MODELING OF A-DLTS SPECTRA OF MOS STRUCTURES

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Summary Acquisition of basic characteristic of defects has become possible through a wide class of measurement techniques which probe the interface, the near interface, as well as the bulk of semiconductor. Results presented here are based essentially on the acoustic version of Deep Level Transient Spectroscopy (A-DLTS) measurements. This method is based on the acoustoelectric response effect observed at the interface. The A-DLTS uses the acoustoelectric response signal (ARS) produced by MOS structure interface when a longitudal acoustic wave propagates through a structure. The ARS is extremely sensitive to external conditions of the structure and reflects any changes in the charge distribution connected with charged traps. The temperature dependence of ARS after bias voltage step application is investigated and the activation energies and some other parameters of traps at the insulator – semiconductor interface are determined. The results obtained form Arrhenius plots of A-DLTS spectra of selected MOS structures are compared with results obtained from modeling of A-DLTS spectra using theoretical model.

1. INTRODUCTION

The interface states in metal – insulator (oxide) – semiconductor (MIS (MOS)) structures have been investigated for more than thirty years using many useful experimental techniques. One of the most important methods is DLTS originally developed in 1974 [1] with some modification (charge version Q-DLTS [2], constant capacitance version CCDLTS [3], acoustic version A-DLTS [4, 5]). The A-DLTS version is high-frequency ultrasonic method based on analysis of acoustoelectric response signal (ARS) of the MOS structure after applied bias voltage steps to the structure at various temperatures that reflects relaxation processes in both semiconductor and interface layer. It was namely found, that the acoustoelectric signal produced by MOS structures strongly depends on the bias voltage applied to the structure and reflects any changes in the space charge distribution due to the external condition changes [5].

2. THEORY

The basic principle of A-DLTS technique consists in utilization of the ARS produced by MOS structure interface when a high frequency acoustic longitudal wave traverses this. The amplitude of the acoustoelectric response can be written in the form

$$U_{ac} = U_i \frac{p_0}{K_i} + U_s \frac{p_0}{K_s} = \frac{Q}{C_i}\frac{p_0}{K_i}\left(1 + \frac{C_i}{C_s}\frac{K_i}{K_s}\right), \quad (1)$$

where U_i and U_s are the voltages on insulator and the equivalent semiconductor capacitance, p_0 is the acoustic pressure amplitude, K_i and K_s are the elastic moduli, C_i and C_s are the capacitances of insulator and space charge region in semiconductor, Q is the accumulated charge. Taking into consideration for the simplification that $K_i \approx K_s$, we can express the Eq. (1) in the form

$$U_{ac} = \frac{Q}{C}\frac{p_0}{K_i}, \quad (2)$$

where C is the total capacitance of the structure.

When a reverse bias voltage U_g is applied to the MOS structure so that the structure is in the deep depletion then for a short time a forward biased injection pulse is superimposed that results in filling of the interface states with majority carriers. A new non-equilibrium depletion condition is established after the filling pulse and due to the thermal emptying of the interface states the accumulated charge and simultaneously the capacitance of the structure is changed. The time development of the ARS after an injection bias pulse reflects changes in the charge distribution in the interface region very sensitively and so reflects relaxation processes associated with the thermally activated emission of excited carriers. It was found that the ARS follows the accumulated charge behavior over the capacitance one [6]. For the MOS structure capacitance as the equivalent capacitance of the series-connected capacitance of the dielectric C_i and depletion layer C_s the transient charge can be expressed then as follows

$$Q(t) = \frac{qwN_t}{2}\left(\frac{C_i}{C_s + C_i}\right)\exp\left(-\frac{t}{\tau}\right), \quad (3)$$

where q is the electronic charge, w is the depletion region width, N_t is the total concentration of investigated centers and τ is the relaxation time.

Using the previous relations (2) and (3) the measured acoustoelectric response signal amplitude for the discrete level can be given by

$$U^0_{ac}(t) = \frac{qwN_t}{2C_s}\frac{p_0}{K}\exp\left(-\frac{t}{\tau}\right) = U_0\exp\left(-\frac{t}{\tau}\right). \quad (4)$$

Including the regime of small-signal excitation, the A-DLTS output signal for the rate window (RW) $\Delta t = t_2 - t_1$ takes the form

$$\Delta U^0_{ac} = U^0_{ac}(t_1) - U^0_{ac}(t_2) = U_0\left(\exp\left(-\frac{t_1}{\tau}\right) - \exp\left(-\frac{t_2}{\tau}\right)\right) \quad (5)$$

where τ is the time constant of the acoustoelectric response delay. Note that Eq. (5) is accurate if the

trap could be refilled to its equilibrium occupancy before each bias voltage step ΔU. Evidently, with the rate window Δt and correspond τ_{max} (for the Lang's method $\tau_{max} = (t_2 - t_1) / \ln(t_2 / t_1)$, the $\Delta U_{ac}{}^0(T)$ (5) peak should appear at the temperature $T = T_{max}$, when the relaxation time is equal to the time constant of emission process ($\tau = \tau_{max}$).

The reciprocal value of τ gives the emission rate which for electrons can be expressed by the relation

$$e = 1/\tau = \sigma_n \langle v_{th} \rangle N_c \exp\left(-\frac{E_a}{k_B T}\right), \qquad (6)$$

were σ_n is the capture cross section, $\langle v_{th} \rangle$ is the thermal velocity, N_c is the effective density of states at the bottom of conduction band and $E_a = E_c - E_T$ is the trap activation energy related to the bottom of conduction band. Applying the appropriate equations for $\langle v_{th} \rangle$ and N_c [5], we can write for the relaxation time in the case of electrons

$$\tau^{-1} = \gamma_n \sigma_n T^2 \exp\left(-\frac{E_a}{k_B T}\right), \qquad (7)$$

were γ_n is constant.

Using the A-DLTS technique based on computer-evaluated isothermal transients and correlation procedure with higher order on-line filters and rectangular weighting function [6], the activation energies E_a and corresponding capture cross-section σ_n of traps can be determined from Arrhenius type dependence $\ln(\tau_{max} T_{max}{}^2)$ versus $1/T_{max}$.

Another method for determining the basic parameters of traps at the insulator – semiconductor interface is the modelling of measured spectra [7]. With several trapping centers being present, $U_{ac}{}^0(t)$ is composed of corresponding components

$$U_{ac}^0(t) = U_{i0} + \sum_{j=1}^{n} U_{j0} \exp\left(-\frac{t}{\tau_j}\right), \qquad (8)$$

where U_{i0} is instantaneous acoustoelectric response of the device and the second term on the right hand of side Eq. (8) is the excess acoustoelectric response due to charging (discharging) the n traps which are capturing (emitting) by the rate $e_j = \tau_j^{-1}$. We can consider that only

$$\tau_j = \tau_{j0} \exp\left(\frac{E_{aj}}{k_B T}\right) \qquad (9)$$

undergoes changes upon scanning the device temperature T.

Using the Eq. (8) and Eq. (9), respectively Eq. (5) for discrete levels we can model the measured A-DLTS spectra for the various rate windows Δt and the activation energies E_a determined from this modelled spectra expressed by the relation

$$\Delta U_{ac}^0(T) = \sum_{j=1}^{n} U_{j0} \left(\exp\left(-\frac{t_1}{\tau_j}\right) - \exp\left(-\frac{t_2}{\tau_j}\right) \right) \qquad (10)$$

can be compared with the activation energies calculated from Arrhenius plots.

3. EXPERIMENTAL

The block diagram of the experimental setup is illustrated in Fig. 1. The computer with analog-digital (ADC) and digital-analog converter (DAC) was used to trigger the system, to generate the injection bias voltage pulse and moreover to record the isothermal transients of the ARS. The bias voltage U_g and the bias voltage step ΔU with pulse width of 200 ms filling traps was generated and then applied to structures. The longitudal acoustic waves of frequency 14.5 MHz were generated by $LiNbO_3$ transducer acoustically bonded to the quartz rod buffer. The MOS structure worked as a receiver transducer, too. The box-car integrator was using for selection of the ARS produced by a structure after detection in the receiver. Then the signal was registered and stored by computer and DAC using technique based on computer-evaluated transients measured at fixed temperatures.

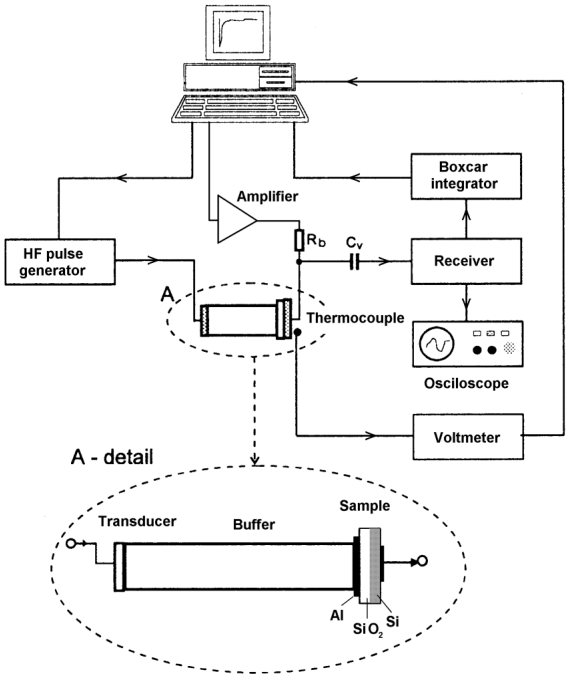

Fig. 1. Experimental arrangement of A-DLTS measurements in block scheme

The investigated Al-SiO_2-Si MOS structures were fabricated on n-type Si substrates with (100) surface orientation and 1 - 20 Ωcm resistivity. The aluminium electrodes were deposited on oxide layer of the thickness of 4nm (sample 1) and 80nm (sample 2) respectively.

4. RESULTS

All characteristics were obtained at the temperature range 160 – 360 K. The basic data were received from sampled acoustoelectric isothermal transients $U_{ac}(t)$ in response to a bias voltage step ΔU at point t_1 and $t_2 = 2\ t_1$ (or $t_3 = 4\ t_1$, $t_4 = 8\ t_1$, …, $t_n = 2^{n-1}\ t_1$) respectively ($t_1 = 0.015$ s, $t_2 = 0.030$ s, $t_3 =$

0.060 s, t_4 = 0.120 s, t_5 = 0.240 s, t_6 = 0.480 s, t_7 = 0.960 s and t_8 = *1.92 s*).

Fig. 2 represents the typical ARS transients measured at various temperatures and the same bias voltage U_g = *-0.2 V* (ΔU = *0.5 V*) for sample 1.

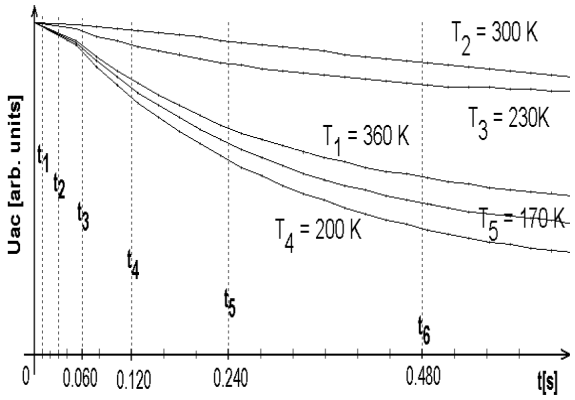

Fig. 2. The ARS transients at various temperatures:T_1 = 360 K, T_2 = 300 K, T_3 = 230 K, T_4 = 200 K and T_5 = 170K

Fig. 3 shows the series of A-DLTS signals determined from the isothermal transients for various time constants.

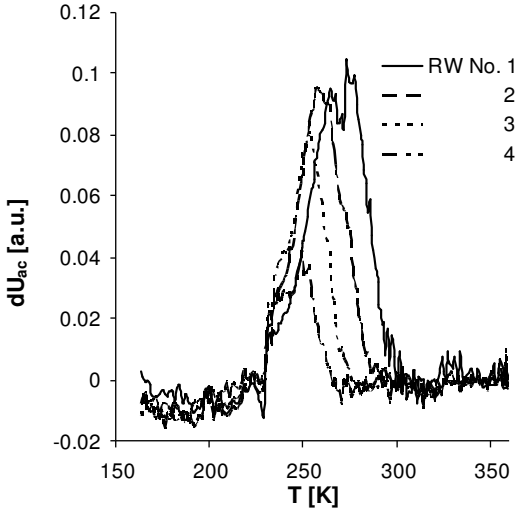

Fig. 3. A set of A-DLTS spectra of sample 1 measured at U_g = - 0.2 V, ΔU = 0.5 V calculated from isothermal transients for the relaxation times 9.13 ms (rate window No. 1), 18.4 ms (2), 36.8 ms (3) and 73.6 ms (4)

The Arrhenius plot (Fig. 4) was constructed using data from Fig. 3 and the activation energy of deep center at the insulator – semiconductor interface as well as corresponding capture cross-section was calculated. The obtained activation energy related to the bottom of conduction band E_a = $E_c - E_T$ = *0.37 eV* with the cross section $5.2x10^{-17}$ cm^2 corresponding to the bias voltage U_g = *-0.2 V*.

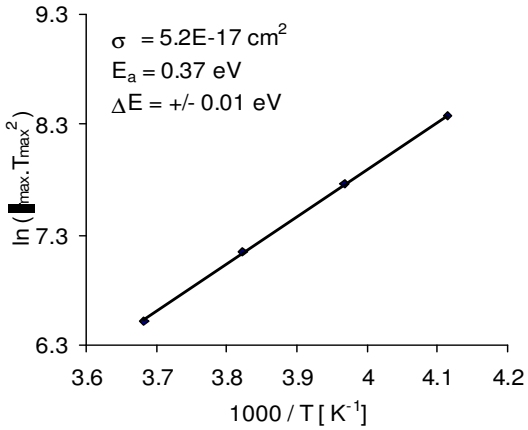

Fig. 4. Arrhenius plot constructed from the positions of the peak maxima of the A-DLTS spectra of sample 1

From A-DLTS spectra for various relaxation times of the sample 1 we also tried to find some information about traps at the insulator-semiconductor interface applying the mathematical methods of simulation. For that it was important to correlate this measured results with its equivalent obtained via an exponential analysis. Using the Eq. (10) for the discrete level we simulate the main peak of measured spectra (Fig. 3) for the point t_1 = 15 ms and t_2 = 30 ms (Fig. 5). We found the energy level E_a' = 0.39 eV, which is very close to the activation energy calculated from Arrhenius plot (Fig. 4).

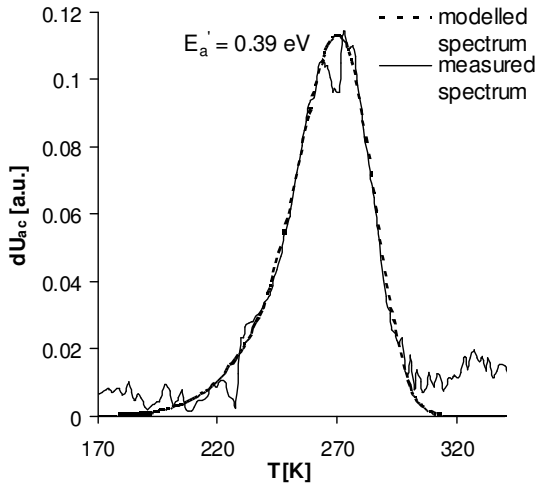

Fig. 5. The simulation peak of A-DLTS spectra of sample1 obtained for the relaxation time 9.13 ms

The Arrhenius plot constructed for the A-DLTS spectra of the sample 2 is illustrated in Fig. 6. The standard $\ln(T_{max}^2\tau_{max})$ versus *1/T* plot provided an activation energy E_a = *0.23 eV* related to the bottom of conductivion band with the calculated cross section $1.7x10^{-18}$ cm^2 corresponding to the bias voltage U_g = *- 3 V* (ΔU = *3V*).

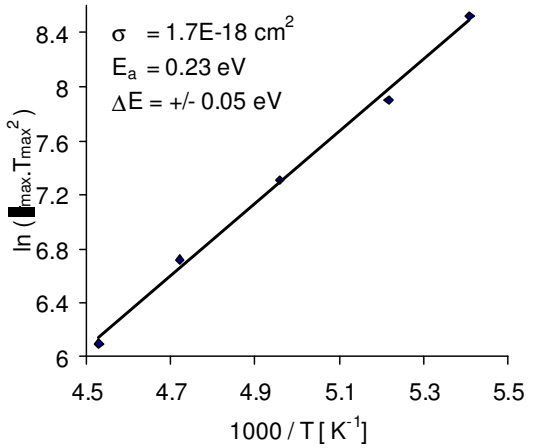

Fig. 6. Arrhenius plot constructed from the positions of the A-DLTS peak maxima of sample 2

Using the simulation we fit the dominant peak of A-DLTS spectra of the sample 2, too. Finally, let us inspect the correlated spectrum $\Delta U_{ac}^{0}(T)$ relevant to t_1 = 15 ms and t_4 = 120 ms (Fig. 7). Now, the dominant peak is characterized by $E_{a1}' = 0.28\ eV$ related to the bottom of conduction band. Another peak with activation energy $E_{a2}' = 0.39\ eV$ was observed, too. We can describe the whole measured A-DLTS spectrum as superposition of the modelled peaks. For that we can suppose another trap which couldn't be find using Arrhenius plots.

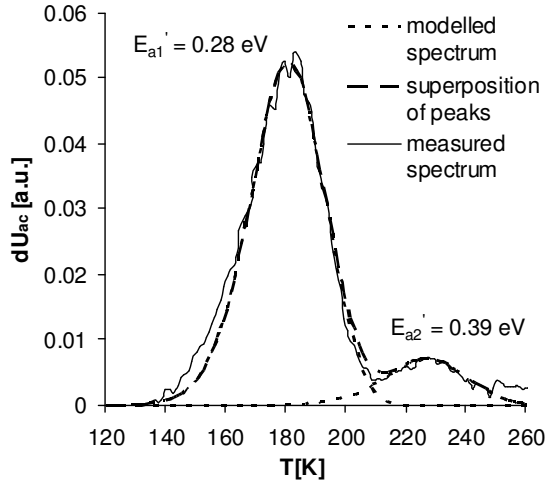

Fig. 7. The simulation peak of A-DLTS spectra of sample2 obtained for the relaxation time 36.8 ms

The obtained energy levels from mathematical modeling of measured A-DLTS spectra confirmed the interface states that are in a reasonable agreement with the results found by Arrhenius plots. But using modeling of A-DLTS spectra we can find and describe another traps at the insulator – semiconductor interface with low concentration.

5. CONCLUSION

The A-DLTS technique based on computer evaluation of transients of acoustoelectric response signal measured at fixed temperature with applying data compression algorithms seems to be an effective method for the investigation of the trap at the insulator-semiconductor interface in MOS structures.

We found some physical parameters of the interface states in Si(n)-SiO_2 MOS structures. Using simulation of A-DLTS spectra we identified the similar activation energies of the deep centers at SiO_2-Si interface as we calculated from Arrhenius plots.

Future study of the parameters of simulated peaks and applying of the several mathematical correlation methods should help us to find the other useful information about the interface states in MOS structures such as the interface state density and so on.

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