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Ultrasonic Treatment-Induced Modification of the Electrical Properties of InAs *p–n* Junctions

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Abstract—The effect of a high-frequency ($f = 5$ MHz) ultrasonic treatment (UST) on the low-temperature ($T = 77$ K) electrical properties of smooth InAs *p–n* junctions has been studied. It is established that the most UST-sensitive parameter is the tunneling current component, which is probably related to the channels of increased conductivity localized near dislocations. The current component determined by the recombination of carriers in the space charge region free of dislocations is less sensitive. The electrical characteristics of *p–n* junctions exhibit a tendency to restoration during the long-term storage of treated samples under laboratory conditions. Possible models of the influence of UST on the electrical properties of smooth InAs *p–n* junctions are discussed.

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InAs and related solid solutions are widely used as base semiconductor materials for the modern optoelectronics. It was established [1–5] that the ultrasonic treatment (UST) of semiconductor structures can improve their properties. The influence of UST on the characteristics of semiconductor materials and structures is usually explained in terms of two models of the interaction of acoustic waves with structural defects. According to the most commonly accepted approach, known as the dislocation model [6, 7], the energy of acoustic waves absorbed by dislocations can stimulate the generation of acoustically active defects and induce their rearrangement, which leads to the modification of the initial properties of materials and structures. The second model, which is less justified theoretically and confirmed experimentally, is based on an assumption concerning the interaction of an acoustic wave with an elastic field of complex defects, which can lead to the transformation of the structure of defects, their dissociation, and changes in the charged state and cross section for trapping carriers [1, 2, 8, 9].

Recently, we established [10, 11] that the forward current–voltage (I–U) characteristics of InAs *p–n* junctions at 77 K can be approximated by two exponential parts. It was shown that, at small forward bias voltages, the I–U curve is determined by a tunneling current passing via the channels of increased conductivity that intersect the *p–n* junction plane. These channels may be related to the Cottrell impurity atmospheres localized at dislocations. At large bias voltages, the dominant process is the recombination of carriers in dislocation-free space charge region of the *p–n* junction.

The inhomogeneous InAs *p–n* junctions are interesting objects for studying the interaction of acoustic waves with defects localized in the space charge region and interpreting the results within the framework of the existing theoretical models. It is also important to study the temporal stability of *p–n* junctions on an UST. This Letter presents the results of our investigation of these issues.

The InAs *p–n* junctions were prepared using the diffusion of preliminarily synthesized $CdAs_2$ into substrates in sealed evacuated quartz ampules [10]. The substrates were cut from an *n*-InAs single crystal ingot (Pure Metals Co, Svetlovodsk, Ukraine). The electron concentration and mobility in the initial *n*-InAs at $T = 300$ K were $n = (2–3) \times 10^{16}$ cm^{-3} and $\mu_n = (2–3) \times 10^4$ cm^2/(V s), respectively; the dislocation density was within $(1–2) \times 10^4$ cm^{-2}; and the X-ray rocking curve width did not exceed 27″. The diffusion of cadmium (acceptor impurity) in InAs was carried out for 1 h at $T \sim 873$ K. The *p–n* junction depth ($\sim 15 \pm 0.5$ μm) was determined from the results of thermo-emf measurements in the course of layer-by-layer etching of *p*-InAs in the stage of fabricating mesa structures with an area of $S = 7 \times 10^{-2}$ cm^2 on the (111)A side. The ohmic contacts were prepared by vacuum deposition of thin layers of zinc and indium on *p*-InAs and indium on *n*-InAs, followed by a heat treatment in purified hydrogen atmosphere.

The samples were subjected to an UST at a frequency of 5 MHz from the substrate side (from which the ohmic contact was preliminarily etched off). The ultrasound was generated by a lithium niobate transducer powered by the output voltage of a high-frequency oscillator. The acoustic contact was provided by vacuum oil. The first treatment (UST-1) was effected at T = 295 K for 1 h at an intensity of ~0.4 W/cm^2. The second exposure (UST-2) was performed for 2 h under the same conditions. Repeated measurements of the characteristics of samples were carried out with nine-month storage under laboratory conditions. The experiments were performed with a series of five samples that possessed close initial characteristics with a spread not exceeding 30%. One of these samples was used as a reference, and its properties remained unchanged during the entire period of experiments. The other four samples, which had been simultaneously treated by ultrasound, exhibited the same trends in the variations in their electrical properties.

Taking into account that the diameter of the Cottrell impurity atmospheres can reach several microns [12], an analysis of the capacitance–voltage (C–U) curves of inhomogeneous p–n junctions must involve the evaluation of the contributions from regions in the vicinity of the Cottrell atmospheres and from a homogeneous part of the junction to the total measured capacitance. Evidently, the equivalent barrier capacitance of an inhomogeneous p–n junction can be expressed as $C_{eq} = C_1 + C_2$, where C_1 is the capacitance of the junction regions in the vicinity of the Cottrell atmospheres and C_2 is the capacitance of the homogeneous part of the junction. In order to evaluate C_1, it was assumed that the Cottrell atmospheres had circular cross sections with a diameter of 4 μm and a dislocation density at the junction was 1×10^4 cm^{-2}. The calculation of C_2 was based on the well-known formulas [13] for sharp and smooth p–n junctions. It was established that the main contribution to C_{eq} is due to the barrier capacitance of a homogeneous part of the p–n junction, which is valid up to a major carrier concentration of $n_0 = p_0 = 2 \times 10^{19}$ cm^{-3} in the vicinity of the Cottrell atmospheres.

Figure 1 shows the results of capacitance–voltage measurements at T = 77 K for the samples in various states. At $U \leq -0.4$ V, the experimental C–U plots for the initial (curve *1*) and ultrasound-treated (curves *2* and *3*) samples are linearized in the C^{-3} versus U coordinates, which is indicative of a nearly linear character of the doping impurity distribution in the p–n junction. The gradient a of the dopant concentration was evaluated from the slopes of linear segments. The space charge region thickness W_0 was evaluated from the barrier capacitance at a zero bias voltage. Data on the parameters of InAs p–n junctions are summarized in the table.

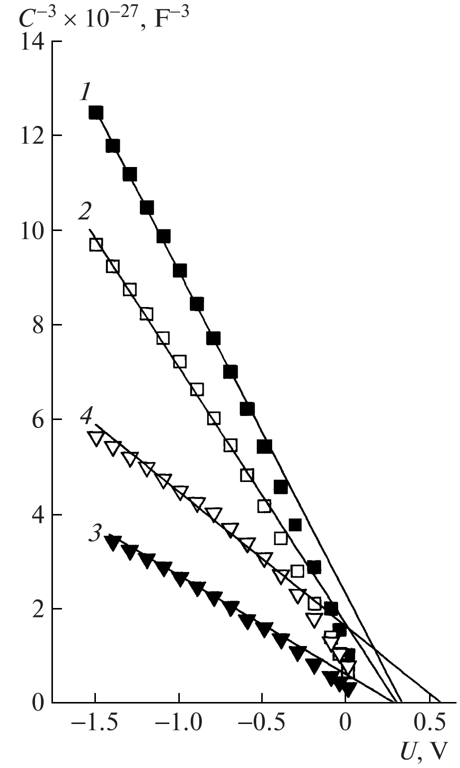

Fig. 1. Capacitance–voltage characteristics of InAs p–n junctions measured at T = 77 K for samples (*1*) in the initial state, (*2*, *3*) after UST-1 and UST-2, respectively, and (*4*) upon a 9-month storage of ultrasound-treated samples under laboratory conditions.

As can be seen from Fig. 1, the capacitance cutoff voltage is $U_c \approx 0.31 \pm 0.03$ V and weakly changes upon the UST. Upon the 9-month storage of ultrasound-

Parameters of InAs p–n junctions at T = 77 K

Sample state	Parameter							
	W_0, μm	a, cm^{-4}	I_{01}, A	I_{02}, A	E_0, meV	β	R_s, Ω	τ_0, s
	1	2	3	4	5	6	7	8
Initial	0.91	7.5×10^{18}	8.0×10^{-9}	5.4×10^{-14}	30	1.7	1.30	4.0×10^{-8}
UST-1	0.80	8.8×10^{18}	1.2×10^{-8}	2.6×10^{-13}	38	1.8	1.25	7.2×10^{-9}
UST-2	0.65	3.1×10^{19}	2.4×10^{-6}	2.6×10^{-13}	74	1.8	1.17	5.8×10^{-9}
Upon 9-month storage	0.84	7.8×10^{18}	3.6×10^{-8}	4.6×10^{-13}	73	2.0	1.34	4.4×10^{-9}

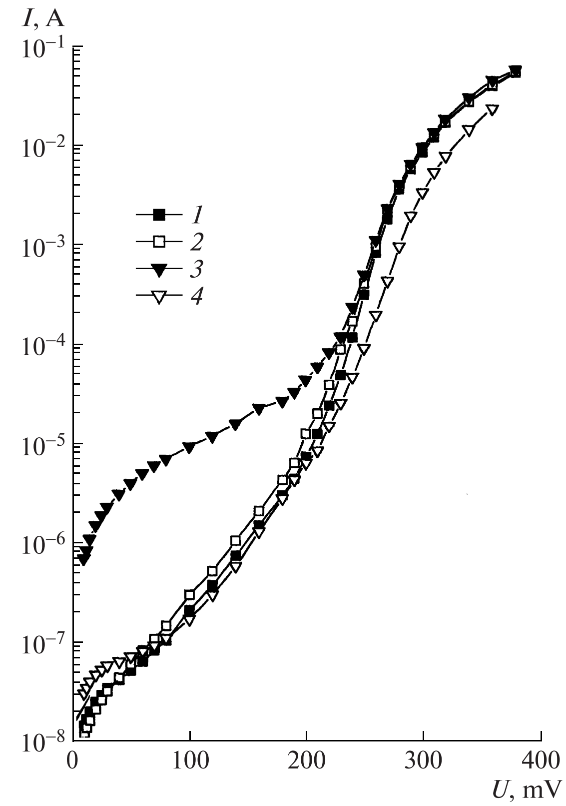

Fig. 2. Forward I–U curves of InAs p–n junctions measured at T = 77 K for samples (*1*) in the initial state, (*2*, *3*) after UST-1 and UST-2, respectively, and (*4*) upon the 9-month storage of ultrasound-treated samples under laboratory conditions.

treated samples, this value exceeded the bandgap width of InAs, which can be related to an inhomogeneous distribution of the charged defects in the space charge region [13] rather than to the influence of a serial resistance (see table) on the high-frequency C–U characteristic [14]. Using the obtained a and W_0 estimates, we can also evaluate the major carrier concentration as $N = n_0 = p_0 = aW_0/2$ at the boundary of the space charge region. For various states of the samples (initial, UST-1, UST-2, and upon a 9-month storage after UST), the estimated carrier concentration are 3.4×10^{14}, 3.5×10^{14}, 1.0×10^{15}, and 3.1×10^{14} cm^{-3}, respectively. These data indicate that a compensated region ($N \ll n$, where n is the carrier concentration in the substrate) is formed at the boundary of InAs p–n junctions in the course of their fabrication. The UST results in a significant decompensation of the indicated region, while a sufficiently long subsequent storage of the samples leads to the recovery of compensation. The tendency to recover the initial distribution of major carriers as the p–n junction boundary upon a 9-month storage of the ultrasound-treated samples shows that the UST produces transformation of the initial defects rather than changes the dopant (cadmium) profile. This transformation exhibits a long-term character at room temperature.

Figure 2 shows the forward I–U curves for the samples in various states, which can be satisfactorily approximated as consisting of the two following exponential regions:

$$I = I_{01}\exp\left(\frac{eU}{E_0}\right) + I_{02}\exp\left[\frac{e(U - IR_s)}{\beta kT}\right], \qquad (1)$$

where I_{01} and I_{02} are the pre-exponential factors for the first and second regions, respectively; E_0 is the characteristic energy; β is the nonideality coefficient; and R_s is the serial resistance. The first term on the right-hand side of formula (1) describes the tunneling current via regions (channels) of increased conductivity of the p–n junctions, while the second term describes the generation–recombination current of a homogeneous region. A deviation from the exponential behavior at large bias voltages ($U > 0.27$ V) is due to the influence of the serial resistance. The recombination lifetime τ_0 of carriers in the space charge region was evaluated from the following formula:

$$I_{02} = \frac{en_iW_0}{\tau_0}S, \qquad (2)$$

where $n_i = 2.1 \times 10^3$ cm^{-3} is the intrinsic carrier concentration in InAs at T=77 K. The parameters of I–U curves estimated using formulas (1) and (2) for the samples in various states are presented in the table.

As is known [15], the elastic stress fields of edge dislocations and impurity atoms interact with one another to form the Cottrell atmospheres. Depending on their size, the incorporated impurity atoms can localize in the regions of either hydrostatic expansion or compression, thus providing the spatial localization of neutral impurities. In addition, there are Coulomb interactions between the charged cores of dislocations and ionized impurities. The impurity atmospheres of dislocations most probably favor the accumulation of defects due to their increased solubility in the field of elastic stresses. According to the string model of a dislocation [6], its segments pinned at the impurities oscillate under the action of ultrasound, generating charged defects and ionizing neutral atoms [7]. Since the internal electric field of the p–n junction can decrease the energy of interaction between the dislocation core and charged defects, the action of ultrasound must be more effective in the space charge region than in quasi-neutral regions, and this is in fact observed in experiments. The local increase in the carriers concentration in the Cottrell atmospheres leads to a decrease in the space charge region thickness and an increase in the probability of carrier tunneling. It should be also noted that the volume electrical properties of the base n-InAs region did not change as a result of the UST.

Thus, it was demonstrated that an UST most significantly influences the tunneling current component related to the channels of increased conductivity that intersect the p–n junction plane. The generation–recombination current of a homogeneous region is less sensitive to the UST. This difference can be related to a transformation of defects in the Cottrell atmospheres as a result of the absorption of ultrasound by dislocations. The UST of InAs p–n junctions does not improve their electrical characteristics, while a long-term storage of samples after the UST leads to a recovery of their initial properties.

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