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A new method for investigating the kinetics of acoustically induced processes in semiconductors with pulsed ultrasound loading

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***Abstract* — The use of pulsed ultrasound loading for dynamic modification of current flow processes in semiconductor materials was considered. It was shown that the revealed features of time, temperature, amplitude, and frequency characteristics of the acoustoconductivity open new methodical possibilities for studying the defective structure of semiconductors.**

Keywords — acoustoconductivity, defects, pulsed ultrasound, conductivity relaxation

I. Introduction

Direct observation of the relaxation of the conductivity σ_{US} of monocrystalline silicon caused by rectangular pulses of ultrasound (US) was first described in [1]. This mode makes it possible to observe and investigate the dynamic (*in-situ*) changes in the electrophysical parameters of the material during ultrasonic loading.

This paper shows the possibility of using the study of acoustoconductivity kinetics for the investigation of metastable defects in semiconductors and diagnostics of their state. It is known that some defects in semiconductors are characterized by bi- and metastable behavior [2, 3]. The interest in metastable defects (MD) in practical terms is due to the possibility of dynamic driving of the semiconductor devices by restructuring such complexes. Due to the widespread use of electronic paramagnetic resonance technique, infrared spectroscopy, non-stationary deep level transient spectroscopy (DLTS), etc., significant progress has been made in understanding the mechanism of metastability. It has been shown that the processes of rearrangement of the defect atomic configuration and change of its charge state are often interrelated and intertwined. The reasons for such transformations can be local deformation, temperature change, electromagnetic field, irradiation, as well as ultrasound load [4, 5]. On the other hand, it is assumed that the main mechanism of acoustic-induced changes in electrophysical parameters in dislocation-free crystals is caused by the metastable nature of individual defect complexes. But the complete theory of interaction of US with MD is still absent. In particular, the kinetics of acoustic-induced changes in the electrophysical and photoelectric parameters of semiconductors, which could help to clarify the mechanism of US action, remains unexplored. The difficulties of such studies are related to the traditional use of US waves in a continuous mode [6-9], which makes it impossible to observe the rapid changes that are determined by the transient conditions. This paper presents the results obtained using a new methodical approach, that is, excitation of ultrasound in the form of rectangular pulses, which allows observation and investigation of the dynamic changes in the characteristics of the material during ultrasound loading. The proposed method is complementary to traditional methods of spectroscopy of defective levels of semiconductors, in particular, DLTS.

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II. Method of acoustoconductivity pulse investigation

The standard acoustic cell layout for studying electrophysical parameters of semiconductor samples is shown in Fig.1 (shown in the circle). The longitudinal US wave excited by a high-frequency (HF) generator using a piezoelectric transducer (lithium niobate plate of Y+36°-slice) is introduced through the buffer plane-parallel plate along the sample thickness parallel to the <110> crystallographic direction. The study of acoustic conductivity kinetics σ_{US} used pulsed US mode (carrier frequency $f_{US} = 5 \div 10$ MHz, pulse repetition frequency $F_i = 400$ Hz, duration of radio pulses $\tau_{US} = 10^{-5} \div 10^{-3}$ s, and their amplitude $U_{US} \leq 20$ V).

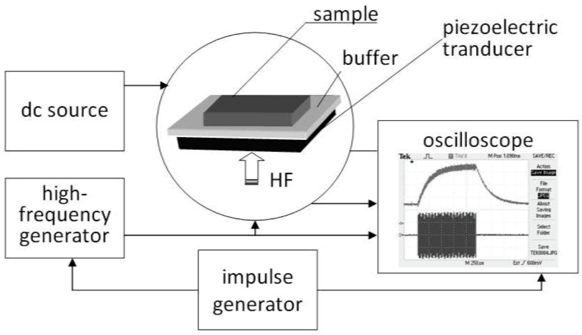

Fig. 1. Flow diagram of the facility for the study of acoustoconductivity kinetics

When the direct current I_0 was passing through the sample, the conductivity voltage U_σ at potential contacts was measured using a digital oscilloscope (Fig.1). The oscilloscope was synchronized with the pulses from the generator of rectangular pulses. In pulse mode, when the US pulse was applied to the sample against the background of the conductivity voltage U_σ^0, an additional acoustic conductivity pulse $\Delta U_0 = K \cdot I_0 / \sigma_{US}$ was observed – see Fig. 2. K is the geometric coefficient, which determined by the sample size. This pulse had the amplitude $\Delta U_\sigma = U_\sigma^{US} - U_\sigma^0$ and was characterized by both leading and falling edges. It turned out that the pulse edges ΔU_σ, which are determined by pulse rise time τ_i and pulse fall time τ_d of the acoustic-induced changes of σ_{US}, significantly exceed the HF pulse edges duration and, at a fixed temperature, are well described by exponential dependences (1) and (2), respectively:

$$\Delta U_0^i(t) = \Delta U_\sigma^{\max}\left(1 - \exp\left(-t/\tau_i\right)\right), \tag{1}$$

$$\Delta U_0^d(t) = \Delta U_\sigma^{\max}\left(1 - \exp\left(-t/\tau_d\right)\right). \tag{2}$$

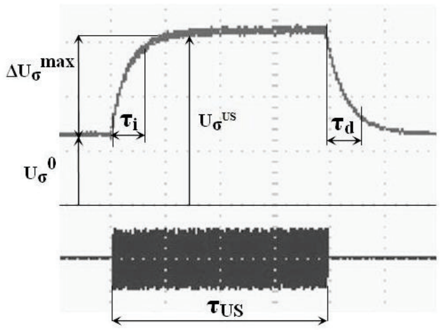

Fig. 2. Oscillograms of the acoustic conductivity pulse ΔU_σ on the sample (top) and the HF pulse applied to the piezoelectric transducer (bottom).

III. Experiment and Results

3.1. Samples

The study was performed using the crystals of dislocation-free crucible *n*-type silicon grown by a floating-zone technique of *n*-Si:P–*Fz*; the concentrations of impurity atoms of phosphorus, oxygen, and carbon were: $N_P \approx 4.8 \cdot 10^{19}$ m^{-3}, $N_O < 5 \cdot 10^{21}$ m^{-3}, $N_C \approx 1.0 \cdot 10^{22}$ m^{-3}, respectively. The samples were irradiated with ^{60}Co γ-quanta at a dose of $D \sim 10^8$ rad at room temperature, and then isochronously annealed to T = 553 K (in steps of 40 K and 20 min duration). Measurements of the concentration n_0 and the mobility μ_0 of electrons by the acoustic Hall method in the temperature range of $100 \div 300$ K in the $I_0 \sim 10^{-6}$ A DC mode and the constant magnetic field B = 0.45 T were performed earlier in [6]. It was found that under the action of US load in the continuous mode at the temperatures $T < 200$ K, the slope of the dependence $n_{US}(T)$ increases slightly, and the concentration of free electrons n_{US} decreases, i.e., there is an acoustic-induced decrease in the concentration $\Delta n = n_0 - n_{US}$. After turning off the ultrasound, σ_{US} returns to its original state. The conductivity $\sigma_0 = e n_0 \mu_0$ for γ-irradiated *n*-Si-*Fz*:P samples at (100 ÷ 200) K is determined by deep acceptor levels in the band gap with energy $E_S - 0.23$ eV [1,6].

3.2. Temperature characteristics of relaxation time

Typical temperature changes of acoustic conductivity, "pulse ΔU_σ", are given in Fig. 3. As can be seen, the pulse rise and pulse fall times ΔU_σ decrease with a change in the temperature of the sample from 133 K to 170 K. Detailed studies of the "pulse ΔU_σ" performed at a constant intensity of ultrasound in a wide temperature range showed that the dependencies $\tau_i(T)$ and $\tau_d(T)$ at some temperature areas are thermoactivated, i.e., described in Arrhenius coordinates

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

where $E_{i,d}$ is the activation energy of the corresponding process.

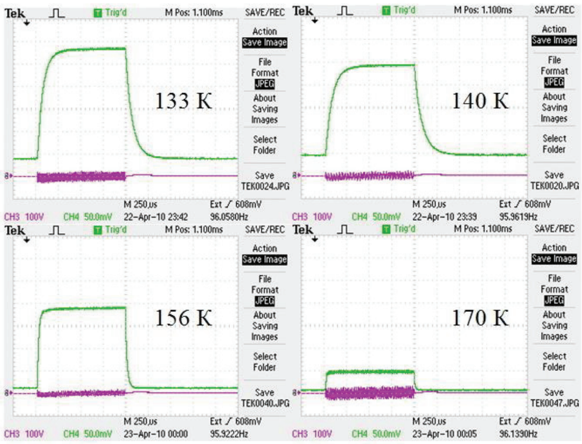

Fig. 3. Oscillograms of the "pulse ΔU_σ" on the sample at four different temperatures: top – voltage pulse, bottom – HF pulse applied to the piezoelectric transducer.

Fig. 4 shows the temperature dependencies of relaxation times. It is seen that the dependencies $\tau_{i,d}(T)$ are not monotonic. This could be the result that the main contribution to the acoustic conductivity at different temperatures is made by various acoustically sensitive defects. This assumption is confirmed by the temperature dependencies of the acoustic-induced signal amplitude shown in Fig. 5.

3.3. Temperature characteristics of the amplitude of acoustic conductivity

Study of the dependence of acoustic-induced conductivity signal amplitude $\Delta U_\sigma(T)$ in a wide temperature range at the US frequency of 8 MHz revealed the presence of several peaks (Fig. 5). The dependence of nonstationary capacitive spectroscopy (DLTS) for electron-irradiated silicon similar to our samples is somewhat correlated with the temperature change of the acoustic conductivity amplitude ΔU_S. It turns out that each peak of $\Delta U_\sigma(T)$ corresponds to a certain defective level of the semiconductor, namely, the level of $E_c - 0.23$ eV (double negatively charged divacancy V_2^{2-}) is related to the temperature of 120 K, $E_c - 0.32$ eV (A-center $V0$) – to 150 K, and $E_c - 0.42$ eV (negatively charged vacancy V^{2-}) – to 200 K [10].

Thus, the first discovered "multi-peak" character of the temperature dependence of the acoustic conductivity voltage $\Delta U_\sigma(T)$ testifies to the predominant contribution of several separate acoustoactive centers to the acoustoconductivity of the sample in different temperature ranges. This conclusion is also confirmed by the investigation of the temperature dependences $\tau_{i,d}(T)$ shown in Fig. 4.

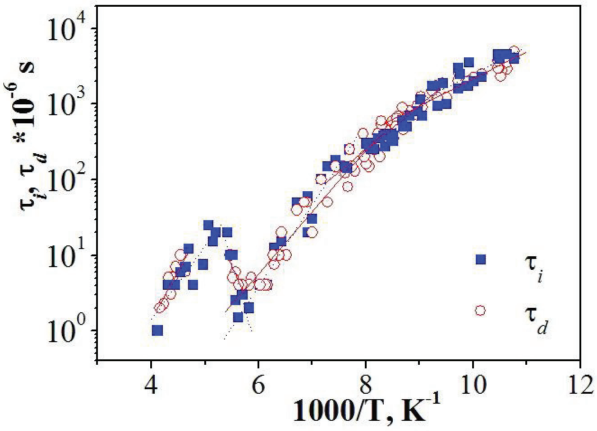

Fig. 4. Temperature dependencies of relaxation times: light circles and solid line are related to τ_i increase; dark squares – to τ_d decrease. Points correspond to experimental data, lines are the linear approximations according to [5] for separate temperature intervals

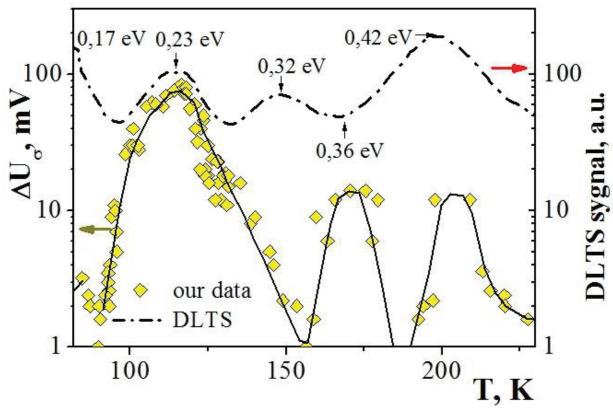

Fig. 5. Amplitude of the "pulse ΔU_σ" vs. temperature for the sample exposed to US pulses at a frequency of 8 MHz (the squares correspond to experimental data, the solid lines – to approximation). Top dotted line relates to DLTS data (DLTS spectra of electron-irradiated Si-*Fz* samples) [10].

3.4. An influence of US frequency on temperature characteristics of acoustic conductivity amplitude

Fig. 6 shows the frequency effects on the temperature dependence of acoustoconductivity amplitude $\Delta U_\sigma(T)$.

The data of time and amplitude characteristics for 8, 31, 55, and 100 MHz frequencies and different temperature ranges, as well as the values of their peak maxima, were used for plotting $\Delta U_\sigma = f(T)$.

Oscillograms of the "pulse ΔU_σ" were obtained in the same temperature range $90 \div 160$ K at different frequencies of US loading: 31, 55, and 100 MHz (the highest modes of the piezoelectric transducer). It is seen that when the US pulse frequency rises, the maximum peak amplitude ΔU_σ is reduced and its shift toward high temperatures is observed. It confirms the frequency-dependent acoustic sensitivity of *n*-Si-*Fz* crystal defective structure.

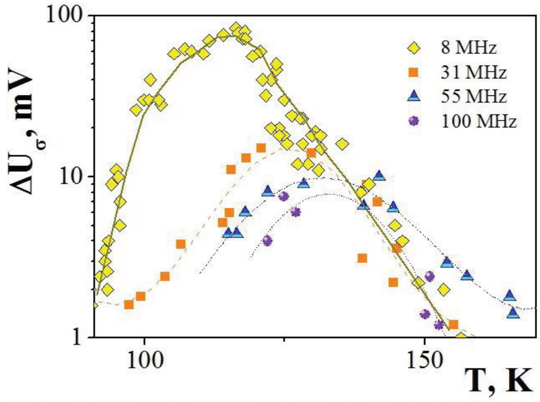

Fig. 6. The "pulse ΔU_σ" amplitude vs. temperature under the US pulses action at 8, 31, 55 and 100 MHz frequencies.

3.5. Amplitude characteristics of acoustoconductivity

Fig. 7 shows the oscillograms of the induced voltage of acoustoconductivity as function of the amplitude of applied US pulse at 133 K. As can be seen, pulse rise and fall edges remain the same at acoustoconductivity amplitude growth at a given temperature.

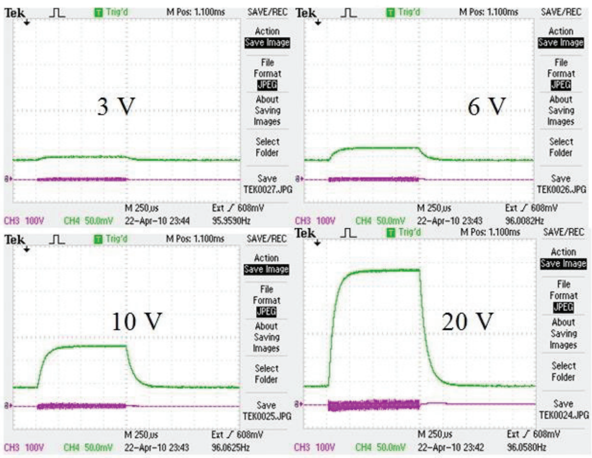

Fig. 7. Oscillograms of the amplitude-time dependencies at 133 K. Top – the pulse of the acoustic conductivity voltage, below – HF pulse applied to the piezoelectric transducer.

For the "peak" considered above, which corresponds to divacancies that determine the acoustoconductivity of the *n*-Si-*Fz* sample in the temperature range $90 \div 160$ K, the results of the study of its amplitude dependence are presented in Fig. 8. Taking into account that at a fixed temperature $T = 133$ K (Fig. 7), $U_\sigma^0 = kI_0 / en_0\mu_0$ and $U_\sigma^{US} = kI_0 / en_{US}\mu_{US}$, the relative acoustic-induced changes in the concentration of free electrons $n_{US}/n_0 = U_\sigma^0 / U_\sigma^{US}$ were calculated. It was assumed that $\mu_{US}(T) \approx \mu_0(T)$ since the predominant mechanism of electron scattering at the temperatures $T > 125$ K is determined by lattice oscillations; hence the mobility $\mu(T)$ is practically independent of ultrasound [1, 6].

Fig. 8 shows that the magnitude of the pulsed acoustic-induced changes in the concentration of conduction electrons $\Delta n_{US} = n_0 - n_{US}$ is directly proportional to ultrasound intensity W_{US}:

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

where the coefficient of proportionality α, which characterizes the effectiveness of US action, is also temperature-dependent (Fig. 8, inset).

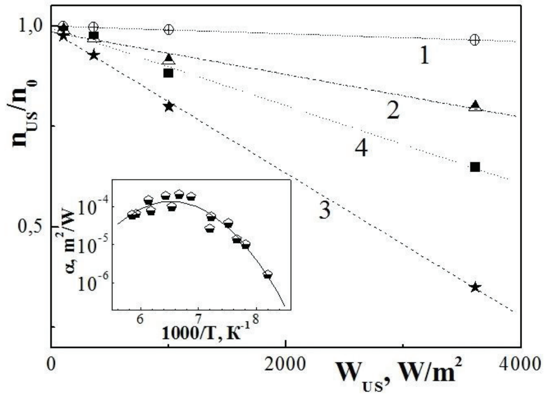

Fig. 8. Amplitude characteristics of relative changes in electron concentration at different temperatures vs. ultrasound intensity for different temperatures: 1 – 128 K; 2 – 133 K; 3 – 142 K; 4 – 163 K. Inset: the temperature dependence of the efficiency coefficient of US action α.

Note, that the maximum acoustically induced change $\Delta n_{max} \approx 2 \cdot 10^{18}$ m^{-3} is achieved at $T \approx 150$ K.

IV. Conclusions

1. The inverse change in the electrical conductivity σ_{US} in γ-irradiated *n*-Si-*Fz* exposed to pulsed US was firstly detected. The effect is determined by the deformation change in the distribution of the metastable defect concentration between different configuration and energy states and the corresponding redistribution of the carrier concentration at these levels.
2. It is established that the temperature dependencies of the rise (τ_i) and fall (τ_d) times of pulse acoustic-induced changes σ_{US} are described by Arrhenius equations; the slope of the experimental characteristics $\tau_{i,d}(T)$ is determined by the activation energy of the corresponding process.
3. The "multi-peak" nature of the temperature dependence of the acoustoconductivity voltage amplitude, which testifies to the predominant contribution of different acoustic-active centers to the acoustoconductivity of the sample at different temperature ranges, is revealed.
4. The possibility of acoustic spectroscopy of metastable defects in semiconductors using the pulsed mode of US loading is shown.

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