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Applications of Silicon–Germanium Heterostructure Devices

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In memory of
Dr Suva Maiti

CONTENTS

PREFACE

Since the first report of SiGe heterostructure bipolar transistors (HBTs) in 1987, there has been tremendous progress in SiGe research. The successful demonstrations of SiGe HBT technology, in both high-performance digital and analogue circuit applications, are the results of over 15 years of steady research progress from initial material preparations in 1984, through device demonstrations from 1987–1992 to large scale circuit fabrication in 1994 and commercial products in 1998.

With the development of the ultrahigh vacuum chemical vapour deposition (UHVCVD) system, which produces highly uniform SiGe heterostructures more rapidly than other methods, such as molecular beam epitaxy (MBE) or low-pressure CVD, only minor modifications to the process flow are required to incorporate the manufacture of SiGe HBTs into a conventional bipolar or complementary metal–oxide-semiconductor (BiCMOS) line. Indeed, SiGe HBTs integrated with CMOS (BiCMOS) circuits have been shown to be substantially cheaper than III–V technology. Qualified full-scale production devices (with cut-off frequencies in the 50–60 GHz range) and circuits using 200 mm wafers in a standard 0.5 μm CMOS line are now available.

SiGe HBTs are superior to Si bipolar junction transistors (BJTs) and comparable to the best GaAs transistors, in that they are ideally suited for low-voltage, low-power wireless communication applications. Promising research results, combined with recent commercialization announcements, have generated considerable optimism. Silicon has been pushed to the 1–2 GHz frequency domain. However, many new RF applications, such as handheld and personal communication systems (PCS), direct broadcast TV, local multipoint distribution systems and wireless LANs, require circuit operation at frequencies up to 30 GHz.

High-speed digital communications (up to 40 Gbps) such as synchronous optical network (SONET) applications also require high-speed devices—typically with a maximum oscillation frequency, f_{max} in excess of 100 GHz. It is now believed that, in many of these markets, SiGe will provide direct competition for GaAs on the grounds of cost and design flexibility. Indeed, it is possible that SiGe technology may eventually be applicable in the frequency range above 30 GHz, where GaAs is currently well established, in projects requiring wireless technology for traffic management and control, such as global positioning systems (GPS), sensor collision avoidance systems, road speed monitors and side airbag triggers.

The application of strained-SiGe to heterostructure field-effect transistors (FETs) is not as well developed as that of HBTs. In MOS technology, scaling the gate length is impeded by lithographic techniques and scaling device width is limited by the relatively low hole mobility of a silicon p-channel metal–oxide-semiconductor field-effect transistor (p-MOSFET). When used in a heterojunction FET, strained-SiGe enhances the mobility of holes but not of electrons. Thus, the current drive of the p-MOSFET is improved, but not that of the n-MOSFET. However, strained-Si grown on a relaxed-SiGe buffer layer improves the electron mobility and current drive of an n-MOSFET. Other important research topics include synthesis of SiGeC, a carbon-containing alloy of SiGe and Si, and quantum-confined structures, which may ultimately offer an alternative to lithographic techniques or serve as single-electron devices.

Integrated optoelectronics is another promising research field for SiGe devices, although development is hindered by the lack of a SiGe light emitter. Detectors and waveguides have been demonstrated, and integrated SiGe and Si devices are possible. Work is underway on a graded buffer layer—a virtual substrate—of SiGe that would permit III–V/SiGe/Si integration. Possible photonic devices are under development including: low-loss optical waveguides, photodetectors for 1.3–1.6 μm, light emitters, long-wave infrared detectors, optical switches and photonic integrated circuits.

In this textbook, we discuss the relevance of SiGe technology to all the above application areas. The main focus of the book is on device applications, backed up by an extensive survey of the literature. Chapter 1 reviews the key developments in SiGe technology from the earliest research to the present day, leading to a brief summary of the current status of SiGe products in the marketplace. Chapter 2 describes key technology issues for the growth of stable strained-SiGe layers using different types of reactors. The effect of the Ge composition on strain and the consequent effect on bandgap and mobility is described. Chapter 3 gives the background theory of the HBT. Chapter 4 describes issues relating to optimal design of SiGe HBTs and considers how device simulation can be used to determine key indicators of device performance. Chapter 5 extends the concepts of chapter 4 to give a number of examples of the use of device simulation to study a wide range of device structures involving application of SiGe.

Chapter 6 describes how growth of a strained silicon (strained-Si) layer on a relaxed-SiGe buffer layer has led to higher values of electron mobility with the resultant enhancement in the high-frequency performance of heterojunction field-effect transistors (HFETs). Strategies for the enhancement of hole mobility using either MOSFET or modulation-doped field-effect transistor (MODFET) structures are given. The impact of both strained-Si MODFETs and MOSFETs as a basis for future deep submicron CMOS is considered. In chapter 7, an alternative approach to the formation of a p-HFET is described, involving growth of a strained-SiGe epitaxial layer on a silicon substrate. Once again, the overall objective is a higher mobility, in this case hole mobility, to improve both the transconductance and bandwidth associated with the p-channel MOSFET.

Chapter 8 discusses design, characterization and application of Schottky diodes, while chapter 9 considers the design and application of optoelectronic devices. Finally, chapter 10 assesses how SiGe technology competes with other alternative technologies in the wireless telecommunications marketplace. It also focuses on how SiGe technology has rapidly matured, allowing its integration into a mixed signal BiCMOS process.

In summary, this book fills a gap in the literature in a rapidly evolving field, as it blends together wide ranging descriptions of SiGe technology, device physics and circuit applications. Where possible, the theoretical material is backed up by computer simulation. An extensive bibliography is provided for each chapter, which helps the reader identify the key stages in the development of SiGe from early research through to its integration in high-performance BiCMOS.

We wish to extend special thanks to Professor S C Jain, Consultant Editor, Institute of Physics Publishing, for his keen interest and valuable comments. We are grateful to Tom Spicer, Commissioning Editor, for his personal support for this project. It was due to the skill and efforts of his colleagues, Simon Laurenson, Production Editor, and Sarah Plenty, Production Controller, that the project could be completed in a relatively short time. They deserve our sincere thanks. The help of the Production Department in removing the deficiencies in several figures is gratefully acknowledged.

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C K Maiti
G A Armstrong
26 October 2000

Chapter 1

INTRODUCTION

Silicon is by far the most widely used semiconductor material and is likely to remain so for the foreseeable future, although from the perspective of an integrated circuit (IC) designer silicon is hardly a perfect semiconductor. Compared with other semiconductors, it is relatively poor in terms of how fast the charge carriers can move through the crystal lattice, which limits the speed at which silicon devices can operate. 'Why is silicon still dominant?' The answer to this question is economics. Silicon is abundant in nature, non-toxic, strong and an excellent conductor of heat. It can be grown to a very high purity and very large diameter (with 12 inch now being contemplated) wafers, and it readily forms a stable insulating film (SiO_2 or Si_3N_4) of high quality. Properties of this kind make silicon a natural choice for IC manufacturing and, in fact, over the past 40 years or so, the performance of silicon ICs and the density of devices per unit area have soared, while the cost per function has plunged (see figure 1.1). ICs are more difficult and more expensive to fabricate from III–V compound semiconductors such as GaAs/AlGaAs or InP. High-quality oxides are scarce in the III–V semiconductors, impeding device integration. High-purity, large diameter crystals are difficult to grow and yield is poor because of more defect density.

For decades, miniaturization has been the key to faster performance of ICs. As the size of a transistor, whether field effect or bipolar, influences its speed of operation, designers have focused on creating ever smaller transistors. The strategy for enhancing the function of an electronic device by reducing its critical dimensions is commonly referred to as scaling. Although scaling has led to improvement in the speed and flexibility of silicon-based electronics, the trend cannot continue indefinitely. Researchers are actively pursuing alternative approaches to boost the speed of electronic devices by introducing 'bandgap engineering'. In silicon technology, two materials may be used in bandgap-engineered transistors: silicon carbide (SiC) and silicon–germanium (SiGe). Silicon

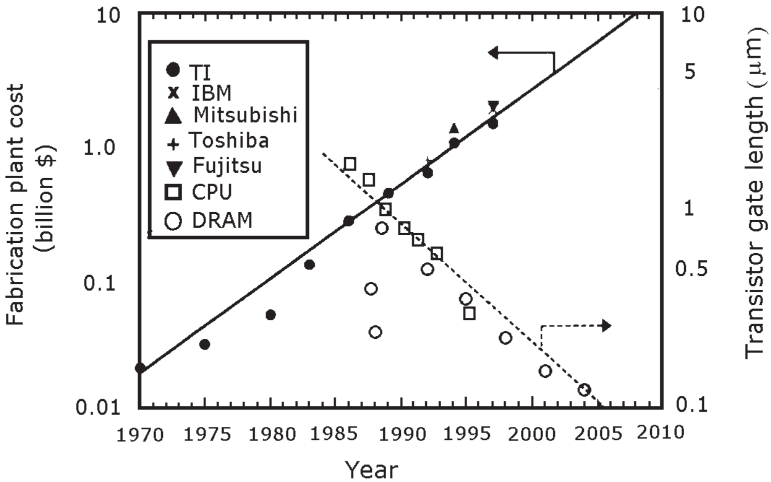

Figure 1.1. Moore's law: the gate length and cost of production lines as a function of time. Source: National Technology Roadmap for Semiconductors, Semiconductor Industry Association, San Jose, USA, 1997. (After Paul D J 1999 *Adv. Mater.* **11** 191–204.)

carbide is a suitable emitter material, since it has a wider bandgap of 2.2 eV, while SiGe is a suitable base material with a lower bandgap which is dependent on the Ge content.

The evolution of SiGe technology has been very rapid. It has gone from laboratory research in less than eight years to a commercial reality. As an example, a 12-bit digital-to-analogue converter (DAC) has been developed jointly by IBM and Analog Devices that processes data at 1.0 Gbit s^{-1}, which matches the speed of the best such circuits built using GaAs technology and it operates on a fraction of the power they require. At present, aggressively designed SiGe transistors have cut-off frequencies in excess of 130 GHz.

In recent years, SiGe transistors, and other devices based on SiGe alloys, have been evident in an increasing number of products. SiGe heterojunction bipolar transistor (HBT) technology has the advantage of relatively simple integration with conventional complementary metal–oxide semiconductor (CMOS) silicon circuits to form a SiGe BiCMOS technology, in which the Si bipolar devices and SiGe HBTs can be integrated for critical high-speed analogue or digital functions. Silicon CMOS can serve for very high density memory or compact on-chip signal processing functions, which cannot be realized in other technologies.

The two most important devices used in silicon technology are the bipolar and field-effect transistors, each having their strengths and

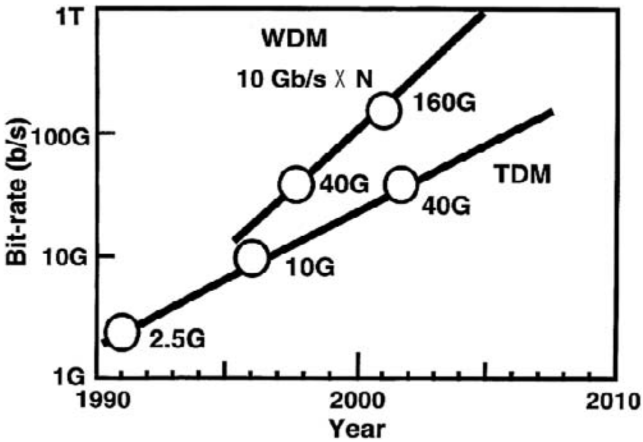

Figure 1.2. Capacity of backbone network. (After Nakamura M 1998 *IEEE ISSCC Tech. Dig.* pp 16–21.)

weaknesses. Bipolar transistors with their high transconductance have predominantly been used in analogue applications, such as small-signal amplification, and in high-speed digital circuits, such as emitter coupled logic (ECL). For digital circuit applications, CMOS technology dominates because of its low power dissipation and high density of integration. The variety of bipolar transistors can, in general, be grouped into those optimized to satisfy the requirements of two major industries: communications and computers.

As all activities of modern society have become information oriented, the need for high-speed and large capacity telecommunications systems is rapidly increasing. The rapid growth in data transmission has also created an urgent demand for increasing transmission capacity in backbone networks. Today, 10 Gb s^{-1} systems are in commercial use. Figure 1.2 shows the predicted trend for optical fibre transmission capacity. Two methods exist for achieving a higher transmission capacity:

(i) time division multiplexing (TDM), and
(ii) wavelength division multiplexing (WDM).

Figure 1.3 shows the relationship between the bit rate and the required cut-off frequency (f_T) of devices from differing technologies. A 10 Gb s^{-1} system with f_T in the range 25–50 GHz can be satisfied using Si bipolar technology, while a 40 Gb s^{-1} system, with corresponding f_T in the range 100–200 GHz, will require SiGe, GaAs or InP HBTs.

In communication applications, the increased importance of transmitting, receiving and interpreting data transmissions at high speeds has generated a need for high-frequency precision analogue circuitry. With

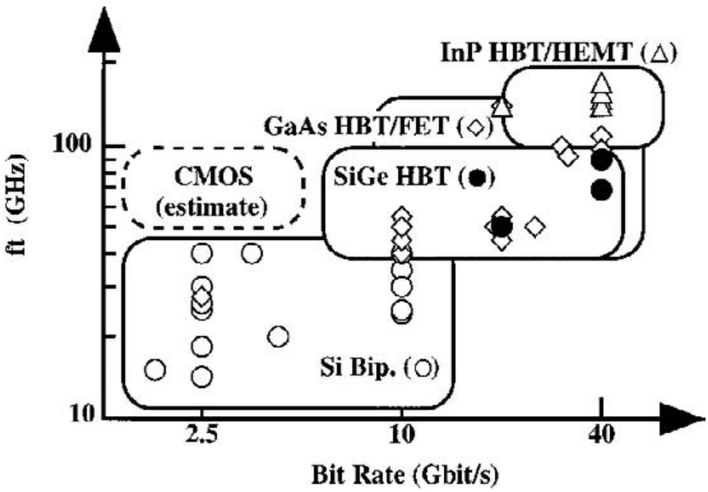

Figure 1.3. Electron devices for backbone network. (After Nakamura M 1998 *IEEE ISSCC Tech. Dig.* pp 16–21).

internet host counts doubling every five to seven months, there is a pressing need for high-speed interconnect circuits [1]. In these circuits, the high operating frequency, high transconductance, close matching of the device parameters and bandgap voltage referencing capabilities of bipolar transistors make them invaluable to the design of analogue circuits.

In the computer industry, the high-frequency performance and high current drive capabilities of bipolar transistors enable the realization of digital circuits with very low gate delay and high fan-out compatibility. The switching delay of a bipolar circuit is made up of three major components. The importance of these two characteristics can be best illustrated by a graph of the ECL gate delay time versus the collector current of the bipolar transistors, as shown in figure 1.4. In the low collector current range, the gate delay is a function of the load resistance, R_L, and the input capacitance of the gate, C_{in}, which is determined by the capacitance of the bipolar transistors as seen from the gate input. In the high collector current range, the gate delay decreases, approaching a minimum set by the total forward transit time of the transistor, τ_F. At higher currents, the product of the combination of extrinsic and intrinsic base resistance and the diffusion capacitance begins to dominate the propagation delay. As is evident from figure 1.4, the realization of low gate delays requires the use of increased collector currents. Thus, if the operating current per gate is a limiting factor, the design should be focused on the reduction of parasitic capacitances. The delay contributed by each part of the transistor is different, depending on the type of circuit used.