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PC OPERATED ACOUSTIC TRANSIENT SPECTROSCOPY OF DEEP LEVELS IN MIS STRUCTURES[1]

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A new version of acoustic deep-level transient spectroscopy (A-DLTS) is presented to study the traps at the insulator-semiconductor interface. The A-DLTS uses an acoustoelectric response signal produced by the MIS structure interface when a longitudinal acoustic wave propagates through a structure. The acoustoelectric response signal is extremely sensitive to external conditions of the structure and reflects any changes in the charge distribution, connected also with charged traps. In comparison with previous version of A-DLTS that closely coincides with the principle of the original DLTS technique, the present technique is based on the computer-evaluated isothermal transients and represents an improved, more efficient and time saving technique. Many tests on the software used for calculation as well as on experimental setup have been performed. The improved A-DLTS method has been applied for the Si(p) MIS structures. The deep-level parameters as activation energy and capture cross-section have been determined.

1. Introduction

Following the work of Lang [1], deep-level transient spectroscopy (DLTS) has become most powerful technique commonly used for the characterization of semiconductor and semiconductor structures because it reveals information about several characteristics of electrically or optically active defects present in such materials. Several useful variants of DLTS have been developed [2-5] and many attemps to improve the defect resolution capabilities of DLTS introducing different types of transient analysis procedure have been reported [6-11].

Recently two different acoustic modifications of transient spectroscopy were introduced. The former, acoustoelectric deep-level transient spectroscopy (AE-DLTS) uses a nonlinear acoustoelectric interaction between the surface acoustic wave (SAW) electric field and the free carriers in semiconductor generating as the result of the interaction

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the transverse acoustoelectric voltage (TAV) across the semiconductor. Transient measurements of the rise and fall times of the resulting TAV signal have been used to study charged traps [12,13]. The latter acoustic technique, called acoustic deep-level transient spectroscopy (A-DLTS) uses an acoustoelectric response signal (ARS) observed at the interface of the semiconductor structure when a longitudinal acoustic wave pulse propagates through the structure. The ARS very sensitively reflects any changes in the space charge distribution due to the trapped charge after an excitation pulse and its transient has been used to characterize the deep levels [14,15].

In this paper we describe a new version of the A-DLTS technique, the principle of which consists in the computer evaluation of isothermal ARS transients. The new system of A-DLTS transient analysis represents a significant improvement over the previous A-DLTS version and time saving due to the computer evaluation of isothermal transients applying the data compression algorithm, that allows a single transient to be sampled at different sample rates permiting several decades at time constants to be observed in one thermal scan. We applied the improved technique to Si(p) MIS structures and obtained results are discussed.

2. Experimental details

The basic principle of the present measurement procedure is the same as the previous version of the A-DLTS technique and consists in the utilization of the ARS produced by MIS structure when a high frequency acoustic wave traverses this. The ARS is proportional as in the case of electromechanical capacitance transducer to the voltage and relative change of capacitance induced by the acoustic wave and for the case of thin planar structure [14] is given by

$$U_{ac} = \frac{Q}{C_i}\frac{p}{K_i} + \frac{Q}{C_w}\frac{p}{K_w} = \frac{Q}{C}\frac{p}{K} \tag{1}$$

where C_i,C_w are the capacitances of insulator and space charge region, respectively, C is the total capacitance of the structure, Q is the accumulated charge, p is the acoustic pressure and K is the elastic modulus assuming that elastic moduli of the structure layers K_i and K_w are approximately equal. When a quiescent reverse bias voltage U_G is applied to the MIS structure so that the structure is in 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. After the filling pulse a new non-equilibrium depletion condition is established and due to the thermal empting of the interface states the accumulated charge and simultaneously the capacitance of the structure is changed. As the ARS is able to reflect changes in the charge distribution in the interface region very sensitively the time development of the ARS after an injection bias pulse reflects relaxation processes associated with the thermally activated emission of excited carriers.

From the acoustoelectric investigation of the MIS structures [14] we can conclude that the ARS follows the accumulated charge behavior over the capacitance one. By presenting the MIS structure capacitance as the equivalent capacitance of the series-connected capacitance of the dielectric and depletion layer the transient charge can be found in the form [3]

$$\Delta Q(t) = -\frac{qwN_t}{2}\left(1 + \frac{C_w}{C_i}\right)^{-1} e^{-\frac{t}{\tau}} \tag{2}$$

where q is the electronic charge, w is the width of depletion region, N_t is the total concentration of the investigated centers and τ is the relaxation time. Using the previous relations (1) and (2) the ARS amplitude transient can be given by

$$U^o_{ac}(t) = \frac{qwN_t}{2C_w}\frac{p_o}{K}e^{-\frac{t}{\tau}} \tag{3}$$

where p_o is the acoustic pressure amplitude. Comparing with the previous version of A-DLTS that uses the analysis of the acoustoelectric transient signal after an injection pulse similarly as in the original DLTS developed for the capacitance transient [1,2] by means of a set of emission rate windows, the present technique is based on the computer-evaluated transients measured at fixed temperatures [16]. The measurement technique allows a single transient to be sampled at up to 8 different sample rates permitting 3 to 4 decades of time constants to be observed in one thermal scan. Because it is necessary to analyze only enough data to obtain the required information , specifically, the time constants of the transient at each temperature, a data compression algorithm was applied. For example if 32 767 data points are taken at a base sample rate 4 kHz, one could store the first 256 points, then extract another 256 points from the same transient by 128 averages of 2 points each, followed by extracting 512 points by 128 averages of 4 points each, etc. This storage scheme allows the transient to be observed at 4 kHz for 64 ms, 2 kHz for 128 ms, 1 kHz for 256 ms etc. up to 31.25 Hz for 8.192 s. Thus many decades of time can be sampled from the same transient without permanently storing or processing redundant data. Sixteen transients were averaged per temperature. The temeperature is then decreased to next temperature and the process is repeated. Additionally,the hard disk memory required to store such data does not need exceed 2.3 kbytes per temperature comparing with 64 kbytes without data compression.

The software for the calculation has been thoroughly checked by performing a series of evaluations on computer-generated simulated transients. The purpose of this was to test the capability of the program to properly reveal the emission rates of the transients and the resolution of the method. The computer-evaluation of the observed isothermal ARS transients could be provided by both using Lang's original scheme [15] and correlation procedure with higher order on-line filters and rectangular weighting function [7]. Using the well known relation expressing the temperature dependence of the relaxation time characterizing the acoustoelectric transient [14] the activation energies and corresponding capture cross-sections could be determined.

The block diagram of the experimental setup is shown in Fig. 1. The computer with analog-digital converter (ADC) and digital-analog converter (DAC) was used to trigger the system, to generate the injection bias voltage pulses as well as to record the isothermal transients of the ARS. The both quiescent bias voltage Ug and the pulse voltage $-Ug$ with pulse width of 100 ms filling traps completely applied to the structures were generated by computer and ADC. A longitudinal ultrasonic wave of frequency 13.2 MHz

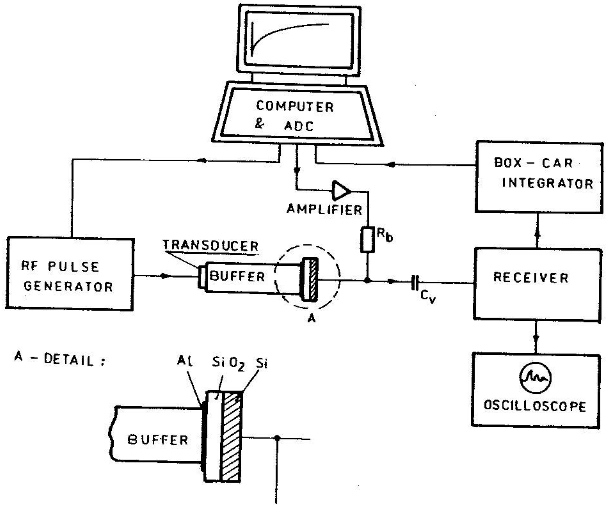

Fig.1. Experimental arrangement of A-DLTS measurements in block diagram

was generated by $LiNbO_3$ transducer acoustically bonded to the quartz rod buffer on the other side of which the investigated MIS structure was bonded. The MIS structure worked as a receiver transducer. The ARS produced by the structure after detection in the receiver was selected by the box-car integrator and consequently registered and stored by computer and DAC using the above described procedure. The schematic illustration of the time arrangement of some experimental parameters corresponding to the isothermal transients scanning process is given in Fig.2.

3. Experimental results

The above described procedure of the new A-DLTS version was applied to well-know Si MIS structures. The investigated Al-SiO_2-Si MIS capacitors were fabricated on p-type Si substrates with (100) surface orientation and 8.3 to 8.7 Ωcm resistivity. The oxide layers were grown by CVD technique to the thickness of 80 nm on which aluminium was deposited using a vacuum evaporation. The detailed capacitor configuration is illustrated in Fig.1.

Fig.3 shows typical ARS transients measured at various temperatures and the same bias voltage conditions. These transients contain only one exponential component corresponding to 0.3 eV trap. Fig.4 represents a series of A-DLTS signals calculated from the isothermal ARS transients for various time constants (sampling times) using the correlation analysis with first order filter. Fig.5 shows the series of A-DLTS spectra for different bias voltages applied to the Si MIS structure and the same time constant . As indicated both by the $C-U$ and $U_{ac}-U$ measurements by increasing U towards negative values the SiO_2-Si interface region passes from deep depletion to nearly accumulation state. As is shown in Fig.5, peaks of the A-DLTS spectra are shifted to lower temperature with the increasing bias pulse voltage, that is characteristic features of the interface states [2].

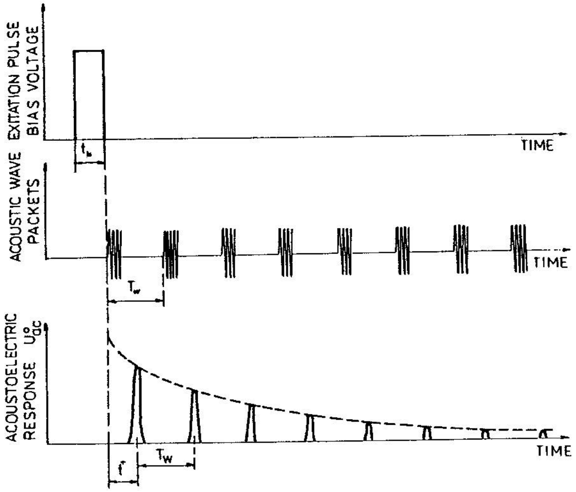

Fig.2. Schematic illustration of the time arrangement of some experimental parameters, t_b is the bias voltage pulse width, $f_w = 1/T_w$ the rate frequency and t^+ the transverse time through the buffer rod.

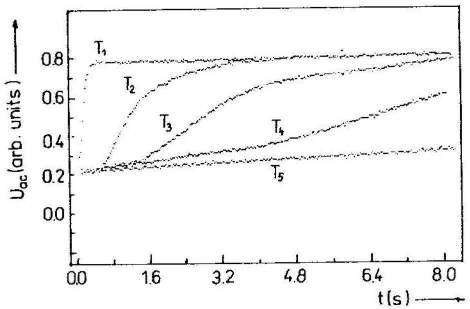

Fig.3. Typical ARS transients at various temperatures, T_1 = 300 K ,T_2 = 270 K ,T_3 = 250 K, T_4 = 230 K and T_5 = 200 K

The activation energies and corresponding capture cross-sections were determined from the Arrhenius plots (Fig.6) constructed for the individual peaks from the A-DLTS spectra at different biases using the relation expressing the temperature dependence of the relaxation time characterizing the acoustoelectric transient. The obtained energy levels 0.47, 0.30, and 0.25 eV above the valence band edge with the cross sections $4.8x10^{-17}$, $1.0x10^{-19}$, and $1.5x10^{-20}cm^2$ corresponding to the bias voltages 2, 4, and

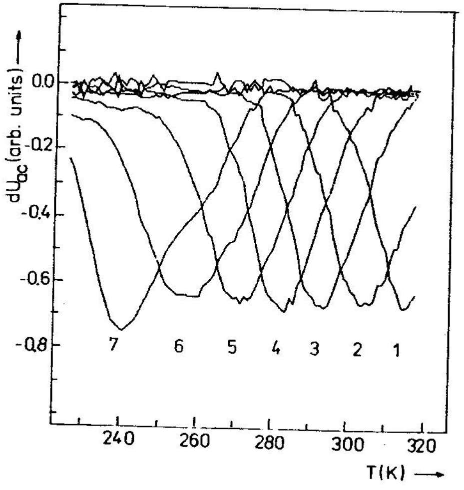

Fig.4. A set of A-DLTS spectra calculated from isothermal transients for various relaxation times, from 18.4 ms (1) to 1.178 s (7) measured at $U_G = 4$ V

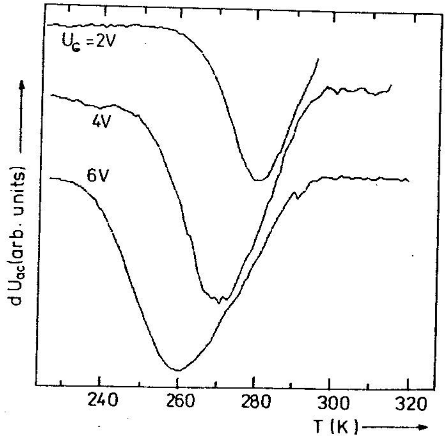

Fig.5. A-DLTS spectra obtained from ARS transients as a function of bias voltage applied to gate of the MIS structure for $\tau = 0.2945s$

6V, respectively, confirms the energy distribution of the interface states that is in a reasonable agreement with the many results found by DLTS and other techniques. The DLTS peaks above the valence band have been observed in many samples made at different gate electrodes and with different oxidation conditions or irradiated and the energetic positions of the interface states beginning at 0.25 eV above the valence band edge agree well with the values obtained by those techniques and are attributed to

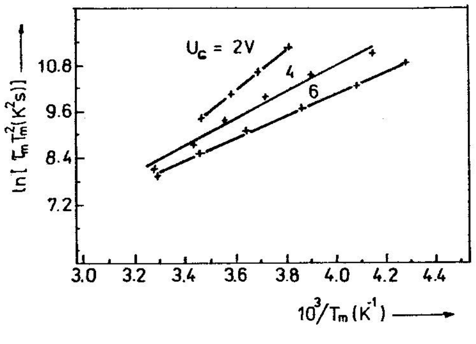

Fig.6. Arrhenius plots constructed and calculated from the positions of the peak maxima using the A-DLTS spectra at different biases U_G= 2,4, and 6 V

various defects [16-23]. The measurement in the inversion state ($U_g = 9$ V) showed the energy level 0.60 eV with corresponding capture cross-section 4.8x10^{-13}cm^2. As the A-DLTS signal originates from the capture of electrons from the valence band into the trap level (hole emission process) it appears as the negative signal in A-DLTS spectra [14], we believe that observed levels are deep acceptor levels.

4. Conclusions

The newly improved A-DLTS technique based on the computer-evaluation of the transients of the acoustoelectric response signal measured at fixed temperatures applying the data compression algorithmus presented here has been proved an effective and succesful method for the investigation of deep levels in MIS structures. The physical parameters of the interface states in Si(p) MIS structures have been determined using the new version of the A-DLTS technique. The evidence of the energy distribution of deep states at $SiO_2 - Si$ interface has been obtained. Future work should involve demonstrating the technique's ability to minimize the errors associated with transient analysis and explore trap defects at higher resolutions yet to be obtained by previous technique.

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