ACOUSTO–ELECTRIC STUDY OF INTERFACE TRAPPING DEFECTS IN GaAs EPITAXIAL STRUCTURES

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A new acousto–electrical method making use of transient transverse acousto–electric voltage (TAV) to study solid state structures is reported. This voltage arises after a surface acoustic wave (SAW) generating the signal is switched off. Related measurements consist in detecting the shape of transient voltage and its spectral and temperature dependence. Both theory and experiment show that this method is an effective tool to characterize trapping centers in the bulk as well as at surfaces or interfaces of epitaxial semiconductor structures.

Key words: acousto-electric, trapping center, epitaxial structure.

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I. INTRODUCTION

Different methods are known to study crystal defects and deep levels in semiconductors in solid state physics. Most of them, including modern Scanning Tunneling Microscopy techniques, allow to characterize surface defects. At the same time multilayer and epitaxial semiconductor structures are strongly influenced by defects [1–3] which can be located at the interfaces between epilayers and substrate. Up to now no appropriate experimental methods exist to characterize these interface defects. Recently some publications reported the transient acousto–electric effect in semiconductors with defects [4–6]. Transient transverse acousto–electric voltage (TAV) generated in semiconductors has already been used in the past [7, 8], but this using has not been aimed to interface defect characterization and has not included corresponding acousto–optical measurements.

If the TAV method is applied some difficulties of interpretation of the experimental results have to be surmounted. The point is that the TAV amplitude strongly depends on several parameters, among them the influence of piezoelectric field strength E_v on local centers has to be mentioned. To avoid these difficulties we propose to measure the transient TAV signal just after the excitation pulse has to be switched off.

II. THEORY

A. MECHANISMS OF THE TAV ORIGIN

TAV is one of the manifestations of ultrasonically activated redistribution of the electrical charges in semiconductors. It is generated across layered systems consisting of piezoelectric and semiconducting materials due to a piezoactive surface acoustic wave (SAW) propagating along the piezoelectric. The SAW piezoelectric field penetrates inside the semiconductor causing charge carriers redistribution in the near surface region.

Two main mechanisms of generating the TAV effect exist in semiconductors. The first one, the so-called "concentration-effect" is due to the variable component of sample conductivity σ_v [9]. It is a result of electron concentration redistribution under the action of the variable piezoelectric field E_v of SAW. Hence, the direct component of the acousto–electric current is defined by:

$$j_0 = \overline{(\sigma_v E_v)}^{T_s} \tag{1}$$

where the averaging is carried out on the acoustic wave period T_s. The relaxation time of this TAV signal component is defined by the Maxwell's relaxation time τ_m of free charge carriers ($\tau_m = \epsilon\epsilon_0/\sigma_0$). Usually τ_m is much less than the period length of SAW. Therefore one can suppose that the relaxation time of the "concentration" TAV is equals to zero.

The second mechanism of the TAV generation is connected with semiconductor defects. The presence of the high–frequency SAW electrical field in the near surface region results in increasing the free charge carriers concentration. This, in turn, causes an increasing of the electrical charge captured on deep trapping levels, which are located either at interface or surface. As a result a direct electrical field perpendicularly to the sample surface is occurring. The amplitude of this "trap" TAV component is proportional to the excess concentration of the charge captured on trap levels [10].

Let us assume that the concentration of this charge is $\Delta n_t(t)$. For the simplest case of only one type of surface defects existing the transient TAV the signal can be written as

$$V_{ae}(t) = C_{ae}\Delta n_t(t) \tag{2}$$

where the coefficient C_{ae} depends on the sample parameters.

The voltage $V_{ae}(t)$ is connected to the relaxation of the electrical nonequilibrum charge trapped by surface defects. As far as the relaxation time does not depend on the particular mechanism of excitation of the electronic subsystem, it is possible to use a standard theoretical approach. The relaxation time τ is a function of trap level parameters. In the following we will consider an n-type semiconductor. Then it holds

$$\tau = \frac{1}{N_c V_T S_n} e^{E_t/kT} \tag{3}$$

where N_c is the density of states of the conductivity band, V_T is a thermal velocity of free electrons, k is Boltzmann's constant, T is temperature, E_t is an energy depth of the electronic trap level counted from the edge of conductivity band and S_n is an effective cross section of electron capture by trap centers.

Usually different types of trap levels exist. In this case the excess concentration Δn_{ti} of charge carriers captured by the i–type surface traps, can be written as:

$$\frac{d\Delta n_{ti}}{dt} = -\frac{\Delta n_{ti}}{\tau_i} + F_i(t) \tag{4}$$

where τ_i represents the characteristic relaxation time of the i–type level, $F_i(t)$ is an external force, which initiates the capturing by surface traps. The physical nature of the said force is connected with the piezoelectric field of SAW.

If the ultrasonic wave amplitude is modulated by rectangular pulses the external force $F(t)$ has the form

$$F(t) = \begin{cases} \text{const}, & 0 < t < T_p \\ 0, & T_p < t \end{cases} \tag{5}$$

where T_p is the pulse duration. The radio frequency impulses and the corresponding TAV pulse are presented on fig. 1. The TAV pulse shows a monotonous increase ("AB") and a monotonous decrease ("BC"). This shape of the TAV signal is typical for the trap component. The measurement of the shape of the transient TAV signal is made along "BC" in fig. 1. Note that in this case the external force vanishes ($F(t) = 0$) during our measurements. In this case the solution of equ. 4 is a decreasing exponential curve with the relaxation time τ_i. For different trap levels in the sample the TAV signal can be expressed by a sum

$$V_{ae}(t) = V_C + \sum_{i=1}^{N} V_i e^{-t/\tau_i} \tag{6}$$

where the times τ_i correspond to various i–levels. The summation has to be carried out over all existing traps in the near surface region. The coefficients V_i are proportional to the concentrations of the various trap types. The first term in equ. 6 presents the contribution of "very slow" levels in TAV. Such levels can exist in the A_2B_6–compounds or in MIS–structures with the relaxation times τ of about some hours while modern A_3B_5 epilayer structures do not have such slow levels. The signs of V_C and V_i are opposite for the electron and hole capture centers.

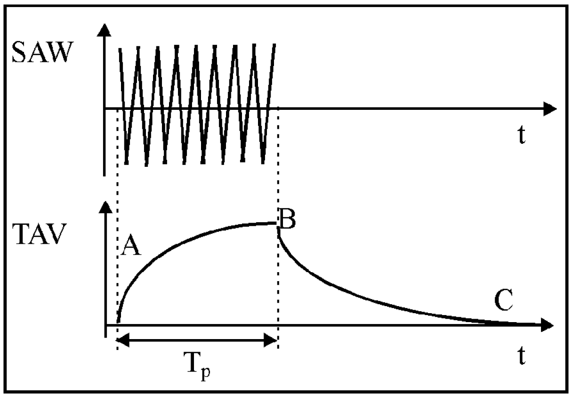

Fig. 1. Time dependence of input rf–voltage V exciting SAW and resulting TAV signal.

Thus, it is possible to determine the relaxation time τ by measuring the TAV signal. The transient TAV relaxation time τ is determined by the rate of thermal emission and trapping of charge carriers on the surface levels. In turn, the rate of reaching the thermodynamic balance between capture centers and conduction zones in a semiconductor structure depends on characteristic parameters of these centers, such as energy depth E_t and effective cross section S_n. The calculation of S_n by means of equ. 3 is successful only if the energy levels E_{ti} is known. For this reason additional information about E_{ti} and relaxation time τ_i is needed. It can be obtained by measuring the optical spectra of TAV signals or the thermal dependence of the TAV signal.

B. ANALYSIS OF TAV SPECTRAL DEPENDENCIES

The illumination of a semiconductor surface changes the distribution of free and captured charge carriers. Now we consider the influence of monochromatic illumination on various components of the TAV signal. For singly charged electron traps the process of electron capturing follows the equation

$$\frac{dn_t}{dt} = C_n n_s (N_t - n_t) - \beta_n n_{s0} n_t \tag{7}$$

where N_t is the concentration of the surface trap levels, n_t is the concentration of captured electrons; n_s is the concentration of the free charge carriers near the semiconductor surface and C_n and β_n are the probabilities for capturing and releasing charge carriers. The concentrations n_t and n_s deviate from their equilibrium values n_{t0} and n_{s0} under the influence of ultrasonic waves:

$$n_t = n_{t0} + \Delta n_t, \qquad n_s = n_{s0} + \Delta n_s. \tag{8}$$

The condition of the thermodynamic balance in the absence of the acoustic wave is

$$C_n n_{s0}(N_t - n_{t0}) - \beta_n n_{s0} n_{t0} = 0. \tag{9}$$

This equation provides the connection between the coefficients C_n and β_n . For the non–degenerate semiconductor we obtain:

$$\beta_n = C_n \exp((E_t - F_{s0})/kT) \tag{10}$$

where F_{s0} is the Fermi level at the surface. By substituting equs. 8 and 10 into equ. 7, we obtain:

$$\frac{d\Delta n_t(\lambda)}{dt} = C_n[(N_t - n_{t0}(\lambda))\Delta n_s \tag{11}$$

$$-(n_{s0}(\lambda) + \Delta n_{s0}(\lambda) + N_c e^{-E_t/kT})\Delta n_t(\lambda)].$$

Note, that Δn_t and Δn_s are averaged over the acoustic wave period. The acousto–electrical voltage component, which is connected to trapped charge, is proportional to the excess charge on the said traps ($V_{ae}{\sim}\Delta n_t$). Performing the measurement of the TAV signal and its shape under quasi–equilibrium conditions, it means:

$$\frac{d\Delta n_t}{dt} = 0. \tag{12}$$

Then, from equ. 11 we receive the following expression for the trap TAV component:

$$V_{ae} \sim \Delta n_t(\lambda) = (N_t - n_{t0}(\lambda)) \tag{13}$$

$$\times \frac{\Delta n_s(\lambda)}{(n_{s0}(\lambda) + \Delta n_{s0}(\lambda) + N_c e^{-E_t/kT})}.$$

The values n_{t0}, Δn_s and Δn_{s0} depend on sample illumination. However, if the photon energy $h\nu$ does not exceed the band gap energy E_G and direct electronic excitation from the valence band to conduction band does not occur, the changes of concentrations n_{s0} and Δn_{s0} are rather small. In this situation the TAV spectra is mainly determined by the first co-multiplier $(N_t - n_{t0}(\lambda))$ in equ. 13. At sample illumination with light photon energies exceede the value determined by equ. 14:

$$E_t = E_G - h\nu \tag{14}$$

the charge carriers transferring from the valence band to capture centers result in the growth of n_{t0}. Then the difference $(N_t - n_{t0}(\lambda))$ in equ. 13 decreases, and a minimum should be observed in the TAV spectrum. If several types of trap levels take part in the TAV signal formation, then several corresponding minima should be observed in the optical TAV spectrum.

C. ANALYSIS OF THE RELAXATION TIME TEMPERATURE DEPENDENCE

The value of an energy position of the deep trap levels E_t can also be obtained from the temperature dependence of the relaxation TAV time τ. This dependence can be obtained from equ. 3. The temperature dependence of N_c and V_T for the nondegenerate semiconductor is well-known: $N_c \sim T^{3/2}$, $V_T \sim T^{1/2}$. For attracting Coulomb center at room temperature $S_n \sim T^{-2}$ [11]. Therefore:

$$N_c(T)V_T(T)S_n(T) \simeq \mathrm{const}(T). \tag{15}$$

If this relation is not absolutly exact, the temperature dependence of expression (15) will be much weaker than the exponential dependence. Consequently, for deep levels ($E_t >> kT$) and small temperature changes the temperature dependence of $(N_c V_T S_n)$ can be neglected in equ. (3). Having two times τ_1 and τ_2 for two different temperatures T_1 and T_2, we can to calculate E_t by equ. (16):

$$E_t = \frac{kT_2 \ln(\tau_1(T_1)/\tau_2(T_2))}{(T_2/T_1) - 1}. \tag{16}$$

One can enhance the precision of E_t determination by using a plot of $\ln(\tau)$ on T^{-1}, if the experiments are done in some temperature range:

$$\ln(\tau(T)) = (E_t/kT) + \mathrm{const}(T) \tag{17}$$

The curves of these dependences are direct lines. The angles of the declination of these plots are set by the value of E_t. Thus it is possible to define the value of E_t for each trap level.

III. SAMPLES AND EXPERIMENTAL TECHNIQUE

We investigated three types of GaAs–samples. The first one labeled a GA–1 is the structures of the epi–layer n-GaAs on the n-GaAs substrate. They were achieved by an industrial vapor phase epitaxy method in the system Ga–$AsCl_3$–H_2. The substrate, 0.35 mm thick, was doped by Te with $N_{\mathrm{Te}} \approx (1 \div 2) \times 10^{18}\mathrm{cm}^{-3}$. The free carrier concentration of the epi–layers, doped by Te too, 6–9 microns thick for different samples, was $(0.6 \div 1.2) \times 10^{15}$

cm^{-3}. The second one labeled as GA–2 consists of a 400μm thick GaAs–substrate with a 1μm thick epitaxial layer of n-GaAs on it. The third sample labeled as GA–3 consists of the GaAs substrate and a 8μm thick epitaxial layer with electron concentration $n \sim 10^{14}$ cm^{-3}. GA–2 and GA–3 samples were fabricated by MOCVD process.

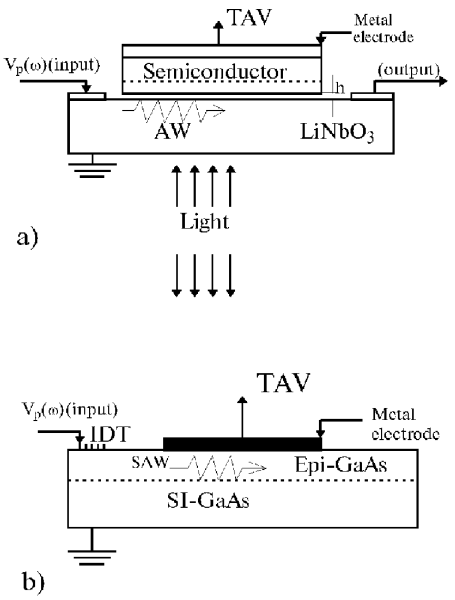

Fig. 2. Two versions of sample arrangements performing transient TAV measurements: a) separate medium configuration, b) integrated configuration.

The samples GA–1 and GA–2 were placed by the epitaxial layer on the lithium niobate plate. On this plate SAW of 6 MHz were excited. The TAV signal was picked up between a bottom ground electrode and a flat metal electrode attached on the upper surface of the GaAs sample as shown in fig. 2, a. This arrangement is very convenient because no special sample preparation is required and sample replacement is easy to do. For example, it is not necessary to form electrical contacts to the samples. As far as GaAs is a piezoelectric material, it can simultaneously play the role of the piezoelectric waveguide as shown in fig. 2, b (for GA–3). In this case SAW of 67 MHz are excited by means of an interdigital transducer deposited on the sample surface. The TAV signal was measured between the ground electrode and the aluminum film which has to be evaporated on the epitaxial layer.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. THE EXPERIMENTAL DEFINITION OF THE TRANSIENT TAV RELAXATION TIMES

The task of the subsequent mathematical procedure consists in finding out the values of V_i , τ_i and N from equ. 6. For this aim it is necessary to determine the number of effectively acting types of surface levels N. Therefore we have to analyze the plots $\ln(V_{ae})$ versus time. For $N = 1$ this dependence should be a straight line. Its slope gives the relaxation time τ. In the case of two or more exponential components this plot has a more complex form. The number of rectilinear sites on these curve corresponds to the number of trap centers. One can define characteristic relaxation times from the declination angles of these directs. In our experiments the values V_i and τ_i were estimated by the interpolation of the transient TAV signal (part "BC" in fig. 1) with the help of a special computer program which had found out the number of different type levels simultaneously. The data obtained from GA–2 show the occurrence of two exponential terms with the decay times of 2 and 12 ms. In fig. 3 the parts "ab" and "bc" of the curve 1 correspond to two types of traps having the relaxation times 2 and 12 ms, respectively. The experiments with the GA–3 sample show two different terms in total TAV signal corresponding to the two parts "ab" and "bc" of the curve 2 shown in fig. 3. We can distinguish two types of trapping centers having relaxation times of 4.5 and 22 ms at room temperature. Four local centers having relaxation times of 2.2, 1, 22 and 1.7 ms were also found in the samples GA–1 at room temperature.

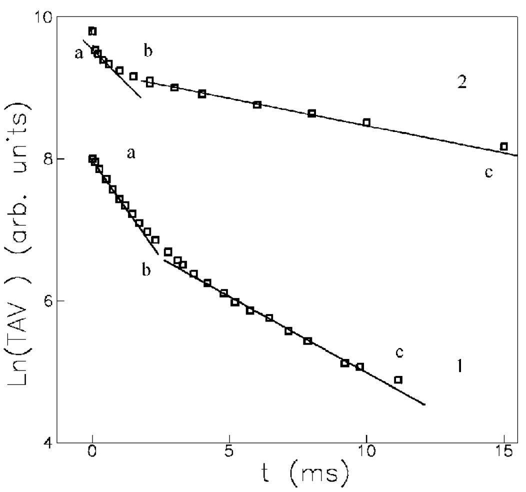

Fig. 3. Logarithmic plot of transient TAV signal versus time. 1 is plot for GA–2 and 2 is plot for GA–3. Parts "ab", and "bc" correspond to different types of trapping centers.

Additional measurements were carried out for a further identification of these trap centers and for the definitions of their parameters. The relaxation time of a transient TAV was measured at various temperatures in the GA–1 samples (see item 2.3). The samples GA–2 and GA–3 were used to measure spectral dependencies of a TAV signal (see item 2.2).

B. TEMPERATURE DEPENDENCES OF THE TRANSIENT TAV

The descending parts of the TAV signal for the GA–1 series at various temperatures are presented on fig. 4. We can see, that the TAV relaxation time decreases with the temperature increase. Our measurements were carried out in the temperature range of 294 to 330 K.

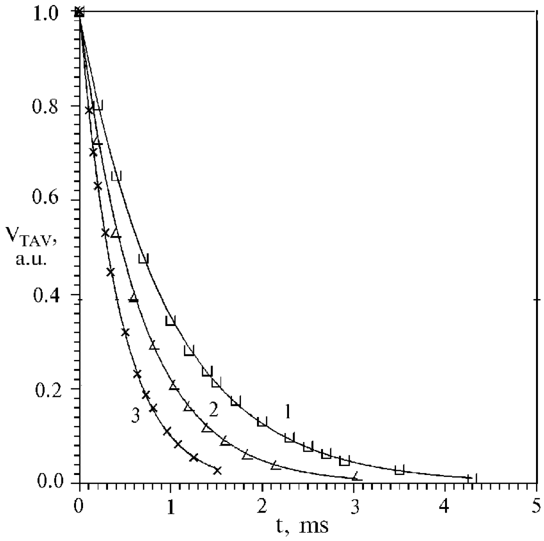

Fig. 4. Shape of the descending parts of the TAV signal at various temperatures for GA–1: 296 K (1), 305 K (2) and 318 K (3). Points — experimental data; curves — theoretical calculation by equ. (6).

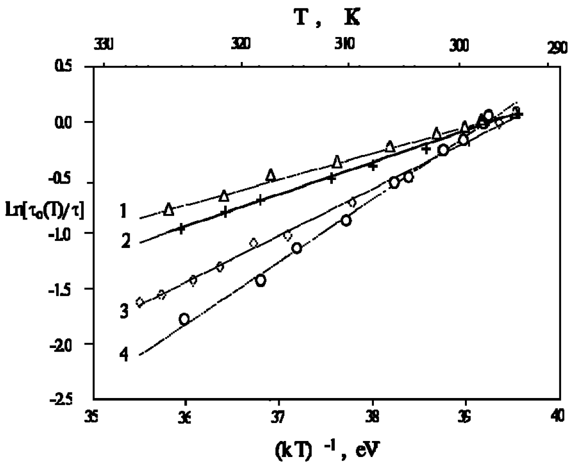

Fig. 5. Dependence of τ on T^{-1} (GA-1). At room temperature the relaxation time τ is equal to 2.2 ms for the plot 1, 1.0 ms plot 2, 22 ms plot 3 and 1.7 ms plot 4. The slops of plots 1, 2, 3 and 4 give four levels E_1, E_2, E_3, E_4, respectively.

The plots of τ on T^{-1} are shown on fig. 5. Practically they are direct lines, angles of declination of these lines give the trap level energy positions E_t. Knowing the characteristic relaxation times of the excess charge τ_i and the energy levels of the interface centers E_{ti}, we can calculate the effective capture cross section S_{ni} for these levels by equ. (3).

Thus, four deep levels were detected at the samples under study. They were designated as levels $E_{1,2,3,4}$. The characteristic parameters of the said centers are presented in the tabl. 1. The characteristics coincidence of the E_4 level and the data from literature [12] allows us to say that E_4 is electron center EL3. The configuration $\mathrm{As}_i V_{\mathrm{Ga}}$ is assigned with this level. Indeed, the excess of the interstitial arsenic (As_i) and the gallium vacancies (V_{Ga}) should be observed in the GaAs, doped by tellurium. Certainly, the tellurium interstitial (Te_i) can be significant at this case too. It is possible to conclude, that level E_1 is the EL17 center [13–15], E_3 being the EL5 center [14]. Level E_2 can be identified as the electron center EL6 [16]. All these levels deal with the vacancies of gallium (V_{Ga}) and arsenic (V_{As}) [13–16].

Samples	Level	Type	E_t, eV	τ, ms	S_n, cm^2
GA–1	E_1	EL17	0.23 ± 0.02	2.2 ± 0.2	0.7×10^{-18}
GA–3	E_1^*	EL17	0.20 ± 0.01	4.5 ± 0.4	1.5×10^{-19}
GA–1	E_2	EL6	0.29 ± 0.02	1.0 ± 0.1	1.6×10^{-17}
GA–1	E_3	EL5	0.42 ± 0.02	22 ± 2	1.4×10^{-16}
GA–1	E_4	EL3	0.56 ± 0.02	1.7 ± 0.2	4×10^{-13}
GA–2	E_4^*	EL3	0.54 ± 0.01	2 ± 0.03	2.5×10^{-13}
GA–3	E_5	EL4	0.48 ± 0.01	22 ± 1	2×10^{-15}
GA–2	E_5^*	EL4	0.48 ± 0.01	12 ± 1	4×10^{-15}

Table 1. Characteristics of interface trapping centers in epi-GaAs at room temperature.

C. EXPERIMENTAL SPECTRA OF THE TRANSIENT TAV

Also, for the determination of trapping level energy the optical spectra of transient TAV are investigated. A sample under investigation is illuminated with the monochromatic light in the range from 0.6 to 1.6 eV. Then TAV signal is separated for partial exponential components with different relaxation times τ_i with the help of a special computer program in general. Each such component is characterized by a certain value of partial amplitude V_i which varies during illumination. The said amplitudes V_i determines the contribution to a total TAV signal of i–type traps having relaxation time τ_i. This contribution reaches the minimum at the illumination of sample surface by monochromatic light with the photon energy equal $E_G - E_{ti}$, in accordance with formula (13). Thus a spectral position of the minimum in a spectrum of the i–partial amplitude $V_i(h\nu)$ determines the appropriate energetic level E_{ti}.

The spectra of partial amplitudes V_i are shown on fig. 6. The plots (1 and 2) are taken from the GA–2 sample for the relaxation times 12 and 2 ms, respectively. The minima on these curves correspond to the two types of deep levels at E_5^*=0.48 eV and E_4^*=0.54 eV below the conduction zone. The plots 3 and 4 are taken from GA–3 sample for the relaxation times 22 ms and 4.5 ms, respectively. The minima on plots 3 and 4 correspond to two types of deep levels at E_5=0.48 eV and E_1^*=0.20 eV below the conduction zone.

Now, knowing the energy positions of trapping centers and the related relaxation times, we can calculate the effective cross sections S_n for the capture of charge carriers by these trap centers. Below, characteristic defect parameters in the epitaxial GaAs structures under study are presented in the Table. The defect identification was done by comparing the energetic position with the literature data on deep levels in GaAs [12,13, 17–20]. One can see, that deep trap levels of the types EL3 and EL17 are detected both with the help of spectral research and measurements of the TAV relaxation times' temperature dependencies.

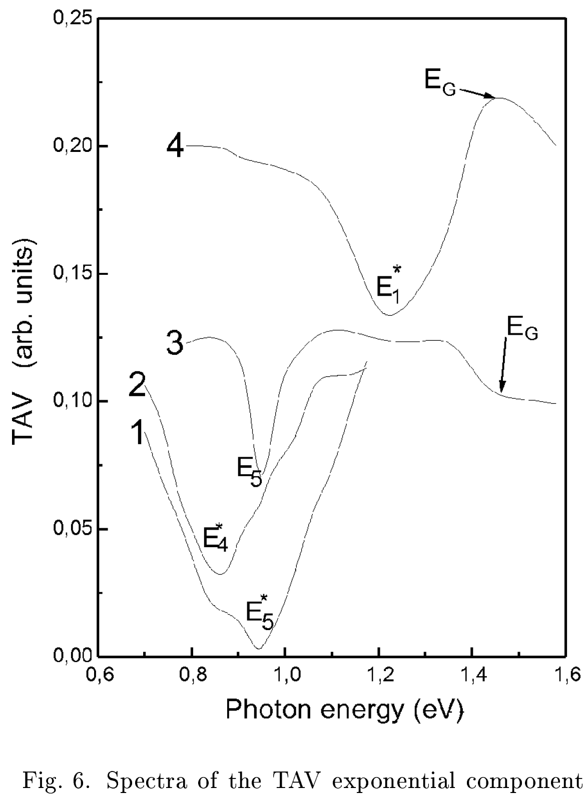

Fig. 6. Spectra of the TAV exponential component. 1 — τ = 12 ms (GA–1); 2 — τ = 2 ms (GA–2); 3 — τ = 22 ms (GA–3); 4 — τ = 4.5 ms (GA–2). The four minima labeled as E_1^*, E_4^*, E_5, E_5^* correspond to the three trapping centers detected in the samples under study. The band gap energy is marked by E_G.

The difference in values of relaxation times for the levels E_1, E_1^* and E_5 ,E_5^* in different samples can be explained as follow. The relaxation time of the captured charge is determined by two parameters — the energy depth E_t of the trapping center and its capture cross–section S_n. The said E_t depends on the atomic structure of the local defect and so does not vary from sample to sample. Conversely, the value S_n depends both on the type of trapping level and on the electrical properties of the semiconductor itself, including the configuration of electrical potential near the defect and its shielding by a free charge. Therefore the characteristic relaxation times for the same trapping levels, but varying on the manufacturing samples, can differ from each other.

V. CONCLUSIONS

The acousto–electric method can be advantageously applied for studying interfaces in modern epilayer semiconductor structures. The experimental data followed by the appropriate mathematical processing allow to estimate the characteristic relaxation time, energy position in the forbidden zone and the electron capture cross–section for each of these centers. By this approach we, for the first time, measured the relaxation times of trap centers.

Investigating the interface between the epitaxial GaAs–layers grown on the substrate by the MOCVD process and the chlorine vapor method we found five different types of trapping defects. They were identified as EL3, EL4, EL5, EL6 and EL17 centers. Their characteristics at room temperature are summarized in the Table.

The different GaAs centers are known to be observed in the samples, achieved by a different technique [13]. The coincidence of the level's parameters permit to conclude that levels EL5 and EL17 can be present in the epitaxial structures reached by the chlorine vapor method as well as by the MOCVD technique.

The method described can also be applied to the investigation of other semiconductor structures, including those based on the Si and A_2B_6 compounds.

Summarizing the obtained results we may conclude that the transient TAV technique is a reasonably simple and effective method for characterizing surface and interface trap centers.

VI. ACKNOWLEDGMENTS

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АКУСТОЕЛЕКТРИЧНЕ ДОСЛІДЖЕННЯ РІВНІВ ЗАХОПЛЕННЯ НА ІНТЕРФЕЙСІ ЕПІТАКСІЯЛЬНИХ СТРУКТУР GaAs

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Робота присвячена методові акустоелектричної релаксаційної спектроскопії глибоких рівнів. Поряд з теоретичним аналізом наведено результати його практичного застосування. Цей метод ґрунтується на вивченні спектральної та температурної залежностей поперечної акустоелектричної напруги, що виникає в п'єзонапівпровідниках при поширенні акустичної хвилі. Він дає змогу досліджувати глибокі рівні в забороненій зоні напівпровідників, що розташовані як безпосередньо на їхній поверхні, так і на межі поділу епішар–підкладка в епітаксіяльних структурах. Зокрема, можливим є визначення характерного часу релаксації заряду на цих рівнях, їхньої енерґетичної глибини залягання та площі поперечного перерізу захоплення носіїв. У роботі подано результати досліджень ряду епітаксіяльних структур на базі арсеніду галію, виготовлених за допомогою MOCVD технології та методу газофазової епітаксії. У цих структурах виявлено п'ять рівнів: EL3, EL4, EL5, EL6 і EL17 та визначено їхні параметри.