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Introduction to the Special Issue on "Terahertz Spectroscopy of Carbon Nanomaterials"

Yun-Shik lee

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Carbon nanomaterials, such as carbon nanotube (CNT) and graphene, have remarkable electrical and optical properties. The transport of charge carriers is ballistic for a long distance; the current density and the carrier mobility exceed the conventional values of semiconductors; the relaxation time of optically-injected carriers is unusually fast. These exceptional properties of carbon nanomaterials have sparked intensive searches for futuristic applications in a wide range from nanometer-scale switches to single molecule detection. In particular, the unique electronic properties lead to strong nonlinear electrodynamics, which implies great potential for high-speed electronics operating at terahertz (THz) switching rates. It is of great importance to understand the THz properties of carbon nanomaterials not only for practical applications but also for fundamental science. THz spectroscopy of carbon nanomaterials is still in its early stage, yet notable progresses have been made both in experimental and theoretical studies for the last several years.

The main thrust of this special issue is to present the recent studies on THz carrier dynamics in low-dimensional carbon nanostructures demonstrating the remarkable THz properties of the unique material systems. The issue includes six invited articles, which review the outstanding progresses made for the last several years, providing a comprehensive overview of the fundamental THz properties of the carbon nanomaterials.

The first article, "Terahertz properties of graphene" by Callum Docherty and Michael Johnston from University of Oxford, UK, reviews THz time-domain spectroscopy (THz-TDS) and related THz measurements of graphene. The article shows that THz-TDS is a powerful tool not only to characterize the free carrier transport but also to probe the interband and intraband response of excited carriers in graphene. The second article, "Terahertz photon mixing effect in gapped graphene" by Chao Zhang and his colleagues from University of Wollongong, Australia, and Chinese Academy of Sciences in Shanghai, China, presents theoretical calculations of the nonlinear frequency mixing in doped graphene with a bandgap. The theoretical study reveals that the intraband nonlinear THz responses of gapped graphene are highly sensitive to the bandgap energy. In the third article, "Spectroscopic study on ultrafast carrier dynamics and terahertz amplified stimulated emission in

Y.-S. lee (✉)
Oregon State University, Corvallis, OR, USA
e-mail: leeys@physics.oregonstate.edu

optically pumped graphene," Taiichi Otsuji and his colleagues from Tohoku University, University of Aizu, and JST-CREST, Japan, review the recent advances in THz spectroscopy of ultrafast carrier dynamics in optically excited graphene. They observed a striking phenomenon that incoming THz pulses are amplified via stimulated emission. The fourth paper, "High-contrast imaging of graphene via time-domain terahertz spectroscopy" by Yun-Shik Lee and his colleagues from Oregon State University, Cornell University, USA, and Yonsei University, Korea, demonstrates THz imaging of single-layer, large-area graphene using THz-TDS. They show that THz imaging with broadband THz pulses is an excellent method to map out local microscopic conductivity in graphene. In the fifth paper, "Terahertz dynamics of quantum-confined electrons in carbon nanomaterials", Junichiro Kono and his colleagues from Rice University, USA, and Osaka University, Japan, present THz-TDS of single-wall CNTs (SWCNTs) and graphene. They observe extremely anisotropic THz conductivities in SWCNTs. They also show that THz properties of graphene are susceptible to the Fermi energy. In the final paper, "Intense terahertz pulse-induced nonlinear responses in carbon nanotubes", Ryo Shimano and his colleagues from University of Tokyo, Japan, demonstrate that strong THz pulses induce nonlinear optical effects in SWCNTs. They observe that electroabsorption instantaneously responds to incident THz waves due to the AC Stark effect of excitons. As a whole, these articles provide a comprehensive review of THz spectroscopy of carbon nanomaterials at present, and also shed light on perspective and path for future research.