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TERAHERTZ EMISSION FROM GaInAs *p-i-n* DIODES PHOTOEXCITED BY FEMTOSECOND LASER PULSES

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Lattice-matched GaInAs *p-i-n* diodes of different *i*-region thicknesses have been MBE grown on *n*-type InP (100) and (111) crystallographic orientation substrates. It has been found that terahertz emission from such structures when illuminated with femtosecond laser pulses can be more efficient than that from the known to date best surface terahertz emitter (111) *p*-InAs. The explanation of the terahertz generation mechanism from *p-i-n* diodes is based on ultrafast photocurrent effects. Anisotropic transient photocurrents causing the 3ϕ azimuthal angle dependence are observed in the sample on (111) substrate. These *p-i-n* structures allow covering a technologically important 1.55 μm range and may provide controllability and compactness of a THz-TDS system when biased with an external voltage source.

Keywords: surface terahertz emitter, *p-i-n* diode, GaInAs

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1. Introduction

Excitation of semiconductor surfaces with femtosecond laser beams is an important technique to generate terahertz (THz) radiation pulses for THz time-domain spectroscopy (TDS) systems and THz imaging [1]. This type of THz radiation sources is a strong candidate for compact THz radiation systems powered by femtosecond fiber lasers with emission wavelengths between 1 and 1.55 μm because it does not require external biasing and materials with a large dark resistivity as it is in the case of photoconductive switches. Most efficiently THz pulses are radiated by femtosecond laser excited surfaces of the narrow gap semiconductors such as InAs [2]. This radiation originates either from nonlinear optical processes or ultrafast photocurrent transients. In the first case, this effect is described phenomenologically as a consequence of the second- (optical rectification – OR) [3] or third-order (Electrical Field Induced OR – EFIOR) [4] optical nonlinearities. On the other hand, THz pulse emission due to ultrafast photocurrents can be achieved through the acceleration of photocarriers by intrinsic electric fields occurring at a semiconductor surface (surface depletion/accumulation fields) [5] or the photo-Dember effect arising due to the spatial separation of the photoexcited electrons and holes at the illuminated surface [6, 7]. The exceptionally large optical-to-THz conversion efficiency of InAs has been explained by Malevich et al. [8] by a joint action of the photo-Dember and EFIOR effects in this material. It was shown in [8] that electric fields caused by the carrier separation at the beginning of the exciting laser pulse result in an anisotropic transient photocurrent at the surface. Lateral components of this photocurrent create electric dipoles that radiate THz signals perpendicular to the air/crystal interface, thus providing a more efficient out-coupling of THz radiation than electric dipoles perpendicular to the interface arising due to the photo-Dember effect. Anisotropic photocurrent components cause the well-defined dependence of the THz pulse amplitude on the azimuthal angle between the optical field and the crystallographic axes; these components are stronger in the *p*-type InAs that has an inversion layer at the surface creating the built-in surface electric field of the same polarity as the photo-Dember field [9]. Because of this, THz emission from *p*-InAs is twice as efficient as from *n*-InAs [10], and the azimuthal angle dependences measured on *p*-type InAs crystals are stronger [11].

The disadvantages of surface THz emitters are related to the complications arising when integrating these components into a compact THz-TDS system geometry. Normally, THz pulses from these emitters photoexcited by a femtosecond laser at an incline angle are radiated in the quasi-reflection direction that makes the fabrication of pig-tailed components inconvenient for fiber-laser based systems. Moreover, the absence of the external electric bias has its downside – emitted THz radiation can be modulated only by chopping the laser beam, which requires additional mechanical parts introduced into the system. In this contribution we provide the solution of both those problems. First of all, we demonstrate THz emission from the surfaces of *p*-*i*-*n* diodes with an active layer sensitive to the laser wavelengths up to 1.7 μm that could be modulated by applying the reverse bias. It has been shown that the externally induced close to the surface electric field enhances THz emission – THz pulse amplitudes larger than those achieved from *p*-InAs crystals were demonstrated. The external bias is also enhancing the contribution of the EFIOR effect in the creation of the radiating electric dipole that, for certain crystallographic orientations, has a substantial lateral contribution and can be used in the line-of-sight geometry of surface THz generation.

2. Experimental details

GaInAs *p*-*i*-*n* structures were grown on *n*-type InP substrates in a molecular beam epitaxy (MBE) reactor SVT-A. The sources used in the MBE were the metallic Ga, In, and As-valved cracker for As_2 production. For doping the Si and Be were used. The substrate temperature during all growth runs was 510 °C as measured by the thermocouple. The indium concentration in the layers was corresponding to the GaInAs composition lattice-matched with the InP substrate. All *p*-*i*-*n* structures consisted of *n*-type InP substrate (carrier concentration ~1.5×10^{18} cm^{-3}), 50 nm *n*-type GaInAs (carrier concentration ~1.5×10^{18} cm^{-3}), unintentionally doped GaInAs, and 50 nm thickness *p*-type GaInAs (carrier concentration ~8×10^{17} cm^{-3}) layers. The width of the unintentionally doped region was different: 200 nm (GaInAs-200), 400 nm (GaInAs-400), and 750 nm (GaInAs-750). The first two were grown on (100) oriented substrates, whereas the third structure (GaInAs-750) on the (111) oriented substrate.

Two laser systems were used in the experimental THz-TDS setups. A femtosecond Yb:KGW laser oscillator has the central wavelength of 1030 nm, the pulse repetition rate 76 MHz, and the pulse duration 75 fs. The second setup was based on an optical parametric amplifier (OPA) ORPHEUS pumped by an amplified Yb:KGW laser PHAROS (both *Light Conversion Ltd.*) providing 160 fs duration, 200 kHz repetition rate pulses with the wavelengths tunable from 600 to 2500 nm. For THz pulse detection GaBiAs photoconductive antennas (*UAB Teravil*) activated by femtosecond 1 μm wavelength pulses were used. Experimental geometries that were employed in this study are presented in Fig. 1.

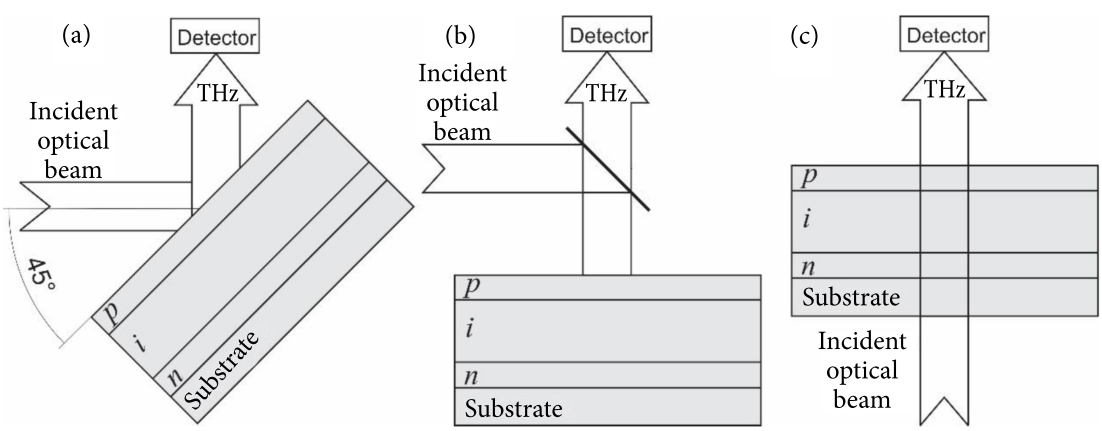

Fig. 1. The geometry of different THz-TDS experiments: (a) when the optical beam excites the sample at 45° angle and the THz pulse is detected at the reflection direction, and when the sample is excited along its surface normal and THz is detected at the reflection (b) or the transmission (c) directions.

The samples were excited either at incline angles or perpendicular to their surface; the THz radiation was monitored either in the transmission or quasi-reflection directions. In the case of signal registration in the transmission direction the structure was photoexcited from the substrate side because THz pulses cannot penetrate a highly conductive InP substrate and are reflected and absorbed by it.

3. Results and discussion

The THz pulse radiated by the GaInAs *p-i-n* diode with the thickest *i*-region is compared in Fig. 2(a) with the signal emitted from the *p*-type InAs crystal ($p = 2 \times 10^{17}$ cm^{-3}) photoexcited at exactly the same conditions using the Yb:KGW 76 MHz oscillator. Both THz transients were detected in the experimental geometry shown in Fig. 1(a). It is seen that the peak-to-peak amplitude of the pulse generated by the diode is ~75% larger than that obtained from the laser excited surface of the *p*-InAs single crystal, which was known up to now as the most efficient surface THz emitter [2]. The structure GaInAs-400 when excited with femtosecond 1030 nm wavelength pulses also showed larger than in the *p*-type InAs optical-to-THz conversion efficiency; only for the *p-i-n* structure with the thinnest *i*-region (GaInAs-200) this efficiency was smaller, but still comparable with the value of this parameter for *p*-InAs.

The performance of two THz emitting GaInAs *p-i-n* structures when excited with tunable wavelength femtosecond pulses generated by OPA is illustrated and compared with the THz excitation spectrum of the *p*-type InAs crystal in Fig. 2(b). All these dependences were measured in the reflection geometry (Fig. 1(a)) with a constant average optical power of 2.5 mW incident on the samples and normalized to the same number of photons. The GaInAs *p-i-n* junction containing the 200 nm wide *i*-region provides signal amplitudes similar to those of *p*-InAs over the spectral range from 1 to 1.7 μm, whilst the sample GaInAs-400 emits THz pulses with approximately 50% larger amplitudes than those emitted from the *p*-type InAs over a wide 0.9–1.5 μm laser wavelength range. The reduction of the radiated THz pulse amplitudes on the short wavelength side is, most probably, caused by the light absorption in the highly *p*-doped top layers of the *p-i-n* structures.

It has to be pointed out that all results plotted in Fig. 2 correspond to the non-saturating range of the exciting optical power. Radiant exposures of the samples by the optical beam from the Yb:KGW

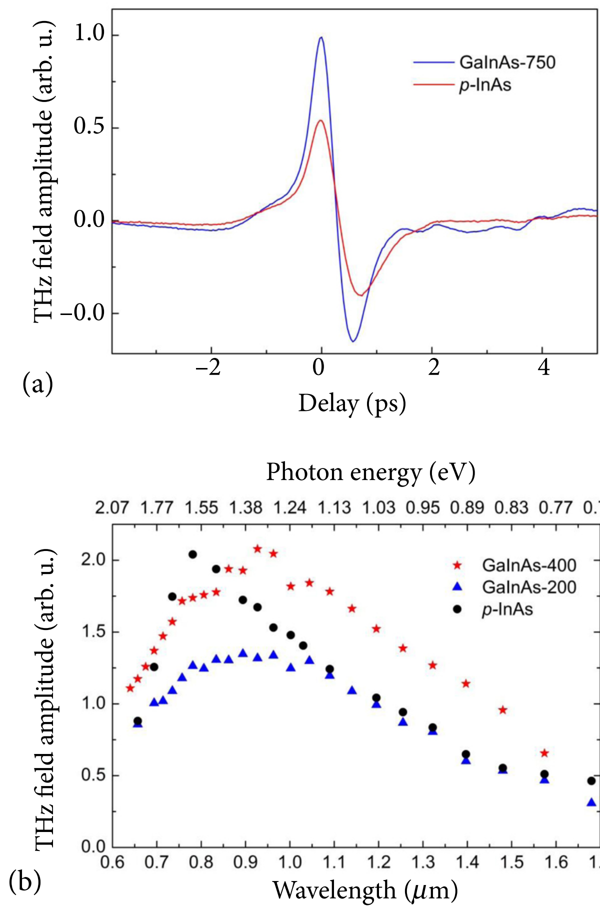

Fig. 2. (a) THz pulses generated by the *p*-InAs crystal and the sample GaInAs-750 excited at 1030 nm wavelength with 10 mW average optical power from the Yb:KGW 76 MHz oscillator. (b) THz excitation spectra for samples GaInAs-200 and GaInAs-400 compared with a similar dependence measured on the *p*-type InAs crystal surface.

laser oscillator were 0.7 nJ/cm^2 (Fig. 2(a)) and for the dependences measured using OPA beams presented in Fig. 2(b) were 64 nJ/cm^2. Figure 3 compares the THz signal amplitudes of *p*-InAs with our *p-i-n* in relation to the exciting average optical power when operating at 1.55 μm. The *p-i-n* structure with the 400 nm wide undoped layer is better THz emitter than *p*-InAs over the whole range of the average optical powers, however, the THz pulse amplitude emitted by that structure tends to saturate at lower optical powers than *p*-InAs.

Different saturation behaviour is not a sole difference between *p-i-n* and bulk InAs THz emitters. It can be seen in Fig. 2(b) that *p-i-n* emitters radiate substantial THz signals even for the laser wavelengths close to the absorption edge of the GaInAs where the excitation is homogeneous over the active region width. It is known that THz emission due to the photo-Dember effect sets on only when the photoexcited electrons reach rather high excess energies [12]. Moreover, investigations performed in the reflection mode at 45° on the sample GaInAs-750 grown on the (111) oriented substrate did not reveal the expected strong cos3ϕ-type dependence of the emitted THz pulse amplitude on the azimuthal angle ϕ between the optical field and the crystallographic axes. All this implies that the physical mechanisms of THz emission from the GaInAs based *p-i-n* structures and the InAs crystal are different. In the following we will discuss briefly possible physical processes leading to THz emission from the femtosecond laser excited GaInAs *p-i-n* junctions.

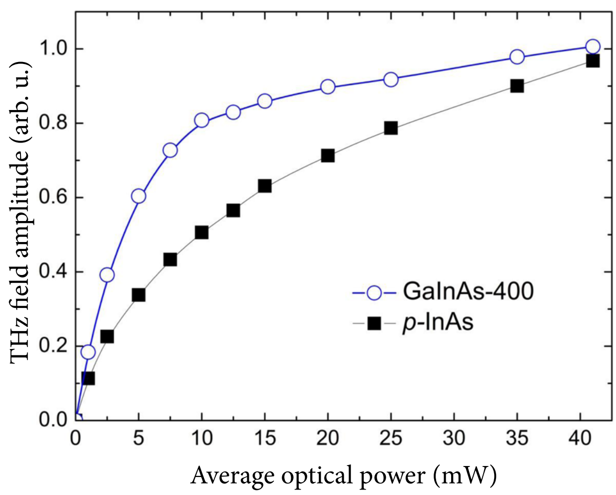

Fig. 3. THz pulse amplitude as a function of average optical power measured on two samples excited by femtosecond optical pulses from OPA at a wavelength of 1.55 μm.

First of all, the onset of THz emission at the optical wavelengths corresponding to the absorption edge of the material, where the photoexcited carrier density gradient is small and the role of the photo-Dember effect is insignificant, points out to the possible effect of the photocurrent surge and electron and hole separation in the built-in electric field of the *i*-layer of the junction. A dynamic dipole created by this separation will be stronger and THz emission will be more efficient in structures with a wider *i*-layer. A similar effect was observed before in different thickness InAs epitaxial layers grown on GaSb substrates [13]. At long wavelengths, when electrons are excited close to the conduction band edge, the dispersion law of this band is still parabolic and its non-sphericity that causes anisotropic photoconductivity and dependence of the radiated THz pulse on the azimuthal angle is weak. Less understandable is the absence of the azimuthal angle dependence of the radiated signal at shorter laser pulse wavelengths. We have performed additional investigations of the experimental conditions leading to the appearance of this dependence.

Figure 4 shows azimuthal angle dependences measured on the sample GaInAs-750 at three experimental geometries. The first two curves correspond to the geometries shown in Fig. 1(b) and (c), respectively. For laser beams impinging on the surface along its normal, which is characteristic of these geometries, THz radiation due to the photocurrent surge effect will not reach the detector and the measured THz pulse will be solely caused by the anisotropic photoconductivity effect. It is interesting to note that the azimuthal angle dependent THz radiation component is much stronger when the sample is illuminated from the substrate side. In this case the majority of photoexcited electrons move in the direction towards the top of the structure and are effectively decelerated by the built-in electric field in the *p-i-n* junction. This will increase their effective time-of-flight across the electric field, increase their lateral displacement, and, therefore, enhance the strength of the dynamic dipole which causes THz emission. A clear cos3ϕ-type dependence on the azimuthal angle was also observed when the sample was excited from the substrate side at an inclined angle and the THz signal was monitored in

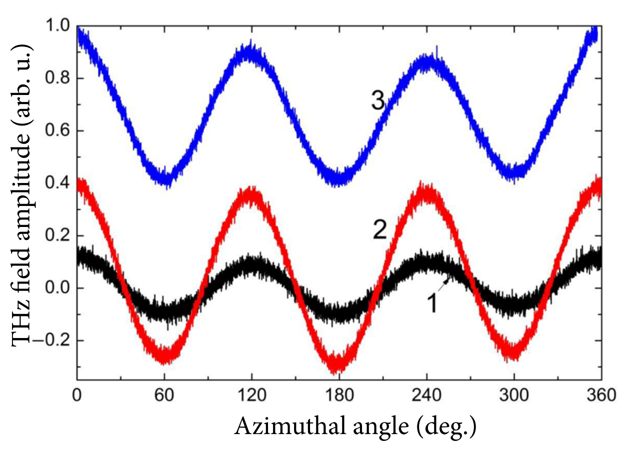

Fig. 4. THz signal azimuthal angle dependences for the sample GaInAs-750 excited with 1 μm wavelength pulses from OPA at comparable average optical powers. Curve (1) is measured by using the experimental geometry shown in Fig. 1(b), curve (2) is experimental geometry shown in Fig. 1(c), and (3) corresponds to the Fig. 1(c) case but when the sample is tilted at a 30° angle rather than perpendicular to an optical beam.

the transmission direction. In the latter case an angle independent offset caused by the photocurrent surge effect was detected.

4. Conclusions

In summary, we have investigated THz emission from GaInAs *p-i-n* structures grown by the MBE technique on InP substrates and excited by femtosecond laser pulses. Three structures with different nominally undoped *i*-layer widths, 200, 400, and 750 nm, were investigated. The sample with the shortest *i*-layer radiated THz pulses with amplitudes comparable to those observed in the case of *p*-type InAs, whereas THz signals generated by other two samples were significantly larger than those from *p*-InAs known as the most efficient surface THz emitter up to date. Efficient THz pulse emission has been observed over a wide range of the exciting optical pulse wavelengths from 1 to 1.5 μm; it was shown that the main physical mechanism of this effect is the photocurrent surge in the built-in electric field of the *p-i-n* junction. The relative importance of the anisotropic photocurrent effect in THz emission was documented only for shorter femtosecond laser wavelengths and when the structures were illuminated from the InP substrate side. Optical-to-THz conversion efficiencies of *p-i-n* devices can be further improved by applying an external reverse bias and by introducing *i*-layers from material with a narrower energy band gap, therefore, these devices could be promissing as THz emitters in compact fiber laser based THz-TDS systems.

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TERAHERCINĖ SPINDULIUOTĖ IŠ GaInAs *p-i-n* DIODŲ, APŠVIESTŲ FEMTOSEKUNDINIAIS LAZERIO IMPULSAIS

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Santrauka

Tiriama THz spinduliuotės emisija iš GaInAs *p-i-n* darinių, užaugintų molekulių pluoštų epitaksijos būdu ant InP padėklų, žadinant juos femtosekundinio lazerio impulsais. Eksperimente tirti trys dariniai, turintys skirtingą nelegiruotosios srities plotį: 200, 400 ir 750 nm. Nustatyta, kad *p-i-n* darinys su siauriausia nelegiruota sritimi generavo THz impulsus, kurių amplitudė, žadinant lazerio bangos ilgiais nuo 1 iki 1,5 μm, buvo panašaus stiprio kaip iš geriausio žinomo paviršinio emiterio *p*-InAs, nors kitų bandinių spinduliuojami impulsai buvo žymiai stipresni. Nustatyta, kad pagrindinis THz emisijos mechanizmas yra fotosrovė, atsiradusi fotosužadintiems krūvininkams judant *p-i-n* sandūros elektriniame lauke. Didesnė anizotropinės fotosrovės mechanizmo įtaka THz emisijai pasireiškė žadinant bandinius trumpesniais lazerio bangos ilgiais iš InP padėklo pusės. Optinės spinduliuotės vertimo į THz efektyvumą galima padidinti prijungus papildomą išorinę įtampą atgaline kryptimi ir panaudojant *i*-sričiai kitą medžiagą su siauresniu draustinių energijų tarpu. Tokie prietaisai gali būti perspektyvūs THz emiteriai kompaktiškose THz laikinės spektroskopijos sistemose, naudojančiose skaidulinius lazerius.