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In Situ Observation of the Relaxation of Conductivity in γ-Irradiated *n*-Type Silicon under the Action of Ultrasound Pulses

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Abstract—Reversible change of the electric conductivity σ_{US} in a temperature range of $T = 110–180$ K has been observed for the first time in gamma-irradiated and partly annealed (280°C) floating-zone grown silicon (*n*-Si-Fz) under the action of pulsed ultrasound (longitudinal wave) at a frequency of 6–10 MHz, intensity up to 4×10^3 W/m^2, and pulse duration within 10^{-5}–10^{-3} s. It is established that the temperature dependences of the parameters of acoustic-wave-induced change of σ_{US} (increase time, τ_i; decay time, τ_d) obey the Arrhenius law. Experimental $\tau_{i,d}(T)$ curves have been used to determine the corresponding activation energies ($E_i \approx 0.09$ eV, $E_d \approx 0.13$ eV) and preexponential factors ($\tau_i^0 \approx 4 \times 10^{-8}$ s, $\tau_d^0 \approx 10^{-9}$ s). The observed phenomenon is interpreted as an acoustic-wave-induced transition between the states of a metastable structural defect.

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Many types of defects in semiconductors exhibit bistable and metastable behavior [1–3]. The interest in metastable defects in practice is related to the possibility of controlling the parameters of semiconductor devices by means of the reversible transformation of defect complexes and, in particular, the use of bistability for creating memory cells of the new generation. Extensive investigations using electron paramagnetic resonance, IR spectroscopy, deep-level transient spectroscopy and other methods yielded significant progress in understanding of the mechanisms of bistability. It was established that the transformation of the atomic configuration of a defect and change in its charged state are frequently interrelated and proceed in a correlated manner. These processes may be caused by local deformation, temperature change, electromagnetic field, radiation, and ultrasound [4–6].

Investigations of the possibility of using ultrasonic loading for the controlled modification of the structure of defects in semiconductor crystals yielded a number of promising results. For example, ultrasound treatment can stimulate the decay [4] and formation [5] of various complexes, rearrangement of defects [6, 7], and formation of nanoparticles [8]. We believe that the main mechanism of acoustic-wave-induced changes in material characteristics of dislocation-free crystals is related to the metastable character of some defect complexes. However, no theory of the interaction of ultrasound with metastable defects has been developed so far. The kinetics of acoustic-wave-induced changes in the electrical properties (in particular, photoelectric parameters) of semiconductors is also almost unstudied, although this knowledge could help to elucidate the mechanisms of ultrasound influence. Difficulties encountered in these investigations were partly related to the traditional use of ultrasonic waves in a continuous regime [4–10], which hindered the observation of fast transient processes.

This Letter presents the results of an investigation in which a new methodological approach has been used for the first time with loading samples by rectangular pulses of ultrasound. This method allows the dynamic changes of material characteristics to be studied in situ under conditions of ultrasonic loading.

The experiments were performed with dislocation-free *n*-type phosphorus-doped silicon crystals grown by floating-zone melting in vacuum (*n*-Si-Fz:P), in which the concentrations of dopant, oxygen, and carbon impurities were $N_P \approx 4.8 \times 10^{19}$ m^{-3}, $N_O < 5 \times 10^{21}$ m^{-3}, and $N_C \approx 1.0 \times 10^{22}$ m^{-3}, respectively. Acoustically active (ultrasound-sensitive) defects were created by irradiating the samples with γ-photons from a ^{60}Co source to a total dose of ~10^8 rad at room temperature, followed by a special annealing to $T = 280$°C (at 20-min-long 40-K steps). This preparation was related to the fact that, according to our recent results [10], the efficiency of ultrasound in the annealed samples increases as compared to the unannealed material.

The charge carrier (electron) concentration n_0 and mobility μ_0 were determined using the Hall effect measurements on standard rectangular samples in a

temperature range of $T = 100$–300 K at a dc current of $I_0 \sim 10^{-6}$ A and a constant magnetic field of $B = 0.45$ T. During ultrasonic loading, the acoustic wave was propagating parallel to the ⟨110⟩ crystallographic direction. The temperature dependences of the Hall effect parameters were performed in a nitrogen cryostat equipped with piezoelectric transducers [11]. This equipment allowed sequential measurements on the same sample to be performed for various states of the defect structure in both the initial and ultrasound-perturbed conditions. The ultrasound was generated by a piezoelectric transducer based on a Y+36° cut lithium niobate plate, to which a harmonic signal from a high-frequency (HF) oscillator was applied.

It was previously established that the conductivity $\sigma = en_0\mu_0$ of γ-irradiated samples of n-Si-Fz:P in a temperature range of $T = 100$–200 K is determined by a deep acceptor level at E_c–0.23 eV in the bandgap [9]. During the ultrasonic loading in a continuous regime at $T < 200$ K, the slope of the $n_{US}(T)$ dependence somewhat increases and the concentration n_{US} of free electrons decreases, which corresponds to an acoustic-wave-induced change $\Delta n = n_0 - n_{US}$.[1] After the ultrasound is switched off, σ_{US} restores in the initial state [10].

In the present study, the kinetics of acoustic-wave-induced conductivity σ_{US} in partly annealed (280°C) n-Si-Fz samples was monitored under the action of pulsed ultrasound (longitudinal wave) at a frequency of $f_{US} = 6$–10 MHz, pulse repetition frequency of $F_i = 400$ Hz, pulse duration within $\tau_{US} = 10^{-5}$–10^{-3} s, and pulse amplitude of V_{US} up to 20 V. The measured response voltage $U_{US}^{\sigma} = kI_0/\sigma_{US}$ (where k is a coefficient determined by the sample geometry) from output potential contacts of the sample was fed into a digital oscilloscope synchronized by a signal from the HF oscillator. Under certain conditions, the acoustic-wave-induced change (decrease) of conductivity σ_{US} was manifested by a "ΔU_σ pulse" that appeared on the background of constant component U_σ (see the typical oscillogram in the inset to Fig. 1). The leading and trailing fronts of this ΔU_σ pulse were significantly wider than the fronts of the HF pulse and, at a constant temperature, could be satisfactorily described by the exponents as follows:

$$\Delta U_\sigma^i(t) = \Delta U_\sigma^{\max}(1 - \exp(-t/\tau_i)), \quad (1)$$

$$\Delta U_\sigma^d(t) = \Delta U_\sigma^{\max}\exp(-t/\tau_d). \quad (2)$$

[1] Here and below, the physical quantities determined in the absence and presence of ultrasound are indicated by subscripts "0" and "US," respectively.

The results of an investigation of the temperature dependence of the ΔU_σ pulse at a constant ultrasound power density $W_{US} = 4 \times 10^3$ W/m^2 (or the pulse intensity $W_{US} = c(V_{US})^2$, where c is an empirical parameter) showed that both $\tau_i(T)$ and $\tau_d(T)$ exhibit a thermoactivation character, that is, obey the Arrhenius law:

$$\tau_{i,d}(T) = \tau_{i,d}^0\exp(E_{i,d}/kT), \quad (3)$$

where $E_{i,d}$ are the activation energies of the corresponding processes. The approximation of the experimental data on $\tau_{i,d}(T)$ in terms of Eq. (3) (Fig. 1) allowed the corresponding activation energies ($E_i \approx 0.09 \pm 0.01$ eV, $E_d \approx 0.13 \pm 0.01$ eV) and preexponential factors ($\tau_i^0 \approx 4 \times 10^{-8}$ s, $\tau_d^0 \approx 10^{-9}$ s) to be determined.

We have also studied the response amplitude characteristics $\Delta U_\sigma = f(W_{US})$. Taking into account that, at a fixed temperature, $U_\sigma^0 = kI_0/en_0\mu_0$ and $U_\sigma^{US} = kI_0/en_{US}\mu_{US}$, the relative acoustic-wave-induced changes in the electron concentration can be calculated as $n_{US}/n_0 = U_\sigma^0/U_\sigma^{US}$. In these calculations we assumed, in accordance with the results of our previous experiments [9, 10], that $\mu_{US}(T) \approx \mu_0(T)$. Indeed, at $T > 125$ K, the scattering of electrons is determined by lattice oscillations and the mobility of electrons is almost not influenced by the ultrasound. As can be seen from the inset to Fig. 2, the amplitude of "pulsed" acoustic-wave-induced changes in the electron concentration $\Delta n_{US} = n_0 - n_{US}$ at all temperatures is proportional to W_{US}:

$$n_{US}/n_0 = 1 - \alpha W_{US}, \quad (4)$$

where the proportionality coefficient α (characterizing the effect of ultrasound) is also temperature dependent. Note also that the maximum acoustic-wave-induced changes in the electron concentration ($\Delta n^{\max} \approx 2 \times 10^{18}$ m^{-3}) is attained at $T \approx 150$ K.

In conclusion of an analysis of the experimental results, it should be also pointed out that (i) the acoustic-wave-induced effects were not related to temperature changes, since the maximum heating due to pulsed ultrasonic loading was <0.1 K; (ii) no evidence was obtained for the dependence of ΔU_σ on the magnetic field; and (iii) no new defects were formed due to ultrasonic loading in either continuous or pulsed regimes (the observed effects were reversible) and the sample microstructure remained unchanged.

The problem of identification of the acoustically active (ultrasound-sensitive) defects (C_s–C_i, P_s–C_i, divacancy complexes) revealed in γ-irradiated samples of n-Si-Fz:P is still unsolved, and additional investigations are necessary to elucidate the mechanism of acoustic-wave-induced transitions. The most

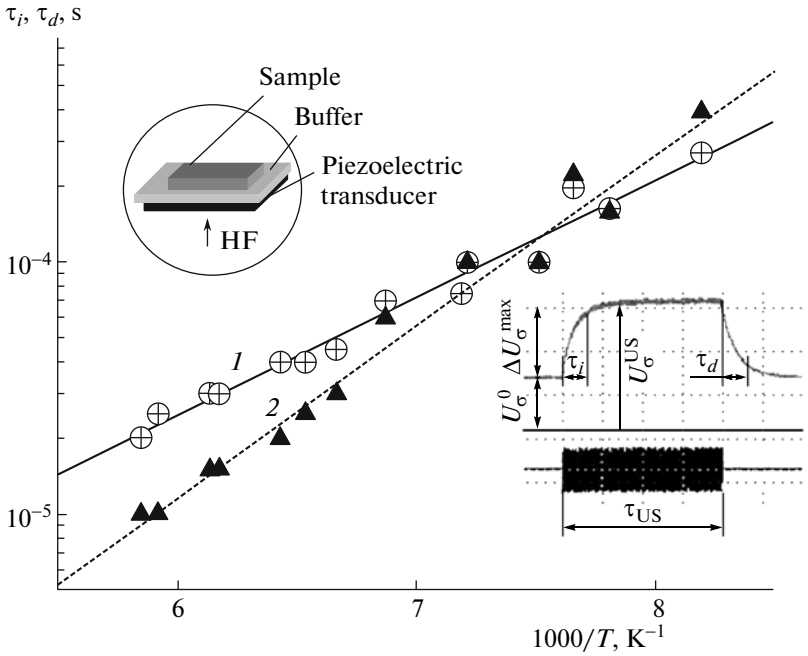

Fig. 1. Temperature dependences of the relaxation times (*1*) τ_i (increase) and (*2*) τ_d (decay). Points present the experimental data, solid and dashed lines show the linear approximation according to Eq. (3). The top inset shows a schematic diagram of the acoustic unit (comprising piezoelectric transducer, acoustic buffer, and sample); the bottom inset shows typical oscillograms of a ΔU_σ pulse measured on the sample and an HF pulse supplied to the piezoelectric transducer.

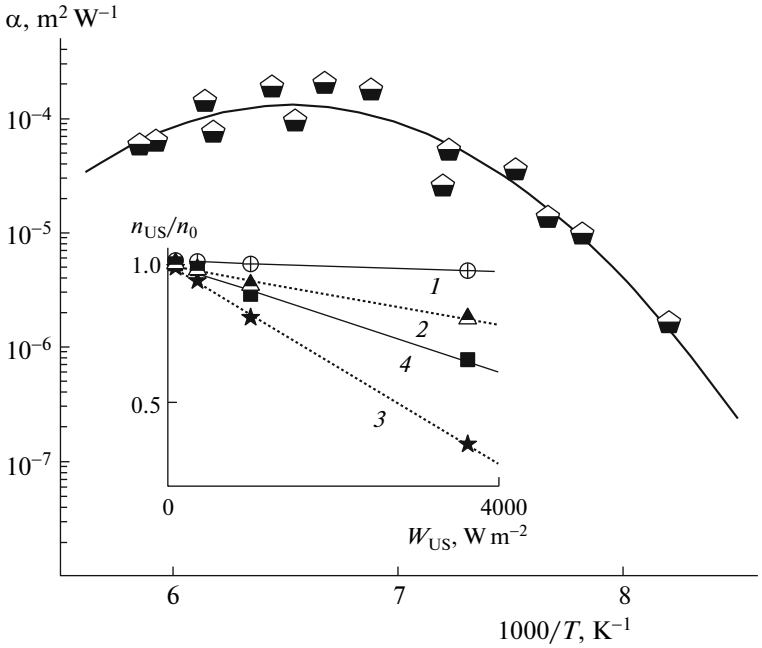

Fig. 2. Temperature dependence of the coefficient α of ultrasound efficiency. The inset shows the amplitude characteristics of relative changes in the electron concentration at various temperatures T (K): (*1*) 128; (*2*) 133; (*3*) 142; (*4*) 163.

important result of this study is the acoustic-wave-induced transition of the defect system of a semiconductor crystal to an excited state, which was observed for the first time in situ on the real time scale. This phenomenon presents additional possibilities for both studying the acoustically active defects in semiconductors and developing pulsed acoustic-wave-controlled devices.

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