Chapter 16
Fundamentals of Semiconductor and Future Aspects

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ABSTRACT

This chapter provides a comprehensive overview of the fundamental principles of semiconductor devices, focusing on their physical properties, operational mechanisms, and the diverse range of applications they support. Key topics include the behaviour of charge carriers in semiconductor materials, the formation and characteristics of p-n junctions, and the operational principles of key devices FETs, CMOS and HEMTs. HEMTs have become a cornerstone in modern electronics due to their superior performance characteristics, including high electron mobility, low noise, and high gain. This chapter delves into the fundamental principles of HEMTs, exploring their unique heterostructure design that leverages materials such as GaAs and AlGaAs to create a high-speed, low-noise transistor. The high-frequency capabilities of HEMTs make them ideal for applications in RF and microwave circuits, satellite communications, and radar systems.

INTRODUCTION

Quantum computing hardware depends on advanced semiconductor technology to manage quantum bits (qubits). There are several types of qubits, such as superconducting qubits, which use superconducting circuits and function at extremely low temperatures, and trapped ion qubits, which employ electromagnetic fields to trap ions, offering high fidelity and relatively long coherence times. Topological qubits utilize exotic particles called anyons, providing potential resistance to decoherence, while spin qubits are based on the spin of electrons in semiconductor materials like silicon or gallium arsenide. Photon qubits use photons to represent qubits, enabling long-distance quantum communication.

Semiconductor materials are essential, with silicon being widely used due to its availability and compatibility with existing CMOS technology, and gallium arsenide providing higher electron mobility for applications like spin qubits and optoelectronics. Quantum dot technology involves small semicon-

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ductor particles that trap single electrons or holes, creating qubits by confining electrons in three spatial dimensions.

Quantum computing hardware faces several challenges. Decoherence is a major issue since quantum states are fragile and easily disturbed by the environment. Scalability is also challenging, as building and maintaining a large number of qubits with error correction is complex. Error correction itself requires additional qubits and sophisticated algorithms to detect and fix errors, while fabrication precision demands extremely high accuracy to manufacture quantum devices at the nanoscale.

Recent advances include improved coherence times through better material purification and qubit design, enhanced error correction techniques, and the development of hybrid quantum systems that combine different types of qubits. Future directions involve integrating quantum computing with classical computing technologies for practical applications, discovering new semiconductors and structures through advances in material science, and developing quantum internet and communication protocols using photon qubits.

Semiconductors form the backbone of modern electronics. Understanding their properties is crucial for anyone involved in electronics, physics, or materials science (Sze & Ng, 2021) (Streetman & Banerjee, 2016). Knowledge of semiconductors enables the design and innovation of various electronic devices such as transistors, diodes, solar cells, and integrated circuits, (Chen, Zhang, & Chen, 2020) (Wang & Sun, 2019). Understanding the electrical properties and behavior of semiconductors allows for the optimization of device performance, power consumption, and efficiency, (Horowitz & Hill, 2015). As technology evolves, the demand for smaller, faster, and more efficient electronic devices increases, (Shin, Park, & Lee, 2021). A deep understanding of semiconductors is essential for pushing the boundaries of what is possible in electronics and to know the technological progress and addressing modern challenges, (Kittel, 2018). Semiconductors enable the development of smaller, faster, and more efficient electronic devices. They foster the creation of new applications and products across various industries and improve the performance and energy efficiency of electronic systems, (Huang, Zhang, & Fang, 2020). In the realm of semiconductor technology, the quest for smaller, faster, and more energy-efficient devices has driven continual innovation. The relentless miniaturization of electronic devices has led to a growing demand for transistors with lower power consumption.

High Electron Mobility Transistors (HEMTs) are crucial for quantum computing due to their high-speed performance and low noise levels. Their capability to operate at very high frequencies enables rapid control and readout of qubits, which leads to efficient quantum gate operations and faster computations. The low noise in HEMTs enhances the signal-to-noise ratio, crucial for preserving quantum state integrity and reducing errors. Additionally, HEMTs improve the precision of qubit state measurements, essential for quantum error correction and information processing. Their compatibility with cryogenic temperatures makes them ideal for use with superconducting qubits and other cryogenically cooled quantum systems. The compact and scalable nature of HEMTs allows for dense integration in quantum circuits, supporting the development of larger and more complex quantum processors. HEMTs are instrumental in qubit control and readout, amplification of quantum signals, and quantum error correction, thus playing a vital role in advancing scalable and efficient quantum computing.

Metal-Oxide-Semiconductor Field-Effect Transistors (MOSFETs), the workhorses of modern electronics, face limitations in scaling due to the phenomenon of short-channel effects, (Mimura & Fukui, 2020). MOSFETs are silicon-based devices widely used in digital and analog circuits for their efficiency and ease of integration. They control current flow via an electric field created by a gate voltage. In contrast, HEMTs (High Electron Mobility Transistors) use III-V compound semiconductors and het-

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