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A study of emission power and spectrum of LT-GaAs based THz photoconductive antennas

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Abstract

Emission spectra of LT-GaAs photoconductive antennas based on epitaxial films of "low-temperature" gallium arsenide (LT-GaAs) are measured in the terahertz frequency region by the Fourier transform spectroscopy.

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Keywords: low-temperature gallium arsenide; photoexcited carriers; photoconductive antennas; terahertz radiation.

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1. Introduction

The recent advent of high-power pulsed lasers, in particular, those with femtosecond pulses (1 fs = 10^{-15} s), opened the way to develop compact generators and detectors of broadband terahertz (THz) radiation, based on the interaction of laser radiation with matter [D. Dragoman et al. (2004)]. Photoconductive antennas (PCA) [D. H. Auston et al. (1984)] or nonlinear optical crystals [Q.Wu et al. (1996)] are commonly used as active conversion elements. From the viewpoint of the effciency of the optical_terahertz conversion, the former case appears more preferable [Y. Cai et al.(1998), Y. C. Shen et al. (2004)]. Currently, gallium arsenide grown by molecular-beam epitaxy at lower temperatures $T < 300$ °C is the most actively studied material for photoconductive antennas. The best structures based on "low-temperature" gallium arsenide (LT-GaAs) exhibit subpicosecond lifetimes of nonequilibrium carriers, relatively good mobilities (~10^3 cm^2/V·s), high dark resistivities and breakdown fields

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(~10^5 V/cm) [S. Gupta et al. (1991), L. Hou et al. (2013)]. It should be noted that properties of particular LT-GaAs structures strongly depend on growth and subsequent annealing conditions. Therefore, the overwhelming majority of works on LT-GaAs is devoted to studies of the photoexcited carrier relaxation dynamics, performed using various "pump-probe" techniques [Y. Cai et al. (1998), Y. C. Shen et al. (2004), S. Gupta et al. (1991), P. A. Loukakos et al. (2002), A. A. Pastor et al. (2012)].

In the previous work [T. M. Burbaev et al. (2013)], we described technological operations of growth and subsequent annealing of epitaxial LT-GaAs films and presented the results of structural studies. The results of the photoexcited carrier dynamics studies were reported in [A.A. Gorbatsevich et al. (2015)]. This paper is devoted to the study of the LT-GaAs-based PCA emission spectra by Fourier transform spectroscopy in the terahertz region.

2. Electric and spectral characteristics of photoconductive antennas

The electrical properties of LT-GaAs films and spectral characteristics of photoconductive antennas (PCAs) were studied on samples prepared by photolithography with planar (V-Au metallization 0.6 μm thick) contact areas and antenna elements of various shapes (Fig. 1 (a)). The samples were placed on special panels in front of a through hole~4mm in diameter, which made it possible to measure terahertz (THz) radiation generated by PCAs in transmission mode, i.e., from the crystalline GaAs substrate side. During measurements, the panel with four pin-contacts was inserted into a corresponding socket with a standard SMA plug at the output. PCA contact areas were connected with conducting paths on the panel by thermoultrasonic microwelding.

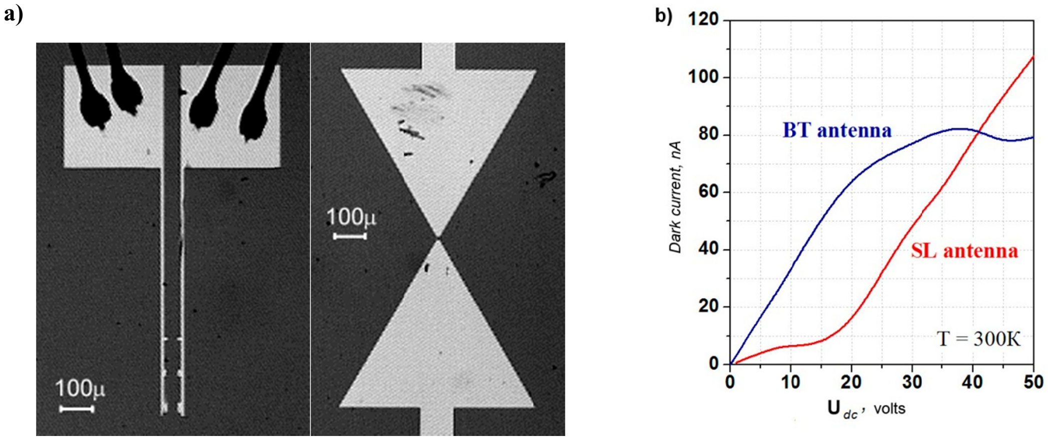

Fig. 1. (a) Micrographs of the fabricated photoconductive stripline (SL) and bow-tie (BT) antennas on the LT-GaAs layer. (b) Measured dark *I_V* characteristics of photoconductive antennas.

Preliminarily, the current-voltage characteristics of fabricated LT-GaAs samples were measured at room temperature. The setup included an adjustable stabilized voltage source and a dc voltage meter determining the circuit current using a resistor (~15 kΩ) connected in series with the sample under study. Figure 1 (b) shows the dark currents of fabricated stripline and bow-tie (Fig. 1 (a)) PCAs, measured as functions of the bias voltage *V*dc applied to the structure in the range of 0–50 V. The characteristic dark resistances of the samples under study were ~10^9 Ω, and estimated resistivity of the LT-GaAs films were about $\rho_{\rm dark} \sim 3 \cdot 10^6$ Ω ·cm.

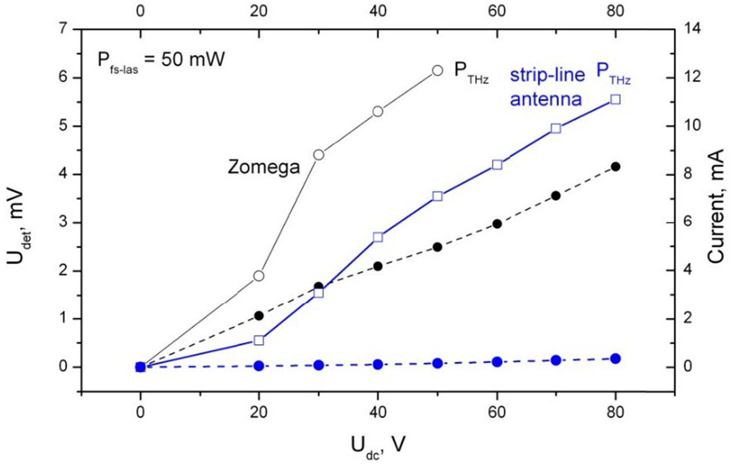

Fig. 2. The emission power (squares) and current (full squares) of stripline photoconductive antennas based on LT-GaAs as function of the bias voltage. The similar characteristics of PCA manufactured by Zomega company (circles and full circles) are also shown

The total emission power of THz radiation was measured with a pyroelectric detector and high-speed superconducting bolometer with a time resolution of ~ 5 ns. The measured THz power of strip-line photoconductive antennas and the current through the antenna as a function of applied bias voltage are shown in Fig. 2. Similar data obtained for one of the best of the PCAs manufactured by Zomega company on semi-insulating GaAs are also shown in Fig. 2.

It should be noted that the ratio (THz Power / current) of investigated antennas significantly exceeds similar values for Zomega antennas. In particular, for U_{dc} = 30 V and femtosecond excitation power of 50 mW, this value is about 60 mV / mA, while for Zomega antenna - only 5.2 mV / mA. Of course, there should be taken into account the difference in antenna geometries, as well as significantly smaller illuminated area of our strip-line antennas as compared with that of Zomega ones, but, nevertheless, it is evident that the effectiveness of the studied antennas is high enough.

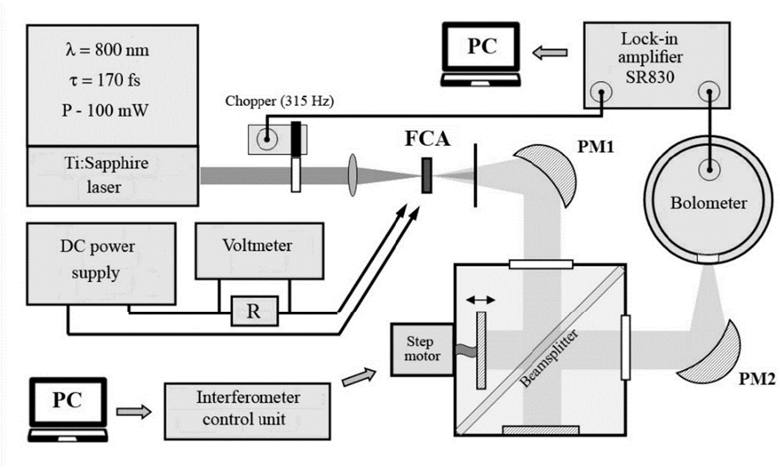

Fig.3. Schematic diagram of the setup for measuring the emission spectra of fabricated photoconductive antennas.

The emission spectra of the PCAs under study were measured in air using a "Grubb-Parsons MK-3" Fourier interferometer. The complete schematic diagram of the setup is shown in Fig. 4. Optical radiation of the Ti:Sa laser, focused by a lens on the LT-GaAs layer region between electrodes, excited photocurrent pulses (with an amplitude proportional to the applied voltage *V*dc) in the antenna, which, in turn, caused generation of THz radiation pulses. This radiation emerged to free space through the substrate, passed through a filter cutting scattered laser radiation and, being collected by parabolic mirror PM1 into a collimated beam, was directed to the Fourier interferometer input.

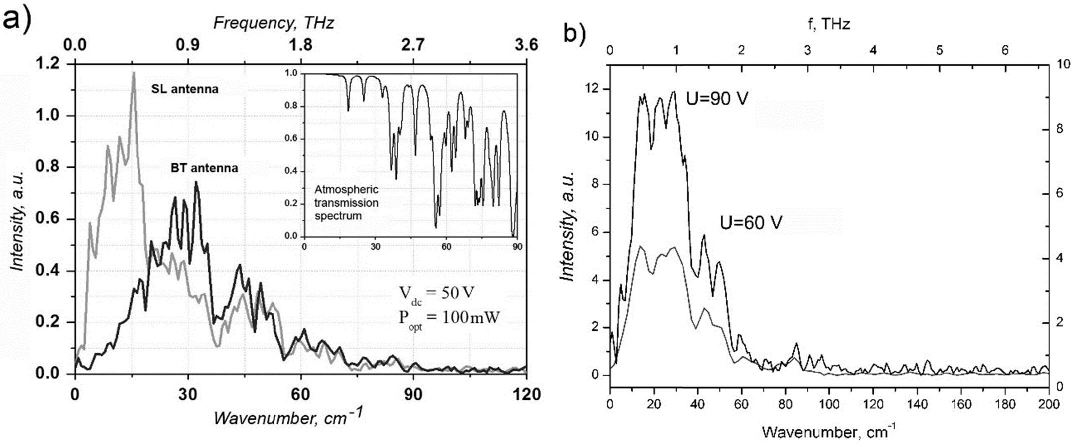

Fig.4. (a) Emission spectrum of photoconductive antennas based on LT-GaAs. The inset shows the tabulated normal conditions transmission spectrum of atmosphere. (b) Emission spectrum of Zomega photoconductive antenna based on semi-insulating GaAs.

The interferometer operated in step-scan mode, implemented by moving the mobile interferometer mirror using a micrometer screw rotated by the step motor. As a beam splitter, a Mylar film 12.5 μm thick was used, which provided a signal maximum at a frequency of 105 cm/1 (3.3 THz). After passing through interferometer, the THz radiation was focused by parabolic mirror PM2 on the entrance window of a germanium bolometer cooled by liquid helium. The signal from the bolometer preamplifier output was fed to an SR830 lock-in amplifier (laser radiation was modulated by a mechanical chopper with a frequency of 315 Hz), then it was digitized by an analog-to-digital converter (ADC) and arrived at the computer for processing interferogram and restoring the emission spectrum using the fast Fourier transform algorithm. The Fourier spectrometer was controlled by a stand-alone microprocessor unit including an ADC, step motor control unit, and the system of data exchange with an external computer.

Figure 4a shows the spectrum of THz radiation generated by fabricated photoconductive antennas at an average optical illumination (800 nm) power of ~100 mW and applied direct voltage *V*dc = 50 V. In this case, the average currents in stripline and bow-tie antennas were 180 and 30 μA, respectively. The spectra were measured with a resolution of ~1 cm^{-1}. In Fig.4b the measured emission spectrum of Zomega antenna is also shown

We can see that the measured spectra exhibit the broad continuous band; the most part of radiation is concentrated in the range of 5-60 cm^{-1} (0.15-1.8 THz). The peaked structure observed in the spectra is mainly caused by atmospheric water vapor absorption, which is confirmed by a comparison of the measured curves with the typical atmospheric transmission spectrum shown in the inset.

Thus, the emission characteristics of photoconductive antennas based on the epitaxial films of "low-temperature" gallium arsenide were studied. The measured emission spectra exhibit pronounced maxima in the terahertz region. It was shown that the antenna configuration has a significant effect on the radiation spectrum shape. For the SL antenna, the intensity maximum is higher and the frequency is lower than those of the BT antenna operating at lower currents. It is important that antenna emitters were fabricated using the standard planar microelectronic technology, which offers prospects for constructing integrated THz phased antenna arrays with controllable directional patterns.

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