Materials for Terahertz Optical Science and Technology

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The terahertz (THz) (0.3–10 THz) part of the electromagnetic spectrum encompasses astonishing prospects for futuristic science and technology as it hosts many exciting and unique spectral signatures beneficial for both fundamental investigations and practical implications. These constitute a wide variety of applications within individual as well as interdisciplinary topics involving astronomy, materials spectroscopy, photonics, biomedical imaging and diagnosis, sensing, metrology, spintronics, wireless communication, nonlinear applications and many more. The spectral significance of terahertz waves was known for decades. However, their deployment in many ways was challenging due to their strong atmospheric absorption. Starting subtly from the pioneering works on Auston terahertz switches, it is only recently that several breakthroughs relating to intense sources, detectors and optical components have essentially bridged the so-called “terahertz technological gap” and fashioned their sovereignty over the current and future cutting-edge technologies.

Exotic platforms set by some prominent developments in THz spectroscopy has persuaded the discovery of multitude of physical phenomena in a variety of classical and quantum material systems. Over the years, a considerable part of terahertz research has been focused on development of broadband and strong-THz emission using laser-driven material systems that have enabled emerging applications in the nonlinear THz spectroscopy. Among them, more prominent techniques include THz generation through optical rectification processes in electro-optical materials, strongly driven currents in optically excited gases (air-plasma), laser induced transient effects in complex oxides, and ultrafast demagnetization processes in topological semimetals. Dirac semimetals have revealed a clear distinction between the physical processes occurring during interband and intraband transitions within individual as well as interdisciplinary topics involving astronomy, materials spectroscopy, photonics, biomedical imaging and diagnosis, sensing, metrology, spintronics, wireless communication, nonlinear applications and many more. The spectral significance of terahertz waves was known for decades. However, their deployment in many ways was challenging due to their strong atmospheric absorption. Starting subtly from the pioneering works on Auston terahertz switches, it is only recently that several breakthroughs relating to intense sources, detectors and optical components have essentially bridged the so-called “terahertz technological gap” and fashioned their sovereignty over the current and future cutting-edge technologies.

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excitations. The works discussed by P. Kuzel et al.\cite{3} and D. Zhao et al.\cite{4} reveal that in bulk-bandgap semiconductors such as low-dimensional nanocrystals and perovskites, the major contribution to their carrier dynamics and charge transport properties is through change in free carrier density in the material during the interband transition using near-infrared pulses, which also reveals the positive change in THz photoconductivity. On the other hand, in Dirac materials such as graphene and topological insulators, the carrier dynamics are strongly influenced by the interplay between the photoinduced change in Drude weight and carrier scattering rate (see the review works by C. In and H. Choi\cite{5}). Interestingly, the carrier dynamics in graphene show positive as well as negative change in the THz photoconductivity indicating both photoinduced absorption and transmission of THz depending on the doping level in graphene. Graphene is one of the most sought material at THz frequencies and hosts exotic dynamical properties for nonlinear and optoelectronic applications. Recently, shining intense THz sources on graphene layer has shown a strong THz nonlinearity and THz higher harmonic generation.
enhancing its capabilities as graphene based ultrafast nonlinear optoelectronic devices at THz frequencies (see the progress report from H. A. Hafez et al.[8]). The charge injection processes in 2D materials-bulk semiconductor interfaces (such as graphene-Si interface and MoS2-Si interface) demonstrate low-threshold, efficient and ultrafast THz modulators (see the progress report on terahertz modulation from P. Gopalan and B. Sensale-Rodriguez[2]). Investigations of carrier dynamics in 2D van der Waals (vdW) materials reveal the formation and relaxation of excitons in the strongly correlated heterostructures, which further demonstrates exciting prospects as ultrafast terahertz devices (see the review on terahertz time resolved spectroscopy from P. Han et al.[9]). In order to strongly enhance the THz conductance in a semiconductor material, a THz near-field microscopy together with the TRTS is employed that reveals enhanced local-field variations at the micro-tip (see the work by N. van Hoof et al.[9]). Further, THz spectrum provides useful spectral fingerprint and a greater scope to investigate and unveil quasiparticle electrodynamics in a variety of strongly correlated transition metal oxides (TMOs) that host several exotic and novel electronic and magnetic phases of quantum matter, as discussed in K. S. Kumar et al.[10]. The continuous THz sources based on quantum cascade lasers (QCL) emitting single frequency and high-power THz beam is used for various table-top applications including sensing, communication, high resolution imaging and nonlinear optics. In the work described by Y. Zeng et al.[11] novel THz cavities were used to manipulate the emission features and beam engineering of THz emission from QCL for enhancing their implications in on-chip communication networks.

THz microcavities in the form of artificially structured subwavelength metamaterials have attracted immense attention in the THz photonics for their tunable and on-demand optical properties. They facilitate enhanced confinement of THz fields in a small mode volume, thereby boosting their applications as ultrasensitive sensors, nonlinear devices, resonant modulators and phase shifters. In the works discussed in Z. Ren et al.[12] and Y.-G. Jeong et al.[13] various devices based on microelectromechanical structures (MEMS) and vanadium dioxide (VO2) interfaced tunable metamaterials are shown to actively modulate the THz waves through electrical/thermal controls. In the MEMS structures, balance between the restoring forces of bimorph cantilevers and the external forces dictate the active reconfiguration, whereas in VO2, change in its conductive properties during the metal-to-insulator transition is used to modulate the THz resonances in metamaterials. Interfacing the graphene layer with metamaterials also enables an efficient modulation of resonant THz waves through voltage control (see the work on graphene metasurfaces from X. Chen et al.[14]). Besides modulation, the metamaterial structures enable enhanced sensitivity of the structures for thin-film sensing, biomolecule sensing and cancer/tumor cell detection at THz frequencies (see the review by M. Beruete and I. Jáuregui-López[15]). The strong THz resonances with the combination of dielectric engineering in metamaterials enable sensitive molecule-specific detection capabilities by enhancing the resonant vibrational/absorption peaks of the target bio/chemical molecules or any material systems, as reported in M. Seo and H.-R. Park[16].

A different class of low-loss metasurfaces fabricated with dielectric materials (see the review by R. T. Ako et al.[17]) with appropriate geometry can assist in sharp guided mode resonances with extremely high quality (Q)-factors (see the work by S. Han et al.[18]). Whispering gallery mode (WGM) resonators offer another exotic platform to realize high Q-factor resonances at THz frequencies that enable capabilities for single molecule sensing with high specificity for medical, chemical and security applications, as discussed in the works reviewed by S. S. Prabhu and V. G. Achanta.[19] An alternative approach to enhance the device sensitivity is shown through total internal reflection of THz waves in a dielectric cavity that allows broadband imaging of cancer tissues, thin film sensing and holographic images (see the review on total internal reflection geometry from Q. Sun et al.[20]). The other applications of engineered metasurfaces include beam steering and wavefront manipulation of THz waves, which is of a considerable interest in the programmable devices and communication applications (see the work on terahertz beam steering from X. Fu et al.[21]).

This special issue presents some of the exciting works that give a flavor of the fascinating science and plethora of technological developments being carried out in the technologically significant THz part of electromagnetic spectrum. Particularly, the new and exciting family of multi-dimensional materials together with the development of efficient sources are set to serve the novel explorations and innovations in the field of THz science and technology. Thus, the prospects arising from establishing a strong interdisciplinary research could potentially enable procuring raindrops galore that could be derived from the sky of THz Science and Technology (see Figure 1).


