Terahertz Technology and Applications

Qi-Ye Wen, Yan Zhang, Sheng-Jiang Chang, Huai-Wu Zhang,
Jun-Cheng Cao and Wei-Wei Liu, *Editors*

UESTC Press

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Preface

Terahertz science is a cutting-edge interdisciplinary area that involves fundamental physics, electronics, optics, advanced materials, biomedicine, astrophysics, environmental science, etc. Recently, it has shown great potential in imaging, wireless communications, radar detection, biomedical diagnostics, materials detection, and national security. Further, as a segment of electromagnetic waves, terahertz waves have tremendous crossovers with many natural science areas, which sets up a platform for scientists from different fields to innovate and incubate new research directions.

Terahertz science and technology has developed very rapidly in China with strong endorsement from government agency, military, and large enterprises. There has been a major thrust towards terahertz science and technology from numerous Chinese universities, research institutes, and group companies. Many Chinese scientists also often show up in the important terahertz international conferences. As far as I know, some practical products have been developed by some institutes in China, and they are already commercializing them. It is not exaggerated terahertz science and technology is setting off an upsurge among Chinese science community. Under such circumstance, we publish this book with the following intentions:

Firstly, we hope this book will include the major breakthroughs in terahertz science made by Chinese scholars. The most active research groups were invited to review their representative research work. By reading this book, readers will get to overview about terahertz science research in China, to know Chinese terahertz research groups, and to understand their progress. This will provide a platform for mutual understandings between Chinese research groups, which in turn will facilitate cooperation and communication.

Secondly, we hope this book will be a good learning resource for junior researchers, graduate students and other professionals who want to know terahertz science and technology. In order to do so, we have invited much-renounced scholars to write tutorial chapters, which cover fundamentals, methods, state-of-the-art research, and trends. On the other hand, we also invited many young researchers to introduce research work in some specific area, which will be good case studies for young researchers. As a new attempt, we hope everyone will learn some knowledge from this book.

As for me, I would like to dedicate this book to several outstanding Chinese pioneers in terahertz field. They are Prof. Sheng-Gang Liu, Prof. Jian-Quan Yao, and Prof. Pei-Heng Wu. I am also very grateful to my friends who actively participate in writing and editing this book. I know them under different circumstances, but we become intimate friends and reliable partners. They kindly accepted my invitation, and brought to the book not just considerable knowledge but passionate enthusiasm. I believe, besides science, these friends are my best treasure in my life.

Sincerely thanks to my friends!

Prof. Qi-Ye Wen

Committee Member of Terahertz Technology and Applications, JEST

Dec. 18, 2016

Chengdu, China

TTA Committee Member
Special Section on Terahertz Technology and Applications,
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Sheng-Jiang Chang received his M.S. degree in laser physics and Ph.D. degree in optical engineering from Nankai University in 1993 and 1996, respectively. From 1998 to 2000, he was invited to City University of Hong Kong and awarded the postdoctoral fellowship with Department of Electronic Engineering, City University of Hong Kong. Since 2000, he has been with the Institute of Modern Optics, Nankai University, where he is presently a full professor and doctorial supervisor with the College of Electronic Information and Optical Engineering. He holds hundreds of publications and more than 10 patents. His current research interests involve microstructural terahertz devices, terahertz time-domain spectroscopy technology, digital image processing, and the applications of artificial neural network in pattern recognition.

Qiang Cheng was born in Anhui Province, China in 1979. He received the B.S. and M.S. degrees from Nanjing University of Aeronautics and Astronautics, Nanjing in 2001 and 2004, respectively, and Ph.D. degree from Southeast University, Nanjing in 2008. He joined the State Key Laboratory of Millimeter Waves, Southeast University in 2008, where he was involved in the development of metamaterials and meta-devices. He is currently a full professor with the Radio Department, Southeast University. He has authored or coauthored more than one hundred publications cited more than 1700 times. Prof. Qiang Cheng served as the vice-chair of the 2008 and 2010 International Workshop on Metamaterials, Nanjing, China. He was a recipient of the 2010 Best Paper Award from New Journal of Physics. He was awarded China's Top Ten Scientific Advances of 2010 and the second class National Natural Science Award in 2014. Now, he leads a group of 15 Ph.D. students and master students in the area of metamaterials, tunable microwaves circuits, microwave imaging, and terahertz systems.

James Kolodzey was born in Philadelphia, Pennsylvania in the USA in 1950. He received the Ph.D. degree in electrical engineering from Princeton University in Princeton, New Jersey in 1986 for research on silicon germanium alloys. From 1986 to 1990, he was an assistant professor of electrical engineering at the University of Illinois at Urbana-Champaign where he established laboratories for the cryogenic studies of high frequency devices and the fabrication of devices by molecular beam epitaxy. Since 1991, he has been in the Department of Electrical and Computer Engineering at the University of Delaware, in Newark, Delaware in the USA, where he is currently the Charles Black Evans Professor of Electrical Engineering. He has over 130 publications in refereed journals and over 100 conference publications.

His research interests include: the fabrication and characterization of high frequency optical and electronic devices; the properties of terahertz sources and detectors; silicon-germanium-tin-carbon materials for infrared optoelectronics; quantum dot devices; spintronic devices, alternative gate dielectrics for CMOS; and interfaces between biological materials and semiconductors. Prof. Kolodzey is a Senior Member of the Institute of Electrical and Electronic Engineers, has several patents, served as chair of conferences, and received awards for research contributions.

Qi-Jie Wang received the B.E. degree in electrical engineering from the University of Science and Technology of China, Hefei, China in 2001, graduating one year in advance, and the Ph.D. degree in electrical and electronic engineering from Nanyang Technological University (NTU), Singapore in 2005, with NTU and Singapore Millennium Foundation (SMF) scholarship. He received the 2005 SMF Post-Doctoral Fellowship at NTU.

Then, he joined the School of Engineering and Applied Science, Harvard University, as a post-doctoral researcher in 2007. In 2009, he was assigned as a joint Nanyang assistant professor at the Microelectronics Division, School of Electrical and Electronic Engineering, and the Physics and Applied Physics Division, School of Physical and Mathematical Sciences. He was promoted to an associate professor in the same department in 2015.

His current research interests are to explore theoretically and experimentally nanostructured semiconductor and fiber-based materials, and nanophotonic devices (nanoplasmonics, photonic crystals, and metamaterials) with an emphasis on all aspects of the problem from design, fabrication, and characterization to integration at system level. He was a recipient of the top prize for the Young Inventor Awards of the SPIE Photonics Europe Innovation Village in 2004, a golden award from the Fifth Young Inventor's Awards from HP and Wall Street Journal in 2005, a co-recipient of the Institution of Engineers Singapore Engineering Achievement Team Award in 2005, and Singapore Young Scientist Award 2014.

Qi-Ye Wen received his B.S. degree from Wuhan University of Technology, Wuhan in 1998, M.S. degree from Guangxi University, Nanning in 2001, and Ph.D. degree from University of Electronic Science and Technology of China (UESTC), Chengdu in 2005. He is now an professor with the School of Microelectronic and Solid-State Electronics, UESTC. He has published more than 100 journal papers with a H-index of 16. One of his papers on THz absorber was selected as the ESI Highly Cited Paper. His research interests include electronic materials and devices for THz wave manipulation, THz communication and imaging.

Yan Zhang received his M. S. degree and Ph.D. degree from Harbin Institute of Technology and Institute of Physics, Chinese Academy of Science in 1996 and 1999, respectively. He is now a professor with the Department of Physics, Capital Normal University. He has published more than 150 journal papers. His research interests include optical information processing, surface plasmoic optics, and THz spectroscopy and imaging.

All the committee members are listed in alphabetical order by the last name.

CONTENTS

· Terahertz Sources and Emitters ·

Chaired by Prof. Hua-Bing Wang and Prof. Jun-Chen Cao

· Terahertz Materials ·

Chaired by Prof. Yan Zhang

· Terahertz Waveguide and Functional Devices ·

Chaired by Prof. Sheng-Jiang Chang

· Terahertz Spectroscopy and Its Applications ·

Chaired by Prof. Wei-Wei Liu

· Terahertz Applications ·

Chaired by Prof. Qi-Ye Wen and Prof. Huai-Wu Zhang

Chapter 1.

Terahertz Sources and Emitters

♦ *Chaired by* Prof. Hua-Bing Wang *and* Prof. Jun-Cheng Cao

Thermal Effect in Superconducting Terahertz Emitters

Xian-Jing Zhou and Hua-Bing Wang

***Abstract*—Terahertz (THz) continuous-wave emitters made from high temperature cuprate superconductor $Bi_2Sr_2CaCu_2O_8$ (BSCCO) single crystals have attracted a lot of research interests with their novel properties, such as the frequency tunability, broad frequency range, and considerable output power. In the development of superconducting THz emitters, there are several blocks, of which the thermal effect is a primary one. In this article, we mainly discussed two aspects of the thermal effect, i.e. hot-spot phenomenon in high-bias regime and cooling efficiency. We also talked about the possible applications in which these superconducting THz emitters can be embedded.**

***Index Terms*—Cooling efficiency, hot-spot, superconductors, terahertz.**

1. Introduction

Terahertz (THz) continuous-wave emitters made from high critical temperature (high-T_c) superconductors have been very attractive THz sources to fill the so-called THz gap[1]. Compared with other THz wave emitters, superconducting THz emitters have several novel properties such as broad frequency tenability, emitting at the desired frequency range—the low THz range. All these features make superconducting THz emitters promising candidates in many practical areas, like nondestructive evaluation, medical diagnostics, and high-speed telecommunications. In this article, we first introduce some fundamental knowledge about superconductor Josephson junctions. Following is a short history of superconducting THz emitters. Then we focus on the recent experimental improvements in the developments of these emitters.

When the temperature of superconductors decreases below the critical temperature T_c, Cooper pairs will be formed in superconductors by combining two electrons with opposite momentum of equal magnitude and with opposite spins. The Cooper pairs can be described with a macroscopic coherent matter wave of which the magnitude is the density of Cooper

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pairs and the phase connected with the current flow. From this macroscopic coherent matter wave, we can deduce the two basic properties of superconductors, i.e. zero resistivity and ideal diamagnetism. London penetration depth λ_L and Ginzburg-Landau coherence length ξ_{GL} are the two characteristic length scales that are of interests. The London penetration depth λ_L refers to the exponentially decaying magnetic field at the surface of a superconductor, while the Ginzburg-Landau coherence length ξ_{GL} indicates a length within which the macroscopic wave function can change.

A large number of superconducting electronic devices are based on the Josephson junction, which is formed by separating two superconductors with a thin non-superconducting barrier. The tunnel current through this barrier, which is known as Josephson current, is proportional to the sine of the phase difference of the macroscopic matter wave of the two superconductors. Thus, we have the first Josephson equation $I=I_c \sin \gamma$, where I_c is the critical current that dependent on specific junction rather than the material properties of the two superconductors and γ is the phase difference of the two superconductors.

When applying a DC voltage to a Josephson junction, the phase difference γ will vary with time t. This can be described by the second Josephson equation $\dot{\gamma} = 2\pi V / \Phi_0$, thus the supercurrent across the junction will flow at a high frequency determined by $f=V/\Phi_0$, where Φ_0 is the flux quantum and V is the applied voltage. For V=1 mV, the oscillating frequency f is about 483.6 GHz. With this property, Josephson junctions have many applications in the high frequency field, either as detectors or as radiation sources. However, the theoretical highest voltage, over which the superconductivity will be destroyed, that a Josephson junction can sustain is determined by the energy gap Δ_0 of the superconductors. As a result, for typical low-T_c superconductors with a low energy gap, the highest frequency is around 700 GHz.

While the property of a Josephson junction can be deduced by considering the tunneling effect of Cooper pairs and quasi particles microscopically, a much simple circuit model proposed by W. C. Stewart and D. E. McCumber which is known as resistance and capacitance shunted junction (RCSJ) model can describe the *I-V* characteristics and dynamic of a Josephson junction very well. In this model as shown in Fig. 1, a practical junction is considered as a parallel connection of an Ohmic resistance, a capacitance, and a supercurrent. The resistance R responses for the quasi particles and the capacitance C is the one that might exist between the two superconducting layers. In some cases, the capacitance can be ignored, and the model turns to be an RCSJ model in this situation.

Since the discovery of the cuprate superconductors in the late 1980s, they have attracted a lot of research interests for their novel superconductivities and high critical temperature which is desired for practical applications. In 1992, R. Kleiner *et al.* found the intrinsic Josephson effect in the layered cuprate superconductor $Bi_2Sr_2CaCu_2O_8$ (BSCCO) single crystals of which the T_c was about 85 K to 95 K[2]. In BSCCO single crystals, as shown in Fig. 2, the two adjacent 0.3 nm thick superconducting CuO_2 layers are separated by the insulating BiO and SrO layers[3]. The Ginzburg-Landau coherence length along the c-axis ξ_c is about 0.1 nm. Thus the intrinsic Josephson junctions (IJJs) naturally occur in BSCCO single crystals with the distance between two adjacent CuO_2 layers about 1.5 nm. As a result, a 1.5 um thick BSCCO single crystal consists of 1000 Josephson junctions in series. Unlike low-T_c superconductors, the gap energy of BSCCO is rather high, making the IJJs much suitable for generating high frequency electromagnetic waves into the THz range.

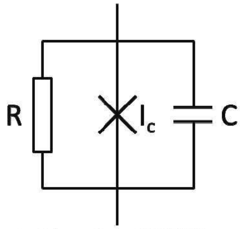


Fig. 1 Resistance and capacitance shunted junction (RCSJ) model of a single Josephson junction.

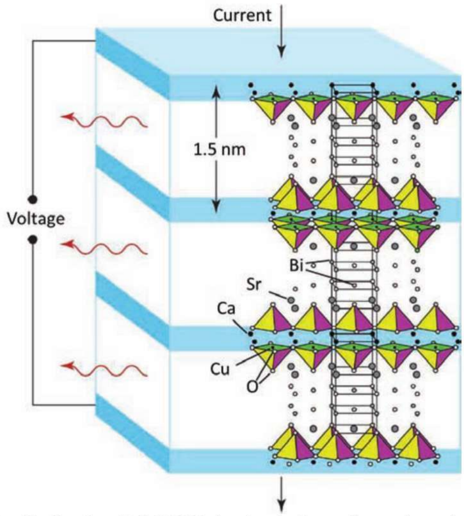


Fig. 2 Schematic of $Bi_2Sr_2CaCu_2O_8$ (BSCCO) intrinsic Josephson junctions. The distance between two superconducting CuO_2 layer is about 1.5 nm. Reuse from [3].

The electro dynamic of a single Josephson junction is governed by the combination of Josephson relations and Maxwell equations, i.e. the so-called sine-Gordon equation. Several electromagnetic states including the electromagnetic wave radiation can be obtained by solving the equation and have been also found experimentally. A famous example allowing high frequency electromagnetic radiation is the Fiske resonance[4] using the whole junction as a resonator. However, the emission power from one Josephson junction is quite small. For IJJs, i.e. Josephson junctions in series, the electrodynamics are governed by the coupled sine-Gordon equations. Much more possible electromagnetic states can exist in this situation. Compared with a single Josephson junction of which the emission power is typically well below 1 nW, the emission power from IJJs can be rather higher, scaled with the square of the junction number, if all the junctions are phase-locked.

In 2007, strong coherent THz emission was detected from BSCCO IJJs stacks[5]. The initial emitter was constructed as a mesa standing on a huge base BSCCO single crystal. The stacks were about 1 μm thick and had lateral dimensions in the 100 μm range which was abandoned in the previous researches. The emission frequency, between 0.5 THz and 0.8 THz, scaled reciprocally with the width of the mesa, emphasizing the geometry resonance's contribution to the phase synchronization between junctions, which was essential for powerful emission.

Following stimulated researches include theoretically solving the coupled sine-Gordon equations to find reasonable explanations for the possible synchronization mechanism[6]-[10], experimentally explaining the underlying physics and searching unforeseen phenomena[11]-[21], and experimentally revising the structure of emitters to enhance the emission power and increase the emission frequency[22]-[25]. Among them, the studies on the thermal effect in superconducting THz emitters are worth discussing with several paragraphs. In the following, we will divide the thermal effect into two parts.

As promising THz sources, superconducting THz emitters are supposed to be used in many practical applications. To this end, prototypes with superconducting THz emitters have also been demonstrated[26]-[30]. Transmission type[26], reflection type[27], and computed tomography[28] imaging systems using superconducting THz emitters show that these sources can be used for security and nondestructive detection. A compacted "THz torch", as shown in Fig. 3, with superconducting THz emitters cooled by liquid nitrogen makes such THz sources much convenient and economical[29].

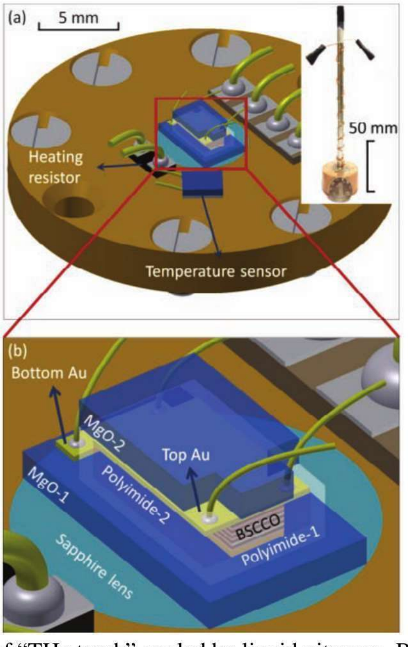
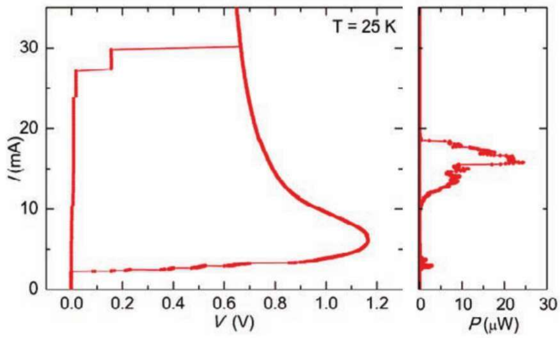


Fig. 3 Schematic of "THz torch" cooled by liquid nitrogen. Reuse from [29].

In the reminder of this article, we will mainly introduce and discuss two aspects: the hot spot domain and cooling effect, of the thermal issues of superconducting THz emitters.

2. Hot Spot Domain

A typical *I-V* characteristic of the superconducting THz emitter is shown in the Fig. 4 (a). Here we focus on the resistive state of the emitter, i.e. where the voltage is non-zero. In Fig. 4 (a) the resistive state is the region where V>0.2 V. Generally, the voltage increased with the increasing bias current. However, after reaching the maximum value, about 1.16 V in the Fig. 4 (a), the voltage started to decrease with the increasing bias current and a back bend curve with a negative slope occurred. Thus we usually divided the IVC into two parts, one with the positive slope called low-bias regime and one with the negative slope called high-bias regime which is also called hot-spot regime which will be explained in the following. In Fig. 4 (a), the regime where I>6 mA is just the high-bias regime as defined previously.



(a) (b)

Fig. 4 Superconducting THz emitter: (a) typical *I-V* characteristic and (b) emission power dependent on the bias current. Reuse from [21].

With the low temperature scanning laser microscopy (LTSLM), H.-B. Wang and his colleagues discovered that there was a hot-spot region of which the local temperature T_L was much higher than the bath temperature T_b and even above the critical temperature T_c of the superconductor while the other part of the emitter was still cold when the emitter was in the high-bias regime[11]-[13]. Following experiments using other methods like the optical thermoluminescent[31],[32] also verified the existence of hot-spot region.

When performing the LTSLM, a focused laser beam with wavelength λ =680 nm was irradiated on the surface of the mesa, and caused a raise of the local temperature with severalK. Then those temperature dependent electrical parameters, like resistivity ρ, varied and induced a global change in the voltage across the mesa. By moving the laser spot and recording the corresponding induced voltage changes $\Delta V(x, y)$, the 2D temperature distribution in the mesa could be captured. The schematic diagram of the LTSLM is shown in Fig. 5.