Technical Physics Letters, Vol. 31, No. 1, 2005, pp. 27–32. Translated from Pis'ma v Zhurnal Tekhnicheskoĭ Fiziki, Vol. 31, No. 1, 2005, pp. 54–66.

Acoustostimulated Expansion of the Short-Wavelength Sensitivity Range of AlGaAs/GaAs Solar Cells

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Received May 25, 2004; in final form, August 10, 2004

Abstract—The effect of ultrasonic waves on the spectral sensitivity of solar energy converters based on AlGaAs/GaAs heterostructures has been studied. Ultrasonic treatment of a zinc-doped graded-gap $Al_xGa_{1-x}As$ film leads to the formation of a surface layer sensitive to electromagnetic radiation in the wavelength range $\lambda < 0.551$ μm. It is established that this layer is formed as a result of the acoustostimulated inward diffusion of zinc from the surface to the bulk of the graded-gap layer. The observed expansion of the short-wavelength sensitivity range and an increase in the efficiency of nonequilibrium charge carrier collection in AlGaAs/GaAs solar cells are due to improvement of the crystal defect structure and the dopant redistribution under the action of ultrasound. *© 2005 Pleiades Publishing, Inc.*

Introduction. The task of controlled variation of the physical properties of semiconductor materials under the action of external factors is an important problem in the physics of semiconductors. As is well known, one such factor is ultrasonic radiation: propagating in a semiconductor crystal, ultrasonic waves change its properties, in particular, the optical characteristics [1]. In the context of solving the above task, it is expedient to continue investigations of the effect of ultrasonic waves on the characteristics of semiconductor devices.

This paper presents the results of experimental investigations of the influence of ultrasonic waves on the spectral characteristics of solar cells based on AlGaAs/GaAs heterostructures. The study was a logical continuation of our previous research [1], which showed that an exposure to ultrasonic radiation leads to a change, depending on the ultrasonic treatment (UST) parameters, in the spectral coefficient of reflection of silicon and gallium arsenide crystals, the base materials of modern semiconductor photoelectronics. To the best of our knowledge, no systematic data on the effect of ultrasonic waves on the working characteristics of GaAs-based solar cells are available. Some published results showed evidence of the positive character of changes in the characteristics of silicon-based solar cells under the action of ultrasonic waves [2, 3].

Gallium arsenide possesses a greater optical absorption coefficient, a wider bandgap, and higher mobilities of charge carriers as compared to the analogous characteristics for silicon, which accounts for the higher efficiency η of solar cells based on the former material. The theoretical limit of η for GaAs solar cells under standard AM1 solar illumination conditions exceeds 30%. The most widely used system in GaAs-based solar cells operating in an AM1 regime with $\eta \geq 17\%$ is a heterostructure of the n^+-GaAs–n-GaAs–p-GaAs–p-$Al_xGa_{1-x}As$ type fabricated by means of a relatively simple liquid phase epitaxy (LPE) method [4, 5].

Experimental. The experiments were performed with AlGaAs/GaAs-based solar cells fabricated using the following technology. The substrates for LPE-grown heterostructures were [111]-oriented single crystal n-GaAs wafers with a thickness of d = 350–400 μm, doped with tin (n^+-GaAs(Sn)) to $N \sim (1.5\text{–}3) \times 10^{18}$ cm^{-3}. The sequential epitaxial layers were n-GaAs(Sn) with a thickness of d = 12–14 μm and an electron density of $N_e = (2\text{–}5) \times 10^{17}$ cm^{-3}; diffusion-doped p-GaAs:Zn with a thickness of 0.8–1.5 μm and a hole concentration $p = 6 \times 10^{17}\text{–}4 \times 10^{18}$ cm^{-3}, obtained by zinc diffusion from the liquid phase; and the frontal p-$Al_xGa_{1-x}As$ with x = 0.3–0.8 and a thickness of l = 0.7–4.5 μm, doped with zinc to $(1\text{–}3) \times 10^{18}$ cm^{-3}. Then, an antireflection coating was formed by anodic oxidation of the uppermost $Al_xGa_{1-x}As$ layer, and ohmic contacts of a certain configuration were formed using the conven-

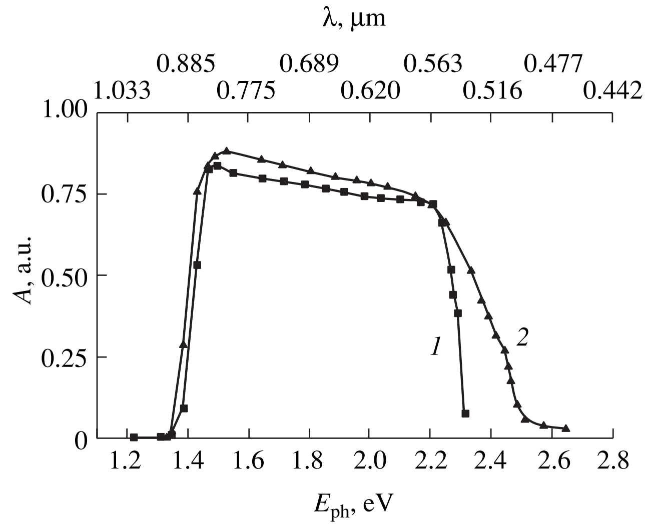

Fig. 1. The spectral characteristic of the photosensitivity A of an AlGaAs/GaAs solar cell (sample 13) measured (*1*) before and (*2*) after the UST at f = 25 MHz and P = 0.25 W/cm^2 for t = 65 min (T = 293 K).

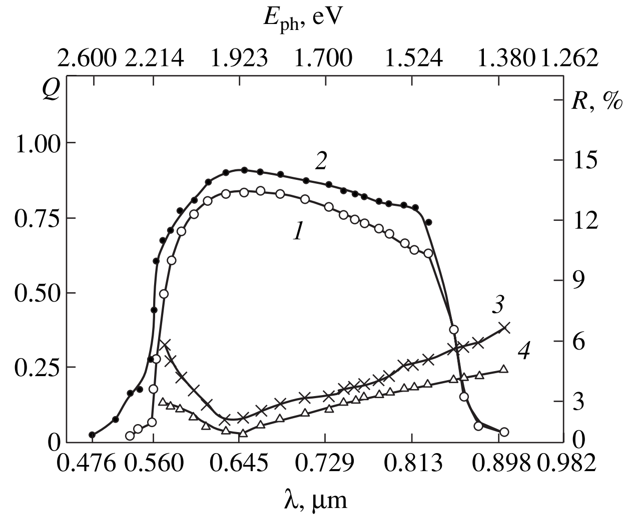

Fig. 2. The spectral dependence of the (*1*, *2*) charge carrier collection efficiency Q and (*3*, *4*) reflection coefficient R of an AlGaAs/GaAs solar cell (sample 13) measured (*1*, *3*) before and (*2*, *4*) after the UST at f = 25 MHz and P = 0.25 W/cm^2 for t = 65 min (T = 293 K).

tional photolithographic technique and electrochemical deposition of silver and nickel. The area M of the entrance window of the AlGaAs/GaAs solar cells varied from 0.25 to 2.25 cm^2.

The characteristics of the AlGaAs/GaAs solar cells were measured using a source imitating solar radiation and operating under conditions corresponding to AM1.5 illumination at a radiant flux power S = 850 W/m^2. The experimental procedure consisted in determining the photoelectric characteristics of the AlGaAs/GaAs solar cells before and after the room-temperature UST with monochromatic ultrasonic waves in various regimes. The monochromatic electromagnetic radiation was incident onto the outer surface of a wide-bandgap p-Al$_x$Ga$_{1-x}$As layer from the side of the entrance window. The AlGaAs/GaAs solar cells were exposed to longitudinal ultrasonic waves in the range of frequencies f = 0.8–25 MHz and power densities P = 0.1–5 W/cm^2 in the entrance window, at a variable exposure time of t = 15–60 min. The ultrasonic waves were transferred from a piezoelectric transducer (driven by a generator) to the AlGaAs/GaAs receiver via a liquid medium.

Parameters of an AlGaAs/GaAs solar cell (sample 13 with M = 0.25 cm^2, measured at T = 293 K, AM1.5, S = 850 W/m^2) before and after UST (f = 25 MHz, P = 0.25 W/cm^2, t = 65 min, T = 293 K)

Parameter	Before UST	After UST
Short-circuit current density I_{SC}, mA/cm^2	20.84	22
Open-circuit voltage V_{OC}, V	0.942	0.946
Filling factor *ff*	0.75	0.75
Efficiency η, %	17.32	18.36
Spectral sensitivity range λ, μm	0.534–900	0.466–0.900

Results and discussion. We studied a total of 30 AlGaAs/GaAs solar cells before and after the UST in various regimes characterized by the parameters f, P, and t. The most significant improvement in the photoelectric characteristics was observed for AlGaAs/GaAs solar cells irradiated with ultrasonic waves at $f \geq 15$ MHz and $P < 1$ W/cm^2 for $t > 45$ min. Figures 1 and 2 and the table present the results of our measurements of the spectral and functional characteristics for sample 13, which is a typical representative of the given series of AlGaAs/GaAs solar cells, with an p-Al$_x$Ga$_{1-x}$As (x = 0.4) layer thickness of l = 4 μm measured before and after the UST at f = 25 MHz and P = 0.25 W/cm^2 for t = 65 min.

Let us consider, in some detail, the data presented in the table and Figs. 1 and 2. The spectral characteristic (photoresponse A versus wavelength λ) of the solar cell measured before the UST exhibits a maximum at λ ≈ 0.775 μm (corresponding to the photon energy E_{ph} = 1.6 eV) followed by a smooth decrease in the photoresponse A in the wavelength interval λ = 0.563–0.775 μm and a sharp decrease in A above this interval at λ = 0.775–0.892 μm (E_{ph} = 1.6–1.39 eV). The occurrence of a maximum in the region of photon energies above the GaAs bandgap width is indicative of the fact that the p–n junction is situated within the AlGaAs layer of the heterostructure. The drop in A in the wavelength range at $\lambda > 0.775$ μm is mostly caused by a decrease in the hole diffusion length L_p determined by the presence of various defects. As is known [7, 8], graded-gap solid solutions feature built-in electric fields favoring more complete and fast charge collection on the electric contacts. Deviation of the shape of the spectral characteristic (photoresponse A) from the rectangular profile, which is manifested by the A value gradually decreasing in the interval λ = 0.775–0.563 μm, shows that the existing electric field gradient in the p-$Al_xGa_{1-x}As$ layer cannot provide for a fast drift and complete collection of nonequilibrium electrons.

An analysis of the data on the response signal amplitude k of the AlGaAs/GaAs solar cells operating as pulsed radiation receivers at λ = 0.700 μm [9, 10] revealed the presence of centers of electron trapping and recombination in the sensitive layer. This was indicated by the slow growth of the response signal amplitude according to the law $k(V) \sim V^n$ with $n = 1/2 < 1$ (V is the bias voltage). The presence of these electrically active centers decreases the electric field strength and increases the probability of carrier trapping in the graded-gap layer. Indeed, it was demonstrated [11] that traps present in the sensitive layer of receivers lead to the formation of regions where the electric field is very small or even absent. This results in a strong trapping of nonequilibrium carriers, leading to polarization of the receiver and, hence, to a decrease in its sensitivity and the response signal amplitude. The same factor (the presence of traps) is responsible for a decrease in the built-in electric field, the trapping of nonequilibrium carriers in the p-$Al_xGa_{1-x}As$ layer, and the observed decrease in the photoresponse amplitude A observed in our samples.

One possible reason for an increase in the short-circuit current I_{SC} observed upon the UST is the ultrasound-induced suppression (neutralization) of the centers of electron trapping and recombination in the sensitive layer, that is, in the region of effective carrier photogeneration [12]. This is confirmed by an increase in the signal amplitude in the wavelength interval λ = 0.775–0.563 μm and by the appearance of a photoresponse in the interval λ = 0.551–0.466 μm. This acoustostimulated expansion of the short-wavelength sensitivity range is clearly illustrated in Fig. 1 (curve *2*). Expansion of the photoresponse toward the long-wavelength region ($\lambda > 0.849$ μm) is much less significant. The acoustostimulated photoresponse at $\lambda > 0.849$ μm due to neutralization of the trapping and recombination centers was reported for a cascade narrowband GaAs photoconverter [13].

The usual way to expand the short-wavelength sensitivity range of $Al_xGa_{1-x}As/GaAs$ solar cells is through (a) an increase in the x component fraction in the $Al_xGa_{1-x}As$ solid solution and (b) a decrease in the p-$Al_xGa_{1-x}As$ layer [6]. However, the action of ultrasonic waves on the AlGaAs/GaAs solar cells under the conditions used in our experiments can change neither the x value nor the thickness of the p-$Al_xGa_{1-x}As$ epilayer. For this reason, we believe that the acoustostimulated photoresponse in the short-wavelength spectral range ($\lambda < 0.551$ μm) is caused, for the most part, by three factors.

Factor 1: the formation of photosensitive subsurface $Al_xGa_{1-x}As$ layers with an increased resistivity ρ as compared to that in the bulk of $Al_xGa_{1-x}As$ as a result of the acoustostimulated inward diffusion of zinc from the surface to bulk of the graded-gap layer. The possibility of this phenomenon is justified by the following considerations and is confirmed by the results of experiments with zinc diffusion in the ultrasonic field presented below.

It is known that, as the photon energy E_{ph} increases, the region of nonequilibrium carrier generation shifts toward the surface of the narrow-bandgap p-$Al_xGa_{1-x}As$ layer in the entrance window. The p-$Al_xGa_{1-x}As$ film in our solar cells, as well as in the semiconductor detectors of nuclear radiation [14], contains “dead” layers, insensitive with respect to the ionizing radiation. The presence of such layers poses problems even for the technology of nuclear radiation detectors, which (being intended for the detection of radiation that has a much lower intensity than solar radiation) are more precise devices than the solar cells. Since the principles of AlGaAs/GaAs solar cells are generally the same as those underlying the operation of nuclear radiation detectors (generation, drift, and collection of nonequilibrium carriers on electric contacts of the detector), the solar cells can also be considered as detectors of electromagnetic radiation, with the entire set of drawbacks inherent in these devices (loss of generated carriers, crystal structure defects, “dead” layers, etc.).

Our analysis showed that the absence of photoresponse (a lack of photosensitivity) observed for the $Al_xGa_{1-x}As$ solar cells in the range $\lambda < 0.551$ μm (Fig. 1, curve *1*) is related to the high conductivity σ of the subsurface region in the p-$Al_xGa_{1-x}As$ layer on the side of the entrance window exposed to the incident electromagnetic radiation. It was established that the zinc concentration N_{Zn} measured using a JSM 5910LV electron microprobe (JEOL, Japan) in a subsurface region with a thickness of $L \leq$ 01–0.15 μm was 2–4 times greater than that in the bulk of the p-$Al_xGa_{1-x}As$ layer. This gradient of N_{Zn} arises in the course of fabrication of the AlGaAs/GaAs solar cells and results in the formation of a Zn-saturated subsurface region with a submicron thickness, which is not sensitive (“dead” layer) with respect to electromagnetic radiation at $\lambda < 0.551$ μm.

The appearance of the photoresponse in this spectral range can be provided by decreasing σ of this nonphotosensitive layer. In the technology of nuclear radiation detectors, the task of creating a high-ohmic subsurface region is usually solved by incorporating lithium atoms into p-Si [14]. A decrease in conductivity of the subsurface region leads to the buildup of an additional (graded-gap) electric field E_v of the same sign as in the entire p-$Al_xGa_{1-x}As$ layer. The appearance of this additional graded-gap layer with the electric field E_v implies an expansion of the spectrally sensitive region of the AlGaAs/GaAs solar cells toward the surface, which must provide for the photoresponse to photons with E_{ph} > 2.25 eV (λ < 0.551 μm). In fact, we observed the appearance of such a photoresponse in AlGaAs/GaAs solar cells upon the UST (Fig. 1, curve *2*), which provided evidence for the acoustostimulated formation of photosensitive p-$Al_xGa_{1-x}As$ layers (or the disappearance of "dead" layers) near the surface of the entrance window.

The results of experimental measurements of the zinc concentration in samples with p-$Al_xGa_{1-x}As$ layer thicknesses up to 50 μm, which had the same initial compositions and N_{Zn} values as those in our AlGaAs/GaAs solar cells, showed that the UST for t = 240–360 min and above led to a three- to fivefold decrease in N_{Zn} in the subsurface layers. In these experiments, the dopant concentration was determined using electron-probe microanalysis with layer-by-layer ion-beam etching [1]. The UST parameters f and P in these experiments were the same as those used for the activation of the AlGaAs/GaAs solar cells. Therefore, the appearance of the photosensitive subsurface p-$Al_xGa_{1-x}As$ layers is related to the acoustostimulated inward diffusion of zinc from the surface to the bulk of the $Al_xGa_{1-x}As$ layer. Theoretical investigation into the effect of ultrasonic waves on the process of impurity diffusion in semiconductors was reported in [15].

Factor 2: the acoustostimulated decomposition of impurity clusters. The existence of this phenomenon is confirmed by the character of variation of the spectral dependence of the efficiency $Q(\lambda)$ of the nonequilibrium charge carrier collection measured in the wavelength interval λ = 0.448–0.982 μm. Figure 2 reveals the effect of UST on $Q(\lambda)$ in the region λ < 0.532 μm As can be seen from these data, the UST increases the spectral sensitivity range from λ = 0.532 μm (curve *1*) to λ = 0.476 μm (curve *2*) and provides for a general increase in the magnitude of $Q(\lambda)$. This result indicates that, in addition to the acoustostimulated diffusion of zinc, the UST produces annealing of the recombination centers [16] and induces decomposition of the impurity clusters similar to that observed in [17]. Both our data [18] and the results reported in [17] show that the UST leads to an increase in the mobility μ of charge carriers. The growth of the drift velocity due to the increase in μ decreases the probability of carrier trapping and, hence, increases the efficiency of charge carrier collection.

In this context, it should be noted that the influence of ultrasound on the spectrum of local states in GaAs-based heterostructures was studied in [19], where it was established that the UST leads to a spatial and chemical ordering of the near-contact regions in these structures. The results concerning the ultrasound-induced reconstruction of the defect subsystem of a crystal [19] generally agree with our data, which also show evidence of a certain improvement in the crystal defect structure in the subsurface regions of solar cells based on A_3B_5 compounds. It is this modification of the subsurface regions under the action of ultrasonic waves that accounts for the observed expansion of the spectral sensitivity range toward shorter wavelengths and an increase in the efficiency of nonequilibrium charge carrier collection.

Factor 3: a change in the character of the electromagnetic radiation reflection from the p-$Al_xGa_{1-x}As$ layer upon UST. It has previously been established that an UST leads to a rearrangement of the system of photoelectrically active defects in semiconductors [20] and modifies their optical properties [1]. In the present investigation, we also studied the effect of UST on the optical reflection coefficient R of the p-$Al_xGa_{1-x}As$ layer in the series of samples where this layer had the same thickness and composition as those in our AlGaAs/GaAs solar cells. The R value was measured as described in [1]. This experiment showed that the UST at f = 20 MHz and P = 0.25 W/cm^2 for t = 60 min and above led to a decrease in the coefficient R, as can be seen from a comparison of the reflectance curves measured before (Fig. 2, curve *3*) and after the UST (curve *4*). The observed decrease in R can be explained using the notions about the acoustostimulated diffusion of impurities [1, 15]. The acoustostimulated inward diffusion of zinc from the surface to the bulk of the p-$Al_xGa_{1-x}As$ layer in the entrance window makes the surface less "metallized," which decreases the reflection coefficient.

The observed shift in the position of the minimum in the $R(\lambda)$ from λ = 0.630 μm toward longer wavelengths (λ = 0.645 μm) after the UST is also indicative of a decrease in the zinc concentration at the sample surface. The UST-induced changes in the composition and structure of the subsurface region in the entrance window also naturally modify the other optical characteristics [7, 20], including the coefficients of optical absorption, transmission, and refraction. A decrease in the reflection coefficient and the corresponding increase in absorption must also be accompanied by the appearance and enhancement of the photoresponse in a certain interval of wavelengths, which was actually observed in experiment. Exact determination of the optical losses and their separation into reflection and absorption types are outside of the scope of this study.

The observed increase in the photoresponse amplitude A in the wavelength interval λ = 0.775–0.563 μm

(Fig. 1, curve *2*) and the growth in the charge carrier collection coefficient Q (Fig. 2, curve *2*) upon UST is related to neutralization of the trapping and recombination centers in the p-$Al_xGa_{1-x}As$ layer. An analysis of the variation in the A and Q values shows evidence in favor of the acoustostimulated transformation of defects, analogous to that previously reported in [12–20], which leads to the neutralization of traps and smoothening of the potential relief of the electric field in the volume of the photosensitive region of a solar cell. This naturally results in a more complete collection of nonequilibrium carriers on the electric contacts of the device, which is confirmed by the passage from $n < 1$ to $n > 1$ in the power dependence of the response, $A \sim V^n$, after the UST of solar cells.

It is necessary to mention the possibility of an acoustic-wave-induced variation of the properties of the anodic oxide, which may also influence the characteristics of photosensitive structures. Indeed there are data suggesting that ultrasound may change the properties of oxides; in particular, it was demonstrated [21] that the UST of a metal–insulator–semiconductor structure decreases the built-in charge in the insulator and reduces the charge of the surface states. Therefore, the coefficients of the reflection R and refraction Ψ of an electromagnetic wave propagating through such an ultrasound-modified insulator layer will differ from the corresponding values prior to the treatment. We also checked for the possibility of the acoustostimulated variation of R and Ψ and the electrical parameters of the anodic oxide. The results of these experiments showed that the characteristics of anodic oxide change upon the UST at the frequencies $f > 50$ MHz, which were not used for the UST of our solar cells. Based on these data, we believe that the influence of the acoustostimulated changes in the optical properties of anodic oxide in our experiments with solar cells was either small or absent.

Therefore, improvement of the functional characteristics of AlGaAs/GaAs solar cells as a result of the UST (see table) is related to residual phenomena such as the redistribution of impurities, the formation of electrically inactive defects, etc.

Conclusions. (1) Irradiation of graded-gap zinc-doped p-$Al_xGa_{1-x}As$ solid solutions with ultrasonic waves at a power density of $P < 1$ W/cm^2 and a frequency of $f > 15$ MHz leads to a decrease in the zinc concentration in the subsurface layer. This result is due to the acoustostimulated inward diffusion of zinc from the surface to the bulk of the graded-gap layer.

(2) The resulting zinc-depleted layer becomes sensitive to electromagnetic radiation with wavelengths $\lambda <$ 0.551 eV as a result of the modified character of the reflection and absorption of the incident radiation. The electric field in the modified graded-gap layer stimulates the effective collection of the nonequilibrium charge carriers generated by photons in this layer, which provides for the appearance of the photoresponse to photons with the energies $E_{ph} > 2.25$ eV.

(3) Irradiation of AlGaAs/GaAs solar cells with ultrasonic waves at $f \geq 15$ MHz and $P \leq 1$ W/cm^2 leads to an increase in the efficiency of collection of the nonequilibrium charge carriers, which is explained by an improved crystal defect structure in the subsurface layer, and expands the short-wavelength sensitivity range to $\lambda = 0.476$ μm.

(4) Although the results of the ultrasound-induced improvement of the characteristics of AlGaAs/GaAs solar cells are not on a record level, the results of our investigation show the high potential of the development of acoustic methods for increasing the efficiency of solar cells based on various semiconductor materials.

Acknowledgments. The authors are grateful to N.N. Chernikov (Moscow) for his help in these investigations.

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Translated by P. Pozdeev