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A NEW IMPROVED PROCEDURE FOR THE DETERMINATION OF SURFACE TRAP LEVELS' DENSITY USING TRANSVERSE ACOUSTOELECTRIC VOLTAGE MEASUREMENTS*

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ABSTRACT

Acoustoelectric measurements have been extensively used for characterizing semiconductor's properties. Recently a theoretical calculation of the acoustoelectric interaction in the semiconductor was presented, in which the additional effect of a current density due to traps at the semiconductor/insulator interface was considered. Using this calculation a modified procedure for the determination of interface or surface states' density was developed, extending the use of TAV versus applied bias V_B measurements to materials with high defect density. The experimental TAV_{EX}-V_B curve is compared with the theoretical expression of the TAV versus surface potential (TAV_{th}-V_S) plot calculated assuming no interface traps. The difference between the two curves is attributed to the presence of interface traps. Measurements have been performed on Si and GaAs samples, and results are in good agreement with more conventional techniques.

I. INTRODUCTION

Nondestructive acoustoelectric measurements have been extensively used to characterize the electrical properties of semiconductors. Various techniques have been developed using Transverse Acoustoelectric Voltage (TAV) measurements. These range from TAV versus bias voltage [1,2] (TAV-V_B), to one and two beam spectroscopy [3,4], temperature [5] and transient time measurements [6]. Important semiconductor parameters such as majority carrier density, type and mobility, interface and fixed oxide charge density, deep-level cross section and activation energy, and excess carrier generation and recombination lifetime can all be determined using TAV measurements. TAV-V_B measurements have been in the past used for characterizing semiconductor/insulator interfaces. Various results have been published especially on Si/SiO_2 [7], HgCdTe/ZnS [8] and GaAs/(Ga_2O_3, As_2O_3) [1] interfaces.

The density D_{it} of interface trap level's can be determined by monitoring the change of the TAV amplitude as a function of applied bias voltage. The principle of this measurement is similar to that of the widely used Capacitance-Voltage (C-V) technique. Variation of the surface potential (V_S) due to the applied bias voltage (V_B) is determined from experimental TAV-V_B curves by comparison and normalization with the theoretical expression of the TAV-V_S curve. The difference between the two curves is attributed to the stretchout effect caused by interface states.

The theory to evaluate the theoretical TAV-V_S curve was developed mostly to explain experimental results on Si/SiO_2 samples, i.e. a semiconductor structure which generally shows a low density of surface or interface states [9,10]. Consequently the presence of interface traps was assumed negligible in the theoretical calculations of the TAV amplitude. Recently a new boundary condition was introduced [11,12] in which the presence of such traps is taken into account, by means of a current density at the interface. As a result, the calculated value of the TAV amplitude decreases as the surface recombination increases. Using this calculation, the procedure for the determination of interface or surface states' density was modified, extending the use of TAV versus applied bias measurements to material with high defect density. This modification is outlined in section II.

In section III we will discuss some interesting measurements performed on Si and GaAs samples. In particular, in one set of experiments performed on a silicon sample, it was possible to change the D_{it}-E_{it} curve as a function of applied pressure. These changes are related to the presence of Si-dangling bonds at the Si/SiO_2 interface [13,14]. The D_{it}-E_{it} curves obtained in this experiment were utilized to calculate the theoretical TAV_{th} vs V_S curves. Furthermore the D_{it}-E_{it} curve obtained for a GaAs sample with TAV measurements was compared with the one obtained with C-V measurement. All presented results seem to confirm our belief that TAV measurements are particularly sensitive to the presence of deep-trap levels in the midgap range of the semiconductor.

II. MODIFIED INTERFACE STATES' DENSITY MEASUREMENT

Acoustoelectric measurements in the separate medium structure utilize Surface Acoustic Waves (SAW) delay lines,

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as shown in the experimental setup in fig. 1. A small window is opened by a photolithographic process on an aluminum film deposited on the surface of the $LiNbO_3$ crystal. The semiconductor under test is placed on top of the window, which constitutes the interaction region. Interaction of the SAW rf electric field with the free carriers in the semiconductor gives rise to a DC acoustoelectric current. At open circuit conditions a voltage can be detected at the back surface of the semiconductor as TAV. This voltage is monitored by a Digital Oscilloscope and a Lock-in analyzer, the acquired data are stored and processed by a IBM PC computer. The variation of the steady state trap population under the influence of the radio frequency (rf) electric field is one of the mechanisms to be considered in order to correctly interpret TAV experimental results [15]. Briefly carriers are captured by traps during one half of the rf cycle and emitted during the other half. Due to the nonlinearity of carrier modulation inherent in the acoustoelectric interaction these two processes have different rates, resulting in a change in the trapped surface charge and in the development of a current density at the semiconductor/insulator interface. The presence of such current density has been considered as a new boundary condition in the theoretical calculation of the acoustoelectric interaction in the semiconductor [11,12]. It can be shown that the theoretical value of the TAV amplitude, TAV_{th}, is proportional to the surface conductivity of the semiconductor and inversely proportional to the surface recombination velocities for electron and hole [12]. If we define as TAV_o the former theoretical expression available in literature [9], in which the current density at the interface was not considered, we can express TAV_{th} as:

$$TAV_{th} = TAV_o \cdot K_{it} \tag{1}$$

and:

$$K_{it} = \frac{1+\omega^2R^2}{\left|1+\frac{V_{SAW}}{\omega}\left(\frac{S_n}{D_n}+\frac{S_p}{D_p}\right)+j\omega R\right|^2} \tag{2}$$

where: $\omega = 2\pi f_{SAW}$; f_{SAW} is the frequency and V_{SAW} the speed of the SAW in the material; D_n, D_p are the diffusion constant for electron and hole, respectively; and S_n, S_p are the surface recombination velocity for electrons and holes, respectively. For the description of the parameter R see reference [9].

As it can be easily seen from eq. 2 , in the case in which S_n and S_p are small, K_{it} is approximately one. Hence we can consider K_{it} as an attenuation term introduced in the theoretical expression of the TAV, in order to properly evaluate the effect of interface traps. The effect of K_{it} on the TAV-V_S theoretical curve is shown on fig. 2. The TAV amplitude of a p-type silicon sample is plotted versus the surface potential V_S, with the net trap density N_t as a parameter. The carrier concentration is assumed to be 10^{15} cm^{-3} and a single trap level is located 0.4 eV from the conduction band. The surface recombination velocities S_n and S_p were calculated as follows:

$$S_n = C_n N_t(1-f(E_{it})) \tag{3a}$$

$$S_p = C_p N_t f(E_{it}) \tag{3b}$$

where C_n and C_p are the capture coefficients for electrons and holes respectively, and $f(E_{it})$ is the Fermi-Dirac distribution calculated at the trap energy [21]. In the calculation shown in fig. 2, C_n and C_p were assumed to be 10^{-9} cm^3 sec^{-1}. As shown, the shape of the TAV-V_S plot changes as the trap density increases. Note that the trap density must be above 10^{12} cm^{-2} in order to have a sharp variation of the TAV_{th}-V_S curve from the TAV_o-V_S curve.

A procedure for the evaluation of the D_{it}-E_{it} curve from TAV measurements has already been presented in the literature [1]. That procedure utilized the previous calculations for the acoustoelectric interaction in the semiconductor and thus the term K_{it} was not considered. Hence the TAV amplitude was assumed to be only proportional to the semiconductor's conductivity at the interface. In this case, since interface trap occupancy varies with the applied bias, the density of states is evaluated from the distortion of the shape of the TAV-V_B curve.

The equation that relates the density of states' D_{it} with the measured TAV voltage is:

$$\frac{dTAV_{EX}}{dV_B} = \left(\frac{C_{TA}}{C_{TA}+C_{SC}+qD_{it}}\right)\cdot\frac{dTAV_{th}}{dV_S} \tag{4}$$

where C_{TA} is the coupling capacitance per unit area and C_{SC} is the space charge capacitance per unit area [17]. A detailed description of the procedure used to evaluate C_{TA} is given in ref. 16. TAV_{th} is the theoretically calculated value of the TAV amplitude while TAV_{EX} is the experimentally obtained value. The interface states' density is obtained by comparing the experimental and theoretical TAV curves. The two curves are normalized, and the variation of V_S relative to a change in V_B is calculated. By knowing the surface potential at different TAV amplitudes, the density D_{it} can be estimated from the derivative of surface potential V_S versus the applied voltage V_B:

$$D_{it} = \frac{C_{TA}}{q}\left[\left(\frac{dV_S}{dV_B}\right)^{-1}+1\right]-\frac{C_{SC}}{q} \tag{5}$$

The effect of interface traps on the TAV-V_B curves cannot be restricted to the stretchout of the curve along the applied bias axis, but also the contribution of the traps to the TAV amplitude must be considered in order to properly evaluate D_{it}. By considering more carefully eq. 4, it can be seen that the value of D_{it} is proportional to the stretchout of the TAV-V_B curve and if the relative surface potential is evaluated, then eq. 5 still holds.

A precise determination of the surface potential and thus of the energy E_{it} of the surface trap, cannot be done in a straightforward manner, since the TAV_{th}-V_S curve is function of D_{it} by means of the attenuation term K_{it}.

An iterative routine was used in order to evaluate the D_{it}-E_{it} curve. Its block diagram is shown in fig. 3. Briefly the V_S vs V_B plot is evaluated by normalizing and comparing the TAV-V_B and the TAV_{th}-V_S curves. The D_{it}-E_{it} curve is then calculated using eq. 5. Initially K_{it} is set to one for all values of surface potential. Once the D_{it}-E_{it} plot is evaluated K_{it} is calculated using eq. 2. In this case S_n and S_p are given by:

$$S_n = \int C_n(\xi) D_{it}(\xi)(1 - f(\xi)) d\xi \tag{6}$$

$$S_p = \int C_p(\xi) D_{it}(\xi) f(\xi) d\xi \tag{7}$$

The integrals are extended over all band-gap. The values utilized for C_n and C_p were either experimentally determined from other measurements or extracted from literature [18]. Once the variation of K_{it} as a function of the surface potential V_s is calculated, the new curve TAV_{th}-V_s is obtained and a new iteration is performed. After few iterations, successive D_{it} plots converge to what is believed to be a more accurate determination of the interface states' density. Results of measurements performed on Si and GaAs samples are discussed in the next section.

III. EXPERIMENTAL RESULTS AND DISCUSSION

In the previous section it has been stated that the value of D_{it} is proportional to the stretchout effect, while the correct determination of the energy E_{it} is directly related to a precise determination of K_{it}. An experimental proof of this statement is given by the results shown in fig. 4. A TAV-V_B measurement was performed on a Si/SiO_2 structure with a large density of interface states. The relative D_{it}-E_{it} curve was evaluated with the old and new procedures. The difference in the two consists in the evaluation of the K_{it} coefficient, and, as it can be easily seen in fig. 4, it results in a shift of the evaluated position of the trap. Furthermore, as expected, the value of D_{it} is the same in both cases. The error in the determination of the position in energy of the trap level is $\sim$ 45 meV, a value comparable with the resolution of C-V measurements. A larger difference is obtained for measurements performed on compound semiconductors or materials with a larger number of surface defects.

On another Si/SiO_2 sample, by means of an applied pressure, it was possible to vary the D_{it}-E_{it} curve [13]. The relative TAV-V_B curves obtained with different values of pressure are shown in fig. 5, with $P_1 < P_2 < P_3 < P_4$. A very interesting phenomenon occurs in this case. As the pressure is increased the negative minimum of the TAV curve decreases in its absolute value, as a result of an increasing attenuation due to the presence of traps. But for the positive part of the curve the effect is opposite, in this case as the pressure is increased, the TAV amplitude also increases. The effect of pressure on the Si/SiO_2 structure is to vary the interaction distance of the Si-dangling bonds with the nearby atoms [13], resulting in an increase of D_{it} for a specific value of energy, E_{it} - E_V = 0.6 eV, as it can be seen in fig. 6. These experimental results match quite accurately some of the theoretical models for the Si/SiO_2 interface already present in literature [14]. The possibility of a direct comparison of our experimental results with theory seems to offer a verification of the theory itself and a confirmation of the particular accuracy and resolution of the new procedure. The D_{it}-E_{it} curves plotted in fig. 6 were utilized for the calculation of K_{it}. The relative TAV_{th}-V_S plots are shown in fig. 7. Please note that in the calculation of the TAV_{th}-V_S plots of fig. 7 the stretchout effect due to the presence of traps is not considered, being it evaluated only when we calculate the relation between V_S and V_B. It is evident the similarity between these curves and the ones obtained experimentally, shown in fig. 5. As the pressure increases, the negative part of the TAV_{th}-V_S curve is attenuated, while the positive part increases. This is due to the fact that as the trap level at E_{it} - E_V = 0.6 eV increases in density, the effect on the TAV amplitude of traps of higher energy is minimized. Again this can be considered an experimental evidence of the accuracy that can be obtained with this new procedure.

The last experiment presented was performed on an undoped GaAs sample with carrier concentration n $\sim$ 1.4 x 10^{13} cm^{-3}, with thermally grown oxide. TAV and C-V measurements were performed, and the resulting D_{it}-E_{it} plots are shown in fig. 8. Values obtained for D_{it} are in good agreement with those already present in literature [19,20]. Due to the nonuniformity of the bias field within the interaction window, values of D_{it} calculated at the band edges with our techniques can be less accurate. Nevertheless the accuracy of the TAV measurement in the midgap range is very high, making this technique very useful for the determination and study of deep trap levels.

CONCLUSIONS

A procedure for the determination of interface or surface states' density utilizing TAV measurements was presented. The procedure is somewhat similar to C-V measurements. TAV-V_B measurements have been performed on Si and GaAs samples, showing the good accuracy and resolution of the new procedure. This technique is particularly sensitive to the presence of interface or surface states in the midgap range, and thus it is extremely useful for the determination and study of deep trap levels.

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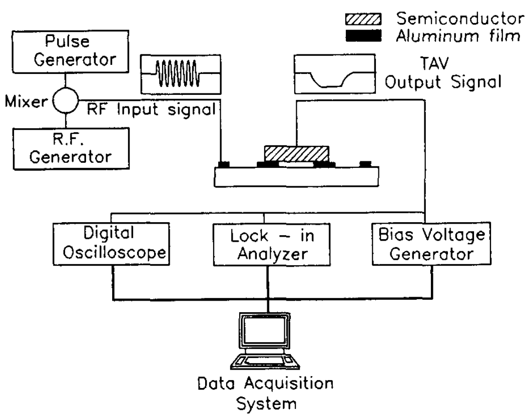

Fig. 1 Experimental setup for TAV measurements using the separate- medium structure.

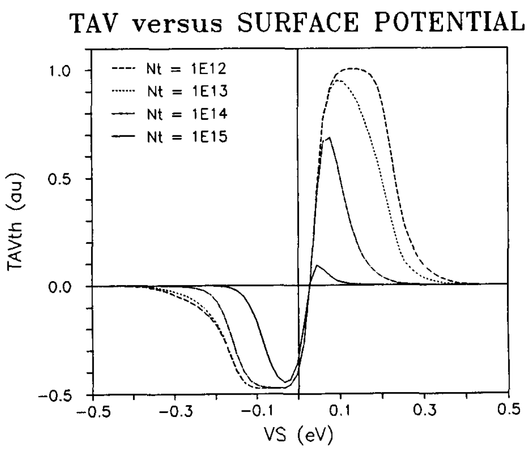

Fig. 2 Theoretical TAV_{th} - V_S curve plotted as a function of the interface trap density N_t.

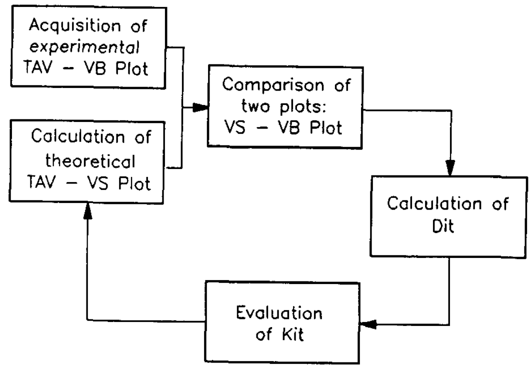

Fig. 3 Block diagram of the new procedure for the determination of interface trap density using TAV measurements.

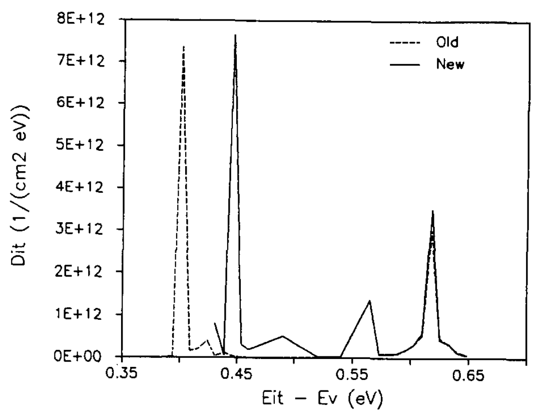

Fig. 4 D_{it} - E_{it} curves for Si samples obtained with the old and new TAV procedures.

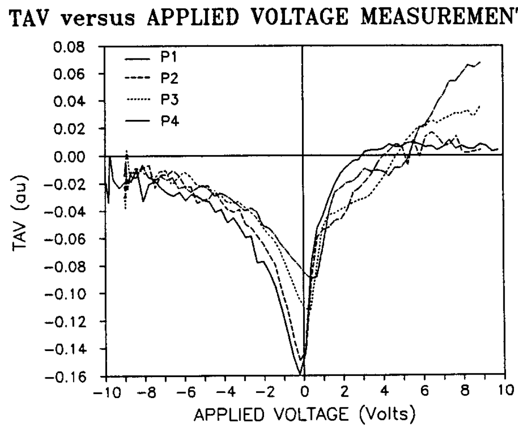

Fig. 5 Experimental TAV-V_B curves obtained for different values of applied pressure ($P_1 < P_2 < P_3 < P_4$).

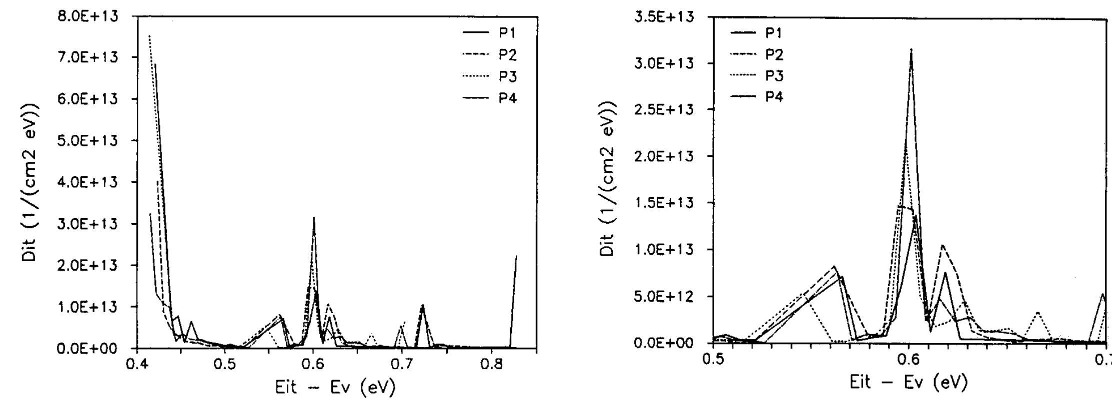

Fig. 6 Relative D_{it} - E_{it} plots calculated from TAV-V_B curves obtained for different values of applied pressure.

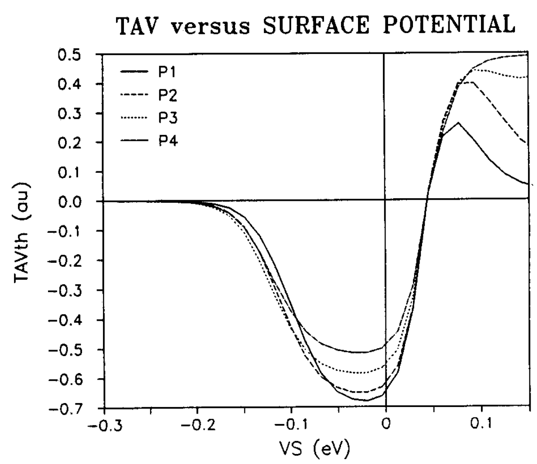

Fig. 7 Calculated TAV_{th} - V_S plots obtained using the D_{it} - E_{it} data of fig. 6.

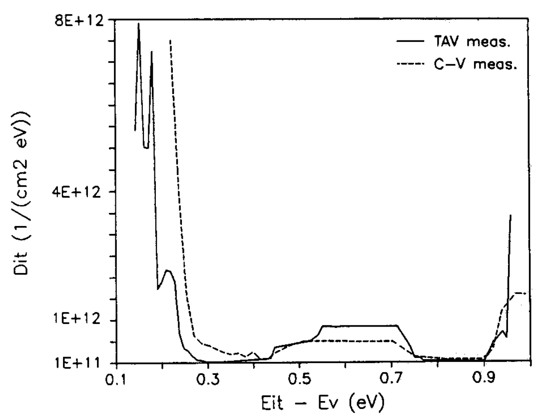

Fig. 8 D_{it} - E_{it} plots evaluated for a GaAs sample with TAV and C-V techniques.