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High-Speed Devices and Circuits with THz Applications

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Devices, Circuits, and Systems

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Vancouver, British Columbia, Canada

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Preface

This book was motivated by the desire to explore the future perspectives of high-frequency technologies by presenting the state-of-the-art results in both new device developments and circuit implementations. It discusses issues for the circuit operation beyond 100 GHz with respect to device physics, circuit implementations, and some technological bottlenecks for system implementations. Also, recent device and circuit results using SiGe technologies as an alternative to Si complementary metal-oxide-semiconductor (CMOS) devices are presented.

Evolutionary device developments let people consider widening the frequency spectrum of interest up to terahertz. For example, as Si CMOS technologies evolve from 65 nm to 40 nm to 28 nm and further, the expected operation frequency of circuits correspondingly increases beyond 100 GHz. Nowadays, several universities and companies pursue developing high-frequency circuits and subsystems that could operate 60, 77, 90, 120, and 300 GHz.

Further challenging research works on nano-electronic devices have been reported, even enabling terahertz operations. Several research directions are challenged. New nano device developments using nanowires or carbon-based elements, e.g., graphene field effect transistors (FETs), carbon nanotubes, etc., seem to be very active research themes around the world in terms of new radio frequency (RF) directions. As the device technology continues to develop, circuit engineers could design integrated circuits (ICs) with higher operation frequencies and develop relevant new applications. It seems that novel devices could lead to the creation of new applications. Also, market needs would guide the direction of future developments, e.g., lower power consumption, higher integration density, and higher speed of operations.

Another exciting technical trend that we observe in the market and experience in daily life is the so-called big bang of Internet data traffic caused by handheld devices, such as laptops, tablets, and smart phones. As the amount of data traffic increases, higher-speed data transmitters and receivers play a greater role in the higher data transfer communications and now get meaningful attention from RF industries. For example, connectivity technology between high-performance computing servers in the data center becomes an important issue with respect to data transfer rates, distance, power consumption, the cost of connectivity modules, and backward/forward compatibilities with concurrent standards technologies. Several companies and research institutions exert their efforts to demonstrate next-generation connectivity technologies to customers.

This book tries to put those modern topics together, e.g., novel/new nano devices, their feasible THz applications, and modern high data transfer technologies. By bringing those heterogeneous topics into one, engineers who work in high-frequency engineering fields or develop devices and circuits considering high-frequency applications are supposed to grasp modern technical trends of nano devices, circuits, and their applications. The contributions are made by several academic institutions and relevant companies. Readers will grasp the future potential of RF products and research trends by reading through several chapters by the international experts in industry and academia.

Chapter 1 is contributed by a researcher at the Tokyo Institute of Technology and discusses THz sensing and imaging devices based on nano devices and materials. Various devices are explained in detail, especially regarding THz imaging. Chapter 2 is written by a researcher at Université Catholique de Louvain, which investigates SOI multigate nanowire FETs. It explains theoretical aspects of nanoscale nanowire MOSFETs, simulation methods, and their results. Chapters 3 and 4 are then devoted to SiGe technologies. They thoroughly discuss the physics of the SiGe heterojunction bipolar transistor (HBT) and present commercially available SiGe HBT devices. Also, several feasible applications using those devices are addressed. Very recent experimental results over 100 GHz are presented. If readers are interested in designing ICs working at beyond 100 GHz, it is recommended to read through those two chapters written by SiGe device experts. Chapter 5 is also very instructive in terms of THz IC design using standard Si CMOS devices, especially for THz imaging application. The author discusses in detail experimental setups for measurements, detection methods, and so on. Chapters 6 to 9 are devoted to high-speed data rate connectivity technologies. Three chapters are contributed by industrial colleagues and one by the University of Toronto. The discussion points range from system design to IC design. Also, they are useful to understand current state-of-the-art technologies in these development fields. Also, relevant standard activities and technical details behind those are addressed. One can have an outlook over these interconnection technology trends by reading those chapters.

It is impossible for me to express my gratitude adequately to all contributors for their sincere and passionate preparation of their chapters. I will remember their contributions and active exchange of their thoughts and ideas. Also, thanks should be given to Dr. Kris Iniewski for giving me an opportunity to edit this comprehensive and valuable book.

Finally, I also thank my lovely wife, Mrs. Hye Won Nam, for her warm support in my completing this book.

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About the Editor

Jung Han Choi received B.S. and M.S. degrees in electrical engineering from the Sogang University, Seoul, Korea, in 1999 and 2001, respectively, and the Dr.-Ing. degree from the Technische Universität München, Munich, Germany, in 2004. From 2001 to 2004, he was a research scientist in the Institute for High-Frequency Engineering at the Technische Universität München. During this time, he worked on high-speed device modeling, thin-film fabrication, network analyzer measurement, and circuit development for high-speed optical communications. From 2005 to 2011, he was with the Samsung Advanced Institute of Technology and the Samsung Digital Media & Communication Research Center, where he worked on the radio frequency (RF) biohealth sensor, nano devices, and RF/millimeter-wave circuit design, including 60 GHz Si complementary metal-oxide-semiconductor (CMOS) integrated circuits (ICs). In 2011 he joined the Fraunhofer Institute (Heinrich-Hertz Institute), Berlin, Germany. Now he is working on high-data-bit-rate transmitter and receiver circuits up to 100 Gb/s, relevant device active/passive modeling, and network analyzer measurement up to 170 GHz.

In 2003, he was awarded the EEEfCOM (Electrical and Electronic Engineering for Communication) Innovation prize for his contribution to the development of the high-speed receiver circuit. His current research interests range from the active/passive device, carbon-based nano device, and its modeling to high-frequency IC design and metamaterials.

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1 Terahertz Technology Based on Nano-Electronic Devices

Yukio Kawano

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1.1 INTRODUCTION

Since the establishment of the Maxwell equation and the discovery of the electromagnetic wave, researchers have been devoted to developing a lot of technologies based on the electromagnetic wave, bringing much change to human life. High-frequency electronics technology has provided radio, television, the cellular phone, and so on.

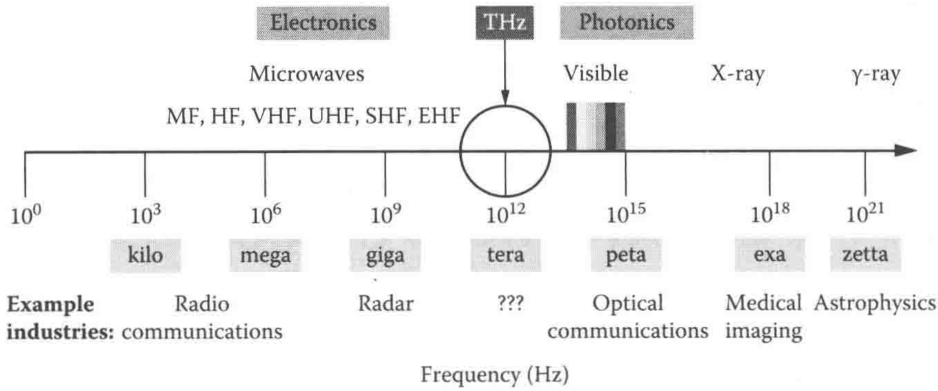

FIGURE 1.1 Chart of the electromagnetic wave spectrum. (Adapted from the THz Science & Technology Network [http://thznetwork.net/].)

From optics and photonics, optical communication, light-emitting diode (LED) lamp, endoscope, etc., have been produced.

The terahertz (THz, 10^{12} Hz) frequency region is located in between the microwave region and the visible light region (Figure 1.1). This region was merely studied by a small number of researchers in limited fields, such as chemical spectroscopy, astronomy, and solid-state physics. However, THz technology is nowadays in strong demand in a large variety of fields, ranging from basic science such as biochemical spectroscopy, astronomy, and materials science to practical science such as environmental science, medicine, agriculture, and security [1, 2]. What is the reason why the THz wave has attracted so much interest? The advantageous properties of the THz wave are that it can be transmitted through objects opaque to visible light and that the corresponding photon energy, 1–100 meV, is in the important energy spectrum for various materials and biomolecules. These features allow various applications of imaging and spectroscopy in this frequency band. Figure 1.2 displays several examples of applications of the THz waves. The measurements shown here illuminate the THz waves onto objects and map intensity distributions of reflected or transmitted THz waves. In some situations, by simultaneously measuring frequency spectra, one is able to identify the contents and characterize their physical/chemical properties. The technique therefore can be used as nondestructive inspection, which is based on the fact that the THz wave is much safer and does not do much damage, compared to the x-ray. In addition to industrial and medical applications, THz technology is also of much importance in basic sciences. For example, in astronomy, materials science, and biochemistry, the detection of very weak THz radiation from interstellar matter in space, electrons in materials, and biomolecules is expected to unlock mysteries behind the generation of the universe, quantum effect in materials, and life activity, respectively.

In the THz region, however, even basic components like detector and source have not been fully established, compared to the technically mature, other frequency regions. This is because the frequency of the THz wave is too high to be handled with conventional high-frequency semiconductor technology. In addition, the photon energy of the THz wave is much lower than band gap energy of semiconductors.

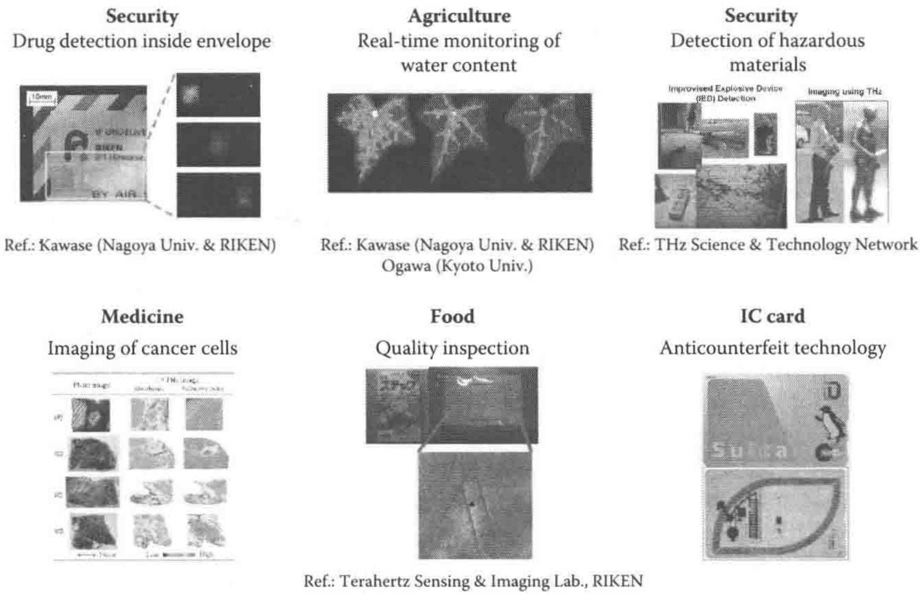

FIGURE 1.2 Various applications of THz imaging and spectroscopy.

For the above reasons, the THz wave is not easy to approach from either side of electronics and optics/photonics. In imaging technology, the THz wave also has a problem of low spatial resolution, which results from much longer wavelengths of the THz waves compared to those of visible light.

The applications of nanoscale materials and devices, however, are opening up new opportunities to overcome such difficulties. Nanostructured devices based on the superconductor, semiconductor, and carbon nanotube have enabled significant improvement in detection sensitivity and spatial resolution. In this chapter, I will describe new THz sensing and imaging technology based on such nano-electronic devices. Moreover, I will show applications of cutting-edge THz measurements to materials researches, which have provided new insight into electronic properties of the materials.

1.2 THz DETECTOR

1.2.1 Overview

THz detectors can be generally categorized into three types: bolometric (thermal) detection, wave detection, and quantum detection. In addition, they are also used as photoconductive antenna, electro-optic device, frequency mixer for heterodyne detection, etc. In this section, I show an overview of various THz detectors and briefly discuss their advantages and disadvantages.

1.2.1.1 Bolometric (Thermal) Detection

This type of detector utilizes temperature rise via THz absorption. As the crystal temperature of the detector decreases, the detection sensitivity is improved, but the detection speed becomes low (a typical time constant is of the order of ms below 4 K). The detected signal is mostly resistance change arising from the rise in the crystal temperature due to the THz absorption. There is another type of readout mechanism: measuring gas pressure via thermal expansion (Golay cell detector). Since all the detectors based on bolometric detection respond to electromagnetic waves in a wide-frequency region, one needs a frequency cutoff filter. Wei et al. [3] recently reported a nanoscaled superconductor bolometer with the ability of a single THz photon detection.

1.2.1.2 Wave Detection

This detector senses the THz electromagnetic wave as a high-frequency wave. A representative device is a Schottky barrier diode detector. The advantages of this detector are high-speed detection (time constant of ~ns) and room temperature operation. This detector is often used in sub-THz regions, because the sensitivity becomes low with increasing the frequency of the incident THz wave.

1.2.1.3 Quantum Detection

In contrast to wave detection, this type of detector senses photons of the THz electromagnetic wave. Solid-state devices based on materials like superconductors and semiconductors usually have energy level spacing corresponding to the THz photon energy (1–100 meV), for example, energy gap of superconductor, impurity level of semiconductor, and energy level spacing due to quantum electron confinement of semiconductor quantum structure. It follows that excess carriers are generated in the devices, when these devices absorb the THz waves. One can detect the THz wave by recording electric signals produced by the carriers. THz detectors based on a nanoscale island connected to electrodes, such as superconductor junctions [4] and semiconductor quantum dots [5, 6], have been presented and demonstrated to exhibit ultra-high sensitivity, including the level of single-photon detection. However, the operation of the superconductor and semiconductor detectors needs a very low temperature environment (<0.3 K). This situation forces one to use a dilution refrigerator or a ^{3}He refrigerator, restricting the range of practical uses.

1.2.1.4 Others

THz time-domain spectroscopy (TDS) is nowadays widely employed in THz research fields. As detectors, the photoconductive antenna and the electro-optic device are used. This measurement allows real-time observation of the oscillatory electric field of the THz wave, providing information on both amplitude and phase of the THz electric field. Though these detectors work under room temperature, their operation requires an expensive femtosecond pulse laser.

Another type is a frequency mixer using a supercomputer in which a beat signal corresponding to the frequency difference with a local oscillator is measured. This type of detector is often used in the fields of astronomy and environmental science.

1.2.2 CNT-Based THz Detector

The carbon nanotube (CNT) is expected to be used as a building block for future nano-electronics, nano-photonics, and nano-mechanics owing to its unique