ISSN 1063-7850, Technical Physics Letters, 2015, Vol. 41, No. 4, pp. 362–365. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © F.S. Gabibov, E.M. Zobov, M.E. Zobov, S.P. Kramynin, E.G. Pashuk, Sh.A. Khalilov, 2015, published in Pis'ma v Zhurnal Tekhnicheskoi Fiziki, 2015, Vol. 41, No. 8, pp. 9–17.

The Effect of Ultrasonic Treatment on the Energy Spectrum of Electron Traps in *n*-GaAs Single Crystals

F. S. Gabibov[a]†, E. M. Zobov[a]*, M. E. Zobov[a], S. P. Kramynin[a], E. G. Pashuk[b], and Sh. A. Khalilov[b]

[a] *Amirkhanov Institute of Physics, Dagestan Scientific Center, Russian Academy of Sciences, Makhachkala, Dagestan, 367003 Russia*

[b] *Dagestan State University, Makhachkala, Dagestan, 367000 Russia*

**e-mail: zem_07@mail.ru*

Received April 13, 2014

Abstract—We have studied the effect of ultrasonic treatment (UST) on the photo- and thermoelectric properties as related to electron traps in *n*-GaAs single crystals. It is shown for the first time that the UST leads to changes in the spectra of photoconductivity and thermostimulated current in *n*-GaAs. A possible mechanism of UST action on the energy spectrum of electron traps is discussed.

DOI: 10.1134/S1063785015040239

The most important properties of semiconductor materials and related device structures are determined by the presence of intrinsic and impurity point defects and complexes thereof, which play the role of centers for charge carrier trapping and recombination [1]. To create effective converters of solar radiation into electricity based on commonly accessible semiconductors, it is necessary to develop new technologies for managing defects, which will provide effective control over the efficiency and spectral range of photosensitivity of solar energy converters.

Gallium arsenide (GaAs) possesses unique photoelectric properties, which have allowed effective detectors of visible and infrared light and solar energy converters to be developed based on this semiconductor [2]. However, the photoelectric properties of GaAs crystals, like those of other semiconductor materials, can change as a result of processes induced by external factors such as temperature and light [3], electric field, radiation, etc. The complexity of processes involving nonequilibrium charge carriers and crystal lattice defects makes the mechanisms of GaAs degradation not completely clear until now. The photoelectric properties are also influenced by inhomogeneous distribution of the point defects, impurities, and their complexes in the volume of crystals, which give rise to macroscopic electric and elastic fields. These fields, in turn, influence the drift, trapping, and recombination of carriers. External factors can modify the character of interaction between point and associated defects with internal electric and elastic fields in the crystal lattice, which can lead both to the decay of complexes and to the formation of new defect–impurity associates. Therefore, investigations aimed at establishing the role of external electric and elastic fields on the energy spectrum of electron states related to defect–impurity centers are topical.

This work was devoted to studying the effect of ultrasonic treatment (UST) on the energy spectrum of electron traps in *n*-GaAs single crystals.

The experiments were performed on 3 × 2 × 1-mm samples of intentionally undoped (background impurity concentration $N < 10^{15}$ cm^{-3}) *n*-type GaAs single crystals with room-temperature resistivity ~10^{10} Ω cm. Crystals with these characteristics are widely used for manufacturing photoelements [2], as well as nuclear radiation and X-ray detectors [4, 5].

Ultrasonic oscillations were transmitted to the sample from a vibrator based on a piezoelement (PE) (Fig. 1) of barium titanate (TBK-3 grade) ceramics shaped as a thin disk with a diameter of $D = 28$ mm and a thickness of $h = 1.1$ mm, which performed radial (contour) vibrations [6]. This kind of action was selected because the given mode of oscillations provided almost one-dimensional (radial) deformation of the sample and the relative deformation amplitude (A_0) was almost the same at all points of the surface. Figure 1 shows a block scheme of the experimental setup comprising harmonic signal generator G (ANR-1105) *1* with frequency modulation; power amplifier *2*; differential amplifier *3*; frequency lock-in detector (FD) *4*; and PE excitation circuit *C*1, *R*1, *R*2. The differential amplifier and lock-in detector form a phase-lock loop (PLL) of the generator frequency tuning. The excitation bridge scheme was chosen so as to ensure a stable maximum amplitude of PE oscillations under PLL control [7]. The UST regime was monitored by voltmeter V (V3-38) *5* and stored in personal

†Deceased.

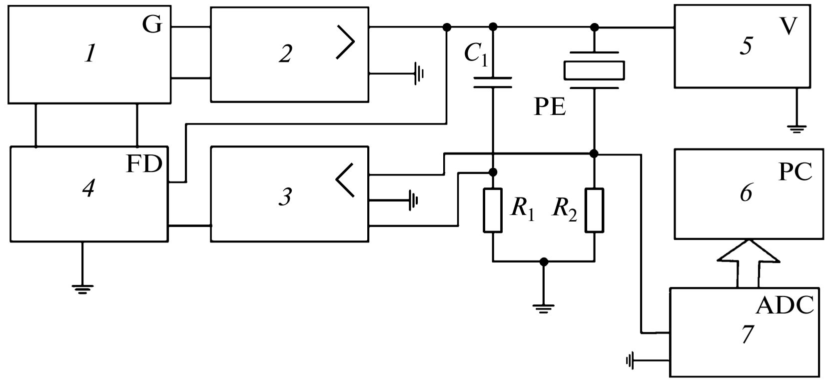

Fig. 1. Block scheme of the experimental setup for UST of crystals (see text for explanations).

computer (PC) *6* via analog-to-digital converter (ADC) *7*.

The differential amplifier was implemented on a high-speed operational amplifier. The lock-in detector consisted of a dual voltage comparator, logical element, and low-pass filter [8]. The power amplifier represented a conventional source follower based on two high-power complementary field-effect transistors [8]. The role of ADC was played by an ATsP-TsAP 14/2 ZETLAB device [9].

Relative deformation amplitude A_0 of the piezoelement (PE) can be calculated using an expression analogous to the well-known Marx formula [10]:

$$A_0 = \frac{2S_{11}I_r}{\pi^2 D^2 d_{31} f_0} = K_r I_r, \qquad (1)$$

where S_{11} is the elastic compliance modulus, d_{31} is the piezoelectric modulus, f_0 is the resonance frequency, and I_r is the PE current at resonance. The PE parameters entering into formula (1) were experimentally determined in accordance with the resonance–antiresonance method [10].

The amplitude–frequency characteristics (AFCs) of the PE measured using a computer-controlled AFC meter based on an ATsP-TsAP 14/2 device. These measurements yielded K_r = 0.0012. Since the PEs exhibited fracture at a current of $I_r \sim 2$ A, the maximum current was limited at 0.5 A. The corresponding relative deformation amplitudes A_0 varied from 10^{-6} to 6×10^{-4}. The most difficult task in implementation of the proposed UST technique was related to stabilization of the sample temperature. For this purpose, the sample was glued (with BF6 glue) to the vibrator surface at a point with $r = 7$ mm, placed into a thermostat, and purged with airflow. The PE current stabilization by the PLL allowed the sample temperature to be kept constant within 1°C. The GaAs single crystal was subjected to UST at a frequency of 111.5 kHz for 124 min at a PE voltage of $U_r = 8$ V, a current of I_r = 0.28 A, and a temperature of 42°C. After the UST, the sample was detached from the PE by holding it in glue solvent (ethyl alcohol).

The photoconductivity of GaAs crystals before and after the UST was studied in a spectral range of $h\nu \approx$ 0.4–1.8 eV by the frequency modulation (lock-in) spectroscopy technique at applied voltages in the region of linear dark current–voltage characteristics (V = 5–15 V). The contacts on samples were prepared by fusing indium into the largest face of the crystal. The photoconductivity response at the modulation frequency was measured by a lock-in INIPAN-233 nanovoltmeter. Measurements of the dark conductivity and the spectra of thermo- and photostimulated current were performed in a temperature interval of T = 90–350 K.

Figure 2 shows the photoconductivity spectra of GaAs single crystals measured at 295 and 90 K. As can be seen, the spectra exhibit a complicated structure. The band of photoconductivity with the maximum at $h\nu_{max} \cong 1.0$ eV and the "red" edge at $h\nu_{ir} \cong 0.76$ eV (Fig. 2, spectra *1* and *1*') is conventionally assigned to EL2 type centers, which are characteristic electron traps in GaAs. According to various reported estimations, the depth of this electron trap varies within E_c = (0.72–0.85) eV [1–4].This trap controls generation–recombination processes in GaAs, as well as charge carrier transport processes in GaAs-based detectors of nuclear radiation [4].

One distinctive feature of EL2 type centers is their ability to pass to a metastable EL2* state. The EL2 $\longrightarrow$ EL2* transition in GaAs upon irradiation in the range of impurity absorption ($h\nu \cong 1.1$–1.25 eV) or by "white" light at $T < 130$ K is accompanied by a decrease in the intensity of photoconductivity, photoinduced capacitance, luminescence, and electric paramagnetic resonance (EPR) signals [3–9]. According to Bagraev [14], the EL2 $\longrightarrow$ EL2* transition in GaAs is related to the passage of As atoms from gallium sites to tetrahedral interstitial sites, which must be accompanied by changes in the energy spectrum of electron states localized in the bandgap of GaAs.

In order to elucidate the stability of EL2 type centers responsible for the photoconductivity of our

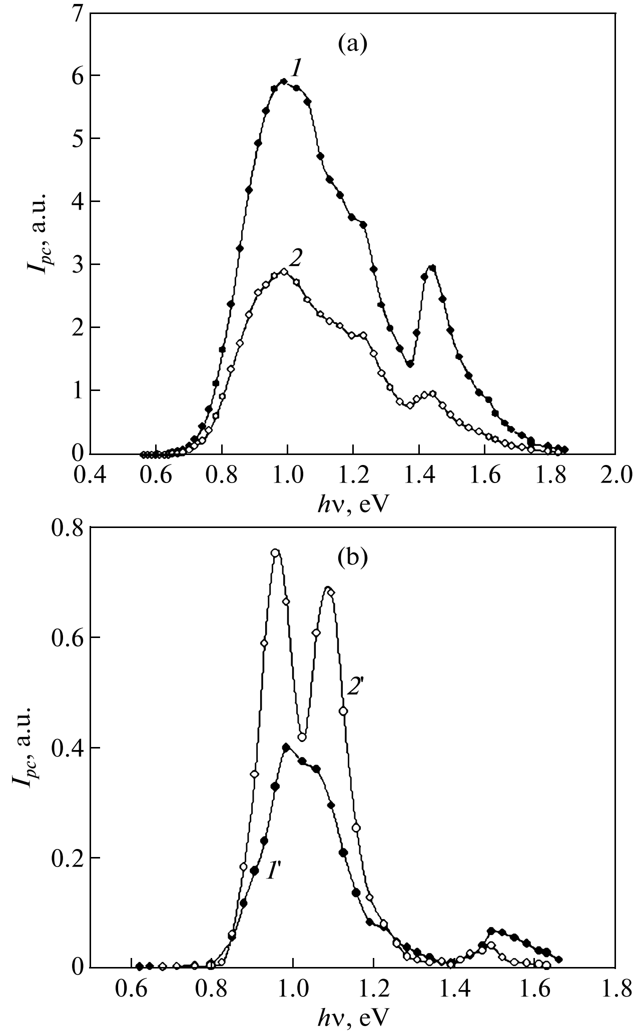

Fig. 2. Photoconductivity spectra of GaAs single crystals measured at (a) 295 K and (b) 90 K: (*1*, *1'*) initial samples (before UST); (*2*, *2'*) processed samples (after UST).

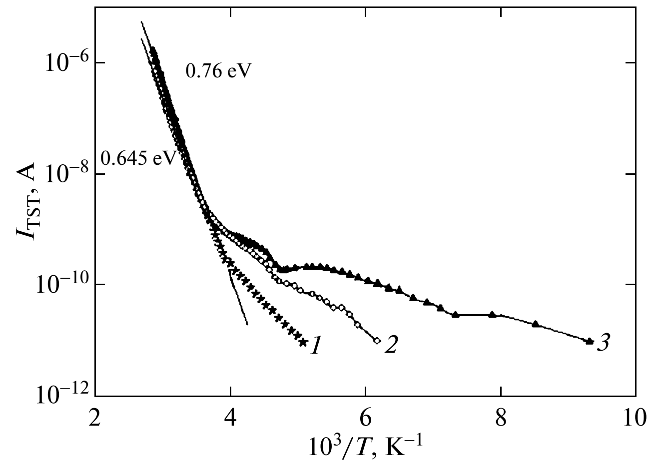

Fig. 3. Temperature dependences of (*1*) dark current and (*2*, *3*) thermostimulated current after and before UST, respectively, in *n*-GaAs single crystals.

n-GaAs single crystals (Fig. 2, spectra *1* and *1'*), we have performed experiments with the samples cooled from room to low (90 K) temperature and exposed to the light of an incandescent lamp or monochromatic light at $h\nu \cong 1.15$ eV. Neither a decrease in the photosensitivity nor narrowing of the spectral composition has been observed. This result implies that photosensitive centers related to the EL2 type traps in our GaAs crystals are incapable of the EL2 $\longrightarrow$ EL2* transition.

Investigation of the temperature dependence of the dark current (Fig. 3, curve *1*) and thermostimulated current (curves *2* and *3*) showed that our *n*-GaAs crystals contained not only EL2 type traps (revealed due to their thermal ionization at temperatures $T > 250$ K), but also some more shallow electron traps that are thermally ionized at temperatures $T < 250$ K. Determination of the characteristic parameters of these traps showed that the energy spectrum of the corresponding electron states contains levels in the energy interval of $E_c = 0.1–0.5$ eV. These traps, despite their donor character, have small electron capture cross sections within $S_t \cong 10^{-18}–20^{-23}$ cm^2, which hinders the process of repeated electron capture. Most probably, these traps also possess small cross sections of photon capture and, hence, can be classified as β type [1].

Electron traps in GaAs with energy levels in the interval within $E_c = 0.1–0.5$ eV have been reported by many researchers. Blanc et al. [20] have suggested that thermostimulated current peaks in the temperature interval of 100–250 K could be related to “paired and unpaired defects.”

A comparative analysis of the photoconductivity and thermostimulated current spectra of *n*-GaAs single crystals measured before and after UST revealed the following laws.

(i) The UST leads to a decrease in the photosensitivity of crystals at T = 295 K (Fig. 2) in both the intrinsic and impurity absorption range.

(ii) The band of low-temperature (90 K) impurity photoconductivity at $h\nu_{max} \approx 1.0$ eV splits into two well-resolved narrow bands ($h\nu_{max} \approx 0.95$ and 1.125 eV) separated by a minimum at $h\nu_{min} \approx 1.025$ eV (Fig. 2b, curve *2*).

(iii) The UST leads to changes in the energy spectrum of β-type electron traps (Fig. 3, curves *2* and *3*).

As for the EL2 type centers, it should be noted that the physicochemical nature of these centers is still not established. It has been pointed out (see review [13]) that EL2 type center is mutually related to antistructure defect As^0_{Ga}, which can be involved in $As_{Ga}As_i$ [19] and $As_{Ga}As_{Ga}$ complexes or more complicated clusters of arsenic atoms [21]. A model proposed by Ikoma and Mochizuki [22] is attractive because it explains the existence of close-lying levels in EL2 centers at depths within $E_c = 0.72–0.86$ eV. The model of Litvinova [12] assumed a relationship of this trap with a complex consisting of As^0_{Ga} and some point defect or impurity.

Proceeding from the associative physicochemical nature of EL2 type centers, it can be suggested that the UST of *n*-GaAs crystals leads to partial decomposition of complexes involving antistructure defects and to some modification of the spectrum of electron states of traps. As a result, the photoconductivity band at $h\nu_{max} \approx 1.0$ eV (Fig. 2b, curve *2'*) splits into two components.

The UST of *n*-GaAs single crystals leads to transformation both of the spectrum of electron states responsible for the photoconductivity of these crystals and the part of the energy spectrum related to β type traps (Fig. 3, curves *2* and *3*).

Thus, the results of this investigation show that the UST ($f = 111.5$ kHz, 124 min at a PE voltage of $U_r = 8$ V, $I_r = 0.28$ A, and a temperature of 42°C) leads to changes in the energy spectrum of electron states in traps representing defect–impurity states of the *n*-GaAs crystal lattice. This effect can be used for controlling the photo- and thermoelectric properties of this semiconductor material.

Acknowledgments. This work is dedicated to the memory of our late old friend and colleague Fazil Seifullaevich Gabibov.

REFERENCES

1. S. M. Ryvkin, *Photoelectric Phenomena in Semiconductors* (Fizmatlit, Moscow, 1963) [in Russian].
2. L. N. Andreev, V. A. Grilikhes, and V. D. Rumyantsev, *Photoelectric Conversion of Concentrated Solar Radiation* (Nauka, Leningrad, 1989) [in Russian].
3. F. S. Gabibov and E. M. Zobov, Inorg. Mater. **49** (8), 754 (2013).
4. E. M. Verbitskaya, V. K. Eremin, A. M. Ivanov, N. B. Strokan, V. I. Vasil'ev, V. N. Gavrin, E. P. Veretenkin, Yu. P. Kozlova, V. B. Kulikov, A. V. Markov, and A. Ya. Polyakov, Semiconductors **38** (4), 472 (2004).
5. R. A. Akhmedulin, V. F. Dvoryankin, G. G. Dvoryankina, Yu. M. Dikaev, M. G. Ermakov, O. N. Ermakova, A. I. Krikunov, A. A. Kudryashov, A. G. Petrov, and A. A. Telegin, Tech. Phys. Lett **28** (1), 15 (2002).
6. W. Mason, *Piezoelectric Crystals and Their Application in Ultrasonics* (Van Nostrand, New York, 1950; IL, Moscow, 1952).
7. A. V. Donskoi, O. K. Keller, and G. S. Kratysh, *Ultrasonic Electrotechnological Setups*, 2nd ed. (Energoizdat, Leningrad, 1982) [in Russian].
8. P. Horowitz and W. Hill, *The Art of Electronics*, 2nd ed. (Cambridge University Press, Cambridge, 1989; Mir, Moscow, 1993), Vol. 3.
9. Electronic Technologies & Metrological Systems Co. (ZETLAB), Catalog; http://www.zetlab.ru
10. J. Marx, Rev. Sci. Instrum. **22** (7), 503 (1951).
11. V. M. Sharapov, V. P. Musienko, and E. V. Sharapova, in *Piezoelectric Transducers*, Ed. by V. M. Sharapov (Tekhnosfera, Moscow, 2006) [in Russian].
12. M. B. Litvinova, Semiconductors **38** (1), 42 (2004).
13. A. N. Georgobiani and I. M. Tiginyanu, Sov. Phys. Semicond. **22** (1), 1 (1988).
14. N. T. Bagraev, Sov. Phys. JETP **73** (4), 764 (1991).
15. Hoon Young Cho, Eun Kyu Kim, and Suk-Ki Min, Phys. Rev. B **39** (14), 10376 (1989).
16. D. W. Fiacher and W. C. Mitchel, Phys. Status Solidi (B) **154** (11), 11 (1989).
17. G. Vicent, D. Bois, and A. Chantre, J. Appl. Phys. **53** (5), 3645 (1982).
18. J. Wagner and J. A. Van Vechten, Phys. Rev. B **35**, 1330 (1987).
19. D. Stievenard and H. J. Van Bardeleben, Rev. Phys. Appl. **23** (5), 803 (1988).
20. J. Blanc, R. Y. Bube, and L. R. Weisberg, J. Phys. Chem. Solids **25**, 225 (1964).
21. B. K. Meyer and J.-M. Spaeth, J. Phys. C: Solid-State Phys. **18** (4), L99 (1985).
22. T. Ikoma and Ya. Mochizuki, Jpn. J. Appl. Phys. **24** (12), L935 (1985).

Translated by P. Pozdeev