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TELLURIUM/GaAs HETEROJUNCTIONS FABRICATED BY THERMAL EVAPORATION IN VACUUM

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Heterostructures containing thin tellurium layers thermally evaporated on differently doped GaAs substrates were systematically investigated by using THz pulse excitation spectroscopy. The observed differences of the THz excitation spectra were explained by the details of the energy band lineups in the heterostructures. Comparison of the simulation results of the heterojunction between tellurium and semi-insulating GaAs with the measured THz pulse emission spectrum allowed one to estimate the electron affinity in the tellurium layer. In addition, a near-infrared photodetector based on the Te heterojunction with n-type GaAs was demonstrated.

Keywords: tellurium/GaAs heterojunction, THz emission spectroscopy, tellurium affinity

1. Introduction

After the discovery of graphene, researchers' interest in various two-dimensional monoelemental materials has greatly increased, as they have unique physical properties that are suitable for applications in electronics, optoelectronics and other areas of modern technology. Thin layers of monoelemental tellurium – a narrow gap semiconductor – are also more often studied. This can be explained by a relatively high hole mobility in tellurium, a tunable (0.35–1 eV) energy bandgap [1] and a superior air stability of the Te layers. However, Te, as an element of the sixth group, does not have donor impurities that allow the creation of p-n junctions, so the separation of photo-excited electrons and holes in photodetectors made of tellurium is not very efficient, and the parameters of the devices are not good enough. This problem is solved using tellurium heterojunctions with various bulk semiconductors and engineering their optimal electron energy band lineups. Such a strategy was chosen when developing efficient self-powered photodetectors with tellurium/germanium [2] and tellurium/silicon [3] heterojunctions.

This work investigated the heterostructures consisting of tellurium layers deposited on various doped GaAs crystal surfaces. Tellurium layers were created using thermal evaporation in a vacuum; the main characteristics of the heterostructure were measured using THz pulse excitation spectroscopy (TES) [4] – the experiments that were already used in our previous work when comparing thin Te layers produced using two user-friendly technologies: the deposition from the chemical solution and the thermal evaporation [5]. Those TES experiments made it possible to estimate the electron affinity of the tellurium – the parameter important for the heterostructure architecture, and to demonstrate the possibilities of using Te/GaAs junctions in infrared photodetectors.

2. Experimental details

Thermally evaporated thin Te layers were obtained by using the equipment VUP-5 (Ukraine) at the residual pressure of the working chamber $P = 3\cdot10^{-4}$ Pa. Evaporation was performed from a molybdenum boat heater ($T = 440\pm5$°C) on GaAs substrates kept at room temperature. All GaAs substrates were cut parallel to (100) crystalline planes, and their nominal charge carrier densities were equal to, respectively, $2\cdot10^{18}$ cm^{-3} (in n-GaAs substrate), 10^{19} cm^{-3} (in p-GaAs substrate) and $5\cdot10^{6}$ cm^{-3} (in a semi-insulating GaAs substrate). The desired tellurium layer thickness of 100 nm was obtained by selecting the mass of the vapourized material (Te-99.99%). The concentration of holes in the Te layer, determined from Hall-effect measurements, was equal to $7\cdot10^{17}$ cm^{-3}. Before evaporation, the substrates were cleaned from organic residues. Layer thickness measurements were performed with a Stylus profilometer Dektak XT.

THz pulse excitation spectroscopy was used to investigate thin Te samples grown on different GaAs substrates. In those experiments, the surface of the samples was excited by varying the wavelength (2.6 to 0.6 μm) of 150 fs optical pulses, which were generated by an optical parametric amplifier (OPA) Orpheus (*Light Conversion Ltd.*) at 200 kHz repetition rate. More details on this experimental technique can be found in Ref. [4].

3. Results and discussion

Figure 1 shows the THz radiation pulses emitted from the investigated Te/GaAs structures illuminated by femtosecond optical pulses of different wavelengths. When the energy of the photon exciting the sample is equal to 0.63 eV (Fig. 1(a)), the amplitude of the emitted THz pulse is highest in the heterostructure formed on n-GaAs and lowest in the structure on SI GaAs. The inverse relationship is observed when the photon energy is increased to 1.11 eV (Fig. 1(b)). In this case, the Te/SI-GaAs heterostructure emits much higher amplitude THz pulses than the remaining two samples.

THz pulses are usually emitted from the surfaces of semiconductors illuminated by a femtosecond laser pulse for two reasons – the spatial separation of photoexcited electrons and holes due to the built-in electric field at the surface, or their different diffusion speeds towards the bulk of the sample. Although the surface field is weak in such a narrow bandgap material as tellurium, the latter mechanism should prevail in it, as in other similar semiconductors, such as InSb [6] or InAs [7]. In tellurium, the mobility of electrons is about 1.5 times higher than the mobility of holes [8], though much less than in A3B5 semiconductors, so a dynamic electric dipole will form on the surface, which conditions the appearance of a THz pulse. The amplitude of that pulse will increase monotonically because increasing the energy of photons will also increase the velocity of electron movement. This is also confirmed by the dependence of the amplitude of THz pulses on the energy of the photons that excite them, shown in Fig. 2.

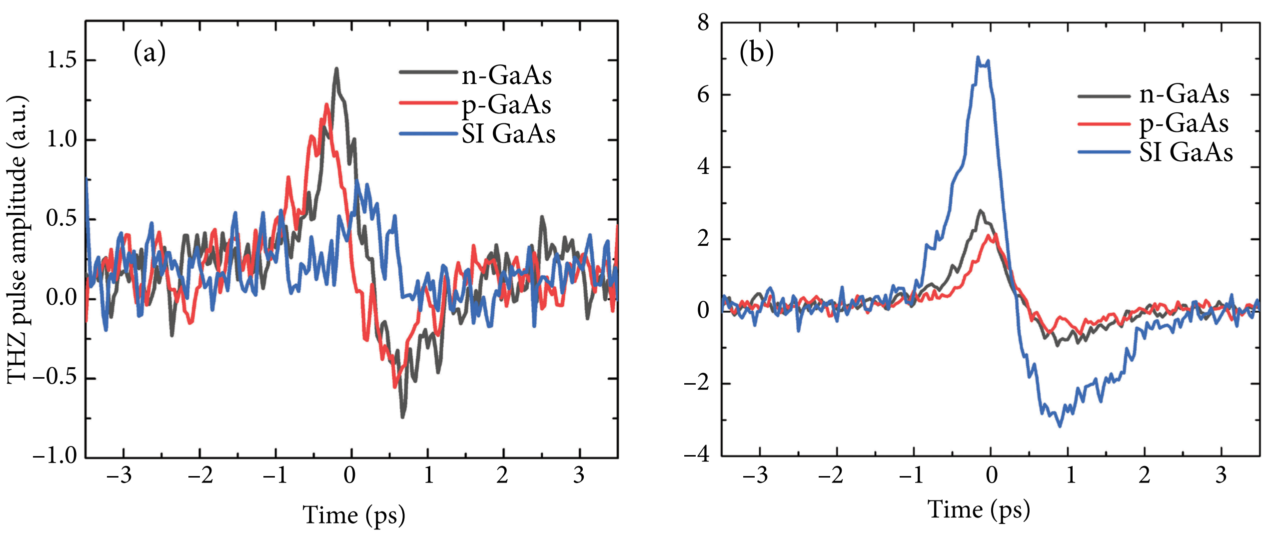

Fig. 1. The measured THz pulse transients of the 100 nm Te thermally evaporated layers grown on GaAs substrates with varying doping: *n*-type, *p*-type and semi-insulating (SI). The THz pulses were measured in reflection geometry, with the exciting laser beam impinging at a 45° angle, having a power of 20 mW with p polarization and a photon energy of (a) 0.63 eV and (b) 1.11 eV.

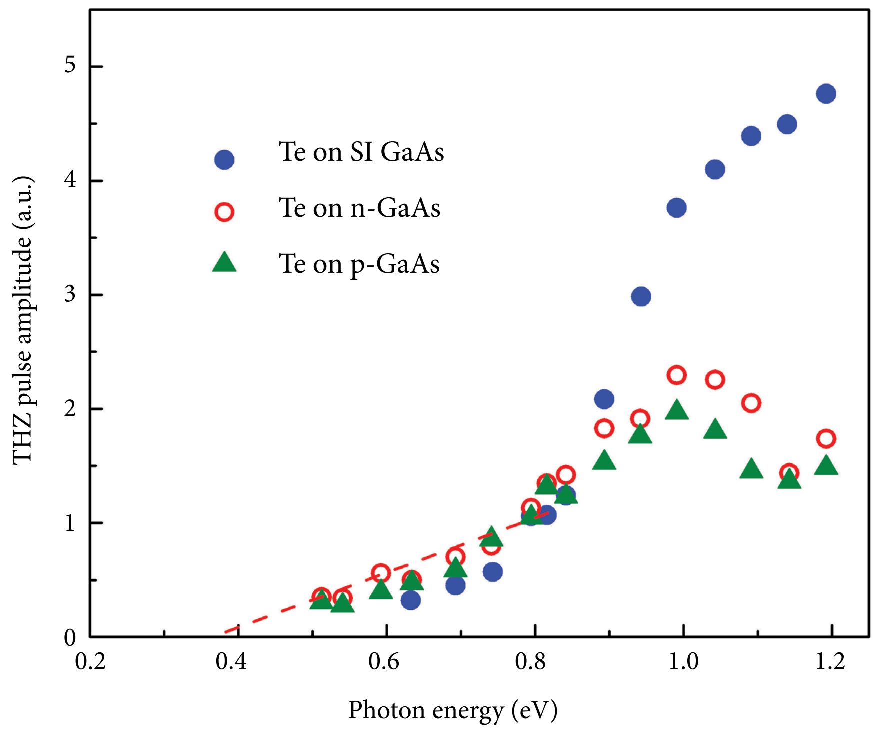

Fig. 2. The THz pulse excitation spectrum of the 100 nm Te layers thermally evaporated on GaAs substrates with varying doping: n-type, p-type and semi-insulating (SI). The Te surface was excited by 20 mW power p polarization optical pulses at different wavelengths and afterwards normalized to the same photon number.

An approximation of the initial parts of these THz excitation spectra crosses the abscissa axis at the energy close to the Te bandgap, indicating that a dynamic dipole is formed in the tellurium layer. In the layers deposited on n- and p-type GaAs substrates, the maxima of TES characteristics are observed at photon energies close to 1 eV, similar to that observed in the Te single crystals, where this shape of the curves was explained in Ref. [4] by the onset of electron scattering to higher and lower mobility conduction band valleys. On the other hand, the spectral characteristic of Te on the SI GaAs sample significantly differs from the measurements on the other two samples. In this case, a strong increase in the amplitude of the THz pulses is observed when the photon energy exceeds about 0.8 eV, and at an energy of 1 eV only a small decrease in the slope of the TES characteristic is observed.

These changes in TES characteristics can be explained by examining the arrangement of energy bands in various Te/GaAs heterostructures. Therefore, the band edge diagrams were calculated using the *Silvaco* TCAD software suite. The electron affinity of Te was set to 4.61 eV assuming that the 100 nm thick tellurium has a work function equal to 4.96 eV [9] and the bandgap 0.35 eV. The other parameters are given in the description of the experiment. The calculation results for GaAs substrates with different doping are shown in Fig. 3.

A comparison of Te heterostructures with differently doped GaAs crystals shows clear differences between them. While the heterostructures of the second type are formed on n- and p-type GaAs, the arrangement of energy bands in the Te heterojunction with SI GaAs is the same as in typical type-I heterostructures. Therefore, the dynamics of electrons in various samples can be different. A higher or lower energy barrier for the electrons moving towards GaAs exists in both tellurium junctions with heavily doped GaAs substrates. The minimum of the conduction band in tellurium is about 0.3 eV above the minimum of this band in n-GaAs, so electrons from Te will immediately enter the high effective mass subsidiary conduction band valleys of GaAs, which will effectively stop

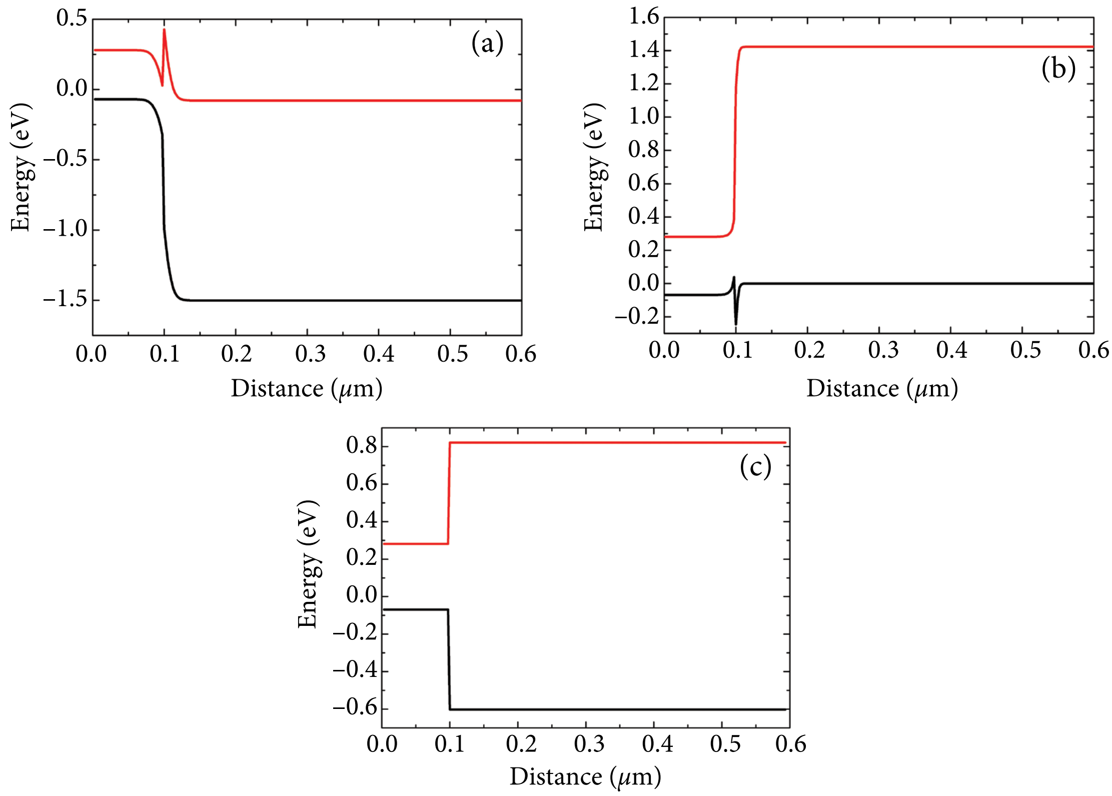

Fig. 3. Computed conduction (red) and valence (black) bands of the Te/GaAs heterojunction as a function of distance from the surface for different substrates doping: (a) n-type GaAs, (b) p-type GaAs, (c) semi-insulating GaAs.

their further movement. On the other hand, electrons cannot enter p-GaAs due to the large barrier separating the two materials.

These problems will not arise if we consider the movement of photoelectrons excited in tellurium through a heterojunction with SI GaAs. Having overcome the offset of the conduction band, the electrons will enter the lowest Γ valley of the conduction band of GaAs, where the mobility of electrons is by an order of magnitude higher than in tellurium, so there will be no obstacles to their further movement and strengthening of the dynamic dipole that is responsible for the THz pulse emission.

It should be noted that the offset of the conduction band in the Te/SI GaAs junction is very sensitive to the electron affinities χ in both materials. When drawing the heterostructures shown in Fig. 3, the GaAs affinity was assumed to be equal to $\chi = 4.61$ eV [9]. In the case of tellurium, various authors indicate rather different values of this parameter: 4.02 [2], 4.2 [3] and 4.61 eV [9]. The height of the barrier between Te and SI GaAs should be very sensitive to this value. The amplitude of the THz pulse radiated from the heterojunction of these materials begins to grow strongly when the photon energy exceeds this height. Therefore, the value of the parameter χ itself in tellurium can be estimated from the threshold of the THz emission efficiency as indicated in Fig. 2. Such an estimate is presented in Fig. 4, in which the abovementioned hetero-

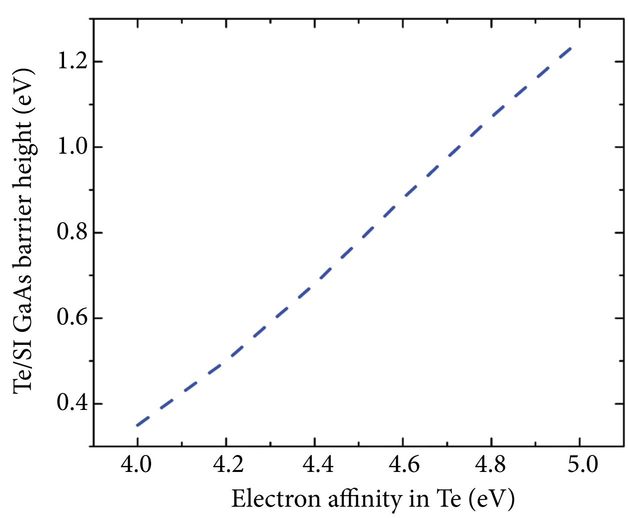

Fig. 4. The calculated Te/SI GaAs barrier hight vs electron affinity in tellurium.

junction barrier height is presented as a function of electron affinity in tellurium. Considering the above, we can see that the barrier height observed in the experiment, which is >0.8 eV, is best matched by the value of $\chi = 4.61$ eV.

The band structure of the heterojunction formed by Te on the n-GaAs surface obtained using this χ value resembles the band alignment for the Te/Si heterostructures investigated in Ref. [3]. Such a II-type band arrangement with an additional built-in electric field region was used there to realize a self-powered photodetector device.

The photodetection principle was tested using a simple sandwich-type structure fabricated by cutting a 1.5 × 1.5 mm^2 large piece from a Te/n-GaAs wafer. The electrical contacts were made of indium, pressed to a tellurium layer and fused to an n-GaAs substrate. Such a photodiode was illuminated from the side of the Te layer. Figure 5 shows the wavelength-dependent photocurrent in this Te/n-GaAs heterostructure device at zero bias voltage. One can see from this figure that the device has a wide photoresponse spectrum with a maximum at about 800 nm.

To investigate the photoresponse of the Te/n-GaAs heterostructure in more detail, we measured the current–voltage characteristic when laser beams of various intensities (wavelength equal to 808 nm) are used for illumination. Such characteristics measured at light intensities ranging from 0 to 78.82 mW/cm^{-2} are shown in Fig. 6. By increasing the light intensity, the photocurrent corresponding to the zero bias voltage continuously increases. Its value corresponding to the maximum used intensity is close to 0.2 μA – nearly two times larger than the photocurrent observed in a self-powered photodiode from the Te/Si heterostructure illuminated at the same laser wavelength [2]. This evidences that Te/GaAs heterostructures can find new applications in near-infrared optoelectronics on the GaAs platform.

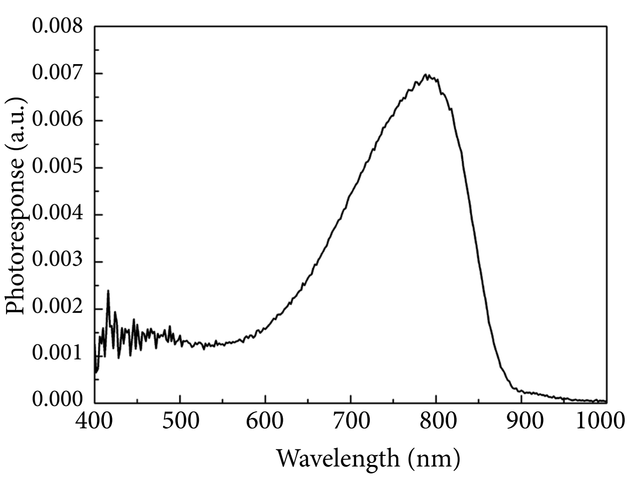

Fig. 5. Photoresponse spectrum at zero bias voltage.

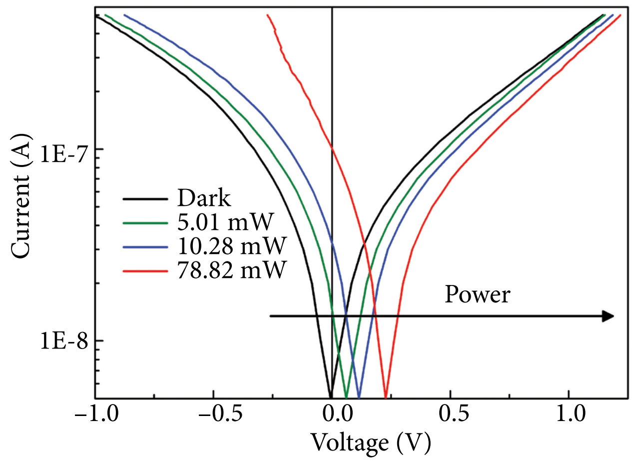

Fig. 6. The current–voltage characteristics in the dark and under illumination by a laser beam of various intensities. The laser wavelength was 808 nm.

4. Conclusions

In summary, the heterostructures consisting of thin tellurium layers thermally evaporated on variously doped GaAs substrates were systematically investigated. The excitation spectra of THz pulses were measured over a wide range of femtosecond optical pulse wavelengths. During the experiment, the energy of the photons was changed from 0.5 to 1.2 eV.

The THz excitation spectra of the heterostructures produced on various GaAs substrates differed from each other. In the heterostructures formed on n- and p-type GaAs substrates, THz pulses were emitted when the laser photon energy exceeded the tellurium bandgap ($\varepsilon_g = 0.35$ eV) and their amplitude increased monotonically until reaching an energy of ~1 eV. Meanwhile, in the tellurium heterostructures with semi-insulating GaAs, the stronger emission of THz pulses started only when the photon energy reached about 0.8 eV and then significantly exceeded the emission from the other two structures.

Those differences were explained by comparing the modelled band structures of the samples. In the heterostructures grown on heavily doped

GaAs substrates, the THz excitation spectra resemble such spectra in bulk Te crystals, so the THz emission occurs mainly from the tellurium layer, because in p-GaAs electrons cannot enter due to the barrier at the boundary between Te and GaAs, while in n-GaAs they are scattered into a small mobile subsidiary conduction band valley. If the Te/SI GaAs heterostructure is photoexcited with photons the energy of which exceeds the height of the barrier, the amplitude of THz pulses increases because electrons from tellurium enter GaAs, where their mobility is higher.

The described studies made it possible to estimate the value of electron affinity in the Te layers. In addition, a Te/GaAs-based near-infrared photodetector was developed for the first time. We believe that Te/GaAs structures may also be promising for the development of various THz photonics components.

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TELŪRO/GaAs HETEROSANDŪROS, PAGAMINTOS TERMIŠKAI GARINANT VAKUUME

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Santrauka

Heterosandūros, pagamintos termiškai garinant plonus telūro sluoksnius ant įvairiai legiruotų GaAs padėklų, buvo sistemingai tiriamos pasitelkiant THz spinduliuotės impulsų žadinimo spektroskopiją. Stebimi THz žadinimo spektrų skirtumai buvo paaiškinti nevienodu elektronų energijos juostų išsidėstymu šiose heterosandūrose. Telūro ir pusiau izoliuojančio GaAs heterosandūrų modeliavimo rezultatų palyginimas su išmatuotu THz impulsų emisijos spektru leido įvertinti elektronų giminingumą telūre. Be to, naudojant darbe tirtą Te heterosandūrą su n-GaAs, pavyko detektuoti artimojo infraraudonojo diapazono spinduliuotę.