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Terahertz generation in InAs epitaxial films

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We present the results of terahertz generation studies under excitation via femtosecond lasers pulses epitaxial films of InAs, which were synthesized on semi-insulating and highly doped GaAs substrates. It is shown that a terahertz emitter based on epitaxial InAs film grown on a heavily doped GaAs *n*-type substrate, has the same terahertz generation efficiency as the InAs-film emitter grown on a semi-isolating GaAs substrate, but it has a significantly better spectral resolution, which is mainly determined by the parameters of the optical delay line and the femtosecond laser's stability.

Keywords: coherent terahertz emitter, InAs epitaxial film, molecular beam epitaxy

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Bulk semiconductor InAs is the most efficient terahertz (THz) emitter at the current moment [1]. It is utilized as a coherent emitter for time-resolved THz spectroscopy by different research groups [2–4]. Epitaxial InAs [4] and InGaAs [5,6] layers grown by molecular-beam epitaxy (MBE) on semiconductor substrates are used to achieve high values of carrier mobility that define the efficiency of THz generation. High-resistance semiconductors GaAs and InAs are often used as substrates. The interpulse distance in sequences of THz pulses generated with such substrates depends on the substrate thickness. This dependence has a negative effect on the spectral resolution of time-resolved THz spectrometers based on these emitters. To eliminate THz pulses reflected from the substrate surface, one needs a semiconductor with a high carrier density that would provide for plasma reflection of THz radiation and its absorption. The use of heavily doped GaAs substrates should help solve the problem of enhancement of the spectral resolution of time-resolved THz spectrometers that would depend only on the parameters of the optical delay line and the stability of operation of a femtosecond laser. Therefore, optimization of the process of growth of semiconductor InAs layers on heavily doped substrates and subsequent examination of the process of THz generation in such structures are relevant and important tasks that need to be completed in order to perfect the technique of time-resolved THz spectroscopy. Note that the spectral resolution of a THz spectrometer (with its emitter being a photoconductive antenna based on undoped GaAs) was enhanced in [7] by introducing a reflective metallic layer between the GaAs working layer and the emitter substrate. Below we present the experimental results of studies into the generation of THz radiation in epitaxial InAs films formed on semi-insulating and heavily doped GaAs substrates.

Epitaxial InAs layers were grown by MBE on semi-insulating and heavily doped GaAs(001) substrates using a RIBER 32P setup fitted with standard effusion cells for all sources (except arsenic). A VAC-500 valved cracker cell operated in the mode of generation of a flux of arsenic molecules As_4 was used as the source of arsenic. Heavily doped substrates were *n*-type semiconductor GaAs wafers with an electron density of $(1-5)\cdot 10^{18}\,\mathrm{cm}^{-3}$. Prior to the deposition of InAs layers onto both semi-insulating and heavily doped substrates, a buffer GaAs layer with a thickness of 200 nm was grown. This layer was deliberately left undoped (in the case of semi-insulating substrates) or doped with silicon (for heavily doped substrates; $n = 5\cdot 10^{18}\,\mathrm{cm}^{-3}$). The thickness of deliberately undoped InAs layers was $2-3\,\mu$m. Optical excitation of the nanostructures was provided by a pulsed Ti:Sapphire laser generating light pulses with a wavelength of 795 nm, a duration of ~ 15 fs, and a repetition frequency of 80 MHz (the pulse energy was 2 nJ, irradiation spot $d \sim 200\,\mu$m). THz radiation was detected by electrooptical gating in the mirror reflection geometry with the use of a coherent time-resolved THz spectrometer. A detailed description of this instrument was given in [8].

Waveforms detected in the experiment were essentially the dependences of the electric field of THz radiation on the time delay between the optical emitter excitation pulse and the probe optical pulse incident on the receiving system of the THz spectrometer. The fast Fourier transform was used to isolate spectral components of the THz field. THz radiation generated by an InAs-based emitter on a semi-insulating substrate had the form of a sequence of pulses (Fig. 1, *a*). The waveform of a THz pulse propagating through free space featured another pulse with an opposite THz field direction that was delayed by 9.15 ps relative to the primary one. The presence of this second pulse is attributable to reflection of THz radiation propagating forward from the rear surface of the substrate. The dependence of the THz pulse amplitude on the intensity of excitation radiation remained linear in nature up to the maximum values used in our experiment. When a time

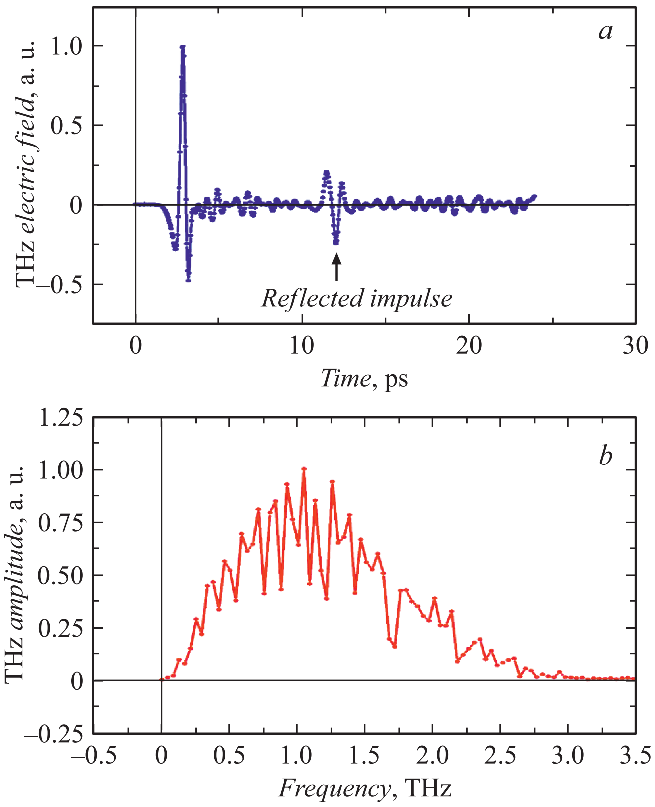

Figure 1. THz radiation generated in an epitaxial InAs layer on a semi-insulating GaAs substrate. *a* — waveform of a THz pulse normalized by $E(\mathrm{SI})_{\max}$; *b* — normalized THz radiation spectrum. $E(\mathrm{SI})_{\max}$ is the maximum amplitude of the electric field of THz radiation generated in an epitaxial InAs layer on a semi-insulating GaAs substrate.

window wider than the interval between the first and the second pulses was used, sine beats emerged in the spectrum (Fig. 1, *b*). The spectral resolution decreases when one narrows down the time window for Fourier transform to the value of the interval between the first and the second pulses. The resolution is in this case defined by the reciprocal of the time interval.

THz radiation generated in the sample based on an epitaxial InAs film synthesized on a doped GaAs substrate had the form of a single primary pulse followed by small-amplitude pulses induced by the scattering of THz radiation off water molecules present in air (Fig. 2, *a*). The maximum amplitude of a THz pulse was of the same order of magnitude as the one measured in experiments with the emitter based on an epitaxial InAs film on a semi-insulating GaAs substrate. Consequently, the spectrum of a THz pulse generated by the emitter based on an epitaxial InAs film synthesized on a doped GaAs substrate had no sine beats (Fig. 2, *b*). Absorption spectral lines were produced by the absorption of THz radiation in the environment. Experiments on the transmission of THz radiation through the samples also provided convincing proof of the lack of a THz pulse associated with reflection from the rear surface of the substrate. The coefficient of transmission of THz radiation remained below $5 \cdot 10^{-5}$ within the entire spectral range. Thus, the obtained results confirmed that THz radiation generated in the forward direction in an epitaxial InAs film synthesized on a doped GaAs substrate is reflected at the InAs/GaAs boundary due to plasma reflection, and the fraction of radiation transmitted through this boundary is absorbed completely in the substrate. Having examined the dependence of the THz pulse amplitude on the intensity of excitation radiation, we found that this dependence is linear in the range of intensities probed in our experiments. The independence of the efficiency of THz generation on the orientation of an InAs crystal in the irradiated interface plane between two media (semiconductor InAs and the environment) was also confirmed experimentally. The dependence of the THz field on the angle between the electric-field vector of a light wave and the incidence plane was sinusoidal in nature (Fig. 3). The THz field does not change on transition from the TM polarization of excitation light to the TE polarization, and the amplitude for the TE polarization becomes smaller. This dependence is governed by the Fresnel formulae that relate the amplitude of a refracted electromagnetic wave to the amplitude of a wave incident on a plane interface between two media with different refraction coefficients.

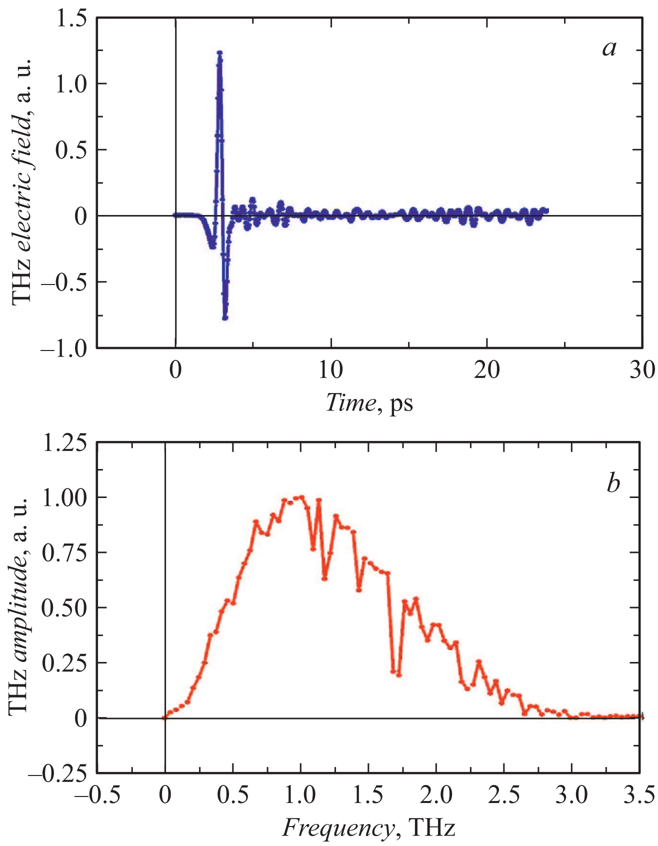

Figure 2. THz radiation generated in an epitaxial InAs layer on a heavily doped GaAs substrate. *a* — waveform of a THz pulse normalized by $E(\mathrm{SI})_{\max}$; *b* — normalized THz radiation spectrum.

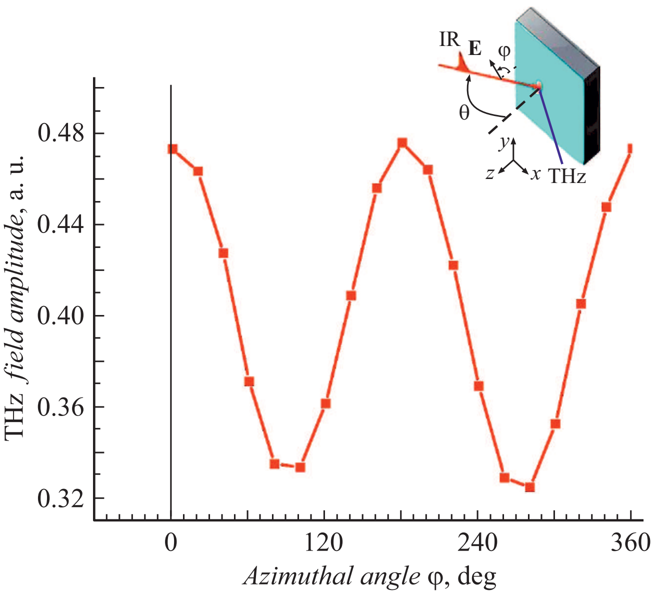

Figure 3. Polarization dependence of the THz field. The geometry of the experiment is shown in the inset (θ is the incidence angle).

The generation of THz radiation upon irradiation of an InAs surface by a femtosecond laser is governed primarily by two processes: photocurrent (upon excitation of electron-hole plasma) and nonlinear optical effects due to optical nonlinearities of the second (optical rectification) and the third (rectification induced by the electric field) order. Since the efficiency of THz generation in an epitaxial InAs film does not depend on the crystal orientation, nonlinear optical effects produce an insignificant contribution to THz generation. In contrast to GaAs with a significant surface field, the surface field in semiconductor InAs is weak. Therefore, the contribution of the drift current of photoexcited electrons to the process of THz generation is likely to be minor. The results of examination of the dependence of THz generation efficiency on the intensity of excitation radiation (specifically, the lack of saturation in the dependence of the THz pulse amplitude on the light intensity) also suggest that this contribution is insignificant. The mentioned lack of saturation is attributable to screening of the surface field due to the separation of photoexcited electrons and holes in this field. Thus, the obtained results of experiments on THz generation in an epitaxial InAs film irradiated with femtosecond light pulses provide an opportunity to determine the possible mechanisms of this process. These mechanisms are underpinned by the generation of photocurrent due to the Dember effect, which is caused by the spatial separation of photoexcited electrons and holes moving with different velocities from the irradiated surface toward the center of the sample (ambipolar diffusion effect), and by the emerging anisotropy in the pulse distribution of photoelectrons due to reflection from the InAs crystal surface (the so-called „jetlike" effect [9]).

To conclude, we note that the results of examination of THz generation in epitaxial InAs layers, which were grown by MBE on semi-insulating and heavily doped GaAs substrates, excited by femtosecond laser pulses were presented in this study. It was established that a THz emitter based on an epitaxial InAs film synthesized on a doped GaAs substrate has the same generation efficiency as that of an emitter based on an epitaxial InAs film on a semi-insulating GaAs substrate, but features a significantly better spectral resolution, which is governed primarily by the parameters of the optical delay line and the stability of a femtosecond laser. The mechanisms of THz generation in an epitaxial InAs film irradiated with femtosecond optical pulses are underpinned both by the generation of photocurrent due to the Dember effect, which is caused by the spatial separation of photoexcited electrons and holes moving with different velocities from the irradiated surface toward the center of the sample, and by the emerging anisotropy in the pulse distribution of photoelectrons due to reflection from the InAs crystal surface.

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Conflict of interest

The authors declare that they have no conflict of interest.

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