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Effect of Ultrasonic Treatment on the Generation Characteristics of a Semiconductor–Glass Interface

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Abstract—It is demonstrated that the temporal variation of the rate of the surface generation of charge carriers at a semiconductor–glass interface can be determined by measuring the kinetics of capacitance relaxation in the semiconductor–glass–metal structure. Ultrasonic treatment of the semiconductor–glass interface decreases the absolute value of the surface generation rate and modifies its temporal dependence.

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Semiconductor–dielectric interfaces, which are involved in most of the modern semiconductor devices, are the most sensitive elements with respect to various external factors. The influence of external factors on the properties of such interfaces has been extensively studied. However, these investigations were mostly devoted to the silicon–silicon dioxide interface, which is most widely used in semiconductor electronics [1–3]. The silicon–silicon dioxide system is not free of disadvantages, which are manifested in some applications. For a relatively high temperature ($T = 900$–1200°C) necessary for the formation of SiO_2 layers leads to a redistribution of impurities in depth of a semiconductor substrate (which is related to a difference in their segregation coefficients [4]) and to the appearance of thermoinduced defects in the semiconductor [5–7].

Using low-melting lead-doped borosilicate glasses, it is possible to obtain dielectric coatings with high insulation characteristics by means of a relatively simple technology. In this context, it is important to study the nature of processes taking place under the action of external factors in lead-doped borosilicate glass coatings. The effects of thermal, mechanical, field, and radiation treatments on the properties of single-crystalline silicon–glass interface have been studied in sufficient detail [8–11].

This Letter presents the results of investigations of the effect of ultrasonic treatment (UST) on the carrier generation characteristics of a semiconductor–multicomponent glass interface. The carrier generation and recombination characteristics of interfaces are most frequently studied using the method of isothermal relaxation of a metal–dielectric–semiconductor (MDS) structure during the formation of an inversion layer [12, 13]. This method is based on the monitoring of the temporal variation of the capacitance of an MDS structure (to which a constant inversion voltage V_1 is applied) under the action of voltage pulses (V_2) corresponding to an increase ($V_2 > V_1$) in the charge of the inversion layer.

The temporal variation of the MDS structure capacitance can be described by the following equation [13]:

$$\frac{1}{C^3(t)}\frac{dC(t)}{dt} = \frac{Sn_\mathrm{i}}{C_\mathrm{d}N_\mathrm{m}e\varepsilon_0} + \frac{n_\mathrm{i}}{C_\mathrm{d}N_\mathrm{m}\phi}\left(\frac{C_\infty}{C(t)} - 1\right)\frac{1}{C_\infty}, \quad (1)$$

where $C(t)$ is the instantaneous value of the capacitance, C_d is the capacitance of the dielectric layer, C_∞ is the capacitance of the MDS structure at the end of relaxation, N_m is the impurity concentration in the semiconductor, n_i is the electron concentration in the intrinsic semiconductor, τ is the lifetime of thermogenerated charge carriers, S is the rate of the surface generation of carriers, e is the relative permittivity of the semiconductor, and ε_0 is the permittivity of vacuum. In deriving Eq. (1), it was assumed [13] that the surface generation rate was constant and did not change in the course of capacitance relaxation.

An analysis of the process of capacitance relaxation in the MDS structure (based on an n-type semiconductor) led to the following conclusions. If the density of surface states is uniformly distributed in the energy interval under consideration, the number of electrons generated per unit time is constant. Therefore, the surface generation rate in this case is constant as well.

However, the distribution of surface states over the bandgap width, as a rule, has a rather complicated shape [9–11]. If the pulsed voltage increase corresponds to an energy region with inhomogeneous distribution of the density of surface states, then the surface generation rate is time dependent. In order to confirm these considerations, we have measured $C(t)$ for an Al–n-Si–glass–Al structure using the method proposed by Zerbst [13]. The lead-containing borosilicate glass had the following composition (wt %): SiO_2, 33; PbO, 40; B_2O_3, 24; Al_2O_3, 2; Ta_2O_3, 1. The initial composition was fused on ⟨100⟩-oriented single crystal silicon plates (KEF-15 grade) at $T = 700°C$ for $t = 30$ min, followed by annealing at $T = 400°C$ for $t = 10$ min.

The experimental approach consisted of measuring the $C(t)$ relaxation curves of the MDS structures before and after the UST. The samples were treated by longitudinal ultrasonic waves with a frequency of f = 2.5 MHz at a power density (intensity) of P = 0.5 W/cm^2 for t = 15 min. The ultrasound was transferred from a transducer (driven by an oscillator) to the sample via a liquid medium. The capacitance relaxation was measured in the dark at a frequency of $F = 150$ kHz in the temperature interval $T = 30$–$50°C$ upon switching the voltage from $V_1 = 4$ V to $V_2 = 22$ V.

The experimental $C(t)$ curves were processed in terms of Eq. (1), from which the surface generation rate S_0 was determined under the assumption that it is time-independent. Then, using the known initial value of the MDS structure capacitance and solving Eq. (1) with respect to the time, we obtain the following relation:

$$t = \frac{B - AC_\infty}{B^2 C_\infty}\ln(C) + \frac{AC_\infty - B}{B^2 C_\infty}\ln(BC - BC_\infty - ACC_\infty) - \frac{1}{BC} + \eta, \quad (2)$$

where

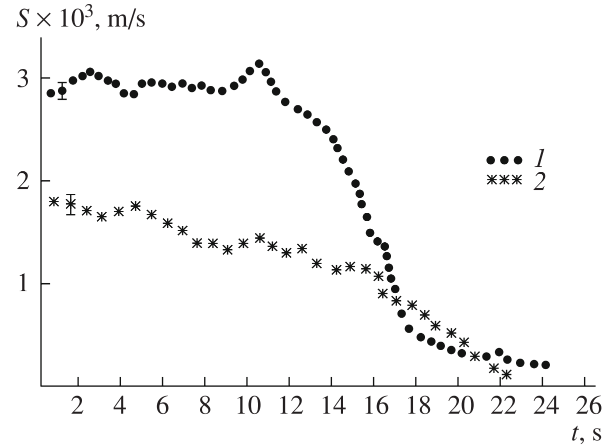
$$A = \frac{Sn_\mathrm{i}}{C_\mathrm{d} N_\mathrm{m} e e_0},$$

$$B = \frac{n_\mathrm{i}}{C_\mathrm{d} N_\mathrm{m}},$$

and η is the integration constant given by the following expression:

$$\eta = -\frac{(B - AC_\infty)}{B^2 C_\infty}\ln(c) + \frac{(AC_\infty - B)}{B^2 C_\infty}\ln(BC_n - BC_\infty - ACC_\infty) + \frac{1}{BC_n}. \quad (3)$$

Using Eqs. (1)–(3) and the experimentally values of $C(t)$, C_d, C_∞, $\mathrm{N_m}$, S, and τ, we can determine $t = t(C/C_\infty)$ and eventually calculate $S = S(t)$. The experimental curves of the surface generation rate $S(t)$ at $T = 32°C$ are presented in the figure. As can be seen, the UST leads to a general decrease in the surface generation rate in the MDS structure and renders the $S(t)$ curve smoother as compared to that prior to the control (unirradiated) one. Taking into account that the distribution of surface states over the bandgap width of silicon upon the UST changes insignificantly (in contrast to the case of MDS structures based on p-type silicon with a SiO_2 layer [14]), we may conclude that the UST of the metal-glass–semiconductor structures leads to a rearrangement of stressed valence bonds at the semiconductor–glass interface with the simultaneous increase in the cross section for the trapping of electrons localized at these bonds.



Experimental curves of the surface generation rate $S(t)$ measured at $T = 32°C$ for (*1*) control (unirradiated) and (*2*) ultrasonically treated Al–n-Si–glass–Al structures.

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