Terahertz RF Electronics and System Integration

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With the advent and fast-paced development of ultrahigh-speed digital interconnects for next-generation computing systems, low-latency broadband wireless communications for fifth generation and beyond, high-resolution imaging techniques and emerging parametric sensing systems for medical/biomedical and security applications, material and structure analyses and evaluations, and deep-space radio astrophysics, and so on, the search for system solutions with larger bandwidth has sparked a growing research in expanding the electromagnetic spectrum into the terahertz (THz) regime. Generally, the THz frequency covers 300 GHz through 10 THz, which presents the most fundamental spectrum gap between electronics and photonics.

This special issue provides a timely and comprehensive review of the state-of-the-art terahertz RF electronic technologies and systems.

It has been well recognized that the THz technologies are among the most challenging in connection with the exploration of the electromagnetic spectrum for practical applications, at least for mass manufacturing and economically viable solutions and applications. This is closely related to a number of difficult and performance-bottlenecking issues in terms of signal generation, frequency conversion, noise control, structure integration, and system packaging, and so forth. In particular, relatively high-power and low-noise THz signal generation and processing at room temperature through solid-state devices, which may offer a wide range of hybrid and monolithic integration with other constituent elements, are still under intensive research worldwide. There have been generally two distinct approaches for THz wave generation, namely, photonics and electronics. The photonic approach is rather expensive and bulky, typically involving multiple optical waves mixing down to millimeter-wave and THz, which can offer a good range of frequency coverage but with poor conversion efficiency and low power output. The electronic approach is to use classical microwave techniques for THz signal generation and processing through nonlinear devices-based frequency multiplications, which has been considered as lower cost and easier-to-integrate into solutions for large-scaled applications, as compared to its photonic counterparts.

The recent advances in both semiconductor technology and packaging solutions have steadfastly improved the device performances for low-cost THz developments and applications. A monolithic InP pHEMT power amplifier with output power approaching milliwatt level with operating frequency beyond 1 THz has been recently reported. On the other hand, the Schottky diode-based frequency multipliers have achieved two orders of magnitude in output power improvement in the last decade, showing about 20 microwatts (μW) near 2.5 THz, comparable to the power

Digital Object Identifier: 10.1109/JPROC.2017.2700658

level that lasers could yield. It is remarkable that silicon- or III-V compound-based plasma wave, Schottky, tunneling, complementary metal–oxide–semiconductor (CMOS), and heterodyne devices and techniques have shown good and steadily improving responsivity and noise equivalent power (NEP) comparable to the photonic detectors. In parallel, THz-oriented system-on-chip and related emerging packaging techniques such as micromachining and 3-D printing have been pushing forward the THz integration technologies at an unprecedented pace. To enable accurate characterization and parameter extractions over broadband spectrum up to THz, innovative measurements and instrumentation have been in the development for tackling some real challenges in the accurate characterization of THz devices, circuits, and systems. Furthermore, advanced structure-engineered techniques such as metasurfaces, which have been successfully demonstrated at low RF frequencies, can also be applied at THz frequencies. In summary, the state-of-the-art all-electronics solutions demonstrated so far for THz RF system development and integration have shown great promise in closing the THz gap and generating widespread THz-based commercial applications.

This special issue is developed to provide a timely and comprehensive review of the state-of-the-art THz RF electronic technologies and systems. A wide range of topics of interest are covered through 12 papers selected for this special issue, which focus on rapidly growing fields of semiconductor diodes, transistor technologies, packaging techniques, measurement approaches, and emerging applications. Those papers are authored and coauthored by well represented research groups in the field around the world. As guest editors, we are fully aware of ever-expanding THz research and development activities, dealing with different aspects of technological challenges and system applications. It is impossible for us to include in this special issue all the topics of interest and all the results of research that are being carried out in the world. THz-related photonic research progress was excluded for example, so that the THz-related electronic research status could be highlighted. The quest for the THz RF electronics development and system integration is enabled by continued improvements and disruptive solutions in processing technologies, device materials, design methodologies, and building structures. Of course, the THz researchers, engineers, and technologists are endowed by genius, funding, and support. The special issue leads the readers to witness and explore the power of the most advanced RF electronics and techniques and also to extrapolate their technological roadmap toward the future.

We are striving to present a comprehensive picture of the THz electronics research landscape with the limited 12 papers selected for publications in this special issue, which set the stage of closing the THz gap even though much more efforts should be invested in a continuous fashion. For a straightforward, logical, and concise presentation, the special issue is organized into five general areas of interest. The first group of papers discusses the advancements of various III–V electronic diode techniques in support of THz signal generation and processing. The second group of papers addresses the HBT and related transistor technologies for THz applications, which are based on Si/SiGe and III–V semiconductor platforms. Those papers highlight the main driving forces for the state-of-the-art development of THz electronic devices and integrated circuits such as the design of sources and detectors beyond 1.0 THz. Those papers show how semiconductor technologies are able to power the advancement of the THz electronics and technologies and applications, while disclosing an interesting revelation of those progressive technologies approaching to end the THz gap practically. The third group of papers is concerned with micromachining techniques and packaging solutions in the development of THz integrated circuits and systems. Those processing and packaging methods provide unique low-loss and high-performance approaches in component fabrication and system integration. The following paper presents research and development of THz metrology, essential to accurate characterization of THz components and systems through advanced measurement and instrumentation techniques. The last paper in the special issue is concluded by the demonstration of THz reflecting and transmitting metasurfaces, which is an example of THz wave control and manipulations, underlining a wide range of potential THz applications. The following is a narrative description of all the selected papers following their order of appearance in the special issue.

The first paper, "THz diode technology: Status, prospects, and applications" by Mehdi *et al.*, reviews the current status of diode technology with focus on GaAs Schottky diodes, detailing some of the different ways for fabricating THz chips. An overview regarding the current state of diode technology and performance for THz frequency multipliers and mixers is presented, along with applications enabled by these diodes.

The second paper, "Status and prospects of high-power heterostructure barrier varactor frequency multipliers" by Stake *et al.*, presents the status of HBV diode frequency multipliers, discussing this diode technology which can offer advantages over conventional solutions. A number of application examples utilizing HBV diodes are presented in the work. It has been shown that the HBV diode can improve the performance of THz sources while simplifying their making.

In the third paper, "Advanced terahertz sensing and imaging systems based on integrated III-V interband tunneling devices" by Liu *et al.*, the development of heterostructure backward tunnel diodes (HBDs) in the InAs/AlSb/AlGaSb material system is reviewed, and it has been demonstrated with detection sensitivity that outperforms the current state of the art. The monolithic integration of HBDs is presented, and the potential of using HBDs for realizing THz systems is discussed, along with the integration of HBDs into waveguides for more advanced THz sensing and imaging.

The fourth paper, "Si/SiGe:C and InP/GaAsSb heterojunction bipolar transistors for THz applications" by Chevalier *et al.*, presents Si/SiGe:C and InP/GaAsSb HBTs which feature specific assets to address submillimeter-wave and THz applications. Process and modeling status and challenges are reviewed. The specific topics of thermal and substrate effects, reliability, and HF measurements are also addressed.

The fifth paper, "InP HBT technologies for THz integrated circuits" by Urteaga *et al.*, reports on THz circuit developments based on InP HBT technologies. This paper also reviews the state of the art in THz-capable InP HBT devices and IC technologies. Challenges in extending transistor bandwidth and in circuit design at THz frequencies are also addressed.

The sixth paper, "SiGe HBT technology: Future trends and TCAD-based roadmap" by Schröter *et al.*, presents a technology roadmap for the electrical performance of high-speed silicon–germanium (SiGe) HBTs. The presented roadmap defines five major technology nodes with the maximum oscillation frequency of a typical THz device structure. An extensive and consistent set of technology and electrical parameters is provided. The challenges and possible solutions for achieving the predicted performance are discussed.

The seventh paper, "Silicon millimeter-wave, terahertz, and high-speed fiber-optic device and benchmark circuit scaling through the 2030 ITRS horizon" by Voinigescu *et al.*, reviews the technology requirements of future 100–300-GHz millimeter-wave (mm-wave) systems-on-chip for various applications. Measurements of state-of-the-art silicon MOSFETs, SiGe HBTs, and of a variety of HBT–HBT and MOS-HBT cascodes are presented from dc to 325 GHz. The challenges facing mm-wave MOSFET and SiGe HBT device and benchmark circuit scaling are discussed along with the comparison of simulations and measurements.

The eighth paper, "Silicon-on-insulator substrates as a micromachining platform for advanced terahertz circuits" by Barker *et al.*, presents a comprehensive overview of the development and utilization of a micromachined SOI fabrication process that has enabled the development of THz components and circuits. It is demonstrated that ultrathin silicon is able to provide the required characteristics to enable the heterogeneous integration of multiple device technologies for future THz system-on-chip (T-SoC) development.

Packages are fundamentally expected to provide a physical housing for THz devices and ICs and reliable signal interconnections from the inside to the outside or *vice versa*. The ninth paper, "Packages for terahertz electronics" by Song, provides a broad overview of recent progress in interconnections and packaging technologies dealing with these issues for THz electronics. In particular, emerging concepts based on commercial ceramic technologies, micromachining, and 3-D-printing technologies are highlighted, along with metallic split blocks with rectangular waveguides.

Also, the tenth paper, "Micromachined packaging for terahertz systems" by Chattopadhyay *et al.*, describes several potential micromachining methods for packaging at THz frequencies. These techniques use photolithographic techniques to produce highly accurate features. Silicon micromachining and electroforming offers the additional advantage of vertical stacking of components. Several integrated systems are discussed to demonstrate these capabilities.

The selected eleventh paper, "Metrology state-of-the-art and challenges in broadband phase-sensitive terahertz measurements" by Naftaly *et al.*, addresses and presents two measurement techniques and discusses the different issues involved in making measurements using these systems. Calibration, verification, and measurement traceability issues are reviewed along with other major challenges. The differences in, and similarities between, the two measurement methods are discussed and analyzed. The operating principles of electro-optic sampling (EOS) are briefly discussed.

Our final paper in the special issue, "Terahertz reflecting and transmitting metasurfaces" by Qu *et al.*, presents a review of developments in wave manipulation from microwave to optical frequencies, together with new results in the THz regime. Generation of phase curves for pixel design requires *a priori* information on material properties at THz frequencies. Fabrication of THz devices entails micromachining in the clean room while their experimental validation demands both amplitude and phase information.

As our readers can figure it out, the special issue aims to serve as a review and reference of current milestones and future outlook in the development of THz electronics and integrations that are tightly related to the progress of various semiconductor technologies, material syntheses, processing techniques, packaging solutions, design methodologies, structure innovations, and measurement approaches. We hope that this special issue will stimulate the imaginations and interests of our readers in this exciting field, which can find many new and important applications that other techniques may fail to support.

ACKNOWLEDGMENT

The guest editors are grateful to the authors of all the submitted papers for their contributions to this special issue, to the reviewers for their constructive comments and suggestions, and to H. Joel Trussell, the Editor-in Chief, Vaishali Damle, the Managing Editor, and J. Sun and M. Meyer, the Publications Editors, for their professional support throughout the preparation of this special issue. ■

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Thomas W. Crowe received the B.S. degree in physics from Montclair State College, Montclair, NJ, USA, in 1980 and the M.S.E.E. and Ph.D. degrees from the University of Virginia (UVA), Charlottesville, VA, USA, in 1982 and 1986, respectively.

He joined the UVA faculty as a Research Assistant Professor of Electrical Engineering in 1986, and was promoted to Research Professor in 1997. He served as the Director of the Semiconductor Device Laboratory from 1987 through 2003. Through his research at UVA, he and his team worked to enable scientific measurements through the development of Schottky diode technology for frequencies ranging from a few hundred gigahertz through 5 THz. His contributions include: improved understanding of the operation, design and manufacture of terahertz diodes, the development of planar diodes and integrated diode circuits including the demonstration of the first planar mixer and varactor multiplier diodes that competed favorably with the previous whisker-contacted devices, and the implementation of advanced CAD tools for terahertz device and circuit design. Throughout this period, his team at UVA was also the premier supplier of diodes for the worldwide terahertz community, including both scientific research teams and the nascent terahertz industry. He has authored over 50 refereed publications and well over 100 conference proceedings papers. He has also presented numerous invited talks throughout the United States, Europe, and Asia. While at UVA, he was the principal investigator (PI) on $25 million of sponsored research from the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), Jet Propulsion Laboratory (JPL), the National Radio Astronomy Observatory (NRAO), the U.S. Army, and the U.S. Air Force, as well as private industry. He founded Virginia Diodes, Inc. (VDI) in 1996. VDI's mission is to accelerate the emergence of terahertz technology as a tool for scientific, security, industrial, and commercial applications. This effort includes both advancing the core technologies and making the latest advancements broadly available through the commercial market. VDI is a thriving small business that has supplied terahertz devices, components, and subsystems to an ever-growing customer base of many hundreds of companies, research laboratories, and universities throughout the world. Through this effort, VDI has developed terahertz sources with unprecedented power and versatility. These are critical for scientific applications such as radio astronomy, plasma diagnostics, and molecular spectroscopy. For example, VDI developed and supplied all of the frequency multipliers for the international ALMA observatory, as well as the LO sources for the terahertz heterodyne receivers on the U.S./German airborne observatory (SOFIA). VDI has also developed compact receiver systems for NASA's atmospheric studies, most recently for CubeSATs. VDI is also focused on test and measurement equipment, including frequency extenders for signal generation, signal analysis, and vector network analysis. For example, fully calibrated network analysis is now routine throughout the frequency range from 50 GHz to 1.1 THz, and VDI systems are now in use up to 1.5 THz. This commercially available technology has greatly expanded our ability to test and verify the characteristics and performance of new terahertz components and systems, and is playing a critical role in the now rapid emergence of the terahertz frequency band.

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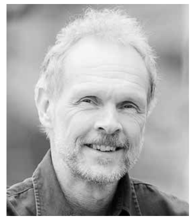
Dr. Deal received the Outstanding Young Engineer Award in 2009, the 2012 IEEE MWCL "Tatsuo Itoh" Best Paper Award, and the 2016 IEEE EDL "George E. Smith" Best Paper Award. His team has also been awarded the Guinness World Record for world's fastest integrated circuit in 2014 for first low-noise amplifiers at 1000 GHz. He remains involved with the IEEE, and is an Associate Editor of the IEEE Microwave and Wireless Components Letters and Co-Editor of the IEEE Transactions on Terahertz Science and Technology.



Michael Schröter (Senior Member, IEEE) received the Dr.-Ing. degree in electrical engineering and the "venia legendi" on semiconductor devices from the Ruhr-University Bochum, Bochum, Germany, in 1988 and 1994, respectively.

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Dr. Wu is a Fellow of the Canadian Academy of Engineering (CAE) and of the Royal Society of Canada (The Canadian Academy of the Sciences and Humanities). He is a Member of Electromagnetics Academy, Sigma Xi, URSI, and IEEE-Eta Kappa Nu (IEEE-HKN). He has held key positions in and has served on various panels and international committees including the chair of Technical Program Committees, International Steering Committees, and international conferences/symposia. In particular, he was the General Chair of the 2012 IEEE Microwave Theory and Techniques (IEEE MTT-S) International Microwave Symposium (IMS). He has served on the Editorial/Review Boards of many technical journals, transactions, proceedings and letters as well as scientific encyclopedia, including as an Editor or Guest Editor. He was the Chair of the joint IEEE chapters of MTT-S/AP-S/LEOS, Montréal, QC, Canada. He is currently the Chair of the newly restructured IEEE MTT-S Montreal Chapter. He is an elected IEEE MTT-S Administrative Committee (AdCom) Member (2006—2015) and has served as Chair of the IEEE MTT-S Transnational Committee, Member and Geographic Activities (MGA) Committee and Technical Coordinating Committee (TCC) among many other AdCom functions. He was an IEEE MTT-S Distinguished Microwave Lecturer (2009—2011). He was the 2016 IEEE MTT-S President. He is the inaugural three-year representative of North America as a Member of the European Microwave Association (EuMA) General Assembly. He was the recipient of many awards and prizes including the first IEEE MTT-S Outstanding Young Engineer Award, the 2004 Fessenden Medal of the IEEE Canada, the 2009 Thomas W. Eadie Medal of the Royal Society of Canada, the Queen Elizabeth II Diamond Jubilee Medal in 2013, the 2013 FCCP Education Foundation Award of Merit, the 2014 IEEE MTT-S Microwave Application Award, the 2014 Marie-Victorin Prize (Prix du Quebec-the highest distinction of Québec in the natural sciences and engineering), the 2015 Prix d'Excellence en Recherche et Innovation of Polytechnique Montréal, and the 2015 IEEE Montreal Section Gold Medal of Achievement.