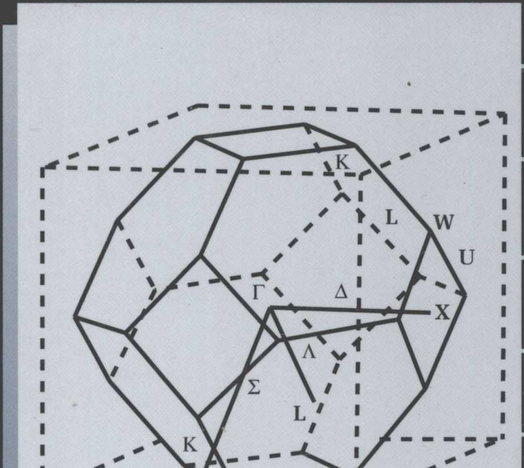
GaAs HIGH-SPEED DEVICES



PHYSICS, TECHNOLOGY, AND CIRCUIT APPLICATIONS

C. Y. CHANG • FRANCIS KAI

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PREFACE

High-speed semiconductor devices are the essential components of digital computers, telecommunication systems, optoelectronics, and advanced electronic systems as they can handle analog and digital signals at high frequencies and high bit rates. The design and development of these devices are vital to the continued growth of the high-tech industries. This book looks at the process advancements in GaAs device fabrication and offers insights into the design of devices, their physical operating principles, and their use in integrated circuits as well as other applications.

The book is organized into five parts: The first part, Chapter 2, discusses gallium arsenide materials and their crystal properties, the electron energy-band structures, hole and electron transport, the crystal growth of GaAs from the melt and the defect density analysis.

The second part consider the fabrication process of gallium arsenide devices and integrated circuits. Chapter 3 covers the epitaxial growth processes, molecular beam epitaxy, and the metal–organic chemical vapor deposition techniques used to grow a single atomic layer. An important feature of the chapter is the research on low-substrate temperature growth epitaxy systems which have been developed for better device fabrication. Chapter 4 gives an introduction on wafer-cleaning techniques and environmental control, wet etching methods and chemicals, and dry etching systems consisting of reactive ion etching and reactive ion-beam etching methods. The rapid thermal process is covered briefly, since it has captured much attention in recent years.

Patterning techniques have become hot issues in silicon as well as in gallium arsenide integrated circuit fabrication. Chapter 5 gives an overview of photolithography and nonoptical lithography techniques that include electron-beam, X-ray, and ion-beam lithography systems.

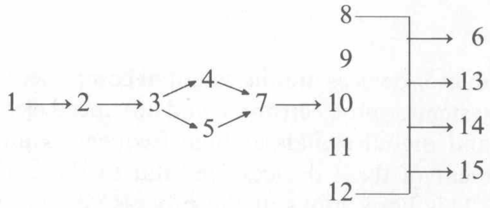
The third part, Chapter 6, discusses device-related physics. Advancements in the fabrication techniques described in the earlier chapters call for more understanding of low-dimensional device physics. The epitaxial processes make gallium arsenide and its related group III–V compounds and solid solutions band structure complex.

Scattering theory and ballistic transport are also discussed, and recent studies using the Monte Carlo method are presented.

The fourth part forms the core of the book. Chapters 7 and 8 develop the ideas on innovative device design and operating principles sketched out in Chapter 1. Chapter 7 considers metal–semiconductor contact systems, the Schottky barrier, ohmic contact formation, and reliability studies. Chapter 8 looks at metal–semiconductor field-effect transistors, the fabrication technology, and the models and the parameters for device analyses. The parasitic effects and noise theory are covered briefly here and developed later in Chapters 13 and 14, since MESFETs are the most popular devices in integrated circuits and integrated circuits applications. Chapter 15 concludes the book with a discussion of high-speed photonic devices and optoelectronic integrated circuits.

The fifth part, Chapters 9 through 12, discusses the heterostructure field-effect (HEMT in Chapter 9), potential-effect (HBT in Chapter 10), and quantum-effect (Chapters 11 and 12) devices. These new devices will have a large impact on high-speed integrated circuits and optoelectronic integrated circuits (OEICs) applications.

In summary, the most effective way to use the book is as follows:



In all of the chapters we have tried to give the reader some idea of the history, even at this early stage of the development of the field. We have included some materials that are not commonly found in standard textbooks nor in collections of professional papers. In doing so, we wanted to give the reader as complete as possible a view of this fast-growing technology.

We are grateful to the many researchers who provided us with information and illustrations from their works. The comments from several reviewers were particularly helpful. Special thanks are due to Drs. Ta-Nien Yuan, Nan-Hong Kuo, Chi-Fu Deng, Simon S. Sze, Han-Ming Hsia, M. Feng, M. F. Chang, P. C. Chao, M. Pilkuhn, M. Razeghi, C. P. Lee, J. P. Duchemin, L. P. Chen, A. Y. Cho, K. Nakamura, J. Nishizawa, N. Yokoyama, A. Usui, H. Tanaka, P. S. D. Lin, T. C. L. G. Sollner, H. I. Smith, C. H. Liu, and S. S. Li for their encouragement, good will, and various assistances, and to the staff who worked with us at John Wiley and Sons, especially George Telecki, Cynthia Hess, and Rosalyn Farkas. Last but not least, we wish to thank our wives Shenn-May Lee and Lih-Nah Hwang.

Hsin-chu, Taiwan
Austin, Texas
June 1994

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GaAs HIGH-SPEED DEVICES

CONTENTS

1

THE DEVELOPMENT OF GALLIUM ARSENIDE DEVICES AND INTEGRATED CIRCUITS

1.1 GALLIUM ARSENIDE DEVICE DEVELOPMENT

In modern computer and telecommunication applications the most important semiconductors for high-speed devices are silicon and gallium arsenide and its related III–V compounds and solid solutions. Recent advancements in fabrication technology have produced the superlattice semiconductor, which is an artificial one-dimensional periodic structure made up of different semiconductor materials with a period of about 100 Å. Superlattice semiconductors include silicon-based materials (e.g., GeSi/Si) and gallium arsenide–based materials (e.g., AlGaAs/GaAs or InGaAs/GaAs) [Sze90].

Silicon's high density and high speed make it a popular material for very large-scale integrated (VLSI) circuit devices. But the III–V compounds have certain speed advantages over silicon in their higher carrier mobilities and effective carrier velocities. The semi-insulating substrates of the III–V compounds provide lower interconnection capacitances. Research on hybrid material systems based on a heteroepitaxial process has shown that an advanced architecture can be developed whereby high-speed GaAs/AlGaAs devices are located on heteroepitaxially grown islands on a silicon wafer (GaAs on Si), integrated with the silicon VLSI circuits by a suitable metallization process. There are promising developments as well in optical communications for silicon wafers, for example, in electronically triggered compound-semiconductor lasers or light-emitting diodes made in heteroepitaxial materials to avoid RCL delays due to on-chip interconnecting lines.

The most popular III–V compound high-speed devices are field-effect transistors. These are voltage-controlled devices. The control electrode is capacitively coupled to the active region of the device, and the charge carriers are separated by an insulator or a depletion layer [Sze90]. It is impossible to grow a good oxide layer on top of the GaAs surface to form the MOSFET as in silicon case. The junction field-effect transistor (JFET) and metal-semiconductor field-effect transistor the MESFET, which were proposed in 1952 and 1966, respectively, are both devices made of a homogeneous semiconductor material such as Si or GaAs.

The JFET is basically a voltage-controlled resistor that employs a *p–n* junction as a "gate" to control the resistance; thus the current flows between two ohmic contacts. JFETs have a lower switching speed than MESFETs, mainly because of the higher input edge capacitances in planar JFET processes. Complementary logic is possible because *p–n* and *n–p* structures can readily be fabricated on the same wafer. This enables us to design SRAM blocks on chip [Roc90]. A 32-bit RISC microprocessor [Ras86] was developed using JFET technology. Later McDonnell Douglas Astronautics Company [Gei87] developed an all-GaAs JFET vector signal processor. The architecture of this processor is optimized for the matrix–vector arithmetic operations for digital signal-processing applications.

The MESFET, however, uses a metal–semiconductor rectifying contact (the Schottky contact) instead of a *p–n* junction for the gate electrode. Another homogeneous FET is the permeable-base transistor (PBT), whose fine metal grids are covered with the semiconductor's epitaxial overgrowth, as will be discussed in Chapter 12. The PBT can be operated at high-current density with high transconductance, as is characteristic of high-speed power devices.

The development of advanced epitaxial growth techniques such as molecular beam epitaxy (MBE) and metal–organic chemical vapor deposition (MOCVD) techniques in the 1970s has enabled the fabrication of high-quality semiconductor heterostructures to be successful. Many other growth techniques, including low-temperature epitaxial growth, are currently being developed in order to facilitate the fabrication of high-quality semiconductor heterostructural devices. Heterojunction FETs include now a large number of family members with different applications. Donor layer devices have one or more *n*-type doped layers. The most extensively investigated donor layer device is the modulation-doped field-effect transistor (MODFET), also called *high-electron-mobility transistor* (HEMT). The pseudomorphic HEMT (discussed in Chapter 9) has a higher mobility than the conventional HEMT, which has a higher cutoff frequency.

The heterojunction bipolar transistor (HBT) was conceived of in 1957, but its implementation was delayed until the early 1980s due to technological difficulties of obtaining a perfect interface between dissimilar semiconductors. It offers substantial improvements in performance over the silicon bipolar transistor. In recent years there have been rapid advancements in HBTs for high-speed SSI and MSI circuits and power device applications. Higher g_m's in HBT are available. Short-channel effects essentially do not exist in HBTs. The theory and application of HBTs will be discussed in Chapter 10. The materials systems most studied for HBTs are semiconductors that have identical lattice constants, such as AlGaAs/GaAs and InGaAs/InP systems.

The III–V compound semiconductors can be used to fabricate quantum-effect transistors and photonic devices. A typical quantum-effect device is a resonant-tunneling transistor where the operation distance is comparable to a de Broglie wavelength, on the order of 200 Å at room temperature [Sze90]. These small dimensions give rise to a quantum size effect that alters the band structures and the densities of state and enhances the device's transport properties.

The basic building block of the quantum-effect device is the resonant-tunneling diode. This diode has a double-barrier structure with four heterojunctions and one quantum well. The number of barriers can be increased, in series, to produce the multiple-well device. Many novel current-voltage characteristics can be obtained by inserting a resonant-tunneling structure into the device to transform it into a resonant-tunneling hot-electron transistor (RHET) or resonant-tunneling bioplar transistor (RTBT). These device can be used to form relatively complex circuit functions at high speed with reduced component counts.

The field of 1D (quantum wires) and 0D (quantum dots) devices is new, and progressing so fast that it is hard to predict future applications. Both systems require nanoscale lithographic techniques. In the electron device field, where ultrasmall structures are necessary for speed and integration, arrays of digital processors are being developed. This architecture may lead to new designs. In the optical field, with the concentration of electrons and holes over fewer k-states, the lower dimensions of injection lasers will enable higher gains [Wei91]. Electrooptic effects can have larger resonances due to the sharpening of the 1D and 0D densities of state compared to quantum wells.

Another major application of compound semiconductor devices is in optoelectronics. It is possible to integrate the field-effect, potential-effect, quantum-effect, and photonic devices to meet the future demands of electronic systems. Chapter 15 discusses the high-speed aspects of semiconductor photonic devices.

1.2 GaAs FOUNDRY

GaAs foundries have improved their production capacities over the years to meet the increasing demand for GaAs IC chips. *Microwave Journal* has done the survey of U.S. GaAs foundries [Ell91]. Of 14 responding foundries, 12 reported on their wafer-handling capabilities. There are plans that involve either expanding capacity to handle wafers of larger diameter or increasing the rate at which wafers of a given size can be processed.

1.2.1 Private/Commercial Requirements

The General Electric operation expects to remain a completely captive facility through 1994. Avantek has historically maintained its facilities exclusively for its own use, but it expects 30% of its capacity to be in the commercial market by 1994. Alpha and Anadigics were alone in relying completely on commercial business in 1991; Harris and TriQuint were not far behind with a 95% commercial business in 1991. Hughes, Litton, Raytheon, Texas Instruments, and TRW forecast rapidly increasing commercial production in 1994.

1.2.2 Analog/Digital Designs

More than 90% of the reported capacity is devoted to the production of analog devices or circuits. Eight of the facilities are now solely doing analog work. Anadigics, Texas Instruments, and TRW have small divisions for digital work. ITT maintains 15% digital capacity, and Raytheon expects to be using 20% of its capacity for digital circuits by 1994. TriQuint, with 70% of its capacity devoted to digital designs, is the firm most seriously involved in the digital market.