(1)}$$

Where, $\dot{Q}$ is the thermal power flowing across the sample, l is the length in between the thermocouples, and A is the cross-sectional area of a sample. Now at a fixed base temperature, it is clear from the above equation that κ becomes a slope if a graph is plotted between $\dot{Q}$ and ΔT.

The absolute technique is usually good for samples that are rectangular, flat, or cylindrical in shape of thickness 1-2 mm [2, 3]. In this technique, the sample whose thermal conductivity needs to be determined is kept in between the heat source and a heat sink, as depicted in Fig. (**1**).

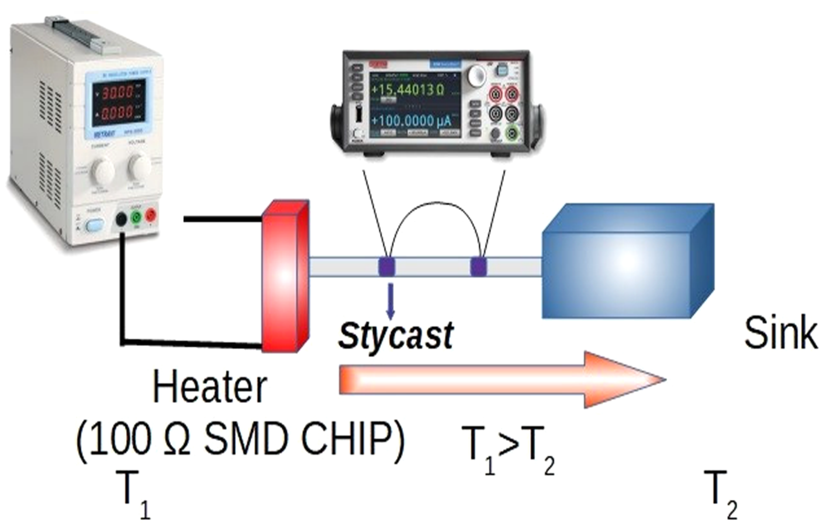

Fig. (1). An experimental setup where the temperature gradient is established across the sample kept in between heater and sink maintained at temperature T_1 and T_2, respectively.

CHAPTER 6

Structural Analysis of Feedback Field Effect Transistor and its Applications

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Abstract: This book chapter provides a comprehensive overview of the Feedback Field-effect Transistor (FBFET), detailing its structure, working principle, and diverse applications. The chapter explores the unique characteristics of FBFETs, including using positive feedback phenomena to enhance current flow, leading to a high on/off current ratio and exceptional subthreshold swing. Subthreshold Swing (SS) is an important parameter in evaluating the performance of a Field-effect Transistor (FET), such as a Feedback Field-Effect Transistor (FBFET). It indicates how efficiently the transistor can switch between the off state and the on state. Essentially, SS measures the sharpness of the transition from the off current (leakage current) to the on current (drive current) in an FET. Additionally, the chapter discusses the different types of device architectures and the operational theory of the device, highlighting its potential as a memory device due to hysteresis effects. This chapter provides a valuable resource for grasping the innovative design and versatile applications of FBFET technology. The optimal steep switching property of the alternative switching technology, *i.e.*, the Feedback Field-effect Transistor (FBFET), has drawn attention. Utilizing the positive feedback phenomena, there is a significant increase in the overall quantity of holes and electrons contributing to drain current. FBFETs have a high on/off ratio of current (~10 10) and a great subthreshold swing (~00 millivolt/decade at 300 Kelvin) due to the positive feedback phenomena. Until the operation starts, the power utilization of the turn-off and on states is very small.

Keywords: Feedback field-effect transistor, Positive feedback, Steep-switching, Subthreshold swing.

INTRODUCTION

Over the span of the preceding six decades, Metal Oxide Semiconductor Field-effect Transistors (MOSFETs) have gone through size reduction to achieve enhanced performance, high density, and cost-effectiveness [1, 2]. While scaling

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has brought numerous advantages, it has also introduced challenges as devices have become smaller. Issues, such as increased operational temperature and power consumption, have emerged significantly [2]. Additionally, the current leakage has risen to the limit that it may exceed dynamic power utilization. Many approaches have been suggested to mitigate power usage and leakage current. Still, progress has been hindered by the MOSFET's theoretical subthreshold swing limit, which stands at around 060 mV/decade at 300 Kelvin [2]. To tackle this, numerous novel devices for steep-switching have been developed to enhance the transistor's subthreshold swing. Some novel devices can be classified as follows: the Negative Capacitance FET (NCFET) utilizes the negative effect of the capacitance of a ferroelectric layer to achieve a steep slope [3 - 7]. In contrast, the phase FET incorporates extra components to exploit the effects of phase transition substances, enabling flexible resistivity switching [8]. The Nano-electro mechanical (NEM) relay operates by mechanically disconnecting and connecting channels [9]. The impact Ionization MOS (IMOS) relies on impact ionization from a high electric field [10 - 12], while the Tunnel FET (TFET) works on the principle of Band-to-band Tunneling (BTBT) [13 - 15].

Positive feedback Field Effect Transistors (FETs) have garnered particular interest. Feedback FETs (FBFETs) exhibit high on-/off current ratios (~10^{10}) and great subthreshold swing (~00 mV/decade 300 kelvin) [16, 17]. Due to these factors, a large number of researchers have shown interest in Field-band FETs (FBFETs) and proposed a variety of FBFET types [18-20], including Z^2-FETs, which means that subthreshold slope is zero and impact ionization is null [21 - 27], and Z^3-FETs zero gate, where subthreshold slope is zero and null impact ionization takes place [28 - 30]. The operating mechanism, types of structures, and transfer properties of FBFETs are all summed up in this chapter.

The enhanced characteristics of FBFETs over standard FETs can be applied to neuromorphic devices in particular or in a circuit of inverters. One of these characteristics concerns a distinct saturation area that changes with gate voltage (Vg). Power provided to a device in both on and off states can be meager, especially at threshold voltage (Vth), and power utilization is small both at the time of ongoing operating state and also in case of off-state.

FBFETs have shown promise as memory devices, particularly in the context of Dynamic Random-access Memory (DRAM) without capacitors. While the concept of 1T-DRAM was introduced around twenty years ago [31], it has largely remained within the realm of academic research. Challenges, such as low reliability, high consumption of power, and suitability issues with standard technologies of processes, like A2RAM [32 - 38] and meta-stable DRAM [32 - 34], have hindered its commercial viability. In contrast, the long-established 1-

transistor 1-capacitor DRAM has managed to address development challenges more effectively. Despite efforts, the 1T-DRAM has not yet proven itself as a feasible replacement for conventional DRAM due to the difficulty in using the scaled capacitor in the bit-cell to match the access transistor [39, 40]. Numerous research efforts have explored the substitution of conventional DRAM with a new type that incorporates FBFETs, showing significant promise [41 - 45]. Recent research has explored the use of FBFETs in DRAM design, leveraging the positive feedback mechanism to create hysteresis through the assemblage in the potential well of charge carriers. This unique approach could potentially lead to the development of a new and promising 1T-DRAM architecture that overcomes current challenges faced by traditional DRAM technologies [46-50].

Creating a new SRAM that is static random access memory using unit cells of the FBFET has been suggested. High-speed memory operation is made possible for the SRAM unit cells by a unique capability brought about by the positive feedback operation. Moreover, a straightforward device topology employing FBFETs addresses the large cell region, which has been identified as a constraint of the traditional SRAM. The FBFET-based SRAM unit cell ensures both efficient switching characteristics and low power consumption due to its small switching current [49 - 51]. This design allows for high-density memory performance with a compact area of $8F^2$. Additionally, the SRAM unit cell, utilizing positive feedback, demonstrates impressive operational performance in terms of retention duration, write speed, and read speed [52 - 62]. These findings show how promising FBFET is for applications using next-generation DRAM/SRAM memory.

Principle of Positive Feedback

Feedback involves sending back a portion or the entire output to the input. In positive feedback, initially, input rises after a single operation, and this enhanced input state continues into the next cycle. This leads to a sustained positive amplification of regenerative cycles. Similar to thyristors, FBFETs have two potential barriers positioned near the channel adjoining the drain and source, as expressed in Fig. (**1**), obstructing the stream of electrons and holes. Conversely, representing the carriers' lowest energy state, a potential wall is simultaneously created along with the potential barrier. Positive feedback occurs as the potential barrier decreases with the supply of a gate voltage. This reduction in the potential barrier enables charge carriers to move to the drain from the source. Electrons or holes may become caught in the potential wall within the region of the channel [63 - 65], impacting the energy band due to the charges generated by carriers confined within the potential wall.

CHAPTER 7

GaN-Based High Electron Mobility Transistor

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Abstract: A next-generation of highly efficient power devices is under development, utilizing wide bandgap semiconductors, such as GaN and SiC. These materials are gaining traction as attractive alternatives to silicon due to their superior properties. GaN, in particular, has garnered significant interest due to its excellent characteristics, such as a high electric field, saturation velocity, electron mobility, and thermal stability. GaN-based High Electron Mobility Transistors (HEMTs) exhibit superior performance, enabling operation at higher currents, voltages, temperatures, and frequencies. As a result, they are well-suited for the next wave of high-efficiency power converters, including applications in electric vehicles, phone chargers, renewable energy systems, and data centers. This chapter aims to provide an overview of the technological and scientific aspects of current GaN HEMT technology, including normally-on and normally-off. It starts by summarizing recent semiconductor market advancements and key application areas. A comparison between GaN and other materials is then presented, followed by a principle of HEMT and calculations of bound charge. The chapter also delves into normally-off GaN HEMT technology, focusing on aspects, like the recessed gate technique, p-GaN gate, and fluorine implantation. Additionally, reliability concerns associated with GaN HEMTs, such as low positive threshold voltage, 2DEG degradation, leakage current, and different degradation types, are examined. Finally, the study touches upon the use of different normally-off techniques in combination form to improve device parameters, such as threshold voltage and 2DEG concentration.

Keywords: AlGaN, Bandgap, Barrier layer, Channel layer, E-mode, GaN, HEMT, Normally-off, Normally-on, Piezoelectric, Polarization.

INTRODUCTION

The foundation of contemporary electronics is semiconductor materials, which allow for altering complex gadgets that drive our technological society. Among these materials, silicon and III-V semiconductors are notable for their unique qualities and wide range of uses. The industry workhorse for a long time has been

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silicon, a fundamental component of semiconductor technology. With time, silicon-based power devices have reached their maximum theoretical limits; design engineers face increasing current, voltage, and power ratings. This has led to the shift of the semiconductor industry towards comprehensive bandgap materials. Wide bandgap materials serve an essential function in the design and performance of HEMTs, offering distinct merits over traditional semiconductor materials, like silicon. Due to their unique properties, gallium nitride and silicon carbide are two prominent wide bandgap materials extensively used. One key advantage of wide bandgap materials is their ability to withstand higher electric fields, leading to higher breakdown voltages compared to silicon. This property enables HEMTs based on GaN to operate at elevated voltages, making them suitable for high-power applications.

Moreover, wide bandgap materials exhibit superior electron mobility, which is essential for high-frequency operation and fast switching speeds in HEMTs. The creation of a 2DEG at the junction boundary within these materials not only boosts electron transport efficiency, but also enhances overall device performance.

Wide bandgap materials also offer exceptional thermal stability, which is critical in maintaining the reliability and performance of devices in high-temperature conditions. This quality makes GaN HEMTs highly attractive for applications where effective heat dissipation is crucial, such as in electrical power control for electric vehicles and renewable energy systems. The properties of different semiconductors are shown in Table **1** [1]. GaN is more exceptional than the other III-V materials for developing heterostructures due to the large energy gap and in-built polarization field. Due to its suitable properties, it is extensively used as an essential component in radar, 5-G communication, and satellite communication [2 - 5].

Table 1. Properties of different semiconductor materials.

Properties	Silicon	Silicon Carbide	Indium Phosphide	Gallium Nitride
Bandgap (eV)	1.12	3.26	1.35	3.4
Carrier mobility (cm^2/V-s)	1500	900	4000	1500
Thermal conductivity (W/m.K)	150	400	80	200
Crystal structure	Diamond cubic	Hexagonal	Zincblende	Wurtzide

High-electron-mobility transistor is a semiconductor device used in high-intensity frequency and power applications. It is particularly known for its capability to operate at RF frequencies [6, 7]. Traditional HEMT is usually normally-on due to the generation of 2-DEG, which acts as the channel at the AlGaN/GaN boundary. GaN materials have piezoelectric properties, and piezoelectric polarization is the principle behind the formation of 2DEG in HEMT. The normally-off HEMT is preferred over the normally-on one because the normally-off HEMT is the ideal device for applications involving fast switching and significant power requirements [8].

WORKING PRINCIPLE

The basic structure of HEMT is created when a layer of higher bandgap (barrier layer) material is grown on a layer of lower bandgap (channel layer). Both the layers have different bandgaps and piezoelectric fields. We know that gallium nitride possesses piezoelectric properties. When two semiconductor layers of distinct lattice constants are brought into contact, the layers stretch or strain, forming a piezoelectric polarization field. A bound charge is generated at the heterointerface of GaN and AlGaN; if the bound charge at the interface is positive, negatively charged electrons tend to neutralize for the positive charge, leading to the generation of 2DEG below the channel layer. Fig. (**1**) depicts the bound charge generated at the AlGaN/GaN junction [1]. The electrons in 2DEG have enhanced mobility, so we use the term high electron mobility transistor. The 2DEG serves as the channel of HEMT, and the gate controls the electron movement amid the source and drain.

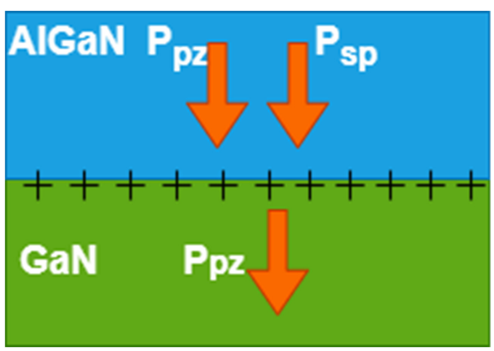

Fig. (1). Bound charge at the interface.

Bound Charge Calculation at the Interface

The bound charge formed at the junction of AlGaN/GaN is primary for the formation of an electron layer in HEMT. The barrier layer and channel layer of GaN HEMT are grown in the [0001] direction. The AlGaN layer on the gallium nitride layer stretches itself to match the properties of the gallium nitride layer. Due to this, a positive bound charge is formed [1]. The following equation can be used to calculate the bound charge:

CHAPTER 8

Advanced Semiconductor Sensing Technologies: Materials and Design Challenges at the Nanoscale

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Abstract: This chapter delves into the intricate realm of semiconductor devices for sensing applications, offering a comprehensive and detailed exploration. It begins with a foundational examination of semiconductor sensing principles, elucidating the fundamental mechanisms that underpin these advanced technologies. The chapter then transitions to the pivotal role of nanoscale materials in enhancing sensing capabilities, emphasizing how these materials revolutionize sensor performance. A meticulous examination of the design considerations for crafting nanoscale semiconductor sensing devices follows, addressing architectural nuances, integration challenges, and concerns related to power consumption and efficiency. The chapter further provides an in-depth discussion on materials synthesis and fabrication techniques, offering an overview of diverse methods for nanomaterial synthesis and the fabrication processes essential for creating these sophisticated devices. Highlighting recent advancements in semiconductor sensing technologies, the chapter unveils state-of-the-art developments and emerging trends. Insightful case studies and real-world applications illustrate these advancements, showcasing how theoretical concepts translate into practical solutions. An in-depth analysis of the challenges and opportunities within the field outlines current obstacles, proposes potential solutions, and envisions future prospects, providing a comprehensive understanding of the landscape. Through engaging case studies, the chapter demonstrates how innovative solutions can be implemented to overcome existing challenges. Further exploration of the critical aspects of testing and characterization of nanoscale semiconductor sensing devices emphasizes the importance of rigorous evaluation. A spectrum of characterization techniques is covered, ensuring a thorough understanding of reliability and durability assessments, ultimately providing readers with a well-rounded and detailed perspective on the future of semiconductor sensing technologies.

Keywords: Advancements, Challenges, Fabrication, Nanomaterials, Sensors, Semiconductors.

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INTRODUCTION

In the intricate tapestry of scientific exploration and technological innovation, sensing technologies emerge as a pivotal thread weaving through diverse realms. Sensors play a crucial role in today's world, serving as the sensory organs that enable the digital transformation of various industries. The significance of sensors lies in their potential to collect real-time data, providing valuable insights that drive efficiency, innovation, and improved decision-making across diverse sectors [1].

In healthcare, sensors play a crucial role in wearable devices, monitoring vital signs, tracking physical activity, and detecting early signs of medical conditions [2]. This promotes proactive healthcare management and personalized treatment plans. Agriculture benefits from sensors optimizing irrigation through soil moisture measurements, monitoring crop health, and employing precision farming for increased yield [3]. The automotive industry relies heavily on sensors, like LiDAR, radar, and cameras for advanced driver assistance and autonomous vehicles, enhancing safety and enabling self-driving capabilities [4, 5].

In manufacturing, sensors contribute to process automation, predictive maintenance, and quality control, boosting productivity and reducing operational costs [6]. In smart cities, sensors monitor and manage urban infrastructure, fostering sustainability and improving the quality of life for residents [7]. The Internet of Things (IoT) heavily depends on sensors, forming interconnected devices for seamless communication, leading to smart homes, grids, and industries [8]. As technology evolves, sensors' significance will grow, influencing advancements in various sectors, like artificial intelligence, machine learning, and data analytics.

In the realm of sensing technologies, semiconductor devices have emerged as integral components, representing a technological frontier that has redefined the landscape of detection and measurements [9, 10]. Semiconductors are fundamental components in the field of sensors and sensing technologies, serving as the building blocks for various sensor types. Semiconductor-based sensors leverage the unique electrical properties of semiconductors to detect and measure physical changes, allowing for precise and reliable sensing across a wide range of applications [11].

One prominent example of semiconductor sensing technology is Metal Oxide Semiconductor (MOS) structures in gas sensing. In these sensors, a semiconductor material is coated with a metal oxide, and the electrical conductivity of the semiconductor changes in the presence of specific gases [12]. Such gas sensors find applications in environmental monitoring, industrial safety, and even in smart homes for detecting gas leaks [13, 14]. Another notable application is the use of semiconductor devices in temperature sensors [15]. Thermistors, which are temperature-sensitive resistors, are made from semiconductor materials. As the temperature changes, the resistance of the semiconductor material also changes proportionally, allowing for accurate temperature measurements [16]. These sensors are extensively used in climate control systems, weather stations, and various electronic devices.

Semiconductors are integral to the development of photodetectors and photodiodes also, which are used in light sensors. The semiconductor material in these sensors generates a current when exposed to light and the current is directly related to the amount of light falling on the sensor. This principle is employed in applications, such as ambient light sensors in smartphones, cameras, and automatic lighting systems [17]. Furthermore, semiconductor-based sensors are crucial in pressure sensing technologies. For instance, piezoresistive sensors use semiconductor materials that change resistance in response to mechanical stress, allowing for accurate pressure measurements. These sensors are commonly found in automotive applications, medical devices, and industrial equipment [18].

The role of semiconductors in sensing technologies is significant because of their versatility, scalability, and ability to integrate with electronic systems. Advances in semiconductor manufacturing processes have led to the development of miniaturized sensors, which are also energy-efficient, making them suitable for diverse applications in today's interconnected and data-driven world [19]. Expanding upon the advanced sensing technologies within the realm of semiconductor applications, the intricacies of innovation that have propelled this field to the forefront of scientific inquiry are important to understand. The integration of nanomaterials with cutting-edge technologies emerges as a transformative force as we delve into the intricate world of advanced semiconductor sensing. The integration of nanomaterials into semiconductor sensing devices unleashes a spectrum of possibilities, fostering innovation in both design and functionality. This chapter serves as a beacon for researchers, engineers, and enthusiasts, exploring the intricate interplay between materials, design, and nanoscale challenges in semiconductor sensing technologies.

FUNDAMENTALS OF SEMICONDUCTOR SENSING

Semiconductor sensing relies on the unique electrical properties of semiconductor materials to detect changes in physical quantities, like light, pressure, temperature, gas concentration, and more. Semiconductor sensors employ various detection mechanisms based on the interaction between charge carriers and the external stimulus. The fundamentals of semiconductor sensing include the knowledge of

CHAPTER 9

Engineering TFET Biosensors: Design Optimization, Analytical Modeling, and Radiation Considerations

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Abstract: This chapter provides a thorough examination of the key factors influencing the development and functionality of Tunnel Field-effect Transistor (TFET) biosensors. It focuses on three main areas: design techniques, analytical modeling for DNA detection, and the impact of radiation-induced effects, particularly X-rays, on TFET sensitivity. Commencing with an overview of TFET biosensors and their importance in biomedical and environmental sensing, the chapter delves into the complexities of design strategies aimed at enhancing sensor performance. It scrutinizes various design methodologies, such as material selection, device architecture, and surface functionalization, highlighting their effects on sensitivity, selectivity, and stability. Following this, the chapter investigates tailored analytical modeling approaches for TFET biosensors in DNA detection applications. It elucidates the theoretical foundations and numerical methods governing DNA sensing mechanisms, encompassing electrostatics modeling, charge transport simulations, and device-level simulations. Practical insights into amalgamating analytical models with empirical data enable the refinement of TFET biosensors for DNA detection, enhancing their precision and dependability. Moreover, the chapter delves into the repercussions of ionizing radiation, specifically X-rays, on TFET biosensor performance. It explores radiation-induced phenomena, such as shifts in threshold voltage, damage to gate oxide, and alterations in sensitivity, elucidating their implications for sensor functionality in radiation-rich settings. Strategies for mitigating these effects and bolstering sensor resilience are discussed to ensure consistent operation across diverse application scenarios.

Keywords: Analytical modeling, Biomedical sensing, DNA detection, Material selection, Radiation-induced effects, Tensitivity, TFET biosensors.

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INTRODUCTION

In the rapidly evolving landscape of sensor technology, tunnel field effect-based biosensors have emerged as pivotal instruments, poised to revolutionize the field with their distinctive blend of capabilities [1 - 10]. These biosensors, characterized by their low power consumption, exceptional sensitivity, and seamless integration with Complementary Metal Oxide Semiconductor (CMOS) technology, have garnered significant attention as versatile platforms for modern sensing applications. In an era marked by the escalating demand for miniature, high-performance biosensing solutions capable of detecting a diverse array of analytes with precision and reliability, TFET biosensors stand out as promising candidates poised to meet these evolving needs. As we embark on a journey through the intricate realm of TFET biosensor engineering, our exploration focuses on three core pillars: design optimization, analytical modeling, and the nuanced consideration of radiation effects. These pillars serve as the cornerstones of TFET biosensor development, guiding efforts to enhance performance, understand underlying physics, and fortify sensors against environmental challenges. Through the investigation of these aspects, we aim to contribute to the betterment of biosensing technology, paving the way for innovative solutions that transcend existing boundaries.

Design optimization consists of a myriad of strategies aimed at tailoring TFET biosensors to achieve optimal performance characteristics. From refining sensitivity and selectivity to minimizing power consumption and fabrication complexity, design optimization strategies play a pivotal role in bolstering the capabilities of TFET biosensors, empowering them to meet the diverse requirements of modern sensing applications. In parallel, our exploration delves into the realm of analytical modeling, offering insights into the underlying physical mechanisms that govern TFET operation. Analytical models serve as invaluable tools for predicting device behavior, unraveling intricate electrical phenomena, and informing design decisions with precision. By leveraging these models, the readers are expected to gain a deeper understanding of TFET biosensor performance under various operating conditions, empowering researchers to refine designs and optimize sensor performance.

Furthermore, the presented investigation extends to the realm of radiation considerations, recognizing the importance of fortifying TFET biosensors against environmental challenges. In an era where radiation exposure is increasingly prevalent in diverse applications, from medical imaging to space exploration, understanding the effects of radiation on biosensor performance is paramount. By exploring strategies to enhance radiation tolerance and mitigate radiation-induced effects, we strive to ensure the reliability and robustness of TFET biosensors in demanding operational environments.

Through this multidimensional exploration, we aim not only to advance the state-of-the-art in TFET biosensor engineering, but also to catalyze transformative advancements in biosensing technology as a whole. By unraveling the intricacies of design optimization, analytical modeling, and radiation considerations, we endeavor to push the boundaries of sensor performance, enabling the development of innovative solutions that address the evolving needs of society.

DESIGN TECHNIQUES FOR TFET BIOSENSORS

Designing Tunnel Field Effect Transistor (TFET) biosensors requires a nuanced understanding of the intricate interplay between device engineering and biosensing principles. TFET biosensors offer remarkable advantages, such as low-power operation, high sensitivity, and compatibility with ongoing CMOS technology, which make them highly promising in a variety of applications, such as healthcare, environmental monitoring, and beyond. In this exploration of design techniques for TFET biosensors, the key strategies aimed at optimizing device performance and enhancing sensitivity, selectivity, and reliability are mentioned. From material selection and device geometry optimization to surface functionalization and signal amplification, each technique plays a vital role in shaping the capabilities and effectiveness of TFET biosensors [7 - 15]. Through this examination, the authors aim to provide insights and practical guidance to researchers and engineers seeking to leverage TFET biosensors for innovative biosensing solutions. Designing TFET biosensor devices involves several key techniques to optimize their performance for specific applications. Here are listed some essential design techniques.

Material Selection

The choice of semiconductor material is critical for TFET biosensors. III-V compound semiconductors, like InAs and GaSb, are often preferred due to their high carrier mobility, which allows for efficient charge transport. Additionally, 2D materials, such as MoS_2 and WSe_2, offer advantages, like tunable bandgaps and large surface-to-volume ratios, making them suitable for biosensing applications. In one of the studies [11, 12], highly sensitive ovarian cancer biomarker detection was made possible with the help of InGaAs/Si heterojunction-based TFET biosensor.

CHAPTER 10

A New Paradigm Shift in the Semiconductor Industry for 6G Technology: A Review

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Abstract: Sixth-generation (6G) wireless communication networks are expected to combine terrestrial, maritime, and aerial communications into a scalable, fast, and resilient network that can support a lot of devices with very low latency requirements. 6G semiconductor materials need to have particular properties in order to satisfy the goals of substantially faster data speeds, reduced latency, and enhanced device connection over earlier generations. Novel semiconductor materials are being discovered, and current ones are being optimized to satisfy the ever-changing needs of 6G technology. With an emphasis on wide bandgap semiconductors, like GaN and SiC, which offer improved efficiency and performance, this overview examines significant developments in semiconductor materials. To satisfy the particular requirements of the next-generation wireless networks, the semiconductor industry will probably witness breakthroughs and advances in these and other components as 6G technology develops. It is anticipated that the advancement of 6G technology will present novel demands and obstacles for semiconductor components. For 6G networks, the semiconductor industry is seeing major paradigm developments. In order to support higher frequencies and data rates, this shift places an emphasis on the integration and shrinking of components. For 6G devices to be widely adopted in a sustainable manner, advances in energy efficiency are essential. The 6G network dimensions with air interface and related prospective technologies are thoroughly outlined in this article. With regards to the 6G network, we primarily focus on a variety of semiconductor materials and components, as well as Key Performance Indicators (KPI), like high thermal conductivity, low noise, and wide bandgap.

Keywords: III-V compound semiconductors, 6G technology, Millimeter wave, Semiconductor device, Terahertz frequency.

INTRODUCTION

While 5G mobile network standards are still in their early stages, the basis for the future 6G wireless network standards is already beginning to take shape. It is acceptable to start thinking about the possible features of 6G technology, even

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though it might not be accessible for a while [1 - 4]. 6G networks will be equipped with more supporting applications than what consumers usually use on their phones because they are anticipated to be more diversified than previous mobile networks. The Internet of Everything (IoE) has led to the development of numerous new vertical services and applications that improve industrial processes, society, and our daily lives [5, 6]. These include mass production, smart housing, smart transit systems, and Virtual Reality (VR) technologies. These applications have a wide range of effects, and there are numerous Quality of Service (QoS) criteria. However, the capabilities of fifth-generation (5G) networks are now short of what is required to enable new vertical applications. As a result, researchers are looking into novel approaches to building and managing 6G networks.

6G networks will replace 5G cellular technology in the near future, as 6G networks will have far greater capacity, lower latency, and the ability to operate at higher frequencies than the 5G network. With latency as low as one microsecond, the 6G network would aim to facilitate communication between the users. Compared to a millisecond's worth of throughput, it would be 1000 times faster. Unlike 5G, which uses mmWave to operate in the microwave frequency range, 6G will use even shorter wavelengths to operate in the Terahertz (THz) region, spanning from 100 GHz to 3 THz. Radio Access Networks (RAN) are greatly impacted by 5G, but 6G networks will have a much greater impact because of a large frequency increase that will reduce the need for antennas nearly everywhere [7].

The Internet of Things (IoT), massive Machine-type Communications (MTC), and other technologies have grown, making 5G far more than just standard cellular networks. It can deliver gigabits per second instead of megabits per second and achieve a 1000x increase in capacity over 4G networks, among other Key Performance Indicators (KPIs) [8]. Target peak rates are stated to be 20 Gbps for the downlink and 10 Gbps for the uplink in a document on 5G scenarios and requirements for access technologies released by the European Telecommunication Standards Institute (ETSI) (3GPP TR 38.913). Table **1** provides further information about the different KPIs. We have also made some educated guesses about how the needs for potential 6G networks would differ from those for 5G [8, 9].

This chapter aims to offer an expert opinion on the most innovative and popular research trajectories that could influence 6G mobile technologies. Though the development of 6G is still in its early stages and some concepts may not become clear for some time, this visionary piece adopts a bold stance in speculating on potential enabling technologies and revolutionary 6G elements, outlining features that go beyond what 5G can offer. First, we provide an overview of the evolution of 6G technology in this chapter. After that, a summary of the 6G market overview and current state is provided. Next, we talk about the 6G technology's uses and semiconductor parts. We have covered new paradigm developments in the semiconductor sector for 6G technology in the section that follows. After that, we discuss the characteristics needed for improved semiconductor materials in 6G. We have gone into great detail about new semiconductor materials for 6G technologies. We finally wrap up this chapter and outline some potential future study topics. The next section covers new paradigm advances in the semiconductor industry for 6G technology. The features required for enhanced semiconductor materials in 6G are then covered. New semiconductor materials for 6G technologies have been covered in great depth. In the end, we discuss several possible areas of future research as we wind up this chapter.

Table 1. KPIs for 5G *vs.* 6G.

Features	6th Gen	5th Gen
Frequency of operation	Up to 1 THz	3 − 300 GHz
Individual data rate	100 Gbps	1 Gbps
U-plane latency	< 0.1 ms	0.5 ms1 [9]
Download data rate	> 1 Tbps	20 Gbps
C-plane latency	< 1 ms	10 ms
Mobility	Up to 1000 km/hr	Up to 500 km/h
Spectral efficiency	100 bps/Hz	30 bps/Hz

EVOLUTION OF 1G TO 6G

Significant technological advancements and conceptual shifts have characterised the remarkable development of mobile telecommunications from 1G to 6G [6, 8, 10 - 13]. Below is a summary of each generation, along with its salient features:

First Generation (1G)

1G represents first-generation wireless mobile communication, which first appeared in the late 1970s and early 1980s. It made use of voice services *via* the Advanced Mobile Phone System (AMPS) and analog technology. With a maximum speed of 2.4 kbps, it used FDMA technology with a channel capacity of 30 kHz, operating in the 824–894 MHz frequency band. Spectrum widening allowed AMPS to increase its capacity by 10 MHz in 1988. In 1982, the US implemented 1G AMPS [10].

CHAPTER 11

Exploring the Depths of Sigma-Delta Analog-to Digital Converters: A Comprehensive Review

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Abstract: Sigma-delta Analog-to-Digital Converters (ADCs) have arisen as critical components in modern electronic systems due to their capability to achieve high-resolution conversions with minimal power consumption. This chapter provides a comprehensive review of sigma-delta ADC architectures, operating principles, design considerations, and applications. It begins by outlining the sigma-delta modulation technique and proceeds to explore various architectures, including first-order, higher-order, and multi-bit sigma-delta converters. The discussion extends to analyzing noise shaping, quantization noise, and dynamic range, which are pivotal in shaping the performance of sigma-delta ADCs. The chapter meticulously addresses design challenges, such as stability concerns, handling non-idealities, and optimizing circuit implementation techniques to achieve peak performance. Furthermore, it explores the evolution of sigma-delta ADC technology, highlighting recent advancements and emerging trends. This includes advancements in oversampling techniques, digital decimation filters, and calibration methods aimed at further enhancing the efficiency and accuracy of sigma-delta ADCs. Finally, the chapter concludes with an overview of the diverse applications of sigma-delta ADCs across various domains. These include their use in communications, sensor interfaces, audio processing, and medical instrumentation, underscoring their versatility and importance in modern electronics. Each application domain benefits uniquely from the precision and efficiency offered by sigma-delta ADCs, making them indispensable in today's technology landscape.

Keywords: ADCs **(**analog-to-digital converters), ∑ΔADCs (sigma-delta analog-to-digital converters), Modulation techniques, Noise shaping, Quantization noise.

INTRODUCTION

ADCs are essential parts of contemporary electronic systems, enabling the transformation of continuous analog signals into digital formats for processing, storage, and transmission [1]. Among the plethora of ADC architectures available,

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∑ΔADCs have attracted much interest since they can provide high-resolution conversions, while consuming relatively low power. This chapter comprehensively explores ∑ΔADCs, elucidating their fundamental principles, architectures, design considerations, performance analysis, recent advancements, and applications.

The modulation technique forms the cornerstone of ∑ΔADCs, leveraging oversampling and noise shaping to attain high-resolution conversion [2, 3]. By exploiting the inherent trade-off between sampling rate and resolution, sigma-delta ADCs can achieve resolutions exceeding those of traditional ADC architectures without necessitating high-precision analog components.

Various architectures of sigma-delta ADCs, including first-order, higher-order, and multi-bit converters, are examined in detail, highlighting their advantages, limitations, and design considerations. The intricacies of stability analysis, non-idealities, and circuit implementation techniques are also discussed, offering insights into achieving optimal performance in practical implementations.

Performance analysis constitutes a crucial aspect of sigma-delta ADC evaluation, encompassing noise shaping, dynamic range, resolution, accuracy, speed, and power consumption. By comprehensively assessing these factors, designers can tailor ∑ΔADCs to meet the requirements of diverse applications spanning communications, sensor interfaces, audio processing, and medical instrumentation.

Furthermore, this chapter delves into recent advancements and emerging trends in sigma-delta ADC technology, including novel oversampling techniques, digital decimation filters, and advanced calibration methods, to enhance performance and efficiency.

In conclusion, this chapter is a valued resource for researchers, engineers, and students seeking a deeper understanding of ∑ΔADCs. By providing a comprehensive overview of architectures, design considerations, performance analysis, recent advancements, and applications, it aims to foster continued innovation and advancement in analog-to-digital conversion.

OVERVIEW OF ANALOG-TO-DIGITAL CONVERTERS (ADCs)

ADCs are essential components in modern electronics [4]. They allow continuous analog signals to be converted into digital representations, making them suitable for storage, processing, and transmission within digital systems. They play a critical role in bridging the analog and digital domains, allowing for the integration of analog signals into digital processing chains.

The quality of the digital output, including resolution, accuracy, and speed, is paramount in determining the overall performance of the ADC. Different ADC architectures offer unique characteristics and trade-offs. The selection of an ADC architecture is determined by the particular requirements of an application, including the required speed, power consumption, resolution, and financial concerns. Some common types include the following:

Successive Approximation ADCs

These ADCs employ a binary search algorithm to establish the digital representation of the incoming signal. They are known for their moderate speed and reasonable resolution.

Flash ADCs

Flash ADCs use an array of voltage comparators to convert an analog input into a digital output directly. They offer high-speed conversion, but are limited in resolution and power efficiency.

Sigma-Delta ADCs

Oversampling and noise-shaping methods are used by sigma-delta ADCs to attain high-resolution conversions, while keeping power consumption relatively low. They are particularly suited for high-resolution applications with low to moderate bandwidth.

Pipeline ADCs

Pipeline ADCs divide the conversion process into multiple stages, each contributing to the ADC's overall resolution. They balance speed and resolution and are commonly used in high-speed applications.

In addition to the architecture, other factors, such as sampling rate, input range, and signal conditioning, influence the performance of ADCs. Noise, linearity, and dynamic range are key factors in guaranteeing the precise and reliable conversion of analog signals into digital format. The first block in Fig. (**1**) is the Anti-alias Filter (AAF), which reduces the input signal's bandwidth to less than half of the sampling frequency. This filter prevents higher-frequency signals from folding back into the frequency range of interest during sampling, thereby avoiding aliasing. Depending on the sampling rate and signal bandwidth relationship, ADCs are typically categorized as Nyquist rate ADCs or oversampled ADCs, such as sigma-delta ADCs. As the sampling rate increases, the transition width of the anti-alias filter also increases proportionally.

CHAPTER 12

Photovoltaic Performance Estimation of Thin Film Lateral Pn-Junction Solar Devices and Comprehensive Consideration of Performances of Various Homo- and Hetero-Junction Structures

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Abstract: This chapter provides a practical theoretical foundation and perspective on the performance of various thin-film lateral pn-junction solar devices under illumination. It focuses on Si- and Ge-based homo-junctions, as well as ZnO/Si (Type-I) and GaN/Si (Type-II) based hetero-junctions. Theoretical models assume poly-crystalline or amorphous semiconductor materials. The study demonstrates that highly-doped Si- and Ge-based homo-junction architectures show great promise for high-performance solar devices. By utilizing published experimental results, the predicted performances of homo-junction and hetero-junction solar devices are primarily compared at room temperature. Additionally, the chapter addresses the behaviors of these devices at low and high temperatures, considering various applications. The results reveal the superiority of Si- and Ge-based homo-junctions. The chapter delves into the theoretical aspects, providing a robust understanding of the principles governing the performance of these solar devices. It evaluates the advantages and challenges associated with each type of junction, offering a comprehensive analysis of their operational efficiencies. Through detailed comparisons and analysis, the study underscores the potential of Si- and Ge-based homo-junctions in advancing solar technology. This investigation into the practical and theoretical aspects of thin-film lateral pn-junction solar devices serves as a valuable resource for understanding their performance under different conditions. It highlights the critical role of material selection and doping strategies in optimizing device efficiency, paving the way for future research and development of high-performance solar technologies.

Keywords: - Lateral pn junction, Ge, GaN, Photovoltaic performance, Si, Thin film, ZnO.

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INTRODUCTION

A pn-junction-based optical rotor operating under external illumination was proposed [1]. Though the device was proposed as a mechanical part for MEMS (Micro Electro Mechanical System) applications [2], its full potentiality has yet to be examined in experiments. Since many MEMS applications [3] must have very low-power operation, because most must work with very small batteries, we need advanced mobile battery-powered devices, not AC power supplies. One possible way is to make a built-in battery that is charged by an external energy source, like optical illumination.

Combinations of various flexible electronics technologies and solar batteries are now being investigated in order to support new advanced applications [4 - 7] because they have high potential for future medical implantation applications [8] and sensor-network applications for the IoT society [9], as well as space applications [10]. Since low-temperature deposition techniques, like mist CVD method [11 - 14], have recently been developed, the above device applications are seen as real targets for the electronics industry. The potential of lateral pin diodes has recently been investigated in order to attain high-performance photodiodes [15 - 18], and the influence of temperature and device thickness is being studied. However, their future potential has yet to be discussed.

In this paper, the author reconsiders the theoretical base for photovoltaic performance estimation of thin film lateral pn-junction solar devices and comprehensively discusses the performances of homo- and hetero-junction devices because it is anticipated that such lateral pn-junction solar devices are much more robust against local damage than the conventional vertical junction structure. In addition, the author reveals by theoretical predictions that the carrier diffusion behaviors of sub-100-nm-thick Si films are quite insensitive to carrier lifetime values [2]. Such characteristic is needed in future various flexible electronics. Though the primary theoretical base was given in an earlier work [19], the physical conditions implicit in the discussion were not deeply considered. Accordingly, this paper revisits the theoretical formulation in order to widen the consideration [20, 21], and some additional theoretical concepts are introduced for the hetero-junction structures and numerically evaluated [20]. Here, various calculations are performed for Si- and Ge-based homo-junction devices and ZnO/Si (Type-I) and GaN/Si (Type-II) based hetero-junction devices [6, 7, 22 - 25] from the viewpoint of future applications. In addition, device design issues are also discussed.

DEVICE STRUCTURES ASSUMED

Though some advanced proposals and experiments have recently been published [5 - 7, 23 - 27], some of them are based on chalcogenide materials because of their promising future potential [5, 20]. On the other hand, this study has paid attention to the ubiquitous society of solar battery devices with their low costs and robustness from the viewpoint of industrial application. So, only well-known materials are assumed in simulations.

A simplified physical image of the thin film lateral pn junction solar device is shown in Fig. (**1**), where the top view of the device is given in Fig. (**1a**), the cross-sectional view of Si- or Ge-based homo-junction device is shown in Fig. (**1b**), that of the n-ZnO/p-Si (or n-GaN/p-Si) hetero-junction device is shown in Fig. (**1c**), and that of the multi-stack architecture is shown in Fig. (**1d**); it is assumed that green light, with a wavelength of 550 nm, directly illuminates to the sheet's top surface [1]. Here, we assume the coordinate system, as shown in Fig. (**1a**).

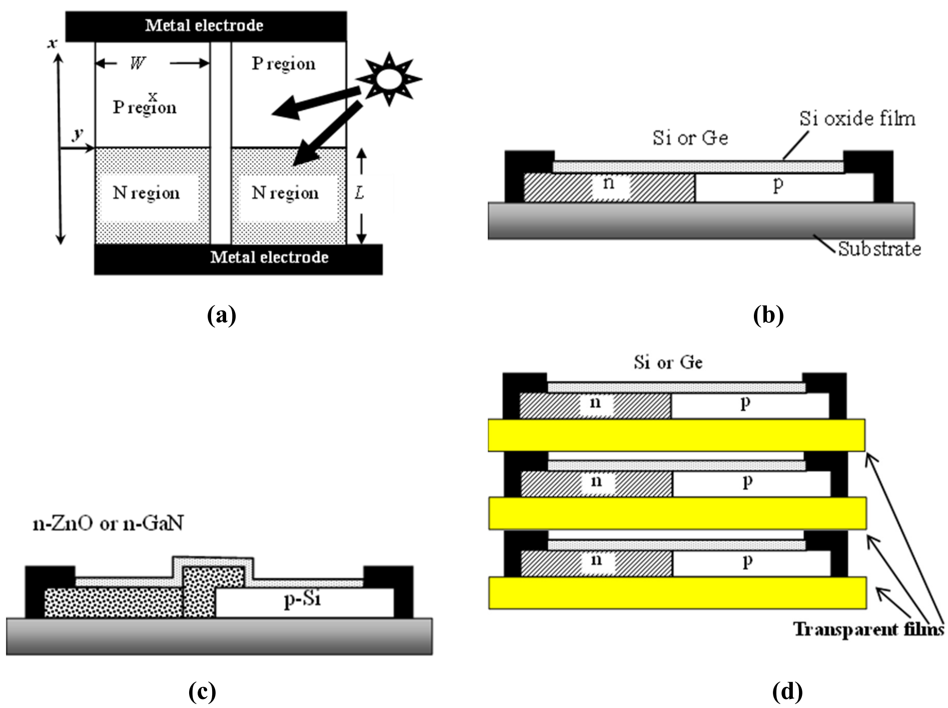

Fig. (1). Schematic representation of the device structure. (**a**) Top view, (**b**) cross-sectional view of Si pn-junction or Ge pn-junction, (**c**) n-ZnO/p-Si or n-GaN/p-Si hetero-pn-junction, (**d**) schematic view of a multi-stack structure.

APPENDIX

This appendix provides additional information discussed in Chapter 9.

The solution to the surface potential is given below:

$$\sigma_k = -\alpha_k / \lambda_k{}^2, \lambda_k{}^2 = 2\beta_k / t_{body}{}^2, \alpha_k = \left[\left(qN_k / \varepsilon_{si} - 2\beta_k / t_{body}{}^2\right)\left(V_{gseff,k}\right)\right]$$

$$T = \left(\sigma_2 - \sigma_1\right)\cosh\left(\lambda_1 X_1\right), O = e^{\lambda_2 X_1}\left[\cosh\left(\lambda_1 X_1\right) - \left(\frac{\lambda_2}{\lambda_1}\right)\sinh\left(\lambda_1 X_1\right)\right]$$

$$P = e^{-\lambda_2 X_1}\left[\cosh\left(\lambda_1 X_1\right) + \left(\frac{\lambda_2}{\lambda_1}\right)\sinh\left(\lambda_1 X_1\right)\right], W = 0.5\left(\sigma_3 - \sigma_2\right)\left[Oe^{-\lambda_2 (X_1 + X_2)} + Pe^{\lambda_2 (X_1 + X_2)}\right]$$

$$F = 0.5\left[Oe^{(\lambda_3 - \lambda_2)(X_1 + X_2)}\left(1 + \frac{\lambda_3}{\lambda_2}\right) + Pe^{(\lambda_3 + \lambda_2)(X_1 + X_2)}\left(1 - \frac{\lambda_3}{\lambda_2}\right)\right]$$

$$G = 0.5\left[Oe^{(-\lambda_3 - \lambda_2)(X_1 + X_2)}\left(1 - \frac{\lambda_3}{\lambda_2}\right) + Pe^{(-\lambda_3 + \lambda_2)(X_1 + X_2)}\left(1 + \frac{\lambda_3}{\lambda_2}\right)\right]$$

$$A_1 = 0.5\left(\sigma_4 - \sigma_3\right)\left[Fe^{-\lambda_3 (X_1 + X_2 + X_3)} + Ge^{\lambda_3 (X_1 + X_2 + X_3)}\right]$$

$$A_2 = 0.5\left[Fe^{(\lambda_4 - \lambda_3)(X_1 + X_2 + X_3)}\left(1 + \frac{\lambda_4}{\lambda_3}\right) + Ge^{(\lambda_4 + \lambda_3)(X_1 + X_2 + X_3)}\left(1 - \frac{\lambda_4}{\lambda_3}\right)\right]$$

$$A_3 = 0.5\left[Fe^{(-\lambda_4 - \lambda_3)(X_1 + X_2 + X_3)}\left(1 - \frac{\lambda_4}{\lambda_3}\right) + Ge^{(-\lambda_4 + \lambda_3)(X_1 + X_2 + X_3)}\left(1 + \frac{\lambda_4}{\lambda_3}\right)\right]$$

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$$B_1 = 0.5(\sigma_5 - \sigma_4)\left[A_2 e^{-\lambda_4 \sum_{k=1}^{4} X_k} + A_3 e^{\lambda_4 \sum_{k=1}^{4} X_k}\right],$$

$$B_2 = 0.5\left[A_2 e^{(\lambda_5 - \lambda_4)\sum_{k=1}^{4} X_k}\left(1 + \frac{\lambda_5}{\lambda_4}\right) + A_3 e^{(\lambda_5 + \lambda_4)\sum_{k=1}^{4} X_k}\left(1 - \frac{\lambda_5}{\lambda_4}\right)\right]$$

$$B_3 = 0.5\left[A_2 e^{(-\lambda_5 - \lambda_4)\sum_{k=1}^{4} X_k}\left(1 - \frac{\lambda_5}{\lambda_4}\right) + A_3 e^{(-\lambda_5 + \lambda_4)\sum_{k=1}^{4} X_k}\left(1 + \frac{\lambda_5}{\lambda_4}\right)\right]$$

$$C_1 = 0.5(\sigma_6 - \sigma_5)\left[B_2 e^{-\lambda_5 \sum_{k=1}^{5} X_k} + B_3 e^{\lambda_5 \sum_{k=1}^{5} X_k}\right],$$

$$C_2 = 0.5\left[B_2 e^{(\lambda_6 - \lambda_5)\sum_{k=1}^{5} X_k}\left(1 + \frac{\lambda_6}{\lambda_5}\right) + B_3 e^{(\lambda_6 + \lambda_5)\sum_{k=1}^{5} X_k}\left(1 - \frac{\lambda_6}{\lambda_5}\right)\right]$$

$$C_3 = 0.5\left[B_2 e^{(-\lambda_6 - \lambda_5)\sum_{k=1}^{5} X_k}\left(1 - \frac{\lambda_6}{\lambda_5}\right) + B_3 e^{(-\lambda_6 + \lambda_5)\sum_{k=1}^{5} X_k}\left(1 + \frac{\lambda_6}{\lambda_5}\right)\right]$$

$$D_1 = 0.5(\sigma_7 - \sigma_6)\left[C_2 e^{-\lambda_6 \sum_{k=1}^{6} X_k} + C_3 e^{\lambda_6 \sum_{k=1}^{6} X_k}\right], D_2 = 0.5\left[C_2 e^{(\lambda_7 - \lambda_6)\sum_{k=1}^{6} X_k}\left(1 + \frac{\lambda_7}{\lambda_6}\right) + C_3 e^{(\lambda_7 + \lambda_6)\sum_{k=1}^{6} X_k}\left(1 - \frac{\lambda_7}{\lambda_6}\right)\right]$$

$$D_3 = 0.5\left[C_2 e^{(-\lambda_7 - \lambda_6)\sum_{k=1}^{6} X_k}\left(1 - \frac{\lambda_7}{\lambda_6}\right) + C_3 e^{(-\lambda_7 + \lambda_6)\sum_{k=1}^{6} X_k}\left(1 + \frac{\lambda_7}{\lambda_6}\right)\right]$$

$$E_1 = 0.5(\sigma_8 - \sigma_7)\left[D_2 e^{-\lambda_7 \sum_{k=1}^{7} X_k} + D_3 e^{\lambda_7 \sum_{k=1}^{7} X_k}\right], E_2 = 0.5\left[D_2 e^{(\lambda_8 - \lambda_7)\sum_{k=1}^{7} X_k}\left(1 + \frac{\lambda_8}{\lambda_7}\right) + D_3 e^{(\lambda_8 + \lambda_7)\sum_{k=1}^{7} X_k}\left(1 - \frac{\lambda_8}{\lambda_7}\right)\right]$$

$$E_3 = 0.5\left[D_2 e^{(-\lambda_8 - \lambda_7)\sum_{k=1}^{7} X_k}\left(1 - \frac{\lambda_8}{\lambda_7}\right) + D_3 e^{(-\lambda_8 + \lambda_7)\sum_{k=1}^{7} X_k}\left(1 + \frac{\lambda_8}{\lambda_7}\right)\right]$$

$$z_1 = e^{\lambda_7 (\sum_{l=1}^{8} X_l)}, z_2 = e^{-\lambda_7 (\sum_{l=1}^{8} X_l)}, z_3 = M + N + A_1 + B_1 + C_1 + D_1 + E_1$$

$$U_8 = \frac{\left(V_{bi,source} - \sigma_1\right) z_2 - \left(V_{bi,drain} + V_{ds} - \sigma_8\right) E_3 - \left(z_3 z_2\right)}{z_2 E_2 - z_1 E_3};$$

$$V_8 = \frac{\left(V_{bi,source} - \sigma_1\right) z_1 - \left(V_{bi,drain} + V_{ds} - \sigma_8\right) E_2 - \left(z_1 z_3\right)}{z_1 E_3 - z_2 E_2}$$

$$U_k = 0.5 \begin{bmatrix} U_{k+1} exp\left(\left(\lambda_{k+1} - \lambda_k\right) \sum_{l=1}^{k} X_l \right) \left(1 + \left(\frac{\lambda_{l+1}}{\lambda_l} \right) \right) + \\ V_{k+1} exp\left(\left(-\lambda_{l+1} - \lambda_l\right) \sum_{l=1}^{k} X_l \right) \left(1 - \left(\frac{\lambda_{l+1}}{\lambda_l} \right) \right) + \\ \left(\sigma_{l+1} - \sigma_l\right) exp\left(-\lambda_l \sum_{l=1}^{k} X_l \right) \end{bmatrix}, k = 1, 2, 3, \ldots 7$$

$$V_k = 0.5 \begin{bmatrix} U_{k+1} exp\left(\left(\lambda_{k+1} + \lambda_k\right) \sum_{l=1}^{k} X_l \right) \left(1 - \left(\frac{\lambda_{k+1}}{\lambda_k} \right) \right) + \\ V_{k+1} exp\left(\left(-\lambda_{k+1} + \lambda_k\right) \sum_{l=1}^{k} X_l \right) \left(1 + \left(\frac{\lambda_{k+1}}{\lambda_k} \right) \right) + \\ \left(\sigma_{k+1} - \sigma_k\right) exp\left(\lambda_k \sum_{l=1}^{k} X_l \right) \end{bmatrix}, k = 1, 2, 3, \ldots 7$$

APPENDIX A: SOLVING EQ. (15)

This appendix provides additional information discussed in Chapter 12.

After $\frac{\partial P(x,T)}{\partial x}$ is multiplied to both sides of eq. (15), the integration yields:

$$\int \frac{\partial P}{\partial x'} \frac{\partial^2 P}{\partial x'^2} dx' - A_p \int P \frac{\partial P}{\partial x'} \frac{\partial P}{\partial x'} dx' - C_P \int P \frac{\partial P}{\partial x'} dx' = 0, \quad \textbf{(A1)}$$

$$\frac{1}{2}\left(\frac{\partial P}{\partial x^{'}}\right)^{2}\Bigg|_{0}^{x} - A_{p}\int_{0}^{x} P\frac{\partial P}{\partial x^{'}}\frac{\partial P}{\partial x^{'}}dx^{'} - C_{P}\,P^{2}\Big|_{0}^{x} = 0, \tag{A2}$$

Here, the second term of eq. (A2) is partially integrated as:

$$\int_{0}^{x} P\frac{\partial P}{\partial x^{'}}\frac{\partial P}{\partial x^{'}}dx^{'} = \left(\frac{1}{2}P^{2}\frac{\partial P}{\partial x^{'}}\right)\Bigg|_{0}^{x} - \frac{1}{2}\int_{0}^{x} P^{2}\frac{\partial^{2} P}{\partial x^{'2}}dx^{'}, \tag{A3}$$

In addition, from a rough estimation of parameter values, we can confirm that $A_{p}\frac{\partial P(x,T)}{\partial x} >> C_{P}$. In this case, from eq. (15), we have:

$$\frac{\partial^{2} P(x,T)}{\partial x^{2}} - A_{p}P(x,T)\frac{\partial P(x,T)}{\partial x} \cong 0, \tag{A4}$$

By inserting eq. (A4) into eq. (A3), we have:

$$\int_{0}^{x} P\frac{\partial P}{\partial x^{'}}\frac{\partial P}{\partial x^{'}}dx^{'} = \left(\frac{1}{2}P^{2}\frac{\partial P}{\partial x^{'}}\right)\Bigg|_{0}^{x} - \frac{A_{P}}{8}\left(P^{4}\right)\Big|_{0}^{x}, \tag{A5}$$

Equation (A5) is inserted into eq. (A2) as:

$$\frac{1}{2}\left(\frac{\partial P}{\partial x^{'}}\right)^{2}\Bigg|_{0}^{x} - A_{p}\left\{\left(\frac{1}{2}P^{2}\frac{\partial P}{\partial x^{'}}\right)\Bigg|_{0}^{x} - \frac{A_{P}}{8}\left(P^{4}\right)\Big|_{0}^{x}\right\} - C_{P}\left(P^{2}\right)\Big|_{0}^{x} = 0, \tag{A6}$$

This is rewritten to:

$$\left(\frac{\partial P(x,T)}{\partial x}\right)^{2} - A_{P}P^{2}(x,T)\frac{\partial P(x,T)}{\partial x} + \frac{A_{P}^{2}}{4}P^{4}(x,T) - 2C_{P}P^{2}(x,T) + P_{00} = 0, \tag{A7}$$

Where:

$$P_{00} = -\left(\frac{\partial P(x,T)}{\partial x}\right)\Bigg|_{0}^{2} + A_{P}P^{2}(0,T)\frac{\partial P(x',T)}{\partial x'}\Bigg|_{0}^{x} - \frac{A_{P}^{2}}{4}P^{4}(0,T) + 2C_{P}P^{2}(0,T), \tag{A8}$$

From eq. (A7), we have the following form for $\frac{\partial P(x,T)}{\partial x}$.

$$\frac{dP(x,T)}{dx} = \frac{1}{2}A_{P}P^{2}(x,T) \pm \sqrt{2C_{P}P^{2}(x,T) - P_{00}}, \tag{A9}$$

This yields the following integration form:

$$\int \frac{dP}{P^2(x,T) \pm 2\frac{\sqrt{2C_P}}{\alpha A_P}\sqrt{P^2(x,T) - P_{00}/2C_P}} = \int \frac{\alpha A_P}{2} dx, \qquad \textbf{(A10)}$$

Equation (A10) cannot be solved analytically as it is, so possible solutions are considered in Appendix B.

APPENDIX B: POSSIBLE SOLUTIONS FOR EQ. (A10)

When we solve eq. (A10), the magnitude of P_{00} must be estimated. Eq. (A8) and Tables **1** and **2** yield the following estimation:

$$P_{00} \sim \left(\frac{P(0,T)}{L_p}\right)^2 \left\{1 - A_p L_p P(0,T) - \frac{1}{4}\left(A_p L_p P(0,T)\right)^2\right\} < 0 \qquad \textbf{(B1)}$$

Where,

$$A_p L_p P(0,T) \sim 1 \quad \text{for } P(0,T)=1\text{x}10^{17}\ \text{cm}^{-3} \qquad \textbf{(B2)}$$

$$A_p L_p P(0,T) \sim 100 \quad \text{for } P(0,T)=1\text{x}10^{20}\ \text{cm}^{-3} \qquad \textbf{(B3)}$$

As a result, we have:

$$-\left(\frac{P(0,T)}{L_p}\right)^2 > P_{00} > -100\left(\frac{P(0,T)}{L_p}\right)^2 \qquad \textbf{(B4)}$$

So, we consider the following two cases.

(i) **$P(0,T) < 10^{17}$cm^{-3}**

In this condition, the influence of the term of P_{00} in eq. (A10) is limited, and so it is discarded. Thus, we have:

$$\int \frac{dP}{P^2(x,T) \pm 2\frac{\sqrt{2C_P}}{A_P}\sqrt{P^2(x,T)}} = \int \frac{A_P}{2} dx, \qquad \textbf{(B5)}$$

This integration is possible.

(ii) **$P(0,T) >> 10^{17}$cm^{-3}**

Equation (B1) is reduced to:

$$P_{00} \sim -\frac{\alpha^2 A_P^2}{4} P^4\left(0,T\right) \tag{B6}$$

APPENDIX C: DERIVATION OF EQUATION (23)

The electron density, ($n_{p,Si}$(x,T)), of the conduction band of the Si film is expressed as:

$$n_{p,Si}\left(x,T\right)=\int_{E_{C,Si}}^{\infty} D_{os,Si}\left(E\left(x\right)\right)f_{FD}\left(T,E\left(x\right)\right)dE \tag{C1}$$

Where, $E_{C,Si}$ is the energy level of the conduction bottom of Si, $D_{os,Si}(E)$ is the density of states of the conduction band, and $f_{FD}(T, E)$ is the Fermi-Dirac function. Since the interface of the conduction band of the hetero-junction has the notch of *Ec*, as shown in Fig. (**2a**), the electron density [$n_{n,ZnO}(x, T)$], which can be injected into the conduction band of the ZnO film, is expressed as:

$$n_{n,\mathrm{ZnO}}\left(0,T\right)=\int_{E_{C,Si}+\Delta E_C}^{\infty} D_{os,Si}\left(E\left(0\right)\right)f_{FD}\left(T,E\left(0\right)\right)dE \tag{C2}$$

Because $\Delta E_c >> k_B T$, the Fermi-Dirac function can be replaced, approximately, with the following exponential function:

$$\begin{aligned} n_{n,\mathrm{ZnO}}\left(0,T\right) &\cong \int_{E_{C,Si}+\Delta E_C}^{\infty} D_{os,Si}\left(E\left(0\right)\right)\exp\left(-\frac{E\left(0\right)-E_F\left(T\right)}{k_B T}\right)dE \\ &\cong n_{p,Si}\left(0,T\right)\int_{\Delta E_C/k_B T}^{\infty}\sqrt{Z}\exp\left(-Z\right)dZ \end{aligned} \tag{C3}$$

Equation (C-3) can be approximately calculated as:

$$n_{n,\mathrm{ZnO}}\left(0,T\right)\cong n_{p,Si}\left(0,T\right)\sqrt{\frac{\Delta E_C}{k_B T}}\exp\left(-\frac{\Delta E_C}{k_B T}\right) \tag{C4}$$

APPENDIX D: FERMI-LEVEL DEFINITIONS OF MATERIALS

Since we have to take into account the ionization fraction of impurities at high-doping levels, the following expressions are introduced. For the Si and Ge films, we have:

$$n_{n0}\left(0,T\right)=\frac{N_D}{1+\frac{1}{2}\exp\left(\frac{E_D-E_F\left(0\right)}{k_B T}\right)} \tag{D1}$$

$$p_{p0}(0,T) = \frac{N_A}{1+4\exp\left(\frac{E_A - E_F(0)}{k_B T}\right)} \tag{D2}$$

$$E_D - E_F(0) = 2\ln(2)\cdot k_B T - k_B T \ln\left[\sqrt{1+8\frac{N_D}{N_C}\exp\left(\frac{E_C - E_D}{k_B T}\right)} - 1\right] \tag{D3}$$

$$E_A - E_F(0) = -\ln(8)\cdot k_B T + k_B T \ln\left[\sqrt{1+16\frac{N_A}{N_V}\exp\left(\frac{E_A - E_V}{k_B T}\right)} - 1\right] \tag{D4}$$

Where, *ND, NA, ED, EA, EF, NC*, and *NV* take the conventional meanings. For degenerate p-type Si and Ge films, the simulations use equations (D2) and (D4). On the other hand, when degenerate n-type ZnO and GaN films are assumed, we have [45]:

$$E_F(x) - E_C = \frac{\hbar^2}{2m^*_{C,ZnO}}\left[3\pi^2\left(n_{n,ZnO}(x,T) + n_{p,Si}(0,T)\right)\right]^{2/3} \tag{D5}$$

for n-ZnO/p-Si junction devices or:

$$E_F(x) - E_C = \frac{\hbar^2}{2m^*_{C,GaN}}\left[3\pi^2\left(n_{n,\mathrm{GaN}}(x,T) + n_{p,Si}(0,T)\right)\right]^{2/3} \tag{D6}$$

for n-GaN/p-Si junction devices , where $m_{c,ZnO}$* is the electron effective mass of the conduction band of ZnO film [46] and $m_{c,GaN}$* is the electron effective mass of the conduction band of GaN film [47].

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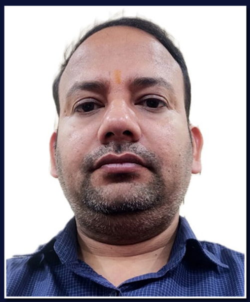

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