Semiconductor Nonlinear Dynamics Study by Broadband Terahertz Spectroscopy

by

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ABSTRACT

Semiconductor nonlinearity in the terahertz (THz) frequency range has been attracting considerable attention due to the recent development of high-power semiconductor-based nanodevices. However, the underlying physics concerning carrier dynamics in the presence of high-field THz transients is still obscure. This thesis introduces an ultrafast, time-resolved THz pump/THz probe approach to the study of semiconductor properties in the nonlinear regime. The carrier dynamics regarding two mechanisms, intervalley scattering and impact ionization, is observed for doped InAs on a sub-picosecond time scale. In addition, polaron modulation driven by intense THz pulses is experimentally and theoretically investigated. The observed polaron dynamics verifies the interaction between energetic electrons and a phonon field. In contrast to previous work which reports optical phonon responses, acoustic phonon modulations are addressed in this study. A further understanding of the intense field interacting with solid materials will accelerate the development of semiconductor devices.

This thesis starts with the design and performance of a table-top THz spectrometer which has the advantages of ultra-broad bandwidth (one order higher bandwidth compared to a conventional ZnTe sensor) and high electric field strength (>100 kV/cm). Unlike the conventional THz time-domain spectroscopy, the spectrometer integrates a novel THz air-biased-coherent-detection (THz-ABCD) technique and utilizes selected gases as THz emitters and sensors. In comparison with commonly used electro-optic (EO) crystals or photoconductive (PC) dipole antennas, the gases have the benefits of no phonon absorption as existing in EO crystals and no carrier life time limitation as observed in PC dipole antennas.

The newly development THz-ABCD spectrometer with a strong THz field strength capability provides a platform for various research topics especially on the nonlinear carrier dynamics of semiconductors. Two mechanisms, electron intervalley scattering and impact ionization of InAs crystals, are observed under the excitation of intense THz field on a sub-picosecond time scale. These two competing mechanisms are demonstrated by changing the impurity doping type of the semiconductors and varying the strength of the THz field.

Another investigation of nonlinear carrier dynamics is the observation of coherent polaron oscillation in n-doped semiconductors excited by intense THz pulses. Through modulations of surface reflection with a THz pump/THz probe technique, this work experimentally verifies the interaction between energetic electrons and a phonon field, which has been theoretically predicted by previous publications, and shows that this interaction applies for the acoustic phonon modes. Usually, two transverse acoustic (2TA) phonon responses are inactive in infrared measurement, while they are detectable in second-order Raman spectroscopy. The study of polaron dynamics, with nonlinear THz spectroscopy (in the far-infrared range), provides a unique method to diagnose the overtones of 2TA phonon responses of semiconductors, and therefore incorporates the abilities of both infrared and Raman spectroscopy.

This work presents a new milestone in wave-matter interaction and seeks to benefit the industrial applications in high power, small scale devices.