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Terahertz Emission from the Surfaces of InAs and Other Narrow-Gap Semiconductors

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THz pulses were used to investigate carrier dynamics in narrow-gap semiconductors. The measurement of the optically induced THz pulse absorption transients provided important insights into electron energy relaxation in the conduction band. In the second set of experiments, THz generation from the surfaces of various semiconductors was studied and compared. It was found that the most efficient THz emitters are semiconductors with a narrow band gap, large intervalley separation in the conduction band, and low nonparabolicity of the main valley.

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1. Introduction

Sub-picosecond duration electrical pulses with the spectral content reaching to the frequencies of several terahertzes (THz pulses), which are generated and sampled by femtosecond-laser-illuminated ultrafast semiconductor switches, are finding numerous applications in spectroscopy and characterization of various materials and devices [1]. In the present contribution we will describe the use of two techniques for characterizing the electron dynamics in various narrow-gap semiconductor (NGS) materials. The first of such experiments is an optical pump–THz probe measurement of the photoexcited electron dynamics, a technique which is normally used for studying carrier recombination in materials with picosecond and shorter lifetimes [2]. In the second experiment — measurement of THz pulses emitted by semiconductor surface illuminated by femtosecond laser radiation — the observed effect gives extensive information on the physical processes that are taking place in the material.

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2. Experimental results and discussion

In the experiments, a femtosecond Ti:sapphire laser (the central wavelength of 800 nm, the pulse duration of 150 fs, the repetition rate of 76 MHz) and photoconductor antennae manufactured from low-temperature MBE-grown GaAs were used. In the optical pump–THz probe setup, two parts of the laser beam were illuminating such antennae used as THz emitter and detector, whereas a third part, arriving at the sample's surface at different time delays, created in it the non-equilibrium carriers. By investigating the THz emission, one of the optical beams impinged at the surface of the semiconductor at 45° angle and the second switched-on the antenna acting as THz pulse detector.

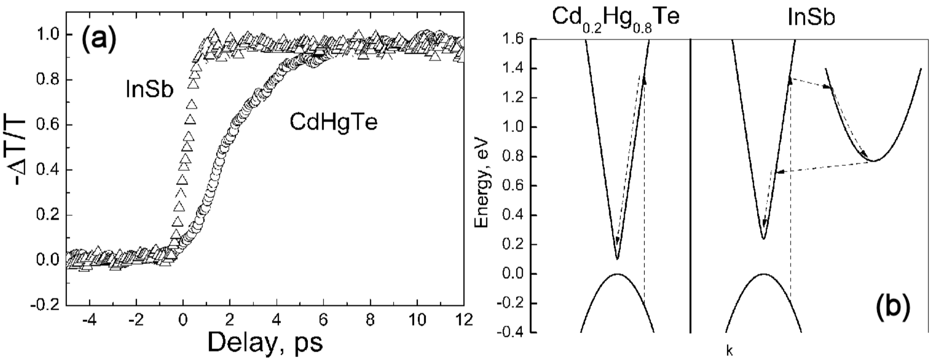

Fig. 1. (a) THz transmission vs. time delay at 80 K for the $Cd_{0.2}Hg_{0.8}Te$ and InSb samples. (b) The electron relaxation processes in $Cd_{0.2}Hg_{0.8}Te$ and InSb samples at 80 K.

Figure 1a shows the rising parts of the optically induced THz absorption transients measured on bulk single-crystalline InSb:Cr and epitaxial $Cd_{0.2}Hg_{0.8}Te$ samples at 80 K. The duration of the rising parts for the latter material is more than 5 times longer than for the former. We explain this difference by the details of the conduction band structure of InSb and $Cd_{0.2}Hg_{0.8}Te$ at high electron energies (Fig. 1b). For $Cd_{0.2}Hg_{0.8}Te$, the photoexcited electrons remain in a highly non-parabolic Γ valley all the time. The slow increase THz absorption in this case is a consequence of the electron energy relaxation and the reduction of their effective mass. The comparison between the experiment and the rate-equation model and the Kane dispersion relation gives the value of the electron energy relaxation time equal to 1 ps. In the case of InSb, the electrons are excited by the Ti:sapphire laser quanta high above the position of the subsidiary L valleys [3] and contribute to the THz absorption only when they cool down and enter the main Γ valley at relatively low energy where the nonparabolicity is less significant than in the case of $Cd_{0.2}Hg_{0.8}Te$.

One of the most important mechanisms leading to THz emission from the surfaces of NGS excited by femtosecond laser pulses are surface photovoltage transients caused by different electron and hole diffusion rates (the photo-Dember effect). When the photo-Dember effect dominates THz emission from a semiconductor surface, the emission becomes stronger with increasing electron excess energy. This is illustrated in Fig. 2 by the THz pulse amplitudes measured at the same experimental conditions on different semiconducting compounds from the InAs–GaAs system. Throughout this system, the gap energy varies from 0.35 eV for InAs to 1.4 eV for GaAs, and the electron excess energies, respectively, from 1.05 eV to 0.15 eV. Therefore, semiconductors with a narrower band gap should be more efficient THz emitters, if the photon energy is fixed and other THz generation mechanisms are negligible.

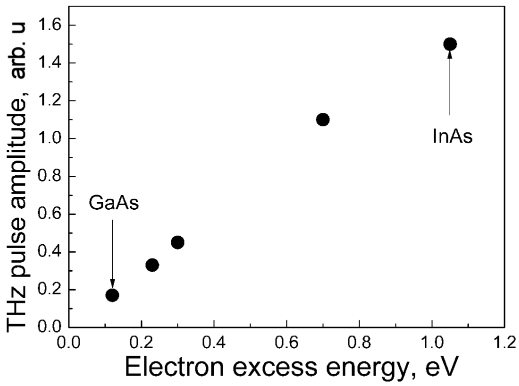

Fig. 2. The THz pulse amplitudes measured at the same experimental conditions on different semiconducting compounds from the InAs–GaAs system.

InSb has a band structure similar to that of InAs, but with twice smaller energy band gap, however, the THz power radiated from this semiconductor surface illuminated by femtosecond Ti:sapphire laser pulses is ≈ 100 weaker. It has been suggested that this reduction of THz emission efficiency is caused by the intervalley scattering of the photoexcited electrons [4]. Excitation spectra of THz radiation from InSb support this conclusion [3]; the intervalley energy separation in the conduction band of InSb evaluated from this dependence is equal to 0.53 eV. It should be pointed out that for longer laser wavelengths around 1.5 μm InSb could be preferable over InAs as THz emitting material.

In $Cd_{0.2}Hg_{0.8}Te$, the excess energies of the electrons should be larger than in III–V NGS such as InAs or InSb, thus $Cd_{0.2}Hg_{0.8}Te$ could be expected to be a better THz emitter than InAs. However, this is not observed experimentally at room temperature [5]; surely highly nonparabolic Γ valley is the main reason of the low THz emission from $Cd_{0.2}Hg_{0.8}Te$. After lowering the temperature to 80 K, the THz pulse power emitted from $Cd_{0.2}Hg_{0.8}Te$ increases by approximately two orders of magnitude (Fig. 3), whereas in the case of InAs — the best THz emitter at room temperature — is only slightly enhanced. The efficiency of the

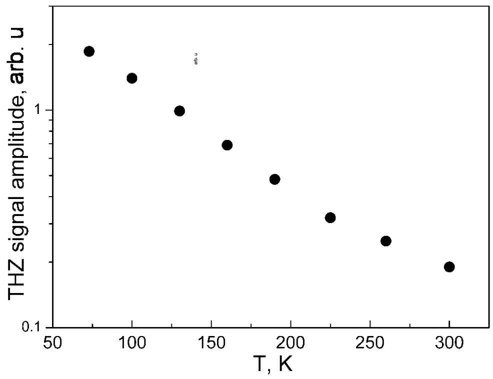

Fig. 3. The THz pulse amplitudes for $Cd_{0.2}Hg_{0.8}Te$ measured at different temperatures of the sample.

photo-Dember effect is enhanced at low temperatures due to the reduction of the electron scattering rates and the increase in their mobility.

In conclusion, the properties desirable for efficient surface THz emitters are the following: large electron mobility (small effective mass) in the main valley; narrow band gap; large intervalley separation in the conduction band; low non-parabolicity of the main valley in the conduction band.

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