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GaAs Microelectronics

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Volume 11

GaAs Microelectronics

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Preface

Interest in GaAs for integrated circuits has increased rapidly over the past several years. Many organizations are conducting research and development in this technology, and production facilities are being established. The primary reason for this interest is performance. Gallium arsenide has a clear advantage over silicon for high-frequency microwave and high-speed digital applications. It also is superior to silicon in applications involving high temperatures or high-radiation environments. Initial motivation for the development of GaAs ICs, particularly in the United States, has been for military applications. Recently, there has been increasing interest in GaAs ICs for commercial applications.

This book addresses the important aspects of GaAs IC technology development ranging from materials preparation and IC fabrication to wafer evaluation and chip packaging. Chapter 1 traces the historical development of GaAs technology for high-speed and high-frequency applications. This chapter summarizes the important properties of GaAs that serve to make this material and its related compounds technologically important. Chapter 2 covers GaAs substrate growth, ion implantation and annealing, and materials characterization, technologies that are essential for IC development. Chapters 3–6 describe the various IC technologies that are currently under development. These include microwave and digital MESFET ICs, the most mature technologies, and bipolar and field-effect heterostructure transistor ICs. The high-speed capability of GaAs ICs introduces new problems, on-wafer testing and packaging. These topics are discussed in Chapters 7 and 8. Applications for GaAs ICs are covered in Chapters 9 and 10. The first of these chapters is concerned with high-speed computer applications; the second addresses military applications. The book concludes with a chapter on radiation effects in GaAs ICs. This is a very important area that has been the basis for much of the government support for GaAs technology development.

The number of engineers and scientists working directly on GaAs IC research, development, or production is increasing rapidly. In addition, others are becoming interested in this technology because of potential applications. This volume of the treatise "VLSI Electronics: Microstructure Science" is directed at these engineers and scientists as well as those who are already working in the field. It will provide a highly useful source of information for these individuals. It will also serve to inform those working in silicon VLSI technology as to the present state of GaAs technology and its future potential.

Gallium arsenide is often referred to as the "material of the future." The future now appears very bright. Gallium arsenide ICs will have an expanding range of applications that may eventually include microwave, digital, and optical functions on a single chip. This is an appropriate time for a book that describes the current state of the art.

WILLIAM R. WISSEMAN

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Chapter 1

GaAs Technology Perspective

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I. INTRODUCTION

Gallium arsenide (GaAs) has been viewed as a semiconductor with the potential to replace silicon in some applications since the late 1950s. Although substantial progress has been made in GaAs technology over the past 30 years, it is only in the last several years that some of

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the early expectations for GaAs devices and integrated circuits have been realized.

Gallium arsenide has several properties that make it a very attractive semiconducting material. First, it has a very high low-field electron mobility (six times that of silicon) giving it the potential for high-frequency performance. Its large bandgap makes high-temperature operation feasible. The large bandgap coupled with a short minority carrier lifetime gives GaAs an advantage over silicon in high-radiation environments. Gallium arsenide substrates can be grown with very high resistivities so that they can be used as a dielectric medium for high-frequency microwave and millimeter-wave integrated circuits. The high-resistivity substrate also simplifies device isolation for digital integrated circuits (ICs).

Sophisticated materials growth techniques have been developed that make it possible to grow III–V heterostructures on GaAs substrates with properties tailored for high-frequency performance. The optical properties of GaAs heterostructures make combinations of GaAs digital, microwave, and optical circuits feasible.

In spite of its great potential, GaAs has properties that have deterred exploitation of its advantages. Some of the disadvantages are associated with the fact that it is a binary semiconductor. Care must be taken to avoid excessive temperatures during processing in order to avoid dissociation of the surface. The use of diffusion to achieve the desired doping properties in silicon has been largely unsuccessful in GaAs. Unlike silicon, GaAs does not have a stable, easily grown native oxide that has been so important to the development of silicon MOSFET technology. The surface of GaAs is more susceptible to attack by chemicals used in semiconductor processing so that different approaches have had to be developed. Finally, GaAs is very fragile and can be easily broken during processing.

During the past several years, the potential advantages of GaAs have begun to outweigh the disadvantages. The technology is now advancing at an accelerated pace with many companies throughout the world involved in research and development and, in many cases, production.

This chapter traces the historical development of GaAs technology for high-speed or high-frequency applications and summarizes the important properties of GaAs and its related compounds. The properties of GaAs discrete devices, particularly with regard to their use in ICs, are then discussed, with emphasis on the GaAs field-effect transistor (FET), the focal point of the large effort now under way in GaAs technology. Advances in materials growth technology have made it possible to tailor material properties and develop new device concepts, and the potential impact of these developments on integrated circuits is discussed.

II. HISTORY OF GaAs TECHNOLOGY DEVELOPMENT

The development of GaAs technology began during the early 1950s. In this section the aspects of the technology development that have had an important influence on high-speed or high-frequency applications of GaAs and its related III–V compounds will be discussed. There has been a parallel development of GaAs and other III–V compounds for optical applications. While it is unquestionably true that these two developmental efforts have benefited each other, particularly in the areas of material and process technology, no attempt will be made to cover the development of GaAs for optical applications. Casey and Panish have given an excellent history of the development of III–V materials for optical applications in their book "Heterostructure Lasers" [1]. It is clear from their discussion that one of the primary benefits of the laser effort to high-speed and high-frequency GaAs devices is the establishment of techniques for preparing III–V heterostructures.

Figure 1 shows some of the important milestones in the development of GaAs technology that relate to high-speed or high-frequency applications. The milestones are categorized in the areas of materials, devices, and

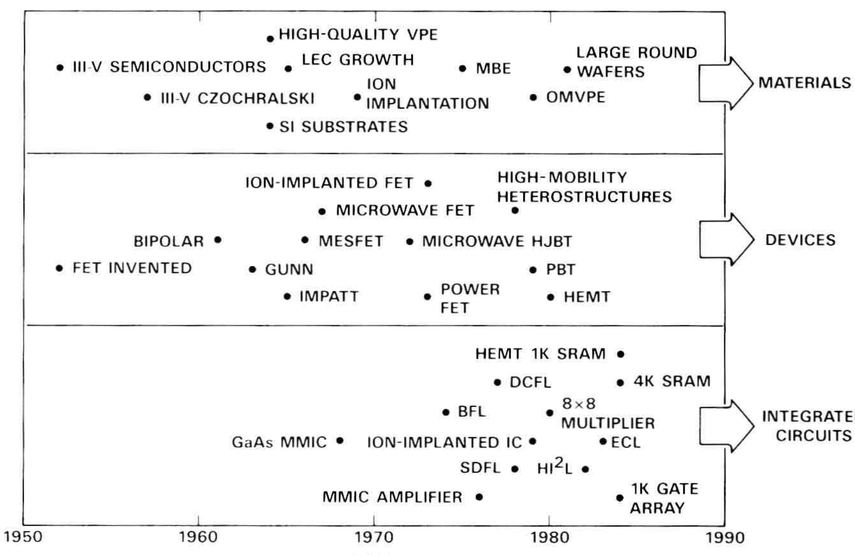

Fig. 1. GaAs technology milestones. Most of the important milestones that occurred during the development of GaAs technology for high-speed and high-frequency applications are shown. References are given in the text.

integrated circuits. These technology advances will be traced in the following sections. Two papers that are published in the September 1984 historical issue of *IEEE Transactions on Microwave Theory and Techniques* have aided in the preparation of this history. The first, by McQuiddy *et al.* traces the development of monolithic microwave integrated circuits (MMICs) [2]. The second, by Greiling, traces the development of GaAs FET digital IC technology [3].

A. The Early Period

Two important events occurred in 1952: Shockley invented the field-effect transistor [4], and Welker reported on the semiconducting properties of III–V compounds [5]. Over thirty years later there is a substantial effort under way to develop GaAs integrated circuits, with the GaAs FET serving as the focal point of much of this development. The path that was taken to reach the present high level of activity was indirect, with many problems encountered and solved along the way.

The bipolar transistor was the dominant device during this period. The initial interest in GaAs centered on the development of a GaAs bipolar transistor that would be superior to silicon transistors for high-frequency applications and that would operate at higher temperatures. Gallium arsenide offered an advantage because of a much higher electron mobility and a larger bandgap. The first GaAs bipolar transistor with rf performance superior to that of silicon and approaching that of germanium was reported in 1961 by Jones and Wurst [6]. This device, with a diffused p-type base and an alloyed n-type emitter, had an f_T value of 730 MHz. There were large efforts supported by substantial government funding aimed at developing GaAs bipolar transistors with improved high-frequency performance. These efforts had limited success, largely due to technological factors [7]. In 1966, von Munch reported on a GaAs bipolar transistor fabricated using a planar process that involved epitaxy and diffusion [8]. The typical values for f_T for these transistors were in the 100–300-MHz range, far less than the expected 1 GHz. It was not until 1980 that Yuan *et al.* reported a GaAs bipolar transistor fabricated using ion implantation with an f_T value of 1 GHz [9,10].

There was an intensive effort in GaAs materials technology during this period that has had a long-term impact on device and IC development. In 1956 Gremmelmeier prepared GaAs single crystals using the Czochralski technique [11]. In 1965, Mullin *et al.* applied the liquid-encapsulated Czochralski (LEC) technique to the growth of GaAs crystals [12]. This approach allows the growth of very high-purity crystals. The Bridgman