

Acoustostimulated Changes in the Density of Surface States and Their Energy Spectrum in *p*-Type Silicon Single Crystals

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Abstract—The effect of ultrasonic treatment at various powers on the density N_{SS} of surface states and their energy spectrum in *p*-type silicon single crystals has been studied. It is established that, depending on the regime of ultrasonic treatment, N_{SS} can either increase or decrease compared to that in the initial single crystals. This is accompanied by a redistribution of the total charge of the surface states over the silicon bandgap width. This phenomenon is related to the fact that an acoustic wave, being an energy carrier, modifies a defect subsystem of the crystal by redistributing the impurity atoms and by generating new defects.

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Previously, it was demonstrated that ultrasonic waves in the megahertz frequency range are capable of modifying the transport properties of charge carriers and the structure of semiconductor materials. Some data on the influence of ultrasound on the bulk and surface of classical (Si) and piezoelectric semiconductors have been reported in [4–7]. These results and the investigations of other researchers in this direction confirmed our concept of acoustostimulated phenomena in semiconductor crystals [1–3], according to which the structural changes in semiconductors are related to the ultrasonic-wave-stimulated diffusion of impurity atoms and to the formation and decomposition of defects and their complexes in the acoustic field.

For deeper insight into the mechanisms of the interactions of elastic oscillations and defects, it is necessary to continue the investigations of acoustostimulated phenomena in semiconductor crystals in various directions. One of these is related to the effect of ultrasound on the surface properties of three-layer structures of the metal–dielectric–semiconductor (MDS) type. This issue is highly important, since the near-surface layers and the surface of a semiconductor with an applied metal contact determine the functional characteristics of semiconductor detectors, solar cells, and other devices.

As is known, various defects can exist in the near-surface layers and at the semiconductor–dielectric interface. These defects can appear (i) during the growth of a dielectric film on a semiconductor substrate, as a result of a difference in the thermal expan-

sion coefficients of the film and substrate that gives rise to elastic deformation of the near-surface layer of the semiconductor crystal and the corresponding change in its energy spectrum [8]; (ii) due to the diffusion of impurity atoms between the bulk and surface of the crystal; (iii) as a result of the formation of SiO₂ clusters [9]; and (iv) under the action of some other factors.

Recently, Parchinskiĭ et al [10, 11] studied the effect of ultrasonic treatment on the properties of MDS structures based on *n*-type silicon. In the present paper, we demonstrate the influence of ultrasound on the electrical characteristics of MDS structures based on silicon single crystals of the *p*-type. The experiments were performed with MD–Si structures thoroughly prepared using a standard technology described below.

The MD–Si structures were prepared using ⟨100⟩- and ⟨111⟩-oriented *p*-Si single crystals with resistivities ranging within $\rho \sim 1\text{--}700\ \Omega\text{ cm}$, having an oxygen concentration of $N_O \leq 10^{15}\text{ cm}^{-3}$ and a dislocation density of $N_D < 10^3\text{ cm}^{-2}$. The dielectric layer was formed by oxidizing single crystal plates in a dry oxygen atmosphere. The control electrode and the ohmic contact were formed by the vacuum deposition of aluminum.

The MD–Si structures were treated by longitudinal ultrasonic waves in a frequency range of $f = 0.8\text{--}25\text{ MHz}$ with a power density (intensity) of $P = 0.1\text{--}5\text{ W/cm}^2$ from the side of the oxide layer. The treatment duration was varied within $t = 15\text{--}90\text{ min}$ at room temperature ($T = 293\text{ K}$). Changes in the sample temperature in the course of ultrasonic treatment were moni-

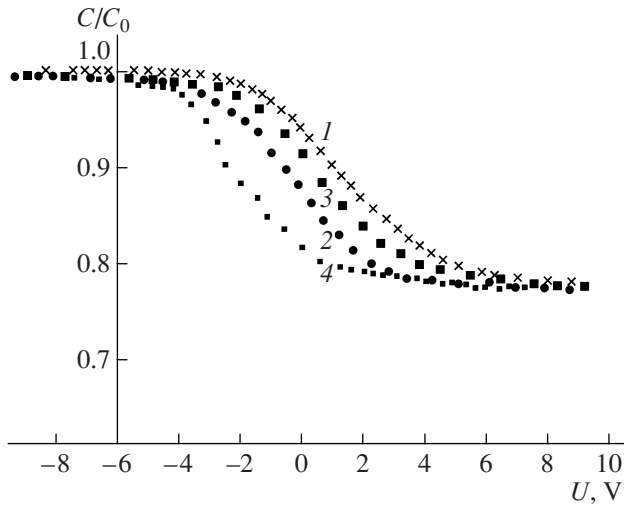


Fig. 1. C–V characteristics of the MD–Si structure ($T = 293$ K, $N_{SS} = 3.12 \times 10^9 \text{ cm}^{-2}$): (1) theoretical curve; (2–4) experimental curves for sample no. 21 measured upon the ultrasonic treatment at $P = 0$ (initial state), $P = 1 \text{ W/cm}^2$, and $P_L = 5 \text{ W/cm}^2$, respectively.

tored. The acoustic waves from a piezotransducer driven by a generator of ultrasound were transmitted to the sample via a liquid medium (ethyl alcohol). The ultrasonic wave power density was determined using radiometric and capillary techniques with an accuracy to within several mW/cm^2 [12]; the wave frequency was measured by an electronic frequency meter connected to the generator.

The charge of the surface states in MD–Si structures was determined using the method of high-frequency capacitance–voltage (C–V) characteristics [13]. These characteristics were measured using the compensation technique on a setup analogous to that described in [14]. The C–V characteristics were measured every 5 min after termination of the ultrasonic treatment. It was established that the most significant changes in the electrical characteristics of MD–Si structures were observed in the samples ultrasonically treated at $f \geq 15$ MHz for $t > 45$ min.

Figure 1 presents experimental C–V characteristics of the MD–Si structure no. 21 ($\rho = 51 \Omega \text{ cm}$), which had an oxide layer with a thickness of $d = 0.5 \mu\text{m}$ and a capacitance of $C_0 = 212 \text{ pF}$. As can be seen from these data, the ultrasonic treatment leads to a shift of the C–V curves along the voltage axis. The curves were shifted toward higher bias voltages U for $P = 0.1$ – 1 W/cm^2 and toward lower U for $P = 1.5$ – 2 W/cm^2 . This behavior is indicative of changes both in the charge built in the oxide layer and in the charge of surface states [13, 15]. It should be noted that the laws of the observed acoustostimulated variation of the C–V characteristics were the same for all MD–Si structures, irrespective of the resistivity ρ of the initial p -Si single crystals.

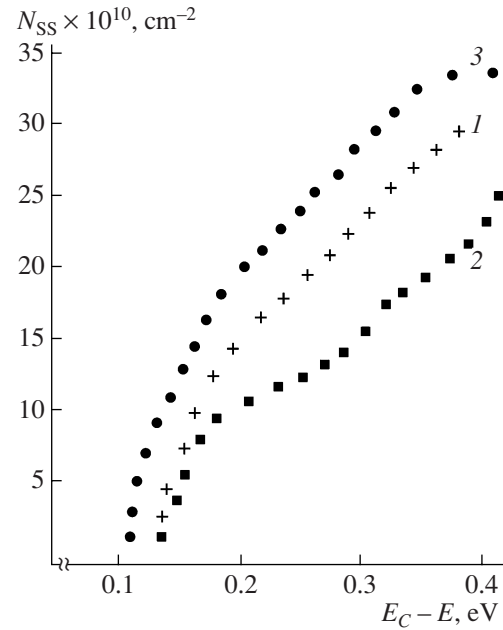


Fig. 2. The energy spectra of the density N_{SS} of the charged surface states observed in the MD–Si structure no. 21 ($T = 293$ K, $f = 15$ MHz): (1) before ultrasonic treatment; (2, 3) after ultrasonic treatments at $P = 1 \text{ W/cm}^2$ and $P_L = 5 \text{ W/cm}^2$, respectively (E_C is the energy of the conduction-band bottom).

Figure 2 shows changes in the energy spectrum of the density N_{SS} of the charged surface states observed in the MD–Si structure no. 21 before (curve 1) and after (curves 2 and 3) ultrasonic treatments at the same frequency ($f = 15$ MHz) and different intensities ($P = 1$ and 5 W/cm^2 , respectively). These data show that the ultrasonic treatment at $P \leq 1 \text{ W/cm}^2$ leads to a decrease in the density of charges surface states down to $N_{SS} = (11\text{--}25) \times 10^{10} \text{ cm}^{-2}$ for $E_C - E = 0.2\text{--}0.4 \text{ eV}$ (Fig. 2, curve 2). In contrast, the passage of ultrasonic waves with a power density of $P \geq 5 \text{ W/cm}^2$ produced an increase in the N_{SS} (Fig. 2, curve 3). We consider such ultrasonic waves to possess the threshold power (moderate power) level $P = P_L$. Ultrasonic waves with threshold powers within $1 \text{ W/cm}^2 \leq P_L \leq 5 \text{ W/cm}^2$ lead to the generation of defects of various types in the bulk and near-surface layers of the semiconductor, the acoustostimulated diffusion of impurities [3, 4], and the escape of some defects at the semiconductor surface [16].

The results described above can be explained as follows. Elastic deformation existing in a transition layer at the (p -Si crystal)–(oxide layer) interface and in the near-surface layers of p -Si single crystal leads to the formation of unstable structural defects [8]. The passage of ultrasonic waves with a power of $P \leq 1 \text{ W/cm}^2$ through such structures stimulates the diffusion of unstable defects and impurity atoms from the surface inward the crystal and their localization in positions

with the absolute minimum of free energy. The acoustostimulated diffusion of charged defects away from the interface leads to a decrease in the density N_{SS} of the charged surface states.

The ultrasonic treatment at a threshold power density of sound (P_L) in the interval $1 \text{ W/cm}^2 \leq P_L \leq 5 \text{ W/cm}^2$ induces the generation of various defects in the bulk and near-surface layers of the semiconductor and also leads to the acoustostimulated diffusion of impurity atoms, which naturally results in a change in N_{SS} . However, the ultrasonic treatment of a semiconductor at a threshold power level has certain specific features, which are apparently related to the production of defects in the near-surface region as described in [16, 17]. Then, impurity atoms diffusing in the ultrasonic field can segregate at such defects and form impurity "clouds" (analogous to the Cottrell atmospheres [18]), which change the charge density in the surface states, as well as their energy spectrum (Fig. 1, curve 3; Fig. 2, curve 3). Therefore, the ultrasonic treatment at a threshold power density leads to the appearance of new defects in the near-surface region of the semiconductor and to the resulting increase in the N_{SS} value.

Thus, the charge density in the surface states and their energy spectrum can be changed by varying the power P of the ultrasonic treatment. The observed acoustostimulated phenomena involving a decrease or increase in N_{SS} are related to the ultrasonic-wave-induced modification of the defect subsystem in the near-surface region of a silicon single crystal. These phenomena are manifested in various p -Si single crystals, irrespective of their resistivity. The most important conclusion is that these effects can be successfully used in practice so as to improve the functional characteristics of MDS-based devices (MD-Si photodetectors, silicon solar cells, etc.).

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